The Search for Charged Lepton Flavour Violation at Belle II

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Outline

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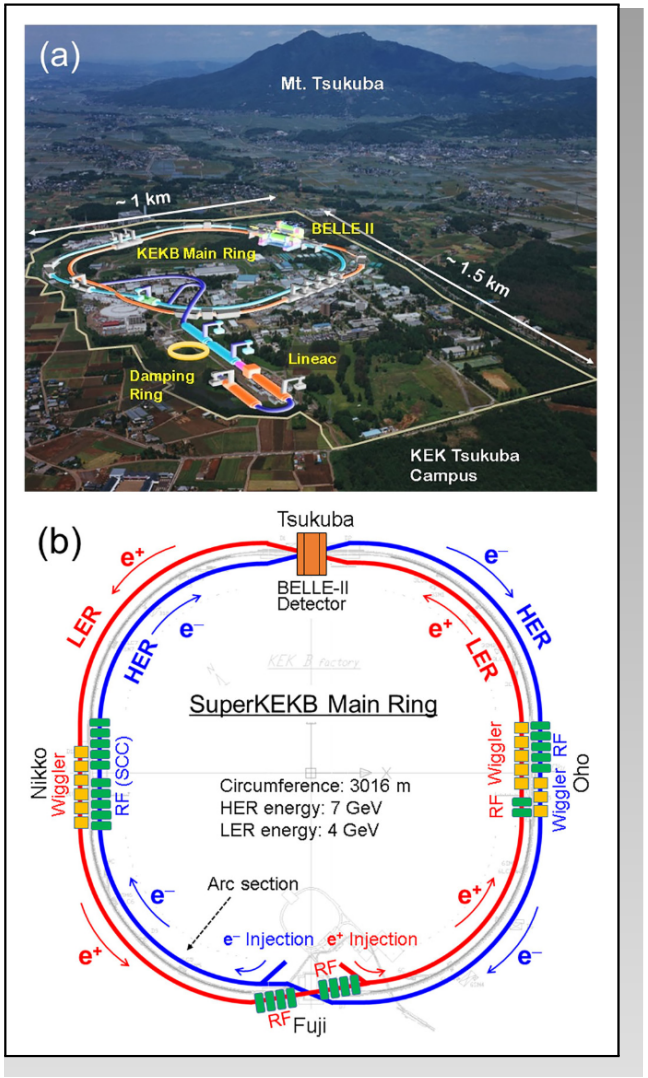
   - Belle II
2. Searching for the Decay Mode $B \to K\tau\ell\,(\ell = e, \mu)$
   - What is Charged Lepton Flavour Violation ?
   - Motivation and New Predictions
   - Previous Searches
   - Our Strategy
   - Current Status
3. Summary and Outlook

Introduction - The Collider and the Detector

- **Belle II** is located in Tsukuba, Japan at the **SuperKEKB accelerator**
- Belle (1999-2010) was originally commissioned to look for **CP violation** via $\Upsilon(4S) \rightarrow B^0\overline{B^0}$
  - First found in 2001, Kobayashi and Maskawa awarded **Nobel Prize** in 2008
- **Intensity Frontier** (complementary to energy frontier)
  - Belle II recently set the world record for instantaneous luminosity at 3 x $10^{34}/cm^2/s$

