The Search for Charged Lepton Flavour Violation at Belle II

Through the ultra rare decay $B^{\pm} \rightarrow K^{\pm}\tau\ell$ ($\ell = e, \mu$)

WNPPC 2020
Banff, Alberta

Trevor Shillington
Supervisor: Steve Robertson

McGill
Physics Department - Département de Physique

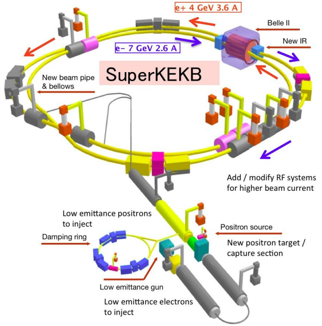
Belle II

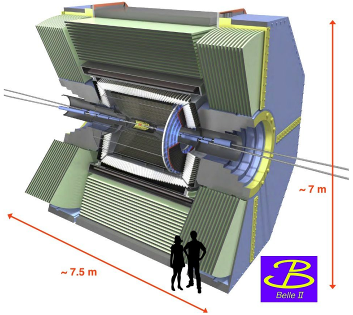
Agenda

- Introduction
  - Belle II
  - Charged Lepton Flavor Violation
- $B^{\pm} \rightarrow K^{\pm}\tau\ell$
  - Previous searches
  - Our strategy
  - Full Event Interpretation (FEI)
- Summary and Outlook
  - What’s next

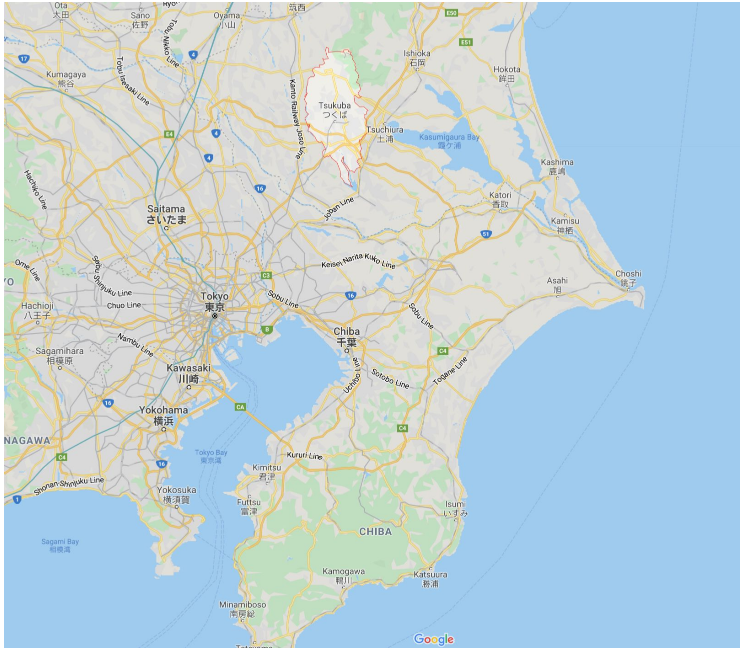
Belle II

- Located in Tsukuba, Japan at the **SuperKEKB** accelerator
- Collides asymmetric $e^- e^+$ beams at 10.58 GeV
- 50x more data than Belle
  - 800 million vs 40 billion B meson pairs
- Began taking data last spring!
- Belle II full dataset: **50ab^{-1}** (~2025)



