

Search for $B^+ \rightarrow \tau^+ \nu_\tau$ decays with a
hadronic tagging method at the Belle II
Experiment

Belle II実験におけるハドロニックタグ手法を
用いた $B^+ \rightarrow \tau^+ \nu_\tau$ 崩壊の探索

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Introduction

Belle II is a Flavour Physics experiment designed to explore physics beyond the Standard Model (SM) and improve the precision of key SM parameters. The experiment and its general-purpose detector operate at the e^+e^- SuperKEKB collider, located at the KEK laboratories in Tsukuba, Japan. The accelerator collides at a center-of-mass energy of 10.58 GeV, corresponding to the $\Upsilon(4S)$ resonance, which predominantly decays into pairs of B mesons. The beams have asymmetric energies to boost the center-of-mass frame, enabling precise measurements of time-dependent charge-parity (CP) violation.

This thesis presents a search for the $B^+ \rightarrow \tau^+\nu_\tau$ decay, a rare SM process with potential sensitivity to New Physics (NP) contributions. Assuming the SM framework and utilizing precise lattice quantum chromodynamics (LQCD) calculations of the B^+ meson decay constant f_B , this decay mode provides a direct determination of the CKM matrix element V_{ub} , independent of measurements from exclusive and inclusive semileptonic $B \rightarrow X_u \ell \nu_\ell$ decays, which are traditionally used for this purpose [3]. Additionally, the theoretical uncertainty in leptonic decays is not expected to be a limiting factor, as estimated by the FLAG working group, which reports an uncertainty below 1% [4].

The $B^+ \rightarrow \tau^+\nu_\tau$ decay is also highly relevant for probing NP models, such as those predicting a charged Higgs boson, including the Two-Higgs-Doublet Model (2HDM) Type II [5]. In these scenarios, the branching fraction of $B^+ \rightarrow \tau^+\nu_\tau$ can be either enhanced or suppressed. A precise measurement of this branching fraction can thus impose stringent constraints on the parameter space of such models.

This study is conducted using the Belle II experiment's Run 1 dataset, corresponding to $387(6) \times 10^6$ $\Upsilon(4S)$ events and an integrated luminosity of 365 fb^{-1} [6]. One B meson is fully reconstructed using a multivariate algorithm trained on hadronic decay modes, while the remaining particles in the event are used to reconstruct the signal decay $B^+ \rightarrow \tau^+\nu_\tau$. Four τ decay modes with a single charged particle in the final state are considered. The signal selection is optimized using simulation, which is then corrected and validated with control samples. Finally, the branching fraction is extracted through a simultaneous two-dimensional maximum likelihood fit of two variables: the residual energy in the electromagnetic calorimeter not associated with the reconstructed B^+B^- pair and the missing mass squared of the event.

Chapter 1

Standard Model: the Physics of Flavour

In this chapter, we outline the theoretical framework essential for studying leptonic B meson decays within the SM and NP scenarios. We introduce the $SU(2)_L$ group governing electroweak interactions, followed by a discussion on gauge-invariant Yukawa couplings. This provides the foundation for describing the Cabibbo-Kobayashi-Maskawa (CKM) matrix, its commonly used parameterizations, and the unitarity triangle.

1.1 Introduction

Flavour Physics, the field that explores the properties and interactions of quarks and leptons, has been pivotal in advancing the SM. In nature, all fundamental matter particles (quarks, charged leptons, and neutrinos) exist in three distinct forms, referred to as flavours. These flavours are organized into three generations of fermions, distinguished by their increasing masses but otherwise identical quantum numbers. Emerging alongside the discovery of the SM's fundamental components, Flavour Physics has evolved to focus on measuring the model's parameters. Most of these parameters are linked to the flavour sector and can be determined through flavour-violating decays. Additionally, these measurements provide valuable constraints on potential NP models. With advancements in experimental and theoretical techniques, the precision of such determinations has reached remarkable levels.

The SM fermions, categorized based on their QCD and QED quantum numbers, $SU(3) \otimes U(1)_{em}$, are depicted in Fig. 1.1, along with some of their properties. Each type of fermion is replicated in three generations.

1.2 Gauge-Invariant Yukawa Couplings and the CKM Matrix

Before the emergence of gauge models in the late 1960s, weak interactions were described using a local two-current interaction framework. This approach, initially proposed by Fermi and later refined by Feynman and Gell-Mann, takes the form:

$$\mathcal{H}_{\text{weak}} = \frac{G_F}{\sqrt{2}} J'^\mu J_\mu'^\dagger \quad (1.1)$$

Here, the Lorentz vector J'_μ represents the *charged current*, so named because it mediates transitions between particles with different electric charges. This current consists of both leptonic and hadronic components:

$$J'_\mu = L_\mu + H_\mu \quad (1.2)$$

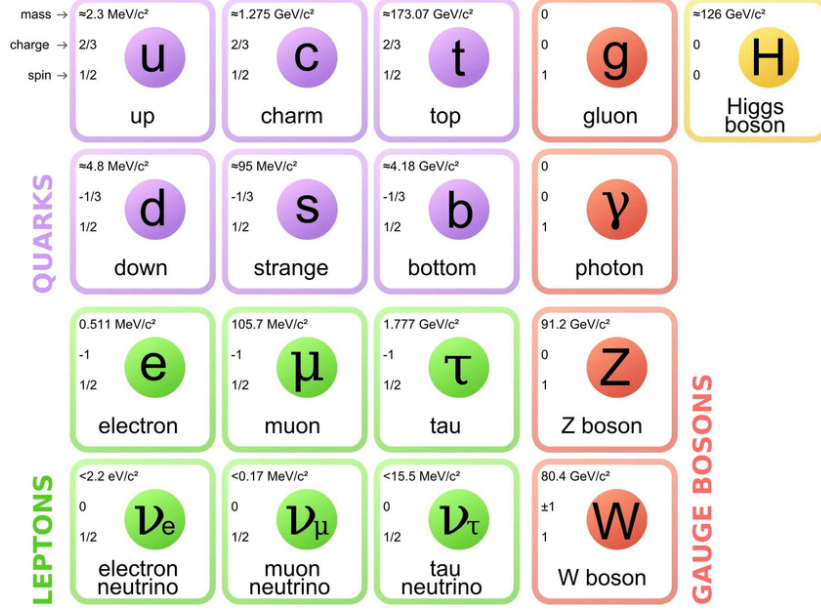


Figure 1.1: Fundamental particles of the SM with some of their properties. On the left the SM fermions grouped into three generations; on the right the SM bosons.

At low energies, the interaction Hamiltonian in Eq. 1.1 effectively describes weak interactions. The Fermi coupling constant, G_F , is given by:

$$G_F = 1.16639 \times 10^{-5} \text{ GeV}^{-2} \quad (1.3)$$

Although G_F is numerically small, its dimensional dependence on the inverse square of mass leads to a non-renormalizable interaction. Higher-order corrections involve loop diagrams with internal propagators, introducing additional powers of G_F and momenta, leading to divergences that cannot be absorbed through renormalization.

However, by introducing a massive mediator, the weak interaction can be reformulated. On dimensional grounds, we express:

$$4\sqrt{2}G_F = \frac{e^2}{M_W^2} \quad (1.4)$$

Here, M_W represents the mass of a hypothesized exchange boson mediating weak interactions. Analogous to the electromagnetic current j_μ^{em} , the weak charged current J'_μ behaves as a Lorentz four-vector. Consequently, we can introduce a massive charged field W_μ , coupling it to J'_μ as:

$$\mathcal{L}_{\text{weak}} = -\frac{g}{2\sqrt{2}} \left(J'^\mu W_\mu^\dagger + J'^{\mu\dagger} W_\mu \right) \quad (1.5)$$

1.3 Chiral decomposition and weak isospin representation

At second order, Eq. 1.5 reproduces Eq. 1.1 as an effective low-energy interaction, with the relation $G_F/\sqrt{2} = g^2/8M_W^2$, where M_W^2 arises from the W_μ field propagator in the low-momentum limit. Although this formulation is not explicitly renormalizable, theories incorporating gauge invariance can be renormalized.

A Dirac spinor field can be decomposed into left- and right-handed components:

$$\chi(x) = \chi_L(x) + \chi_R(x) \quad (1.6)$$

where:

$$\chi_L(x) = a_L \chi(x), \quad \chi_R(x) = a_R \chi(x) \quad (1.7)$$

The projection operators are defined as:

$$a_L = \frac{1}{2}(1 - \gamma_5), \quad a_R = \frac{1}{2}(1 + \gamma_5) \quad (1.8)$$

For massless fields, these chiral components coincide with helicity eigenstates, forming irreducible representations of the Lorentz group. Experimental evidence from weak decays such as $n \rightarrow p e^- \bar{\nu}_e$, $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$, and $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$ confirms that weak interactions exclusively involve left-handed leptons and right-handed antileptons. This observation leads to the left-handed weak interaction Lagrangian:

$$\mathcal{L}_\mu^e = 2\bar{e}_L(x)\gamma_\mu\nu_{eL}(x) = \bar{e}(x)\gamma_\mu(1 - \gamma_5)\nu_e(x) \quad (1.9)$$

This suggests that the electron and its neutrino form a weak-isospin doublet under the $SU(2)_L$ symmetry:

$$\psi_L = \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}, \quad \psi_R = e_R \quad (1.10)$$

Since $SU(2)_L$ only acts on left-handed fermions, it is referred to as the *weak isospin* group.

1.4 Quark representation and CKM matrix

Similarly, left-handed quarks organize into $SU(2)_L$ doublets:

$$Q_j = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad \begin{pmatrix} c_L \\ s_L \end{pmatrix}, \quad \begin{pmatrix} t_L \\ b_L \end{pmatrix} \quad (1.11)$$

while right-handed quarks are singlets:

$$U_j = u_R, c_R, t_R, \quad D_j = d_R, s_R, b_R \quad (1.12)$$

Flavour non-universality arises from Yukawa couplings to the Higgs field, which generate mass terms. Diagonalizing the resulting quark mass matrices reveals the Cabibbo-Kobayashi-Maskawa (CKM) matrix, describing the misalignment between mass and weak eigenstates:

$$\hat{V}_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \quad (1.13)$$

This unitary 3×3 matrix governs flavour-changing interactions mediated by $W^\pm$ bosons. Its elements, such as V_{ud} , determine the coupling strengths between different quark flavours.

1.5 Standard Parameterization

As a unitary matrix, the CKM matrix is initially described by three mixing angles and six complex phases. However, five of these phases can be absorbed into the quark fields as unobservable parameters, leaving three physical mixing angles $\theta_{12}, \theta_{23}, \theta_{13}$ and one CP-violating phase δ . Using the shorthand $s_{ij} = \sin \theta_{ij}$ and $c_{ij} = \cos \theta_{ij}$, the standard parameterization is:

$$\hat{V}_{CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \quad (1.14)$$

Experimentally, the CKM matrix exhibits a hierarchical structure:

$$s_{12} \sim 0.2, \quad s_{23} \sim 0.04, \quad s_{13} \sim 4 \times 10^{-3} \quad (1.15)$$

This hierarchy indicates that flavour-changing transitions are suppressed, and quark masses span several orders of magnitude.

1.6 Unitarity triangle

The hierarchical nature of the CKM matrix enables an alternative and convenient parametrization to estimate the magnitude of flavour-violating processes. One such representation is the Wolfenstein parameterization:

$$\hat{V}_{CKM} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4) \quad (1.16)$$

Here, $\lambda = |V_{us}| \sim 0.2$ is the small expansion parameter, while A , ρ and η are $\mathcal{O}(1)$. For improved precision, the parameters can be redefined as:

$$\lambda, \quad A, \quad \bar{\rho} = \left(1 - \frac{\lambda^2}{2}\right)\rho, \quad \bar{\eta} = \left(1 - \frac{\lambda^2}{2}\right)\eta \quad (1.17)$$

The CKM matrix's unitarity condition imposes several relations between its elements, which can be tested experimentally. One such relation is:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \quad (1.18)$$

This equation can be represented as a triangle in the complex plane, known as the unitarity triangle (UT), as shown in Fig. 1.2. When normalized to unity, the apex of the triangle is given by $(\bar{\rho}, \bar{\eta})$, while the sides are defined as:

$$R_b = \left| \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right| = \left(1 - \frac{\lambda^2}{2}\right) \frac{1}{\lambda} \frac{|V_{ub}|}{|V_{cb}|} \quad (1.19)$$

$$R_t = \left| \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} \right| = \frac{1}{\lambda} \frac{|V_{tb}|}{|V_{cb}|} \quad (1.20)$$

The angles of the triangle are often referred to as:

$$\alpha \equiv \phi_2, \quad \beta \equiv \phi_1, \quad \gamma \equiv \phi_3 \quad (1.21)$$

The UT can be experimentally determined through the analysis of flavour-violating decays of K and B mesons. In this context, the side R_b and the angle γ play a crucial role. These

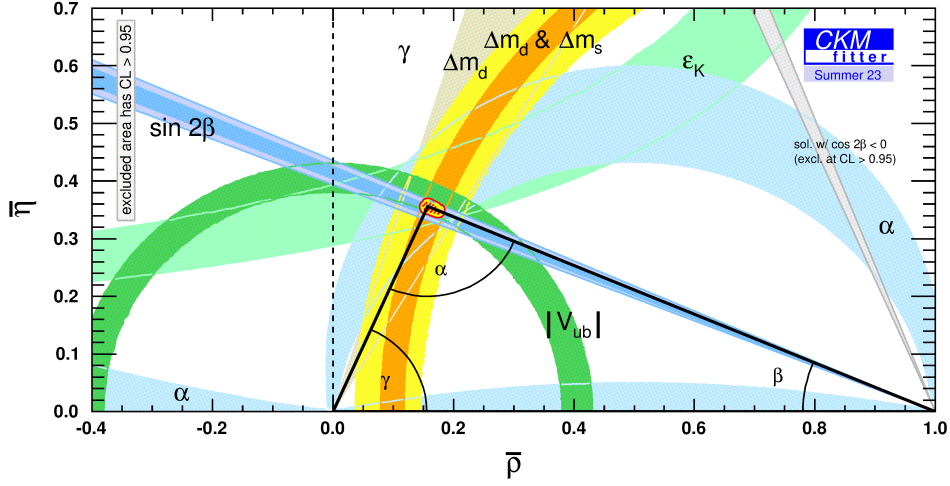


Figure 1.2: Unitary Triangle and constraints in the $(\bar{\rho}, \bar{\eta})$ plane from CKM fitter 2023.

parameters are sensitive to the magnitudes and CP-violating phases of the CKM matrix elements V_{ub} and V_{cb} , which can be extracted from B decays mediated by tree-level charged current interactions. Since such processes are largely unaffected by potential NP effects, it is reasonable to assume negligible NP contributions in these measurements. Consequently, determining $|V_{ub}|$, $|V_{cb}|$ and $\gamma = \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$ provides a baseline or "reference" unitarity triangle that defines the CKM matrix without NP interference.

In contrast, the side R_t and the angle β are linked to CKM elements involving the top quark and are extracted from loop-induced flavour-changing neutral current (FCNC) processes. These observables, being strongly suppressed in the SM, are particularly sensitive to NP effects. However, using them to independently determine the CKM matrix is challenging due to their potential NP contributions.

To investigate NP contributions to flavour-violating observables, a systematic approach is necessary. First, the CKM matrix and the UT should be determined as accurately as possible using tree-level decays, which are largely unaffected by NP. These results serve as inputs to predict rare, loop-induced FCNC processes under the SM framework. Comparing these predictions with experimental data can reveal discrepancies that point to NP effects. However, claiming the discovery of NP requires a thorough understanding of the SM contributions and their uncertainties to ensure the observed deviations are significant.

Chapter 2

Leptonic decays of B mesons

Leptonic B meson decays, which occur via first-order weak interactions mediated by the W boson in the SM, provide a clean framework for theoretical analysis. Among these, the purely leptonic decays $B^+ \rightarrow \ell^+ \nu_\ell$, where $\ell = (e, \mu, \tau)$ are particularly significant due to their well-defined theoretical predictions. The decay $B^+ \rightarrow \ell^+ \nu_\ell$ also plays a crucial role in exploring NP. For decays involving electrons and muons, the SM predicts dominance by tree-level W boson processes, with potential contributions from new physics being significantly suppressed relative to the SM predictions.

2.1 Theoretical Overview

In the SM, the weak charged decay of the B meson, $B^+ \rightarrow \ell^+ \nu_\ell$, occurs through the annihilation of the heavy and light quarks inside the meson. This process is mediated by a charged current interaction, as depicted in Fig. 2.1. The branching fraction for this decay is given by:

$$\mathcal{B}(B^+ \rightarrow \ell^+ \nu_\ell) = \frac{G_F^2 m_B m_\ell^2}{8\pi} \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B \quad (2.1)$$

where m_B and m_ℓ denote the masses of the B meson and the lepton, respectively, while τ_B represents the B meson lifetime. The decay constant f_B encapsulates the hadronic matrix element of the axial-vector current, parameterized as $p_B^\mu f_B$. This quantity is determined through LQCD calculations, whereas all other parameters in Eq. 2.1 are measured experimentally.

Due to helicity suppression, the branching fraction is strongly dependent on the lepton mass. Consequently, the $B^+ \rightarrow \tau^+ \nu_\tau$ decay has the highest expected branching fraction among leptonic decays and is the only mode with experimental evidence. The expected ratios for the decay rates among different lepton species follow the pattern $\tau : \mu : e \approx 1 : 10^{-3} : 10^{-7}$, with SM predictions [7] given by:

$$\mathcal{B}_\tau = (7.7 \pm 0.6) \times 10^{-5}, \quad \mathcal{B}_\mu = (3.5 \pm 0.3) \times 10^{-7}, \quad \mathcal{B}_e = (8.1 \pm 0.6) \times 10^{-12} \quad (2.2)$$

Past measurements of $\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau)$ by Belle and BaBar employed two independent approaches for reconstructing the tag-side B meson (B_{tag}), utilizing either semileptonic decays [8] [9] or hadronic decays [10] [11]. The combined average from Belle and BaBar, as reported by the Particle Data Group (PDG) [12], is $(1.09 \pm 0.24) \times 10^{-4}$, which is in agreement with the SM expectation.

Within the SM, the observation of $B^+ \rightarrow \tau^+ \nu_\tau$ provides a direct method to determine f_B , given that $|V_{ub}|$ is typically extracted from semileptonic B decays. Conversely, if f_B is precisely computed using LQCD, an accurate measurement of the branching fraction allows for an independent determination of $|V_{ub}|$. Additionally, the ratio $|V_{ub}|/|V_{td}|$ can be inferred by

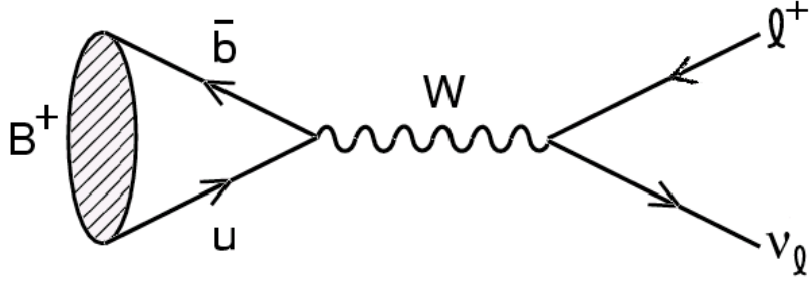


Figure 2.1: Illustration of a leptonic B meson decay.

comparing $\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau)$ with the measured mass difference Δm_d of heavy and light neutral B_d mesons, which is precisely determined from B_d mixing studies.

While this method offers a theoretically clean dependence on relevant parameters, practical experimental challenges complicate its implementation. The muon channel provides a simpler reconstruction due to the clean detection of the muon. However, its helicity suppression results in an extremely rare branching fraction, making observation difficult. Conversely, the tau channel has a relatively larger branching fraction, but its reconstruction is complicated by the presence of multiple neutrinos in the final state. This introduces significant background contamination, making event selection and suppression of unwanted processes more challenging.

2.2 Implications of $B^+ \rightarrow \tau^+ \nu_\tau$ in New Physics

The study of the decay $B^+ \rightarrow \tau^+ \nu_\tau$ is also crucial in the search for NP, as it provides a means to constrain NP parameters. In the 2HDM Type II [5], this decay receives an additional contribution from a charged Higgs boson at tree level, as illustrated in Fig. 2.2.

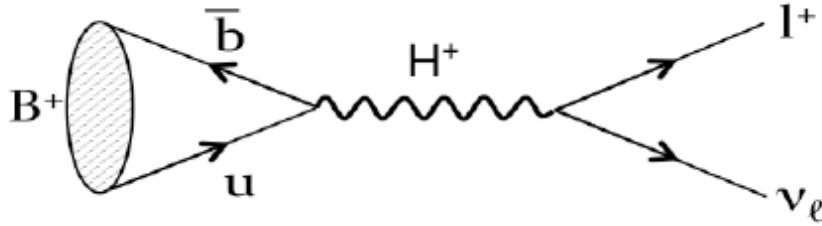


Figure 2.2: Diagram of a leptonic B meson decay mediated by a charged Higgs boson.

The charged Higgs Yukawa couplings depend on the parameter $\tan \beta = v_2/v_1$, which is the ratio of the vacuum expectation values of the two Higgs doublets. Both the $W^\pm$ and $H^\pm$ bosons contribute to the effective Fermi interaction:

$$\frac{G_F}{\sqrt{2}} V_{ib} ([\bar{u}_i \gamma_\mu (1 - \gamma_5) b][\bar{l} \gamma_\mu (1 - \gamma_5) \nu] - R_l [\bar{u}_i (1 + \gamma_5) b][\bar{l} (1 - \gamma_5) \nu]) \quad (2.3)$$

where the term R_l is given by:

$$R_l = \tan^2 \beta \left(\frac{m_b m_l}{m_{H^-}^2} \right) \quad (2.4)$$

The pseudo-scalar coupling of the charged Higgs boson $H^\pm$ is expressed as:

$$-if_B \left(\frac{m_B^2}{m_b} \right). \quad (2.5)$$

This modifies the branching fraction of the decay, which in the presence of NP takes the form:

$$\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau) = \mathcal{B}_{SM} \times \left(1 - \tan^2 \beta \frac{M_{B^\pm}^2}{m_{H^\pm}^2} \right)^2 \quad (2.6)$$

By comparing the experimentally measured branching fraction with the SM prediction, it is possible to exclude certain regions in the $(m_{H^\pm}, \tan \beta)$ parameter space.

2.3 Decay Modes of the τ Lepton

The τ lepton is unique among the leptons, as it is the only one capable of decaying into hadrons, owing to its relatively large mass ($\approx 1.77 \text{ GeV}/c^2$). Table 2.1 summarizes the most common decay modes of the τ , with the most frequent being:

- Leptonic decays, $\tau \rightarrow \ell \bar{\nu}_\ell \nu_\tau$ ($\ell = e, \mu$), as illustrated in Fig. 2.3:

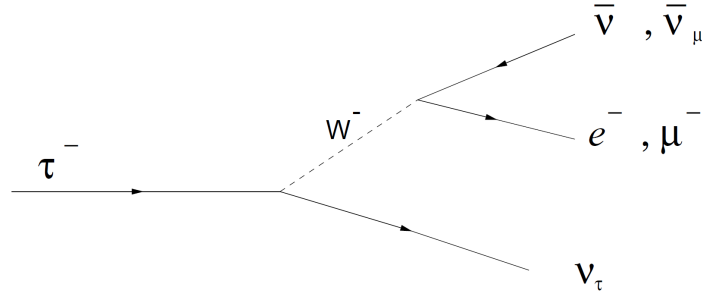


Figure 2.3: Diagram representing the leptonic decays of the τ lepton.

- Hadronic decays, such as $\tau \rightarrow \pi \nu_\tau$, $\tau \rightarrow \rho \nu_\tau$, and $\tau \rightarrow a_1 \nu_\tau$, where the ρ and a_1 resonances decay into two and three pions, respectively, as shown in Figs. 2.4 and 2.5.

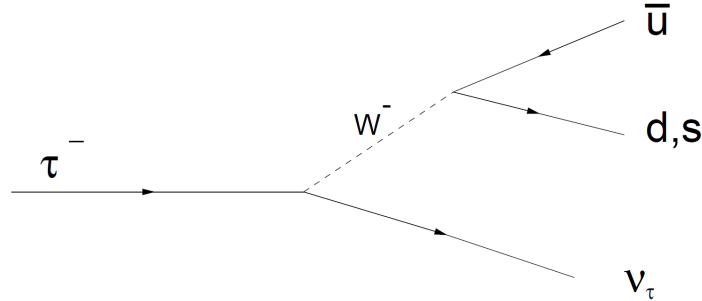


Figure 2.4: Illustration of a τ lepton decaying into a single pion.

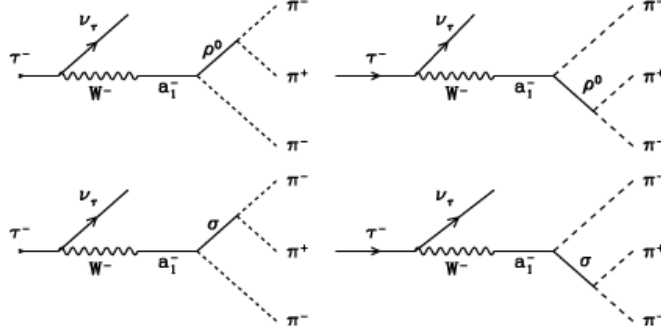


Figure 2.5: Illustration of a τ lepton decaying into three pions via a_1 and ρ resonances.

Table 2.1: Branching fractions of the main τ -decay modes.

Decay mode	$\mathcal{B} \%$
$e^+ \nu_e \bar{\nu}_\tau$	17.82 ± 0.04
$\mu^+ \nu_\mu \bar{\nu}_\tau$	17.39 ± 0.04
$\pi^+ \bar{\nu}_\tau$	10.82 ± 0.05
$\pi^+ \pi^0 \bar{\nu}_\tau$	25.49 ± 0.08
$\pi^+ 2\pi^0 \bar{\nu}_\tau$	9.26 ± 0.1
$\pi^+ \pi^- \pi^+ \bar{\nu}_\tau$	9.02 ± 0.05

Chapter 3

Belle II experiment overview

The Belle II experiment is designed to primarily improve the measurements of SM parameters and search for NP in the flavour sector by studying B meson properties. It is located at the interaction point of the e^+e^- beams circulating in the SuperKEKB accelerator at KEK laboratories in Tsukuba, Japan. The SuperKEKB facility is designed to collide electrons and positrons at center-of-mass energies near the Υ resonances, particularly at the $\Upsilon(4S)$ resonance ($\sqrt{s} = 10.58 \text{ GeV}$), which is just above the threshold for B meson pair production. With asymmetric beam energies, the accelerator provides a boost to the center-of-mass system, enabling time-dependent CP violation measurements. Data collection began in 2018, initially for accelerator and detector commissioning. The facility is set to progressively increase collision intensity, aiming for a design integrated luminosity of 50 ab^{-1} around 2035, as shown in Fig. 3.1.

The illustrations and technical specifications are sourced from the Belle II Technical Design Report [13] and the Belle II Physics Book [7], with updates reflecting the latest luminosity projections.

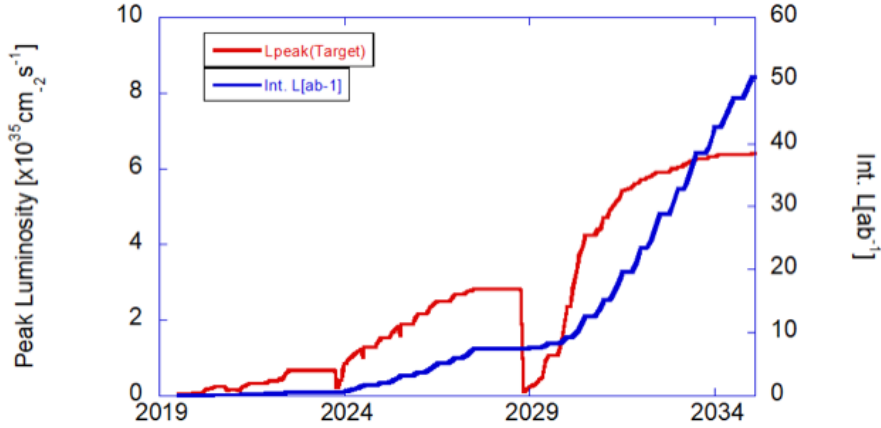


Figure 3.1: Integrated and instantaneous luminosity projection of SuperKEKB accelerator in the next years.

3.1 SuperKEKB collider

SuperKEKB is an asymmetric electron-positron collider and an upgrade of the KEKB facility, designed to increase the instantaneous luminosity by approximately a factor of 40, of the order of $10^{35} \text{ cm}^{-2} \text{ s}^{-1}$. The key elements driving this increase in luminosity are a reduction in the beam size at the collision point by a factor of 20, from around and a doubling of the beam

currents compared to KEKB values (see Table 3.1). This approach, known as the "nano-beam" scheme, was pioneered by P. Raimondi for the Italian Super B-factory [14].

	LER(e^+)	HER(e^-)	
Energy	4.000	7.007	GeV
Half crossing angle	41.5		<i>mr</i> ad
Horizontal emittance	3.2	4.6	<i>nm</i>
Emittance ratio	0.27	0.25	%
Beta functions at IP (x/y)	32 / 0.27	25 / 0.30	<i>mm</i>
Beam currents	3.6	2.6	<i>A</i>
Beam-beam parameter	0.0881	0.0807	
Luminosity	$8 \cdot 10^{35}$		$cm^{-1}s^{-1}$

Table 3.1: Design parameters of SuperKEKB accelerator.

The majority of data is recorded at the $\Upsilon(4S)$ resonance but the beams at SuperKEKB can also operate in energy ranges corresponding to resonant states such as $\Upsilon(1S)$ (with a mass of $9.46 \text{ GeV } c^{-2}$) and $\Upsilon(6S)$ (with mass $11.24 \text{ GeV } c^{-2}$). Electrons are generated in a pre-injector by directing a pulsed laser onto a cold cathode target. They are then accelerated by a linear accelerator (Linac) to 7 GeV and injected into the High Energy Ring (HER) of SuperKEKB. Positrons are produced by colliding electrons with a tungsten target, after which they pass through a damping ring to reduce their emittance. Once the required emittance is reached, they are accelerated to 4 GeV in the Linac and injected into the Low Energy Ring (LER). The layout of the collider is shown in Fig. 3.2.

The peak luminosity delivered by SuperKEKB reached $5.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ in December 2024, and the dataset used for this analysis, of the order of 365 fb^{-1} [6], was collected at the $\Upsilon(4S)$ resonance between 2019 and 2022. As already stated, the SuperKEKB/Belle II experiment aims to collect high-statistics data of B meson pairs to explore NP beyond the SM. But still, the so-called Sudden Beam Loss (SBL) events represent one of the major obstacles, which cause substantial beam losses and damage to the Belle II detector, and so reduce the data-taking efficiency (see Appendix A) [15].

3.2 Belle II detector

The Belle II detector is an upgraded version of its predecessor, the Belle detector, featuring entirely new components or significant enhancements [13] (see illustration in Fig. 3.3).

The coordinate system utilized is defined as follows: the origin is located at the Interaction Point (IP), $r \in [0, \infty]$ represents the radial distance from the IP on the transverse plane, $z \in [-\infty, \infty]$ denotes the longitudinal distance from the IP, with positive values indicating the forward direction. The azimuthal angle $\phi \in [-\pi, \pi]$ is set to zero in the upward direction, and the polar angle $\theta \in [0, 2\pi]$ is defined with zero pointing towards the forward region. Occasionally, a Cartesian coordinate system is employed, with the z -axis aligned with the electron beam axis (forward direction), the y -axis upwards, and the x -axis directed to the right. The detector has approximate cylindrical symmetry around the z -axis, although there is significant forward-backward asymmetry, which enhances solid angle coverage in the boost direction (forward from IP).

The Belle II detector is structured with the following sub-detector systems, from the innermost to the outermost:

- **Pixel Detector (PXD):** Composed of two layers of pixel detectors using DEPFET technology, which provides 2D position measurements.

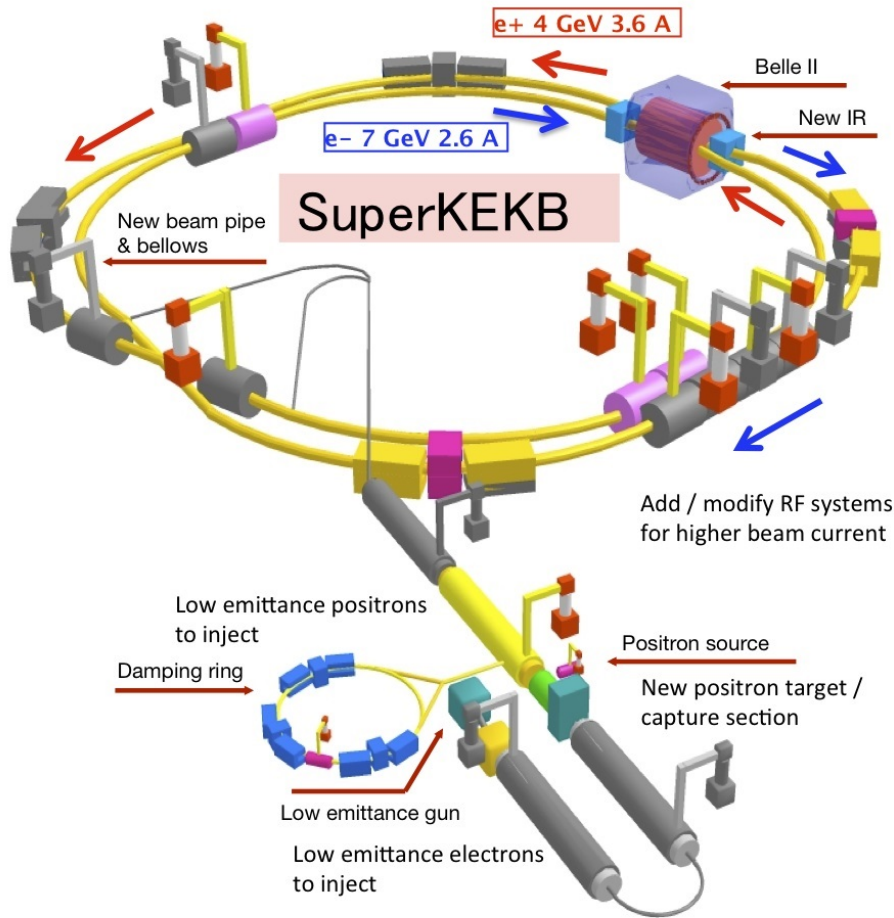


Figure 3.2: Illustration of the SuperKEKB collider.

- **Silicon Strip Detector (SVD):** This consists of four layers of Double-Sided Silicon Strip Detectors that offer 2D position data. It plays a key role in both online and offline track reconstruction. Together with the PXD, the SVD forms the Vertex Detector (VXD) of Belle II.
- **Central Drift Chamber (CDC):** A helium-ethane wire drift chamber with 56 layers, employing both stereo and longitudinal geometries for position detection. It is used for tracking, triggering, and particle identification tasks.
- **Particle Identification System (TOP, ARICH):** Includes a Time-Of-Propagation (TOP) counter with a Cerenkov quartz radiator in the barrel region and a Ring-Imaging Cerenkov (RICH) detector using an aerogel radiator in the end-cap regions.
- **Electromagnetic Calorimeter (ECL):** A homogeneous calorimeter constructed with CsI(Tl) crystals, designed to measure the energy of photons and energy deposits from charged particles, aiding in particle identification.
- **Superconducting Coil:** A NbTi/Cu coil generating a uniform magnetic field of 1.5 T along the beam axis in the internal detector region. The KLM detector's iron structure is used to return the magnetic field lines.

- **K_L and μ System (KLM):** Comprised of alternating layers of Resistive Plate Chambers and iron plates in the barrel regions, along with scintillator strips in the end-cap regions. It provides a total interaction length of 3.9 in the barrel region and is used to detect K_L mesons and muons that escape the internal detector region.