SuperKEKB: The Collider



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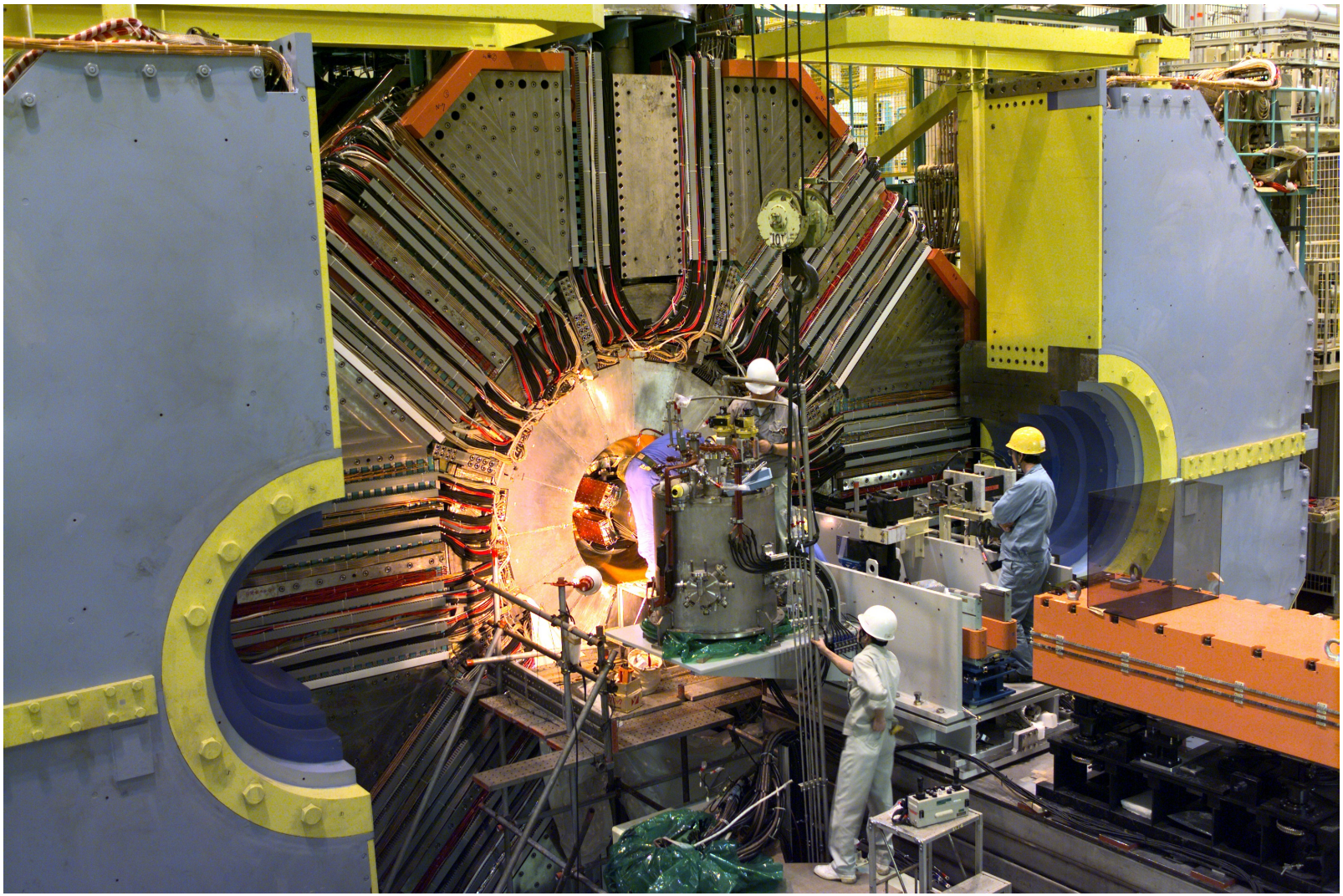
- Asymmetric e^+e^- collider
- 3 km circumference
- Started operations in 2018
- **40x higher luminosity** than KEKB
  - **2x** beam currents
  - **20x** smaller beam spot
- Operates at 10.58 GeV
  - Mass resonance of the $\Upsilon(4S)$ meson
  - $\Upsilon(4S)$ decays 96% of the time to $B\overline{B}$ pairs

*. Source : J. Vac. Sci. Technol. A 37, 021602 (2019) ; https ://doi.org/10.1116/1.5083928