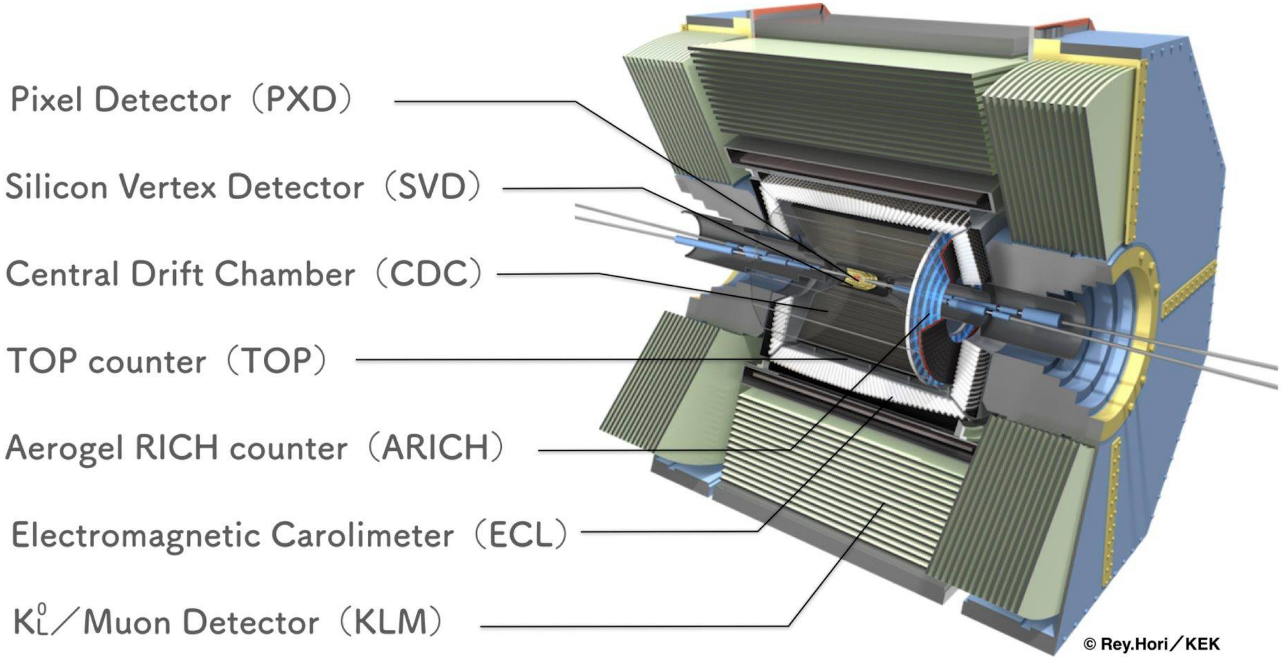


Source: https://www.belle2.org/project/super_kekb_and_belle_ii/



Source: Google Maps

Belle II


Pixel Detector (PXD)
Silicon Vertex Detector (SVD)
Central Drift Chamber (CDC)
TOP counter (TOP)
Aerogel RICH counter (ARICH)
Electromagnetic Carolimeter (ECL)
K_L^0／Muon Detector (KLM)
© Rey.Hori／KEK

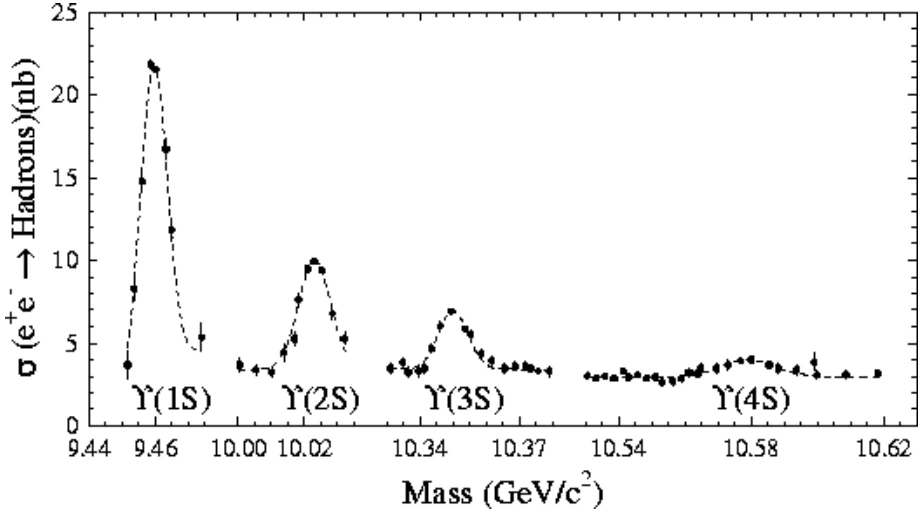
Belle II

- The Belle II experiment is operated at an energy of 10.58 GeV
- This is the energy of the Υ(4S) resonance ($b\bar{b}$)
- Υ(4S) decays almost exclusively to a $B\bar{B}$ pair (over 96%) → **“B factory”**
  - Roughly half to B^+B^- and half to $B^0\bar{B}^0$
- Υ(4S) is just above the threshold for a BB pair (10.56 GeV) → low momentum

B Mesons:

$B^+ = u\bar{b}$ $B^0 = d\bar{b}$

$B^- = \bar{u}b$ $\bar{B}^0 = \bar{d}b$



Source: https://www.classe.cornell.edu/public/lab-info/upsilon.html

Lepton Flavor Conservation

- Lepton Flavor Conservation (LFC):

  L_e, L_μ, L_τ numbers are conserved in the SM

- Lepton Flavor Conservation in the Standard Model is a result of the assumption that neutrinos don't have mass

  ...or do they?

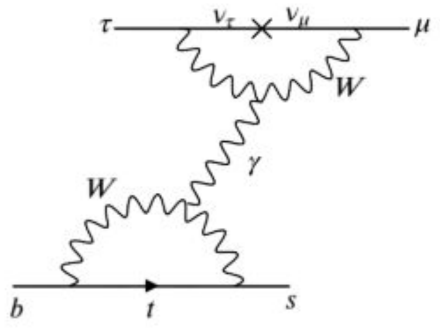
Q/e	$L_e = -1$	$L_\mu = -1$	$L_\tau = -1$
$\begin{matrix} 0 \\ +1 \end{matrix}$	$\begin{pmatrix} \overline{\nu}_e \\ e^+ \end{pmatrix}$	$\begin{pmatrix} \overline{\nu}_\mu \\ \mu^+ \end{pmatrix}$	$\begin{pmatrix} \overline{\nu}_\tau \\ \tau^+ \end{pmatrix}$

Q/e	$L_e = 1$	$L_\mu = 1$	$L_\tau = 1$
$\begin{matrix} 0 \\ -1 \end{matrix}$	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}$	$\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}$	$\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$

Source: https://www.nuclear-power.net/laws-of-conservation/law-conservation-lepton-number/

Lepton Flavor Violation (LFV)

- Neutrino physics (eg. SNO) have shown that neutrinos have an oscillatory nature
  - → **neutrinos violate LFC**
- With LFV established in neutrinos, this implies that all LFV processes are also allowed at some level (including charged leptons, at the loop level)
- Loop diagrams are highly suppressed because the branching fraction is $\propto m^2_{\upsilon}/M^2_W$



Example of an allowed loop level B → Kτμ diagram

- So *why* are we looking?