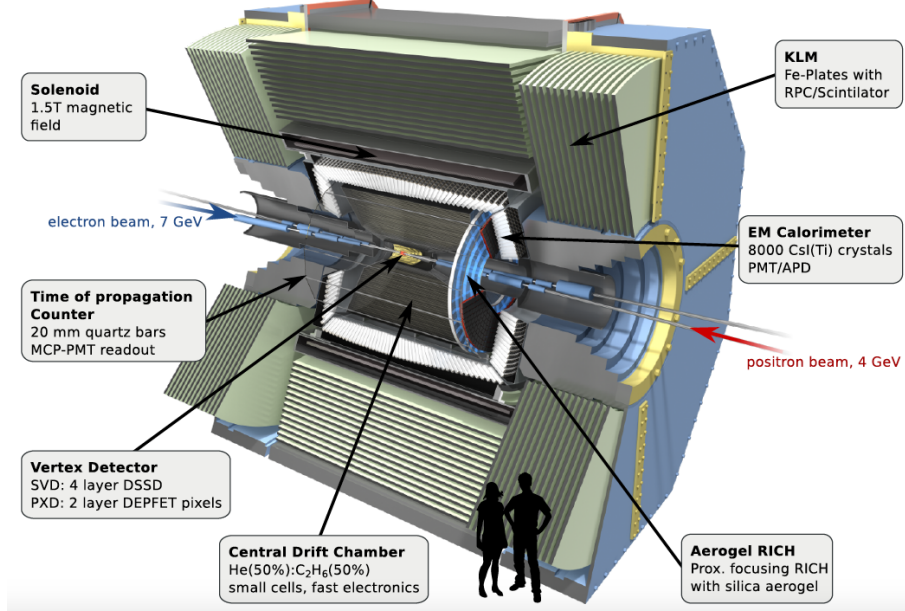


Figure 3.3: Illustration of the Belle II detector and each sub-detector.

3.2.1 Vertex detector (VXD)

The VXD is a six-layer silicon detector designed to enhance the precision of charged particle vertex measurements. Positioned around a beryllium beam pipe with a 10 mm radius, the VXD spans a radius range of 14–135 mm and covers a polar angle of 17° to 150° . The inner two layers are composed of depleted P-channel field-effect transistor pixel (DEPFET) sensors (PXD) (Fig. 3.4), while the outer four layers use double-sided silicon strip sensors (SVD) (Fig. 3.5). Each module features rectangular sensors arranged cylindrically, ensuring overlap in the azimuthal direction to minimize inefficiencies from sensor gaps. The PXD consists of an array of 768×250 DEPFETs per module, with pixel sizes ranging from approximately $55\text{--}85\ \mu\text{m}^2$. The granularity is finer near the interaction point (IP) to improve tracking precision. The decay point of particles is determined by extrapolating tracks reconstructed by the CDC (Central Drift Chamber) to the hits on the VXD, with a typical impact parameter accuracy of $15\ \mu\text{m}$ for 3 GeV/c tracks. A special note: at the time when the data used for this analysis was taken, only two out of the twelve modules had the second layer of the PXD installed. This setup was intended to compensate for the insufficient efficiency of one module in the first layer.

3.2.2 Central drift chamber (CDC)

The CDC is a cylindrical drift chamber positioned outside the VXD, for the tracking of charged particles (Fig. 3.6). It also provides low-momentum particles' identification by measuring their energy deposition. The chamber has an inner diameter of 160 mm and an outer diameter of 1130 mm, covering a polar angle range from 17° to 150° . The wires within the chamber are aligned with the magnetic field symmetry axis, forming cells with a sense wire surrounded by nine field wires. The chamber consists of 56 layers, with the cells in the radial direction having

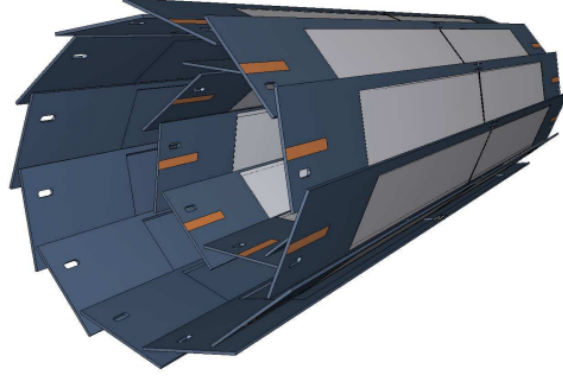


Figure 3.4: Illustration of the PXD.

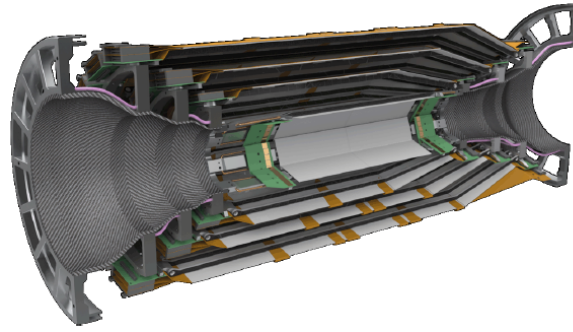


Figure 3.5: Illustration of the SVD.

a size of 8 mm for the innermost eight layers and 18 mm for the outer layers. In the azimuthal direction, the cell size is 6 mm for the innermost layer and 18 mm for the outermost layer. There are two types of wires: axial wires, which are parallel to the magnetic field symmetry axis, and stereo wires, which are slightly tilted in the azimuthal direction. The stereo wires are further classified into U-type and V-type based on their twist direction, with the angle of twist ranging from 45.4 to 74 milliradians. The chamber uses a gas mixture of 50% helium and 50% ethane, offering benefits such as a small radiation length, high resolution, and excellent energy loss resolution.

3.2.3 System for particle identification (TOP and ARICH)

The Aerogel Ring Imaging Cherenkov (ARICH) and Time-of-Propagation (TOP) detectors are designed to identify high-momentum charged particles, particularly for pion-kaon discrimination, which is challenging for other detectors. Both detectors rely on the Cherenkov angle, which is the angle between the direction of particle momentum and the emitted Cherenkov light. This angle is dependent on the particle's velocity, and for particles with the same momentum, it varies with the particle's mass. Thus, the mass of a particle can be estimated from its Cherenkov angle, for tracks with the same momentum and angle of incidence.

The ARICH detector (Fig. 3.7) is a disc-shaped structure that covers a forward region with a polar angle of 14° – 30° . It is equipped with hybrid avalanche photodetectors positioned 200 mm in front of a two-layer, 20 mm thick silica aerogel, as shown in Fig. 3.7. The aerogels have refractive indices of 1.045 and 1.055, and the two layers are designed so that the Cherenkov rings produced in the aerogel overlap on the photodetector, accounting for their offset and differences in Cherenkov angle.

The TOP detector covers the barrel region with a hexadecagonal arrangement of 16 quartz

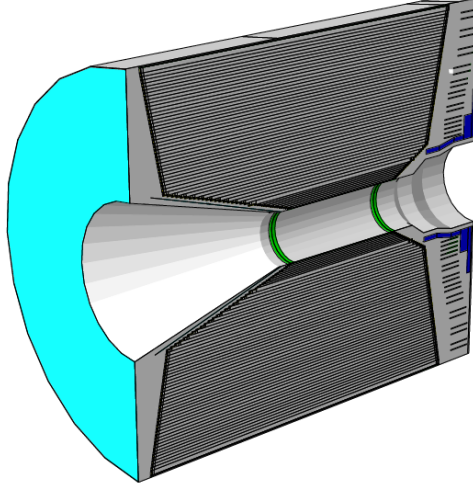


Figure 3.6: Illustration of the CDC.

plates, each measuring $2600 \times 450 \times 20$ mm. These plates act as Cherenkov radiators, with one of the modules shown in Fig. 3.8. The thin structure of the TOP detector helps reduce mass and enables the CDC to have a larger lever arm. Each quartz plate has a mirror glued to its forward end face, while the backward end face is equipped with a prism and photodetectors. Cherenkov photons generated by charged particles are reflected within the quartz plates and travel to the photodetectors. The timing and position of the Cherenkov photons are measured using micro-channel-plate photomultiplier tubes with high time resolution, capable of detecting photon arrival times to within 50 picoseconds.

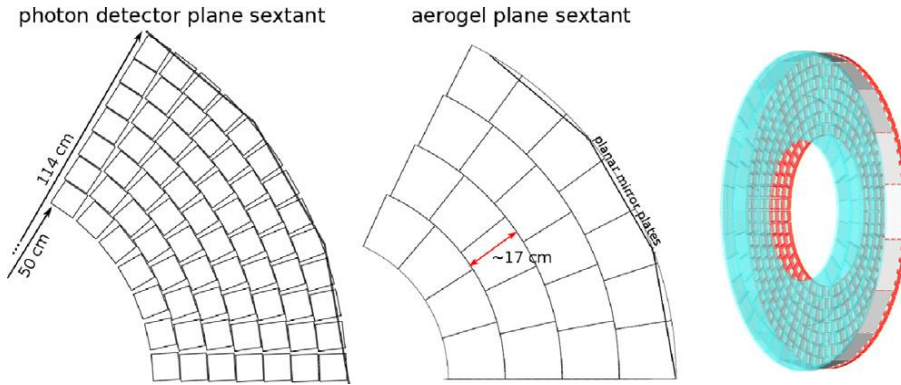


Figure 3.7: Illustration of the Belle II ARICH. Arrangement of photodetectors (left), aerogel plates (center), and image exported from detector simulation (right)).

3.2.4 Electromagnetic calorimeter (ECL)

The ECL is designed for photon detection from electromagnetic showers, electron identification, and triggering. The detector consists of 8,736 Thallium-doped Cesium Iodide (CsI) crystals, arranged as shown in Fig. 3.9. The crystals are cylindrically arranged with an inner diameter of 125 cm, and the end cap is positioned 196 cm in front of and 102 cm behind the

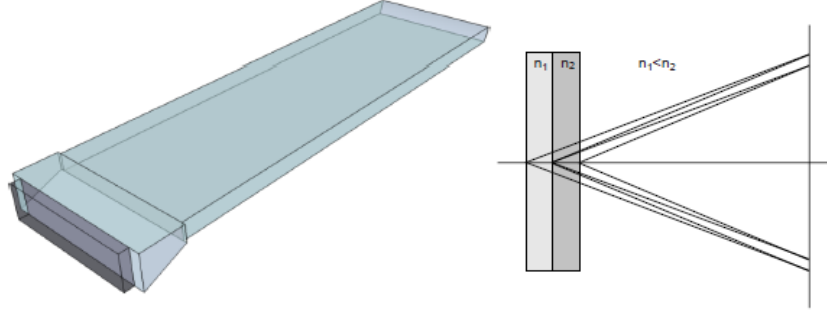


Figure 3.8: Illustration of the system for the PID: one TOP counter module (left), principle of operation of the proximity focusing ARICH with a non-homogeneous aerogel radiator in the focusing configuration (right).

interaction point (IP). The calorimeter covers a polar angle range of 12.4° – 155.1° , corresponding to 92% of the solid angle, with a 1° gap between the barrel and the end cap. The crystals have trapezoidal shapes, with varying dimensions depending on their position. Typically, the crystals measure 6×6 cm on the front face and have a length of 30 cm, corresponding to 16.2 radiation lengths. Each crystal is wrapped in a $200 \mu\text{m}$ polytetrafluoroethylene (PTFE) layer, a $25 \mu\text{m}$ aluminium layer, and a $25 \mu\text{m}$ mylar sheet. A photon detector, with dimensions of $10 \times 20 \text{ cm}^2$, is glued to the outer end face of each crystal. The same CsI crystals and photodetectors used in the Belle detector are also employed in the Belle II detector.

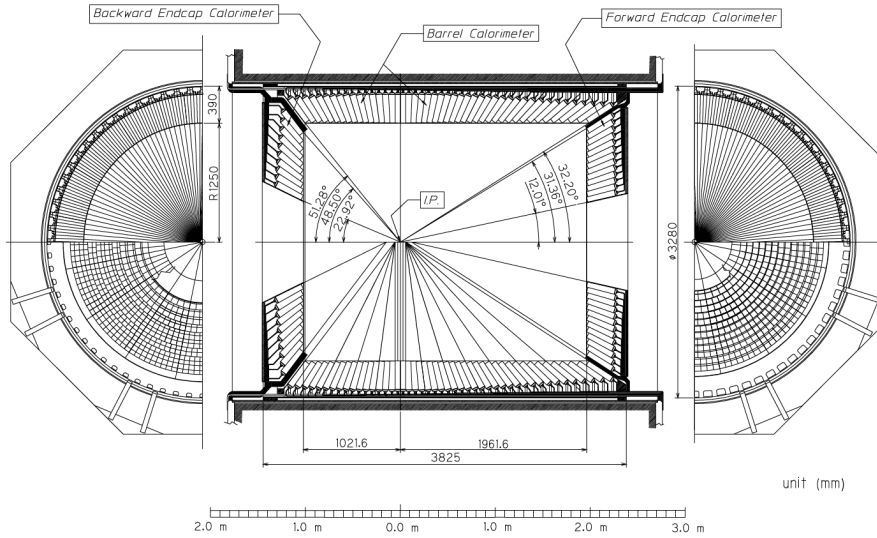


Figure 3.9: Overall configuration of the Belle II ECL. The upper (lower) half of the side panels represent the layout in the barrel (end-cap) region.

3.2.5 K_L - muon detector (KLM)

The KLM is designed to detect hadron showers caused by long-lived neutral particles, such as K_L^0 , and to identify muons, which have a high penetrability through materials. The KLM is composed of a barrel section with an octagonal cylindrical shape and a disc-shaped end-cap section. It consists of 15 iron plates, each 4.7 cm thick, alternating with 14 charged particle detectors, providing a total of 3.9 interaction lengths in the vertical direction. The barrel section covers a polar angle range of 45° – 125° , while the end-cap section extends to cover the

range of 20° – 155° , beyond the barrel section. The KLM employs two types of charged-particle detectors: scintillation counters and resistive plate chambers (RPCs). Scintillation counters are used in the inner two layers of the end-cap and the barrel to handle neutron backgrounds from the accelerator, while RPCs are used in the outer 13 layers of the barrel section.

3.2.6 Trigger system

The trigger system at Belle II consists of a set of electronic components designed to process detector information and initiate the data acquisition pipeline. Its main objectives are to identify events of interest, determine their event times, and suppress data acquisition for high-cross-section QED events within a specified bandwidth. Typical event rates are ultimately reduced to a trigger rate of under 30 kHz. The trigger system relies on complex logic circuits, including electronics and field-programmable gate arrays (FPGAs), to process the incoming data. The trigger signal must be issued and sent to the DAQ system within $5\ \mu\text{s}$ of event occurrence. Fig. 3.10 illustrates the schematic of the trigger system. Sub-triggers based on data from the CDC, ECL, TOP, and KLM detectors reconstruct objects from the respective hit information, sending details such as the number of tracks, number of clusters, and energy sums from ECL clusters. This information is then forwarded to the global reconstruction logic (GRL), where it is matched between sub-triggers. The processed data is passed to the global decision logic (GDL), which adjusts the timing for beam crossings and triggers the DAQ system. The trigger configurations are adjusted as needed depending on the trigger rates and instantaneous luminosity during each experimental period.

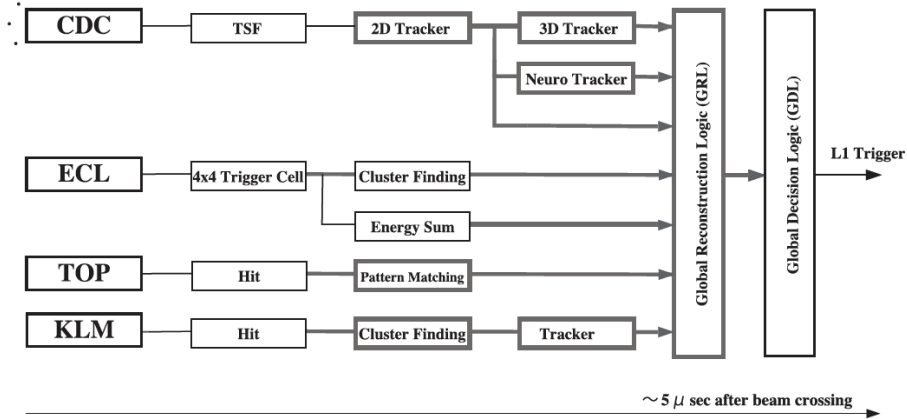


Figure 3.10: Schematic view of the Belle II Level-1 trigger system.

3.2.7 Data acquisition system (DAQ) and High-level trigger

The DAQ system is designed to process data acquisition with an L1 trigger rate coming at a maximum of 30 kHz with a dead time of 1% to store information from all the sub-detectors. The system is shown in Fig. 3.11. The trigger timing distribution system (TTD) is responsible for the distribution of the 127 MHz system clock synchronized to the 509 kHz of the SuperKEKB accelerator radio frequency and the distribution of the L1 trigger timing. When the front-readout electronics on the detectors receive the trigger signal from the TTD, the event data is fragmented and read out to a common readout board COPPER board on readout computers. This readout is performed using a bi-directional high-speed serial communication protocol Belle2link designed for data readout at a speed of 2.54 Gbps via optical fibre. From winter 2021, COPPER boards are gradually converted to PCIe40 boards to enable more stable and faster readout. The event rate is filtered by one-fifth by applying

the high-level trigger (HLT) from the reconstructed objects on the computers. Data health during data acquisition is checked at any time by fault detection in various parts of the system and by human monitoring of physical quantities using the reconstructed events. As the data size of PXD is large, information on the regions of interest, which is extrapolated from the tracks reconstructed by CDC and SVD, is determined by HLT to limit the data acquisition area of PXD. The raw data and its backup copy are transferred and stored in two data centers at KEK and Pacific Northwest National Laboratory (and BNL) using the Belle II distributed computing system.

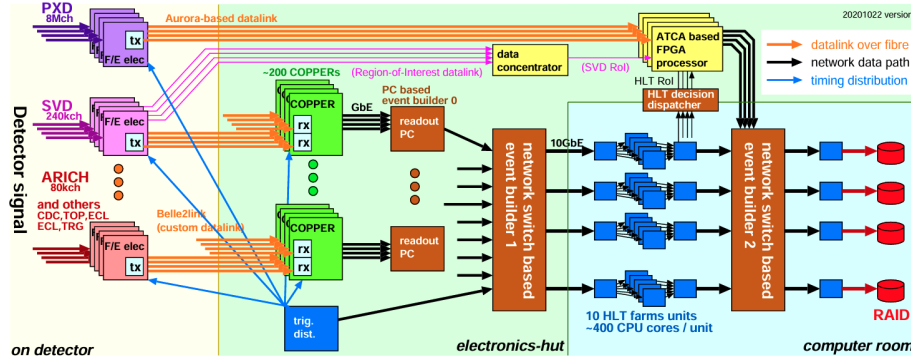


Figure 3.11: Schematic view of the Belle II DAQ.

Chapter 4

Reconstruction and cut-based event selection

The purpose of this study is to measure the $B^+ \rightarrow \tau^+ \nu_\tau$ decay branching ratio ($\mathcal{B}$) using data collected by the Belle II experiment at the SuperKEKB electron-positron collider between 2019 and 2022 at a center-of-mass energy of 10.58 GeV ($\Upsilon(4S)$ resonance), which corresponds to an integrated luminosity of 365 fb^{-1} .

This chapter describes the reconstruction and the event selection. The $B^+ \rightarrow \tau^+ \nu_\tau$ signal is searched using decays of the τ lepton with one charged particle in the final state: $\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$, $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$, $\tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$, $\tau^+ \rightarrow \rho^+ \bar{\nu}_\tau$ with $\rho^+ \rightarrow \pi^+ \pi^0$ and ρ being the $\rho(770)$. Fig. 4.1 shows a sketch of this decay. A multivariate technique-based tool, the *Full Event Interpretation*, selects one B meson used for tagging in each event, and the signal selection is then described in detail.

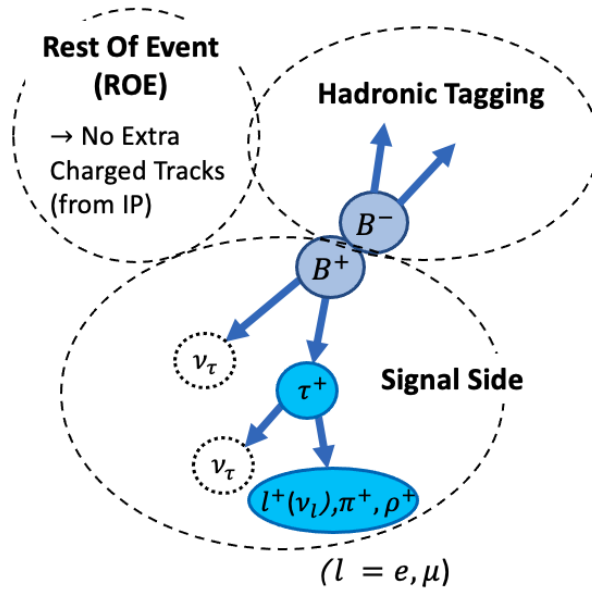


Figure 4.1: Sketch of the $B^+ \rightarrow \tau^+ \nu_\tau$ decay. First, a hadronic B decay is reconstructed on the tag side. The other B is searched using the τ lepton 1-prong decays. We require no extra charged tracks from the Interaction Point (IP).

4.1 Tools and dataset

The primary tool used for reading and analyzing data is ROOT, a versatile scientific software developed by CERN. ROOT offers essential features for managing large datasets and is primarily based on the C++ programming language.

In addition, the Belle II collaboration has developed a specific tool, the Belle II AnalySis Framework (BASF2), to process the data. The raw data from the detector undergoes calibration, reconstruction, and is stored on tape using PANTHER-based data summary tape (DST) files [16]. PANTHER is a custom serialization format. After each experiment, the calibration constants are recomputed and stored in the Belle Condition Database. The data are then reprocessed into a compact format, known as mDST files, which are compressed and reduced versions of the data summary files in ROOT format. BASF2 handles the reconstruction and processing of the mDST files.

BASF2 is written in C++ and Python, and incorporates third-party libraries such as EvtGen, GEANT4, and ROOT. The framework is divided into various packages, each addressing different aspects of data processing, including: data acquisition, Monte Carlo event generation, detector and sub-detector simulation, track reconstruction, event visualization, and physics analysis. These packages include libraries, modules, and data objects. The libraries, implemented in C++, provide functionality shared across different modules. Modules are small processing units that operate on event data, performing self-contained tasks. A sequence of modules forms a processing chain, and information shared between modules is encoded in data objects. These data objects are stored in a common DataStore, which all modules can read from and write to. Examples of data objects include *Track*, *ECLCluster*, *Particle*, and *ParticleList*. To use BASF2, users must provide a steering file written in Python.

For implementing Machine Learning algorithms and generating plots, Python and specific third-party libraries are employed.

The data have been initially organized into ten files: eight containing Monte Carlo simulations for the key physics processes, and two containing experimental data from Belle II. One dataset corresponds to the 365 fb^{-1} data collected at the $\Upsilon(4S)$ resonance mass peak (with $n_{\Upsilon(4S)} = 387(6) \times 10^6$ $\Upsilon(4S)$ mesons); the other dataset contains 42 fb^{-1} of data (around 10% of the total data) recorded 60 MeV below the $\Upsilon(4S)$ resonance mass peak, referred to as the *off-resonance data*. Since no B mesons are produced in this dataset, it represents a pure $e^+e^- \rightarrow (q\bar{q}, \tau^+\tau^-)$ data sample.

The simulated event categories are as follows:

- $e^+e^- \rightarrow \Upsilon(4S) \rightarrow (B^\pm \rightarrow \tau^\pm \nu_\tau)(B^\mp \rightarrow \text{generic})$ with luminosity of 324.5 ab^{-1}
- $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^+B^-$ with luminosity of 2.8 ab^{-1}
- $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\bar{B}^0$ with luminosity of 2.8 ab^{-1}
- $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, c, s$) with luminosity of 1 ab^{-1}
- $e^+e^- \rightarrow \tau^+\tau^-$ with luminosity of 0.6 ab^{-1}

Each Monte Carlo sample is normalized to the data luminosity of 365 fb^{-1} to describe the sensitivity of the Belle II experiment in the search for $B^+ \rightarrow \tau^+\nu_\tau$ decay.

4.2 Tagging method

Both simulation samples and experimental data undergo the Full Event Interpretation (FEI) [17], a multivariate hierarchical algorithm designed to fully reconstruct and "tag" one of the two B mesons in over 30 hadronic decay modes. For this reason, it is referred to as B_{tag} . The

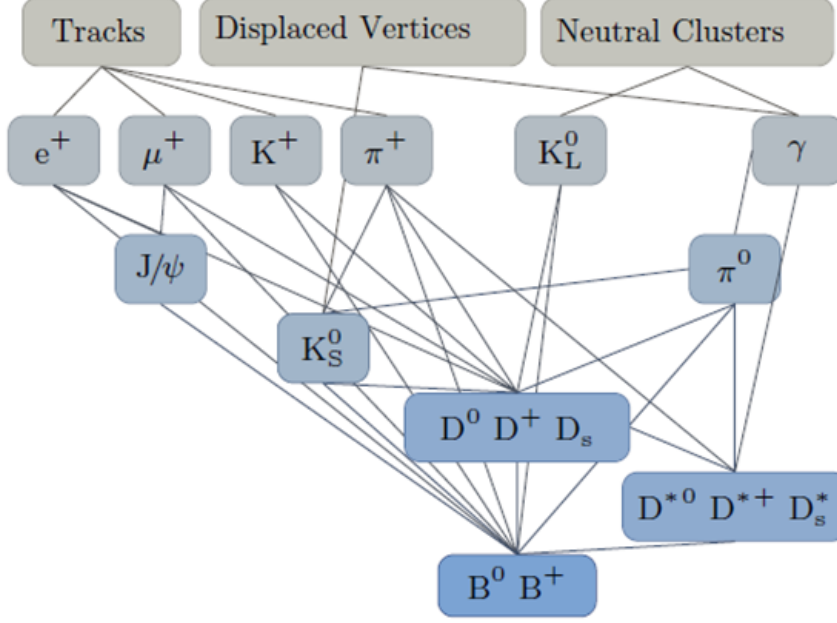


Figure 4.2: Scheme of the FEI hierarchical object reconstruction.

method is depicted in Fig. 4.2. In this analysis, a hadronic tagging approach is used, as it yields the cleanest tagged sample, with the kinematics of the reconstructed candidates being well understood.

The output of the FEI algorithm is a list of potential B_{tag} candidates, each assigned a probability ($\mathcal{O}_{FEI}$). A higher $\mathcal{O}_{FEI}$ indicates a higher purity of the candidate. We apply the following requirements: at least three tracks with $dr < 0.5$ cm, $|dz| < 2$ cm, and θ within the CDC acceptance range ($0.297 < \theta < 2.67$), a momentum $p > 100$ MeV for all charged particles, a reconstructed energy $E > 4$ GeV, and at least three ECL neutral clusters with $E > 100$ MeV and θ within the CDC acceptance range.

On average, the multiplicity of B_{tag} candidates in signal events is 1.02. One B_{tag} candidate per event is retained, specifically the one with the highest $\mathcal{O}_{FEI}$ value, and a $\mathcal{O}_{FEI}$ threshold of 0.001 is applied. The fraction of $\Upsilon(4S)$ events with a correctly reconstructed B_{tag} candidate is approximately 0.30% for B^+ , with a purity of 29%.

To distinguish between events with correctly reconstructed B_{tag} candidates and misreconstructed events, two kinematic variables are used: the beam-energy-constrained mass,

$$M_{bc} = \sqrt{(E_{beam}^*)^2/c^4 - |\vec{p}_{tag}^*|^2/c^2} \quad (4.1)$$

and the energy difference

$$\Delta E = E_{tag}^* - E_{beam}^*,$$

where $\vec{p}_{tag}^*$ (E_{tag}^*) is the reconstructed momentum (energy) of the B_{tag} and E_{beam}^* is the beam energy, all calculated in the center-of-mass (c.m.) frame. We require: $M_{bc} > 5.27$ GeV/ c^2 and $-0.15 < \Delta E < 0.1$ GeV. Since ΔE is also used as a training feature in the FEI algorithm, the non- $B\bar{B}$ background is modified, specifically forcing $e^+e^- \rightarrow (q\bar{q}, \tau^+\tau^-)$ events to peak at zero.

Events with a B_{tag} candidate can be divided into two main categories based on their M_{bc} distributions. The first category consists of signal and peaking background from $\Upsilon(4S) \rightarrow B^+B^-$ with a correctly reconstructed B_{tag} , where the M_{bc} distribution peaks around the nominal B mass. The second category includes continuum background, $e^+e^- \rightarrow q\bar{q}$ ($q =$

u, d, c, s) and $e^+e^- \rightarrow \tau^+\tau^-$, as well as combinatorial background from $\Upsilon(4S) \rightarrow B^0\bar{B}^0$ or B^+B^- where the B_{tag} is misreconstructed, and is characterized by a smooth M_{bc} distribution. Figure 4.3 illustrates the M_{bc} distribution in the MC simulation.

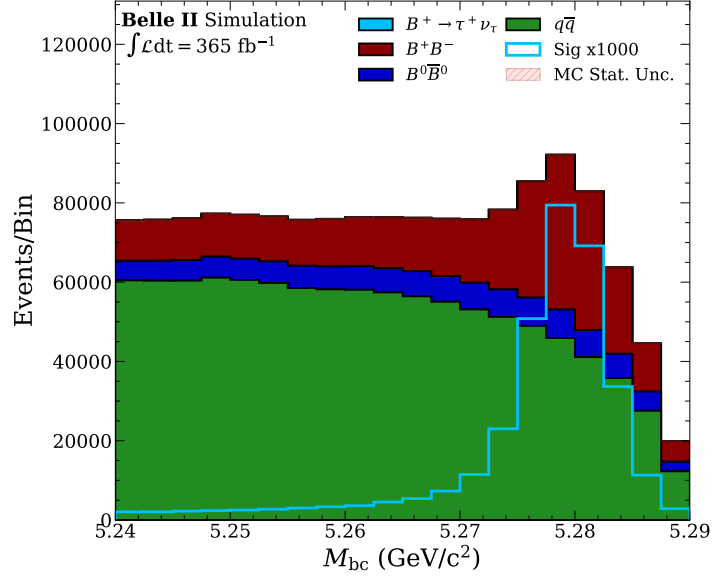


Figure 4.3: M_{bc} distribution in MC simulation.

4.3 Event pre-selection criteria

In events where a B_{tag} is reconstructed, the requirement is the presence of only one additional track with the opposite charge, consistent with the decay mode of a τ lepton, which produces one charged particle in the final state.

After all the tracks associated with the B_{tag} have been removed, we require the reconstruction of only one **good track** (that will be considered as a signal candidate) and no additional **ROE tracks**, where ROE stands for Rest of Event, what is not associated with the B_{tag} and B_{sig} . A **good track** is defined as a track satisfying $dr < 0.5$ cm, $|dz| < 2$ cm θ in the CDC acceptance ($0.297 < \theta < 2.67$), reconstructed energy $E < 5.5$ GeV and momentum $p > 0.5$ GeV. A **ROE track** is defined as a track satisfying $dr < 0.5$ cm and $|dz| < 2$ cm, and θ in CDC acceptance. (The used coordinate system is explained in Sec. 3.2)

The particle identification criteria used to differentiate between electron, muon, and pion hypotheses are based on multivariate classifiers that incorporate data from all sub-detectors, except for the PXD and SVD in the case of muon and pion hypotheses. This data is then integrated into a Boosted Decision Tree (BDT) for electrons or a likelihood function for muons and pions. The likelihood for each sub-detector is expressed as follows:

$$\frac{\mathcal{L}(particle)}{\mathcal{L}(e) + \mathcal{L}(\mu) + \mathcal{L}(\pi) + \mathcal{L}(K) + \mathcal{L}(p) + \mathcal{L}(d)} \quad (4.2)$$

Particle identification criteria are employed to select the following decay modes of the τ lepton:

- $\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$, machine learning-based
- $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$, likelihood-based
- $\tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$, likelihood-based

- $\tau \rightarrow \rho^+ \bar{\nu}_\tau$ with $\rho^+ \rightarrow \pi^+ \pi^0$, likelihood-based

The selected categories all together correspond to approximately 71.5% of all τ decays.

We divide the selected tracks as described in the following:

- If the selected track satisfies the electron PID criteria greater than 90%, it is identified as an electron and the event is assigned to the electron category.
- If the selected track satisfies the muon PID criteria greater than 90%, it is identified as a muon and the event is assigned to the muon category.
- If the selected track satisfies the pion PID criteria greater than 60%, it is identified as a pion and it can be included in the $\tau \rightarrow \pi \nu$ or $\tau \rightarrow \rho \nu$ channel.

These PID selection criteria are designed to differentiate electrons, muons, and pions with efficiencies of 99%, 82%, and 97%, respectively, while maintaining misidentification rates of 1%, 5%, and 3%. For the specific $\pi^+ \pi^0 \bar{\nu}_\tau$ decay mode, one π^0 candidate is reconstructed, and the invariant mass of the $\pi^+ \pi^0$ system is required to lie within the range $625 < m_{\pi^+ \pi^0} < 925$ MeV. If multiple candidates satisfy this condition, the one with the invariant mass closest to the ρ^+ mass is selected. For the remaining π^0 candidates, two ECL neutral clusters not used in the reconstruction of the B_{tag} candidate are paired, and photon quality criteria are applied. Additionally, an invariant mass cut is imposed on the $\gamma\gamma$ pair, requiring $120 < m_{\gamma\gamma} < 145$ MeV.

The ECL neutral clusters not associated with the B_{tag} are also subject to a clean-up aiming at rejecting fake clusters from the beam-induced background, charged hadrons that fail the matching to tracks, and neutral hadrons, using the output of two different multivariate algorithms, trained in the $B^0 \rightarrow D^* \ell \nu$ control sample, called **beamBackgroundSuppression** and **fakePhotonSuppression**. The requests for all the ECL neutral clusters are the number of cluster hits in ECL, $N_{hit,ECL} > 1.5$, θ in the CDC acceptance ($0.297 < \theta < 2.67$), cluster energy $E_\gamma > 55$ MeV.

All the criteria defining the signal preselection are summarized in Table 4.1.

Table 4.1: Pre-selection criteria and ECL cluster clean-up

Particles	Selections
good track	$dr < 0.5$ cm, $ dz < 2$ cm, $p > 0.5$ GeV, $E < 5.5$ GeV
e^+	good track, eID criteria > 0.9
μ^+	good track, μID criteria > 0.9
π^+	good track, πID criteria > 0.6
π^0	$120 < m_{\gamma\gamma} < 145$ MeV
ρ^+	$625 < m_{\pi^+ \pi^0} < 925$ MeV
γ (from π^0)	$N_{hit,ECL} > 1.5$, θ in the CDC acceptance $E_\gamma > 80$ MeV ($0.8536 < \cos \theta < 0.9563$) $E_\gamma > 30$ MeV ($-0.6252 < \cos \theta < 0.8462$) $E_\gamma > 60$ MeV ($-0.8660 < \cos \theta < -0.6521$)
ROE tracks (=0)	$dr < 0.5$ cm, $ dz < 2$ cm, θ in CDC acceptance
ROE γ	$E > 55$ MeV and $N_{hit,ECL} > 1.5$ beamBackgroundSuppression > 0.5 fakePhotonSuppression > 0.05

4.4 Cut-based continuum rejection

Event shape variables, i.e. the variables related to the momentum-weighted distribution of all particles in the detector, are crucial in discriminating between the continuum and $B\bar{B}$ components. The continuum events present a peculiar back-to-back production, the $B\bar{B}$ ones instead present a spherical symmetry, as shown in Fig. 4.4.

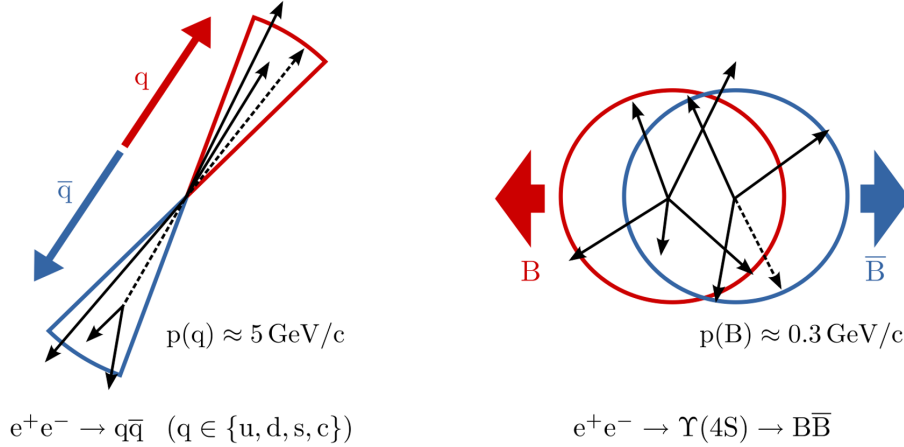


Figure 4.4: The momentum-weighted distribution of all particles in the detector for the continuum and $B\bar{B}$ components

To suppress the continuum background, we first apply loose cuts on the following observables: $\cos\theta_T$ and the ratio of Fox-Wolfram polynomials R_2 . The first variable, $\cos\theta_T$, is the cosine of the angle between the thrust axis of the B_{tag} and its recoil, where the thrust axis is the axis that maximizes the sum of the projected momenta of a collection of particles in the event. This variable is powerful because $B\bar{B}$ events have approximately uniform distribution while continuum events peak at 1. We require $|\cos\theta_T| < 0.9$. The second variable, R_2 , is a measure of the degree of sphericity of the event with lower values for $B\bar{B}$ events and higher values for continuum events. We applied a loose cut of $R_2 < 0.6$.

