Feasibility of $R(X)$ at Belle II

Searching for lepton universality violation in inclusive semileptonic $B$ decays

Peter Lewis | University of Bonn
KEK-FF | 10 Feb 2023
This talk contains public material from PhD/Masters theses

These results are *unpublished* and *unapproved* and should *not* be considered official collaboration results

Only plots with the “Belle II” label are Belle II plots!
An intriguing claim…

The **strongest** test of \(\tau/\ell\) universality will come from the *inclusive* measurement:

\[
\mathcal{R}(X) = \frac{\mathcal{B}(B \rightarrow X\tau\nu)}{\mathcal{B}(B \rightarrow X\ell\nu)}
\]

This has **never**\(^\star\) been measured. Why? What makes us think that we can?

\(^\star\)(there are two near-exceptions)
First: why $R(X)$?

Fully inclusive $B$ decays:

- $\sim 2/3$ overlap with $D$ and $D^*$
- $\sim 1/3$ contribution from $D^{**}$ and nonresonant $X_c$

Fully inclusive $D$ decays:

- $\sim 1/4$ overlap with typical list of exclusive $D$ modes
- The rest: *ugly stuff!* $\nu, K_L^0, N\pi^0$…

$R(X)$ is critical **cross-check** of $R(D^{(*)})$ and a partially **complementary** test of LU
Multiple LEP experiments measured

\[ R(X) = \frac{\mathcal{B}(b' \to X\tau\nu)}{\mathcal{B}(b' \to X\ell\nu)} \]

From which \( R(X) \) can be inferred

A puzzle: their measurements of \( \mathcal{B}(b' \to X\tau\nu) \) are completely saturated by current \( D/D^* \) BFs

An update is urgently needed
A recent, intriguing analysis at Belle…

…was not published. Why?

Jan Hasenbusch PhD thesis
U. Bonn, 2017
Here’s how this analysis works…

**Tag-side $B$ meson**
- Fully reconstructed (hadronic FEI)
- Tight tag quality selections

**Signal lepton:**
- High electron or muon likelihood

**X system:**
- Everything else in the event…
- (passing quality criteria)
How can we identify $X_{\tau\nu}$?

- $p_l$: lepton momentum distribution (insufficient by itself)
How can we identify $X_{\tau\nu}$?

- $p_{l_i}$: lepton momentum distribution
- $m_{miss}^2$: missing mass (adds information but is also insufficient)
How can we identify $X\tau\nu$?

- $p_i$: lepton momentum distribution
- $m_{\text{miss}}^2$: missing mass
- $M_X$: invariant mass of “X” (adds some orthogonal information)

So, just use a 3D fit?
It’s not that simple… inclusive *modeling* is **hard**

What modeling do we depend on?

- **All** $B \to X\ell\nu$ decays
- (all other $B$ decays)
- **All** $X$ decays
- All continuum processes
- All detector effects (acceptance, efficiency, backgrounds, etc…)

What could be the culprit?

![Data/MC agreement in sideband](image-url)
**Conclusions**  The discrepancy between data and MC at $m_{\text{miss}}^2 < 0$ GeV has a complex origin.

Extensive work to understand mismodeling

Important insights:

- Detector effects are far too small
- Beam backgrounds are far too small
- The culprit appears to be somewhere in the *physics simulation*

Ultimately **not approved** because solution couldn’t be found…
Belle II approach:

1. First learn **everything we can** about $X$
   a. What’s **in** there?
   b. What determines the **shape**?
   c. What’s **modeled** well/poorly?
2. Only then do we attempt extraction

Let’s talk about $X$…

X: what's in there?

Poorly measured, poorly described

Almost all of this includes **exactly one** $D$ decay…

Well-known exclusive modes
X: what’s in there?

