Search for the rare decay $B^0 \to \tau^+\tau^-$ at the Belle II Experiment

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Belle II

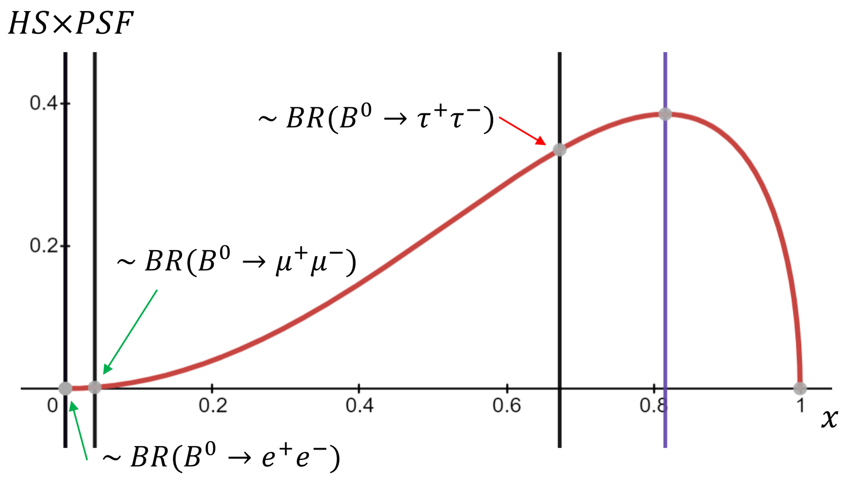
Abstract

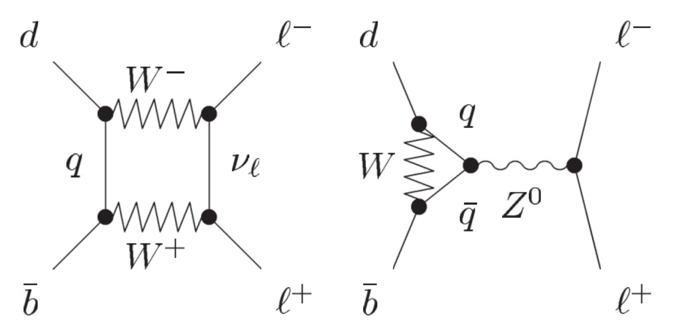
We aim to search for the rare decay $B^0 \to \tau^+\tau^-$ at the Belle II experiment using the superKEKB asymmetric electron-positron collider. While the standard model predicts the decay mode to have a low branching fraction, various extensions of the model expect enhancements. The results will be obtained with data samples corresponding to an integrated luminosity of 363 fb^{-1} collected at the $\Upsilon(4S)$ resonance. We use a hadronic tagging method that reconstructs fully accompanying B mesons and attempts to identify signals from the remaining part of the event. The result of this study will be the measurement or upper limit setting of the branching fraction of the decay. We present the results based on Monte Carlo simulation samples.

1. Theory

1.1. Standard Model (SM) Prediction: Theoretical Calculation with the Effective Field Theory

$$\mathcal{B}(B^0 \to \ell^+\ell^-) = \frac{G_F^4 M_W^4 M_B^3}{8\pi^5 \Gamma_B} \cdot \underbrace{f_B^2}_{\text{Decay constant}} \cdot \underbrace{|V_{tb}^* V_{td}|^2}_{\text{CKM elements}} \cdot \underbrace{\frac{4m_\ell^2}{M_B^2}}_{\substack{\text{Helicity suppression}\\(HS)}} \cdot \underbrace{\sqrt{1-\frac{4m_\ell^2}{M_B^2}}}_{\substack{\text{Phase space factor}\\(PSF)}} \cdot |C_A(\mu)|^2$$





