Rare decays at LHCb

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The LHCb detector

The LHCb detector is a single arm spectrometer which covers the forward region at LHC.

\[ \Delta \rho / \rho \sim 0.4\% \] at 5 GeV, \( \sigma_{IP} = 20 \, \mu m \) for high \( p_T \) tracks.

\[ \pi / K \] separation: \( \epsilon_K \sim 90\% \), 5\% \( \pi \rightarrow K \) mis-id.

\[ \pi / \mu \] separation: \( \epsilon_\mu \sim 97\% \), 1-3\% \( \pi \rightarrow K \) mis-id.
Rare decays: FCNC processes

Decays mediated via Flavour Changing Neutral Currents (FCNC) occur at loop order and are suppressed in the SM.

New particles can affect the decay rates or the angular distributions of the final state particles.
Rare decays: outline

Test of the Minimal Flavour Violation hypothesis

1) Measuring $V_{td}/V_{ts}$ using the $b \rightarrow d(s)\ell\ell$ transitions
$B^+ \rightarrow \pi^+(K^+)\mu^+\mu^-$ [LHCb JHEP 10 (2015) 034]

Sensitivity to Wilson coefficients

2) Very rare decays $B_s^0 \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$ [$C_{10}$, $C_S$, $C_P$] [Nature 522 (2015) pp. 68-72]

3) Angular analyses using $b \rightarrow s\ell\ell$ transitions [$C_7$, $C_9$, $C_{10}$] :
   - $B^0 \rightarrow K^{*0} (\rightarrow K^+\pi^-)\mu^+\mu^-$ decays [LHCb, JHEP 02 (2016) 104]
   - $B_s^0 \rightarrow \Phi(K^+K^-)\mu^+\mu^-$ decays [LHCb, JHEP 09 (2015) 179]

Lepton universality

4) Branching fraction measurements of $b \rightarrow s\ell\ell$ transitions $B^+$
$\rightarrow K^+\mu^+\mu^-$ and $B^+ \rightarrow K^+ e^+e^-$ [LHCb, PRL113 (2014) 151601]
Minimal flavour violation

Comparing the CKM elements obtained via loop and tree level processes tests the MFV hypothesis that NP flavour structure = SM flavour structure.

\[ \Lambda > \frac{4.4 \text{ TeV}}{|V_{ti}^*V_{tj}|/|c_{ij}|^{1/2}} \sim \begin{cases} 1.3 \times 10^4 \text{ TeV} \times |c_{sd}|^{1/2} \\ 5.1 \times 10^2 \text{ TeV} \times |c_{bd}|^{1/2} \\ 1.1 \times 10^2 \text{ TeV} \times |c_{bs}|^{1/2} \end{cases} \]

Mass scale of new physics

Lower mass limit on NP if a generic flavour structure is assumed for NP (i.e. NOT the MFV hypothesis)

arXiv:1002.0900
Testing MFV using the CKM element ratio $V_{td}/V_{ts}$

As top quarks don't hadronise, $V_{td}$ and $V_{ts}$ cannot be measured directly with tree diagrams,

$\rightarrow$ use unitarity constraints from CKM matrix

A. Bazavov et. al. [arXiv:1602.03560]
$B^+ \rightarrow \pi^+ \mu^+ \mu^- :$ branching fraction measurement

$$\mathcal{B}(B^+ \rightarrow \pi^+ \mu^+ \mu^-) = (1.83 \pm 0.24 \pm 0.05) \times 10^{-8}$$

First observation of a b→d transition mediated by both penguin and box diagrams

Cabibbo suppressed

Cabibbo favoured

arXiv:1509.00414
Calculating $V_{td}$ ($V_{ts}$) with $B^+ \rightarrow \pi^+ (K^+)\mu^+ \mu^-$ decays
Wilson coefficients

An example of a well-known effective theory

Contributing loops factorised out to give effective couplings, parameterised by the Wilson Coefficients

As the Wilson Coefficients 'describe the loops' in the diagram they are sensitive to NP
$B^0_s \rightarrow \mu^+ \mu^-$ and $B^0 \rightarrow \mu^+ \mu^-$ [$C_{10}, C_s, C_p$]

LHCb and CMS data combined:

$$B(B^0_s \rightarrow \mu^+ \mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}, \quad B^0_s$$

$$B(B^0 \rightarrow \mu^+ \mu^-) = (3.8^{+1.6}_{-1.4}) \times 10^{-10}, \quad B^0$$