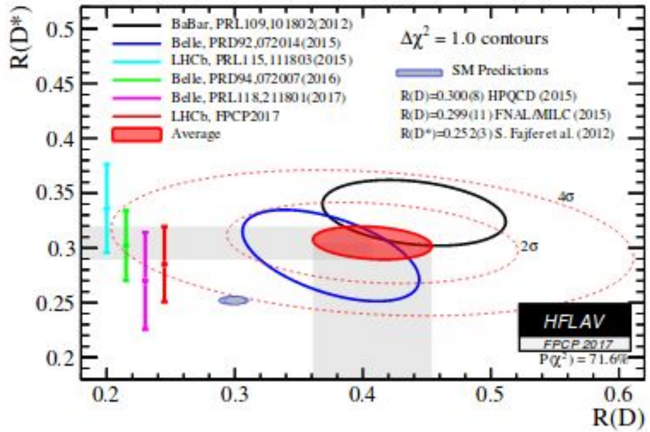
Charged Lepton Flavor Violation

- **Why search for it?**
- Many extensions of the SM predict an increased CLFV rate
- Particularly in the 2-3 gen leptons (i.e. muon and tau)
- Moreover, the recent B-physics anomalies:

$$\left(R^{exp}_{D^{(*)}} > R^{SM}_{D^{(*)}} \text{ and } R^{exp}_{K^{(*)}} < R^{SM}_{K^{(*)}}\right)$$

→ Hint at possible violation of **Lepton Flavor Universality**

- There is no known way to bring about lepton flavor non-universality without inducing LFV



$$R(D^{(*)}) = \frac{\Gamma(B \to D^{(*)}\tau\bar{\nu})}{\Gamma(B \to D^{(*)}\ell\bar{\nu})} \qquad R_{K^{(*)}} = \frac{\Gamma(B \to K^{(*)}\mu^+\mu^-)}{\Gamma(B \to K^{(*)}e^+e^-)}.$$

Plot and formulas taken from: 1. Li, Y. & Lü, C.-D. Recent anomalies in B physics. Sci. Bull. 63, 267–269 (2018).

Charged Lepton Flavor Violation

- Many of the theories attempting to incorporate the B-physics anomalies specifically increase the branching fraction of $B^{\pm} \rightarrow K^{\pm}\tau\ell$
- In these models, BR($B^{\pm} \rightarrow K^{\pm}\tau\ell$) can be as high as 10^{-6}
- Belle II will be able to place limits down to a few $\times 10^{-6}$

- If found, direct evidence of physics beyond the SM
- If not found, can place strict limits on theories with induced CLFV

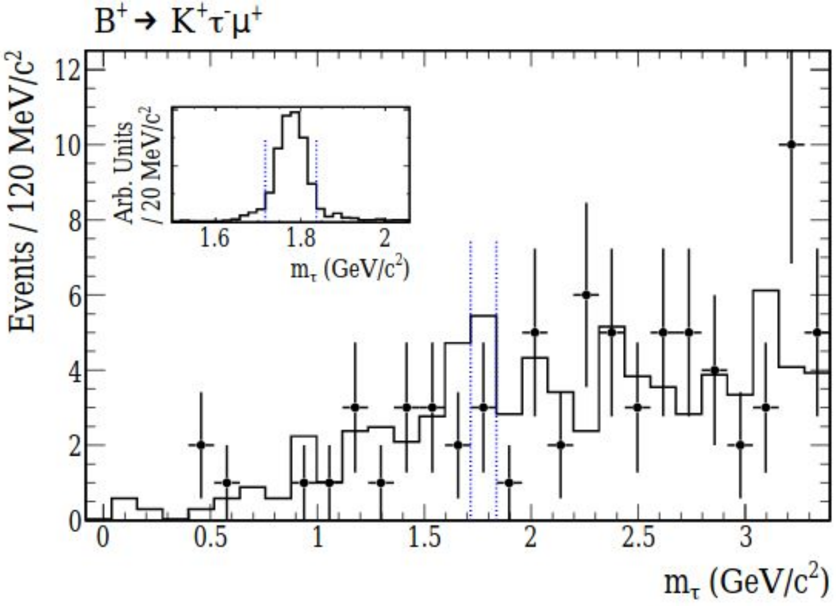
Model	Decay Mode	Branching Fraction Limits
Singlet Vector Leptoquark U_1 [9]	$B \to K\tau\mu$	$\gtrsim$ few x 10^{-7}
Triplet Vector Leptoquark [7]	$B \to K\tau\mu$	$\lesssim 3$ x 10^{-6}
Triplet Vector Leptoquark [7] with $R_{\nu\nu} < 1.2$	$B \to K\tau\mu$	$\gtrsim 5$ x 10^{-9}
Two Scalar Leptoquark [10]	$B \to K\tau^{\pm}\mu^{\mp}$	$\gtrsim 1.1$ x 10^{-7} and $\lesssim 6.5$ x 10^{-7}
Three-site Pati-Salam Gauge Model (PS^3) [11]	$B^{\pm} \to K^{\pm}\tau^{\pm}\mu^{\mp}$	$> 10^{-6}$
Three-site Pati-Salam Gauge Model (PS^3) [11]	$B^{\pm} \to K^{\pm}\tau^{\mp}\mu^{\pm}$	≈ 0
Pati-Salam with Minimal Matter Content [12]	$B \to K\tau\mu$	$\gtrsim 10^{-6}$
Gauged Horizontal $SU(2)$ Symmetry [13]	$B \to K\tau\mu$	$\gtrsim 1.3$ x 10^{-8} and $\lesssim 5.2$ x 10^{-6}
Belle II Limit at 50 ab^{-1}	$B \to K\tau\ell$	2 to 3 x 10^{-6}