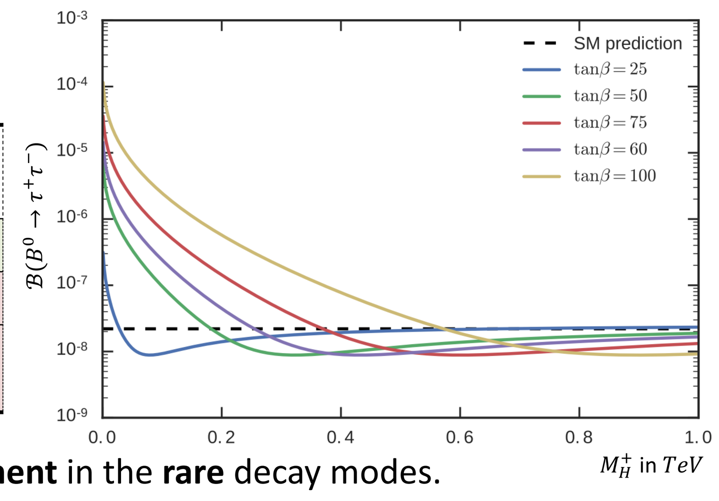
Standard Model Box and Penguin Diagram of $B^0 \to \ell^+\ell^-$

- For $B \to \tau\tau$, **BR** is **much higher** because of its **large mass.** However, it is **hard** to deal with because
  - τ cannot be detected directly by the detector
  - Sub-decay modes have missing particle
- For $B \to \mu\mu$, **BR** is **100** times smaller, but muons can be identified with detector level ⇒ relatively **easier** to study
- For $B \to ee$, **BR** is too small to measure

1.2. Beyond the Standard Model (BSM)

RARE !!

	Theory	Branching fraction	Free parameters (for Enhancement)
SM prediction		$(2.22 \pm 0.19){\times}10^{-8}$ (2014)	-
BSM	2HDM	It can be several orders of magnitude higher	$tan\beta$, M_{H^+}
	Leptoquark		$\frac{\lvert\lambda^{33}\lambda^{13*}\rvert}{M_S^2}$



- Free parameters of BSM models make it possible to expect **enhancement** in the **rare** decay modes.
- The study of $B^0 \to \tau^+\tau^-$ can help to **constraint free parameters** of BSM models
- **Better Theory!**

2. Previous Studies

2.1. Previous studies for the $B^0 \to \ell\ell$ decay modes

	SM prediction	Measurement: Detector	Measurement: Upper Limit	Measurement: Measurement
$B^0 \to e^+e^-$	$(2.48 \pm 0.21){\times}10^{-15}$ [1] (2014)	LHCb	$2.5{\times}10^{-9}$ [2] (2020) (90 % CL) $3.0{\times}10^{-9}$ [2] (2020) (95 % CL)	-
$B^0 \to \mu^+\mu^-$	$(1.06 \pm 0.09){\times}10^{-10}$ [1] (2014)	ATLAS	$2.1{\times}10^{-10}$ [3] (2019) (95 % CL)	-
		LHCb	$3.4{\times}10^{-10}$ [4] (2017) (95 % CL)	-
$B^0 \to \tau^+\tau^-$	$(2.22 \pm 0.19){\times}10^{-8}$ [1] (2014)	LHCb	$1.6{\times}10^{-3}$ [5] (2017) (90 % CL) $2.1{\times}10^{-3}$ [5] (2017) (95 % CL)	-
		BABAR	$4.1{\times}10^{-3}$ [7] (2006) (90 % CL)	-

3. $B\bar{B}$ data

3.1. Number of $B\bar{B}$ data

	Cross section (nb)	Integrated lum. (ab^{-1})	$B\bar{B}$ data
BABAR	1.1	0.210	$232 \pm 3{\times}10^6$
LHCb	~500000*	0.003	~$1500{\times}10^6$
Belle	0.81	0.953	$772{\times}10^6$
Belle II LS	1.1	363	$399{\times}10^6$
Belle II 5 ab^{-1}	1.1	5.0	$5500{\times}10^6$
Belle II 50 ab^{-1}	1.1	50.0	$55000{\times}10^6$

※ Belle II LS: The data collected before the Long Shutdown (LS) period of the Belle II experiment.

