Rare b and c decays at LHCb

Maximilian Schlupp
on behalf of the LHCb collaboration,

HQL, 26th May 2016
Blacksburg VA
The $b \rightarrow s\ell^+\ell^-$ system

- Today’s focus: $b \rightarrow s\ell^+\ell^-$ decays

- Standard model: Flavor changing neutral currents (FCNC) forbidden on tree-level

- New heavy particles can contribute virtually to the tree or loop-level
  - Can modify branching fractions and angular observables

2016-05-26

Maximilian Schlupp, Rare $b$ and $c$ decays
The $b \rightarrow s l^+ l^-$ system

• Today’s focus: $b \rightarrow s l^+ l^-$ decays

• Model independent description: effective field theory

\[ \mathcal{H}_{\text{eff}} \propto G_F V_{tb} V_{ts}^* \sum_i C_i \mathcal{O}_i \]
The $b \to s l^+ l^-$ system

- Today’s focus: $b \to s l^+ l^-$ decays
- Model independent description: effective field theory

$$\mathcal{H}_{\text{eff}} \propto G_F V_{tb} V_{ts}^* \sum_i C_i O_i$$

Effective couplings (Wilson coefficients)

Local Operators
The $b \to s \ell^+ \ell^-$ system

- Today’s focus: $b \to s \ell^+ \ell^-$ decays

- Model independent description: effective field theory

\[ \mathcal{H}_{\text{eff}} \propto G_F V_{tb} V^*_{ts} \sum_i C_i \mathcal{O}_i \]

"New Physics" contributions:

\[ \Delta \mathcal{H}^{NP} \propto \frac{\epsilon}{\Lambda_{NP}^2} \mathcal{O}_i \]

Effective couplings (Wilson coefficients)

Local Operators

NP coupling

NP scale
The $b \to s l^+ l^-$ system

- Today’s focus: $b \to s l^+ l^-$ decays

- Model independent description: effective field theory

The $b \to s l^+ l^-$ system provides an excellent laboratory for precision tests of the SM

$$H_{eff} \propto G_F V_{tb} V_{ts}^* \sum_i C_i O_i$$

$$\Delta H^{NP} \propto \epsilon \Lambda_{NP}^2 O_i$$

New Physics” contributions:

Effective couplings
(Wilson coefficients)

Local Operators

NP coupling

NP scale
The $b \rightarrow s l^+ l^-$ system

- Today’s focus: $b \rightarrow s l^+ l^-$ decays

- Model independent description: effective field theory

\[ \mathcal{H}_{eff} \propto G_F V_{tb}V_{ts}^* \sum_i C_i \mathcal{O}_i \]

- Photon penguin
- EW penguin
- (Pseudo-)scalar penguin

$C_7$
$C_9$ (vector)
$C_{10}$ (axial-vector)
$C_S(P)$
The $b \rightarrow s l^+ l^-$ system

- Today’s focus: $b \rightarrow s l^+ l^-$ decays

- Model independent description: effective field theory

$$H_{\text{eff}} \propto G_F V_{tb} V_{ts}^* \sum_i C_i \mathcal{O}_i$$

$B \rightarrow X_s \ l^+ l^-$  $B^{0}_{(s)} \rightarrow l^+ l^-$

- Photon penguin  $C_7$  ✓  ✗
- EW penguin  $C_9$  ✓  ✗
- (Pseudo-)scalar penguin  $C_{10}$  ✓  ✓
- $C_{S(P)}$  ✓  ✓
First observation of $B_s^0 \rightarrow \mu^+ \mu^-$

- Extremely rare b-hadron decay
  - Flavour changing neutral current
  - Helicity suppressed

- Purely leptonic: experimentally & theoretically clean

- SM prediction [Bobeth et al, PRL 112 (2014) 101801]
  
  \[
  \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.66 \pm 0.23) \times 10^{-9}
  \]
  
  \[
  \mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (1.06 \pm 0.09) \times 10^{-10}
  \]

