Recent results on lepton universality and flavor violation from Belle II

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Where we stand

- ~3σ anomalies in tests of Lepton Flavor Universality observed at LHCb, Belle, and BaBar.

\[
R(D^{(*)}) = \frac{B(B \rightarrow D^{(*)}\tau\nu)}{B(B \rightarrow D^{(*)}\ell\nu)} \\
R(K) = \frac{B(B \rightarrow K_{ee})}{B(B \rightarrow K_{\mu\mu})} + \text{angular observables}
\]

- What about Belle II?
Tree Level
$R(X_e/\mu)$

- Test light lepton universality in inclusive semi-leptonic B decays.

- Reconstruct companion B as a tag in $O(10\,000)$ hadronic channels via Full Event Interpretation\cite{1}.

- Select well identified lepton on signal side.

- Challenge: Keeping sample composition under control.

- $X\ell\nu$ signal yields extracted in 10 bins of $p_\ell$ in B-frame.
  - Constrain secondary lepton, fake lepton and continuum contributions from sidebands.

\cite{1}: Comput. Softw. Big Sci. 3 (2019) 1, 6
\[ R(X_{e/\mu}) \]

\[ R(X_{e/\mu}) = \frac{B(B \to Xe\nu)}{B(B \to X\mu\nu)} = \frac{\epsilon_{Xe\nu}N_{Xe\nu}}{\epsilon_{Xe\nu}N_{Xe\nu}} \]

\[ R(X_{e/\mu})^{p_\ell^* > 1.3 \text{ GeV}} = 1.033 \pm 0.010^{\text{stat.}} \pm 0.020^{\text{syst.}} \]

- Most precise LFU test with semi-leptonic B decays!
- Compatible with SM at 1.2\(\sigma\)\[1\].
- Agreement with \(R(D^*_e/\mu)\) from Belle at 0.6\(\sigma\)\[2\].

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Lepton ID</th>
<th>(X_e\ell\nu) BFs</th>
<th>(X_e\ell\nu) FFs</th>
<th>Statistical</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rel. unc. of (R(X_{e/\mu}))</td>
<td>1.8%</td>
<td>0.1%</td>
<td>0.2%</td>
<td>1.0%</td>
<td>2.2%</td>
</tr>
</tbody>
</table>

Key performance driver: LeptonID

- Control of lepton identification crucial to all LFU tests.
- Calibrated in several well understood control channels. \( \Rightarrow \) corrections are close to 1.0 and measured to \( O(0.1 - 2\%) \) for electrons and muons. ~Approaching Belle precision.

- Constantly improving our understanding.
- Expect lepton identification uncertainties to decrease!
$R(D), R(D^*), R(X)$ – Prospects

- Expect the first competitive results for $R(D)$ and $R(D^*)$ soon, precisions reaching 4% $R(D^*)$, 6% $R(D)$ with 5 ab$^{-1}$.

- Unique capability for an inclusive measurement: $R(X)$. Expect 10-20% precision with current sample (424 fb$^{-1}$).

- Last measured at LEP, no input from Belle or BaBar.

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Belle II, arXiv: 2207.06307
Electroweak Penguins
Preparing for $R(K^{(*)})$

- Search for $B \rightarrow K^{*}(892)\ell\ell$ in three modes:
  
  \[
  B^0 \rightarrow K^{*0}(K^+\pi^-)\ell\ell \\
  B^+ \rightarrow K^{*+}(K^+\pi^0, K_S^0\pi^+)\ell\ell
  \]

- Continuum and $B\bar{B}$ backgrounds vetoed via BDT on event shape, kinematics and vertex quality.

- Signal extracted in 2D unbinned fit to $M_{bc}, \Delta E$.

- Integrated measurement over $q^2$ range with vetoes around photon conversion and charmonium resonances ($J/\psi, \psi(2S)$).

- Equivalent performance in electron and muon modes.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Observed Events</th>
<th>Branching Fraction</th>
<th>PDG2020 Branching Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \rightarrow K^*ee$</td>
<td>$22 \pm 6$</td>
<td>$1.42 \pm 0.48 \pm 0.09$</td>
<td>$1.19 \pm 0.20$</td>
</tr>
<tr>
<td>$B \rightarrow K^*\mu\mu$</td>
<td>$18 \pm 6$</td>
<td>$1.19 \pm 0.31^{+0.08}_{-0.07}$</td>
<td>$1.06 \pm 0.09$</td>
</tr>
</tbody>
</table>
Preparing for $R(K^{(*)})$: $R_K(J/\psi)$

- $R_K(J/\psi) = \frac{B(B \to KJ/\psi(\to ee))}{B(B \to KJ/\psi(\to \mu\mu))}$
- Highly pure, high statistics normalisation channel for $R(K)$.
- Tree level - expected to be free from NP effects.
- $J/\psi$ known to respect LFU within 0.31%.
- Signal extracted in 2D unbinned fit to $M_{bc}, \Delta E$.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Belle II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{K^+}(J/\psi)$</td>
<td>$1.009 \pm 0.022 \pm 0.008$</td>
</tr>
<tr>
<td>$R_{K^0_S}(J/\psi)$</td>
<td>$1.042 \pm 0.042 \pm 0.008$</td>
</tr>
</tbody>
</table>

- Take lepton ID corrections from inclusive $J/\psi$ sample.

$M_{bc} = \sqrt{E_{\text{beam}}^2 - p_B^*}$

Belle II, arXiv: 2207.11275
$R(K^{(*)})$ Prospects

- Heavily limited by sample size.
- Belle II will provide competitive and independent checks of $R(K^{(*)})$ anomalies with a few ab$^{-1}$.

