Rare decays at LHCb

Fatima Soomro
On behalf of the LHCb collaboration

Presented at DISCRETE 2014: Fourth Symposium on Prospects in the Physics of Discrete Symmetries, 2-6 December 2014, King’s College London
Rare decays

- Decays involving $b \rightarrow s$ quark transitions (also $c \rightarrow u$ and $s \rightarrow d$)
- Within the Standard Model (SM) only the *charged current* mediates flavour changing transitions at tree level

- Flavour changing neutral currents (FCNC) are *only* allowed via loop diagrams
  - Contribution in SM suppressed
  - Sensitive to NP particles contributing to the loop

A wider overview of LHCb activities: N. Harnew in Friday’s plenary session
Rare decays: operators and *Wilson coefficients*

\[ H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \left[ C_i(\mu) O_i(\mu) + C_i'(\mu) O_i'(\mu) \right] \]

- **Decay rates** e.g. in $B_{(s)} \rightarrow \mu^+ \mu^-$, $D^0 \rightarrow \mu^+ \mu^-$ etc
- **Lorentz structure** via angular distributions in $B \rightarrow \ell^+ \ell^- K^{(*)}$ and photon polarization in $B \rightarrow X_s \gamma$ decays
The LHCb detector [J. Instrum. 3 (2008) S08005]

A dedicated flavour physics experiment at the LHC.

Has recorded 3 fb$^{-1}$ of luminosity from $pp$ collisions at 7 and 8 TeV

- Precise vertex reconstruction: a dedicated silicon detector (VELO) around the $pp$ interaction point
- Excellent particle identification: $5\%$ $\pi \rightarrow K$ rate for $95\%$ $K$ identification efficiency
- Clean muon identification: $\pi \rightarrow K$ rate of $1\%$ for $98\%$ $\mu$ identification efficiency
- Excellent mass resolution: typically 7-20 MeV

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Rare decays at LHCb

04 Dec 14
1 Very rare decays

2 $B \to \ell^+ \ell^- K^{(*)}$ decays

3 $\gamma$ polarization in $b \to s \gamma$
$B_s \rightarrow \mu^+ \mu^-$ and $B^0 \rightarrow \mu^+ \mu^-$
Very rare decays

$B_s \to \mu^+ \mu^-$ and $B^0 \to \mu^+ \mu^-$

CKM and helicity suppressed in the SM, theory prediction:

$$\begin{align*}
BR(B_s \to \mu^+ \mu^-) &= (3.65 \pm 0.23) \times 10^{-9} \\
BR(B^0 \to \mu^+ \mu^-) &= (1.06 \pm 0.09) \times 10^{-10}
\end{align*}$$

Bobeth et al. PRL 112 101801 (2014)

Branching fraction can be significantly enhanced in models with new scalar or pseudoscalar contributions, e.g. models with extended Higgs sector
**B_{(s)}^0 → μ^+μ^- analysis strategy**

Analysis strategy shared by many rare decay analyses at LHCb

- Perform analysis in bins of dimuon invariant mass and a multivariate classifier (BDT) which rejects combinatorial background
  ⇒ BDT is calibrated on a $B_{(s)}^0 → h^+h'^-$ data sample

- Particle identification cuts to reject specific B (or D) decays

- BR normalized to well known channels: $B^+ → J/\psi K^+$ and $B^0 → K^+\pi^-$

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Full likelihood combination of LHCb and CMS data (1/3)

Highlights of the combination (arXiv:1411.4413)

- The two datasets are combined and treated as a “single” experiment
- Simultaneous fit in 8 BDT bins (LHCb) and 12 categories (CMS)
- Shared parameters
  - Branching ratios of the signal ($B_s \rightarrow \mu^+\mu^-$, $B^0 \rightarrow \mu^+\mu^-$) and normalization channel ($B^+ \rightarrow J/\psi K^+$)
  - The ratio of hadronization fraction $f_s/f_d$
- $\Delta \Gamma$ correction taken into account by CMS (LHCb already did it)
- $\Lambda_b \rightarrow p\mu\nu$ added to the fit with updated BR and simulation

**LHCb analysis:** Phys. Rev. Lett. 111 (2013) 101805

**CMS analysis:** Phys. Rev. Lett. 111 (2013) 101804
Measured branching ratios v/s theory prediction

\[ BR(B_s \rightarrow \mu^+ \mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9} \]

\[ BR(B^0 \rightarrow \mu^+ \mu^-) = (3.65 \pm 0.23) \times 10^{-9} \]

\[ BR(B_s \rightarrow \mu^+ \mu^-) = (3.65 \pm 0.23) \times 10^{-9} \]

\[ BR(B^0 \rightarrow \mu^+ \mu^-) = (1.06 \pm 0.09) \times 10^{-10} \]
Full likelihood combination of LHCb and CMS data (3/3)

