Semileptonic and rare heavy flavour decays at LHCb

PIC 2019, Taipei

Mark Smith on behalf of the LHCb collaboration

September 2019
Data collected:

- Run 1: 3 fb$^{-1}$ at 7–8 TeV
- Run 2: 6 fb$^{-1}$ at 13 TeV

$\sigma(pp \rightarrow B^\pm X)$: JHEP 12, 026 (2017)

- 7 TeV: $43.0 \pm 0.2 \pm 2.5 \pm 1.7 \mu$b.
- 13 TeV: $86.6 \pm 0.5 \pm 5.4 \pm 3.4 \mu$b.
Semileptonic decays

- Copious
- Theoretically ‘clean’ - FFs
- Access to CKM elements
- Experimentally difficult - neutrinos

\[ W^{-} \rightarrow l^{-} \bar{\nu}_{l} \]

\[ b \rightarrow c \]

LHCb:
Semileptonic decays

\[ R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu\tau)}{\mathcal{B}(B \to D^{(*)}\mu\nu\mu)} \]

BaBar:
PRL 109, 101802 (2012)
PRD 88, 072012 (2013)

Belle:
PRD 92, 072014 (2015)
PRL 118, 211801 (2017)
PRD 97, 012004 (2018)

LHCb:
PRL 120, 171802 (2018)
PRD 97, 072013 (2018)
PRL 115, 111803 (2015)

Uncertainty from \( B \to D^{**}l^+\nu_l \)
$B \rightarrow D^0 \mu^- \nu_\mu X$ branching fractions

Run 1 dataset - 3 fb$^{-1}$ at 7–8 TeV:

Take $B^-$ from $\bar{B}_{s2}^* \rightarrow B^- K^+$ and constrain $B^-$ kinematics.

Fit $m^2_{\text{miss}}$ for $B^- \rightarrow D^0 \mu^- \bar{\nu}_\mu X$ components.

BFs of $B^- \rightarrow D^0 \mu^- \bar{\nu}_\mu$, $B^- \rightarrow D^{*0} \mu^- \nu_\mu$, $B^- \rightarrow D^{**0} \mu^- \nu_\mu$:

$$f_{D^0} = \frac{\mathcal{B}(B^- \rightarrow D^0 \mu^- \bar{\nu}_\mu)}{\mathcal{B}(B^- \rightarrow D^0 \mu^- \bar{\nu}_\mu X)}$$

$$f_{D^{*0}} = \frac{\mathcal{B}(B^- \rightarrow D^{*0} \mu^- \nu_\mu)}{\mathcal{B}(B^- \rightarrow D^{*0} \mu^- \nu_\mu X)}$$

$$f_{D^{**0}} = \frac{\mathcal{B}(B^- \rightarrow D^{**0} \mu^- \nu_\mu)}{\mathcal{B}(B^- \rightarrow D^{**0} \mu^- \nu_\mu X)}$$

$$f_{D^0} = 0.25 \pm 0.06$$

$$f_{D^{*0}} = 0.21 \pm 0.07$$

$$f_{D^{**0}} = 1 - f_{D^0} - f_{D^{*0}}$$
More $R(X)$

All hadron species at LHCb!

Consider $B_c$ decays in Run 1:

- Take $\tau^+ \rightarrow \mu^+ \nu_\tau \nu_\mu$ (17.4%)
- 3D template fit to kinematic variables

$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)} = 0.71 \pm 0.17 \pm 0.18$$

Major systematics:

- Simulation stats: Reducible
- $B_c \rightarrow J/\psi$ FF: Reducible with lattice - see here

Compatible with SM expectations at $\sim 2\sigma$
FCNC are rare processes
Good place to look for NP!

Some deviations from the SM observed in $b \to s l^- l^-$:

- $B \to K^* \mu^+ \mu^-$ angular analysis
  JHEP 1602, 104 (2016)
- $d\mathcal{B}(B_s^0 \to \phi \mu^+ \mu^-)/dq^2$
  JHEP 09, 179 (2015)
- $d\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)/dq^2$
  JHEP 06, 133 (2014)

A question of hadronic uncertainties?
Test of lepton universality - theoretically clean.

\[ R(K^{(*)}) = \frac{\int_{q_{\text{min}}^2}^{q_{\text{max}}^2} d\Gamma[B \rightarrow K^{(*)} \mu^+ \mu^-]}{\int_{q_{\text{min}}^2}^{q_{\text{max}}^2} d\Gamma[B \rightarrow K^{(*)} e^+ e^-]} dq^2 \]

