

Towards a measurement of CP violation in $\tau^\pm \rightarrow h^\pm \pi^- \pi^+ \nu_\tau^{(-)}$ using Belle II detector

*Vers une mesure de la violation de CP dans
 $\tau^\pm \rightarrow h^\pm \pi^- \pi^+ \nu_\tau^{(-)}$ avec le détecteur Belle II*

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direction de **Aurélien MARTENS**.

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Farah MAWAS

Composition du jury

Membres du jury avec voix délibérative

Achille STOCCHI

Professeur des universités, Université Paris-Saclay / IJ-
CLab

Président

John Michael RONEY

Professeur des universités, University of Victoria

Rapporteur & Examineur

Stephane MONTEIL

Professeur des universités, Laboratoire de Physique de
Clermont Auvergne

Rapporteur & Examineur

Emilie PASSEMAR

Maîtresse de conférences, Jefferson Lab & Indiana U.

Examinatrice

Titre : Vers une mesure de la violation de CP dans $\tau^\pm \rightarrow h^\pm \pi^- \pi^+ \bar{\nu}_\tau^{(\pm)}$ avec le détecteur Belle II

Mots clés : violation CP, lepton tau, nouvelle physique, Belle II, désintégrations hadroniques, pion

Résumé : Alors que la violation de la symétrie de charge-parité (CPV) a été mesurée dans le secteur hadronique dans différents canaux, aucune preuve significative de CPV n'a été trouvée dans le secteur leptonique. Il est donc particulièrement intéressant de rechercher la CPV dans les désintégrations du lepton tau étant donné qu'il peut se désintégrer en une variété de canaux hadroniques différents. En effet, des études théoriques suggèrent que les désintégrations hadroniques du tau pourraient présenter des effets de violation CP, mais seulement en présence de nouvelle physique. Parmi celles-ci, les canaux de désintégration en trois hadrons $\tau^- \rightarrow h^- h^+ h^- (\geq 0\pi^0) \nu_\tau$ sont particulièrement intéressants grâce à leurs résonances intermédiaires et leurs distributions angulaires.

Cette thèse présente une étude préparatoire de la violation CP dans la désintégration $\tau^- \rightarrow \pi^- \pi^+ \pi^- (\geq 0\pi^0) \nu_\tau$ en utilisant des données simulées par Monte Carlo et des données collectées par le détecteur Belle II qui est situé au collisionneur e^+e^- SuperKEKB. Des critères de sélection, basés sur des contraintes cinématiques, sont appliqués afin de supprimer divers types de bruit de fond et d'obtenir des échantillons de désintégration signal aussi purs que possible. Des corrections liées aux sélections d'identification des particules sont également appliquées. Ce travail compare les distributions des observables pour les données de Belle II

aux simulations MC, et les trouve en bon accord.

Pour quantifier la violation CP dans ce canal de désintégration, des observables angulaires spécifiques formant des distributions de produit triple sont exploitées. Des asymétries CP sont construites et pondérées selon des combinaisons de ces observables. Les outils développés dans ce travail contribuent à poser les bases des recherches futures de CPV dans les désintégrations hadroniques du tau dans Belle II.

De plus, cette thèse présente une étude des systématiques pour l'introduction d'un polarimètre Compton dans le cadre de la mise à jour de Belle II et SuperKEKB. L'ajout d'un faisceau d'électrons polarisés vise à ouvrir des opportunités de nouvelle physique. Des mesures précises de la polarisation sont requises. Parmi les différentes techniques potentielles, celle utilisant la diffusion Compton est la meilleure pour mesurer la polarisation du faisceau d'électrons. Dans ce contexte, cette thèse se concentre sur l'étude systématique de la performance du polarimètre à ajouter, en particulier en implémentant une simulation dédiée, en identifiant les sources d'incertitudes, et en évaluant leur impact sur la mesure de la polarisation. Ce travail est utile pour la conception du système de polarimètre, qui contribue à la mise à jour de Belle II.

Title : Towards a measurement of CP violation in $\tau^\pm \rightarrow h^\pm \pi^- \pi^+ \bar{\nu}_\tau$ using Belle II detector

Keywords : CP violation, tau lepton, new physics, Belle II, hadronic decays, pion

Abstract : While Charge Parity violation (CPV) has been measured for the hadronic sector in different channels, no significant evidence of CPV has been found in the leptonic sector. Therefore, it is particularly compelling to search for CPV in tau lepton decays given that it can decay to a variety of different hadronic channels. In fact, theoretical studies suggest that hadronic tau decays might exhibit CP-violating effects, but only in presence of new physics. Among these, the three hadrons decay channels $\tau^- \rightarrow h^- h^+ h^- (\geq 0\pi^0) \bar{\nu}_\tau$ are particularly interesting thanks to their intermediate resonances and angular distributions.

This thesis presents a preparatory study of CP violation in the decay $\tau^- \rightarrow \pi^- \pi^+ \pi^- (\geq 0\pi^0) \bar{\nu}_\tau$ using Monte Carlo simulated data and collected data by the Belle II detector which is located at the SuperKEKB e^+e^- collider. Selection criteria, based on kinematic constraints, are applied to suppress various types of background and obtain signal decay samples as clean as possible. Corrections related to particles identification selections are also applied. This work compares the distributions of the observables for Belle II data to the MC simulations, finding them to be in good agreement.

To quantify CP violation in this decay channel, specific angular observables forming triple-product distributions are exploited. CP asymmetries are constructed and weighted according to combinations of these observables. The tools developed in this work help lay the groundwork for future work to search for CPV in hadronic tau decays in Belle II.

Additionally, this thesis presents a study of systematics for the introduction of a Compton polarimeter as part of the Belle II and SuperKEKB upgrade. The addition of a polarized electron beam aims to open New Physics opportunities. Precise polarization measurements are required. Among the different potential techniques, the one using Compton scattering is the best for measuring the polarization of the electron beam. In this context, this thesis focuses on the systematic study of the performance of the polarimeter to be added, in particular, by implementing a dedicated simulation, identifying the sources of uncertainties, and evaluating their impact on the polarization measurement. This work is useful for the design of the polarimeter system, which contributes to the Belle II upgrade.

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Synthèse

La violation de la symétrie de charge-parité (CPV) est un phénomène fondamental de la physique des particules. Elle est directement liée à une énigme : l'univers est fait presque uniquement de matière, pourtant les lois de la physique prédisent qu'il aurait dû contenir autant de matière que d'antimatière.

La violation de CP a été étudiée dans le Modèle Standard. Elle a déjà été observée dans le secteur des quarks, par exemple dans les désintégrations des kaons et des mésons B. Cependant, cela n'est pas le cas pour le secteur leptonique. Les découvertes faites ne suffisent pas à expliquer l'asymétrie observée entre matière et antimatière dans l'univers. Cela laisse penser qu'il existe d'autres sources de violation de CP, peut-être au-delà du Modèle Standard.

Le secteur leptonique est l'un des endroits où ces nouveaux effets pourraient apparaître. Le lepton tau, en particulier, est intéressant grâce à sa masse relativement élevée et à la richesse de ses désintégrations. Certains canaux de désintégration pourraient montrer des effets de violation de CP, mais seulement si de nouveaux phénomènes interviennent au-delà du Modèle Standard.

Cette thèse s'inscrit dans ce cadre. Elle présente une étude préparatoire de la violation de CP dans le canal de désintégration du tau en trois hadrons, un canal dont les distributions angulaires sont sensibles à la symétrie CP. L'analyse repose à la fois sur des données simulées par Monte Carlo et sur des données réelles collectées par le détecteur Belle II, auprès du collisionneur SuperKEKB au Japon.

Afin d'éliminer le bruit de fond, des critères de sélection basés sur des contraintes cinématiques ont été appliqués. Des échantillons de signal de grande pureté ont été obtenus. Des corrections liées à l'identification des particules ont aussi été appliquées pour améliorer l'accord entre les distributions simulées et les données réelles. La comparaison des distributions angulaires montre un bon accord global, avec encore quelques différences à étudier plus en détail.

Pour aller plus loin, des observables angulaires sensibles à la violation de CP ont été construites. Ces observables permettent de définir des asymétries pondérées, plus sensibles à de possibles effets de nouvelle physique. Une estimation des asymétries de charge pour les données Monte Carlo a été effectuée. Les outils méthodologiques et logiciels développés dans cette thèse sont une première étape vers une recherche complète de la violation de CP dans les désintégrations hadroniques du tau à Belle II.

En parallèle, une deuxième partie du travail a porté sur une étude liée à l'introduction d'un polarimètre Compton concernant la mise à jour du détecteur Belle II et du collisionneur SuperKEKB. L'ajout d'un faisceau d'électrons polarisés représente une amélioration importante pour la physique à Belle II.

Le rôle du polarimètre Compton est de mesurer la polarisation du faisceau d'électrons en temps réel. Cela repose sur la diffusion Compton d'un faisceau laser sur le faisceau d'électrons.

Dans le cadre de cette thèse, une étude systématique a été faite pour identifier et estimer les sources d'incertitude qui pourraient affecter la mesure de polarisation du faisceau d'électrons. L'effet de chacune de ses sources a été estimé à l'aide de la simulation, sur la mesure de la polarisation. Ces études sont essentielles pour assurer un suivi continu de la polarisation pendant le fonctionnement du collisionneur. Enfin, les études montrent que la mesure de la polarisation du faisceau d'électrons peut être obtenue avec une précision de l'ordre du pourcent.

En résumé, cette thèse apporte deux contributions. D'abord, elle pose les bases expérimentales et méthodologiques pour la recherche de violation de CP dans les désintégrations hadroniques du tau avec Belle II. Ensuite, elle participe à l'étude des aspects systématiques nécessaires à l'introduction d'un faisceau polarisé dans SuperKEKB, à travers l'étude des erreurs systématiques du polarimètre Compton.

1 - Introduction

The Standard Model (SM) of particle physics is a theoretical framework that describes the fundamental particles of the universe and their interactions through electromagnetic, weak, and strong forces. The SM has progressively been built in the third quarter of the 20th century to account for experimental observations. Since the 70's, nearly all experimental observations agree with this model. Only the presence of neutrinos oscillations requires addition of their masses to the model, which suggests that, yet unknown, ingredients are missing. It also has further limitations that leave some questions unresolved. One of these limitations is the dominance of matter in the universe; even though an equal amount of matter and anti-matter have been produced at the big bang, as theoretically expected. Moreover, gravity is not present in this model. These quests motivate ongoing searches for physics beyond the SM.

1.1 . The Standard Model

The SM is a relativistic quantum field theory that models fundamental particles and their interactions [1]. It classifies elementary particles into two categories : fermions and bosons (see Fig. 1.1). Fermions have a spin of 1/2. Mediator gauge bosons have a spin of 1. The SM also includes the Higgs boson which is a scalar particle with spin 0. All of the SM particles have been experimentally observed, with the exception of right-handed neutrinos.

Fermions

Fermions include quarks and leptons; each of these categories is organized into three generations. The first generation contains the up u and down d quarks, the electron e^- and its corresponding neutrino ν_e . The second generation contains the charm c and strange s quarks, the muon μ^- and its corresponding neutrino ν_μ . The third generation contains the top t and bottom b quarks, the tau τ^- and its corresponding neutrino ν_τ . For each particle there is an anti-particle counterpart. The combination of one quark and one anti-quark form a meson. An example of a meson is a charged pion π which has a valence-quark content of $u\bar{d}(\pi^+)$ or $\bar{u}d(\pi^-)$ and a mass of $139.57 \text{ MeV}/c^2$, a neutral pion π^0 which is a superimposition of quark-antiquark states $\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$

Standard Model of Elementary Particles

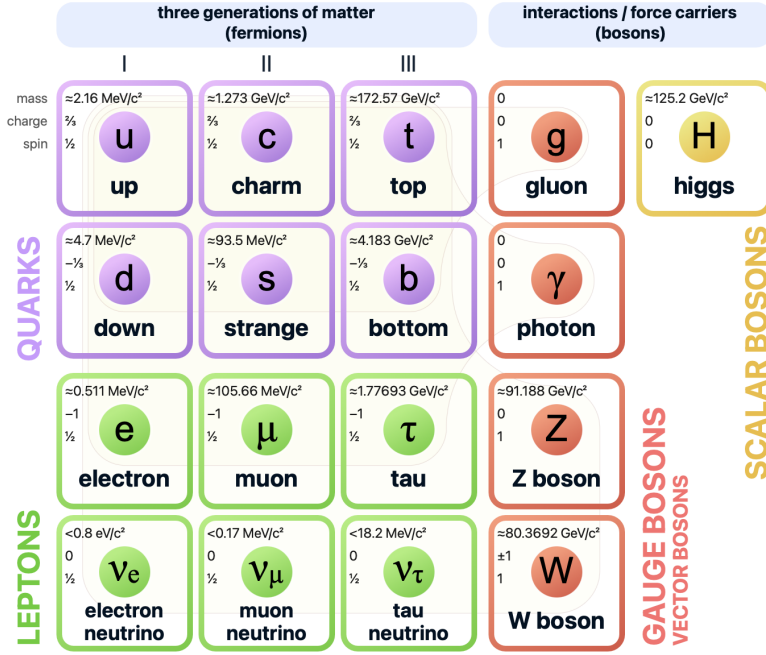


Figure 1.1 – The Standard Model of particles [2].

and has a mass of $134.98 \text{ MeV}/c^2$. Pions have spin 0, isospin $I = 1$, and negative parity. Another example of a meson is a charged kaon which has a valence-quark content of $u\bar{s}$ (K^+), $s\bar{u}$ (K^-), a neutral kaon of $d\bar{s}$ (K^0), or $s\bar{d}$ ($\bar{K}^0$) and a mass of $493.68 \text{ MeV}/c^2$. Kaons have spin 0, isospin $I = \frac{1}{2}$, and negative parity [3]. Other examples also used in this thesis are : charged a_1 meson ($a_1^\pm$) which has a mass of about $1230 \text{ MeV}/c^2$, a valence-quark content of $u\bar{d}$ (a_1^+) or $d\bar{u}$ (a_1^-), spin 1, isospin $I = 1$, and positive parity. A neutral a_1 meson (a_1^0) has a similar mass of about $1230 \text{ MeV}/c^2$, a valence-quark content of $\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$, spin 1, isospin $I = 1$, and positive parity. An ω meson has a mass of $782.66 \text{ MeV}/c^2$, a valence-quark content of $\frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$, spin 1, isospin $I = 0$, and negative parity. A ρ^0 meson has a mass of about $775 \text{ MeV}/c^2$, a valence-quark content of $\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$, spin 1, isospin $I = 1$, and negative parity [3]. A system of three quarks or three anti-quarks forms a baryon (an example of such is a proton p). Combinations of quarks are called hadrons. In addition, there are experimental discoveries of exotic hadrons composed of more than three quarks. A tetraquark consists of two quarks and two antiquarks. A pentaquark is composed of four quarks and one antiquark. An example of a tetraquark is the $Z_c(3900)$, which was observed by the BESIII Collaboration in $e^+e^- \rightarrow \pi^0\pi^0 J/\psi$ [4].

An example of a pentaquark is $P_c(4450)^+$ which was observed by the LHCb collaboration in the decay $\Lambda_b^0 \rightarrow J/\psi K^- p$ [5].

Bosons

Gauge bosons ensure the interaction between fermions. Photons γ mediate the electromagnetic interaction, $W^\pm$ and Z bosons mediate the weak interaction, and eight gluons g mediate the strong interaction.

The Higgs boson was the latest discovery of the SM in 2012 [6]. It is related to the scalar Higgs field, which has a non-zero vacuum expectation value (v). This causes electroweak symmetry to break. Through this mechanism, the $W^\pm$ and Z bosons acquire well-defined masses. (For example $m_W = \frac{1}{2}gv$, with m_W the mass of the $W^\pm$, g the weak coupling constant, associated to the $SU(2)_L$ gauge symmetry and v is 246 GeV). Thanks to this mechanism also, the photon remains massless. Fermions obtain their masses via Yukawa couplings to the Higgs field, with coupling strengths proportional to their masses. In the SM, heavier fermions therefore have larger couplings to the Higgs boson.

1.1.1 . The Strong and Electroweak Interactions

The interactions of particles in the SM are described by gauge theories, based on the symmetry group

$$SU(3)_C \times SU(2)_L \times U(1)_Y.$$

$SU(3)_C$ represents the strong interaction depicted by Quantum Chromodynamics (QCD). $SU(2)_L \times U(1)_Y$ represents the electroweak interaction, which combines the electromagnetic and weak forces. Only left (L) states are involved in the weak isospin interaction. Left (L) and right (R) states are involved in the weak hypercharge Y interaction.

Quantum Chromodynamics (QCD)

QCD is a quantum field theory that describes the strong interaction between particles with a color charge. The theory is based on the non-Abelian gauge group $SU(3)_C$. Its mediators are eight massless gluons, which have a color charge. The QCD Lagrangian is given by

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4}G_{\mu\nu}^a G^{a\mu\nu} + \sum_f \bar{\psi}_f (i\gamma^\mu D_\mu) \psi_f$$

where

- ψ_f is the Dirac spinor field for a quark of flavor f ,
- $\bar{\psi}_f = \psi_f^\dagger \gamma^0$ is the Dirac adjoint,

- γ^μ are the gamma matrices that ensure Lorentz invariance,
- D_μ is the QCD covariant derivative

$$D_\mu = \partial_\mu - ig_s T^a G_\mu^a,$$

with

- $T^a = \lambda^a/2$ are the SU(3) generators,
- $G_{\mu\nu}^a$ is the gluon field strength tensor

$$G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a + g_s f^{abc} G_\mu^b G_\nu^c,$$

- f^{abc} are the structure constants of SU(3),
- G_μ^a are the eight gluon fields,
- g_s is the strong coupling constant.

Quarks and gluons are never isolated. In fact, they are always grouped into color neutral hadrons. This phenomenon is known as confinement in QCD. QCD also has asymptotic freedom, meaning that for very high energy processes the strong coupling becomes weak. In this regime, quarks and gluons behave almost as free particles [7] [8].

The Electroweak Theory

The electroweak theory is based on the $SU(2)_L \times U(1)_Y$ symmetry, which unifies the electromagnetic and weak forces. It couples its gauge bosons to fermions through the weak isospin T and hypercharge Y . The electroweak Lagrangian is given by :

$$\mathcal{L}_{EW} = -\frac{1}{4}W_{\mu\nu}^a W^{a\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \sum_f \bar{\psi}_f (i\gamma^\mu D_\mu) \psi_f,$$

where the covariant derivative is

$$D_\mu = \partial_\mu - igT^a W_\mu^a - ig'Y B_\mu,$$

with

- W_μ^a and B_μ are the gauge fields of the $SU(2)_L$ and $U(1)_Y$ groups, respectively,
- T^a are the generators of $SU(2)_L$,
- Y is the weak hypercharge,
- g and g' are the gauge couplings of $SU(2)_L$ and $U(1)_Y$, respectively.

The electroweak symmetry is spontaneously broken via the Higgs mechanism, which results in massive gauge bosons $W^\pm$ and Z , and a massless photon A_μ . The neutral gauge bosons B_μ (from $U(1)_Y$) and W_μ^3 (third component of $SU(2)_L$) mix through the rotation

$$\begin{pmatrix} A_\mu \\ Z_\mu \end{pmatrix} = \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} B_\mu \\ W_\mu^3 \end{pmatrix}$$

where θ_W is the weak mixing angle, called Weinberg angle. The mass matrix of the neutral gauge bosons is diagonalized, providing the physical photon and the Z boson.

Parity violation in weak interactions was first measured experimentally, then accounted for in the SM by assigning the $SU(2)_L$ symmetry to act only on left-handed fermions. Consequently, the charged weak interaction, mediated by $W^\pm$ bosons, is maximally chiral as it couples only to left-handed fermions and right-handed antifermions. On the other hand, the neutral current interaction mediated by the Z boson involves both vector and axial-vector couplings, so it couples to left- and right-handed fermions, but with different strengths [1].

1.2 . C,P,T transformations

Charge Conjugation (C)

The C transformation replaces particles with their corresponding antiparticles. In simple terms, this operation changes the sign of all internal quantum numbers, such as the electric charge, the baryon number and the lepton number. For example, an electron e^- subject to charge conjugation becomes a positron e^+ .

Parity (P)

The P transformation is a spatial inversion that changes the spatial coordinates of a particle : $\vec{x} \rightarrow -\vec{x}$. This operation tests the symmetry of physical laws under mirror reflection. For example, parity is conserved in a process which remains unchanged if viewed in a mirror.

Time Reversal (T)

The T transformation reverses the time direction of a process : $t \rightarrow -t$. This operation inverts momenta and spin directions, keeping positions unchanged. Time-reversal symmetry states that fundamental interactions should remain invariant if the direction of time is reversed.

These discrete symmetries are important for understanding the fundamental interactions. The electromagnetic interaction conserves C, P and T symmetries. The strong interaction also conserves them up to a possible CP-violating term, which experiments constrain to be extremely small [9]. In contrast, the weak interaction violates them.

1.3 . CP Violation

CP symmetry, combining charge (C) and parity (P) symmetries, is a fundamental symmetry in the universe. When this symmetry is conserved, physics remains the same for decays in case involved particles are replaced with their anti-particles (representing C-symmetry) and left (right) parity is replaced with right (left) parity (representing P-symmetry). Violation of this symmetry generates differences between decays of the particles and their corresponding anti-particles that could be measured. That is called a CP violation.

The combined CP symmetry was first thought to be conserved in all interactions. Then, its violation was discovered through the decays of neutral kaons [10]. The violation of CP suggests that the laws of physics are not entirely identical under the combined operations of charge and parity transformations.

Despite the violations of the C, P, and CP symmetries, the CPT symmetry is conserved. The CPT theorem states that any Lorentz-invariant local quantum field theory must be invariant under the combined transformation of CPT. This means that even if the C, P, or T symmetries were individually violated, the CPT symmetry remains exact [11].

1.3.1 . Quark Mixing and Cabibbo-Kobayashi-Maskawa (CKM) Matrix

Some history

Cabibbo first introduced the concept of quark mixing after observing that weak decays which conserve strangeness ($\Delta S = 0$), such as $\pi^+ \rightarrow \mu^+ \nu_\mu$, occurred with full strength, while strangeness-changing decays ($\Delta S = 1$), such as $K^+ \rightarrow \mu^+ \nu_\mu$, were suppressed [12]. He suggested that the weak interaction couples to a linear combination of the d and s quarks, represented by a real mixing angle also called Cabibbo angle θ_C , with $\sin \theta_C \simeq 0.225$ [3] for the observed suppression. Explicitly, the weak current couples to

$$d' = d \cos \theta_C + s \sin \theta_C,$$

which explains why transitions involving the s quark are naturally suppressed relative to those involving only the d quark.

Kobayashi and Maskawa then generalized this idea [13] by extending it to three generations of quarks, leading to the CKM matrix. This mixing matrix contains a complex phase, which is the origin of the CP violation in the SM.

The matrix

The matrix comes from a difference between the weak interaction eigenstates and the mass eigenstates of the quarks. By diagonalizing the mass matrices of up-type and down-type quarks separately, the charged weak interactions are described in a unitary mixing matrix following

$$\mathcal{L}_{\text{weak}} = -\frac{g}{\sqrt{2}} \bar{u}_L^i \gamma^\mu V_{ij} d_L^j W_\mu^+ + \text{h.c.}$$

where $u_L^i = (u, c, t)_L$ and $d_L^j = (d, s, b)_L$ are the left-handed up-type and down-type quark fields, respectively, and V_{ij} are the elements of the CKM matrix V_{CKM} . As a unitary 3×3 matrix, V_{CKM} is described using three mixing angles and one complex CP-violating phase, which represents the minimal set of parameters required to allow CP violation within a model of three generations of quarks. The matrix is given by

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

where the complex phase (usually found in V_{ub} or V_{td}) causes CP violation. Off-diagonal elements are responsible for the suppression of flavor-changing interactions. The experimental amplitudes of the matrix are approximated as [14] :

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} \approx \begin{pmatrix} 0.974 & 0.226 & 0.004 \\ 0.226 & 0.973 & 0.041 \\ 0.009 & 0.040 & 0.999 \end{pmatrix}.$$

Wolfenstein parametrization

Various parametrizations of the matrix exist, however the most used is the Wolfenstein parametrization which depends on four main parameters λ , A , ρ and η . It calculates the matrix elements as function of $\lambda \approx 0.225$ also known as the sine of the Cabibbo angle

$$V_{\text{CKM}} \approx \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

with A , ρ and η are real parameters determined from real experimental data. η is the parameter responsible for the CP violating effects. The values of these parameters are obtained thanks to many measurements [15].

Unitarity of the matrix

The CKM matrix is unitary, so $VV^\dagger = V^\dagger V = 1$. This property is also the reason the rows and columns of the matrix are orthonormal. This is respected through six orthogonality conditions

$$\sum_i V_{ij} V_{ik}^* = \delta_{jk} \text{ and } \sum_j V_{ij} V_{kj}^* = \delta_{ik}$$

One interesting example of these relations is

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

which forms a closed triangle in the complex plane, known as the unitarity triangle (see Fig. 1.2). The shape and angles of this triangle represent the strength and nature of CP violation. Precision measurements of the sides and angles of this triangle, usually labeled as α , β and γ , are important tests of the SM. β and γ are defined as the relative phase between two adjacent sides of the triangle [16]:

$$\beta = \arg\left(\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right) = \text{atan}\left(\frac{\bar{\eta}}{(1 - \bar{\rho})}\right)$$

$$\gamma = \arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) = \text{atan}\left(\frac{\bar{\eta}}{\bar{\rho}}\right)$$

where $\bar{\rho}$ and $\bar{\eta}$ are redefined Wolfenstein parameters, related to ρ and η by higher-order corrections in λ

$$\bar{\rho} = \rho \left(1 - \frac{\lambda^2}{2}\right); \quad \bar{\eta} = \eta \left(1 - \frac{\lambda^2}{2}\right)$$

and in leading order, they coincide with ρ and η . α can be deduced by the relation

$$\alpha + \beta + \gamma = \pi.$$

Global fits of measured data show excellent self consistency as demonstrated by UTfit [17] and CKMfitter [18] collaborations, see Fig. 1.3 and 1.4 respectively.

1.3.2 . Types of CPV

CP Violation in mixing

CP violation in mixing occurs when the probability for a neutral meson to oscillate into its antiparticle is different from that of the reverse process. For example

$$B^0 \rightarrow \bar{B}^0 \rightarrow \bar{f}, \quad \bar{B}^0 \rightarrow B^0 \rightarrow f$$

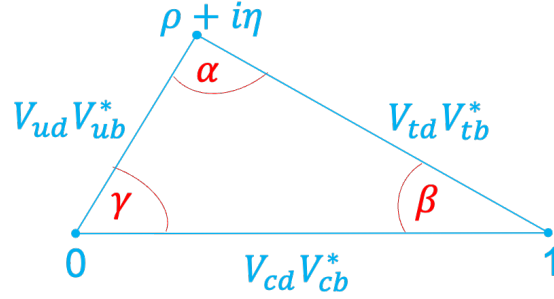


Figure 1.2 – The unitarity triangle that verifies the relation $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$. The angles α , β , and γ are directly related to CP violating observables.

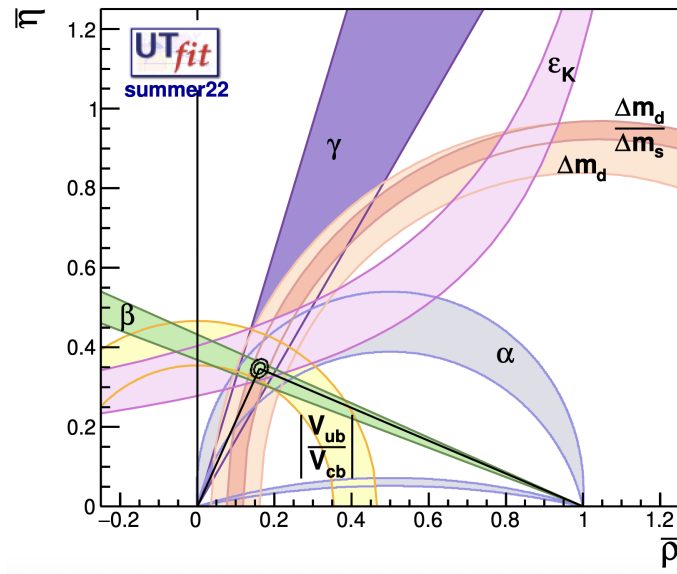


Figure 1.3 – Global fits of the CKM unitarity triangle in the $\bar{\rho} - \bar{\eta}$ plane by the UTfit collaboration [17]. Constraints from tree-level processes and loop processes are combined to obtain the full fit. The apex of the triangle is constrained within the data.

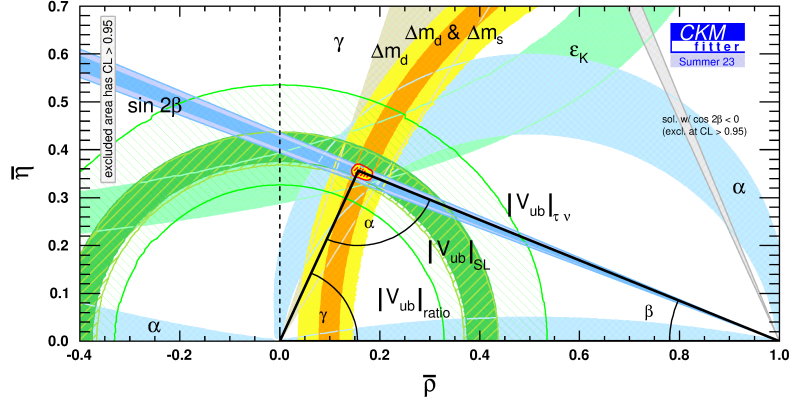


Figure 1.4 – Global fits of the CKM unitarity triangle in the $\bar{\rho} - \bar{\eta}$ by the CKM fitter collaboration [18]. Bands correspond to individual constraints : $\sin 2\beta$ in blue, ε_K in green, $\Delta m_d(\Delta m_s)$ in yellow (orange), α in light blue, and γ in tan.

The asymmetry is created if the probability for $B^0 \rightarrow \bar{B}^0$ differs from that of $\bar{B}^0 \rightarrow B^0$. There have been searches for this CPV. For example, Belle measured the same-sign dilepton charge asymmetry in $B^0 - \bar{B}^0$ mixing :

$$A_{CP} = (-1.1 \pm 7.9_{\text{stat}} \pm 8.5_{\text{syst}}) \times 10^{-3},$$

It found no evidence for CP violation and set upper limits consistent with zero [19]. Similarly, BaBar previously measured this asymmetry using inclusive dilepton sample :

$$A_{CP} = (0.5 \pm 1.2_{\text{stat}} \pm 1.4_{\text{syst}}) \times 10^{-2},$$

also finding no evidence of CP violation [20]. Thus CP violation in mixing has not been observed for B mesons yet.

However, CP violation in mixing is established in the $K^0 - \bar{K}^0$ system. The CP asymmetry in K_L decays, called semileptonic charge asymmetry is

$$A_{CP}(K_L) \equiv A_L = (3.32 \pm 0.06) \times 10^{-3},$$

consistent with a nonzero indirect CP-violation parameter [21].

CP Violation in decay

CP Violation in decay occurs when the decay rate of a particle to a final state is different from the decay rate of the antiparticle to its CP eigenstate final state. For example

$$B \xrightarrow{A} f, \quad \bar{B} \xrightarrow{\bar{A}} \bar{f}$$

This is also called direct CPV. It requires at least two amplitudes with different weak and strong phases. For example, Belle II measured the asymmetry in the $B^0 \rightarrow K^+\pi^-$ decay [22] :

$$A_{CP}(K^+\pi^-) = -0.072 \pm 0.019_{\text{stat}} \pm 0.007_{\text{syst}}.$$

Another example, LHCb measured CPV in the decay $B^0 \rightarrow \pi^+\pi^-$ [23] :

$$A_{CP}(\pi^+\pi^-) = -0.0824 \pm 0.0033_{\text{stat}} \pm 0.0033_{\text{syst}}.$$

Additionally, BaBar measured direct CP violation in the same decays, finding

$$A_{CP}(K^+\pi^-) = -0.107 \pm 0.018_{\text{stat}}^{+0.007}_{-0.004_{\text{syst}}}$$

with a significance of 5.5σ for the $(K^+\pi^-)$ channel, and for $\pi^+\pi^-$ channel :

$$\begin{aligned} C_{\pi\pi} &= -0.21 \pm 0.09_{\text{stat}} \pm 0.02_{\text{syst}} \\ S_{\pi\pi} &= -0.60 \pm 0.11_{\text{stat}} \pm 0.03_{\text{syst}}, \end{aligned}$$

confirming CP violation in both channels [24].

CP Violation in the interference between mixing and decay

CP violation in the interference between mixing and decay occurs when a neutral meson can decay to a final state via two paths : directly or after mixing with its antiparticle. For example

$$\begin{aligned} B^0 &\rightarrow f, \quad B^0 \rightarrow \bar{B}^0 \rightarrow f \\ \bar{B}^0 &\rightarrow f, \quad \bar{B}^0 \rightarrow B^0 \rightarrow f. \end{aligned}$$

The interference between the two amplitudes, potentially carrying different weak phases, yields to a CP asymmetry. This CPV has been observed in B decays. For example, the time-dependent CP asymmetry in the $B^0 \rightarrow J/\psi K_S^0$ decay was observed by measuring $\sin(2\beta)$, an angle in the CKM unitarity triangle. This was performed by Belle [25] :

$$\sin 2\beta = 0.99 \pm 0.14_{\text{stat}} \pm 0.06_{\text{syst}},$$

BaBar [26] :

$$\sin 2\beta = 0.59 \pm 0.14_{\text{stat}} \pm 0.05_{\text{syst}}$$

and LHCb [27] :

$$\sin 2\beta = 0.73 \pm 0.07_{\text{stat}} \pm 0.04_{\text{syst}}.$$

These measurements were the first and have been improved greatly since then.

1.3.3 . Observation of CPV in the quark sector

CP violation was first observed in the neutral kaon system in the Cronin and Fitch experiment [10]. The neutral kaons K^0 and $\bar{K}^0$ mix through weak interactions to form two mass eigenstates : short-lived K_S and long-lived K_L . These are approximately CP eigenstates :

$$K_S \approx K_1 \text{ (CP-even) and } K_L \approx K_2 \text{ (CP-odd)}.$$

If CP were conserved, K_S would only decay to two pions (CP-even), and K_L would only decay to three pions (CP-odd). However, the experiment showed that K_L decayed in some events to two pions, which is a CP-even final state. This proved that CP symmetry was not always conserved in weak interactions.

An important later observation was CPV in the B mesons. BaBar [28] and Belle detectors [29] observed CP violation in the $B^0 - \bar{B}^0$ system. The measurement of CPV in $B^0 \rightarrow J\psi K_s$ helped confirm the Kobayashi-Maskawa mechanism. CP violation in the B sector includes direct components and components that result from mixing.

Further measurements in other systems have validated our understanding of CP violation in the quark sector. Direct CP violation in the kaon system was established by the KTeV [30] and NA48 [31] experiments, which measured the parameter ϵ' , indicating that CP violation occurs not only via mixing but also directly in decay amplitudes. In hadronic B decays, BaBar and Belle observed direct CP violation in the channel $B^0 \rightarrow K^+\pi^-$ [32, 33], providing further evidence that the CKM phase leads to observable asymmetries in decay rates. The LHCb experiment has extended the studies by observing CP violation in charged B decays like $B^\pm \rightarrow DK^\pm$ [34], as well as in the B_s^0 system where direct CP violation has been established in decays such as $B_s^0 \rightarrow K^-\pi^+$ [35]. More recently, LHCb has also succeeded at the first observation of CP violation in charm decays [36], and a precise measurement of the time-integrated CP asymmetry in $D^0 \rightarrow K^-K^+$ [37], showing that even the up-type quark sector exhibits CP-violating effects, although at a much smaller level. In addition, LHCb has recently found the first evidence of CP violation in the baryon sector, using angular correlations in $\Lambda_B^0 \rightarrow pK^-\pi^+\pi^-$ decays [38].

1.3.4 . Observation of CPV in the leptonic sector

Unlike in the quark sector, CP violation has not been observed in the leptonic sector [39]. In the SM, CPV effects are negligible for charged leptons. The only possible source of CP violation among leptons is through the neutrino mixing matrix PMNS (Pontecorvo-Maki-Nakagawa-Sakata) [40]. This makes the lepton sector a probe for new

physics beyond the SM (BSM). For example, BSM theories use additional sources of CP violation in the lepton sector to explain the baryon asymmetry of the universe [41].

Searches of CPV in neutrino oscillations

The discovery of neutrino oscillations [42] demonstrated that neutrinos have mass, unlike previously posited, and that they mix between flavor states. This calls for an extension of the SM. The mixing of flavor states is described by the PMNS matrix, which can include a complex phase that violates CP symmetry [43].

In order to have CP asymmetry, the probability of oscillation of neutrinos and that of antineutrinos would be different. The example channels are $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$. A difference in the oscillation probability of these channels depends on the value of the CP-violating phase δ_{CP} . This can be detected in neutrino experiments. For example, the NOvA experiment has found large CP violating effects with limited statistical significance [44]. A new generation of experiments, such as DUNE [45] and Hyper-Kamiokande [46], is precisely set to test the CP violation in the leptonic sector.

1.3.5 . CPV in the bosonic sector

To search for CPV in the bosonic sector, the focus relies on the study of the interactions of the Higgs boson with other particles. For example, by studying specific angles between decaying Higgs particles such as $H \rightarrow ZZ^* \rightarrow 4l$ [47], or by searching for signs of interference between CP-even and CP-odd effects in Higgs production [48].

CP violation in the bosonic sector has not been observed. Future experiments like the High-Luminosity LHC (HL-LHC) and future colliders like the ILC and FCC, will precisely probe small signs of CP violation [49].

1.4 . Tau

The tau is the heaviest charged lepton, with a mass of $1.77694 \pm 9 \times 10^{-5}$ GeV [3]. As a lepton, it does not interact strongly. However, unlike lighter leptons, the electron and muon, tau can decay into hadronic final states through electroweak and strong interactions. In fact, it decays into a neutrino and a virtual W boson through the weak interaction. This boson hadronizes via the strong interaction into mesons. Thanks to its relatively large mass, the tau has the possibility to decay into different final states, including purely leptonic and semi leptonic channels. Tau decays are a rich environment in testing the SM and

going beyond it.

Tau decays are particularly interesting in the study of CP violation. In fact, CPV has been observed in the quark sector, but not in the lepton sector. The hadronic decays of the tau allow interference between different decay amplitudes through weak and strong phases, enabling the construction of CP-odd observables, including angular asymmetries and triple product measurements.

1.4.1 . The tau discovery

The τ lepton was discovered in 1975 at SLAC where electron and positron beams were colliding [50]. The produced events of $\tau^+\tau^-$ pairs were observed to decay into final states containing tracks with missing energy. An example of an event is where a τ^+ decayed as $\mu^+\nu_\mu\bar{\nu}_\tau$ and a τ^- decayed as $e^-\bar{\nu}_e\nu_\tau$. 24 signal candidates of $e\mu$ were identified with a statistically significant excess over the expectations of the background. By discriminating variables such as the momentum of the lepton and the invariant mass of the $e\mu$ system, the signal events were isolated. The mass of the discovered τ lepton was estimated in a range of 1.6 and 2 GeV. This discovery led to a third generation of leptons and strongly suggested a third generation of quarks.

1.4.2 . CPV in tau decays

CP violation has been well studied in K and b -hadron decays and mixing (when applicable), such as neutral kaons and B mesons, but not as much in charged current processes such as purely leptonic decays. Direct CP violation is created due to an interference between different decay amplitudes that have different CP-violating and CP-conserving phases. As leptonic decays do not involve quarks, the CKM matrix phase becomes highly suppressed; only higher-order corrections are involved in this case.

In order to have a measurable CP asymmetry, we should consider at least two amplitudes that contribute to the same final state. Each amplitude has a certain magnitude, a CP-odd phase ϕ_i (weak phase), and a CP-even phase θ_i (strong phase coming from final-state interactions). Thus, the amplitude A_f representing a specific decay path can be written as [51] :

$$A_i = |a_i|e^{i\phi_i}e^{i\theta_i}. \quad (1.1)$$

Considering a particle P that decays to a final state f , the decay amplitude of the process $P \rightarrow f$ and its CP-conjugated process $\bar{P} \rightarrow \bar{f}$ are given respectively by

$$A_f = a_1e^{i\theta_1}e^{i\phi_1} + a_2e^{i\theta_2}e^{i\phi_2}$$

$$\bar{A}_{\bar{f}} = a_1 e^{i\theta_1} e^{-i\phi_1} + a_2 e^{i\theta_2} e^{-i\phi_2}$$

taking into account only two amplitudes for simplicity, where a_i ($i = 1, 2$) is the magnitude of the i -th amplitude (real coefficient), θ_i is the strong phase and ϕ_i is the weak phase of the i -th amplitude. CP asymmetry can be constructed as follows :

$$A_{CP} = \frac{\Gamma(\bar{P} \rightarrow \bar{f}) - \Gamma(\bar{P} \rightarrow f)}{\Gamma(\bar{P} \rightarrow \bar{f}) + \Gamma(\bar{P} \rightarrow f)} = \frac{|\bar{A}_{\bar{f}}|^2 - |A_f|^2}{|\bar{A}_{\bar{f}}|^2 + |A_f|^2}$$

$$A_{CP} = \frac{2a_1 a_2 \sin(\theta_1 - \theta_2) \sin(\phi_1 - \phi_2)}{a_1^2 + a_2^2 + 2a_1 a_2 \cos(\theta_1 - \theta_2) \cos(\phi_1 - \phi_2)}$$

In order to obtain a non-zero direct CP asymmetry in decay, two elements are needed. First, a difference in the weak phases ϕ_i between the interference amplitudes. Second, non-trivial strong phase differences θ_i that originate from final-state interactions. Combining these two allow for an observable decay asymmetry between τ^- and τ^+ [51].

