Search for new physics in semileptonic B-decays

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on behalf of the LHCb collaboration

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Semileptonic B-decays

B-decays with a missing daughter: neutrino

• Large statistics: high precision

• Neutrinos: partially reconstructed decays
Semileptonic B-decays

Many interesting analyses:

- Lepton universality
- CP violation in mixing
- CKM matrix elements
- Production cross-sections

This talk
Lepton universality: $R(D^*)$

• Measuring the ratio of branching fractions:

$$R(D^*) \equiv \frac{\mathcal{B}(\bar{B}^0 \to D^{*-} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*-} \mu^- \bar{\nu}_\mu)}$$

• Standard Model prediction is theoretically clean:

$$R(D^*) = 0.252 \pm 0.003 \quad \text{PRD 85 (2012) 094025}$$

• Tree-level processes sensitive to new physics: charged higgs, leptoquarks
Measurement in LHCb

**signal:**

\[ \text{signal: } \]

\[ B \rightarrow D^* \rightarrow D^0 \rightarrow \pi, \pi \]
\[ B \rightarrow D^* \rightarrow D^0 \rightarrow K, K \]
\[ B \rightarrow D^* \rightarrow \tau, \nu \]
\[ B \rightarrow \mu, \nu \]

**normalization:**

\[ \text{normalization: } \]

\[ B \rightarrow D^* \rightarrow D^0 \rightarrow \pi, \pi \]
\[ B \rightarrow \mu, \nu \]

Signal and normalization channel have same visible final state.
Fit variables

Kinematics between two channels are very different:

\[ \mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau) \quad \mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu) \]

- Missing mass: calculated using the B flight direction
- Muon energy in center-of-mass
- \( q^2 \): 4-momentum transfer of lepton system
Fits in highest $q^2$ bins

- Fits performed using three-dimensional templates
- Projections in $m^2_{\text{miss}}$ and $E^*_{\mu}$ in bins of $q^2$
- Signal most visible in high $q^2$ bin
Results

\[ \mathcal{R}(D^*) = 0.336 \pm 0.027({\text{stat}}) \pm 0.030({\text{syst}}) \]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Reference</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle</td>
<td>PRD 82 (2010) 072005</td>
<td>657\times10^6 BB (Inclusive Tag)</td>
</tr>
<tr>
<td>BaBar</td>
<td>PRD 88 (2013) 072012</td>
<td>471\times10^6 BB (Hadronic Tag)</td>
</tr>
<tr>
<td>Belle</td>
<td>PRD 92 (2015) 072014</td>
<td>772\times10^6 BB (Hadronic Tag)</td>
</tr>
<tr>
<td>LHCb</td>
<td>PRL 115 (2015) 11108</td>
<td>3.0 fb^{-1} (\tau \rightarrow \mu \nu \nu)</td>
</tr>
</tbody>
</table>

\[ \mathcal{R}(D^*) \equiv \frac{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\tau^+\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\mu^+\bar{\nu}_\mu)} \]

Good consistency between experiments

PRL 115 (2015) 111803

Fajfer et al, PRD 85 (2012) 094025
Prospects for analyses in LHCb:
- analysis of $R(D^*)$ is extended to $R(D)$ vs. $R(D^*)$
- hadronic $R(D^*)$, $\tau^- \rightarrow \pi^-\pi^-\pi^+\nu_\tau$
- other hadron species, like $\Lambda_c$, $B_c$, $B_s$
CP violation in mixing

\[ \mathcal{P}(B_q \to \bar{B}_q) \neq \mathcal{P}(\bar{B}_q \to B_q) \]

Flavour specific asymmetry:

\[ a_{fs} = \frac{\Gamma(\bar{B}_q \to B_q \to f) - \Gamma(B_q \to \bar{B}_q \to \bar{f})}{\Gamma(\bar{B}_q \to B_q \to f) + \Gamma(B_q \to \bar{B}_q \to \bar{f})} \]

Semileptonic decays are flavour-specific:

\[ a_{sl} \text{ is very small in SM} \]

\[ a_{sl}^s = (2.22 \pm 0.27) \times 10^{-5} \quad \text{for } B_s^0 \]

\[ a_{sl}^d = (-4.7 \pm 0.6) \times 10^{-4} \quad \text{for } B^0 \]

