Recent Belle II results related to lepton-flavor universality and violation

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on behalf of the Belle II collaboration

The Dark Side of The Universe, Sydney
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(Prelude)
Anomalies in lepton flavour universality tests at flavour experiments
Lepton Flavour Universality in the Standard Model

- The Standard Model postulates that electroweak couplings of gauge bosons ($Z, W^\pm$) to leptons ($e, \mu, \tau$) are independent of lepton flavour → **Lepton Flavour Universality (LFU)**

\[
\begin{align*}
W^- &\quad e^- & g_e &\quad \bar{\nu}_e \\
W^- &\quad \mu^- & g_\mu &\quad \bar{\nu}_\mu \\
W^- &\quad \tau^- & g_\tau &\quad \bar{\nu}_\tau
\end{align*}
\]

- Observation of LFU violation would clearly indicate existence of physics beyond the Standard Model.
LFU anomalies in $b \rightarrow c \tau \nu$ transitions

- Semileptonic $B$ decays via $b \rightarrow c$ tree-level transition → excellent probe to test LFU for all three lepton generations.

- Branching fractions of exclusive decays to charmed mesons $B \rightarrow D^{(*)}\ell\nu$ calculated in the SM with high precision, $\mathcal{O}(0.1\%)$.

- Rate of $b \rightarrow c \tau \nu$ transitions may be enhanced wrt. $b \rightarrow c(e, \mu)\nu$ in several beyond-SM scenarios.

- Combined measurements of the ratio of branching fractions $R(D^{(*)})$, by Belle, BaBar, LHCb presently in tension with the SM at $\approx 3\sigma$.

\[ R(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)}\ell\nu)}{\mathcal{B}(B \rightarrow D^{(*)}\ell\nu)} \]

[1] https://indico.cern.ch/event/1187939/
LFU anomalies in $b \to s\ell\ell$ transitions

- Loop-induced, Cabibbo-suppressed Flavour-Changing Neutral Current decays → highly sensitive to non-SM contributions in loop.

- Recent measurement of $R(K)$ from LHCb [*] found $3.1\sigma$ tension with the SM.

- Anomalies at $\approx 2\sigma$ level also seen in angular observables (e.g. $B^0 \to K^{*0} \mu^+\mu^-$ [**]) and $R(K^*)$ [***] at LHCb.

$R(K) = \frac{\mathcal{B}(B^+ \to K^+\mu\mu)}{\mathcal{B}(B^+ \to K^+ee)}$


[**] LHCb, PRL 125 (2020) 011802

Where does Belle II stand?
The SuperKEKB $e^+e^-$ collider at KEK, Japan, and the Belle II detector

- **SuperKEKB**: asymmetric $e^+ - e^-$ collider at (and near) the $\Upsilon(4S)$ energy.

- **Belle II**: near-hermetic $4\pi$ coverage to efficiently reconstruct inclusive final states with missing energy, excellent capability of reconstructing neutral particles ($\gamma, \pi^0, K^0_S$), improved vertexing.

- Collected $\int L \, dt = 363 \text{ fb}^{-1}$ at $\Upsilon(4S)$ (BaBar: $\approx 420 \text{ fb}^{-1}$, Belle: $\approx 700 \text{ fb}^{-1}$).

\[ \beta\gamma = 0.28 \]

眼界 (7 GeV)

眼界 (4 GeV)

![World record on June 22nd 2022]

$L = 4.7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

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The Belle II detector overview

**Tracking** ($p_T$ rel. resol. $\approx 0.4\%$, $dE/dx$ for PID)

- **Time of Propagation (TOP)**
  20 mm thick quartz radiators for time of flight and Cherenkov PID

- **Vertexing** ($d_0, z_0$ resol. $\approx 15\mu m$)
  - **Pixel Vertex Detector (PXD)**
    2 layer pixel detector (8MP)
    DEPFET technology
  - **Silicon Vertex Detector (SVD)**
    4 layer double-sided strips
    20-50 ns shaping time
  - **Central Drift Chamber (CDC)**
    Proportional wire drift chamber
    15k sense wires in 56 layers