Table 1: Various predictions on the branching fractions of $B \to K\tau\mu$. Note that some of these are highly dependent on other observables. See text for details.

$B^{\pm} \rightarrow K^{\pm}\tau\ell$ – Previous Searches

BaBar, 2012:

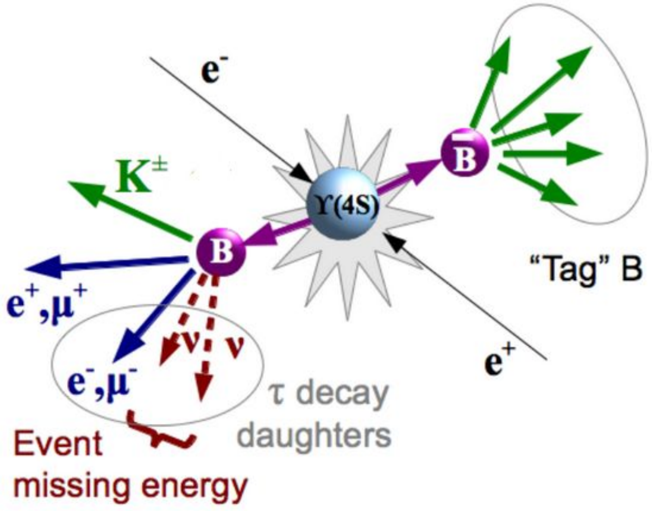
- Found no evidence for $B^{\pm} \rightarrow K^{\pm}\tau\ell$ decays and set a 90% confidence level upper limit on each branching fraction at the level of a **few times 10^{-5}** [1]
- Belle II will increase this by at least an order of magnitude



[1] 1. Lees, J. P. et al. Search for the decay modes B±→h±τ l. Phys. Rev. D - Part. Fields, Gravit. Cosmol. 86, (2012).

$B^\pm \to K^\pm \tau \ell$ (ℓ=e,μ) – Searching for CLFV

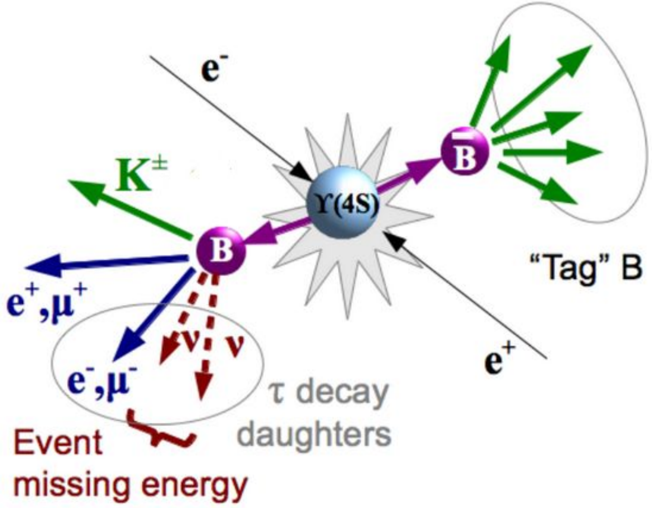
- Now we are motivated!
- But there are neutrinos in τ decay products (missing energy)
- **Issue:** How to reconstruct the decay without knowing neutrino energies?
- **Solution:** Reconstruct the opposite B to recover some information



