$b \rightarrow s\ell\ell$: angular analyses and studies with muons

Eluned Smith

RWTH Aachen

on behalf of the LHCb collaboration

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Why rare $b \rightarrow s\ell\ell$ decays?

NB: this talk covers $b \rightarrow s\mu\mu$ decays at LHCb, for $b \rightarrow see$ decays (including LFU results) see Albert Puig’s talk (up next!)

- $b \rightarrow s\ell\ell$ transitions are forbidden at tree level $\rightarrow$ suppressed decays in the SM maybe be more sensitive to new physics (NP) effects.
- Virtual new physics particles $\rightarrow$ high mass reach.

$b \rightarrow s\ell\ell$ in the SM

Possible contributions from NP
Use of effective theories in $b \rightarrow s\ell\ell$ SM predictions

- The heavy physics in $b \rightarrow s\ell\ell$ decays can be integrated out to give effective couplings, parameterised by the Wilson Coefficients ($C_i$).
- $b \rightarrow s\ell\ell$ transitions are most sensitive to the coefficients $C_{9/10}$.

As the Wilson Coefficients 'describe the loops' in the diagram, they are sensitive to NP.
Measuring $b \rightarrow sll$ transitions

- Angular analyses and branching fraction measurements
$B^0 \rightarrow K^{*0} \left[ \rightarrow K^+\pi^- \right] \mu^+\mu^-$ angular analysis $[C_7, C_9, C_{10}]$

Angular decay fully described by the dilepton mass ($q^2$) and the angles $\cos(\theta_{1})$, $\cos(\theta_{K})$ and $\phi$:

$$\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^3(\Gamma + \bar{\Gamma})}{d\Omega} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell \right]$$

Fraction of longitudinal polarisation of the $K^*$

Forward-backward asymmetry of the dilepton system

3D fit to all three angles (in $q^2$ bins), exploiting the correlations between the $S_i$, $F_L$ and $A_{FB}$ terms to obtain their respective values (+ swave - see back-up).
$B^0 \rightarrow K^{*0} \rightarrow K^+ \pi^- \mu^+ \mu^-$ angular analysis: Results

Normalisation (detector acceptance/systematics partially cancel)

Signal

LHCb

Candidates / 11 MeV/c^2

Candidates / 11 MeV/c^2

Candidates / 0.1 π rad

Candidates / 0.1 π rad

$1.1 < q^2 < 6.0 \text{ GeV}^2/c^4$
$B^0 \rightarrow K^{*0} [\rightarrow K^{+}\pi^- ]\mu^+\mu^-$ angular analysis: Results

Generally very good agreement with the Standard Model

[LHCb]

$F_L$

$q^2 [\text{GeV}^2/c^4]$ $A_{FB}$

$q^2 [\text{GeV}^2/c^4]$ $S_3$

$q^2 [\text{GeV}^2/c^4]$ $S_4$

[104]

[JHEP 02 (2016) 104]
$B^0 \rightarrow K^{*0} [\rightarrow K^+\pi^-] \mu^+\mu^-$ angular analysis: Results

Reduce form factor dependence

Can construct ratios of angular observables where form-factors cancel at leading order:

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

$P_5'$ plot: Bins 4/5 = local SM tension of 2.8 and 3.0$\sigma$. Global tension = 3.4$\sigma$, assuming tension due to shift in Wilson coeff. $Re(C_9)$ (LHCb only)
\[ B^0 \rightarrow K^{*0} [\rightarrow K^+\pi^- ] \mu^+\mu^- \] branching fraction

The differential branching fraction also shows some tension at low \( q^2 \).
Performance comparison: $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

**CMS**

$N(B^0 \rightarrow K^{*0} \mu^+ \mu^-) = 346 \pm 24$

- Data
- Total fit
- Corr. tag sig.
- Mistag sig.
- Background

$\sigma^2: 1.00 - 6.00 \text{ GeV}^2$

Signal yield: 346 \pm 24

PLB 753 (2016) 453

$N(B^0 \rightarrow K^{*0} \mu^+ \mu^-) = 624 \pm 30$

**LHCb**

$1.1 < q^2 < 6.0 \text{ GeV}^2/c^4$

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$N(B^0 \rightarrow K^{*0} \mu^+ \mu^-) = 275 \pm 35$

**ATLAS**

$\sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1}$

Preliminary

$ATLAS\text{-CONF-2017-023}$

$q^2 \in [1.1, 6.0] \text{ GeV}^2$
$B^0_s \rightarrow \phi[\rightarrow K^+K^-]\mu^+\mu^- [C_7, C_9, C_{10}]$

Equivalent process of $B^0 \rightarrow K^{*0}\mu^+\mu^-$ for $B^0_s$ mesons.