Belle II: The Detector



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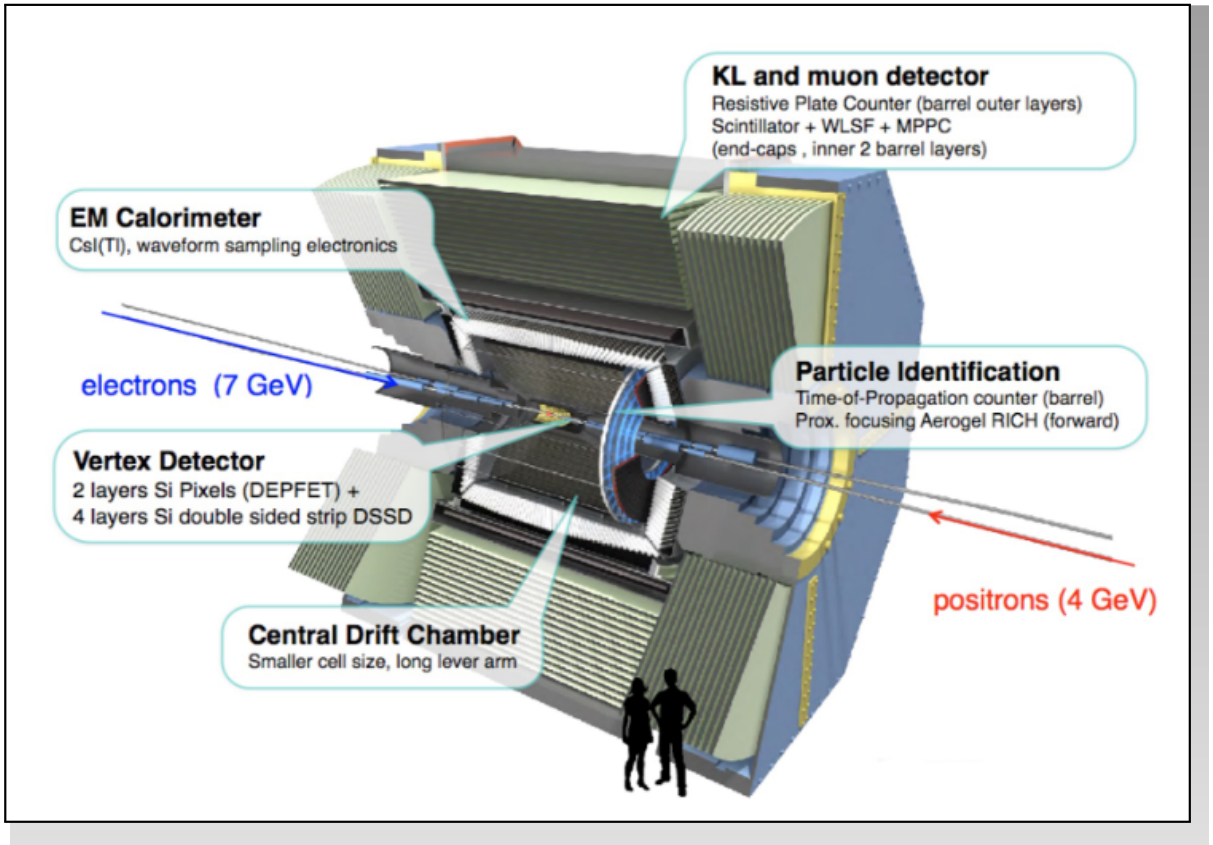
†. Source : https ://physicsworld.com/wp-content/uploads/2018/04/BELLE-II.jpg

Belle II: The Detector

- **50x more** data than Belle
- Belle II is a **Super B factory**
  - 40 billion B meson pairs (vs 800 million at Belle)
- ...but also a charm/tau factory
  - 65 billion ccbar pairs
  - 45 billion tau pairs
- Full dataset by 2030
  - 50 ab^{-1} total
  - Currently at 180 fb^{-1}
  - vs 711 fb^{-1} @Belle
  - vs 429 fb^{-1} @BaBar ‡



‡. source : Matvienko, Dmitry. (2018). The Belle II experiment : status and physics program. EPJ Web of Conferences. 191. 02010. 10.1051/epjconf/201819102010.