Run 1 + 2015 + 2016 - 5 fb\(^{-1}\)

Run 1 - 3 fb\(^{-1}\)

BaBar:
PRD 86, 032012 (2012)

Belle:
PRL 103, 171801 (2009)

Best precision from LHCb
Deviations from SM of \(\sim 2.5 \sigma\)
Test of lepton universality - theoretically clean.

\[ R(K^{(*)}) = \frac{\int_{q_{min}}^{q_{max}} d\Gamma[B \rightarrow K^{(*)} \mu^+ \mu^-] dq^2}{\int_{q_{min}}^{q_{max}} d\Gamma[B \rightarrow K^{(*)} e^+ e^-] dq^2} \]

Best precision from LHCb

Deviations from SM of \( \sim 2.5 \sigma \)
\( B^+ \rightarrow K^+ \mu^\pm e^\mp \)

Run 1 dataset - 3 fb\(^{-1}\) at 7–8 TeV:
- Lepton flavour violation forbidden in SM.
- Models to explain \( b \rightarrow sll \) can lead to LFV.
- BF of order \( 10^{-8} \) possible. JHEP 06, 072 (2015)

*Order of magnitude improvement on previous BaBar limits*

\[ \text{Mode} \quad \begin{array}{c|c|c|c} 
B^+ \rightarrow K^+ \mu^+ e^- & 3.9 \pm 1.1 & 2 & 6.4 \times 10^{-9} \\
B^+ \rightarrow K^+ \mu^- e^+ & 0.9 \pm 0.6 & 1 & 7.0 \times 10^{-9} 
\end{array} \]

PRD 73, 092001 (2006)
Run 1 dataset - 3 fb$^{-1}$ at 7–8 TeV

Search for $B^0$ and $B^0_s$ decays:

- Hadronic $\tau^+$ decay:
  $$\tau^+ \rightarrow \pi^+ \pi^- \pi^+ \bar{\nu}_\tau$$

- Can solve the $B$ kinematics with a twofold ambiguity.
- Peak in $M_B$

No signal, limits set at 90% CL:

$$\mathcal{B}(B^0_s \rightarrow \tau^\pm \mu^{\mp}) < 3.4 \times 10^{-5}$$
$$\mathcal{B}(B^0 \rightarrow \tau^\pm \mu^{\mp}) < 1.2 \times 10^{-5}$$

- Factor 2 improvement for $B^0$ wrt BaBar search
- PRD 77, 091104 (2008)
- First search for $B^0_s$
\[ B^+ \rightarrow \mu^+ \mu^- \mu^+ \nu_\mu \]

Run 1 + 2016 datasets

- \( B^+ \rightarrow \mu^+ \nu_\mu \) helicity suppressed.
- Belle: \((6.46 \pm 2.22 \pm 1.60) \times 10^{-7}\)
- PRL 121, 031801 (2018)
- Scope for observable new physics.
- One track final state.

Include \( \gamma^* \rightarrow \mu^+ \mu^- \):

- Lift helicity suppression
- 3-track vertex

Fit corrected mass

\[ m_{corr} = \sqrt{M_{\mu\mu\mu}^2 + |p^2_\perp| + |p_\perp|} \]

peaks at \( B \) mass when missing a \( \nu_\mu \).

No signal seen - limit set:

\[ \mathcal{B}(B^+ \rightarrow \mu^+ \mu^- \mu^+ \nu_\mu) < 1.6 \times 10^{-8} \]
Looking forward at LHCb

<table>
<thead>
<tr>
<th>7 - 8 TeV</th>
<th>13 TeV</th>
<th>14 TeV</th>
<th>HL-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>Run 2</td>
<td>Run 3</td>
<td>Run 4</td>
</tr>
<tr>
<td>2010 - 2012</td>
<td>2015 - 2018</td>
<td>2021 - 2023</td>
<td>2026 - 2029</td>
</tr>
<tr>
<td>3 fb⁻¹</td>
<td>9 fb⁻¹</td>
<td>23 fb⁻¹</td>
<td>50 fb⁻¹</td>
</tr>
</tbody>
</table>

Upgrade I:
CERN-LHCC-2012-007

Upgrade II:
CERN-LHCC-2017-003

Much work done:
- LHCb has much high quality data.

Much work to be done:
- Many (unique) measurements still to make.
- These are exciting times.

arXiv:1808.08865

LHCb
Semi-leptonic $B$ decays at the LHC

- High branching fraction: $\mathcal{B}(B \rightarrow Xl\nu_l) \approx 10\%$.
- Theoretically ‘clean’ → only calculate one hadronic current.
- Large $B$ production cross-section.
- Large quantity of $\Lambda_b$, $B_s$ and $B_c$.
- Muon to trigger on at L0.

