Rare Beauty and Charm Decays at LHCb

Chris Parkinson
Imperial College London
on behalf of the LHCb collaboration

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Outline

- $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ angular analysis, including
  - Measurement of angular observables
  - Measurement of the $A_{FB}$ zero-crossing point ($q_0^2$)

- Branching fraction measurements/limits
  - $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
  - $B_s^0 \rightarrow \phi \mu^+ \mu^-$
  - $B^+ \rightarrow \pi^+ \mu^+ \mu^-$
  - $B \rightarrow \mu^+ \mu^- \mu^+ \mu^-$
  - $B \rightarrow \mu^+ \mu^-$
  - $D^0 \rightarrow \mu^+ \mu^-$
LHCb is a forward detector ($2 < \eta < 5$) designed to study heavy flavour physics.

- LHCb has excellent vertex and momentum resolution, PID and $\mu$-ID...
- Each of these are critical for studies of heavy flavour physics.
Rare Decays at LHCb

- LHCb is searching for physics beyond the Standard Model (SM) by studying rare B and D meson decays
- The rare decays considered here are Flavour Changing Neutral Current processes
  - These are mediated by loop diagrams in the SM
- New physics particles can make significant contributions to these diagrams

New physics contributions can affect:
- The Lorentz structure, accessible through angular analysis
- The total amplitude, accessible through branching fraction measurement
- Indirect searches at LHCb are complimentary to direct searches at the GPDs
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ Angular Analysis

LHCb-CONF-2012-008
Angular Analysis Motivation

- The angular distribution of the rare decay $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ is sensitive to new physics contributions.
- It is parameterised by 6 $q^2$-dependent amplitudes (9 angular terms) and is described in terms of three angles, $\theta_{\ell}$, $\theta_K$ and $\phi$, and $q^2 = m_{\mu\mu}^2$.

Fitting these angles allows access to theoretically clean, experimentally accessible angular observables:

- $F_L$, the fraction of $K^{*0}$ longitudinal polarisation
- $A_{FB}$, the forward-backward asymmetry
- $S_3 \propto A_T^2 (1 - F_L)$, the asymmetry in $K^{*0}$ transverse polarisation [1]
- $A_{IM}$, a T-odd CP asymmetry
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ Angular Analysis Motivation

- These observables allow separation between the SM and a variety of new physics models.
- Each observable is extracted in 6 non-uniform bins in the range $4m_{\mu}^2 < q^2 < 19 \text{ GeV}^2/c^4$ plus the theoretically interesting region $1 < q^2 < 6 \text{ GeV}^2/c^4$.

Plots taken from talk by D. Straub at Moriond EW. [link]
Events isolated using multivariate (BDT) selection
Isolate peaking backgrounds and reject with PID requirements
e.g. $B_s^0 \rightarrow \phi \mu^+ \mu^-$ with $K \rightarrow \pi$ mis-ID
LHCb(1.0 fb$^{-1}$) : $900 \pm 34$ signal events
$B/S \approx 0.25$ in region $5230 < m_{B^0} < 5330$ MeV$/c^2$

![Angular Analysis $m_{B^0}$ Distribution](chart.png)

**LHCb Preliminary**

$0 < q^2 < 19$ GeV$/c^4$
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ Angular Analysis Results

- 4D fit to 3 angles and mass
- Larger data sample enables measurements of $S_3$ and $A_{IM}$
- Error bars include systematic uncertainties
- Data points at average $q^2$ of signal candidates in data
- These are the most precise measurements to-date [preliminary]
- The results are consistent with the SM prediction [2]
The SM predicts $A_{FB}$ to change sign at a well defined point in $q^2$

This zero-crossing point $q_0^2$ is largely free from form-factor uncertainties

Extracted through a 2D fit to the foward- and backward-going $m_{B^0}$ and $q^2$ distributions

- The world's first measurement of $q_0^2$, at $q_0^2 = 4.9^{+1.1}_{-1.3}$ GeV$^2$/c$^4$ [preliminary]
- This is consistent with SM predictions which range from $4 - 4.3$ GeV$^2$/c$^4$ [2, 3, 4]
\[ B^0 \rightarrow K^{*0} \mu^+ \mu^- \text{ and } B^0_s \rightarrow \phi \mu^+ \mu^- \text{ differential branching fractions} \]