<table>
<thead>
<tr>
<th>Observables</th>
<th>Belle 0.71 ab$^{-1}$</th>
<th>Belle II 5 ab$^{-1}$</th>
<th>Belle II 50 ab$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_K$ ([1.0, 6.0] GeV$^2$)</td>
<td>28%</td>
<td>11%</td>
<td>3.6%</td>
</tr>
<tr>
<td>$R_K$ (&gt; 14.4 GeV$^2$)</td>
<td>30%</td>
<td>12%</td>
<td>3.6%</td>
</tr>
<tr>
<td>$R_{K^*}$ ([1.0, 6.0] GeV$^2$)</td>
<td>26%</td>
<td>10%</td>
<td>3.2%</td>
</tr>
<tr>
<td>$R_{K^*}$ (&gt; 14.4 GeV$^2$)</td>
<td>24%</td>
<td>9.2%</td>
<td>2.8%</td>
</tr>
<tr>
<td>$R_{X_s}$ ([1.0, 6.0] GeV$^2$)</td>
<td>32%</td>
<td>12%</td>
<td>4.0%</td>
</tr>
<tr>
<td>$R_{X_s}$ (&gt; 14.4 GeV$^2$)</td>
<td>28%</td>
<td>11%</td>
<td>3.4%</td>
</tr>
</tbody>
</table>

Belle II, PTEP 2019 (2019) 12, 123C01
Tau Sector
Searches for LFV in the $\tau$ sector

- SuperKEKB is not only a $B$ factory but also a $\tau$ factory.
- $\sigma(Y(4S)) = 1.05 \text{nb}$
  $\sigma(\tau\tau) = 0.92 \text{nb}$
- $\sim$1 million $\tau$ pairs per $\text{fb}^{-1}$.
- Several dedicated low multiplicity triggers at Belle II.
- Rich possibility to search for LFV effects in 52+ channels!

Region expected to be sensitive to new physics.
\( \tau \rightarrow \ell \alpha \) (invisible)

- Can enter from new physics models such as light long-lived ALP.

- Best limits \( m_\alpha \in [0.1 - 1.6] \text{GeV} \) range from ARGUS (476 pb\(^{-1}\)), no studies at Belle or BaBar.

- \( \mathcal{B}(\tau \rightarrow \ell \alpha) \propto \frac{1}{f_\alpha^2} \).
\( \tau \rightarrow \ell \alpha \) (invisible): Strategy

- Require exactly 4 tracks.
  - Signal lepton
  - 3-prong tag: \( \tau^+ \rightarrow \pi^+\pi^+\pi^-\nu \)
- Veto neutrals (\( \gamma, \pi^0 \))

- Suppress reducible background \((q\bar{q}, \ell\ell, \ell\ell\ell\ell, \ell\ell\ell h, \tau \rightarrow h\nu)\)
  via selection criteria optimised on \( \tau \rightarrow \ell\nu\bar{\nu} \) (irreducible background with same signature).

- Signal Extraction in energy of lepton in \( \tau \) pseudo rest frame:
  \( E_\tau = \sqrt{s}/2, \hat{p}_\tau = -\hat{p}_{3\pi} \)

Belle II, F. Tenchini ICHEP2022

\( \ell = e \)
$\tau^+ \rightarrow \ell^+ \alpha$ (invisible): Result

- 95% C.L. upper limit using the CLs method.
- No significant excess found in 62.8 fb$^{-1}$.
- 2.2 to 14 times better limit than ARGUS ($m_\alpha$ and $\ell$ channel dependent).

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**Belle II preliminary**

$\int L dt = 62.8$ fb$^{-1}$

$B(\tau \rightarrow e\alpha)/B(\tau \rightarrow e\bar{\nu}_e\nu_e)$ vs $M_\alpha$ [GeV/c$^2$]

$B(\tau \rightarrow \mu\alpha)/B(\tau \rightarrow \mu\bar{\nu}_\mu\nu_\mu)$ vs $M_\alpha$ [GeV/c$^2$]
Conclusion

• Recent Belle II results related to lepton flavor universality:
  • $R(X_{e/\mu})$ ⇒ Precise LFU test. First step to $R(X)$
  • $B \to K^* \ell\ell$ ⇒ Preparation for $R(K^{(*)})$
  • $B \to K J/\psi$
  • $\tau \to \ell\alpha$ ⇒ Most stringent limit.

• Our understanding of lepton identification is constantly improving ⇒ expect a decrease in the systematics associated with lepton ID.

• Belle II will provide input to $R(D^{(*)}), R(X)$ soon.

• Larger sample needed before weighing in on $R(K^{(*)})$.

• A rich possibility to search for LFV in the $\tau$ sector.
  Will push sensitivity into the region exposed to new physics as we head towards 50ab$^{-1}$. 
Backup
SuperKEKB and Belle II

- Nanobeam collision scheme.
- World record luminosity $4.65 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$
  - 2 times Belle record.
  - Aiming another order of magnitude higher.
- Nearly $4\pi$ coverage.
- Excellent charged particle identification and neutral particle reconstruction.
Data Collection

• Now in Long Shutdown 1 to replace Pixel Detector and other maintenance.

• 424 fb\(^{-1}\) collected before Long Shutdown 1.
  • 363 fb\(^{-1}\) at \(\sqrt{s} = m_{Y(4S)} = 10.58\text{GeV}\)
  • 42 fb\(^{-1}\) at 10.52GeV (off-resonance)
  • 19 fb\(^{-1}\) at 10.75GeV for exotic hadron searches

• Matches BaBar (550fb\(^{-1}\)) and challenges Belle (1ab\(^{-1}\)) due to improved reconstruction performance.