- Partially reconstructed signal.
- No beam energy constraint.
- Hard to make an exclusive HLT selection. Use an MVA.
- Many backgrounds.
- Need lots of simulation.
Semi-leptonic $B$ decays at the LHC

Ascertain $B$ kinematics up to two-fold ambiguity.

Ciezarek et al. JHEP (2017):21

\[ m_{vis}, p_T \]

![Diagram](image)

Estimate corrected mass:

\[ m_{corr} = |p_T'| + \sqrt{|p_T'|^2 + m_{vis}^2} \]

$p_T'$ is visible momentum transverse to $B$ flight.
\[ \tau \text{ reconstruction: } \tau^+ \rightarrow \mu^+ \bar{\nu}_\tau \nu_\mu \ (17.4\%) \]

\[ m_{\text{miss}}^2 \]

**Variable** | **Definition** | **\( \mu \)** | **\( \tau \)**
---|---|---|---
\( m_{\text{miss}}^2 \) | \((p_B - p_{\text{vis}})^2\) | peaks at 0 | \( m_\tau < q^2 < 3270 \text{ MeV} \)
\( q^2 \) | \((p_B - p_{D^*})^2\) | \(0 \text{ MeV} < q^2 < 3270 \text{ MeV}\) | hard
\( E_{\mu}^* \) | \( E_\mu \) in B frame | | soft
Muonic $R(D^*)$ method

- 3D template fit.
  - $\mu$ mis-ID and combinatorial taken from data.
  - All other templates from simulation with systematic variations.

- Major backgrounds:
  - $B \rightarrow D^{**} \mu \nu$
  - $B \rightarrow D^{*+} X_c, X_c \rightarrow X \mu \nu$
  - Reduce with charged isolation.

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PIC 2019
Semileptonic and rare decays
September 2019 5 / 20
Muonic $R(D^*)$ - results

Run 1, 3 fb$^{-1}$:

$R(D^*) = 0.336 \pm 0.027$ (stat) $\pm 0.030$ (syst)

2.1 $\sigma$ deviation from SM prediction

Major systematics:
- Simulation sample size $\rightarrow$ reducible
- mis-ID sample size $\rightarrow$ reducible
- $B \rightarrow D^* \tau \nu$ form-factor $\rightarrow$ scale with data
$\tau$ reconstruction: $\tau^+ \rightarrow \pi^+ \pi^- \pi^+ \bar{\nu}_\tau (\pi^0)$ (13.9%)

$K(D^*) = \frac{\mathcal{B}(B \rightarrow D^* \tau \nu_\tau)}{\mathcal{B}(B \rightarrow D^+ \pi^+ \pi^- \pi^+)}$

- Require external input to turn $K(D^*)$ into $R(D^*)$.
- Reconstructable $\tau$ decay vertex $\rightarrow$ background reduction!
- Estimate $B$ kinematics (backup).

![Diagram of $\tau$ decay reconstruction](LHCb simulation)
Major backgrounds:
- $B \rightarrow D^{*+} \pi^+ \pi^- X$.
  - Reduced with $\tau$ flight distance cut.
- $B \rightarrow D^{*+} X_c$
  - $X_c \rightarrow \pi^+ \pi^- \pi^- X$.
  - Reduced with a multivariate discriminator.

Normalisation fit to $m(D^{*+}3\pi)$:

![Graph showing data, total model, Gaussian, Crystal Ball, and background candidates.](image)

- Data
- Total Model
- Gaussian
- Crystal Ball
- Background

$\sqrt{s} = 8$ TeV

![Graph showing LHCb simulation with BDT response.](image)
Run 1, 3 fb$^{-1}$. Fit $q^2$, $t_\tau$, BDT classifier:

$R(D^{*-}) = 0.291 \pm 0.019(stat) \pm 0.026(syst) \pm 0.013(BR)$
$B \to D^0 \mu^- \nu_\mu X$ branching fractions

$B \to D \mu^+ \nu_\mu X$ background significant source of uncertainty - measure it!

Take $B^-$ from $\bar{B}^*_s \to B^- K^+$ and constrain $B^-$ kinematics.

