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Thesis for the Doctor of Philosophy

Search for the $B^0 \rightarrow \tau^+ \tau^-$ at the Belle II experiment



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Graduate School of Hanyang University

August 2025

Thesis for the Doctor of Philosophy

Search for the $B^0 \rightarrow \tau^+ \tau^-$ decay at the Belle II experiment

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A Thesis submitted to the graduate school of
Hanyang University in partial fulfillment of the requirements
for the degree of Doctor of Philosophy

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August 2025

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이 논문을 김철훈의 박사학위 논문으로 인준함

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Abstract

Search for the $B^0 \rightarrow \tau^+\tau^-$ decay at the Belle II experiment

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We present the results of a search for the rare decay $B^0 \rightarrow \tau^+\tau^-$ at the Belle II experiment using the SuperKEKB asymmetric electron-positron collider. The results are based on Monte Carlo simulation samples, corresponding to the $\Upsilon(4S)$ data sample with an integrated luminosity of 363 fb^{-1} . For stable data-taking, the trigger slow control system plays a crucial role, and its description is provided.

The Standard Model predicts that the branching fraction of this decay mode is highly suppressed, while several extensions of the model expect enhancements. A hadronic tagging method is employed to fully reconstruct one of the B mesons, and the signal is searched for in the remainder of the event.

The upper limit on the branching fraction of the decay $B^0 \rightarrow \tau^+\tau^-$ is estimated as

$$\mathcal{B}(B^0 \rightarrow \tau^+\tau^-) < 2.20 \times 10^{-3}$$

at the 90% confidence level.

Chapter 1

Introduction

Decays of B mesons into pairs of oppositely charged leptons are useful for probing new physics beyond the Standard Model. These decays have very small branching fractions in the Standard Model (SM), but some beyond-the-SM (BSM) models predict the possibility of enhancements.

This chapter begins with an overview of the effective field theory (EFT) in Section 1.1. The SM predictions are then summarized in Section 1.2, followed by possible enhancements expected in beyond-the-SM scenarios in Section 1.3, both discussed within the EFT framework. Finally, we review relevant results from previous experimental searches in Section 1.4.

1.1 Effective field theory

Effective field theory is based on the assumption that the Standard Model emerges as a low-energy approximation of an extended fundamental theory [1].

The concept and construction of effective field theory can be found in [2]. The obtained effective Hamiltonian $\mathcal{H}_{\text{eff}}$ contains local operators that describe processes

at low energies, and can be written as

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \sum_i V_{\text{CKM}}^i C_i(\mu) Q_i, \quad (1.1)$$

where the index i denotes different operators, G_F is the Fermi coupling constant, V_{CKM} are the Cabibbo–Kobayashi–Maskawa (CKM) matrix elements [3], Q_i are the local operators, and $C_i(\mu)$ are the Wilson coefficients evaluated at scale μ .

The operators relevant to the decay $b \rightarrow d\ell^+\ell^-$ in the SM are

$$Q_S = m_b(\bar{b}P_L d)(\bar{\ell}\ell), \quad (1.2)$$

$$Q_P = m_b(\bar{b}P_L d)(\bar{\ell}\gamma_5\ell), \quad (1.3)$$

$$Q_A = (\bar{b}\gamma^\mu P_L d)(\bar{\ell}\gamma_\mu\gamma_5\ell), \quad (1.4)$$

where $P_L = (1 - \gamma_5)/2$, m_b is the b -quark mass, and γ_μ, γ_5 are the Dirac matrices. The Wilson coefficients C_S , C_P , and C_A correspond to scalar, pseudo-scalar, and axial-vector interactions, respectively.

The effective Hamiltonian in the SM then becomes

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \frac{\alpha_{\text{em}}}{\sin^2 \theta_W} V_{tb}^* V_{td} [C_S(\mu) Q_S + C_P(\mu) Q_P + C_A(\mu) Q_A], \quad (1.5)$$

where α_{em} is the fine-structure constant and θ_W is the Weinberg angle. The terms V_{tb}^* and V_{td} are elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, reflecting the quark flavor mixing.

1.2 SM prediction

In the Standard Model, these $B^0 \rightarrow \ell^+ \ell^-$ ($\ell = e, \mu$ or τ) decays can be explained using box and penguin diagrams, as illustrated in Figure 1.1.

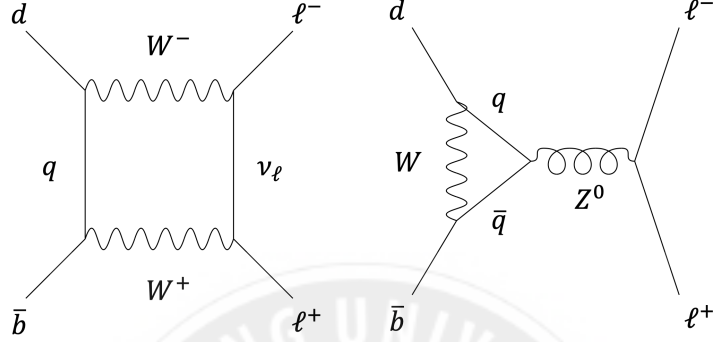


Figure 1.1: The standard model box and penguin diagram of $B^0 \rightarrow \ell^+ \ell^-$ ($q = t, c$ or u)

The decay $B^0 \rightarrow \tau^+ \tau^-$ proceeds via flavor-changing neutral current (FCNC) processes, which are highly suppressed at the tree level and occur only through higher-order loop diagrams.

To get the effective Hamiltonian describing the $b \rightarrow d \ell^+ \ell^-$ transition under SM, we should consider the coefficient C_S and C_P in the equation 1.5. The coefficient C_S receives contributions from Higgs boson exchange, but in the SM these are suppressed by a factor of $\mathcal{O}(M_B^2/M_W^2)$ and can be neglected [4]. The coefficient C_P gets a contribution in the same order of magnitude from the would-be neutral Goldstone boson and can also be neglected [4]. The resulting effective Hamiltonian can be expressed as below [1].

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \frac{\alpha_{em}}{\sin^2 \theta_W} V_{tb}^* V_{td} C_A(\mu) (\bar{b} \gamma^\mu P_L d) (\bar{\ell} \gamma_\mu \gamma_5 \ell) \quad (1.6)$$

The dominant SM contribution is from Q_A . The Wilson coefficient $C_A(\mu)$ en-

capsulates the short-distance physics at the energy scale μ , including contributions from box and penguin diagrams. The operator $(\bar{b}\gamma^\mu P_L d)(\bar{\ell}\gamma_\mu\gamma_5\ell)$ describes an axial-vector interaction between the b and d quarks and the charged leptons ℓ .

This structure leads to a strong helicity suppression proportional to m_ℓ^2 , making decays into light leptons (electrons and muons) extremely rare, while the branching fraction for $B^0 \rightarrow \tau^+\tau^-$ can be comparatively enhanced.

The branching fraction for the decay $B^0 \rightarrow \ell^+\ell^-$ in the Standard Model is given by

$$\mathcal{B}(B^0 \rightarrow \ell^+\ell^-) = \frac{G_F^4 M_W^4 M_B^3}{8\pi^5 \Gamma_B} \cdot f_B^2 \cdot |V_{tb}^* V_{td}|^2 \cdot \frac{4m_\ell^2}{M_B^2} \cdot \sqrt{1 - \frac{4m_\ell^2}{M_B^2}} \cdot |C_A(\mu)|^2, \quad (1.7)$$

where G_F is the Fermi coupling constant, M_W is the mass of the W boson, M_B and Γ_B are the mass and total decay width of the B^0 meson, respectively, and f_B is the B^0 decay constant. The term $|V_{tb}^* V_{td}|$ represents the relevant CKM matrix elements, while the factor $4m_\ell^2/M_B^2$ reflects the helicity suppression (HS) characteristic of purely leptonic decays. The phase space factor (PSF) $\sqrt{1 - 4m_\ell^2/M_B^2}$ further suppresses the decay rate for lighter leptons. The Wilson coefficient $C_A(\mu)$ encapsulates the short-distance contributions at the renormalization scale μ .

Figure 1.2 illustrates the relation between $HS \times PSF$ and x (Here, $x = 2m_\ell/M_B$). For the $B^0 \rightarrow \tau^+\tau^-$ decay, the branching fraction is relatively large due to the heavy mass of the τ lepton. However, its experimental reconstruction is challenging because τ leptons decay before reaching the detector, resulting in final states with missing particles. In contrast, although the branching fraction for $B^0 \rightarrow \mu^+\mu^-$ is approximately two orders of magnitude smaller, muons can be identified directly at the detector level, making the decay experimentally more accessible. The $B^0 \rightarrow e^+e^-$ decay mode has a branching fraction that is too small to be observed with

current experimental sensitivity.

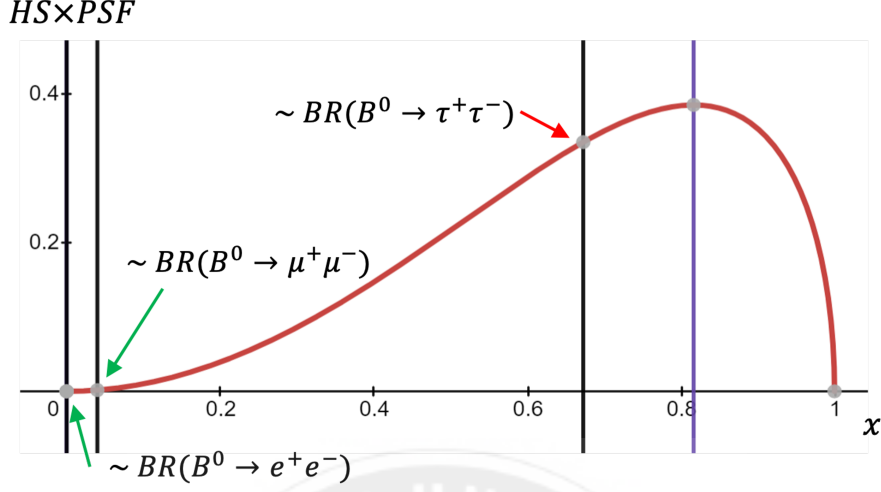


Figure 1.2: HS×PSF graph.

1.3 BSM theories

In this section, two extensions of SM are discussed: The two Higgs-doublet model, and leptoquark model.

1.3.1 Two Higgs-Doublet Model (2HDM)

In the two Higgs-doublet model (2HDM) of type II, the Higgs sector contains two doublet scalar fields. This leads to additional charged and neutral Higgs bosons ($H^\pm, A^0$) which can replace the role of the W and Z bosons in the decay [4]. In Figure 1.3, a box and a penguin diagram are shown where the H^+ and A^0 replace the W and Z boson, respectively. By including these new particles, sizable effects on Wilson coefficients C_S and C_P defined in Eq. (1.8), can occur. The Wilson coefficient C_A is not influenced by the 2HDM and remains unchanged. Comprising the effects from the 2HDM, the branching ratio reads as follows

$$\begin{aligned}
\mathcal{B}(B^0 \rightarrow \ell^+ \ell^-)_{\text{2HDM}} &= \frac{G_F^4 M_W^4}{128 \pi^5} \frac{M_B^3}{\Gamma_B} f_B^2 |V_{tb}^* V_{td}|^2 \sqrt{1 - \frac{4m_\ell^2}{M_B^2}} \\
&\times \left[\left(M_B C_P(\mu) - \frac{2m_\ell}{M_B} C_A(\mu) \right)^2 + \left(1 - \frac{4m_\ell^2}{M_B^2} \right) M_B^2 C_S^2(\mu) \right].
\end{aligned} \tag{1.8}$$

The Wilson coefficients C_S and C_P depend on the mass of the charged Higgs (M_{H^+}) and on the ratio of the vacuum expectation values of the two Higgs fields ($\tan \beta$). In Figure 1.4, the theoretical values of the branching ratio $\mathcal{B}(B^0 \rightarrow \tau^+ \tau^-)$ in the 2HDM as a function of M_{H^+} is shown. Depending on $\tan \beta$ and M_{H^+} , the influence on $\mathcal{B}(B^0 \rightarrow \tau^+ \tau^-)$ from the 2HDM can be large.

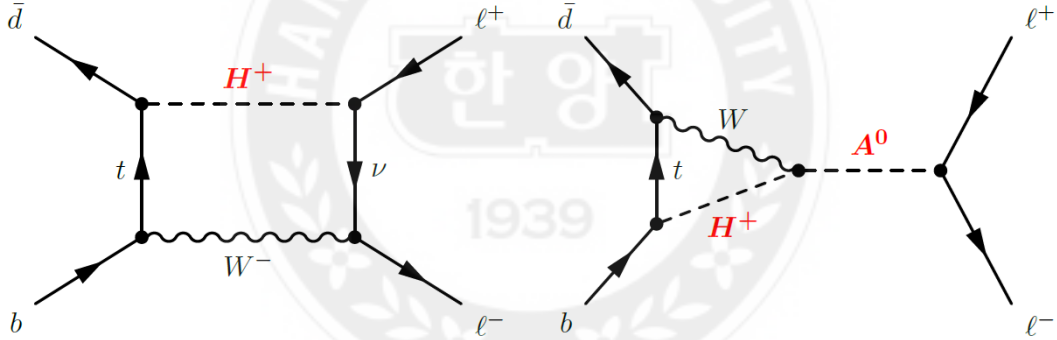


Figure 1.3: Dominant diagrams for the decay $B^0 \rightarrow \ell^+ \ell^-$ in the 2HDM with large $\tan \beta$ ($\ell = e, \mu, \tau$) [1].

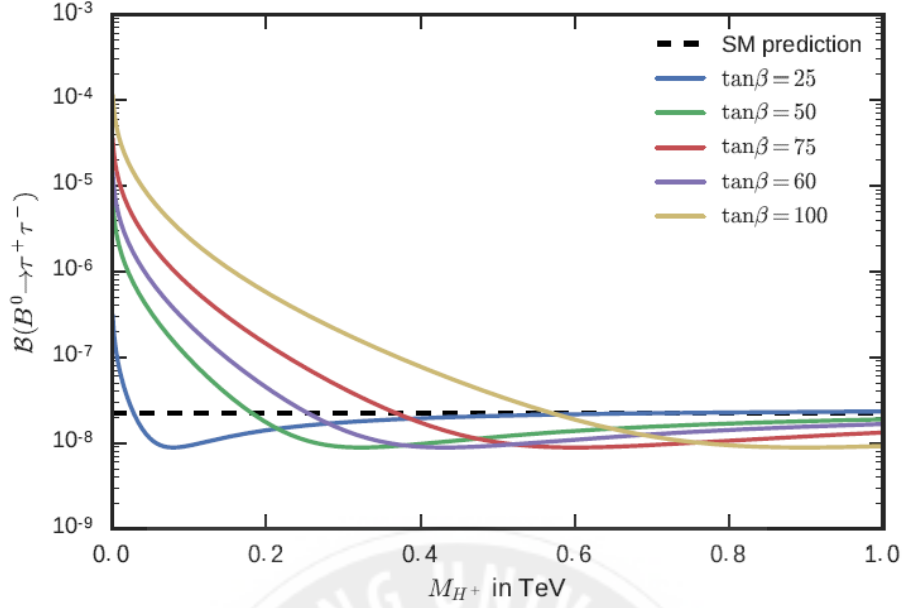


Figure 1.4: $\mathcal{B}(B^0 \rightarrow \tau^+ \tau^-)$ in the 2HDM as a function of M_{H^+} for different $\tan \beta$ values [1].

1.3.2 Leptoquarks

In the presence of leptoquarks, certain Wilson coefficients that are negligible within the Standard Model may become sizable.

The Wilson coefficients in leptoquark models depend on the couplings λ_{ij} between quarks and leptons, where i and j denote the generation indices. By comparing the measured branching fractions $\mathcal{B}(B^0 \rightarrow \ell^+ \ell^-)$ with Standard Model predictions, these couplings can be constrained for different generations. Table 1.1 summarizes the constraints.

The effective Hamiltonian describing the $b \rightarrow d \ell^+ \ell^-$ transition described by leptoquark model is like below.

$$\mathcal{H}_{\text{eff}} \sim [C_S^{NP}(\mu)Q_S + C_P^{NP}(\mu)Q_P + C_A(\mu)Q_A] \sim \Lambda \quad (1.9)$$

New contribution arise from a parameter Λ .

$$[C_S^{NP}(\mu)Q_S + C_P^{NP}(\mu)Q_P] \sim \frac{|\lambda^{33}\lambda^{13*}|}{M_S^2} \quad (1.10)$$

A dedicated search for $B^0 \rightarrow \tau^+\tau^-$ at Belle II will further tighten the constraints on couplings to the third lepton generation.

Decay	Coupling involved	Upper bound of the couplings (GeV^{-2})
$B_d \rightarrow e^+e^-$	$\frac{ \lambda^{31}\lambda^{11*} }{M_S^2}$	$< 1.73 \times 10^{-5}$
$B_d \rightarrow \mu^+\mu^-$	$\frac{ \lambda^{32}\lambda^{12*} }{M_S^2}$	$(1.5, 3.9) \times 10^{-9}$
$B_d \rightarrow \tau^+\tau^-$	$\frac{ \lambda^{33}\lambda^{13*} }{M_S^2}$	$< 1.28 \times 10^{-6}$

Table 1.1: Constraints on the leptoquarks couplings obtained from $B^0 \rightarrow \ell^+\ell^-$ decays [5].

1.4 Previous Experiments

There has been no observation of the decay $B^0 \rightarrow \ell^+\ell^-$ to date. Table 1.2 summarizes the Standard Model (SM) predictions [6] and the latest experimental results for each lepton flavor mode.

For the electron channel, the SM predicts an extremely suppressed branching fraction of $\mathcal{O}(10^{-15})$, primarily due to helicity suppression. The most stringent upper limits have been set by the LHCb experiment, with $\mathcal{B}(B^0 \rightarrow e^+e^-) < 2.5 \times 10^{-9}$ at 90% confidence level (CL) [7].

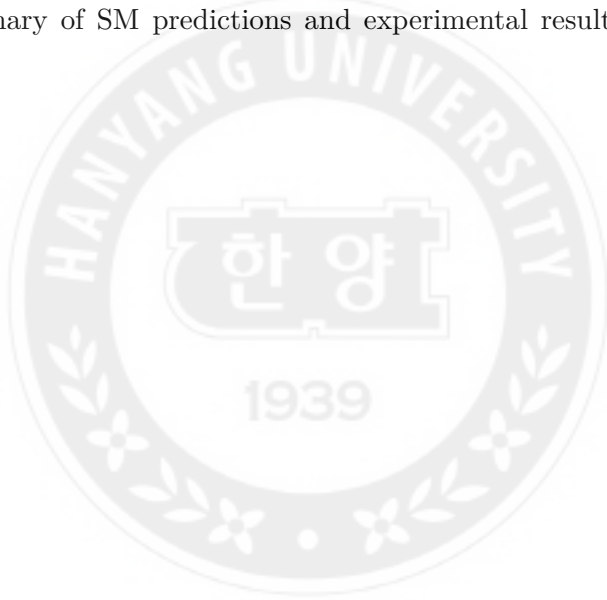
For the muon channel, the predicted branching fraction is $\mathcal{O}(10^{-10})$, and both LHCb and ATLAS have provided measurements and upper limits approaching this scale. Although no statistically significant excess has been observed, reported central values remain consistent with the SM prediction within uncertainties.

The $B^0 \rightarrow \tau^+\tau^-$ decay is the least helicity suppressed and is predicted to occur

at the level of $\mathcal{O}(10^{-8})$. However, the experimental sensitivity is limited by the challenges in reconstructing final states with multiple neutrinos. The most stringent upper limits are at the 10^{-3} level, reported by LHCb [6], BaBar [8].

	SM Prediction	Measurement		
		Detector	Upper Limit	Measurement
$B^0 \rightarrow e^+ e^-$	$(2.48 \pm 0.21) \times 10^{-15}$ (2014) [6]	LHCb	2.5×10^{-9} (90 % CL) (2020) [7] 3.0×10^{-9} (95 % CL) (2020) [7]	-
$B^0 \rightarrow \mu^+ \mu^-$	$(1.06 \pm 0.09) \times 10^{-10}$ (2014) [6]	LHCb	3.4×10^{-10} (2017) (95 % CL) [9]	$(0.15^{+0.12+0.02}_{-0.10-0.01}) \times 10^{-9}$ (2017) [9]
		ATLAS	2.1×10^{-10} (95 % CL) (2019) [10]	$(-0.19 \pm 0.16) \times 10^{-9}$ (2019) [10]
$B^0 \rightarrow \tau^+ \tau^-$	$(2.22 \pm 0.19) \times 10^{-8}$ (2014) [6]	LHCb	1.6×10^{-3} (90 % CL) (2017) [11] 2.1×10^{-3} (95 % CL) (2017) [11]	-
		BaBar	4.1×10^{-3} (90 % CL) (2006) [8]	-

Table 1.2: Summary of SM predictions and experimental results for $B^0 \rightarrow \ell^+ \ell^-$ decays.



Chapter 2

The Belle II experiment at the SuperKEKB collider

The Belle II experiment operates at the SuperKEKB collider, an asymmetric-energy electron–positron collider located at KEK in Tsukuba, Japan. This chapter provides an overview of the SuperKEKB accelerator and the Belle II detector system, which is designed to perform high-precision measurements of rare B meson decays and search for physics beyond the Standard Model.

Section 2.1 introduces the SuperKEKB collider. Section 2.1 describes the Belle II detector, consisting of multiple sub-detectors arranged cylindrically around the interaction point. The tracking system, composed of the beam pipe, pixel and silicon strip vertex detectors (PXD and SVD), and central drift chamber (CDC), is explained in Section 2.2.1. The electromagnetic calorimeter (ECL) is introduced in Section 2.2.2. Particle identification (PID) is covered in Section 2.2.3, including the time-of-propagation (TOP) detector, aerogel ring-imaging Cherenkov (ARICH) detector, and the K_L^0 and muon detector (KLM). Section 2.2.4 outlines the trigger and data acquisition (DAQ) system, including the hardware trigger, DAQ infrastructure,

and the high-level trigger (HLT).

2.1 The SuperKEKB collider

The SuperKEKB accelerator circulates electrons and positrons in opposite directions through a tunnel of approximately 3 km in circumference [12]. The beams are asymmetric in momentum: the electron beam is operated at around 7 GeV/ c , while the positron beam is maintained at around 4 GeV/ c . At a single point on the ring, known as the interaction region, the two beams are brought into nearly head-on collision, producing a center-of-mass energy of around 10.58 GeV. This energy corresponds to the $\Upsilon(4S)$ resonance, which is optimal for $B\bar{B}$ pair production. The center-of-mass energy can be tuned to collect data at other Υ resonances within the range of approximately 9.4 to 11 GeV, supporting the non- B physics component of the Belle II physics program [13]. Figure 2.1 shows cross section around the Υ resonances.

2.1.1 Beam energy

Due to the beam energy asymmetry in the SuperKEKB collider, the Belle II detector is geometrically asymmetric along the beam axis. In the Belle II coordinate system, the forward direction is defined as the direction of the high-energy electron beam (7 GeV) (clockwise), whereas the backward direction corresponds to the direction of the lower-energy positron beam (4 GeV) (counter-clockwise) (Figure 2.2).

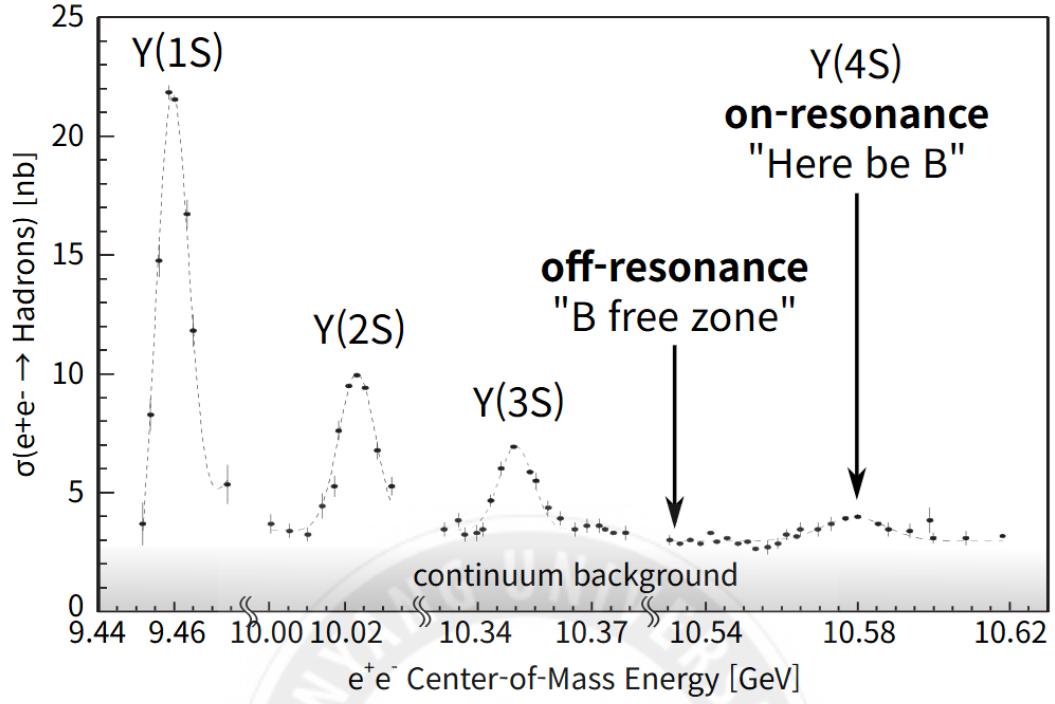


Figure 2.1: Cross section around the Υ resonances [14].