The golden ratio

\[
R = \frac{BR(B^0 \to \mu^+ \mu^-)}{BR(B_s \to \mu^+ \mu^-)}
\]

The $B^{0}_{(s)} \to \mu^+ \mu^-$ result rules out significant SUSY phase space and places constraints on any new (pseudo)scalar particles [e.g. arXiv:1310.2556]
Rare decay searches
Rare strange decays

- Rare strange decays, mediated by an $s \to d$ transition have the strongest CKM suppression:

\[ A = A_0 \left( C_{SM} \frac{1}{M_W^2} + C_{NP} \frac{1}{\Lambda^2} \right) \]

where $C_{SM} \sim V_{ts} V_{td} \sim 10^{-4}$


\[ \text{BR}(K_s \to \mu^+ \mu^-) = (5.1 \pm 1.5) \times 10^{-12} \]

- LHCb search with $1 \text{ fb}^{-1}$ of data:

\[ \text{BR}(K_s \to \mu^+ \mu^-) < 9(11) \times 10^{-9} \text{ @90(95)\% CL} \]

JHEP 01 (2013) 090
Rare strange decays

• LHCb can probe the more interesting region of $BR(K_s \rightarrow \mu^+\mu^-) < 10^{-10}$
  ⇒ Trigger development required

• HyperCP observed three $\Sigma^+ \rightarrow p^+\mu^+\mu^-$ candidates all with the same $m_{\mu^+\mu^-}$
  PRL 94, 021801 (2005)

⇒ light higgs, dark boson... ?
⇒ LHCb aims to confirm/reject this observation
Rare charm decays

D mesons provide a unique window into **up type FCNCs**

- SM: $10^{-13} < BR(D^0 \to \mu^+ \mu^-) < 6 \times 10^{-11}$
- Could be up to $10^{-9}$ in some NP models
Rare charm decays

D mesons provide a unique window into **up type FCNCs**

- SM: $10^{-13} < BR(D^0 \rightarrow \mu^+\mu^-) < 6 \times 10^{-11}$
  

- Could be upto $10^{-9}$ in some NP models

**LHCb analysis**

- Use $D^{*+}$ tagged sample of $D^0(\mu^+\mu^-)$
- BDT to reject combinatorial background
- Yield from 2D fit to $m(D^0)$ and $\Delta m(D^{*+} - D^0)$
- Normalize to $D^0 \rightarrow \pi^+\pi^-$

**LHCb, 1 fb$^{-1}$** [PLB 725(2013) 15-24]: $BR(D^0 \rightarrow \mu^+\mu^-) < 6.2(7.6) \times 10^{-9}$ at 90(95)% CL
Rare charm decays

\[ D^+ \rightarrow \pi^+ \mu^+ \mu^- \text{ PLB 724(2013) 203-212} \]

\[ D^+ \rightarrow \pi^- \mu^+ \mu^+ \text{ PLB 724(2013) 203-212} \]

- \( \rho, \omega \) and \( \phi \) resonances in the \( \mu^+ \mu^- \) system
- Search for signal performed in
  - \( [250 < m_{\mu^+\mu^-} < 252] \) and
  - \( [1250 < m_{\mu^+\mu^-} < 2000] \) MeV/c^2
- Lepton number violating decay; can be mediated by Majorana neutrinos
- Analysis performed in bins of \( m_{\pi^+\mu^-} \)
Very rare decays

$B \rightarrow \ell^+ \ell^- K(\ast)$ decays

$\gamma$ polarization in $b \rightarrow s \gamma$

Summary

Rare charm decays

$D^+ \rightarrow \pi^+ \mu^+ \mu^-$ PLB 724(2013) 203-212

$D^+ \rightarrow \pi^- \mu^+ \mu^+$ PLB 724(2013) 203-212

Results at 90 (95) % CL

$BR(D^+ \rightarrow \pi^+ \mu^+ \mu^-) < 7.3(8.3) \times 10^{-8}$

$BR(D_s^+ \rightarrow \pi^+ \mu^+ \mu^-) < 4.1(4.8) \times 10^{-7}$

$BR(D^+ \rightarrow \pi^- \mu^+ \mu^+) < 2.2(2.5) \times 10^{-8}$

$BR(D_s^+ \rightarrow \pi^- \mu^+ \mu^+) < 1.2(1.4) \times 10^{-7}$

A factor of 50 improvement upon previous results ⇒
### Other very rare decays at LHCb