LHCb-CONF-2012-008

LHCb-CONF-2012-003
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ and $B^0_s \rightarrow \phi \mu^+ \mu^-$ differential branching fractions

- LHCb(1.0 fb$^{-1}$) : $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ : 900 ± 34 signal events

- Measurement of the $B^0_s \rightarrow \phi \mu^+ \mu^-$ branching fraction reported at Moriond EW
  - LHCb(1.0 fb$^{-1}$) : $B^0_s \rightarrow \phi \mu^+ \mu^-$ : 77 ± 10 signal events
  - $\mathcal{B}(B^0_s \rightarrow \phi \mu^+ \mu^-) = (0.778 \pm 0.097(stat) \pm 0.061(syst) \pm 0.278(B)) \times 10^{-6}$ [preliminary]

- The most precise measurements to-date and are consistent with SM expectations [5]
First observation of $B^+ \rightarrow \pi^+ \mu^+ \mu^-$

LHCb-CONF-2012-006
First observation of $B^+ \rightarrow \pi^+ \mu^+ \mu^-$

- The $B^+ \rightarrow \pi^+ \mu^+ \mu^-$ decay is a $b \rightarrow d \ell \ell$ transition

- In the SM the branching fraction is $\sim 25x$ smaller than analogous $B^+ \rightarrow K^+ \mu^+ \mu^-$ ($b \rightarrow s \ell \ell$) transition and can be enhanced in new physics models

- Can also be used for measurement of $\frac{V_{td}}{V_{ts}}$ from penguin diagrams

- The SM prediction is $\mathcal{B}(B^+ \rightarrow \pi^+ \mu^+ \mu^-) = 1.96 \pm 0.21 \times 10^{-8}$ [6]

- Current limit set by BELLE at $\mathcal{B}(B^+ \rightarrow \pi^+ \mu^+ \mu^-) < 6.9 \times 10^{-8}$ at 90% C.L. [7]

- A major background comes from mis-identified $B^+ \rightarrow K^+ \mu^+ \mu^-$ decays

- A critical analysis issue is separating these two decays
  - The $K - \pi$ separation provided by the LHCb RICH detectors is crucial
First observation of $B^+ \rightarrow \pi^+ \mu^+ \mu^-$

- This is the first observation of a $b \rightarrow d \ell \ell$ transition
- LHCb($1.0 \text{ fb}^{-1}$) : $B^+ \rightarrow \pi^+ \mu^+ \mu^-$ : $25.3^{+6.7}_{-6.4}$ signal events
  - $5.2\sigma$ excess above background
- The measurement is consistent with the SM prediction

\[ B(B^+ \rightarrow \pi^+ \mu^+ \mu^-) = (2.4 \pm 0.6(\text{stat}) \pm 0.2(\text{syst})) \times 10^{-8} \] [preliminary]

- The rarest B decay ever observed
Search for $B \rightarrow \mu^+ \mu^- \mu^+ \mu^-$

LHCb-CONF-2012-010
Search for $B \rightarrow \mu^+\mu^-\mu^+\mu^-$

- No search for $B \rightarrow \mu^+\mu^-\mu^+\mu^-$ performed until now
- Can be mediated by decay to new physics S,P particles where both decay $\rightarrow \mu^+\mu^-$
- P particle could explain hyperCP observation of 3 events with mass $\approx 214$ MeV [8]
- Expect 4$\mu$ final state from $B_s^0 \rightarrow J/\psi \phi$
  - where $J/\psi \rightarrow \mu^+\mu^-$ and $\phi \rightarrow \mu^+\mu^-$
- Non-resonant SM prediction $< 10^{-10}$ [9]
Search for $B \rightarrow \mu^+\mu^-\mu^+\mu^-$

- Now excluding $J/\psi$ and $\phi$ resonant windows ...
- Observed number of non-resonant events consistent with background expectation

![Graph showing $B^0_s \rightarrow \mu^+\mu^-\mu^+\mu^-$ (non-resonant)](image)

- Branching fraction limits set using CL$_S$ method and phase-space model:
  \[
  \begin{align*}
  \mathcal{B}(B^0_s \rightarrow \mu^+\mu^-\mu^+\mu^-) &< 1.3 \times 10^{-8} \\
  \mathcal{B}(B^0 \rightarrow \mu^+\mu^-\mu^+\mu^-) &< 5.4 \times 10^{-9}
  \end{align*}
  \] at 95% C.L. [preliminary]