- $K/\pi$ identification (1.8$\%$ $\pi$ fake rate @ $\epsilon_K = 90\%$)

- $\mu$ identification (2-1$\%$ $\pi, K$ fake rate @ $\epsilon_\mu = 95\%$

- $K_L$ and $\mu$ system (KLM)
  RPC and Scintillator+SiPM between iron plates

- **Magnetic Field**
  1.5 T superconducting magnet

- **EM Calorimeter (ECL)**
  8k CsI Crystals, 16 $X_0$, PMT/APD readout

- $\gamma$ reconstruction ($\langle \sigma_{\pi^0} \rangle$ resolution: $\approx 6$ MeV), $e$ identification (1-0.01$\%$ $\pi, K$ fake rate @ $\epsilon_e = 95\%$

- **Aerogel RICH (ARICH)**
  Proximity focusing RICH with silica aerogel

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Current Belle II tests of lepton flavour universality:

tree-level \((b \rightarrow c\ell\nu)\)
Test LFU with inclusive semileptonic $B$ decays by measuring the ratio:

$$R(X_{e/\mu}) = \frac{\mathcal{B}(B \rightarrow Xe\nu)}{\mathcal{B}(B \rightarrow X\mu\nu)}$$

- **Tag** one $B$ (from $\Upsilon(4S) \rightarrow B\bar{B}$) in fully hadronic decays to enhance purity and constrain final-state kinematics.

- Rely mostly on precise reconstruction of the "signal side" lepton. Only minimal selection applied on the decay products of the (complex) hadronic system $X$.

Backgrounds → *continuum* $e^+e^- \rightarrow q\bar{q}$ ($q \in \{u,d,s,c\}$), hadrons faking leptons, secondary leptons from $b \rightarrow c \rightarrow (\ell, s)$ cascades.
**$R(X_{e/\mu})$ - Analysis strategy**

- Tight selection on $B_{tag}$ quality using kinematic constraints and output of Full Event Interpretation [*] BDT classifier.
- Electron 4-momentum corrected for bremsstrahlung.
  - Validated in $J/\psi \rightarrow e^+e^-$ control channel.
  - Lepton identification requirements (see next slide).
  - $p^*_\ell > 1.3$ GeV/$c^2$ (in $B_{sig}$ rest frame) $\rightarrow$ reject most $B \rightarrow X\tau\nu$, suppress fakes & secondaries.
- Continuum background suppressed via BDT based on observables describing event symmetries.

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[*] Comput.Softw.Big Sci. 3 (2019) 1, 6

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R(\(X_e/\mu\)) - Lepton identification

- Muon ID via likelihood ratio: \(\text{PID}_\mu = \frac{\mathcal{L}_\mu}{\sum_i \mathcal{L}_i} \), \(\mathcal{L}_i = \prod_d \mathcal{L}_i^d\).

- Electron ID via BDT with calorimetric shower shapes [*].

  - \(h(\pi, K) \rightarrow e\) mis-ID probability reduced by \(> \times 2\) wrt. likelihood ratio.

- Efficiencies calibrated in data with several, independent control samples. Corrections to simulation close to unity, measured to a precision of \(\mathcal{O}(0.1 - 2\%)\) for both lepton flavours.

\( R(X_{e/\mu}) \) - Signal extraction

**Belle II Preliminary**

\[
\int \mathcal{L} \, dt = 189 \, \text{fb}^{-1}
\]

**SR (correct \( \ell \) charge), pre-fit**

- \( B_{\text{sig}}^{0,+} \rightarrow X \ell^+ \nu \)
- \( B_{\text{sig}}^{0,+} \rightarrow X \ell^- \nu \)

**CR (wrong \( \ell \) charge)**

- \( B \rightarrow X \ell \nu : X = D, D^*, D^{**}, \text{non resonant hadronic decays} \)
- Continuum background normalisation constrained with 18 fb\(^{-1}\) of off-resonance data.
- Normalisation of fakes and secondaries constrained in control regions with “wrong lepton charge” \((Y(4S) \rightarrow B_{\text{tag}}^{+,0}, B_{\text{sig}} \rightarrow X \ell^+ \nu + \text{c. c.})\)

- Electron and muon channels are fitted simultaneously in 10 \( p_\ell^* \) bins each via maximum likelihood template fit, with \( B \rightarrow X \ell \nu \) yields free floating parameters.