<table>
<thead>
<tr>
<th>Decay</th>
<th>NP scenario tested</th>
<th>95% upper limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s \rightarrow \mu\mu\mu\mu$</td>
<td>Some SUSY scenarios</td>
<td>$&lt; 1.6 \times 10^{-8}$</td>
<td>(PRL. 110, 211801)</td>
</tr>
<tr>
<td>$B_d \rightarrow \mu\mu\mu\mu$</td>
<td>Some SUSY scenarios</td>
<td>$&lt; 6.6 \times 10^{-9}$</td>
<td>(PRL. 110, 211801)</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu\mu\mu$</td>
<td>LFV</td>
<td>$&lt; 5.6 \times 10^{-8}$</td>
<td>(arXiv 1409.8548)</td>
</tr>
<tr>
<td>$B_s \rightarrow e\mu$</td>
<td>RPV, Lepto quarks</td>
<td>$&lt; 1.4 \times 10^{-9}$</td>
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<tr>
<td>$B_d \rightarrow e\mu$</td>
<td>RPV, Lepto quarks</td>
<td>$&lt; 3.7 \times 10^{-9}$</td>
<td>(PRL. 111, 141801)</td>
</tr>
<tr>
<td>$B \rightarrow X\mu^+\mu^+$</td>
<td>4th generation majorana $\nu$ as function of $m_\nu$</td>
<td></td>
<td>See Rev. D 85, 112004</td>
</tr>
</tbody>
</table>
### Introduction

Very rare decays

$B \rightarrow \ell^+ \ell^- K^{(*)}$ decays

$\gamma$ polarization in $b \rightarrow s \gamma$

### Summary

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Rare decays at LHCb

04 Dec 14
$B^0_d \to K^{*0} \mu^+ \mu^-$

The decay can be described by three angles ($\theta_l$, $\theta_K$, $\phi$) and the dimuon invariant mass squared ($q^2$)

✓ The decay rate an be written as a function of the $K^{*0}$ polarization amplitudes
⇒ observables measure the interference between them
✓ Sensitive to $O_7$, $O_9$ and $O_{10}$ and their right handed counter parts
✓ Construct observables where form factor uncertainties are minimal
Very rare decays

$B_d^0 \rightarrow K^*\mu^+\mu^-$ Angular analysis

Using a folding technique over the $\phi$ angle, the decay rate can be written as a function of only 4 variables (compared to 12)

- $A_{FB}$: The dimuon forward backward asymmetry
- $F_L$: Fraction of longitudinal $K^*$ polarization
- $A^2_T/S_3$: Asymmetry sensitive to the (virtual) photon polarization
- $A_9$: A CP asymmetry

Powerful (and many) probes of NP. Example from Generalized Supersymmetric Model

Example of theory predictions (From JHEP 0901:019,2009)
Very rare decays

\[ B_d^{0} \rightarrow K^{*0} \mu^+ \mu^- \] results

Theory predictions from JHEP 07 (2011) and references therein.

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Rare decays at LHCb
$B_d^0 \rightarrow K^{*0} \mu^+ \mu^-$ angular analysis - II

- Can introduce different angular foldings to access different angular terms
- Observables where form-factor uncertainties cancel at leading order

$$P'_{4,5} = S_{4,5}/\sqrt{F_L(1-F_L)}$$

**A local discrepancy of 3.7σ observed in $P'_{5}$. Probability to observe at least one bin as discrepant or more is 0.5%**
Explaining the $P'_5$ anomaly [in progress]

- **LHCb measurement was followed by a lot of theoretical activity**
- Conclusions differ because different inputs have been used in these analyses
  - e.g. using only high $q^2$ LHCb measurements, the discrepancy becomes smaller