After applying this cut-based continuum suppression, we find that 99% of the $\tau^+\tau^-$ component is removed. Table 4.2 shows the signal and background cut flow starting from the events passing the preselection.

Table 4.2: Efficiency breakdown of the cut-based continuum rejection; in pre-selection we report the events satisfying pre-selection criteria in Table 4.1

Selections	$B \rightarrow \tau\nu$	$q\bar{q}$	$\tau\tau$
preselection	100%	100%	100%
$ \cos\theta_T < 0.9$	86%	40%	17%
$R_2 < 0.6$	73%	34%	1%

Figure 4.5 shows the distributions of these observables in off-resonance data and MC simulation scaled to the off-resonance luminosity. As it is clear, the continuum simulations do not model correctly experimental data: in the next section, Sec. 4.5, we will present how we treat this simulation's mis-modeling.

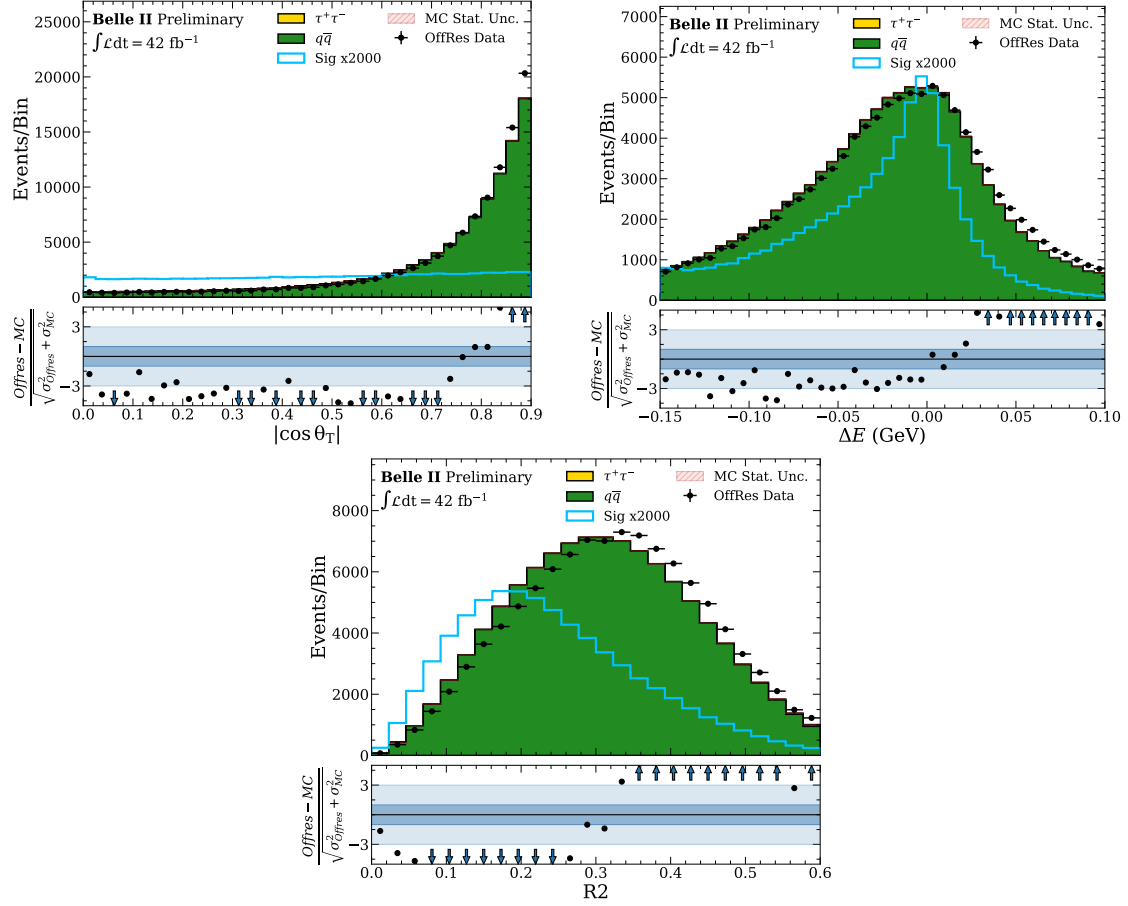


Figure 4.5: Distributions of $|\cos \theta_T|$, ΔE and R_2 for continuum MC and off-resonance data, after the cut-based continuum rejection requirements. Signal MC is also shown for comparison, scaled by a factor of 2000 to make it visible.

4.5 Continuum background modeling

Continuum events make a significant part of the background, especially for hadronic τ decay modes. After the cut-based continuum rejection of Sec. 4.4 the remaining amount of background is still significant. Therefore, it is important to have a robust estimation of the fractions and the shapes of the most important observables, like the ones used in the final fit to extract signal yields.

Ideally, we could use the off-resonance data to model any distribution after applying the final selection. Since Belle II takes 10% of the data off-resonance, the low statistics are sufficient to estimate the expected total yield of this background but it prevents having a good estimation of the shapes of the distributions. The alternative is to use MC simulations for which we have high statistics samples available. Belle II MC simulations of continuum events do not model correctly experimental data in both the total yield and shapes of many observables. Table 4.3 shows the ratio of off-resonance data and MC simulations yields after the continuum rejection requirements described in Sec. 4.4.

Table 4.3: Continuum MC simulations to Off-resonance data scaling factors

Mode	Scale Factor
$e^+\nu_e\bar{\nu}_\tau$	0.94 ± 0.03
$\mu^+\nu_\mu\bar{\nu}_\tau$	0.95 ± 0.02
$\pi^+\bar{\nu}_\tau$	0.92 ± 0.02
$\rho^+\bar{\nu}_\tau$	0.724 ± 0.008

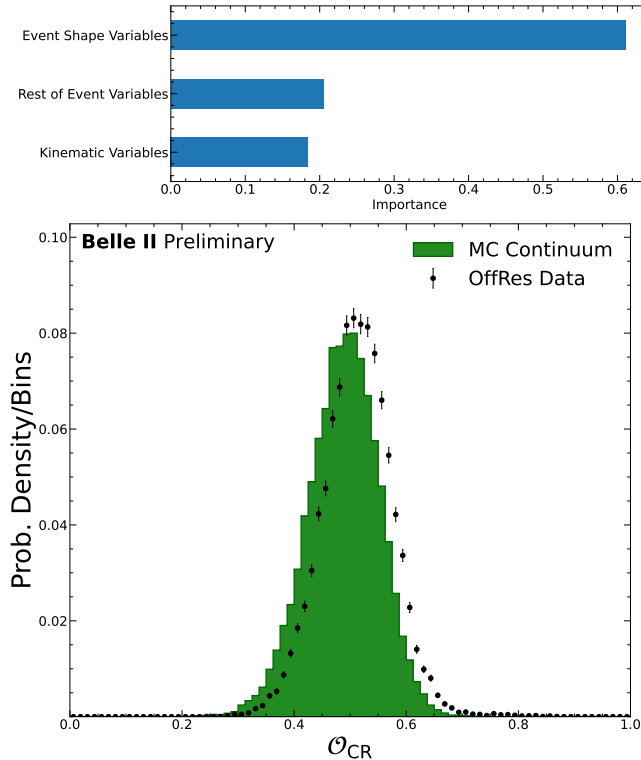


Figure 4.6: Continuum Reweight FBDT performance plots: variable importance, the greater the importance the greater the mismodeling (top plot). Train-Test comparison (bottom plot).

Therefore we use off-resonance data scaled by on-resonance/off-resonance luminosity ratio to estimate the total continuum yield in the on-resonance data. To exploit its higher statistics

we use continuum simulations to describe the shapes of the expected continuum components in on-resonance data.

To improve the MC simulations and data agreement, we reweight the MC simulations events by exploiting a multivariate analysis aiming at identifying and correcting the data-MC simulations discrepancies following the method in [18]. The Fast Boosted Decision Tree (FBDT) classifier [19] is used for this continuum reweighting. We use 200 fb⁻¹ equivalent continuum MC simulated events and the entire off-resonance data for the calibration of the FBDT.

The hyperparameters ($N_{trees} = 200$, $depth = 2$, $shrinkage = 0.1$) are optimized to minimize the training-test Area Under the Curve (AUC) difference. The variables used for training are event shape-related, ROE-related, and kinematic quantities. We do not include the variables that are used to extract the $\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau)$ in the training process. Since off-resonance data is taken 60 MeV under the $\Upsilon(4S)$ mass peak, it is necessary to reweight the energy to the on-resonance one; in particular, we reweight M_{bc} and ΔE as for Eq. 4.3 and 4.4.

$$M_{bc} = \sqrt{\frac{E_{on}^2}{4} - \frac{E_{on}^2}{E_{off}^2} p_B^{*2}} \quad (4.3)$$

$$\Delta E = \frac{E_{on}}{E_{off}} E_B^* - \frac{E_{on}}{2} \quad (4.4)$$

We describe here the general idea of the reweighting procedure we adopted. We train a classifier using off-resonance data as *signal* and continuum MC as *background*: if the off-resonance data and continuum MC simulations had the same shape, the output of the classifier for both the samples would be the same; otherwise, the classifier would reveal the differences. Fig. 4.6 shows the FBDT output distributions and variables' importance. It is possible to reweight the continuum MC simulations to the shape of the off-resonance data, defining the weight w_{CR} for event x to be as Eq. 4.5

$$w_{CR}(x) = \frac{\mathcal{O}_{CR}(x)}{1 - \mathcal{O}_{CR}(x)}, \quad (4.5)$$

where $\mathcal{O}_{CR}(x)$ is the output of the classifier for event x . It is possible to use Eq. 4.5 as weights if $\mathcal{O}_{CR}$ approximates a probability. In Fig. 4.7 we show $\mathcal{O}_{CR}$ vs D/(D+M) linearity comparison, where D indicates off-resonance data and M continuum simulations. Since it presents an approximate linearity, the definition in 4.5 is correct.

Figure 4.8 shows a comparison between the off-resonance data and continuum MC before and after the reweighting normalized to the same total yield.

4.6 Continuum Suppression

To further suppress continuum events, we train a second FBDT classifier, with continuum MC simulations treated as *signal* and $B\bar{B}$ MC simulations as *background*. Only variables with satisfying data-MC agreement after the continuum reweighting are added to the continuum suppression classifier. We note that the FBDT tool can manage weighted events.

Since leptons and hadrons channels show different data-MC agreements for different event shape variables, we train separately leptons and hadrons, obtaining two different outputs, $\mathcal{O}_{CS}(\text{lep})$ and $\mathcal{O}_{CS}(\text{had})$.

The hyperparameters for both the FBDT are the same ($N_{trees} = 300$, $depth = 2$, $shrinkage = 0.1$), and are optimized to obtain the best ROC Curve (largest AUC and acceptable test-training agreement). FBDTs output and ROC Curves are shown in Figure 4.9 for leptonic modes and Figure 4.10 for hadronic modes.

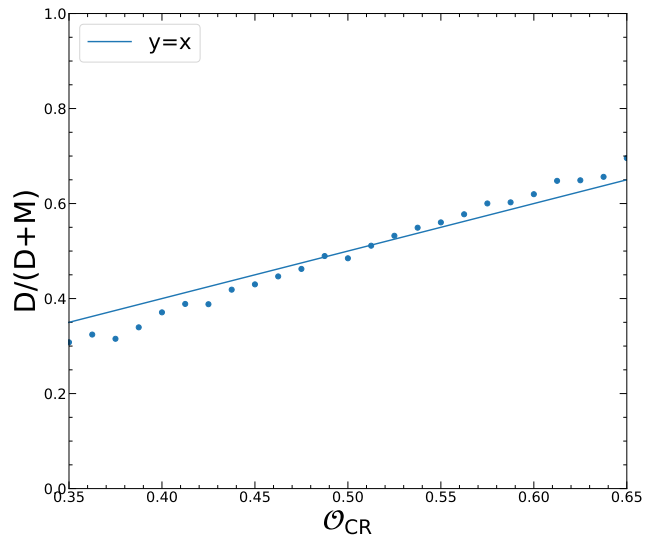


Figure 4.7: $\mathcal{O}_{\text{CR}}(x)$ vs $D/(D+M)$ linearity comparison, where D indicates off-resonance data and M continuum simulations.

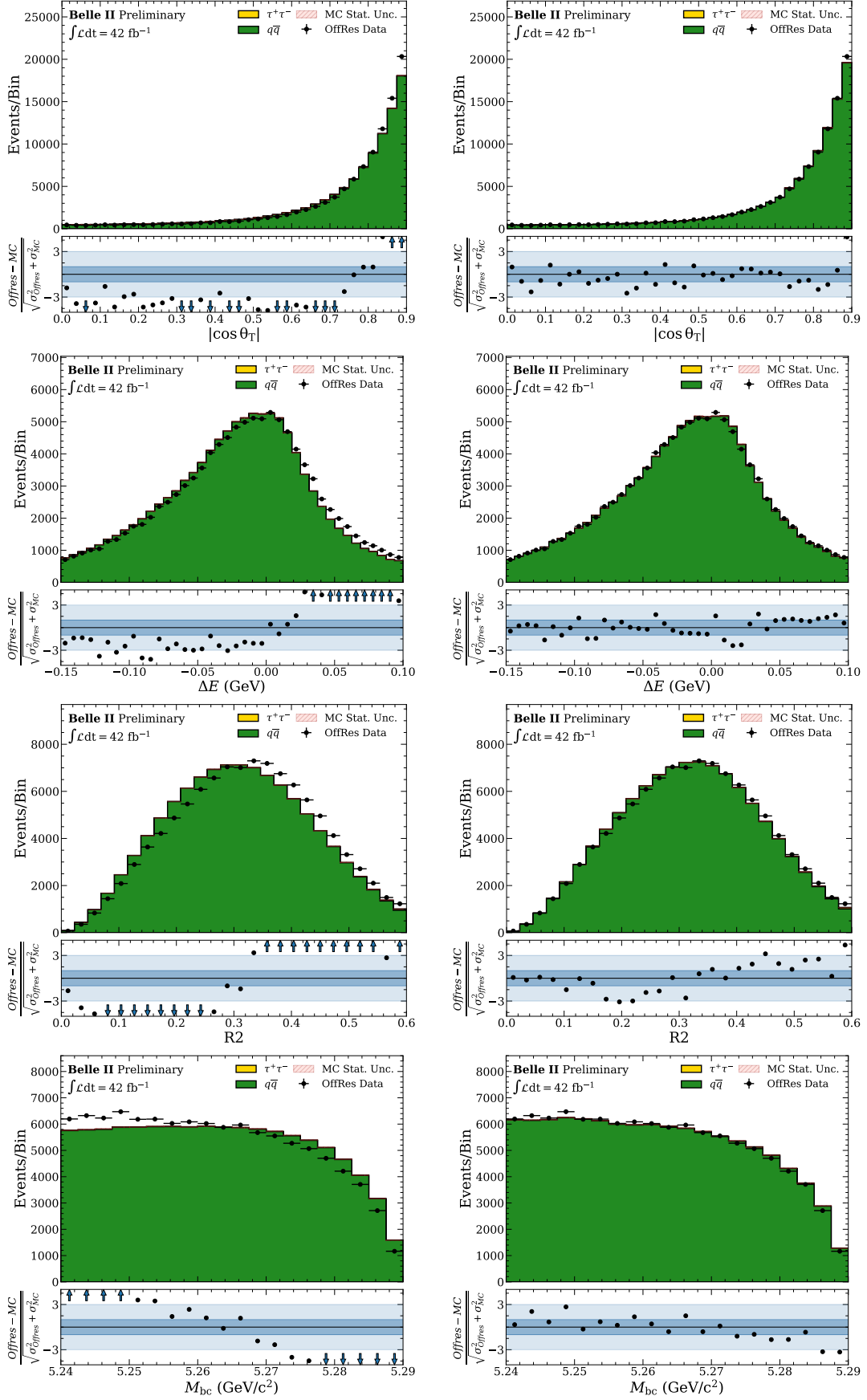


Figure 4.8: Off-resonance data vs continuum MC agreement before (left) and after (right) the reweighting for the most mis-modeled quantities.

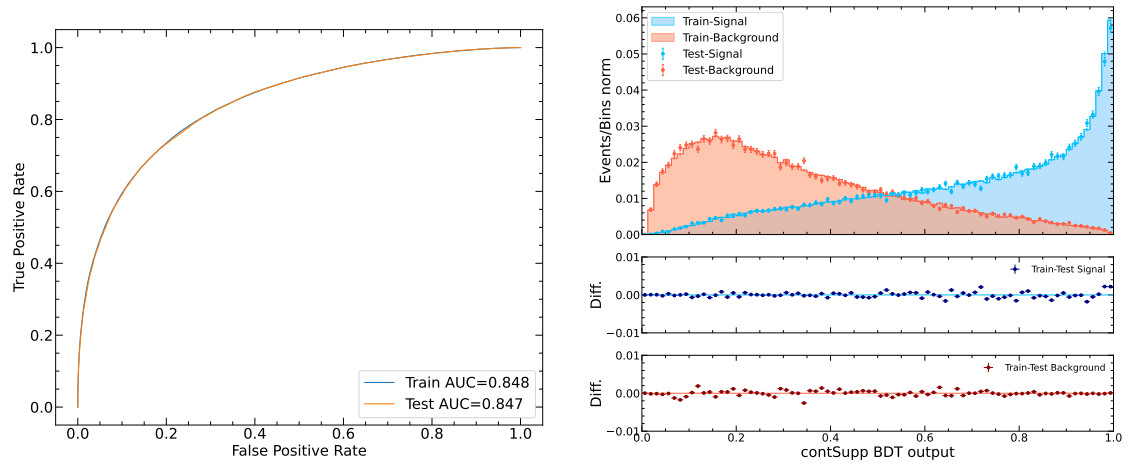


Figure 4.9: Continuum Suppression FBDT(lep) performance plots: on top the ROC curve, and on the bottom the over-training plot

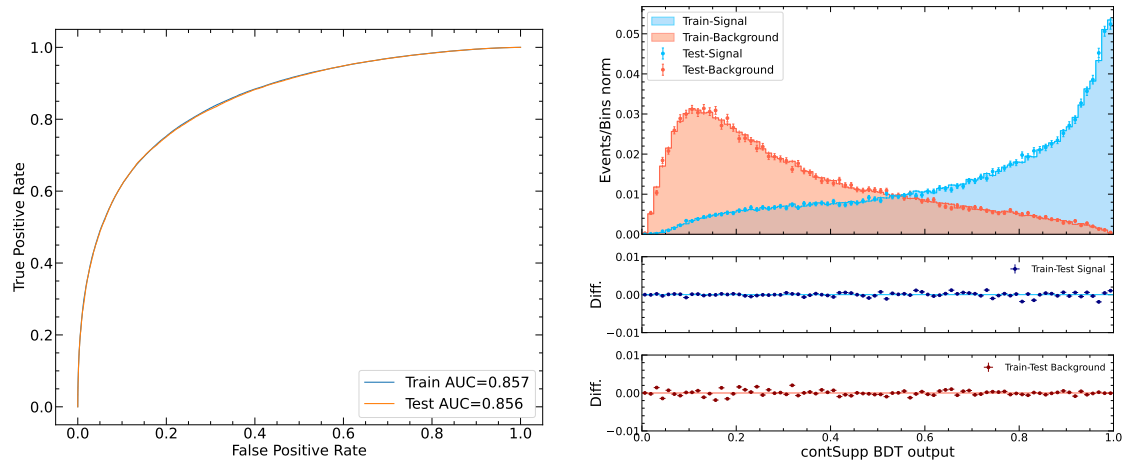


Figure 4.10: Continuum Suppression FBDT(had) performance plots: on top the ROC curve, and on the bottom the over-training plot

Chapter 5

Signal selection optimization

To optimize the signal selection optimization, we extract four signal yields, one for each τ decay channel. All the cleaned-up clusters from ECL are considered to form two discriminating observables: the total residual energy in the ECL ($E_{\text{ECL}}^{\text{extra}}$), and the squared missing four-momentum (M_{miss}^2) calculated using the known beam energies and all the visible reconstructed objects, including cleaned-up ECL energy clusters, and the tracks not coming from the IP:

$$p_{\text{miss}}^* = (2E_{\text{beam}}^*, 0, 0, 0) - p_{\text{tag}}^* - p_{\text{sig}}^* - p_{\text{ROE}}^* \quad (5.1)$$

where p_{tag}^* , p_{sig}^* , p_{ROE}^* are respectively the B_{tag} , the signal candidate, and the ROE objects four-momenta in the center of mass frame. For signal, $E_{\text{ECL}}^{\text{extra}}$ should be zero or a small value caused by beam background hits or imperfections in reconstruction, as neutrinos do not interact in the ECL. On the other hand, background events tend to have higher $E_{\text{ECL}}^{\text{extra}}$ values, due to additional clusters arising from unassigned tracks and misreconstructed neutral clusters from either the B_{tag} or B_{sig} . We then fix and apply a cut $E_{\text{ECL}}^{\text{extra}} < 1$ GeV. Leptonic τ decay channels in the signal are characterized by a high M_{miss}^2 while hadronic decay channels typically have a lower value. This variable is particularly useful for managing combinatorial backgrounds in leptonic decays and for controlling continuum backgrounds in hadronic decays. These variables are shown in Figure 5.1 and 5.2 for each τ decay channel, after the cut-based event selection as explained in Chapter 4. We use $E_{\text{ECL}}^{\text{extra}}$ and M_{miss}^2 to extract the signal yields, and so the $\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau)$ through a 2D maximum likelihood fit to its data distribution. Other variables are also exploited to enhance the signal to the background.

We exploit the output of the FEI discriminant $\mathcal{O}_{\text{FEI}}$, the continuum suppression output $\mathcal{O}_{\text{CS}}$, the momentum of the reconstructed daughter of the τ^+ (e^+ , μ^+ , π^+ , and ρ^+) in the laboratory frame P_{cand} . These variables are shown in Figures 5.3- 5.6, after the cut-based event selection.

$\mathcal{O}_{\text{CS}}$ provides discrimination against continuum, especially needed for hadronic τ decay modes. A tighter requirement on $\mathcal{O}_{\text{FEI}}$ reduces the signal abundance but improves the purity. An additional requirement on P_{cand} is effective especially on hadronic modes, being produced in a sequence of two-body decays.

We optimize the selection requirements for these variables, scanning various configurations of cut values for the smallest expected statistical uncertainty estimated by fitting the signal on Toy MC pseudo-experiments.

We determine the branching fraction $\mathcal{B}$ by performing a simultaneous maximum likelihood fit across all four τ^+ categories. The probability density functions (PDFs) are 2D histograms of M_{miss}^2 and $E_{\text{ECL}}^{\text{extra}}$, with a uniform binning of 10×10 , spanning the ranges $-10 < M_{\text{miss}}^2 < 26 \text{ GeV}^2/c^4$ and $0 \leq E_{\text{ECL}}^{\text{extra}} < 1 \text{ GeV}$. Five parameters are left free in the fit: the common branching fraction $\mathcal{B}$ and the total background yield for each of the four decay modes, $n_{b,k}$, where $k = e^+, \mu^+, \pi^+$ or ρ^+ . The signal yields, $n_{s,k}$, depend on the common floating fit

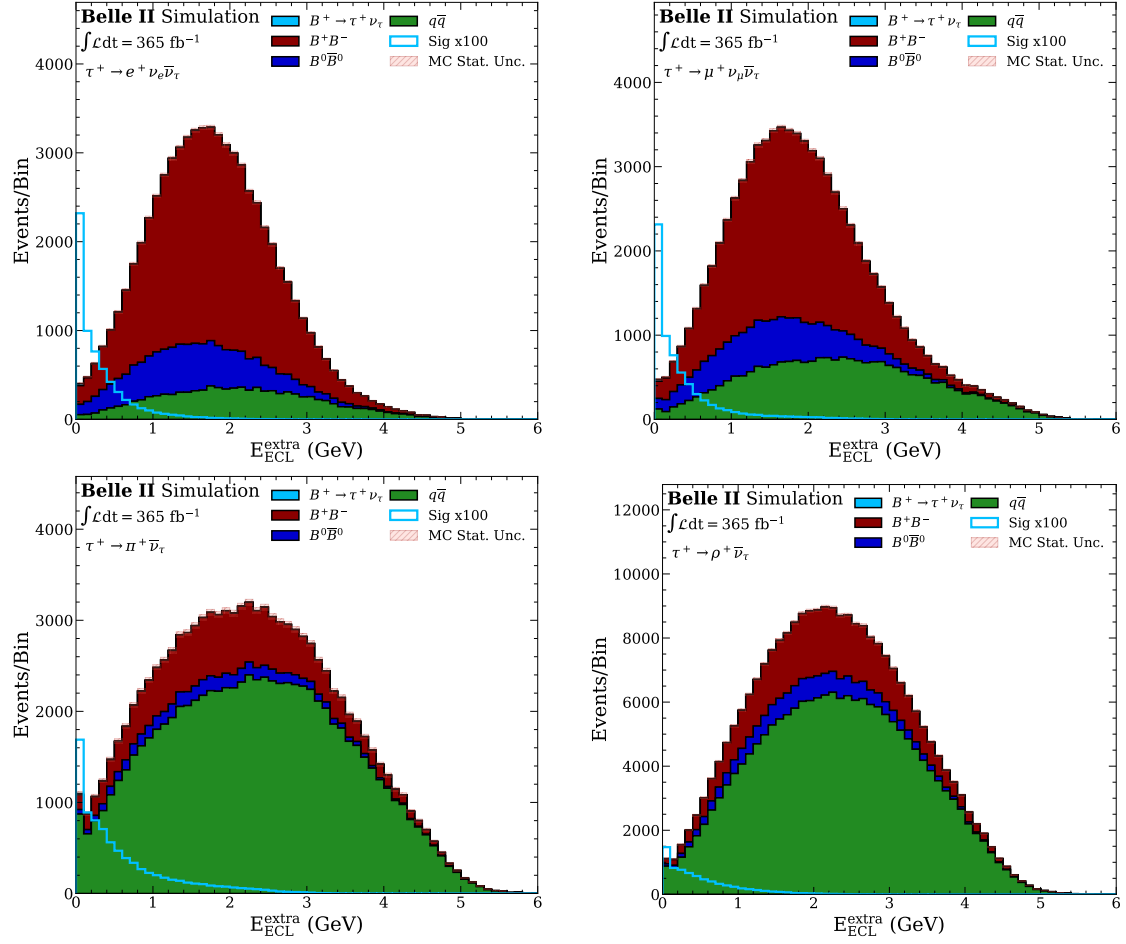


Figure 5.1: Distribution of $E_{\text{ECL}}^{\text{extra}}$ in simulation for the four τ decay modes after the cut-based event selection. Continuum MC has been re-weighted and normalized to off-resonance data. Signal MC is also scaled by a factor of 100 to make it visible.

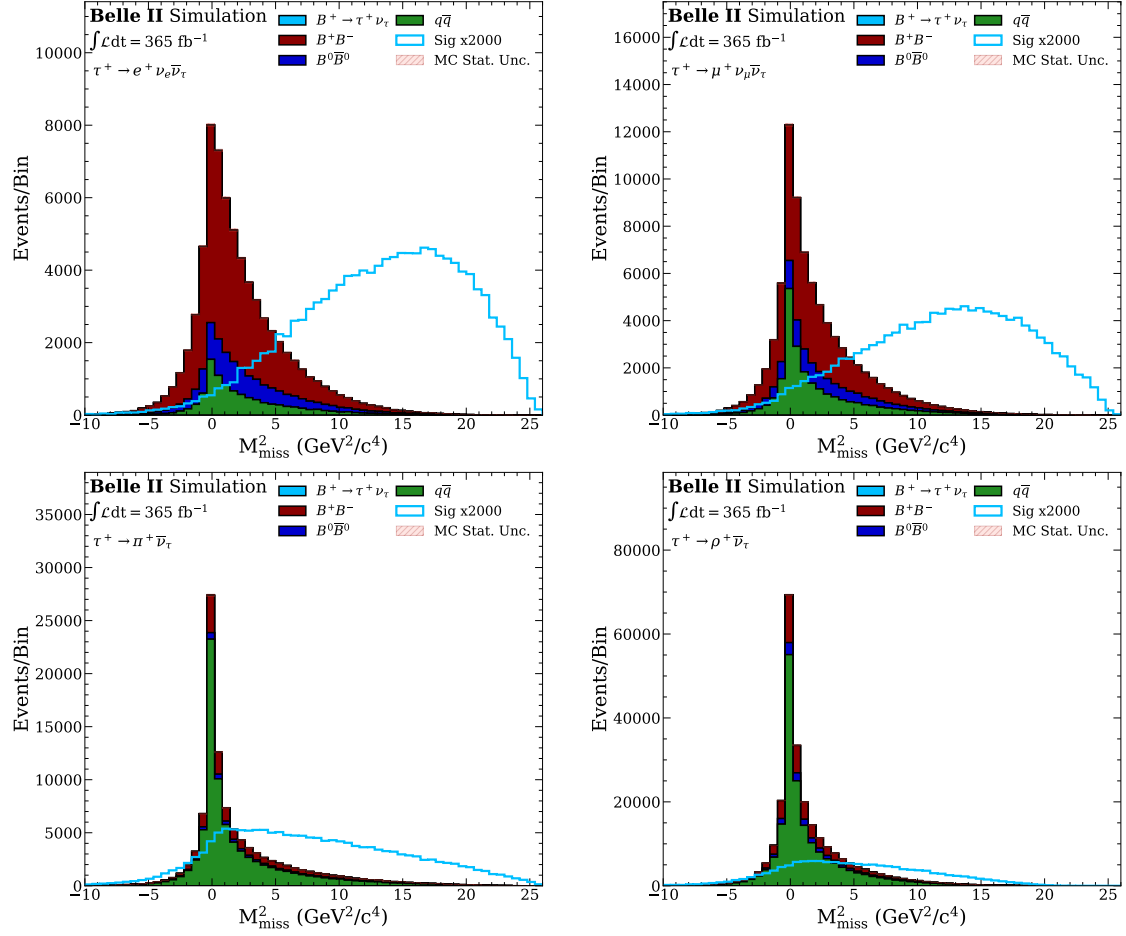


Figure 5.2: Distribution of M^2_{miss} in simulation for the four τ decay modes after the cut-based event selection. Continuum MC has been re-weighted and normalized to off-resonance data. Signal MC is also scaled by a factor of 100 to make it visible.

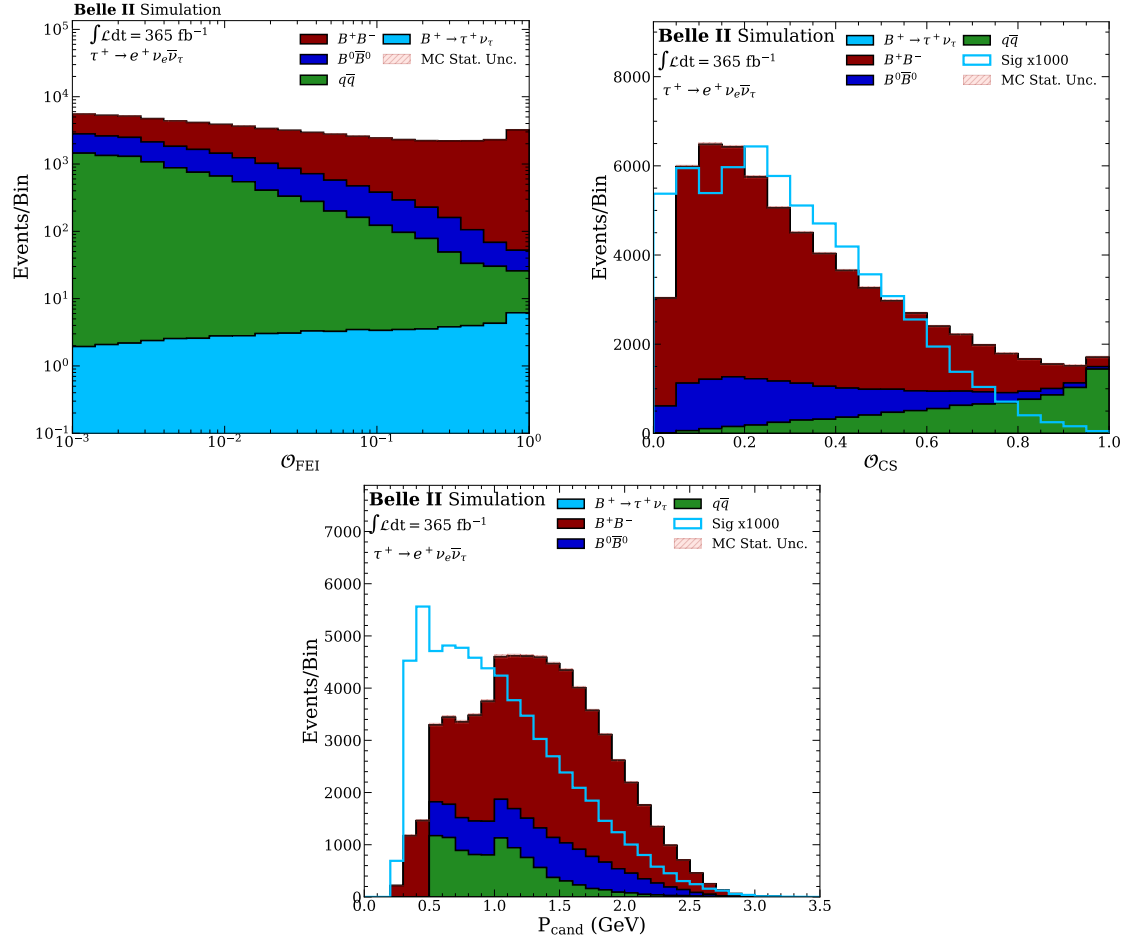


Figure 5.3: MC distributions of the selection variables for the electron mode, after the cut-based event selection.

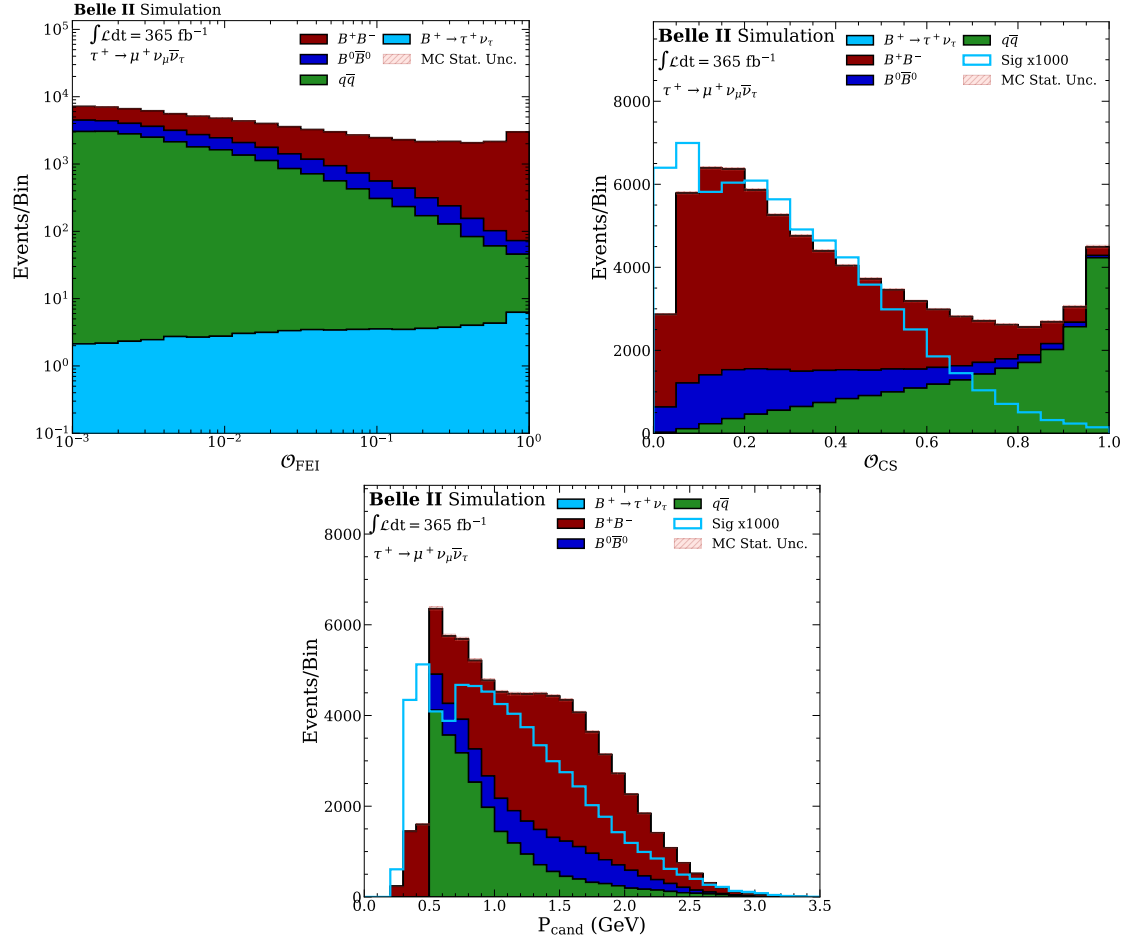


Figure 5.4: MC distributions of the selection variables for the muon mode, after the cut-based event selection.

