LHCb Results on Semileptonic $B/B_s/\Lambda_b$ Decays

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on behalf of the LHCb Collaboration
Outline

• The LHCb detector and data sample
• Semileptonic decays at LHCb
• Results on $b$ production fractions and $B_s$ decays
• Outlook: form factors, CKM and decays with taus
The LHCb detector

- RICH Detectors
- Particle ID
- Muon System
- Vertex Locator
- VELO
- Tracking stations
- Calorimeters

Proton beam

Collision point

\[ \sigma (pp \rightarrow b\bar{b}X) = (284 \pm 20 \pm 49) \mu b \] @ \( \sqrt{s}=7 \) TeV

(obtained on a sample of semileptonic decays!)


All b hadrons produced

\( B^0, B^+, B_s, B^{**}, \Lambda_b, \Sigma_b, \ldots \)
Great LHC(b) performance!

Currently taking data @ L = 4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} (\text{flat})

(design luminosity: 2 \times 10^{32})

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Large and clean samples

\[ \bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu \quad \rightarrow D^0 \pi^+ \quad \rightarrow K^- \pi^+ \]

370 pb\(^{-1}\)

500k events

\[ \Delta m \text{ compatible with world average} \]
Semileptonic B decays at LHCb

• “Calibration tool” and hadronization studies
  – $b\bar{b}$ cross section
  – flavour tagging performance
  – production fractions of $B$, $B_s$, $\Lambda_b$

• CP Violation through semileptonic asymmetries
  $\rightarrow$ see Zhou’s talk in WG IV

• Exclusive decays of $B_s$ and $\Lambda_b$
  – Composition of the inclusive SL width
  – Improved systematic uncertainties on CP asymmetries
  – Measurement of form factors
  – Measurements of CKM parameters $|V_{ub}|/|V_{cb}|$
    (e.g. $B_s \rightarrow K^{(*)}\mu\nu$)

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Semileptonic $B$ decays at LHCb

- Experimental signature: charm-hadron + muon
- Use large IP wrt to primary vertex to suppress “prompt” charm background
- Use charm to tag $b$ hadron species:
  \[ B^+/B^0/B_{s}/Λ_b \]
  \[ \rightarrow D^0Xμ^-ν \qquad \rightarrow D_sXμ^-ν \]
  \[ \rightarrow D^+Xμ^-ν \qquad \rightarrow Λ_cXμ^-ν \]
- Subtract cross-feed, e.g.
  \[ B_s \rightarrow (D_s^{**} \rightarrow DK)Xμ^-ν \quad \rightarrow B^0+/→D_sKXμ^-ν \]
  - $D^0K$, $D^0p$ final states
  - other available measurements
Production fractions directly related to yields of different charmed hadrons, after correcting for cross-feeds i.e.

\[
f_q = BR(b \rightarrow B_q) \quad \frac{f_s}{f_u + f_d} = \frac{n_{\text{corr}}(\bar{B}_s^0 \rightarrow D \mu)}{n_{\text{corr}}(B \rightarrow D^0 \mu) + n_{\text{corr}}(B \rightarrow D^+ \mu)} \times \frac{\tau_{\bar{B}_s^0} + \tau_{B^0}}{2\tau_{B^0}}.
\]

\[
\frac{f_{\Lambda_b}}{f_u + f_d} = \frac{n_{\text{corr}}(\Lambda_b^0 \rightarrow D \mu)}{n_{\text{corr}}(B \rightarrow D^0 \mu) + n_{\text{corr}}(B \rightarrow D^+ \mu)} \times \frac{\tau_{\bar{B}_s^0} + \tau_{B^0}}{2\tau_{\Lambda_b^0}} (1 - \xi).
\]

Determine cross-feeds with \(D^0K\) and \(D^0p\) control samples. For instance:

\[
n_{\text{corr}}(\Lambda_b^0 \rightarrow D \mu) = B(\Lambda_c^+ \rightarrow pK^- \pi^+)\frac{n(\Lambda_c^+ \mu^-)}{\epsilon(\Lambda_b^0 \rightarrow \Lambda_c^+)} + 2B(D^0 \rightarrow K^- \pi^+)\frac{n(D^0 \mu^-)}{\epsilon(\Lambda_b^0 \rightarrow D^0 p)}.
\]

Perform analysis in 3 (\(\eta\)) x 5 (\(p_T\)) bins, 2<\(\eta\)<5, \(p_T\)≤14 GeV

Measurements based on single-muon, low-\(p_T\) (1 GeV) trigger

Efficiencies depend on hadronic composition

- Determine different contributions directly on data (see later)
D⁰ and D⁺ samples