- Quadratic equation for $B^- K^+$ energy $\to$ pick minimum value for real solution.

$$m_{\text{min}} = \sqrt{m_B^2 + m_K^2 + 2m_B \sqrt{p_K^2 \sin^2 \theta + m_K^2}}$$

- Constrain signal and background from $m_{\text{min}} - m_B - m_K$ distribution.
- Calculate $m_{\text{miss}}^2$ assuming the signal decay.
Fit $m_{\text{miss}}^2$ for $B^- \rightarrow D^0 \mu^- \bar{\nu}_\mu X$ components.

Relative BFs of $B^- \rightarrow D^0 \mu^- \bar{\nu}_\mu$, $B^- \rightarrow D^{*0} \mu^- \nu_\mu$, $B^- \rightarrow D^{**0} \mu^- \nu_\mu$:

\[
f_{D^0} = 0.25 \pm 0.06
\]

\[
f_{D^{*0}} = 0.21 \pm 0.07
\]

\[
f_{D^{*0}} = 1 - f_{D^0} - f_{D^{**0}}
\]
\[ R(J/\psi) = \frac{\mathcal{B}(B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)} \]

- Probing same physics as \( R(D^*) \). SM expectation 0.25 – 0.28.

- Only available at LHCb.

As per \( R(D^*) \) use kinematic distributions: \( m_{\text{miss}}^2, Z(q^2, E_\mu^2) \).
- Additionally consider \( B_c^+ \) decay-time.
- \( B_c^+ \rightarrow J/\psi \) form-factors are unkown - estimated from fit to enriched sample of the normalisation mode.

![Graph showing LHCb simulation, Signal, and Mis-ID distributions for decay time in ps.](image)
$R(J/\psi)$ results

3D template fit: $B_c$ decay-time, $m_{miss}^2$, $Z$.

$$R(J/\psi) = 0.71 \pm 0.17 \pm 0.18$$

- Compatible with SM at $2\sigma$.
- First evidence of decay $B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau$.
- Largest systematics from $B_c \rightarrow J/\psi$ form-factor and limited simulation sample size - both can be improved.

- Lattice form-factor calculation is on the way - see here
We can measure $\Lambda_b \rightarrow \Lambda_c^+ \mu^- \nu_\mu$ differential BF $\rightarrow$ form-factor shape.

- Measure yield of $\Lambda_b \rightarrow \Lambda_c^+ \mu^- \nu_\mu$ in 14 bins of $1 < w < 1.43$.
- Take lower $q^2$ solution.
- Correct for selection efficiency.
- Correct for feed-down from $\Lambda_c^{*+} \rightarrow \Lambda_c^+ \pi^+ \pi^-$ - extracted from data.
- Unfold $w$ resolution.
Angular analyses?

If the tension persists we can learn more about new physics with angular and kinematic variables.

- BaBar has compared $q^2$ with theory: PRD 88, 072012 (2013)
- Belle has measured $\tau$ polarisation: PRL 118, 211801 (2017)
- Unfolding needs careful consideration at LHCb.

Approximate $\gamma_z \beta_z^B \approx \gamma_z^{vis} \beta_z^{vis}$ - $B \rightarrow D^* \mu\nu$, $B \rightarrow D^* \tau\nu$, $\tau \rightarrow \mu\nu\nu$
Theoretical uncertainties


Unfolded data from Belle: BELLE-CONF-1612

| $|V_{cb}|$ | BGL: Data + lattice | CLN: Data + lattice |
|---------|----------------------|---------------------|
|         | $0.0417^{+0.020}_{-0.021}$ | $0.0382(15)$ |

- Slight change in $R(D) - R(D^*)$ prediction.
- Hard to make a model independent measurement.

More data needed → new Belle result!
Hadronic $R(D^*)$ - kinematics

Two-fold ambiguity in determining $\tau$ momentum:

$$|p_\tau| = \frac{(m_{3\pi}^2 + m_\tau^2) |p_{3\pi}| \cos \theta_{\tau,3\pi} \pm E_{3\pi} \sqrt{(m_\tau^2 - m_{3\pi}^2)^2 - 4m_\tau^2 |p_{3\pi}|^2 \sin^2 \theta_{\tau,3\pi}}}{2(E_{3\pi}^2 - |p_{3\pi}|^2 \cos^2 \theta_{\tau,3\pi})}$$

where $\theta_{\tau,3\pi}$ is the angle between the $3\pi$ system 3-momentum and the $\tau$ flight. Take maximum allowed angle:

$$\theta^\text{max}_{\tau,3\pi} = \arcsin \left( \frac{m_\tau^2 - m_{3\pi}^2}{2m_\tau |p_{3\pi}|} \right)$$

Same for $B$ momentum where $Y$ represents the $D^*-\tau^+$ system:

$$|p_{B^0}| = \frac{(m_Y^2 + m_{B^0}^2) |p_Y| \cos \theta_{B^0,Y} \pm E_Y \sqrt{(m_{B^0}^2 - m_Y^2)^2 - 4m_{B^0}^2 |p_Y|^2 \sin^2 \theta_{B^0,Y}}}{2(E_Y^2 - |p_Y|^2 \cos^2 \theta_{B^0,Y})}$$

with:

$$\theta^\text{max}_{B^0,Y} = \arcsin \left( \frac{m_{B^0}^2 - m_Y^2}{2m_{B^0} |p_Y|} \right)$$
Table 1: Systematic uncertainties in the extraction of $\mathcal{R}(D^*)$.