Angular variables consistent with the SM. $P'_5$ cannot be measured as $B^0_s \rightarrow \phi\mu^+\mu^-$ not self-tagging.

In bin $1 < q^2 < 6$ GeV/$c^2$ the data is $3.3\sigma$ from the SM prediction.
Further $b \rightarrow s \ell\ell$ branching fractions

LHCb $B^0 \rightarrow K^{*0}\mu^+\mu^-$ [JHEP 11 (2016) 047]

LHCb $B^0_s \rightarrow \phi\mu^+\mu^-$ [JHEP 09 (2015) 179]

LHCb $B^+ \rightarrow K^+\mu^+\mu^-$ [JHEP 06 (2014) 133]

$\Lambda_b^0 \rightarrow \Lambda\mu^+\mu^-$ [JHEP 06 (2015) 115]

LHCb $B^0 \rightarrow K^{0}\mu^+\mu^-$ [JHEP 06 (2014) 133]

$B^+ \rightarrow K^{*+}\mu^+\mu^-$ [JHEP 06 (2014) 133]

slide: C. Langenbruch, b2ll workshop, Munich 2018
$b \rightarrow s \ell\ell$ transitions in baryons

- Baryon sector still relatively unexplored compared to mesons
- Measurements can complement those from meson sector
The decays $\Lambda_b^0 \rightarrow \Lambda^0 \mu^+ \mu^-$ and $\Lambda_b^0 \rightarrow p K\mu^+ \mu^-$

Differential branching fraction and angular analysis

First observation and CPV measurements

![Graphs showing differential branching fractions and angular analyses with data points and fitted curves.](image-url)

![Graphs showing decay products and CPV measurements with theoretical and experimental data.](image-url)
CPV in $\Lambda^0_b \rightarrow pK\mu^+\mu^-$

Baryon production asymmetries not well known: use $\Delta A_{cp}$ and triple products

Proportional to $\sin\chi$

$$C_T \equiv \vec{p}_{\mu^+} \cdot (\vec{p}_p \times \vec{p}_{K^-})$$

$$C_T \equiv \vec{p}_{\mu^-} \cdot (\vec{p}_p \times \vec{p}_{K^+})$$

$$A_T \equiv \frac{N(C_T > 0) - N(C_T < 0)}{N(C_T > 0) + N(C_T < 0)}$$

$$\bar{A}_T \equiv \frac{N(-C_T > 0) - N(-C_T < 0)}{N(-C_T > 0) + N(-C_T < 0)}$$

$$a_{CP}^{T-odd} \equiv \frac{1}{2} (A_T - \bar{A}_T)$$

$$a_{CP}^{T-odd} \equiv \frac{1}{2} (A_T + \bar{A}_T)$$

$$a_{CP}^{T-odd} = (1.2 \pm 5.0 \text{(stat)} \pm 0.7 \text{(syst)}) \times 10^{-2} \rightarrow \text{no significant CPV}$$

- Measure $\Delta A_{CP} = A_{CP}(\Lambda^0_b \rightarrow pK^-\mu^+\mu^-) - A_{CP}(\Lambda^0_b \rightarrow J/\psi pK^-)$

$\Delta A_{CP} = ( -3.5 \pm 5.0 \text{ (stat)} \pm 0.2 \text{ (syst)}) \times 10^{-2} \rightarrow \text{no significant CPV}$
Global fits

- Global fits performed by theorists to a range of results from $b \rightarrow s\ell\ell$ measurements
- Will also discuss interpretations of global fits
Global fits

- Sub-divide between ‘clean’ observables (LFU measurements - see next talk) and ‘dirty’ observables (e.g. angular analyses)
- Just LFU $\rightarrow \sim 4\,\sigma$ deviations
- Combining all measurements $\rightarrow$ over $5\,\sigma$ deviations


one example of a global fit, many others out there (!)