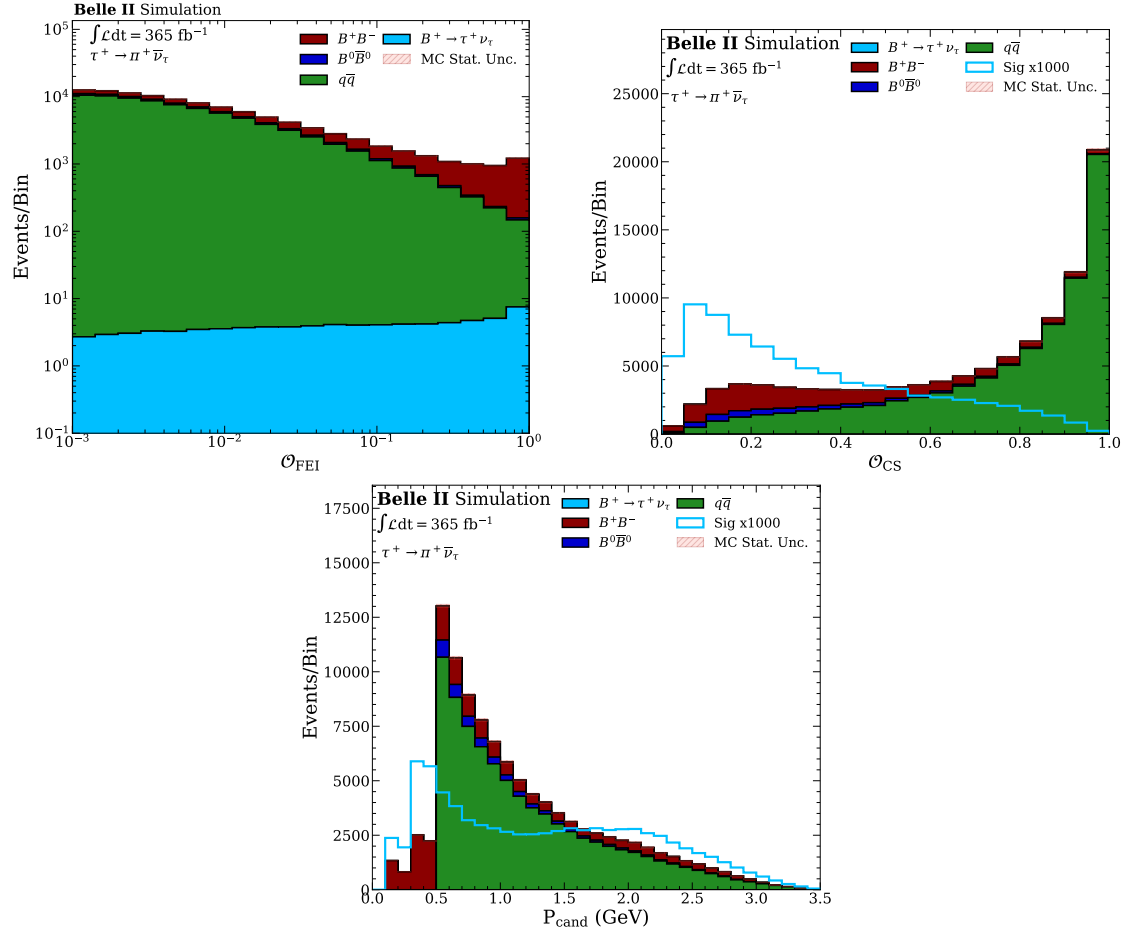


Figure 5.5: MC distributions of the selection variables for the pion mode, after the cut-based event selection.

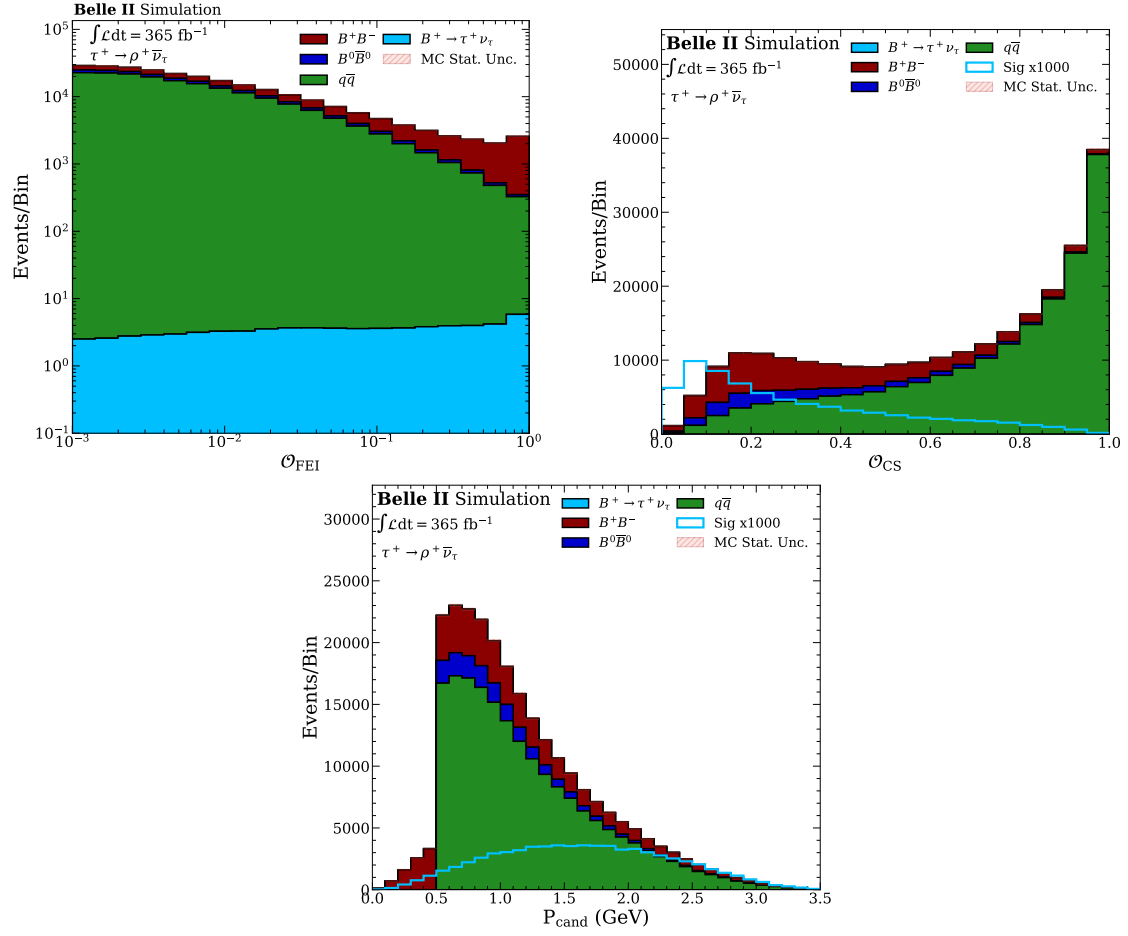


Figure 5.6: MC distributions of the selection variables for the rho mode, after the cut-based event selection.

parameter $\mathcal{B}$ and fixed quantities, and are given by:

$$n_{s,k} = 2n_{B^+B^-} \varepsilon_k \mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau) \quad (5.2)$$

where $n_{B^+B^-} = n_{\Upsilon(4S)} f^{+-}$, with $f^{+-} = 0.5113_{-0.0108}^{+0.0073}$ being the branching fraction $\mathcal{B}(\Upsilon(4S) \rightarrow B^+ B^-)$ as estimated in [3]. Here, ε_k represents the efficiency of reconstructing a $B^+ \rightarrow \tau^+ \nu_\tau$ decay in category k (for any type of real τ decay). The efficiencies ε_k , which are estimated through simulations and corrected for MC mis-modeling, are presented in Tab. 5.1. These efficiencies account for the τ^+ branching fractions and cross-feed, as predicted by the simulation. The composition of each reconstructed τ decay, in terms of its decay mode, is shown in Tab. 5.2, which also highlights the relevant contributions from cross-feed.

Performing a grid scan of the selection requirements on all the considered variables, we estimate the expected uncertainty of each choice, repeating a full Toy MC study for each τ category independently. Specifically, for each configuration of cuts, we extract 10000 pseudo-datasets from the $E_{\text{ECL}}^{\text{extra}}$ and M_{miss}^2 distributions obtained by the MC simulation, and for each pseudo-dataset, we determine the signal yield. In the fit, the signal and background probability density functions (PDFs) are fixed to the ones given by the MC and the signal yield n_s and the background yield n_b are parameters allowed to float. The relative uncertainty expected for a particular configuration of cuts for each τ decay channel is estimated as $\langle \sigma_{n_{s,k}} \rangle / \langle n_{s,k} \rangle$. The calibrations explained in Chapter 6 are also applied.

The optimized quantities are $\mathcal{O}_{\text{FEI}}$, $\mathcal{O}_{\text{CS}}$, and P_{cand} , and the configurations that provide the smallest uncertainties are summarized in Tab. 5.1. Figures 5.7 - 5.10 show the MC distributions of the selection variables after the optimized selection is applied.

Table 5.1: Signal selection after optimization. ϵ is the efficiency of a $B^+ \rightarrow \tau^+ \nu_\tau$ event to be reconstructed in each signal category.

mode	PID	M_{bc} (GeV)	$\mathcal{O}_{\text{FEI}}$	$\mathcal{O}_{\text{CS}}$	P_{cand} (GeV)	ϵ (10^{-4})
e	> 0.9	> 5.27	> 0.01	< 0.8	> 0.5	7.3
μ				< 0.6		7.6
π	> 0.6			< 0.6	> 1.4	3.4
ρ				< 0.7	> 1.65	3.1

Table 5.2: Composition of each reconstructed τ decay from $B^+ \rightarrow \tau^+ \nu_\tau$ in terms of decay mode. The row denotes the reconstructed final state, and the columns represent the generated decay mode. The off-diagonal entries reflect the amount of cross-feed between channels.

Reco \ True	e^+ (%)	μ^+ (%)	π^+ (%)	ρ^+ (%)	other(%)
e^+	97	0.1	0.1	0	2.8
μ^+	0	87	0.9	0.1	12
π^+	0.1	3.3	55.7	16	24.9
ρ^+	0.4	4.5	27.8	61.2	6.1

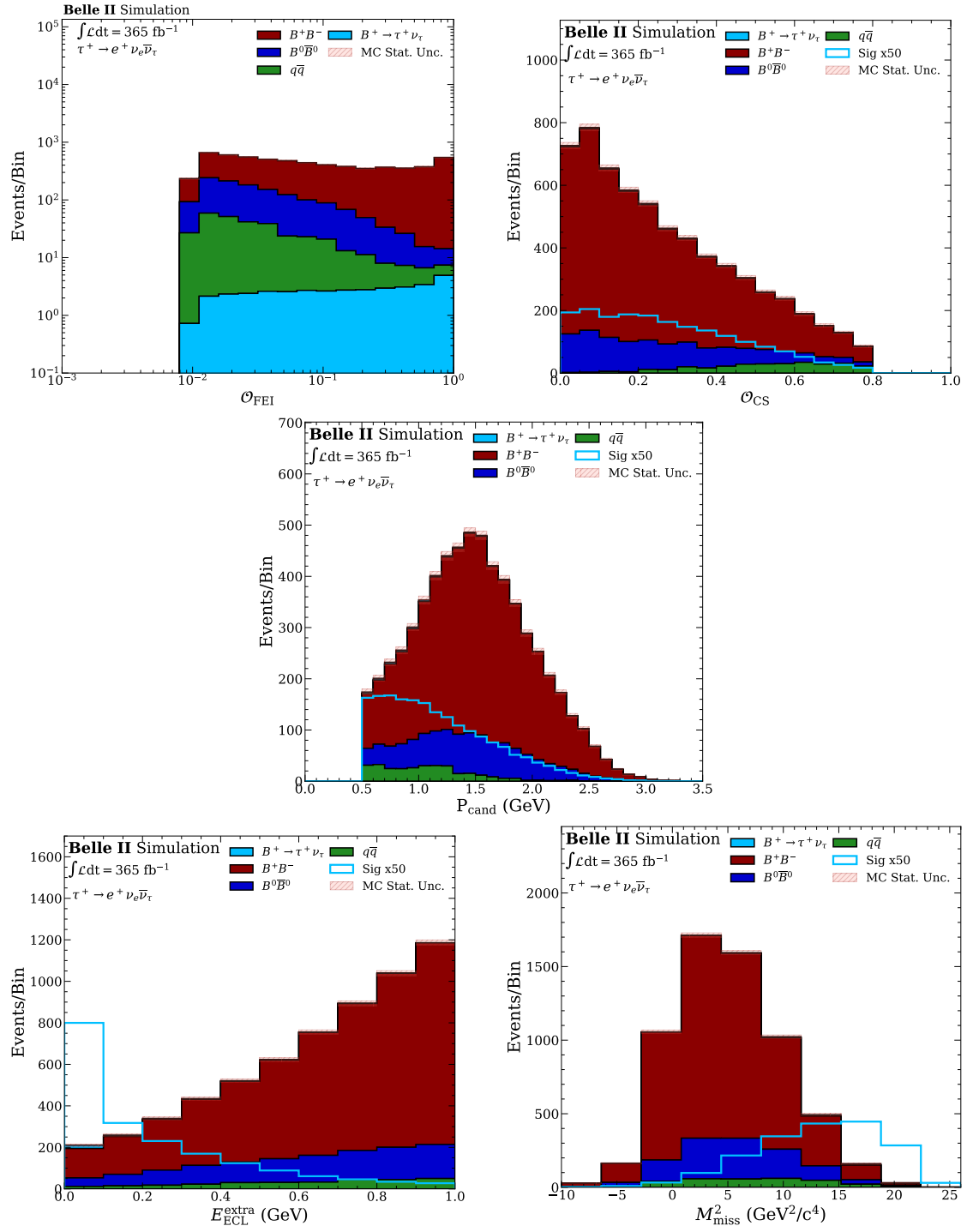


Figure 5.7: MC simulations of the selection and fit variables for the electrons with the optimal selection applied.

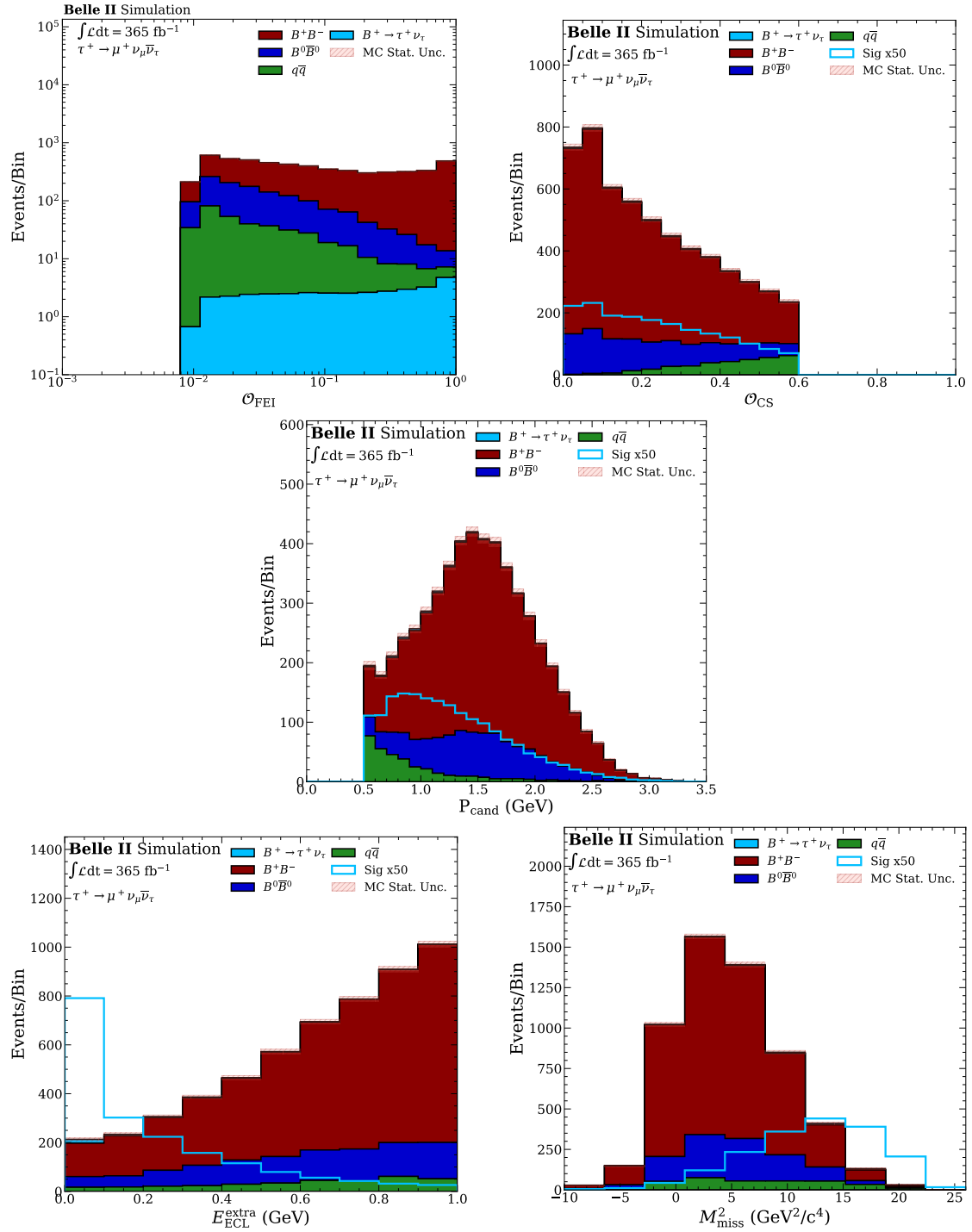


Figure 5.8: MC simulations of the selection and fit variables for the muons with the optimal selection applied.

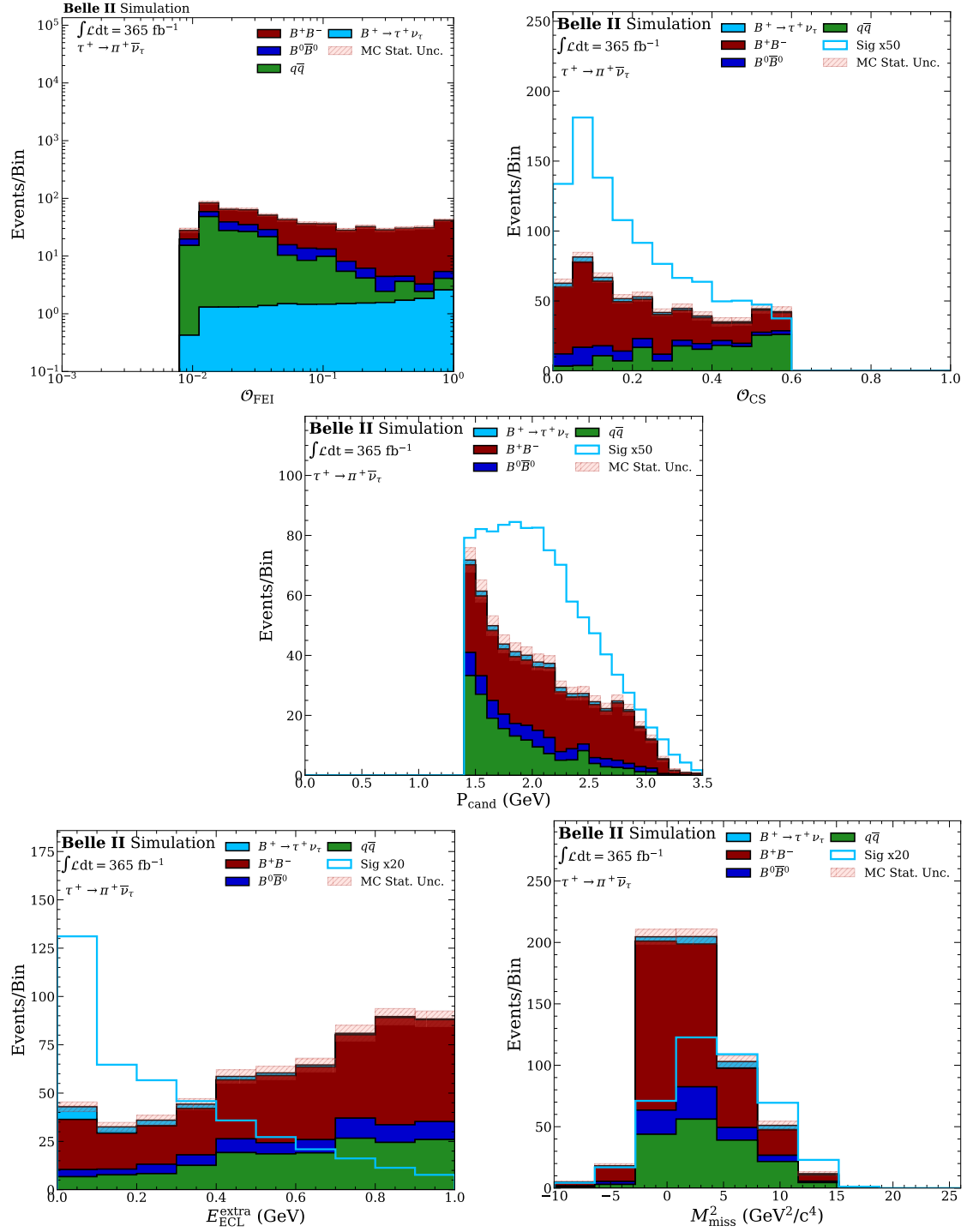


Figure 5.9: MC simulations of the selection and fit variables for the pions with the optimal selection applied.

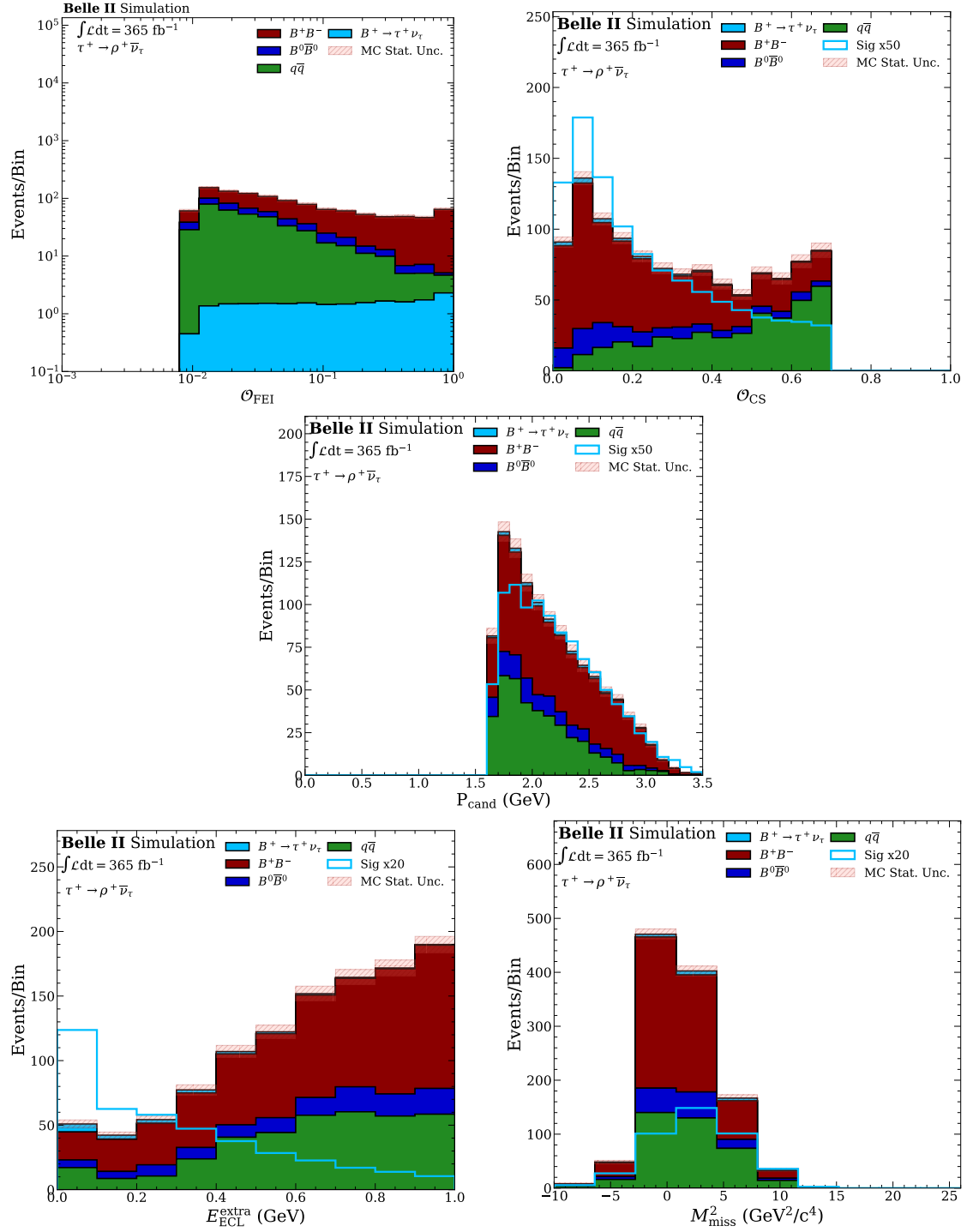


Figure 5.10: MC simulations of the selection and fit variables for the rho with the optimal selection applied.

Chapter 6

Simulations calibration

This chapter summarizes the calibration for MC simulations. The calibration procedures adopt both correction factors officially provided by the Belle II collaboration and self-developed correction factors specifically for this analysis.

6.1 FEI reconstruction efficiency correction

The FEI algorithm is a fundamental tool in this analysis, since, by identifying and removing the decay products of the companion B_{tag} , we can isolate the experimental signatures of the $B^+ \rightarrow \tau^+ \nu_\tau$ decay. However, MC simulations do not correctly model reconstruction efficiencies in many of the B_{tag} decay modes, at least at the current level of developments in Belle II. The B_{tag} reconstruction efficiency ϵ_{tag} is a factor of the $B^+ \rightarrow \tau^+ \nu_\tau$ selection efficiency $\epsilon_{B^+ \rightarrow \tau^+ \nu_\tau}$. At first order, we may consider $\epsilon_{B^+ \rightarrow \tau^+ \nu_\tau} = \epsilon_{tag} \times \epsilon_{signal-side}$, so a mis-modeling $\Delta\epsilon$ would induce the same relative error in the branching ratio estimation from the measured signal yield. For this reason, the FEI reconstruction needs to be calibrated on data control samples. This calibration is performed on $B \rightarrow X \ell \nu$ and $B \rightarrow D^{(*)} \pi$ control samples for $M_{bc} > 5.27$ GeV, so we also apply this cut and fix it in our analysis. The effects of this correction can be seen in Fig. 6.1.

Here is the list of reconstructed channels and corresponding decay mode IDs:

1. $B_{had}^+ \rightarrow \bar{D}^0 \pi^+$	13. $B_{had}^+ \rightarrow \bar{D}^0 D^{0*} K^+$	25. $B_{had}^+ \rightarrow D^- \pi^+ \pi^+ \pi^0$
2. $B_{had}^+ \rightarrow \bar{D}^0 \pi^+ \pi^0$	14. $B_{had}^+ \rightarrow \bar{D}^{0*} D^{0*} K^+$	26. $B_{had}^+ \rightarrow J/\psi K^+$
3. $B_{had}^+ \rightarrow \bar{D}^0 \pi^+ \pi^0 \pi^0$	15. $B_{had}^+ \rightarrow D_s^+ \bar{D}^0$	27. $B_{had}^+ \rightarrow J/\psi K^+ \pi^+ \pi^-$
4. $B_{had}^+ \rightarrow \bar{D}^0 \pi^+ \pi^+ \pi^-$	16. $B_{had}^+ \rightarrow \bar{D}^{0*} \pi^+$	28. $B_{had}^+ \rightarrow J/\psi K^+ \pi^0$
5. $B_{had}^+ \rightarrow \bar{D}^0 D^+$	17. $B_{had}^+ \rightarrow \bar{D}^{0*} \pi^+ \pi^0$	29. $B_{had}^+ \rightarrow J/\psi K_S^0 \pi^+$
6. $B_{had}^+ \rightarrow \bar{D}^0 D^+$	18. $B_{had}^+ \rightarrow \bar{D}^{0*} \pi^+ \pi^0 \pi^0$	30. $B_{had}^+ \rightarrow \Lambda_c^- p \pi^+ \pi^0$
7. $B_{had}^+ \rightarrow \bar{D}^0 D^+ K_S^0$	19. $B_{had}^+ \rightarrow \bar{D}^{0*} \pi^+ \pi^+ \pi^-$	31. $B_{had}^+ \rightarrow \Lambda_c^- p \pi^+ \pi^- \pi^+$
8. $B_{had}^+ \rightarrow \bar{D}^{0*} D^+ K_S^0$	20. $B_{had}^+ \rightarrow \bar{D}^{0*} \pi^+ \pi^+ \pi^- \pi^0$	32. $B_{had}^+ \rightarrow \bar{D}^0 p \bar{p} \pi^+$
9. $B_{had}^+ \rightarrow \bar{D}^0 D^{+*} K_S^0$	21. $B_{had}^+ \rightarrow D_s^{+*} \bar{D}^0$	33. $B_{had}^+ \rightarrow \bar{D}^{0*} p \bar{p} \pi^+$
10. $B_{had}^+ \rightarrow \bar{D}^{0*} D^{+*} K_S^0$	22. $B_{had}^+ \rightarrow D_s^+ \bar{D}^{0*}$	34. $B_{had}^+ \rightarrow D^+ p \bar{p} \pi^+ \pi^-$
11. $B_{had}^+ \rightarrow \bar{D}^0 D^0 K^+$	23. $B_{had}^+ \rightarrow \bar{D}^0 K^+$	35. $B_{had}^+ \rightarrow D^{+*} p \bar{p} \pi^+ \pi^-$
12. $B_{had}^+ \rightarrow \bar{D}^{0*} D^0 K^+$	24. $B_{had}^+ \rightarrow D^- \pi^+ \pi^+$	36. $B_{had}^+ \rightarrow \Lambda_c^- p \pi^+$

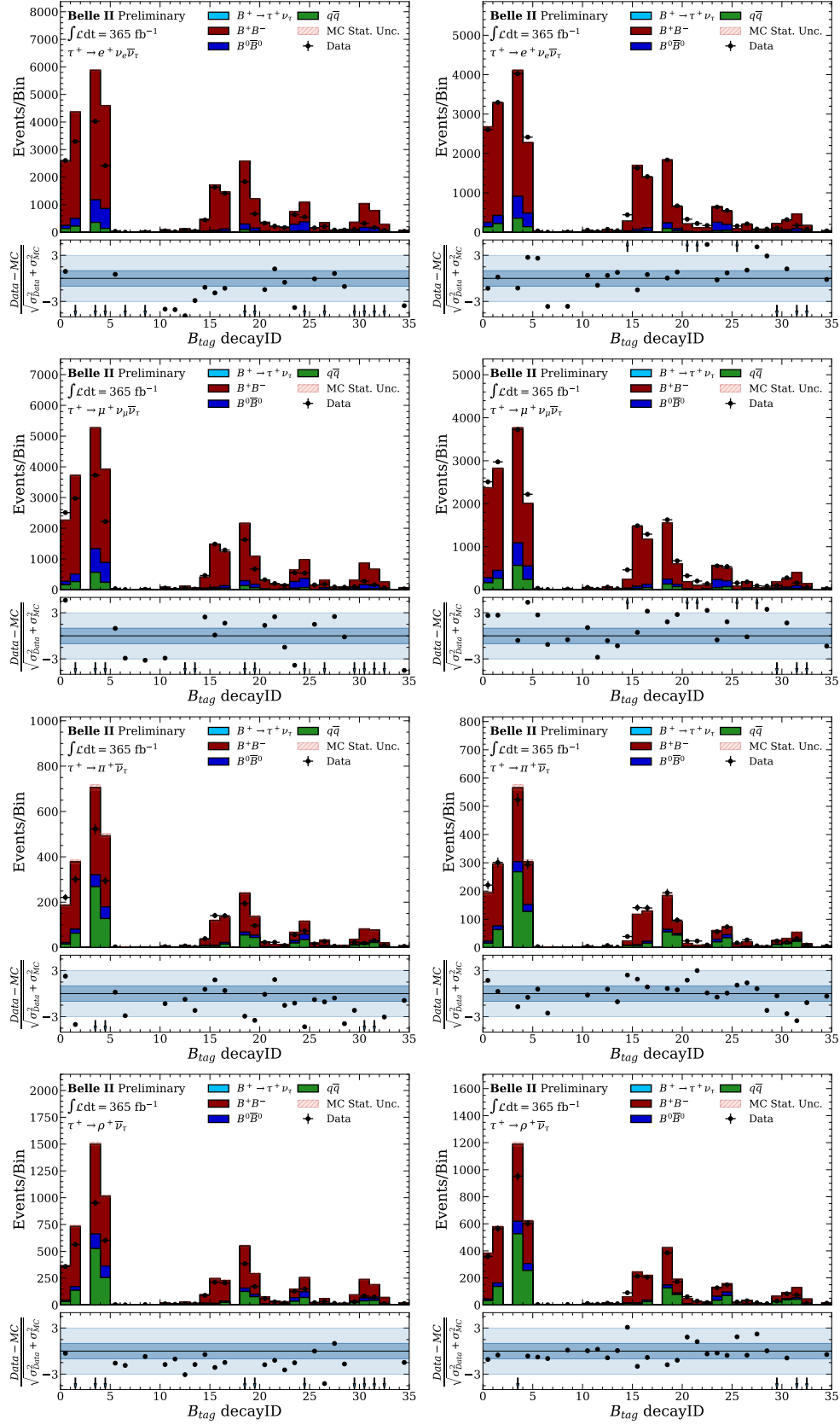


Figure 6.1: B_{tag} decayIDs before (left) and after (right) the calibration divided per channels: e^+ , μ^+ , π^+ and ρ^+ (from top to bottom).

6.2 Tracking efficiency correction

The efficiency of tracks with momentum ranging from 0.2 to 3.5 GeV/c are assessed using $e^+e^- \rightarrow \tau^+\tau^-$ events, where one τ decays leptonically and the other τ decays hadronically into three charged pions. A lepton candidate and two pion candidates are reconstructed so that the sum of the charges is ± 1 . Track reconstruction efficiency is then evaluated using the remaining track, which has a charge of ∓ 1 . All the efficiencies are consistent between data and simulation as functions of transverse momentum, polar angle, and azimuth angle, respectively. As a result, we do not implement any corrections but assign a systematic uncertainty to the reconstruction efficiencies for tracks above 0.2 GeV. This uncertainty is predominantly due to the charge asymmetry in the efficiencies.

6.3 Lepton identification efficiency correction

To correct the efficiencies and fake rates of lepton identification between data and MC simulations, we use corrections from official Belle II tables that describe dependencies on momentum and polar angle. The corrections are calculated by comparing data and simulation on pure samples of electrons and muons from inclusive decays $J/\psi \rightarrow \ell^+\ell^-$, and low multiplicity processes $e^+e^- \rightarrow \ell^+\ell^- (\gamma)$ and $e^+e^- \rightarrow e^+e^- \ell^+\ell^-$.