<table>
<thead>
<tr>
<th>Model uncertainties</th>
<th>Absolute size ($\times 10^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated sample size</td>
<td>2.0</td>
</tr>
<tr>
<td>Misidentified $\mu$ template shape</td>
<td>1.6</td>
</tr>
<tr>
<td>$\bar{B}^0 \to D^{*+}(\tau^-/\mu^-)\bar{\nu}$ form factors</td>
<td>0.6</td>
</tr>
<tr>
<td>$\bar{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections</td>
<td>0.5</td>
</tr>
<tr>
<td>$\mathcal{B}(\bar{B} \to D^{<strong>}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \to D^{</strong>}\mu^-\bar{\nu}_\mu)$</td>
<td>0.5</td>
</tr>
<tr>
<td>$\bar{B} \to D^{**}(\to D^{*}\pi\pi)\mu\nu$ shape corrections</td>
<td>0.4</td>
</tr>
<tr>
<td>Corrections to simulation</td>
<td>0.4</td>
</tr>
<tr>
<td>Combinatorial background shape</td>
<td>0.3</td>
</tr>
<tr>
<td>$\bar{B} \to D^{**}(\to D^{*+}\pi)\mu^-\bar{\nu}_\mu$ form factors</td>
<td>0.3</td>
</tr>
<tr>
<td>$\bar{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Total model uncertainty</strong></td>
<td><strong>2.8</strong></td>
</tr>
</tbody>
</table>
$R(D^*)$ average

BaBar (2012), had. tag
0.332 ± 0.024 ± 0.018

Belle (2015), had. tag
0.293 ± 0.038 ± 0.015

Belle (2017), (had. tau)
0.270 ± 0.035 ± 0.027

Belle (2019), sl.tag
0.283 ± 0.018 ± 0.014

LHCb (2015), (muonic tau)
0.336 ± 0.027 ± 0.030

LHCb (2018), (had. tau)
0.280 ± 0.018 ± 0.029

Average
0.295 ± 0.011 ± 0.008

SM pred. average
0.258 ± 0.005

PRD 95 (2017) 115008
0.257 ± 0.003

JHEP 1711 (2017) 061
0.260 ± 0.008

JHEP 1712 (2017) 060
0.257 ± 0.005

HFLAV
Spring 2019
$\Lambda_b \to \Lambda_c$ form-factor

$\Lambda_b \to \Lambda_c^+ \mu^- \nu_\mu$ decay described by 6 FF.

- Take infinite heavy quark mass $\to$ Isgur-Wise function $\xi_B(w)$
  
  $$w = \mathbf{v}_{\Lambda_b} \cdot \mathbf{v}_{\Lambda_c^+} = (m_{\Lambda_b}^2 + m_{\Lambda_c}^2 - q^2) / 2m_{\Lambda_b} m_{\Lambda_c^+}$$

- Differential decay rate:
  
  $$\frac{d\Gamma}{dw} = GK(w)\xi_B^2(w)$$

$G$ is a constant, $K(w)$ is a known kinematic factor.

Parametrise $\xi_B(w)$, i.e. with Taylor expansion:

$$\xi_B(w) = 1 - \rho^2(w - 1) + \frac{1}{2}\sigma^2(w - 1)^2 + \ldots$$

<table>
<thead>
<tr>
<th>$\rho^2$</th>
<th>Approach</th>
<th>Ref.</th>
</tr>
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<tbody>
<tr>
<td>1.35 ± 0.13</td>
<td>QCD sum rules</td>
<td>PLB 629, 27 (2005)</td>
</tr>
<tr>
<td>1.2_{-1.1}^{+0.8}</td>
<td>Lattice</td>
<td>PRD 57, 6948 (1998)</td>
</tr>
<tr>
<td>1.51</td>
<td>HQET + relativistic wave function</td>
<td>PRD 73, 094002 (2006)</td>
</tr>
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