Testing the Standard Model with rare decays at LHCb

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on behalf of the LHCb collaboration

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A) Forbidden modes

- Lepton Flavour Violating modes (LFV, virtually forbidden through neutrino mixing):
  
  \[ \nu \xrightarrow{W} l \]
  
  \[ \nu \equiv \sum_{\alpha=e,\mu,\tau} U_{i\alpha} \nu_i \]  
  
  \([i=1,2,3]\]
  
  Smaller than \(\sim O(10^{-40})\).

B) Suppressed modes

- Decays that are mediated by the flavour-changing-neutral-currents (FCNC):
  1. GIM (BF<10^{-6})
  2. and/or CKM
  3. and/or helicity suppressed (BF<10^{-9})
A) Forbidden modes

- Large LFV is expected in numerous New Physics (NP) scenarios (SUSY, Extra Dimension, Little Higgs, Pati-Salam leptoquarks,...)

$$\text{SM+NP: } \sim 10^{-6-10}$$

- In LHCb we have looked for:

\[ \tau \rightarrow \mu\mu\mu \]

\[ B_{(s)} \rightarrow e^\pm \mu^\mp \]

\[ D^0 \rightarrow e^\pm \mu^\mp \]
Forbidden modes (LFV searches)

\[ \tau \rightarrow \mu \mu \mu \quad B(\tau^- \rightarrow 3\mu) < 4.6 \times 10^{-8} \text{ at } 90\% \text{ CL} \]

- Analysis performed on 3 fb\(^{-1}\) of LHCb data
- 70% of taus from \( D_s \rightarrow \tau \nu \)
- Calibrate and normalise to \( D_s \rightarrow \Phi(1020)(\rightarrow \mu^+\mu^-)\mu^- \)
- Limit set at the level of B-factories (impressive in hadronic environment)
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\[ D^0 \rightarrow e^\pm \mu^\mp \quad B(D^0 \rightarrow e^\pm \mu^\mp) < 1.5 \times 10^{-8} \text{ at 90\% CL} \]

➤ Analysis performed on 3 fb\(^{-1}\) of LHCb data
➤ Signal candidates selected from \(D^*+ \rightarrow D^0\pi\)
➤ Normalised to \(D^0 \rightarrow K^-\pi^+\)
➤ Main background from mis-identified \(D^0 \rightarrow \pi^+\pi^-\) (misID \(\sim 2\times10^{-8}\))
➤ Limit improved by a factor of 20!

\[ B(s) \rightarrow e^\pm \mu^\mp \]

➤ Analysis performed on 1 fb\(^{-1}\) of LHCb data
➤ Normalise to \(B^0 \rightarrow K^+\pi^-\), calibrate on \(B^0 \rightarrow h^+h^-\)
➤ Background mostly combinatorial from \(bb \rightarrow e^+/\mu^-/X\)
➤ Limits improved by a factor of 20!
➤ New 2 times lower bounds on Pati-Salam lepto-quark masses

<table>
<thead>
<tr>
<th>Mode</th>
<th>Limit</th>
<th>90% C.L.</th>
<th>95% C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B_s^0 \rightarrow e^\pm \mu^\mp)</td>
<td>Expected</td>
<td>1.5 \times 10^{-8}</td>
<td>1.8 \times 10^{-8}</td>
</tr>
<tr>
<td></td>
<td>Observed</td>
<td>1.1 \times 10^{-8}</td>
<td>1.4 \times 10^{-8}</td>
</tr>
<tr>
<td>(B^0 \rightarrow e^\pm \mu^\mp)</td>
<td>Expected</td>
<td>3.8 \times 10^{-9}</td>
<td>4.8 \times 10^{-9}</td>
</tr>
<tr>
<td></td>
<td>Observed</td>
<td>2.8 \times 10^{-9}</td>
<td>3.7 \times 10^{-9}</td>
</tr>
</tbody>
</table>
Suppressed modes

- Rare modes are not all necessarily “rare” in terms of the candidate yields:
  - The first period of data taking (Run 1) at LHC has produced unprecedented samples of rare decay processes in LHCb:
    - ~300 x 10^9 b-hadrons (and factor ~20 more c-hadrons)
  - Compare: Belle and BaBar collected together ~2.4 x 10^9 B mesons
Suppressed modes

…combined with the LHCb’s high signal sensitivity and background rejection

➤ large boost in the forward region (~15 for B’s)
➤ luminosity levelling (very low pile-up)
➤ hadron, lepton, photon identification (K+/−, π+/−, π0, γ, μ+/−, e+/−)
➤ triggers on di-electron, photon and hadronic final states (in addition to di-muons)

…the channels with branching fractions (BF) ~10^{-6} (e.g. B^+→K^+μ^+μ^-) yield in more than 4k selected signal candidates.