<table>
<thead>
<tr>
<th>Coeff.</th>
<th>best fit</th>
<th>$1\sigma$</th>
<th>$2\sigma$</th>
<th>pull</th>
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</thead>
<tbody>
<tr>
<td>$C_9^\mu$</td>
<td>$-1.56$</td>
<td>$[-2.12, -1.10]$</td>
<td>$[-2.87, -0.71]$</td>
<td>$4.1\sigma$</td>
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<tr>
<td>$C_{10}^\mu$</td>
<td>$+1.20$</td>
<td>$[+0.88, +1.57]$</td>
<td>$[+0.58, +2.00]$</td>
<td>$4.2\sigma$</td>
</tr>
<tr>
<td>$C_9^e$</td>
<td>$+1.54$</td>
<td>$[+1.13, +1.98]$</td>
<td>$[+0.76, +2.48]$</td>
<td>$4.3\sigma$</td>
</tr>
<tr>
<td>$C_{10}^e$</td>
<td>$-1.27$</td>
<td>$[-1.65, -0.92]$</td>
<td>$[-2.08, -0.61]$</td>
<td>$4.3\sigma$</td>
</tr>
</tbody>
</table>

$C_9^\mu = -C_{10}^\mu$  
$C_9^e = -C_{10}^e$  
$C_9 = C_{10}^e$  

Pull assuming 1D variation only and just LFU measurements $\rightarrow$ increased tension when including angular analyses
What could be causing this anomaly?

**pessimistic**

Long distance SM effects

**optimistic**

Short distance NP effects
Data driven measurements of short and long distance interference

- Due to the difficulty of modelling Charmonium resonances, the $J/\psi$ and $\psi(2S)$ are generally removed from data when looking at just the short-distance contributions.
- Vector resonances producing dimuon pairs could mimic a contribution to $C_9$ allowing $C_9$ to be expressed as

$$C_{9\text{eff}} = C_9 + Y(q^2)$$

- Possible that the deficiency in muons could be due to destructive interference from such Charmonium resonances.
Data driven approach → fit to unbinned data in $q^2$ for the data $B^+ \rightarrow K^+ \mu^+ \mu^-$

Express $Y(q^2)$ in terms of the sum of the magnitude and phases of the vector meson resonances ($\rho, \omega, \phi, J/\psi, \psi(2S), \psi(X)$) → model these contributions as a sum of Breit Wigners with individual width and phase.
Data driven measurements of short and long distance interference

- Four solutions fit data well reflecting the unknown sign of the $J/\psi$ and $\psi(2S)$ phases (NB resolution dominants these resonances widths)
- The phases that are measured suggest a small contribution to the short-distance component in the dimuon mass regions far from the $J/\psi$ and $\psi(2S)$ masses, given the assumptions made in model.
The increased data collected at the LHCb detector means that the Cabibbo-suppressed $b \rightarrow d \ell \ell$ modes are becoming more of interest.
Why $b \to d\ell\ell$ transitions?

- Combining $b \to s\ell\ell$ with their Cabibbo-suppressed partner allows a measurement of $V_{td}/V_{ts}$ and thus a test of Minimal Flavour Violation.
- Expect branching fractions to be $\sim 25$ times smaller than $s$ quark partner
Examples of $b \rightarrow d \ell \ell$ transitions

$\mathcal{B}(B^0_s \rightarrow K^{*0} \mu^+ \mu^-)$

$\rightarrow \mathcal{K}^{0} \mu^+ \mu^-$

$= (2.9 \pm 1.0 \pm 0.2 \pm 0.3) \times 10^{-8}$

$\mathcal{B}(\Lambda_b^0 \rightarrow \rho \pi^- \mu^+ \mu^-)$

$\Lambda_b^0 \rightarrow p \bar{K}^+ \mu^+ \mu^-$

$= (6.9 \pm 1.9 \pm 1.1^{+1.3}_{-1.0}) \times 10^{-8}$
Conclusions and outlook

- Number of anomalies in $b \rightarrow s\ell\ell$ transitions, consistent with a deficit in the muon channel
- Could be theoretical limitations or new physics
- More data necessary to further qualify this, as well as development in theory
- Advent of Belle 2 and further runs at the LHC will yield interesting results
Back-up slides
Data driven measurements of short and long distance interference

Following the notation of Ref. [40], the $CP$-averaged differential decay rate of $B^+ \to K^+ \mu^+ \mu^-$ decays as a function of the dimuon mass squared, $q^2 \equiv m_{\mu\mu}^2$, is given by

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 \alpha^2 |V_{tb}V_{ts}^*|^2}{128\pi^5} |k| |\beta| \left\{ \frac{2}{3} |k|^{2} \beta^2 |C_{10} f_+(q^2)|^2 + \frac{4m_{\mu}^2 (m_B^2 - m_K^2)^2}{q^2 m_B^2} |C_{10} f_0(q^2)|^2 \right. $$

$$ + \left. |k|^2 \left[ 1 - \frac{1}{3} \beta^2 \right] \left| C_9 f_+(q^2) + 2C_7 \frac{m_b + m_s}{m_B + m_K} f_T(q^2) \right|^2 \right\}, \quad (1)$$

where $|k|$ is the kaon momentum in the $B^+$ meson rest frame.

