Recent results in $B$-physics

Peter Mandeville Lewis | The University of Hawaii at Manoa
DPF-Pheno 2024 | Pittsburgh
Why $b$-physics?

Rich flavor dynamics

- **CKM** close to *unit matrix*: loops, boxes, large CP asymmetries, flavor oscillations are visible
- Straightforward NP enhancements to heavy $b$ vertex could be competitive to small SM contributions

Theoretically tractable

- **Hadronic component** is (usually) *factorizable* from weak component
- Heavy quark methods useful, with $\Lambda_{\text{QCD}}/m_b \sim 0.1$

*A powerful and clean window to NP...*
Why $b$-physics?

Rich flavor dynamics

- **CKM** close to unit matrix: loops, boxes, large CP asymmetries, flavor oscillations are visible
- Straightforward NP enhancements to heavy $b$ vertex could be competitive to small SM contributions

Theoretically tractable

- **Hadronic component** is (usually) factorizable from weak component
- Heavy quark methods useful, with $\Lambda_{\text{QCD}}/m_b \sim 0.1$

*A powerful and clean window to NP...*
**Hot topic: Lepton Universality**

*LU:* no lepton flavor preference in nature

Evidence of violation (LUV) in semileptonic decays:

\[
R(H_{\tau/\ell}) = \frac{\mathcal{B}(B \to H_{\tau}\nu)}{\mathcal{B}(B \to H_{\ell}\nu)}
\]

\[
H = D, D^*, X, \pi, \ldots
\]

\[
\ell = e, \mu
\]

(interesting hints in *angular observables* too!)

Longstanding \( \sim 3\sigma \) tension with SM from BaBar, Belle, LHCb, Belle II… *a sign of NP?*
Hot topic: flavor-changing neutral currents

No tree-level SM process

- $b \to s \ell^+ \ell^-$: experimentally clean, theoretically more challenging (factorization breaks down due to photon exchange)
- $b \to s \nu \nu$: theoretically clean (no photon exchange), experimentally challenging (two missing neutrinos)

Signs of tension with SM:

- Branching fractions and **angular observables**
- $R_K$ and $R_{K^*}$ ratios (*gone now? Thanks LHCb!*)

$$R_{K^*} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

Lingering (and consistent) signs of NP here too!
How?

\textbf{\textit{B}}-factories (\textit{BaBar}, Belle, Belle II)

- $e^+e^-$ colliders on $\gamma(4S)$ resonance ($\rightarrow B\bar{B}$)
- \textbf{Low cross-section} $\rightarrow$ high luminosity
- Full kinematics known
- \textbf{Spherical} events
- Exactly one collision per trigger

\textbf{Hadron colliders (LHCb, ATLAS, CMS…)}

- Parton collisions produce $b\bar{b}$ pairs
- Hadronize into all sorts of $b$ mesons \textit{and} baryons
- High cross-section
- Full kinematics not known
- Production preferentially \textbf{along beam

\textit{Introduction}
How?

\( B \)-factories (BaBar, Belle, Belle II)
- \( e^+e^- \) colliders on \( \gamma(4S) \) resonance (\( \rightarrow B\bar{B} \))
- Low cross-section \( \rightarrow \) high luminosity
- Full kinematics known
- Spherical events
- Exactly one collision per trigger

Hadron colliders (LHCb, ATLAS, CMS…)
- Parton collisions produce \( b\bar{b} \) pairs
- Hadronize into all sorts of \( b \) mesons and baryons
- High cross-section
- Full kinematics not known
- Production preferentially along beam

\( \sim25\% \) of \( bb \) pairs are in LHCb acceptance
Belle II

- Nearly hermetic detector
- Modest boost; $B$ mesons fly $\sim 100$ µm
- Ideal for **neutral** or **invisible** final states
- World-record luminosity before *Long Shutdown 1*, which has just ended
- Current results use $\leq 362$ fb$^{-1}$ at $\Upsilon(4S)$: similar to BaBar and Belle already, but $< 1\%$ of target
LHCb

- Single-arm forward spectrometer
- Large boost; $B$ mesons fly $\sim 1$ cm (easily resolvable)
- Excels at **charged particle** final states, notably **muons**
Recent results: Lepton Universality
Belle II: $R(X_{\tau/\ell})$

First measurement of $R(X_{\tau/\ell})$ as an inclusive test of the $b \to c\tau\nu$ anomaly

(Accepted by PRL, April 2024)
The $b\to c\tau\nu$ excess

Q: What if the “anomaly” is just a shared systematic?

