Rare decays from LHCb and CMS

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On behalf of the LHCb collaboration

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Rare decays – What and why?

- Processes through loop diagrams or CKM suppressed
  - Typically $B < \mathcal{O}(10^{-6})$

- Indirect new physics searches
  - The lower SM BF allow BSM contributions to stand out

- Typical loop topologies
  - Flavour-changing neutral currents (penguin/box diagrams)

- Will focus on rare decays of $b$ quarks
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$B_{(s)}^0 \rightarrow \mu^+\mu^-$ – Motivation

Precise SM prediction

$B_s^0 \rightarrow t W^+ Z^0 W^- s$ $B_s^0 \rightarrow t W^+ W^- s$

$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$

$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

Sensitive to new physics

$B_s^0 \rightarrow t X^+ X^0 W^- s$ $B_s^0 \rightarrow t X^+ \nu W^- s$

Two muons → Experimentally clean
\[ B_{(s)}^{0} \rightarrow \mu^{+} \mu^{-} - \text{LHCb and CMS} \]

**LHCb**

\[ \mathcal{B}(B_{s}^{0}) = (2.9^{+1.1}_{-1.0}) \times 10^{-9} (4.0\sigma) \]

\[ \mathcal{B}(B^{0}) < 7.4 \times 10^{-10} (95\%) \]

**CMS**

\[ \mathcal{B}(B_{s}^{0}) = (3.1^{+1.0}_{-0.9}) \times 10^{-9} (4.3\sigma) \]

\[ \mathcal{B}(B^{0}) < 1.1 \times 10^{-9} (95\%) \]


**What if the data were combined?**
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\[ B_{(s)}^0 \rightarrow \mu^+ \mu^- \quad \text{LHCb + CMS} \]

\[ B(B_s^0) = (2.8^{+0.7}_{-0.6}) \times 10^{-9} \]

\[ B(B^0) = (3.9^{+1.6}_{-1.4}) \times 10^{-9} \]

- Combined:
  - \( B_s^0 \) fit > 6.2\( \sigma \)
  - \( B^0 \) fit > 3.2\( \sigma \)

- \( \sim 2\sigma \) from SM

- Great advert for combined effort

Nature 522 (2015) 68
Radiative decay of $B_{(s)}^0$

SM predictions vary wildly
- $\mathcal{B} \sim 2 \times 10^{-7} - 5 \times 10^{-6}$
- Highly sensitive to QCD effects
- Tests QCD factorisation

Sensitive to New Physics
- Particularly RH currents

Limits set (90% conf):
- $\mathcal{B}(B_s^0) < 1.5 \times 10^{-6}$
- $\mathcal{B}(B^0) < 7.3 \times 10^{-6}$

$B_s^0 \rightarrow \phi\gamma$ — photon polarisation at LHCb

- **SM** $b \rightarrow s\gamma \sim$ left-handed
  - Small right-handed component ($m_s \neq 0$)
  - $A^\Delta_{SM} = 0.047^{+0.029}_{-0.025}$

- Time dependent analysis

\[ \mathcal{P}(t) \sim e^{-\Gamma_s t} \times \{ \cosh(\Delta\Gamma_s t/2) - A^\Delta \sinh(\Delta\Gamma_s t/2) \} \]

- In ratio with $B^0 \rightarrow K^{*0}\gamma$
  - $A_{SM}^\Delta = -0.98^{+0.46+0.23}_{-0.52-0.20}$

arXiv:1609.02032
$B^0 \rightarrow K^*(892)^0 \mu^+ \mu^-$ angular analysis

- FCNC process
- Angular variables less susceptible to hadronic FF
- Sensitive to Wilson coeffs $C_9$ and $C_{10}$ (& others)
  (vector and axial-vector)

Three angles and $q^2$

![Graphs showing distributions of candidate events and signal yield](image.png)
$B^0 \rightarrow K^*(892)^0 \mu^+ \mu^-$ angular analysis

- Angular dependence from 6 amplitudes (+ 2 for S-Wave)
  - Helicity and spin components
  - $A_{0,\parallel,\perp}^{L,R}$ ($A^L_S$)
- Many observables formed from amplitudes, e.g.

  $$F_L = \frac{|A_L^0|^2 + |A_R^0|^2}{|A_L^0|^2 + |A_R^0|^2 + |A_L^\parallel|^2 + |A_R^\parallel|^2 + |A_L^\perp|^2 + |A_R^\perp|^2}$$

  $$A_{FB} = \frac{3 \text{Re}(A_L^\parallel A_L^{\perp*} + A_R^\parallel A_R^{\perp*})/2}{|A_L^0|^2 + |A_R^0|^2 + |A_L^\parallel|^2 + |A_R^\parallel|^2 + |A_L^\perp|^2 + |A_R^\perp|^2}$$

  $$P_5' = \frac{\sqrt{2} \text{Re}(A_L^0 A_L^{\perp*} + A_R^0 A_R^{\perp*})}{\sqrt{F_L(1 - F_L)}}$$