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

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**$R(X_{e/\mu})$ - Results**

<table>
<thead>
<tr>
<th>Source</th>
<th>$R(X_{e/\mu})$ uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical</td>
<td>1.0</td>
</tr>
<tr>
<td>Lepton identification</td>
<td>1.8</td>
</tr>
<tr>
<td>$X_c\ell\nu$ branching fractions</td>
<td>0.1</td>
</tr>
<tr>
<td>$X_c\ell\nu$ form factors</td>
<td>0.2</td>
</tr>
<tr>
<td>Total</td>
<td>2.2</td>
</tr>
</tbody>
</table>

- Compatible with the Standard Model prediction [*] of $R(X_{e/\mu})_{SM} = 1.006 \pm 0.001$ within 1.2σ.

- Also consistent with Belle result [**] using $B \rightarrow D^{*}\ell\nu$ decays: $R(D^{*}_{e/\mu}) = 1.01 \pm 0.01$ (stat.) $\pm 0.03$ (sys.)

- This is the most precise LFU test with semileptonic $B$ decays to date.

\[
R(X_{e/\mu}) = 1.033 \pm 0.010 \text{ (stat.)} \pm 0.020 \text{ (sys.)}
\]

- Theory uncertainties largely cancel in ratio.

⚠ Precision limited by systematic uncertainties related to lepton ID.

[*] M. Rahimi, K. Vos, JHEP 11, 007 (2022)

[**] Phys. Rev. D 100, 052007 (2019), 711 fb⁻¹
Prospects for Belle II

- Alongside $R(D^{(*)})$, Belle II has unique capability for an *inclusive* measurement: $R(X)$.

- Complementary test of LFU w/ semileptonic $B$ decays, no published results from Belle and BaBar.

> Belle II Snowmass White Paper (2021) [Link]

- With current Belle II dataset of 363 fb$^{-1}$, the expected precision of both $R(X), R(D^{(*)})$ is of order 10-20%.

- New results for both analyses are highly anticipated.
Belle II lepton flavour violation searches with tau lepton decays
LF(U)V at Belle II with $\tau$ leptons

- SuperKEKB is (also) a $\tau$-factory! $\rightarrow \approx 10^6 e^+e^- \rightarrow \tau^+\tau^- \text{ pairs/fb}^{-1} \approx e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B} \text{ pairs/fb}^{-1}$.

- Abundance of $\tau$ lepton pairs can be exploited as a high-precision probe for both:

1) LFU tests.

2) Searches for Lepton Flavour (and/or Number) Violating processes, prohibited (or strongly suppressed) in the SM.
• Any observation of lepton flavour (or number)-violating (LFV) decays → direct evidence of beyond-SM physics.

• Many models predict LFV \( \tau \) decays with branching ratios of \( \mathcal{O}(10^{-8} - 10^{-10}) \) \([\ast]\).

• Plenty (>52) of channels accessible at Belle II through dedicated low multiplicity triggers (c.f. Chia-Ling’s talk).

\([\ast]\) S. Banerjee et al., arXiv:2203.14919v2 (2022)
LFV in $\tau$ decays

- Missing energy signatures in LFV tau decays may be explained by light bosons such as ALPs [*] ($m_a \lesssim 2$ GeV).
- Best limits on $\frac{\mathcal{B}(\tau \rightarrow \ell \alpha)}{\mathcal{B}(\tau \rightarrow \ell \nu_\ell \nu_\tau)} \left(\mathcal{B}(\tau \rightarrow \ell \alpha) \propto 1/f_a^2\right)$ set by ARGUS in 1995 (476 pb$^{-1}$).