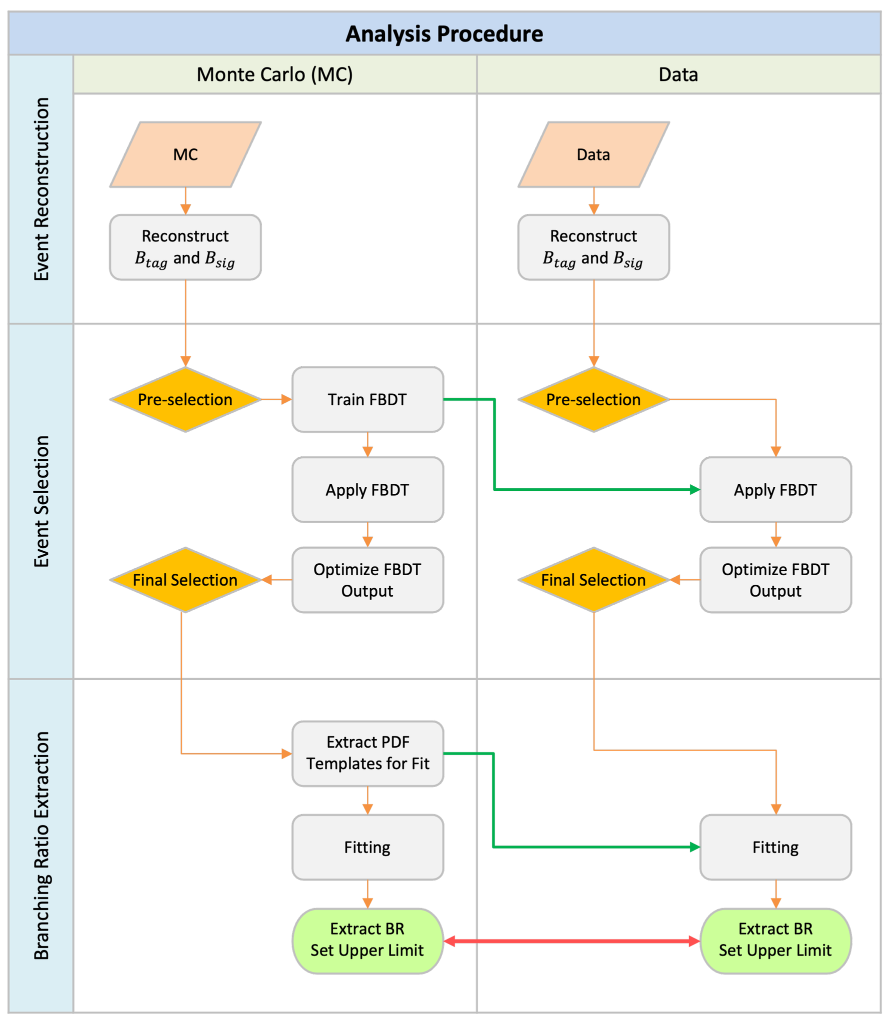
3.2. Rough Estimation of the required luminosity

- $Br(B^0 \to \tau^+\tau^-) \sim 2{\times}10^{-8}$
  - # of B^0: 1
    - then $2{\times}10^{-8}$ $B^0 \to \tau^+\tau^-$ process
  - # of B^0: $1{\times}10^8$
    - then 2 $B^0 \to \tau^+\tau^-$ process
  - # of B^0: $100{\times}10^8 = \mathbf{10^{10}}$
    - then 200 $B^0 \to \tau^+\tau^-$ process (roughly statistically meaningful)
- 1 ab^{-1} : $\sim 1000{\times}10^6 = 10^9$ $B\bar{B}$ pair
- 10 ab^{-1}: $\mathbf{10^{10}}$ $B\bar{B}$ pair
- Roughly, integrated luminosity of ~***10 ab^{-1}*** is required.

※ The calculation is based on SM.
※ Note that this calculation does not consider any efficiencies. It means that much more integrated luminosity is required to measure the $B^0 \to \tau^+\tau^-$ process.