6.4 Pion identification efficiency correction

The pion ID efficiency and the difference between data and MC are corrected based on official Belle II correction tables. The correction is applied depending on the momentum and polar angle of the tracks. We exploit a sample of pions from inclusive decays of $K_S^0 \rightarrow \pi^+\pi^-$, $D^{*+} \rightarrow D^0 \pi^+$, and $\Lambda^0 \rightarrow p \pi^-$. Fig. 6.2 shows the efficiency and misidentification tables used.

6.5 π^0 reconstruction efficiency

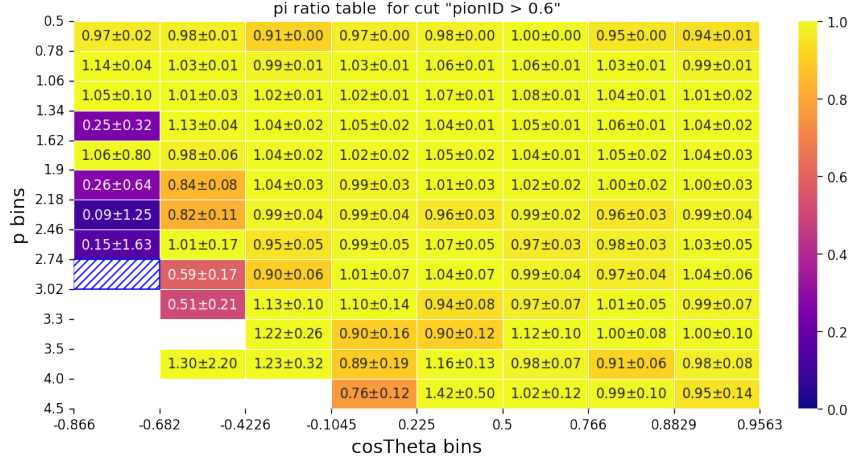
We adopt correction factors for efficiencies of π^0 from ρ candidates depending on their momentum, as listed in Tab. 6.1.

Table 6.1: correction factors for efficiencies of π^0 .

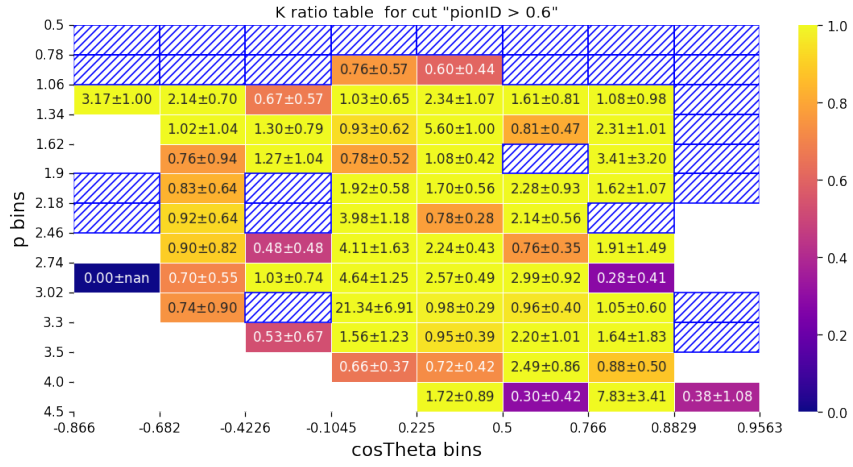
Momentum Range (GeV)	Correction Factor
(0.05, 0.2)	0.960 ± 0.0061
(0.4, 0.6)	0.985 ± 0.042
(0.6, 0.8)	1.032 ± 0.053
(0.8, 1.0)	1.033 ± 0.042
(1.0, 1.5)	1.052 ± 0.047
(1.5, 2.0)	1.060 ± 0.047
(2.0, 3.0)	1.023 ± 0.048

6.6 Branching fractions in MC

Since the Branching Fractions (BFs) used to generate the MC B^+B^- and $B^0\bar{B}^0$ samples are not the latest World Averages reported in the PDG [12], we reweight our MC simulations input values to the mean PDG values for all the decays reported in the Tab. 6.2 and 6.3. They present an uncertainty, so we associate this with a systematic effect.



(a)



(b)

Figure 6.2: (a) Table of pion efficiency data MC ratios with uncertainties and (b) same Table for Kaon fake rates

Further, we correct the BF of the D meson decays since they occur in almost all our background events. Many of their decays are measured quite well with small uncertainties such as semileptonic D decays or the most abundant fully hadronic decays like $D \rightarrow K\pi$ or $D \rightarrow K\pi\pi$ with several different combinations of the decay product's charges. However, a large remaining fraction of D decays is not very well measured, as we can see in Tab. 6.2 and 6.3. We associate a systematic to this difference reweighting the BF of each D component in the MC simulations to the PDG value using the MC truth.

6.7 Shape correction of fit variables

$E_{\text{ECL}}^{\text{extra}}$ and M_{miss}^2 , as described in Chapter 5, are the most discriminating variables between $B^+ \rightarrow \tau^+ \nu_\tau$ signal and backgrounds. The region $E_{\text{ECL}}^{\text{extra}} > 0.5$ GeV, in which a negligible percentage of signal events is present, is partially opened and a non-negligible discrepancy in the distribution in data and MC simulations is observed, as for Fig. 6.3 and 6.4.

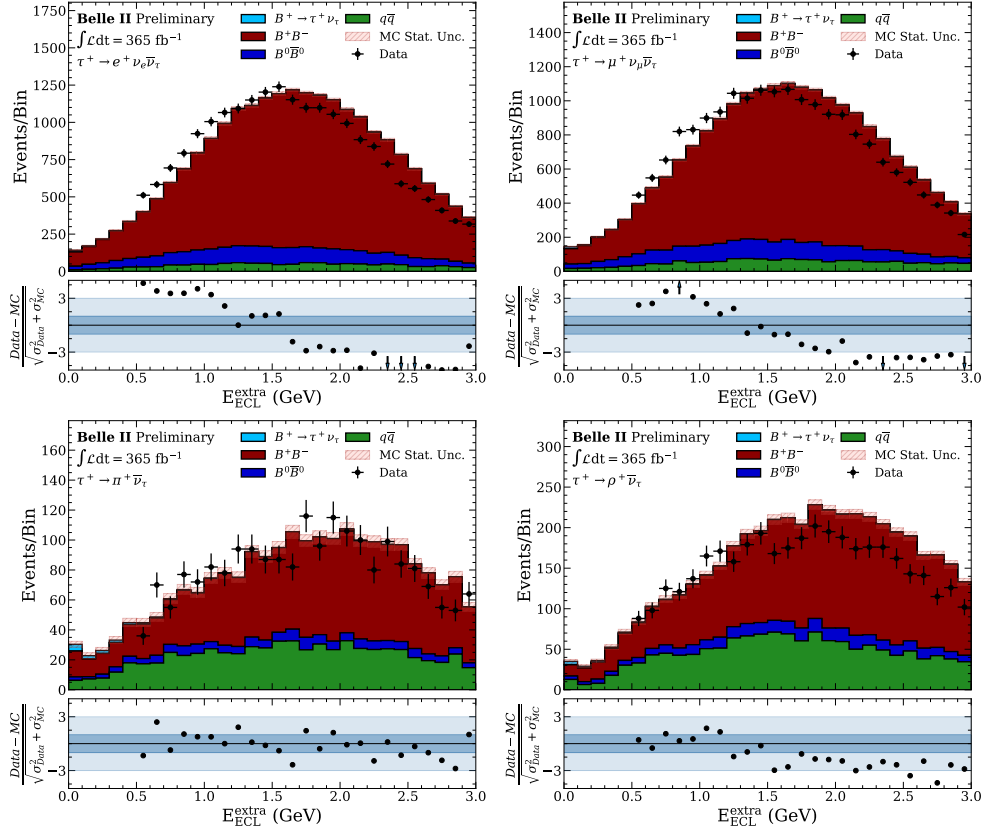


Figure 6.3: $E_{\text{ECL}}^{\text{extra}}$ distribution for the four signal channels in the $E_{\text{ECL}}^{\text{extra}} > 0.5$ GeV sideband.

We identified the cause of the Data/MC disagreement to be a mis-modeling of the reconstruction efficiency that impacts the ECL neutral cluster multiplicity ($n_{\gamma\text{extra}}$). Initially, a correction to the photon efficiency is applied to the ECL clusters in the ROE using a random removal method. This is due to the fact that photon reconstruction efficiency in data is generally lower than that in simulation. In the MC simulation, a photon is excluded from the reconstruction with a probability $1 - \omega$, where ω represents the ratio of photon reconstruction efficiency in data to that in simulation. To implement this, a repeatable sequence of random values between 0 and 1 is generated, and a photon is removed if the corresponding random value exceeds ω . The ω values, which range between 0.8 and 1.0, are determined from data and simulation samples of $e^+e^- \rightarrow \mu^+\mu^- \gamma$ events as a function of missing momentum and

Table 6.2: List of B^+B^- decays reweighted in MC: the input branching fractions values in MC, the last PDG values, and the associated systematics are shown.

B decay	MC BF %	PDG BF %	Sys. Unc.
$B^- \rightarrow D_0^{*0} l^- \nu$	3.9×10^{-3}	$(4.2 \pm 0.75) \times 10^{-3}$	0.295%
$B^- \rightarrow D_1^0 l^- \nu$	7.6×10^{-3}	$(6.6 \pm 1.1) \times 10^{-3}$	0.232%
$B^- \rightarrow D_1^{*0} l^- \nu$	4.3×10^{-3}	$(4.2 \pm 0.9) \times 10^{-3}$	0.138%
$B^- \rightarrow D_2^{*0} l^- \nu$	3.7×10^{-3}	$(2.9 \pm 0.3) \times 10^{-3}$	0.044%
$B^- \rightarrow D^{*0} \pi \pi l^- \nu$	2.63×10^{-3}	$(2.16 \pm 1.02) \times 10^{-3}$	0.046%
$B^- \rightarrow D^0 \pi \pi l^- \nu$	5.3×10^{-4}	$(6.3 \pm 8.8) \times 10^{-4}$	0.068%
$B^- \rightarrow D^{*0} \eta l^- \nu$	2.01×10^{-3}	$(3.77 \pm 3.77) \times 10^{-3}$	0.434%
$B^- \rightarrow D^0 \eta l^- \nu$	2.01×10^{-3}	$(3.77 \pm 3.77) \times 10^{-3}$	0.467%
$B^- \rightarrow D^{*0} l^- \nu$	5.48	5.50 ± 0.11	0.709%
$B^- \rightarrow D^{*0} \tau^- \nu$	1.42	1.88 ± 0.20	0.294%
$B^- \rightarrow D^{*0} a_1^-$	1.88	1.9 ± 0.5	0.193%
$B^- \rightarrow D^{*0} \rho^-$	9.8×10^{-3}	$(9.8 \pm 1.7) \times 10^{-3}$	0.503%
$B^- \rightarrow D^{*0} \pi^-$	4.90×10^{-3}	$(5.18 \pm 0.15) \times 10^{-3}$	0.12%
$B^- \rightarrow D^{*0} D_s^{*-}$	1.71	1.71 ± 0.24	0.048%
$B^- \rightarrow D^{*0} D_s^-$	8.2×10^{-3}	$(8.2 \pm 1.7) \times 10^{-3}$	0.091%
$B^- \rightarrow D^0 l^- \nu$	2.31	2.41 ± 0.07	0.239%
$B^- \rightarrow D^0 \tau^- \nu$	6.9×10^{-3}	$(7.7 \pm 2.5) \times 10^{-3}$	1.282%
$B^- \rightarrow D^0 a_1^-$	4.5×10^{-3}	$(4 \pm 4) \times 10^{-3}$	0.438%
$B^- \rightarrow D^0 \rho^-$	1.34	1.34 ± 0.18	0.041%
$B^- \rightarrow D^0 \pi^-$	4.68×10^{-3}	$(4.68 \pm 0.13) \times 10^{-3}$	0.062%
$B^- \rightarrow D^{*0} D_s^{*-}$	7.6×10^{-3}	$(7.6 \pm 1.6) \times 10^{-3}$	0.068%
$B^- \rightarrow D^0 D_s^-$	9.0×10^{-3}	$(9.0 \pm 0.9) \times 10^{-3}$	0.029%
$B^- \rightarrow other$	1	1 ± 0.5	3.4%
$B^- \rightarrow D^0$:			
$D^0 \rightarrow K^- incl.$	56	54.7 ± 2.8	0.018%
$D^0 \rightarrow K^0/\bar{K}^0 incl.$	39.9	47 ± 4	0.768%
$D^0 \rightarrow K^+ incl.$	3.6	3.4 ± 0.4	0.558%
$D^0 \rightarrow K^{*-} incl.$	12.6	15 ± 9	1.162%
$D^0 \rightarrow \bar{K}^{*0} incl.$	9.1	9 ± 4	0.347%
$D^0 \rightarrow K^{*0} incl.$	9.1	2.8 ± 1.3	0.269%
$B^- \rightarrow D^+$:			
$D^+ \rightarrow K^- incl.$	30.5	25.7 ± 1.4	0.002%
$D^+ \rightarrow K^0/\bar{K}^0 incl.$	57.5	61 ± 5	0.175%
$D^+ \rightarrow K^+ incl.$	6.8	5.9 ± 0.8	0.003%
$D^+ \rightarrow K^{*-} incl.$	4.5	6 ± 5	0.233%
$D^+ \rightarrow \bar{K}^{*0} incl.$	19.4	23 ± 5	0.043%
$D^+ \rightarrow K^{*0} incl.$	19.4	< 6.66	0.016%

Table 6.3: List of $B^0\bar{B}^0$ decays reweighted in MC: the input branching fractions values in MC, the last PDG values, and the associated systematics are shown.

B decay	MC BF %	PDG BF %	Sys. Unc.
$\bar{B}^0 \rightarrow D_0^{*+} l^- \nu$	3.62×10^{-1}	$(3.9 \pm 0.7) \times 10^{-1}$	0.044%
$\bar{B}^0 \rightarrow D_1^{*+} l^- \nu$	7.04×10^{-1}	$(6.16 \pm 1.01) \times 10^{-1}$	0.07%
$\bar{B}^0 \rightarrow D_1^{'0} l^- \nu$	4.01×10^{-1}	$(3.9 \pm 0.8) \times 10^{-1}$	0.042%
$\bar{B}^0 \rightarrow D_2^{*+} l^- \nu$	3.47×10^{-1}	$(2.73 \pm 0.3) \times 10^{-1}$	0.018%
$\bar{B}^0 \rightarrow D^{*+} \pi \pi l^- \nu$	4.8×10^{-2}	$(2.01 \pm 0.95) \times 10^{-1}$	0.088%
$\bar{B}^0 \rightarrow D^+ \pi \pi l^- \nu$	1.6×10^{-2}	$(5.79 \pm 8.23) \times 10^{-2}$	0.585%
$\bar{B}^0 \rightarrow D^{*+} \eta l^- \nu$	2.17×10^{-1}	$(4.09 \pm 4.09) \times 10^{-1}$	0.088%
$\bar{B}^0 \rightarrow D^+ \eta l^- \nu$	2.17×10^{-1}	$(4.09 \pm 4.09) \times 10^{-1}$	0.284%
$\bar{B}^0 \rightarrow D^{*+} l^- \nu$	5.11	5.11 ± 0.11	0.084%
$\bar{B}^0 \rightarrow D^{*+} \tau^- \nu$	1.31	1.58 ± 0.9	0.397%
$\bar{B}^0 \rightarrow D^{*+} a_1^-$	1.29	1.9 ± 1.3	0.03%
$\bar{B}^0 \rightarrow D^{*+} \rho^-$	6.8×10^{-1}	$(6.8 \pm 0.9) \times 10^{-1}$	0.059%
$\bar{B}^0 \rightarrow D^{*+} \pi^-$	2.74×10^{-1}	$(2.74 \pm 0.13) \times 10^{-1}$	0.015%
$\bar{B}^0 \rightarrow D^{*+} D_s^{*-}$	1.77	1.77 ± 0.14	0.004%
$\bar{B}^0 \rightarrow D^{*+} D_s^-$	8.04×10^{-1}	$(8.0 \pm 1.1) \times 10^{-1}$	0.016%
$\bar{B}^0 \rightarrow D^+ l^- \nu$	2.31	2.24 ± 0.07	0.163%
$\bar{B}^0 \rightarrow D^+ \tau^- \nu$	6.4×10^{-1}	1.05 ± 0.23	0.351%
$\bar{B}^0 \rightarrow D^+ a_1^-$	6.0×10^{-1}	$(6 \pm 3.3) \times 10^{-1}$	0.234%
$\bar{B}^0 \rightarrow D^+ \rho^-$	7.57×10^{-1}	$7.6 \pm 1.2 \times 10^{-1}$	0.09%
$\bar{B}^0 \rightarrow D^+ \pi^-$	2.52×10^{-1}	$(2.51 \pm 0.08) \times 10^{-1}$	0.026%
$\bar{B}^0 \rightarrow D^{*+} D_s^{*-}$	7.4×10^{-1}	$(7.4 \pm 1.6) \times 10^{-1}$	0.051%
$\bar{B}^0 \rightarrow D^+ D_s^-$	7.23×10^{-1}	$(7.2 \pm 0.8) \times 10^{-1}$	0.04%
$\bar{B}^0 \rightarrow other$	1	1 ± 0.5	0.7%
$\bar{B}^0 \rightarrow D^0$:			
$D^0 \rightarrow K^- incl.$	56	54.7 ± 2.8	0.001%
$D^0 \rightarrow K^0/\bar{K}^0 incl.$	39.9	47 ± 4	0.009%
$D^0 \rightarrow K^+ incl.$	3.6	3.4 ± 0.4	0.005%
$D^0 \rightarrow K^{*-} incl.$	12.6	15 ± 9	0.013%
$D^0 \rightarrow \bar{K}^{*0} incl.$	9.1	9 ± 4	0.005%
$D^0 \rightarrow K^{*0} incl.$	9.1	2.8 ± 1.3	0.003%
$\bar{B}^0 \rightarrow D^+$:			
$D^+ \rightarrow K^- incl.$	30.5	25.7 ± 1.4	0.007%
$D^+ \rightarrow K^0/\bar{K}^0 incl.$	57.5	61 ± 5	1.394%
$D^+ \rightarrow K^+ incl.$	6.8	5.9 ± 0.8	0.025%
$D^+ \rightarrow K^{*-} incl.$	4.5	$6 \pm 0.298\%$	
$D^+ \rightarrow \bar{K}^{*0} incl.$	19.4	23 ± 5	0.05%
$D^+ \rightarrow K^{*0} incl.$	19.4	< 6.66	0.131%

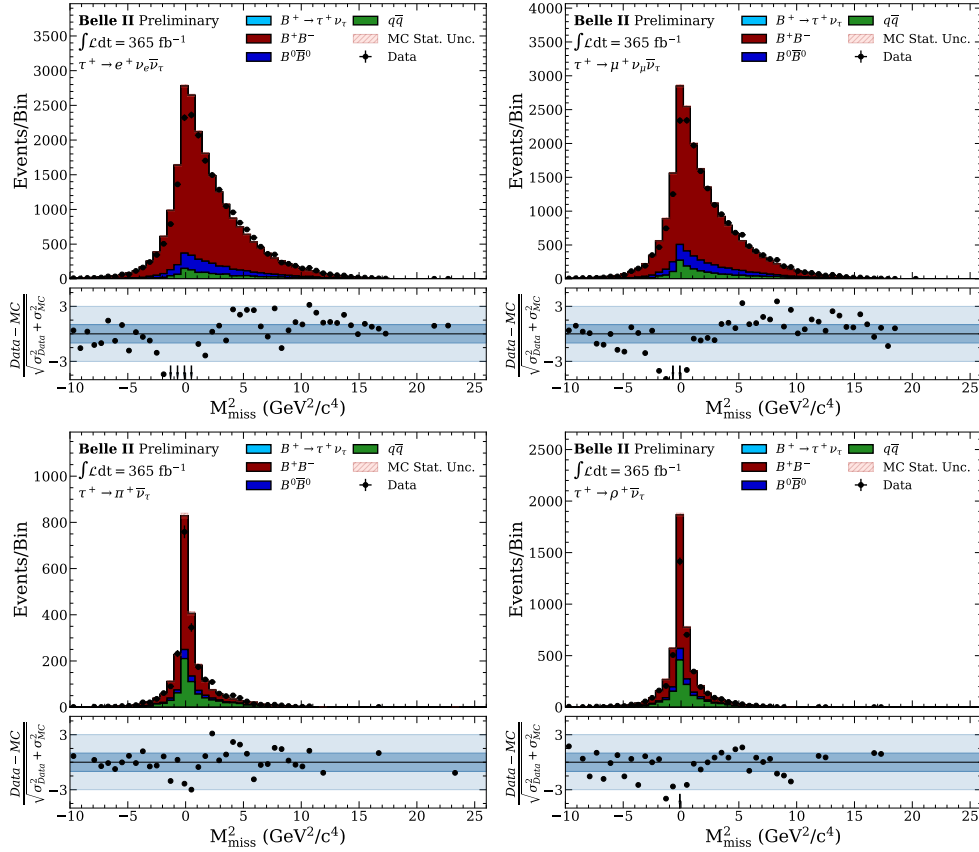


Figure 6.4: M^2_{miss} distribution for the four signal channels in the $E_{\text{ECL}}^{\text{extra}} > 0.5$ GeV sideband.

its angular direction (θ, ϕ) .

After applying the photon efficiency correction, the distributions of $E_{\text{ECL}}^{\text{extra}}$ in data and simulation still show slight discrepancies. Figure 6.5 (left) illustrates the $n_{\gamma\text{extra}}$ distribution. In Figure 6.6, the $E_{\text{ECL}}^{\text{extra}}$ distributions for different values of $n_{\gamma\text{extra}}$ (3,4,5,6,7,8) are shown with the number of events in simulation scaled to data. This is done to verify that the shapes of $E_{\text{ECL}}^{\text{extra}}$ match for a fixed multiplicity of $n_{\gamma\text{extra}}$. The agreement is found to be satisfactory for any fixed $n_{\gamma\text{extra}}$.

Therefore, we conclude that the simulation approximately models the $E_{\text{ECL}}^{\text{extra}}$ distribution in each $n_{\gamma\text{extra}}$ bin, although the normalization differs from the data. To align the simulation expectations with the data, we apply a bin-by-bin correction to $n_{\gamma\text{extra}}$ using control samples:

- **$B\bar{B}$ Background:** The *Extra Tracks* control sample is created by selecting events with more tracks originating from the IP and with momenta less than 0.5 GeV. The $n_{\gamma\text{extra}}$ corrections derived from the Extra-Tracks sample are then applied to reweight the $B\bar{B}$ background simulation. Additional details can be found in Subsection 6.7.1.
- **Leptonic Signal:** A $B \rightarrow D^* \ell \nu$ decay is reconstructed in the signal side, and the resulting corrections are applied to reweight the signal simulation for leptonic decay modes. More information is provided in Subsection 6.7.2.
- **Hadronic Signal:** The DoubleTag sample is constructed by reconstructing two distinct non-overlapping hadronic tag B mesons with opposite charges within the same event. This sample is then used to reweight the signal simulation for hadronic modes. Details are available in Subsection 6.7.3.

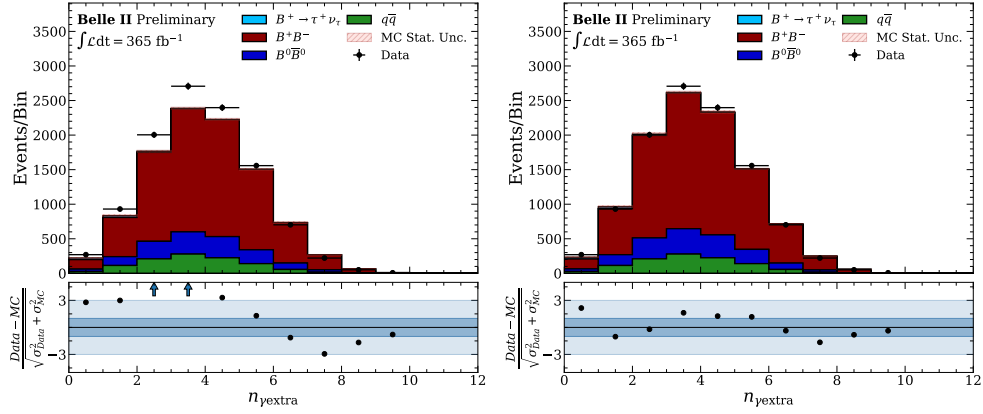


Figure 6.5: Distributions of $n_{\gamma\text{extra}}$ in data and simulation for $E_{\text{ECL}}^{\text{extra}} < 1$ GeV before (left) and after (right) applying the $n_{\gamma\text{extra}}$ calibration

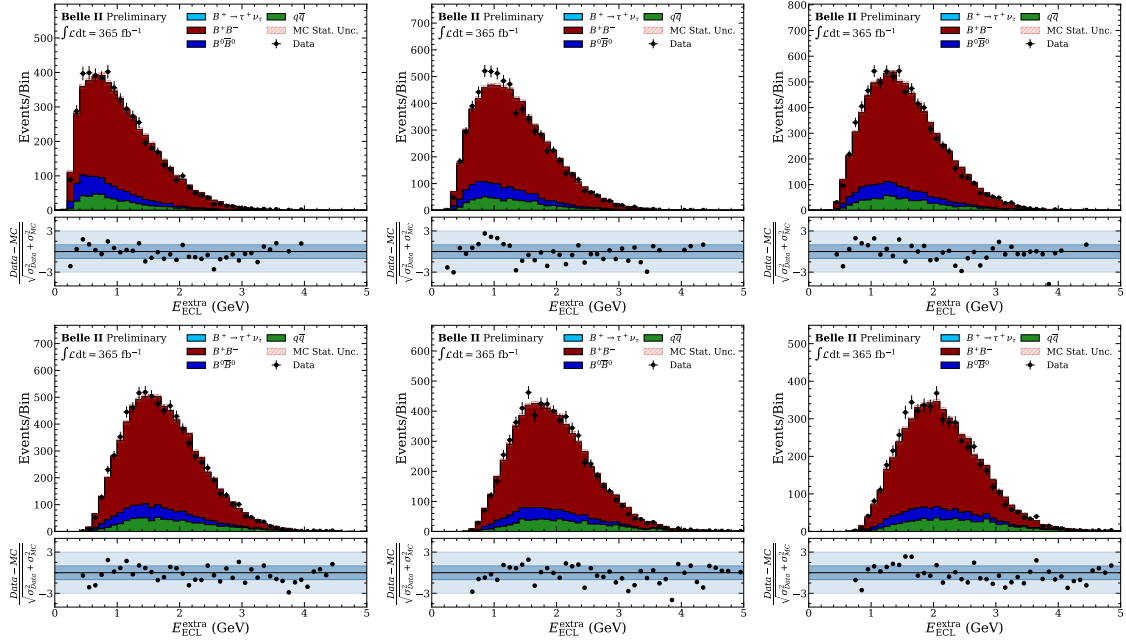


Figure 6.6: $E_{\text{ECL}}^{\text{extra}}$ distribution as a function of $n_{\gamma\text{extra}}$ with the number of events in simulation scaled to data for the electron channel. The first row shows the $E_{\text{ECL}}^{\text{extra}}$ with $n_{\gamma\text{extra}} = 3, 4, 5$. The second row shows the $E_{\text{ECL}}^{\text{extra}}$ with $n_{\gamma\text{extra}} = 6, 7, 8$.

The correction factors derived from the various Control Samples are summarized in Table 6.4. Figures 6.7 and 6.8 display the $E_{\text{ECL}}^{\text{extra}}$ and M_{miss}^2 distributions for each signal decay mode following the application of these corrections. Figure 6.5 (right) shows the $n_{\gamma\text{extra}}$ distribution after the corrections have been applied.

Table 6.4: Bin-by-bin evaluation of the correction found in the different control samples: the background values are computed in the *Extra Tracks* control sample for the 4 channels; the signal corrections are taken from the $B^+ \rightarrow D^{*0}\ell^+\nu_\ell$ (Double Tag) control sample for the leptonic (hadronic) channels

Extra γ Mult.	Background				Signal	
	e^+	μ^+	π^+	ρ^+	e^+/μ^+	π^+/ρ^+
0	1.101(42)	1.041(43)	1.001(123)	0.803(112)	1.093(102)	0.986(30)
1	1.190(24)	1.191(25)	1.162(71)	1.052(66)	0.972(76)	1.062(20)
2	1.168(16)	1.159(17)	1.034(48)	1.078(48)	1.051(89)	1.044(17)
3	1.111(13)	1.117(14)	0.995(40)	1.024(37)	0.904(105)	1.035(18)
4	1.061(11)	1.046(12)	0.989(37)	0.981(32)	0.917(154)	0.977(20)
5	1.023(11)	0.975(12)	0.996(39)	0.986(31)	0.935(251)	0.916(25)
6	0.970(12)	0.960(12)	0.940(41)	0.962(31)	—	—
7	0.894(13)	0.931(13)	0.997(49)	0.978(33)	—	—
8	0.863(15)	0.912(15)	0.992(62)	1.028(39)	—	—
9	0.844(18)	0.905(18)	1.053(84)	1.003(47)	—	—

6.7.1 *Extra Tracks* control sample

We define a control sample of $B^+ \rightarrow \tau^+\nu_\tau$ events that contain more than two tracks in the ROE to assess the corrections for the $E_{\text{ECL}}^{\text{extra}}$ distribution in the $B\bar{B}$ background simulation. This sample represents the same background composition for $B\bar{B}$ but does not include signal events. The control sample is identified using two distinct track requirements: $N_{\text{IP Tracks}} > 1$ and $N_{\text{Signal-like Tracks}} = 0$. The **IP Tracks** include all tracks in the ROE whose impact parameter relative to the IP is less than 2 cm along the z axis and 0.5 cm in the transverse plane, with no additional momentum conditions. The **Signal-like Tracks** criterion is similar but also includes a requirement for the track momentum to exceed 0.5 GeV. On average, the control sample contains 3.2 $N_{\text{IP Tracks}}$ per event. Figure 6.9 shows the $n_{\gamma\text{extra}}$ distribution for data and MC in this control sample for each signal channel, which allows us to extract correction factors for reweighting the MC background.

6.7.2 $B^+ \rightarrow D^{*0}\ell^+\nu_\ell$ control sample

We use the $B^+ \rightarrow D^{*0}\ell^+\nu_\ell$ ($\ell = e, \mu$) control sample to determine the corrections for reweighting the signal MC in the leptonic τ decay categories. Similar to the $B^+ \rightarrow \tau^+\nu_\tau$ case, $E_{\text{ECL}}^{\text{extra}}$ is expected to peak at 0. For each event, the signal B_{sig} decays into $D^{*0}\ell^+\nu_\ell$ without any extra tracks in the ROE. The hadronic B_{tag} selection follows the same criteria as in the main analysis. The signal side involves the reconstruction of D^{*0} in its decays to $D^0 \pi^0$ and $D^0 \gamma$, with $D^0 \rightarrow K^- \pi^+$, $K_S^0 \pi^+ \pi^-$, and $K^- \pi^+ \pi^+ \pi^-$. After reconstruction, we apply all necessary corrections, including continuum-reweighting, normalization, PID corrections, ROE clusters clean-up, and more. To enhance the purity of the sample, we require the lepton's

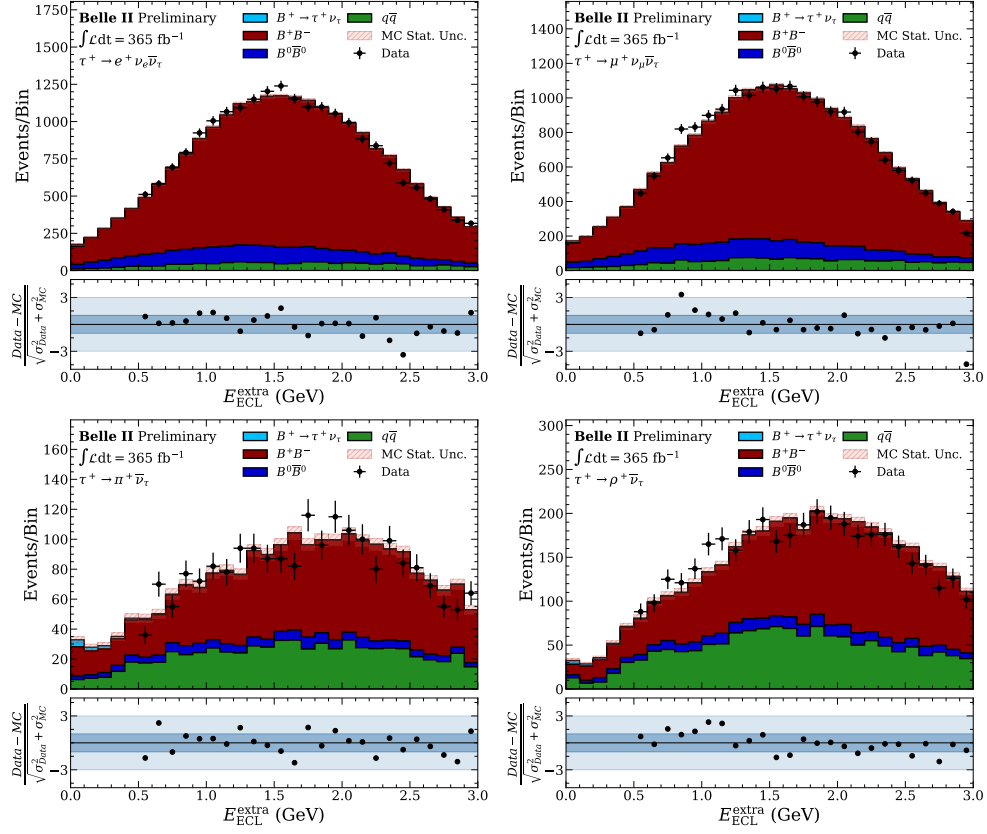


Figure 6.7: $E_{\text{ECL}}^{\text{extra}}$ distribution for the four signal channels after applying all the corrections the $E_{\text{ECL}}^{\text{extra}} > 0.5$ GeV sideband.

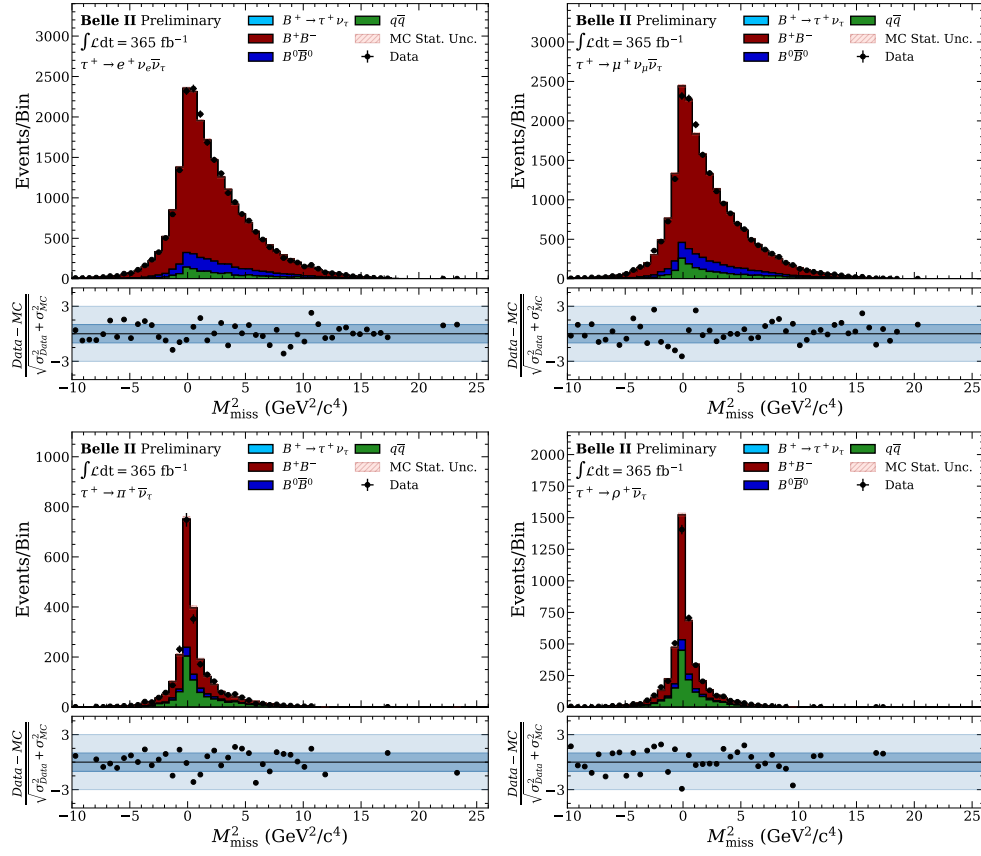


Figure 6.8: M_{miss}^2 distribution for the four signal channels after applying all the corrections in the $E_{\text{ECL}}^{\text{extra}} > 0.5$ GeV sideband.