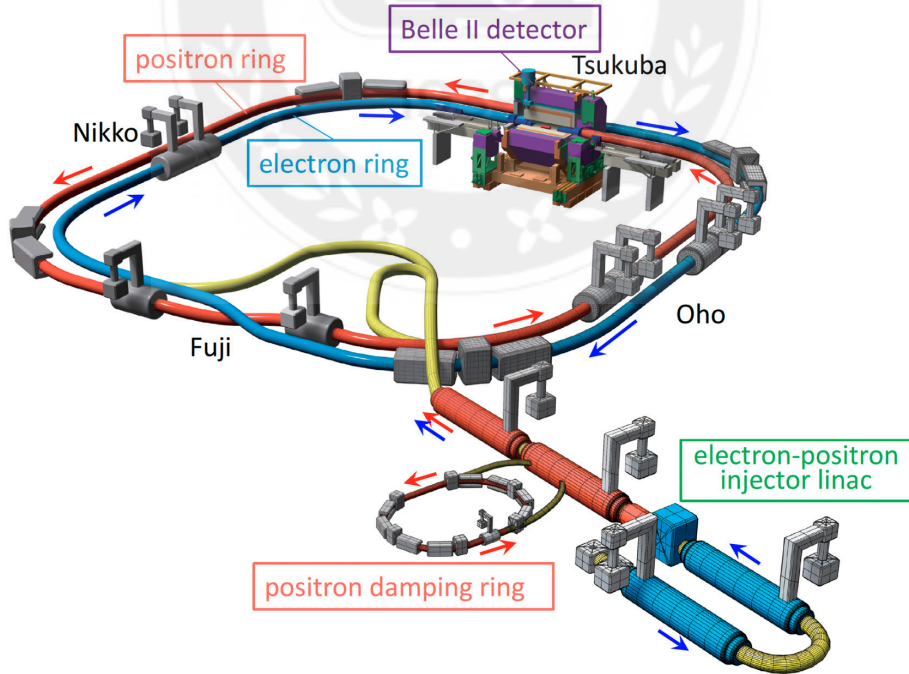


Figure 2.2: Schematic view of SuperKEKB. The electron and positron rings have four straight sections named Tsukuba, Oho, Fuji, and Nikko. The electron and positron beams collide at the interaction point in the Tsukuba straight section [15].

2.1.2 Luminosity

The total number of events N is given by the time-integrated luminosity as

$$N = \int_0^T L \sigma dt, \quad (2.1)$$

where L is the instantaneous luminosity, σ is the cross section, and T is the duration of the experiment [12].

The instantaneous luminosity is expressed as

$$L = \frac{\gamma_{\pm}}{2er_e} \left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right) \left(\frac{I_{\pm} \xi_{y\pm}}{\beta_y^*}\right) \left(\frac{R_L}{R_{\xi_{\pm}}}\right), \quad (2.2)$$

where all quantities are defined in Table 2.1.

The vertical beam-beam parameter $\xi_{y\pm}$ is given by

$$\xi_{y\pm} = \frac{r_e}{2\pi\gamma_{\pm}} \cdot \frac{N_{\mp}\beta_y^*}{\sigma_y^*(\sigma_x^* + \sigma_y^*)} R_{\xi_{\pm}} \propto \frac{N_{\mp}}{\sigma_x^*} \sqrt{\frac{\beta_y^*}{\varepsilon_y}}, \quad (2.3)$$

which describes the strength of beam-beam interaction in the vertical direction.

By substituting Eq. (2.3) into Eq. (2.2), we find that L is proportional to inverse of the square root of β_y^* . This relationship can be written as

$$L \propto \frac{1}{\sqrt{\beta_y^*}}. \quad (2.4)$$

This implies that reducing β_y^* leads to an increase in luminosity.

Symbol	Description
L	Instantaneous luminosity
$\gamma_{\pm}$	Lorentz factor of the electron (−) or positron (+) beam
e	Elementary charge
r_e	Classical electron radius
σ_x^*, σ_y^*	Horizontal and vertical beam sizes at the interaction point (IP)
$I_{\pm}$	Beam current of electron (−) or positron (+)
β_y^*	Vertical beta function at the IP
$\xi_{y\pm}$	Vertical beam-beam parameter for electron or positron beam
R_L	Luminosity reduction factor
$R_{\xi\pm}$	Beam-beam reduction factor
$N_{\mp}$	Number of particles in a bunch
ε_y	Vertical emittance

Table 2.1: Definition of symbols used in the luminosity formula.

2.2 Belle II detector

The Belle II detector is constructed around the interaction region with the objective of detecting and measuring as many of the particles produced in SuperKEKB collisions as possible. It is composed of multiple sub-detector systems, each designed to fulfill a specific function: tracking the trajectories of charged particles, measuring the energy of photons, identifying particle types, reconstructing long-lived hadrons, and detecting muons. While each system is optimized for a particular task, several serve multiple roles.

The Belle II detector consists, from the Interaction Point (IP) outward, of an inner silicon tracker comprising a PiXel Detector (PXD), a Silicon Vertex Detector (SVD), a Central Drift Chamber (CDC), two dedicated particle identification systems, the Aerogel Ring-Imaging Cherenkov detector (ARICH) in the forward endcap

and the Time-Of-Propagation (TOP) detector in the barrel region, an Electromagnetic CaLorimeter (ECL), a superconducting solenoid for a homogeneous magnetic field of 1.5 T, and a K_L and a Muon detector (KLM). A detailed description of the Belle II detector is in reference [13].

The vertex detector (PXD + SVD) achieves excellent resolution in the transverse and longitudinal directions with d_0, z_0 resolution of approximately $15\,\mu\text{m}$. Tracking is performed using the PXD, SVD, and CDC, providing a transverse momentum resolution of about 0.4% and particle identification via specific energy loss dE/dx . Charged particle identification is achieved using the TOP and ARICH detectors, offering a kaon efficiency ϵ_K of 90% with a pion fake rate of 1.8%. The ECL is responsible for photon reconstruction with an energy resolution of $\sigma_{\pi^0} \approx 0.6\,\text{MeV}$, and also for electron identification with 95% efficiency and a pion fake rate of 0.01%. The KLM provides muon identification with 95% efficiency and a pion fake rate of 1% [16]. The combination of sub-detector for particle identification is summarized in Table 2.2.

Table 2.2: Sub-detector combination for particle identification.

	SVD	TOP & ARICH	ECL	KLM	—
Charged	—	$\pi^\pm, K^\pm, p^\pm, d^\pm$	$e^\pm$	$\mu^\pm$	PXD + SVD + CDC
Neutral	K_S^0	—	γ, K_L^0	K_L^0	—

2.2.1 Tracking system

At Belle II, the reconstruction of charged particles and the measurement of their momenta and charges are performed by an integrated tracking system consisting of six layers of silicon detectors and a central drift chamber (CDC). These components surround the beam pipe and operate within a uniform axial magnetic field of 1.5 T,

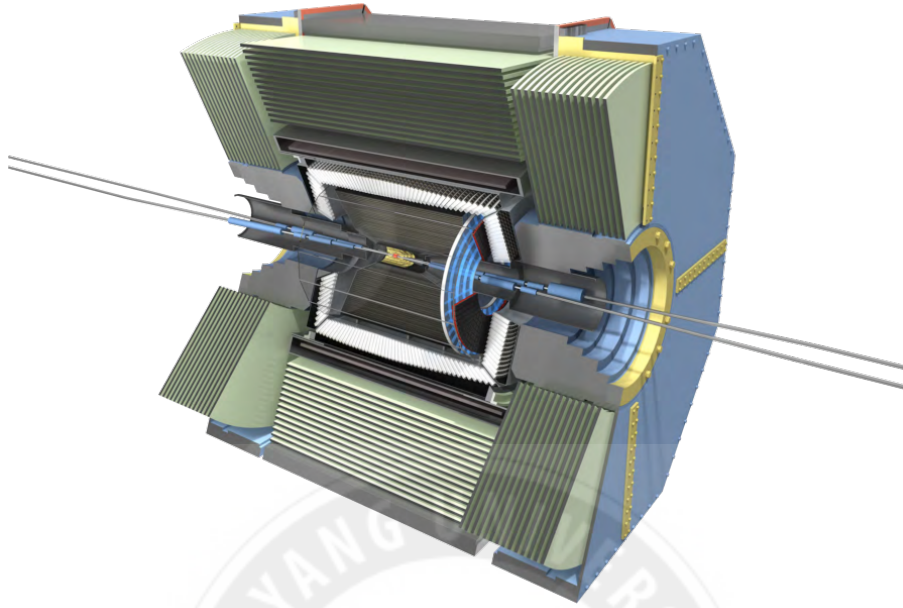


Figure 2.3: The Belle II detector [14].

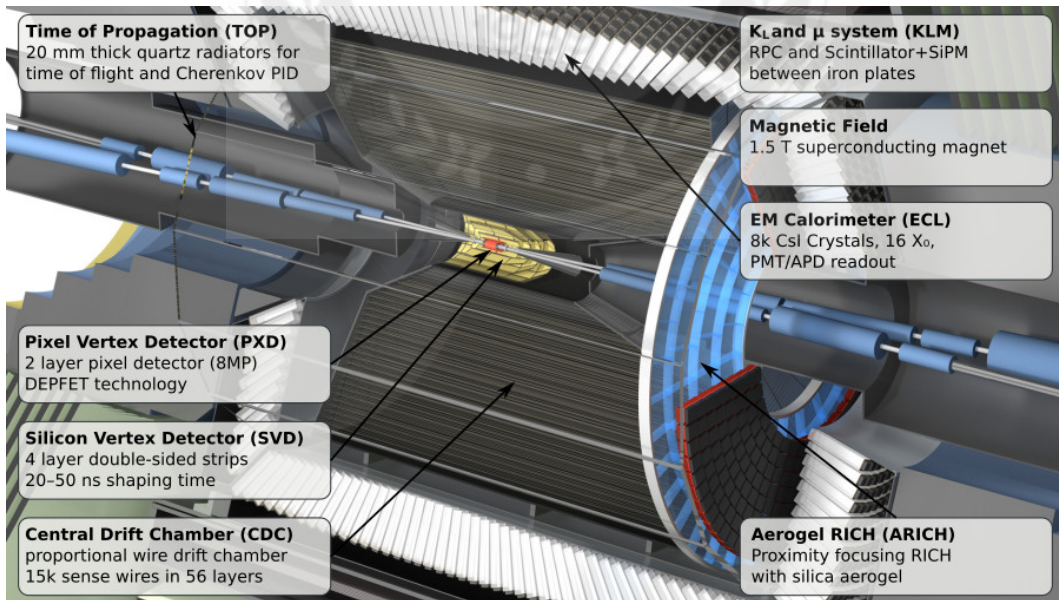
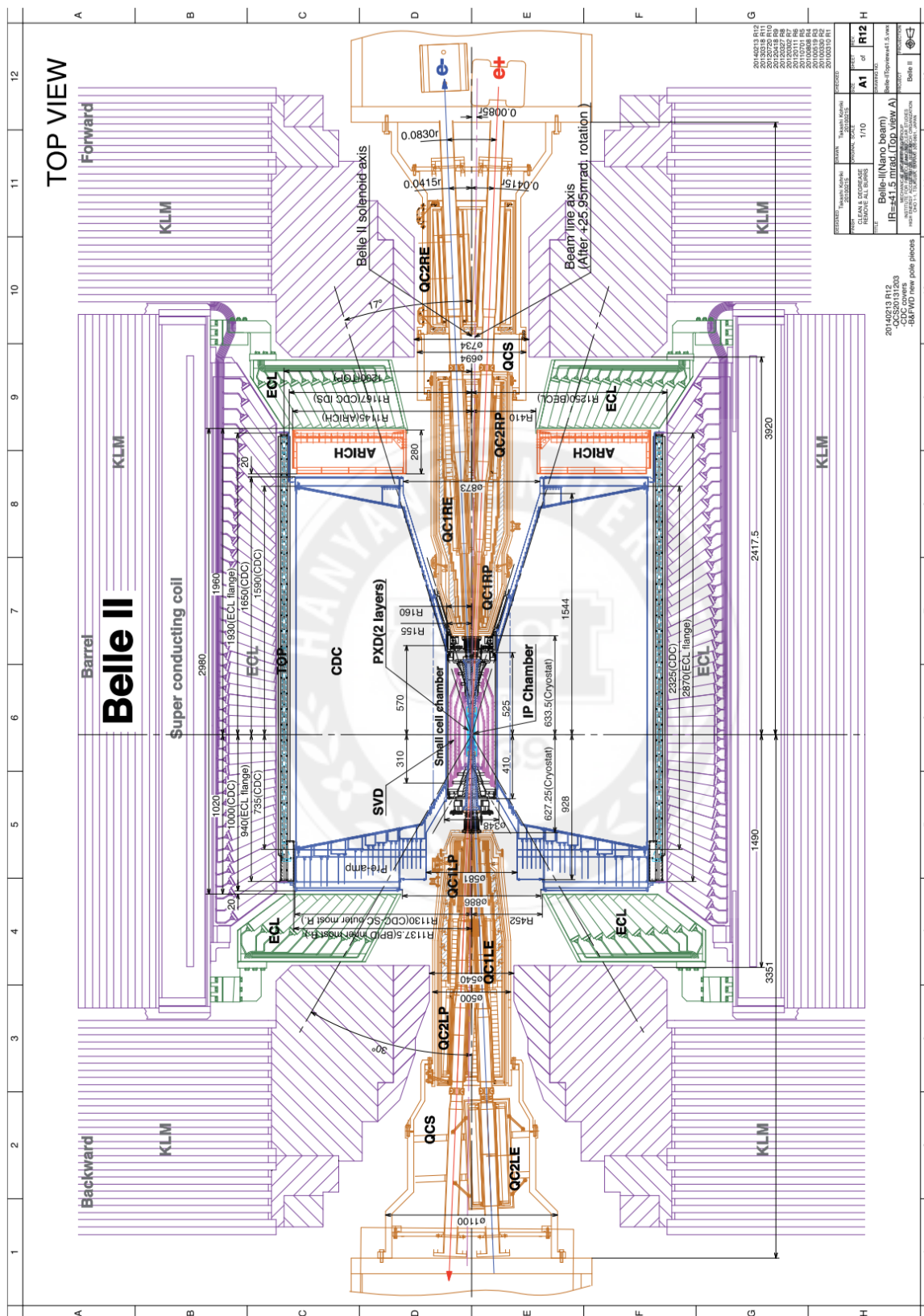


Figure 2.4: Closeup of the Belle II detector indicating all the different sub detectors [14].



confined inside a cylindrical volume of 3.4 m in diameter and 4.4 m in length. The magnetic field is aligned with the z -axis and is generated by an aluminum-stabilized superconducting solenoid composed of a NbTi/Cu alloy. The solenoid encloses all sub-detectors up to the KLM, and the magnetic flux returns through the iron yoke that forms the outermost layer of the detector.

2.2.1.1 Beam pipe

Although the beam pipe is not an active detector component, it plays a crucial role in isolating the detector from the interaction region, which resides in the low-pressure vacuum of the SuperKEKB accelerator. The beam pipe is a cylindrical structure designed to be as thin as possible in order to minimize energy loss of traversing particles. At the same time, it must effectively absorb the majority of soft synchrotron X-rays emitted by the circulating beams, thereby preventing them from reaching the inner detector components. Without this shielding, such X-rays would contribute significantly to the background noise, particularly affecting the innermost subdetector, the Pixel Detector (PXD) [14].

2.2.1.2 Silicon-pixel vertexing detector (PXD)

The first active subdetector encountered by particles emerging from the interaction point (IP) is the Pixel Detector (PXD), which serves as the innermost component of the vertex detector system [14]. The PXD provides precise spatial measurements of charged particle trajectories by detecting the position of each particle as it traverses the detector with high granularity. By combining the trajectories of multiple particles, their point of origin—referred to as the vertex—can be reconstructed with high precision. This vertex typically corresponds either to the location of the primary e^+e^- collision or to the secondary decay point of a short-lived parent

particle.

The PXD is based on DEPFET (Depleted P-channel Field Effect Transistor) silicon sensor technology and is segmented into approximately 8 million pixels, each measuring as small as $50 \times 55 \mu\text{m}^2$. It comprises two cylindrical layers located at radii of 14 mm and 22 mm from the IP, providing optimal resolution for vertex reconstruction in the high-background environment near the beam pipe.

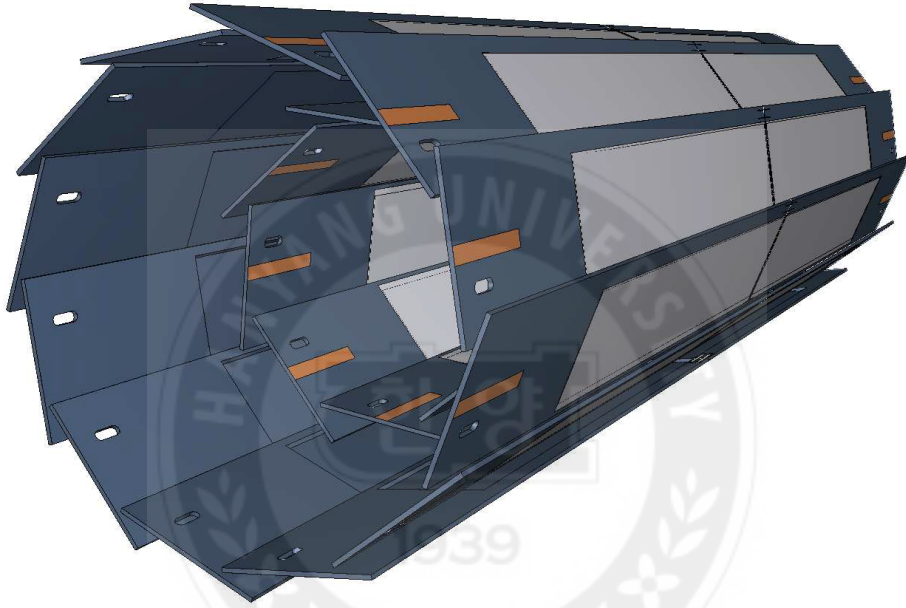


Figure 2.6: The Silicon-pixel vertexing detector (PXD) [13].

2.2.1.3 Silicon-strip vertexing detector (SVD)

The Silicon Vertex Detector (SVD) constitutes the outer part of the vertex detector system in Belle II. It is composed of four layers of double-sided silicon microstrip sensors, with strip pitches as small as $50 \mu\text{m}$ [14]. These sensors extend the outer radius of the vertex detector up to 140 mm from the interaction point.

A double-sided strip detector provides high spatial resolution comparable to that of a pixel detector; however, it does not offer direct two-dimensional position measurements. Instead, each side of the sensor contains strips aligned along orthog-

onal directions, allowing independent measurements of one-dimensional positions. By combining the readout from both sides, the two-dimensional hit position of a charged particle on the sensor can be reconstructed.

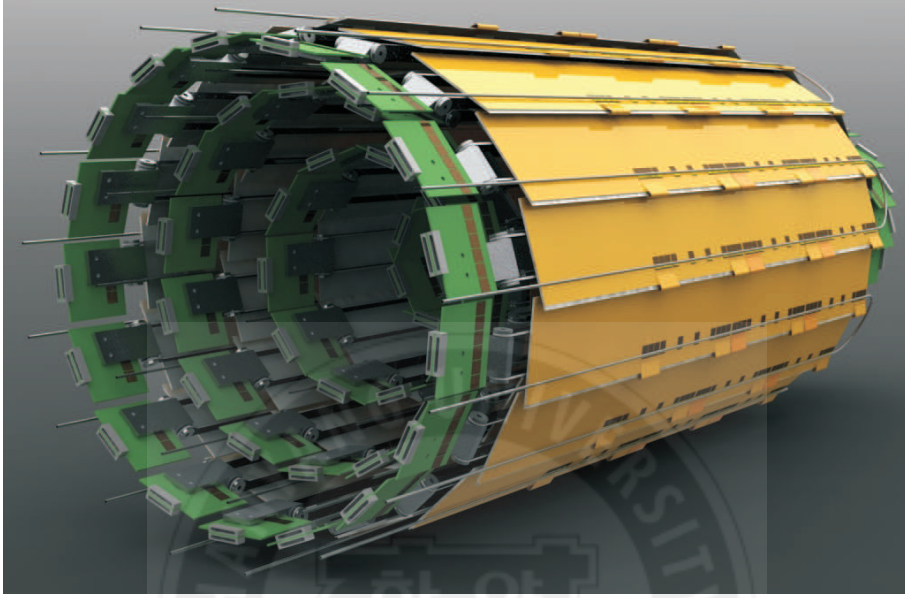


Figure 2.7: The Silicon-strip vertexing detector (SVD) [13].

2.2.1.4 Central Drift Chamber (CDC) detector

The main tracking detector in Belle II is the Central Drift Chamber (CDC), which surrounds the vertex detector and operates within a 1.5 T magnetic field. The CDC is filled with a gas mixture of helium and ethane ($\text{He-C}_2\text{H}_6$) and contains an array of sense wires that serve as the primary detection elements [14].

As a charged particle traverses the CDC volume, it ionizes the gas along its path. The resulting ionization electrons drift toward the nearest sense wires under the influence of an electric field. Near the wires, gas amplification occurs, producing detectable signals, commonly referred to as “hits.” A typical particle trajectory results in a sequence of such hits, enabling precise reconstruction of the particle’s path.

By measuring the drift time of the electrons to the sense wires, the radial distance from the wire to the point of ionization can be inferred. Each hit defines a so-called “drift circle,” within which the particle must have passed tangentially. The combination of multiple drift circles significantly enhances the spatial resolution beyond what would be expected from wire spacing alone (see Figure 2.8 and 2.9).

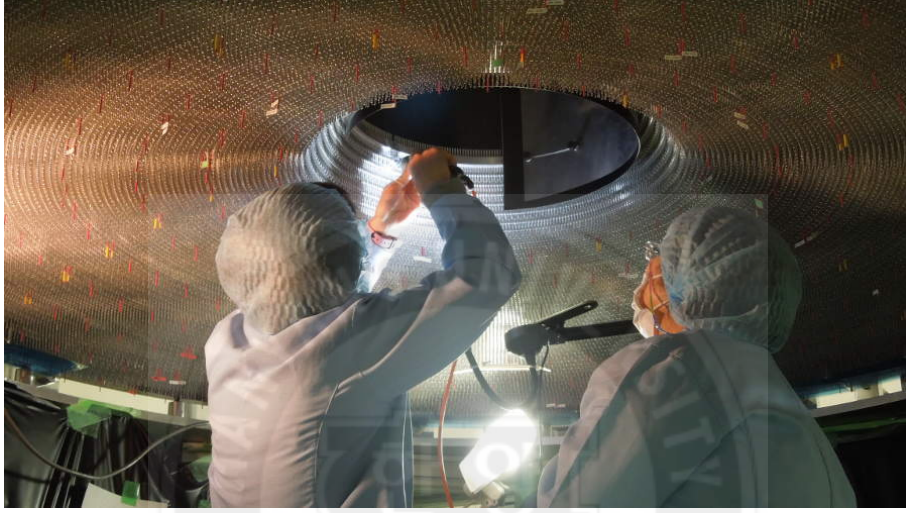


Figure 2.8: The Central Drift Chamber (CDC) detector [14].

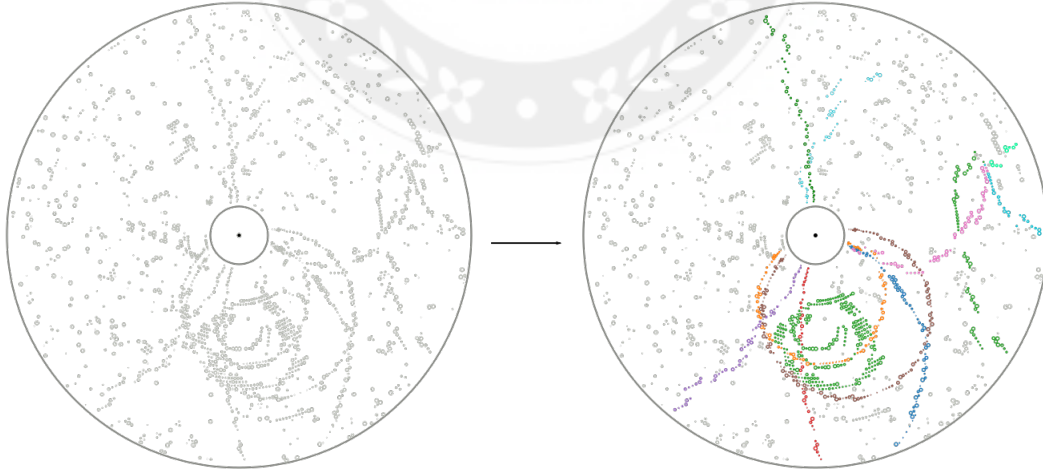


Figure 2.9: View of a simulated event in an x-y cross section of the CDC [14].

2.2.2 Electromagnetic Calorimeter (ECL) detector

The Electromagnetic Calorimeter (ECL) is primarily responsible for measuring the electromagnetic energy of particles, in particular photons and electrons produced in e^+e^- collisions. In conjunction with information from the tracking system, the ECL contributes to particle identification by distinguishing, for instance, electrons from muons. While electron tracks typically deposit their full energy and terminate within the calorimeter, muons pass through with minimal energy loss as minimum-ionizing particles, thus providing complementary information for classification.

The ECL comprises 8736 thallium-doped caesium iodide (CsI(Tl)) scintillating crystals. When an incident particle interacts with a crystal, it produces scintillation light, the intensity of which is proportional to the deposited energy. By measuring the deposited energy, the energy of the incoming particle can be inferred, assuming the particle is fully stopped and deposits all of its energy in the ECL. In practice, many particles do not deposit all of their energy within the calorimeter, and calibration procedures are therefore required to accurately translate the scintillation response into energy measurements [14].