1.4.3 . CPV in hadronic tau decays

CP violation has been studied in some hadronic tau decay channels. Among the most potentially sensitive to CPV with respect to other τ decay modes, are processes involving a kaon such as $\tau^\pm \rightarrow K_S^0 \pi^\pm \bar{\nu}_\tau^{(-)}$ [52]. The advantage of such decays is that they are suppressed within the SM, thus their potential sensitivity to NP contributions might be larger. However, a disadvantage is the presence of CPV in this decay, predicted by the SM. In particular, decays that involve hadronic resonances, such as the $K^*(892)$ vector meson, can introduce significant strong phases. When these phases differ between interfering amplitudes and combine with the weak phase from the CKM matrix, CP violation might be observed [51].

State of the art of CPV in τ decays

A well studied tau decay system which involves strangeness is $\tau^- \rightarrow K_S^0 \pi^- \nu_\tau$. This has been studied theoretically in [52, 53]. The disadvantage of the choice of such a system is the presence of neutral kaon system, thus the presence of CPV within the SM. BABAR collaboration has measured this CPV in $\tau^- \rightarrow K_S^0 \pi^- (\geq 0\pi^0) \nu_\tau$ [54]. CP asymmetry is defined as

$$A_{CP} = \frac{\Gamma(\tau^+ \rightarrow \pi^+ K_S^0 (\geq 0\pi^0) \bar{\nu}_\tau) - \Gamma(\tau^- \rightarrow \pi^- K_S^0 (\geq 0\pi^0) \nu_\tau)}{\Gamma(\tau^+ \rightarrow \pi^+ K_S^0 (\geq 0\pi^0) \bar{\nu}_\tau) + \Gamma(\tau^- \rightarrow \pi^- K_S^0 (\geq 0\pi^0) \nu_\tau)} \quad (1.2)$$

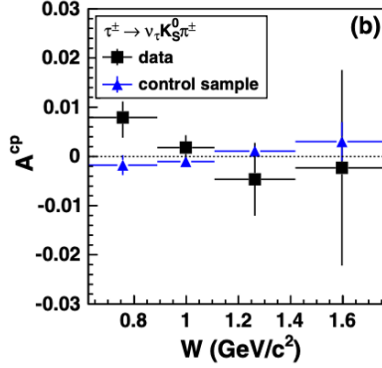


Figure 1.5 – CP asymmetry as function of the invariant mass of the $K_S\pi$ system in the decay of $\tau^\pm \rightarrow K_S^0\pi^\pm\nu_\tau$, as measured by the Belle collaboration [55]. Experimental data are black squares and control sample is represented by blue triangles.

where Γ is the branching ratio. The SM prediction is [52] :

$$A_{CP} = (0.36 \pm 0.01)\%.$$

By measuring a difference in the number of observed events with $\tau^- \rightarrow K_S^0\pi^-\nu_\tau$ and $\tau^+ \rightarrow K_S^0\pi^+\nu_\tau$, CP asymmetry at BaBar was found as

$$A_{CP} = (-0.36 \pm 0.23 \pm 0.11)\%,$$

which is 2.8σ deviation away from the expected value in the SM. Belle collaboration has also measured it [55] without including the neutral pions. No asymmetry was found at the level of 10^{-2} (see Fig. 1.5). There is also an ongoing similar study that is being done using Belle II data.

Motivation

As CP violation is being studied in the channel $\tau^+ \rightarrow K_S^0\pi^+\nu_\tau$, it is also interesting to study CPV in other hadronic tau decays. For example, $\tau^- \rightarrow K^-\pi^-\pi^+\nu_\tau$ would potentially be a good channel to search for CPV. One other advantage is the low branching ratio of order 10^{-3} of this decay, which makes the CP asymmetry easier to measure since :

$$A_{CP} = \frac{|A_{SM} + A_{NP}|^2 - |\bar{A}_{SM} + \bar{A}_{NP}|^2}{|A_{SM} + A_{NP}|^2 + |\bar{A}_{SM} + \bar{A}_{NP}|^2} \simeq \frac{2|A_{NP}| \cdot |A_{SM}|}{|A_{NP}|^2 + |A_{SM}|^2} \quad (1.3)$$

where A_{SM} is the SM amplitude and A_{NP} is the NP amplitude. We would have a higher sensitivity to the interference term of amplitudes when A_{SM} and A_{NP} are of similar order of magnitude. However for the $\tau^\pm \rightarrow K^\pm\pi^\mp\pi^\pm\nu_\tau$ decays, there are many backgrounds, mainly the

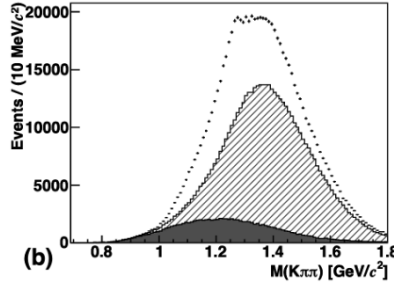


Figure 1.6 – Invariant mass of the $K\pi\pi$ system. Signal data of $\tau \rightarrow K\pi\pi$ is given in black with their uncertainties, the hash region represents the background of three hadrons, dominated by $\tau \rightarrow \pi\pi\pi$ and the small gray area represents the other backgrounds [56].

dominant background is $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$ which has a branching ratio of $8.4 \pm 0.3\%$ (see Fig. 1.6), and so if one intends to measure CPV in $\tau^- \rightarrow K^- \pi^- \pi^+ \nu_\tau$, it is required to have a good knowledge and control over the background channels, especially $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$. Thus, it is necessary to study first-hand CPV in the decay $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$ to confirm that there is no CPV, which would be extremely beneficial before a complete and precise measurement of CPV in $\tau^- \rightarrow K^- \pi^- \pi^+ \nu_\tau$. One would need this control channel to be really controlled and well known, and not just assumed as having no CPV. Or else, if CPV were to be found in $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$, then that would be extremely interesting. Therefore, we investigate this decay. On another note, no measurement of CPV in $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$ or in $\tau^- \rightarrow K^- \pi^- \pi^+ \nu_\tau$ has yet been made to our knowledge.

Now, the motivation to include neutral pions is a different matter. Theoretically, an exploration of CPV in the system $\tau^- \rightarrow N\pi\nu_\tau$ with $N = 2, 3$ and 4 has been done in [57]. New physics is assumed to originate from a charged Higgs boson model. For $N=2$, CPV is not possible. In fact, due to isospin conservation, the two-pion final state cannot be produced out of a spin 0 Higgs boson. Therefore, no CPV is expected in $\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$ for example. However, for $N = 3$, the final states $\pi^- \pi^+ \pi^-$ or $\pi^- \pi^0 \pi^0$ can be produced through a scalar exchange (Higgs boson). This allows for interference between the SM and NP amplitudes, which is a requirement for CPV. These decays are dominated by the intermediate resonances :

$$\tau^\pm \rightarrow a_1^\pm (\pi^\pm \pi^+ \pi^-) \pi^0 \nu_\tau \text{ (axial-vector resonance)}$$

$$\tau^\pm \rightarrow a_1^0 (\pi^+ \pi^- \pi^0) \pi^\pm \nu_\tau \text{ (axial-vector resonance)}$$

$$\tau^\pm \rightarrow \omega (\pi^+ \pi^- \pi^0) \pi^\pm \nu_\tau \text{ (vector resonance)}$$

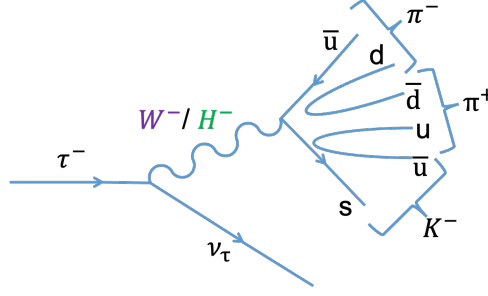


Figure 1.7 – Feynman diagram of $\tau^- \rightarrow K^- \pi^+ \pi^- \nu_\tau$, in the SM the boson exchanged is a W^- , in another model beyond the SM that would be a charged Higgs H^- .

$$\tau^\pm \rightarrow \omega(\pi^+ \pi^-) \pi^\pm \nu_\tau \text{ (vector resonance)}$$

$$\tau \rightarrow \rho^0(\pi^+ \pi^-) \pi^\pm \nu_\tau \text{ (vector resonance)}$$

which already contain π^0 . Ideally, one would reconstruct the neutral pions; however, it is not an easy task, so the idea is to study CPV in the $\tau^- \rightarrow \pi^- \pi^+ \pi^- (n \geq 0 \pi^0) \nu_\tau$ without explicitly reconstructing the neutral pions.

Formalism

In order for the CPV to occur, an interference of two diagrams is needed. The SM diagram is represented by the exchange of a W boson, and the New Physics contribution is represented by the exchange of a charged Higgs H boson (see Fig. 1.8). The effective Hamiltonian in the SM for the $\tau^- \rightarrow K^- \pi^+ \pi^- \nu_\tau$ is given as [58]

$$H_{eff}^{SM} = \frac{G_F}{\sqrt{2}} \sin \theta_C [\bar{\nu}_\tau \gamma_\mu (1 - \gamma_5) \tau] [\bar{s} \gamma^\mu (1 - \gamma_5) u] + \text{h.c.} \quad (1.4)$$

where G_F is Fermi constant, θ_C is Cabibbo angle. The effective Hamiltonian taking into consideration the new physics effects reads [58]

$$H_{eff}^{NP} = \frac{G_F}{\sqrt{2}} \sin \theta_C [\eta_S \bar{\nu}_\tau (1 + \gamma_5) \tau \bar{s} u + \eta_P \bar{\nu}_\tau (1 + \gamma_5) \tau \bar{s} \gamma_5 u] + \text{h.c.} \quad (1.5)$$

where η_S is a scalar parameter and η_P is a pseudo-scalar parameter. The NP can be represented for example by a charged Higgs boson, considering that charged Higgs-fermion couplings could violate CP.

Methodology

The idea originates from the paper [58] studying CP violation in $\tau^- \rightarrow K^- \pi^+ \pi^- \nu_\tau$ (see Fig. 1.7). We adapt it to the case of $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$. It is based on an angular measurement. CP asymmetry is

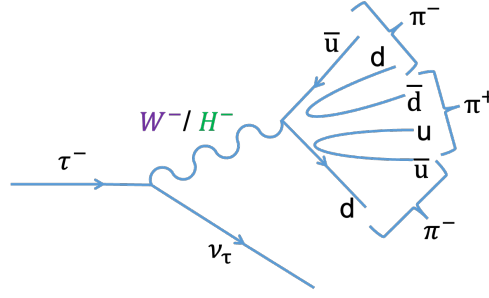


Figure 1.8 – Feynman diagram of $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$, in the SM the boson exchanged is a W^- , in another model beyond the SM that would be a charged Higgs H^- .

i	$h_i(\gamma, \beta)$	$\iint [h_i(\gamma, \beta)]^2 \sin \beta d\gamma d\beta$	
1	1	4π	CP-even
2	$3 \cos^2 \beta - 1$	$16\pi/5$	
3	$\sin^2 \beta \cos 2\gamma$	$16\pi/15$	
4	$\sin^2 \beta \sin 2\gamma$	$16\pi/15$	
5	$\sin \beta \sin \gamma$	$4\pi/3$	
6	$\sin \beta \cos \gamma$	$4\pi/3$	CP-odd
7	$\cos \beta$	$4\pi/3$	
8	$\sin 2\beta \cos \gamma$	$16\pi/15$	
9	$\sin 2\beta \sin \gamma$	$16\pi/15$	

Figure 1.9 – Angular functions and their normalization factors [58]. The functions 1, 2, 3, 8 and 9 are CP-even, and the functions 5, 6 and 7 are CP-odd.

measured by comparing different angular observables weighted differential widths.

The theoretical studies based on $\tau^- \rightarrow K^- \pi^+ \pi^- \nu_\tau$ in [58] suggest weighting the differential asymmetry with angular functions. These angular functions are combinations of the hadronic angles, or observables. The definitions of the angles are present in Section 4.7. There are nine functions, so nine asymmetries can be measured. Each asymmetry is weighted with a certain function. Each symmetry has a certain sensitivity, and there would be clear advantages of using one or the other. In fact, six of these functions are CP-even, meaning that they are useful to calculate to do checks and validations. The other three functions are CP-odd, which are used to calculate the CP asymmetry (see Fig. 1.9).

The asymmetry studied for the $K^- \pi^+ \pi^-$ system can be visualized in Fig. 1.10. The goal is to do this study for the $\pi^- \pi^+ \pi^-$ system.

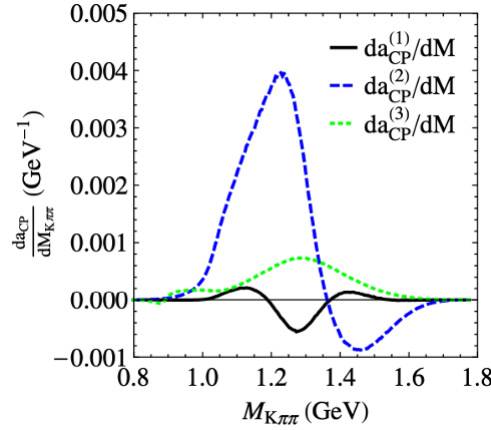


Figure 1.10 – Differential asymmetry weighted with the $K\pi\pi$ system invariant mass [58]. The weighting functions are represented as 1 : $\sin \beta \sin \gamma$ in black, 2 : $\sin \beta \cos \gamma$ in blue and 3 : $\cos \beta$ in green. The most sensitive asymmetry is through $\sin \beta \cos \gamma$. With $\cos \beta$, the distribution is always positive. Otherwise, it alternates around 0.

Differential width and asymmetry

The total integrated asymmetry is given by

$$A = \frac{1}{\Gamma_{tot}} \left(\frac{d\Gamma_i^{\tau^+}}{dPS} - \frac{d\Gamma_i^{\tau^-}}{dPS} \right) ds_1 ds_2 \quad (1.6)$$

where $\frac{d\Gamma_i^{\tau^\pm}}{dPS}$ is the differential branching fraction of the $\tau^\pm$ events on the phase space, i corresponds to specific angular observables ($i \in [1, 9]$), s_j ($j = 1, 2$) is the invariant mass of two opposite sign pions, and Γ_{tot} is the total branching fraction defined as :

$$\Gamma_{tot} = \int \frac{d\Gamma^{(\tau^+ + \tau^-)}}{ds} ds \quad (1.7)$$

$$= \int \frac{d\Gamma^{(\tau^+)}}{ds} ds + \int \frac{d\Gamma^{(\tau^-)}}{ds} ds \quad (1.8)$$

Integrating the Γ over the $\cos \beta$ and γ angles gives :

$$\int \int \int \frac{d\Gamma}{ds} ds d\cos \beta d\gamma = \int \frac{d\Gamma}{ds} ds \times \int_{-1}^1 d\cos \beta \int d\gamma \quad (1.9)$$

$$= \int \frac{d\Gamma}{ds} ds \times 2 \times 2\pi \quad (1.10)$$

The average of Γ weighted by the angular functions $h_i(\gamma, \beta)$ ($i \in [1, 9]$) reads :

$$\left\langle \frac{d\Gamma}{ds} h_i(\gamma, \beta) \sin \beta \right\rangle = \frac{\int \frac{d\Gamma}{ds} \sin \beta h_i(\gamma, \beta) d\beta d\gamma}{\int \sin \beta h_i(\gamma, \beta) d\beta d\gamma} \quad (1.11)$$

The asymmetry in each bin reads :

$$a(b) = \frac{\sum_1^{N_b^{\tau+}} \sin \beta h_i(\gamma, \beta) - \sum_1^{N_b^{\tau-}} \sin \beta h_i(\gamma, \beta)}{(\sum_b(N_b^{\tau+} + N_b^{\tau-})) \text{bin width}(b)} \quad (1.12)$$

We can introduce coefficients c_i (check [59] equation 5)

$$\frac{d\Gamma}{dQ^2 ds_1 ds_2 d\gamma d \cos \beta} = \sum_{i=1}^9 c_i(Q^2, s_1, s_2) h_i(\gamma, \beta) \quad (1.13)$$

$$\frac{d\Gamma}{dQ^2 ds_1 ds_2} = \int \frac{d\Gamma}{dQ^2 ds_1 ds_2 d\gamma d \cos \beta} \times h_j(\gamma, \beta) d\gamma d\beta \quad (1.14)$$

$$= \sum_{i=1}^9 c_i(Q^2, s_1, s_2) \int h_i(\gamma, \beta) h_j(\gamma, \beta) \quad (1.15)$$

$$= \sum_{i=1}^9 c_i(Q^2, s_1, s_2) \int h_i^2(\gamma, \beta) \quad (1.16)$$

$\int h_i(\gamma, \beta) h_j(\gamma, \beta) = 0$ if $i \neq j$ which is why in the paper the normalization factor in the table is given as $h_i^2(\gamma, \beta)$ and not $h_i(\gamma, \beta)$.

Neatly,

$$\Gamma_{tot} = \frac{1}{2} \int \frac{d\Gamma^{\tau+} + d\Gamma^{\tau-}}{dQ^2 ds_1 ds_2 d\gamma d \cos \beta} dQ^2 ds_1 ds_2 d\gamma d \cos \beta \quad (1.17)$$

$$= \frac{1}{2} \int (c_{1+} + c_{1-}) dQ^2 ds_1 ds_2 \quad (1.18)$$

$$= \int c_{1+} dQ^2 ds_1 ds_2 \quad (1.19)$$

for $i=1$, $c_{1+} = c_{1-}$.

In $d\Gamma_i^{(-)}$, the $(-)$ refers to CP-odd,

$$\frac{d\Gamma_i^{(-)}}{dQ^2} = \frac{1}{2} \int \left(\frac{d\Gamma_+}{dQ^2 ds_1 ds_2 d \cos \beta d\gamma} - \frac{d\Gamma_-}{dQ^2 ds_1 ds_2 d \cos \beta d\gamma} \right) \times h_i(\gamma, \beta) d \cos \beta d\gamma ds_1 ds_2 \quad (1.20)$$

$$= \frac{1}{2} \int (c_{i+}(Q^2, s_1, s_2) - c_{i-}(Q^2, s_1, s_2)) ds_1 ds_2 \times \int h_i^2(\gamma, \beta) d \cos \beta d\gamma. \quad (1.21)$$

$$\frac{1}{\Gamma_{\text{tot}}} \frac{d\Gamma_i^{(-)}}{dQ^2} = \frac{\int (c_{i+}(Q^2, s_1, s_2) - c_{i-}(Q^2, s_1, s_2)) ds_1 ds_2}{\int (c_{1+}(Q^2, s_1, s_2) + c_{1-}(Q^2, s_1, s_2)) ds_1 ds_2 dQ^2} \times \int h_i^2(\gamma, \beta) d\cos\beta d\gamma. \quad (1.22)$$

For example, when the rate is integrated over the full phase space we get

$$a_1^+(b) = \int \frac{1}{\Gamma_{\text{tot}}} \frac{d\Gamma_1^{(+)}}{dQ^2} \quad (1.23)$$

$$= 1. \quad (1.24)$$

The long term aim of this work is to perform first CPV experimental analysis of $\tau^- \rightarrow K^- \pi^+ \pi^- \nu_\tau$ and $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$.

2 - Belle II detector

2.1 . SuperKEKB accelerator

SuperKEKB is an asymmetric 3 km circumference electron-positron collider situated in Tsukuba (located around 50 km from Tokyo), Japan. The electron beam circulates at 7 GeV in the high energy ring (HER), and the positron beam circulates at 4 GeV in the low energy ring (LER) (see Fig. 2.1).

During the experiment that runs continuously for several hours, losses of the electrons occur. To solve this, an operation called top-up is performed. Fresh electrons are regularly injected on top of circulating bunches in the accelerator, about every minute. This injection is at a much faster rate than the beam lifetime.

Electrons are generated using a photocathode radio frequency (RF) gun. The RF gun produces electron bunches with a charge of about 5 nC and emittance of about (10mm.mrad). The cathode is made of a metal composite (IrCe), which is characterized by a good quantum efficiency. A Nd : YAG laser system provides the laser pulses that cause photoemission [60]. Electrons are produced at around 1MeV. They are then injected into the LINAC at a few MeV to a few GeV, then into the HER.

Positrons are produced out of electrons. Hitting electrons on a fixed tungsten target creates bremsstrahlung photons that lead to the production of electron-positron pairs inside the target. Positrons are first injected into the damping ring in which their momentum spread and emittance are reduced. They are also grouped into tightly packed bunches before being accelerated up to the LER.

Electrons and positrons collide at the interaction point (IP) at the resonance $\Upsilon(4S)$ which corresponds to an energy of 10.58GeV in the center-of-mass frame. This resonance predominantly decays into B-meson pairs, making it ideal for studying B-meson decays and flavor physics. However, collisions of electrons and positrons at this energy produce other processes that contribute to a continuum background (see Fig. 2.2). The values for the cross sections of these processes are shown in Table 2.1. Even though SuperKEKB operates most of the time at the $\Upsilon(4S)$ resonance, it also runs at $\Upsilon(5S)$, and also at off-resonance energies. The off-resonance runs are useful for studying bottomonium spectroscopy and potential signs of new physics [61].

SuperKEKB collider has a design luminosity of $6 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$, which is 30 times the luminosity of KEKB, its predecessor. The goal is

to accumulate a total integrated luminosity of 50 ab^{-1} . It has collected 424 fb^{-1} of total integrated luminosity for good runs : 363 fb^{-1} of data at the $\Upsilon(4S)$ resonance, 42 fb^{-1} of data below the $\Upsilon(4S)$ resonance and 19 fb^{-1} of data above the $\Upsilon(4S)$ resonance [62]. It has achieved the highest instantaneous luminosity record of $2.22 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ in June 2020, and broke this record reaching $4.71 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ in June 2022. It broke its record again, reaching $5.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ in December 2024 [63]. The luminosity of the electron-positron interaction reads [64] :

$$L = \frac{\gamma_{\pm} \xi_y^{\pm} I_{\pm}}{2e r_e \beta_y^*} \left(1 + \frac{\sigma_y^*}{\sigma_x^*} \right) R_L R_{\xi_y} \quad (2.1)$$

where $\gamma_{\pm}$ is the Lorentz factor, $I_{\pm}$ is the beam current, β_y^* is the vertical beta function at the IP, R_L is the geometrical reduction factor, $\xi_y^{\pm}$ is the vertical beam-beam parameter and R_{ξ_y} is called the beam-beam parameter (note that it is different than the vertical beam-beam parameter). This parameter measures the non-linear electromagnetic interactions between the colliding bunches. In fact, when two high-density particle beams collide, the strong electromagnetic field of one beam focuses the other (if beams are of opposite charge), causing a perturbation in the particle trajectories. While increasing the bunch density increases the luminosity, it also increases the beam-beam parameter. To mitigate the beam-beam effect, an upper limit can be determined beyond which the beam quality decreases, leading to instabilities, a loss of focus at the IP and emittance growth.

It can be seen from Eq. 2.1 that the luminosity increases by increasing the beam current and reducing the beta function. A high luminosity in SuperKEKB is achieved thanks to its nano-beam scheme (see Fig. 2.3 for the geometry of the collision). It consists of squeezing the beams in order to make them "flat" at the IP, which increases the collision rate through high density beams of particles colliding. This scheme can also be achieved by reducing the vertical beta function to have a tight focus of the beams in the interaction region. The collision beams are then asymmetric with a smaller vertical size than the horizontal one. This shape is particularly useful for reducing beam-beam interactions that are disruptive during collisions.

2.2 . Belle II

Belle II detector is located around the interaction region of the electron and positron beams. It is cylindrically shaped and is formed of several sub-detectors that surround the interaction point (see Fig. 2.4). Each subdetector has a specific role in the global performance of the

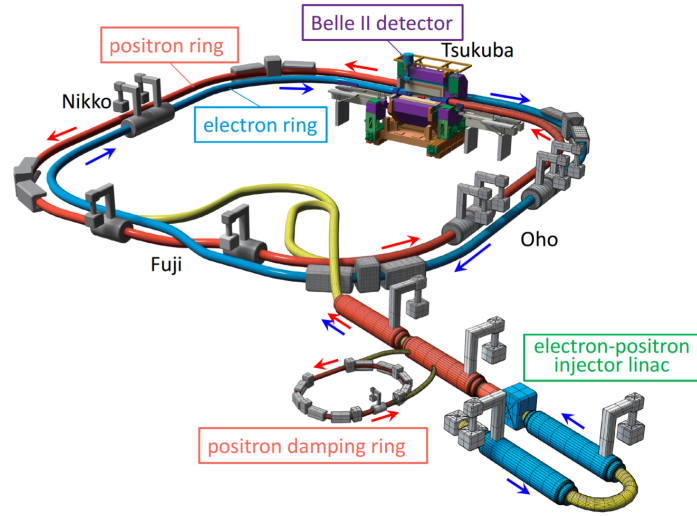


Figure 2.1 – Schematic view of SuperKEKB accelerator [65]. It includes a high energy ring where electrons travel (in blue), a low energy ring where positrons travel (in red), an electron-positron injector linear accelerator (LINAC), and a positron damping ring of 1.1 GeV.

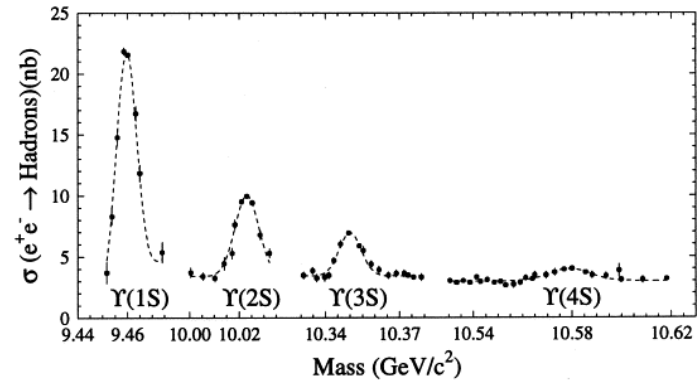


Figure 2.2 – Cross section as function of the center of mass energy of the e^+e^- collision [66].

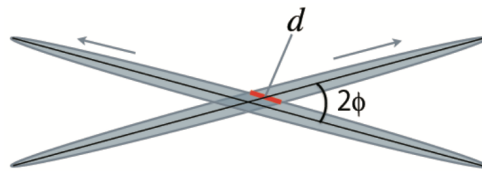


Figure 2.3 – Scheme representing the collision geometry of the beams at the interaction point [73]. The angle separating the beams is $2\Phi = 83$ mrad.

Process	Cross-section (nb)
$\tau^+\tau^-$	0.919
$\Upsilon(4S)$	1.11
$u\bar{u}$	1.61
$d\bar{d}$	0.40
$s\bar{s}$	0.38
$c\bar{c}$	1.30
e^+e^-	300
$\mu^+\mu^-$	1.147
$e^+e^-e^+e^-$	39.7
$e^+e^-\mu^+\mu^-$	18.9
$e^+e^-\tau^+\tau^-$	0.182

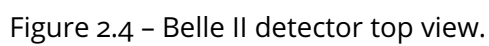
Table 2.1 – Cross sections of e^+e^- going to different processes, at $\sqrt{s}=10.58$ GeV [67, 68, 69, 70, 71, 72]. $\tau^+\tau^-$ is the process we are interested in. All the other processes are considered as background in our analysis.

experiment. In the following sections, I describe each of the components. Belle II has already collected data with 575 fb^{-1} of total integrated luminosity (see Fig. 2.5). For reference, the BaBar experiment collected a total integrated luminosity of around 513 fb^{-1} [74]. The Belle experiment, on the other hand, collected a total luminosity of about 1 ab^{-1} [75]. In this thesis, I analyze a fraction of the data collected, corresponding to 364 fb^{-1} of luminosity.

Belle II can detect six types of charged particles : electrons, muons, pions, kaons, protons, and deuterons. It can identify the particles and distinguish between the different types based on their interactions with the detector subsystems. It can detect neutral particles : photon, neutron and long kaon K_L^0 .

2.2.1 . Vertex detector

The vertex detector (VXD) is the subdetector closest to the IP, so it is the first system with which charged particles interact. Its role is to precisely determine the trajectories of charged particles around the interaction region. It also reconstructs the decay vertices of particles resulting from collisions. It is designed to be well resistant to high radiation generated by electron beams. The VXD consists of two components : the pixel detector (PXD) and the silicon vertex detector (SVD) (see Fig. 2.6).



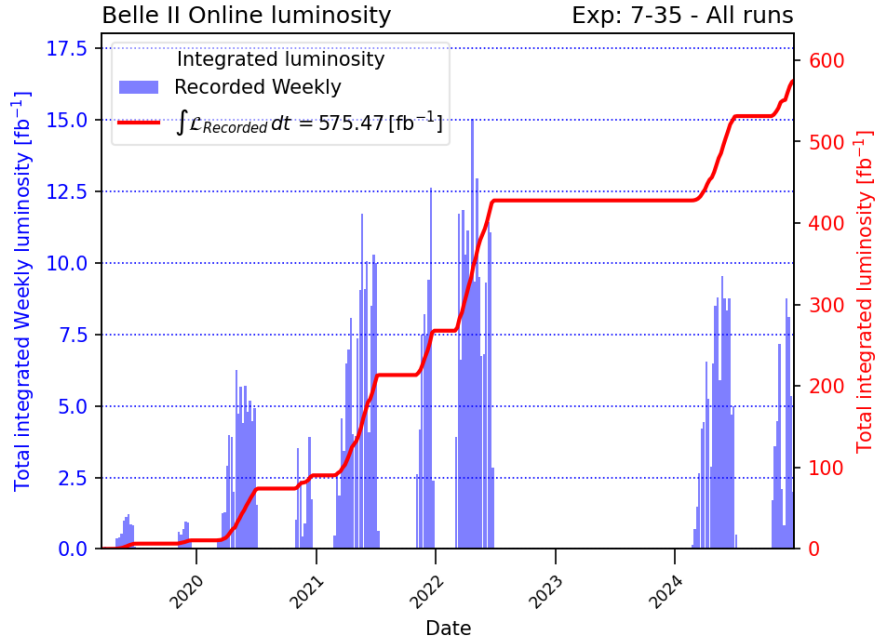


Figure 2.5 – Total integrated weekly luminosity of Belle II [62]. Blue bins represent the integrated luminosity per week, and the red curve is the total integrated. Data collection started in 2019, there was a long shutdown LS1 that began in 2022. Run resumed in 2024.

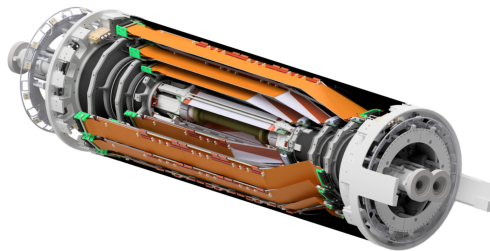


Figure 2.6 – View of the vertex detector, formed by the pixel detector and the silicon vertex detector [76].

PXD

The PXD consists of two layers of DEPFET (DEpleted Field Effect Transistor) pixel sensors [77], designed to provide precise tracking measurements for charged particles. The inner layer has 8 ladders, the outer layer has 12, and each ladder is of 768×250 pixels. The PXD layers are positioned at radii of 14 mm (inner) and 22 mm (outer) from the beam pipe [78]. The DEPFET pixels are constructed on thin detector-grade silicon with a silicon frame. PXD has in fact a fine granularity that provides a high spatial resolution (see Fig. 2.7). The readout electronics and power lines are positioned outside the sensitive volume of the detector [61]. This design allows for efficient data collection. It is unfortunate that during the data collection in 2024, PXD suffered some limited damage due to sudden beam loss (SBL). SBL are the beam losses that occur suddenly after very few turns of the electron bunches without any prior warning. It is a phenomenon that became common in Belle II community and was investigated by accelerator experts for some time. By fear of causing additional damage to the PXD, it was switched off during the run in 2024 to shield it from radiation.

The PXD layer served until 2022. Then a second layer of PXD was installed in 2023. PXD2 was constructed and commissioned during the PXD1 operation. It has the same technology as PXD1 but with a complete layer that fills the gap with the SVD [79].

The PXD has a hit efficiency of about 99% [80].

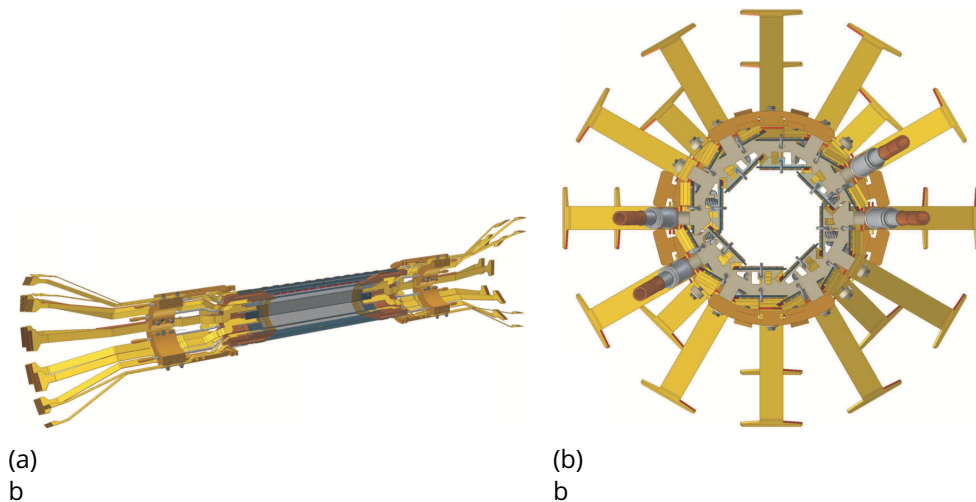


Figure 2.7 – PXD detector view : (a) in 3D, (b) along the beam pipe [73].

SVD

The SVD provides precise vertex reconstruction of charged particles. It has four layers of double-sided silicon strip sensors (DSSDs) positioned at radii of 39, 80, 104, and 135 mm from the beam pipe. The 172 DSSD sensors are arranged in ladders that form a cylindrical shape around the beam pipe (see Fig. 2.8) [81]. When charged particles pass through the silicon strips, they ionize them, which generate signals that allow their detection. The resolution of the position is about 7–11 μm in the azimuthal ($r\phi$) direction (perpendicular to the beamline) and 23–35 μm in the longitudinal (z) direction (along the beamline). This accuracy allows for good reconstruction of the decay vertices, especially for short-lived particles.

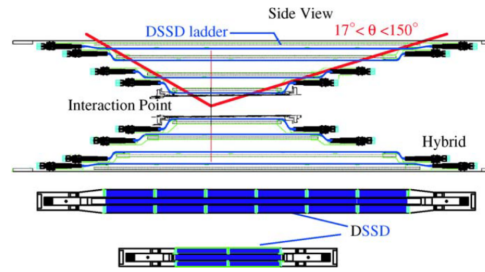


Figure 2.8 – Longitudinal cross section of the SVD [82].

2.2.2 . Central Drift Chamber

The central drift chamber (CDC) is mainly used to measure the precise momenta of the charged particles. It has 14336 sense wires organized in 56 layers filled with a low Z helium-ethane ($\text{He-C}_2\text{H}_6$) gas admixture. It has an optimal performance, thanks to the minimization of multiple Coulomb scattering. These wires are arranged in nine superlayers (see Fig. 2.9), alternating between axial configurations (aligned with the z -axis of the detector) and stereo configurations (twisted forming an angle up to 80 mrad) (see Fig. 2.10). Both configurations are used to determine the r and z positions of the particle. As it precisely measures tracks, the CDC has a single-hit spatial resolution of approximately 100 μm and a polar angle acceptance ranging from 17° to 150° .

Technically, as particles pass through the CDC, they ionize its gas mixture. Due to applied voltage, the resulting electrons drift toward the sense wires, leading to the generation of a signal called CDC hit. The energy loss distribution dE/dx of the particles can then be measured. This measurement of drift time contributes to the reconstruction of the full momentum of the track. Furthermore, by measuring the energy loss, the CDC is a key element for particle identification (PID)

using Bethe-Bloch formula. In fact, it can identify the particles through their ionization profiles which depend on their momenta. This can be useful, especially for particles of low momenta or that do not reach PID systems due to acceptance limitation. The performance of PID based on CDC data is studied by the performance group.

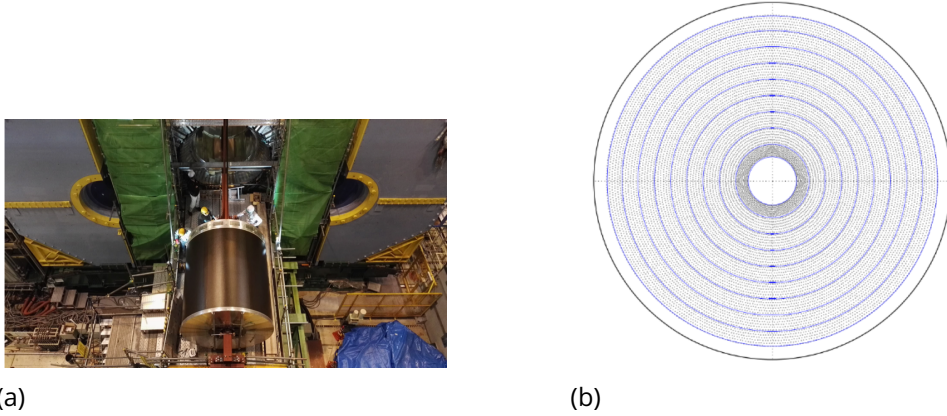


Figure 2.9 – (a) Photo of the central drift chamber being installed into Belle II [83], (b) CDC detector view along $r\Phi$ where we can see the nine super-layers [83].



Figure 2.10 – Wire layers of the drift chamber (a) axial : parallel to the beam-pipe, (b) stereo : skewed [83].

2.2.3 . Particle Identification system

For particle identification (PID), Belle II has two main components : time-of-propagation (TOP), which is used in the barrel region and Aerogel Ring Imaging Cherenkov (ARICH), which is used in the endcap regions.

TOP

TOP is a Cherenkov detector that is used to identify particles. TOP consists of 16 detector modules, each containing two quartz bars, resulting in a total length of 2.5 to 2.6 m, a width of 44 to 45 cm, and a thickness of 2 cm (see Fig. 2.11). These quartz radiators are positioned along the outer walls of CDC and are equipped with a mirror at the forward

end to reflect Cherenkov light toward the photodetectors at the backward end. In fact, as a charged particle passes through the quartz bar, it emits Cherenkov light within a characteristic angle θ_C . The emitted photons travel through the quartz bar and are detected at the end by micro-channel plate photomultipliers (MCP-PMTs). A Cherenkov image can be reconstructed in 3D using the hit position (x,y) of the photons on the photodetectors and their precise hit time.

By measuring the Cherenkov angle, one can deduce the velocity β of the particle, based on :

$$\cos \theta_C = \frac{1}{\beta n}$$

where n is the refractive index of the medium. Then, by combining the velocity and the information of the momentum measured typically from the CDC, one can deduce the mass of the particle using :

$$\beta = \frac{p}{\sqrt{p^2 + m^2}}$$

and thus make a PID assumption based on the mass. A focusing system is also implemented to separate the photons according to their wavelengths, which improves the PID efficiency. Advanced waveform sampling readout electronics are also added. These achieve a time resolution of approximately 50 ps. This allows us to distinguish between kaons and pions, as the time of propagation of their resulting photons differs by about 100 ps at an energy of 2 GeV. An expansion wedge is also used at the photodetector end to reduce hit occupancy and further improve timing precision [61].

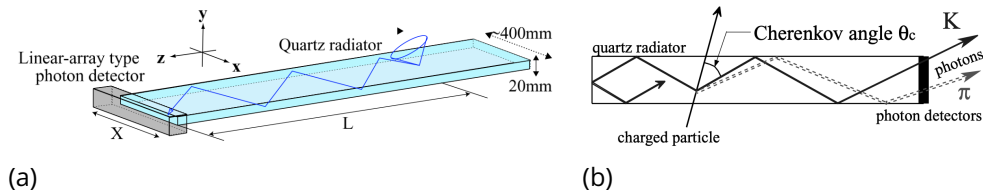


Figure 2.11 – (a) Scheme of TOP counter side-view (b) Cherenkov photons reflecting in a quartz bar of TOP [73].

ARICH

ARICH counter is used to improve particle identification by detecting Cherenkov radiation. It consists of a silica aerogel radiator and a plane of hybrid avalanche photon detector (HAPD), which are separated by an expansion volume (see Fig. 2.12). This design allows Cherenkov photons to form detectable rings on the photon detectors (see

Fig. 2.13). To optimize photon detection while conserving the Cherenkov emission angle resolution, the system uses two layers of aerogel with different refractive indices : $n_1 = 1.045$ for the upstream layer and $n_2 = 1.055$ for the downstream layer. This technique increases the number of detected photons, improving the accuracy of PID measurements. The HAPD is specifically designed to detect single photons with high granularity, thanks to its 144 channels detecting photoelectrons. This system has a resolution for photon detection that is $\sigma_\theta = 14.3$ mrad per photon. This resolution allows for the correct identification of particles, especially in a challenging momentum range of 0.4 GeV to 4 GeV [61].