Or a problem with the (shared) theory description?

Is there anything we can do except measure $R(D)$ and $R(D^*)$ over and over again?

Consider...
Composition of $B \rightarrow X\ell\nu$ events

(not well-known, not clean, missing $\nu$, $K_L^0$ ...)

Used $B \rightarrow D\ell\nu$

Well-known, clean decays (mostly $K^{\pm}, \pi^{\pm}$)

No missing particles

Used $B \rightarrow D^*\ell\nu$

So then: how can we use “not well-known” as the signal?
General strategy

Use a **data-driven corrections** for the “not well-known” stuff...

**Tag-side B meson**
- Fully reconstructed
- Tight tag quality selections

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

**X system:**
- Everything else in the event...
- (passing quality criteria)
Data-driven corrections

The *invariant mass of the X system* controls the **physics** we know the least about.

\[
M_X^2 = \left( \frac{E_X}{p_X} \right)^2
\]

\[
M_{\text{miss}}^2 = \left[ \left( \frac{E_{\text{CMS}}}{p_{\text{CMS}}} \right) - \left( \frac{E_{\text{CMS}}/2}{-p_{\text{Btag}}} \right) - \left( \frac{E_\ell}{p_\ell} \right) - \left( \frac{E_X}{p_X} \right) \right]^2
\]

\[
q^2 = \left[ \left( \frac{E_{\text{CMS}}/2}{-p_{\text{Btag}}} \right) - \left( \frac{E_X}{p_X} \right) \right]^2
\]

*Using* \(M_X\) *to reweight the signal* **fixes** the observed mismodeling.
Belle II: \( R(X_{\tau/\ell}) \) results

From 2D fit to lepton momentum and \( M_{\text{miss}}^2 \)

Constraints **inferred** on \( R(D(*)) \) are weak, *but*:

- **Statistics dominant**, with **<0.4% of the target**
  **Belle II dataset**
  - (even the systematics are statistics-dominant*)

- **Independent** of \( R(D(*)) \) measurement: \( \sim 0.4\% \) statistical overlap, different theory descriptions, different observable

*Take-home*: Belle II has developed a powerful and independent new test of the \( b \to c \tau \nu \) anomalies driven by **new inclusive techniques**

\[
R(X_{\tau/\ell}) = 0.228 \pm 0.016 \text{ (stat)} \pm 0.036 \text{ (syst)}
\]

SM: 0.223 ± 0.005
LHCb: New $R(D^+)$ and $R(D^{*+})$
LHCb: New $R(D^+)$ and $R(D^{*+})$

*Main goal:* measure isospin-related $R(D^+)$ to complement $R(D^0)$ [LHCb 2023*]

Simultaneous measurement shares visible final state: $[D^+ \rightarrow K^+ \pi^+ \pi^+] + \mu^-$

Control of many classes of backgrounds essential...
Signal extraction

3D binned fit:

- **Variables**: $m_{\text{miss}}^2, E_\text{l}^*, q^2$
- **Components**:
  - Signal ($D$ and $D^*$)
  - Normalization ($D$ and $D^*$)
  - Feed-down from 1P $D^{**}$ states
  - Muon mis-ID
  - (other charm, neutronic, combinatorial background)
- **Simultaneous fit to four data samples**:
  - **Signal sample** ($D^+\mu^-$)
  - 1p sample ($D^+\mu^-\pi^-$)
  - 2p sample ($D^+\mu^-\pi^+\pi^-$)
  - 1K sample ($D^+\mu^-K^\pm$)
Two new and promising methods* for simulation and reweighting used

Summary

- Compatible with SM at $0.78\sigma$
- Compatible with previous world average at $1.09\sigma$
- Uncertainties from stats and systematics approximately equal
  - (Dominant systematics remain FFs and BFs)

Take-home: new $R(D)$ channel, with new methods, unlocked at LHCb
Recent results: FCNCs
Belle II: $B^+ \rightarrow K^+ \nu \bar{\nu}$

Evidence for $B^+ \rightarrow K^+ \nu \bar{\nu}$ decays

(Accepted by PRD, Feb 2024)
Belle II: $B^+ \rightarrow K^+ \nu \nu$

Two approaches run in parallel:

- **Inclusive tag (ITA):** no reconstruction of second $B$. High efficiency, high backgrounds.
- **Hadronic tag (HTA):** strict reconstruction of second $B$. Low efficiency, low backgrounds.