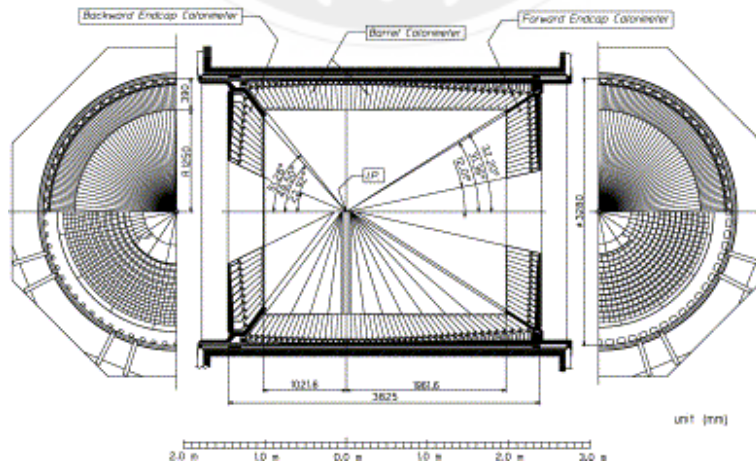


Figure 2.10: The Electromagnetic Calorimeter (ECL) detector [18].

2.2.3 Particle Identification

Belle II employs a combination of particle identification techniques to distinguish between various charged particle species. These include time-of-propagation measurements, Cherenkov radiation detection, and ionization energy loss (dE/dx) measurements in the silicon tracker and the Central Drift Chamber (CDC). The complementary nature of these observables allows for effective separation of pions, kaons, protons, and leptons over a wide momentum range.

For each reconstructed charged track, particle identification (PID) is performed based on likelihoods from various sub-detectors. For a given charged particle hypothesis $i \in \{e, \mu, \pi, K, p\}$, probability density functions (PDFs) of discriminating variables are constructed using either simulation or control data samples [19].

Assuming that the measurements of sub-detectors are mutually independent, the total likelihood $\mathcal{L}_i$ is calculated as the product of the individual sub-detector likelihoods:

$$\mathcal{L}_j = \prod_{\text{det} \in \{\text{SVD}, \text{CDC}, \dots\}} \mathcal{L}_i^{\text{det}}, \quad (2.5)$$

where j denotes the detector type.

The likelihood ratio is then used to define the probability of the particle being of species i :

$$\text{PID}_i = \frac{\mathcal{L}_i}{\sum_k \mathcal{L}_k}, \quad i, k \in \{e, \mu, \pi, K, p\}. \quad (2.6)$$

The Figure 2.11 is one of example of PID: The CDC (dE/dx) distribution.

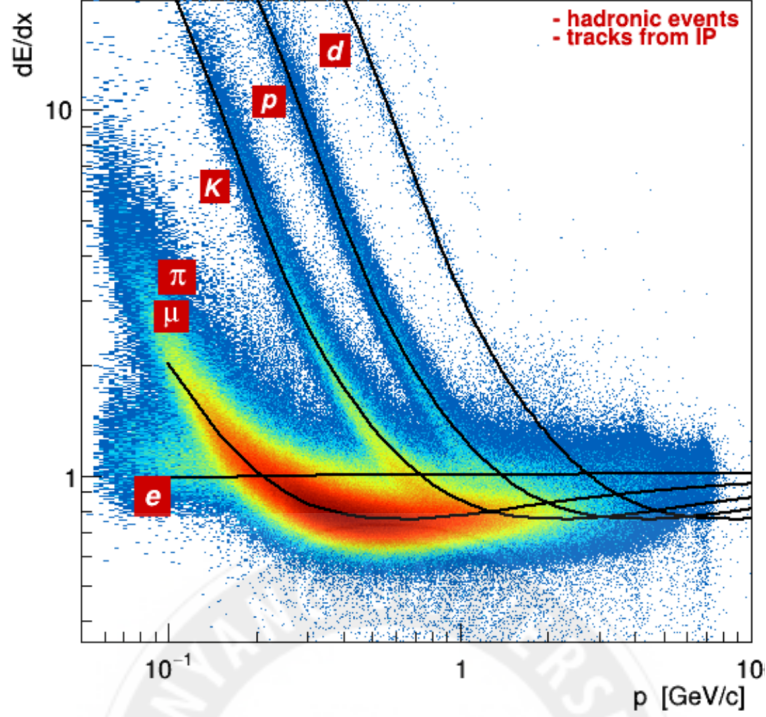


Figure 2.11: The CDC (dE/dx) distribution [19].

2.2.3.1 Time of propagation detector (TOP)

The Time-Of-Propagation (TOP) detector provides particle identification capabilities in the barrel region of the Belle II detector [14]. This sub-detector consists of quartz bars and operates based on the Cherenkov effect. When a charged particle traverses the quartz medium, it emits Cherenkov photons at an angle that depends on its velocity. By combining this velocity information with the particle momentum measured by the tracking system, the particle mass can be inferred, allowing identification of the particle species.

The emitted Cherenkov photons are confined within the quartz bars by total internal reflection and propagate to the TOP sensor plane (Figure 2.12). The detector reconstructs the Cherenkov emission angle by measuring the propagation time of individual photons from their point of emission to the sensor plane. At

a fixed momentum, heavier particles travel at lower velocities and therefore emit Cherenkov light at smaller angles. This leads to longer average photon path lengths and correspondingly longer time-of-propagation values.

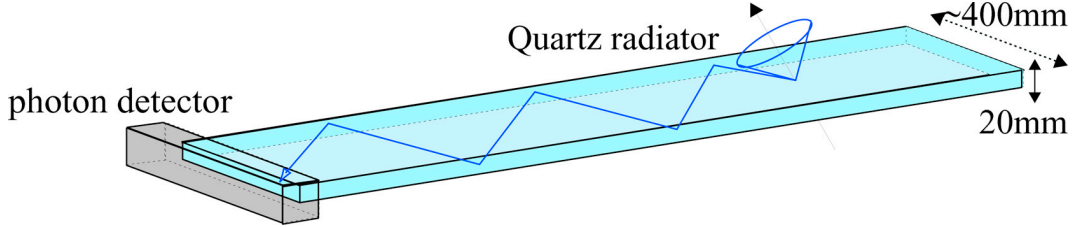


Figure 2.12: Schematic overview of the TOP counter [20]. Cherenkov photons emitted by charged particles traversing the quartz radiator are confined by total internal reflection and propagate to the photon detectors located at the bar end. The TOP counter measures the propagation time of the photons to reconstruct the Cherenkov angle for particle identification.

2.2.3.2 Aerogel Ring-Imaging Cherenkov (ARICH) detector

The Aerogel Ring-Imaging Cherenkov (ARICH) detector is another dedicated particle identification subdetector in Belle II, using aerogel as its radiator medium. It consists of 420 photon detection modules arranged in seven layers, covering a radial range from 0.56 m to 1.14 m. A total of 248 aerogel tiles are installed on the detector endcaps. It covers the forward region of the detector [14].

As with the quartz radiator in the TOP counter, Cherenkov photons are emitted when a charged particle with sufficient velocity passes through the aerogel. Unlike the quartz in TOP, however, the aerogel does not confine the Cherenkov photons. Instead, the photons form a cone of Cherenkov light around the particle trajectory, which is projected onto the photon detector plane as a ring with a characteristic radius. This radius provides information on the Cherenkov angle and thus serves as an independent source of particle mass identification.

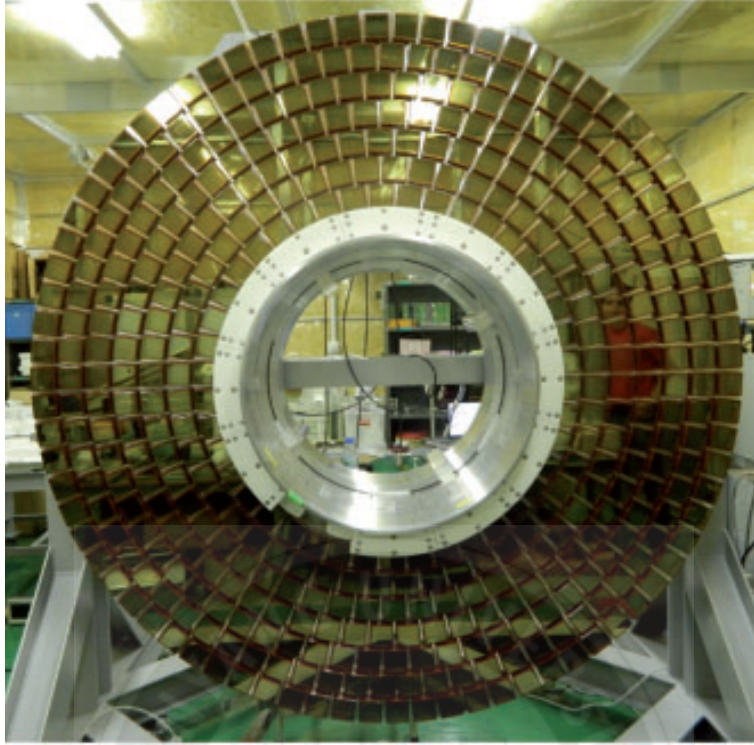


Figure 2.13: The Aerogel Ring-Imaging Cherenkov (ARICH) detector [13].

2.2.3.3 K_L^0 and muon detector

The K_L^0 and muon (KLM) detector identifies muons and long-lived neutral particles, such as K_L^0 mesons, which are not absorbed by the inner detector systems [14]. It is composed of alternating layers of 4.7 cm thick iron plates and active detector elements. The iron plates also serve as the magnetic flux return path for the central solenoid. In the inner layers, the active detectors are scintillator strips, while in the outer layers they are glass-electrode resistive plate chambers (RPCs), filled with a gas mixture between the electrodes. Charged particles passing through the KLM ionize the gas, and the resulting signals are collected via applied high voltage. The RPC structure of the KLM is shown in Figure 2.14

The barrel region of the KLM covers polar angles from 45° to 125° , while the forward and backward endcaps extend the coverage to the regions between 20° – 45°

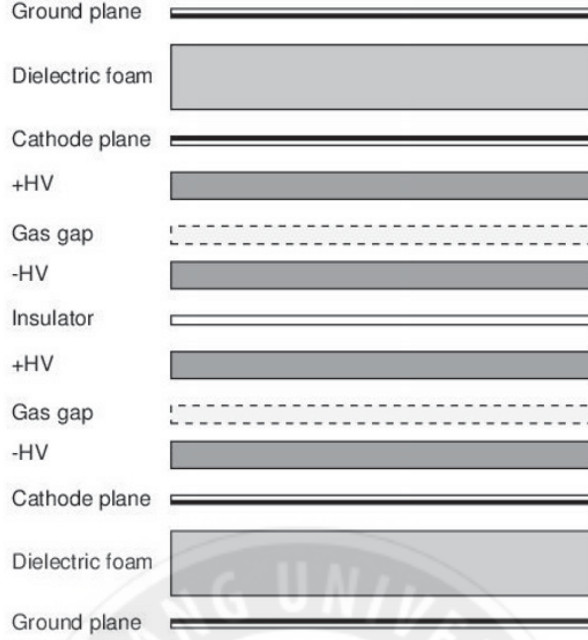


Figure 2.14: The RPC structure of the K_L^0 and muon (KLM) detector [21, 22].

and 125° – 155° , respectively.

2.2.4 Trigger and data acquisition system

The Belle II online system, which includes the Data Acquisition (DAQ) system, the Level 1 Trigger (L1 or TRG), and the High Level Trigger (HLT). These trigger systems are designed to filter out as much uninteresting data as possible before it reaches the first storage hard disk. Simplified diagram of the data flow through trigger and data acquisition system is given in Figure 2.15.

2.2.4.1 Hardware trigger system

The Belle II Level 1 (L1) online trigger (TRG) is required to achieve almost 100 % trigger efficiency for $\Upsilon(4S) \rightarrow B\bar{B}$ events and nearly high efficiency for other physics processes of interest within 30 kHz maximum trigger rate under the harsh beam background environment of SuperKEKB. The readout system requires the

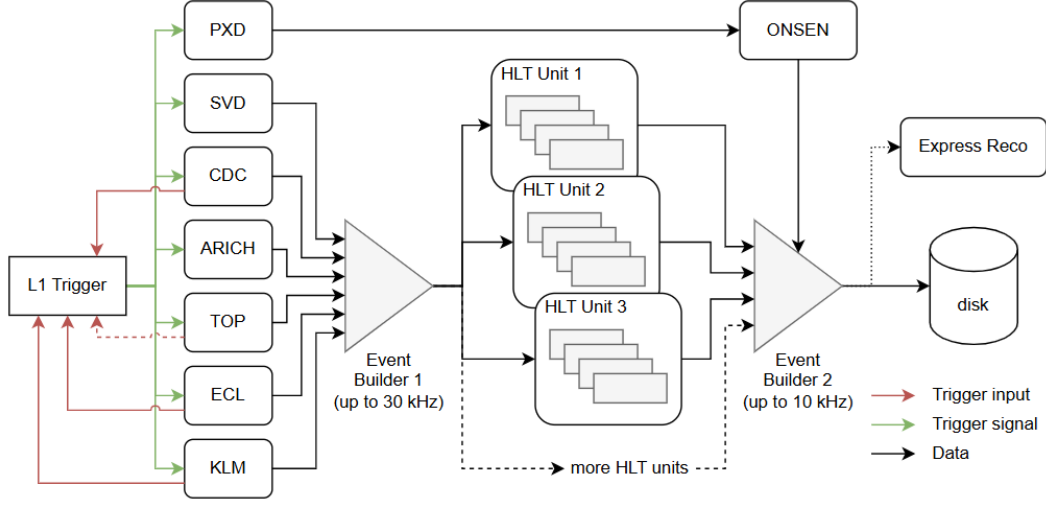


Figure 2.15: Simplified diagram of the Belle II data flow [14].

trigger latency to be under $4.4 \mu\text{s}$. The cross section and trigger rate of physical processes at the Belle II target luminosities are listed in Table 2.3.

Physics process	Cross section (nb)	Rate (Hz)
$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$	1.1	880
$e^+e^- \rightarrow q\bar{q}$	3.4	2700
$e^+e^- \rightarrow \mu^+\mu^-$	0.8	640
$e^+e^- \rightarrow \tau^+\tau^-$	0.9	720
Bhabha ^a	44.0	350 ^c
$\gamma\gamma^a$	2.4	19 ^c
$e^+e^- \rightarrow e^+e^- + 2\gamma^{ab}$	13.0	10000 ^d
Total	~ 130	~ 20000

^a $\theta_{lab} \geq 17^\circ$

^b $p_t \geq 0.1 \text{ GeV}$

^c Pre-scaled by factor of 1/100.

^d Estimated from the Belle level 1 trigger rate.

Table 2.3: The total cross section from physics processes at the $\Upsilon(4S)$ energy region and expected trigger rates at the peak luminosity of $80 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ [23, 24].

A schematic overview of the Belle II hardware trigger system is shown in Fig-

ure 2.16. There are four sub-trigger systems, which are the CDC trigger, the ECL trigger, the TOP trigger, and the KLM trigger. The CDC trigger provides two- and three- dimensional (2D and 3D) charged track information [25]. The ECL trigger provides total energy, cluster information, and Bhabha identification information of electromagnetic particles [23, 26]. The TOP trigger provides precise timing and hit topology information. The KLM trigger provides muon track information [24].

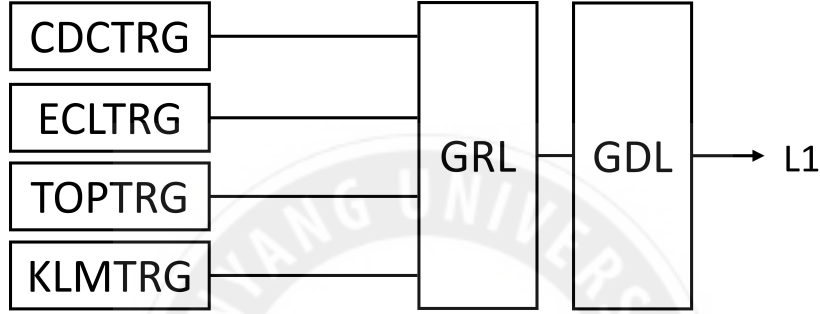


Figure 2.16: A schematic overview of the Belle II trigger system [24]. The trigger system consists of the CDC / ECL / TOP and KLM triggers. The GRL collects all signals from each sub-trigger and delivers its matching information output to the GDL. The GDL generates a final decision with the matching information and sub-trigger outputs. L1 is the final level 1 trigger decision.

The Global Reconstruction Logic (GRL) generates matching information based on all the sub-trigger outputs. The matching information and sub-trigger outputs are delivered to the Global Decision Logic (GDL), and the GDL makes the final trigger decision, called the L1 decision. Finally, the L1 decision is forwarded to the Belle II Data AcQuisition (DAQ) system [27]. For stable operation of the trigger system upon beam collision, a reliable controlling and monitoring system is mandatory.

2.2.4.2 Belle II DAQ system

Each of the Belle II sub-detector systems has its front-end electronics (FEE) readout system, which, except PXD, sends data to the unified back-end readout system. The back-end system consists of readout boards called COMmon

Pipelined Platform for Electronics Readout (COPPER) [28] and readout servers [29]. The COPPERs receive sub-detector front-end data, including trigger data through “Belle2link” [30] which utilizes Xilinx Rocket I/O for high-speed serial data transfer. The bandwidth of the Belle2link is up to 3.125 Gbps. The estimated event size from the FEE is 100 kB and 1 MB for the non-PXD detectors and the PXD, respectively [27].

At the designed luminosity of $80 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, the expected average trigger rate is 20 kHz, so we set 30 kHz as a designed trigger rate for the DAQ system conservatively [27].

2.2.4.3 High-level trigger (HLT)

High-level trigger system receives the full raw subdetector data for each triggered event and performs an immediate full reconstruction which is similar to that used offline. Based on the result of this reconstruction, events are classified and either stored to a local offline storage hard disk drive or discarded.

Chapter 3

Trigger slow control system of the Belle II experiment

During Belle II operation, upon beam collisions, the trigger system must be consistently controlled and its status carefully monitored during data acquisition to protect against unexpected situations. For this purpose, a dedicated slow control system has been developed for the Belle II trigger system, based on the custom-made Belle II DAQ and slow control framework¹.

Approximately seventy thousand configuration parameters are saved to the Belle II central database server at the start and end of each run. These parameters play an essential role in the offline validation of data quality for each run. In addition, around three thousand real-time variables are continuously stored in the Belle II main archiving server, and trends of selected variables are regularly used for both online and offline monitoring.

Various operator interface tools have been implemented and are actively used.

¹This chapter is based on a paper published in Nuclear Instruments and Methods in Physics Research Section A (NIMA), for which the author of this dissertation is both the first and corresponding author [31] (see Appendix B.1).

When configuration parameters are not correctly applied, or when certain processes terminate unexpectedly, the slow control system detects the anomaly, halts the data-taking process, and issues an alarm.

This chapter provides a detailed overview of the trigger slow control system developed for the Belle II experiment. Section 3.1 introduces the general architecture and functionality of the Belle II slow control system. Section 3.2 presents the framework of the trigger slow control system, including its configuration database (Section 3.2.1), data archiving mechanism (Section 3.2.2), and operator interface tools (Section 3.2.3). Section 3.3 describes the software implementation, while Section 3.4 introduces various user interface panels developed for the system. These panels include the local run control panel, main control panel, Level 1 trigger rate plot, GDL panel, and ECL trigger panels. Finally, Section 3.5 discusses the operational aspects of the trigger slow control system based on real operation experience at Belle II.

3.1 Belle II slow control system

The primary tasks of the Belle II slow control systems are to manage operations of sub-systems, to provide and store configuration parameters to sub-systems, and to collect status and environmental conditions of sub-systems. In order to accomplish these tasks, three fundamental sub-components have been developed; run control, log collector, and operator interface [32]. Four core techniques are used to build the components; the network communication based on EPICS [33] and NSM2 [34], databases based on PostgreSQL [35], the Graphical User Interface (GUI) based on the Control System Studio (CSS) [36] and Process Variable (PV) [37] archiving via EPICS archiver appliances. The Belle II DAQ / slow control software package,

named “daq_slc,” contains all components. Each component is briefly explained below.

First, network communication between slow control processes is handled via EPICS and a software package named “Network Shared Memory 2 (NSM2)”, a software library that enables the synchronization of the shared memory on each node using UDP and TCP communications over the network [27]. The synchronization interval usually several seconds [32]. The NSM2 is a custom-made tool for network communication by the Belle II collaboration. The NSM2 is an advanced version of NSM [34], which was used at the Belle experiment. A daemon process called “nsm2d” takes care of all communication over the network segments [32]. Based on NSM2, we prepared NSM2 nodes, which are building blocks of the network communication between sub-systems through the daemon process. An NSM2 node reads some values from a hardware system, converts it to NSM2 format, and distributes it to the Belle II network. The NSM2 makes it possible for each operator to control systems remotely with minimized interference with each other. Belle II ARICH slow control system uses a particular type of NSM2 node, which is suitable for high voltage control [38]. Belle II SVD slow control system case, network communication is based on EPICS [39]. Different from ARICH and SVD case, the trigger slow control system uses NSM2.

Second, the PostgreSQL database management system is used for managing configuration parameters and logging information [32].

Third, GUI tools are based on the Control System Studio (CSS), which is an Eclipse-based tool for creating control systems [36]. The CSS is originally designed for EPICS variables, but it also accepts NSM2 variables through a custom plugin on the CSS and an interface process, named nsm2socket [32]. A GUI can communicate with NSM2 nodes via a single TCP/IP connection to the nsm2socket [32].

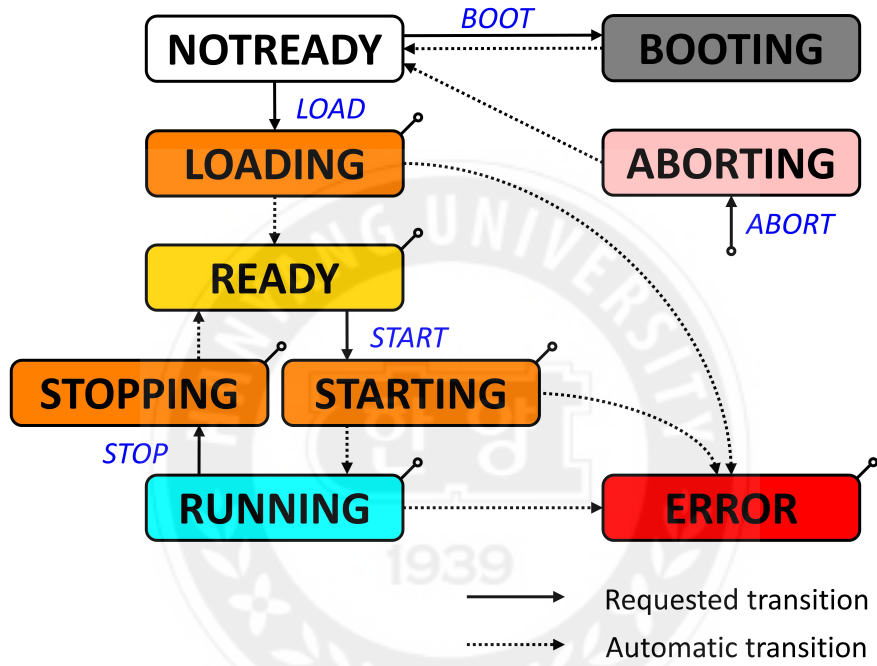


Figure 3.1: Run control state diagram [32]. This diagram shows how the Belle II experiment handles a run. The round boxes denote the status of an NSM2 node, and the texts outside of the boxes are requests. A node status can be checked and changed by operators. The ABORTING state is reached from LOADING / READY / STOPPING / STARTING / RUNNING / ERROR states by an ABORT request (Lines with small circles connect the states to the ABORT request line).

The last one is the EPICS archiver appliance, which is an implementation of an archiver for EPICS control system. The EPICS archiver appliance records the history of PVs in real-time. In order to record the history of NSM2 variables, a process called “nsm2cad” converts NSM2 variables to EPICS PVs because the EPICS Archiver Appliance can record EPICS PVs only [37].

The run control system manages the DAQ systems and sub-detector systems via NSM2 to follow the state diagram shown in Figure 3.1 [32]. The run control requests (requested by operators) and the run control states are listed in Table 3.1 and 3.2, respectively.

Table 3.1: List of run control requests.

Request	Meaning
LOAD	Load parameters
START	Start a run
STOP	Stop a run
ABORT	Abort the state transition and reset the state
BOOT	(Re)initialize the system

3.2 Trigger slow control system framework

The stable operation of the trigger system is essential for the steady data acquisition of the Belle II experiment. The trigger slow control system makes it possible to operate the trigger system efficiently and stably. In order to cooperate with the rest of the slow control system, the trigger slow control system is constructed upon the Belle II common daq_slc framework, described in Subsection 3.1. The primary tasks of the trigger slow control system are shown below.

- (a) Makes logs of problematic events and sends it to the central logging server.

Table 3.2: List of run control states.