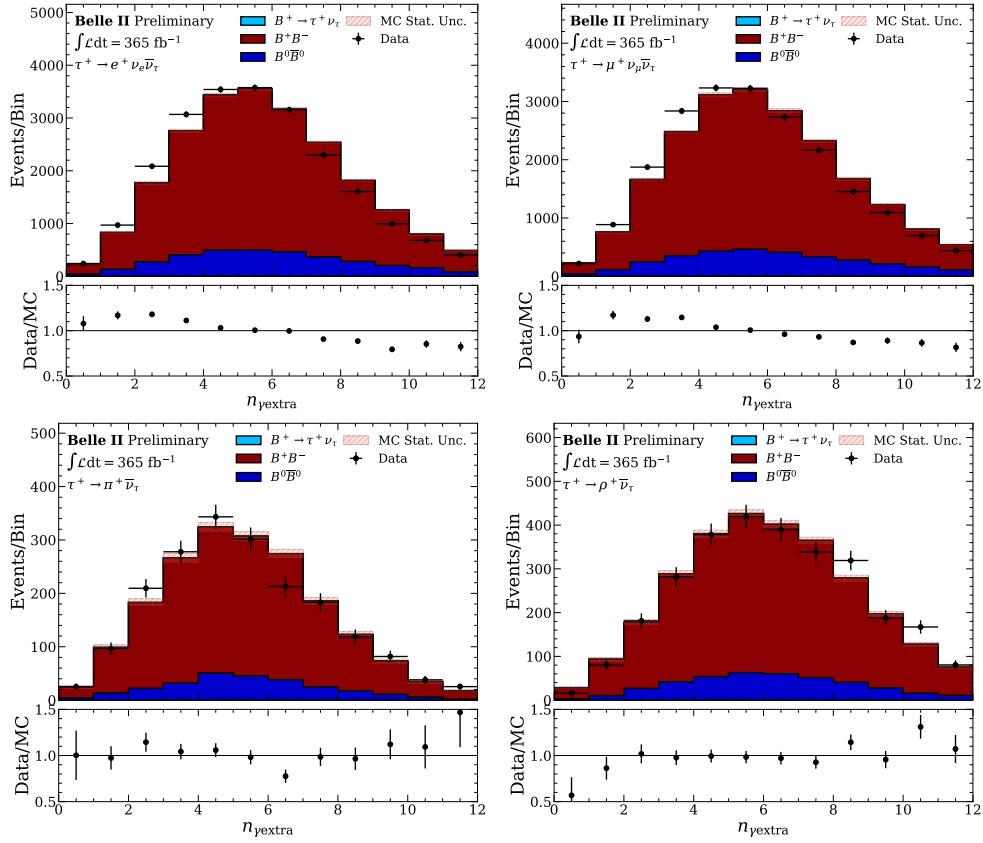


Figure 6.9: Distributions of $n_{\gamma\text{extra}}$ in the *Extra Tracks* control sample for the four signal channels. The continuum component is subtracted.

momentum to exceed $1.5 \text{ GeV}/c$, and the energy of the γ from the $D^{*0} \rightarrow D^0 \gamma$ decay must be greater than 170 MeV . The majority of the sample (84%) consists of correctly reconstructed $B^+ \rightarrow D^{*0} \ell^+ \nu_\ell$, while the remaining 16% includes misreconstructed events such as $B^+ \rightarrow D^{*+} \ell^+ \nu_\ell$, $B^+ \rightarrow D^0 \ell^+ \nu_\ell$, and other channels. Figure 6.10a shows the $n_{\gamma\text{extra}}$ distribution for data and MC in this control sample, from which correction factors are extracted to reweight the signal MC in the leptonic τ decay categories.

We also use this sample to validate the signal efficiency between data and simulation, finding a Data/MC ratio of $0.96(4)$ after all selection and calibration steps. Figure 6.11 provides the Data/MC comparison for $E_{\text{ECL}}^{\text{extra}}$ and M_{miss}^2 .

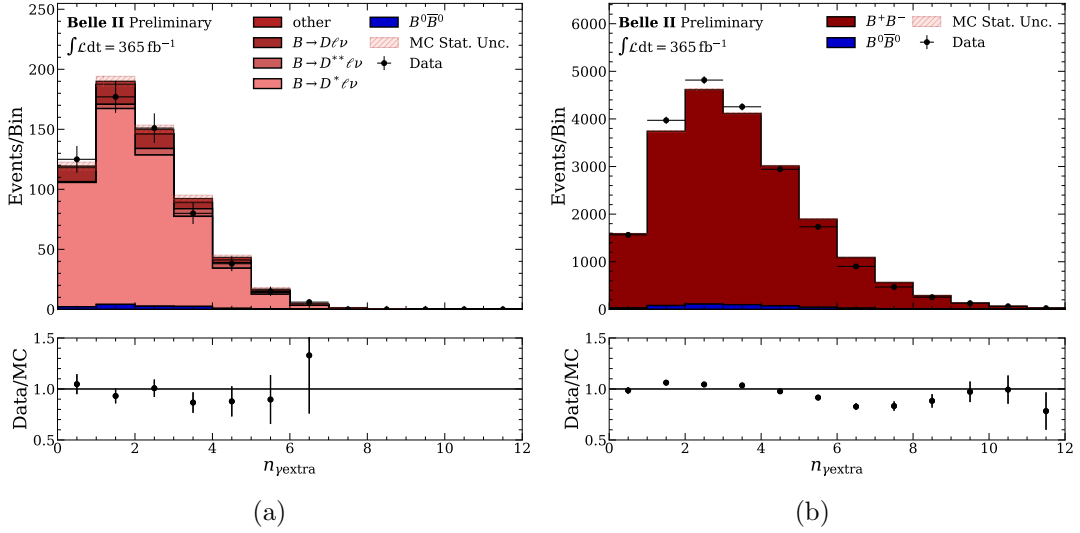


Figure 6.10: Distributions of $n_{\gamma\text{extra}}$ in the $B^+ \rightarrow D^{*0} \ell^+ \nu_\ell$ (a) and Double Tag (b) control samples. The continuum component is subtracted.

6.7.3 Double Tag control sample

The Double Tag control sample is utilized to apply corrections for hadronic τ decays in the signal simulation. In this sample, events with two non B candidates with opposite charges are reconstructed using the hadronic FEI algorithm. We require no extra tracks in the ROE. Also for this control sample, $E_{\text{ECL}}^{\text{extra}}$ is expected to peak at 0. We apply all necessary corrections, including continuum-reweighting, normalization, PID corrections, and ROE clusters clean-up, consistent with the main analysis. Figure 6.10b shows the agreement between Data and MC in this control sample, from which correction factors are obtained to reweight the MC signal for the hadronic τ decay categories. Figure 6.12 displays the Data/MC comparison for $E_{\text{ECL}}^{\text{extra}}$ and M_{miss}^2 .

6.8 Signal embedding

This specific control sample is built as a double-check for the data/MC efficiency and it is also useful to check the simulation modeling in the signal region. It consists of generic $B\bar{B}$ events where the signal-side $B^+ \rightarrow \tau^+ \nu_\tau$ is artificially inserted. The signal embedding sample is based on the clean $B^+ \rightarrow K^+ J/\psi$ decay channel, with $J/\psi \rightarrow \ell^- \ell^+$ ($\ell = e, \mu$). This decay mode can be exclusively reconstructed on data and simulated $B\bar{B}$ sample. The reconstructed signal-side $B^+ \rightarrow K^+ J/\psi$ is removed from the event, and replaced by a simulated $B^+ \rightarrow \tau^+ \nu_\tau$. The ROE and the generic tag-side are still from the $B^+ \rightarrow K^+ J/\psi$ event. The $B^+ \rightarrow \tau^+ \nu_\tau$ signal-side, together with all the particles in its decay chain, is extracted from the simulated

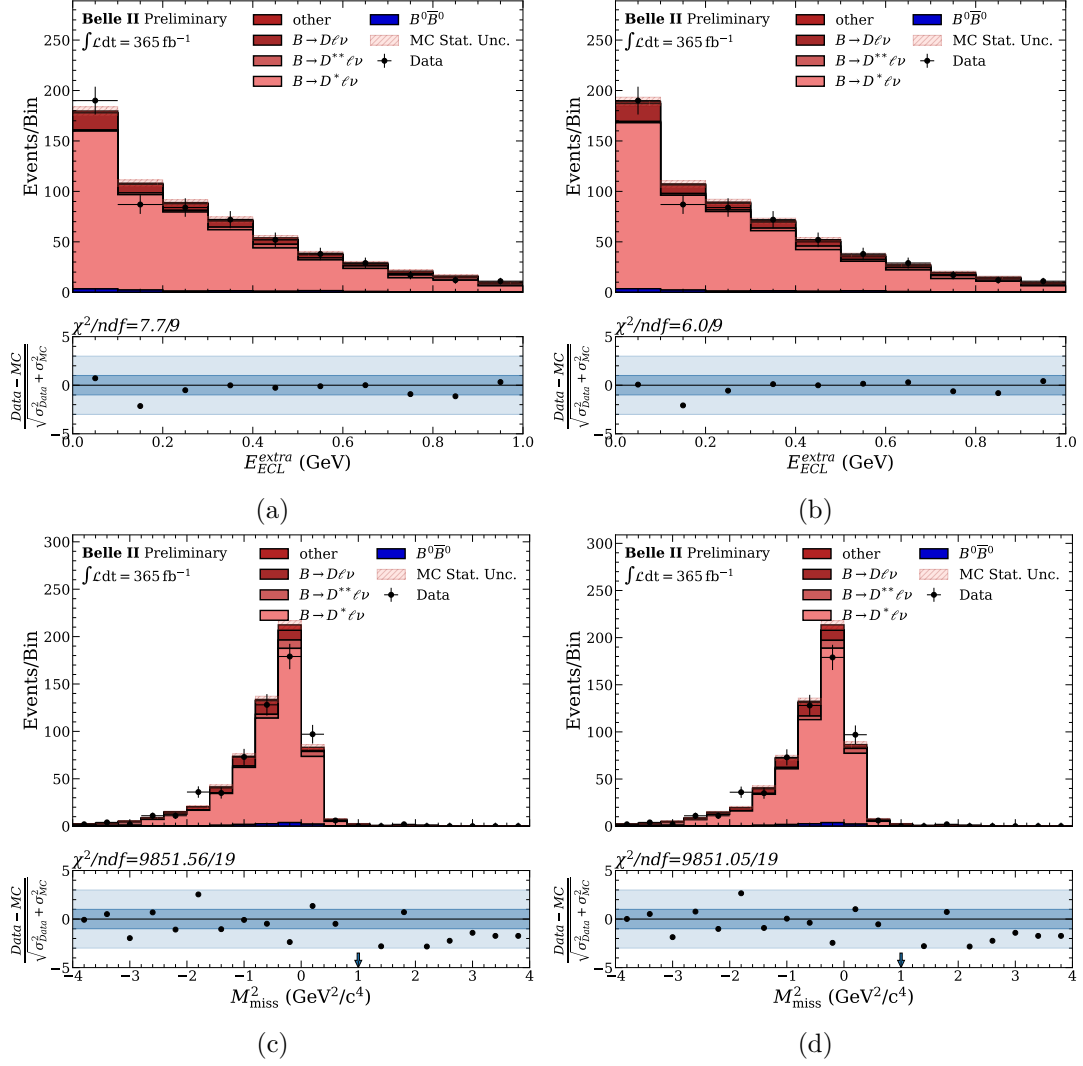


Figure 6.11: $B \rightarrow D^* \ell \nu$ control sample. (a) $E_{\text{ECL}}^{\text{extra}}$ without the correction, (b) $E_{\text{ECL}}^{\text{extra}}$ after the corrections, (c) M_{miss}^2 without the correction, and (d) M_{miss}^2 after the corrections.

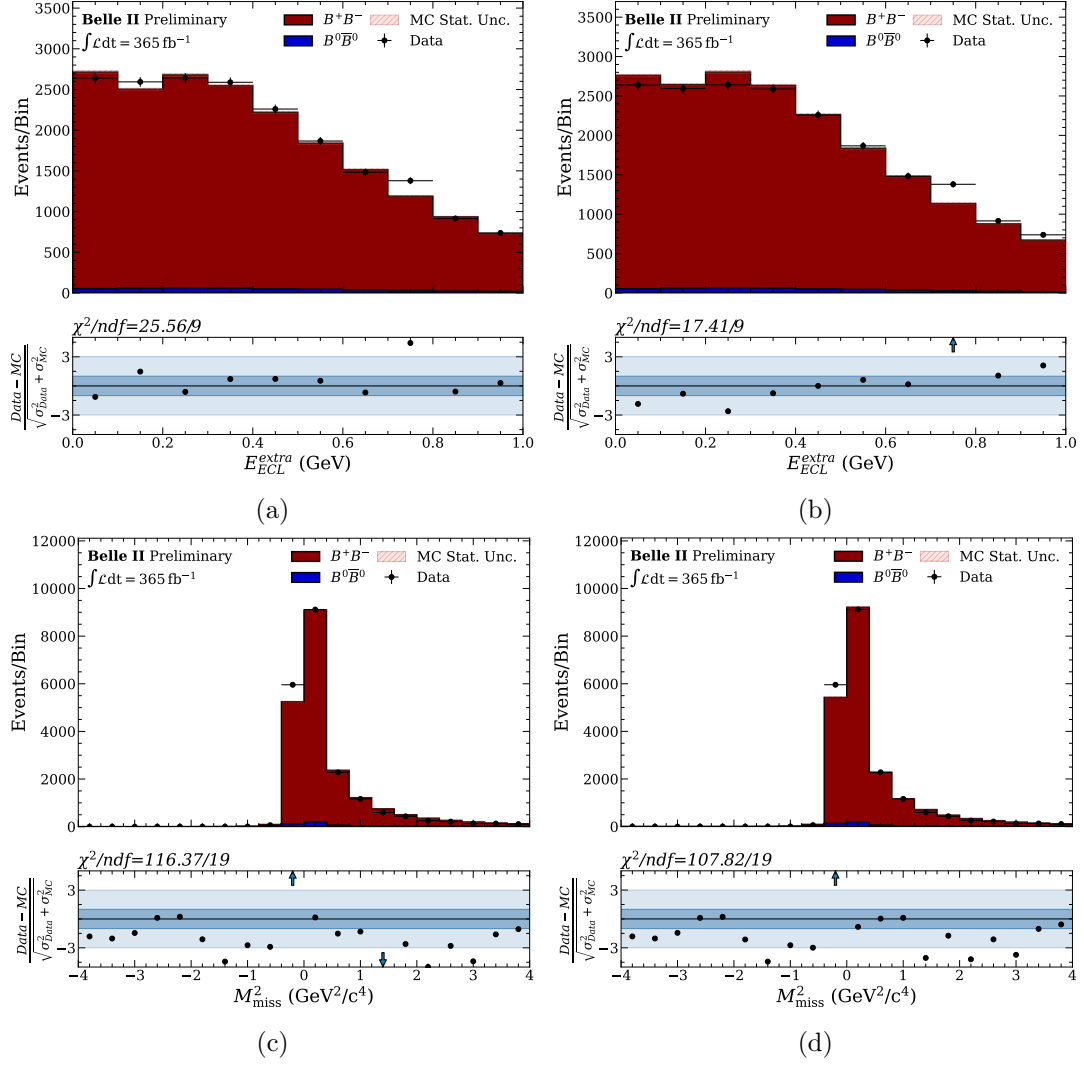


Figure 6.12: Double Tag control sample. (a) E_{ECL}^{extra} without any correction, (b) E_{ECL}^{extra} after the corrections, (c) M_{miss}^2 without any correction, and (d) M_{miss}^2 after the corrections.

sample. To combine this signal side with the tag side and the ROE of the $B^+ \rightarrow K^+ J/\psi$ event, the detector-level objects (tracks, clusters, etc) associated with the simulated $K^+ J/\psi$ particles are isolated. They are reconstructed with the same criteria adopted in the main analysis. The signal efficiency estimated between Data and MC is 1.02 ± 0.18 . Fig. 6.13 shows the distribution for $E_{\text{ECL}}^{\text{extra}}$ and M_{miss}^2 , and Fig. 6.14 shows the distribution of other variables.

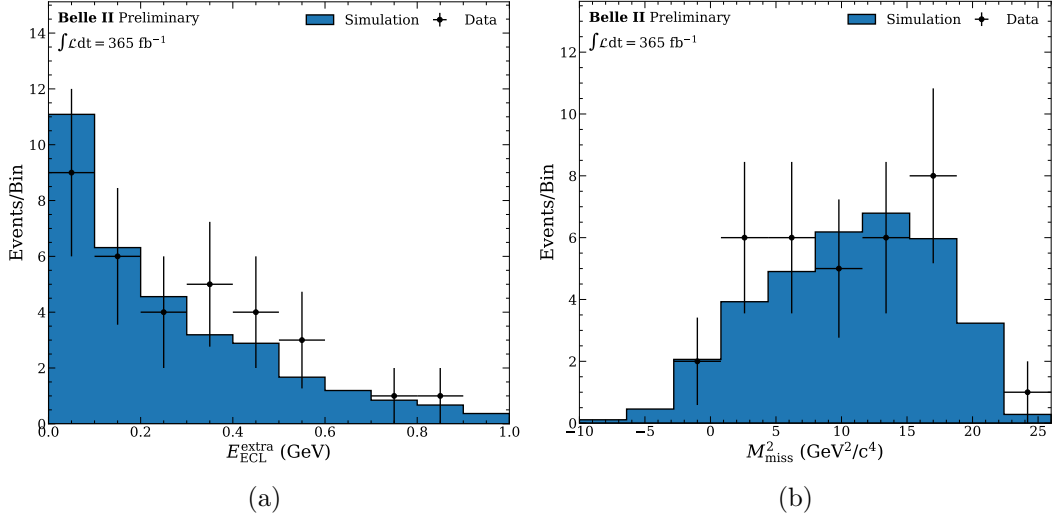


Figure 6.13: $E_{\text{ECL}}^{\text{extra}}$ and M_{miss}^2 distributions for the signal embedding control sample

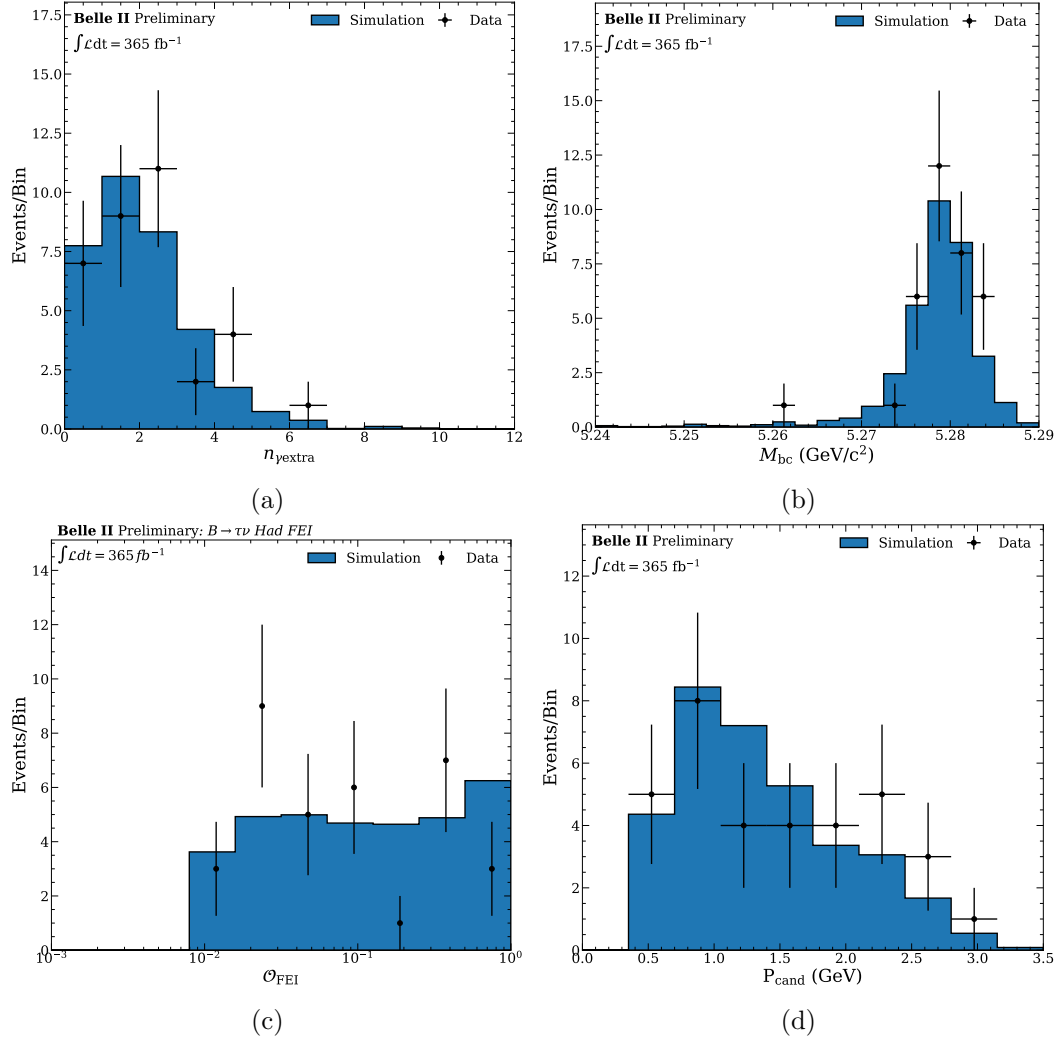


Figure 6.14: $n_{\gamma\text{extra}}$, M_{bc} , $\mathcal{O}_{\text{FEI}}$ and P_{cand} distributions for the signal embedding control sample

Chapter 7

Validation

We validate the corrections on the continuum and $B\bar{B}$ simulations using respectively the off-resonance data and signal sideband data. We employ four sideband regions for this validation, requiring $E_{\text{ECL}}^{\text{extra}} > 500 \text{ MeV}$ for the $E_{\text{ECL}}^{\text{extra}}$ sideband, $M_{\text{bc}} < 5.26 \text{ GeV}/c^2$ for the M_{bc} sideband, $M_{\text{miss}}^2 < 4 \text{ GeV}^2/c^4$ for the M_{miss}^2 sideband (leptons), $P_{\text{cand}} < 1.2 \text{ GeV}/c$ for the P_{cand} sideband (hadrons). We conclude that the Data/MC agreement in the control regions is satisfying.

7.1 Checks with off-resonance data

We use off-resonance data, as presented in Chapter 4, to validate the continuum background shape and yield. Figures 7.1 and 7.2 show the off-resonance Data/MC comparison. The agreement is good.

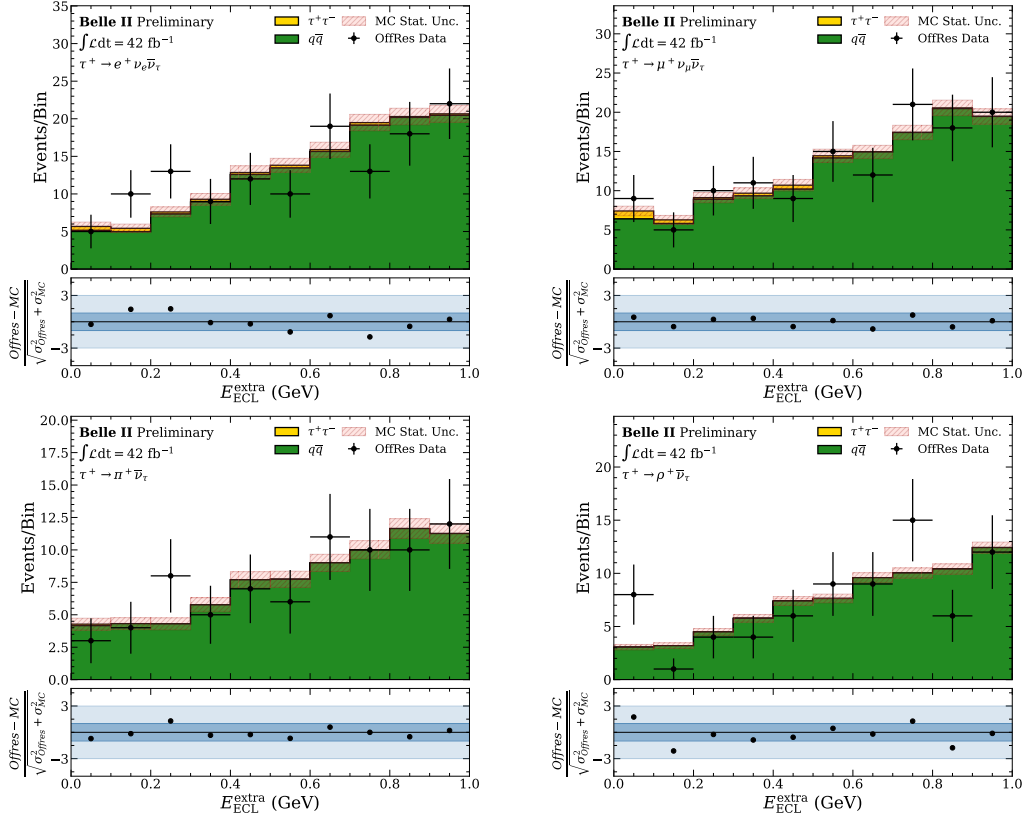


Figure 7.1: $E_{\text{ECL}}^{\text{extra}}$ distribution of off-resonance data and MC continuum for each τ^+ decay channel.

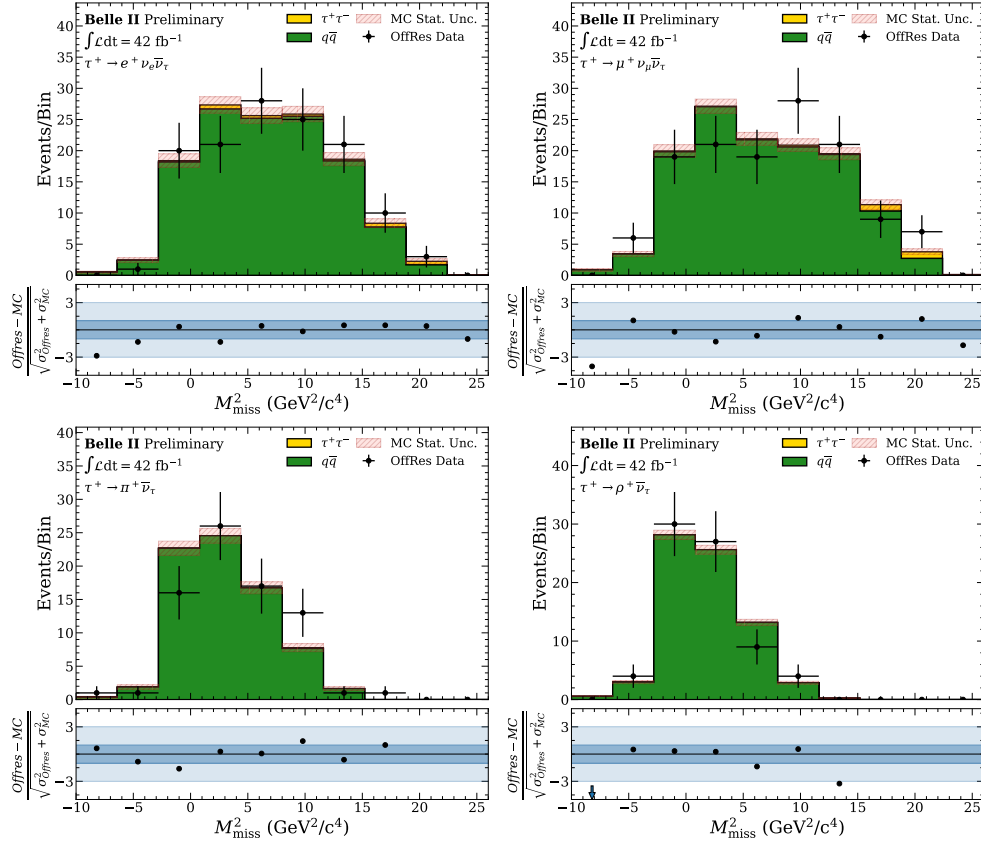


Figure 7.2: M_{miss}^2 distribution of off-resonance data and MC continuum for each τ^+ decay channel.

7.2 Sideband of $E_{\text{ECL}}^{\text{extra}}$

We studied the $E_{\text{ECL}}^{\text{extra}}$ sideband control sample, obtained by requiring $E_{\text{ECL}}^{\text{extra}} > 500 \text{ MeV}$. The signal yield in this region is negligible, ensuring that we remain blind to signal in data. Figure 7.3 and 7.4 shows the distributions of the analysis fit variables. The agreement is good.

7.3 Sideband of M_{bc}

We studied the M_{bc} sideband control sample, obtained by requiring $M_{bc} < 5.26 \text{ GeV}/c^2$. The signal yield in this region is negligible, ensuring we remain blind to signal in data. Figure 7.5 and 7.6 shows the distributions of the analysis fit variables including the signal region $E_{\text{ECL}}^{\text{extra}} < 0.5 \text{ GeV}$. The agreement is good.

7.4 Sideband of M_{miss}^2 for leptons

We studied the M_{miss}^2 sideband control sample, obtained by requiring $M_{\text{miss}}^2 < 4 \text{ GeV}^2/c^2$, for the lepton channels. The signal yield in this region is negligible, ensuring that we remain blind to signal in data and also check the low $E_{\text{ECL}}^{\text{extra}}$ energy region. Figure 7.7 shows $E_{\text{ECL}}^{\text{extra}}$ distribution for electron and muon channels. The agreement is good. Only for the muon channel, we see a $\sim 2\sigma$ excess of data compared with MC for $0.8 < E_{\text{ECL}}^{\text{extra}} < 1 \text{ GeV}$ and we found this discrepancy to be related to the B_{tag} decay modes corresponding to $D^0\pi^-\pi^0$, $D^0\pi^-\pi^+\pi^-$, and $D^0\pi^-\pi^+\pi^-\pi^0$, and associate to this effect a systematic uncertainty.

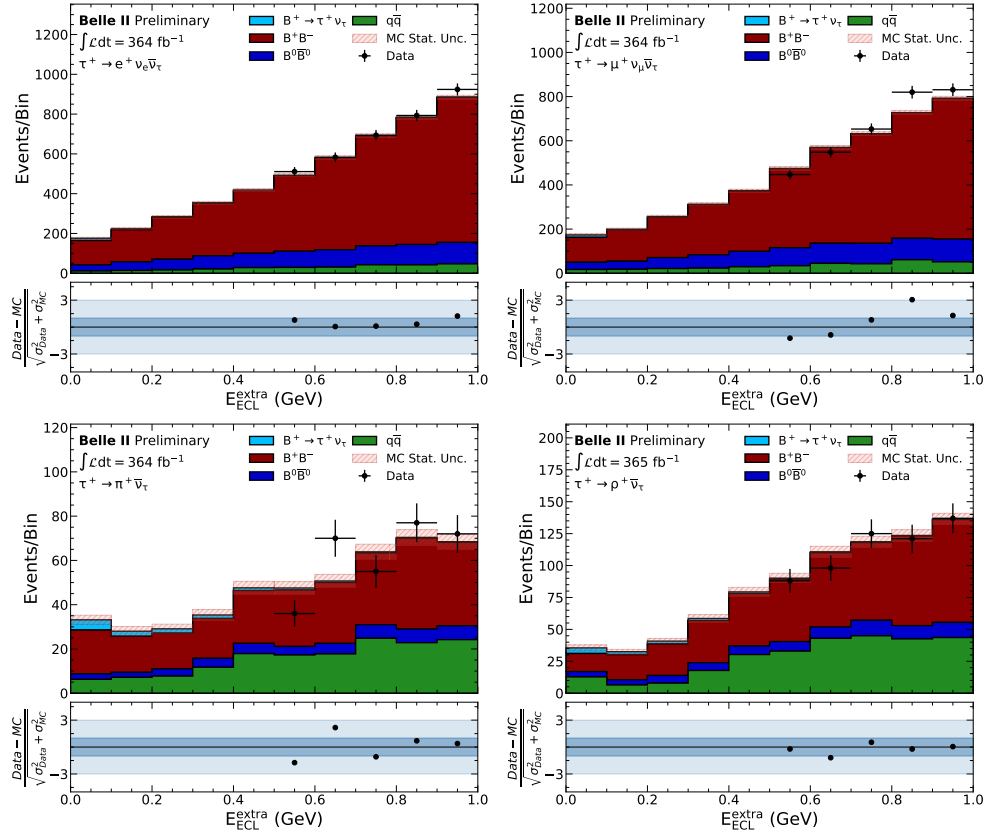


Figure 7.3: $E_{\text{ECL}}^{\text{extra}}$ distribution for the four signal channels after applying all the corrections in the $E_{\text{ECL}}^{\text{extra}} > 0.5$ GeV sideband.

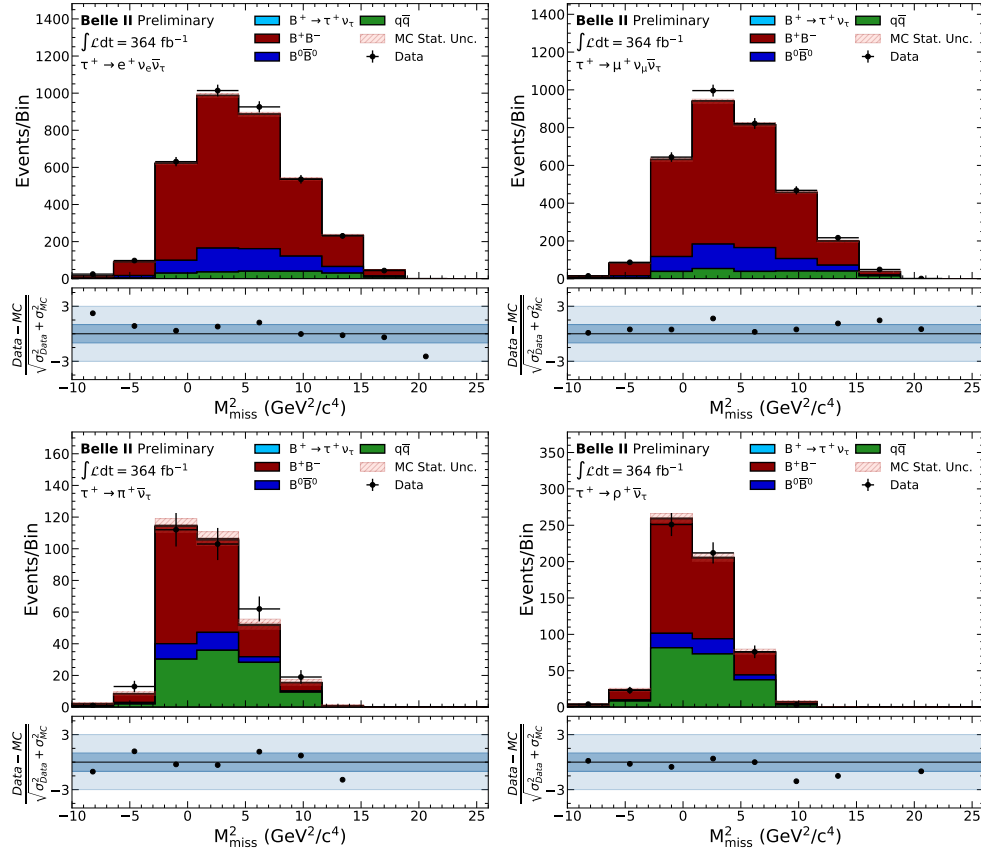


Figure 7.4: M_{miss}^2 distribution for the four signal channels after applying all the corrections in the $E_{\text{ECL}}^{\text{extra}} > 0.5$ GeV sideband.