$B^{\pm} \to K^{\pm}\tau\ell$ (ℓ=e,μ) - Method

- Reconstruct "Tag" B meson
  - How to do this efficiently? FEI
- Recover the 4-momentum of the Tag B
  - $p_{tag} = -p_{sig}$
- Use this with the Kaon and lepton 4-momentum to indirectly reconstruct tau mass
- The indirectly reconstructed tau mass peaks sharply for signal and has a broad distribution for background

$$\vec{p}_\tau = -\vec{p}_{\rm tag} - \vec{p}_h - \vec{p}_\ell,$$
$$E_\tau = E_{\rm beam} - E_h - E_\ell,$$
$$m_\tau = \sqrt{E_\tau^2 - |\vec{p}_\tau|^2},$$

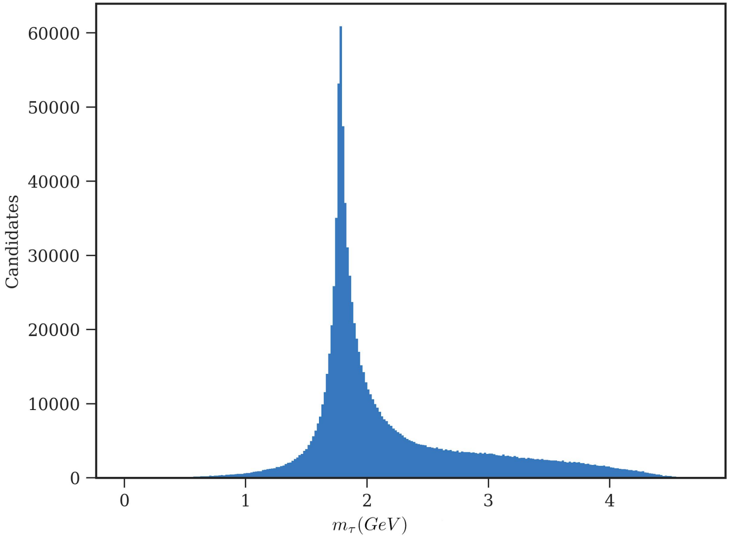


$B^\pm \to K^\pm \tau \ell$ (ℓ=e,μ) - Method

- Reconstruct "Tag" B meson
  - How to do this efficiently? FEI
- Recover the 4-momentum of the Tag B
  - $p_{tag} = -p_{sig}$
- Use this with the Kaon and lepton 4-momentum to indirectly reconstruct tau mass
- The indirectly reconstructed tau mass peaks sharply for signal and has a broad distribution for background

$$\begin{aligned} \vec{p}_\tau &= -\vec{p}_{\text{tag}} - \vec{p}_h - \vec{p}_\ell, \\ E_\tau &= E_{\text{beam}} - E_h - E_\ell, \\ m_\tau &= \sqrt{E_\tau^2 - |\vec{p}_\tau|^2}, \end{aligned}$$

Tau mass reconstructed using Signal MC11

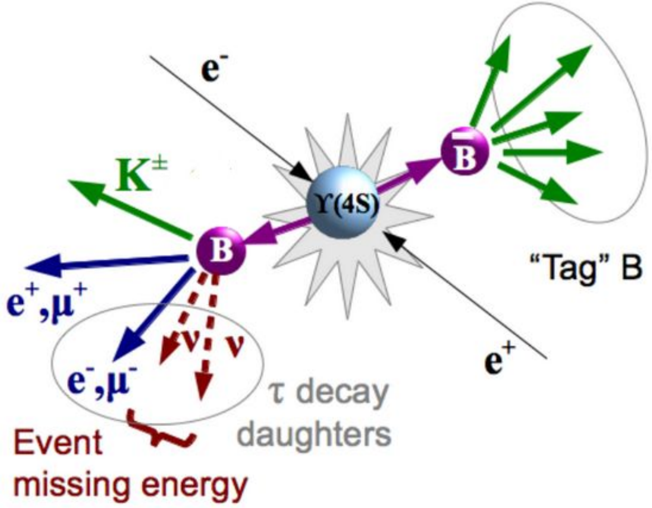


(m_τ =1.78 GeV)

$B^\pm \to K^\pm \tau \ell$ (ℓ=e,μ) – Method

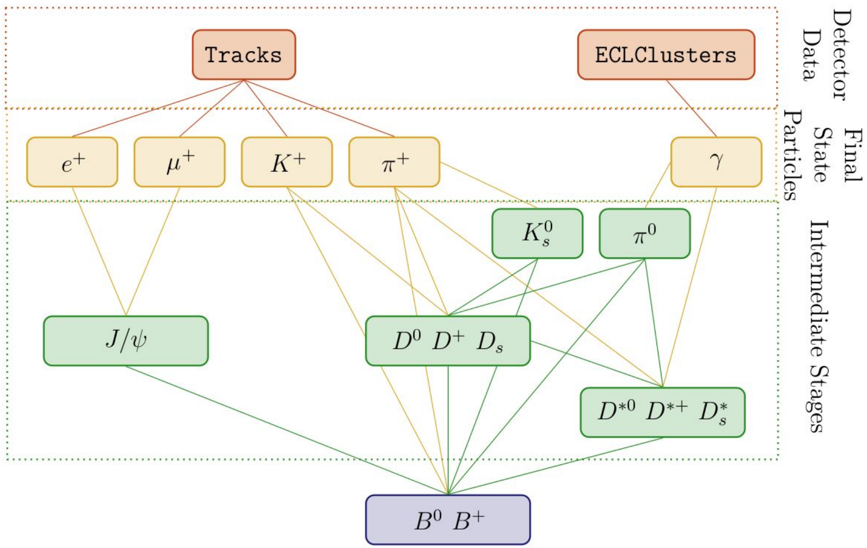
- Reconstruct “Tag” B meson
  - How to do this efficiently? FEI
- Recover the 4-momentum of the Tag B
  - $p_{tag} = -p_{sig}$
- Use this with the Kaon and lepton 4-momentum to indirectly reconstruct tau mass
- The indirectly reconstructed tau mass peaks sharply for signal and has a broad distribution for background

