Rare semileptonic $b$-hadron decays at LHCb

Espen Eie Bowen
on behalf of the LHCb collaboration

July 4th, 2016
SUSY 2016, Melbourne, Australia
Rare decays as a probe for New Physics

- Talk will focus on $b \to s \ell^+ \ell^-$ transitions
- Rare FCNC processes are only possible via loop diagrams in SM
  - Highly suppressed
- New, heavy particles in SM extensions can enter the loop and modify observables
  - e.g. enhance/suppress $B$, alter angular distributions, new sources of $CP$ violation
Theoretical formalism

- Rare $b$-hadron decays are a multi-scale problem: $m_W \gg m_b > \Lambda_{\text{QCD}}$
- Measurements interpreted in Operator Product Expansion framework
  - All degrees of freedom above a given energy scale are integrated out
  - Introduce set of Wilson coefficients, $C_i$, and local operators, $O_i$, encoding coupling strength and Lorentz structure

\[ \mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i (C_{i}^{\text{SM}} + C_{i}^{\text{NP}}) O_i \]

- $b \to s\ell^+\ell^-$ transitions sensitive to $C_7, C_9, C_{10}$
Angular analysis of $B^0 \rightarrow K^{*0}(\rightarrow K^+\pi^-)\mu^+\mu^-$

- Decay fully described by dimuon invariant mass squared, $q^2$, and three angles $\vec{\Omega} = (\cos \theta_\ell, \cos \theta_K, \phi)$

\[
\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^3(\Gamma + \bar{\Gamma})}{d\vec{\Omega}} = \left. \frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^3(\Gamma + \bar{\Gamma})}{d\vec{\Omega}} \right|_{\text{P-wave}} = \frac{9}{32\pi} \left[ \frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell + F_L \cos^2 \theta_K \cos 2\theta_\ell + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi + \frac{4}{3}A_{FB} \sin^2 \theta_K \cos \theta_\ell + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi + S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right]
\]

- $F_L, A_{FB}, S_i$ combinations of $K^{*0}$ amplitudes which depend on the Wilson coefficients and the form factors

- Pollution from $K^+\pi^-$ in S-wave configuration also taken into account
Angular analysis of $B^0 \rightarrow K^{*0} (\rightarrow K^+ \pi^-) \mu^+ \mu^-$

- First full angular analysis of the decay through a maximum likelihood fit to the data
- Full Run I dataset
- Fit performed in $796 < m(K^+ \pi^-) < 996 \text{MeV}/c^2$ region
- Simultaneous fit to $m(K^+ \pi^-)$ to constrain S-wave fraction
- Projections shown for $q^2$ bin $1.1 < q^2 < 6.0 \text{GeV}^2/c^4$
\[ B^0 \rightarrow K^{*0} \mu^+ \mu^- \] fit results - \( F_L, A_{FB}, S_5 \)

- Full set of CP-averaged and CP-asymmetric angular terms and their correlations
- General good agreement with the SM prediction
- Some tension observed in \( S_5 \)
- SM [ABSZ]

[JHEP 02 (2016) 104]
$B^0 \rightarrow K^*\mu^+\mu^-$ fit results - $P'_5$

- Also determine “less form factor dependent” observables e.g.
  \[
P'_5 = \frac{S_5}{\sqrt{F_L(1 - F_L)}}
\]
- Local tension with SM predictions (2.8$\sigma$ and 3.0$\sigma$)
- SM [DHMV]
Angular moments analysis and zero crossing points

- Observables also measured using angular moments analysis
- Robust estimator even for small datasets
- Allows finer binning in $q^2$
- Statistically less precise than result of maximum likelihood fit

Determine zero crossing points by parameterising the angular distribution in terms of $q^2$ dependent decay amplitudes

$q^2(S_5) \in [2.49, 3.95] \text{ GeV}^2/c^4$ at 68% C.L.
$q^2(A_{FB}) \in [3.40, 4.87] \text{ GeV}^2/c^4$ at 68% C.L.
$q^2(S_4) < 2.65 \text{ GeV}^2/c^4$ at 68% C.L.
Differential branching fraction of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

- For $796 < m(K^+\pi^-) < 996$ MeV/$c^2$ the $K^{*0}$ found predominately in P-wave
- Previous $d\mathcal{B}/dq^2$ measurement made with 1/3 of Run I dataset
- S-wave fraction ($F_S$) expected at level of < 10%
  - Treated as a systematic uncertainty

- New $d\mathcal{B}/dq^2$ measurement using full Run I dataset explicitly accounting for S-wave contribution
- $F_S$ determined from fit to $m(K^+\pi^-)$ and decay angle $\cos \theta_K$
**Measurement of $F_S$ in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$**

