Rare decays at the LHC

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on behalf of the LHCb collaboration, including results from ATLAS, CMS and LHCb

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Tests of lepton universality
- $\mathcal{R}(K)$, $\mathcal{R}(K^*)$, $\mathcal{R}(D^*)$

Angular analyses and differential branching fractions measurements
- $B^0 \rightarrow K^{*0}\mu^+\mu^-$, $B^0_s \rightarrow \phi\mu^+\mu^-$
- $B^0_s \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$
Introduction

- Rare decays mediated by Flavour Changing Neutral Currents
- No tree-level diagrams in the SM, loop suppressed transitions
- Very sensitive to beyond the SM contributions

![Diagram of rare decays](image)

- Possible new physics effects on branching fractions (BF), angular observables, CPV, ...
- Powerful to constrain beyond the SM scenarios
- Different tensions with the SM already observed
Run I: $pp$ collisions at $\sqrt{s} = 7/8$ TeV
- Recorded 3 fb$^{-1}$ by LHCb and 29.4 fb$^{-1}$ by ATLAS/CMS

Run II: $pp$ collisions at $\sqrt{s} = 13$ TeV
- Recorded 2 fb$^{-1}$ by LHCb and 45 fb$^{-1}$ by ATLAS/CMS
- Expected 8 fb$^{-1}$ by LHCb and 100 fb$^{-1}$ by ATLAS/CMS by 2018 end

Beauty cross-section doubled at Run II energy
- Plenty of data are coming!
Test of lepton universality in $B^+ \to K^+$ dileptonic decays, $\mu^-$ vs $e^-$

The branching fraction ratio is close to one in the SM

$$\mathcal{R}(K) = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} = 1 \pm \mathcal{O}(10^{-2})$$

LHCb Run I measurement in $1 < q^2 < 6 \text{ GeV}^2/c^4$ most precise to date

Compatible with SM at $2.6\sigma$

Expected statistical uncertainty $\approx 0.03$ after Run II, size of current systematic uncertainty

Systematic uncertainty dominated by signal and background parametrization, to be reduced in the future
Test of lepton universality analogous to $\mathcal{R}(K)$ in $B^0 \rightarrow K^{*0} l^+ l^-$

LHCb Run I preliminary measurement in low- and central-$q^2$ regions, $0.045 < q^2 < 1.1 \text{ GeV}^2/c^4$ and $1.1 < q^2 < 6.0 \text{ GeV}^2/c^4$, recently presented at CERN

Very challenging analysis due to the different ways muons and electrons interact with the detector

$\mathcal{R}(K^*)$ measured relative to $B^0 \rightarrow K^{*0} J/\psi (\rightarrow l^+ l^-)$, to reduce systematic uncertainties

$K^{*0}$ reconstructed as $K^+ \pi^-$ within 100 MeV from $K^*(892)^0$ resonance

Blind analysis to avoid experimental biases
$\mathcal{R}(K^*)$ preliminary

- Low (central)-$q^2$ result compatible with SM at $2.2 - 2.4(2.4 - 2.5)\sigma$
- Similar behaviour shown by $\mathcal{R}(K)$ measurement
- Statistically dominated measurement, with slightly larger uncertainties than $\mathcal{R}(K)$ one, expected at $\approx^{+0.040}_{-0.027}$ level after Run II
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ differential branching fraction

- Measured differential branching fractions in $q^2$ for $B^0 \rightarrow K^{*0} \mu^+ \mu^-$, $B^0_s \rightarrow \phi \mu^+ \mu^-$ and $\Lambda^0_b \rightarrow \Lambda \mu^+ \mu^-$ found lower than SM predictions with tensions at $2 - 3\sigma$.