[Graph showing decay processes and branching fractions]

arXiv:1307.5024
$B^0_s \rightarrow \mu^+ \mu^-$ and $B^0 \rightarrow \mu^+ \mu^-$ $[C_{10}, C_s, C_p]$

LHCb and CMS data combined:

CMS and LHCb (LHC run I)

arXiv:1307.5024
$B^0 \rightarrow K^{*0} [\rightarrow K^+ \pi^-] \mu^+ \mu^-$ angular analysis [$C_7, C_9, C_{10}$]

Angular decay fully described by the dilepton mass ($q^2$) and the angles $\cos(\theta)_l$, $\cos(\theta)_k$ and $\phi$:

\[
\frac{d^4\Gamma[\overline{B}^0 \rightarrow \overline{K}^{*0} \mu^+ \mu^-]}{dq^2 \, d\Omega} = \frac{9}{32\pi} \sum_i I_i(q^2) f_i(\overline{\Omega})
\]

Decay rate as a function of $q^2$

Angular observables related to the Wilson Coefficients

Spherical harmonics
$B^0 \rightarrow K^{*0} [\rightarrow K^+ \pi^-] \mu^+ \mu^-$ angular analysis: Results

Use $B^0 \rightarrow K^{*0} J/\psi$ as control channel.
$B^0 \rightarrow K^{*0} [\rightarrow K^+ \pi^-] \mu^+ \mu^-$ angular analysis: Results

Simultaneous mass fits

1D projections of angles from 3D fit
$B^0 \rightarrow K^{*0} \rightarrow K^+ \pi^- \mu^+ \mu^-$ angular analysis: Results

Form factor free observables

Can construct ratios of angular observables where form-factors cancel, giving clean theoretical predictions:

$$P'_5 = S_5 / \sqrt{F_L (1 - F_L)}$$

$P'_5$ plot: Bins 4/5 = local SM tension of 2.8 and 3.0σ. Global tension= 3.4σ, assuming tension due to shift in Wilson coeff. $\Re e(C_9)$
$B_s^0 \to \phi \left[ \to K^+ K^- \right] \mu^+ \mu^- [C_7, C_9, C_{10}]$

Equivalent process of $B^0 \to K^{*0} \mu^+ \mu^-$ for $B_s^0$ mesons.

Angular variables consistent with the SM. $P'_5$ cannot be measured as $B_s^0 \to \phi \mu^+ \mu^-$ not self-tagging.

In bin $1 < q^2 < 6$ GeV/$c^2$ the data is $3.3\sigma$ from the SM prediction.
Global fits

An example of a fit to many results from $b \to s \ell\ell$ transitions. 3-4σ tension with SM observed in the $C_9$ Wilson coefficient.
**Lepton universality**

The quantity:

\[
R_k = \frac{\int \Gamma(B^+ \to K^+ \mu^+ \mu^-)/dq^2 \cdot dq^2}{\int \Gamma(B^+ \to K^+ e^+ e^-)/dq^2 \cdot dq^2}
\]

differs from unity only due to phase space.

Theoretically clean as matrix elements cancel.

Experimentally challenging due to electrons.

\[
R_K = 0.745^{+0.090+0.036}_{-0.074-0.036} \implies 2.6 \sigma \text{ from SM}
\]

Deficit of \( b \to s \mu^+ \mu^- \) transitions, tension in same direction as measurements previously discussed.
Conclusions

- Flavour observables in rare decays allow for NP searches and can place many strong constraints on NP models.
- Some tensions with the SM observed, particular within $b \rightarrow s\ell\ell$ transitions.
- Many rare decay analyses performed with LHC Run 1 data and many more results to come using the Run 1 and first Run 2 datasets.
Back-up slides
$\Lambda_b^0 \rightarrow \Lambda^0 \mu^+ \mu^-$ differential branching fraction

$b \rightarrow s \ell \ell$ transition in the baryon sector
Global fits $b \rightarrow s \ell\ell$ decays

Decays included in fit in *Altmannshofer et al.* with tension $> 1.9 \sigma$ in a Wilson Coefficient.