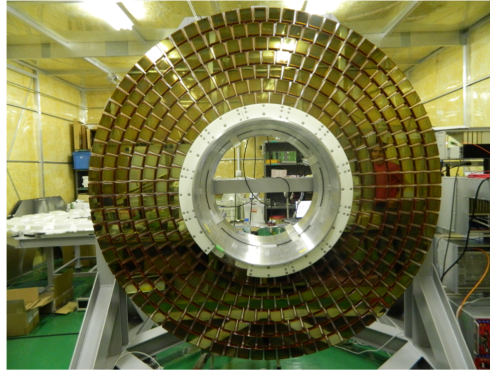


Figure 2.12 – Picture of ARICH : plane of HAPD photon detectors [61].

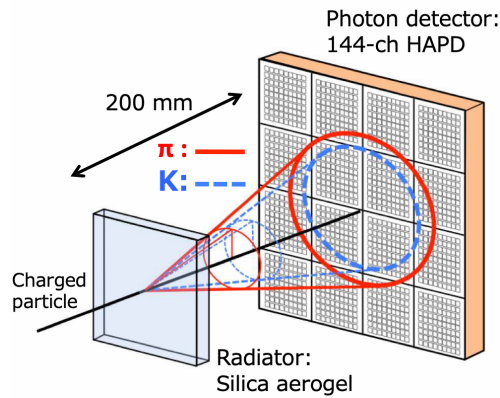


Figure 2.13 – Cherenkov rings created on the HAPD sensors of ARICH counter [84]. This shows how ARICH can distinguish pions from kaons. The solid (dotted) line represents Cherenkov light emitted from a pion (kaon).

Particle identification

The charged particles identification (PID) is based on the computation of the likelihood variable for all sub-detectors. Each sub-detector contributes a likelihood $\mathcal{L}_i$ for a particle to be identified of type i (where i can be e, μ, π, K, p , or d). The total likelihood $\mathcal{L}_i$ is then the sum over the likelihood for all sub-detectors. The PID variable is defined as the normalized likelihood :

$$\text{PID}(i) = \frac{\mathcal{L}_i}{\mathcal{L}_e + \mathcal{L}_\mu + \mathcal{L}_\pi + \mathcal{L}_K + \mathcal{L}_p + \mathcal{L}_d}.$$

For hadron identification [85], a likelihood ratio is constructed to compare two hypotheses, α and β , using data from the CDC (dE/dx), time of flight (TOF), and the number of photons from the ARICH sub-detector. This ratio is given by [86]

$$L(\alpha : \beta) = \frac{\mathcal{L}_\alpha^{\text{CDC}} \mathcal{L}_\alpha^{\text{TOF}} \mathcal{L}_\alpha^{\text{ACC}}}{\mathcal{L}_\alpha^{\text{CDC}} \mathcal{L}_\alpha^{\text{TOF}} \mathcal{L}_\alpha^{\text{ACC}} + \mathcal{L}_\beta^{\text{CDC}} \mathcal{L}_\beta^{\text{TOF}} \mathcal{L}_\beta^{\text{ACC}}}.$$

In case a sub-detector fails to provide a likelihood, a value of 0.5 is returned to avoid any bias in the identification. The identification of kaons and pions are made through the variables KID and πID , given by :

$$\begin{aligned} KID &= \mathcal{L}(K : \pi) \\ \pi ID &= \mathcal{L}(\pi : K) = 1 - KID. \end{aligned}$$

For example, the efficiency of kaon identification can be seen in Fig. 2.14.

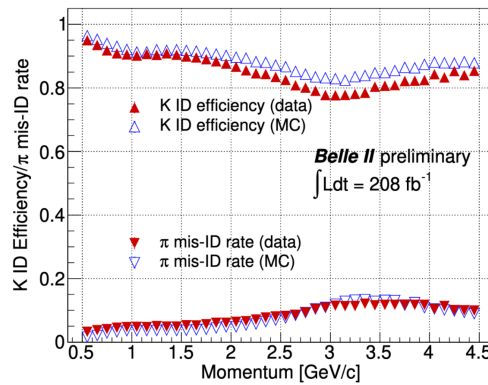


Figure 2.14 – Kaon identification efficiency as function of track momentum [87] for data compared to MC. The efficiency is around 90%, we have an overall good kaon identification. We also have the efficiency of the identification of pions misidentified as kaons, which is around 6%.

2.2.4 . Electromagnetic calorimeter

The electromagnetic calorimeter (ECL) serves to measure the energies of photons and electrons. It detects gamma rays and neutral pions and distinguishes electrons from hadrons, particularly pions. It consists of 8736 crystals of thallium-doped cesium iodide CsI (Ti) that cover, in a projective geometry, a significant majority of the solid angle in the center-of-mass frame [61]. These crystals form a 3 m long barrel with an inner radius of 1.25 m and a polar angle of 12.4° to 155.1° . Each of these crystals (see Fig. 2.15) emits scintillation light proportional to the energy deposited by the interacting particle. This light is captured by two photodiodes that convert it to an electric signal [88]. Then both outputs are summed to produce one robust signal and sent to the preamplifiers for additional processing. This signal represents a detailed map of the energy deposition in the calorimeter and provides information on the energy and type of the interacting particles. In addition, the ECL implements pulse-shape discrimination, allowing it to separate electromagnetic showers from hadronic showers. This is a new feature of Belle II with respect to Belle. The ECL has an energy resolution ranging from 4% at 100 MeV to 1.6% at 8 GeV. Its angular resolution varies from 13 mrad for low energy particles to 3 mrad for high energy particles. Its π^0 mass resolution is around $4.5 \text{ MeV}/c^2$ [61].

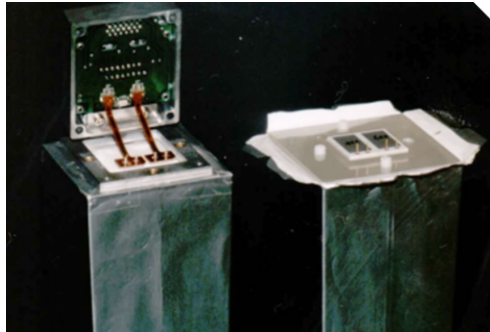


Figure 2.15 – Picture of an ECL crystal attached to its photodetectors [88].

2.2.5 . Long kaon and muon detector

The K_L^0 and Muon Detector (KLM) is the outermost detector of Belle II. It is specifically designed to identify muons and neutral kaons. It has a structure of 15 4.7 cm thick iron plates sandwiched with 14 active detector layers, placed outside of the solenoid. Due to their 3.9 interaction lengths, the iron plates serve as absorber material, allowing the K_L^0 mesons to shower hadronically. Also, thanks to this structure, the detection of muons of momenta above 600 MeV/c is effective. This is

valid since muons do not lose energy through bremsstrahlung radiation and so travel further and out of the ECL, unlike electrons. The KLM is formed by a barrel region and end-caps. The barrel region covers a polar angle ranging from 45° to 125° and contains Resistive Plate Chambers (RPC) with glass electrodes that are the main active detector elements (see Fig. 2.16). The endcap regions and innermost barrel layers contain rather layers of scintillator strips. These strips are coupled with wavelength-shifting fibers, which makes the light collection better and the signal readout faster. This helps alleviate the long dead time associated with RPCs in these high background rates (mainly of neutrons) regions [61] (see Fig. 2.17). The KLM can distinguish between muons and hadrons. In the case of a neutral hadronic shower, the particle is identified as a K_L^0 meson. The direction of the shower is reconstructed from the spatial distribution of hits in the KLM. Assuming that K_L^0 originated from the interaction point, this direction allows to estimate the meson momentum. In contrast, in the case of a charged track with characteristic range and transverse deflection, the particle is identified as a muon. The efficiency of muon detection exceeds 93% (see Fig. 2.18).

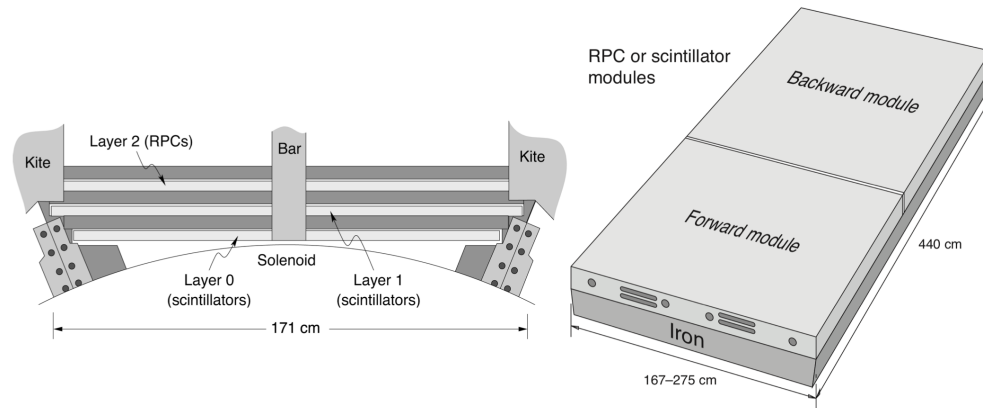


Figure 2.16 – KLM barrel region. There are glass-electrode RPCs in the outer 13 layers and scintillators in the 2 innermost barrel layers [89].

2.2.6 . Trigger system

Thanks to a high luminosity and fast bunch-crossing rate, a large number of events are produced at SuperKEKB. As there are 2500 bunches in the beam that collide every 4 ns, the event generation is at a very high rate. If all events were saved, the required data storage would be massive. Having a bunch cross frequency of 250 MHz and assuming that an event was generated at each bunch crossing, the event rate would be 250×10^6 events/s. Assuming an event size of 100 kB, the storage required would be 25 TB/s, which would be extremely huge

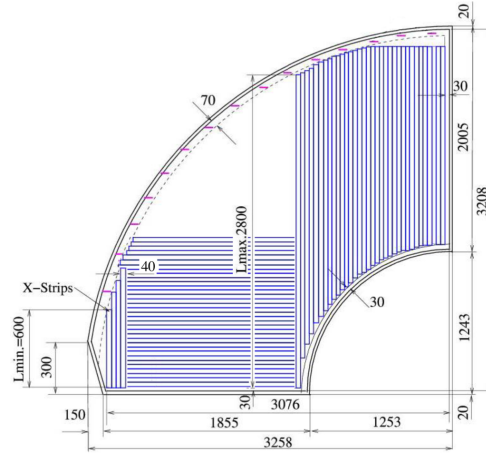


Figure 2.17 – Endcap scintillator of the KLM [89]. There are 16800 strips in total. The strips are attached to wavelength shifting fibers and read out by silicon photomultiplier (SiPMs) as light sensors [61].

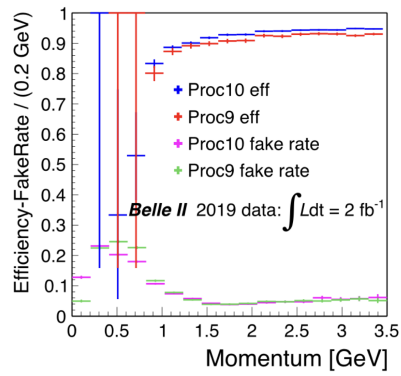


Figure 2.18 – Muon efficiency in the KLM as function of the momentum of the particle [89]. Proc are different productions of Belle II MC simulated data. The fake rate corresponds to the probability of misidentifying a hadron (mainly pions) as a muon.

and impossible to handle. This is why a trigger system is essential to make data storage much more manageable. Its job is to select and filter events in real time, making sure to reject background events and only keep relevant data for later analysis. The trigger system is composed of a Level-1 (L1) hardware trigger and a software-based High-Level Trigger (HLT). If not for these triggers, the Data Acquisition (DAQ) system would not be able to deal with the amount of data to be collected.

Moreover, the trigger system is needed to suppress background processes with extremely high rates. This can be visualized in the list of the cross section of the processes in Table 2.1. For example, the signal process $\tau^+\tau^-$ has a cross section of 0.919nb. This means that it occurs much less frequently with respect to background processes like Bhabha scattering (e^+e^-), which dominates with a cross section of 300nb. By removing these backgrounds, the trigger can efficiently select physics events of interest as well.

L1

L1 is an online trigger that decides fast and in real time to keep or discard an event. Using firmware-based reconstruction algorithms and advanced 3D tracking logic, L1 can filter out high background rates such as Bhabha scattering and beam-gas scattering events [61]. All while keeping a high efficiency for physics events, L1 can make 30000 trigger decisions per second (30 kHz) at maximum, which corresponds to the maximum input rate allowed by the DAQ system, and a latency (duration between an event happening and the trigger system making its decision to keep or reject it) of 5 μ s.

L1 processes trigger signals coming mainly from the CDC and the ECL triggers. These signals are then merged into a single decision using a Global Decision Logic (GDL) that is implemented on Field Programmable Gate Arrays (FPGAs). The event data are stored in a ring buffer. And in case the event is to be kept, its data are transferred through the Belle II link to the front-end readout boards of all subdetectors except PXD [61].

HLT

HLT is a software-based system that takes final decisions on whether to keep or discard an event. It further filters out background events that have previously passed through the L1 trigger, by using sophisticated software algorithms. These algorithms require reconstruction of particle trajectories, calculation of event topologies, and analysis of the physical properties of particles. More advanced than the L1

trigger that simply makes a keep or reject decision, the HLT also adds a certain tag to each event, classifying it by its physics process. Having around 20 units, HLT can have a total of 6400 processes running simultaneously in parallel to make trigger decisions. It also takes at most 300 ms per event to choose whether the event is stored or discarded. HLT refines the selection of events and reduces the trigger rate to 10 kHz for final storage [61].

HLT work is organized into three domains : monitoring, skims, and software optimization.

B2monitoring In order to ensure that the trigger runs efficiently and stably, some monitoring is required on its system. B2monitoring is designed to evaluate the performance of trigger algorithms in real time. It consists of two main parts : Data Quality Monitoring (DQM) [90] and Mirabelle [91]. DQM shows plots of each run of experiments, which can be monitored online by Belle II Control Room (CR) shifters. These plots display rates, latencies, efficiencies, and background suppression parameters in real time. Mirabelle adapts these plots by showing them for each run. Considering the trigger rate, B2monitoring tracks the event rates at the L1 and the HLT levels and guarantees that their output rates (30 kHz for L1 and 10 kHz for HLT) stay within their limits. It can then identify unexpected drops or spikes in these rates, helping to detect trigger issues.

2.2.7 . My contribution to the High Level Trigger

I completed my service task and became an author in Belle II. I worked essentially on HLT monitoring and skim. Regarding monitoring, I made some changes to the Mirabelle monitoring webpage [91]. In a plot showing the mean processing time per section for many parameters, I added two new parameters to the plot. The changes are taken into account after merging my code into the software of the collaboration. In the end, it seems rather easy, but it was not a simple task. In fact, I had struggled for a while to understand the code. I took some time to figure out how the software works, how to manipulate it, and how to include the necessary correct modifications. I made some tests before pushing and merging them into the official software. It was fun and exciting to see my changes on an official website of Belle II, which will be helpful for many.

Second, I fixed an error in the code. The way an opening angle was calculated was wrong, and I fixed the formula. I also had to learn how the code in HLT skimming works and how to apply my modifications. An angle was defined as the difference between the angle θ of two 4-

vector particles, while it should have been its sum. So when I implemented the correct formula, I did some tests to make sure that nothing else was modified. The test did not show any change in the skimming efficiency of all other skims, only a change in the skim involved, within a reasonable amount (see Fig. 2.20, 2.21).

Third, I added more plots to the Mirabelle website that relate to the L1 trigger. This plot shows the efficiency of the triggers "online" on the webpage. This is very useful for shifters in Belle II Control Room, to keep observing it and to check all variables (the histogram) are within the correct ranges. I contributed to a few other tasks that I will not discuss here.

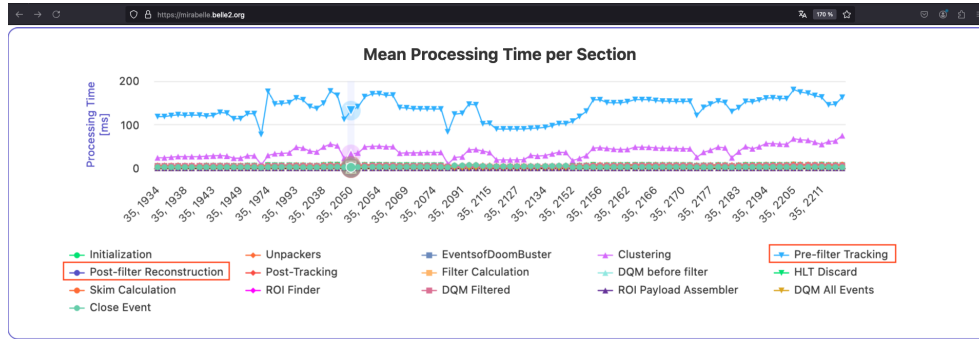


Figure 2.19 – HLT monitoring on Mirabelle [91], showing the mean processing time per section as function of the run/experiment of Belle II for different parameters. There was a parameter showing the tracking/reconstruction. I removed it and added the correct code to take into consideration the pre-filter tracking and post-filter reconstruction.

2.3 . Basf2

The Belle II Analysis Software Framework (basf2) is a software developed and used by the Belle II collaborators for data processing and analysis in the Belle II collaboration. It is adapted from Belle's framework basf with advanced features. Basf2 is written in C++ and provides a Python interface. Having access to many modules and configurations, basf2 can perform multiple tasks, including Monte Carlo simulations, event reconstruction, and variable computation used for physics analyses. Each of the modules is responsible for a specific task. The data is processed event by event using ROOT. The framework is often updated with new releases, which also requires new data processing and simulations. There are also light-releases that are targeted for physics analyses.

Skims				
skim accept 1 track1 cluster	$opAng = V4p1.Theta() - V4p2.Theta()$	80 (3.37%)	80 (3.37%)	1.0
skim accept 2 tracks		680 (28.62%)	680 (28.62%)	1.0
skim accept b2bcluster 3D		863 (36.32%)	863 (36.32%)	1.0
skim accept b2bclusterhigh phi		497 (20.92%)	497 (20.92%)	1.0
skim accept b2bclusterlow phi		840 (35.35%)	840 (35.35%)	1.0
skim accept bhabha		305 (12.84%)	305 (12.84%)	1.0
skim accept bhabha all		520 (21.89%)	520 (21.89%)	1.0
skim accept bhabhae1		152 (6.40%)	152 (6.40%)	1.0
skim accept dstar 1		3 (0.13%)	3 (0.13%)	1.0
skim accept dstar 2		27 (1.14%)	27 (1.14%)	1.0
skim accept dstar 3		27 (1.14%)	27 (1.14%)	1.0
skim accept dstar 4		2 (0.08%)	2 (0.08%)	1.0
skim accept fourlep		120 (5.05%)	120 (5.05%)	1.0
skim accept gamma gamma		143 (6.02%)	143 (6.02%)	1.0
skim accept hadron		307 (12.92%)	307 (12.92%)	1.0
skim accept hadronb		312 (13.13%)	312 (13.13%)	1.0
skim accept hadronb1		145 (6.10%)	145 (6.10%)	1.0
skim accept hadronb2		121 (5.09%)	121 (5.09%)	1.0
skim accept jpsi		27 (1.14%)	27 (1.14%)	1.0
skim accept kshort		59 (2.48%)	59 (2.48%)	1.0
skim accept l1 nn info		2376 (100.00%)	2376 (100.00%)	1.0
skim accept lambda		64 (2.69%)	64 (2.69%)	1.0
skim accept mumu ltrk		80 (3.37%)	80 (3.37%)	1.0
skim accept mumu ltrk		124 (5.22%)	124 (5.22%)	1.0
skim accept mumu highmass		38 (1.60%)	38 (1.60%)	1.0
skim accept mumu tight or highm		46 (1.94%)	46 (1.94%)	1.0
skim accept mumutight		35 (1.47%)	35 (1.47%)	1.0
skim accept offip		40 (1.68%)	423 (17.80%)	15.0
skim accept radee		411 (17.30%)	411 (17.30%)	1.0
skim accept radmumu		40 (1.68%)	40 (1.68%)	1.0
skim accept single photon 10eV		485 (20.41%)	485 (20.41%)	1.0
skim accept single photon 20eV barrel		411 (17.30%)	411 (17.30%)	1.0
skim accept single photon 20eV endcap		299 (12.58%)	299 (12.58%)	1.0
skim accept tau 2trk		627 (26.39%)	627 (26.39%)	1.0
skim accept tau Ntrk		459 (19.32%)	459 (19.32%)	1.0
skim accept tau tau		605 (25.46%)	605 (25.46%)	1.0
skim total result		2376 (100.00%)		NaN

Figure 2.20 – List of skims before the change, so the opening angle is miscalculated as a difference of the 2 4-vectors of particles.

Skims				
skim accept 1 track1 cluster	$opAng = V4p1.Theta() + V4p2.Theta()$	85 (3.56%)	85 (3.56%)	1.0
skim accept 2 tracks		678 (28.42%)	678 (28.42%)	1.0
skim accept b2bcluster 3D		873 (36.59%)	873 (36.59%)	1.0
skim accept b2bclusterhigh phi		499 (20.91%)	499 (20.91%)	1.0
skim accept b2bclusterlow phi		857 (35.92%)	857 (35.92%)	1.0
skim accept bhabha		299 (12.53%)	299 (12.53%)	1.0
skim accept bhabha all		514 (21.54%)	514 (21.54%)	1.0
skim accept bhabhae1		151 (6.33%)	151 (6.33%)	1.0
skim accept dstar 1		3 (0.13%)	3 (0.13%)	1.0
skim accept dstar 2		27 (1.13%)	27 (1.13%)	1.0
skim accept dstar 3		27 (1.13%)	27 (1.13%)	1.0
skim accept dstar 4		2 (0.08%)	2 (0.08%)	1.0
skim accept fourlep		122 (5.11%)	122 (5.11%)	1.0
skim accept gamma gamma		151 (6.33%)	151 (6.33%)	1.0
skim accept hadron		308 (12.91%)	308 (12.91%)	1.0
skim accept hadronb		310 (12.99%)	310 (12.99%)	1.0
skim accept hadronb1		145 (6.08%)	145 (6.08%)	1.0
skim accept hadronb2		121 (5.07%)	121 (5.07%)	1.0
skim accept jpsi		27 (1.13%)	27 (1.13%)	1.0
skim accept kshort		59 (2.47%)	59 (2.47%)	1.0
skim accept l1 nn info		2386 (100.00%)	2386 (100.00%)	1.0
skim accept lambda		65 (2.72%)	65 (2.72%)	1.0
skim accept mumu ltrk		73 (3.06%)	73 (3.06%)	1.0
skim accept mumu 2trk		123 (5.16%)	123 (5.16%)	1.0
skim accept mumu highmass		38 (1.59%)	38 (1.59%)	1.0
skim accept mumu tight or highm		46 (1.93%)	46 (1.93%)	1.0
skim accept mumutight		35 (1.47%)	35 (1.47%)	1.0
skim accept offip		25 (1.05%)	441 (18.48%)	15.0
skim accept radee		409 (17.14%)	409 (17.14%)	1.0
skim accept radmumu		40 (1.68%)	40 (1.68%)	1.0
skim accept single photon 10eV		494 (20.70%)	494 (20.70%)	1.0
skim accept single photon 20eV barrel		417 (17.48%)	417 (17.48%)	1.0
skim accept single photon 20eV endcap		302 (12.66%)	302 (12.66%)	1.0
skim accept tau 2trk		635 (26.61%)	635 (26.61%)	1.0
skim accept tau Ntrk		460 (19.28%)	460 (19.28%)	1.0
skim accept tau tau		603 (25.27%)	603 (25.27%)	1.0
skim total result		2386 (100.00%)		NaN

Figure 2.21 – List of skims after the change, so the opening angle is calculated correctly as a difference of the 2 4-vectors of particles. The skims are exactly the same except for the corresponding skim.

2.3.1 . Monte Carlo simulations

Monte Carlo (MC) simulations model the creation of particles and their interaction at the interaction point. They are useful for analysis studies, especially in event selection and efficiency estimation. There are different generators, each simulates a certain process. KKMC [92] is used for $e^+e^- \rightarrow \tau^+\tau^-$, TAUOLA [93] for τ decays, and PYTHIA [94] and EvtGen [95] for $q\bar{q}$ and $b\bar{b}$ events, respectively. PHOTOS [96] is for radiated photons in the final state. BabaYaga@NLO [97] is for radiative processes $e^+e^- \rightarrow e^+e^-(\gamma)$. GEANT4 [98] models the detector response and TSIM [99] models the simulation of the trigger system.

MC samples are labeled depending on the processing campaign and can be run-independent or run-dependent. Run-independent (ri) means that the background is simulated within fixed detector conditions. Run-dependent (rd) means that the modeling of the background represents actual run conditions but is obtained with a random triggering. To do so, the random triggers record the detector activity at arbitrary times, regardless of any physics collision. An unbiased frame of the machine and detector background is then obtained. These background frames are then overlaid onto simulated events to ensure that MC reproduces the same background as seen in real data.

As each run has its own background levels, the performance of the detector varies in each run. In order to well simulate the MC, we use rd simulations. By generating values for each run with background conditions and levels that match those observed in experimental data, rd is very necessary to compare MC with data.

2.3.2 . Experimental data

The data sample is a total of 575fb^{-1} . Each experiment has several runs. Most of the luminosity corresponds to the $\Upsilon(4S)$ resonance. Some runs are on different resonances, and others are at off-resonance.

2.3.3 . Skims

The skim is a list of additional selections that can be applied to further reduce data storage. It helps selecting certain events that are specific to certain physics analyses. Events that pass the criteria are then given a "flag". Skims are done on MC simulations and experimental data. There are three types of skim when studying τ decays. The one used for the analysis used in this manuscript is tauThrust, which will be explained later.

3 - Compton polarimeter

3.1 . Upgrade of Belle II and SuperKEKB

3.1.1 . Motivation

An upgrade of the SuperKEKB accelerator and its Belle II detector [100] is advisable. Several reasons are part of the motivation for this. The aim of SuperKEKB is to collect an integrated luminosity of 50 ab^{-1} . It was meant to be reached within about 15 years of full operation at a maximum instantaneous luminosity of $8 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ (see Fig. 3.1.) Unfortunately, the maximum luminosity reached in 2022 is $5.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ [63]. Instantaneous luminosity improvements are needed to reach 50 ab^{-1} . Some issues were observed that made the collection of data of such a luminosity no longer possible without further improvement, pushing through the limits of the experiment. One issue that has been observed is the sudden beam losses. These are losses of the beam that occur suddenly with very few turns without any prior warning. This has been especially a problem in events where the current in the bunch increases the limit of 0.7 mA [101]. However, the real cause of them is still being identified. Some hypotheses have been made as to why these happened, but none is unambiguously confirmed. These losses can degrade accelerator components, especially the collimators [101]. They cause the beam to be aborted and thus lost. The abort system of the beam is indeed fast and its role is to protect the hardware of the accelerator and experiment of high current beams that are possibly damage causing [101]. However, losses already occurred inside the detector, when small parts of the PXD subdetector have been damaged a little (see Fig. 3.2). The great majority of PXD system is still functional fortunately, it has been turned off out of precaution though during the run 2024b. These losses can also induce an increase in the detector backgrounds. For these reasons, it is necessary to resolve all the issues and to improve the accelerator and detector for a better overall performance and a better physics analysis.

3.1.2 . Upgrade features

The upgrade aims to focus on parts related to both the detector and the accelerator. Concerning the accelerator, the upgrade is essential to achieve its target luminosity. It involves a critical issue related to beam coupling in the horizontal and vertical directions. These beam couplings, if not controlled, the beam shape becomes distorted and the focus at the IP gets reduced. In order to reduce these couplings,

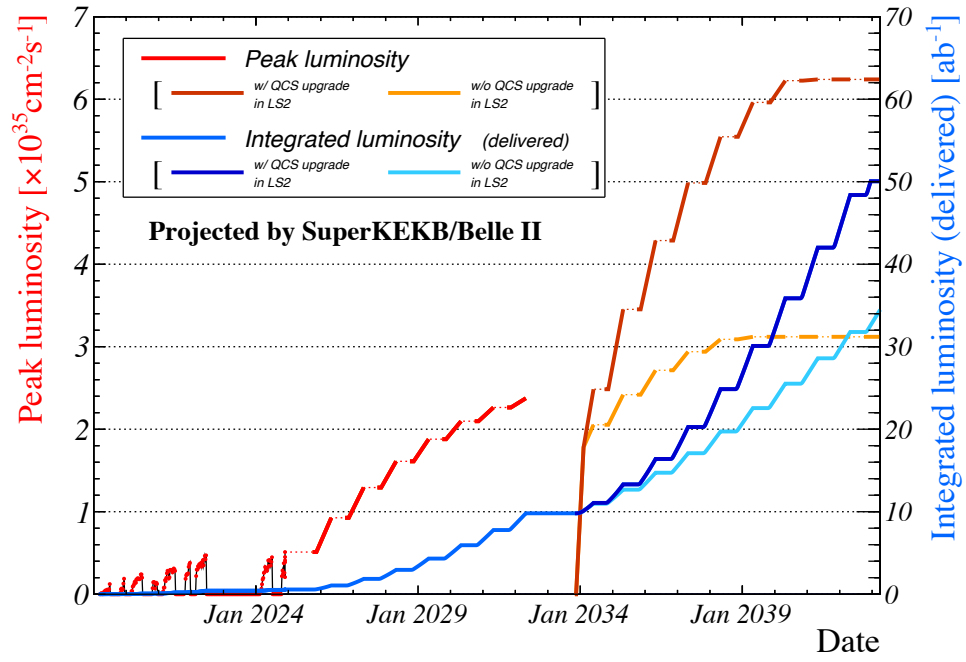


Figure 3.1 – Belle II luminosity projection over the years. Red curve is the instantaneous luminosity and blue is the integrated luminosity. Data collection started in 2019. In 2044 it is planned to reach 50 ab^{-1} after 25 years of operation [102].

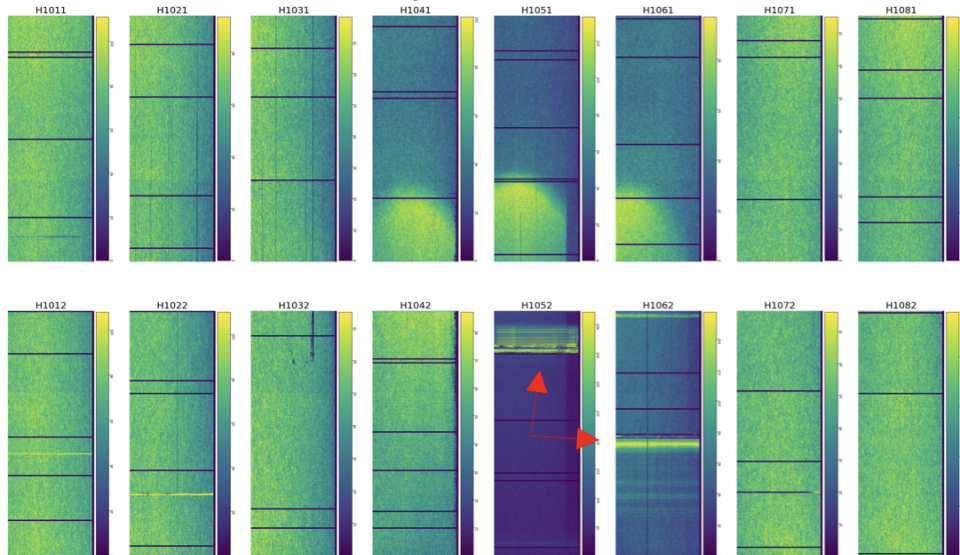


Figure 3.2 – View of the PXD2 after the beam loss [79]. A part has been slightly impaired.

the interaction region should be improved and the beams should be kept focused. This can be achieved by the integration of advanced quadrupole magnets and optics systems that fine-tune the beam particles' trajectories [100] (see Fig. 3.3). In fact, these magnets aim to control and adjust the size and shape of the beams in the horizontal and vertical directions, by making sure that the beams converge precisely at the point of collision. Squeezing the beams to very narrow sizes results in higher collision rates and higher luminosity. Upgrading the accelerator thus allows for a critical improvement in the luminosity.

Concerning the detector, one of them is to modify the tracking system by improving the efficiency and resolution of the collected tracks. This represents a challenge as a result of the high luminosity of Super-KEKB. So, the plan is to deal with all the background, but also with the lower momentum track particles that are more difficult to track in the presence of the backgrounds. In particular, it targets the acquisition and processing of data in the Central Drift Chamber (CDC) and the Silicon Vertex Detector (VTX). Advanced machine learning algorithms are to be introduced to improve the reconstruction of particle trajectories. These algorithms would increase the tracking efficiency, including that of the low momentum particles. In addition, analysis of finer details of the particle interactions would be possible. For example, an event where the vertex has been displaced, which happens when particles deviate from expected trajectories, would be better detected. The upgraded system will detect tracks more efficiently, especially those that form complex event topologies [100].

Another aspect related to the detector focuses on improving both the reconstruction and identification of long-lived neutral kaons K_L^0 , as their neutral charge and relatively long lifetimes make them difficult to measure. Thanks to the precision and resolution that would be gained in the CDC and VTX and to an improved granularity, it will be easier to detect and reconstruct the trajectories and vertices of these kaons more accurately [100], which are displaced from the primary IP at some times and traveling long distances from the IP before decaying. This would be very beneficial for Belle II analyses dealing with K_L^0 , especially those studying CP violation.

3.2 . Addition of polarized electron beam

3.2.1 . Goals

An important aspect included in the upgrade of the accelerator is the addition of polarized electrons. The Chiral Belle program is planned to polarize the electrons before colliding them. The main goal for this is

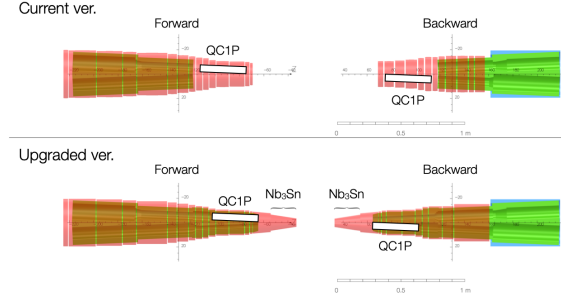


Figure 3.3 – Design of the magnets near the interaction region. Top figure represents the actual version, and bottom represents the new version. Pink represents the anti-solenoid coils and green the iron shield. Taken from [100]. The magnets QC1P will be positioned 100 mm closer to the IP. New magnetic yokes on QC1P will be installed too. This would eliminate a large part of vertical offsets that are caused by magnets. This would also make the beam trajectory more parallel to the magnet’s axis and cancel the horizontal-vertical couplings. This would decrease the beam emittance too [100].

an improvement of the global physics reach of the detector [100, 103], this while preserving the performances of the accelerator, especially by maintaining the luminosity. This addition would essentially expand the possibilities in the program of physics studies [104]. It would allow for high sensitive studies of the dark sector at a center-of-mass energy of 10 GeV, which could not have been possible previously. It would also allow for a precise measurement of the form factor $\tau g - 2 F_2$ (10 GeV) with a sensitivity of approximately 10^{-6} [105], going beyond the current limits. It would also allow higher precision studies of $\tau \rightarrow \mu\gamma$ and $\tau \rightarrow e\gamma$ decays which are forbidden in the SM.

Moreover, the polarization of the electron beam allows for high-precision electroweak measurements. One can determine the left-right asymmetry A_{LR} , which is the difference in cross sections for left handed and right handed polarized electron beams colliding with unpolarized positrons. Specifically, for the process $e^+e^- \rightarrow f\bar{f}$, with f being a fermion, the asymmetry is :

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \propto g_A^e \cdot g_V^f$$

where g_A^e is the axial-vector coupling of the electron and g_V^f the vector coupling of the fermion. This approximation holds for s -channel processes, but it is not valid when $f = e$, since in that case t -channel contributions (Bhabha scattering) must also be taken into account. Through the asymmetry, Chiral Belle could precisely measure the neutral current vector couplings g_V^f for leptons and heavy quarks, at the

10.58 GeV center-of-mass energy. This allows to probe the running of $\sin^2 \theta_W^{\text{eff}}$ with unprecedented precision. In fact, the sensitivity on A_{LR} is estimated in Fig. 3.4 for different final-state fermions. It is performed with 40 ab^{-1} of data and 70% polarization on the electron beam. The expected precision on the vector couplings and their contribution to determine $\sin^2 \theta_W^{\text{eff}}$ can be seen in Fig. 3.5.

Final State Fermion	SM A_{LR} (statistical error & sys from 0.5% P_e) for 40 ab^{-1}	Relative Error
b-quark (selection eff.=0.3)	-0.0200 ± 0.0001	0.5%
c-quark (eff. = 0.3)	+0.00546 ± 0.00003	0.5%
tau (eff. = 0.25)	-0.00064 ± 0.000015	2.4%
muon (eff. = 0.5)	-0.00064 ± 0.000009	1.5%
Electron (barrel) (eff. = 0.36)	+0.00015 ± 0.000003	2.0%

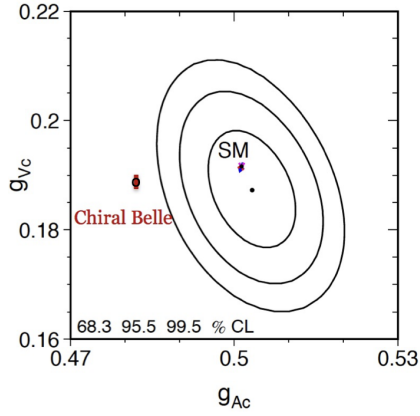
Figure 3.4 – Statistical errors on the asymmetry A_{LR} measurements for different final state fermion (b, c, τ, μ, e) [106].

3.2.2 . Key elements

The electrons of the high energy ring are so far not polarized. In fact, the process of intra beam scattering (IBS) leading to some particles losses from the beam happens more quickly than the process of radiative polarization which leads to natural polarization of the beam in the main SuperKEKB ring. More details about these processes are given in sections 3.3 and 3.3.1 respectively. So, SuperKEKB needs to be upgraded in order to have polarized beams. This requires several modifications. The first thing is to produce polarized electrons. The plan is to send a circularly polarized laser on a GaAs (Gallium Arsenic) photocathode target. This is represented in Fig. 3.6 showing the apparatus of

c-quark:

Chiral Belle ~7 times more precise

**b-quark:**

Chiral Belle ~4 times more precise

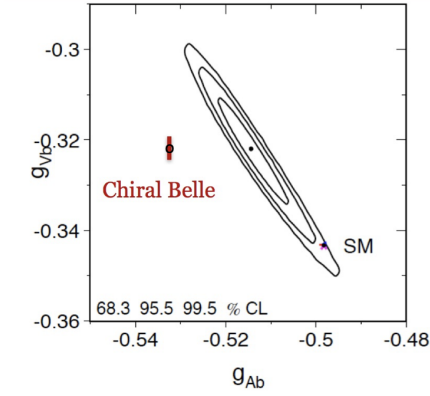
with 20 ab⁻¹

Figure 3.5 – The expected uncertainty bands of $\sin^2 \theta_W^{\text{eff}}$ for Chiral Belle compared to other experiments (such as ALEPH, DELPHI). This was adapted from [106]. One would gain at least 4 times the actual precision. [107].

a gun that is designed to produce a polarized electron beam. The photocathode for SuperKEKB is designed to photo-emit electron bunches with charge of 4 nC, vertical emittance of 20 mm-mrad and horizontal emittance of 50 mm-mrad. The material surface would also be prepared in such a way as to optimize efficiency in the photo-emission process, by using a treatment that makes it easier for electrons to depopulate the surface [104]. So, these GaAs cathodes could produce a polarized beam with a high efficiency, but they have a very short lifetime. This can be problematic and expensive to replace very often. So researchers at BNL are focusing their studies on extending its lifetime. This is based on a new technology of a superlattice structure [108]. This design, by essentially improving the mobility of charge carrier, significantly increases the quantum efficiency. Its layered structure is much more efficient than a conventional lattice structure [108]. This can be seen in Fig. 3.7.

After the creation of the electron bunches following a longitudinal polarization, the next step would be to turn their polarization immediately to vertical while they are still at low energy, by making them pass through a Wien filter [110, 111]. Using crossed electric and magnetic fields, this device carefully manipulates the polarization without changing the velocity of the electrons, the energy or the direction of the electron bunch. A vertically polarized bunch is then easier to carry through the accelerator ring. The bunches are injected into the 600 m LINAC

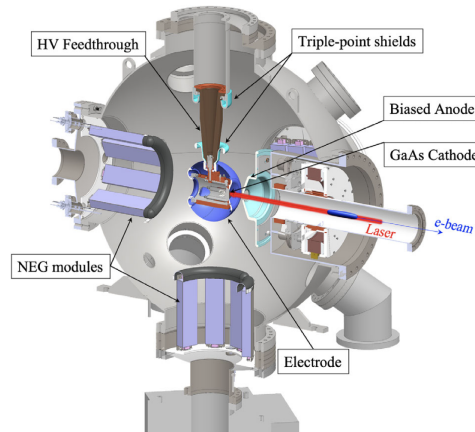


Figure 3.6 – Scheme of the BNL apparatus [109]. It is a HVDC gun designed to produce a polarized electron beam. When illuminated by the laser, the GaAs cathode emits electrons. The polarization of the electrons is controlled by that of the laser, enabling the creation of spin-polarized electron beams. The biased anode is used to accelerate and direct the electrons thanks to a high-voltage (HV) feed through supplying the necessary electric field. The system's NEG (Non-Evaporable Getter) modules are used to reduce contamination by maintaining ultra-high vacuum [109].

where they are accelerated and gain energy reaching 7 GeV. They are then injected into the accelerator ring as top-up bunches. The vertical polarization at this point must be preserved. Then, just before the interaction point, the spin should be changed to longitudinal to collide longitudinally polarized electrons. The direction of the spin can be visualized in Fig. 3.8. The idea of colliding longitudinally polarized electrons rather than vertically polarized electrons can be explained simply. The definition of polarization is given in Section 3.4.1. The interaction of the particles depends on the helicity of the particles, which is the projection of the spin on the axis of the particle's momentum axis. This helicity for ultra-relativistic particles is the same as the chirality. When the spins of the interacting particles are vertical, this quantity becomes null. That is why we need to change the spin direction once again before the IP. This change is achieved by a magnetic element called spin rotator (see Fig. 3.9). This one is called the Left Rotator (L-Rot). Another spin rotator is needed to rotate the spin back to the vertical position after the interaction point. It is called the Right Rotator (R-Rot). The spin rotator that is likely to do the job requires combined-function solenoid-quadrupole magnets. This means that the section in the ring needs to be changed in a way that allows for the modification of some magnet positions. Essentially, two dipole-solenoid combined function magnets

are to replace the two dipole magnets that are present on both sides of the interaction point; four B2E dipoles in total are to be changed. The advantage is that other magnets will not have to be relocated. This is being studied by the collaborators in BNL [112]. They need to be studied very well so that they do not cause any loss in the luminosity.