$F_S$ determined in two regions:

- $m(K^+\pi^-) \in [644, 1200]$ MeV/$c^2$ and
- $m(K^+\pi^-) \in [796, 996]$ MeV/$c^2$

Explicit modelling of $m(K^+\pi^-)$ system

- P-wave: Relativistic BW
- S-wave: LASS
Differential branching fraction of $B^0 \rightarrow K^* \mu^+ \mu^-$  \[\text{[arXiv:1606.04731]}\]

- **First** exclusive measurement of $d\mathcal{B}(B^0 \rightarrow K^*(892)\mu^+ \mu^-)/dq^2$

\[
\frac{d\mathcal{B}[B^0 \rightarrow K^*(892)\mu^+ \mu^-]}{dq^2} = \frac{R_\epsilon}{(q^2_{\text{max}} - q^2_{\text{min}})} \frac{(1 - F_{S|1200}^{1644})n_{K^*\mu^+ \mu^-}}{(1 - F_{S|J/\psi K^*0}^{1644})n_{J/\psi K^*0}} B(B^0 \rightarrow J/\psi K^*(892)\mu^+ \mu^-) B(J/\psi \rightarrow \mu^+ \mu^-)
\]

- Results compatible with SM predictions
  - SM \[\text{[arXiv:1503.05534]}\]
  - Also consistent with pattern of lower branching fractions for $b \rightarrow s \mu^+ \mu^-$ transitions than predicted by theory
    - e.g. $B(B^+ \rightarrow K^+ \mu^+ \mu^-), B(B^0_s \rightarrow \phi \mu^+ \mu^-), B(\Lambda_b^0 \rightarrow \Lambda \mu^+ \mu^-)$
    - Large theoretical uncertainties, correlated across $q^2$

- First exclusive measurement of $d\mathcal{B}(B^0 \rightarrow K^*(892)\mu^+ \mu^-)/dq^2$
Interpretation

- Several attempts to interpret LHCb data by performing global fits
- Consistent picture, data favours modified vector coupling ($C^\text{NP}_9$) at $\sim [3, 4]\sigma$

Possible interpretation

- NP physics scenario, e.g. new vector $Z'$, leptoquarks, etc
- Problem with our understanding of QCD, e.g. not properly estimating contribution from charm loops
**New:** $B^0 \rightarrow K^+\pi^-\mu^+\mu^-$ in the $K^*_{0,2}(1430)^0$ region

- Analyses of $B^0 \rightarrow K^+\pi^-\mu^+\mu^-$ at LHCb have previously focused on the $K^*(892)^0$
- Region of $m(K^+\pi^-) \sim 1430\text{ MeV}/c^2$ contains contributions from $K^*_1(1410)^0$, $K^*_0(1430)^0$ and $K^*_2(1430)^0$
- Allows for a complementary measurement of $b \rightarrow s\mu^+\mu^-$ transitions
**New:** \( B^0 \rightarrow K^+\pi^-\mu^+\mu^- \) in the \( K_{0,2}^* (1430)^0 \) region

- Measurements performed in the \( 1330 < m(K^+\pi^-) < 1530 \text{ MeV}/c^2 \) region at low \( q^2 \)

1. **Differential branching fraction as a function of \( q^2 \)**
   - 5 \( q^2 \) bins: [0.1,0.98], [1.1,2.5], [2.5,4.0], [4.0,6.0], [6.0,8.0] \( \text{GeV}^2/c^4 \)
   - Normalised to \( B^0 \rightarrow J/\psi K^* (892)^0 \)

2. **Angular analysis**
   - Single \( q^2 \) bin: [1.1,6.0] \( \text{GeV}^2/c^4 \)
   - S-, P- and D-wave contributions considered for first time
   - Requires new orthonormal basis of angular functions
New: $d\mathcal{B}/dq^2$ in the $K_{0,2}^*(1430)^0$ region

\[
\frac{d\mathcal{B}(B^0 \to K^+\pi^-\mu^+\mu^-)}{dq^2} = \frac{1}{(q_{\text{max}}^2 - q_{\text{min}}^2)} f_{K^*(892)^0} \mathcal{B}(B^0 \to J/\psi K^*(892)^0) \mathcal{B}(J/\psi \to \mu^+\mu^-) \\
\times \mathcal{B}(K^*(892)^0 \to K^+\pi^-) \frac{N_{K^+\pi^-\mu^+\mu^-}}{(1 - F_{J/\psi K^*0}^J) N_{J/\psi K^*0}^J} \frac{\mathcal{E}_{J/\psi K^*0}}{\mathcal{E}_{K^+\pi^-\mu^+\mu^-}}
\]

