Rare decays, radiative decays and $b \rightarrow sll$ transitions at LHCb

Andrew Crocombe,
on behalf of the LHCb collaboration

University of Warwick
Rare decays - Searching for new physics

- Rare decays are rare in the context of the Standard Model (SM)
- Flavour-changing neutral current (FCNC) processes are of particular interest
- They are heavily suppressed and so new physics (NP) can appear at a similar or larger level as SM contributions
- New particles can appear at loop or tree level
- Search both for small deviations in precisely predicted SM processes and for forbidden processes that can only occur through NP

- A rich field with many interesting current anomalies and prospects
- For results on lepton flavour universality see talk by J. Albrecht
$$B_{(s)}^0 \rightarrow \mu^+ \mu^-$$

- A “golden channel” rare decay mode, loop and helicity suppressed in the SM
- Both theoretically and experimentally clean
- Search carried out with 3 fb$^{-1}$ Run 1 and 1.4 fb$^{-1}$ Run 2 data
- Results in the first single experiment observation of $B_s^0 \rightarrow \mu^+ \mu^-$ (with a significance of 7.8σ), first measurement of the $B_s^0 \rightarrow \mu^+ \mu^-$ effective lifetime and sets a limit on $B^0 \rightarrow \mu^+ \mu^-$

\[ \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9} \]
\[ \tau(B_s^0 \rightarrow \mu^+ \mu^-) = 2.04 \pm 0.44 \pm 0.05 \ \text{ps} \]
\[ \mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 3.4 \times 10^{-10} \ \text{[95% C.L]} \]

- All of these are consistent with SM predictions, setting stringent limits on possible NP models

Photon polarisation in $B^{0}_s \rightarrow \phi \gamma$

- First study of photon polarisation in a radiative $B^{0}_s$ decay
- Study carried out with 3 fb$^{-1}$ Run 1 data
- Extract the polarisation parameter $A^\Delta$ from the decay time distribution of events

$A^\Delta = -0.98^{+0.46+0.23}_{-0.52-0.20}$

- Agrees with the SM expectation within 2 standard deviations

$A^\Delta_{SM} = 0.047^{+0.029}_{-0.025}$

Branching fractions in $b \to sll$ decays

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

$B_s^0 \to \phi \mu^+ \mu^-$

$B^0 \to K^0 \mu^+ \mu^-$

$B^+ \to K^+ \mu^+ \mu^-$

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

Cited references:
- JHEP 11 (2016) 047
- JHEP 04 (2017) 142
- JHEP 09 (2015) 179
- JHEP 06 (2014) 133

A. Crocombe

Rare decays, radiative decays and $b \to sll$ transitions

Moriond QCD 2018
Branching fractions in $b \to sll$ decays

- The differential branching fractions of a variety of $b \to sll$ processes all tend to be systematically lower than SM predictions.
- While there is no individually large tension, perhaps this is pointing towards some consistent deviation from the SM?

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

- Four body final state, with the system described by 3 angles and the invariant mass squared of the dimuon system ($q^2$)
- The angular distribution provides access to observables that are sensitive to new physics
- These observables depend on Wilson coefficients and hadronic form factors
- Try to construct ratios of observables with less form factor dependence (e.g. $P'_5$)
- LHCb measurement of $P'_5$ from run 1 data (3 fb$^{-1}$) shows local tensions with the SM at a combined significance of 3.4$\sigma$

[JHEP 02 (2016) 104]
Descotes-Genon et al.
[JHEP 12 (2014) 125]
Altmannshofer and Straub
\[ B^0 \rightarrow K^{*0} \mu^+ \mu^- \] angular analysis