[*] L. Calibbi et al., JHEP09 (2021) 173

Belle II current dataset can already be used to set more stringent limits.
• Search for an \textit{invisible} (pseudo)scalar light boson $\alpha$ with $m_\alpha \in (0, 1.6) \text{ GeV}/c^2$.

• Use plane orthogonal to thrust axis to divide \textit{tag} (3-prong) hemisphere and signal hemisphere.

• 2-body decay $\tau \to \ell \nu_\ell \nu_\tau$ irreducible background in $\tau_{\text{sig}}$ rest frame, depending on $m_\alpha$.

• Due to undetected neutrinos, boost to the $\tau_{\text{sig}}$ \textit{pseudo}-rest frame:

\begin{align*}
\tau_{\text{sig}} \text{ direction: } & \quad \frac{\vec{p}_{3h}}{|\vec{p}_{3h}|} \\
\tau_{\text{sig}} \text{ energy: } & \quad \approx \frac{\sqrt{s}}{2} \\
\text{(neglecting ISR)}
\end{align*}
Reducible backgrounds ($\tau \rightarrow \pi \nu$, continuum, $ee\ell\ell, eehh$) suppressed via selection optimised on $\tau \rightarrow \ell \nu \nu$ → 96% ($e$), 92% ($\mu$) purity w/ 9.1-17.9% signal efficiency ($m_\alpha$-dependent).

Normalised branching fraction of $\tau \rightarrow \ell \alpha$ extracted via maximum likelihood template fit to $x_\ell = \frac{E_\ell^*}{m_\tau c^2/2}$ (in $\tau_{\text{sig}}$ pseudo-rest frame).

Partial cancellation of lepton ID uncertainties in branching fraction ratio due to differing kinematics.
No significant signal is observed $\rightarrow$ derived 95% CL upper limits on $\frac{\mathcal{B}(\tau \to \ell \alpha)}{\mathcal{B}(\tau \to \ell \nu \bar{\nu})}$ (using CLs method).

Limits are between 2 and 14 times lower than ARGUS, depending on $m_\alpha$ and lepton flavour.

Sensitivity degraded by 35% due to systematics (mostly from lepton ID).
(Preparing for) Belle II tests of LFU:
loop-induced \((b \rightarrow s\ell\ell)\)
Prospects for Belle II

- Belle II LFU tests with rare electroweak penguins ($b \to s\ell\ell'$) will be competitive w/ LHCb with a dataset of 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>

The Belle II Physics Book, *PTEP* 2020 (2020) 2, 029201 (erratum)
Preparing for $R(K)$: $r_{J/\psi}^K$ in $B \to J/\psi K$ decays

- Measure the $r_{J/\psi}^K$ ratio for decays $B^+(B^0) \to J/\psi(\ell^+\ell^-)K^+(K_S^0)$ [+ c.c.]

$$r_{J/\psi}^K = \frac{\mathcal{B}(B^+ \to J/\psi(\to \mu\mu)K)}{\mathcal{B}(B^+ \to J/\psi(\to ee)K)} = \frac{N_{J/\psi(\mu\mu)K}}{N_{J/\psi(ee)K}} \cdot \frac{\epsilon_{J/\psi(ee)K}}{\epsilon_{J/\psi(\mu\mu)K}}$$

Belle II arXiv: 2207.11275, 189 fb$^{-1}$

- Fully resolved final state(s), very pure selection (90-95%) via mass cuts on intermediate resonances ($J/\psi, K_S^0$) and PID criteria on leptons and charged kaons.

- Branching fractions and $r_{J/\psi}^K$ extracted from 2D unbinned ML fit to $\Delta E, M_{bc}$ distributions.

$$M_{bc} = \sqrt{(s/2)^2 - |\vec{p}_B|^2}$$

$$\Delta E = E_{B^*} - \sqrt{s}/2$$

In agreement w/ Belle [*] and w/ the SM.