State	Meaning
NOTREADY	Parameters are not loaded yet
LOADING	Parameters are being loaded
READY	Ready to start a run
STOPPING	Run is being stopped
STARTING	Run is being started
RUNNING	Run is ongoing
ERROR	Problem detected
ABORTING	Abort sequence is ongoing
BOOTING	(Re)initialization is ongoing

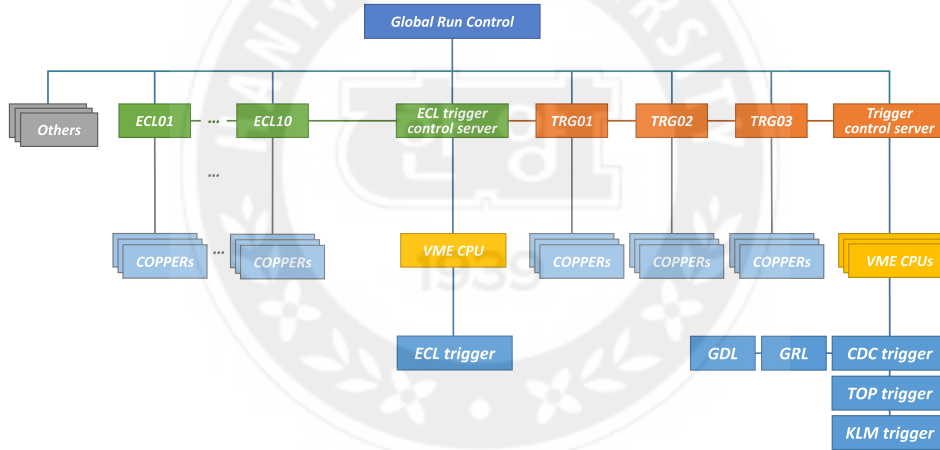


Figure 3.2: The trigger slow control system server structure. This diagram shows how the trigger slow control related servers are connected to the Belle II network. “Others” in the gray-colored box denote servers related to other sub-detectors; PXD, SVD, CDC, ARICH, TOP, and KLM. The TRG01/02/03 and the ECL01 to 10 servers are COPPER control servers. All the sub-trigger except the ECL trigger is connected to the trigger control server via corresponding VME CPUs. The ECL trigger system is connected to the ECL trigger control server via a VME CPU.

- (b) Saves experimental parameters automatically at every run start and stop.
- (c) Provides real-time monitoring plots.
- (d) Takes local run data.

(e) Troubleshooting.

In order to accomplish these tasks, the trigger system is connected to the Belle II main run control, central database, and archiver servers. Figure 3.2 shows the connections between the trigger system servers, and to the main run control server.

To communicate through NSM2, we run several NSM2 nodes on the servers of the trigger system. The NSM2 nodes collect values from sub-trigger systems and convert them to NSM2 variables. NSM2 variables are then converted into three formats: configuration database, archiver, and operator interface format (Figure 3.3). The purpose of the configuration database format is to put experimental parameters from hardware to the configuration database server and vice versa. The goal of the archiver format is to save the trend of the values and view their history later. The operator interface format aims to display values of interest on an operator panel or change hardware settings from an operator panel. We will explain each part further in the following subsections.

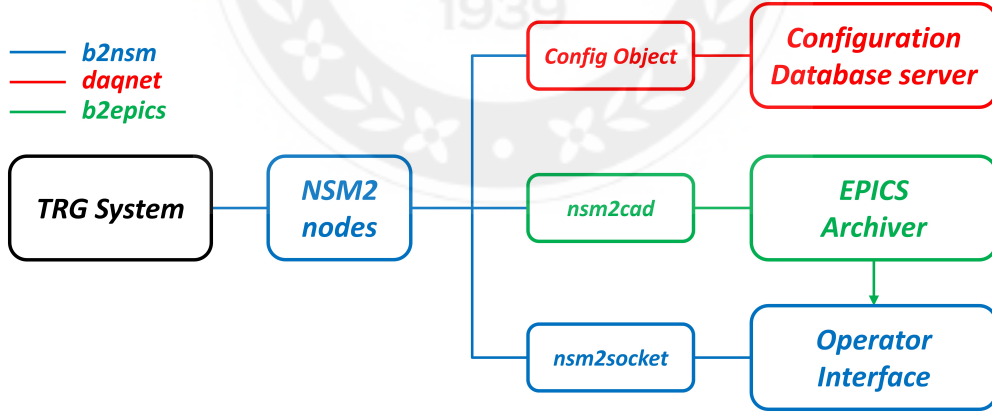


Figure 3.3: NSM nodes and network diagram. NSM2 nodes are connected to three network lines: b2nsm, daqnet, and b2epics. The b2nsm is for NSM2 communication, the daqnet is for connections to the database server, and b2epics is for EPICS PVs. “Config object,” which is a C++ object of an NSM2 node, converts NSM2 variables to suitable for the configuration database format. “nsm2cad” and “nsm2socket” are explained in the previous section.

3.2.1 Configuration database

A run-recording process automatically stores 67,662 experimental parameters to the central database server by run number when a run starts/ends. The parameters are mainly firmware versions and setting parameters. Some slow control settings, such as NSM2 port settings and including/excluding NSM2 nodes in run control (RC) scheme information, are also stored.

The GDL bits are stored: the input bits, the final trigger decision output bit, the output bits of PSNM (Pre-Scale aNd Mask), and administrative bits. The sub-trigger rates processed by GRL are stored. The CDC trigger bits are stored: the track segment finder (TSF), the event timing finder (ETF), and the 2D / 3D tracking information [24]. The ECL trigger bits are stored: the trigger cell (TC) noise, TC noise fitting parameter, FADC Analysis Module (FAM) pedestals, FAM rates, FAM temperature, the Trigger Merger Module (TMM) temperature, and the ECL Trigger Master (ETM) physics bits [23, 26].

We use the stored parameters to validate the run quality. A log-collecting process automatically gathers the status of the NSM2 nodes and sends it to the central database server. We can check when problems happened and chase the origin of them with the collected logs.

We can also manually save sets of experimental parameters to the central database server, and NSM2 nodes can retrieve them. An example is given in Sub-section 3.4.1.

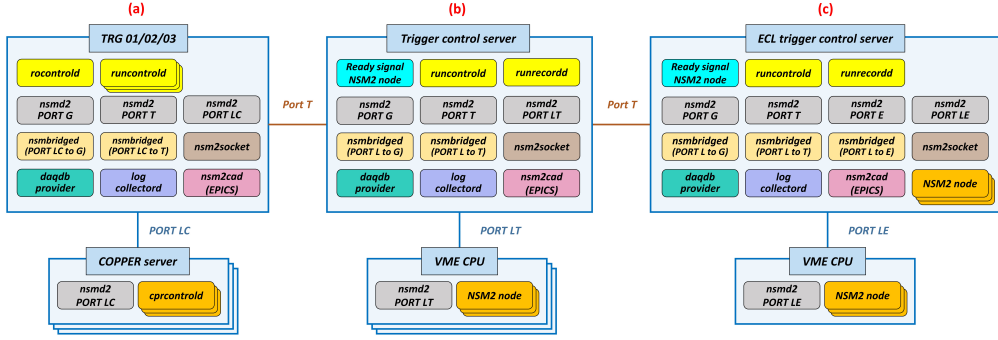


Figure 3.4: Schematic of the trigger slow control processes. (a) Each TRG 01 and 02 server has 6 COPPER servers. TRG 03 server has 2 COPPER servers. There are three “runcontrolld” on TRG 01 server. Each TRG 02 and 03 server has a single “runcontrolld”. (b) There are 16 NSM2 nodes on 7 VME CPUs in total. (c) There are 6 NSM2 nodes on the ECL trigger control server and 3 NSM2 nodes on a single VME CPU. (PORT G, T, E, LT, LE, and LC means PORT Global, Trigger, ECL, Local Trigger, Local ECL trigger, and Local COPPER.)

3.2.2 Archiver

We archive 3,303² EPICS PVs to the Belle II main archiver server³. These are mainly variables to judge the stability of trigger systems such as the temperatures of modules, the pedestal levels, the luminosity, and the trigger rates.

The GDL bits are archived: the input bits, the final trigger decision output bit, the output bits of PSNM, and administrative bits. The sub-trigger rates processed by GRL are archived. Track rate from IP and track rate outside IP, which the CDC generates, are archived. The ECL trigger bits are archived: TC noise, pedestal, hit-rate, FAM board temperature, TMM board temperature, ETM physics bit, and accelerator/detector luminosity. TOP L1 trigger rates are archived. KLM L1 trigger rates are archived.

Some of them are plotted on CSS and monitored by trigger experts during a run in real-time.

²The Belle II archiver server is capable of storing 80,000 values. The trigger group have 5,000 slots.

³The default archiving period is 10 seconds, and the minimum period is 1 second.

3.2.3 Operator interface tools

User-friendly, intuitive, and reliable GUI is highly required for stable operation. We use CSS, which is widely used in the high energy physics community. NSM2 variables can be read/written on CSS by nsm2socket process and CSS NSM2 plugin. They convert the NSM2 variables to be handled by CSS. We show a few examples of frequently used operator interface panels in section 3.4 in detail.

- The trigger local run control panel
- The trigger main control panel
- The Level 1 trigger plot
- The GDL main panel
- The ECL trigger panels

3.3 Implementation of the trigger slow control system

Figure 3.4 shows all processes for the trigger slow control system. The processes are coded with the daq_slc package. Each process in the figure is explained below [32].

- Ready signal NSM2 node

The ready signal NSM2 node on the ECL trigger control server collects all signals necessary for generating the ECL trigger ready signal. The ready signal NSM2 node on the trigger control server collects all signals necessary for generating the final integrated trigger ready signal, including the ECL trigger ready signal.

- nsmbridged

This daemon process gives network communication between two different NSM2 networks with different port numbers. For example, nsmbridged (LT to G) is a bridge between nsmd2 (LT) and nsmd2 (G).

- nsm2socket

This process converts NSM variables to suitable for operator interfaces.

- daqdbprovider

The Belle II central database server is not directly connected to local networks.

This daemon connects the local server to the main database server.

- logcollectord

Logs are collected to the Belle II central database server by this daemon process.

- nsmd2cad

This daemon process converts NSM variables to EPICS Processed Variables (PV).

- NSM2 nodes

NSM2 nodes are fundamental building blocks of collecting information and sending commands to the sub-trigger modules.

- COPPER control nodes (cprcontrold)

COPPER control nodes are fundamental building blocks of collecting information and sending commands to the read-out boards.

The Trigger Slow Control System Main Panel

Last update: 191204(WED), ver 1.2.42

For the TRG Expert Shifts! Phase III Started from 25 Mar. 2019

- (1) = (2) + (3)
 (2) System Readiness: Parameter, links, temperature, etc.
 (3) RC STATE: RC(Run Control) node status
 (4) Local / Global
 (5) Parameter Reset
 (6) System Initialization
 (7) Open Sub-trigger detail panel

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
TRG	READY	READY	RUNNING	GLOBAL	Reset	Init Locked	
GDL ☒	READY	READY	RUNNING	GLOBAL	Reset	Init Locked	Detail
GRL/CDC ☒	READY	READY	RUNNING	GLOBAL	Reset	Init Locked	Detail
ECL ☒	READY	READY	RUNNING	GLOBAL	Reset	Initialization	Detail
TOP ☐	OFF	OFF	OFF	OFF	Reset	Init Locked	Detail
KLM ☒	EXCLUDED	READY	RUNNING	GLOBAL	Reset	Init Locked	Detail

Global Runtype	null	Global Runno	5440	TRG SYSTEM is in	GLOBAL
Global TRGtype	poisson	Global Expno	10	ECL SYSTEM is in	GLOBAL

TRG SLC processes

TRG Run #: 5440

TRG01 RUNNING

TRG02 RUNNING

TRG03 OFF

RCBTRGSRV RUNNING

STOP

ABORT

BOOT

TRG (BTRSRV) SLC processes

Run #: 5440

RCBTRGSRV RUNNING

TRGGDL RUNNING

TRGGRL RUNNING

TRGT2D0 RUNNING

TRGT2D1 RUNNING

TRGT2D2 RUNNING

TRGT2D3 RUNNING

TRGT3D0 RUNNING

TRGT3D1 RUNNING

TRGT3D2 RUNNING

TRGT3D3 RUNNING

TRGTNN0 RUNNING

TRGTNN1 RUNNING

TRGTNN2 RUNNING

TRGTNN3 RUNNING

TRGTSF0 RUNNING

TRGTSF1 RUNNING

TRGETF0 RUNNING

KLMTRG OFF

TRG_READY RUNNING

STOP

ABORT

BOOT

ECL SLC processes

ECL Run #: 5440

RCECLTRG RUNNING

STOP

ABORT

BOOT

TRGECL (BTRGCTR) SLC processes

Run #: 5440

RCECLTRG RUNNING

ECLTRG_FAM RUNNING

ECLTRG_TMM RUNNING

ECLTRG_ETM RUNNING

ECLTRG_FAM_PAR RUNNING

ECLTRG_TMM_PAR RUNNING

ECLTRG_ETM_PAR RUNNING

ECLTRG_READY RUNNING

STOP

ABORT

BOOT

Figure 3.6: The trigger main control panel in operation. If a run is stable, all run related parts are shown in light-blue color. The KLM trigger and TRG03 are excluded in this example of a test run for maintenance. Depending on purpose of a test run, we can easily exclude/include sub-triggers and COPPER control servers.

3.4 Trigger slow control panels

3.4.1 Local run control panel

We regularly take a local run data set for steady improvement of the trigger system, such as calibration or new firmware confirming purposes. For taking a local run data set easily, the trigger local run control panel is prepared (Figure 3.5). Before a run, an operator can change experimental parameters according to the purpose of

the run by using the dropdown button in the red squared box. By clicking the load button, a pre-saved set of experimental parameters on the central database server is loaded. During a run, status of COPPERs, such as the sizes of the total stored data (bytes) and data-storing rates, are displayed.

3.4.2 Main control panel

Figure 3.6 is a screenshot of the trigger main control panel in a test run during a stable operation. Trigger experts utilize this panel mainly for monitoring the trigger system status. All run related boxes are shown in light-blue color if everything works well during a physics run. When the trigger slow control system detects a problem, it automatically stops the run and shows which parts have the problem on the main panel.

The third block is for integrated trigger information, and the fourth block is for sub-trigger information. Except for the TOP trigger, all sub-triggers are included in the trigger RC scheme (Figure 3.1). The TOP trigger group has a slow control tool that is not based on the Belle II slow control framework, yet. It will also be converted and included in the trigger main RC scheme. The fifth block gives run information: global run type, trigger type, run number, and experimental number. The sixth to ninth blocks correspond to Figure 3.2. Trigger experts can use these blocks in the same way as controlling the trigger local run panel.

We also prepared a read-only version of the panel for the Control Room (CR) shift crew members who are the main operators of the Belle II data taking. Opening detail panels and the trigger local run control panel, and reset/initialization buttons are deactivated, but an alarm exists in this version.

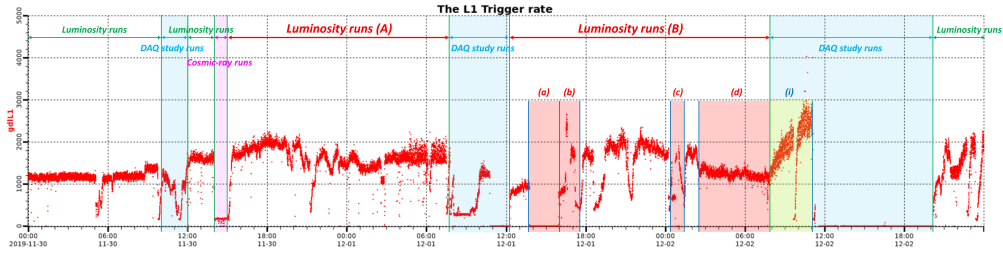


Figure 3.7: The L1 trigger plot. A screen shot of the L1 trigger archived PV displayed on CSS. The x-axis is time, and the range is between November 30, 2019, 00:00 JST and December 3, 2019, 00:00 JST. The unit of the y-axis is hertz (Hz). The L1 trigger rate is between 1 kHz and 2 kHz during physics runs.

Last NSM update **Wed Dec 4 20:11:05 JST 2019** (If not updated, please restart CSS)

GDL Trigger rate

duration 553.2036743164062

Total Trigger rate		Timing difference		Fraction of timing source	
	Rate(Hz)	Scaler			
commonL1	23955.9	164392.0	top-rvc	0.0	0.0
gdlL1	57976.8	397853.0	ecl-rvc	9.0	2824.1
			cdc-rvc	9.0	55147.6
				(should be 4~6)	378438.0
					psn_timing
					0.0
					rnd_timing
					1.7
					12.0

GDL status Enable detectors to check GDL status

READY ☐ CDC ☒ ECL ☐ TOP ☐ KLM

Link status

☒ ECL **READY** ☒ KLM **READY** ☒ TOP **READY** ☐ ETF **OFF**

☒ GRL **READY** ☐ EKLK **OFF** ☐ T3D **OFF**

Current trigger type **Change trigger type**

BEAM Beam 20191203_col Cosmic+Random10k 20191029_2_poi20Hz_col

20191203_col Cosmic 20191031_cosmic_ecltiming Cosmic+Random15k 20191115_dph_c2_local

GDL0075p_non Random 20191025_cosmic_cdtiming Cosmic+Random20k 20191018_poi20k

Cosmic+Random2k 20191122_col Cosmic+Random25k 20191106_toptrg

Cosmic+Random5k 20191025_hie Cosmic+Random30k 20191009_cospoi30k_ecltiming

Figure 3.8: The GDL detail main panel. The first block shows several real-time trigger rates. The following two blocks are for checking the GDL status. Sub-trigger status and link status can be included/excluded to generate the GDL status with checkboxes. The last block is for setting the trigger type. Trigger type and related parameters can be changed with the ellipse-shaped button.

3.4.3 Level 1 trigger rate plot

The level 1 trigger is the final output of the trigger system, and its rate can be used as one of the direct indicators of the trigger system, so it should be archived and monitored. Figure 3.7 is a screenshot of the L1 trigger rate plot. If the rate suddenly drops or soars without a corresponding change in accelerator conditions, it is suspected that the trigger system has a problem. Then, the CR shift crew members should stop a run and call a trigger expert shift crew member. The DAQ study runs are mainly for DAQ study, and also for each sub-detector study. During the cosmic-ray runs, the GDL parameter setting is different from the parameters for the physics (luminosity) runs, so the L1 trigger rate is noticeably different from that of physics runs. The luminosity runs in the period (B) are relatively less stable than the luminosity runs in the period (A) because several problems ((a) to (d)) happened in the period (B).

The luminosity runs in the period (A) in Figure 3.7 are relatively stable than that in the period (B) where several problems happened.

- (a) No L1 trigger rate, due to beam problem.
- (b) The GDL timing problem happened.
- (c) Same as (b)
- (d) Sudden decrease of the L1 trigger rate.

In the period (i), ECL expert did local run study in order to chase the origin of (d).

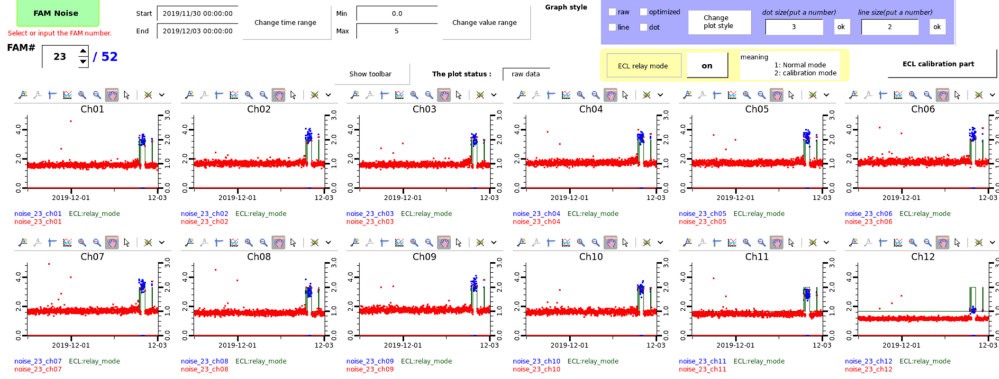


Figure 3.9: The FAM module noise monitoring panel. The x-axis is time: the range is between November 30, 2019, 00:00 JST and December 3, 2019, 00:00 JST, same as Figure 3.7. The left-hand side y-axis is for noise value (red/blue dots), and the unit is ADC count (1 ADC count corresponds to 5.25 MeV). The right-hand side y-axis denotes the ECL operation modes (green line, 1: the normal mode, 2: the local work mode). With the normal setting, the FAM noise level is near 2 ADC counts (red dots), and with the local work setting, the FAM noise level is between 3 and 4 ADC counts depending on the local study (blue dots). The channel 12 is a null-channel. We can change the range of x and y axes, and style of both of the plots by the corresponding setting interface on the panels.

3.4.4 GDL panel

Figure 3.8 is the GDL main panel. Sub-trigger rates and link status of data-taking are displayed on the GDL main panel. With this panel, we can set several GDL parameters for specific purposes such as physics (beam) run, cosmic-ray run, test runs with a random (Poisson) trigger rate, and a cosmic-ray + random trigger rate. We can test the DAQ system stability with an increased random trigger rate.

3.4.5 ECL trigger panels

The ECL trigger system consists of 3 sub-modules, which are the FADC Analysis Module (FAM), the Trigger Merger Module (TMM), and the ECL Trigger Master (ETM) [23, 26].

Figure 3.9 is a FAM noise monitoring panel and the plots in the figure are based

on archived PVs. This figure shows an example of how we exploit the trigger slow control system in real use. There are also other panels showing the FAM pedestal, hit-rate, average hit-rate, the TMM temperature, and the ETM physics bits plots. We use all these plots for operating the ECL trigger system stably. Especially, FAM hit-rates and average hit-rates PVs are utilized not only by the trigger group but also by the SuperKEKB side for beam tuning. Additionally, the ECL trigger slow control system provides an automatic parameter setting function depending on run condition.

3.5 Trigger slow control in operation

A read-only version of the trigger main panel and the L1 trigger rate plots are used by CR shift crew members. If a run stops automatically by the trigger slow control system or CR shift crew members find a problem in the trigger side with the operator interfaces, they contact the trigger expert shift crew members by internal chat or a phone call.

If a trigger expert shift crew member finds a problem or gets a message/phone call from CR shift crew members, the trigger expert first checks which part shows the problem and follows recovery procedures. If the problem is due to the slow control system itself, the trigger expert can easily recover whole processes on the trigger control servers, COPPER control servers, and all sub-servers of both of them by scripts (Figure 3.2). If the problem is due to a sub-trigger system, the trigger expert can follow the troubleshooting procedure provided by the corresponding sub-trigger group. If the trigger expert cannot recover the systems by following the procedures, then the real expert of the sub-trigger is called.

Chapter 4

Search for $B^0 \rightarrow \tau^+ \tau^-$

In this chapter, we describe a sensitivity study of the $B^0 \rightarrow \tau^+ \tau^-$ search using hadronic B tagging. The chapter is structured as follows.

Section 4.1 describes the data and MC samples used in the study. Section 4.2 briefly introduces the Belle II analysis software framework. Section 4.3 outlines the hadronic B -tagging method and sub-decays modes of the tag-side B^0 meson. Section 4.4 explains the reconstruction of the tag-side B^0 , signal-side B^0 , and the rest of event (ROE). Section 4.5 describes the event selection criteria, including kinematic requirements, continuum suppression, and lepton pair mass cuts. Section 4.6 discusses the signal efficiency and background yield.

Machine learning-based background suppression is introduced in Section 4.7, followed by a dedicated study of the main background contribution from ROE K_L^0 in Section 4.8.

Section 4.9.1 presents the signal extraction method, including a description of the signal-extracting variable and the masking techniques. Finally, Section 4.10 describes the method used to estimate the upper limit on the branching fraction of $B^0 \rightarrow \tau^+ \tau^-$.

4.1 Data sample and Monte Carlo simulation sample

The Belle II simulation software has been continuously improved, and the version of the generated samples depends on the development release used. Among the available samples, the `MC15_ri_b` sample is used in this analysis. Here, `MC15` refers to the 15th Monte Carlo production campaign, `ri` stands for run-independent, and the final letter `b` is determined based on the alphabetic order corresponding to the data-taking period.

The signal Monte Carlo (MC) sample is generated centrally by the Belle II data production group using a decay file (see Listing A.1). A total of 16 million beam background overlaid events are generated. The sample is processed with the hadronic Full Event Interpretation (FEI) algorithm (skim code: 11180500). The algorithm is described in the section 4.3.

For background Monte Carlo (MC) samples, the Belle II data production group centrally generates several sets of samples, including generic B -meson decays and non-resonant $q\bar{q}$ processes (Figure 2.1). The generic B -meson samples include various decay modes of $B^0\bar{B}^0$ and B^+B^- pairs produced at the $\Upsilon(4S)$ resonance, and are used to model backgrounds from generic $B\bar{B}$ events. The non-resonant $q\bar{q}$ samples, which represent light quark pair production processes ($q = u, d, s, c$), are generated to simulate backgrounds from $e^+e^- \rightarrow q\bar{q}$ events. Hereafter, these non-resonant $q\bar{q}$ samples are referred to as *continuum*. For the generic B meson samples, $B^0\bar{B}^0$ (mixed) and B^+B^- (charged), the number of events corresponds to 3 ab^{-1} for each. Ten percent of the sample is used for FEI training, so the number of events corresponds to 2.8 ab^{-1} is used. For the continuum samples ($q = u, d, s$ or c), the

number of event corresponds to 1.0 ab^{-1} is used. The samples are skimmed with the hadronic FEI algorithm (skim code: 11180500).

4.2 Belle II Analysis Software Framework

Data processing at Belle II is handled using the Belle II analysis software framework (`basf2`). The framework is designed to divide the workflow into small, independent units called modules, which run sequentially along a predefined path. Each module is configured using a steering file. Modules exchange information through a shared object store, which also keeps track of relationships between data objects in an event.

The data is processed in several phases. Raw detector data, such as hits and energy deposits, are reconstructed into physical quantities like tracks and clusters. These are then used to form high-level objects, such as charged particle tracks. The resulting high-level data is used to calculate particle-level observables, including four-momentum and event-shape variables [17, 40].

4.3 Hadronic tagging

Measuring the branching fraction of rare decays that include undetectable neutrinos in the final state is experimentally difficult. However, the presence of a second B meson in each event allows one to constrain the decay kinematics through a technique known as **tagging**. In this technique, each $\Upsilon(4S)$ event is conceptually divided into two parts: the signal side, which contains the tracks and clusters consistent with the decay of the signal B_{sig} meson, and the tag side, which contains the remaining particles associated with the decay of the accompanying B_{tag} meson [41].