- These measurements are consistent with SM predictions
- Worlds first limit on $B \rightarrow \mu^+\mu^-\mu^+\mu^-$
The Search for $B \rightarrow \mu^+\mu^-$ and $D^0 \rightarrow \mu^+\mu^-$

LHCb-PAPER-2012-007

LHCb-CONF-2012-005
The Search for $B \to \mu^+\mu^-$ and $D^0 \to \mu^+\mu^-$

- World best limits on $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ reported at Moriond EW
- The branching fractions are sensitive to contributions from new scalar particles
  - New limits constrain e.g. the SUSY parameter space at high tan $\beta$
- SM prediction $B(B_s^0 \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$
- SM prediction $B(B^0 \to \mu^+\mu^-) = (0.10 \pm 0.01) \times 10^{-9}$

<table>
<thead>
<tr>
<th>mode</th>
<th>limit</th>
<th>at 95% C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0 \to \mu^+\mu^-$</td>
<td>expected bg+SM</td>
<td>$7.2 \times 10^{-9}$</td>
</tr>
<tr>
<td></td>
<td>expected bg only</td>
<td>$3.4 \times 10^{-9}$</td>
</tr>
<tr>
<td></td>
<td>observed</td>
<td>$4.5 \times 10^{-9}$</td>
</tr>
<tr>
<td>$B^0 \to \mu^+\mu^-$</td>
<td>expected</td>
<td>$1.13 \times 10^{-9}$</td>
</tr>
<tr>
<td></td>
<td>observed</td>
<td>$1.03 \times 10^{-9}$</td>
</tr>
</tbody>
</table>

- Worlds best limit on $D^0 \to \mu^+\mu^-$ decay:
  - $B(D^0 \to \mu^+\mu^-) < 1.3 \times 10^{-8}$ at 95% C.L. [preliminary]
  - An order of magnitude improvement from previous experiments [10] and is consistent with the SM prediction [11]
Summary

- $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ angular analysis
  - Worlds most precise measurement of angular observables
  - Worlds first measurement of the $A_{FB}$ zero-crossing point ($q_0^2$)
    - LHCb-CONF-2012-008

- Branching fraction measurements/limits
  - $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ [Worlds most precise measurement]
    - LHCb-CONF-2012-008
  - $B_s^0 \rightarrow \phi \mu^+ \mu^-$ [Worlds most precise measurement]
    - LHCB-CONF-2012-003
  - $B^+ \rightarrow \pi^+ \mu^+ \mu^-$ [First observation]
    - LHCb-CONF-2012-006
  - $B \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ [Worlds first limit]
    - LHCb-CONF-2012-010
  - $B \rightarrow \mu^+ \mu^-$ [Worlds best limit]
    - LHCb-PAPER-2012-007
  - $D^0 \rightarrow \mu^+ \mu^-$ [Order of magnitude improvement in limit]
    - LHCB-CONF-2012-005
References


\[ \frac{1}{\Gamma} \frac{d^4 \Gamma}{d \cos \theta_{\ell} d \cos \theta_K d \hat{\phi} dq^2} = \frac{9}{16\pi} \left\{ F_L \cos^2 \theta_K + \frac{3}{4} (1 - F_L)(1 - \cos^2 \theta_K) + F_L \cos^2 \theta_K (2 \cos^2 \theta_{\ell} - 1) + \frac{1}{4} (1 - F_L)(1 - \cos^2 \theta_K)(2 \cos^2 \theta_{\ell} - 1) + S_3 (1 - \cos^2 \theta_K)(1 - \cos^2 \theta_{\ell}) \cos 2 \hat{\phi} + \frac{4}{3} A_{FB} (1 - \cos^2 \theta_K) \cos \theta_{\ell} + A_{Im} (1 - \cos^2 \theta_K)(1 - \cos^2 \theta_{\ell}) \sin 2 \hat{\phi} \right\} \]
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$

LHCb Preliminary

- Data
- Corrected MC
- Uncorrected MC

arb. units

BDT response

arb. units

0.2 0.4 0.6 0.8 1

0 1 2 3 4

Data
Corrected MC
Uncorrected MC
\[ B^0 \rightarrow K^{*0} \mu^+ \mu^- \]