Artuso, Borissov, Lenz arXiv:1511.09466
How to measure $a_{sll}^s$

Looking at the decay: $B_s \rightarrow D_s (\rightarrow K K \pi) \mu \nu_\mu$

$$\frac{a_{sll}^s}{2} = \frac{1}{1 - f_{bkg}} (A_{raw} - A_{det} - f_{bkg}A_{bkg})$$

Fit $D_s$ candidates:

$$A_{raw} = \frac{N(D_s^- \mu^+) - N(D_s^+ \mu^-)}{N(D_s^- \mu^+) + N(D_s^+ \mu^-)}$$

Correct for:

- detection asymmetries:
  $$A_{det} = \frac{\varepsilon(f) - \varepsilon(\bar{f})}{\varepsilon(f) + \varepsilon(\bar{f})}$$
- background
Selecting $D_s$

Three regions:
- different selection
- different backgrounds
- same methods
Signal Extraction

Candidates / (2.5 MeV/c²)

LHCb
$\phi\pi$

$K^* K$

$NR$

$m(K^+K^-\pi^\pm)$ [MeV/c²]
Detection asymmetry: tracking

- Two methods:
  - $D^*$ partially reconstructed
  - $J/\Psi \rightarrow \mu\mu$ tag-and-probe

Combining both:

![Graph showing $A_{\text{track}}(\pi^\pm)$ vs. $p$ in GeV/c for LHCb Magnet up and Magnet down]

$A_{\text{track}}(\pi^\pm)$ [%]

$PRL\ 117\ (2016)\ 061803$
Results $a_{s1}^{s}$

using 3fb$^{-1}$:

$$a_{s1}^{s} = (0.39 \pm 0.26\text{(stat)} \pm 0.20\text{(syst)})\%$$

\[ \text{LHCb:} \]
\[ \text{PRL 117 (2016) 061803} \]

\[ \text{D0:} \]
\[ \text{PRD 105 (2014) 012002 (dimuon)} \]
\[ \text{PRL 110 (2013) 011801 (asls)} \]

\[ \text{HFAG:} \]
\[ \text{arXiv:1412.7515 (asld)} \]
Conclusion

• Measurement of lepton universality:

\[ \mathcal{R}(D^*) = 0.336 \pm 0.027\text{(stat)} \pm 0.030\text{(syst)} \]

→ consistent with SM at 2.1σ

• Measured \( a_{s1}^s \) using the full run-I dataset (3fb\(^{-1}\)):

\[ a_{s1}^s = (0.39 \pm 0.26\text{(stat)} \pm 0.20\text{(syst)})\% \]

→ most precise measurement of CP violation in the \( B_s \) system to date

• Stay tuned for updates in run-II
Back-Up
The LHCb Detector

2011: $\mathcal{L} = 1 \text{ fb}^{-1}$
2012: $\mathcal{L} = 2 \text{ fb}^{-1}$

Muon Chambers

muon ID efficiency: 97%

IP resolution: $20 \mu\text{m} @ \text{high-}p_T$

2011: $\mathcal{L} = 1 \text{ fb}^{-1}$
2012: $\mathcal{L} = 2 \text{ fb}^{-1}$

VELO

Tracking

Magnet

RICH

HCAL

ECAL
Fits for $R(D^*)$ in low $q^2$ bins

PRL 115 (2015) 111803
Systematic uncertainties in $R(D^*)$

Table 1: Systematic uncertainties in the extraction of $R(D^*)$.