Channel | Signal (RAW) | Prompt D | Combinatorial
---|---|---|---
D⁰µνX | 27666 ± 167 | 695 ± 43 | 1492 ± 30
D⁺µνX | 9257 ± 110 | 362 ± 34 | 1150 ± 22

Use also wrong charm-lepton charge correlations for background estimates

3 pb⁻¹
2D fit to ln(IP/mm) and charm hadron invariant mass
**Ds and Λc samples**

**Table:**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Signal (RAW)</th>
<th>Prompt D</th>
<th>Combinatorial</th>
<th>Λc reflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>D_sμνX</td>
<td>2192 ± 64</td>
<td>63 ± 16</td>
<td>985 ± 145</td>
<td>387 ± 132</td>
</tr>
<tr>
<td>Λ_cμνX</td>
<td>3028 ± 112</td>
<td>43 ± 17</td>
<td>589 ± 27</td>
<td></td>
</tr>
</tbody>
</table>

**Figure:**

2D fit to ln(IP/mm) and charm hadron invariant mass.

Use also wrong charm-lepton charge correlations for background estimates.

**Text:**

- **PRD 85, 032008 (2012)**
- 3 pb⁻¹
- Measurements of the Ds and Λc samples.
- The fitted yields for RS are derived from directly produced events.
- The fitted yields consist of the Ds signal, the Prompt sample, and the Dfb background.
- The background subtraction is assigned to reflect the modelling uncertainties.
- A conservative 3% systematic uncertainty in the simulation is considered.
- The IP distribution is fitted using a logarithmic function.
- The IP/mm is used for the Ds component.
- Invariant mass spectra for RS combinations are shown in the figure.
- Monte Carlo simulation and background studies are also employed.
Results: $f_s$

\[
\frac{f_s}{f_u + f_d} = 0.134 \pm 0.004^{+0.011}_{-0.010}.
\]

Compare with:

\[
\frac{f_s}{f_u + f_d} = 0.128 \pm 0.012 \quad (LEP)
\]

\[
= 0.164 \pm 0.026 \quad (Tevatron)
\]

Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bin-dependent errors</td>
<td>1.0</td>
</tr>
<tr>
<td>$\mathcal{B}(D^0 \to K^- \pi^+)$</td>
<td>1.2</td>
</tr>
<tr>
<td>$\mathcal{B}(D^+ \to K^- \pi^+ \pi^+)$</td>
<td>1.5</td>
</tr>
<tr>
<td>$\mathcal{B}(D_s^+ \to K^- K^+ \pi^+)$</td>
<td>4.9</td>
</tr>
<tr>
<td>$\bar{B}_s^0$ semileptonic decay modelling</td>
<td>3.0</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>2.0</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>2.0</td>
</tr>
<tr>
<td>Lifetime ratio</td>
<td>1.8</td>
</tr>
<tr>
<td>PID efficiency</td>
<td>1.5</td>
</tr>
<tr>
<td>$\bar{B}_s^0 \to D^0 K^+ X \mu^- \bar{\nu}$</td>
<td>$^{+4.1}_{-1.1}$</td>
</tr>
<tr>
<td>$\mathcal{B}(B^0 \to D_s^+ K X \mu^- \bar{\nu})$</td>
<td>2.0</td>
</tr>
<tr>
<td>Total</td>
<td>$^{+8.6}_{-7.7}$</td>
</tr>
</tbody>
</table>

No $p_T$ dependence

3 pb$^{-1}$
Results: $f_{\Lambda_b}$

$$
\left[ \frac{f_{\Lambda_b}}{f_u + f_d}(p_T) \right] = (0.404 \pm 0.017 \pm 0.027 \pm 0.105) \times [1 - (0.031 \pm 0.004 \pm 0.003) p_T \ (GeV)].
$$

Systematically dominated (26%) by $BF(\Lambda_c \rightarrow pK\pi)$

Consistent with CDF in same kinematic region
Baryon fraction higher at low $p_T$

CDF: $(0.281 \pm 0.012 \pm 0.011 \pm 0.128 \pm 0.056 \pm 0.086)$

$$\langle p_T \rangle_{\text{CDF}} = 14.1 \text{GeV}$$

LEP: $0.110 \pm 0.035$
arXiv:1010.1589

$$\langle p_T \rangle_{\text{LEP}} = 40 \text{GeV}$$

PRD 85, 032008 (2012)

3 pb$^{-1}$

Not flat over $p_T$!
B_s exclusive SL decays

- Contrary to lighter B mesons, not much is known experimentally on exclusive B_s decays
- Final states with D^0K can be used to measure B_s \rightarrow D_s^{(*)} \nu

\[ D_{s1}^*, D_{s2}^* \rightarrow D^{(*)} K \]

\[ D_{sJ}^{(*)} \rightarrow D_s^{(*)+} + n(\pi^0 \text{ or } \gamma) \]