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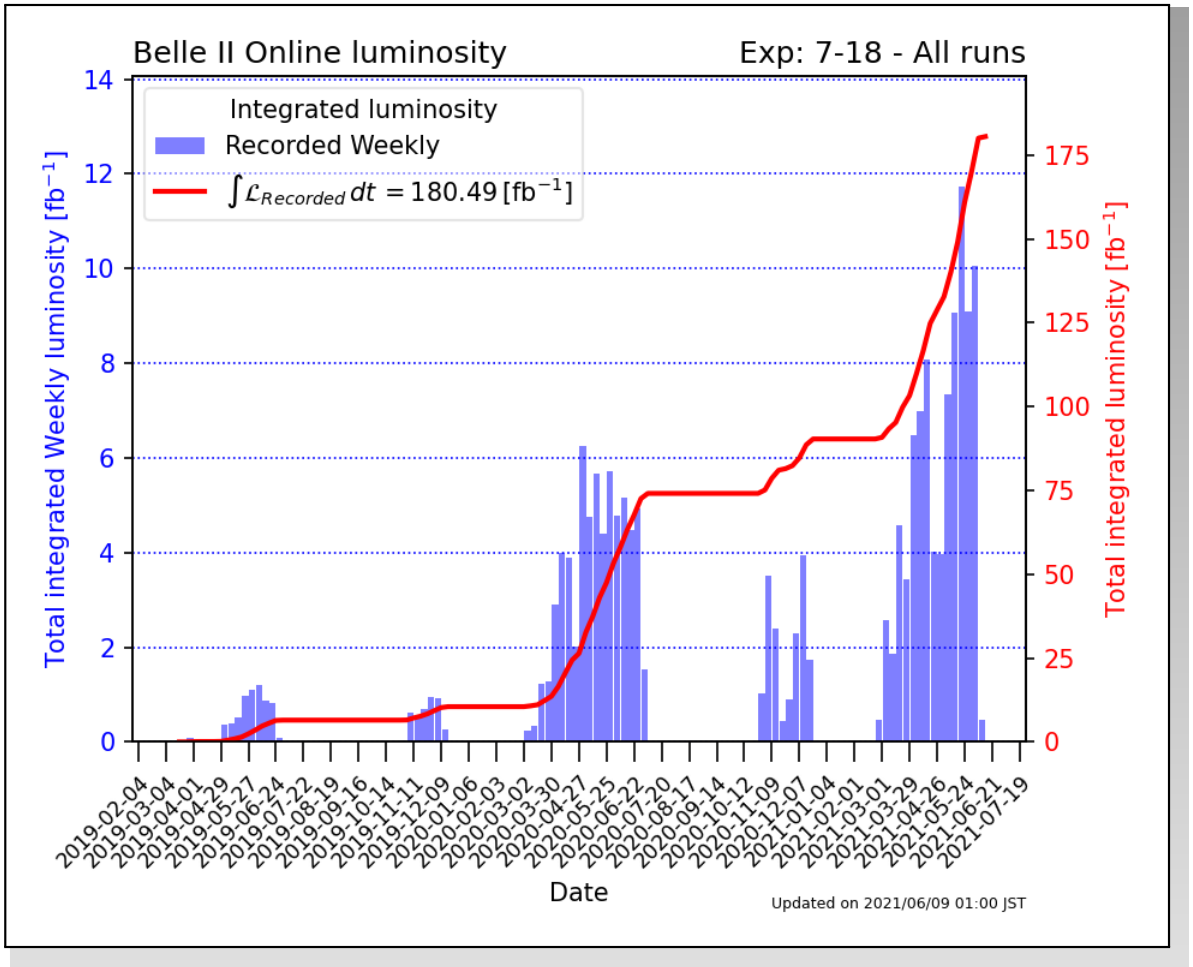


What is Charged Lepton Flavour Violation (CLFV) ?

- 3 generations (flavours) of leptons
- Each flavour gets a number associated with it
  - $+1$ for particles
  - -1 for anti-particles
- These 3 numbers are conserved in the Standard Model
  - Stems from the assumption that neutrinos have no mass