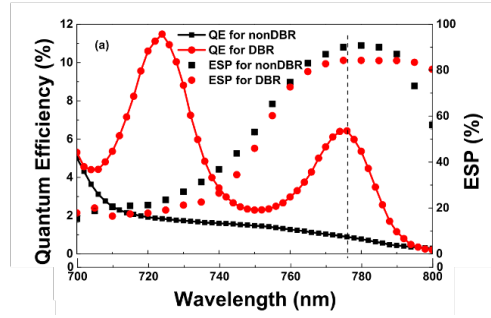


Figure 3.7 – The quantum efficiency (QE) is given for superlattice and conventional lattice structures as function of the wavelength of the detected photons [108]. Black curve represents the QE for the conventional lattice (non DBR; non Distributed Bragg Reflector) and red curve represents the QE for a superlattice (DBR; multi-layer lattice). There is a significant increase in the QE for the superlattice across the wavelengths. This proves the effectiveness of this layered design. ESP corresponds to electron-spin polarization.

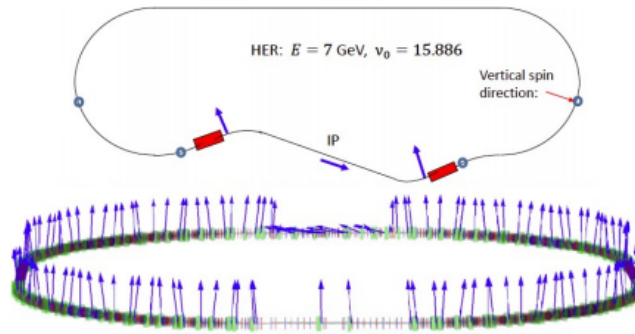


Figure 3.8 – Spin direction inside the accelerator ring. It is vertical all the way except in the interaction region where it is longitudinal. Top figure is from [104], bottom is from [113].

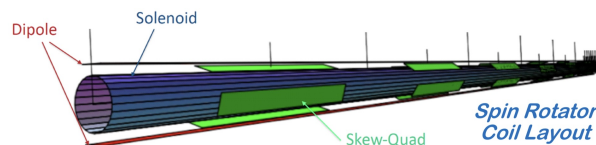


Figure 3.9 – A scheme of a compact spin rotator, taken from [104].

3.3 . Polarization measurement

In order to optimize the electron beam polarization, one needs to precisely measure it in real time. I describe the possible techniques in this section. We would like to measure the polarization not only in real time in the accelerator but also at the IP in the long term. We are essentially interested in the beam polarization at the IP and so in a polarization measurement at the IP. We need to take into account the beam dynamics in the ring. When the electrons are traveling in the accelerator submitted to a magnetic field, their spin is subject to the phenomenon of Larmor precession, which causes their spin vector to rotate around the direction of this magnetic field at a certain frequency [114] (see Fig. 3.10). This precession does not generate the polarization itself. However, the polarization of the beam can be generated via different mechanisms, such as synchrotron radiation. In fact, when electrons emit radiation while traveling in the accelerator, spin states flip with different probabilities. Some spin states become depopulated. This process, known Solokov-Ternov effect, gradually leads to a natural polarization of the beam [115].

By making sure that the spin orientation is known and beam dynamics are controlled at the IP, we can obtain a correct measurement of the polarization. We can measure the polarization at the IP by studying $e^+e^- \rightarrow \tau^+\tau^-$ events [116] [117]. Knowing the polarization at the IP is very important, but this technique can be extremely slow, so we would need to study other techniques. In fact, we can measure the polarization of an electron beam in the accelerator in real time through these processes : Mott scattering, Møller scattering and Compton scattering [118].

Mott scattering is the process by which an electron of a low energy scatters off an atom, interacting with its nucleus and its electrons. As the electrons are ultra-relativistic at the IP, this method can rather be applied at the photocathode, where the beam is at low energy. Even though applying this method is very destructive, as the electrons lose a large part of their energy and deviate from their initial trajectories and the beam is no longer useful for injection into the accelerator, it can be used to ensure that the polarization is correct before the acceleration stage.

Møller process is the inelastic scattering of two electrons on each other $e^-e^- \rightarrow e^-e^-$. It happens with a transfer of a considerable amount of energy. This process is subject to large effects of QED corrections reaching 1% [119]. So, using this method is not very precise. However, this process affects the Touschek lifetime in the beam, as explained in Section 3.7.1. In fact, if the electron beam is polarized, the

cross section of the Møller scattering changes depending on the spins of the electrons. In other terms, the scattering rate of Møller scattering depends on the polarization. So, for a polarized beam, Møller scattering changes the Touschek lifetime. Therefore, by measuring variation of the Touschek lifetime, we can extract indirectly the beam's polarization [120]. This technique can be used to perform a fast diagnostic of the polarization. For example, in synchrotrons, the beam polarization increases over time, and it has been observed that by controlling the effects of Møller scattering on the Touschek lifetime, one can ensure that the beam polarization is building up as expected.

Compton process is explained further in Section 3.3.1. In fact, it is optimal for ultra-relativistic electrons. The effects of QED corrections are of 0.1% [121], which means that the precision of the polarization can also reach this order of magnitude, which is better than the precision needed.

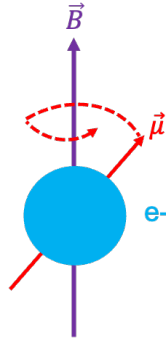


Figure 3.10 – Scheme representing the spin precession of an electron. As the electron is subject to a magnetic field $\vec{B}$, its magnetic moment $\vec{\mu}$ rotates around this magnetic field at a specific frequency.

3.3.1 . Measurement using Touschek lifetime

Touschek effect is the process of particles scattering off each other inside a single bunch, called intra-beam scattering (IBS). As there are too many electrons in a restrained volume of space, which is called bunch, they repel because of the Coulomb force. This causes large changes in the momenta of the particles, which potentially leads to loss of particles from the beam as they would no longer be contained in the geometric acceptance of momentum of the detector. The time during which the beam keeps its electrons before they undergo IBS losses is called Touschek lifetime. It is about 3×10^2 s in the high energy ring [122]. This process is sensitive to the dynamics and energy distribution of the

beam. This time τ_T depends on the polarization P based on Eq. 3.1 [123]

$$\frac{1}{\tau_T(P)} = a[C(\xi) + F(\xi)P^2]N \quad (3.1)$$

where a is a proportionality constant depending on machine and beam parameters, N is the number of particles in the bunch, $C(\xi)$ is the polarization independent component of the Touschek lifetime, $F(\xi)$ is a polarization dependent component scaling with P^2 and $\xi = \left(\frac{\Delta p_m}{\gamma \sigma_{p\perp}}\right)^2$ with $\frac{\Delta p_m}{p}$ the momentum acceptance and γ the Lorentz factor. We can see from this equation that the polarization is quadratically related to the Touschek lifetime. One can choose to have fewer variables and make the equation simpler, by studying a ratio of the Touschek lifetime with and without polarization effects under the same beam and machine conditions. This is represented in Eq. 3.2

$$\frac{\tau_T(P=0)}{\tau_T(P)} = 1 + \frac{F(\xi)}{C(\xi)}P^2 \quad (3.2)$$

This quadratic effect can be visualized in Fig. 3.11. This lifetime for Su-

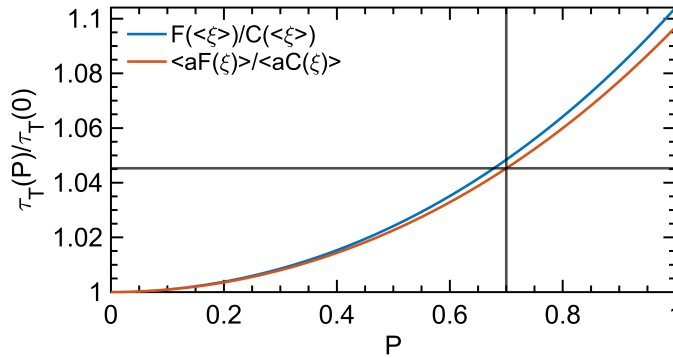


Figure 3.11 – Ratio of Touschek lifetime with (the red distribution) and without (the blue distribution) polarization as function of the polarization of the electron beam. The quadratic effect is well represented [124].

perKEKB is much shorter than the time it takes to polarize the beam naturally, which is about 10^2 s [125]. This is essentially caused by the high current of 2.6 A and the low emittance of 3.2 nm of the beam [126]. This means that the beam experiences significant losses due to IBS before polarization can occur, leading to very low or negligible polarization of the beams. The method here consists of studying Touschek lifetime in the beam in order to measure its polarization. For this, a polarimeter that relies on Møller scattering can be used to measure the beam

polarization of electrons at low energy (≈ 200 keV) [127]. This method of beam polarization measurement is favorable in the short term as it does not require the whole setup for Chiral Belle. Its main goal is to make a fast check by proving that the polarized spin vectors can be preserved in the ring by confirming the feasibility of both injection and transportation of polarized electrons in the accelerator ring. The complete Chiral Belle application, by adding the Compton polarimeter and spin rotators, can be done at a later stage [124].

As a matter of fact, it is more favorable to use a Compton polarimeter than a Møller polarimeter to make the polarization measurement. This can be explained in Fig. 3.11. A 1% uncertainty in the measurement of the Touschek lifetime ratio (y-axis) creates an uncertainty of about 10% in the measurement of the polarization (x-axis). However, with the Compton polarimeter, as the QED corrections are 10 times less, the uncertainty becomes 10 times better for the measurement of the polarization.

3.3.2 . Measurement using Compton scattering

This technique consists of exploiting Compton scattering to measure the polarization of the electrons. By sending a laser on the electron beam in the ring, a measurement of the electron beam polarization can be achieved. The advantages of this method are the measurement with a high precision of 1% over five minutes [128] and in real time of the polarization for each bunch. This will be discussed in detail in the following sections. I did simulations of the interaction of the laser with the electron beam and studies of the photon distribution, its energy and its detection in a photon detector. I explain in section 3.4.4 the theoretical physics part. Then in section 3.5, I describe the model used. In Section 3.6, I describe the backgrounds added to the model. In Section 3.7.1, I give the results of the simulations made and in Section 3.8, I give a brief summary of the work done.

3.3.3 . Measurement using taus

A technique studied in [116] consists in measuring the beam polarization by using tau leptons. It relies on the dependence of the polarization of tau on that of the electron beam. It suggests studying certain tau decays like $\tau^\pm \rightarrow \pi^\pm \nu_\tau$. By measuring the momentum and angular distribution of the final particles, such as the pion, one can infer the polarization of the tau, since the momentum of the pion depends on the spin of the tau, being right handed or left handed [116]. In turn, the spin of the tau reflects the polarization of the electron beam. So, analyzing a very large number of tau decay events and studying the kinematics of the final particles allows for an accurate measurement of

the average electron beam polarization (see Fig. 3.12). This technique can be very sensitive, but by exploiting a sufficient number of events $e^+e^- \rightarrow \tau^+\tau^-$, a measurement of the polarization of the electron beam might be possible. Considering Belle II, which expects to collect about 10^9 $\tau^+\tau^-$ events with its target luminosity, the measurement could be feasible. The advantage of this technique over the Compton polarimeter technique is the direct measurement at the IP, without uncertainty resulting from the transport from the polarimeter to the IP [104]. The absolute precision of this technique is similar to that of Compton, about 0.5% [104].

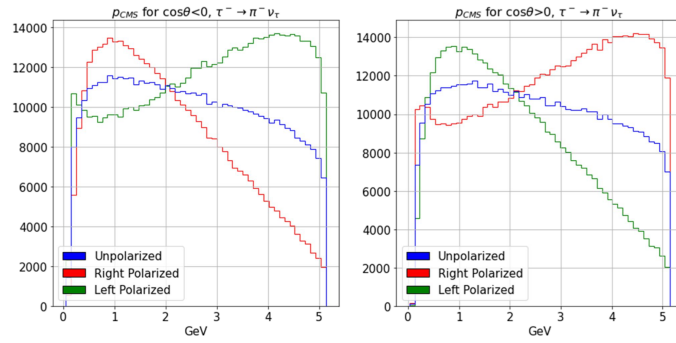


Figure 3.12 – Simulated momentum distributions in the center of mass reference frame for the decay $\tau^- \rightarrow \pi^- \nu_\tau$. On the left, the case where $\cos\theta < 0$. On the right, the case where $\cos\theta > 0$. Blue means the electron beam is unpolarized, red means it is right polarized, and green means it is left polarized. We have different distributions depending on the polarization.

3.4 . Theory

3.4.1 . Polarization

Particle spin is defined as the intrinsic angular momentum of the particle in the rest frame [129]. However, unlike classical angular momentum, spin does not result from any physical rotation of the particle. It is instead a quantum mechanical property not directly related to a classical physical concept, yet it is essential to determine how the particle behaves under specific symmetries and how it interacts with other particles and fields. For an electron, the spin corresponds to a quantum number of $s = 1/2$. The projections along the z-axis, would then be $m_s = 1/2$ or $-1/2$. For a photon, the spin has a quantum number of $s = 1$. The spin projection perpendicular to the direction of motion (longitudinal component, $m_s = 0$) does not exist as the photon is massless, so the spin projection along the direction of motion be-

comes the only component, which is defined as helicity. A photon has then two helicity states : 1 or -1 which correspond to right-handed and left-handed circular polarizations, respectively.

The polarization represents the average over a statistical ensemble of the individual spin orientations. Its magnitude vanishes for random spin orientations. For a laser, a bunch of photons, the polarization can be linear, circular or a combination of both (elliptical). For a beam of electrons, the polarization can be longitudinal (horizontal or vertical) or transversal. For our studies, exploiting Compton scattering, the laser beam is chosen as circularly polarized and the electron beam as mainly longitudinally polarized.

3.4.2 . Compton scattering

Compton scattering is a fundamental process in quantum electrodynamics. Its Feynman diagram is represented in Fig. 3.13. It supports the particle nature of electromagnetic radiation, proving that a photon can behave like a particle. When scattering off electrons, Arthur Compton observed that high energy photons are subjected to a change of wavelength, thus transfer of energy.

In the process, a photon is incident on an electron giving a scattered photon and an emerging electron. The scattered particles have energies different than those of the initial ones, due to the energy and momentum exchange between the photon and electron.

More particularly for our experiment, the electron beam travels at an energy of $E_e = 7\text{GeV}$, the incident photon is supposed to be sent at $E_\lambda = 2.4\text{eV}$ and wavelength λ at an angle θ_0 with respect to the axis of the electron beam. The scattered photons have an energy of E_γ and wavelength γ , and travel at an angle of θ . (see Fig. 3.14).

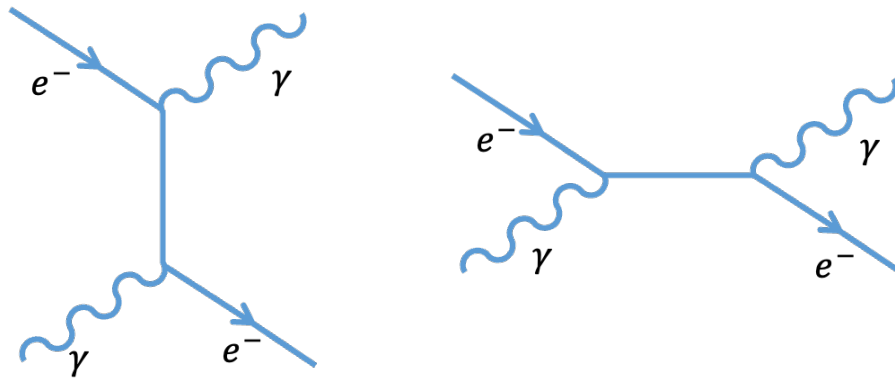


Figure 3.13 – Feynman diagram of Compton scattering.

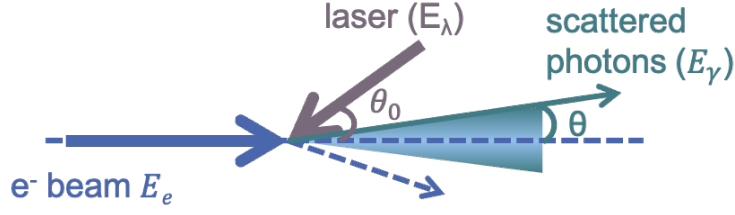


Figure 3.14 – Compton scattering.

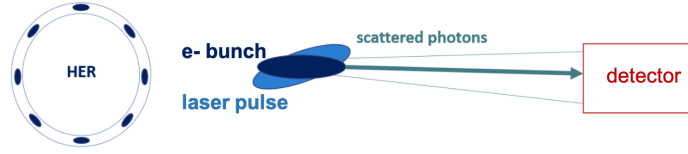


Figure 3.15 – On the left is shown the electron beam as bunches in the high energy ring. There are about 2500 bunches in SuperKEKB. On the right is shown a schematic view of the Compton interaction point : electron and laser bunches. The scattered photons are emitted in a cone reaching the photon detector.

3.4.3 . Luminosity of interaction : general and simplified

We have an interaction of an electron beam with a laser. Before giving the formula of luminosity of this interaction, let us recall some notions. The phase space of the electron beam is represented by the position and momentum distributions of the beam. As these parameters are correlated, the shape of the phase space is elliptical. The emittance of the beam is measured by its transverse size and angular divergence. The transverse dynamics of the beam are governed by the Twiss parameters $\alpha(s)$, $\beta(s)$ and $\gamma(s)$. s is the longitudinal position of the beam. $\alpha(s)$ relates the focusing strength and the beam size, $\beta(s)$ to the beam's envelope function and $\gamma(s)$ to the beam's angular spread. $\alpha(s)$ and $\gamma(s)$ can be expressed as function $\beta(s)$ as such

$$\alpha(s) = -\frac{\beta'(s)}{2}$$

$$\gamma(s) = \frac{1 + \alpha(s)^2}{\beta(s)}$$

where $\beta'(s)$ is the derivative of β as function of s .

The number of interactions between an electron and a photon due to a Compton interaction is given by [130] :

$$N = f_{rep} \int dt d^3\vec{r} d^3\vec{p}_e d^3\vec{p}_\gamma \rho_e \rho_\gamma \sqrt{(\vec{v}_e - \vec{v}_\gamma)^2 - \frac{(\vec{v}_e \times \vec{v}_\gamma)^2}{c^2}} \frac{d\sigma}{d^3\vec{p}_e d^3\vec{p}_\gamma} \quad (3.3)$$

with f_{rep} the repetition frequency, the integral is made over time and the momenta of the incoming electron and photon of the process, ρ is the particle density, $\vec{v}$ is the particle velocity, σ is the cross section. Now, this is the complete physical formula. We make some approximations to make it simpler and represent it in its common form. We assume that the interaction region is limited in space and the envelope function is constant. Thus, we set $\alpha = 0$ for simplicity. Taking into account this effect would only correspond to a mild reduction of luminosity. In this case $\gamma(s) = \frac{1}{\beta(s)}$ as in the inverse of the envelope function. In this case, the particle density can be expressed fully as :

$$\rho(x, x', y, y', t, s, E) = N \frac{e^{-\frac{x^2}{2\sigma_x^2} - \frac{x'^2}{2\sigma_{x'}^2}} e^{-\frac{y^2}{2\sigma_y^2} - \frac{y'^2}{2\sigma_{y'}^2}} e^{-\frac{(z-\beta ct)^2}{2\sigma_z^2} - \frac{E^2}{2\sigma_E^2}}}{2\pi\sigma_x\sigma_{x'} 2\pi\sigma_y\sigma_{y'} 2\pi\sigma_z\sigma_E}$$

where x (y) is the particle horizontal (vertical) position, x' (y') the particle's trajectory angle in the horizontal (vertical) plane, expressed as $x' = dx/ds$ ($y' = dy/ds$), the derivative of the horizontal (vertical) position with respect to the longitudinal position s , t is the time coordinate and E the energy. The standard deviations of the Gaussian distributions σ_x and $\sigma_{x'}$ (σ_y and $\sigma_{y'}$) represent the beam's transverse spread in the horizontal (vertical) position and angle, respectively. σ_z is the standard deviation of the particle distribution in the longitudinal direction, and σ_E is the beam energy spread, βc is the velocity of the particle. We can make another approximation by considering that the collision of both beams happens in the horizontal plane, in which both beams would have the same vertical position, but the horizontal and longitudinal coordinates would be different. The vertical size of the electron beam is about $0.22 \mu\text{m}$ [131], which justifies the approximations. The luminosity represents the rate of collision of particles. The simplified formula of the instantaneous luminosity would be

$$\mathcal{L} = \frac{fBN_eN_l}{2\pi} \frac{1}{\sqrt{\sigma_{y,l}^2 + \sigma_{y,e}^2} \sqrt{\sigma_{x,l}^2 + \sigma_{x,e}^2 + \tan^2 \phi (\sigma_{z,l}^2 + \sigma_{z,e}^2)}} \quad (3.4)$$

where f is the collision frequency, B is the number of bunches per beam, N_e is the number of electrons per bunch and N_l is the number of photons per laser pulse, ϕ is the crossing angle of the beams in the horizontal plane, $\sigma_{x,l}$ and $\sigma_{y,l}$ are the transverse sizes of the laser beam, $\sigma_{x,e}$ and $\sigma_{y,e}$ are the transverse sizes of the electron beam [130].

3.4.4 . Compton cross section

The Compton cross-section, averaged over scattered particles spins is given by [132, 133] :

$$\begin{aligned} \frac{d\sigma}{dy_C d\Phi_{obs}}(x_C, y_C) = & \frac{d\sigma_0}{dy_C} + \frac{d\sigma_{\perp}}{dy_C} \cos(2(\Phi_{obs} - \Phi_{las})) P_{lin} \\ & + \frac{d\sigma_{\parallel}}{dy_C} P_{circ} (P_T f_T \cos(\Phi_{obs} - \Phi_{elec}) + P_z f_L) \quad (3.5) \end{aligned}$$

- $y_C = \frac{E_{\gamma}}{E_e}$ and $x_C = \frac{2E_2 E_{\lambda}}{m_e^2} (1 + \cos\theta_0)$
- Φ_{obs} is defined by the azimuthal angle of the scattered photon in the transverse plane $\Phi_{obs} = \arctan \frac{Y}{X}$ where Y and X are the spatial coordinates in that plane.
- Φ_{las} (Φ_{elec}) is the azimuthal angles of linear laser polarization (longitudinal electron polarization).
- $\frac{d\sigma_i}{dE_{\gamma}}$ ($i = (0, \perp, \parallel)$) are functions expressed as

$$\frac{d\sigma_0}{dy_C}(x_C, y_C) = \frac{\alpha^2}{2x_C m_e^2} \left[\frac{1}{1-y_C} + 1 - y_C - \frac{4y_C}{x_C(1-y_C)} \left(1 - \frac{y_C}{x_C(1-y_C)} \right) \right]$$

$$\frac{d\sigma_{\perp}}{dy_C}(x_C, y_C) = \frac{\alpha^2}{2x_C m_e^2} \left[\frac{-4y_C}{x_C(1-y_C)} \left(1 - \frac{y_C}{x_C(1-y_C)} \right) \right]$$

$$\frac{d\sigma_{\parallel}}{dy_C}(x_C, y_C) = \frac{\alpha^2}{2x_C m_e^2} \frac{y_C}{x_C(1-y_C)}$$

with $\nu_0 = c/\lambda$, λ the laser wavelength, h the Planck constant, c the speed of light in vacuum, m_e the electron rest mass, $\pi - \theta_{in}$ the crossing angle between the two beams, $\beta = \sqrt{1 - 1/\gamma^2}$ such as $\gamma = E_e/m_e c^2$ is the Lorentz factor and α the fine structure constant.

•

$$f_T(x_C, y_C) = -\sqrt{(x_C + 1)y_C \left(\frac{x_C}{x_C + 1} - y_C \right)}$$

$$f_L(x_C, y_C) = \left(1 - \frac{2y_C}{x_C(1-y_C)} \right) x_C(2 - y_C).$$

- P_{lin} is the linear laser polarization, considered as uncertainty on the polarization since the laser is mainly circularly polarized.
- P_{circ} is the circular laser polarization, it is ideally ± 1 .
- P_T is the transverse electron polarization, considered as an asymmetry in the transverse plane.
- P_z is the longitudinal electron polarization, taken in general as 0.7.

It is interesting to note that all the parameters above are defined in the laboratory frame. We see that the cross section has a nominal cross section at Born level, and a term dependent on the linear polarization and another term dependent of the circular laser polarization, both of which are independent of the electron beam polarization. Lastly, a term depending on the electron beam polarization.

3.5 . Description of the model

3.5.1 . Laser and electron beams

The main goal is to determine the polarization of the electrons, assuming that the laser polarization is well known. So, the idea is to measure the differential cross section and control the laser polarization in order to extract the longitudinal polarization of the electrons. We have two observables : E_γ and Φ_{obs} . As the scattered photons travel in a narrow cone, it is extremely difficult to measure their angle of observation. So the differential cross section is integrated on the angle Φ_{obs} from 0 to 2π and becomes

$$\frac{d\sigma}{dE_\gamma}(x, E_\gamma) = A(x, E_\gamma) + B(x, E_\gamma) \cdot P_z P_{circ} \quad (3.6)$$

where $A = \frac{d\sigma_0}{dE_\gamma} 2\pi$ and $B = \frac{d\sigma_{||}}{dy} f_L 2\pi$. It is interesting to note that the dependence on P_T and P_{lin} vanishes. Thus, only the product $P_z P_{circ}$ can be extracted. Since A and B are functions depending only on x and E_γ , (x is very well known), we can use Eq. 3.6 to extract the longitudinal electron polarization, knowing precisely the laser beam polarization that we will assume circular.

We simulate the interaction of a laser having parameters defined in Table 3.1 with an electron beam having parameters in Table 3.2. Then we study the scattered photon energy distribution in a photon detector. This was done to extract the longitudinal polarization of the electrons.

The laser system is supposed to be integrated in the SuperKEKB accelerator. Along with a detector for scattered particles, and an additional vacuum chamber that would allow the interaction between laser and electron beams.

Simulation description : Electron beam is modeled as bunches of electrons of mean energy $E_e = 7$ GeV and a standard deviation of $\sigma/E_e = 6.3 \times 10^{-4}$. Each bunch has a charge of 10 nC. The simulated linear polarization is 0.7, and the transverse polarization 0. The laser is simulated with beam sizes of 0.5 mm in the x, y and z directions. Its

Table 3.1 – Nominal laser beam parameters used for the simulation.

Symbol	Parameter	Value
P_{circ}	Circular polarization	–1
P_{lin}	Linear polarization	0
$\sigma_x/\sigma_y/\sigma_z$	Beam size in x , y , and z	$500\ \mu\text{m} / 500\ \mu\text{m} / 500\ \mu\text{m}$
λ	Wavelength	515 nm
$f_{rep.}$	Repetition rate	250 MHz
U	Pulse energy	20 nJ
θ_{in}	Polar incidence angle	8.9°
ϕ_{in}	Azimuthal incidence angle	28°

Table 3.2 – Nominal electron beam parameters used for the simulation.

Symbol	Parameter	Value	
μ_E	Beam energy	7 GeV	
σ_δ	Beam energy spread	6.3×10^{-4}	
Q_e	Bunch charge	10 nC	
T_{rev}	Revolution period	10 μs	
$P_\perp$	Transverse polarization	0	
P_z	Longitudinal polarization	0.7	
		horizontal (x)	vertical (y)
$\epsilon_{x,y}$	Emittance [m·rad]	4.49×10^{-9}	4.5×10^{-11}
$\beta_{x,y}$	Beta function [m]	96.46	127.09
$\alpha_{x,y}$	Divergence	–8.72	9.45
$\eta_{x,y}$	Dispersion [m]	–0.083	-1.1×10^{-9}
$\eta'_{x,y}$	Dispersion slope	–0.0035	6.8×10^{-11}

wavelength corresponds to 515nm, its power of 5 Watts and repetition frequency f_{rep} of 250 MHz, $\omega = \frac{hc}{Q_e \lambda}$, $E_L = \frac{power}{f_{rep}}$, $n_L = \frac{E_L}{(Q_e \omega)}$.

3.5.2 . Event generation

An experiment is defined as an interaction of laser pulses and electron bunches. A toy is a thousand generation-fitting experiments. This interaction is generated using a Monte-Carlo accept-reject method. Depending on whether or not the conditions are fulfilled, the generated value is either accepted and added to the data or rejected. The generated total integrated cross section of the Compton interaction is :

$$\sigma_C = \frac{2\pi r_e^2}{x_c} \left[\left(1 - \frac{4}{x_c} - \frac{8}{x_c^2} \right) \log(1 + x_c) + \frac{1}{2} + \frac{8}{x_c} - \frac{1}{2(1 + x_c)^2} \right. \\ \left. + P_C P_z \left(\left(1 + \frac{2}{x_c} \right) \log(1 + x_c) - \frac{5}{2} + \frac{1}{1 + x_c} - \frac{1}{2(1 + x_c)^2} \right) \right]. \quad (3.7)$$

The mean number of expected Compton photons is calculated as : $n_{exp.} = \sigma_C \mathcal{L}$ per bunch crossing. It is estimated following this luminosity of interaction :

$$\mathcal{L} = \frac{\lambda U Q_e}{2\pi h c q_e \sqrt{\sigma_{y,l}^2 + \sigma_{y,e}^2} \sqrt{\sigma_{x,l}^2 + \sigma_{x,e}^2 + \tan^2 \frac{\theta_{in}}{2} (\sigma_{z,l}^2 + \sigma_{z,e}^2)}}, \quad (3.8)$$

where U denotes the laser pulse energy and q_e the elementary charge. The actual number of photons is then simulated using Poisson distribution with mean $n_{exp.} \approx 0.06$ with the given nominal parameters, that for each bunch crossing. For ϕ and y_c generating random numbers using uniform distributions in the range $[0, 2\pi]$ and $[y_{min}, y_{max}]$, respectively, where

$$y_{min} = x_c / (2\gamma^2 (1 - \cos \theta_{max}) + x_c), \quad (3.9)$$

$$y_{max} = x_c / (1 + x_c), \quad (3.10)$$

within assumptions that are valid with a precision better than 10^{-6} . The emission polar angle of photons is computed as

$$\theta_\gamma = \arccos \left(\frac{1 - \frac{x_c(1-y_c)}{2\gamma^2 y_c}}{\beta} \right).$$

The longitudinal polarization of the electrons is then fit and the pull function is studied. It is given by :

$$\text{pull}(P_z) = \frac{P_z^{gen} - P_z^{fit}}{\sigma_{P_z}^{fit}}$$

where P_z^{fit} is the extracted value from the simulations, P_z^{gen} is the generated value and $\sigma_{P_z^{fit}}$ is the statistical error on the extracted value. Ideally, the pull distribution is Gaussian having mean 0 and width 1. The width differing from 1 indicates that the error in the fitted value of the polarization is not properly estimated. In order to control biases and estimate the polarization accurately, we generated thousands of experiments in toys.

3.5.3 . The photon detector

Electron and laser bunches collide with 4ns time intervals. The photon detector is supposed to measure scattered photons with respect to this time interval, which motivates a choice of a scintillation crystal that is radiation tolerant with a fast fluorescence detector. BaF₂ crystal, as a fast scintillator with a typical decay time of 0.9ns[134], could do the job in case its intrinsic slow component (typically 650ns decay time) is reduced by doping the crystal with Yttrium or using solar blind photodetectors.

To choose the correct length of the crystal material, we first calculated the deposited energy of photons in the detector by integrating the longitudinal profile on the crystal's length L_{det} [135] :

$$E = E_0 \Gamma(a, bL_{det})$$

where

$$\Gamma(a, bL_{det}) = \frac{1}{\Gamma(a)} \int_0^{bL_{det}} t^{a-1} e^{-bt} dt$$

is the incomplete gamma function. Then we calculate the leakage energy such as :

$$E_{leakage} = \frac{E_0 - E_{dep}}{E_0}$$

where E_0 is the electron beam energy. We show the fraction of leakage energy as a function of the length of the material (see Fig. 3.16) for different energy ranges. The leakage energy as a function of the energy for different lengths is shown in Fig. 3.17. We determined roughly that a minimum of 25cm of length is needed to keep the leakage of the mean energy below 10% for scattered photons of 1.5GeV.

The scintillation light is planned to be detected using a photomultiplier (PMT), well chosen to maintain the temporal characteristics of the signal pulse. The PMT can be positioned either on the ground below the scintillation crystal of approximately one meter, as the light being guided from the crystal's output to the PMT's photocathode, or directly adjacent to the crystal with a short light guide. The final placement decision will be made later in the design process, considering factors such

as the energy and temporal spreads induced by light guiding. Additionally, careful shielding of the detector might be needed considering potential residual fringe fields from nearby magnetic elements of the SuperKEKB lattice and radiation at the beam level. The readout electronics will be situated nearby on the ground. The analog section of the acquisition chain will be carefully examined, and signals will be processed, post-digitization, utilizing a Field Programmable Gate Array (FPGA) to generate histograms for each bunch at a frequency of 250MHz. The detailed design of the detector and readout system will be developed in the coming years, relying on experimental work led by a prototype detector.

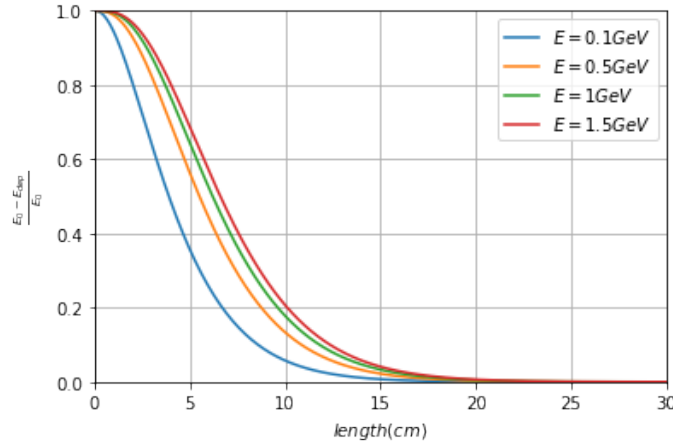


Figure 3.16 – Leakage energy as function of the crystal length for different initial electron beam energies 0.1, 0.5, 1 and 1.5GeV.

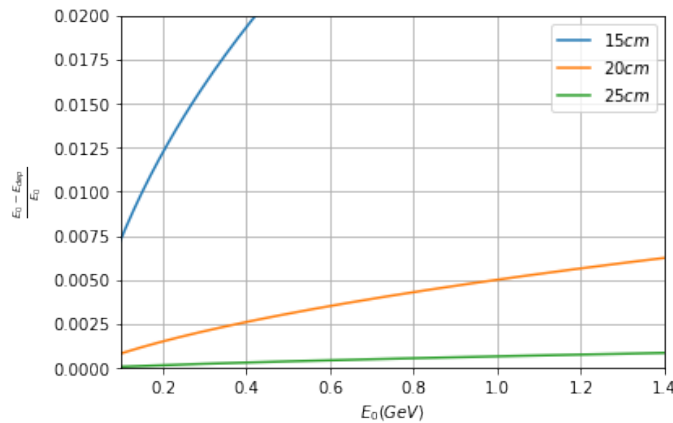


Figure 3.17 – Leakage energy as function of the initial energy of the electron beam for the crystal lengths : 15, 20 and 25cm.

The transverse position of the photons at the entrance plane of the detector reads

$$x_D = \delta_x + x_e + \tan(\delta_{x'} + x'_e)L + \cos \phi \tan \theta_\gamma L$$

$$y_D = \delta_y + y_e + \tan(\delta_{y'} + y'_e)L + \sin \phi \tan \theta_\gamma L$$

where $\delta_{x,y}$ ($\delta_{x',y'}$) accounts for spatial (angular) misalignments, x_e (y_e) is electron beam parameter in the x (y) direction, L is the detector length.

3.6 . Backgrounds

Backgrounds of photon energy measurement are Bremsstrahlung radiation on the beam gas in the vacuum chamber, synchrotron radiation and Compton radiation of beam electrons on blackbody radiation of the vacuum chamber. The main background studied are Bremsstrahlung and Compton radiations [136].

3.6.1 . Synchrotron radiation

Charged high energy particles, such as electrons, that are accelerated radially while traveling in a circular trajectory in a magnetic field emit radiation called synchrotron radiation [129]. It is produced within a narrow forward cone with typical opening angle of $1/\gamma$. It can represent a background event that must be taken into account, especially when studying the interaction of the electrons in the accelerator and the detector. To study how this might affect the Compton scattered photons distribution, we simulate the spectrum of this synchrotron radiation. We assume a 4 mm copper window in front of the photon detector. The number of photons passing through that window without interaction is calculated using

$$N_{th} \approx \int_{E=E_{min}}^{\infty} \frac{dN}{dE}(E) \exp(-t_{Cu}\rho_{Cu}/\lambda_{a,Cu}(E))dE \quad (3.11)$$

$$\frac{dN}{dE}(E) = \sqrt{3}\alpha \frac{\theta_B}{2\pi} \frac{\gamma}{E_c} \int_{x=E/E_c}^{\infty} K_{5/3}(x)dx \quad (3.12)$$

where $K_{5/3}(x)$ is a modified Bessel function of the second kind. The total energy coming from synchrotron radiation that will be deposited in the detector is expected to be 3 keV per bunch crossing. The distribution of synchrotron radiation has a peak at very low energies, contrary to that of Compton scattering radiation. This contribution is not considered in the model studied at this stage. And a GEANT4 simulation would be needed for more accurate studies.

3.6.2 . Bremsstrahlung radiation

Charged high energy particles that are deflected after interacting with the electric field of a nucleus emit a radiation called bremsstrahlung radiation. This can represent background events for the Compton radiation. We have to include it in our simulations to see its effect on the distribution of photons. This is needed to be able to distinguish it from Compton scattered photons. The bremsstrahlung interaction of electrons with the residual gas of the beam pipe can be represented in Fig. 3.18. This pressure in the HER, just for reference, is given in Fig. 3.19. The luminosity of the interaction of the electrons with the bremsstrahlung photons is defined by

$$L_{BG} = \beta N_e \frac{LP}{k_B T} \quad (3.13)$$

where N_e is the number of electrons per bunch crossing, $L=20$ m is the distance of section in the accelerator where the Compton interaction point is supposed to be located at, $P = 5 \times 10^{-8}$ Pa is the average residual gas pressure in that section, $T=300$ K is the vacuum pipe temperature and k_B is Boltzmann constant. The approximated differential cross-section of this interaction is [137]

$$\frac{d\sigma_{BG}}{dy_c} = \frac{4\alpha r_e^2}{y_c} \left[\left(\frac{4(1-y_c)}{3} + y_c^2 \right) \left(Z^2 \log \frac{184.15}{Z^{1/3}} + Z \log \frac{1194}{Z^{2/3}} \right) \right. \quad (3.14)$$

$$\left. + \frac{1-y_c}{9}(Z + Z^2) \right] \quad (3.15)$$

where α is the fine-structure constant and Z the average atomic number of residual gas atoms. We do not have a fixed known value. Even after contacting experts of backgrounds in the collaboration. But the value has been estimated previously by KEKB as $Z = 7$ [138], and had a good experimental to simulated ratio. The value 7 corresponds, in fact, to CO molecules that are present in the beam pipe. As the effective atomic number in the positron ring was measured at about 2.2, we decided to try both values in our simulations. Specifically, we considered gas atomic numbers of 2.2 and 7. The number of bremsstrahlung photons is shown as a function of the photon energy in Fig. 3.21 for $Z = 2.2$ and $Z = 7$. The cross section of the interaction for $Z = 2.2$ and 7 and when considering a stochastic term in the resolution term is shown in Fig. 3.20. The distribution of scattered photons is shown in Fig. 3.22, comparing the inclusion of both of these types of gas in the simulation. We see the Compton photon distribution in the green curve.

With the integration of a $Z = 2.2$ beam gas background, it has a similar shape as the one without this type of background, however, it has few events per bin more. The distribution with a $Z = 7$ beam gas background also has a similar shape and many more events per bin. But, after integration on $[E_{cut-off}, \mu_E]$, the differential cross section reads

$$\sigma_{BG} = \frac{2Z\alpha r_e^2}{9} \left(-2 \log(\epsilon) \left(1 + Z + 12 \log\left(\frac{1194}{Z^{2/3}}\right) \right) - (1 - \epsilon) \left(2(1 + Z) + (15 - 9\epsilon) \log\left(\frac{1194}{Z^{2/3}}\right) \right) - 3Z(5 - 8\epsilon + 3\epsilon^2 + 8 \log(\epsilon)) \log\left(\frac{184.15}{Z^{1/3}}\right) \right) \quad (3.16)$$

with $\epsilon = E_{cut-off}/\mu_E$. The minimum energy of an emitted bremsstrahlung photon is assigned as $E_{cut-off} = 1$ MeV. We then simulated the number of photons randomly following a Poisson distribution. The choice of Z in the simulation is taken into account in the systematics studies, as shown in Section 3.7.2.

