Very Rare Decays
at LHCb

Hannah Evans on behalf of the LHCb Collaboration
Beauty Conference, 2 - 6th May 2016
Introduction

Why study very rare decays?

• highly suppressed in the Standard Model
• branching fractions greatly enhanced by new physics models

Outline

→ $B^{0}_{(s)} \rightarrow \mu^{+} \mu^{-}$

→ LFV decays; $B^{0}_{(s)} \rightarrow e^{+} \mu^{-}$ and $\tau^{-} \rightarrow \mu^{-} \mu^{+} \mu^{-}$

→ $B^{0}_{(s)} \rightarrow \mu^{+} \mu^{-} \mu^{+} \mu^{-}$
"$B^0(s) \rightarrow \mu^+ \mu^-$ Motivation"

**In the Standard Model (SM)**

- flavour changing neutral currents, helicity and CKM suppressed
  \[
  \mathcal{B}(B^0_s \rightarrow \mu^+ \mu^-) = (3.66 \pm 0.23) \times 10^{-9} \\
  \mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (1.06 \pm 0.09) \times 10^{-10}
  \]

- progress in Lattice QCD calculations, expect reduced uncertainty to $\sim 3\%$

**Beyond the SM**

- branching fractions enhanced by (pseudo-)scalar contributions
  - indirect search for new physics
  - branching fraction ratio has more precise predictions and probes flavour structure
CMS and LHCb $B^0_{(s)} \rightarrow \mu^+ \mu^-$

Combined Analysis  
[Nature 522, 68, 2015]

Data set

- Run 1 data set; 25 fb$^{-1}$ from CMS, 3fb$^{-1}$ from LHCb

Analysis strategy

- cut based preselection

- data binned by multivariate analysis (MVA) response
  - CMS data split also by year of data taking and barrel/endcap muon detection

- simultaneous fit to invariant mass distributions
  - nuisance parameters shared between CMS and LHCb
CMS and LHCb $B^0(s) \rightarrow \mu^+ \mu^-$

Combined Analysis [Nature 522, 68, 2015]

Analysis strategy

- $B^+ \rightarrow J/\psi K^+$ decay used to normalise observed to produced $B^0$ and $B^0_s$ mesons
- Backgrounds modelled in the fit;
  - combinatorial
  - semi-leptonic; $B^0 \rightarrow \pi^+ \mu^- \nu_\mu$, $B^0_s \rightarrow K^+ \mu^- \nu_\mu$, $\Lambda_b \rightarrow p \mu^- \nu_\mu$, $B^{0(\pm)} \rightarrow \pi^{0(\pm)} \mu^+ \mu^-$
  - mis-identified $B^0(s) \rightarrow h^+ h^-$ decays

Distribution of invariant mass for the six best MVA bins.
$B^0_{(s)} \rightarrow \mu^+ \mu^-$ Results

Branching fraction results

\[ B(B_s^0 \rightarrow \mu^+ \mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9} \text{ at 6.2 } \sigma \]
\[ B(B^0 \rightarrow \mu^+ \mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10} \text{ at 3.0 } \sigma \]

Compatibility with SM at 1.2 $\sigma$ for $B_s^0$ and 2.2 $\sigma$ for $B^0$.

Results for ratio of branching fractions

\[ R = \frac{B(B^0 \rightarrow \mu^+ \mu^-)}{B(B_s^0 \rightarrow \mu^+ \mu^-)} = 0.14^{+0.06}_{-0.08} \]

within 2.3 $\sigma$ of SM prediction.

[Nature 522, 68, 2015]
\( B^0_{(S)} \rightarrow \mu^+ \mu^- \) Future Studies

### Branching fractions

- production cross-section approximately doubled in Run 2
- improve measured precision as theoretical precision increases
- measured \( B^0 \rightarrow \mu^+ \mu^- \) branching fraction \( \sim 4 \) times large than predicted
- current measurements allow new physics at same size as P5’ observed effect

**For P5’ see JHEP 02 (2016) 104, arXiv:1604.04042 and Konstantinos’ talk earlier today.**

### \( B^0_s \rightarrow \mu^+ \mu^- \) effective lifetime

- sensitive to the asymmetry parameter
- independent probe of new physics
- accessible in near future
- LHCb could achieve an uncertainty of 5\% for 46 fb\(^{-1}\) on the effective lifetime