4. Analysis Procedure

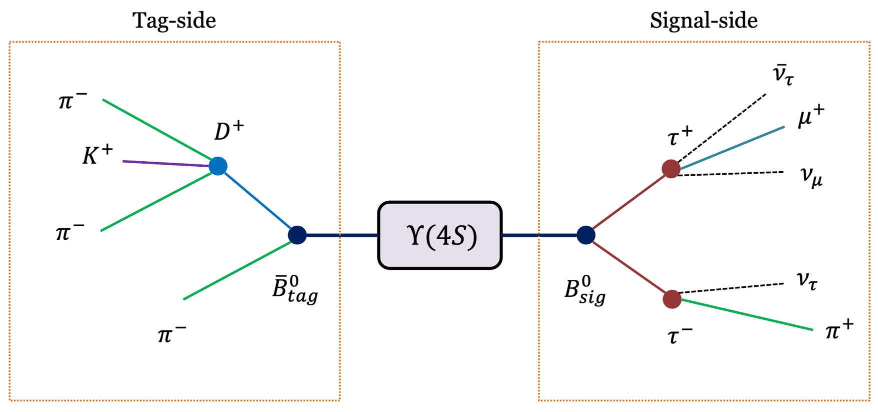
4.1. Analysis Procedure

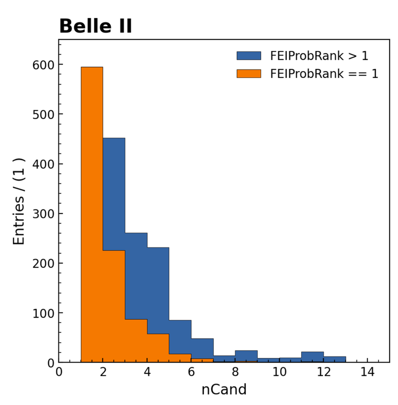


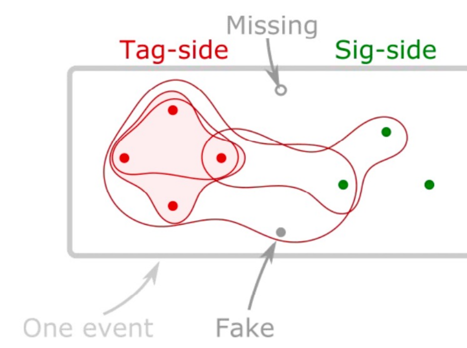
- Blind Analysis
  - The prejudice of analysts can affect the result.
  - To minimize the bias, the blind-procedure should be done. ⇒ Blind: Monte Carlo (MC), Unblind: Data
- The blind analysis is ongoing. Unblinding needs the permission of the Belle II analysis committee.

5. Event Reconstruction

5.1. Example of Reconstruction







5.2. Tag-Side Reconstruction

5.2.1. Full Event Interpretation (FEI) Method
- Exploiting the **advantage** of the Belle II
  - ***The full understanding of the initial state***
- A lot of B decay channels
  - "$\mathcal{O}(1000)$ B decays" ⊗ "$\mathcal{O}(100)$ D decays"
  - ⇒ ***$\mathcal{O}(10^5)$ possible channels***

5.2.2. Hadronic FEI
- Full Event Interpretation (FEI) Method
  - Very low ***efficiency*** ($\mathcal{O}(10^{-3})$)
  - Very high purity / Excellent kinematic Information

5.2.3. Best Tag Selection (BTS)
- Choose a candidate with the highest ***FEI probability value***, which is the Fast Boosted Decision Tree (FBDT) output