<table>
<thead>
<tr>
<th>( q^2 ) (GeV(^2/)c(^4)) range</th>
<th>Signal Yield</th>
<th>Background Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 4m_{\mu}^2 &lt; q^2 &lt; 2.00 )</td>
<td>162.4 ± 14.2</td>
<td>27.7 ± 3.8</td>
</tr>
<tr>
<td>( 2.00 &lt; q^2 &lt; 4.30 )</td>
<td>71.4 ± 10.7</td>
<td>37.1 ± 4.1</td>
</tr>
<tr>
<td>( 4.30 &lt; q^2 &lt; 8.68 )</td>
<td>270.5 ± 18.8</td>
<td>58.8 ± 5.5</td>
</tr>
<tr>
<td>( 10.09 &lt; q^2 &lt; 12.90 )</td>
<td>167.0 ± 14.9</td>
<td>41.7 ± 4.5</td>
</tr>
<tr>
<td>( 14.18 &lt; q^2 &lt; 16.00 )</td>
<td>113.0 ± 11.7</td>
<td>17.1 ± 3.0</td>
</tr>
<tr>
<td>( 16.00 &lt; q^2 &lt; 19.00 )</td>
<td>115.0 ± 12.4</td>
<td>23.9 ± 3.6</td>
</tr>
<tr>
<td>( 1.00 &lt; q^2 &lt; 6.00 )</td>
<td>195.2 ± 16.9</td>
<td>75.8 ± 6.0</td>
</tr>
<tr>
<td>( 4m_{\mu}^2 &lt; q^2 &lt; 19.00 )</td>
<td>900.0 ± 34.4</td>
<td>206.2 ± 10.3</td>
</tr>
</tbody>
</table>
$B^0 \to K^{*0} \mu^+ \mu^-$
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$

![Graph showing $dB/df^2$ vs $q^2$]
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$

![Graph showing $d\mathcal{B}/dq^2$ vs $q^2$]
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$

$\frac{4c^2}{2 \text{ GeV}^2 q^0}$

$F_L$

$q^2 [\text{GeV}^2/c^4]$
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$

LHCb Preliminary
$B^0 \to K^{*0} \mu^+ \mu^-$

![Graph showing $A_{FB}$ vs. $q^2$ for $B^0 \to K^{*0} \mu^+ \mu^-$ decay. The graph displays data points from LHCb experiments, with theoretical predictions shown in different colors. The x-axis represents $q^2$ in [GeV$^2$/c$^4$], and the y-axis represents $A_{FB}$. The graph includes LHCb Preliminary data.]
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$
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$B^0 \rightarrow K^{*0} \mu^+ \mu^-$
$B^0 \rightarrow K^{*0}\mu^+\mu^-$
$B^0 \rightarrow K^{*0}\mu^+\mu^-$
\( \mathbf{B^0 \to K^*0 \mu^+\mu^-} \)