<table>
<thead>
<tr>
<th>Decay</th>
<th>obs.</th>
<th>$q^2$ bin</th>
<th>SM pred.</th>
<th>measurement</th>
<th>pull</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{B}^0 \rightarrow \bar{K}^*0 \mu^+ \mu^-$</td>
<td>$F_L$</td>
<td>[2, 4.3]</td>
<td>$0.81 \pm 0.02$</td>
<td>$0.26 \pm 0.19$</td>
<td>ATLAS $+2.9$</td>
</tr>
<tr>
<td>$\bar{B}^0 \rightarrow \bar{K}^*0 \mu^+ \mu^-$</td>
<td>$F_L$</td>
<td>[4, 6]</td>
<td>$0.74 \pm 0.04$</td>
<td>$0.61 \pm 0.06$</td>
<td>LHCb $+1.9$</td>
</tr>
<tr>
<td>$\bar{B}^0 \rightarrow \bar{K}^*0 \mu^+ \mu^-$</td>
<td>$S_5$</td>
<td>[4, 6]</td>
<td>$-0.33 \pm 0.03$</td>
<td>$-0.15 \pm 0.08$</td>
<td>LHCb $-2.2$</td>
</tr>
<tr>
<td>$\bar{B}^0 \rightarrow \bar{K}^*0 \mu^+ \mu^-$</td>
<td>$P'_5$</td>
<td>[1.1, 6]</td>
<td>$-0.44 \pm 0.08$</td>
<td>$-0.05 \pm 0.11$</td>
<td>LHCb $-2.9$</td>
</tr>
<tr>
<td>$\bar{B}^0 \rightarrow \bar{K}^*0 \mu^+ \mu^-$</td>
<td>$P'_5$</td>
<td>[4, 6]</td>
<td>$-0.77 \pm 0.06$</td>
<td>$-0.30 \pm 0.16$</td>
<td>LHCb $-2.8$</td>
</tr>
<tr>
<td>$B^- \rightarrow K^- \mu^+ \mu^-$</td>
<td>$10^7 \frac{dBR}{dq^2}$</td>
<td>[4, 6]</td>
<td>$0.54 \pm 0.08$</td>
<td>$0.26 \pm 0.10$</td>
<td>LHCb $+2.1$</td>
</tr>
<tr>
<td>$\bar{B}^0 \rightarrow \bar{K}^0 \mu^+ \mu^-$</td>
<td>$10^8 \frac{dBR}{dq^2}$</td>
<td>[0.1, 2]</td>
<td>$2.71 \pm 0.50$</td>
<td>$1.26 \pm 0.56$</td>
<td>LHCb $+1.9$</td>
</tr>
<tr>
<td>$\bar{B}^0 \rightarrow \bar{K}^0 \mu^+ \mu^-$</td>
<td>$10^8 \frac{dBR}{dq^2}$</td>
<td>[16, 23]</td>
<td>$0.93 \pm 0.12$</td>
<td>$0.37 \pm 0.22$</td>
<td>CDF $+2.2$</td>
</tr>
<tr>
<td>$B_s \rightarrow \phi \mu^+ \mu^-$</td>
<td>$10^7 \frac{dBR}{dq^2}$</td>
<td>[1, 6]</td>
<td>$0.48 \pm 0.06$</td>
<td>$0.23 \pm 0.05$</td>
<td>LHCb $+3.1$</td>
</tr>
</tbody>
</table>
$B_s^0 \rightarrow \mu^+ \mu^-$ results from Atlas

$\sqrt{s} = 7$ TeV
$\int Ldt = 2.4$ fb$^{-1}$

arXiv:1204.0735
NP models: contribution to $C_9$ arXiv:1308.1501

$Z'$ models

- $Z'$ models involve tree-level exchange of a heavy neutral boson ($Z'$) with a flavour-changing $b \to s$ coupling.
- $Z'$ models allow for significant contributions to the $C_9$ vector coefficient which could accommodate tensions in $b \to s\ell\ell$ measurements.
- Best fit values for $C_9$ global fits and constraints from $B_s$ meson mixing favour a light $Z'$ with mass of order $1\text{TeV}$. To avoid constraints from di-lepton searches, the $Z'$ coupling to SM fermions must be $\sim$ an order of magnitude less than those of the SM $Z$. 
NP models: contribution to $C_9$ arXiv:1308.1501

Models with partial composites

- Most well-motivated to contribute to $C_7$ coefficients, contributions could be large enough to significantly reduce tension in $C_9$ coefficient.
- To contribute $C_9$ would require several cancellations in the V-A coefficient $C_{10}$ and properties of muons would be strongly dependent on chirality.

MSSM

- Contributions to $C_9$ from $Z$ penguins, charged Higgs (box and loops), Higgsinos (box and loops) all negligible.
- MSSM can affect $C_7$ which could soften tensions.