- New physics sensitivity w.r.t. SM axial-vector current:
  - Possible new scalar or pseudoscalar contributions

\[
\mathcal{B} \propto \left(1 - \frac{4m_\mu^2}{M_B^2}\right) |C_S - C_S'|^2 + \left|(C_P - C_P') + \frac{2m_\mu}{M_B^2} (C_{10} - C_{10}')\right|^2
\]
First observation of $B_s^0 \rightarrow \mu^+ \mu^-$

- First joined analysis of LHC data by two experiments
  - Simultaneous fit to LHCb and CMS data
- First observation of $B_s^0 \rightarrow \mu^+ \mu^-$
  - 6.2$\sigma$ significance (expected 7.2$\sigma$)
  \[ \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9} \]
- First evidence of $B^0 \rightarrow \mu^+ \mu^-$
  - 3.0$\sigma$ significance (expected 0.8$\sigma$)
  \[ \mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10} \]

ATLAS result: Jaroslav, after the coffee
Angular analysis of $B^0 \to K^* \mu^- \mu^+$

- Additional outgoing particle
  - No helicity suppression
  - Allows vector contributions (esp. photon) instead of only axial-vector
  - Sensitive to $C_7$, $C_9$, $C_{10}$

- Full angular analysis of $B^0 \to K^* \mu^- \mu^+$ decays
Angular analysis of $B^0 \rightarrow K^* \mu^- \mu^+$

- Full angular analysis of $B^0 \rightarrow K^* \mu^- \mu^+$ decays
  - Parametrize decay in helicity angles $\vec{\Omega} = (\theta_L, \theta_K, \phi)$ and $q^2 = m^2_{\mu \mu}$

→ Full 4D angular acceptance

\[
\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^3(\Gamma + \bar{\Gamma})}{d\vec{\Omega}} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_L \right. \\
- F_L \cos^2 \theta_K \cos 2\theta_L + S_3 \sin^2 \theta_K \sin^2 \theta_L \cos 2\phi \\
+ S_4 \sin 2\theta_K \sin 2\theta_L \cos \phi + S_5 \sin 2\theta_K \sin \theta_L \cos \phi \\
+ \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_L + S_7 \sin 2\theta_K \sin \theta_L \sin \phi \\
+ S_8 \sin 2\theta_K \sin 2\theta_L \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_L \sin 2\phi \right]
\]
Angular analysis of $B^0 \rightarrow K^* \mu^- \mu^+$

- Full angular analysis of $B^0 \rightarrow K^* \mu^- \mu^+$ decays
  - Parametrize decay in helicity angles $\Omega = (\theta_l, \theta_K, \phi)$ and $q^2 = m_{\mu\mu}^2$

→ Full 4D angular acceptance

Set of coefficients $F_L, A_{FB}, S_i$ depending on Wilson coefficients $C_7, C_9, C_{10}$ and $B^0 \rightarrow K^*$ form factors

→ Measure in bins of $q^2$

$\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^3(\Gamma + \bar{\Gamma})}{d\Omega} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell 
- F_L \cos^2 \theta_K \cos 2\theta_\ell + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi 
+ S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi 
+ \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_\ell + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi 
+ S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right]$
Angular analysis of $B^0 \rightarrow K^*\mu^-\mu^+$

- Use $K\pi\mu\mu$ invariant mass as discriminating variable
  - Veto charmonium resonances in $q^2$ region

Control channel: $B^0 \rightarrow J/\psi K^*$
About 350k events

Signal channel: $B^0 \rightarrow K^*\mu^-\mu^+$
About 2400 events in Full LHC Run 1 data

- Unbinned maximum likelihood fit to $K\pi\mu\mu$ mass and three decay angles
  - Fit $K\pi$ mass simultaneously to constrain S-wave contribution
Angular analysis of $B^0 \rightarrow K^* \mu^- \mu^+$

- First measurement of the full set of angular observables

Citations:
- LHCb [JHEP 02 (2016) 104]
- CMS [PLB 753 (2016) 424]
- BaBar [PRD 93 (2016) 052015]
- CDF [PRL 108 (2012) 081807]
- Belle [PRL 103 (2009) 171801]
Angular analysis of $B^0 \rightarrow K^* \mu^- \mu^+$