The Full Event Interpretation (FEI) is a exclusive tagging algorithm based

on machine learning for Belle II analysis [41]. The FEI automatically constructs plausible B_{tag} meson decay chains compatible with the observed tracks and clusters, and estimates the probability that each decay chain correctly represents the true decay process using gradient-boosted decision trees. The term “exclusive” refers to the reconstruction of a particle (here, the B_{tag}) under the assumption of a specific decay channel.

The performance of an exclusive tagging algorithm is typically characterized by three quantities. The **tagging efficiency** ($N_{\text{tag}}/N_{\Upsilon(4S)}$) refers to the fraction of $\Upsilon(4S)$ events which can be tagged. The **tag-side efficiency** ($N_{\text{correct}}/N_{\Upsilon(4S)}$) denotes the fraction of $\Upsilon(4S)$ events with a correct tag. The **tag-side purity** ($N_{\text{correct}}/N_{\text{tag}}$) is defined as the fraction of the tagged $\Upsilon(4S)$ events with a correct tag) of the tagged events.

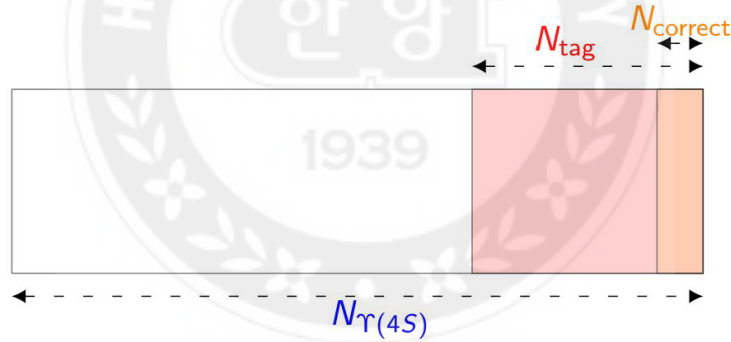


Figure 4.1: FEI quantities [42].

Figure 4.2, Schematic overview of the FEI. The B mesons are reconstructed hierarchically; using the detector output, final state particle candidates are formed, and combined to intermediate particles until the final B candidates are formed. The probability of each candidate to be correct is estimated by an MVA algorithm. The probabilities are fed into the subsequent MVA methods.

Hadronic tagging only uses hadronic B decay channels for the reconstruction.

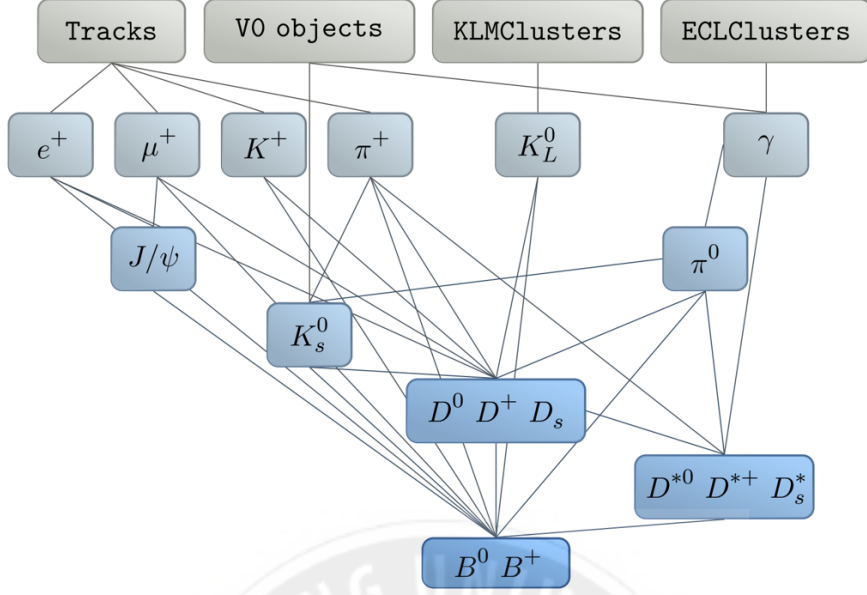


Figure 4.2: Hierarchical reconstruction of B candidates in the FEI algorithm [41].

Hence, the four-momentum of the reconstructed B_{tag} is well known and the tagged sample is very pure. However, hadronic tagging suffers from a low tagging efficiency. It is only possible for a tiny fraction of the recorded events, because the branching fraction of explicit fully hadronic decay chains is very small. A typical hadronic B decay has a branching fraction of $\mathcal{O}(10^{-3})$.

4.3.1 B^0 meson from hadronic decay-channels

The following hadronic channels are used to reconstruct B^0 mesons:

- | | | |
|--|--|---|
| 1. $B^0 \rightarrow D^- \pi^+$ | 6. $B^0 \rightarrow \bar{D}^0 \pi^+ \pi^-$ | 11. $B^0 \rightarrow D^- D^+ K_S^0$ |
| 2. $B^0 \rightarrow D^- \pi^+ \pi^0$ | 7. $B^0 \rightarrow D^- D^0 K^+$ | 12. $B^0 \rightarrow D^{*-} D^+ K_S^0$ |
| 3. $B^0 \rightarrow D^- \pi^+ \pi^0 \pi^0$ | 8. $B^0 \rightarrow D^- D^{*0} K^+$ | 13. $B^0 \rightarrow D^- D^{*+} K_S^0$ |
| 4. $B^0 \rightarrow D^- \pi^+ \pi^+ \pi^-$ | 9. $B^0 \rightarrow D^{*-} D^0 K^+$ | 14. $B^0 \rightarrow D^{*-} D^{*+} K_S^0$ |
| 5. $B^0 \rightarrow D^- \pi^+ \pi^+ \pi^- \pi^0$ | 10. $B^0 \rightarrow D^{*-} D^{*0} K^+$ | 15. $B^0 \rightarrow D_s^+ D^-$ |

- | | | |
|--|--|---|
| 16. $B^0 \rightarrow D^{*-}\pi^+$ | 22. $B^0 \rightarrow D_s^+ D^{*-}$ | 28. $B^0 \rightarrow \bar{D}^0 p \bar{p}$ |
| 17. $B^0 \rightarrow D^{*-}\pi^+\pi^0$ | 23. $B^0 \rightarrow D_s^{*+} D^{*-}$ | 29. $B^0 \rightarrow D^- p \bar{p} \pi^+$ |
| 18. $B^0 \rightarrow D^{*-}\pi^+\pi^0\pi^0$ | 24. $B^0 \rightarrow J/\psi K_S^0$ | 30. $B^0 \rightarrow D^{*-} p \bar{p} \pi^+$ |
| 19. $B^0 \rightarrow D^{*-}\pi^+\pi^+\pi^-$ | 25. $B^0 \rightarrow J/\psi K^+\pi^-$ | 31. $B^0 \rightarrow \bar{D}^0 p \bar{p} \pi^+\pi^-$ |
| 20. $B^0 \rightarrow D^{*-}\pi^+\pi^+\pi^-\pi^0$ | 26. $B^0 \rightarrow J/\psi K_S^0 \pi^+\pi^-$ | 32. $B^0 \rightarrow \bar{D}^{*0} p \bar{p} \pi^+\pi^-$ |
| 21. $B^0 \rightarrow D_s^{*+} D^-$ | 27. $B^0 \rightarrow \Lambda_c^- p \pi^+\pi^-$ | |

Only hadronic B^0 candidates with an beam-constrained mass above 5.2 GeV and an absolute deviation of the energy from the beam energy below 0.5 GeV are considered [43].

4.3.2 Charmed mesons decay channels

Charmed mesons sub-decay channels are specified in this subsection.

D^0 meson from hadronic decay-channels

The following hadronic channels are used to reconstruct D^0 mesons:

- | | | |
|--|--|---|
| 1. $D^0 \rightarrow K^-\pi^+$ | 6. $D^0 \rightarrow \pi^-\pi^+$ | 11. $D^0 \rightarrow K_S^0 \pi^+\pi^-$ |
| 2. $D^0 \rightarrow K^-\pi^+\pi^0$ | 7. $D^0 \rightarrow \pi^-\pi^+\pi^0$ | 12. $D^0 \rightarrow K_S^0 \pi^+\pi^-\pi^0$ |
| 3. $D^0 \rightarrow K^-\pi^+\pi^-\pi^+$ | 8. $D^0 \rightarrow \pi^-\pi^+\pi^-\pi^+$ | 13. $D^0 \rightarrow K^- K^+$ |
| 4. $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$ | 9. $D^0 \rightarrow \pi^-\pi^+\pi^+\pi^-\pi^0$ | 14. $D^0 \rightarrow K^- K^+ \pi^0$ |
| 5. $D^0 \rightarrow K^-\pi^+\pi^+\pi^-\pi^0$ | 10. $D^0 \rightarrow K^- K^+$ | 15. $D^0 \rightarrow K^- K^+ K_S^0$ |

Only hadronic D^0 candidates with an invariant mass between 1.7 GeV and 1.95 GeV are considered [43].

D^0 meson from decay-channels with K_L^0

Due to the different kinematic properties, D^0 mesons from decay-channels which include a K_L^0 are processed separately by the FEI. The following channels are used to reconstruct D^0 mesons:

- | | |
|--|--|
| 1. $D^0 \rightarrow K_L^0 \pi^0$ | 3. $D^0 \rightarrow K_L^0 \pi^+ \pi^- \pi^0$ |
| 2. $D^0 \rightarrow K_L^0 \pi^+ \pi^-$ | 4. $D^0 \rightarrow K^- K^+ K_L^0$ |

There are no further cuts applied to D^0 candidates with K_L^0 [43].

D^+ meson from hadronic decay-channels

The following hadronic channels are used to reconstruct D^+ mesons:

- | | | |
|--|--|---|
| 1. $D^+ \rightarrow K^- \pi^+ \pi^+$ | 5. $D^+ \rightarrow \pi^- \pi^+ \pi^+$ | 9. $D^+ \rightarrow K_S^0 \pi^+ \pi^0$ |
| 2. $D^+ \rightarrow K^- \pi^+ \pi^+ \pi^0$ | 6. $D^+ \rightarrow K^- K^+ \pi^+$ | |
| 3. $D^+ \rightarrow K^- \pi^+ \pi^+ \pi^+ \pi^-$ | 7. $D^+ \rightarrow K^- K^+ \pi^+ \pi^0$ | 10. $D^+ \rightarrow K_S^0 \pi^+ \pi^- \pi^+$ |
| 4. $D^+ \rightarrow K^- \pi^+ \pi^+ \pi^0 \pi^0$ | 8. $D^+ \rightarrow K_S^0 \pi^+$ | 11. $D^+ \rightarrow K^+ K_S^0 K_S^0$ |

Only hadronic D^+ candidates with an invariant mass between 1.7 GeV and 1.95 GeV are considered [43].

D^+ meson from decay-channels with K_L^0

Due to the different kinematic properties, D^+ mesons from decay-channels which include a K_L^0 are processed separately by the FEI. The following channels are used to reconstruct D^+ mesons:

- | | | |
|--|--|--------------------------------------|
| 1. $D^+ \rightarrow K_L^0 \pi^+$ | 3. $D^+ \rightarrow K_L^0 \pi^+ \pi^- \pi^+$ | 5. $D^+ \rightarrow K^+ K_L^0 K_L^0$ |
| 2. $D^+ \rightarrow K_L^0 \pi^+ \pi^0$ | 4. $D^+ \rightarrow K^+ K_L^0 K_S^0$ | |

There are no further cuts applied to D^+ candidates with K_L^0 [43].

D^{+*} meson from decay-channels

The following channels are used to reconstruct D^{+*} mesons:

1. $D^{+*} \rightarrow D^0 \pi^+$
2. $D^{+*} \rightarrow D^+ \pi^0$
3. $D^{+*} \rightarrow D^+ \gamma$

Only D^{+*} candidates with a released energy in the decay between 0 GeV and 0.3 GeV are considered [43].

$D^*(2010)^0$ meson from decay-channels

The following channels are used to reconstruct $D^*(2010)^0$ mesons:

1. $D^*(2010)^0 \rightarrow D^0 \pi^0$
2. $D^*(2010)^0 \rightarrow D^0 \gamma$

Only $D^*(2010)^0$ candidates with a released energy in the decay between 0 GeV and 0.3 GeV are considered [43].

D_s^+ meson from hadronic decay-channels

The following hadronic channels are used to reconstruct D_s^+ mesons:

1. $D_s^+ \rightarrow K^+ K_S^0$
2. $D_s^+ \rightarrow K^+ \pi^+ \pi^-$
3. $D_s^+ \rightarrow K^+ K^- \pi^+$
4. $D_s^+ \rightarrow K^+ K^- \pi^+ \pi^0$
5. $D_s^+ \rightarrow \pi^+ \pi^+ \pi^-$
6. $D_s^+ \rightarrow K^+ K_S^0 \pi^+ \pi^-$
7. $D_s^+ \rightarrow K^+ K^- \pi^+ \pi^- \pi^+$
8. $D_s^+ \rightarrow \pi^+ \pi^+ \pi^- \pi^0$
9. $D_s^+ \rightarrow K_S^0 \pi^+$
10. $D_s^+ \rightarrow K_S^0 \pi^+ \pi^0$
11. $D_s^+ \rightarrow K^+ K_S^0 K_S^0$

Only hadronic D_s^+ candidates with an invariant mass between 1.68 GeV and 2.1 GeV are considered [43].

D_s^+ meson from decay-channels with K_L^0

Due to the different kinematic properties, D_s^+ mesons from decay-channels which include a K_L^0 are processed separately by the FEI. The following channels are used to reconstruct D_s^+ mesons:

1. $D_s^+ \rightarrow K^+ K_L^0$
2. $D_s^+ \rightarrow K^+ K_L^0 \pi^+ \pi^-$
3. $D_s^+ \rightarrow K^- K_L^0 \pi^+ \pi^+$
4. $D_s^+ \rightarrow K_L^0 \pi^+$
5. $D_s^+ \rightarrow K_L^0 \pi^+ \pi^0$

There are no further cuts applied to D_s^+ candidates with K_L^0 [43].

D_s^{*+} meson from decay-channels

The following channels are used to reconstruct D_s^{*+} mesons:

1. $D_s^{*+} \rightarrow D_s^+ \gamma$
2. $D_s^{*+} \rightarrow D_s^+ \pi^0$

Only D_s^{*+} candidates with a released energy in the decay between 0 GeV and 0.3 GeV are considered [43].

4.4 Reconstruction

The reconstruction code has been created using the `basf2` software package, specifically version `light-2305-korat`.

In this analysis, the entire event is conceptually divided into three parts (figure 4.3):

- The hadronic B_{tag}^0 candidate, reconstructed via the FEI algorithm.
- The signal $B^0 \rightarrow \tau^+ \tau^-$ candidate, reconstructed using all detector-level objects not associated with the B_{tag}^0 candidate.

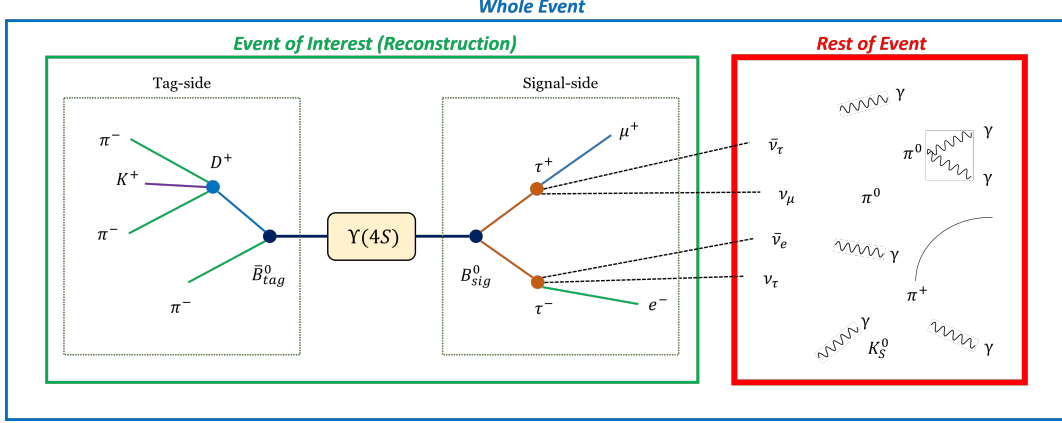


Figure 4.3: Schematic diagram of the reconstruction.

- The Rest Of the Event (ROE), defined as all detector-level objects not assigned to either the B_{tag}^0 or the B_{sig}^0 candidate.

Due to the presence of two to four neutrinos in the final state, direct kinematic reconstruction of the signal-side B meson is not possible. Instead, kinematic information is inferred from the ROE, taking advantage of the well-defined initial state provided by the $\Upsilon(4S)$ resonance at Belle II.

The possible signal-side sub-decay channels are summarized in Table 4.1. Only leptonic decay modes (01,02, and 03) of the signal-side B meson are considered in this analysis. Hereafter, we refer to Mode 01 as the ee **mode**, Mode 02 as the $e\mu$ **mode**, and Mode 03 as the $\mu\mu$ **mode**.

4.4.1 Tag-side B^0

The FEI algorithm is applied to simulated samples to reconstruct the tag-side B meson decaying hadronically. In such cases, the energy and momentum of the B_{tag} candidate can be estimated by summing the 4-momenta of its final-state particles [44].

Before running the FEI tag reconstruction, the following pre-selection (skim) is

	Mode	Branching Fraction
01	$\tau^+/\tau^- \rightarrow \mu\nu\bar{\nu}/\mu'\nu\bar{\nu}$	3.0 %
02	$\tau^+/\tau^- \rightarrow \mu\nu\bar{\nu}/e\nu\bar{\nu}$	6.2 %
03	$\tau^+/\tau^- \rightarrow e\nu\bar{\nu}/e'\nu\bar{\nu}$	3.2 %
04	$\tau^+/\tau^- \rightarrow \mu\nu\bar{\nu}/\pi\nu$	3.8 %
05	$\tau^+/\tau^- \rightarrow e\nu\bar{\nu}/\pi\nu$	3.9 %
06	$\tau^+/\tau^- \rightarrow \mu\nu\bar{\nu}/\rho\nu$	8.9 %
07	$\tau^+/\tau^- \rightarrow e\nu\bar{\nu}/\rho\nu$	9.1 %
08	$\tau^+/\tau^- \rightarrow \pi\nu/\pi\nu$	1.2 %
09	$\tau^+/\tau^- \rightarrow \pi\nu/\rho\nu$	5.5 %
10	$\tau^+/\tau^- \rightarrow \rho\nu/\rho\nu$	6.5 %
Total		51.3 %

Table 4.1: Branching fractions of $\tau^+\tau^-$ decay modes.

Mode	Branching Fraction
$\tau^+ \rightarrow \mu\nu\bar{\nu}$	$(17.39 \pm 0.04) \%$
$\tau^+ \rightarrow e\nu\bar{\nu}$	$(17.82 \pm 0.04) \%$
$\tau^+ \rightarrow \pi\nu$	$(10.82 \pm 0.05) \%$
$\tau^+ \rightarrow \pi\pi^0\nu$	$(25.49 \pm 0.09) \%$
$\tau^+ \rightarrow \pi\pi\pi\nu$	$(9.31 \pm 0.05) \%$

Table 4.2: Branching fractions of main τ^+ decay modes.

applied to all events to reduce computing time and reject low-multiplicity processes.

- Each event must contain at least three tracks with $|z_0| < 2 \text{ cm}$, $|d_0| < 0.5 \text{ cm}$, and $p_T > 0.1 \text{ GeV}/c$. Here, $|z_0|$ and $|d_0|$ are the distances of the point of closest approach (POCA) of a track to the origin along the longitudinal (z) and transverse (r, ϕ) directions, respectively.
- Each event must contain at least three ECL clusters with energy $E > 0.1 \text{ GeV}$, located within the CDC acceptance region ($17^\circ < \theta < 150^\circ$).
- The visible energy of the event must satisfy $E_{\text{vis}} > 4 \text{ GeV}$, to suppress diphoton and low-multiplicity background processes. E_{vis} is calculated in the center-of-mass frame by summing the energies of all tracks and neutral clusters that meet the above criteria.

The output of the FEI classifier, which provides an independent probability that the B_{tag} candidate is correctly reconstructed, hereafter referred to as the “signal probability” $\mathcal{P}_{\text{FEI}}$. A requirement of $\mathcal{P}_{\text{FEI}} > 0.001$ is applied to save computing time.

For each event, only the B_{tag} candidate with highest value of $\mathcal{P}_{\text{FEI}}$ is taken among the ones passing the FEI skim, so that the tag-side is unambiguously defined. The distribution of this variables are shown in the Figure 4.5 (a). This procedure is referred to as the Best Tag Selection (BTS).

4.4.2 Signal-side B^0

The detector objects not associated with the B_{tag} candidate are used to reconstruct the signal-side $B^0 \rightarrow \tau^+ \tau^-$ decay [44]. All tracks on the signal side must satisfy the following requirements:

- Track origin close to the interaction point: $|d_0| < 2 \text{ cm}$, $|z_0| < 4 \text{ cm}$, to reject beam background tracks.
- Polar angle within the CDC acceptance: $17^\circ < \theta < 150^\circ$.
- At least 20 CDC hits to ensure reliable particle identification via dE/dx measurements.
- Transverse momentum $p_T > 0.1 \text{ GeV}/c$, to remove low-momentum beam background tracks.
- Track energy $E < 5.5 \text{ GeV}$, to suppress Bhabha electrons.

Muons are identified as tracks with a likelihood-based PID score $\text{PID}(\mu) > 0.5$. Electrons and positrons are required to have $\text{PID}(e) > 0.5$, based on the BDT-based PID.

4.4.3 Rest of event (ROE)

For each $\Upsilon(4S)$ candidate, the rest of the event (ROE) is defined as all detector-level objects not used in the reconstruction of either the B_{tag} or the B_{sig} meson. Charged tracks in the ROE are selected according to the following criteria [44].

- Tracks must originate near the interaction point: $|d_0| < 2 \text{ cm}$, $|z_0| < 4 \text{ cm}$.
- Polar angle within CDC acceptance: $17^\circ < \theta < 150^\circ$.
- At least 20 hits in the CDC, to ensure reliable particle identification via dE/dx .
- Transverse momentum $p_T > 0.1 \text{ GeV}/c$.

Events are required to have exactly zero charged tracks in the ROE that satisfy these criteria. If one or more such tracks are found, the corresponding $\Upsilon(4S)$ candidate is rejected.

Neutral clusters used for identifying photons from π^0 decays are selected based on the following conditions (pi0:eff30_May2020).

- Number of (weighted) crystals in the ECL cluster must satisfy $N_{\text{crystals}} > 1.5$, where $N_{\text{crystals}} = \sum_{i \in \text{cluster}} w_i$, and the weights w_i account for overlapping clusters.
- Cluster polar angle must fall within the CDC acceptance ($17^\circ < \theta < 150^\circ$), to reject clusters originating from missing tracks.
- Cluster energy threshold depends on the ECL region. Tighter thresholds are required for endcaps due to higher background levels:
 - Forward ECL: $E > 80$ MeV
 - Barrel ECL: $E > 30$ MeV
 - Backward ECL: $E > 60$ MeV

By above condition, $\pi^0 \rightarrow \gamma\gamma$ candidates are reconstructed from a pair of photons satisfying the following:

- $120 \text{ MeV}/c^2 < M(\gamma\gamma) < 145 \text{ MeV}/c^2$
- Azimuthal angle between the two photons: $-1.5 \text{ rad} < \varphi < 1.5 \text{ rad}$
- Angle between the two photons: $< 1.4 \text{ rad}$

These reconstruction criteria for π^0 are set to ensure good agreement between data and simulation, while retaining a reasonable reconstruction efficiency of approximately 30%.

ROE cluster study is done at the signal extraction stage of this analysis 4.9.1.

4.5 Event Selection

This section describes the selection criteria used to separate $B^0 \rightarrow \tau^+ \tau^-$ signal events from background.

4.5.1 Tag-side B^0 kinematics

To improve the purity of the sample, additional requirements are applied to the B_{tag} candidates reconstructed by the FEI algorithm. Two kinematic variables are used.

- The energy difference:

$$\Delta E = E_{B_{\text{tag}}}^{\text{CM}} - E_{\text{beam}}^{\text{CM}},$$

- The beam-constrained mass:

$$M_{\text{bc}} = \sqrt{\left(\frac{E_{\text{beam}}^{\text{CM}}}{c^2}\right)^2 - \left(\frac{|\vec{p}_{B_{\text{tag}}}^{\text{CM}}|}{c}\right)^2}.$$

Events are selected using the following requirements:

$$M_{\text{bc}} > 5.27 \text{ GeV}/c^2, \quad -0.15 < \Delta E < 0.1 \text{ GeV}.$$

The distributions of these variables are shown in Figure 4.5 (b) and (c).

4.5.2 Continuum suppression

Continuum events decays to light hadrons. These events are strong collimated due to the large momentum. On the contrary, $B\bar{B}$ events are uniformly distributed [14]. The event shape is shown in Figure 4.4.