<table>
<thead>
<tr>
<th>Work</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decotes-Genon, Matias, Virto PRD 88 074002 (2013)</td>
<td>Global fit to $b \to s\gamma$ and $b \to sll$ data</td>
</tr>
<tr>
<td></td>
<td>Find a 4.5σ discrepancy from SM. Fit favours $C^{NP}_9 = -1.5$</td>
</tr>
<tr>
<td>Altmannshofer, Straub EPJC 73 2646 (2013)</td>
<td>Global analysis, discrepancy of 3σ, can be described by modified $C_9^{(f)}$. Can be explained by a flavour changing $Z'$</td>
</tr>
<tr>
<td>JHEP 01 (2014) 069</td>
<td>Also favour a $Z'$ but at a higher mass</td>
</tr>
<tr>
<td></td>
<td>The discrepancy becomes 2σ</td>
</tr>
<tr>
<td>Jaeger and Camalich JHEP 05 (2013) 043</td>
<td>Also try to address the size of form factor uncertainties in the large recoil (low $q^2$) region</td>
</tr>
</tbody>
</table>
Differential branching fractions of $B \to K^{(*)}\mu^+\mu^-$

If $C_{9}^{NP} = -1.5$, we expect to see a suppression of the $B \to K^{(*)}\mu^+\mu^-$ rate.

LHCb results from JHEP 08 (2013) 131 and JHEP 06 (2014) 133
Differential branching fractions of $B \rightarrow K^{(*)} \mu^+ \mu^-$

- The decays rates and $P_5'$ seem to be compatible with a negative $C_9^{NP}$
- LHCb has recently observed $c \bar{c}$ contribution in the high $q^2$ region ($\sim 18$ MeV$^2$/c$^4$)
- Open question: are $c \bar{c}$ contributions correctly accounted for in theory predictions?

See arXiv:1406.0566 for an interesting discussion
Lepton universality and $Z'$

- If the $P'_5$ and the differential decay rates are indeed due to a $Z'$, couldprobe its couplings to leptons. Lepton universality requires that:

$$R_K = \frac{\int dB(B^+ \rightarrow K^+\mu^+\mu^-)/dq^2}{\int dB(B^+ \rightarrow K^+e^+e^-)/dq^2} = 1 \pm O(10^{-3})$$

- For the $e^+e^-$ mode, difficult to determine efficiency due to bremstrahlung.  
  ⇒ Take double ratio with respect to the $J/\psi \rightarrow \mu^+\mu^-$ and $J/\psi \rightarrow e^+e^-$ modes

LHCb measurement with 3 fb$^{-1}$

$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$$

⇒ Compatible with the SM at 2.6σ
In near future

Many decay modes and measurements in the pipeline:

- $R_K$ measurement in the $K^*$
- Analysis of $\Lambda_b \to \Lambda \mu^+ \mu^-$ (3 fb$^{-1}$, early 2015)
- Full angular analysis of $B_d \to K^{*0} \mu^+ \mu^-$ (3 fb$^{-1}$, early 2015)
- Angular analysis of $B_s \to \phi \mu^+ \mu^-$ (3 fb$^{-1}$, well advanced)
- ...
Photon polarization in $b \rightarrow s\gamma$ transitions
\[ B_d \to K^{*0} e^+ e^- (1/2) \]

- BR measured with 1 fb\(^{-1}\) \cite{JHEP 05 (2013) 159}
- Huge complimentarity to \( B_d \to K^{*0} \mu^+ \mu^- \) due to the low \( q^2 \) (\( m_{e^+e^-} \)) reach
- Assumption of massless leptons is true in \( B_d \to K^{*0} e^+ e^- \) case!

Angular analysis with 3 fb\(^{-1}\):
- performed in \([0.02^2 < q^2 (m_{e^+e^-}) < 1]\) GeV/c\(^2\)
- use three angles \( \cos \theta_K, \cos \theta_l \) and \( \phi \)
- to measure \( F_L, A_T^{(2)}, A_T^{(Im)} \) and \( A_T^{(Re)} \)

Their relative contribution varies with \( q^2 \)
**Introduction**

Very rare decays

**B → ℓ⁺ ℓ⁻ K(∗) decays**

γ polarization in $b → s γ$

**Summary**

$B_d \rightarrow K^{*0} e^+ e^− (2/2)$

3 fb$^{-1}$ sensitivities from toy MC

<table>
<thead>
<tr>
<th>$\sigma_{\text{stat}}$</th>
<th>$F_L$</th>
<th>$A_T^{\text{Re}}$</th>
<th>$A_T^{(2)}$</th>
<th>$A_T^{\text{Im}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.07</td>
<td>0.17</td>
<td>0.25</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{syst}}$</td>
<td>0.03</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
</tr>
</tbody>
</table>

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**Angular analysis with 3 fb$^{-1}$:**