This is something only Belle II can do...
**Belle II: \(K^{\nu\nu}\)**

\[ B^+ \to K^+\nu\nu \] signal extraction

**Variables**

- \(\eta\): a signal classifier* remapped so that signal is **flat**
- \(q^2_{\text{rec}}\): inferred neutrino mass squared

**ITA:**

- Simultaneous on-/off-resonance fit
- \((4 \text{ bins in } \eta)\times(3 \text{ bins in } q^2_{\text{rec}})\)

**HTA:**

- Fit to six bins of signal classifier \(\eta(BDTh)\)

*(the key is extensive controls/validations)*
Belle II: $K_{\nu\nu}$

$B^+ \rightarrow K^+\nu\bar{\nu}$: results

Combined ITA and HTA:

- Signal strength ($\mu_{\text{SM, short-range}} = 1$):
  \[\mu = 4.6 \pm 1.0\text{(stat)} \pm 0.9\text{(syst)} = 4.6 \pm 1.3\]

- Branching fraction:
  \[2.3 \pm 0.5\text{(stat)}^{+0.5}_{-0.4}\text{(syst)} \times 10^{-5} = (2.3 \pm 0.7) \times 10^{-5}\]

ITA and HTA results are compatible, independent, and both approximately equally limited by stats and systematics

Take-home: first evidence for $K^+\nu\bar{\nu}$ (3.5$\sigma$), BF in excess of SM by 2.7 $\sigma$; enabled by new inclusive techniques
LHCb: \( B^0 \rightarrow K^{*0} \mu^+ \mu^- \)

LHCb-PAPER-2024-011 (LHC EFT slides)

Complementary followup to

PHYSICAL REVIEW D 109, 052009 (2024)

Determination of short- and long-distance contributions in \( B^0 \rightarrow K^{*0} \mu^+ \mu^- \) decays

R. Aaij et al.*
(LHCb Collaboration)
LHCb: $B^0 \rightarrow K^{*0}\mu^+\mu^-$

**Context:**
- Longstanding **tensions** in angular analyses of $b \rightarrow s\mu^+\mu^-$
- Tensions in $P_5'$ (coefficient in angular decay rate*) can be related to tensions in the $C_9$ Wilson Coefficient in EFT

But is this NP or **non-local QCD**?

Can’t ignore the resonances; interference could be far from poles
Analysis concept

Signal description:

- Signal amplitudes parameterized with local and non-local contributions using a dispersion relation (effective $C_9$)

Fit:

- 4D unbinned fit (three helicity angles* + full $q^2$)
- Determines 150 parameters:
  - Wilson coefficients
  - Magnitude and phase on 1-particle contributions
  - 2-particle contribution
  - Form factors
  - Everything...
Results

Wilson coefficients from fit:

- Global tension with SM at $1.5\sigma$
- Mostly driven by $2.1\sigma$ tension in $C_9$ (again)
- First result including the whole $q^2$ range
  - (equivalent to $\ell\ell$ invariant mass)
- The data prefer more non-local contributions than in SM
  - (but not enough to explain the tension)
  - Consistent with PRD 109, 052009

Take-home: A tension in $C_9$ persists, and it isn’t due to long-range QCD effects
Conclusions

Progress in LUV and $b \rightarrow c \tau \nu$ anomalies:

- First inclusive $R(X)$, at Belle II
- First $R(D^*)$ at LHCb
- Plus more, not featured today!
- Tension remains at $\sim 3\sigma$

Progress in FCNCs:

- Intriguing hints of NP in Belle II-only $B \rightarrow K \nu \nu$
- Tension in angular analysis of $b \rightarrow s \ell \ell$ persists and isn’t explainable by long-range QCD

This is a tiny fraction of what Belle II and LHCb are up to, not to mention ATLAS and CMS B-physics programs

Look for an explosion of new results in the next several years!
Thank you!
R(X) reweighting

Reweight $X\ell\nu$ based on $M_X$, backgrounds based on $(p_\ell, M_X)$

Preference for more $K^0_L$?