- Latest Run I LHCb (JHEP 11 (2016) 047) and CMS (PLB 753 (2016) 424-448) $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ BF measurements in agreement with SM predictions arXiv:1503.05534 (LCSR) & PRD 89 (2014) 094501 (Lattice)

- Main systematic uncertainty from knowledge of normalization channel, i.e. $\mathcal{B}(B^0 \rightarrow J/\psi K^{*0})$
\[ B^0 \rightarrow K^{*0} \mu^+ \mu^- \text{ angular analysis} \]

- Study of the full angular distribution of the final state particles \((\theta_l, \theta_K, \phi)\)
- Described by eight observables \(A_{FB}, F_L, S_i\), function of Wilson coefficients

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

- Observables in which hadronic form factors uncertainties cancels at leading order can be defined like

\[
P'_5 \equiv \frac{S_5}{\sqrt{F_L (1 - F_L)}}
\]

JHEP 05 (2013)137
$B^0 \to K^{*0} \mu^+ \mu^-$ angular analysis

- $P'_5$ LHCb local deviation from SM DHMV:
  - $2.8\sigma$ in $4.0 < q^2 < 6.0 \text{ GeV}^2/c^4$; $3.0\sigma$ in $6.0 < q^2 < 8.0 \text{ GeV}^2/c^4$
- Statistically dominated measurement

SM predictions
DHMV: JHEP 12 (2014) 125

Data
LHCb: JHEP 02(2016)104
ATLAS: ATLAS-CONF-2017-023
CMS: CMS-PAS-BPH-15-008
Belle: arXiv:1604.04042
LHCb measured the differential branching fraction in $q^2$ and performed a full angular analysis of $B^0_s \to \phi \mu^+ \mu^-$ with Run I data (JHEP 1509 (2015) 179).

The measured BF is below SM predictions (EPJC 75 (2015) 382 & arXiv:1503.05534), as seen in other $b \to s \mu^+ \mu^-$ processes.

BF in $1 < q^2 < 6 \text{ GeV}^2/c^4$ interval more than $3\sigma$ lower than SM.

Angular observables compatible with SM predictions.

Differential BF dominated by statistical uncertainty.
Test of lepton universality in $B^0 \to D^*$ semileptonic decays, $\tau^-$ vs $\mu^-$ (not a rare decay but interesting in the context of LFU tests)

The branching fraction ratio is theoretically clean

$$\mathcal{R}(D^*) = \frac{\mathcal{B}(B^0 \to D^*\tau\nu_\tau)}{\mathcal{B}(B^0 \to D^*\mu\nu_\mu)} = 0.252 \pm 0.003$$

LHCb Run I measurement, with $\tau$ measured in $\mu\nu_\mu\nu_\tau$, consistent with SM prediction at $2.1\sigma$

$\mathcal{R}(D^*)$ world average exceed the SM predictions by $3.4\sigma$

Including the $\mathcal{R}(D^*)$-$\mathcal{R}(D)$ correlation, the SM tension is at about $3.9\sigma$
\[ B^0_s \rightarrow \mu^+\mu^- \text{ and } B^0 \rightarrow \mu^+\mu^- \]

- Very small branching fractions precisely predicted in the SM, very useful to constrain new physics scenarios

- Combined analysis of CMS and LHCb Run I data: observation of the \( B^0_s \) mode (6.2\( \sigma \)) and evidence for \( B^0 \rightarrow \mu^+\mu^- \) (3.0\( \sigma \)) (Nature 522 (2015) 68-72)

- Latest LHCb analysis including 1.4 fb\(^{-1}\) of Run II data (arXiv:1703.05747)
  - \( B^0_s \rightarrow \mu^+\mu^- \) observed at 7.8\( \sigma \) and most precise BF determination to date
  - No evidence (1.6\( \sigma \)) of \( B^0 \rightarrow \mu^+\mu^- \)
  - First measurement of \( B^0_s \rightarrow \mu^+\mu^- \) effective lifetime

\[
\tau_{\mu^+\mu^-} = \frac{\int t \ \Gamma(B^0_s(t) \rightarrow \mu^+\mu^-) dt}{\int \Gamma(B^0_s(t) \rightarrow \mu^+\mu^-) dt}
\]

- All results in agreement with SM expectations
$B_s^0 \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$