LHCb detector discussed in other talks (by K. Müller, P.Robber, R.S Coutinho, O.Steinkamp, P.Piucci)
Suppressed modes

• The **main observables** for the rare decays:
  - Branching Fractions (BF)
  - Differential BF’s
  - angular observables (for 4 particle final states)
  - effective lifetime
  - CP state specific (tagged observables)

• Precise **theory predictions** are paramount, especially for the measured rare modes (e.g. $B_{0s} \rightarrow \mu^+\mu^-$, $B^0 \rightarrow K^*\mu^+\mu^-$)

• The FCNC processes are well described within the **Effective Field Theory**

**Example:** One of the cleanest and rarest of these decays

$B_s \rightarrow \mu^+\mu^-$

(a) The “W box”  (b) The “Z penguin” (i)  (c) The “Z penguin” (ii)
Effective approach

...local 4-point interactions of different allowed “symmetry types” together describe the full decay

• Leading to the separation of perturbative (short distance, operators) and non-perturbative (long distance effects, Wilson coef.) in the effective hamiltonian:

\[
\mathcal{M}(B_{(s)}^0 \rightarrow \mu^+ \mu^-) = \langle \mu^+ \mu^- | \mathcal{H}_{\text{eff},q} | B_{(s)}^0 \rangle + \mathcal{O}(p^2/M_W^2) \\
\simeq \frac{G_F}{\sqrt{2}} \sum_i \left( C_i(\lambda) \times \langle \mu^+ \mu^- | \mathcal{O}_i | B_{(s)}^0 \rangle \right)
\]
• Lorentz invariance and other conservation laws restrict the number of allowed (short distance) contributions to each decay mode:

\[ B_s \to \mu^+ \mu^- \]

- **Effective approach**
  - Very precise Standard Model predictions, main uncertainty from CKM:
    \[
    \begin{align*}
    \mathcal{BR}(B_s \to \mu^+ \mu^-)_{<t><CP>} &= 3.66 \pm 0.23 \times 10^{-9} \ (6.4\% \ unc.) \\
    \mathcal{BR}(B_d \to \mu^+ \mu^-)_{<t><CP>} &= 1.06 \pm 0.09 \times 10^{-10} \ (8.5\% \ unc.)
    \end{align*}
    \]

- The leptonic and hadronic current factorise into **non-perturbative hadronic current** (calculable in Lattice QCD) and **perturbative leptonic 4-point operators**

- (dominant in the SM)
Effective approach

- Lorentz invariance and other conservation laws restrict the number of allowed (short distance) contributions to each decay mode:

\[ B_s \rightarrow \mu^+ \mu^- \]

The leptonic and hadronic current factorise into non-perturbative hadronic current (calculable in Lattice QCD) and perturbative leptonic 4-point operators.

- New Physics can enter any mode through any of the allowed operators by modifying the respective weights (Wilson coefficients, \( C \)).
Advantages of an effective approach

- Effective Hamiltonian is general:
  
  **MFV test:** In case of Minimal Flavour Violation the short distance Hamiltonians for B, D and K meson decays only differ due to the hadronic effects and CKM elements.

  \[ C^{bs} = C^{bd} = C^{cu} = C^{sd} \]

  \[ R = \frac{\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)}{\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-)} = \frac{\tau_{B_d}}{1/\Gamma_H} \left( \frac{f_{B_d}}{f_{B_s}} \right)^2 \left| \frac{V_{td}}{V_{ts}} \right|^2 \frac{M_{B_d}^2}{M_{B_s}^2} \sqrt{1-\frac{4m^2_u}{M_{B_d}^2}} = 0.0295^{+0.0028(8.7\%)}_{-0.0025(7.7\%)} \]

  - Top mass, Wilson coefficients, and \( V_{tb} \) cancel in theory predictions
  - Experimental side: no need for the (full) normalisation