- Four body final state, with the system described by 3 angles and the invariant mass squared of the dimuon system \((q^2)\)
- The angular distribution provides access to observables that are sensitive to new physics
- These observables depend on Wilson coefficients and hadronic form factors
- Try to construct ratios of observables with less form factor dependence (e.g. \(P'_5\))
- LHCb measurement of \(P'_5\) from run 1 data (3 fb\(^{-1}\)) shows local tensions with the SM at a combined significance of 3.4\(\sigma\)

\[ [JHEP 02 (2016) 104] \\
[CMS-BPH-15-008] \\
[ATLAS-CONF-2017-023] \\
[Phys. Rev. Lett. 118, 111801 (2017)] \]
Global fits

- Global fits can be carried out to take into account multiple measurements

- Global fits favour a modified SM vector-current $C_9^{NP}$ up to 4.9σ
- Whether this is new physics or the effect of underestimated QCD uncertainties remains to be seen

$b \rightarrow dll$ transitions

- Further suppressed in SM by CKM factor $|V_{td}/V_{ts}|^2$ compared to $b \rightarrow sll$
- Provide similar but complementary information
- Some of the rarest decays that we have the potential to observe at the moment, will require more data for angular analyses
- Will be important to see if similar anomalies are seen in these decay as are seen in their $b \rightarrow sll$ counterparts

\[
\begin{array}{c}
\text{B}^0_s & \text{b} & \bar{\text{t}} & \text{d} \\
\text{W} & \text{Z}/\gamma & \mu^+ & \mu^-
\end{array}
\]
**$b \to dll$ transitions**

- So far the decay $B^+ \to \pi^+ \mu^+ \mu^-$ has been observed by LHCb and can be used in combination with $B^+ \to K^+ \mu^+ \mu^-$ and lattice results to measure $|V_{td}/V_{ts}|$

- Also have observed $\Lambda_b^0 \to p\pi^- \mu^+ \mu^-$ and seen evidence for $B^0 \to \pi^- \pi^- \mu^+ \mu^-$ at LHCb

\[
\begin{align*}
\mathcal{B}(B^\pm \to \pi^\pm \mu^+ \mu^-) &= (1.83 \pm 0.24 \pm 0.05) \times 10^{-8} \\
\mathcal{B}(\Lambda_b^0 \to p\pi^- \mu^+ \mu^-) &= (6.9 \pm 1.9 \pm 1.1^{+1.3}_{-1.0}) \times 10^{-8} \\
\mathcal{B}(B^0 \to \pi^- \pi^- \mu^+ \mu^-) &= (2.11 \pm 0.51 \pm 0.15 \pm 0.16) \times 10^{-8}
\end{align*}
\]

\[
\left| \frac{V_{td}}{V_{ts}} \right| = 0.201 \pm 0.020 \\
\text{Du et al} \\
\text{[Phys. Rev. D93 (2016) 034005]}
\]

---

**[JHEP 10 (2015) 034]**

**[JHEP 04 (2017) 029]**

\[ B_s \rightarrow \overline{K}^{*0} \mu^+ \mu^- \]

- Further CKM suppressed version of \( B^0 \rightarrow K^{*0} \mu^+ \mu^- \)
- Could be used to measure \( |V_{td}/V_{ts}| \) in a similar way as done between \( B^+ \rightarrow \pi^+ \mu^+ \mu^- \) and \( B^+ \rightarrow K^+ \mu^+ \mu^- \)
- Perform a search using 3 fb\(^{-1}\) Run 1 and 1.6 fb\(^{-1}\) Run 2 data
- Normalise the decay to \( B^0 \rightarrow J/\psi[\rightarrow \mu^+ \mu^-]K^{*0} \)

[LHCb-PAPER-2018-004]
First evidence for $B_s \rightarrow \bar{K}^*0 \mu^+ \mu^-$

- Provides first evidence for this decay with significance of $3.4\sigma$
- First measurement of the branching fraction: NEW!

$$\mathcal{B}(B_s \rightarrow \bar{K}^*0 \mu^+ \mu^-) = (3.0 \pm 1.0\text{(stat)} \pm 0.2\text{(sys)} \pm 0.3\text{(norm)}) \times 10^{-8}$$
Search for $\Lambda_c^+ \rightarrow p\mu^+\mu^-$

