Rare $B$ decays at LHCb

Albert Puig on behalf of the LHCb collaboration
The LHCb experiment
The LHCb experiment

Precise tracking
Good mass and IP resolution
Good vertex resolution
The LHCb experiment

Calorimeter system
Trigger
Photon reconstruction

Excellent particle identification
$\pi/K$ separation over 2-100 GeV
Powerful muon id

[JINST 3 (2008) S08005]
The LHCb data taking

LHCb Cumulative Integrated Recorded Luminosity in pp, 2010-2016

- Run 1
- Run 2

<table>
<thead>
<tr>
<th>Year</th>
<th>Integrated Recorded Luminosity (1/fb)</th>
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<tbody>
<tr>
<td>2010</td>
<td>0.04 /fb</td>
</tr>
<tr>
<td>2011</td>
<td>0.35 /fb</td>
</tr>
<tr>
<td>2012</td>
<td>2.08 /fb</td>
</tr>
<tr>
<td>2013</td>
<td>1.11 /fb</td>
</tr>
<tr>
<td>2014</td>
<td>0.32 /fb</td>
</tr>
<tr>
<td>2015</td>
<td>1.67 /fb</td>
</tr>
<tr>
<td>2016</td>
<td>3.25 /fb</td>
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</tbody>
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- 2010 (3.5 TeV): 0.04 /fb
- 2011 (3.5 TeV): 1.11 /fb
- 2012 (4.0 TeV): 2.08 /fb
- 2015 (6.5 TeV): 0.32 /fb
- 2016 (6.5 TeV): 1.67 /fb
Rare $B$ decays

Rare decays of heavy mesons are FCNC (forbidden at tree level and thus highly suppressed) sensitive to quantum corrections from degrees of freedom at larger scales.

Indirect approach to New Physics searches complementary to that of GPDs
- Use well-predicted observables to look for deviations
$b \rightarrow \ell^+ \ell^-$ transitions in the SM

These decays can be predicted very cleanly thanks to the fact that there is only one hadronic parameter ($F_B$), which can be computed by lattice QCD

$$BR(B^0 \rightarrow \ell^+ \ell^-) = \frac{\tau_B G_F^4 M_W^2 \sin^4 \theta_W}{8\pi^5} |C_{10} V_{tb} V_{tw}^*| F_B^2 m_B m_{\ell}^2 \sqrt{1 - \frac{4m_{\ell}^2}{m_B^2}}$$

They are doubly suppressed in the SM: FCNC and helicity

Decay with taus is x250 more abundant than the muonic one (assuming Lepton Universality), but it’s experimentally very challenging
$B \to \mu^+\mu^-$: a 30-year-old story

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LHCb has added part of the data collected in Run 2 (up to 4.4fb$^{-1}$) and largely improved the analysis (30% stat error reduction for $B^0 \rightarrow \mu \mu$)

$$BR(B^0_s \rightarrow \mu^+ \mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$

$$BR(B^0 \rightarrow \mu^+ \mu^-) < 3.4 \times 10^{-10} \text{ at 95\% CL}$$
**B\to\mu^+\mu^-** update with Run 2 data

LHCb has added part of the data collected in Run 2 (up to 4.4fb$^{-1}$) and largely improved the analysis (30% stat error reduction for $B^0\to\mu\mu$)

$$BR(B_S^0\to\mu^+\mu^-) = (3.0 \pm 0.6 \pm 0.3) \times 10^{-9}$$

First single experiment observation of $B_S$ mode (7.8\sigma)

![Graph showing candidates per 50 MeV/c^2](image-url)
**B_s → μ⁺μ⁻ lifetime measurement**

In the case of NP, new contributions can come from \( C_S \) and \( C_P \) (more details in Tom’s talk).

While large effects are ruled out, observables such as

\[
\mathcal{A}_{\Delta \Gamma}^{\ell^+\ell^-} = \frac{\Gamma_{B_s, H \to \ell^+\ell^-} - \Gamma_{B_s, L \to \ell^+\ell^-}}{\Gamma_{B_s, H \to \ell^+\ell^-} + \Gamma_{B_s, L \to \ell^+\ell^-}}
\]

can be used to break degeneracy.
$B_s \rightarrow \mu^+\mu^-$ lifetime measurement

$$\tau(B_s^0 \rightarrow \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05 \text{ ps}$$
$B \rightarrow \tau^+ \tau^-$