<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>$\bar{B} \rightarrow D^{*+}(\tau^-/\mu^-)\bar{\nu}$ form factors</td>
<td>0.6</td>
</tr>
<tr>
<td>$\bar{B} \rightarrow D^{**}H_c(\rightarrow \mu\nu X')X$ shape corrections</td>
<td>0.5</td>
</tr>
<tr>
<td>$\mathcal{B}(\bar{B} \rightarrow D^{<strong>}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \rightarrow D^{</strong>}\mu^-\bar{\nu}_\mu)$</td>
<td>0.5</td>
</tr>
<tr>
<td>$\bar{B} \rightarrow D^{**}(\rightarrow D^*\pi\pi)\mu\nu$ 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>$\bar{B} \rightarrow D^{**}(\rightarrow D^{*+}\pi)\mu^-\bar{\nu}_\mu$ form factors</td>
<td>0.3</td>
</tr>
<tr>
<td>$\bar{B} \rightarrow D^{**}(D_s \rightarrow \tau\nu)X$ fraction</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Total model uncertainty</strong></td>
<td><strong>2.8</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Normalization uncertainties</th>
<th>Absolute size ($\times 10^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated sample size</td>
<td>0.6</td>
</tr>
<tr>
<td>Hardware trigger efficiency</td>
<td>0.6</td>
</tr>
<tr>
<td>Particle identification efficiencies</td>
<td>0.3</td>
</tr>
<tr>
<td>Form-factors</td>
<td>0.2</td>
</tr>
<tr>
<td>$\mathcal{B}(\tau^- \rightarrow \mu^-\bar{\nu}<em>\mu\nu</em>\tau)$</td>
<td>$&lt; 0.1$</td>
</tr>
<tr>
<td><strong>Total normalization uncertainty</strong></td>
<td><strong>0.9</strong></td>
</tr>
<tr>
<td><strong>Total systematic uncertainty</strong></td>
<td><strong>3.0</strong></td>
</tr>
</tbody>
</table>
Measuring $\alpha_s$ in LHCb

We start with a different amount of $B_s^0$ and $\bar{B}_s^0$ mesons:

$$A_P = \frac{\sigma(pp \rightarrow B_s^0) - \sigma(pp \rightarrow \bar{B}_s^0)}{\sigma(pp \rightarrow B_s^0) + \sigma(pp \rightarrow \bar{B}_s^0)}$$

$\Delta m \approx 18 \text{ ps}^{-1}$
$\Gamma \approx 1.5 \text{ ps}$

→ rapid oscillations dilute production asymmetry
Detection Asymmetries

\[ A_{\text{det}} = \frac{\varepsilon(f) - \varepsilon(\bar{f})}{\varepsilon(f) + \varepsilon(\bar{f})} \]

Due to:
• left-right asymmetric detector
• interaction asymmetries
• asymmetric pattern recognition

\[ \frac{a_{\text{sl}}}{2} = \frac{1}{1 - f_{\text{bkg}}} \left( A_{\text{raw}} - A_{\text{det}} - f_{\text{bkg}}A_{\text{bkg}} \right) \]

courtesy M. Vesterinen
Detection Asymmetries

\[ A_{\text{det}} = \frac{\varepsilon(f) - \varepsilon(\bar{f})}{\varepsilon(f) + \varepsilon(\bar{f})} \]

- largely measured by reversing magnet polarity
- measure the remaining asymmetry using data-driven methods

\[ \frac{a_{\text{sl}}}{2} = \frac{1}{1 - f_{\text{bkg}}} (A_{\text{raw}} - A_{\text{det}} - f_{\text{bkg}} A_{\text{bkg}}) \]
Results $\alpha_{s1}^s$ in bins

\[ \alpha_{s1}^s = (0.39 \pm 0.26\text{(stat)} \pm 0.20\text{(syst)})\% \]
Backgrounds in $\alpha_s^{SL}$

Table 1: Branching fractions ($\mathcal{B}$), efficiency ratios ($\varepsilon_{\text{sig}}/\varepsilon_{\text{bkg}}$), background-over-signal ratio ($f_{\text{bkg}}/f_{\text{sig}}$) and effective asymmetries for the different background sources. The branching fractions are obtained from the PDG [1]. The signal branching fraction is $\mathcal{B} = (7.9 \pm 2.4)\%$. The $b$-hadron fractions from the $pp$ collision are $f_u/f_s = f_d/f_s = (3.86 \pm 0.22)$ [2] and $f_{\Lambda_b^0}/f_s = (2.34 \pm 0.31)$ [3].