  **Lepton Flavour Universality test:** even the hadronic effects cancel in the ratio between the leptonic B decays to kaons and different leptons:

  \[ \mathcal{R}(K)_{SM} = \frac{\mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \rightarrow K^+e^+e^-)} = 1 \pm \mathcal{O}(10^{-3}) \]

  (.due to phase space)

  \[ C. Bobeth et al., JHEP 07 (2007) 040, arxiv:0709.4174 \]
LHCb’s results: $b \rightarrow s l^+ l^-$
The combined significances (w.r.t. the null hypothesis, using Wilk’s theorem)

- **6.2σ obs.** (expected 7.2σ in SM)
- **3.2σ obs.** (expected 0.8σ in SM)

*Cross-checked with Feldman-Cousins: 3.0σ (official significance)*

The first **observation** of $B_s \rightarrow \mu \mu$ decay and the first **evidence** of $B_d \rightarrow \mu \mu$. 
Rare di-lepton modes

\[ B(s) \rightarrow \mu^+ \mu^- \]

- The combined central values w.r.t. the null hypothesis, using Wilk's theorem
  - \( \text{BR}(B_s \rightarrow \mu^+ \mu^-) = 3.9 \pm 1.6 \times 10^{-9} \)
  - \( \text{BR}(B_d \rightarrow \mu^+ \mu^-) = 5.6 \pm 2.7 \times 10^{-9} \)

The first observation of \( B_s \rightarrow \mu^+ \mu^- \) decay and the first evidence of \( B_d \rightarrow \mu^+ \mu^- \).

Results from ATLAS’ compatible

\[ \text{BR}(B_s \rightarrow \mu^+ \mu^-) = 0.9^{+1.1}_{-0.8} \times 10^{-9} \ (2\sigma) \]
\[ \text{BR}(B_d \rightarrow \mu^+ \mu^-) < 4.2 \times 10^{-10} \ (95\% \text{ CL}) \]

New LHCb results (including Run 2 data and effective lifetime measurement) expected (very) soon.
Lepton Flavour Universality Test

• R(K) is **precisely predicted in the SM**:

\[
\mathcal{R}(K)^{SM} = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)} = 1 \pm \mathcal{O}(10^{-3})
\]

(..due to phase space)

• R(K) has been **determined by the B-factories** with a precision of 20-50%:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>(q^2) (GeV(^2))</th>
<th>(R_K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaBar*</td>
<td>0.1 – 16.0</td>
<td>1.00(\pm 0.31) (+0.25) (-0.25) ± 0.07</td>
</tr>
<tr>
<td></td>
<td>0.1 – 8.12</td>
<td>0.74(\pm 0.40) (+0.31) (-0.31) ± 0.06</td>
</tr>
<tr>
<td></td>
<td>&gt; 10.11</td>
<td>1.43(\pm 0.65) (+0.65) (-0.65) ± 0.12</td>
</tr>
<tr>
<td>Belle**</td>
<td>0.00 – 16.0</td>
<td>1.03(\pm 0.19) (+0.19) (-0.19) ± 0.06</td>
</tr>
</tbody>
</table>

* PRD 86 (2012) 032012
** PRL 103 (2009) 171801

• R(K) is **sensitive to various NP models**: new scalar and pseudo-scalar interactions or \(Z'\) bosons
Lepton Flavour Universality Tests

$\mathcal{R}(K)$ in LHCb

$R(K)$ is determined in the **dilepton mass squared ($q^2$) range:** $1 < q^2 < 6 \text{ GeV}^2/c^4$

- excludes the resonant J/$\psi$ region and higher $\psi(2S)$ resonances
- makes precise theoretical estimates possible

..and as a double ratio w.r.t the respective resonant $B^+ \rightarrow J/\psi K^+$ modes to cancel potential sources of systematics:

$$R_K = \frac{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} d\Gamma(B^+ \rightarrow K^+ \mu\mu) dq^2}{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} d\Gamma(B^+ \rightarrow K^+ ee) dq^2} = \left( \frac{N_{K\mu\mu}}{N_{Kee}} \right) \left( \frac{N_{KJ/\psi(ee)}}{N_{KJ/\psi(\mu\mu)}} \right) \left( \frac{\epsilon_{Kee}}{\epsilon_{K\mu\mu}} \right) \left( \frac{\epsilon_{KJ/\psi(ee)}}{\epsilon_{KJ/\psi(\mu\mu)}} \right)$$