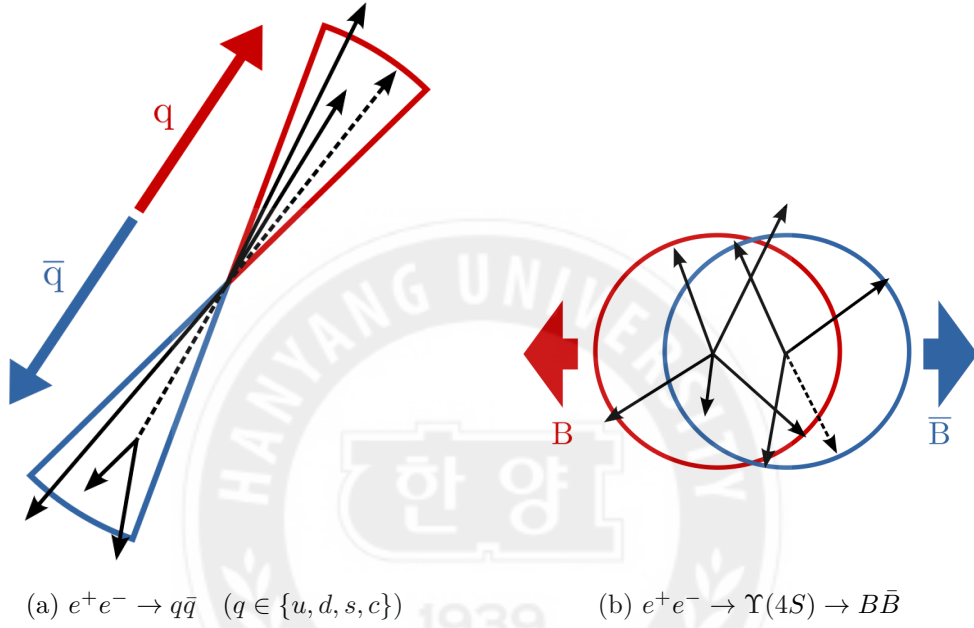


Figure 4.4: Event shape.

To suppress background from continuum $e^+e^- \rightarrow q\bar{q}$ processes, two variables are used.

The ratio of the second to zeroth Fox–Wolfram moments, denoted as R_2 , characterizes the sphericity of the event and distinguishes spherical $B\bar{B}$ events from jet-like continuum events. The R_2 variable is defined as,

$$R_2 = \frac{H_2}{H_0}. \quad (4.1)$$

The l -th Fox–Wolfram moments is defined as

$$H_l = \sum_{i,j} \frac{|\vec{p}_i||\vec{p}_j|}{E_{\text{event}}^2} P_l(\cos \theta_{i,j}), \quad (4.2)$$

where $\vec{p}_i$ and $\vec{p}_j$ are the momenta of particles i and j , $\theta_{i,j}$ is the angle between them, E_{event} is the total energy of the event, and P_l denotes the Legendre polynomial of order l [14].

The variable $\cos \theta_{\text{TBT0}}$, computed on the tag-side, measures the angle between the thrust axis of the tag-side and the signal-side B meson. It is defined as

$$T = \frac{\sum_{i=1}^N |\vec{T} \cdot \vec{p}_i|}{\sum_{i=1}^N |\vec{p}_i|}, \quad (4.3)$$

where $\vec{p}_i$ is the momentum of the i -th particle in the event, and $\vec{T}$ is the unit vector (thrust axis) that maximizes the value of T .

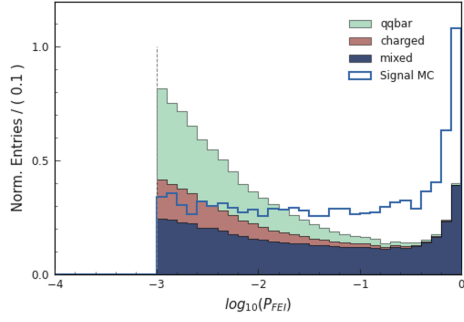
Both variables exploit the topological differences between signal and continuum events to enhance the signal purity. The following cuts are applied.

$$R_2 > 0.2, \quad \cos \theta_{\text{TBT0}} < 0.9$$

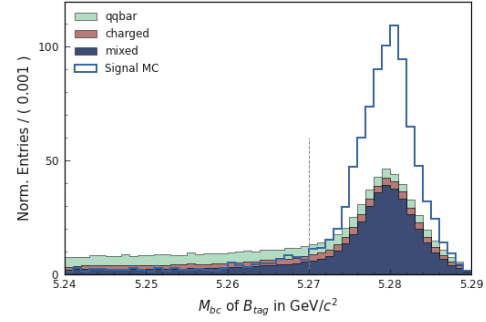
The distribution of the variables are shown in Figure 4.5 (d) and (e).

4.5.3 ROE neutral particles

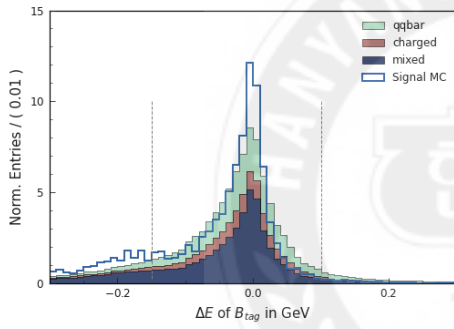
Events containing any neutral particles in the ROE are rejected. In particular, no π^0 , K_S^0 , or Λ candidates are allowed in the ROE. The distribution of number of ROE π^0 and K_S^0 are shown in the figure 4.6.



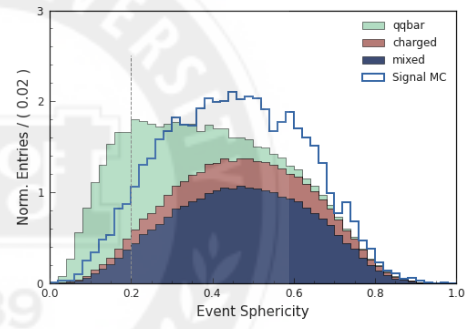
(a) $\mathcal{P}_{\text{FEI}}$



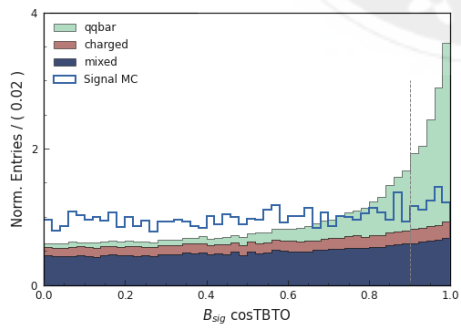
(b) M_{bc}



(c) ΔE



(d) R_2



(e) $\cos \theta_{\text{TBTO}}$

Figure 4.5: Selection variables.

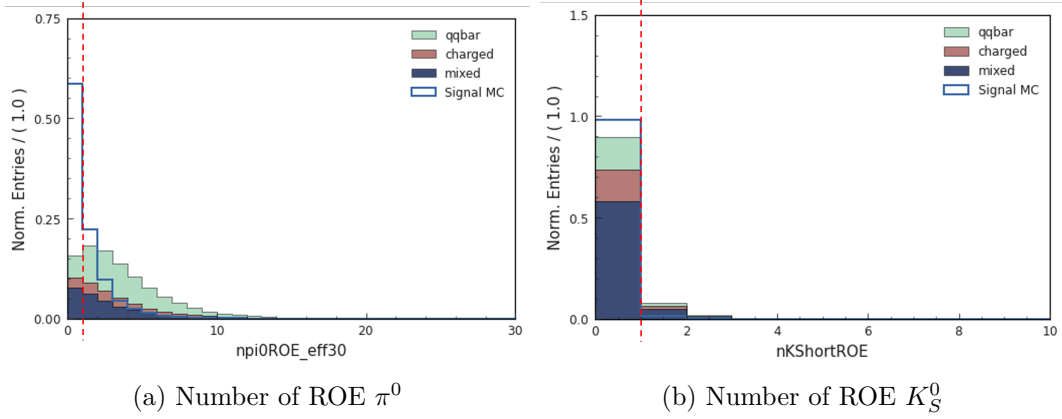


Figure 4.6: Number of ROE neutral particles.

4.5.4 Lepton pair mass

The invariant mass of the oppositely charged lepton pair which corresponds to the signal side B^0 is used to suppress backgrounds from photon conversions ($\gamma \rightarrow e^+e^-$) and charmonium ($c\bar{c}$) resonances such as $J/\psi \rightarrow \ell^+\ell^-$.

To reject photon conversion background, events with low invariant mass are removed by requiring

$$M(e^+e^-) > 0.3 \text{ GeV}/c^2$$

as shown in Figure 4.8 (a).

Charmonium background from decays such as $B^0 \rightarrow J/\psi X$, with $J/\psi \rightarrow \ell^+\ell^-$, is suppressed by vetoing events where the lepton pair invariant mass lies within the J/ψ mass window:

$$3.00 \text{ GeV}/c^2 < M(\ell^+\ell^-) < 3.20 \text{ GeV}/c^2.$$

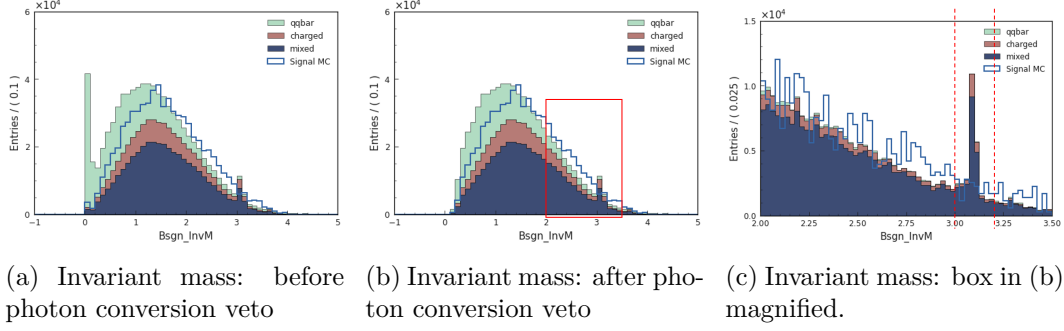


Figure 4.7: Invariant mass distribution of the signal-side B^0 candidates. Subfigure (a) shows the distribution before applying the photon conversion veto, while (b) shows the distribution after the veto. Subfigure (c) is an enlarged view of the red-boxed region in (b). The J/ψ veto is applied.

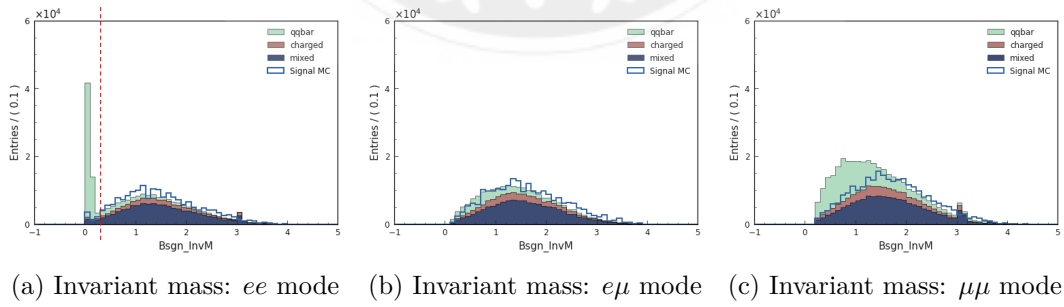


Figure 4.8: Mode by mode invariant mass distribution of signal side B^0 candidates. The photon conversion veto is applied in the ee mode.

4.5.5 Best Candidate Selection

After all the selection, resulting event multiplicity is suppressed to 1.003. To ensure a single candidate per event, a Best Candidate Selection (BCS) method is applied based on the particle identification likelihoods of the final-state leptons:

- $\mu^+\mu^-$ mode: maximize $\mathcal{L}_\mu \cdot \mathcal{L}_\mu$
- $\mu^\pm e^\mp$ mode: maximize $\mathcal{L}_\mu \cdot \mathcal{L}_e$
- e^+e^- mode: maximize $\mathcal{L}_e \cdot \mathcal{L}_e$

Here, $\mathcal{L}_\mu$ and $\mathcal{L}_e$ denote the likelihoods for muon and electron hypotheses, respectively.

Among possible combinations, the one that maximizes the corresponding likelihood product is selected as the signal candidate. In case of multiple candidates with identical likelihood products, a priority is assigned in the following order:

$$\mu^+\mu^- > \mu^\pm e^\mp > e^+e^-.$$

This ordering is based on the fact that muon identification is generally more reliable and less influenced by background than electron identification.

4.6 Signal efficiency and background yield

Signal and background yield after reconstruction and selection is summarized in the Table 4.3. Here, *signal* refers to the number of reconstructed signal events. The background yields are categorized as follows: *bg_mx* denotes the mixed generic $B\bar{B}$ background, *bg_ch* corresponds to charged generic B^+B^- background, *bg_uu*,

bg_dd , bg_ss , and bg_cc represent the continuum backgrounds, $e^+e^- \rightarrow q\bar{q}$ processes, where $q = u, d, s, c$, respectively.

The signal efficiency is defined as the number of selected signal events divided by the total number of generated events. In this analysis, it is calculated as $\frac{3,369}{16,000,000}$, corresponding to 2.11×10^{-4} .

Background yields are normalized to an integrated luminosity of 363 fb^{-1} , corresponding to the collected data sample. The bg_mx background is the dominant component, accounting for approximately 84%. The strategy to separate this background from the signal is discussed in Sections 4.7 and 4.8.

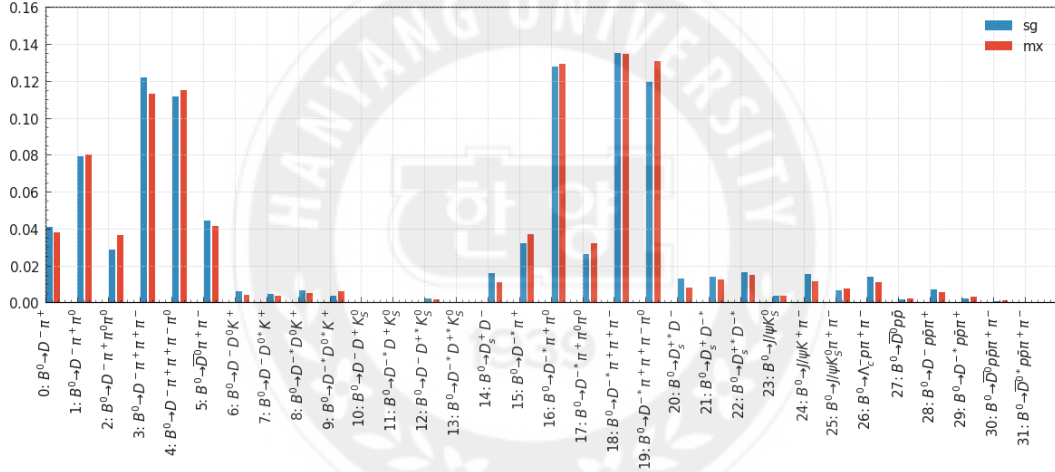


Figure 4.9: FEI mode by mode signal and mixed background yield rate after selection (sg: signal, mx: mixed background).

Figure 4.9 shows signal and mixed background rate after selection. Signal and (mixed) background rate of each mode shows almost same fraction. Hence, there is no significant FEI mode.

Selection	signal	bg_mx	bg_ch	bg_uu	bg_dd	bg_ss	bg_cc
# of generated Events	16 M	2,800 fb ⁻¹	2,800 fb ⁻¹	1,000 fb ⁻¹	1,000 fb ⁻¹	1,000 fb ⁻¹	1,000 fb ⁻¹
Reconstruction ^a	23,095	5,550,745	4,374,203	3,361,180	823,310	466,022	3,721,353
# of ROE Good Track == 0	10,174	468,698	257,184	129,973	32,919	21,162	167,620
BtagMbc > 5.27	7,906	270,215	75,246	26,223	6,744	4,423	32,591
-0.15 < BtagDeltaE < 0.1	6,532	23,043	65,092	22,953	5,914	3,817	28,361
Sphericity > 0.2	6,123	220,744	61,637	14,381	3,714	2,374	19,564
Btag_cosTBT0 < 0.9	5,412	194,112	52,902	7,162	1,844	1,103	9,268
# of ROE π^0 == 0	3,573	65,105	9,071	547	151	120	913
# of ROE K_S^0 == 0	3,528	58,905	8,113	476	129	101	769
# of ROE Λ == 0	3,453	55,713	7,526	434	119	95	715
Photon conversion BG veto	3,435	55,268	7,445	341	97	77	662
J/ψ veto	3,373	53,558	7,182	338	97	77	659
BCS	3,369	53,387	7,169	338	96	77	658
Sig. Eff. & Norm. BG yield	2.11×10^{-4}	6,921	929	123	35	23	239

^a Reconstruction including FEI skim, BTS and $\mathcal{P}_{\text{FEI}} > 0.001$

Table 4.3: Signal and background yields for each selection.

4.7 Background suppression with machine learning

FastBDT [45], the default multivariate analysis (MVA) algorithm in the Belle II software, implements a uniform stochastic gradient boosting algorithm. It performs equal-frequency binning of input features, mapping continuous variables to integers. This approach speeds up training compared to other boosting algorithms. Background MC samples are scaled down proportionally to the number of signal events to match the train sample size [46].

The FBDT input variable candidates are shown in Figure 4.10 and 4.11. The description of the variables are given in Table 4.4. The FBDT is trained with MC sample for background suppression with three variables: the missing energy (`miss_E`, Figure 4.10 (a)), the missing mass squared (`miss_M2`, Figure 4.11 (f)), and the signal B meson invariant mass (`Bsgn_invM`, Figure 4.11 (g)).

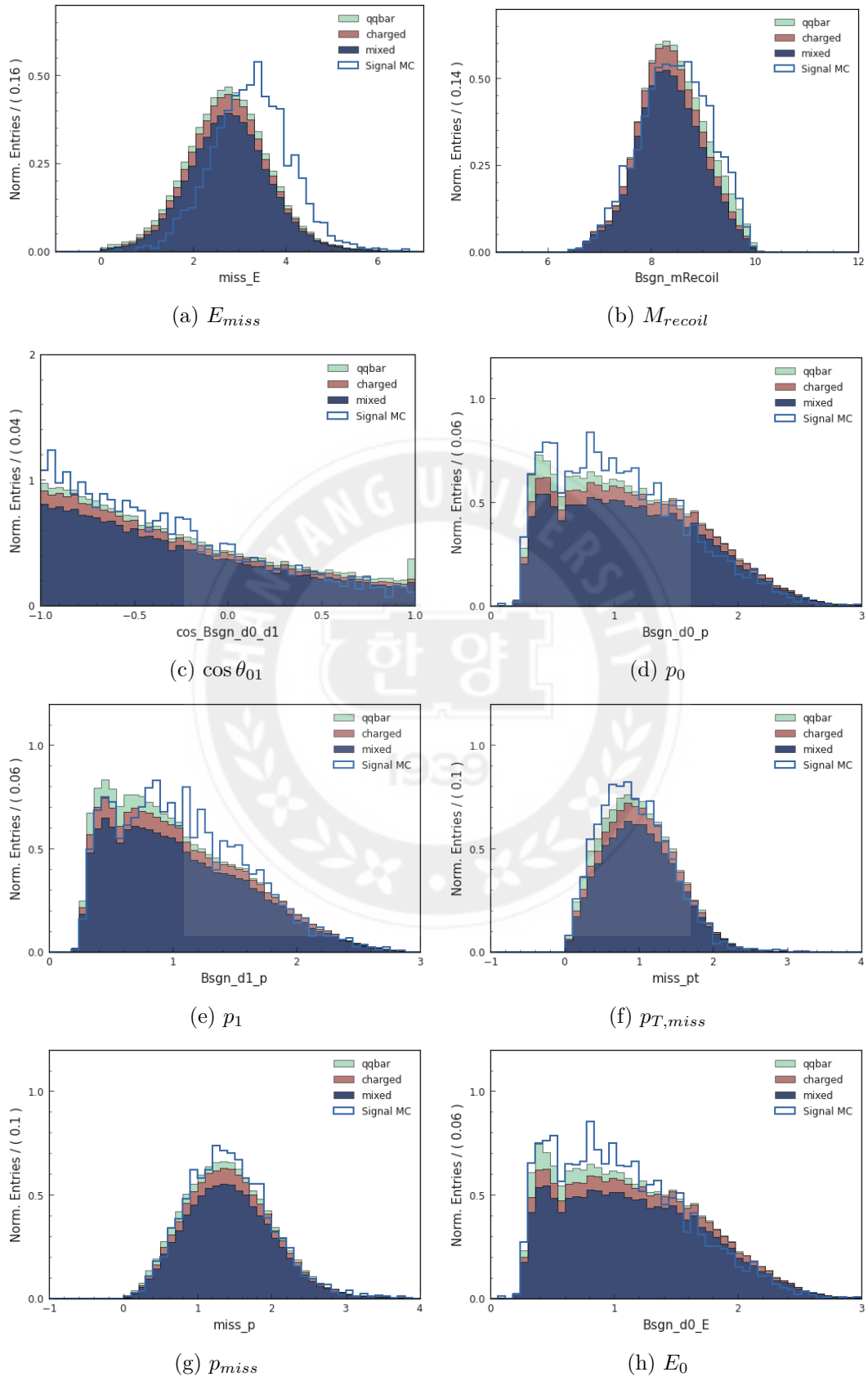


Figure 4.10: FBDT input variable candidates.

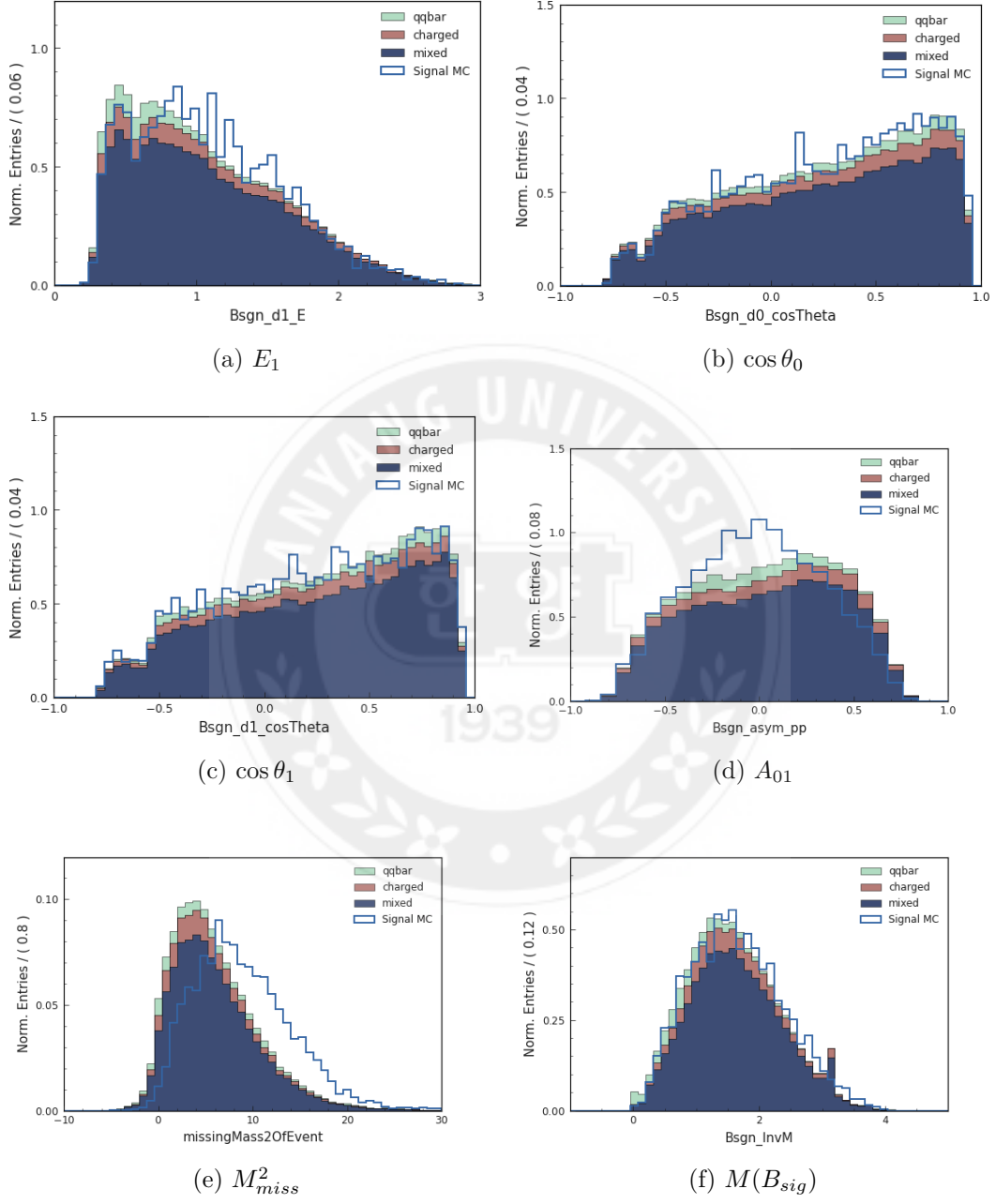


Figure 4.11: FBDT input variable candidates (continued).

Variable	Description
E_{miss}	The missing energy.
M_{recoil}	Invariant mass of the system recoiling against the B_{sig} .
$\cos \theta_{01}$	Angle between B_{sig} daughters.
p_i	Absolute value of the momentum of B_{sig} daughters.
$p_{T,\text{miss}}$	Absolute value of the transverse component of the missing momentum in the event.
p_{miss}	Absolute value of the missing momentum in the event.
E_i	Energy of B_{sig} daughters.
$\cos \theta_i$	Polar angle of B_{sig} daughters.
A_{01}	Momentum asymmetry of B_{sig} daughters.
M_{miss}^2	Missing mass squared of the event.
$M(B_{\text{sig}})$	Invariant mass of B_{sig} .

Table 4.4: The FBDT input variable candidates [1, 14]

Figure 4.12 shows the linear Pearson correlation coefficients among the training variables, including the observable E_{ECL} . Significant correlations are observed between some input features and E_{ECL} , indicating potential issues in variable selection. This suggests that the choice of input variables should be reconsidered to avoid bias in the analysis.

The FBDT output for both training and testing samples and the Receiver Operating Characteristic (ROC) curve, is shown in Figure 4.13. The ROC curve illustrates the trade-off between signal efficiency and background rejection, and the area under the curve (AUC) provides a single scalar value to quantify the overall performance of the classifier, with a value closer to 1 indicating better discrimination power.

The FBDT evaluates the importance of input features by summing the separation gain of each cut across all trees and nodes in the model. Figure 4.14 shows the resulting ranking of the input variables based on their importance in the training.