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

LHS: $L_e = 0, L_\mu = 0, L_\tau = 0$

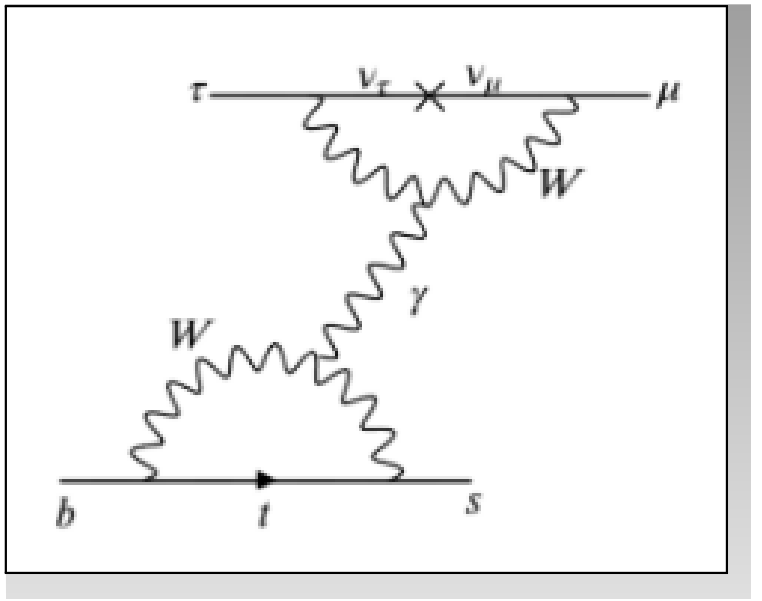
RHS: $L_e = 1, L_\mu = 0, L_\tau = -1$

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

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

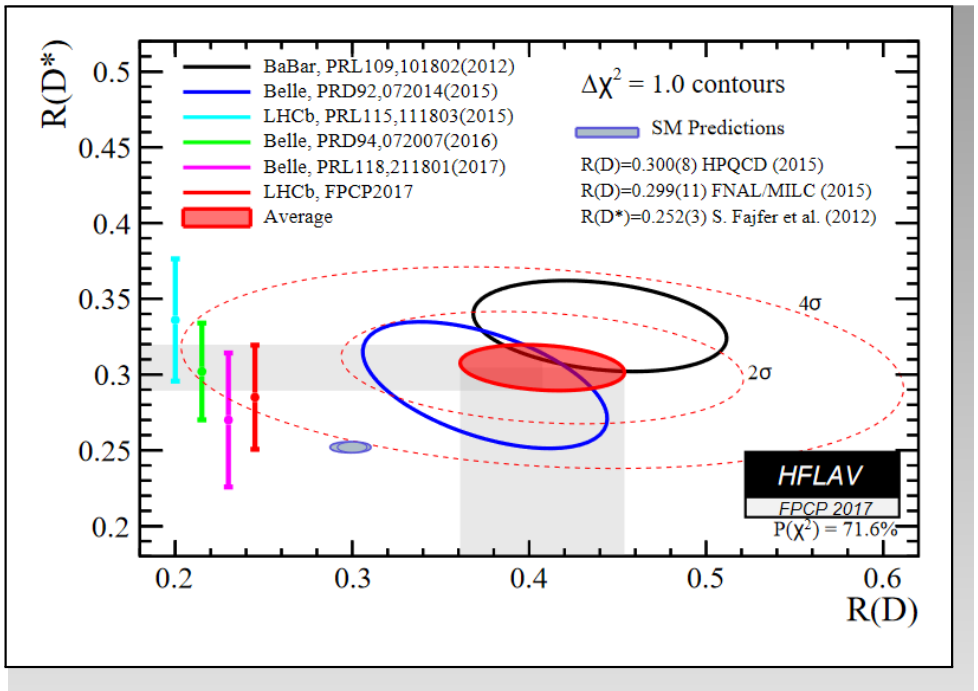
What is Charged Lepton Flavour Violation (CLFV) ?

- But neutrinos **DO** have mass, and LFV is known to exist via **neutrino oscillation**
  - e.g. $\nu_e \to \nu_\mu$
- Even with neutrino oscillations, the Standard Model predicts LFV in the charged sector at a level that is **far below experimental observation**
  - Suppressed by a factor of $\frac{m_\nu^2}{m_W^2}$
- So why are we so motivated ?



Example of a SM allowed loop level $B \to K\tau\mu$ Feynman diagram

Motivation : Lepton Flavour (non)-Universality



§Recent hints of Lepton Flavour non-universality via

$$R(D^{(*)}) = \frac{\Gamma(B \to D^{(*)}\tau\overline{\nu})}{\Gamma(B \to D^{(*)}\ell\overline{\nu})}$$

- **Lepton Flavour Universality** (LFU)
  - All three flavours have the same coupling to the electroweak gauge bosons Z and $W^{\pm}$
  - Branching fractions involving leptons do not depend on flavour
- Recent results such as the B-anomalies ($R(D^{(*)}), R(K)$) show tension with the SM and hint at lepton flavour non-universality
- **There is no known way to include lepton flavour non-universality without inducing CLFV** ¶

§. source : Li, Y. Lü, C.-D. Recent anomalies in B physics. Sci. Bull. 63, 267–269 (2018)