<table>
<thead>
<tr>
<th>( q^2 ) range (GeV(^2)/c(^4))</th>
<th>( dBF/dq^2 ) ((\times 10^{-7}) GeV(^{-2})c(^4))</th>
<th>( A_{FB} )</th>
<th>( F_L )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 4m^2_{\mu} &lt; q^2 &lt; 2.00 )</td>
<td>( 0.68 \pm 0.07 \pm 0.05 )</td>
<td>0.00( ^{+0.08}_{-0.07} ) 0.01</td>
<td>0.31( ^{+0.09}_{-0.06} ) 0.03</td>
</tr>
<tr>
<td>( 2.00 &lt; q^2 &lt; 4.30 )</td>
<td>( 0.30 \pm 0.05 \pm 0.02 )</td>
<td>-0.20( ^{+0.08}_{-0.07} ) 0.01</td>
<td>0.74( ^{+0.09}_{-0.08} ) 0.02</td>
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<tr>
<td>( 4.30 &lt; q^2 &lt; 8.68 )</td>
<td>( 0.54 \pm 0.05 \pm 0.05 )</td>
<td>0.16( ^{+0.05}_{-0.05} ) 0.01</td>
<td>0.57( ^{+0.05}_{-0.05} ) 0.04</td>
</tr>
<tr>
<td>( 10.09 &lt; q^2 &lt; 12.89 )</td>
<td>( 0.50 \pm 0.06 \pm 0.04 )</td>
<td>0.27( ^{+0.06}_{-0.06} ) 0.01</td>
<td>0.49( ^{+0.06}_{-0.07} ) 0.03</td>
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<tr>
<td>( 14.18 &lt; q^2 &lt; 16.00 )</td>
<td>( 0.59 \pm 0.07 \pm 0.04 )</td>
<td>0.49( ^{+0.04}_{-0.06} ) 0.05</td>
<td>0.35( ^{+0.07}_{-0.06} ) 0.02</td>
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<tr>
<td>( 16.00 &lt; q^2 &lt; 19.00 )</td>
<td>( 0.44 \pm 0.05 \pm 0.03 )</td>
<td>0.30( ^{+0.07}_{-0.07} ) 0.04</td>
<td>0.37( ^{+0.06}_{-0.07} ) 0.04</td>
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<tr>
<td>( 1.00 &lt; q^2 &lt; 6.00 )</td>
<td>( 0.42 \pm 0.04 \pm 0.04 )</td>
<td>-0.18( ^{+0.06}_{-0.06} ) 0.01</td>
<td>0.66( ^{+0.06}_{-0.06} ) 0.04</td>
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<table>
<thead>
<tr>
<th>( q^2 ) range (GeV(^2)/c(^4))</th>
<th>( A_{IM} )</th>
<th>( 2S_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 4m^2_{\mu} &lt; q^2 &lt; 2.00 )</td>
<td>( 0.06^{+0.11}_{-0.10} +0.00 ) (-0.10 -0.03 )</td>
<td>0.02( ^{+0.20}_{-0.21} ) 0.00</td>
</tr>
<tr>
<td>( 2.00 &lt; q^2 &lt; 4.30 )</td>
<td>( -0.02^{+0.10}_{-0.06} +0.05 ) (-0.06 -0.01 )</td>
<td>-0.05( ^{+0.18}_{-0.12} ) 0.05</td>
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<tr>
<td>( 4.30 &lt; q^2 &lt; 8.68 )</td>
<td>( 0.02^{+0.07}_{-0.07} +0.01 ) (-0.07 -0.01 )</td>
<td>0.18( ^{+0.13}_{-0.13} ) 0.01</td>
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<tr>
<td>( 10.09 &lt; q^2 &lt; 12.89 )</td>
<td>( -0.01^{+0.11}_{-0.11} +0.02 ) (-0.11 -0.03 )</td>
<td>-0.22( ^{+0.20}_{-0.17} ) 0.02</td>
</tr>
<tr>
<td>( 14.18 &lt; q^2 &lt; 16.00 )</td>
<td>( -0.01^{+0.08}_{-0.07} +0.04 ) (-0.07 -0.02 )</td>
<td>0.04( ^{+0.15}_{-0.19} ) 0.04</td>
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<tr>
<td>( 16.00 &lt; q^2 &lt; 19.00 )</td>
<td>( 0.06^{+0.09}_{-0.10} +0.03 ) (-0.10 -0.05 )</td>
<td>-0.47( ^{+0.21}_{-0.10} ) 0.03</td>
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<tr>
<td>( 1.00 &lt; q^2 &lt; 6.00 )</td>
<td>( 0.07^{+0.07}_{-0.07} +0.02 ) (-0.07 -0.01 )</td>
<td>0.10( ^{+0.15}_{-0.16} ) 0.02</td>
</tr>
</tbody>
</table>
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$

Events / (0.2 GeV $^2 c^4$) vs. $q^2$ (GeV$^2 c^4$)

LHCb Preliminary

Preliminary LHCb
$B^+ \rightarrow \pi^+ \mu^+ \mu^-$
$B^+ \rightarrow \pi^+ \mu^+ \mu^-$
$B^+ \rightarrow \pi^+ \mu^+ \mu^-$

![Graph showing $M_{\pi\mu\mu}$ distribution with LHCb Preliminary results.](image-url)
$B_s^0 \rightarrow \phi \mu^+ \mu^-$

![Graph showing $d\mathcal{B}/dq^2$ as a function of $q^2$ (GeV$^2$/c$^4$).](image)