- performed in $[0.02^2 < q^2 (m_{e^+ e^-}) < 1]$ GeV/$c^2$
- use three angles $\cos \theta_K$, $\cos \theta_l$ and $\phi$
- to measure $F_L$, $A_T^{(2)}$, $A_T^{(\text{Im})}$ and $A_T^{(\text{Re})}$

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Expected for winter conferences 2015!!

angular analysis : $\cos \theta_l$, $\cos \theta_K$, $\tilde{\phi}$
Photon polarization in $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$

Measure the up-down asymmetry of the photon direction in the frame formed by the two pions

Conceptually similar to the P-parity violation experiment of Wu et. al (1956)
LHCb analysis of $B^+ \rightarrow K^+\pi^-\pi^+\gamma$

- Observed over 13000 $B^+$ signal candidates in 3 fb$^{-1}$
- The analysis is performed in bins of background subtracted $m_{K\pi\pi}$
LHCb analysis of $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$  

PRL 112 (2014) 161801

- Combining the absolute $A_{ud}$ in the four bins, the photon polarization is observed to be different from zero at 5.2σ
- Theoretical input required in order to actually measure the value of the polarization and interpret it in terms of New Physics

First experimental observation of a non-zero photon polarization in $b \rightarrow s \gamma$ transition!
Summary

- LHCb is well suited to study rare heavy flavour decays
  ⇒ Large $b$ and $c$ production x-sections, excellent particle identification capability
- Most stringent limits on FCNC decays of up and down type quarks, lepton flavour violation in $B$ and $\tau$ decays
  ⇒ NP phase space is shrinking rapidly
- $B \to \mu^+ \mu^- K^{(*)}$ decays show interesting anomalies ($P_5'$).
  ⇒ Theoretical interpretation is under way
  ⇒ Update of $B_d \to K^*0 \mu^+ \mu^-$ with full statistics coming soon
  ⇒ Analysis of $B_s \to \phi \mu^+ \mu^-$ and the $\tau$ couplings of the $Z'$ and can shed more light
- First ever observation of a non-zero photon polarization in $B^+ \to K^+ \pi^- \pi^+ \gamma$ decays
  ⇒ Theory input required to actually measure the value of the polarization
  ⇒ Photon polarization measurement in $B_s \to \phi \gamma$ coming soon

More results: (Link to LHCb public results page)
**Outlook: LHCb will continue to lead the heavy flavour physics program**

<table>
<thead>
<tr>
<th></th>
<th>Run 1</th>
<th>LHC era</th>
<th>HL-LHC era</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Run 2</td>
<td>Run 3</td>
<td>Run 4</td>
</tr>
<tr>
<td>$B(B^0 \rightarrow \mu^+\mu^-)$/$\overline{B}(\bar{B}^0 \rightarrow \mu^+\mu^-)$</td>
<td>CMS</td>
<td>$&gt;100%$</td>
<td>71%</td>
</tr>
<tr>
<td></td>
<td>LHCb</td>
<td>220%</td>
<td>110%</td>
</tr>
<tr>
<td>$\phi_s(B_s^0 \rightarrow J/\psi\phi)$</td>
<td>ATLAS</td>
<td>0.11</td>
<td>0.05–0.07</td>
</tr>
<tr>
<td></td>
<td>LHCb</td>
<td>0.05</td>
<td>0.025</td>
</tr>
<tr>
<td>$\phi_s(B_s^0 \rightarrow $ $\phi\phi)$</td>
<td>LHCb</td>
<td>0.18</td>
<td>0.12</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>LHCb</td>
<td>7°</td>
<td>4°</td>
</tr>
<tr>
<td></td>
<td>Belle II</td>
<td>—</td>
<td>11°</td>
</tr>
<tr>
<td>$A_T(D^0 \rightarrow K^+K^-)$</td>
<td>LHCb</td>
<td>$3.4 \times 10^{-4}$</td>
<td>$2.2 \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>Belle II</td>
<td>—</td>
<td>$18 \times 10^{-4}$</td>
</tr>
<tr>
<td>$q_0^2 A_{FB}(K^{*0}\mu^+\mu^-)$</td>
<td>LHCb</td>
<td>10%</td>
<td>5%</td>
</tr>
<tr>
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<td>Belle II</td>
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<td>50%</td>
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<tr>
<td>$t \rightarrow qZ$</td>
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<td>...</td>
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</tr>
<tr>
<td></td>
<td>CMS</td>
<td>$100 \times 10^{-5}$</td>
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<tr>
<td>$t \rightarrow q\gamma$</td>
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<td>...</td>
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