---

**LHCb (a)**

$B^+ \rightarrow J/\psi K^+$ Signal

**LHCb (b)**

$B^+ \rightarrow J/\psi K^+$ Signal

$m(K^+\mu^+\mu^-) [\text{MeV}/c^2]$
Lepton Flavour Universality Tests

$\mathcal{R}(K)$ Results (LHCb Run 1)

- Electrons are tricky:
  - efficiency to detect an electron is 50% smaller
  - mass distribution of electron modes depends strongly on the associated photons
  - bremsstrahlung causes migration in the di-lepton mass squared range

$$\mathcal{R}(K) = 0.745^{+0.090}_{-0.074}\text{(stat)} \pm 0.036\text{(syst)}$$

- most precise measurements up to date
- $\mathcal{R}(K)$ compatible with the SM at 2.6$\sigma$

- Individual BF's (LHCb):
  - Electron mode BF agrees with the SM ($0<q^2<6$ GeV$^2$/c$^4$):
    $$\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-) = [1.56^{+0.19}_{-0.15}\text{(stat)}^{+0.06}_{-0.04}\text{(syst)}] \times 10^{-7}$$
  - Muon mode BF lower than the SM ($0<q^2<15$ GeV$^2$/c$^4$).

PRL 113 (2014) 151601

JHEP 06 (2014) 133
Lepton Flavour Universality Tests

$\mathcal{R}(K)$ Results \textit{(LHCb Run 1)}

- Electrons are tricky:
  - efficiency to detect an electron is 50% smaller
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- Most precise measurements up to date
- $\mathcal{R}(K)$ compatible with the SM at $2.6 \sigma$

- $B(B^+ \to K^+ \mu^+ \mu^-) = (1.56^{+0.19}_{-0.15}^{(\text{stat})} \pm 0.06^{+0.04}_{-0.04}^{(\text{syst})}) \times 10^{-7}$
- $\mathcal{R}(K) = 0.745^{+0.090}_{-0.074}^{(\text{stat})} \pm 0.036^{(\text{syst})}$

- Electron mode BF agrees with the SM ($0 < q^2 < 6 \text{ GeV}^2/c^4$)
- Muon mode BF lower than the SM ($0 < q^2 < 15 \text{ GeV}^2/c^4$).

- Individual BF's (LHCb):

- Gauge width, $172^{+20}_{-19}$ events

- JHEP 06 (2014) 133
Rare semi-leptonic decays

- Measured BF on the lower side than predicted by the SM
  
  **LHCb**: arXiv:1606.04731, **CMS**: PLB 753 (2016) 424

- Angular distributions sensitive to NP effects
- 3 angles and di-lepton mass squared mapped to optimised variables to reduced form factor dependencies
- Significant local tension in one of the variables

\[
B^0 \rightarrow K^* \mu^+ \mu^-
\]

- Very challenging (statistics, resolution, trigger)
- Simplified angular analysis performed (in agreement with SM)

**LHCb**: LHCb-PAPER-2014-066, **SM**: PRD 93 (2016) 014028

Global fit at **3.4σ** from SM predictions
Rare di-lepton modes

Very interesting for the **Lepton Flavour Universality tests**

**More abundant** than the di-muon modes (helicity suppression less severe):

\[
B(B_s \rightarrow \tau^+ \tau^-)^{SM} = (7.73 \pm 0.49) \times 10^{-7}
\]

Previous limit from BaBar (only on \(B^0\)):

\[
B(B^0 \rightarrow \tau^+ \tau^-) < 4.1 \times 10^{-3} \quad @ \text{90\% C.L.}
\]

Bobeth et al., PRL 96 (2006) 241802, arxiv:hep-ex/0511015

**New result!**

![Graph showing R(D) and R(D*) values with error bands and data points from BaBar, Belle, and LHCb experiments.](image-url)

HFAG Average, \(\Delta \chi^2 = 67\%\)

Rare di-leptonic modes

\[ B_{(s)} \rightarrow \tau^+ \tau^- \]