[For P5’ see JHEP 02 (2016) 104, arXiv:1604.04042 and Konstantinos’ talk earlier today.]
Lepton Flavour Violating Decays

- Lepton Flavour Violating (LFV) decays are allowed in the SM in the context of massive neutrinos
  - branching fractions $\sim 10^{-40}$ or less, beyond experimental sensitivity
- beyond the SM theories can greatly enhance LFV decay branching fractions
  - an observation would be unambiguous sign of new physics
- anomalies in electroweak penguins motivate searches for LFV decays
- present searches for $B_{(s)}^0 \rightarrow e^+ \mu^-$ and $\tau^- \rightarrow \mu^- \mu^+ \mu^-$ at LHCb

See talk by Michael Morello on Thursday for LFV in charm decays at LHCb.
$B^0 (s) \rightarrow e^+ \mu^-$


**Theory**
- SM branching fraction $\sim 10^{-54}$
- allowed in BSM theories; SUSY, heavy singlet Dirac neutrinos, Pati-Salam model

**Data set**
- 1.0 fb$^{-1}$ of 7 TeV data from LHCb

**Analysis strategy**
- cut based preselection
- data binned by MVA response
- simultaneous fit to invariant mass in bins
- normalisation channel is $B^0 \rightarrow K^+ \pi^-$
- calibration using decays $J/\psi \rightarrow l^+ l^-$

Lepto-quark coupling present in Pati-Salam model.
$B^0_{(s)} \rightarrow e^+ \mu^-$ Results

Results consistent with background expectations.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Limit</th>
<th>90 % C.L.</th>
<th>95 % C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0_s \rightarrow e^\pm \mu^\mp$</td>
<td>Expected</td>
<td>$1.5 \times 10^{-8}$</td>
<td>$1.8 \times 10^{-8}$</td>
</tr>
<tr>
<td></td>
<td>Observed</td>
<td>$1.1 \times 10^{-8}$</td>
<td>$1.4 \times 10^{-8}$</td>
</tr>
<tr>
<td>$B^0 \rightarrow e^\pm \mu^\mp$</td>
<td>Expected</td>
<td>$3.8 \times 10^{-9}$</td>
<td>$4.8 \times 10^{-9}$</td>
</tr>
<tr>
<td></td>
<td>Observed</td>
<td>$2.8 \times 10^{-9}$</td>
<td>$3.7 \times 10^{-9}$</td>
</tr>
</tbody>
</table>

Upper limit computed with CLs method.
$B^0_{(s)} \rightarrow e^+ \mu^-$ Results

Limits on lepto-quark mass can be computed from branching fraction limits:

$$M_{LQ}(B^0_{s} \rightarrow e^+ \mu^-) > 107 \ (101) \text{ TeV/c}^2 \text{ at 90\% (95\%) C.L.}$$

$$M_{LQ}(B^0 \rightarrow e^+ \mu^-) > 135 \ (125) \text{ TeV/c}^2 \text{ at 90\% (95\%) C.L.}$$

Search for $\tau \rightarrow \mu^- \mu^+ \mu^-$

**In the SM**
- occurs with massive neutrinos
- branching fraction $< 10^{-40}$
- beyond currently experimental sensitivity

**Beyond the SM**
- new physics particles in loops increase decay rates
- tree level decays allowed with new physics particles
- branching fraction up to $\sim 10^{-9} - 10^{-7}$

- large $\tau$ production cross-section at the LHC $\sim 85 \mu b$ at 7 TeV
- clear decay signature
Search for $\tau^{-} \rightarrow \mu^{-} \mu^{+} \mu^{-}$

Data set
- 3fb$^{-1}$ LHCb Run1 data set

Analysis strategy
- cut based preselection
- signal-background discrimination uses
  - MVA for 3-body topological decays
  - MVA for muon identification
  - $\tau$ invariant mass
- simultaneous fit to invariant mass in bins
- normalisation and calibration with $D_s^{-} \rightarrow \phi (\mu^{+} \mu^{-}) \pi^{-}$

\[ \tau \rightarrow \mu^- \mu^+ \mu^- \]

**Results**

- Results consistent with background expectation.
- Observed limit from phase space model:
  \[ \mathcal{B}(\tau \rightarrow \mu^- \mu^+ \mu^-) < 4.6 \times 10^{-8} \] at 90\% (95\%) C.L.
- Limit varies if different BSM mechanism induces LFV, observed limits varies as:
  \[ \mathcal{B}(\tau \rightarrow \mu^- \mu^+ \mu^-) < (4.1 - 6.8) \times 10^{-8} \] at 90\% C.L.
- CLs method used to get the limits.
- LHCb limit not competitive with B-factories, but measurement reduces world limit
Search for $B^0_{(s)} \to \mu^+ \mu^- \mu^+ \mu^-$