- **First** $d\mathcal{B}/dq^2$ measurement of $B^0 \to K^+\pi^-\mu^+\mu^-$ in this region of $m(K^+\pi^-)$
- $B^0 \to J/\psi K^*(892)^0$ yield measured in $796 < m(K^+\pi^-) < 996$ MeV/$c^2$
  - $f_{K^*(892)^0}$ accounts for $m(K^+\pi^-)$ window
  - $F_{J/\psi K^*0}^J$ corrects for S-wave fraction

LHCb preliminary
New: Angular analysis in the $K_{0,2}^*(1430)^0$ region  

- $CP$-averaged differential decay rate of $B^0 \rightarrow K^+\pi^-\mu^+\mu^-$ decays with the $K\pi$ system in a S-, P- or D-wave configuration is expanded in an orthonormal basis of angular functions, $f_i(\Omega)$, [PRD92(2015)033013]

\[
\frac{d\Gamma}{dq^2 d\Omega} = C \times \left\{ \sum_{i=1}^{41} f_i(\Omega) \Gamma_i(q^2) \right\} \quad \text{with} \quad \Gamma_i(q^2) = \Gamma_i^L(q^2) + \eta_i^{L\rightarrow R} \Gamma_i^R(q^2)
\]

- Orthonormal angular basis constructed from spherical harmonics $Y^m_{\ell} \equiv Y^m_{\ell}(\theta, \phi)$ and reduced spherical harmonics $P^m_{\ell} \equiv \sqrt{2\pi} Y^m_{\ell}(\theta, \phi, 0)$

- $\Gamma_i(q^2)$ combinations of $K_j^{*0}$ amplitudes with $\Gamma_1(q^2)$ corresponding to the total rate

- Define 40 normalised angular moments which forms set of observables

\[
\overline{\Gamma}_i(q^2) = \frac{\Gamma_i(q^2)}{\Gamma_1(q^2)}
\]
New: Angular analysis in the $K^*_{0,2}(1430)^0$ region  [LHCb-PAPER-2016-025]

- Observables measured using an angular moments analysis
  - Likelihood fit impossible due to complicated angular expression and limited statistics

- Distributions of the decays angles within $\pm 50$ MeV/$c^2$ of the nominal $B^0$ mass
  - Blue: estimated signal distribution obtained from the angular moments model
  - Red: projected background from upper mass sideband

![Graphs showing angular distributions](image-url)
New: Angular analysis in the $K^*_{0,2}(1430)^0$ region [LHCb-PAPER-2016-025]

- Specific moments point towards large interference between S- and P-wave states
- Evidence for a suppressed D-wave contribution
  - $F_D < 0.29$ @ 95% C.L.
  - Low w.r.t expectation from amplitude analysis of $B^0 \rightarrow J/\psi K\pi$ [PRD90(2014)112009]
- Access to full information, including extraction of Wilson coefficients requires form-factor predictions
  - Only very preliminary predictions exist
  - Hope measurement will stimulate further theory effort
Summary

- Flavour observables in rare decays allow for NP searches and can place many strong constraints on NP models
- Several interesting tensions observed in $b \rightarrow s\ell^+\ell^-$ processes
- Still many interesting results are foreseen with LHCb Run I dataset
  - Major effort to compare observables between $b \rightarrow s\mu^+\mu^-$ and $b \rightarrow se^+e^-$ e.g. $\phi$, $K^*0$, $\Lambda(*)$
  - Understand the effect of $c\bar{c}$ resonances by measuring the interference of resonant and penguin contributions in $B^+ \rightarrow K^+\mu^+\mu^-$
- Run II data will boost precision even further!

Further LHCb talks @ SUSY2016

Gerco Onderwater, “Tests of Lepton Flavour Universality and searches for Lepton Flavor Violation at LHCb”, tomorrow
The LHCb experiment

▶ LHCb is the dedicated heavy flavour physics experiment at the LHC
▶ Its primary goal is to look for indirect evidence of new physics in $CP$ violation and rare decays of $b$- and $c$-hadrons
▶ Requirements:
  1. Excellent tracking
     ▶ momentum resolution($\Delta p/p \sim 0.4\% \sim 0.6\%$)
     ▶ impact parameter resolution ($\sigma_{IP} \sim 20\ \mu m$)
     ▶ primary vertex resolution (13 $\mu m$ in $x$ and $y$ and 71 $\mu m$ in $z$)
  2. Excellent decay time resolution ($\sigma_\tau \sim 45\ fs$)
  3. Excellent particle identification
Tracking system (TT, IT, OT)  Rich detectors  Calorimeters  Vertex Locator  Magnet  Muon system
First observation of $B_s^0 \rightarrow \mu^+ \mu^-$