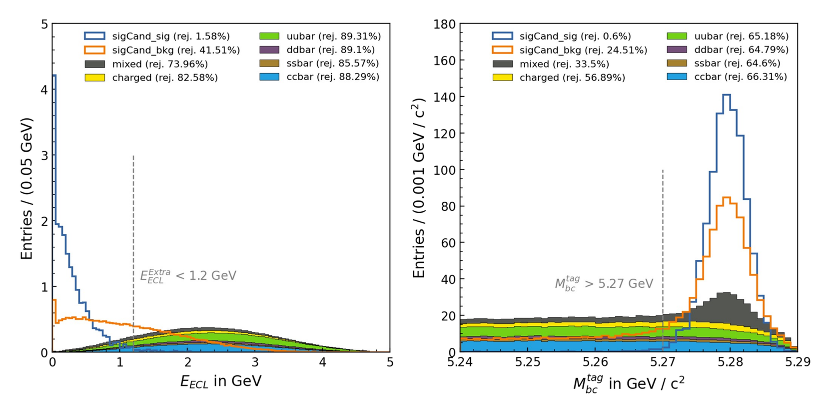
5.3. Signal-Side Reconstruction

Name	τ decay modes
e^+e^-	$\tau \to e\nu_e\nu_\tau$, $\tau \to e\nu_e\nu_\tau$
$e^\pm\mu^\mp$	$\tau \to e\nu_e\nu_\tau$, $\tau \to \mu\nu_\mu\nu_\tau$
$e^\pm\pi^\mp$	$\tau \to e\nu_e\nu_\tau$, $\tau \to \pi\nu_\tau$
$\mu^+\mu^-$	$\tau \to \mu\nu_\mu\nu_\tau$, $\tau \to \mu\nu_\mu\nu_\tau$
$\mu^\pm\pi^\mp$	$\tau \to \mu\nu_\mu\nu_\tau$, $\tau \to \pi\nu_\tau$
$\pi^+\pi^-$	$\tau \to \pi\nu_\tau$, $\tau \to \pi\nu_\tau$

$B^0 \to \tau^+\tau^-$ sub-decay channels

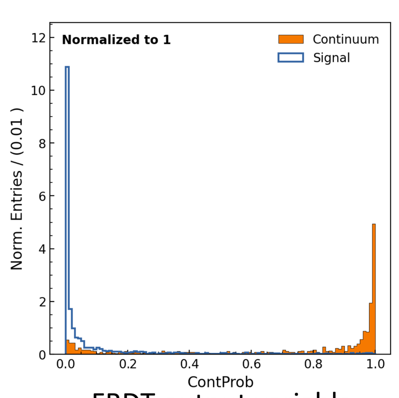
6. Event Selection

6.1. Pre-Selection

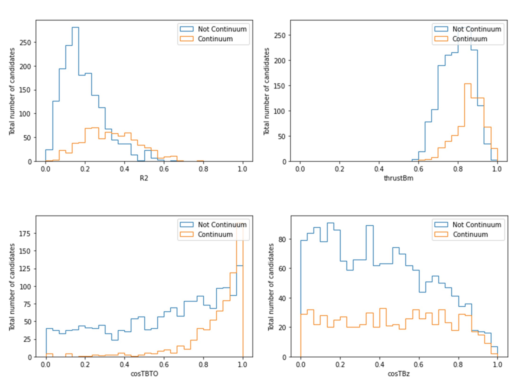


- The purpose of the pre-selection:
  - To make the FBDT process efficient, eliminate obvious background before the FBDT
- Five variables: E_{ECL}, M_{bc}^{tag}, ΔE^{tag}, $\mathcal{N}^{tag}$ and M_{miss}^2