Mismodeling is fixed in all other variables!
### Belle II: $R(X)$ uncertainties

$R(X_{\tau/\ell})$ uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty [%]</th>
<th>$\epsilon$</th>
<th>$\mu$</th>
<th>$\ell$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental sample size</td>
<td></td>
<td>8.8</td>
<td>12.0</td>
<td>7.1</td>
</tr>
<tr>
<td>Simulation sample size</td>
<td></td>
<td>6.7</td>
<td>10.6</td>
<td>5.7</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td></td>
<td>2.9</td>
<td>3.3</td>
<td>3.0</td>
</tr>
<tr>
<td>Lepton identification</td>
<td></td>
<td>2.8</td>
<td>5.2</td>
<td>2.4</td>
</tr>
<tr>
<td>$X_{c\ell}\nu$ $M_X$ shape</td>
<td></td>
<td>7.3</td>
<td>6.8</td>
<td>7.1</td>
</tr>
<tr>
<td>Background ($p_t, M_X$) shape</td>
<td></td>
<td>5.8</td>
<td>11.5</td>
<td>5.7</td>
</tr>
<tr>
<td>$X\ell\nu$ branching fractions</td>
<td></td>
<td>7.0</td>
<td>10.0</td>
<td>7.7</td>
</tr>
<tr>
<td>$X\tau\nu$ branching fractions</td>
<td></td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>$X_{c\tau}(\ell)\nu$ form factors</td>
<td></td>
<td>7.4</td>
<td>8.9</td>
<td>7.8</td>
</tr>
</tbody>
</table>

**Total**                                    |                  | 18.1       | 25.6  | 17.3   |

Uncertainties that will likely scale as statistical uncertainties with luminosity.
LHCb: New $R(D^+)$ and $R(D^{*+})$

Context: **2023 result** from LHCb for $R(D^0)$ and $R(D^{*0,+})$

- Run 1 (3.0 fb$^{-1}$)
- First simultaneous measurement of $R(D^*)$ and $R(D^0)$ at a hadron collider
- Muonic tau decay (high BF, high backgrounds)

**Complementary measurement with charged $D^+$ now needed...**
**Belle II: $K\nu\nu$**

$B^+ \rightarrow K^+\nu\nu$ analysis

**Background suppression**

- **ITA**: Two consecutive Boosted Decision Trees (BDTs)
  - BDT$_1$: basic filter; kinematics, **event shapes**
  - BDT$_2$: trained on events with BDT$_1$ > 0.9
  - Validated with **embedding procedure** using $B^+ \rightarrow K^+ J/\psi$:
    - "Delete" muons from $J/\psi$ decay
    - Replace $K^+$ with simulated signal $K^+$
- **HTA**: Single BDT (BDTh)
Two new methods

Form Factor variations: **HAMMER**

- Efficient reweighting of MC for FF variations and NP scenarios
- Developed by Belle II collaborators with theorists; **first use** in this analysis

Tracker-only **ultra-fast simulation**

- “Turn off” all but tracker in simulation → faster simulations → reduced uncertainty from MC stats
- Effects of missing detectors emulated in analysis
- Multi-dimensional reweightings and QED corrections
- Excellent agreement achieved
LHCb: $B^0 \rightarrow K^{*0}\mu^+\mu^-$

$b\rightarrow s\ell\ell$ angular distributions

$$\frac{1}{d\Gamma/dq^2 dq^2 d\cos \theta \, d\cos \theta_K \, d\varphi} = \frac{9}{8\pi} \left\{ \frac{2}{3} \left[ (F_S + A_S \cos \theta_K) (1 - \cos^2 \theta) \right. \right.$$

$$\left. + A_S^3 \sqrt{1 - \cos^2 \theta_K} \sqrt{1 - \cos^2 \theta} \cos \varphi \right]$$

$$+ (1 - F_S) \left\{ 2 F_L \cos^2 \theta_K (1 - \cos^2 \theta) \right. \right.$$

$$\left. + \frac{1}{2} (1 - F_L) (1 - \cos^2 \theta_K) (1 + \cos^2 \theta) \right\}$$

$$\frac{1}{2} P_1 (1 - F_L)(1 - \cos^2 \theta_K)(1 - \cos^2 \theta) \cos 2\varphi$$

$$+ 2 P_5^* \cos \theta_K \sqrt{F_L (1 - F_L)} \sqrt{1 - \cos^2 \theta_K} \sqrt{1 - \cos^2 \theta} \cos \varphi \left\} \right\}$$