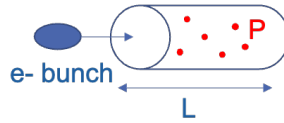


Figure 3.18 – Beam pipe containing gas particles that are uniformly distributed, having a pressure P . The electron bunch interacts with these particles through bremsstrahlung interaction.

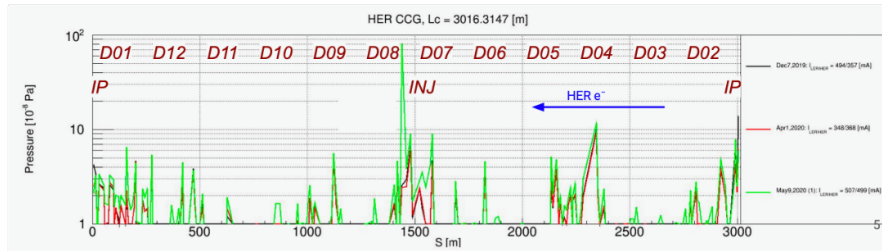


Figure 3.19 – Pressure in the beam pipe in the electron ring [139].

3.6.3 . Compton scattering on thermal photons

The third background that was simulated is the Compton scattering on thermal photons present in the vacuum pipe of the accelerator

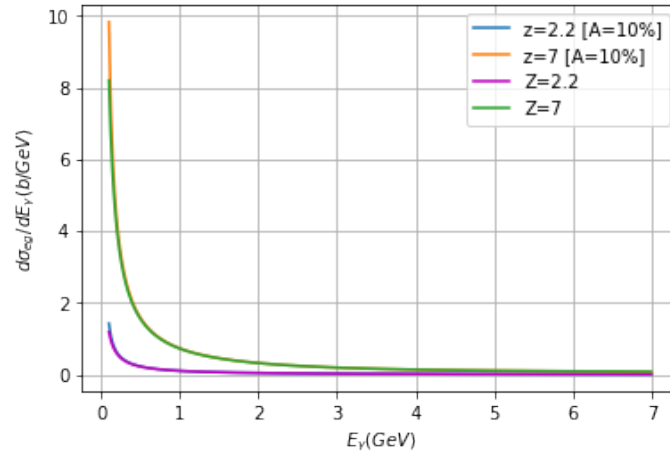


Figure 3.20 – Differential cross section of bremsstrahlung radiation as function of the energy of the photons for mean atomic number Z as 2.2 and 7; A being the stochastic term in the energy resolution of the detector.

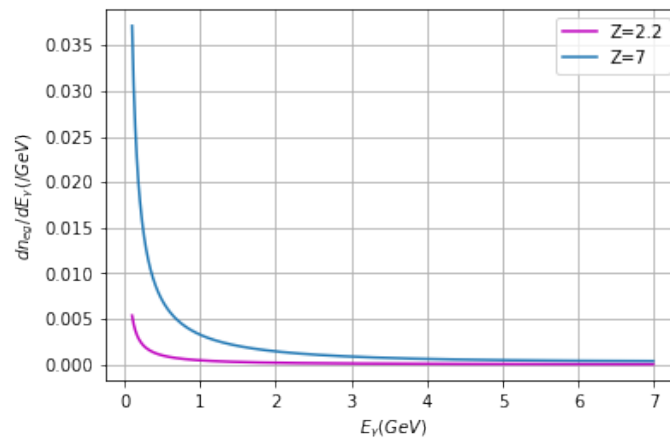


Figure 3.21 – Number of measured photons as function of their energy.

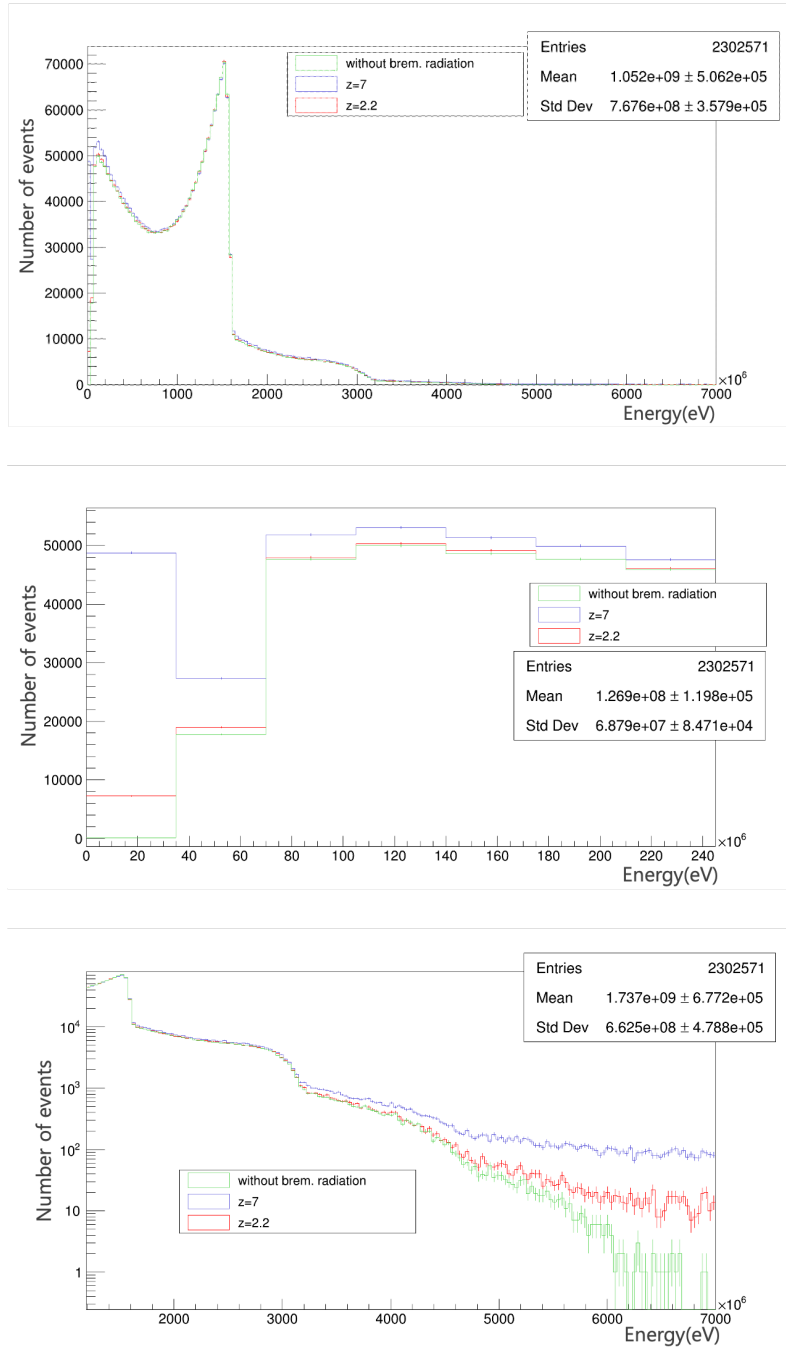


Figure 3.22 – Energy spectra superposed with beam gas bremsstrahlung for z=0, 2.2 and 7 on the top; from 0 to 7 GeV, in the middle; from 0 to 2.4 GeV and on the bottom; from 2 to 7 GeV in the log scale.

ring. The number of scattered photons is then calculated as the thermal photon density convolution to the Compton cross section [140] :

$$\frac{dN_{BB}}{dy_C} = \frac{Q_e L_s}{2\pi^2 q_e c^3 \hbar^3} \int_{\theta_0=0}^{\pi} \int_{\omega=\omega_0}^{\infty} \frac{d\sigma}{dy_C}(\theta_0, \omega) \frac{w^2(1 + \cos(\theta_0))}{e^{(\omega/(k_B T))} - 1} d\omega d\cos(\theta_0) \quad (3.17)$$

$$\omega_0 = \frac{m_e^2 c^4 y_C}{2(1 + \cos(\theta_0))(1 - y_C)\mu_E} \quad (3.18)$$

where $\pi - \theta_0$ is the angle. The distribution of the photon spectrum is shown in Fig. 3.23. As with synchrotron radiation, the copper window placed in front of the detector filters out the low energy part of the spectrum. There are around 0.04 produced black-body photons per bunch crossing depositing around 700keV of energy in the detector. Although this may seem small, the photon spectrum can extend up to energies of about 100MeV. As a result, this background contributes to the lowest-energy bins in the measured photon spectrum, a region that is insensitive to polarization. Thus, these bins are not included in the fit. We do not include the contribution of thermal photons in the simulation [141].

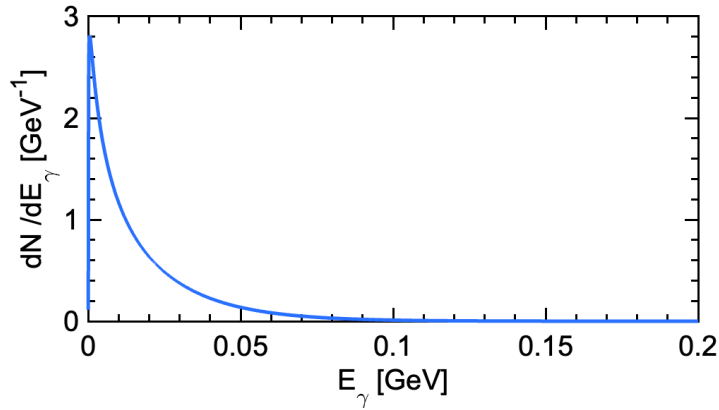


Figure 3.23 – Distribution of the emitted photons out of the interaction of electrons with thermal photons emitted by the black-body radiation [141].

3.7 . Simulation

We simulate a Monte Carlo toy to test the fitting method and estimate the preliminary systematic uncertainties. Before the complete study, the fitting procedure was validated with signal-only pseudo

experiments. We generate events that correspond to different data-taking durations or acquisition time t_{dt} that range from 1 to 25 minutes. For each value of t_{dt} , we simulate a thousand toy MC experiments. The estimated statistical precision for a single bunch is shown in Fig.3.24. For each bunch that lasts more than $t_{dt} = 5\text{min}$ has a statistical precision of around 1% [141].

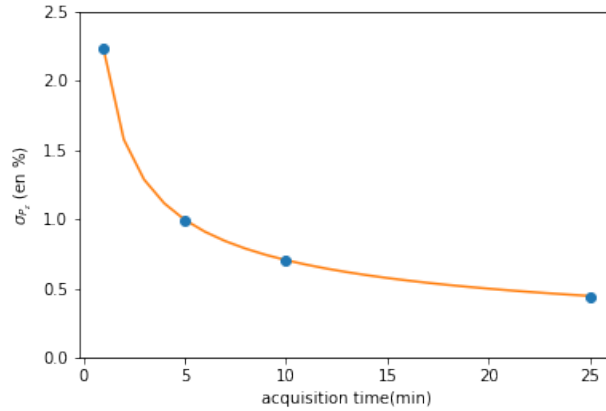


Figure 3.24 – σ_{P_z} versus acquisition time (min).

3.7.1 . Results

The Monte Carlo generated data and the fit results along with its individual contributions are shown in Fig. 3.25. The fit is excellent, reflecting the specific energies of Compton and Bremsstrahlung radiation [141].

3.7.2 . Systematic study

Different parameters are changed to study their effect on the model. Table 3.3 shows the parameters studied. Default parameters are represented as configuration (A). It has the ideal settings for the experiment. The distribution of the longitudinal polarization is extracted at 0.6999 ± 0.0099 (see Fig. 3.26). The pull distribution is also shown in the same figure. The results of the simulations for all configurations are given in Table 3.4. A summary of the systematic uncertainties is given in Table 3.5. Mis-knowledge of the laser beam polarization and the modeling of the backgrounds contribute the most to the uncertainties. I give brief explanations of the systematics studied in the following sections.

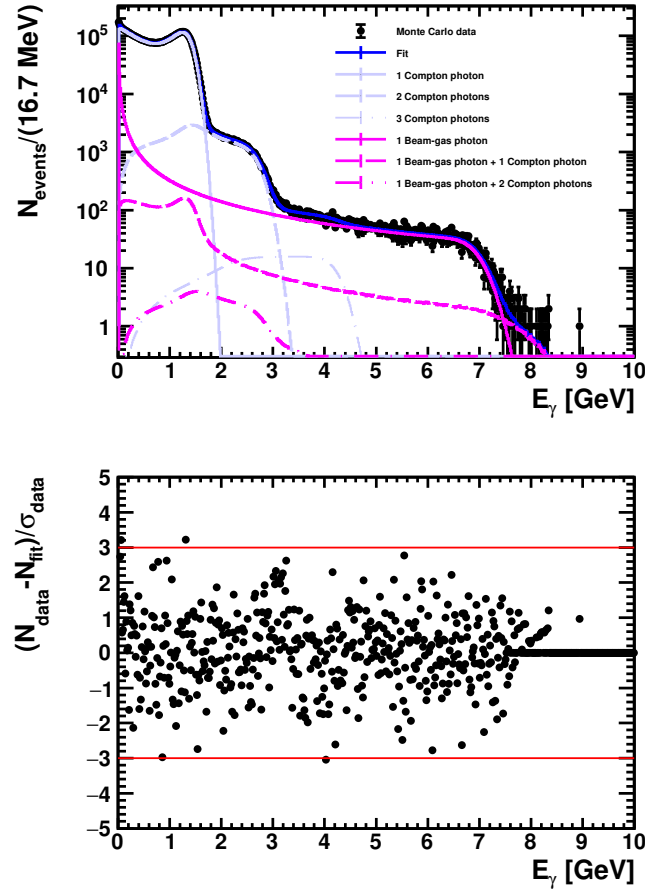


Figure 3.25 – Top shows the energy distribution of a Monte Carlo (MC) experiment representing 25 min of data taking in the Compton polarimeter. The black dots with error bars represent the simulated data. The blue line represents the fit result. It is the sum of the contributions related to Compton scattering in light purple (one-photon as a plain line, two-photons as a dashed line and three-photons as a dash-dotted line) and those related to Bremsstrahlung in magenta (one Bremsstrahlung photon as a plain line, one Bremsstrahlung photon and one Compton photon as a dashed line and one Bremsstrahlung photon and two Compton photons in dash-dotted line). Bottom shows the residuals of the fit normalized by the statistical uncertainty in the simulated data. The red lines represent three standard deviations between the fit and the simulated data [141].

type	P_z^{gen}	A^{gen}	$m.s.^{gen}$	dx^{gen}	dy^{gen}	P_T^{gen}	P_{lin}^{gen}	P_{circ}^{gen}
A	0.7	0.1	1.1	0	0	0	0	-1
B	0.7	0.1	1.03	0	0	0	0	-1
C	0.7	0.03	1.1	0	0	0	0	-1
D	0.7	0.01	1.1	0	0	0	0	-1
E	0.3	0.03	1.1	0	0	0	0	-1
F	0.7	0.1	1.0	0	0	0	0	-1
G	0.7	0.03	1.0	0	0	0	0	-1
H	0.7	0.1	1.1	1 mm	0	0	0	-1
I	0.7	0.1	1.1	2 mm	0	0	0	-1
J	0.7	0.1	1.1	0	1 mm	0	0	-1
K	0.7	0.1	1.1	0	0	0.3	0	-1
L	0.7	0.1	1.1	0	0	0	-0.05	-0.99

Table 3.3 – Definition of parameters of all configurations, *gen* means generated parameters values for every configuration of the simulation program; *dx* and *dy* are misalignments on the detector with respect to the electron beam axis. (The miscalibration scale is a free parameter in the fit, however for F and G it is a fixed parameter.)

type	$\langle P_z \rangle$	σ_{P_z}	$\mu_{P_z}^{pull,fit}$	$\sigma_{P_z}^{pull,fit}$	$\langle m.s. \rangle$	$\sigma_{m.s.}$	$\mu_{m.s.}^{pull}$	$\sigma_{m.s.}^{pull,fit}$	χ^2	σ_{χ^2}
A	0.6999	0.0099	-0.0469	0.9583	1.1	0.0003	0.0149	0.9934	176	20
B	0.7002	0.0112	-0.0130	0.9312	1.0299	0.0022	-0.0031	0.9878	220.07	910.97
C	0.6999	0.0088	0.0009	0.9594	1.1001	0.0002	-0.4765	1.004	152.53	18.24
D	0.6991	0.00855	-0.112	0.9614	1.1001	0.0001	-0.9108	1.015	150	17.35
E	0.2999	0.0086	-0.0156	1.006	1.1001	0.0002	-0.4394	1.069	152.9	18.55
F	0.6999	0.0095	-0.009182	0.9594	1	0	N/A	N/A	159.6	19.59
G	0.7005	0.0086	0.03982	0.9818	1	0	N/A	N/A	139.4	17.46
H	0.7008	0.0099	0.0600	0.9607	1.0999	0.0003	0.0910	1.014	176	19
I	0.7045	0.0099	0.4189	0.9452	1.0998	0.0003	0.4135	1.01	176.5	19.9
J	0.7	0.0099	-0.0317	0.9574	1.1	0.0003	0.0628	0.9773	175.9	19.9
K	0.7	0.0099	0.0167	0.973	1.1	0.0003	-0.0045	0.9867	175.69	19.8
L	0.7001	0.0104	-0.0133	0.9622	1.1	0.0003	0.0034	1.024	175.3	19.3

Table 3.4 – Results of simulations for each configuration; $\langle P_z \rangle$ is the mean extracted electron longitudinal polarization, σ_{P_z} is its standard deviation, $\mu_{P_z}^{pull,fit}$ is the mean of the pull function for P_z , $\sigma_{P_z}^{pull,fit}$ is its standard deviation, $\langle m.s. \rangle$ is the mean fitted miscalibration scale, $\sigma_{m.s.}$ is its standard deviation, $\mu_{m.s.}^{pull}$ is the mean of the pull function of $m.s.$, $\sigma_{m.s.}^{pull,fit}$ is its standard deviation.

Table 3.5 – Systematic uncertainties on the extraction of the electron polarization.

Source	Uncertainty on $P_z(\%)$
Laser beam polarization	0.30
Backgrounds	0.16
Fit procedure	0.080
Beam energy	0.050
Spatial misalignment	0.015
Angular misalignment	0.015
Longitudinal misalignment	0.015
Transverse electron beam polarization	0.015
Total	0.35

Laser beam polarization

The most dominant contribution to the uncertainties is not knowing the polarization of the laser beam well. It makes an uncertainty of 0.3%. In order to reduce this bias, precise knowledge and monitoring of the laser polarization are essential. In fact, the degree of circular polarization is directly related to the systematic uncertainty of measuring the electron polarization. Imperfections or deviations in the laser's polarization, even when small, eventually propagate into the final result, affecting the polarization of the electron. So, the laser polarization must be well controlled. The distributions of the polarization and its pull are in Fig. 3.27. In this configuration L the laser polarization is simulated at -0.95 instead of perfectly circular, and a linear component of -0.05 is added. We see that the extraction of the electron polarization is good, and its distribution has a good shape in comparison with the default configuration. Also, the pull distribution is well fitted into a Gaussian.

Background modeling

Background modeling is the second most dominant contribution. It is very important to take into consideration the effect of the background modeling on the fit. We mostly focused on studying the contribution of bremsstrahlung photons. To estimate the uncertainty due to the beam gas model, in each MC experiment we generate the background with a random variation of the atomic number Z of the beam gas with a Gaussian distribution of center at $Z = 2.50$ and width of $\sigma_Z = 0.07$. We fix $Z = 2.50$ in the fit. We get a bias of 0.16%.

Fitting procedure

We study the systematic uncertainty related to the fit model. We fit the signal while keeping the calibration scale and the stochastic term of the detector resolution free. We fit both of these parameters along with the beam polarization. We obtain a relative precision of 10^{-4} and 10^{-3} , respectively. This has no significant bias. However, we obtain a significant bias of 8×10^{-4} on the polarization P_z in the signal only fit procedure. Although it disappears when we improve the stochastic term of the detector resolution from $0.1 \text{ GeV}^{1/2}$ to $0.03 \text{ GeV}^{1/2}$, we cannot be sure to have this order of resolution, so we fix a systematic uncertainty of 0.08% to the polarization extraction [141].

Beam energy shift

We study the systematic uncertainty related to the knowledge of the electron beam energy. In fact, the beam energy is considered a known parameter in the fit procedure. However, fitting this parameter with a calibration scale and the detector energy resolution did not give useful information about the beam energy due to strong correlations. Instead, we perform the simulation with a shift of the energy by $10\mu_E\sigma_\delta \approx 44\text{MeV}$ and study its effect on the bias of the polarization extraction. This resulted in a bias of 0.05%, added as systematic uncertainty. This $10\mu_E\sigma_\delta$ is chosen as it is larger than any observed energy change in Belle II [142].

Misalignments

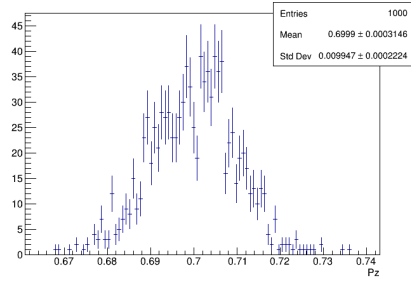
Misalignments in the detector in the longitudinal or transverse direction can lead to an uncertainty of 0.015%. One should take into consideration the fact that detectors do not align perfectly with the beam. So misalignments studies are important. By adding a shift of the Compton interaction point and/or the detector along the beam direction, it was proven that having a detector misaligned of up to 2 mm does not impact the energy distribution of the scattered photons nor the extraction of the electron polarization, shown in Figs. 3.28, 3.29 and 3.30.

Transverse electron beam polarization

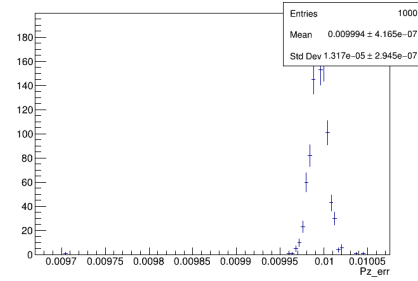
When we do not control the transverse electron polarization, this adds up to 0.015% uncertainty in the extraction of the longitudinal electron polarization. Indeed, it is important to know it well, to be able to

control it, and to keep it at the lowest possible value. Pulls are present in Fig. 3.31.

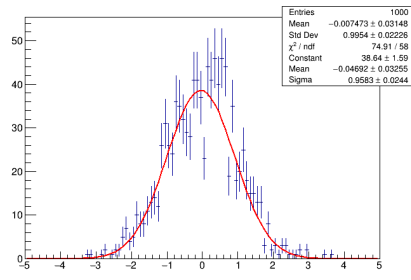
The other configurations have been studied and the results of the polarization extraction are given in Figs. 3.32, 3.33, 3.34, 3.35, 3.36 and 3.37.



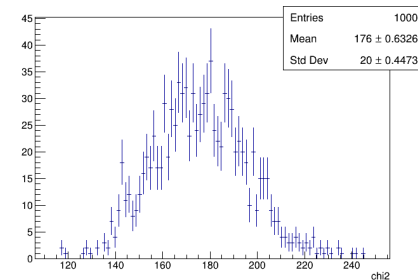
(a) Pz



(b) Pz err



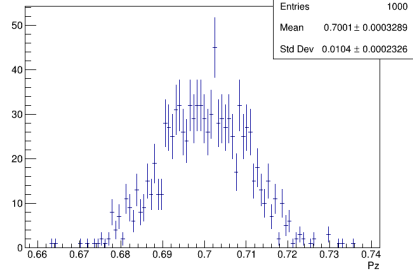
(c) Pull Pz



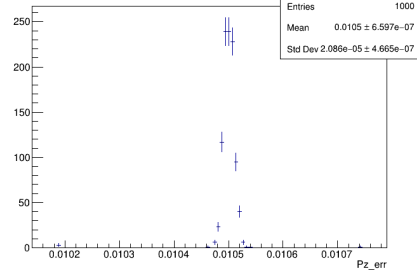
(d) Chi2

Figure 3.26 – Plots for A miscalibration scale = 1.1, resolution energy = 0.1, Pz = 0.7, with electron beam energy convolution.

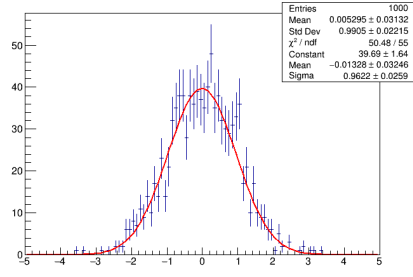
3.8 . Conclusion



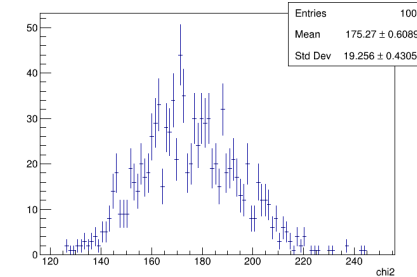
(a) P_z



(b) $P_z \text{ err}$



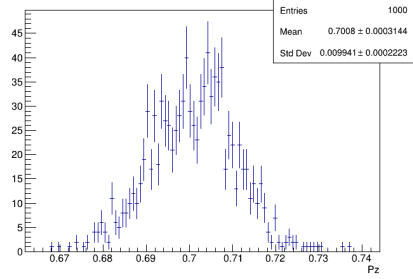
(c) Pull P_z



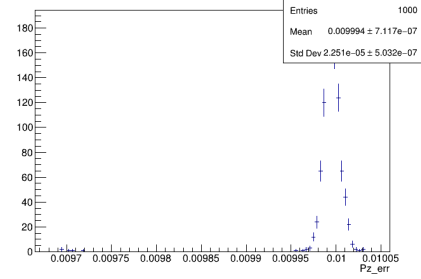
(d) Chiz

Figure 3.27 – Plots for L miscalibration scale=1.1, resolution energy=0.1, $P_z=0.7$, with electron beam energy convolution, $P_{las}^{lin}=-0.05$, $P_{las}^{circ}=-0.95$

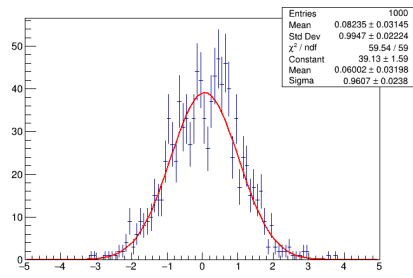
We have studied the simulation of the systematics related to the inclusion of a Compton polarimeter to the SuperKEKB accelerator. This polarimeter is intended to precisely measure the polarization of the electrons. It is part of the upgrade that is planned for SuperKEKB, along with the other modifications of the accelerator such as spin rotators and of the detector. The longitudinal polarization of the electrons is found to be well extracted without bias considering a one-per-mille precision with the simulated parameters of the laser and electron beams. The extraction of the polarization is not subjected to change with the change of the circular laser polarization, as long as this polarization is known. Nor does it change with the integration of a nuisance to the transverse electron polarization. This extraction is affected with



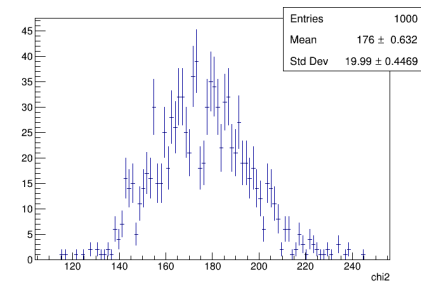
(a) Pz



(b) Pz err



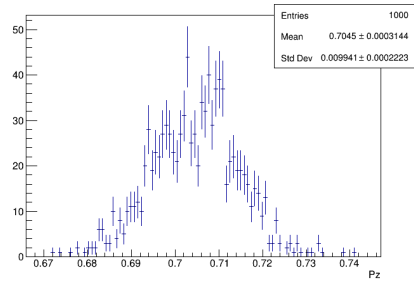
(c) Pull Pz



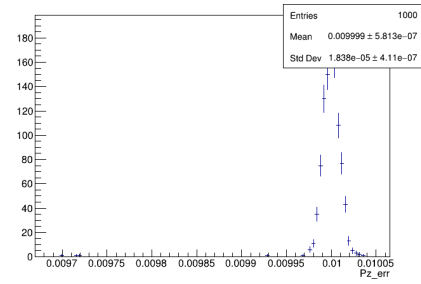
(d) Chi2

Figure 3.28 – Plots for H miscalibration scale = 1.1, resolution energy = 0.1, Pz = 0.7, with electron beam energy convolution, with misalignment dx = 1 mm.

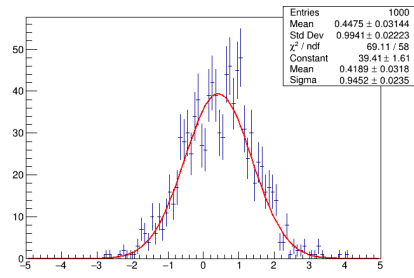
a bias of 0.4% taking into account a misalignment of the detector with respect to the electron beam axis of 2 mm.



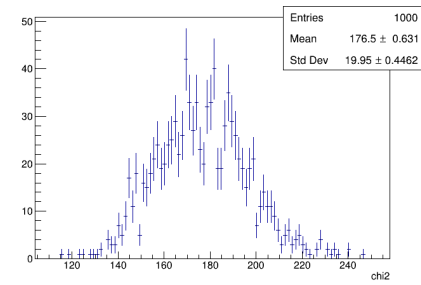
(a) P_z



(b) P_z err

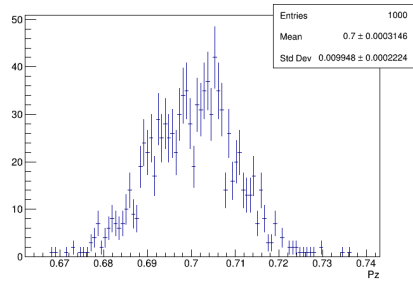


(c) Pull P_z

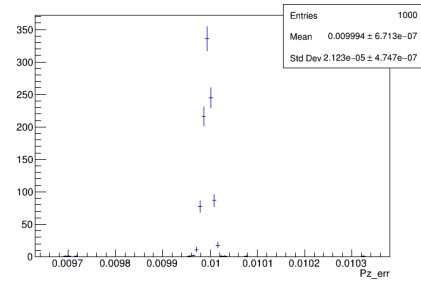


(d) χ^2

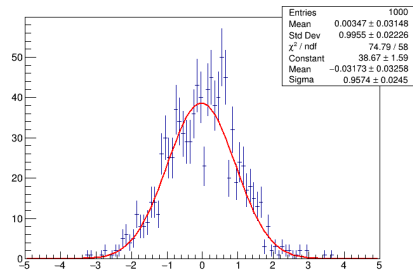
Figure 3.29 – Plots for I miscalibration scale = 1.1, resolution energy = 0.1, P_z = 0.7, with electron beam energy convolution, with misalignment dx = 2 mm.



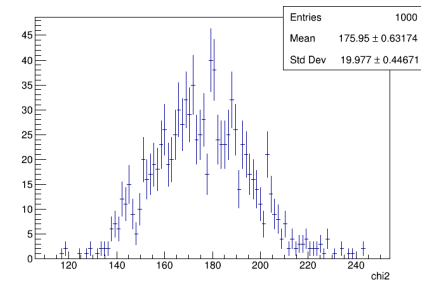
(a) P_z



(b) P_z err

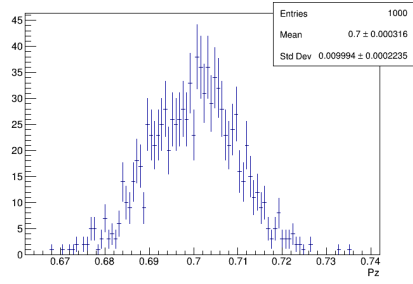


(c) Pull P_z

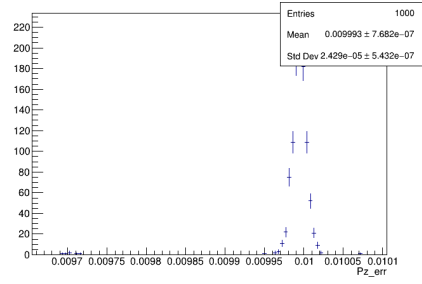


(d) χ^2

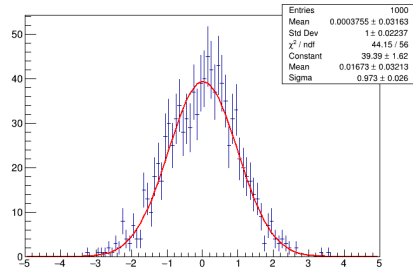
Figure 3.30 – Plots for J miscalibration scale = 1.1, resolution energy = 0.1, P_z = 0.7, with electron beam energy convolution, with misalignment $dy = 1$ mm.



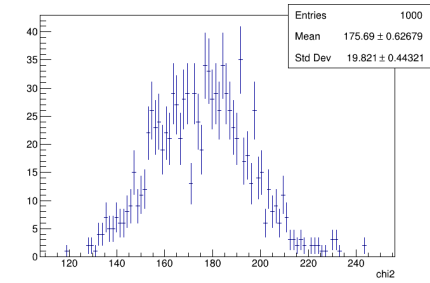
(a) P_z



(b) $P_z \text{ err}$

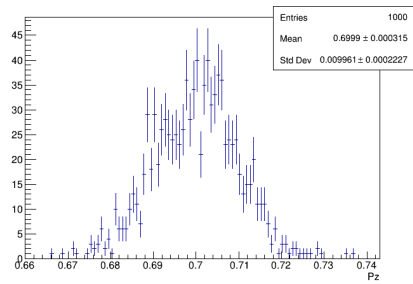


(c) Pull P_z

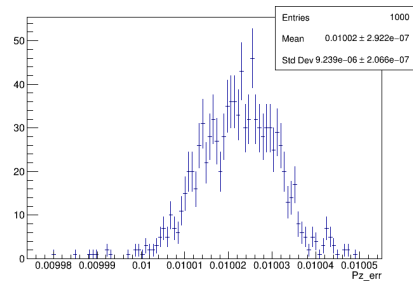


(d) χ^2

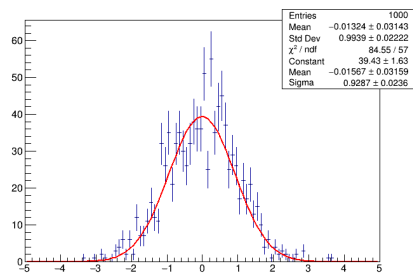
Figure 3.31 – Plots for K miscalibration scale=1.1, resolution energy=0.1, $P_z=0.7$, with electron beam energy convolution, $P_T=0.3$



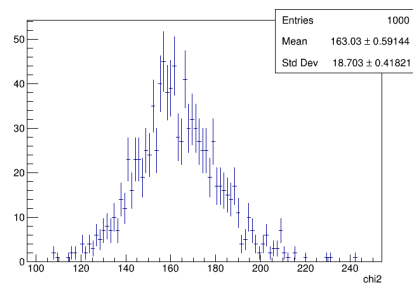
(a) P_z



(b) P_z err

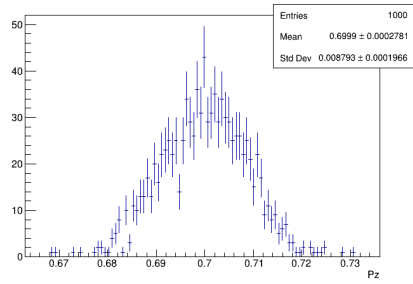


(c) Pull P_z

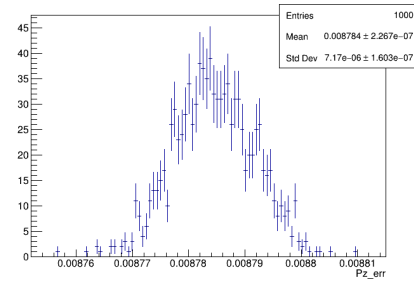


(d) χ^2

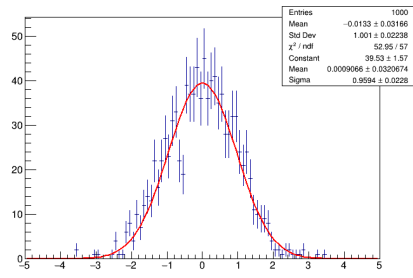
Figure 3.32 – Plots for B miscalibration scale = 1.03, resolution energy = 0.1, P_z = 0.7, with electron beam energy convolution.



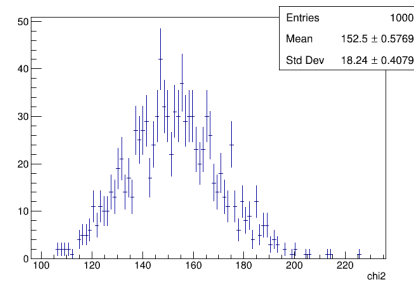
(a) P_z



(b) P_z err

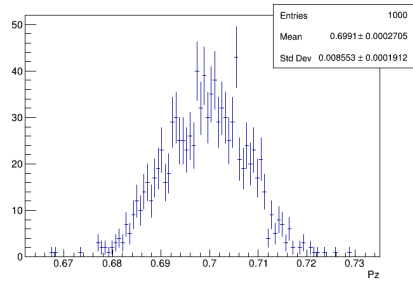


(c) Pull P_z

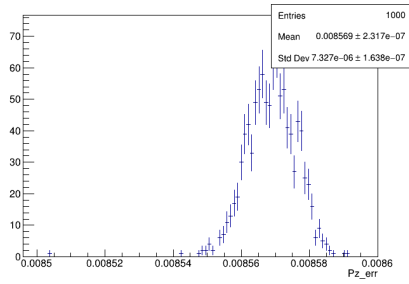


(d) χ^2

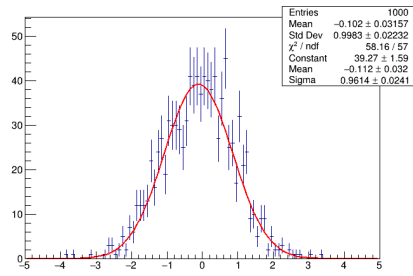
Figure 3.33 – Plots for C miscalibration scale = 1.1, resolution energy = 0.03, P_z = 0.7, with electron beam energy convolution.



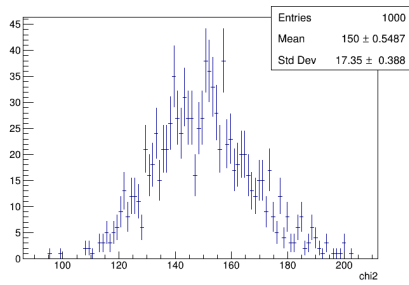
(a) P_z



(b) P_z err

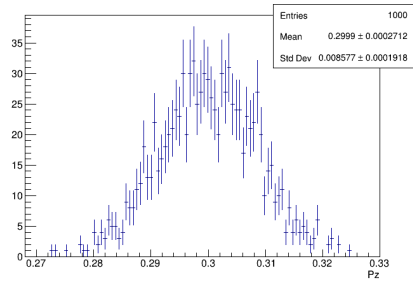


(c) Pull P_z

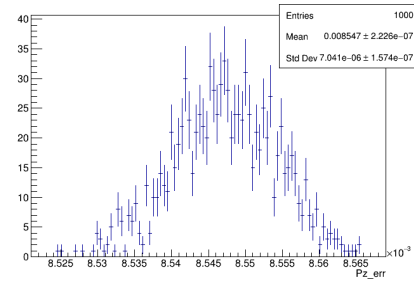


(d) χ^2

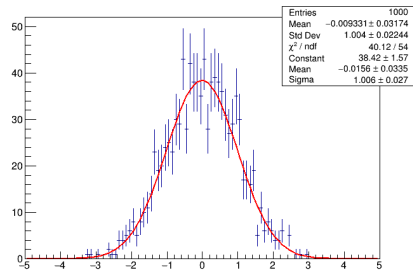
Figure 3.34 – Plots for D miscalibration scale = 1.1, resolution energy = 0.01, $P_z = 0.7$, with electron beam energy convolution.



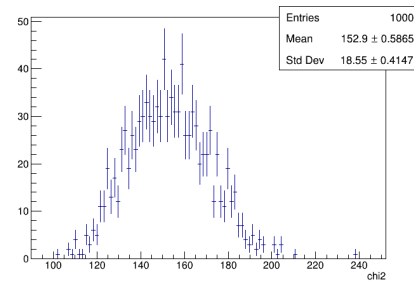
(a) P_z



(b) P_z err

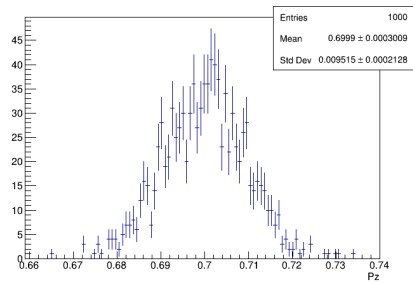


(c) Pull P_z

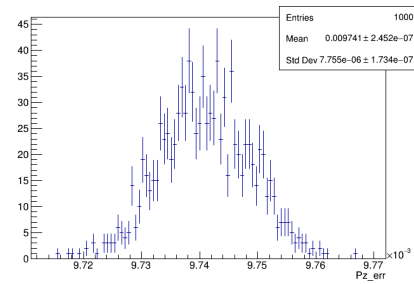


(d) χ^2

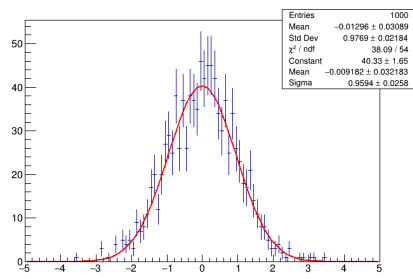
Figure 3.35 – Plots for E miscalibration scale = 1.1, resolution energy = 0.03, P_z = 0.3, with electron beam energy convolution.