More abundant than $B_s \rightarrow \mu \mu$, but extremely challenging
- No separation between $B_s$ and $B^0$

Analysis of Run 1 data with $\tau \rightarrow 3\pi\nu$
- Use $B \rightarrow D^+ (\rightarrow K\pi\pi) D_s^- (KK\pi)$ as control channel
- Use Dalitz plane to separate signal/background, then fit MVA

$BF(B_s^0 \rightarrow \tau\tau) < 6.8 \times 10^{-3}$ at 95% CL
$BF(B^0 \rightarrow \tau\tau) < 2.1 \times 10^{-3}$ at 95% CL
Lepton flavour universality

In the SM, leptons are identical copies of one another so processes involving $e$, $\mu$, $\tau$ must have the same strength up to Higgs corrections and lepton-mass-dependent phase space effects.

Measurements of lepton flavour universality constitute a theoretically very clean way to access the effects of new physics phenomena.
In 2014, a discrepancy of 2.6σ with the SM was observed in the ratio of branching fractions of $B^+ \rightarrow K^+ \mu^+ \mu^-$ with respect to $B^+ \rightarrow K^+ e^+ e^-$

$$R_K = \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)} = 0.745^{+0.090}_{-0.074} \text{(stat) } \pm 0.036 \text{ (syst)}$$

Theory predicts $R_K$ to be unity up to a very good precision

$$R_K^{\text{SM}} = 1 + \mathcal{O}(10^{-2})$$
$R_{K^*}$

Similar to $R_K$, also with a similar prediction

- Split analysis in two $q^2$ bins: low (0.045–1.1 GeV$^2$) and central (1.1–6 GeV$^2$), with different physics contributions
Very complex analysis, need to control muon/electron efficiencies with very high confidence

- Use a double ratio with non-rare, control $B^0 \rightarrow K^{*0} J/\psi(\rightarrow \ell^+\ell^-)$ modes to control systematics

- Fit sample according to the number of bremsstrahlung photons recovered in the electron reconstruction

- Split sample according to how it was triggered (electron, hadron, other) and merge likelihoods
$R_{K^*}$

\[
R_{K^{*0}} (0.045 < q^2 < 1.1 \text{ GeV}^2/c^4) = 0.660^{+0.110}_{-0.070} \pm 0.024 \\
R_{K^{*0}} (1.1 < q^2 < 6.0 \text{ GeV}^2/c^4) = 0.685^{+0.113}_{-0.069} \pm 0.047
\]
$R_{K^*}$

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LFU: prospects

$R_K$ and $R_{K^*}$ have produced interesting tensions with the SM, which need to be explored further.

LHCb is pursuing a wide program of LFU studies in $b \rightarrow s \ell \ell$ decays:
- Further $R$ measurements, including both Run 2 data and other decay channels
- LFU in angular distributions

Also studying LFU in tree-level semileptonic decays (see C. Bozzi’s talk)
Conclusions

Searches for New Physics with rare $B$ decays have pushed the SM to the limit, and interesting tensions have appeared

$B_s \rightarrow \mu \mu$ BF compatible with SM so far, but more precision needed. Measurements of $B^0 \rightarrow \mu \mu$ BF and the $B_s \rightarrow \mu \mu$ lifetime also needed, as there is still room for NP

Interesting hints of Lepton Flavour Universality violation have been observed and need to be pursued harder

- Other tensions with the SM observed in $b \rightarrow s \mu \mu$ decays will be discussed in C. Marin’s talk

Stay tuned, New Physics may be around the corner!
Thank you
$B \to \tau^+ \tau^-$

LHCb simulation

$M_{\pi^+\pi^-}$ [MeV/c$^2$]

$M_{\pi^+\pi^-}$ [MeV/c$^2$]

Decays

[PRL 118 (2017) 251802]
BaBar, Belle and LHCb have observed an enhancement of $\tau$ with respect to $\mu$ in $B \rightarrow D^{(*)}\ell \nu_\ell$ decays at the level of 4.0$\sigma$ with respect to SM predictions.

[HFLAV, Winter 2016]


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Possible pattern: mass-dependent coupling of NP to different lepton generations?
$R_{K^*}$ remmstrahlung photons
$R_{K^*}$ muon fits

![Graphs showing $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ and $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ with pull distributions and mass distributions in $m(K^+\pi^-\mu^+\mu^-)$ for different $q^2$ intervals.](https://example.com/graphs.png)
$R_{K^*}$ combined likelihoods