- LHCb analyses the **full Run 1 dataset**
- Use **hadronic tau decays**
  \[ B(\tau^\pm \rightarrow \pi^\pm \pi^\mp \pi^\mp \bar{\nu}_\tau) = (9.31 \pm 0.05)\% \]
- \( B_s \) and \( B^0 \) mode inter-separable
- Analysis **optimised for \( B_s \) mode**
- Large background from random 6-pion combinations
- **Normalise** to
  \[ B^0 \rightarrow D^+ (\rightarrow \pi^+ K^- \pi^+) \] \( D_s^- (\rightarrow K^- K^+ \pi^-) \)
  BF ~ 0.03% ~10k candidates

Normalisation channel:
Rare di-leptonic modes

\[ B_{(s)} \rightarrow \tau^+ \tau^- \]

- Tau’s decay via an intermediate resonance:

\[ \tau^- \rightarrow a_1^-(1260)\nu_\tau \rightarrow \rho^0(770)\pi^-\nu_\tau \]

- Two stage neural network used to select and categorise signal and background events for the final fit. Based on kinematics, geometry and isolation.

- LHCb sets limits assuming either \( B_s \) or \( B_d \):

\[
\mathcal{B}(B^0_s \rightarrow \tau^+ \tau^-) < 3.0 \times 10^{-3} \quad \text{@ 95% C.L.} \\
\mathcal{B}(B^0 \rightarrow \tau^+ \tau^-) < 1.3 \times 10^{-4} \quad \text{@ 95% C.L.}
\]

Most sensitive region (in SM expect 0.2 events ~17%)
Global fits

Global fits are instrumental in knowing which kind of NP to look for and where

**Example:** S. Descotes-Genon, et al [JHEP 06 (2016) 092]

- Including $b \rightarrow s \mu^+ \mu^-$, $b \rightarrow s e^+ e^-$, $b \rightarrow s \gamma$

\[ B \rightarrow K l^+ l^- \quad B \rightarrow l^+ l^- \quad B \rightarrow \phi l^+ l^- \]

- Many scenarios tested…

a **negative** $C_9$ (EM penguin) alleviates the tensions

- Possible explanations: $Z'$, leptoquarks, …
P-resonance searches
P-resonance searches

In 2005 HyperCP: Measured $\Sigma^+ \rightarrow p\mu^+\mu^-$

Measured branching fraction is:

$B(\Sigma^+ \rightarrow p\mu^+\mu^-) = (8.6^{+6.6}_{-5.4} \pm 5.5) \cdot 10^{-8}$


Agrees to SM (short distance contributions small ($\sim 10^{-12}$), dominated by long distance ($\sim 10^{-8}$))

...is the di-muon mass hinting to a new intermediate $P \rightarrow \mu^+\mu^-$ resonance at $\sim 214\text{MeV}$?
LHCb finds ~ 13 candidates (4σ) in Run1 data

Tantalising fluctuations around 214MeV (thought not significant..)
N=1.6(1.9) candidates
P-resonance searches (indirect)

\[ B_{(s)} \rightarrow \mu^+ \mu^- \mu^+ \mu^- \]

- Sensitive to intermediate resonances (MSSM sgoldsino's, P,S→μ^+μ^-)

- Very low SM predictions: \(~3.5 \times 10^{-11}\)

- Previous limits (LHCb, 1fb\(^{-1}\))

\[ \mathcal{B}(B^0_s \rightarrow \mu^+ \mu^- \mu^+ \mu^-) < 1.6 \times 10^{-8} \]
\[ \mathcal{B}(B^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-) < 6.6 \times 10^{-9} \]

- Many improvements to the new analysis (normalisation, multivariate selection) and including the additional 2fb\(^{-1}\) of Run 1 data.


P-resonance searches (indirect)

Assume short lived S and P resonances
(no displacement)

Very efficient multivariate classifier
(removes 97.8% of combinatorics)

Apply vetoes on the resonances
(lose 35% of signal):

\[ \phi: \; 0.95 < m(\mu^+ \mu^-) < 1.09 \text{ GeV}/c^2 \]
\[ J/\psi: \; 3.00 < m(\mu^+ \mu^-) < 3.20 \text{ GeV}/c^2 \]
\[ \psi(2S): \; 3.60 < m(\mu^+ \mu^-) < 3.80 \text{ GeV}/c^2 \]

Improved upper limits by more than 6 times!