$$
\begin{aligned}
\vec{p}_\tau &= -\vec{p}_{\rm tag} - \vec{p}_h - \vec{p}_\ell, \\
E_\tau &= E_{\rm beam} - E_h - E_\ell, \\
m_\tau &= \sqrt{E_\tau^2 - |\vec{p}_\tau|^2},
\end{aligned}
$$



Full Event Interpretation (FEI)

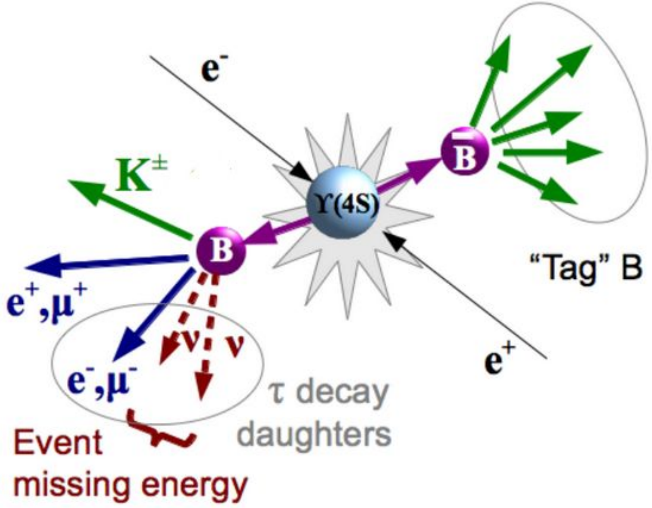
- FEI is an algorithm developed for Belle II as a reconstruction method for one of the B mesons (the tag-side B, B_{tag})
- Utilizes a neural network to train the FEI on ~100 million MC events
- FEI uses thousands of decay channels to reconstruct B_{tag}
- Uses both hadronic and semileptonic tagging:
  - Hadronic decay channels have very good kinematics and the tagged sample is very pure, but only a fraction of the decays are hadronic
  - Semileptonic decay channels dominate the branching fraction, meaning high efficiency but suffer from missing kinematics, thus low purity



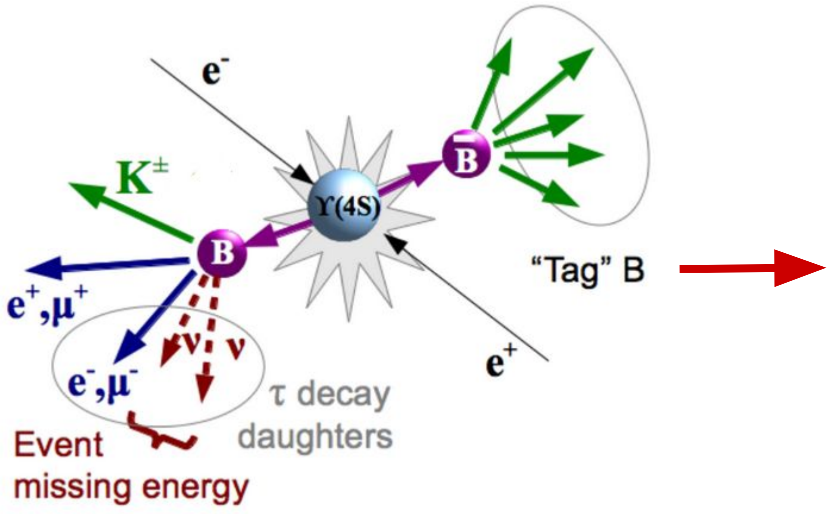
Full Event Interpretation (FEI)