¶. Glashow et al., 2014

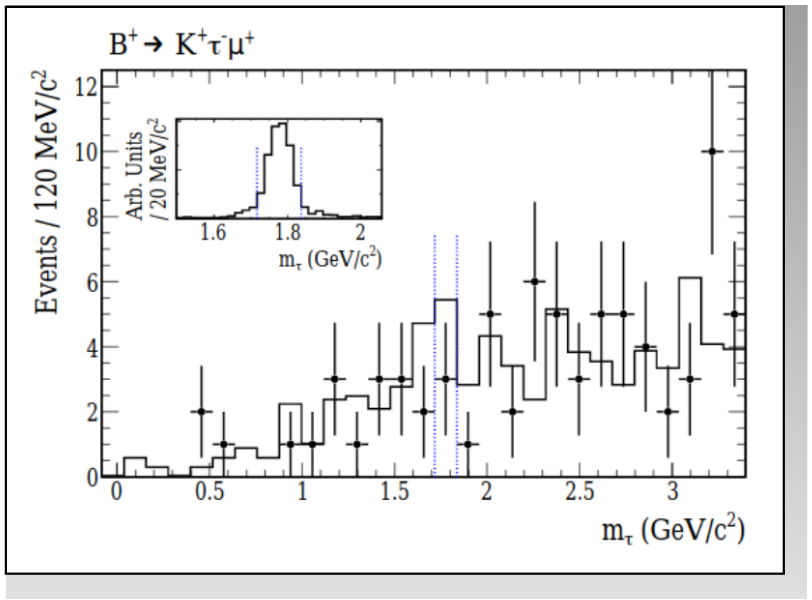
Motivation: New Physics

Model	Decay Mode	Branching Fraction Limits
Singlet Vector Leptoquark U_1 (Angelescu et al., 2018)	$B \to K\tau\mu$	$\gtrsim$ few x 10^{-7}
Triplet Vector Leptoquark (Bečirević et al., 2016)	$B \to K\tau\mu$	$\lesssim 3$ x 10^{-6}
Triplet Vector Leptoquark with $R_{\nu\nu} < 1.2$ (Bečirević et al., 2016)	$B \to K\tau\mu$	$\gtrsim 5$ x 10^{-9}
Two Scalar Leptoquark (Bečirević et al., 2018)	$B \to K\tau^{\pm}\mu^{\mp}$	$\gtrsim 1.1$ x 10^{-7} and $\lesssim 6.5$ x 10^{-7}
Three-site Pati-Salam Gauge Model (PS^3) (Bordone et al., 2018)	$B^{\pm} \to K^{\pm}\tau^{\pm}\mu^{\mp}$	$> 10^{-6}$
Three-site Pati-Salam Gauge Model (PS^3) (Bordone et al., 2018)	$B^{\pm} \to K^{\pm}\tau^{\mp}\mu^{\pm}$	≈ 0
Pati-Salam with Minimal Matter Content (Heeck & Teresi, 2018)	$B \to K\tau\mu$	$\gtrsim 10^{-6}$
Gauged Horizontal $SU(2)$ Symmetry (Guadagnoli et al., 2018)	$B \to K\tau\mu$	$\gtrsim 1.3$ 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}

- Various predictions on the branching fraction of $B \to K\tau\mu$. Note that some of these are highly dependent on other observables.
- Some models predict $BR(B \to K\tau\ell)$ to be as high as 10^{-6}, within reach of Belle II

$B \to K\tau\ell\,(\ell = e, \mu)$: Previous Searches

- BaBar 2012 ‖
  - Found no evidence for $B \to K\tau\ell$ with 429 fb^{-1} of data
  - Set a 90% CL upper limit on each branching fraction at the level of a few x 10^{-5}
- LHCb 2020 **
  - Found no evidence for $B^+ \to K^+\mu^-\tau^+$ using B^{*0}_{s2} decays
  - Set a 90% CL upper limit on the branching fraction at < 3.9 x 10^{-5}
- Belle II will be able to get down to at least $\mathcal{O}(10^{-6})$