- First measurement of the full set of angular observables

  $P'_5 = S'_5 / \sqrt{F_L(1 - F_L)}$

- Disentangle form factor from short distance physics effects?
  → Create ratio of observables with minimal form factor dependence, e.g. [S. Descotes-Genon et al., JHEP 12 (2014) 125]

LHCb [JHEP 02 (2016) 104]
CMS [PLB 753 (2016) 424]
BaBar [PRD 93 (2016) 052015]
CDF [PRL 108 (2012) 081807]
Belle [PRL 103 (2009) 171801]
Angular analysis of $B^0 \rightarrow K^* \mu^- \mu^+$

- Less form factor dependent variable
  \[ P'_5 = \frac{S_5}{\sqrt{F_L(1 - F_L)}} \]

- Local discrepancy of $\sim 3\sigma$ in two $q^2$ bins

- Global analysis of the $B^0 \rightarrow K^* \mu^- \mu^+$ decay topology finds tension of $3.4\sigma$ w.r.t. the SM

- Full LHC Run 1 data confirms tension in $P'_5$ from LHCb 1/fb measurement

- If tensions are due to “real” physical effects
  \[ \Rightarrow \text{observe discrepancies in other } b \rightarrow s \text{ decays} \]
Angular analysis of $B^0 \to K^* \mu^- \mu^+$

- Large class of possible $b \to s$ transitions
- Several “tensions”, but individually not significant

What can we learn from the “big picture”???

→ Perform global analysis
Global fit to combined $b \rightarrow s$ observables

- Combined $b \rightarrow s$ data: 88 measurements by 6 experiments
  - $B^0 \rightarrow K^* \mu^- \mu^+$
  - $B_s^0 \rightarrow \mu^- \mu^+$
  - $B \rightarrow X_s \mu^- \mu^+$
  - $B \rightarrow X_s \gamma$

- Separate SM from “new physics” (NP) effects

\[ \mathcal{H}_{eff} \propto \sum_i \left( C_i^{SM} + C_i^{NP} \right) O_i \]
Global fit to combined $b \rightarrow s$ observables

- Combined $b \rightarrow s$ data: 88 measurements by 6 experiments
  - $B^0 \rightarrow K^*\mu^-\mu^+$
  - $B_s^0 \rightarrow \mu^-\mu^+$
  - $B \rightarrow X_s\mu^-\mu^+$
  - $B \rightarrow X_s\gamma$

- Separate SM from “new physics” (NP) effects

\[ H_{\text{eff}} \propto \sum_i \left( C_i^{SM} + C_i^{NP} \right) \mathcal{O}_i \]

Global fit favours non-SM vector-like contribution (3–5σ)

[Descotes-Genon et al., arXiv:1510.04239]

Global fit to combined $b \to s$ observables

- Combined $b \to s$ data: 88 measurements
  - $B^0 \to K^*\mu^-\mu^+$
  - $B_s^0 \to \mu^-\mu^+$
  - $B \to X_s\mu^-\mu^+$
  - $B \to X_s\gamma$

- “Clearly new Physics”?

- Separate SM from “new physics” (NP) effects

\[ \mathcal{H}_{\text{eff}} \propto \sum_i \left( \alpha^{SM}_i - \alpha^{NP}_i \right) C_i \]

What can cause this??

- Not well-known QCD contributions?