6.2. Final Selection



FBDT output variable



FBDT input variables

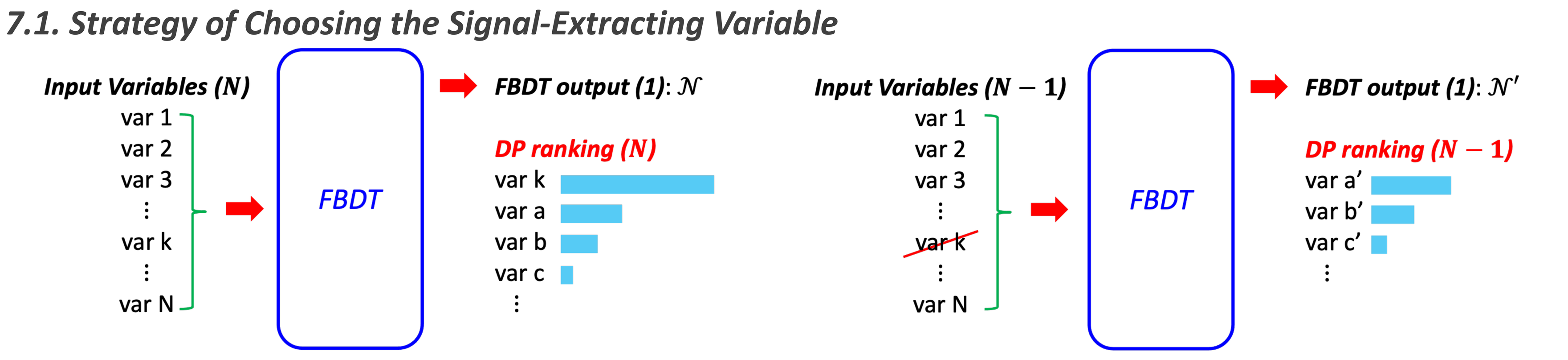
- Binary classification: ex) Signal vs. Background
- Using one of the machine learning algorithms: FBDT
  - Multivariate Analysis (MVA)
    - Gather discriminating power (DP) from variables
    - Small DPs ⇒ FBDT ⇒ ***Large DP***
  - Target variable design: TopoAna Tool (MC matching)

Selection	Selection Value	SigCand_sig (%)	SigCand_bkg (%)	mixed (%)	charged (%)	uubar (%)	ddbar (%)	ssbar (%)	ccbar (%)
Pre-Selection	$E_{ECL}^{Extra} < 1.2$ GeV	1.58 (83/5,249)	41.51 (65047/156,718)	73.96 (243,064/328,654)	82.58 (199,285/241,317)	89.31 (705,792/790,271)	89.10 (177,533/199,243)	85.57 (115,801/135,327)	88.29 (711,417/805,790)
	$M_{bc}^{tag} > 5.27$ GeV/c²	0.60 (31/5,166)	24.51 (22,464/91,671)	33.50 (28,669/85,590)	56.89 (23,912/42,032)	65.18 (55,067/84,479)	64.79 (14,066/21,710)	64.60 (12,613/19,526)	66.31 (62,581/94,373)
	$\lvert \Delta E_{tag} \rvert < 100$ MeV	4.93 (253/5,135)	17.4 (12,040/69,207)	15.88 (9,039/56,921)	18.11 (3,281/18,120)	17.86 (5,254/29,412)	18.16 (1,388/7,644)	18.91 (1,307/6,913)	18.84 (5,990/31,792)
	$\mathcal{N}_{tag} > 0.05$	21.30 (1,040/4,882)	41.55 (23,751/57,167)	46.70 (22,361/47,882)	88.83 (13,181/14,839)	91.38 (22,075/24,158)	91.64 (5,733/6,256)	90.72 (5,086/5,606)	89.26 (23,031/25,802)
	$0.5 < M_{miss}^2 < 25$ (GeV/c²)²	8.38 (322/3,842)	6.54 (2,186/33,416)	12.25 (3,127/25,521)	13.99 (232/1,658)	30.29 (631/2,083)	34.99 (183/523)	26.73 (139/520)	16.1 (446/2,771)
	Total	32.94 (1,729/5,249)	80.07 (125,488/156,718)	93.19 (306,260/328,654)	99.41 (239,891/241,317)	99.82 (788,819/790,271)	99.83 (198,903/199,243)	99.72 (134,946/135,327)	99.71 (803,465/805,790)
	Remaining Total	67.06 (3,520/5,249)	19.93 (31,230/156,718)	6.81 (22,394/328,654)	0.59 (1,426/241,317)	0.18 (1,452/790,271)	0.17 (340/199,243)	0.28 (381/135,327)	0.29 (2,325/805,790)
FBDT Cont. Supp.	$\mathcal{N}_{Cont.} > x.xx$	-	-	-	-	-	-	-	-
FBDT	-	-	-	-	-	-	-	-	-