- Rare baryonic $c \rightarrow u\ell\ell$ FCNC process
- Search for non-resonant component carried out on 3 fb$^{-1}$ Run 1 data
- Normalise to the resonant $\Lambda_c^+ \rightarrow p\phi$ mode
- No significant non-resonant component is found, as such a limit is set:
  \[ \mathcal{B}(\Lambda_c^+ \rightarrow p\mu^+\mu^-) < 9.6 \times 10^{-8} \text{ } [95\% \text{ C.L.}] \]
- This is the best set limit on this mode
- In addition, the resonant $\Lambda_c^+ \rightarrow p\omega$ mode is observed for the first time at 5$\sigma$ with branching fraction:
  \[ \mathcal{B}(\Lambda_c^+ \rightarrow p\omega) = (9.4 \pm 3.2 \pm 1.0 \pm 2.0) \times 10^{-4} \]

Evidence for $\Sigma^+ \rightarrow p\mu^+\mu^-$

- Rare baryonic $s \rightarrow d\mu\mu$ FCNC process
- Previous evidence for this decay reported by the HyperCP collaboration, with the observed events all having very similar dimuon invariant mass [Phys. Rev. Lett. 94, 021801 (2005)]
- LHCb search carried out on $3\text{ fb}^{-1}$ Run 1 data
- Evidence for the decay at the level of $4\sigma$, no significant structure in $m_{\mu^+\mu^-}$

$$B(\Sigma^+ \rightarrow p\mu^+\mu^-) = (2.1^{+1.6}_{-1.2}) \times 10^{-8}$$

Summary

• Rare decays provide powerful probes of the SM and potential NP scenarios

• LHCb has the ability to make a wide variety of rare decay measurements
  • Rare decay observables can provide stringent limits on NP models
  • Measurements in $b \to sll$ transitions seem to be pointing towards a modification of the SM
  • The range of $b \to dll$ measurements that are possible are opening up with more data, will tensions be seen here as well?
  • Baryonic charm and strange FCNC decays are probing largely unexplored CKM transitions

• More and more analyses are being carried out with the larger LHC Run 2 datasets, keep watching for more results from LHCb!
Backup
Angular observables

• Complex angular distribution

\[
\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^4(\Gamma + \bar{\Gamma})}{dq^2 d\Omega} = \frac{9}{32\pi} \left[ \frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \\
+ \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_l \\
- F_L \cos^2 \theta_K \cos 2\theta_l + S_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi \\
+ S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + S_5 \sin 2\theta_K \sin \theta_l \cos \phi \\
+ \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_l + S_7 \sin 2\theta_K \sin \theta_l \sin \phi \\
+ S_8 \sin 2\theta_K \sin 2\theta_l \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \right].
\]

\begin{align*}
P_1 &= \frac{2 S_3}{(1 - F_L)} = A_T^{(2)}, \\
P_2 &= \frac{2 A_{FB}}{3 (1 - F_L)}, \\
P_3 &= \frac{-S_9}{(1 - F_L)}, \\
P_{4,5,8}' &= \frac{S_{4,5,8}}{\sqrt{F_L(1 - F_L)}}, \\
P_{6}' &= \frac{S_7}{\sqrt{F_L(1 - F_L)}}.
\end{align*}

Observables with reduced form factor dependence
Wilson coefficients

- Can parameterise an effective field theory for $b \to s$ transitions with the Hamiltonian:

$$\mathcal{H}_{\text{eff}} \propto V_{tb} V_{ts}^* \sum_i (C_i \mathcal{O}_i + C'_i \mathcal{O}'_i)$$

- New physics can either modify the existing Wilson coefficients or add new operators.
- $C_9$ and $C_{10}$ quantify contributions through the vector and axial-vector couplings.

Wilson coefficient (short distance physics)
Local operators
Right handed counterparts (suppressed in SM)