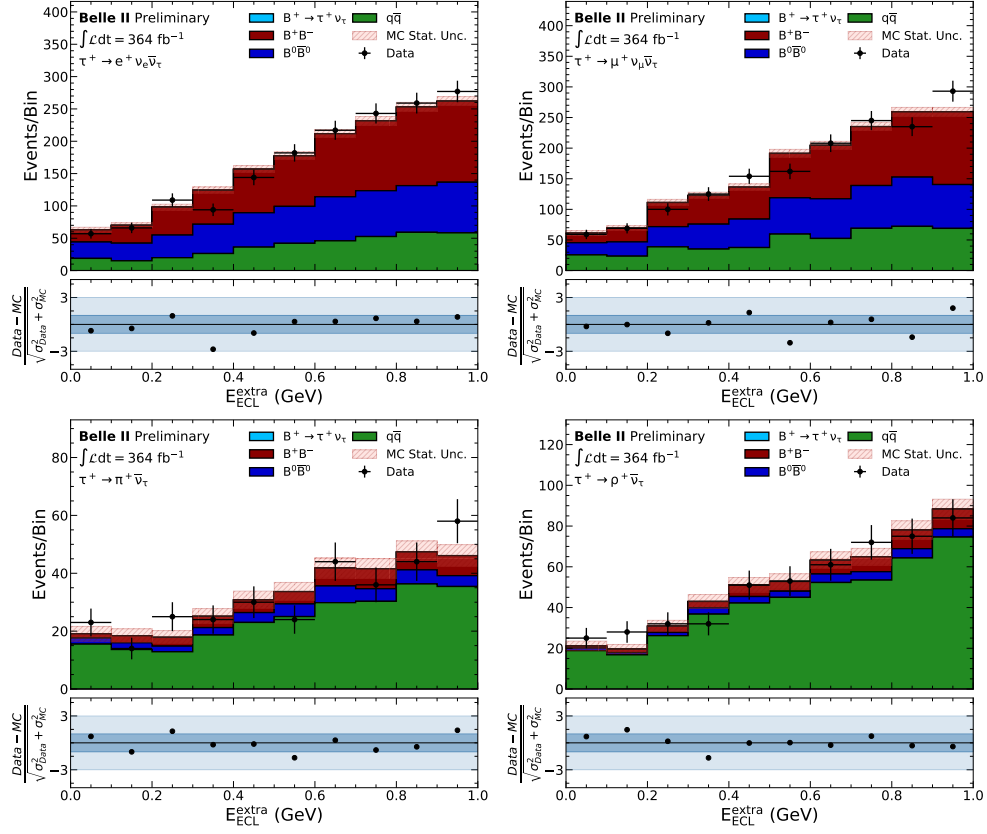


Figure 7.5: $E_{\text{ECL}}^{\text{extra}}$ distribution for the four signal channels after applying all the corrections in the $M_{bc} < 5.26 \text{ GeV}/c^2$ sideband.

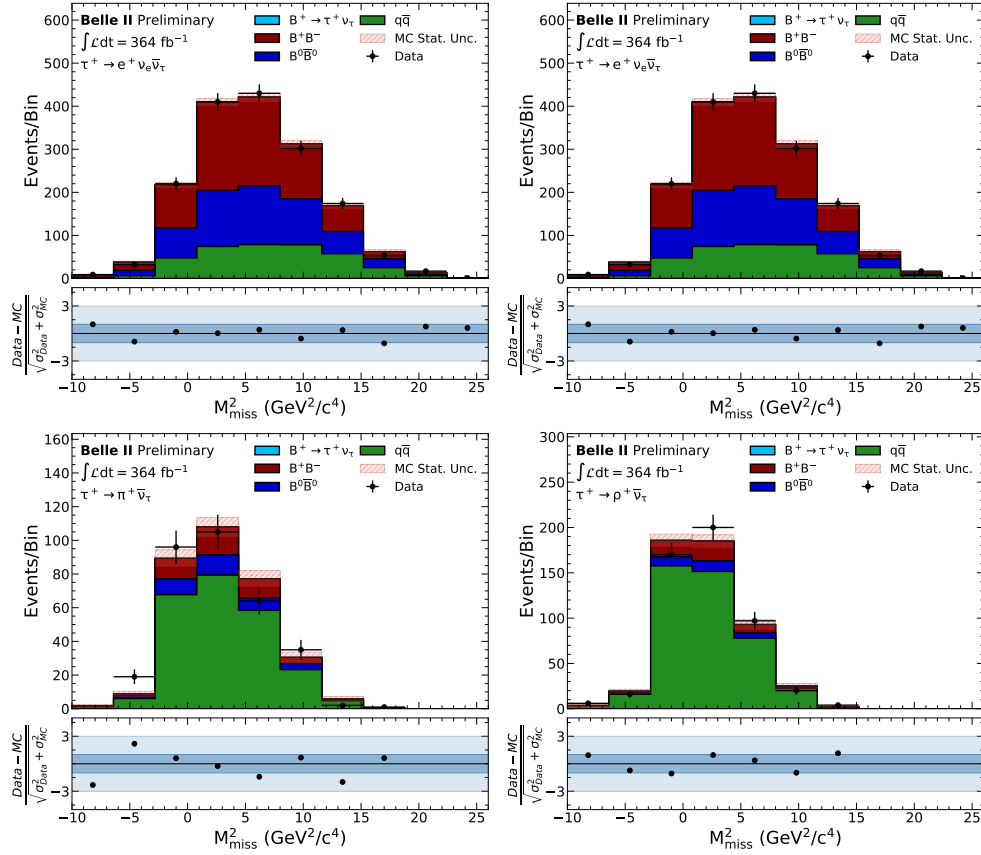


Figure 7.6: M^2_{miss} distribution for the four signal channels after applying all the corrections in the $M_{bc} < 5.26 \text{ GeV}/c^2$ sideband.

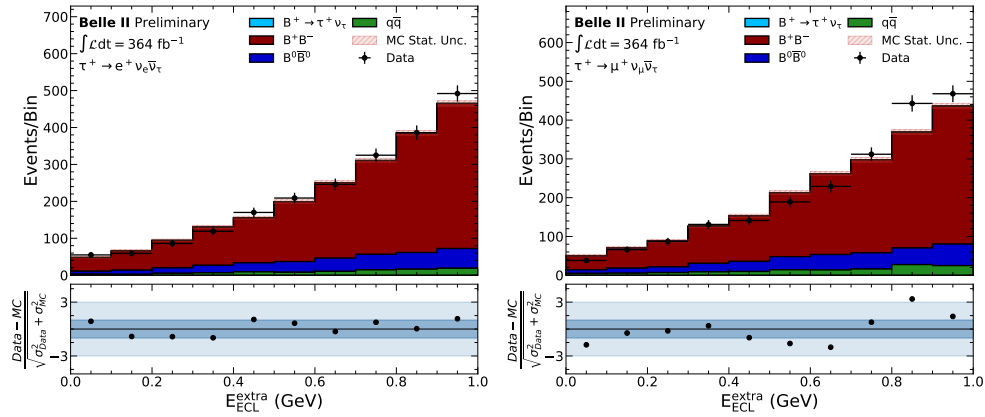


Figure 7.7: E^{extra}_{ECL} distribution in the leptonic channels after applying all the corrections in the $M^2_{\text{miss}} < 4 \text{ GeV}^2/c^2$ sideband.

7.5 Sideband of P_{cand} for hadrons

We studied the P_{cand} sideband control sample, obtained by requiring $P_{\text{cand}} < 1.2 \text{ GeV}/c$, for the hadron channels. The signal yield in this region is negligible, ensuring that we remain blind to signal in data and also check the low $E_{\text{ECL}}^{\text{extra}}$ energy region. Figure 7.8 shows $E_{\text{ECL}}^{\text{extra}}$ distribution for pion and ρ channels. The agreement is good.

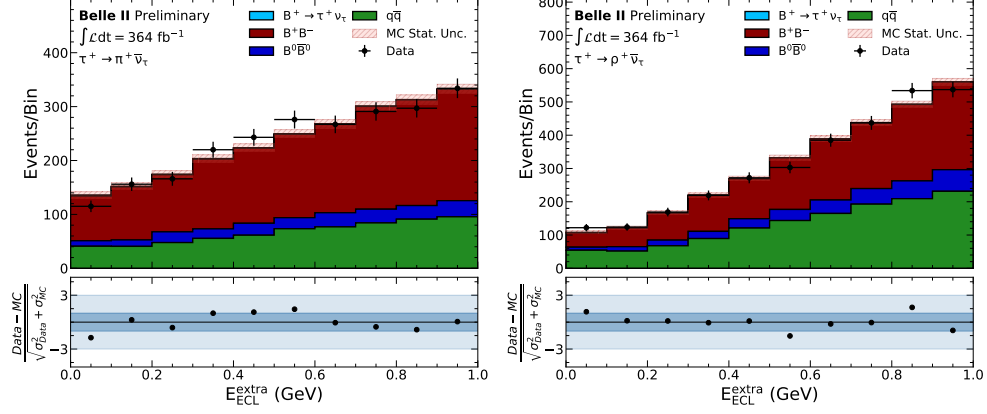


Figure 7.8: $E_{\text{ECL}}^{\text{extra}}$ distribution in the hadronic channels after applying all the corrections in the $P_{\text{cand}} < 1.2 \text{ GeV}/c$ sideband.

Chapter 8

Branching ratio extraction

We extract the $B^+ \rightarrow \tau^+ \nu_\tau$ branching ratio using a 2D simultaneous fit to $E_{\text{ECL}}^{\text{extra}}$ and M_{miss}^2 variables, with the branching ratio as a floating parameter common to the four reconstructed τ^+ modes. The other four floating parameters are the background yields, one yield for each τ^+ mode, left to float independently. The software used is RooFit [20] from the ROOT package. The four signal and background 2D PDFs are fixed in the fit and their shapes are taken from MC simulation and corrected following the procedure explained in Chapter 6. The templates do not present uncertainty in RooFit, but we consider separately each systematic uncertainty, as explained in Chapter 9. The Likelihood of the simultaneous fit is the product of the four likelihoods for the single τ^+ mode, reported in Chapter 5.

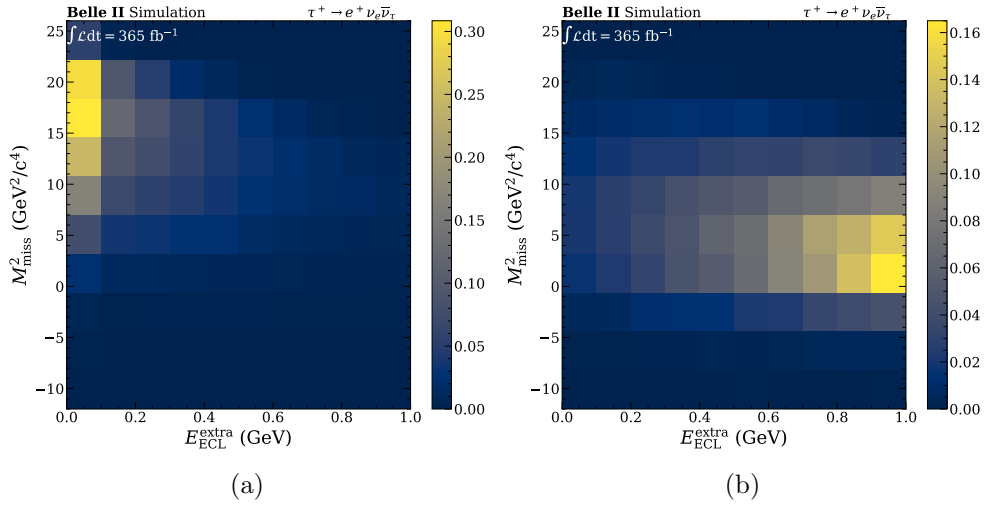


Figure 8.1: Two-dimensional PDFs of $E_{\text{ECL}}^{\text{extra}}$ and M_{miss}^2 from simulation for signal (a) and background (b) in the electron channel.

8.1 Sensitivity with ToyMC study

We estimate the sensitivity to the branching ratio of $B^+ \rightarrow \tau^+ \nu_\tau$ with a luminosity equivalent to the Belle II Run1 dataset, performing a 2D simultaneous maximum likelihood fit on $E_{\text{ECL}}^{\text{extra}}$ and M_{miss}^2 described above, with 10000 Toy MC pseudo-experiments in which the $E_{\text{ECL}}^{\text{extra}}$ and M_{miss}^2 distributions are extracted, using Poisson probability, from binned distribution of signal and background. The bin size is 100 MeV for $E_{\text{ECL}}^{\text{extra}}$ and 3.6 GeV^2/c^4 for M_{miss}^2 . For signal events, the shape is a binned distribution taken from signal MC simulation. Its integral is scaled to the data sample, using PDG [12] branching ratio $\mathcal{B}_{\text{input}} = 1.09 \times 10^{-4}$. Figures 8.1 -

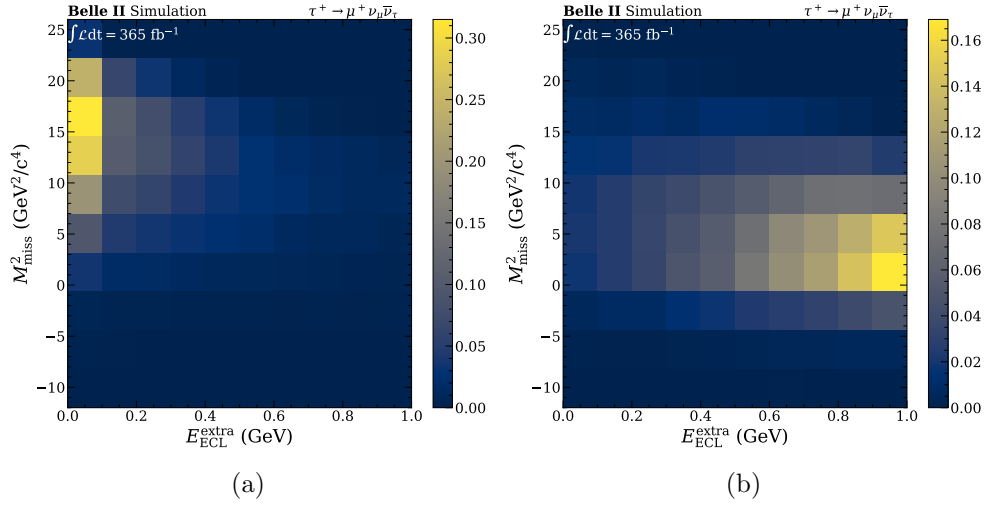


Figure 8.2: Two-dimensional PDFs of $E_{\text{ECL}}^{\text{extra}}$ and M_{miss}^2 from simulation for signal (a) and background (b) in the muon channel.

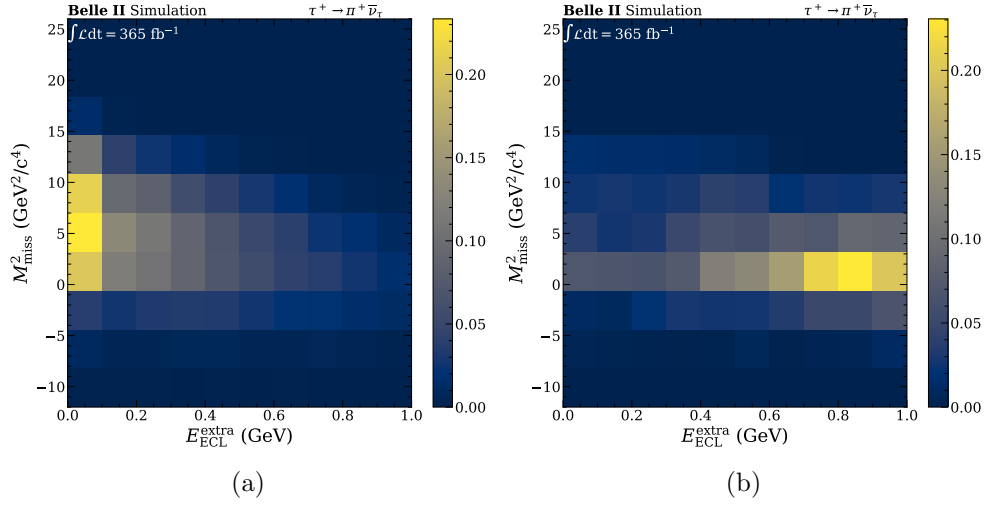


Figure 8.3: Two-dimensional PDFs of $E_{\text{ECL}}^{\text{extra}}$ and M_{miss}^2 from simulation for signal (a) and background (b) in the pion channel.

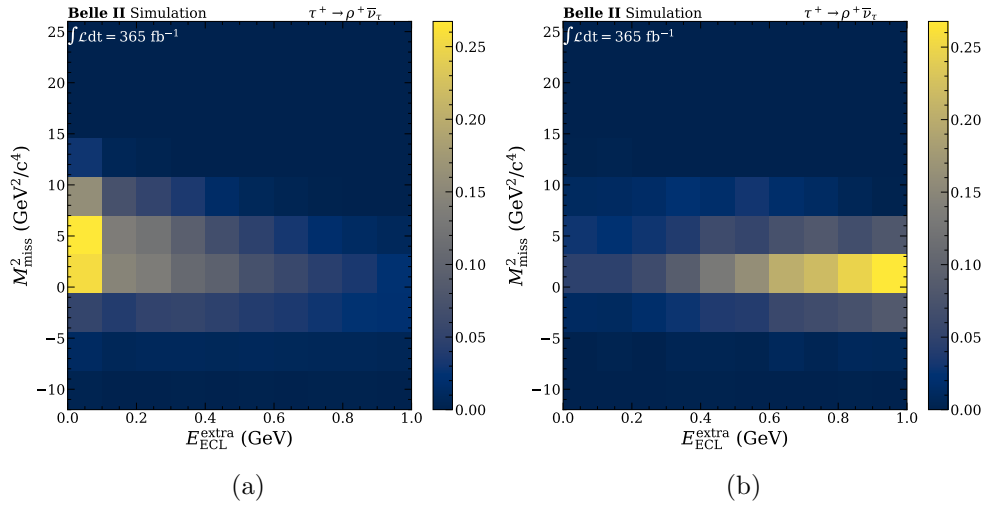


Figure 8.4: Two-dimensional PDFs of $E_{\text{ECL}}^{\text{extra}}$ and M_{miss}^2 from simulation for signal (a) and background (b) in the rho channel.

8.4 show the $E_{\text{ECL}}^{\text{extra}}$ and M_{miss}^2 from which the 2D PDFs are obtained, where the color stands for the PDF probability in each bin.

We estimate the expected uncertainty and bias by taking the average of the 10000 fit results (fitted $\mathcal{B}$ value and its fitted uncertainty).

We obtain a mean $\mathcal{B}_{\text{TOYs}} = 1.09(45) \times 10^{-4}$, corresponding to a 41% expected statistical uncertainty, and no bias. Figure 8.5 shows the distribution of the fitted $\mathcal{B}$ and the corresponding pull distribution, defined as $(\mathcal{B}_{\text{fit}} - \mathcal{B}_{\text{input}})/\sigma_{\text{fit}}$.

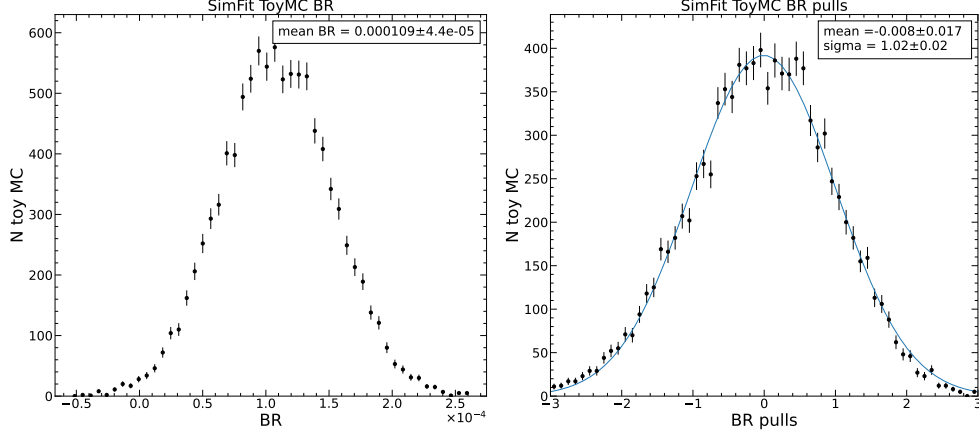


Figure 8.5: Toy MC Branching Ratio distribution (left) and its pull (right)

We assessed the robustness of the fit procedure, performing a linearity test. We repeated the Toy study (10000 Toy experiments) with 15 values of signal branching fraction (used to generate the signal toy events) from 0.5 to 2 times the PDG value used as input. We observe a linear and very stable slope, with a bias within 2% in all ranges as shown in Fig. 8.6.

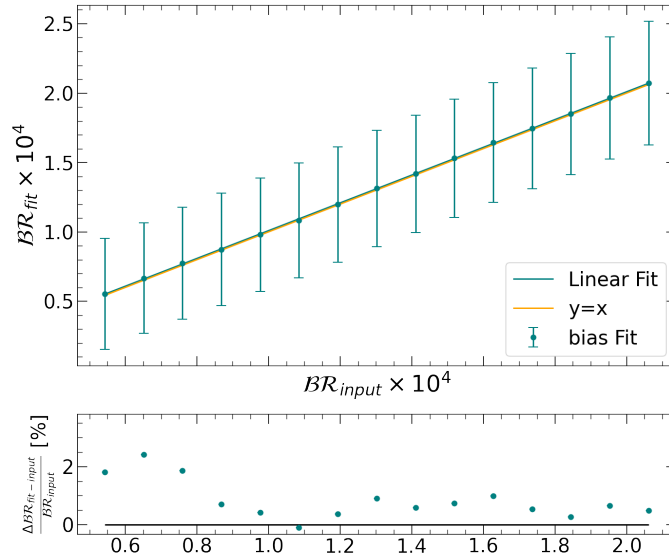


Figure 8.6: Results of various TOY Monte Carlo studies utilizing different Branching Ratio inputs, ranging from $0.5\times$ to $2\times$ the nominal value. **Top:** Comparison of Input value vs. Fit value (mean of the TOY). **Bottom:** Difference in percent.

Finally, we extrapolated the relative uncertainty (only the statistical one) at a future increasing luminosity, as shown in Fig. 8.7.

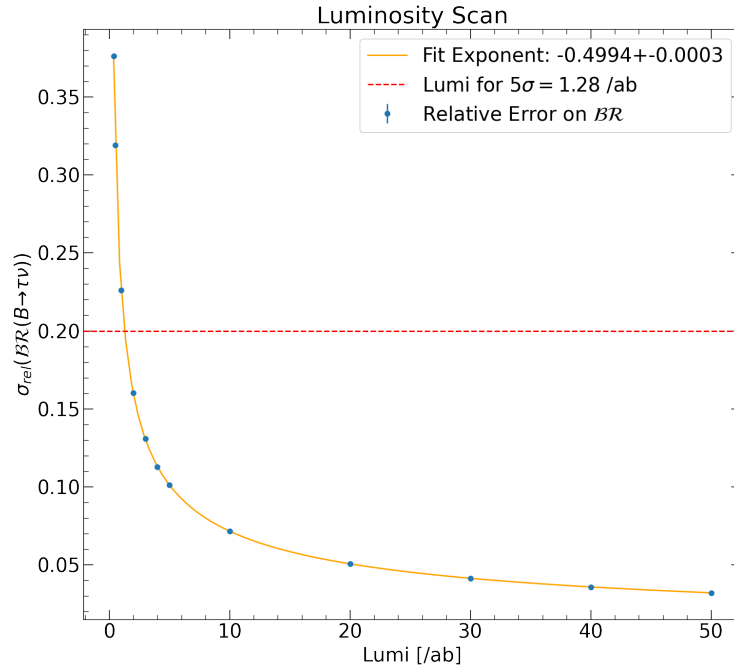


Figure 8.7: Results of various TOY Monte Carlo studies utilizing different integrated luminosities, ranging from the actual to 50 ab^{-1} . **Dotted Line:** Luminosity where a 5σ statistical significance is reached.

8.2 Final Fit and Result using data

As explained in the previous section, we extract $\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau)$ from an extended 2D maximum likelihood fit to the binned $E_{\text{ECL}}^{\text{extra}}$ and M_{miss}^2 distributions. Five parameters, the $\mathcal{B}$ and the four background yields are unconstrained in the fit.

We find:

$$\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau) = (1.24 \pm 0.41 \pm 0.19) \times 10^{-4} \quad (8.1)$$

Here, the first uncertainty is statistical, and the second is systematic (details on systematic uncertainties can be found in Chap. 9). To assess the goodness of fit, we generate pseudo-datasets using simulated distributions and reapply the fit to the resulting pseudo-data and we find that in 11% of the cases, the χ^2 values from the pseudo-data are worse than those from the data. In Figure 8.8 we show the projections of the fit for $E_{\text{ECL}}^{\text{extra}}$ and M_{miss}^2 distributions. In Figure 8.9 we show the signal-enhanced ($M_{\text{miss}}^2 > 10 \text{ GeV}^2/c^4$) fit projection for $E_{\text{ECL}}^{\text{extra}}$ distribution. The comparison of fitted background yields to the MC expectations is summarized in Table 8.1. Table 8.2 shows the values of $\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau)$ obtained by fitting all four τ^+ categories simultaneously and also by fitting each category independently.

We observe evidence of the signal with a significance of 3.0σ , which is determined through a hypothesis test by convolving the likelihood profile with a Gaussian distribution, where the width is defined by the total systematic uncertainty. The test statistic is computed as $-2 \log(\mathcal{L}/\mathcal{L}_0)$, where $\mathcal{L}$ is the likelihood with the signal yield allowed to vary, and $\mathcal{L}_0$ is the likelihood with the signal yield fixed to zero. We generate one million pseudo-datasets using the background-only PDF under the assumption of no signal, repeating the fitting process. The significance is then extracted from the p-value, which is the fraction of fit results having a test statistic value less than the one obtained from the data. This is illustrated in Fig. 8.10.

Table 8.1: Observed and expected (365 fb^{-1}) values of the background yields in the fit.

Parameter	Observed value	Expected value
n_{b,e^+}	4907 ± 71	4846 ± 24
n_{b,μ^+}	4620 ± 69	4493 ± 24
n_{b,π^+}	454 ± 22	461 ± 9
n_{b,ρ^+}	772 ± 28	811 ± 11

Table 8.2: Observed values of the signal yields and branching fractions, obtained from single fits for each τ^+ decay modes and the simultaneous fit.

Decay mode	n_s	$\mathcal{B}(10^{-4})$
Simultaneous	94 ± 16	1.24 ± 0.41
e^+	13 ± 16	0.51 ± 0.63
μ^+	40 ± 20	1.67 ± 0.83
π^+	31 ± 13	2.28 ± 0.93
ρ^+	6 ± 25	0.42 ± 1.82

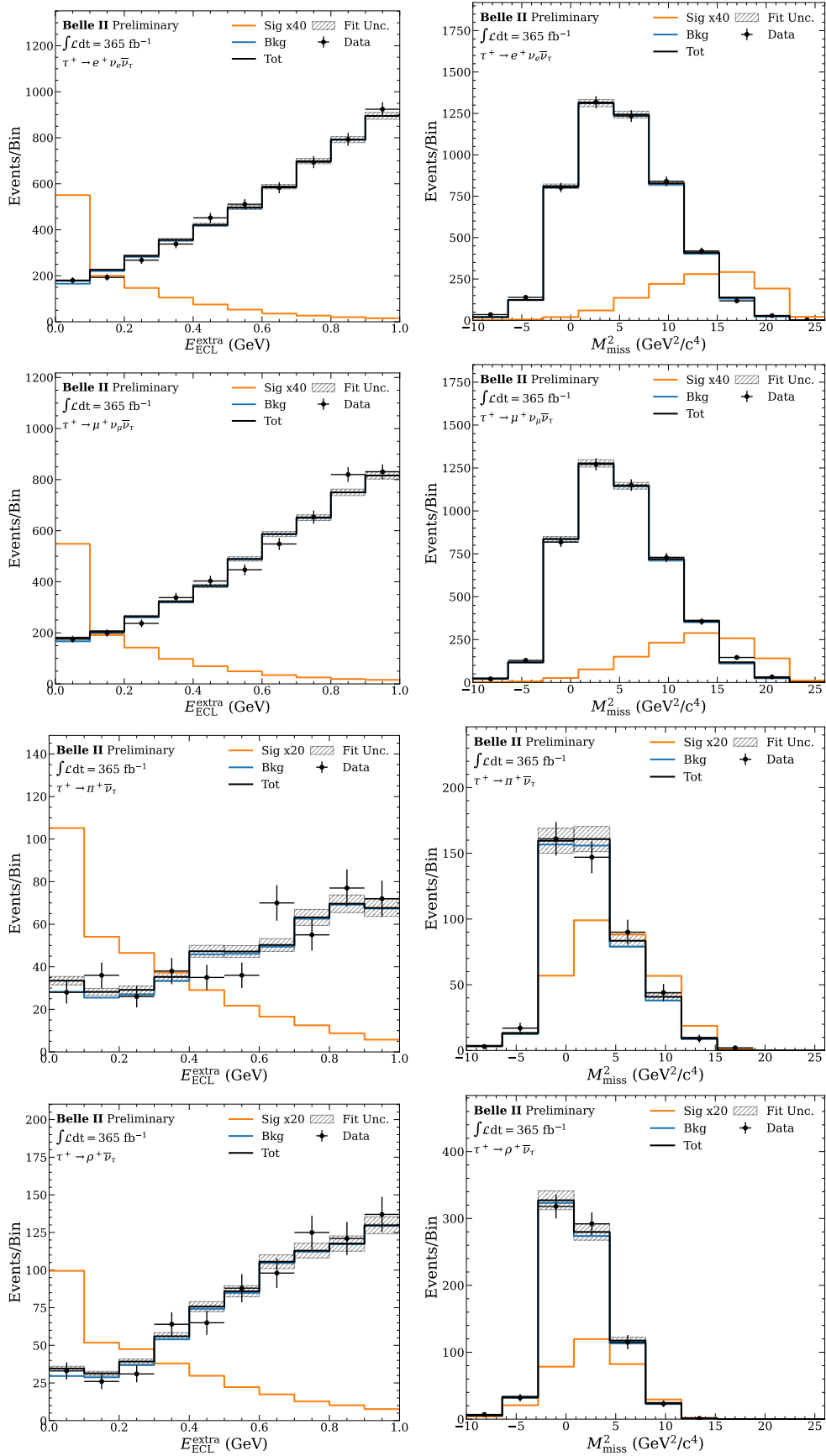


Figure 8.8: $E_{\text{ECL}}^{\text{extra}}$ (left) and M_{miss}^2 (right) post-fit distributions for each τ^+ category. The signal component is scaled by a factor of 40 for leptonic channels and 20 for hadronic channels to make it visible.

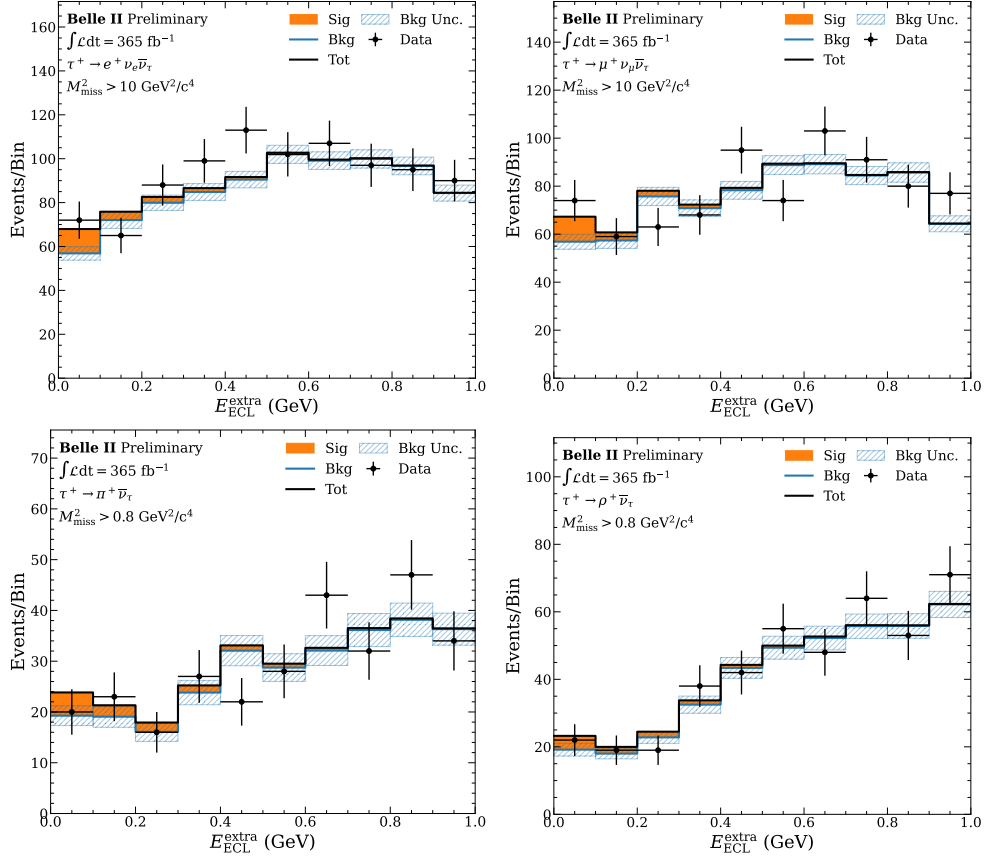


Figure 8.9: First row: post-fit distributions of $E_{\text{ECL}}^{\text{extra}}$ for the leptonic channels in the signal enriched region $M_{\text{miss}}^2 > 10 \text{ GeV}^2/c^4$. Second row: post-fit distributions of $E_{\text{ECL}}^{\text{extra}}$ for the hadronic channels in the signal enriched region $M_{\text{miss}}^2 > 0.8 \text{ GeV}^2/c^4$.

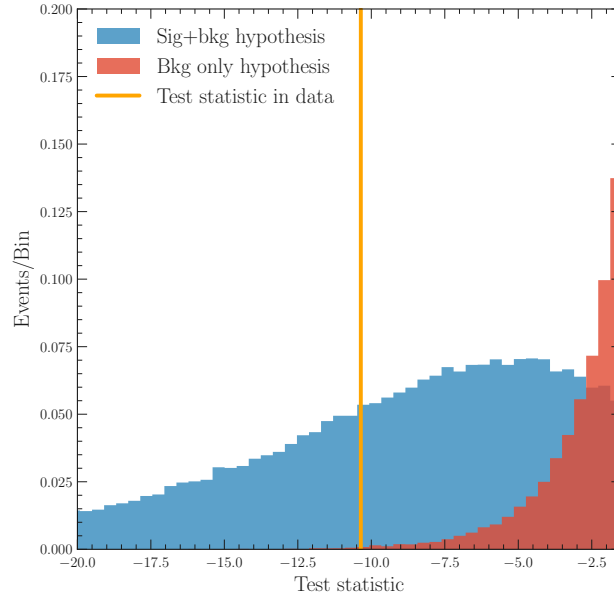


Figure 8.10: Test statistic distribution for the signal+background and the background-only hypotheses and the test statistic calculated using data.

8.2.1 Consistency checks

The robustness of the fit results is tested by splitting the total dataset into 4 smaller datasets with equal luminosity and then by checking the single fit of the 4 different categories used for the simultaneous fit. Fig. 8.11 shows the consistency of 8 fitted $\mathcal{B}$ s, 4 corresponding to the split datasets simultaneous fit results and the other 4 corresponding to the single fits of the 4 categories. We see consistency between the different results.

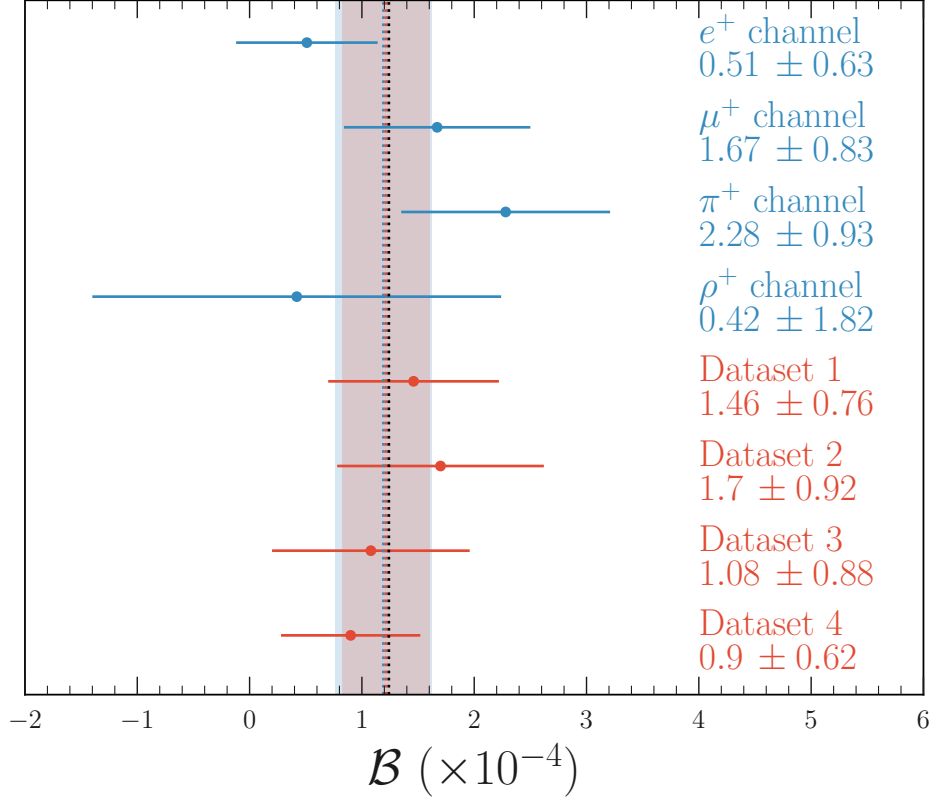


Figure 8.11: Distribution of the fitted $\mathcal{B}$ used for the consistency check. The black dotted line is the measured $\mathcal{B}$ from the simultaneous fit.