**D → ? (overlapping contributions):**

<table>
<thead>
<tr>
<th>Neutrinos</th>
<th>$D^0$</th>
<th>$D^{+/-}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+$ anything</td>
<td>$(6.49 \pm 0.11)%$</td>
<td>$(16.07 \pm 0.30)%$</td>
</tr>
<tr>
<td>$\mu^+$ anything</td>
<td>$(6.8 \pm 0.6)%$</td>
<td>$(17.6 \pm 3.2)%$</td>
</tr>
<tr>
<td>$K^-$ anything</td>
<td>$(54.7 \pm 2.8)%$</td>
<td>$(25.7 \pm 1.4)%$</td>
</tr>
<tr>
<td>$\bar{K}^0$ anything + $K^0$ anything</td>
<td>$(47 \pm 4)%$</td>
<td>$(61 \pm 5)%$</td>
</tr>
<tr>
<td>$K^+$ anything</td>
<td>$(3.4 \pm 0.4)%$</td>
<td>$(5.9 \pm 0.8)%$</td>
</tr>
</tbody>
</table>

A large fraction of the time the $D$ cannot be fully reconstructed.
What \( M_X \) (invariant mass) \textit{would} look like if we made no \textbf{reconstruction errors in the} \( X \) (except \textit{neutrinos})

What it \textit{really} looks like (in MC)…

… how does this shape arise?
$M_x$ shape describes the **underlying physics**... smeared out by (relatively well-modeled) **detector effects**

Minimum $X_c$ mass ($m_D, m_{D^*}$);

~2/3 of events
Reconstruction errors

Contributions to $M_X$ misreconstruction by error type

![Graph showing contributions to $M_X$ misreconstruction by error type.](image)

- Mostly $K_L^0/\nu$
- Mostly $\gamma$

Note: one event can have several of these errors at once

Mostly *missing* and *extra*, which are largely irreducible
Utilizing shape of $M_X$

The $M_X$ shape is sensitive to the types of modeling that are hardest to do right:

- Inclusive $K_L^0$ BF
- $D^{**}$ and nonres. BF
- Modeling of high-multiplicity $D$ decays

**Implication:** $M_X$ gives us a handle on all of the physics modeling that impacts $m_{\text{miss}}^2 + \ldots$
Why not just fix the modeling instead?

Conclusions from extensive work by current team:

- **Branching fractions** are a big piece of the puzzle (particularly $D \to K^0_L X$) but cannot solve it entirely
- The **phase-space modeling** using in ~40% of $D$ decays is significant/unfixable
- The PDG inclusive and exclusive BFs cannot be reconciled

Fixing this at generator level is not feasible; instead, use $M_x$ to **reweight** our MC…

<table>
<thead>
<tr>
<th>Decay</th>
<th>PDG $D^0$ BF / %</th>
<th>PDG $D^+$ BF / %</th>
<th>MC $D^0$ BF / %</th>
<th>MC $D^+$ BF / %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^-$</td>
<td>54.7 ± 2.8</td>
<td>25.7 ± 1.4</td>
<td>56.1</td>
<td>30.5</td>
</tr>
<tr>
<td>$K^0/\bar{K}^0$</td>
<td>47 ± 4</td>
<td>61 ± 5</td>
<td>40.0</td>
<td>57.5</td>
</tr>
<tr>
<td>$K^+$</td>
<td>3.4 ± 0.4</td>
<td>5.9 ± 0.8</td>
<td>3.7</td>
<td>7.0</td>
</tr>
<tr>
<td>$K^*-$</td>
<td>15 ± 9</td>
<td>6 ± 5</td>
<td>12.7</td>
<td>4.6</td>
</tr>
<tr>
<td>$K^{*0}$</td>
<td>9 ± 4</td>
<td>23 ± 5</td>
<td>9.1</td>
<td>19.3</td>
</tr>
<tr>
<td>$K^{*+}$</td>
<td>2.8 ± 1.3</td>
<td>&lt; 6.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Henrik Junkerkalefeld
Why is $M_X$ so nice for this?

It controls the **part** of the reconstruction that we know the least about …

Very reliable

Does it work?
Event weights from data/MC ratio in $M_X$ (high-$p_T$ sideband) 

**Applied** to all events 

Mismodeling is **magically** “healed” in all other variables!

Henrik Junkerkalefeld
A path forward

- $M_X$ reweighting unlocks $R(X)$ at Belle II…
- …but a huge amount remains to be learned about inclusive modeling of the $D$ decays

Look for $R(X)$ in La Thuile!