The parameters $f_{0,+,T}$ denote the scalar, vector and tensor $B \to K$ form factors.

Insert term into eq. above

$C_{9}^{\text{eff}} = C_9 + Y(q^2),$ 

where the term $Y(q^2)$ describes the sum of resonant and continuum hadronic states appearing in the dimuon mass spectrum. In this analysis $Y(q^2)$ is replaced by the sum of vector meson resonances $j$ such that

If $n^\ast \pi^\pm /2$ term disappears in eq.1

assumes no continuum hadronic states (e.g. no DDbar)

where $\eta_j$ is the magnitude of the resonance amplitude and $\delta_j$ its phase relative to $C_9$.

$$C_{9}^{\text{eff}} = C_9 + \sum_j \eta_j e^{i\delta_j} A_j^{\text{res}}(q^2), \quad (3)$$
Baryon production asymmetries not well known: use $\Delta A_{cp}$ and triple products
Sensitivity of methods may differ depending on strong phase interference

### $\hat{T}_{\text{even}}, \hat{T}_{\text{odd}}$ amplitudes

\[ a_{CP}^{\hat{T}_{-\text{odd}}} \propto \cos(\delta_{\text{even}} - \delta_{\text{odd}}) \sin(\phi_{\text{even}} - \phi_{\text{odd}}) \]

not sensitive if $\delta_{\text{even}} - \delta_{\text{odd}} = \pi/2$ or $3\pi/2$

### $A_1, A_2$ amplitudes

\[ A_{CP} \propto \sin(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2) \]

not sensitive if $\delta_1 - \delta_2 = 0$ or $\pi$

$\delta =$ strong phase, $\phi =$ weak phase

- Measure $\Delta A_{CP} = A_{CP} (\Lambda_b^0 \rightarrow pK^- \mu^+ \mu^-) - A_{CP} (\Lambda_b^0 \rightarrow J/\psi pK^-)$
- $\Delta A_{CP} = (-3.5 \pm 5.0 \text{ (stat)} \pm 0.2 \text{ (syst)}) \times 10^{-2} \rightarrow$ no significant CPV
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$: S-wave pollution

- S wave: $K^+\pi^-$ doesn’t come from $K^{*0}$ (P-wave) but from spin 0 configuration
- Introduces additional terms in decay amplitude

$$\frac{1}{d(\Gamma + \tilde{\Gamma})/dq^2} \frac{d^3(\Gamma + \tilde{\Gamma})}{d\tilde{\Omega}} \bigg|_{S+P} = (1 - F_S) \left(\frac{1}{d(\Gamma + \tilde{\Gamma})/dq^2} \frac{d^3(\Gamma + \tilde{\Gamma})}{d\tilde{\Omega}} \bigg|_P + \frac{3}{16\pi} F_S \sin^2 \theta_\ell + \text{S-P interference} \right)$$

$$\frac{1}{d(\Gamma + \tilde{\Gamma})/dq^2} \frac{d(\Gamma + \tilde{\Gamma})}{d\cos \theta_i d\cos \theta_K d\phi} \bigg|_{S+P} = (1 - F_S) \left(\frac{1}{d(\Gamma + \tilde{\Gamma})/dq^2} \frac{d(\Gamma + \tilde{\Gamma})}{d\cos \theta_i d\cos \theta_K d\phi} \bigg|_P + \frac{3}{16\pi} \left[ F_S \sin^2 \theta_\ell + S_{S1} \sin^2 \theta_\ell \cos \theta_K \right.ight.$$

Expanding S-P interference terms:

$$+ S_{S2} \sin 2\theta_i \sin \theta_K \cos \phi$$
$$+ S_{S3} \sin \theta_i \sin \theta_K \cos \phi$$
$$+ S_{S4} \sin \theta_i \sin \theta_K \sin \phi$$
$$+ S_{S5} \sin 2\theta_i \sin \theta_K \sin \phi \bigg].$$

- To determine $F_S$ more precisely, exploit difference in $m_{K^+\pi^-}$ mass shape between P-, S-wave and fit simultaneously to $m_{K^+\pi^-}$
- $m_{K^+\pi^-}$ line shape in S-wave: LASS model (Nucl. Phys. B296 (1988) 493), P-wave, Breit-Wigner
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$: systematics

- Analysis statistically dominated (and still will be in Run 2)