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**First observation:** \( \bar{B}_s \rightarrow D_{s2}^{*+} X \mu^- \bar{\nu} \)

\[ D_{s1}^{(2536)^+} \rightarrow D^* (2007)^0 K^+ \] (missed \( \pi^0 \) or \( \gamma \))

\[ D_{s2}^{(2573)^+} \rightarrow D^0 K^+ \]

Significance: 8.3 \( \sigma \)

\[
\frac{\mathcal{B}(\bar{B}_s^0 \rightarrow D_{s2}^{*+} X \mu^- \bar{\nu})}{\mathcal{B}(\bar{B}_s^0 \rightarrow D_{s1}^+ X \mu^- \bar{\nu})} = 0.61 \pm 0.14 \pm 0.05.
\]

\[
\frac{\mathcal{B}(\bar{B}_s^0 \rightarrow D_{s2}^{*+} X \mu^- \bar{\nu})}{\mathcal{B}(\bar{B}_s^0 \rightarrow X \mu^- \bar{\nu})} = (3.3 \pm 1.0 \pm 0.4)\%,
\]

\[
\frac{\mathcal{B}(\bar{B}_s^0 \rightarrow D_{s1}^+ X \mu^- \bar{\nu})}{\mathcal{B}(\bar{B}_s^0 \rightarrow X \mu^- \bar{\nu})} = (5.4 \pm 1.2 \pm 0.5)\%,
\]

**Most precise measurements of \( B_s \rightarrow D_s^{**} \nu \) decays!**
| $V_{xb}$ | with exclusive decays?

- Need to reconstruct rest frame observables
- Neutrino reconstruction:
  - Determine B flight direction vector from the separation of primary and B decay vertices
  - Get neutrino momentum with two-fold ambiguity
  - Resulting $q^2$ resolution is similar to that observed in B factories
- First steps: measure BF's and form factors in $B_s$ and $\Lambda_b$ decays
- Ultimate goal: measure $|V_{ub}|$ in exclusive $B_s$ and $\Lambda_b$ decays
- Input from lattice/LCSR needed
**Proof of principle**

**Figure 8 (color online).** Measured proton identification efficiency as a function of the $s$ component. The dotted line represents the combinatoric background, the bigger dashed line (red) the baryon. The different components are stacked: the dotted line represents the combinatoric background, the bigger dashed line (red) the baryon. The smaller dashed line (blue) the meson. The ratio has been fixed to the measured value.

- Use $D$ and $D^{**}$ form factors for $D_s$ and $D_s^*$
- Constrain relative fractions
  - $D_s^*/D_s = D^{**}/D = 2.42$

**Figure 9 (color online).** Measured kaon identification efficiency as a function of the $s$ component. The dotted line represents the combinatoric background, the bigger dashed line (red) the hadron. The smaller dashed line (blue) the meson. The ratio has been fixed to the measured value.

- Fix $\Lambda_c(2595)^+ / \Lambda_c(2625)^+$ ratio to value predicted in Ref. [19]

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Neutrino reconstruction outlined above not appropriate on $\tau \to \mu \nu \nu$ (too many neutrinos!)

Try to kinematically reconstruct 3-prong decays $\tau^\pm \to \pi^+\pi^-\pi^\pm\nu_\tau$

$$|\tilde{\rho}_\tau| = \frac{(m_{3\pi}^2 + m_\tau^2)|\tilde{\rho}_{3\pi}| \cos \theta \pm E_{3\pi} \sqrt{(m_{3\pi}^2 - m_\tau^2)^2 - 4m_\tau^2 |\tilde{\rho}_{3\pi}|^2 \sin^2 \theta}}{2(E_{3\pi}^2 - |\tilde{\rho}_{3\pi}|^2 \cos^2 \theta)}$$

Main problems: two-fold ambiguity (four-fold when going to B), non-physical solutions due to momentum and vertex resolutions

High track multiplicities should not be a problem, see e.g. $B_\text{(s)} \to D_\text{(s)} \pi \pi \pi$
More on D** states

B → Dπππ analysis clearly shows D_1(2420) and D_*^+(2460) signals, confirming and extending Belle’s evidence for 3-body decays of D** mesons.

→ Search for radial excitations D^{(*)}.'
Semileptonic $B/B_s/\Lambda_b$ decays are an important part of the LHCb physics program

• Precise measurements of production fractions
• Improving knowledge of exclusive decays
• Neutrino reconstruction will allow for form factor measurements and eventually to determine $|V_{cb}|, |V_{ub}|$ with $B_s/\Lambda_b$ decays
• Measurements of $B \rightarrow D(\ast)\tau\nu$ through 3-prong $\tau$ decays should be viable