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<tr>
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<th>SM</th>
<th>LHCb</th>
<th>CMS+LHCb</th>
<th>ATLAS</th>
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<tbody>
<tr>
<td>$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)(10^{-9})$</td>
<td>$3.66 \pm 0.23$</td>
<td>$3.0 \pm 0.6^{+0.3}_{-0.2}$</td>
<td>$2.8^{+0.7}_{-0.6}$</td>
<td>$0.9^{+1.1}_{-0.8}$</td>
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<tr>
<td>$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)(10^{-10})$</td>
<td>$1.06 \pm 0.09$</td>
<td>$&lt; 3.4$</td>
<td>$3.9^{+1.6}_{-1.4}$</td>
<td>$&lt; 4.2$</td>
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Upper limits at 95% C.L.
\[ B_s^0 \rightarrow \mu^+\mu^- \text{ and } B^0 \rightarrow \mu^+\mu^- \]

- Decay time distribution from mass fit (sPlot)
- Strategy validated on \( B^0 \rightarrow K^+\pi^- \)
- \( \tau(B_s^0 \rightarrow \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05 \text{ ps} \)

- CMS prospects for Run II: \( \delta B(B_s^0 \rightarrow \mu^+\mu^-) \approx 14\% \) (CMS-PAS-FTR-14-015)
- LHCb: expected statistical uncertainty on \( B_s^0 \rightarrow \mu^+\mu^- \approx 0.33 \times 10^{-9} \) at Run II end, level of current systematic uncertainties. Main systematic source given by the knowledge of \( f_s/f_d \)
- No limiting systematic uncertainties foreseen for \( B^0 \rightarrow \mu^+\mu^- \) study
Summary

- LFU tests showed deviations with respect to SM predictions between $2-4\sigma$, consistent among each other.
- Differential BF in $b \rightarrow s\mu^+\mu^-$ processes consistently lower than SM predictions at $2-3\sigma$ level, compatible with LFU results.
- Anomaly at $3\sigma$ level for $P'_5$ angular observable in $B^0 \rightarrow K^{*0}\mu^+\mu^-$.
- $B^0/B^0_s \rightarrow \mu^+\mu^-$ BF probed down to $10^{-9}/10^{-10}$ level, very useful to constrain new physics scenarios.
Prospects

- Increasing precisions by a factor 2.6 – 2.8 with LHC Run II, no limiting systematic uncertainties foreseen
- New measurements coming soon (LHCb side)
  - $\mathcal{R}(K)$ including 2015-16 data
  - $\mathcal{R}(\phi)$ including 2015-16 data
  - $\mathcal{R}(D^*)$ with $\tau$ measured in $\pi^+\pi^-\pi^-\nu_\tau$
  - LFU test with $B^0_s \rightarrow D^{(*)}_s \tau\nu_\tau$
  - LFU test with $\Lambda^0_b \rightarrow \Lambda^{+\ast}_c \tau\nu_\tau$
- + updates with Run II data
- Are we approaching new physics? Let’s see...
Backup Slides
LHCb status and prospects

- **Run I**: recorded 1 and 2 fb$^{-1}$ at \( \sqrt{s} = 7 \) and 8 TeV, respectively
- **Run II**: recorded 2 fb$^{-1}$ at \( \sqrt{s} = 13 \) TeV by 2016 end, expected 8 fb$^{-1}$ by 2018 end
- Beauty cross-section in LHCb acceptance doubled at Run II energy

\[
\frac{\sigma(pp \rightarrow b\bar{b}X, 13 \text{ TeV})}{\sigma(pp \rightarrow b\bar{b}X, 7 \text{ TeV})} = 2.14 \pm 0.02 \pm 0.13 \quad \text{PRL 118 (2017) 052002}
\]
- Beauty events recorded by 2016 end

\[
\frac{N_b(\text{Run I + 2015-16})}{N_b(\text{Run I})} \approx 2.4
\]

→ Statistical uncertainties ÷ 1.5
- Beauty events expected after Run II completion

\[
\frac{N_b(\text{Run I+Run II})}{N_b(\text{Run I})} \approx 6.7
\]

→ Statistical uncertainties ÷ 2.6