- Some have physical meaning
  - $F_L$: Fraction of the longitudinal component of $K^{*0}$
  - $A_{FB}$: Dimuon forward-backward asymmetry
$B^0 \to K^{*0} \mu^+ \mu^-$ angular analysis – LHCb and CMS

Longitudinal $K^{*0}$ fraction

Forward-backward asymmetry

CMS

20.5 fb$^{-1}$ (8 TeV)

Data

〈 SM, LCSR 〉

〈 SM, Lattice 〉

LHCb

SM from ABSZ


JHEP 02 (2016) 104

10 / 16
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ angular analysis – LHCb

- Local $\sim 3\sigma$ deviations
- $\Delta \text{Re}(C_9) = -1.0 \pm 0.3$
  - Consistent with new vector particle
  - QCD effects (charm)?

Amplitudes fitted with low $q^2$ ansatz, $(a + bq^2 + c/q^2)$

$q_0^2(A_{FB}) = [3.40, 4.80] \text{GeV}^2$ (SM $4.36^{+0.33}_{-0.31}$)

$B^0 \rightarrow K^+\pi^-\mu^+\mu^-$ and $B^0 \rightarrow K^*(892)^0\mu^+\mu^-$

- $K^+\pi^-$ system in S- and P-wave
- SM predictions for P-wave only
- Need S-wave fraction to extract BF measurement
- Ratio of spin states S- & P-wave important for understanding hadronic effects

\[
F_S = 0.101 \pm 0.017(\text{stat}) \pm 0.009(\text{syst}) \quad [1.1 \leq q^2 < 6.0 \text{ GeV}^2]
\]

\[
\frac{d\mathcal{B}}{dq^2} = (0.392^{+0.020}_{-0.019}(\text{stat}) \pm 0.010(\text{syst}) \pm 0.027(\text{norm})) \times 10^{-7} \text{ GeV}^{-2}
\]
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$B^\pm \to \pi^\pm \mu^+ \mu^-$ differential BF and $A_{CP}$ at LHCb

- $b \to dll$ transition
  - More suppressed than $b \to sll$

- Access to CKM element $|V_{td}|$
  - $|V_{td}/V_{ts}|$ with $K^+ \mu \mu$

- Not exclusively a top loop
  - CP asymmetry non-zero

JHEP 10 (2015) 034
$B^{\pm} \rightarrow \pi^{\pm} \mu^{+} \mu^{-}$ differential BF and $A_{CP}$

$$
\begin{align*}
A_{CP} &= -0.11 \pm 0.12 \pm 0.01 \\
|V_{td}| &= 7.2^{+0.9}_{-0.8} \times 10^{-3} \\
|V_{ts}| &= 3.2^{+0.4}_{-0.4} \times 10^{-2} \\
\frac{|V_{td}|}{|V_{ts}|} &= 0.24^{+0.05}_{-0.04} \\
&= 0.20 \pm 0.02
\end{align*}
$$

**CKM tests important**

- RD CKM competitive with $B^{0}_{(s)}$ mixing
- $1 - 3\sigma$ deviations of global (tree) fits to measurements

arXiv:1602.03560
Other recent rare decays at LHCb

Can only give a taste of the full rare decays program:

Recent

- Ratio BF $B^+ \rightarrow K^+ \mu^+ \mu^- / B^+ \rightarrow K^+ e^+ e^-$
  - $R(K) = 0.74 \pm 0.10$, $2.6\sigma$ deviation from SM.
- Search for Hidden bosons in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
- $B_s^0 \rightarrow \phi \mu^+ \mu^-$ diff. BF and angular
- $\Lambda^0_b \rightarrow \Lambda^0 \mu^+ \mu^-$ diff. BF and angular
- $B^0 \rightarrow K^{*0} e^+ e^-$ angular analysis
- $B_{(s)}^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ BF
- Search for $\tau^- \rightarrow \mu^- \mu^+ \mu^-$
- Ratio BF $B^+ \rightarrow K^+ \mu^+ \mu^- / B^+ \rightarrow K^+ e^+ e^-$

Many more in the works
Conclusions

- A rich and varied rare decays programme at the LHC
- Rare decays a speciality of LHCb
  - GPDs can contribute
- Collaboration between the experiments yield valuable
- Interesting hints at departures from the SM
- More to come with LHC Run II data
Rare decays from LHCb and CMS

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LHCb and CMS

LHCb

- Excellent momentum resolution
- Excellent PID
- Excellent vertexing

CMS

- Excellent energy resolution
- Full acceptance
- Vast integrated luminosity