- Uncertainties due to lepton ID reduced wrt. Belle by a factor $\sim 2$. 

<table>
<thead>
<tr>
<th></th>
<th>Belle II (2022)</th>
<th>Belle (2021)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_{J/\psi}^{K^+}$</td>
<td>$1.009 \pm 0.022$ (stat.)$\pm 0.008$ (sys.)</td>
<td>$0.994 \pm 0.011$ (stat.)$\pm 0.010$ (sys.)</td>
</tr>
<tr>
<td>$r_{J/\psi}^{K_S^0}$</td>
<td>$1.042 \pm 0.042$ (stat.)$\pm 0.008$ (sys.)</td>
<td>$0.993 \pm 0.015$ (stat.)$\pm 0.010$ (sys.)</td>
</tr>
</tbody>
</table>

[*] Belle, JHEP 03 (2021) 105, 711 fb$^{-1}$
Preparing for $R(K^*)$: rediscovery of $B \rightarrow K^*(892)\ell^+\ell^-$

- Measure the branching fraction of $B \rightarrow K^*(892)\ell^+\ell^-$ in three $K^*$ decay modes: 1) $K^{*0} \rightarrow K^+\pi^-$, 2) $K^{*+} \rightarrow K_S^0\pi^+$, 3) $K^{*+} \rightarrow K^+\pi^0$ [ + c.c.]

- Dilepton mass ($q^2$) window vetoes to reject $J/\psi, \psi(2S)$ charmonium resonances and $\gamma$ conversions.

- Use BDT based on event shape, kinematics and vertexing to reject continuum and $B\bar{B}$ backgrounds → 98% bkg. rej. @ 65-70% sig. eff.

- 2D unbinned ML fit to $\Delta E, M_{bc}$ distributions.

- Results compatible w/ world averages (PDG):

$$\mathcal{B}(B \rightarrow K^*\mu^+\mu^-) = (1.19 \pm 0.31^{+0.08}_{-0.07}) \times 10^{-6},$$

$$\mathcal{B}(B \rightarrow K^*\ell^+\ell^-) = (1.42 \pm 0.48 \pm 0.09) \times 10^{-6},$$

$$\mathcal{B}(B \rightarrow K^*\ell^+\ell^-) = (1.25 \pm 0.30^{+0.08}_{-0.07}) \times 10^{-6}.$$
Summary and conclusions
Recent, world-leading results of Belle II were showcased:

- Most precise LFU test with inclusive semileptonic $B$ decays ($R(X_{e/\mu})$).

- Most stringent upper limits on invisible scalar boson production in LFV $\tau \to \ell \alpha$ decays.

Exciting new results for LF(U)V ahead for Belle II, with both:

- Increased dataset size (critical for $b \to s\ell\ell$).

- Ongoing improvements in experimental techniques for lepton identification to reduce systematic uncertainties.
Backup material
$R(X)$ at LEP and theoretical expectations

\[ \langle \mathcal{B} \rangle = (2.41 \pm 0.23)\% , \text{ quoted as the average rate of an admixture of } b\text{-flavoured hadrons to decay semileptonically to } X\tau \]

\[ \mathcal{B}(B \to X_c \tau \nu)_{SM} = (2.45 \pm 0.10)\% \]

\[ R(X_c)_{SM} = 0.223 \pm 0.004 \]

Marco Milesi, DSU2022
Beam-energy constrained variables @ $B$-factories

\[ M_{bc} = \sqrt{\left(\sqrt{s}/2\right)^2 - |\vec{p}_{B^*}|^2} \]

\[ \Delta E = E_{B^*} - \sqrt{s}/2 \]

Fig. 42: $\Delta E$ and $M_{bc}$ distributions for $B^+ \rightarrow [D^0 \rightarrow K^-\pi^+(\pi^0)]\pi^+$ simulated events in Belle II (blue) and comparison with Belle (black). The red curve shows the distribution for continuum background. Beam background is included in the simulation.

The Belle II Physics Book, PTEP 2020 (2020) 2, 029201 (erratum)