**SM prediction**

$$B(B_s^0 \rightarrow \mu^+ \mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$

$$B(B^0 \rightarrow \mu^+ \mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

C. Bobeth et al., PRL 112, 101801 (2014)

**LHCb + CMS**

$$B(B_s^0 \rightarrow \mu^+ \mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$

Significance of 6.2$\sigma$ and compatible with SM at 1.2$\sigma$

$$B(B_s^0 \rightarrow \mu^+ \mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$

Significance of 3.0$\sigma$ and compatible with SM at 2.2$\sigma$
Differential branching fractions - volume I

- Large LHCb datasets allows for precise measurements of the $d\mathcal{B}/dq^2$ of $b \to s\mu^+\mu^-$ processes.
- Results hint towards lower rates than predicted by theory.
  - Theory uncertainty are correlated across $q^2$.
Differential branching fractions - volume II

- Similar experiment/theory disagreement seen in other channels
  - $\frac{d\mathcal{B}}{dq^2}[B^0_s \rightarrow \phi \mu^+ \mu^-]$ is 3.3σ from SM prediction in $1.1 < q^2 < 6.0 \text{ GeV}^2/c^4$
- All branching fraction measurements potentially point to new physics in $C_9$
  - e.g. new vector $Z'$
New: Angular analysis in the $K_{0,2}^*(1430)^0$ region

The transversity-basis moments of the first 10 (of 41) orthonormal angular functions outlined in [PRD92(2015)033013]

<table>
<thead>
<tr>
<th>$i$</th>
<th>$f_i(\Omega)$</th>
<th>$\Gamma_i^{L,tr}(q^2)$</th>
<th>$\eta_i^{L\rightarrow R}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$P_0 Y_0^0$</td>
<td>$</td>
<td>H_0</td>
</tr>
<tr>
<td>2</td>
<td>$P_0 Y_0^0$</td>
<td>$2 \left( \frac{2}{\sqrt{5}} Re(H_0 D_\parallel^* + Re(S H_0^<em>) + 2 \frac{2}{\sqrt{5}} Re(H_\parallel D_\parallel^</em> + H_\parallel D_\perp^*) \right)$</td>
<td>&quot;</td>
</tr>
<tr>
<td>3</td>
<td>$P_1 Y_0^1$</td>
<td>$\frac{\sqrt{5}}{7} (</td>
<td>D_\parallel</td>
</tr>
<tr>
<td>4</td>
<td>$P_3 Y_0^3$</td>
<td>$\frac{6}{\sqrt{35}} \left( - Re(H_\parallel D_\parallel^* + H_\perp D_\perp^<em>) + \sqrt{3} Re(H_0 D_0^</em>) \right)$</td>
<td>&quot;</td>
</tr>
<tr>
<td>5</td>
<td>$P_4 Y_0^4$</td>
<td>$\frac{2}{7} \left( -2(</td>
<td>D_\parallel</td>
</tr>
<tr>
<td>6</td>
<td>$P_0 Y_2^0$</td>
<td>$\frac{1}{2 \sqrt{5}} \left(</td>
<td>D_\parallel</td>
</tr>
<tr>
<td>7</td>
<td>$P_1 Y_2^1$</td>
<td>$\frac{\sqrt{5}}{35} Re(H_\parallel D_\parallel^* + H_\perp D_\perp^<em>) - \frac{2}{7} Re(S H_0^</em>) - \frac{4}{7} Re(H_0^* D_0^*)$</td>
<td>&quot;</td>
</tr>
<tr>
<td>8</td>
<td>$P_2 Y_2^2$</td>
<td>$\frac{1}{10} \left(</td>
<td>D_\parallel</td>
</tr>
<tr>
<td>9</td>
<td>$P_3 Y_2^3$</td>
<td>$\frac{3}{5 \sqrt{7}} \left( Re(H_\parallel D_\parallel^* + H_\perp D_\perp^<em>) + 2 \sqrt{3} Re(H_0 D_0^</em>) \right)$</td>
<td>&quot;</td>
</tr>
<tr>
<td>10</td>
<td>$P_4 Y_2^4$</td>
<td>$\frac{2}{7 \sqrt{5}} \left(</td>
<td>D_\parallel</td>
</tr>
</tbody>
</table>

The S-, P- and D-wave transversity amplitudes are denoted as $S^{L,R}$, $H_{\{0,\|,\perp\}}^{L,R}$, and $D_{\{0,\|,\perp\}}^{L,R}$, respectively.