<table>
<thead>
<tr>
<th>Source</th>
<th>$F_L$</th>
<th>$S_{3-S_9}$</th>
<th>$A_{3-A_9}$</th>
<th>$P_{1-P_8}'$</th>
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</thead>
<tbody>
<tr>
<td>Acceptance stat. uncertainty</td>
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<td>&lt; 0.01</td>
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<td>Data-simulation differences</td>
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<td>$m(K^+\pi^-)$ model</td>
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<td>&lt; 0.01</td>
<td>&lt; 0.03</td>
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<td>Background model</td>
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<td>&lt; 0.02</td>
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<tr>
<td>$m(K^+\pi^-\mu^+\mu^-)$ model</td>
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<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
<td>&lt; 0.02</td>
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<tr>
<td>Det. and prod. asymmetries</td>
<td>–</td>
<td>–</td>
<td>&lt; 0.01</td>
<td>&lt; 0.02</td>
</tr>
</tbody>
</table>
Definition of $J_i$ terms in decay rate (the complex amplitudes are the terms which are sensitive to the Wilson coefficients):

\[
\begin{align*}
J_1^q &= \frac{\left(2 + \beta^2_\mu\right)}{4} \left[|A_{\perp 0}|^2 + |A_{\parallel 0}|^2 + (L \rightarrow R)\right] + \frac{4m^2_\mu}{q^2} \Re(A_{\perp 0}A_{\perp R} + A_{\parallel 0}A_{\parallel R}) \\
J_2^q &= |A_{\perp 0}|^2 + |A_{\parallel 0}|^2 + \frac{4m^2_\mu}{q^2} \left[|A_{\mu}|^2 + 2\Re(A_{\perp 0}A_{\perp R})\right] \\
J_3^q &= \frac{\beta^2_\mu}{4} \left[|A_{\perp 0}|^2 + |A_{\parallel 0}|^2 + (L \rightarrow R)\right] \\
J_4^q &= \beta^2_\mu \left[\Re(A_{\perp 0}A_{\perp R}) + (L \rightarrow R)\right] \\
J_5^q &= \sqrt{2}\beta_\mu \left[\Re(A_{\perp 0}A_{\perp R}) - (L \rightarrow R)\right] \\
J_6^q &= 2\beta_\mu \left[\Re(A_{\parallel 0}A_{\parallel R}) - (L \rightarrow R)\right] \\
J_7^q &= \sqrt{2}\beta_\mu \left[\Im(A_{\perp 0}A_{\perp R}) - (L \rightarrow R)\right] \\
J_8^q &= \frac{\beta^2_\mu}{\sqrt{2}} \left[\Im(A_{\perp 0}A_{\perp R}) + (L \rightarrow R)\right] \\
J_9^q &= \beta^2_\mu \left[\Im(A_{\parallel 0}A_{\parallel R}) + (L \rightarrow R)\right]
\end{align*}
\]

with $\beta^2_\mu = (1 - 4m(\mu)^2/q^2)$. The angular distribution therefore depends on 7 $q^2$ dependent complex amplitudes ($A_{0,R}^{L,R}$, $A_{\parallel 0,R}^{L,R}$, $A_{\perp 0,R}^{L,R}$, and $A_i$) corresponding to different polarisation states of the $B \rightarrow K^*V^*$ decay.

define CP-averaged observables $S_i$ and CP-violating observables $A_i$ according to

\[
S_i = \frac{J_i + \bar{J}_i}{(d\Gamma + d\bar{\Gamma})/dq^2}
\]

\[
A_i = \frac{J_i - \bar{J}_i}{(d\Gamma + d\bar{\Gamma})/dq^2}.
\]
The LHCb detector

The LHCb detector is a single arm spectrometer which covers the forward region at LHC.

\[ \Delta p/p \sim 0.4\% \text{ at } 5 \text{ GeV}, \ \sigma_{IP} = 20 \ \mu m \text{ for high } p_T \text{ tracks.} \]

**π/K separation:** \( \epsilon_K \sim 90\%, \ 5\% \pi \rightarrow K \) mis-id.

**π/μ separation:** \( \epsilon_\mu \sim 97\%, \ 1-3\% \pi \rightarrow K \) mis-id.
The minimal flavour violation hypothesis

- The excellent agreement with theory of flavour measurements places stringent constraints on the mass scale, $\Lambda$, of new physics $\rightarrow$ if new physics is assumed to have a generic flavour structure of $\mathcal{O}(1) \rightarrow \Lambda$ as high as $10^4$ TeV (Ann.Rev.Nucl.Part.Sci.60:355, 2010)

- The MFV hypothesis offers solution to this flavour problem:
  Assume NP flavour structure = SM flavour structure

- Comparing the CKM elements obtained via loop and tree level processes tests the MFV hypothesis.