Chapter 9

Systematic uncertainties

In this section, we will detail all systematic evaluations, outlining how they contribute to the final result and the methodology used for their computation. In general, we apply variations on the sources of the largest systematic effects and evaluate the impact on the fitted branching ratio. This is performed by repeating the Toy MC studies, generating pseudo-experiments extracted from simulations p.d.f.s and repeating the fit with the modified assumptions from the different systematics effects. In the cases where the uncertainties in systematics correction do not affect the signal yields, as the number of $\Upsilon(4S)$, the fraction of B^+B^- , and the uncertainty on the tracking efficiency, the systematic uncertainty is propagated to the branching ratio uncertainty.

Table 9.1: Summary of systematic uncertainties (syst.) on the fitted branching fraction presented as relative uncertainties. The effect of each source is evaluated in the simultaneous fit of the four signal modes. The last three sources do not affect the signal yields.

Source	Syst.
Simulation statistics	13.3%
Fit variables PDF corrections	5.5%
Decays branching fractions in MC	4.1%
Tag B^- reconstruction efficiency	2.2%
Continuum reweighting	1.9%
π^0 reconstruction efficiency	0.9%
Continuum normalization	0.7%
Particle identification	0.6%
Number of produced $B\bar{B}$ pairs	1.5%
Fraction of B^+B^- pairs	2.1%
Tracking efficiency	0.2%
Total	15.5%

We identified and assessed the following systematics:

- **Simulation Statistics:** The systematic uncertainty related to the statistics of the simulation is evaluated by fluctuating the bin contents of the 2D histogram PDFs, assuming a Poisson distribution.
- **Fit Variables PDF Corrections:** To evaluate the systematic corrections to the $n_{\gamma\text{extra}}$

multiplicity, the bin-by-bin corrections are varied using Gaussian variations, with the variance derived from control samples.

- **Branching Fractions in MC Simulation:** To address potential discrepancies between the data and simulation arising from the branching fractions of the B and D meson decays in the MC simulation, we apply Gaussian variations to those branching fractions, with the variance determined from the latest PDG uncertainty [12].
- **Tag B^- Reconstruction Efficiency:** The B_{tag} reconstruction efficiency is calibrated using the $B^+ \rightarrow X\ell^+\nu_\ell$ and $B^+ \rightarrow D^*\pi^+$ control samples. We generate alternative calibration factor sets from the covariance matrix of the nominal calibration.
- **Continuum Reweighting:** Due to the limited size of the off-resonance sample, the continuum MC reweighting is affected. We apply a bootstrapping procedure and resample the training and test sets of the FBDT to generate different reweighting factors.
- **π^0 Reconstruction Efficiency:** Events containing a pion in the final state are categorized into the ρ (π) category if a π^0 is (is not) found in the $\rho^+ \rightarrow \pi^+\pi^0$ decay. Mis-modeling of π^0 reconstruction efficiency affects only the hadronic τ^+ decays. We analyze the data and MC agreement for the π^0 reconstruction efficiency in $D^{*0}(\rightarrow D^0\pi^0)\pi^+$ and $D^0 \rightarrow K^-\pi^+(\pi^0)$ decays over specific momentum ranges. Correction factors are determined for the MC π^0 efficiency, and a systematic uncertainty is assessed using a π^0 removal procedure. A random sequence is generated, and based on efficiency corrections, π^0 is removed, and the two γ s are reassigned to the ROE. The bias is negligible.
- **Continuum Normalization:** The continuum background fraction is varied by the statistical uncertainty of the off-resonance sample, producing alternative background PDFs via a Poisson distribution.
- **Particle Identification Efficiency:** The systematic uncertainty associated with lepton and hadron identification efficiency and fake rates is estimated from pure samples of pions and leptons in $D^{*+} \rightarrow D^0 (\rightarrow K^-\pi^+)\pi^+$, $\Lambda^0 \rightarrow p\pi^-$, $K_S^0 \rightarrow \pi^+\pi^-$, and $J/\psi \rightarrow \ell^+\ell^-$ data and MC samples. We assess the impact of these variations on the branching fraction fit by adjusting the PDF shapes and selection efficiencies based on the 1σ variations of lepton identification, π identification, and fake rate probabilities from control samples.

Chapter 10

Discussion

10.1 Comparison of the result with previous measurements

We compare our result with previous measurements. Fig. 10.1 shows the comparison of the $\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau)$ measurement from past experiments and the theoretical ones, using inclusive and exclusive $|V_{ub}|$ measurements [3].

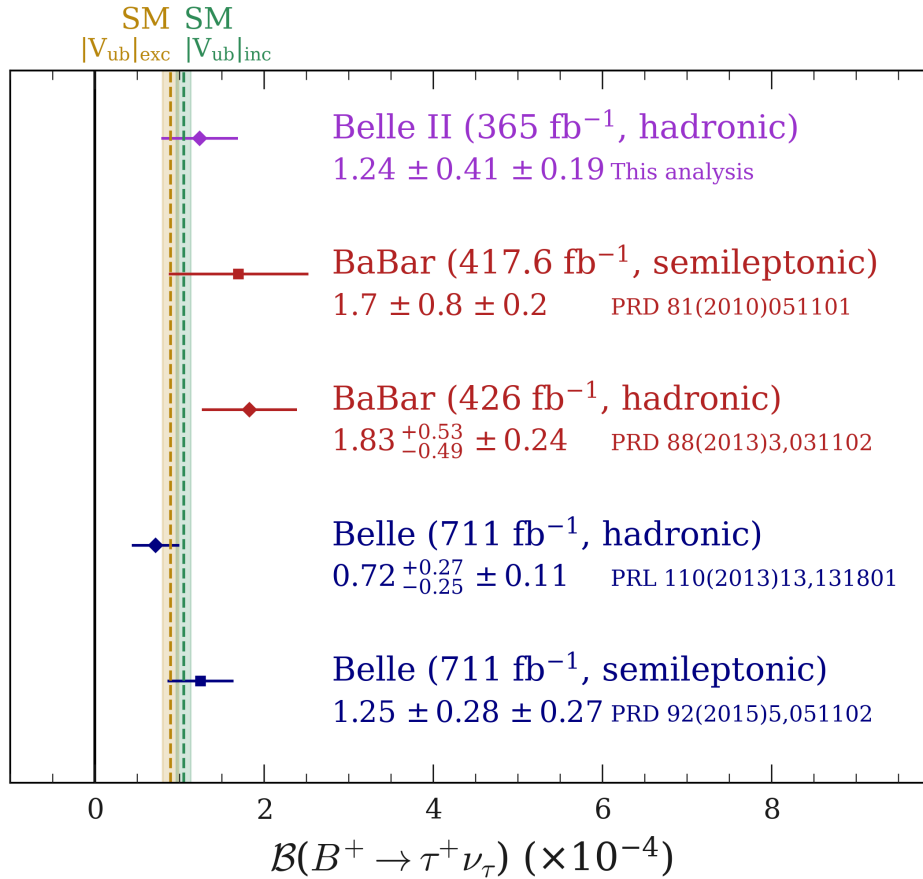


Figure 10.1: Branching fraction $\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau)$ measured by Belle II compared with the past measurements and the two SM expectation values, one calculated using the exclusive value $|V_{ub}| = (3.75 \pm 0.06 \pm 0.19) \times 10^{-3}$ and the other with the inclusive one $|V_{ub}| = (4.06 \pm 0.12 \pm 0.11) \times 10^{-3}$.

10.2 Combination with Belle result and new world average

We want to combine the Belle II result $x_{Belle2} = (1.24 \pm 0.41 \pm 0.19) \times 10^{-4}$ with the Belle one, particularly the combination obtained for the hadronic and semileptonic tagging analysis $x_{Belle} = (0.91 \pm 0.19 \pm 0.11) \times 10^{-4}$ [8]. Assuming a Gaussian distribution for x_{Belle2} and x_{Belle} and no correlation between the systematic uncertainties, we combine the two measurements with a weighted average:

$$\hat{x} = w_{Belle}x_{Belle} + w_{Belle2}x_{Belle2} \quad (10.1)$$

$$\sigma_{\hat{x}} = \frac{1}{\sqrt{w_{Belle} + w_{Belle2}}} \quad (10.2)$$

where $w_i = \frac{1}{1/\sigma_i^2}$. We obtain

$$\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau)_{Belle+Belle2} = (0.97 \pm 0.20) \times 10^{-4}, \quad (10.3)$$

where both statistical and systematic uncertainties are combined in quadrature. Assuming the SM, and using $f_B = 190.0(13)$ MeV [4], we can extract a measurement of the CKM matrix element

$$|V_{ub}| = [3.90_{-0.43}^{+0.38}] \times 10^{-3}, \quad (10.4)$$

with a relative uncertainty of $\sim 10\%$.

Finally, we want to combine the Belle II result with the last PDG average $\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau)_{PDG} = (1.09 \pm 0.24) \times 10^{-4}$. Assuming a Gaussian distribution for each measurement and no correlation between the systematic uncertainties, we obtain:

$$\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau) = (1.12 \pm 0.21) \times 10^{-4}. \quad (10.5)$$

10.3 Constraints on New Physics parameters

Using the new world average, we determine, separately for the exclusive value $|V_{ub}| = (3.75 \pm 0.06 \pm 0.19) \times 10^{-3}$ and inclusive value $|V_{ub}| = (4.06 \pm 0.12 \pm 0.11) \times 10^{-3}$ measurements [3], 68%, 90% and 99% C.L. exclusion regions in the parameter space of the 2HDM type II $[m_{H^\pm}, \tan \beta]$, where $m_{H^\pm}$ is the charged Higgs mass and $\tan \beta$ is the ratio of the vacuum expectation values of the two Higgs doublets, as discussed in Sec. 2.2. Figure 10.2 shows the exclusion plots with the old world average $\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau)_{PDG} = (1.09 \pm 0.24) \times 10^{-4}$. Figure 10.3 shows the exclusion plots with the new world average $\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau) = (1.12 \pm 0.21) \times 10^{-4}$. As in previous measurements, the constraints on the charged Higgs mass set a lower limit at the order of TeV for high $\tan \beta$ but with increased precision.

We include in the combined study from [1] the new $\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau)$ world average and the newest ATLAS result from a direct search of $H^+ \rightarrow \tau \nu$, with H^+ produced in top decays or in association with it, in the hMSSM [2]. In Fig. 10.4 we show the combined 95% C.L. exclusion region: $B^+ \rightarrow \tau^+ \nu_\tau$ exclusion region improves but the combined analysis excludes almost all the region.

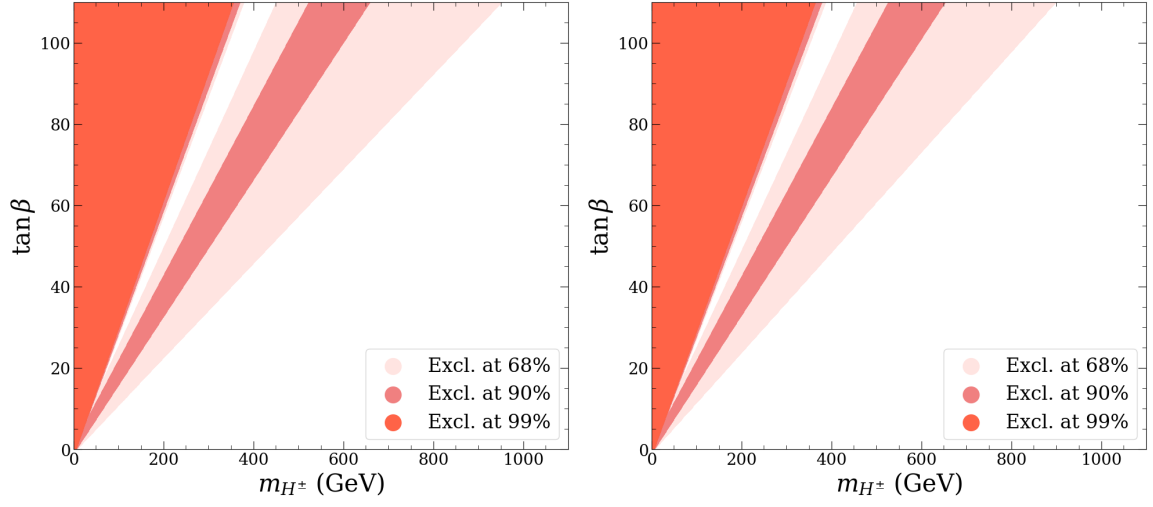


Figure 10.2: 68%, 90%, and 99% C.L. exclusion regions in the $[m_{H^\pm}, \tan \beta]$ plane using the old world average $\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau)_{PDG} = (1.09 \pm 0.24) \times 10^{-4}$ and exclusive (left) and inclusive (right) measurements of $|V_{ub}|$.

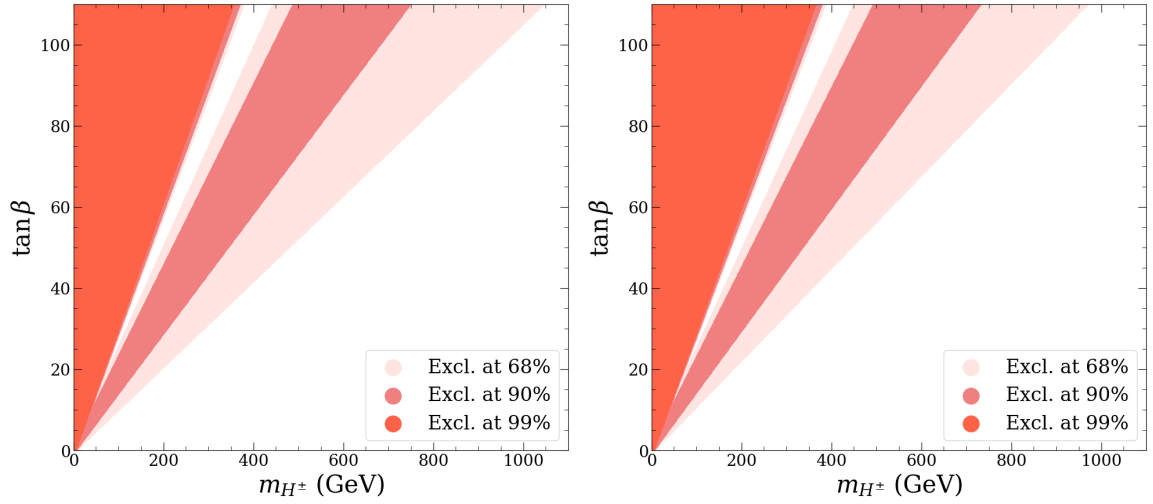


Figure 10.3: 68%, 90%, and 99% C.L. exclusion regions in the $[m_{H^\pm}, \tan \beta]$ plane using the new world average $\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau) = (1.12 \pm 0.21) \times 10^{-4}$ and the exclusive (left) and inclusive (right) measurements of $|V_{ub}|$.

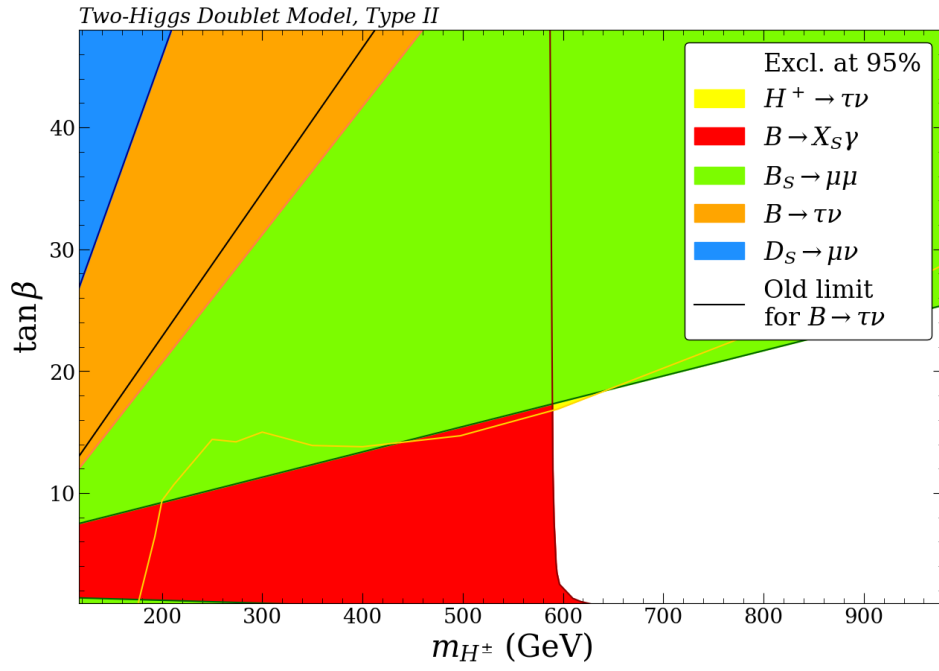


Figure 10.4: 95% C.L. exclusion region in the $[m_{H^\pm}, \tan \beta]$ plane from the combined study from [1] with the new $\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau)$ world average and the newest ATLAS result from a direct search of $H^+ \rightarrow \tau \nu$ in the hMSSM [2]. Almost all the region is excluded.

Conclusions

In this thesis, we presented the search for $B^+ \rightarrow \tau^+ \nu_\tau$ decays at the Belle II experiment using the Run 1 dataset, which corresponds to an integrated luminosity of 365 fb^{-1} . The analysis focused on extracting the branching fraction for this rare decay. Signal events were identified through τ lepton decays into a single charged particle, and after optimizing the selection criteria, correcting simulations, and validating the results, a 2D maximum likelihood fit was performed on the $E_{\text{ECL}}^{\text{extra}}$ and M_{miss}^2 distributions for each τ^+ decay mode. The resulting branching fraction from the simultaneous fits is:

$$\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau) = (1.24 \pm 0.41 \pm 0.19) \times 10^{-4} \quad (10.6)$$

where the first uncertainty is statistical, and the second is systematic. The fit produced a p-value of 11%, and the signal was observed with a significance of 3σ , accounting for systematic uncertainties. Under the SM assumption, this branching fraction yields a measurement of the CKM matrix element $|V_{ub}| B^+ \rightarrow \tau^+ \nu_\tau = [4.41_{-0.89}^{+0.74}] \times 10^{-3}$.

The result is consistent with previous measurements from the Belle and BaBar experiments and aligns well with the SM prediction. By combining this result with the world average, we also place constraints on possible new physics contributions, such as the mass of the charged Higgs boson and the ratio of vacuum expectation values $[m_{H^\pm}, \tan \beta]$ in the 2HDM Type II.

In future developments, efforts may focus on optimizing the signal selection to reduce the statistical uncertainty on the signal yield, improving background rejection through advanced neural networks, and more accurately estimating and rejecting the peaking background contribution.

Acknowledgment

Completing this PhD has been a significant journey in my life, and it would not have been possible without the support, encouragement, and guidance of many people. I would like to express my heartfelt gratitude to everyone who contributed to this accomplishment.

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Finally, I would like to dedicate this thesis to all the mentors, friends, and family who have been part of my academic journey. Your belief in my abilities has been my greatest strength.

Thank you all.

Appendix A

Beam Loss Monitor in SuperKEKB/Belle II

The SuperKEKB/Belle II experiment is focused on collecting high-statistics data from B meson pairs to investigate potential NP. The upgraded KEKB accelerator, now known as SuperKEKB, achieved a world record luminosity of $5.1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ in 2024, with ongoing efforts aimed at further increasing luminosity. A key challenge in this process is the occurrence of Sudden Beam Loss (SBL) events, which lead to significant beam losses and cause damage to the Belle II detector. To address this challenge, we have developed advanced beam diagnostics, installing several loss monitor detectors and enhancing beam abort systems. The diagnostic system is designed to pinpoint the onset of beam losses with high precision, while the upgraded abort system ensures rapid disposal of any anomalous beams, minimizing potential damage.

My contributions focused on analyzing the data from the Bunch Oscillation Recorder (BOR), which ultimately led to the installation of additional detectors along the SuperKEKB rings. Additionally, I was involved in the upgrade and installation of new CLAWS (Scintillator Light and Waveform Sensors), which enhanced the beam abort timing by 5-10 μs during the 2024 operational period.

A.1 BOR Analysis

The BOR system is designed to track beam positions on a bunch-by-bunch basis over several turns, right before a beam abort. Before the Belle II Long Shutdown 1 (LS1), only a single BOR was installed on each ring, primarily serving as a monitor for the Bunch Feedback System. However, this configuration was insufficient for accurately identifying the location and cause of SBL events. After calibrating the BOR output data and converting the counts to millimeters, we analyzed beam oscillations recorded in 2022. Our analysis revealed that in many cases, oscillations began several beam cycles prior to the actual losses.

Figure A.1 presents an example of a beam loss event from June 9, 2022, at 04:26:20 (QCS Quench) for the BOR output corresponding to the LER. The first row shows the calibrated output for horizontal oscillations, and the second row shows the vertical oscillations; the third row corresponds to the Bunch Current Monitor (BCM) output, and the fourth row shows the BCM loss. Vertical lines indicate the start of oscillations or beam loss, and in this case, the vertical oscillations in the BOR start 9.29 μs before the BCM loss. Upon analyzing all SBLs from 2022, we observed that in most cases, the BOR's orbit change occurs before the BCM loss.

The next step involved comparing the BOR data with that from the loss monitors we installed as part of the advanced beam diagnostic system. Figure A.2 compares the timing of the BOR oscillations and the fastest loss monitor timing. In general, the beam orbit change

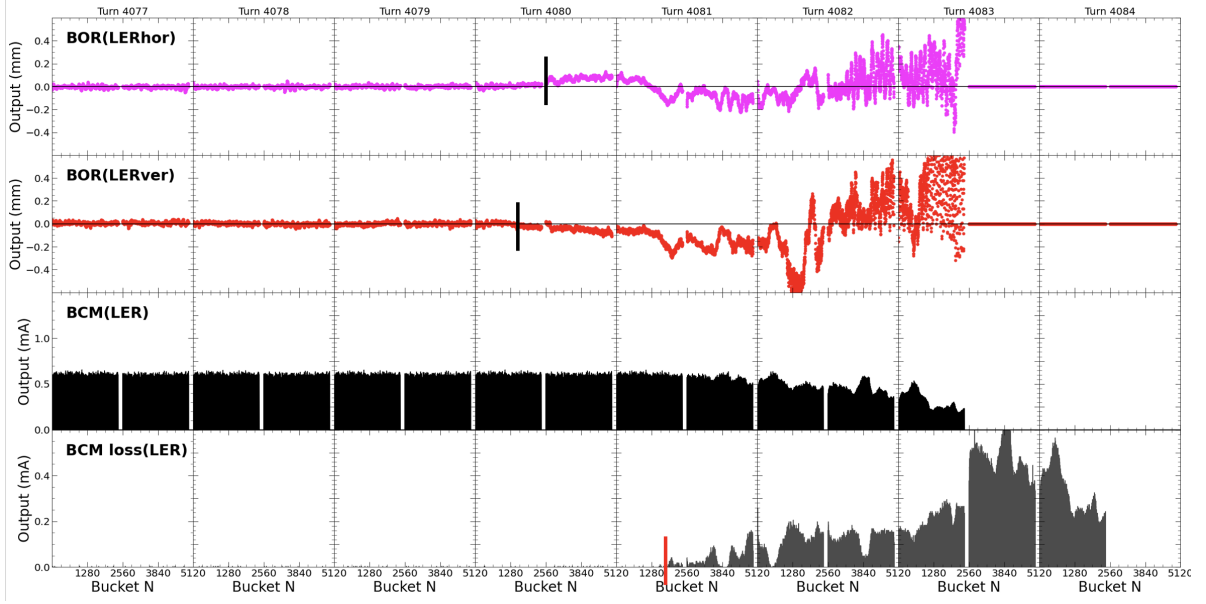


Figure A.1: BOR output for both horizontal (first row) and vertical (second row) oscillations and BCM output (third row) and BCM loss (fourth row); vertical lines show the start of oscillation/beam loss.

starts either before or at the same time as the loss monitors. However, after the D06V2 collimator was closed, a change in trend was observed.

Following these insights, BOR was utilized as an additional monitoring system to study the internal processes of the accelerator. Between the 2022 and 2024 shutdowns, a new BOR system was developed and installed, and it is currently in operation during SuperKEKB runs. Research and development on an enhanced BOR system are underway to enable its use as a new abort signal source.

A.2 New CLAWS Installation

CLAWS sensors are $1.3 \text{ mm} \times 1.3 \text{ mm}$ Silicon Photomultipliers paired with a $3 \text{ cm} \times 3 \text{ cm} \times 3 \text{ mm}$ Plastic Scintillator, designed to be sensitive to penetrating charged particles. These sensors have a fast rising edge ($< 4 \text{ ns}$), an amplitude of 100-150 mV, and a signal decay time of approximately 50-70 ns.

During LS1, four CLAWS sensors were installed around the D05V1 collimator as shown in Figure A.4. One sensor was placed upstream of the collimator, and the remaining three were positioned downstream.

By early 2024, the commissioning of the newly installed CLAWS sensors was completed. Figure A.5 shows a typical signal recorded during a beam abort. Sensors 1 (upstream) and 4 (most downstream) detected larger beam losses, especially during SBL events. The loss around the collimator caused all CLAWS sensors to saturate. Sensor 2 was chosen as the abort sensor to accommodate a wider threshold range for abort signals. Initially, the abort threshold was set at 35 mV, but this was later increased to 100 mV by the end of the 2024 spring run. The pulse width (duration) of the signal was also incorporated into the abort logic to differentiate SBLs from other beam losses or noise. During SBL events, significant beam losses typically lasted over $1 \mu\text{s}$, and an abort request was triggered when the beam loss signal exceeded 180 ns in duration. An injection veto was also added to the D05 CLAWS abort logic to prevent abort requests for 1 ms after injection. This veto timing was refined during the 2024 spring operations. Integration studies for CLAWS into the abort system were

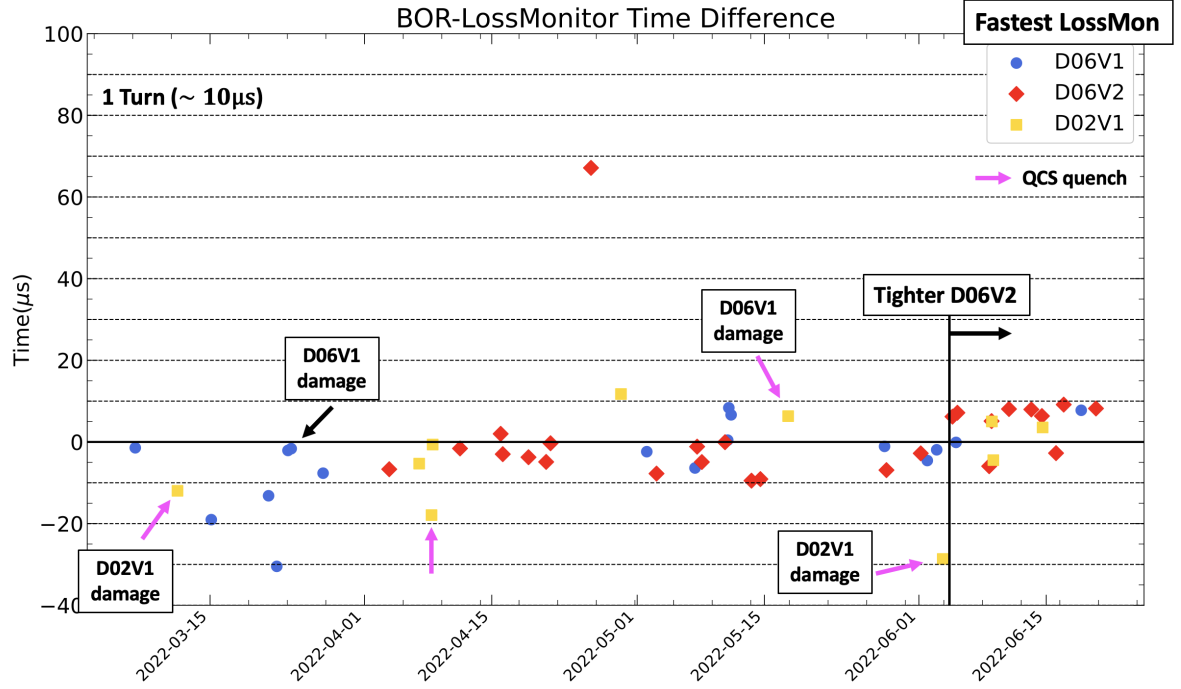


Figure A.2: Comparison of the BOR oscillation start timing and fastest loss monitor timing. In general, the change in beam orbit begins before or at the same time as the loss monitors. After the collimator D06V2 was closed, a shift in the trend is observed.

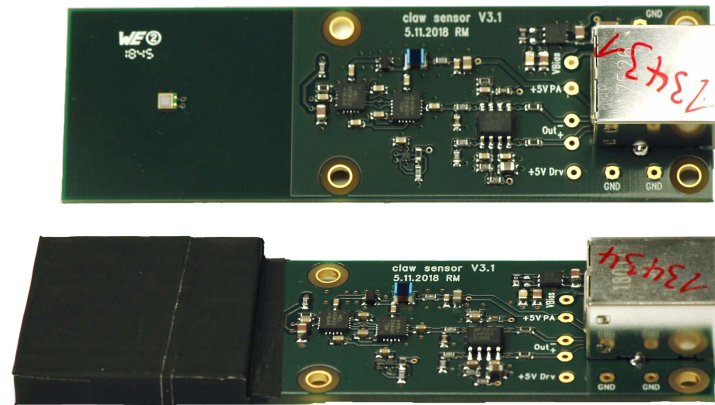


Figure A.3: CLAWS sensors: 1.3 mm $\times$ 1.3 mm Silicon Photomultiplier and 3 cm $\times$ 3 cm $\times$ 3 mm Plastic Scintillator.

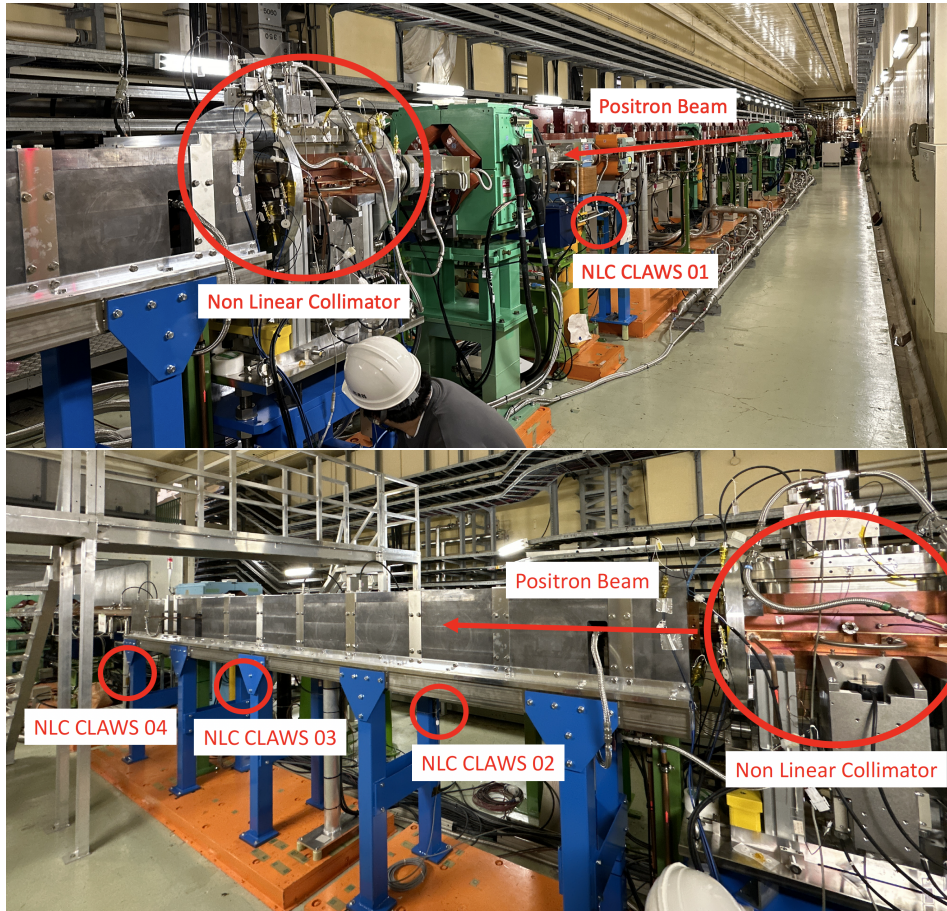


Figure A.4: New CLAWS sensors installed around the D05V1 collimator: (top) one sensor positioned upstream, (bottom) three sensors placed downstream.

carried out by generating pseudo-abort requests with the new CLAWS sensor. These requests were compared with the responses from the operational abort trigger system. In most cases, CLAWS pseudo-abort requests were faster than the operational abort trigger, with response times depending on which sensor initiated the request first. The tests demonstrated the CLAWS system's effectiveness, with only one instance of an unnecessary abort request during the commissioning period. Given the infrequent occurrence (approximately once per week), this was considered acceptable for beam operations.

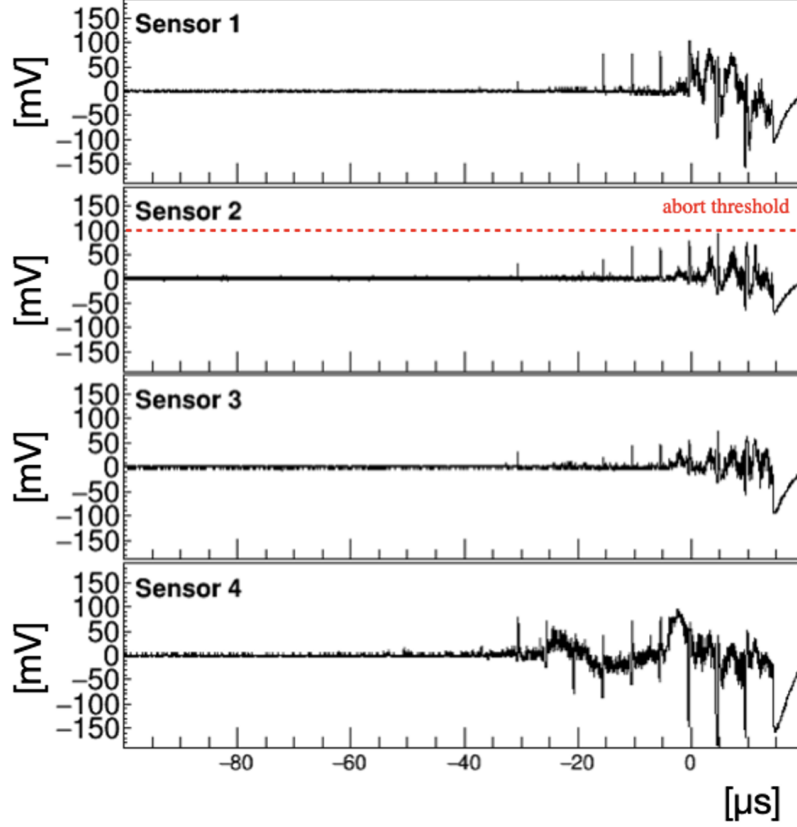


Figure A.5: Typical outputs of CLAWS sensor. The signal magnitudes correspond to the beam loss magnitude detected at each sensor.

Following these successful tests, CLAWS sensors were officially integrated as the abort sensor for the SuperKEKB LER by the end of March 2024. During the spring 2024 operations, the D05V1 CLAWS recorded 168 SBL events in the LER, generating the fastest abort request signal in 148 of these cases, typically 5-10 μs earlier than the second-fastest source. This enhancement is expected to significantly reduce beam losses and mitigate damage to the IR components. Due to the strong performance of the D05V1 CLAWS, additional units were installed around the D06V1 collimator during the 2024 summer shutdown, and further installations are planned for the 2025 long shutdown.

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