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\mathcal{B}$ [%]</th>
<th>$\mathcal{B}(c \rightarrow \mu)$ [%]</th>
<th>$\varepsilon_{\text{sig}}/\varepsilon_{\text{bkg}}$</th>
<th>$f_{\text{bkg}}/f_{\text{sig}}$ [%]</th>
<th>$A_{\text{bkg}}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow D^{(<em>)0}D_s^{(</em>)+}X$</td>
<td>7.9 ± 1.4</td>
<td>6.5 ± 0.1</td>
<td>4.34</td>
<td>5.8 ± 1.1</td>
<td>−0.6 ± 0.6</td>
</tr>
<tr>
<td>$B^0 \rightarrow D^0D_s^{(*)+}X$</td>
<td>5.7 ± 1.2</td>
<td>6.5 ± 0.1</td>
<td>4.08</td>
<td>4.4 ± 1.0</td>
<td>−0.18 ± 0.13</td>
</tr>
<tr>
<td>$B^0 \rightarrow D^-D_s^{(*)+}X$</td>
<td>4.6 ± 1.2</td>
<td>16.1 ± 0.3</td>
<td>6.41</td>
<td>5.6 ± 1.5</td>
<td>−0.18 ± 0.13</td>
</tr>
<tr>
<td>$B_s^0 \rightarrow D_s^{(<em>)-}D_s^{(</em>)+}$</td>
<td>4.5 ± 1.4</td>
<td>8.1 ± 0.4</td>
<td>3.68</td>
<td>1.0 ± 0.3</td>
<td>−</td>
</tr>
<tr>
<td>$\Lambda_b^0 \rightarrow \Lambda_c^+D_s^{(*)+}X$</td>
<td>10.3$^{+2.1}_{-1.8}$</td>
<td>4.5 ± 1.7</td>
<td>4.51</td>
<td>3.0 ± 1.4</td>
<td>+0.5 ± 0.8</td>
</tr>
<tr>
<td>$B^- \rightarrow D_s^+K^-\mu^-\nu X$</td>
<td>0.061 ± 0.010</td>
<td>−</td>
<td>2.43</td>
<td>1.3 ± 0.2</td>
<td>0.6 ± 0.6</td>
</tr>
<tr>
<td>$\bar{B}^0 \rightarrow D_s^+K_S^0\mu^-\nu X$</td>
<td>0.061 ± 0.010</td>
<td>−</td>
<td>2.89</td>
<td>1.1 ± 0.2</td>
<td>0.18 ± 0.13</td>
</tr>
</tbody>
</table>
Systematic uncertainties in $a_{sl}^s$

Table 1: Overview of contributions in the determination of $a_{sl}^s$, averaged over Dalitz plot regions, magnet polarities and data taking periods, with their statistical and systematic uncertainties. All numbers are in percent. The central value of $a_{sl}^s$ is calculated according to Eq. 3. The uncertainties are added in quadrature and multiplied by $2/(1 - f_{bkg}) = 2.45$, which is the same for all twelve subsamples, to obtain the uncertainties on $a_{sl}^s$.

<table>
<thead>
<tr>
<th>Source</th>
<th>Value</th>
<th>Stat. uncert.</th>
<th>Syst. uncert.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{raw}$</td>
<td>0.11</td>
<td>0.09</td>
<td>0.02</td>
</tr>
<tr>
<td>$A_{track}(K^+K^-)$</td>
<td>-0.01</td>
<td>0.00</td>
<td>0.03</td>
</tr>
<tr>
<td>$A_{track}(\pi^-\mu^+)$</td>
<td>-0.01</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>$A_{PID}$</td>
<td>0.01</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>$A_{trig}$(hardware)</td>
<td>-0.03</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>$A_{trig}$(software)</td>
<td>0.00</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>$f_{bkg}A_{bkg}$</td>
<td>-0.02</td>
<td>–</td>
<td>0.03</td>
</tr>
<tr>
<td>$f_{bkg}$</td>
<td>–</td>
<td>–</td>
<td>0.06</td>
</tr>
<tr>
<td>Total $a_{sl}^s$</td>
<td>0.39</td>
<td>0.26</td>
<td>0.20</td>
</tr>
</tbody>
</table>

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