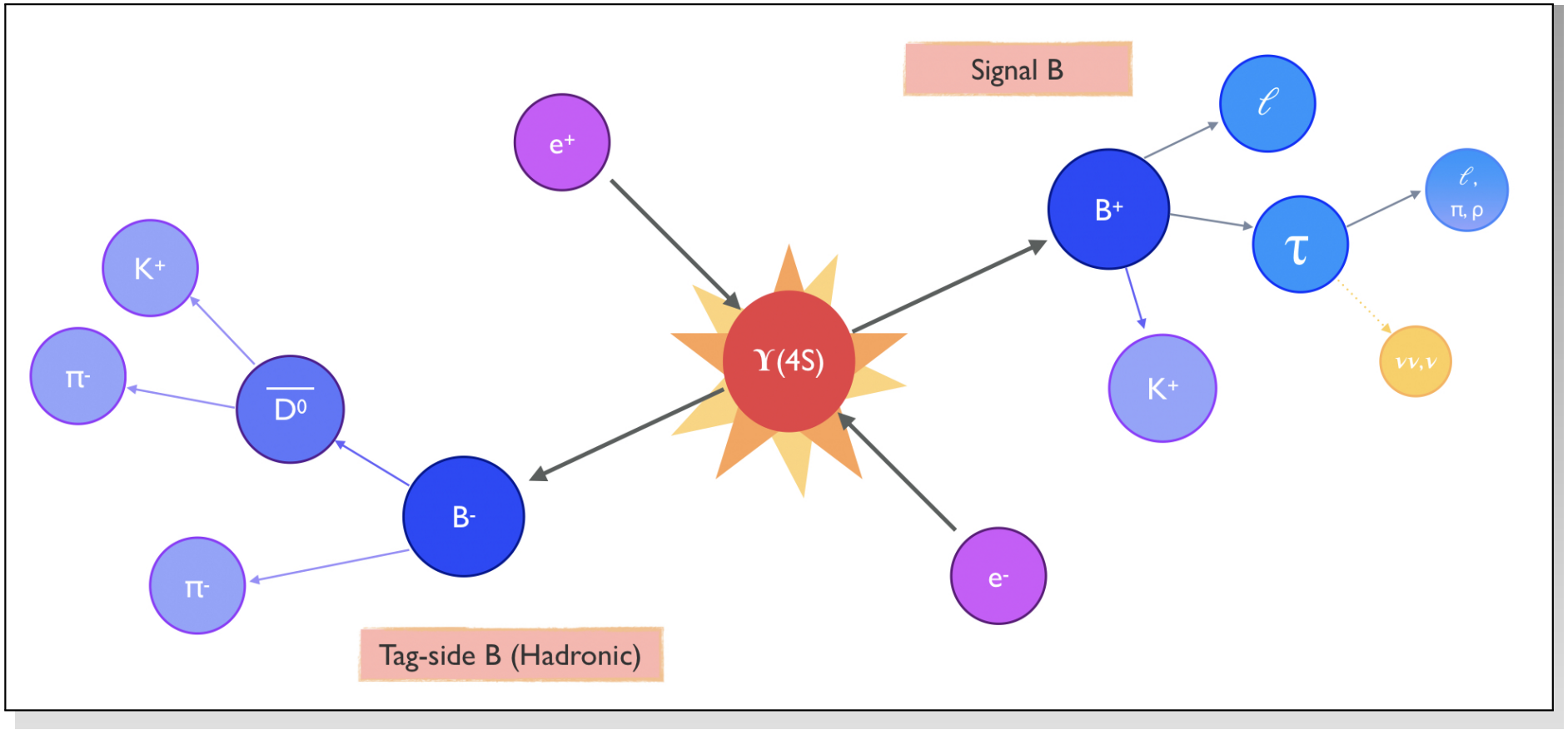


Some results from BaBar (2012)

‖. Lees, J. P. et al. Search for the decay modes $B^{\pm} \to h^{\pm}\tau\ell$. Phys. Rev. D 86, (2012).

**. LHCb collaboration. Search for the lepton flavour violating decay $B^+ \to K^+\mu^-\tau^+$ using B^{*0}_{s2} decays. JHEP 06 (2020) 129