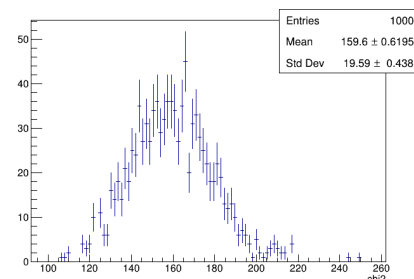
(a) P_z



(b) P_z err

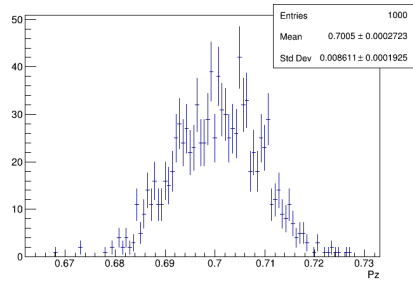


(c) Pull P_z

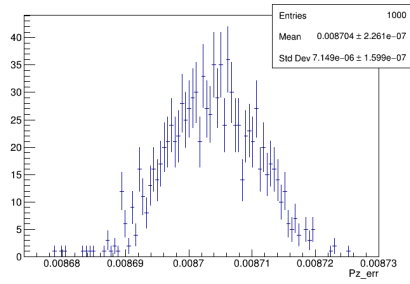


(d) χ^2

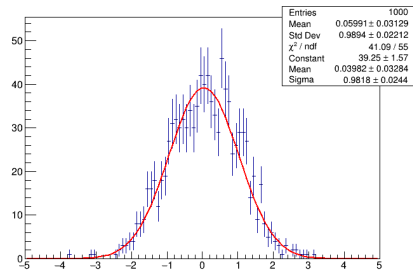
Figure 3.36 – Plots for F miscalibration scale = 1.0, resolution energy = 0.1, P_z = 0.7, with electron beam energy convolution.



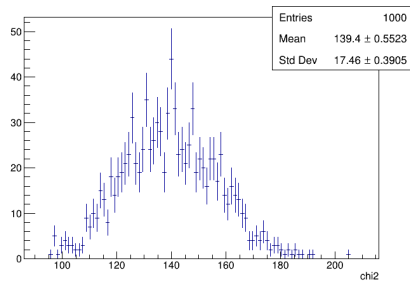
(a) Pz



(b) Pz err



(c) Pull Pz



(d) Chi2

Figure 3.37 – Plots for G miscalibration scale = 1.0, resolution energy = 0.03, Pz = 0.7, with electron beam energy convolution.

4 - Analysis of $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$ decays

In this chapter, I describe the analysis. First, I describe the Monte Carlo (MC) simulation of the events. I explain then each of the preselections and selections applied to the MC events. I apply later corrections to the MC samples so that the comparison with the data can be well performed.

4.1 . Event simulation

We simulate the production of tau pair events using basf2 software and modules. We generate our MC samples with conditions similar to Belle II data taking. For the analysis, we use generic simulated runs of tau pair events, which represent the signal and generic simulated backgrounds : $c\bar{c}$, $u\bar{u}$, $d\bar{d}$, $s\bar{s}$, $B^0\bar{B}^0$, $B^+\bar{B}^-$, $\mu^+\mu^-$, e^+e^- , e^+e^-ll , $llXX$, where l is a lepton : e, μ and X is any particle. The generation of tau pair samples in Belle II is explained in Sec. 2.3.1.

We used release light-2406-ragdoll of basf2 software to produce our events. We process MC15rd for the generation of the MC samples. For data, we use proc13 and prompt data processing. The total integrated luminosity of the samples studied is of $364fb^{-1}$. This involves experiments 7 to 26. For MC, we take into consideration the number of streams produced. For example, for the tau pair production, there are four streams meaning that there are $4 * 364 = 1456fb^{-1}$ of integrated luminosity for tau pair MC. Each channel has a number of streams of MC related to compare with data, depending on the cross section of the interaction. The number of streams for each channel of MC can be seen in Table 4.1.

Channel	Streams
$\tau^+\tau^-$	4
$q\bar{q}$	4
$B\bar{B}$	4
$\mu^+\mu^-$	1
e^+e^-	0.1
$e^+e^-\ell^+\ell^-$	1
h^+h^- ISR	1
$\ell^+\ell^-XX$	4

Table 4.1 – Number of streams used for each simulated channel.

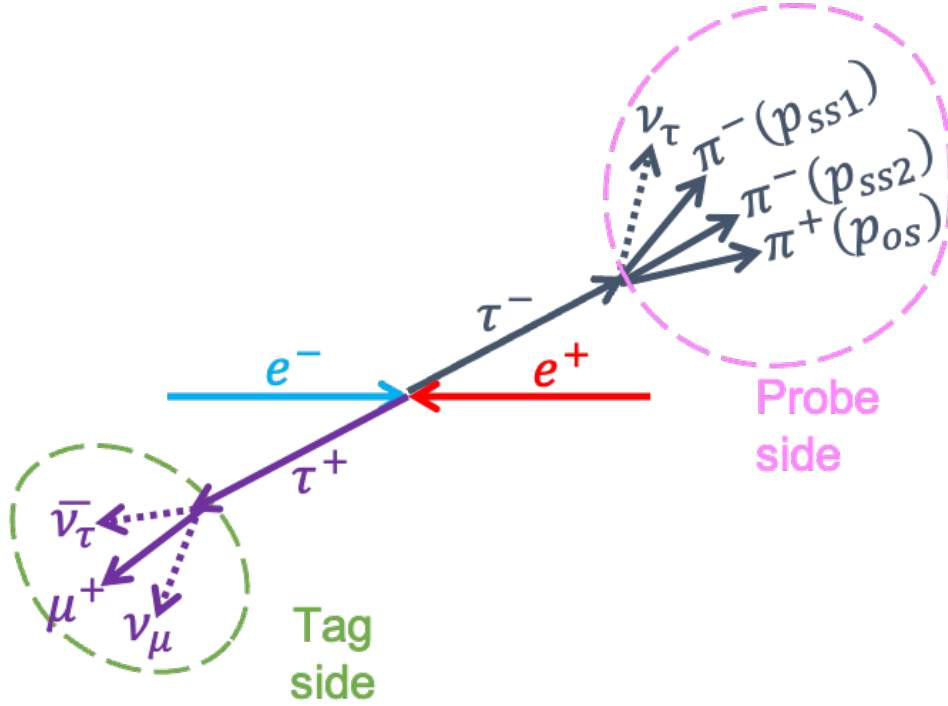


Figure 4.1 – Event diagram in the center-of-mass frame. Electron and positron collide producing two back to back taus. On the probe side, or signal side, the tau decays in our signal mode $\pi^- \pi^+ \pi^- \nu_\tau$. On the other side, called tag side, the tau is chosen to decay leptonically as $\mu^+ \nu_\mu \bar{\nu}_\tau$.

Event topology

Events are produced via $e^+ e^- \rightarrow \tau^+ \tau^-$ processes. The taus are back to back in the center-of-mass frame. One tau decays in the signal channel $\pi^- \pi^+ \pi^- \nu_\tau$. The other decays to the tag side channel $\mu^+ \nu_\mu \bar{\nu}_\tau$. The event topology can be seen in Fig. 4.1. Charge-conjugate modes, such as $\pi^+ \pi^- \pi^+ \bar{\nu}_\tau$ for the signal side and $\mu^- \bar{\nu}_\mu \nu_\tau$ for the tag side, are implied in this work. Other tag channels might be added in the future. Collaborators have studied inclusive tags [143].

4.2 . Preselections

The preselections are the list of selections that are applied even before the actual selections. All our events are generated with respect to these conditions. The purpose of preselections is to keep most of the useful signal events while removing most of the background. An event is accepted when there are exactly four measured tracks, corresponding to the three pions and the muon. Each track is required to

originate from the IP. To fulfill this condition, the distance closest to the IP is chosen to be less than 0.5 cm in the transverse plane and between -3 and 3 cm in the longitudinal direction.

Additional conditions are applied for each type of particle. Muons are identified by a likelihood-based method. The variable determining this probability of the identification of the muon is called muonID. Our muons must have a muonID greater than 0.5. This selection is surely not enough for the analysis, this is only first level selections.

Pions fulfill the conditions of a good track. We started by also applying a pionID greater than 0.5. The identification of the pion uses combined likelihoods from detector sub-systems :

$$KID \equiv \mathcal{L}(K : \pi) = \frac{\mathcal{L}(K)}{\mathcal{L}(K) + \mathcal{L}(\pi)},$$

$$\pi ID \equiv \mathcal{L}(\pi : K) = 1 - KID.$$

where πID is defined as the probability that a track is a pion given the competing kaon hypothesis, and vice versa for KID .

One of the taus is reconstructed from the tracks of the three pions. Its invariant mass must be less than 2GeV. This removes reconstructed particles that do not correspond to tau by constraining its mass.

The other tau is reconstructed from the muon.

We also fill a list of K_S^0 . We choose the K_S invariant mass to be between 0.4776 and 0.5176GeV, corresponding to its mass. This list is added in the processing of events, so that we can make a veto in the analysis stage.

We also save photon lists, to remove background events with photons but also to get a sample of signal free of π^0 s, if needed.

Concerning event related preselections, the thrust value must be larger than 0.8, and the missing energy of the event must not be negative. Thrust is a variable related to the event shape. It determines the degree of alignment of the final state particles along the axis of the two fermions production in the lab frame. It is defined as the maximum of the sum of the projected momenta on a unit vector, normalized by the total momentum [144] :

$$d = \frac{\max_{\vec{r}} \vec{r} \cdot d(\vec{r})}{\sum_a |\vec{p}_a|}$$

with

$$d(\vec{r}) = \sum_a \vec{p}_a \cdot \vec{r} \theta(\vec{p}_a \cdot \vec{r})$$

where $\vec{r}$ is an arbitrary unit vector and θ is a unit step function. When the thrust value is close to 1, it means that the event is jet-like. When its value is close to 0.5, the event is isotropic.

The total efficiency of the preselections is 20%.

A skim flag is also chosen in the steering file. Tau Thrust skim is applied. Events must pass the following criteria to be accepted :

1. The number of good tracks has to range between 0 and 7.
2. An event must have a zero total charge of the good tracks.
3. An event is divided into two hemispheres by thrust axis. It selects the topologies 1×1 , 1×3 , 1×5 and 3×3 .
4. The thrust value must be greater than 0.8.
5. The visible energy of the event in the CMS frame must be less than 10.4 GeV.

This skim is the most adapted to our analysis of 3×1 topology.

4.3 . Selections

In order to further purify our signal, I applied selections to the MC samples. We can distinguish different types of background, coming from the tag side or the probe side. Our selections are categorized into these main types; event related, tag or probe side related. Among the event related selections, we apply a veto on the K_S^0 particles. In fact, kaon mixing contributes to CP violation in the SM. We need to remove backgrounds that contain a neutral kaon in order to remove background induced CP violation. Events must have exactly zero K_S^0 . Second, an event is only accepted when it has two hemispheres, the probe side where the tau decayed into pions and the tag side where the tau decayed to a muon. We make sure the pions are on one side and that the muons are on the other, and no mixing between the two sides by checking the cosine of the angle between each of the pions direction to the thrust to be of same sign with respect to each other and to be of opposite sign with respect to the cosine of the angle of the muon to the thrust :

$$\cos \theta_{CMS}^{thrust} \pi^{sub-leading} \times \cos \theta_{CMS}^{thrust} \pi^{leading} > 0,$$

$$\cos \theta_{CMS}^{thrust} \pi^{sub-leading} \times \cos \theta_{CMS}^{thrust} \pi^{OS} > 0 \text{ and}$$

$$\cos \theta_{CMS}^{thrust} \pi^{sub-leading} \times \cos \theta_{CMS}^{thrust} \mu < 0.$$

such as π^{OS} is the pion of opposite sign to the τ , $\pi^{sub-leading}$ and $\pi^{leading}$ are the pions of same sign to the τ , The sub-leading pion has a smaller momentum to the leading one in the hadronic rest frame, defined in

details in Sec. 4.7. The selections related to the tag side include choosing muons of a muon likelihood higher than 0.99. It also includes removing events that contain photons, since photons are often produced with hadronic tau decays as these hadronic decays contain neutral pions that give photons. So removing photons on the tag side reduce some of the hadronic background. Concerning the probe side selections, the pionIDNN of the leading pion is chosen greater than 0.9. pionIDNN is an improved variable from the pionID. pionIDNN uses neural network and is recommended by the performance group. When studying our probe side background, which is dominated by $K\pi\pi$, in 78% of cases the kaon corresponds to the hadron having the largest momentum. So we make a cut of 0.9 only on the largest momentum of same sign hadron. For the 2 other hadrons, we keep the pionIDNN at 0.5. Also, the invariant masses of both the system formed of the leading pion and opposite pion, and that formed by the sub-leading pion and opposite pion are selected greater than 0.3GeV, in order to remove the decaying events of $\pi\pi^0(\rightarrow \gamma e^+e^-)$. To visualize the effect of this selection, we represent 2D plots of these invariant masses for the signal : where $\tau^- \rightarrow \pi^-\pi^+\pi^-\nu_\tau$ in Fig. 4.2, where $\tau^- \rightarrow \pi^-\pi^+\pi^-(>0\pi^0)\nu_\tau$ in Fig. 4.3 and for the probe and tag background in Figs. 4.4 and 4.5. Another selection to remove the majority of this specific mode of background is $p_T^{OS\pi} > 0.3$. In fact, the reconstructed OS pion is, in that case, an electron/positron coming originally from a π^0 , so we remove many of this background as the transverse momentum p_t is related to the mother particle. This can be seen in Fig. 4.6. As for the tau selections, the particle system reconstructed from the three pions is required to have a flight distance of less than 1cm. This reduces the contribution from hadronic interaction of true pions in the detector. And the χ^2 probability is chosen larger than 10^{-3} to have a vertex of good enough quality. This selection can be visualized in Fig. 4.7. Lastly, we add a selection related to the energies of the reconstructed particles of the decay under study. We define a variable $\delta E_{\text{missing}}$ related to the difference between the CMS energy and the sum of the energies of the reconstructed tracks :

$$\delta E_{\text{missing}} = E_{\text{CMS}} - \sum E_{\text{reconstructed particles}}^{\text{CMS}} \quad (4.1)$$

$$= E_{\text{CMS}} - (E_{\pi^{ss1}}^{\text{CMS}} + E_{\pi^{ss2}}^{\text{CMS}} + E_{\pi^{os}}^{\text{CMS}} + E_{\mu}^{\text{CMS}}). \quad (4.2)$$

We request a cut on this variable :

$$\delta E_{\text{missing}} < (2 + \text{missing energy in CMS}) \quad (4.3)$$

where the missing energy in CMS is related mainly to the energy that was not detected, including neutrinos, photons or neutral pions. To see

how efficient this selection is, we show the $\delta E_{\text{missing}}$ variable versus the missing energy in CMS. After applying the list of all the selections mentioned above, the 2D plot for the tau pair signal where $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$ is in Fig. 4.8. Many probe background events are removed thanks to this selection, as seen in Fig. 4.9. This plot is also shown for the tag background in Fig. 4.10 where a large number of tag background events are removed. Fig. 4.11 shows that the majority of $q\bar{q}$ background events are also removed.

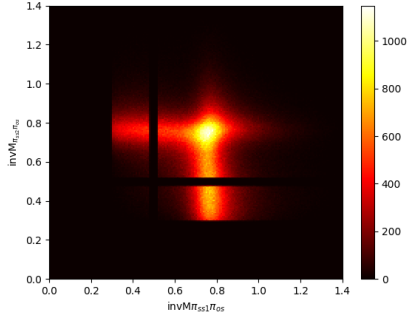


Figure 4.2 – 2D plot of the invariant mass of the leading pion and opposite sign pion $\text{inv}M_{\pi_{ss2}\pi_{os}}$ versus the invariant mass of the sub-leading pion and opposite sign pion $\text{inv}M_{\pi_{ss1}\pi_{os}}$ for signal $\tau^+(\mu^+)\tau^-(\pi^-\pi^+\pi^-)$.

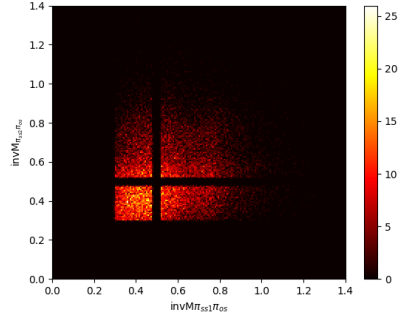


Figure 4.3 – 2D plot of the invariant mass of the leading pion and opposite sign pion $\text{inv}M_{\pi_{ss2}\pi_{os}}$ versus the invariant mass of the sub-leading pion and opposite sign pion $\text{inv}M_{\pi_{ss1}\pi_{os}}$ for signal $\tau^+(\mu^+)\tau^-(\pi^-\pi^+\pi^-\pi^0)$.

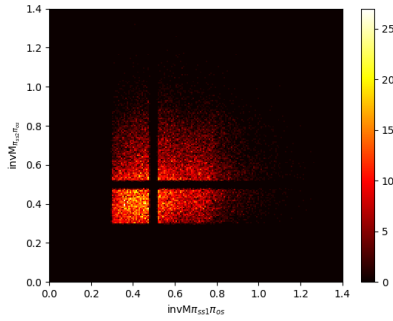


Figure 4.4 – 2D plot of the invariant mass of the leading pion and opposite sign pion $\text{inv}M_{\pi_{ss2}\pi_{os}}$ versus the invariant mass of the sub-leading pion and opposite sign pion $\text{inv}M_{\pi_{ss1}\pi_{os}}$ for the $\tau^+\tau^-$ probe background.

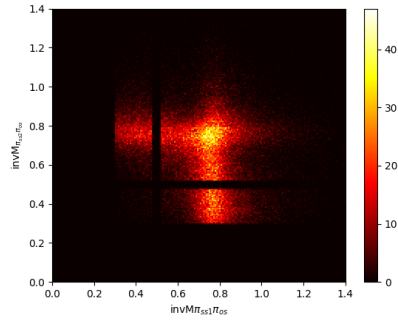


Figure 4.5 – 2D plot of the invariant mass of the leading pion and opposite sign pion $\text{inv}M_{\pi_{ss2}\pi_{os}}$ versus the invariant mass of the sub-leading pion and opposite sign pion $\text{inv}M_{\pi_{ss1}\pi_{os}}$ for the $\tau^+\tau^-$ tag background.

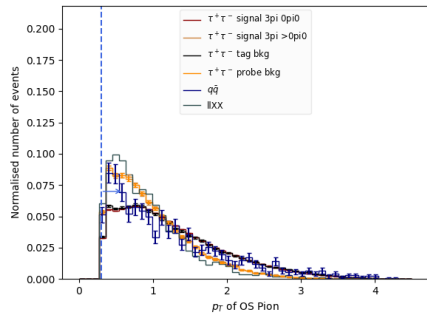


Figure 4.6 – The transverse momentum of the opposite sign pion for the signal events and the background events. All backgrounds have been included but only the ones which actually contribute are plotted. The error bars are plotted for all distributions but some channels have larger error bars that can be seen. The blue vertical line shows where the selection is applied.

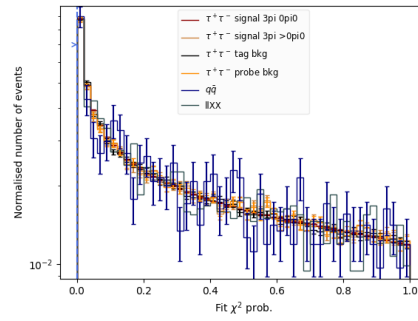


Figure 4.7 – Fit χ^2 probability of the vertex, for the signal events and the background events. All backgrounds have been included but only the ones which actually contribute are plotted. The error bars are plotted for all distributions but some channels have larger error bars that can be seen. The blue vertical line shows where the selection is applied.

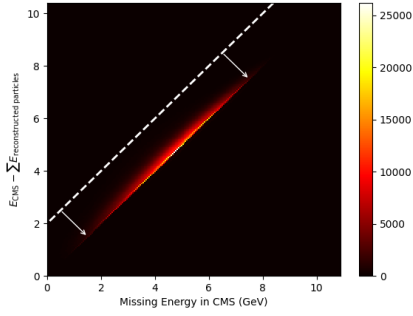


Figure 4.8 – $\delta E_{\text{missing}}$ for the signal $\tau^+(\mu^+)\tau^-(\pi^-\pi^+\pi^-)$. The white hatched line and arrows represent the applied selection and the region where events are removed.

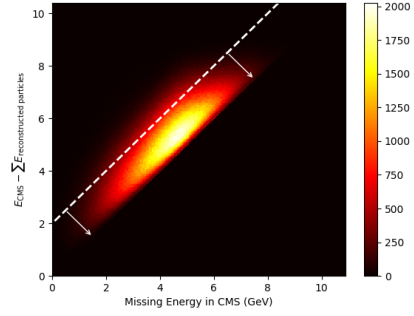


Figure 4.9 – $\delta E_{\text{missing}}$ for the $\tau^+\tau^-$ probe background. The white hatched line and arrows represent the applied selection and the region where events are removed.

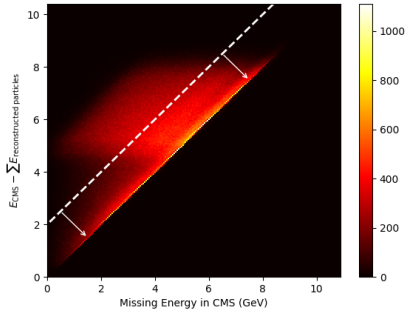


Figure 4.10 – $\delta E_{\text{missing}}$ for the $\tau^+\tau^-$ tag background. The white hatched line and arrows represent the applied selection and the region where events are removed.

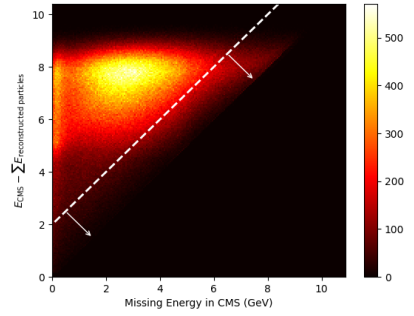


Figure 4.11 – $\delta E_{\text{missing}}$ for the $q\bar{q}$ background. The white hatched line and arrows represent the applied selection and the region where events are removed.

Efficiencies on selections

The efficiency on each of the selection applied separately on our MC samples and the total efficiency of all selections is present in Table 4.2. The total yields are present in Table 4.3.

In addition, pion identification performance is shown as signal efficiency versus background rejection in Figs. 4.12, 4.13 and 4.14. Signal efficiency measures the fraction of true pion tracks that are correctly identified as pions. Background rejection measures the fraction of non-pion tracks (predominantly kaons) that are rejected by the same selection.

	Signal ($3\pi + 0\pi^0$)	Signal ($3\pi + (\geq 1\pi^0)$)	Tag-side Bkg.	Probe-side Bkg.
$n(K_S^0) = 0$	0.912 ± 0.0001	0.7913 ± 0.0002	0.8504 ± 0.0002	0.2465 ± 0.001
μ_{ID}	0.9161 ± 0.0001	0.915 ± 0.0001	0.4051 ± 0.0003	0.9102 ± 0.0007
$n_\gamma = 0$	0.5171 ± 0.0002	0.0158 ± 0.0001	0.0783 ± 0.0001	0.3209 ± 0.0011
topology	0.998 ± 0.0	0.9988 ± 0.0	0.7214 ± 0.0002	0.9866 ± 0.0003
$\Delta E, E_{miss}$	0.9916 ± 0.0	0.851 ± 0.0002	0.5435 ± 0.0003	0.9369 ± 0.0006
π_{ID}	0.8814 ± 0.0001	0.8995 ± 0.0002	0.9046 ± 0.0002	0.8565 ± 0.0009
$M(\pi^+, \pi^-)$	0.9822 ± 0.0	0.9639 ± 0.0001	0.9785 ± 0.0001	0.9531 ± 0.0005
p_T	0.9192 ± 0.0001	0.8868 ± 0.0002	0.857 ± 0.0002	0.854 ± 0.0009
flight dist.	0.9982 ± 0.0	0.9968 ± 0.0	0.9953 ± 0.0	0.6082 ± 0.0012
vertex	0.91 ± 0.0001	0.9022 ± 0.0002	0.809 ± 0.0002	0.2628 ± 0.0011
all	0.3174 ± 0.0002	0.0074 ± 0.0	0.0208 ± 0.0001	0.0291 ± 0.0004

Table 4.2 – Efficiencies applied on MC15rd samples.

	Signal ($3\pi + 0\pi^0$)	Signal ($3\pi + (\geq 1\pi^0)$)	Tag-side Bkg.	Probe-side Bkg.
	7204830	3687750	3589806	169376
$n(K_S^0) = 0$	6571118 ± 2563	2918134 ± 1708	3052899 ± 1747	41756 ± 204
μ_{ID}	6600255 ± 2569	3374383 ± 1836	1454311 ± 1205	154170 ± 392
$n_\gamma = 0$	3725597 ± 1930	58446 ± 241	281229 ± 530	54351 ± 233
topology	7190422 ± 2681	3683220 ± 1919	2589657 ± 1609	167099 ± 408
$\Delta E, E_{miss}$	7144246 ± 2672	3138115 ± 1771	1951102 ± 1396	158687 ± 398
π_{ID}	6350343 ± 2519	3317275 ± 1821	3247300 ± 1802	145065 ± 380
$M(\pi^+, \pi^-)$	7076441 ± 2660	3554663 ± 1885	3512525 ± 1874	161440 ± 401
p_T	6622476 ± 2573	3270401 ± 1808	3076576 ± 1754	144645 ± 380
flight dist.	7191978 ± 2681	3675851 ± 1917	3572828 ± 1890	103022 ± 320
vertex	6556275 ± 2560	3327126 ± 1824	2904325 ± 1704	44516 ± 210
all	2286511 ± 1512	27124 ± 164	74548 ± 273	4929 ± 70

Table 4.3 – Yields applied on MC15rd samples.

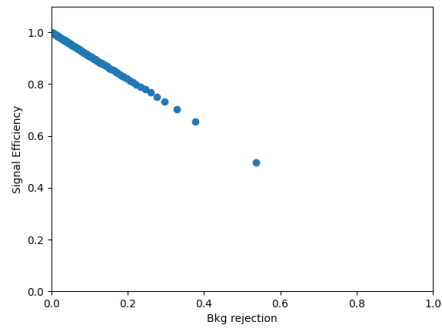


Figure 4.12 – PionID signal efficiency versus background rejection for the opposite sign pion.

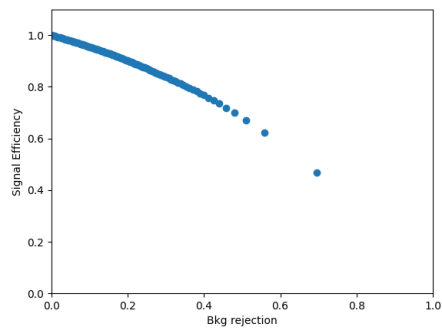


Figure 4.13 – PionID signal efficiency versus background rejection for the sub-leading pion.

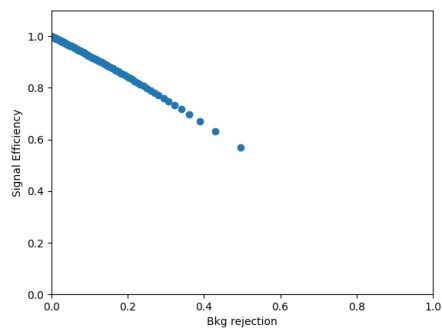


Figure 4.14 – PionID signal efficiency versus background rejection for the leading pion.

Remaining modes

After applying the selections, the remaining tau decay modes are shown in Table 4.4 representing the signal as a τ decaying to 3π without any neutral pion, and in Table 4.5 the signal events of τ decaying to 3π with at least one neutral pion.

We define two types of background : probe side related background and tag side related background. The ones that contribute to the probe side are shown in Table 4.6. The largest is from $\tau^- \rightarrow K^- \pi^+ \pi^-$ events that contribute to half of the probe side backgrounds. The ones that contribute to the tag side background are presented in Table 4.7. The most common is $\tau^- \rightarrow \pi^- \nu_\tau$ which contributes to 88% of all other modes.

After applying the selections, we obtain a signal purity of 0.9561 ± 0.0001 and a background-to-signal ratio B/S of 0.0459 ± 0.0001 .

Table 4.4 - $\tau^\pm$ Signal ($3\pi + 0\pi^0$) decay modes

Decay Mode	Decay
$\tau \rightarrow \nu_\tau \pi^- \pi^- \pi^+$	2286511 ± 1512
sum of all decay modes	2286511 ± 1512

Table 4.5 - $\tau^\pm$ Signal ($3\pi + (\geq 1\pi^0)$) decay modes

Decay Mode	Decay
$\tau \rightarrow \nu_\tau \pi^- \pi^- \pi^+ \pi^0$ (including $\omega \rightarrow \pi^- \pi^+ \pi^0$)	26845 ± 164
$\tau \rightarrow \nu_\tau \pi^- \pi^- \pi^+ \pi^0 \pi^0$ (including $\omega \rightarrow \pi^- \pi^+ \pi^0$)	270 ± 16
$\tau \rightarrow \nu_\tau \pi^- \pi^- \pi^+ \eta (\rightarrow \gamma\gamma)$	7 ± 3
$\tau \rightarrow \nu_\tau \pi^- \pi^- \pi^+ \eta (\rightarrow \pi^0 \pi^0 \pi^0)$	1 ± 1
$\tau \rightarrow \nu_\tau \pi^- \pi^- \pi^+ \pi^0 \pi^0 \pi^0$	1 ± 1
sum of all decay modes	27124 ± 165

Table 4.6 - Probe-side Bkg. decay modes

Decay Mode	Decay
$\tau \rightarrow \nu_\tau \pi^- \pi^+ K^-$	2975 ± 55
$\tau \rightarrow \nu_\tau \pi^- \pi^- \pi^+ K_L^0$	1529 ± 39

Decay Mode	Decay
$\tau \rightarrow \nu_\tau \pi^- \pi^- \pi^- \pi^+ \pi^+$	157 ± 13
$\tau \rightarrow \nu_\tau \pi^- K^- K^+$	129 ± 11
$\tau \rightarrow \nu_\tau \pi^- \pi^- \pi^+ K_S^0$	71 ± 8
$\tau \rightarrow \nu_\tau K^- \omega (\rightarrow \pi^- \pi^+ \pi^0)$	11 ± 3
$\tau \rightarrow \nu_\tau \pi^- \pi^0$	11 ± 3
$\tau \rightarrow \nu_\tau \pi^- \pi^+ K^- \pi^0$	8 ± 3
$\tau \rightarrow \nu_\tau K^- \omega (\rightarrow \pi^- \pi^+)$	8 ± 3
$\tau \rightarrow \nu_\tau \pi^- f_1 (\rightarrow \pi^- \pi^- \pi^+ \pi^+)$	8 ± 3
$\tau \rightarrow \nu_\tau \pi^- K_L^0 \eta (\rightarrow \pi^- \pi^+ \gamma)$	5 ± 2
$\tau \rightarrow \nu_\tau K^- \eta (\rightarrow \pi^- \pi^+ \pi^0)$	3 ± 2
$\tau \rightarrow \nu_\tau \pi^- K_L^0 \eta (\rightarrow \pi^- \pi^+ \pi^0)$	2 ± 1
$\tau \rightarrow \nu_\tau \pi^- K_S^0$	2 ± 1
$\tau \rightarrow \nu_\tau K^- \eta (\rightarrow \pi^- \pi^+ \gamma)$	1 ± 1
$\tau \rightarrow \nu_\tau K^- \phi (\rightarrow K^- K^+)$	1 ± 1
$\tau \rightarrow \nu_\tau \pi^- K_S^0 \eta (\rightarrow \pi^- \pi^+ \gamma)$	1 ± 1
$\tau \rightarrow \nu_\tau \pi^- K_S^0 \eta (\rightarrow \pi^- \pi^+ \pi^0)$	1 ± 1
$\tau \rightarrow \nu_\tau \pi^- \pi^0 \pi^0$	1 ± 1
$\tau \rightarrow \nu_\tau \pi^- \pi^- \pi^+ \omega (\rightarrow \pi^- \pi^+ \pi^0)$	1 ± 1
$\tau \rightarrow \nu_\tau \pi^- \pi^- \pi^+ \eta (\rightarrow \pi^- \pi^+ \gamma)$	1 ± 1
$\tau \rightarrow \nu_\tau \pi^- \pi^- \pi^+ \eta (\rightarrow \pi^- \pi^+ \pi^0)$	1 ± 1
$\tau \rightarrow \nu_\tau \pi^- f_1 (\rightarrow \pi^- \pi^+ \eta (\rightarrow \pi^- \pi^+ \gamma))$	1 ± 1
$\tau \rightarrow \nu_\tau \pi^-$	1 ± 1
sum of all decay modes	4929 ± 70

Table 4.7 – Tag-side Bkg. decay modes

Decay Mode	Decay
$\tau \rightarrow \nu_\tau \pi^-$	66541 ± 258
$\tau \rightarrow \nu_\tau \pi^- \pi^0$	3335 ± 58
$\tau \rightarrow \nu_\tau K^-$	2730 ± 52
$\tau \rightarrow \nu_\tau \pi^- K_L^0$	1021 ± 32
$\tau \rightarrow \nu_\tau \bar{\nu}_e e^-$	293 ± 17
$\tau \rightarrow \nu_\tau \pi^- \pi^0 \gamma$	180 ± 13
$\tau \rightarrow \nu_\tau \pi^- \pi^0 \pi^0$	150 ± 12
$\tau \rightarrow \nu_\tau K^- K_L^0$	107 ± 10
$\tau \rightarrow \nu_\tau \pi^- K_S^0$	53 ± 7
$\tau \rightarrow \nu_\tau \pi^- K_L^0 K_L^0$	36 ± 6
$\tau \rightarrow \nu_\tau K^- \pi^0$	29 ± 5
$\tau \rightarrow \nu_\tau \pi^- \pi^0 K_L^0$	13 ± 4

Decay Mode	Decay
$\tau \rightarrow \nu_\tau \pi^- \pi^+ K^-$	9 ± 3
$\tau \rightarrow \nu_\tau a_1^- (\rightarrow \pi^- \gamma)$	9 ± 3
$\tau \rightarrow \nu_\tau \rho^- (\rightarrow \pi^- \gamma)$	8 ± 3
$\tau \rightarrow \nu_\tau \pi^- K_S^0 K_L^0$	8 ± 3
$\tau \rightarrow \nu_\tau \pi^- \pi^0 \pi^0 \pi^0$	8 ± 3
$\tau \rightarrow \nu_\tau K^- K_S^0$	7 ± 3
$\tau \rightarrow \nu_\tau \pi^- \pi^0 \pi^0 K_L^0$	3 ± 2
$\tau \rightarrow \nu_\tau \pi^- \pi^0 \pi^0 \pi^0 \pi^0$	2 ± 1
$\tau \rightarrow \nu_\tau \pi^- \pi^0 K_S^0$	2 ± 1
$\tau \rightarrow \nu_\tau K^- \pi^0 K_L^0$	2 ± 1
$\tau \rightarrow \nu_\tau \pi^- \pi^- \pi^+ K_L^0$	1 ± 1
$\tau \rightarrow \nu_\tau \pi^- \pi^+ K^- \pi^0$	1 ± 1
sum of all decay modes	74548 ± 273

Efficiencies

The detailed efficiencies are given in Table 4.8. The reconstruction efficiency is 96%. The skimming efficiency is 95%.

Reconstruction	0.9651 ± 0.0088
Preselection	0.2054 ± 0.0192
Skim efficiency	0.9560 ± 0.0215
Selections efficiency	0.3174 ± 0.0002
CDC trigger efficiency	0.9644 ± 0.0001
ECL trigger efficiency	0.6412 ± 0.0003
Trigger	0.9838 ± 0.0001
Total	0.0592 ± 0.0057

Table 4.8 – Efficiencies of preselections, selections, skim and trigger. Total efficiency is of 6%. The preselection efficiency is 20% which is low due to the cut on the pion identification ($\text{pionID} > 0.9$).

4.4 . Trigger

We studied the impact of the triggers on the analysis. CDC triggers that we studied are :

- fff, ffy : number of 2D tracks is ≥ 3 . Both have same efficiency but ffy has a smaller trigger rate with z vertex cut.
- fyo, ffo : number of 2D tracks is 2 or ≥ 3 and the opening angle of CDC is 90° .
- stt : number of tracks ≥ 1 , $p > 0.7\text{GeV}$.

Among the ECL triggers, we use the ones defined below :

- hie : cluster energy sum $> 1\text{GeV}$.
- lml12 : N cluster ≥ 3 , at least 1 cluster energy $\geq 0.5\text{ GeV(Lab)}$.

The yields on MC and data for each of the triggers is given in Table 4.9. After applying the corrections of pionID on the pions and muonID on the muon, the yields in MC and data for each of the triggers is given in Table 4.10.

Trigger	MC Yield	Data Yield
stt	440657.75	349125
ffo	144471.5	108897
ffy	521424.75	385017
fyo	530983.5	382038
fff	141477.5	110262
hie	362888.25	277210
lml12	326247.0	249074
any	595141.5	473697

Table 4.9 – Yields after applying each trigger and the combined trigger ("any"). MC and data after selection samples. MC yields are scaled by $1/4$ to account for 1 stream out of 4.

Trigger	MC Yield (weighted)	Data Yield (weighted)
stt	356158	349125
ffo	116263	108897
ffy	418265	385017
fyo	427621	382038
fff	113413	110262
hie	291041	277210
lml12	261705	249074
any	481317	473697

Table 4.10 – Weighted yields after applying each trigger and the combined trigger ("any"). MC yields are scaled by 1/4 to account for 1 stream out of 4 and corrections of the 3 pions and muon ID are applied.

The efficiency for an ECL trigger is calculated as :

$$\epsilon_{\text{ECL trigger}} = \frac{\text{\#events passing the ECL trig and any of the CDC trigs}}{\text{\#events passing any of the CDC triggers}}$$

and that of a CDC trigger as :

$$\epsilon_{\text{CDC trigger}} = \frac{\text{\#events passing the CDC trig and any of the ECL trigs}}{\text{\#events passing any of the ECL trigs}}$$

The triggers efficiencies for ECL triggers can be seen in Fig. 4.15, similarly for CDC triggers in Fig. 4.16. In addition, the ECL (and CDC) triggers efficiencies per experiment number can be seen in Figs. 4.17 and 4.18.

The ratios of the triggers efficiencies for the data to MC, for the CDC triggers are shown in Figs. 4.19, 4.20 and 4.21, for the ECL triggers in Figs. 4.22, 4.23 and 4.24, and for total triggers in Figs. 4.25, 4.26 and 4.27. We observe a significant discrepancy between data and MC for the ECL triggers. The impact of this disagreement on the analysis remains to be evaluated. To do so, we can check whether there is any charge-dependent behavior, and if so, assign an appropriate systematic uncertainty.

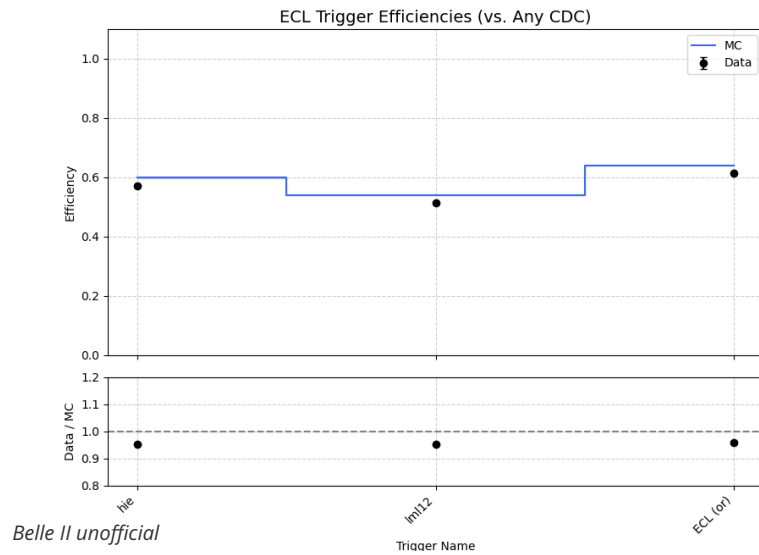


Figure 4.15 – Trigger efficiency for each of the CDC applied triggers, and the total trigger efficiency in "any" for MC samples in blue and for data as points. Data and MC are in good agreement for both triggers. Trigger efficiency is about 80% after applying both.