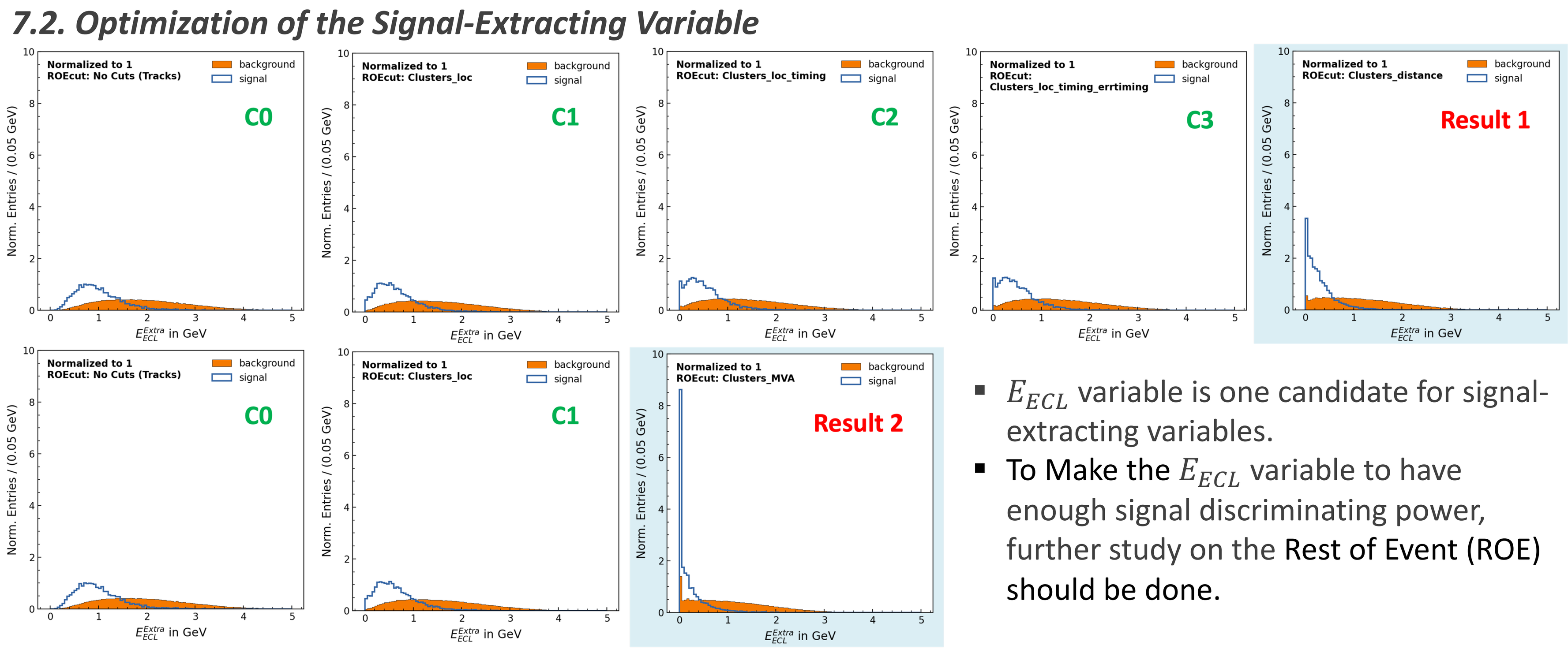
Rejection rate / Yield of signal, generic and continuum background

7. Branching Fraction Extraction

7.1. Strategy of Choosing the Signal-Extracting Variable



7.2. Optimization of the Signal-Extracting Variable



- E_{ECL} variable is one candidate for signal-extracting variables.
- To Make the E_{ECL} variable to have enough signal discriminating power, further study on the Rest of Event (ROE) should be done.

Conclusion / Plan

The first trial of the event reconstruction and selection process has been done. We plan to proceed with the branching fraction extraction process and then set the first version of the upper limit on the $B^0 \to \tau^+\tau^-$ process. After experiencing the whole blind analysis process, we will revisit and optimize each step of the process.