The selection criterion on the FBDT output is optimized using the Punzi figure

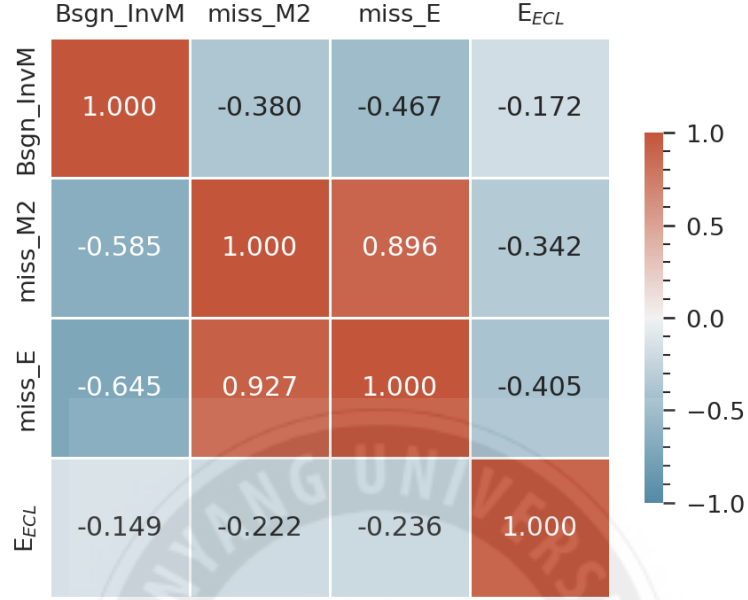


Figure 4.12: Correlation matrix of the variables used plus the E_{ECL} .

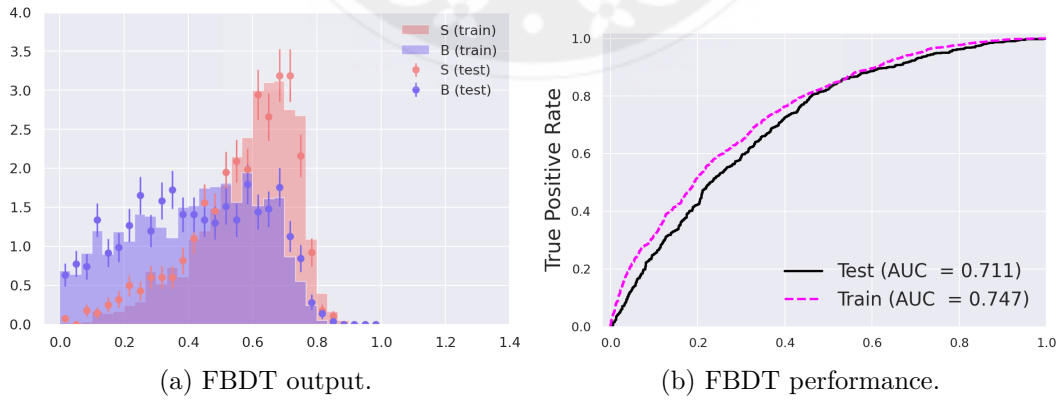


Figure 4.13: FBDT output of test and training samples for the supervised FBDT training (a) and performance in terms of ROC (b).

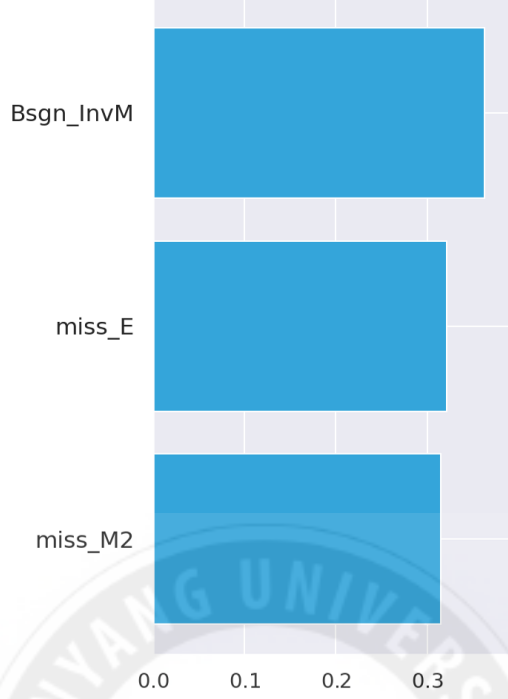


Figure 4.14: The ranking of the used variables in terms of their importance for the training.

of merit (FOM) [47]:

$$\mathcal{F}(t) = \frac{\varepsilon_{\text{sig}}(t)}{\frac{3}{2} + \sqrt{N_{\text{bkg}}(t)}}, \quad (4.4)$$

where t is the threshold on the FBDT output [46]. In Figure 4.13 (a), the values of $\varepsilon_{\text{sig}}(t)$ and $N_{\text{bkg}}(t)$ are computed using the number of signal and background events to the left of the threshold t . Here, $\varepsilon_{\text{sig}}(t)$ denotes the signal efficiency, and $N_{\text{bkg}}(t)$ represents the number of background events. The figure of merit graph is shown in Figure 4.15.

The current FastBDT test uses only a small number of input variables. To improve background suppression, the input variables should be reviewed and improved. After finding a good setup, the FastBDT output can be applied in the event selection to improve signal sensitivity.

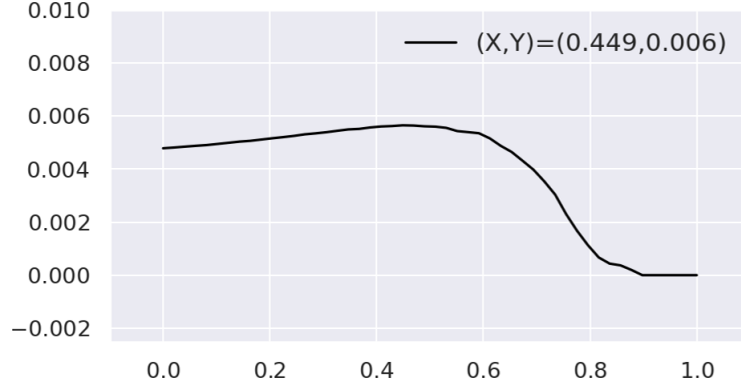


Figure 4.15: Figure of merit. The x-axis is the threshold t and the y-axis is $\mathcal{F}(t)$.

4.8 Main background study: ROE K_L^0

TopoAna [48] is a general-purpose tool for event-type analysis in inclusive Monte Carlo samples, widely used in high energy physics experiments. To investigate the dominant background source of the $B^0 \rightarrow \tau^+\tau^-$ decay, the **TopoAna** package is utilized.

As discussed in Section 4.6, the bg_mx background is the dominant component. Since it originates from B^0 meson decays, its event topology closely resembles that of the signal, making it more likely to be misidentified as signal. Therefore, this section focuses on a detailed study of this background with **TopoAna**.

The major background sources and yields are summarized in Table 4.5 and to show the ratio graphically, the missing mass squared variable is shown 4.16.

One of example explicit full decay chain of the background event which has the same final state as signal is shown below.

$$\begin{aligned}
\Upsilon(4S) &\rightarrow B^0 \bar{B}^0, \\
B^0 &\rightarrow \rho^+ D^-, \quad \bar{B}^0 \rightarrow \mu^- \bar{\nu}_\mu D^+, \\
\rho^+ &\rightarrow \pi^0 \pi^+, \quad D^- \rightarrow \pi^- \pi^- K^+, \quad D^+ \rightarrow \mu^+ \nu_\mu \bar{K}^0, \\
\bar{K}^0 &\rightarrow K_L^0
\end{aligned}$$

RowNo.	Decay mode	Nick Name	Yield	Percentage (%)
1	$B^0 \rightarrow \mu^+ \nu_\mu D^-$	mD	5531	9.87
2	$\bar{B}^0 \rightarrow \mu^- \bar{\nu}_\mu D^+$	mD	5657	10.10
3	$B^0 \rightarrow \mu^+ \nu_\mu D^{*-}$	mDstar	4828	8.61
4	$\bar{B}^0 \rightarrow \mu^- \bar{\nu}_\mu D^{*+}$	mDstar	4915	8.77
5	$B^0 \rightarrow e^+ \nu_e D^-$	eD	7123	12.71
6	$\bar{B}^0 \rightarrow e^- \bar{\nu}_e D^+$	eD	6829	12.19
7	$B^0 \rightarrow e^+ \nu_e D^{*-}$	eDstar	5926	10.57
8	$\bar{B}^0 \rightarrow e^- \bar{\nu}_e D^{*+}$	eDstar	5739	10.24
9	Others	others	9487	16.92
Total	-	-	56035	100.00

Table 4.5: Yields of background decay modes that result in the same final states as the signal events.

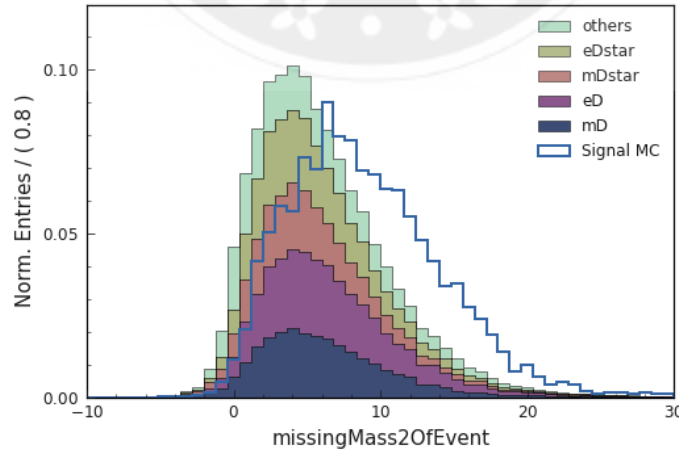


Figure 4.16: Missing mass squared. The main backgrounds are labeled.

$$(\Upsilon(4S) \rightarrow \mu^+ \mu^- \nu_\mu \bar{\nu}_\mu \pi^0 K_L^0 \pi^+ \pi^- \pi^- K^+)$$

By investigating the event topology, we find that the major background source is the decay $B^0 \rightarrow K^0 \tau^+ \tau^-$, in which the K^0 can be either in the K_S^0 or K_L^0 state. If the kaon in the decay is not reconstructed, the final state particles are the same as for the signal decay $B^0 \rightarrow \tau^+ \tau^-$.

The number of K_L^0 remain in the rest of event (ROE), “nKLongROE”, is shown in the Figure 4.17. Conceptually, signal event should have the value of this variable as zero, because no remaining particle should be there. This variable has almost no discriminative power.

Identifying K_L^0 remains one of the challenging points of this analysis, as the Belle II detector has limited sensitivity to K_L^0 detection. Further studies are required to improve the reconstruction performance of K_L^0 .

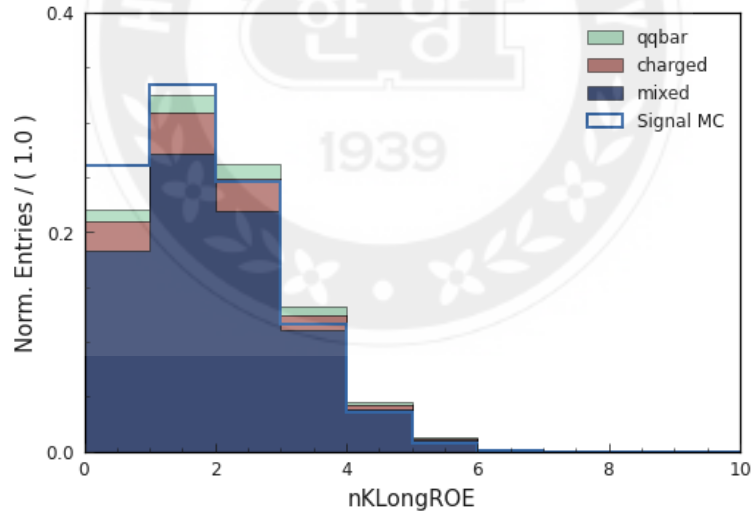


Figure 4.17: Number of K_L^0 in the rest of event (ROE).

4.9 Signal Extraction

4.9.1 Signal extracting variable

The variable E_{ECL} is used as the signal-extracting variable. Distributions under various selection conditions are shown in Subsection 4.9.3, and the final distribution used for the signal extraction is presented in Section 4.10.

For each event candidate, it is defined as the sum of the energies of all ECL clusters in the ROE:

$$E_{\text{ECL}} = \sum_{i=1}^N E_i \quad (4.5)$$

where N is the number of clusters in the ROE. By default, this sum includes contributions from electronic noise, beam background photons, and neutral hadronic split-off processes. Beam background photons originate from processes such as synchrotron radiation, pair production, radiative Bhabha scattering, and beam-gas Bremsstrahlung. Fake photons can arise when hadrons produce secondary showers or when energy deposits are split into multiple clusters in the ECL. To suppress such contamination, selection criteria (called masks) can be applied to the clusters used in calculating E_{ECL} [46].

4.9.2 Photon discriminating variables

A number of variables are used to distinguish background photons from those originating from B mesons [46, 14].

- **clusterE**: The energy deposited in the calorimeter. The beam background photons are usually of very low energy and are more abundant in the forward and backward endcap regions because they are the result of showers from particles

from the beam, starting often far from the IP. Most of the beam background can be removed by simple cuts on clusterE in different detector regions [46].

- **clusterTiming:** This variable is defined as the time difference, $t - t_0$, between the cluster time (t) and the time of collision (t_0). Beam background photons can be generated whenever beams travel through the beam pipe, so their time distribution is broad and independent of the collision time t_0 . However, for signal photons and fake photons generated shortly after collision, the clusterTiming distribution is expected to peak at zero [46].
- **clusterErrorTiming:** This variable denotes the photon timing uncertainty in the ECL. This uncertainty represents the timing window that contains 99% of true photons. Its parametrization depends on the true energy deposition in the highest-energy crystal and the local beam background level. Since the timing distribution is non-Gaussian, this variable is computed for each photon individually. The quantity $|\text{clusterTiming}/\text{clusterErrorTiming}| < 1$ is designed to yield a 99% timing efficiency for true photons originating from the interaction point. The efficiency is approximately flat as a function of energy and is largely independent of beam background conditions. Clusters with abnormally large values of **clusterErrorTiming** typically indicate failed waveform fits in the ECL and are removed from most physics photon lists [14].
- **minC2TDist:** The distance (in cm) between the cluster and its nearest track. Since the fake photons correspond to clusters that are close to the original tracks, minC2TDist is expected to peak at low values for them. This is measured by the point of closest approach for the particle track extrapolated into the calorimeter during the reconstruction, taking into account the material effects [46].
- **clusterNHits:** The sum of the weights w_i ($w_i \leq 1$) of all crystals in an ECL

cluster. For non-overlapping clusters, this is equal to the number of crystals in the cluster. In the case of energy splitting between adjacent clusters, this can be a non-integer value [14].

- **beamBackgroundSuppression:** Returns the output of an MVA classifier that uses shower-related variables to distinguish true photon clusters from beam background clusters. Class 1 is for true photon clusters while class 0 is for beam background clusters [14]. The classifier output is shown in Figure 4.18 (a).
- **fakePhotonSuppression:** Returns the output of an MVA classifier that uses shower-related variables to distinguish true photon clusters from fake photon clusters (e.g. split-offs, track-cluster matching failures etc.). Class 1 is for true photon clusters while class 0 is for fake photon clusters [14]. The classifier output is shown in Figure 4.18 (b).

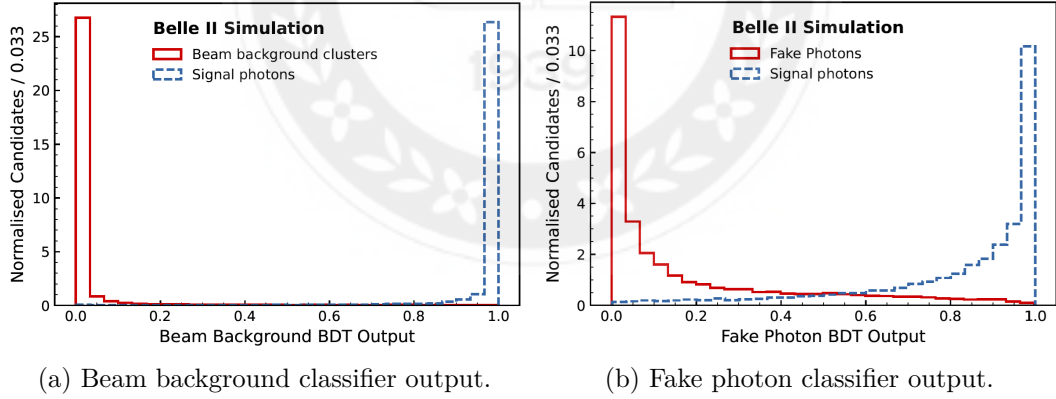


Figure 4.18: Distributions of the classifier outputs for (a) beam background clusters and (b) fake photon candidates [49].

4.9.3 ROE masks

Using the variables described in the previous section, various combinations of selection criteria are applied to the ROE clusters to improve the E_{ECL} distribution.

Each combination is referred to as a *mask*. The masks examined in this analysis, ordered by increasing complexity, are listed in Table 4.6. The resulting E_{ECL} distributions for each mask are shown in Figure 4.19. As expected, tighter masks lead to improved resolution, with the distributions becoming more sharply peaked near zero.

Mask Type	Cluster Cuts
Mask 0	No cuts
Mask 1	clusterNHits > 1.5 θ_{cluster} in CDCAcceptance clusterE > [80, 30, 60] MeV (fwd, brr, bwd)
Mask 2	Mask 1 + clusterTiming < 200 ns
Mask 3	Mask 2 + clusterTiming / clusterErrorTiming > 2.0
Mask 4	Mask 3 + minC2TDist > 20 cm
Mask 5	Mask 1 + beamBackgroundSuppression > 0.1 + fakePhotonSuppression > 0.1

Table 4.6: ROE mask types.

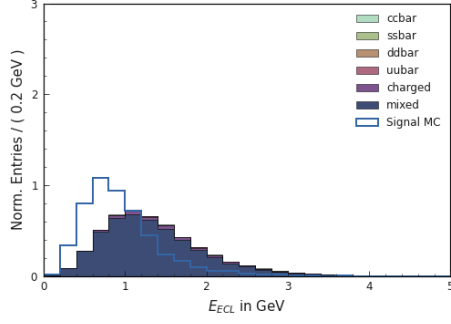
4.10 Upper limit estimation on $\mathcal{B}(B^0 \rightarrow \tau^+ \tau^-)$

We choose the E_{ECL} variable with mask 5 as signal extracting variable (Figure 4.20). Several signal windows are considered in E_{ECL} in the range $0 - X$ GeV, where X ranging from 0.25 GeV to 1 GeV in steps of 0.25 GeV.

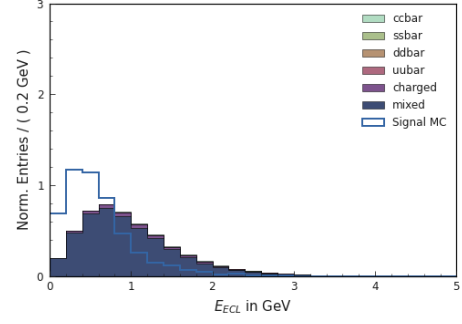
Assuming no signal events are observed, the expected upper limit on the branching fraction is calculated as follows:

$$\mathcal{B}(B^0 \rightarrow \tau^+ \tau^-) < \frac{N^{\text{UL}}}{\epsilon_{\text{sig}} \cdot 2 \cdot f^{00} \cdot N(B\bar{B})}, \quad (4.6)$$

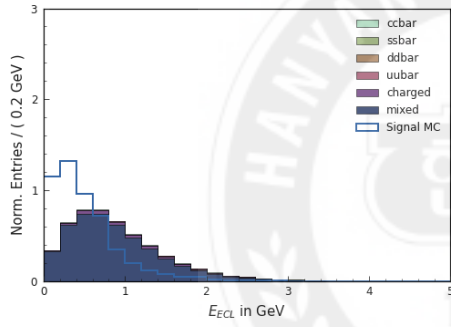
where N^{UL} is the upper limit on the number of signal candidates, (ϵ_{sig}) is the



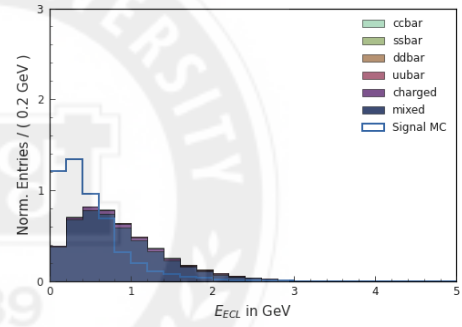
(a) Mask 0



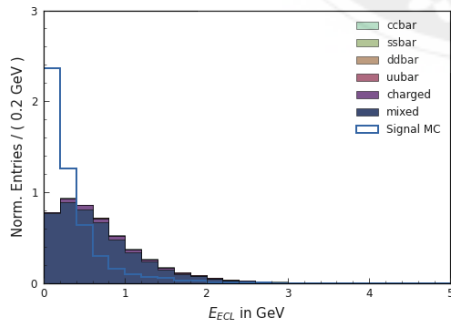
(b) Mask 1



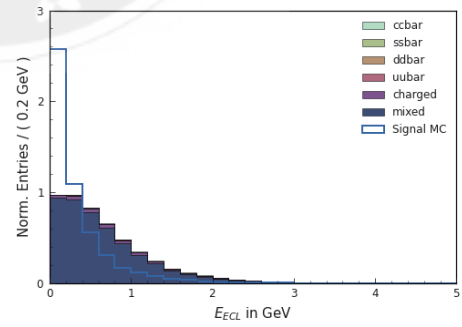
(c) Mask 2



(d) Mask 3



(e) Mask 4



(f) Mask 5

Figure 4.19: Distributions of E_{ECL} with different masks.

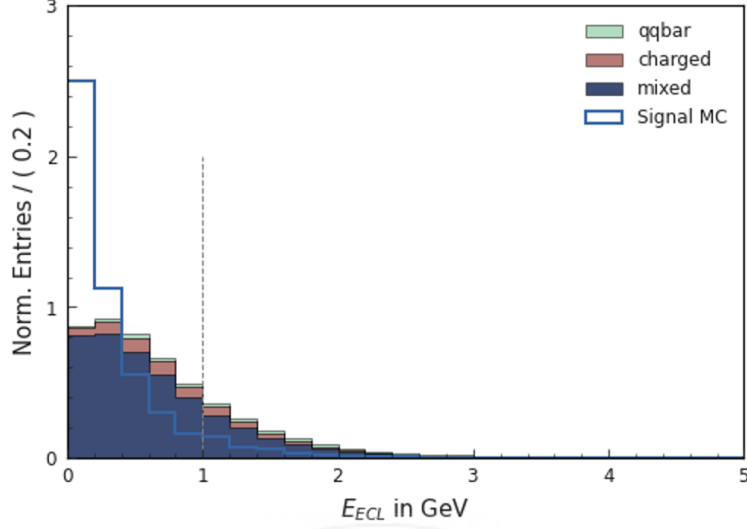


Figure 4.20: E_{ECL} variable with mask 5 for UL calculation.

signal efficiency, f^{00} is the fraction of $B^0\bar{B}^0$ events, and $N(B\bar{B})$ denotes the total number of produced $B\bar{B}$ pairs in the data set [46]. The factor 2 accounts for the presence of two B mesons in each $\Upsilon(4S) \rightarrow B\bar{B}$ event. The signal efficiency (ϵ_{sig}) and the expected background yield are evaluated within each signal window.

In this study, $N(B\bar{B})$ is estimated to be $(387 \pm 6) \times 10^6$, corresponding to an integrated luminosity of 363 fb^{-1} . The value of f^{00} is taken to be $(48.6 \pm 0.6)\%$ [50].

The upper limit on the number of signal candidates (N^{UL}) is determined under the assumption of no signal observation, by solving the following equation:

$$1 - \alpha = \sum_{k=0}^n P(k; \mu), \quad (4.7)$$

where $1 - \alpha$ is the desired confidence level, μ is the unknown true expectation value, and $P(k; \mu)$ denotes the probability of observing k events given the mean μ [46]. This calculation is performed using the frequentist method developed by W. Rolke [51], as implemented in the ROOT framework [52].

The Rolke algorithm employs a profile likelihood method that assumes a Poisson

distribution for the signal and a Gaussian model for the background. The likelihood function is given by:

$$L(\mu, b, \sigma \mid x, y) = \frac{(\mu + b)^x}{x!} \exp(-(\mu + b)) \times \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(y - b)^2}{2\sigma^2}\right), \quad (4.8)$$

where μ is the signal expectation, b is the expected background with uncertainty σ , and x and y are the observed number of events for signal and background, respectively. The uncertainties in the x and y are treated as nuisance parameters and modeled using a Gaussian probability density function [46].

The upper limits obtained for each signal window are summarized in Tables 4.7 to 4.10. Here, BG_{mx} , BG_{ch} , and BG_{qq} represent the mixed, charged, and continuum background contributions, respectively. The total background yield, BG_{tot} , is defined as the sum of these three components.

The window defined as the range $0 - X$ GeV is selected as the optimal choice. The corresponding upper limit on the branching fraction is 2.2×10^{-3} at the 90% confidence level (CL), where only the statistical uncertainty is considered.

Window	Upper Limit (CL 90%)	Sig. Eff.	Sig.	BG _{tot}	BG _{mx}	BG _{ch}	BG _{qq}
[0, 0.25]	2.2×10^{-3}	1.2×10^{-4}	1924	1838	1708	103	28
[0, 0.50]	2.3×10^{-3}	1.7×10^{-4}	2670	3684	3323	297	64
[0, 0.75]	2.4×10^{-3}	1.9×10^{-4}	2985	5184	4589	481	114
[0, 1.00]	2.5×10^{-3}	2.0×10^{-4}	3135	6248	5459	628	162

Table 4.7: Upper limit results depending on the signal window range (all modes).