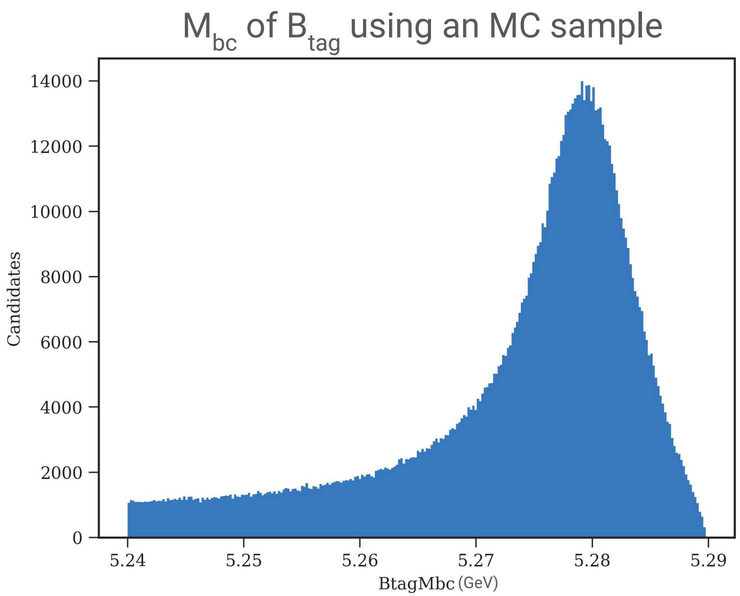
FEI:

- Allows you to precisely determine the 4-momentum of the signal-side B, B_{sig}
- Also restricts the tracks and cluster hits allowed for reconstruction of B_{sig}
- Result: significant simplifications of signal side reconstruction



Full Event Interpretation (FEI)





m_B = 5.279 GeV

Summary and Outlook

- CLFV is a good place to look for new physics
- $B^{\pm} \rightarrow K^{\pm}\tau\ell$ is specifically interesting given the recent B-anomalies

- Belle II has been taking data for ~1 year (full dataset to be complete ~2025)
- We continue to test and optimize our reconstruction on Monte-Carlo (generic MC and 200 million signal MC events)

- **In the end, we hope to improve the upper limits on BR($B^{\pm} \rightarrow K^{\pm}\tau\ell$) to a few x$10^{-6}$**

Thank You!

Physics Department - Département de Physique

Backup slides

Luminosity

The design (peak) luminosity of the SuperKEKB accelerator: $\mathbf{8 \times 10^{35}\ cm^{-2}s^{-1}}$

40x greater than that of the KEKB accelerator

20x smaller beam focus

2x current

Charm factory: 65 billion cc pairs in full dataset

Tau factory: 45 billion tau pairs created in full dataset

Blind Analysis

To avoid experimenter bias we are doing this analysis “blind”.

In the context of our study, our signal is the indirectly reconstructed tau mass.

Therefore, we will not be looking at the reconstructed tau mass within ±175 MeV/c^2 of the nominal tau mass in data until our selection is finalized.

Background Suppression 1

Background events with B → K(ccbar); (ccbar) → $\ell^+\ell^-$ can pass signal selection

For B → Kτe (B → Kτμ) ; τ → e or π (τ → μ or π),

remove **3.03 < $m_{\ell\ell}$ < 3.14** GeV/c^2 (For J/psi)

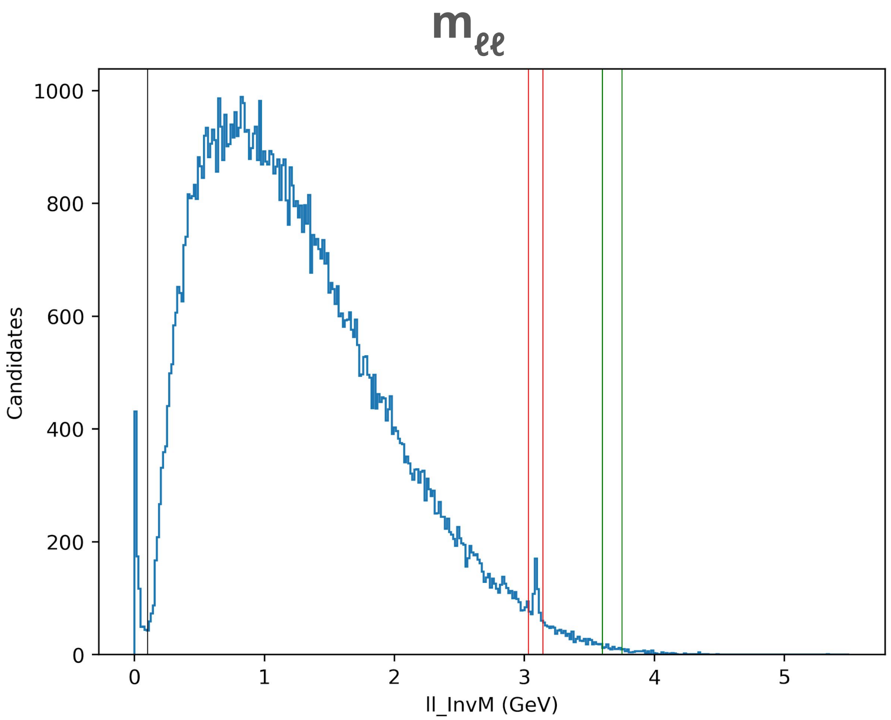
remove **3.60 < $m_{\ell\ell}$ < 3.75** GeV/c^2 (For ψ(2S))