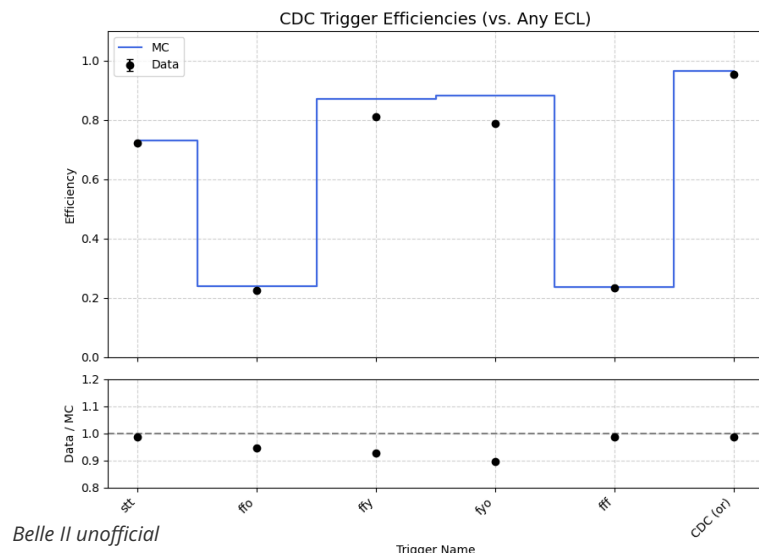


Figure 4.16 – Trigger efficiency for each of the CDC applied triggers, and the total trigger efficiency in "any" for MC samples in blue and for data as points. Data and MC are in good agreement for all triggers except for fff and fyo. Trigger efficiency is above 95% after applying all.

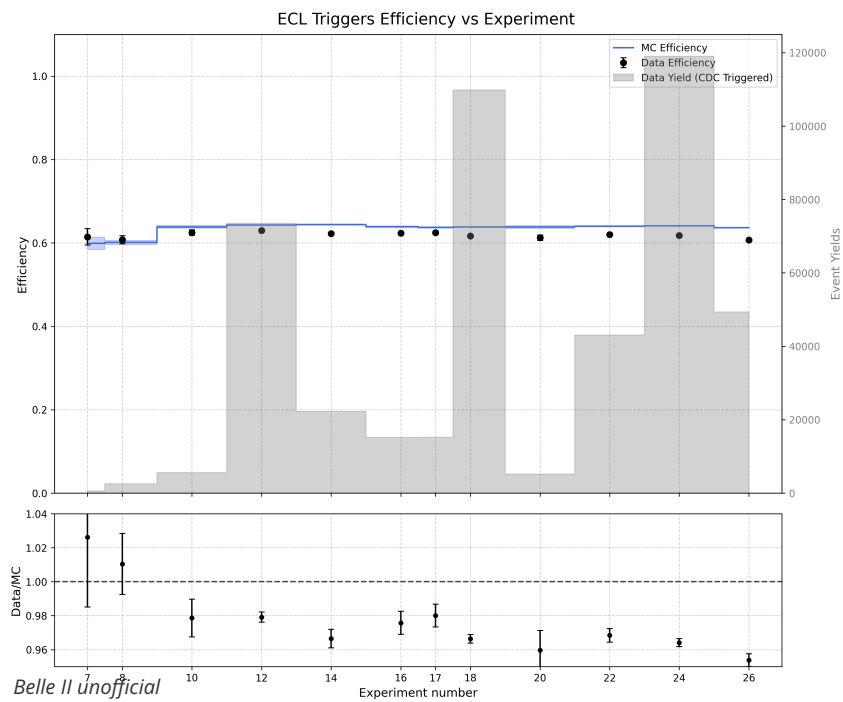


Figure 4.17 – ECL Trigger efficiency per experiment number.

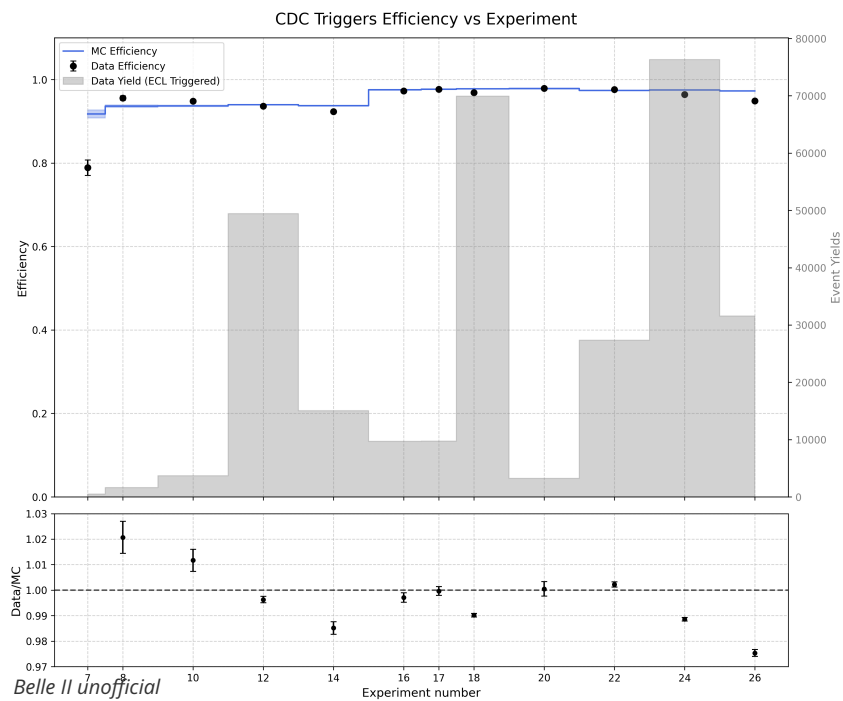


Figure 4.18 – CDC Trigger efficiency per experiment number.

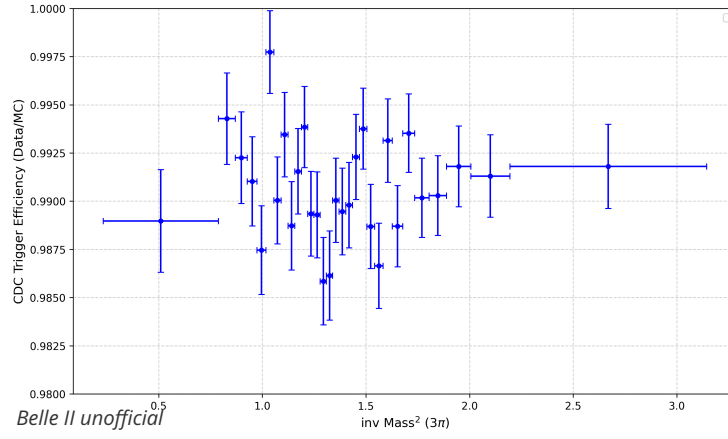


Figure 4.19 – CDC trigger efficiency for Data over MC versus $\text{inv}M^2(3\pi)$.

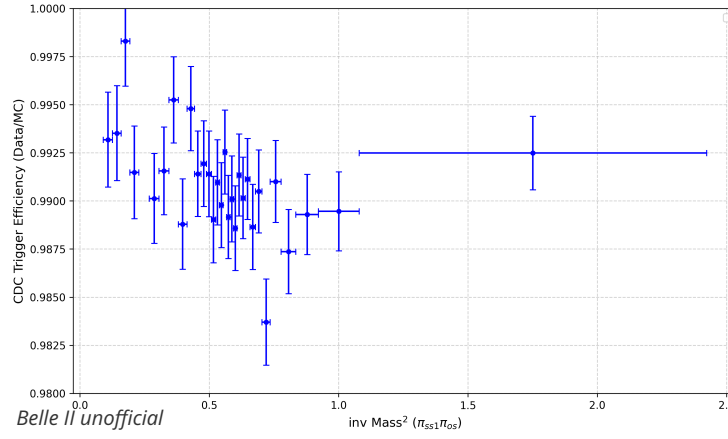


Figure 4.20 – CDC trigger efficiency for Data over MC versus $\text{inv}M^2(\pi_{ss1}\pi_{os})$.

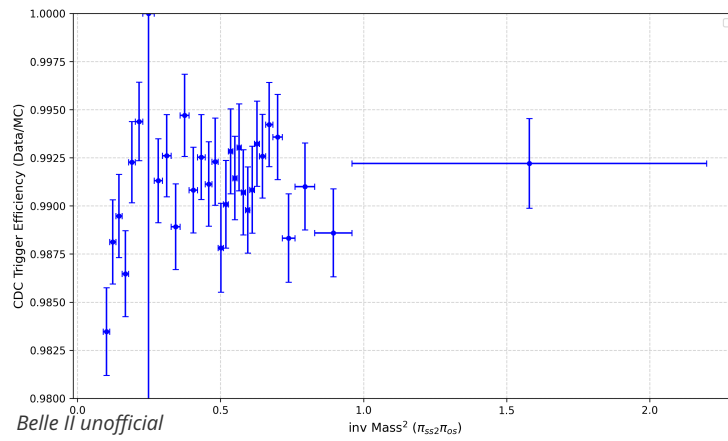


Figure 4.21 – CDC trigger efficiency for Data over MC versus $\text{inv}M^2(\pi_{ss2}\pi_{os})$.

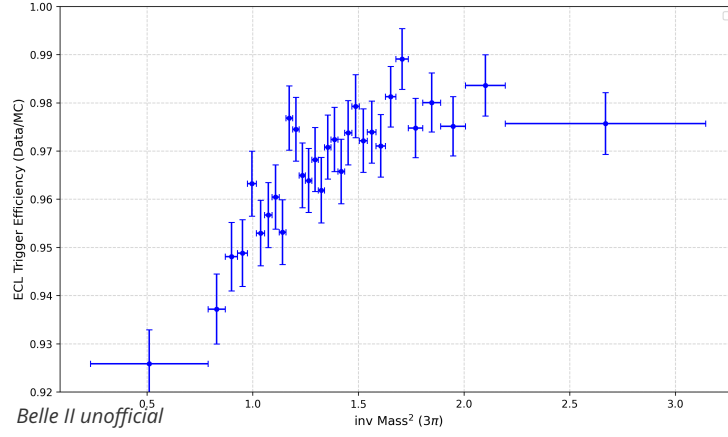


Figure 4.22 – ECL trigger efficiency for Data over MC versus $\text{inv}M^2(3\pi)$.

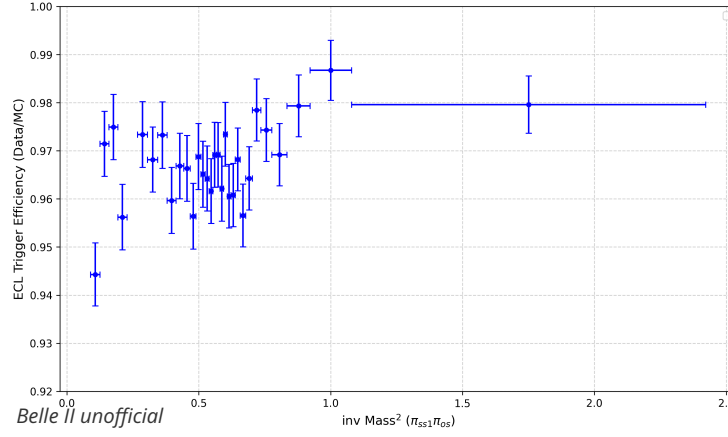


Figure 4.23 – ECL trigger efficiency for Data over MC versus $\text{inv}M^2(\pi_{ss1}\pi_{os})$.

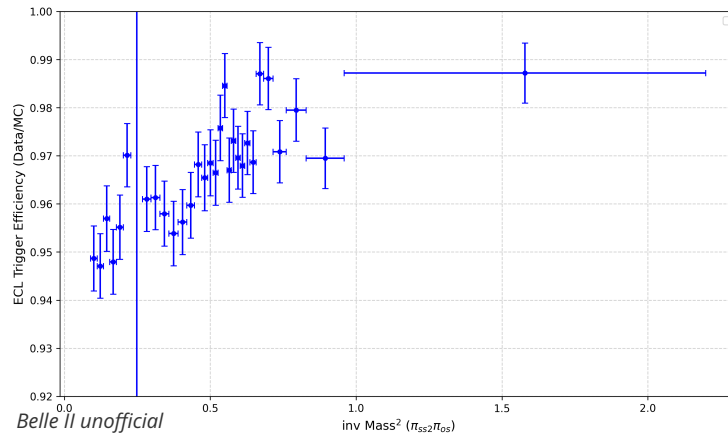


Figure 4.24 – ECL trigger efficiency for Data over MC versus $\text{inv}M^2(\pi_{ss2}\pi_{os})$.

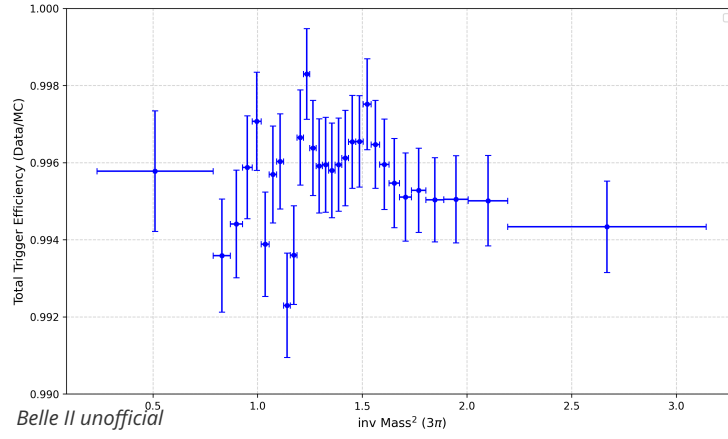


Figure 4.25 – Total trigger efficiency for Data over MC versus $\text{invM}^2(3\pi)$.

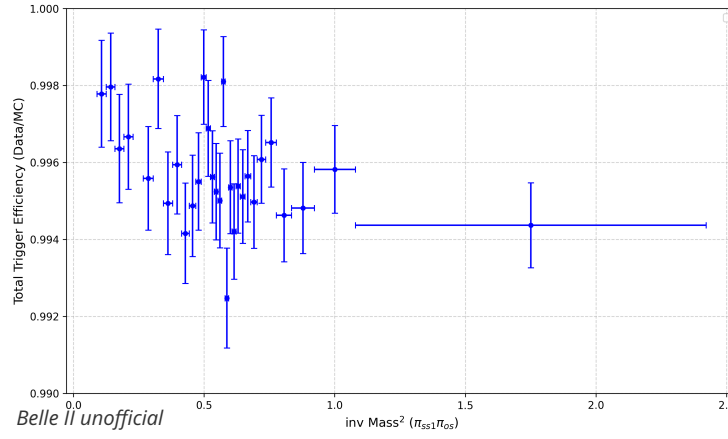


Figure 4.26 – Total trigger efficiency for Data over MC versus $\text{invM}^2(\pi_{ss1}\pi_{os})$.

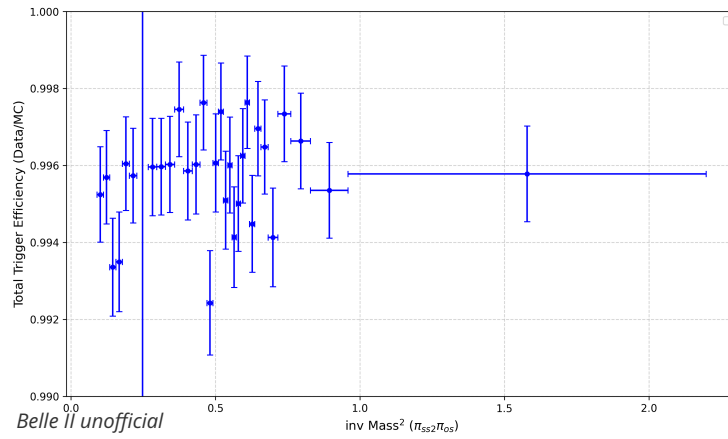


Figure 4.27 – Total trigger efficiency for Data over MC versus $\text{invM}^2(\pi_{ss2}\pi_{os})$.

4.5 . Corrections

PID Corrections : Belle II determination of particle ID is not perfect, and we need to account for that by adding corrections to the MC samples. So, we calculate weights for our event samples and apply them to see the effect of these corrections, basically to better represent the data samples. Now, these corrections may introduce additional asymmetry on our samples, so I show the MC studies of that in Section 4.9.

We calculate the corrections related to the cut on the muonID in the steering file based on "leptonid official rel6 mc15rd" global tag. These are calibrations applied directly before the processing of the events.

Additionally, we apply the corrections due to the cuts on the pionID. These are calculated based on the systematics framework of Belle II [85] [145]. We apply corrections of pionID>0.9 to the leading pion and pionID>0.5 for the two other pions. This framework generates the correction weights in bins of the momentum, $\cos \theta$ and charge of the pion.

4.6 . Data vs MC comparison

After applying all selections, including the triggers "or" of all the ECL and CDC types, and the corrections on the pion ID and muon ID selections, we plot the distributions of comparison of the data to the different types of MC in Figs. 4.28, 4.29, 4.30, 4.31, 4.32, 4.33 and 4.34.

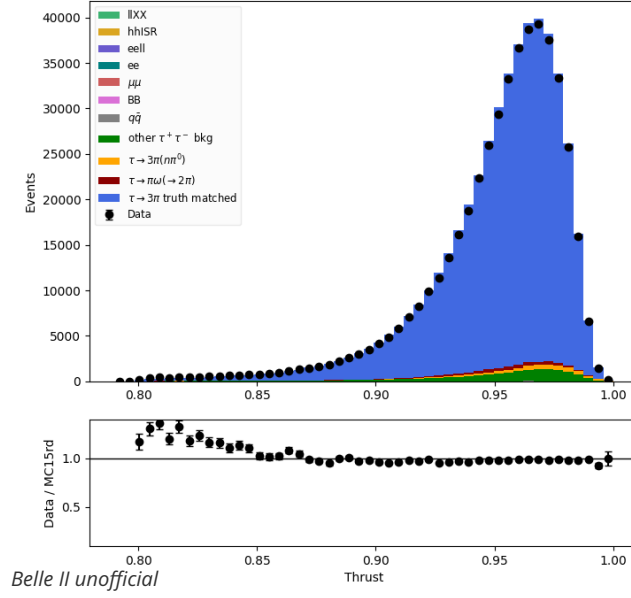


Figure 4.28 – Thrust after corrections and after selections and trigger.

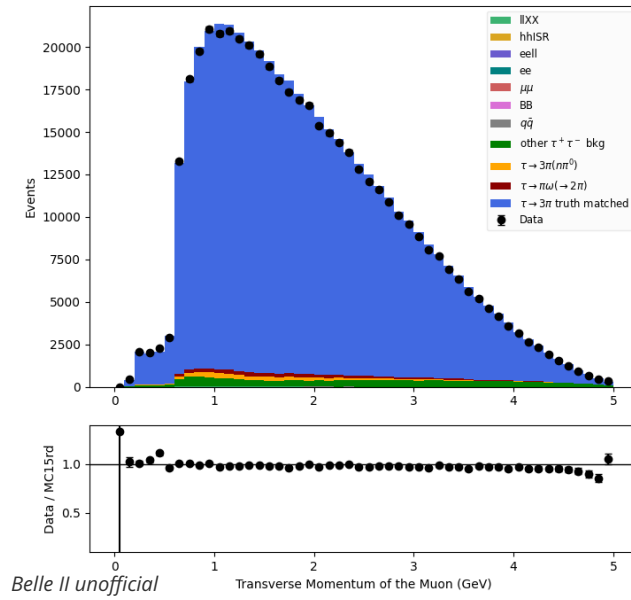


Figure 4.29 – Muon transverse momentum after corrections and after selections and trigger.

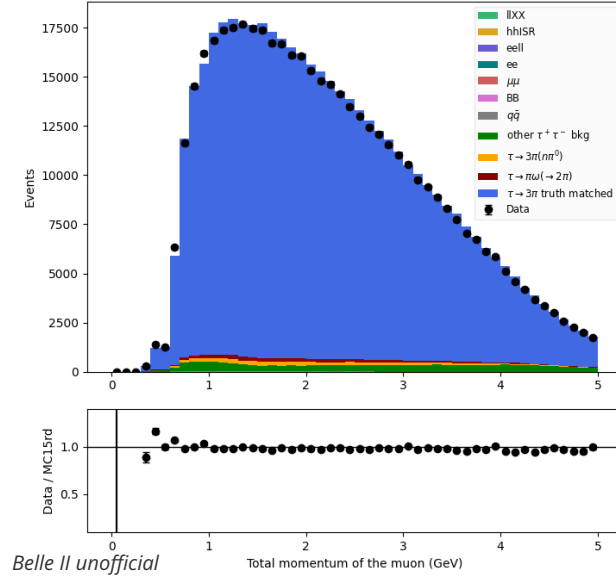


Figure 4.30 – Muon momentum after corrections and after selections and trigger.

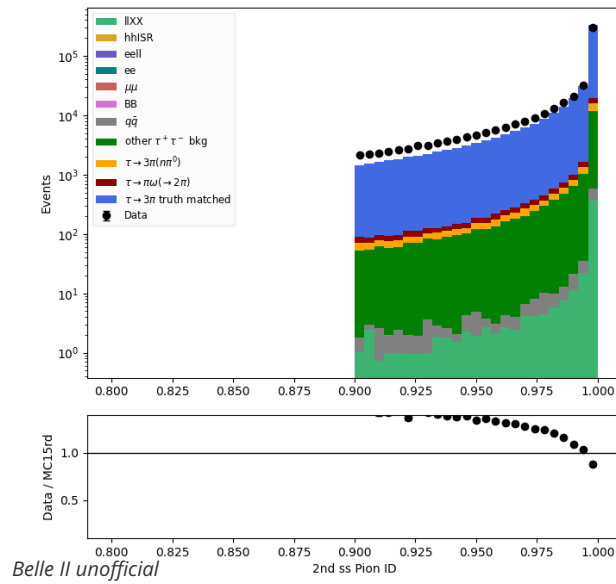


Figure 4.31 – PionIDNN of the leading pion after corrections and after selections and trigger (in log scale).

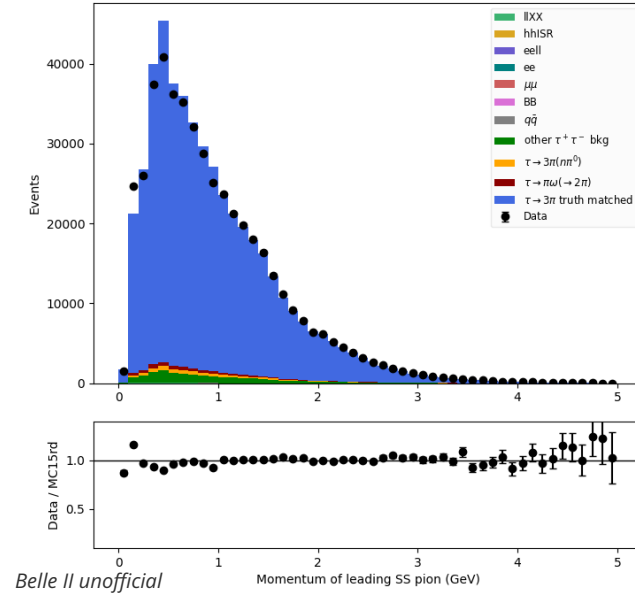


Figure 4.32 – Momentum of the leading pion after corrections and after selections and trigger.

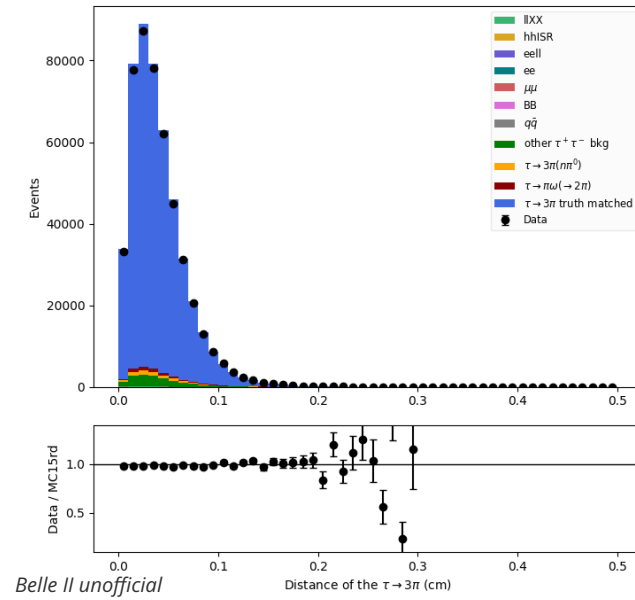


Figure 4.33 – Vertex distance after corrections and after selections and trigger.

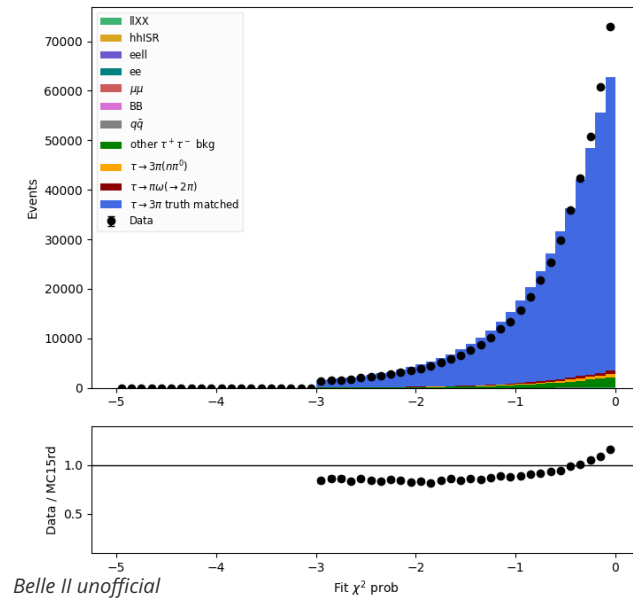


Figure 4.34 – χ^2 probability of the vertex measurement after corrections and after selections and trigger. A large discrepancy between data and MC can be seen, especially for the last bin. This remains to be investigated.

4.7 . Observables

The observables are defined in the hadronic rest frame formed by the pion system. First, we define some useful notions :

- $\vec{p}^{ss1}$ is the momentum of the pion with the same sign as its decaying tau, in the hadronic rest frame. $ss1$ is the sub-leading pion, as it has the smaller momentum with respect to the other same sign pion
- $\vec{p}^{ss2}$ is the momentum of the pion with the same sign as its decaying tau, in the hadronic rest frame. $ss2$ is the leading pion, as it has the larger momentum with respect to the other same sign pion
- $\vec{p}^{OS}$ is the momentum of the pion with the opposite sign with respect to its decaying tau, defined in the hadronic rest frame
- $\vec{n}_L$ is the direction of the CMS frame in the hadronic rest frame, which is the tau direction in the hadronic rest frame :

$$\vec{n}_L = -\frac{\vec{p}_{CMS}^{ss1} + \vec{p}_{CMS}^{ss2} + \vec{p}_{CMS}^{OS}}{E_{CMS}^{ss1} + E_{CMS}^{ss2} + E_{CMS}^{OS}}$$

- $\vec{n}_\perp$ is the vector product between the two pions of same sign, which represents the direction perpendicular to the plane formed by the two same sign pions :

$$\vec{n}_\perp = \frac{\vec{p}^{ss1} \times \vec{p}^{ss2}}{|\vec{p}^{ss1} \times \vec{p}^{ss2}|}$$

- $x = \frac{2E_h}{\sqrt{s}}$ where $\sqrt{s}$ is the center of mass energy and E_h is the energy of the hadronic system in the CMS frame
- Q is the invariant mass of the hadronic system

$$Q^2 = (E^{ss1} + E^{ss2} + E^{OS})^2 - (\vec{p}^{ss1} + \vec{p}^{ss2} + \vec{p}^{OS})^2$$

The angles are then defined as [146] :

- β : angle between $\vec{n}_L$ and $\vec{n}_\perp$

$$\cos\beta = \vec{n}_L \cdot \vec{n}_\perp$$

$$\sin\beta = \sqrt{1 - \cos^2\beta}$$

- γ : defines the hadrons orientation within their production plane

$$\cos\gamma = -\frac{\vec{n}_L \cdot \vec{p}^{OS}}{|\vec{n}_L \times \vec{n}_\perp|}$$

$$\sin\gamma = \frac{(\vec{n}_L \times \vec{n}_\perp) \cdot \vec{p}^{OS}}{|\vec{n}_L \times \vec{n}_\perp|}$$

The advantage of β and γ Euler angles is that they are observable even when the tau rest frame is not reconstructed.

defining them in the center-of-mass frame, I then proceeded to boost them through Lorentz boost to the hadronic rest frame, where the system of three pions is at rest. Then I did the correct calculations for each angle.

These hadronic angles play an important role in the analysis. We study their distributions, but mostly we use them as weights for the calculation of the CP asymmetry in the tau decay. The distributions of these hadronic functions can be seen in Figs. 4.36, 4.37, 4.38, 4.39, 4.40 and 4.41.

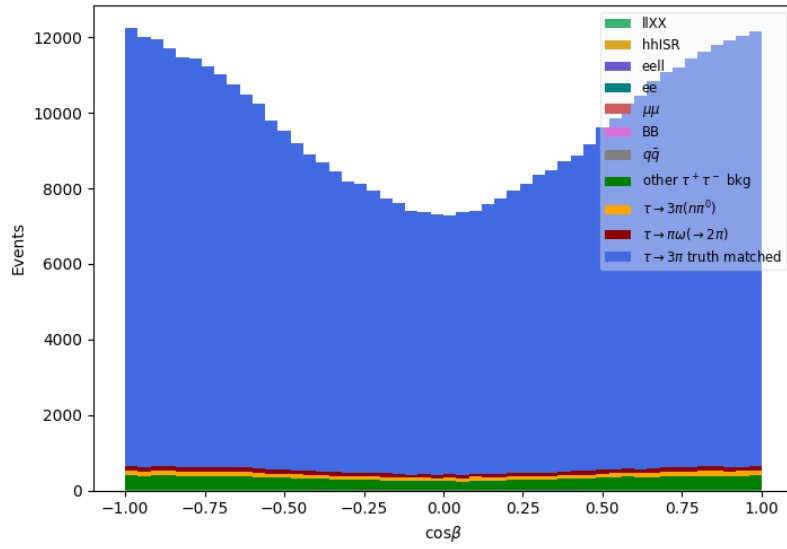


Figure 4.36 – $\cos\beta$ distribution showing each category of the MC distributions.

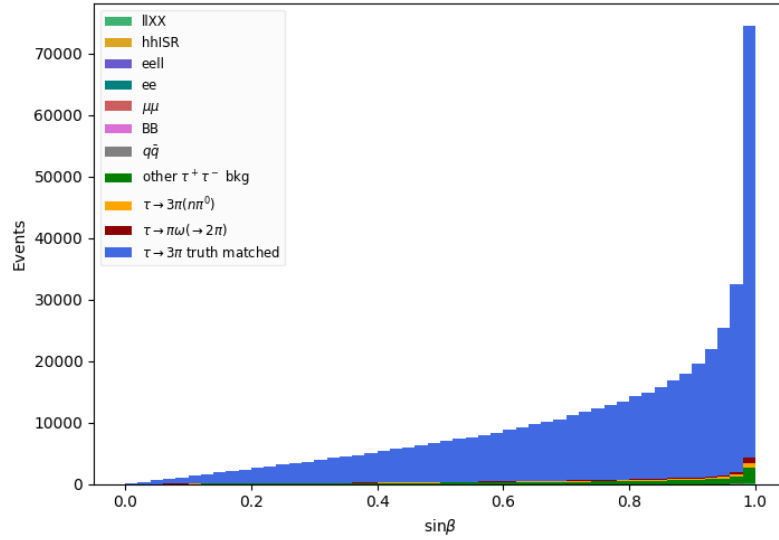


Figure 4.37 – $\sin\beta$ distribution showing each category of the MC distributions.

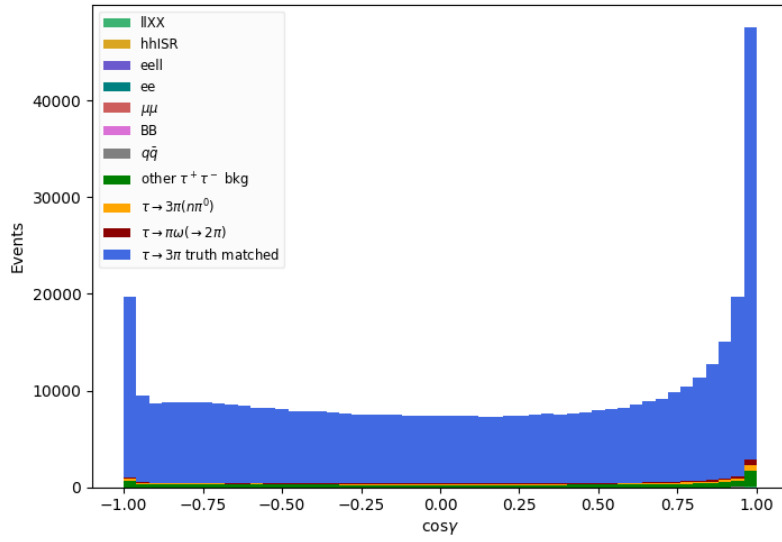


Figure 4.38 – $\cos\gamma$ distribution showing each category of the MC distributions.

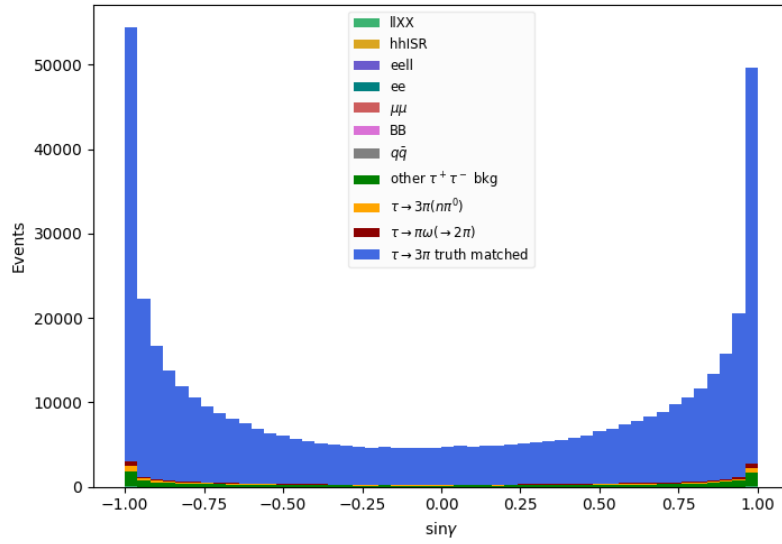


Figure 4.39 – $\sin\gamma$ distribution showing each category of the MC distributions.

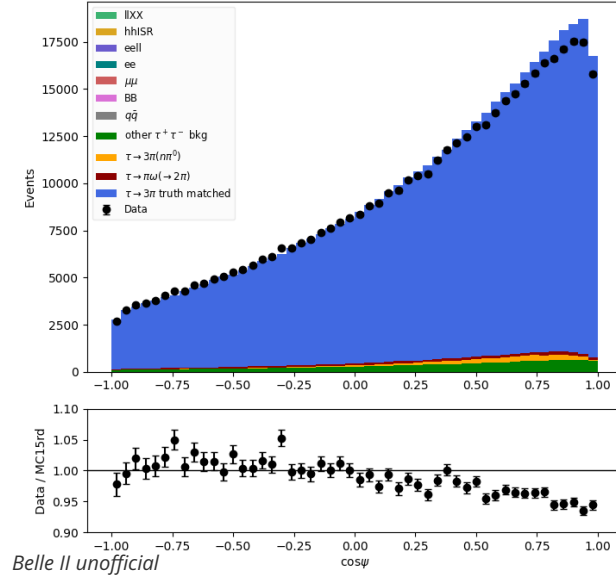


Figure 4.40 – $\cos\psi$ distribution showing each category of the MC distributions and data.

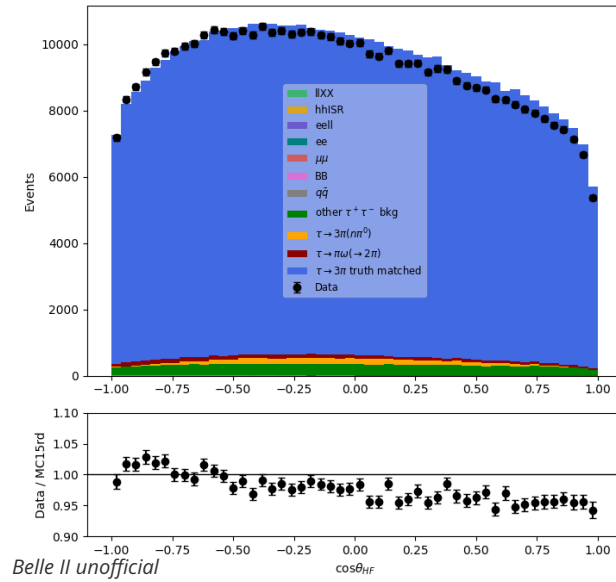


Figure 4.41 – $\cos\theta$ distribution showing each category of the MC distributions and data.

Invariant masses

The invariant masses distributions of MC simulated events compared to data events are presented in Figs. 4.42, 4.43, 4.44 and 4.45.

Additionally, to study how well the invariant masses are reconstructed, I calculate the acceptance for these invariant masses. The acceptance is defined as :

$$\text{Acceptance} = \frac{\text{\#events of MC reconstructed signal}}{\text{\#events of generator-level signal}}.$$

The plots of the invariant mass acceptances are shown in Figs. 4.46, 4.47, 4.48 and 4.49. We can see that we can retrieve 6% as the maximum efficiency in these plots, corresponding to the total efficiency of the MC signal that we have. This validation is important because, when the acceptance is not flat, we would need to apply bin-by-bin corrections to the invariant mass distributions. On the other hand, a flat acceptance would only require a global correction factor, which is easier to handle.

Acceptance studies

As a complement to the acceptance for the invariant mass distributions, I studied the 2D acceptance of the invariant masses of each two pions of opposite signs. I show the distributions of the invariant mass squared of the sub-leading pion and opposite-sign pion versus the invariant mass squared of the leading pion and opposite-sign pion. In each bin, I calculate the acceptance, which corresponds to the ratio of the MC reconstructed signal to the generator-level signal. I measured these 2D acceptance plots for ten bins of Q^2 . The binning of Q^2 is chosen in a way to have (almost) an equal number of events for each bin. The acceptance ratios and errors for the 2D plots are presented in Figs. 4.50 and 4.51.

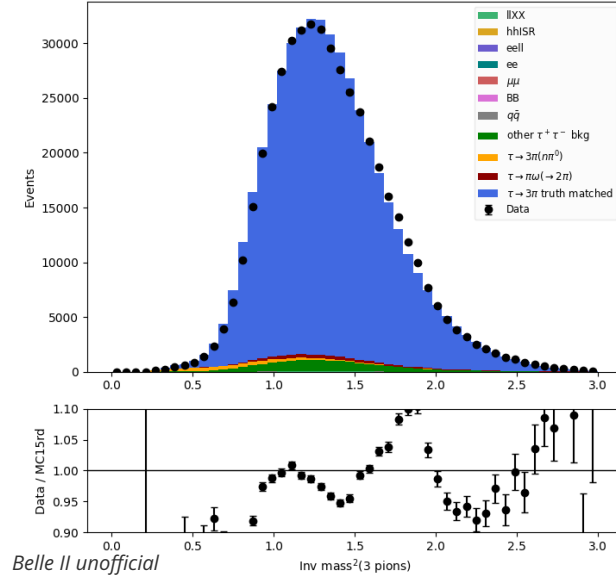


Figure 4.42 – $\text{inv}M^2_{3\pi}$ distribution showing each category of the MC distributions and data.

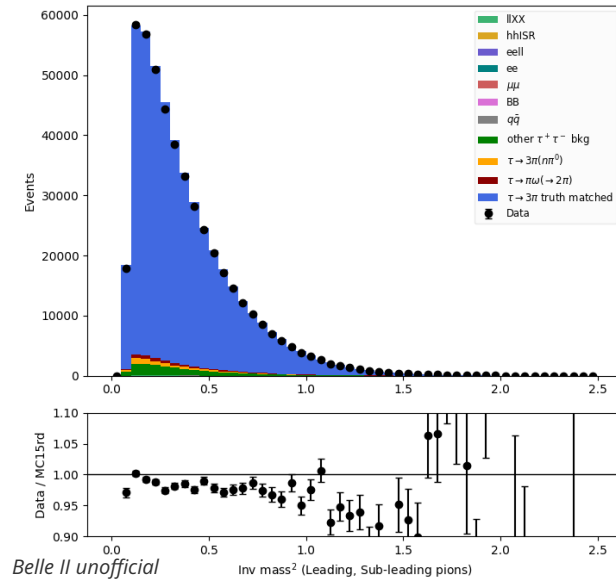


Figure 4.43 – $\text{inv}M^2_{\pi_{ss1}\pi_{ss2}}$ distribution showing each category of the MC distributions and data.

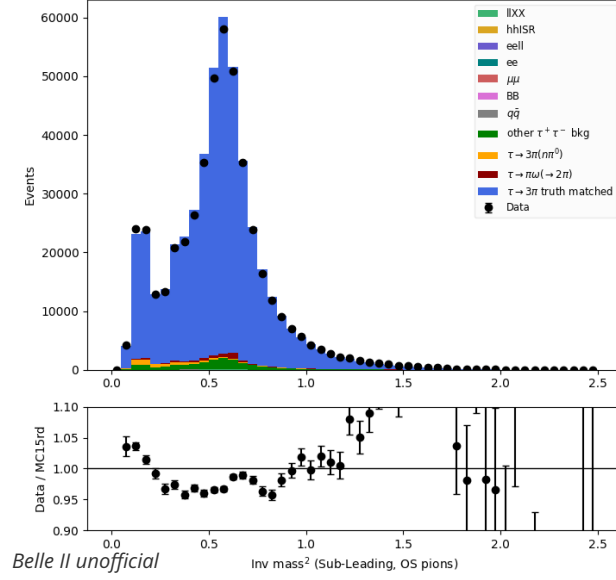


Figure 4.44 – $\text{inv}M_{\pi_{ss1}\pi_{os}}^2$ distribution showing each category of the MC distributions and data.