Window	Upper Limit (CL 90%)	Sig. Eff.	Sig.	BG _{tot}	BG _{mx}	BG _{ch}	BG _{qq}
[0, 0.25]	4.7×10^{-3}	2.9×10^{-5}	464	480	454	24	3
[0, 0.50]	4.6×10^{-3}	4.2×10^{-5}	675	981	907	69	6
[0, 0.75]	4.7×10^{-3}	4.9×10^{-5}	784	1394	1272	112	11
[0, 1.00]	4.8×10^{-3}	5.3×10^{-5}	846	1686	1528	144	16

Table 4.8: Upper limit results depending on the signal window range (ee mode).

Window	Upper Limit (CL 90%)	Sig. Eff.	Sig.	BG _{tot}	BG _{mx}	BG _{ch}	BG _{qq}
[0, 0.25]	3.9×10^{-3}	3.9×10^{-5}	631	596	553	37	7
[0, 0.50]	3.9×10^{-3}	5.5×10^{-5}	885	1208	1095	101	13
[0, 0.75]	4.1×10^{-3}	6.2×10^{-5}	994	1706	1523	162	22
[0, 1.00]	4.3×10^{-3}	6.5×10^{-5}	1045	2054	1811	210	34

Table 4.9: Upper limit results depending on the signal window range ($e\mu$ mode).

Window	Upper Limit (CL 90%)	Sig. Eff.	Sig.	BG _{tot}	BG _{mx}	BG _{ch}	BG _{qq}
[0, 0.25]	3.3×10^{-3}	5.2×10^{-5}	829	764	703	43	20
[0, 0.50]	3.5×10^{-3}	6.9×10^{-5}	1110	1496	1322	129	46
[0, 0.75]	3.8×10^{-3}	7.5×10^{-5}	1207	2086	1796	208	82
[0, 1.00]	4.0×10^{-3}	7.8×10^{-5}	1244	2510	2122	276	113

Table 4.10: Upper limit results depending on the signal window range ($\mu\mu$ mode).

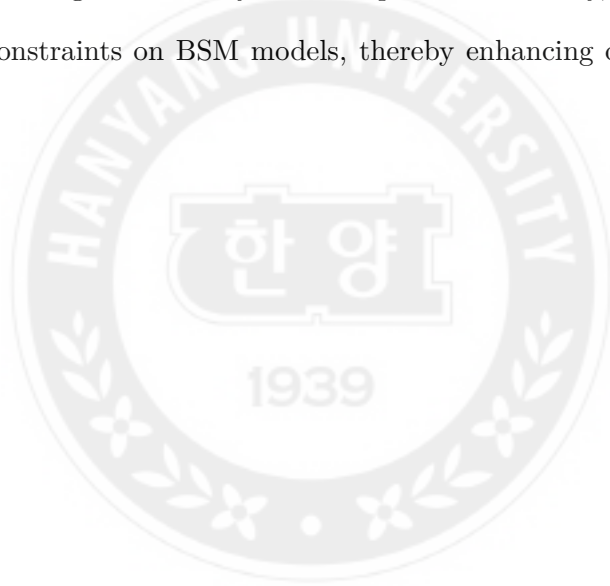
Chapter 5

Conclusion

In this dissertation, a study of the rare decay $B^0 \rightarrow \tau^+ \tau^-$ is presented. Theoretical motivations are discussed by reviewing the predictions of the Standard Model and possible enhancements from beyond the Standard Model (BSM) scenarios, including Two-Higgs-Doublet Models (2HDM) and leptoquark models. An overview of the Belle II experiment and the SuperKEKB collider is provided. A detailed description of the trigger slow control system, which is essential for stable data-taking, is provided. The $B^0 \rightarrow \tau^+ \tau^-$ decay is studied using the established experimental setup.

The trigger slow control system has been developed based on the Belle II DAQ and slow control software framework. The system stores configuration parameters in the Belle II central database server at each run start and stop, and continuously records EPICS process variables (PVs) in the main archiver server. The intuitive graphical user interface (GUI) panels help operators monitor and control the status of the trigger system and respond to problematic situations. The slow control system is crucial for the stable operation of the trigger system, which is essential for efficient data acquisition.

The search for the decay $B^0 \rightarrow \tau^+ \tau^-$ is performed using Monte Carlo simulation samples, which correspond to the $\Upsilon(4S)$ data sample with an integrated luminosity of 363 fb^{-1} . An upper limit on the branching fraction is estimated as 2.2×10^{-3} at the 90% confidence level. The obtained upper limit is consistent in order of magnitude with previous experimental results from LHCb (1.6×10^{-3}) and BaBar (4.1×10^{-3}), both at the 90% confidence level. This sensitivity study demonstrates that the Belle II experiment is well-designed for searches of rare B decays involving neutrinos in sub-decays. We expect a stronger upper limit as more data are collected toward the Belle II target luminosity. With improved sensitivity, future results can provide tighter constraints on BSM models, thereby enhancing our understanding of new physics.



Appendix A. Signal MC decay file

Listing A.1: Decay File

```
# EventType: 1120600000
# Descriptor: [B0 -> tau+ tau-]cc
# NickName: Bd_tautau
# Documentation: SM B-> tau tau signal with SLL model,
taus decay as they like
# Tested: Yes
# PhysicsWG: EWP
# Responsible: Sam Cunliffe
# Email: sam.cunliffe@desy.de
# Cuts: None
# Date: 20170614
#
Decay Upsilon(4S)
0.5          B0sig          anti-B0 VSS;
0.5          anti-B0sig B0 VSS;
Enddecay
#
Decay B0sig
1.000        tau+          tau-          SLL;
Enddecay
CDecay anti-B0sig
#
End
```

Appendix B. Trigger slow control system

B.1 The NIMA paper

Nuclear Inst. and Methods in Physics Research, A 1014 (2021) 165748



Trigger slow control system of the Belle II experiment

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ARTICLE INFO

Keywords:
Slow control system
Trigger
Data acquisition

ABSTRACT

The Belle II experiment at the SuperKEKB e^+e^- collider in KEK, Japan, started physics data-taking with a complete detector from early 2019. An online trigger system is indispensable for the Belle II experiment to reduce the beam background events associated with high electron and positron beam currents without sacrificing the target physics-oriented events. During the Belle II operation upon beam collision, the trigger system must be consistently controlled and its status must be carefully monitored in the process of data acquisition against unexpected situations. For this purpose, we have developed a slow control system for the newly developed Belle II trigger system based on the custom-made Belle II DAQ/slow control package. Around seventy thousand configuration parameters are saved in the Belle II central database server for every run when a run starts and stops. These parameters play an essential role in offline validation of the quality of runs. Around three thousand real-time variables are stored in the Belle II main archiving server, and the trend of some of these variables are regularly used for online and offline monitoring purposes. Various operator interface tools have been prepared and used. When the configuration parameters are not correctly applied, or some of the processes are unexpectedly terminated, the slow control system detects it, stops the data-taking process, and generates an alarm. In this article, we report how we constructed the Belle II trigger slow control system, and how we successfully managed to operate during its initial stage.

1. Introduction

The Belle II experiment [1] at the SuperKEKB [2] e^+e^- collider in KEK, Japan, started physics data-taking with a complete detector from early 2019. Belle II and SuperKEKB are the successors of Belle [3] and KEKB [4].

The target instantaneous luminosity of SuperKEKB is 40 times higher, and the target integrated luminosity is 50 times higher than its predecessor (Table 1). The Belle II detector is designed to cope with

the increase of the event rate as well as the harsh beam background at the target luminosity. Likewise, the trigger system has been upgraded to have robustness and flexibility, and a corresponding slow control system has been prepared to ensure physics data-taking. We use a custom-developed software package for data acquisition and slow control. Especially, a custom-made network memory sharing technique is one of core technique of the package.

In this paper, we describe the trigger slow control system of the Belle II experiment. Section 2 briefly describes the Belle II detector

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<https://doi.org/10.1016/j.nima.2021.165748>

Received 27 January 2021; Received in revised form 12 August 2021; Accepted 13 August 2021

Available online 17 August 2021

0168-9002/© 2021 Published by Elsevier B.V.

B.2 Configuration database

Table B.1: The list of experimental parameters that are automatically stored on the Belle II central configuration database server by every run.

Sub-trigger ^a	NSM2 nodes	Num. of par.s	Comments
TRGGDL	TRGGDL	6,031	inp/ftd/psn/adm_rate ¹² , prescale parameters, etc.
TRGGRL/CDC	TRGGRL	27	Firmware info., sub-trigger rates.
	TRGTSF0	80	Firmware info., the track segment finder (TSF) 2/4/6/8 info.
	TRGTSF1	65	Firmware info., the track segment finder (TSF) 1/3/5/7 info.
	TRGETF0	14	The event timing finder (ETF) information
	TRGT2D0~3	60	Firmware info., the 2D tracking info.
	TRGT3D0~3	60	Firmware info., the 3D tracking info.
TRGECL	ECLTRG_FAM	2,145	Firmware info., TC noises, pedestals, rates, temperatures, etc.
	ECLTRG_FAM_PAR	57,471	The FAM firmware setting parameters. Most of parameters from this node is for noise fitting
	ECLTRG_TMM	94	Firmware info., temperatures, etc.
	ECLTRG_TMM_PAR	73	The TMM firmware setting parameters
	ECLTRG_ETM	209	Firmware info., physics bits, etc.
	ECLTRG_ETM_PAR	75	The ETM firmware setting parameters
TRGTOP	-	-	-
TRGKLM	KLMTRG	7	Only basic run info. ¹³ , no KLMTRG parameters
READY_SIG	TRG_READY	26	Sub-trigger readiness
Run Control Info.	RCBTRGSRV	167	Run control related information on the btrgsrv server
	RCECLTRG	71	Run control related information on the btrgctr server
	TRG01	72	Run control related information on the trg01 server
	TRG02	72	Run control related information on the trg02 server
Read out Info.	ROPC901	71	Read out related information on the trg01 server
	ROPC902	71	Read out related information on the trg02 server
Copper Info.	COPPER	715	COPPER control related info. on the cpr11001/3/5/7/9, 15001, 11002/4/6/8, and 15002 servers
Total		67,662	

^a Below the middle line, this column categorized with the integrated trigger ready signal and the node type (runcontrol/rocontrol/copcontrol).

B.3 Archiver

Table B.2: The list of archived trigger EPICS PVs

Sub-trigger	PV name	Num. of PVs	Comments
TRGGDL	TRGGDL:inp/ftd/psn/adm_rate	970	inp/ftd/psn/adm_rate ¹²
TRGGRL/CDC	TRGGRL:rate_2D/ECL/KLM/TOP	7	Sub-trigger rates
	TRGTSF0/1:rate.TSFX_Y	136	Track rate from IP, Track rate outside IP
TRGECL	ECLTRG_FAM_NOI:noise	624	The FAM TC noise
	ECLTRG_FAM:ped	624	The FAM TC pedestal
	ECLTRG_FAM:hitrate	624	The FAM TC hit-rate
	ECLTRG_FAM:rate	93	Various average of the FAM TC hit-rate
	ECLTRG_FAM:tempH/L	104	The FAM board temperature
	ECLTRG_TMM:tempH/L	14	The TMM board temperature
	ECLTRG_ETM:phy.bit	51	The ETM output
	ECLTRG_LUM:acc/lumi	6	Accelerator/Detector Luminosity
TRGTOP	TOP:L1	22	The TOP L1 trigger rate
TRGKLM	KLM:L1	28	The KLM L1 trigger rate
Total		3,303	

B.4 The control script of TRG SLC

```
(b2trg@btrgsrv1 ~)$ slctr check

#####
##### [ TRIGGER SLOW CONTROL SCRIPT ] #####
#####          except TRGECL          #####
#####
#####
##### The srvsic control script #####
#####

>> check option is selected.

>> Local NSM related
[ Normal ] Local NSM port 9122 is well running.

>> Global NSM related
[ Normal ] Global NSM port 9020 is well running. // For connection to CR server
[ Normal ] Global NSM port 9290 is well running. // For connection to TRG

>> NSM bridges
[ Normal ] nsmbridge(9122=>9020) is well running. // For connection to CR server ( GBTRGSRV )
[ Normal ] nsmbridge(9122=>9290) is well running! // For connection to TRG ( BBTRGSRV )

>> NSM socket for CS-studio(GUI)
[ Normal ] nsm2socket port 9090 is well running.

>> Recording parameters on configuration DB: btrgsrv1 as provider for VMES
[ Normal ] daqdbprovider process is well running.

>> Send local log to the central log ( b2db/logdaq ).
[ Normal ] logcollector process is well running.

>> Related to Runcontrol
[ Normal ] RUNCONTORLD precess is well running. // RCBTRGSRV
[ Normal ] RUNRECORD precess is well running. // RECORDSRV

>> NSM nodes Related to TRG/ECLTRG readiness
[ TIMEOUT ] TRG_READY process is timed out!! ==> Try recover or qsol

>> For displaying and editing TRG expert shift information
[ Normal ] TRG_EXPERT process is well running.
```

Figure B.1: The control script of TRG SLC. This script can check / reboot / recover / kill the processes of TRG SLC.

```

##### The vmetrgl3 control script #####
#####

>> check option is selected.

>> Local NSM related
[ Error ] Local NSM port 9122 is not running!

>> NSM socket for CS-studio(GUI)
[ Normal ] nsm2socket port 9090 is well running.

>> TRG NSM nodes on vmetrgl3
[ Normal ] TRGT2D0 process is well running.
[ Normal ] TRGT2D2 process is well running.
[ Normal ] TRGT3D3 process is well running.

##### The vmetrgl6 control script #####
#####

>> check option is selected.

>> Local NSM related
[ Normal ] Local NSM port 9122 is well running.

>> NSM socket for CS-studio(GUI)
[ Normal ] nsm2socket port 9090 is well running.

>> TRG NSM nodes on vmetrgl6
[ Normal ] TRGETF0 process is well running.
[ Normal ] TRGT3D0 process is well running.
[ Normal ] TRGT3D2 process is well running.

##### The vmetrgl8 control script #####
#####

>> check option is selected.

>> Local NSM related
[ Normal ] Local NSM port 9122 is well running.

>> NSM socket for CS-studio(GUI)
[ Normal ] nsm2socket port 9090 is well running.

>> TRG NSM nodes on vmetrgl8
[ Normal ] TRGGDL process is well running.
[ Normal ] TRGGRL process is well running.
[ Normal ] TRGT3D1 process is well running.

```

Figure B.2: The control script of TRG SLC (continued).

```

##### #####
#####   The vmetrgr19 control script   #####
##### #####

>> check option is selected.

>> Local NSM related
[ Normal ] Local NSM port 9122 is well running.

>> NSM socket for CS-studio(GUI)
[ Normal ] nsm2socket port 9090 is well running.

>> TRG NSM nodes on vmetrgr19
[ Normal ] TRGTSF1 process is well running.

##### #####
#####   The vmetrgr20 control script   #####
##### #####

>> check option is selected.

>> Local NSM related
[ Normal ] Local NSM port 9122 is well running.

>> NSM socket for CS-studio(GUI)
[ Normal ] nsm2socket port 9090 is well running.

>> TRG NSM nodes on vmetrgr20
[ Normal ] TRGT2D1 process is well running.
[ Normal ] TRGT2D3 process is well running.

```

Figure B.3: The control script of TRG SLC (continued).

```

##### #####
##### The vmtrg21 control script #####
##### #####

>> check option is selected.

>> Local NSM related
[ Normal ] Local NSM port 9122 is well running.

>> NSM socket for CS-studio(GUI)
[ Normal ] nsm2socket port 9090 is well running.

>> TRG NSM nodes on vmtrg21
[ Normal ] TRGTSF0 process is well running.

##### #####
##### The vmeusa control script #####
##### #####

>> check option is selected.

>> Local NSM related
[ Normal ] Local NSM port 9122 is well running.

>> NSM socket for CS-studio(GUI)
[ Normal ] nsm2socket port 9090 is well running.

>> TRG NSM nodes on vmeusa
[ Normal ] KLMTRG process is well running.

##### #####
##### EPICS process control (btrgsrv) #####
##### #####

>> check option is selected.

[ Normal ] EPICS(nsm2cad) process is well running.

```

Figure B.4: The control script of TRG SLC (continued).

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국문 초록

본 연구는 SuperKEKB 비대칭 에너지 전자-양전자 충돌기에서 Belle II 검출기를 이용하여 희귀 붕괴 $B^0 \rightarrow \tau^+\tau^-$ 에 대한 탐색 결과를 제시한다. 해당 결과는 $\Upsilon(4S)$ 에너지에서 수집된 적분 휘도 (integrated luminosity) 363 fb^{-1} 데이터에 해당하는 몬테카를로 시뮬레이션 샘플을 기반으로 한다. 안정적인 데이터 수집에 트리거 슬로우 컨트롤 시스템이 중요한 역할을 하며, 본문에 설명하였다.

표준모형은 $B^0 \rightarrow \tau^+\tau^-$ 모드의 붕괴율이 매우 낮다고 예측하지만, 여러 확장 이론에서는 이를 증가시킬 수 있는 가능성을 제시한다. 본 연구에서는 하나의 B 중간자를 완전하게 재구성하는 하드론릭 태깅 (hadronic tagging) 기법을 사용하며, 나머지 사건에서 신호를 탐색한다.

$B^0 \rightarrow \tau^+\tau^-$ 의 붕괴율에 대해 신뢰도 90 % 에서 다음과 같이 상한을 설정하였다.

$$\mathcal{B}(B^0 \rightarrow \tau^+\tau^-) < 2.20 \times 10^{-3}$$

감사의 글 (Acknowledgments)

긴 박사과정 동안 중 감사의 글을 작성하고 있는 제 모습을 상상하곤 했습니다. 드디어 이 순간이 왔네요. 많은 분들을 만났고 도움을 받았습니다. 감사의 마음을 담아 한 분 한 분 떠올려 봅니다.

지도 교수님이신 천병구 교수님께 감사드립니다. 베풀어주신 은혜 진심으로 감사드립니다. 연구를 지도해 주시고, 용기를 북돋아주시고, 제 능력을 믿어주셔서 감사합니다. 박사 과정 동안 여러 조언과 지도를 통해서 성장할 수 있었습니다.

한양대학교 김태정 교수님, 한양대학교 김항배 교수님, 성균관 대학교 이명재 교수님, 중앙대학교 최수경 교수님 학위 논문을 지도해 주셔서 감사합니다.

I thank Prof. Karim Trabelsi for his guidance in Belle II data analysis and for providing a good research environment at the KEK TYL laboratory. I am grateful to Dr. Yuuji Unno from our research group (the ECL trigger group) for guiding my research and answering many technical questions. I would also like to thank the Belle II trigger group members: Prof. Yoshihito Iwasaki, Prof. Taichiro Koga, Dr. Hideyuki Nakazawa, Prof. Yun-Tsung Lai, and Dr. Steffen Bähr. Thanks to Nanae Taniguchi from the CDC group. Special thanks to Prof. Mikihiro Nakao for his help in writing the TRG SLC paper and for developing the trigger slow control system. I also thank Mikhail Remnev for his technical support during the system development. I am also grateful to all members of the Belle II collaboration.

우리 연구실 선배님들 감사드립니다. 고영문 박사님, 신복균 박사님, 조언해 주시고 상담해 주셔서 감사합니다. 김성현 박사님, 이인수 박사님, Belle II 실험에 잘 적응할 수 있도록 도와주셔서 감사합니다. 오랜 시간 동안 함께 여러 일을 겪고 많은 이야기를 나눈 우리 연구실 조한얼에게 감사합니다. 데이터 분석 잘 마무리하고 졸업까지 힘내길 바랍니다. 학부 연구생으로 있었던 임성래에게 감사하며, 미국 유학 생활 무사히 마치길 바랍니다. 학부 연구생으로 있었고, 현재는 김태정 교수님 연구실

소속인 권우연에게도 감사하고 박사과정 힘내길 바랍니다.

ECL 트리거 그룹으로 객원 멤버로서 랩미팅에 참여했던 고려대학교 김영준 학생에게도 감사합니다. 트리거 슬로우 컨트롤 시스템 개발을 같이 진행한 경상대학교 장은지에게도 감사합니다.

Belle II 분석에 큰 도움을 주신 연세대학교 권영준 교수님께 감사드립니다. 연세대학교 랩미팅에 참여하여 많은 도움을 받았습니다. 트리거 슬로우 컨트롤 시스템 개발과 Belle II 데이터 분석에 많은 도움을 주신 박석희 박사님 감사합니다. 김경호 박사님, 조성진 박사님, 김용규, 김재영, 김찬호, 김현아, 이찬영, 박준우, 모두들 제가 연세대에 방문할 때마다 아낌없이 지식을 공유해 주셔서 감사합니다.

고려대학교 김경태 박사님, 고려대학교 문현기 박사님, 서울대학교 문태진 박사님, KEK 연구소 배한욱 박사님, 숭실대학교 나이정을 비롯한 한국 Belle II 그룹 분들에게도 감사합니다. 덕분에 KEK 연구소 및 각종 학회에서 즐거운 시간을 보낼 수 있었습니다.

끈이론 연구실 신상진 교수님, 서운석 박사님, Shigenori Seki 박사님, 배한, 송근호 박사님, 김태운, 오은석에게 감사합니다. 양자광학 연구실 이광걸 교수님, Dilip Kumar Singh 교수님, 이중성 박사님, 윤승진 박사님, 이지원 박사님, Tai Trinh Cong 박사님 감사합니다. 송승재, 안기현 박사님, 이관훈, 심성용 박사님, 김선우 박사님, 유광욱 박사님, Trung Minh Huynh 박사님, Leu Xuan Loc 박사님을 비롯한 한양대학교 물리학과 대학원분들에게도 감사드립니다.

한양대학교 물리학과 금룡 멤버들 감사드립니다. 박진석, 조영우, 조윤성, 홍종익, 강민규, 김강훈, 김홍준, 박재우, 서정현, 이현수, 임경택 모두 감사드립니다. 학부생 시절부터 지금까지 항상 응원해 주셔서 감사합니다. 앞으로도 좋은 인연 이어나갔으면 합니다.

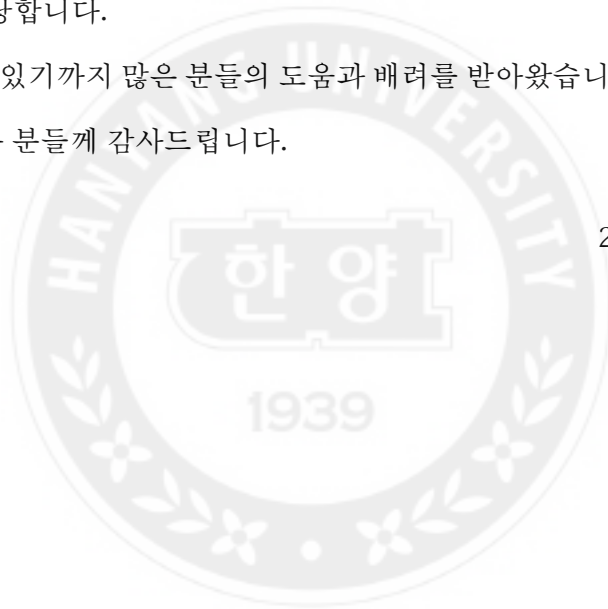
고등학교 친구들에게 감사합니다. 일본 출장 중 많은 시간을 함께한 오승철에게도 감사드립니다. 한국에서 그리고 일본에서 여러 번 만나서 많은 이야기를 나눈 박찬호에게 감사하고, 찬호를 통해 알게 되어 친해진 장준수에게도 감사드립니다. 카톡으

로 여러 퀴즈를 내고 각종 게임을 추천해 주었으며 이런저런 얘기를 나눈 조영재에게 감사합니다. 보고 싶다고 전화해주던 최형석 감사합니다. 가끔씩 만나 방탈출 게임을 하는 등 같이 어울렸던 강민호, 김기연, 김도국, 김동인, 전영준, 정종근, 한희재에게 감사합니다. 잊을 수 없는 제주도 여행을 함께한 김효겸 감사합니다. 한양대학교 학부 시절을 함께한 김규태, 김남수, 이준에게도 감사합니다. 나를 잊지 않고 가끔씩 안부를 물어봐 주던 중학교 친구 이민철에게도 감사합니다.

부모님께 감사드립니다. 우리 삼형제, 철진이형, 철승이에게도 감사합니다. 길었던 박사 학위 과정 동안 묵묵히 응원해 주시고 지지해 주시고 지원해 주셔서 감사합니다. 우리 가족 사랑합니다.

지금의 제가 있기까지 많은 분들의 도움과 배려를 받아왔습니다. 크고 작은 인연을 통해 만난 모든 분들께 감사드립니다.

2025년 6월 김철훈



Declaration of Ethical Conduct in Research

I, as a graduate student of Hanyang University, hereby declare that I have abided by the following Code of Research Ethics while writing this dissertation thesis, during my degree program.

"First, I have strived to be honest in my conduct, to produce valid and reliable research conforming with the guidance of my thesis supervisor, and I affirm that my thesis contains honest, fair and reasonable conclusions based on my own careful research under the guidance of my thesis supervisor.

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Thesis Supervisor : CHEON BYUNG GU
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연구 윤리 서약서

본인은 한양대학교 대학원생으로서 이 학위논문 작성 과정에서 다음과 같이 연구 윤리의 기본 원칙을 준수하였음을 서약합니다.

첫째, 지도교수의 지도를 받아 정직하고 엄정한 연구를 수행하여 학위논문을 작성한다.

둘째, 논문 작성시 위조, 변조, 표절 등 학문적 진실성을 훼손하는 어떤 연구 부정행위도 하지 않는다.

셋째, 논문 작성시 논문유사도 검증시스템 "카피킬러"등을 거쳐야 한다.

2025년06월04일

학위명 : 박사

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