Additionally, for B → Kτe; τ → e or π,

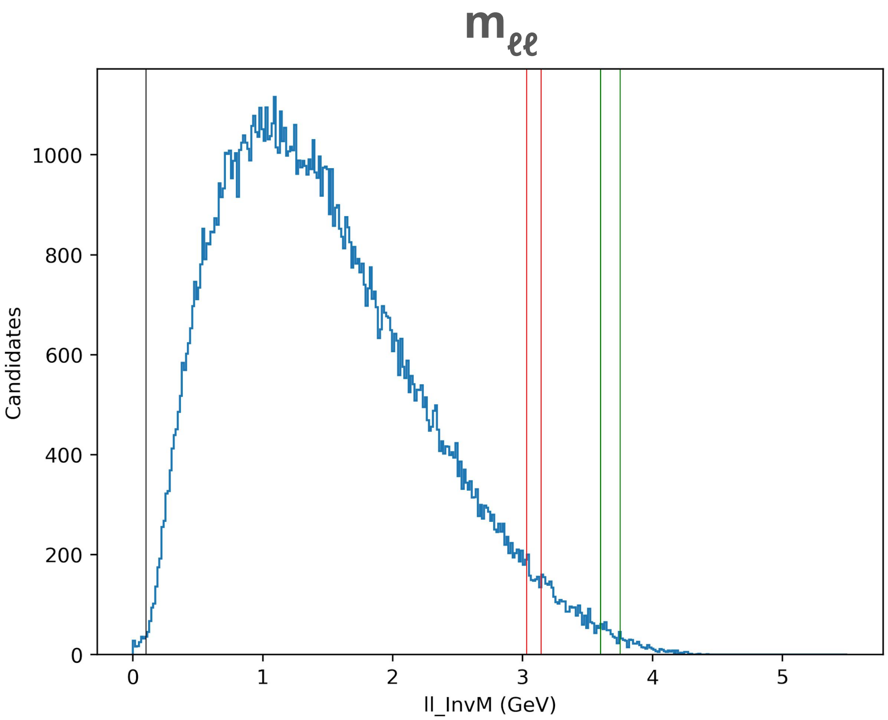
remove **$m_{\ell\ell}$ < 0.1** GeV/c^2 (for events consistent with photon conversion)

$m_{\ell\ell}$ = Invariant mass of primary lepton and tau daughter

Generic MC12 Charged (Hadronic FEI)



Signal MC12 $B^+ \rightarrow K^+\tau^-e^+$ (Hadronic FEI)



Background Suppression 2

Background due to BB events: sources differ based on primary lepton charge

For all modes,

remove **$m(K\pi) < 1.95$** GeV/c^2

From BaBar:

For **$B^+ \rightarrow K^+\tau^-\ell^+$**, this removed 97-99% of the background, and retained 32-37% of signal

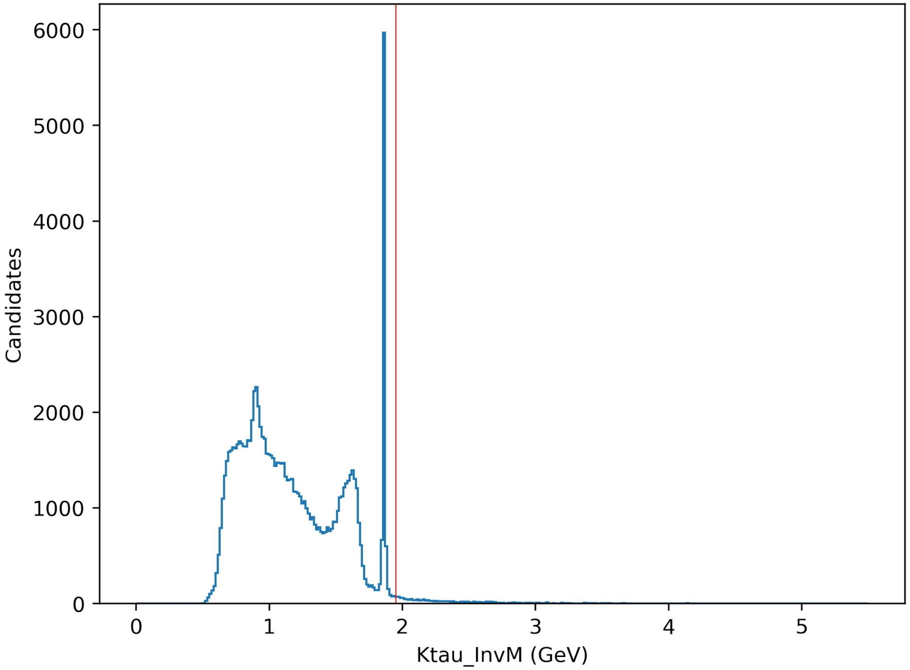
For **$B^+ \rightarrow K^+\tau^+\ell^-$**, this removed 92-96% of the background, and retained 63% of signal

$m(K\pi)$ = Invariant mass of K and B_{sig} daughter with opposite charge to K

$B^+ \to K^+ \tau^- e^+$

Generic MC12 Charged (Hadronic FEI)

m(Kπ)



Signal MC12 $B^+ \to K^+ \tau^- e^+$ (Hadronic FEI)

m(Kπ)