Global fit favours non-SM vector-like contribution

More data & theoretical work necessary
Rare charm decays

beautiful
Search for $D^0 \rightarrow e^- \mu^+$ decays

- The observation of lepton-flavor violation would be a striking evidence for “new physics”

- Search for lepton-flavor violation in the charm-sector
  - In RPV SUSY: $O(\lesssim 10^{-6})$ [Burdman et al., PRD 66 (2002) 014009]

- Exploit small $\Delta m$ in $D^{*+} \rightarrow D^0 \pi^+$ decays to suppress background

- Challenge: mis-identified $D^0 \rightarrow \pi^- \pi^+$ background

- Simultaneous fit to $\Delta m$ and $m(e^+\mu^-)$ in three bins of a multivariate classifier
  - No signal found \rightarrow limit (CLs method)

\[ \mathcal{B}(D^0 \rightarrow e^\pm \mu^\mp) < 1.3 \times 10^{-8} \text{ at 90\% CL} \]
Summary

- The rich and flavorful observables in rare b and c decays provide an excellent laboratory to test the SM

- Several interesting anomalies observed in the $b \rightarrow s l^+ l^-$ system
  - More data & theoretical work is needed to conclude

- Additional deviations in lepton-flavor universality tests observed
  - Talk by Anna Lupato, tomorrow, 10.55 am

- Interesting flavor data is coming
  - LHCb Run 2 → tripling the dataset
  - But also competition is good for the business

Most stringent limits

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \rightarrow \mu^+ \mu^-$</td>
<td>$&lt; 6.2 \times 10^{-9}$</td>
</tr>
<tr>
<td>$D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$</td>
<td>$&lt; 5.5 \times 10^{-7}$</td>
</tr>
<tr>
<td>$D^+ \rightarrow \pi^+ \mu^+ \mu^-$</td>
<td>$&lt; 7.3 \times 10^{-8}$</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow \pi^+ \mu^+ \mu^-$</td>
<td>$&lt; 4.1 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

LHCb, PLB 725 (2013) 15
LHCb, PLB 728 (2014) 234
LHCb, PLB 724 (2013) 203
Congratulations to our colleagues of SuperKEKB & Belle2!

The SuperKEKB accelerator has achieved the “first turns” of positron and electron beams! [kek.jp/en/NewsRoom/Re…](kek.jp/en/NewsRoom/Re…)

There are decades of fascinating flavor-physics to come!
Backup
Angular analysis of $B^0 \rightarrow K^* \mu^- \mu^+$

- First full angular analysis: measurement of the full set of CP-averaged & CP-asymmetry observables...

- SM predictions:
  - [Altmannshofer & Straub, EPJC 75 (2015) 382]
First observation of $D^0 \rightarrow K^- \pi^+ \mu^- \mu^+$

- Similar analyses possible in the charm-sector
  - E.g.: $c \rightarrow u$ FCNCs
    - $D^0 \rightarrow \pi^- \pi^+ \mu^- \mu^+$
    - $D^0 \rightarrow K^- K^+ \mu^- \mu^+$

- Important reference channel is $D^0 \rightarrow K^- \pi^+ \mu^- \mu^+$

- First measurement of the branching fraction of $D^0 \rightarrow K^- \pi^+ \mu^- \mu^+$ decays in the $q^2$ region around the $\rho/\omega$ resonances

$$B(D^0 \rightarrow K^- \pi^+ \mu^+ \mu^-) = (4.17 \pm 0.12\,\text{(stat)} \pm 0.40\,\text{(syst)}) \times 10^{-6}$$

- First step towards $c \rightarrow u$ FCNCs measurements
LHCb & Belle II—Healthy interplay

- $B_s$ System
  - CPV in $J/\psi\phi$, $\phi\phi$
  - CPV in Mixing
  - $B \rightarrow \mu\mu$

- CKM phase $\gamma$ in $B \rightarrow DK$
- CPV in $B_d$
- $B \rightarrow X_s \pi$ (exclusive)
- $B \rightarrow X_\gamma$ (exclusive)
- Charm physics
- Semi-leptonic $B$ decays

- $\tau$ - physics: LFV
  - $B \rightarrow D, D^* \tau\nu$

- $B \rightarrow X_s \pi$ (inclusive)
- $B \rightarrow X_\gamma$ (inclusive)
- $B \rightarrow \tau\nu, \mu\nu$
- $B \rightarrow K^{*}\nu\nu, B \rightarrow \nu\nu$

“$B_s$ & charged tracks”

Important cross checks

“inclusive & neutrals”