$B \to K\tau\ell\,(\ell = e, \mu)$: Our Strategy

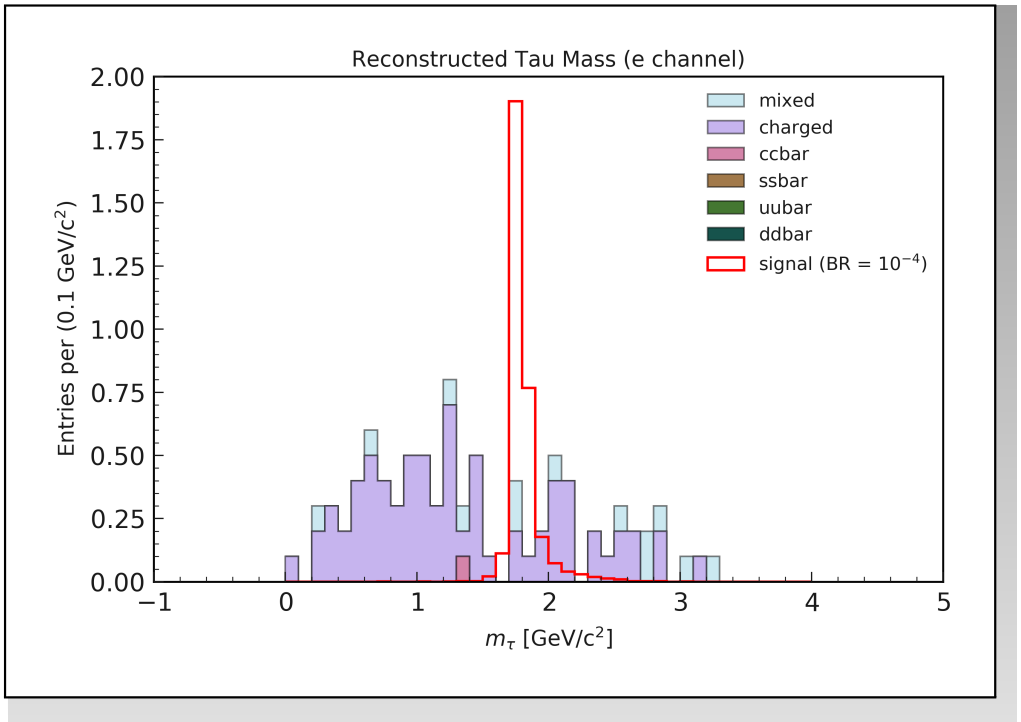


$B \to K\tau\ell\,(\ell = e, \mu)$: Our Strategy

1. Use the Full Event Interpretation (FEI)[††] algorithm to reconstruct the "tag-side" B-meson, B_{tag}
   - Utilises a neural network to train on $\mathcal{O}(10^8)$ MC events
   - Uses thousands of decay channels to reconstruct B_{tag}
2. $\vec{p}_{B_{tag}} = -\vec{p}_{B_{sig}}$
3. Combine this with the kaon and primary lepton to reconstruct the tau

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

4. The tau mass is our signal variable, which peaks sharply for signal and is relatively flat for background



Reconstructed tau mass for $B^+ \to K^+\tau^+e^-$ in the $\tau \to e\nu\nu$ channel using $2\,\text{ab}^{-1}$ of generic MC and 50 million signal MC events[‡‡], both scaled to $200\,\text{fb}^{-1}$

††. Keck, T., Abudinén, F., Bernlochner, F.U. et al. The Full Event Interpretation. Comput Softw Big Sci 3, 6 (2019).

‡‡. assuming a BR = 10^{-4}

$B \to K\tau\ell\,(\ell = e, \mu)$: Current Status

§§

- Currently focused on the mode $B^+ \to K^+\tau^+e^-$
- Working with MC samples to optimize search and reduce backgrounds such as:
  - photon conversion events
  - charmonium background
  - semi-leptonic D decays
- Possibility of running on a small dataset this summer (180-200 fb^{-1})

§§. Cover art for David Bowie's single "Where Are We Now?". Copyright Columbia or the graphic artist.

$B \to K\tau\ell\,(\ell = e, \mu)$: Summary and Outlook

- Belle II is a state-of-the-art Super B factory with a **rich physics program**
- The large **50 ab^{-1} dataset** allows us to probe for New Physics beyond the Standard Model
- $B \to K\tau\ell\,(\ell = e, \mu)$ is a prime place to look for **New Physics**
- If found, it is **direct evidence** of physics beyond the Standard Model
- If not, it can help place strict limits on new models
- Exciting decade for flavour physics - Stay tuned ! !

Thank you :)

Back-up Slides

Back-up Slides

$B^+ \to K^+\tau^+e^-$ Tau Mass Plots for $2\,\text{ab}^{-1}$ of MC