In the SM

• strongly suppressed

• resonant decay $B^0_s \to J/\psi(\mu^+ \mu^-)\phi(\mu^+ \mu^-)$

• non-resonant decay $B^0_{(s)} \to \mu^+ \mu^- \gamma(\mu^+ \mu^-)$

Beyond the SM

• significant enhancements

• MSSM allows $B^0_{(s)} \to P(\mu^+ \mu^-)S(\mu^+ \mu^-)$, $S$ and $P$ are sgoldstino particles

• HyperCP Collaboration found evidence for $\Sigma^+ \to p\mu^+ \mu^-$ consistent with $\Sigma^+ \to pP(\mu^+ \mu^-)$ where $m_P = 214.3+/-0.5\text{MeV}/c^2$

$B(B^0_s \to J/\psi(\mu^+ \mu^-)\phi(\mu^+ \mu^-)) = (2.3 \pm 0.9) \times 10^{-9}$

$B(B^0_{(s)} \to \mu^+ \mu^- \gamma(\mu^+ \mu^-)) < 10^{-10}$


Search for $B^{0}_{(s)} \rightarrow \mu^{+}\mu^{-}\mu^{+}\mu^{-}$

Data Set

- 1.0 fb$^{-1}$ of 7 TeV data from LHCb

Analysis Strategy

- cut-based selection, requires 4 well constructed muons
- resonant $B^{0}_{s} \rightarrow J/\psi \phi$ decays removed with mass vetoes and used to optimise selection
- $B^{0} \rightarrow J/\psi (\mu^{+}\mu^{-}) K^{*0}(K^{+}\pi^{-})$ used for normalisation

Invariant mass fit for normalisation mode $B^{0} \rightarrow J/\psi (\mu^{+}\mu^{-}) K^{*0}(K^{+}\pi^{-})$. 

[PRL 110, 211801 (2013)]
Result for $B^0_{(s)} \rightarrow \mu^+\mu^-\mu^+\mu^-$

Results consistent with background expectation;
- one event in $B^0$ mass window
- zero events in $B^0\_S$ mass window

Non-resonant $B^0_{(s)} \rightarrow \mu^+\mu^-\mu^+\mu^-$ phase space model, at 90% (95%) C.L.

$$\mathcal{B}(B^0_{s} \rightarrow \mu^+\mu^-\mu^+\mu^-) < 1.6 (1.2) \times 10^{-8}$$
$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-\mu^+\mu^-) < 6.6 (5.3) \times 10^{-9}$$

Limits for MSSM with $m_{P(S)} = 214.3$ MeV/c$^2$ (2.5 GeV/c$^2$), at 90% (95%) C.L.

$$\mathcal{B}(B^0_{s} \rightarrow PS) < 1.6 (1.2) \times 10^{-8}$$
$$\mathcal{B}(B^0 \rightarrow PS) < 6.3 (5.1) \times 10^{-9}$$

CLs method used to set limits.
Summary

• First observation of $B^0_s \to \mu^+ \mu^-$ and first evidence for $B^0 \to \mu^+ \mu^-$ on the combined CMS and LHCb Run 1 data
  - higher than predicted $B^0$ yield and tension from ratio of branching fractions
  - measured precision leave room for new physics
  ➡ Run 2 will make is clearer; improved $\mathcal{B}(B^0 \to \mu^+ \mu^-)$ and $B^0_s \to \mu^+ \mu^-$ effective lifetime

• Searched for LFV $B^0_{(s)} \to e^+ \mu^-$ at 7 TeV at LHCb
  - no signal observed, stringent lepto-quark lower mass bounds

• Searched for LFV $\tau^- \to \mu^- \mu^+ \mu^-$ on full Run 1 data at LHCb
  - no signal observed, set upper branching fraction bounds

• MSSM sgoldsino particles searched for in $B^0_{(s)} \to \mu^+ \mu^- \mu^+ \mu^-$ at 7 TeV at LHCb
  - limits set for branching fractions and MSSM branching fractions

Very rare decays are statistically limited, Run 2 will significantly improve reach of new physics searches.