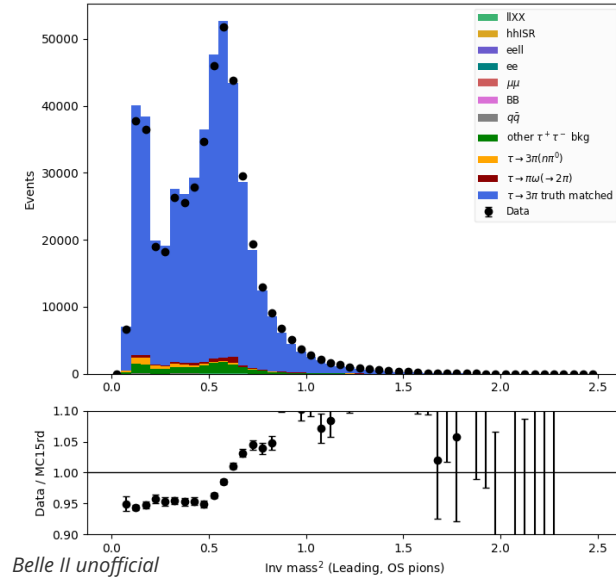


Figure 4.45 – $\text{inv}M_{\pi_{ss2}\pi_{os}}^2$ distribution showing each category of the MC distributions and data.

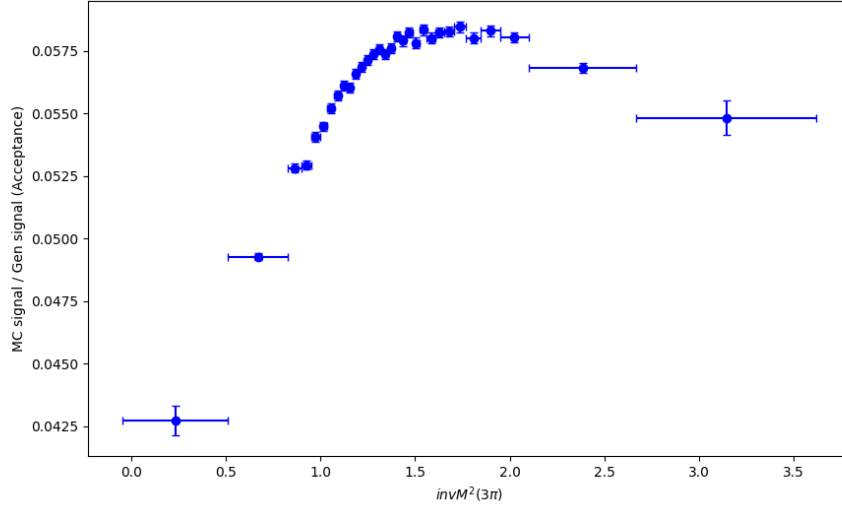


Figure 4.46 – Acceptance of Q^2 : ratio of the signal MC reconstructed distribution the generated signal distribution.

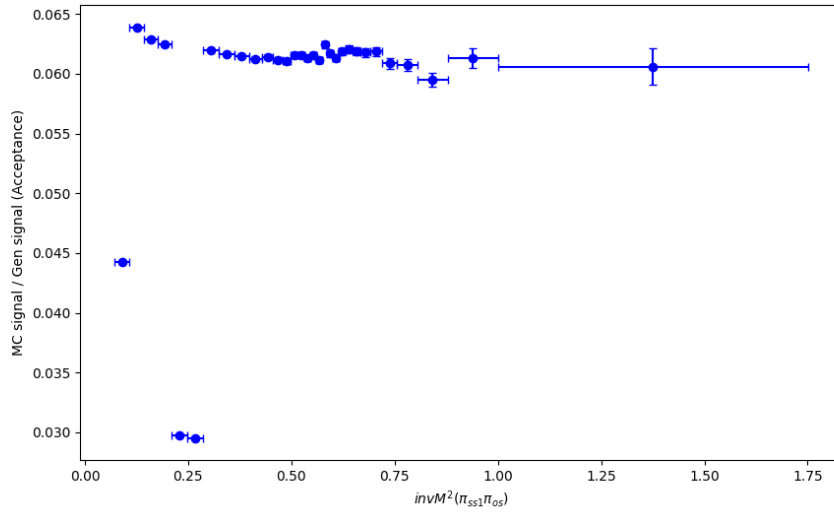


Figure 4.47 – Acceptance of $invM^2[\pi_{ss1}\pi_{os}]$: ratio of the signal MC reconstructed distribution the generated signal distribution.

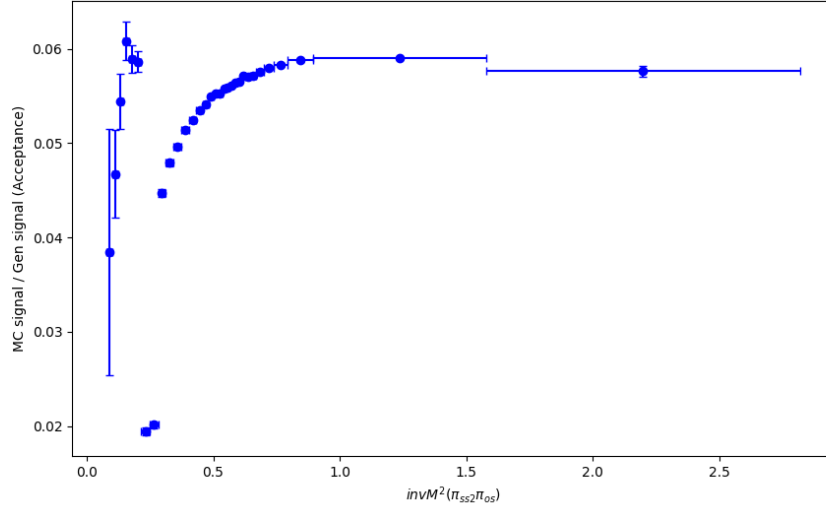


Figure 4.48 – Acceptance of $invM^2[\pi_{ss2}\pi_{os}]$: ratio of the signal MC reconstructed distribution the generated signal distribution.

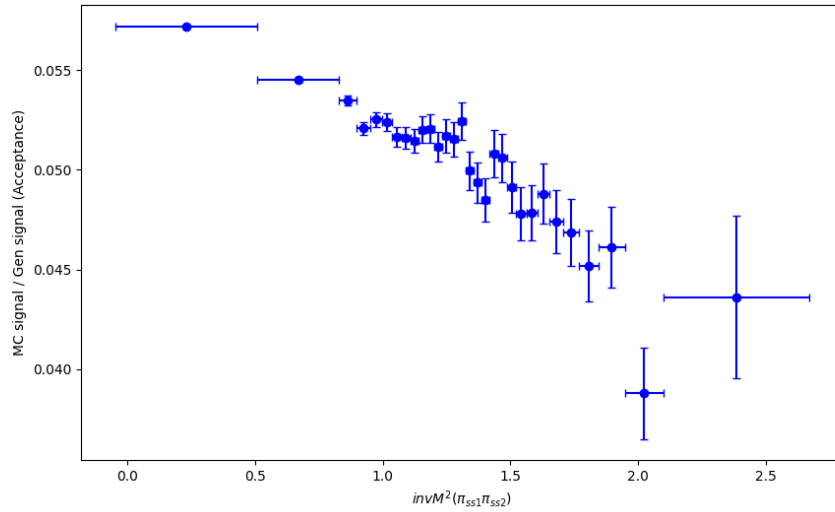


Figure 4.49 – Acceptance of $invM^2[\pi_{ss1}\pi_{ss2}]$: ratio of the signal MC reconstructed distribution the generated signal distribution.

Figure 4.50 – Acceptance plots for bins 1 to 10

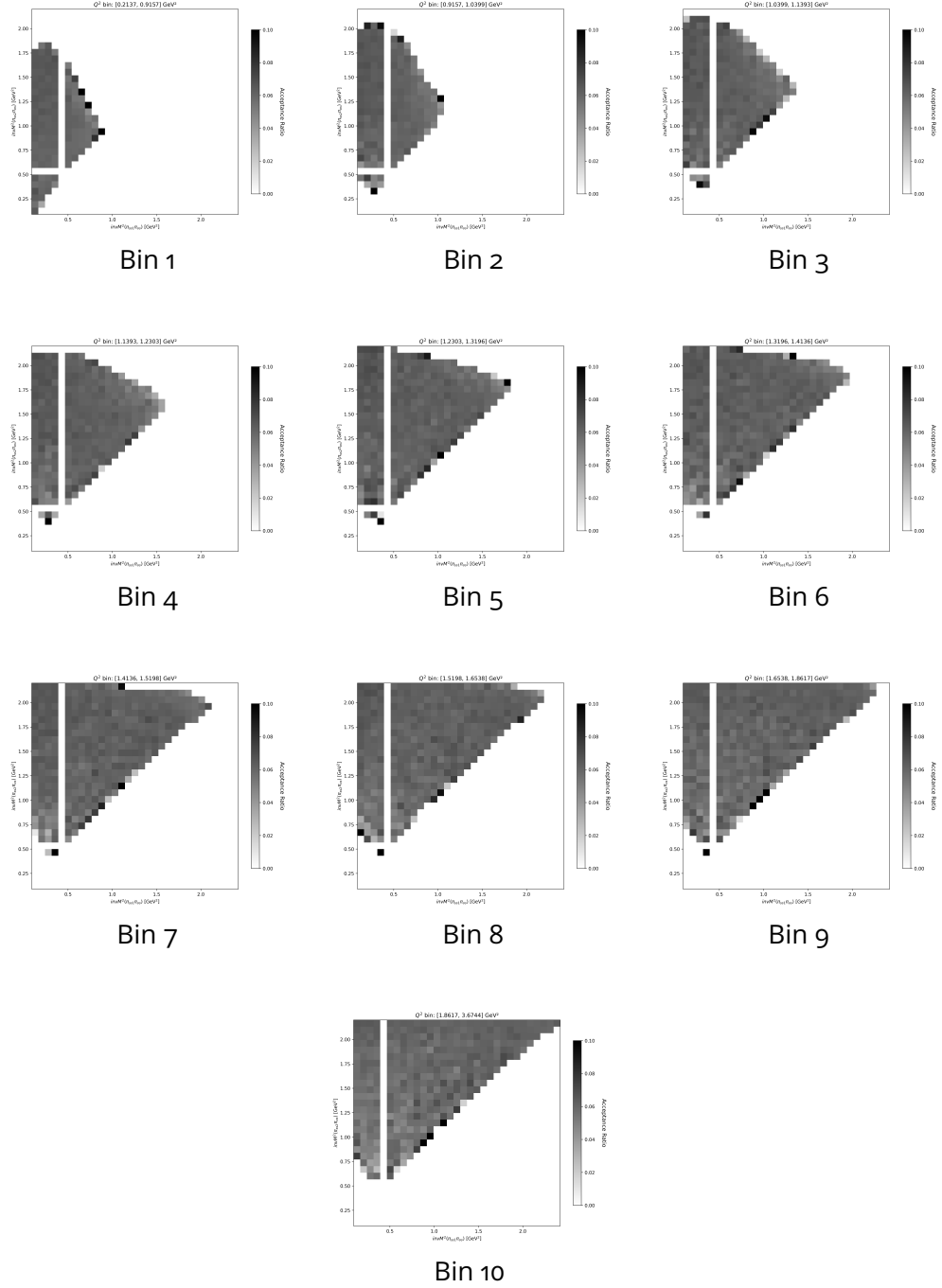
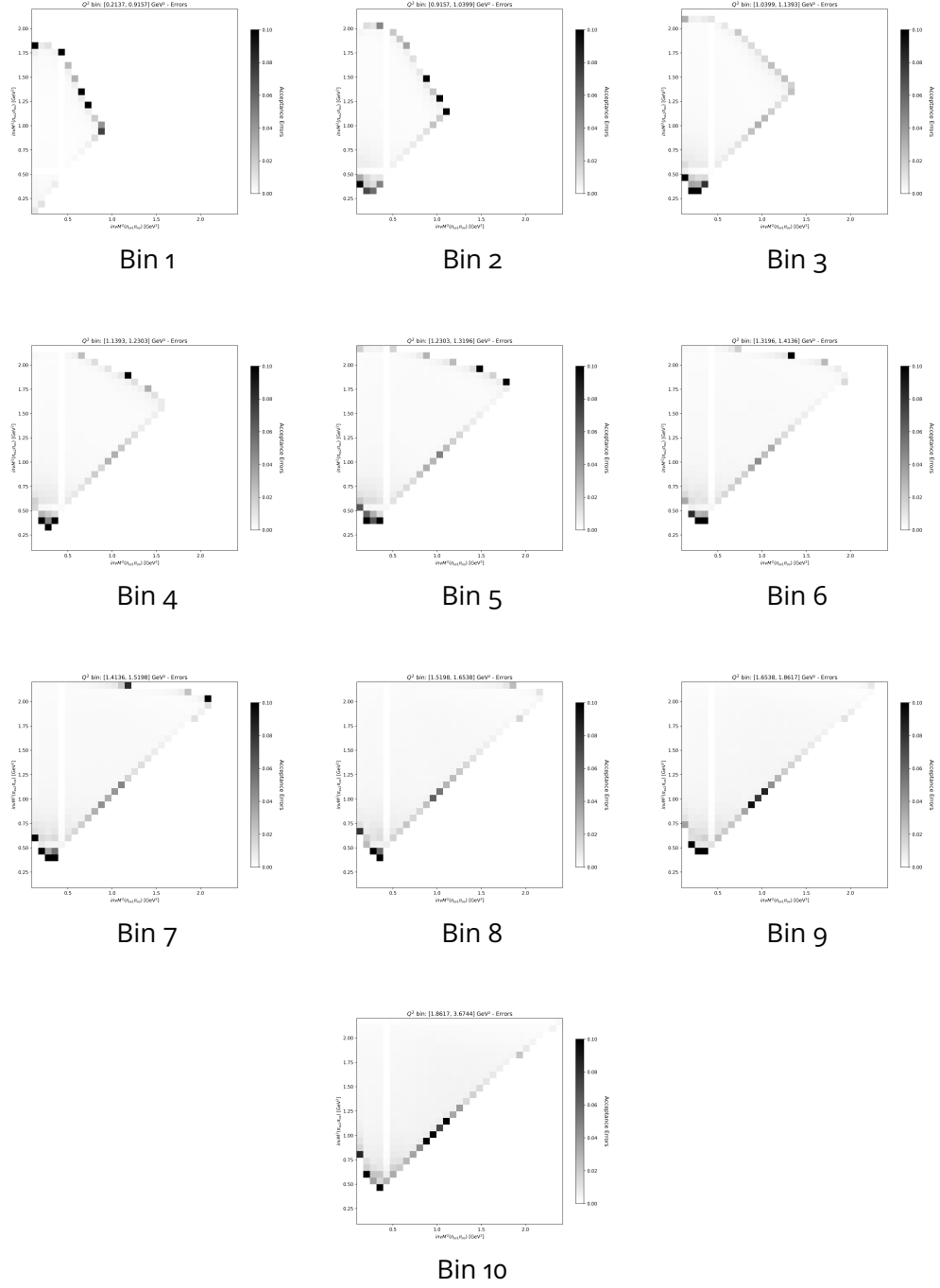


Figure 4.51 – Error plots for bins 1 to 10



4.8 . Investigation of angular asymmetries

Angular asymmetry, see Section 1.4.3 for the technique that we intend to implement. It needs first to be validated on the MC. We describe here the tools to do so.

We define the asymmetry

$$A = \frac{N_+ - N_-}{N_+ + N_-} \quad (4.4)$$

where N_+ and N_- are the number of events corresponding to $\tau^+ \rightarrow \pi^+\pi^-\pi^+\bar{\nu}_\tau$ and $\tau^- \rightarrow \pi^-\pi^+\pi^-\nu_\tau$.

$$A_w = \frac{\sum_{i=1}^{N_+} w_i^+ - \sum_{j=1}^{N_-} w_j^-}{\sum_{i=1}^{N_+} w_i^+ + \sum_{j=1}^{N_-} w_j^-} \quad (4.5)$$

$$= \frac{N_+ \overline{w^+} - N_- \overline{w^-}}{N_+ \overline{w^+} + N_- \overline{w^-}} \quad (4.6)$$

where $\overline{w^\pm} = \frac{1}{N_\pm} \sum_{i=1}^{N_\pm} w_i^\pm$ is the weight representing the corrections applied on our events. The error on the asymmetry reads then

$$\sigma^2[A] = \left(\frac{dA}{dN_+} \right)^2 \sigma^2[N_+] + \left(\frac{dA}{dN_-} \right)^2 \sigma^2[N_-] \quad (4.7)$$

$$= \left(\frac{dA}{dN_+} \right)^2 N_+ + \left(\frac{dA}{dN_-} \right)^2 N_- \quad (4.8)$$

$$= \frac{1}{N_{\text{tot}}} (1 - A^2) \quad (4.9)$$

where $N_{\text{tot}} = N_+ + N_-$ is the total number of events. The error on the weighted asymmetry can be written as

$$\sigma_{\text{tot}}^2[A_w - A] = \sigma_N^2[A_w - A] + \sigma_w^2[A_w - A] \quad (4.10)$$

with $\sigma_N^2[A_w - A]$ representing the error with respect to N and given by

$$\sigma_N^2[A_w - A] = \left(\frac{d(A_w - A)}{dN_+} \right)^2 N_+ + \left(\frac{d(A_w - A)}{dN_-} \right)^2 N_- \quad (4.11)$$

$$= \sigma^2[A] \frac{a^2(a(1 + A^2) + 2A)^2}{(1 + aA)^4} \quad (4.12)$$

$$a \equiv \frac{\overline{w^+} - \overline{w^-}}{\overline{w^+} + \overline{w^-}} \quad (4.13)$$

and $\sigma_w^2[A_w - A]$ representing the error with respect to w and given by

$$\begin{aligned}\sigma_w^2[A_w - A] &= \left(\frac{d(A_w - A)}{d\bar{w}^+} \right)^2 \sigma^2[\bar{w}^+] + \left(\frac{d(A_w - A)}{d\bar{w}^-} \right)^2 \sigma^2[\bar{w}^-] \quad (4.14) \\ &= \sigma^2[A] 2 \frac{(1+a)^2(1+A)\sigma^2[\bar{w}^-] + (1-a)^2(1-A)\sigma^2[\bar{w}^+]}{(1+aA)^4 (\bar{w}^+ + \bar{w}^-)^2} \quad (4.15)\end{aligned}$$

$$\sigma^2[\bar{w}^\pm] = \frac{\sigma^2[w^\pm]}{N_\pm} \quad (4.16)$$

4.9 . CP Asymmetry

Asymmetry :

$$A(i) = \frac{N_+^{(i)}\bar{w}^+ - N_-^{(i)}\bar{w}^-}{N_{tot}}$$

where :

$N_+^{(i)}$: number of events where $\tau^+ \rightarrow \pi^+\pi^-\pi^+\bar{\nu}_\tau$ in the bin i ,

$N_-^{(i)}$: number of events where $\tau^- \rightarrow \pi^-\pi^+\pi^-\nu_\tau$ in the bin i ,

N_{tot} : total number of events in all bins,

$\bar{w}^\pm = \frac{1}{N_\pm} \sum_{i=1}^{N_\pm} w_i^\pm$: the mean of the weight.

Error on asymmetry :

$$\sigma_w^{2(i)}(A) = \left(\frac{dA(i)}{d\bar{w}^+} \right)^2 \sigma^2(\bar{w}^+) + \left(\frac{dA(i)}{d\bar{w}^-} \right)^2 \sigma^2(\bar{w}^-) \quad (4.17)$$

$$= \frac{N_+ \sigma^2(\bar{w}^+) + N_- \sigma^2(\bar{w}^-)}{N_{tot}^2} \quad (4.18)$$

with $\sigma^2(\bar{w}^\pm) = \frac{1}{N_\pm - 1} \sum_{i=1}^{N_\pm} (w_i^\pm - \bar{w}^\pm)^2 \frac{1}{N_\pm}$

$$\sigma_N^{2(i)}(A) = \left(\frac{dA(i)}{dN_+} \right)^2 N_+ + \left(\frac{dA(i)}{dN_-} \right)^2 N_- \quad (4.19)$$

$$= \frac{\bar{w}^{+2} N_+ + \bar{w}^{-2} N_-}{N_{tot}^2} \quad (4.20)$$

$$\sigma^{2(i)}(A) = \sqrt{\sigma_w^{2(i)}(A) + \sigma_N^{2(i)}(A)} \quad (4.21)$$

Asymmetry difference (for example between reco sel and reco sel + trigger) :

$$A_S - A_T = \frac{N_+^S \bar{w}_S^+ - N_-^S \bar{w}_S^-}{N_S^{tot}} - \frac{N_+^T \bar{w}_T^+ - N_-^T \bar{w}_T^-}{N_T^{tot}}$$

$$N_S^{tot} = \epsilon^{tot} N_T^{tot}$$

$$N_S^+ = \epsilon^+ N_T^+$$

$$N_S^- = \epsilon^- N_T^-$$

$$A_S - A_T = \frac{\epsilon^+ N_T^+ \bar{w}_S^+ - \epsilon^- N_T^- \bar{w}_S^-}{\epsilon^{tot} N_T^{tot}} - \frac{N_T^+ \bar{w}_T^+ - N_T^- \bar{w}_T^-}{N_T^{tot}}$$

$$\sigma_N^2(A_S - A_T) = \left(\frac{\partial(A_S - A_T)}{\partial N_T^+} \right)^2 N_T^+ + \left(\frac{\partial(A_S - A_T)}{\partial N_T^-} \right)^2 N_T^- \quad (4.22)$$

$$= \frac{N_T^- (\epsilon^- \bar{w}_S^- - \epsilon^{tot} \bar{w}_T^-)^2 + N_T^+ (\epsilon^+ \bar{w}_S^+ - \epsilon^{tot} \bar{w}_T^+)^2}{\epsilon^{tot2} N_T^{tot2}} \quad (4.23)$$

$$\begin{aligned} \sigma_w^2(A_S - A_T) &= \left(\frac{\partial(A_S - A_T)}{\partial \bar{w}_S^+} \right)^2 \sigma^2(\bar{w}_S^+) + \left(\frac{\partial(A_S - A_T)}{\partial \bar{w}_S^-} \right)^2 \sigma^2(\bar{w}_S^-) \\ &\quad + \left(\frac{\partial(A_S - A_T)}{\partial \bar{w}_T^+} \right)^2 \sigma^2(\bar{w}_T^+) + \left(\frac{\partial(A_S - A_T)}{\partial \bar{w}_T^-} \right)^2 \sigma^2(\bar{w}_T^-) \end{aligned} \quad (4.24)$$

$$\begin{aligned} &= \frac{1}{N_T^{tot2}} \left(N_t^{-2} \left(\frac{\epsilon^{-2}}{\epsilon^{tot2}} \sigma^2(\bar{w}_S^-) + \sigma^2(\bar{w}_T^-) \right) \right. \\ &\quad \left. + N_t^{+2} \left(\frac{\epsilon^{+2}}{\epsilon^{tot2}} \sigma^2(\bar{w}_S^+) + \sigma^2(\bar{w}_T^+) \right) \right) \end{aligned} \quad (4.25)$$

with :

$$\sigma^2(\bar{w}_S^+) = \frac{1}{(N_S^+ - 1)} \sum_{i=0}^{N_S^+} (w_{S_i}^+ - \bar{w}_S^+)$$

$$\sigma^2(\bar{w}_S^-) = \frac{1}{(N_S^- - 1)} \sum_{i=0}^{N_S^-} (w_{S_i}^- - \bar{w}_S^-)$$

$$\sigma^2(\bar{w}_T^+) = \frac{1}{(N_T^+ - 1)} \sum_{i=0}^{N_T^+} (w_{T_i}^+ - \bar{w}_T^+)$$

$$\sigma^2(\bar{w}_T^-) = \frac{1}{(N_T^- - 1)} \sum_{i=0}^{N_T^-} (w_{T_i}^- - \bar{w}_T^-)$$

The asymmetries calculated for the signal at the generator level (blue distribution) and the MC reconstructed signal (red distribution) and the MC reconstructed signal after applying the PID corrections (green distribution) are shown in Figs. 4.52, 4.53, 4.54, 4.55, 4.56, 4.57, 4.58, 4.59 and 4.60. The asymmetry at the generator level for almost all angular distributions is compatible with zero. However, we see a positive asymmetry in the $\cos \beta$ weighted asymmetry at the generator level. We consider that, out of construction, $\cos \beta$ is a P-odd quantity. In order to calculate the CP asymmetry, we also need to flip the sign of $\cos \beta$. So for τ^+ we use $\cos \beta$ distribution and for τ^- we use $-\cos \beta$ distribution. This way we get a CP asymmetry weighted with $\cos \beta$. The plot of the correct asymmetry weighted by $\cos \beta$ is shown in Fig. 4.61. The generator-level asymmetry is compatible with zero. Another thing to notice is that we get an asymmetry different than zero in the MC reconstructed signal, for the unweighted distribution. However, when we weight the asymmetry with an angular distribution, the asymmetry at the MC level is also compatible with zero. In order to validate the compatibility with zero of the asymmetry values, I show the total integrated asymmetries in the Table. 4.11. Additionally, the addition of PID corrections increases the asymmetry for some cases but not all angular functions. It can be clearly seen for the unweighted asymmetry where we have an asymmetry of 3.3×10^{-3} after the PID corrections compared to 1.9×10^{-3} before the PID corrections.

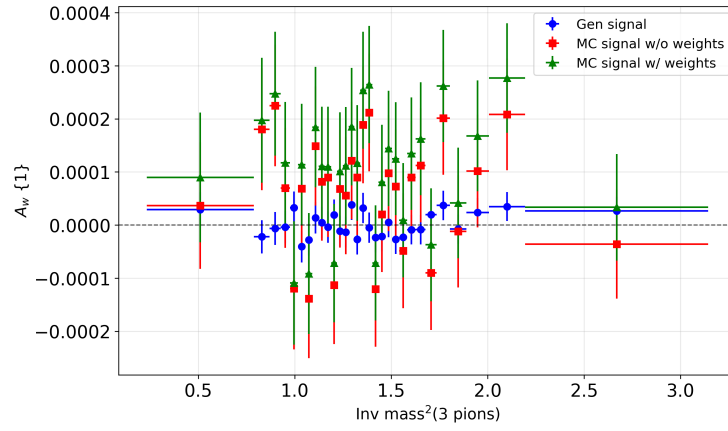


Figure 4.52 – The asymmetry non-weighted as function of the invariant mass squared of the 3π .

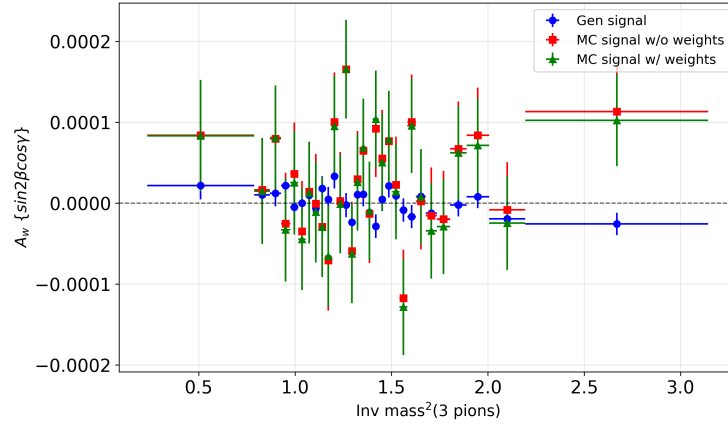


Figure 4.53 – Asymmetry weighted by $\sin(2\beta)\cos(\gamma)$ as function of the invariant mass squared of the 3π .

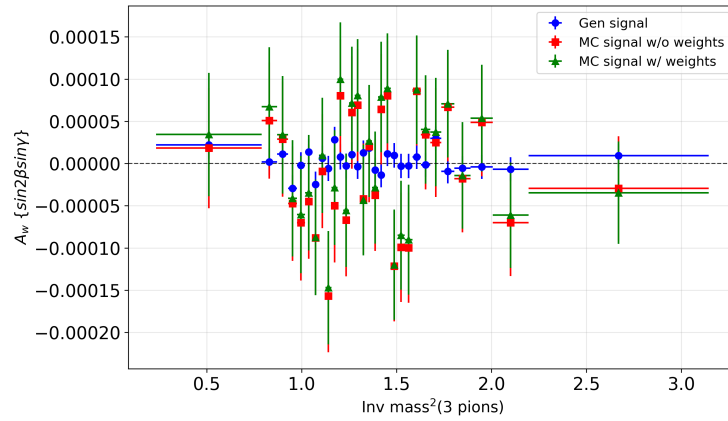


Figure 4.54 – Asymmetry weighted by $\sin(2\beta)\sin(\gamma)$ as function of the invariant mass squared of the 3π .

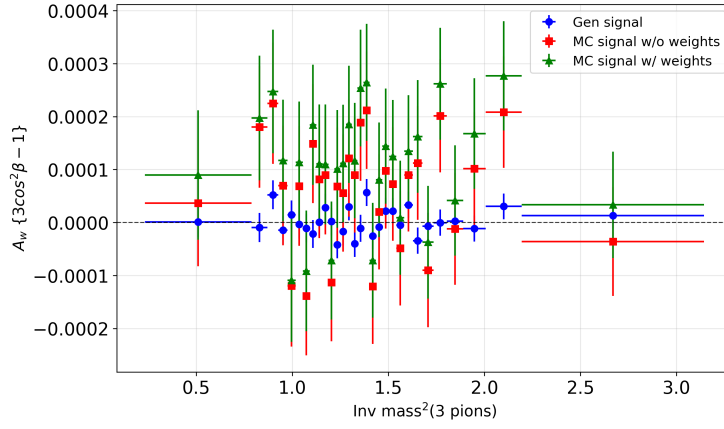


Figure 4.55 – Asymmetry weighted by $3 \cos^2 \beta - 1$ as function of the invariant mass squared of the 3π .

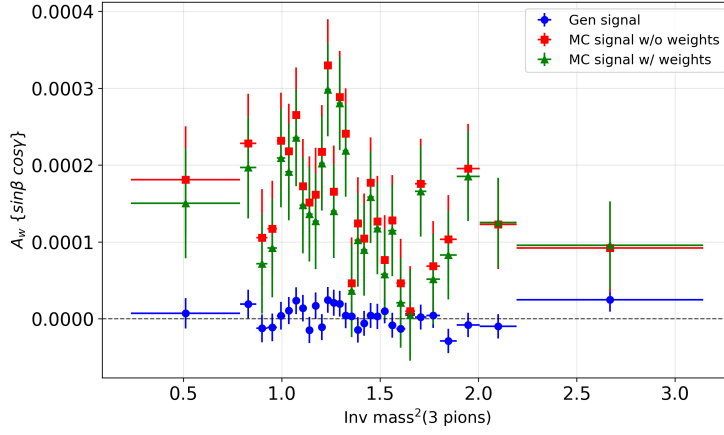


Figure 4.56 – Asymmetry weighted by $\sin \beta \cos \gamma$ as function of the invariant mass squared of the 3π .

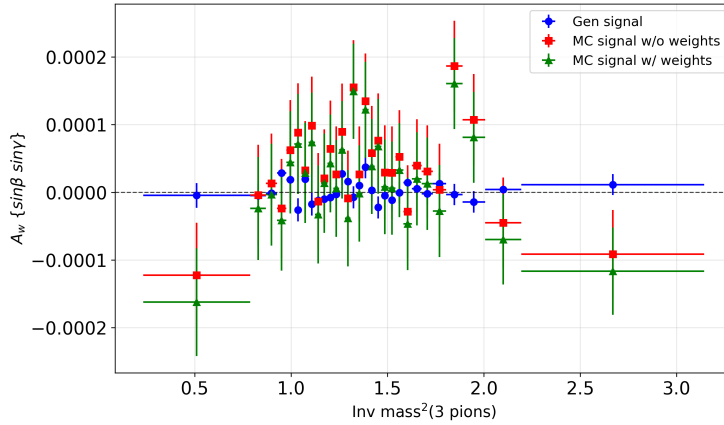


Figure 4.57 – Asymmetry weighted by $\sin \beta \sin \gamma$ as function of the invariant mass squared of the 3π .

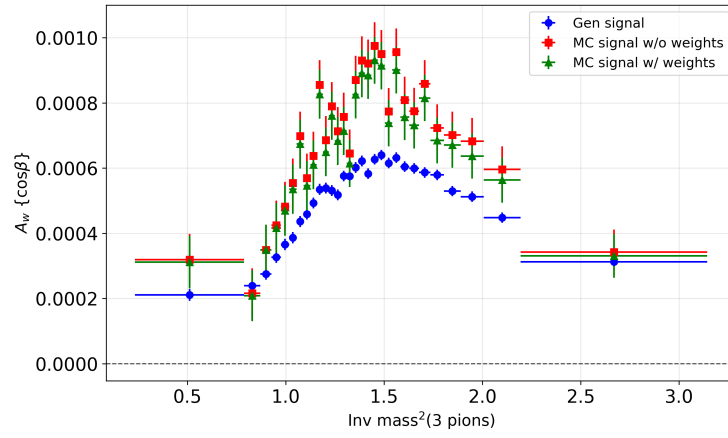


Figure 4.58 – Asymmetry weighted by $\cos \beta$ as function of the invariant mass squared of the 3π .

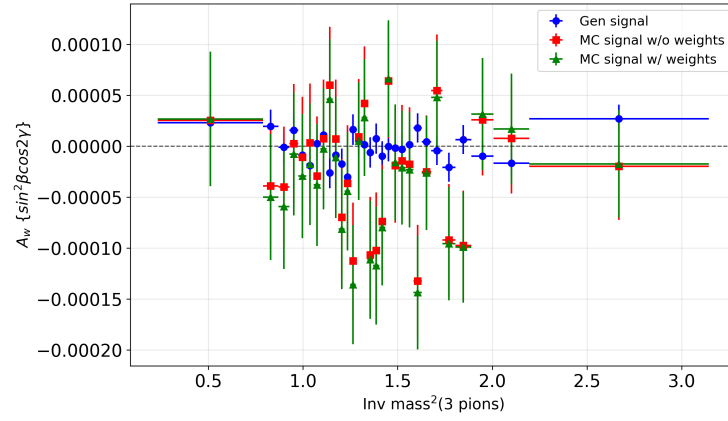


Figure 4.59 – Asymmetry weighted by $\sin^2 \beta \cos 2\gamma$ as function of the invariant mass squared of the 3π .

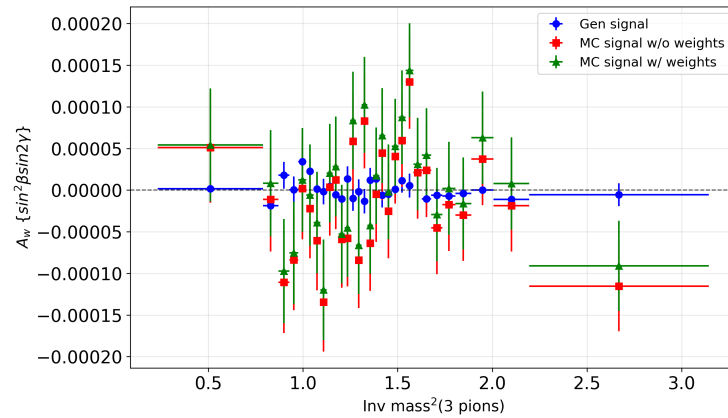


Figure 4.60 – Asymmetry weighted by $\sin^2 \beta \sin 2\gamma$ as function of the invariant mass squared of the 3π .

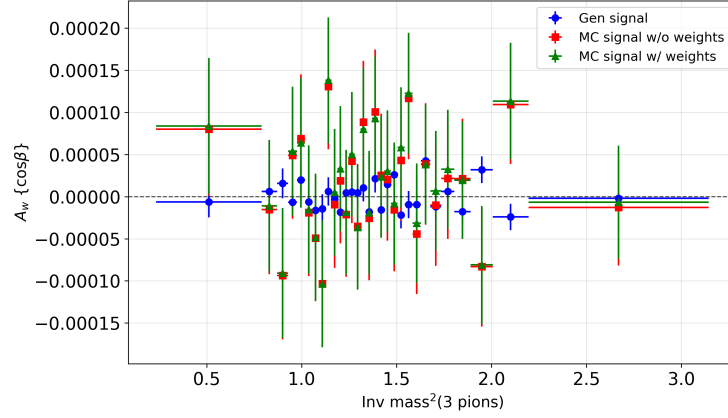


Figure 4.61 – Asymmetry weighted by $\cos \beta$ as function of the invariant mass squared of the 3π , after sign flip.

Table 4.11 – Asymmetries for different angular functions for the three studied categories : generated level signal (Gen), MC reconstructed signal (MC), and MC reconstructed signal with PID corrections (MC + PID). All results are given in units of 10^{-3} .

Weighted asymmetry	Gen	MC	MC + PID
1	0.04 ± 0.16	1.9 ± 0.6	3.3 ± 0.6
$3 \cos^2 \beta - 1$	0.05 ± 0.14	1.9 ± 0.6	3.3 ± 0.6
$\sin^2 \beta \cos 2\gamma$	-0.03 ± 0.08	-0.7 ± 0.3	-1.0 ± 0.3
$\sin^2 \beta \sin 2\gamma$	0.04 ± 0.08	-0.4 ± 0.3	0.1 ± 0.3
$\sin \beta \sin \gamma$	0.06 ± 0.09	1.1 ± 0.4	0.5 ± 0.4
$\sin \beta \cos \gamma$	0.09 ± 0.09	4.7 ± 0.3	4.1 ± 0.3
$\cos \beta$	0.02 ± 0.09	0.4 ± 0.4	0.6 ± 0.4
$\sin 2\beta \cos \gamma$	0.03 ± 0.08	0.8 ± 0.3	0.7 ± 0.3
$\sin 2\beta \sin \gamma$	0.08 ± 0.08	-0.3 ± 0.4	-0.05 ± 0.4

4.10 . Conclusion

I performed a beginning of analysis of 3-prong semi-leptonic τ decays where I studied data / MC agreements. I also started to look at variation of selections, reconstruction efficiency versus phase space of the τ decay. I also started to look at influence of selection and reconstruction on the asymmetry observables. This work paves the way towards a fit measurement of CPV in semi-leptonic 3-prong τ decays.

5 - Conclusion

In conclusion, it is very motivating to understand what extends beyond the theoretical framework of the Standard Model. Although this model describes the fundamental particles and their interactions, it does not explain the excess of matter over antimatter in the universe. Studying the violation of Charge-Parity (CP) symmetry contributes in explaining this matter-antimatter asymmetry. CP violation has been studied and measured in the hadronic sector through multiple decay channels, but no significant evidence has yet been measured in the leptonic sector. This motivates searches of CP violation in the leptonic sector.

The tau, as the heaviest lepton, is unique in the possibility of decaying into hadrons. Theoretical studies suggest that these tau hadronic decays can exhibit CP violation. Among the possible decay channels, the decay $\tau^- \rightarrow \pi^- \pi^+ \pi^- (\geq 0\pi^0) \nu_\tau$ is particularly interesting. Thanks to the presence of intermediate resonances and the angular distributions of the final-state particles, the observables within this decay are sensitive to the effects of CP violation.

In this manuscript, I presented my work that contributes to the search for CP violation within $\tau^- \rightarrow \pi^- \pi^+ \pi^- (\geq 0\pi^0) \nu_\tau$ within Belle II. A high purity signal is obtained after different selection criteria are applied. These criteria are based on precise kinematic constraints to distinguish the signal well from background processes that behave like signal. Furthermore, corrections related to the efficiencies of particle identification algorithms were also applied to the Monte Carlo (MC) simulated events. Comparison of the observables distributions from the data collected by Belle II to the MC simulated data was also performed. Good agreement was found between the data and the MC divided by signal and background processes.

In order to measure the CP violation in this decay, specific angular observables are exploited. These observables are designed to be sensitive to CP violation. By constructing combinations of these observables and using them as weights, it is possible to define weighted CP asymmetries to enhance the sensitivity of the measurement. The methodology and software tools developed as part of this work provide a solid foundation for the CP violation measurement in this specific decay and later on more extensive searches for CP violation in hadronic tau decays at Belle II.

Complementarily, this thesis also presented a study of systematic effects for the Belle II upgrade concerning the introduction of a

Compton polarimeter. The addition of a polarized electron beam to the SuperKEKB collider is meant to open new opportunities for physics beyond the Standard Model. This requires a measurement with very high precision of the polarization of the electron beam. Among the techniques for this measurement, Compton scattering is considered the most effective for obtaining the beam polarization directly at the interaction point.

In this context, this thesis presented the study of systematic uncertainties that impact the precision of the electron polarization measurement. The work included working on a simulation model of the Compton polarimeter, identifying potential sources of systematic uncertainty, and evaluating their impact on the measurement of the electron polarization. The results obtained are very important for the design and optimization of the polarimeter system. This contribution is essential for the Belle II upgrade program.

Technically, the polarimeter exploits Compton scattering of a circularly polarized laser sent to the electron beam to measure the polarization of the beam. Specifically, the differential cross section of the process is, in part, dependent on the longitudinal polarization of the electron beam and the circular polarization of the laser. As the laser polarization is ideally well controlled, the electron beam polarization can be extracted.

Therefore, the Compton polarimeter allows for high-precision control of the electron beam polarization during data taking with a precision of about 1%. This is beneficial for any physics measurement or analysis that involves polarization-sensitive observables, such as electroweak precision tests and searches for lepton flavor violation. A precise and accurate measurement of the beam polarization is needed to avoid misinterpretation of observed effects as New Physics rather than as instrumental uncertainties. The design of the polarimeter and the study of its systematic uncertainties are thus main features to the exploitation of the physics potential of polarized collisions at SuperKEKB.

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