For the S/P scenario, assume short lived
m(S) of 2.6GeV and m(P) of 214.3MeV

SM: BF~3.5*10^{-11}
Rare charm and strange decays
More rare modes

Rare charm and strange decays:
➤ Charm: FCNC involving up-type quarks (c→u)
➤ **Short-distance** contributions strongly suppressed (GIM, m_{c,s}<<m_t) <10^{-18}
➤ **Long-distance** contributions (e.g. D →γγ→μ^+μ^-) can be larger ~10^{-5}
➤ Possible NP contributions harder to distinguish

\[ D^0 \rightarrow \mu^+ \mu^- \]

➤ Long distance effects can be constrained by measuring D^0→γγ:
BF(D →μ^+μ^-) SM prediction ~ 6*10^{-11}

➤ LHCb has analysed 0.9fb of 7TeV data:

\[ \mathcal{B} (D^0 \rightarrow \mu^+ \mu^-) < 6.2 (7.6) \times 10^{-9} \text{ at } 90\% \text{ (95\%) CL}. \]

Rare charm and strange decays:

- FCNC involving up-type quarks ($c \rightarrow u$)
- Short-distance contributions strongly suppressed (GIM, $m_c, s \ll m_t < 10^{-18}$)
- Long-distance contributions (e.g. $D \rightarrow \gamma\gamma \rightarrow \mu^+\mu^-$) can be larger $\sim 10^{-5}$
- Possible NP contributions harder to distinguish

**Observation of $D^0 \rightarrow K^\pm \pi^\mp \mu^- \mu^+$ in the $\rho - \omega$ region in $\mu^- \mu^+$ mass [LHCb, arXiv:1510.08367]**

**Search for $D^0 \rightarrow \pi^- \pi^+ \mu^- \mu^+$ [LHCb, PLB 728 (2014) 234]**

**Search for $D^0 \rightarrow \mu^- \mu^+$ [LHCb, PLB 725 (2013) 15]**

**Search for $D^{+ (s)} \rightarrow \pi^+ \mu^- \mu^+$ [LHCb, PLB 724 (2013) 203]**

**Search for $D^0 \rightarrow e^- \mu^+$ [LHCb, PLB 754 (2016) 167]**
More rare modes

- $K_L \rightarrow \mu^+\mu^-$
- $K_S \rightarrow \mu^+\mu^-$

- Measured BF = $(6.84 \pm 0.11) \times 10^{-9}$
- In agreement with SM

- Not measured yet...
- Previous limit: $<3.2 \times 10^{-7}$ (90% CL)
- SM expectation: $(5.0\pm1.5) \times 10^{-12}$

- LHCb 1fb$^{-1}$ analysis improves this by 30 times:
  
  \[
  \mathcal{B}(K_S^0 \rightarrow \mu^+\mu^-) < 11(9) \times 10^{-9}
  \]

- New LHCb 2fb$^{-1}$ analysis improves the limit even further:
  
  \[
  \mathcal{B}(K_S^0 \rightarrow \mu^+\mu^-) < 6.9(5.8) \times 10^{-9} \text{ at 95 (90)%}
  \]
More rare modes

- Measured BF = \( (6.84 \pm 0.11) \times 10^{-9} \)
- In agreement with SM

- Not measured yet…
- Current limit: \(<3.2 \times 10^{-7}\) (90% CL)

- LHCb is dedicated for beauty and charm, but not limited to.
- Sensitivity after upgrade: \(~ 10^{-12}\)
- Sensitive also to other modes, such as \(K_S \rightarrow \pi^0 \mu^+ \mu^-\)

..and MFV NP affecting the B decays would be
\(~ O(1)\) below the current experimental kaon limits

A. Crivellin et al, arXiv:1601.00970v3
No LFV...

$P' \ @ \ 3.4\sigma$

$B(s) \to \mu\mu$

$R(D^*) \ @ \ 4.0\sigma$

$R(K) \ @ \ 2.6\sigma$

$B(B_s \to \phi\mu\mu)$
Summary

- Effective approach has historically played a crucial role in understanding the underlying theory from both direct and indirect measurements:
  - **1933**: First model for the weak decays. Same coupling for the beta decay and muon decay suggested underlying structure (V-A)
  - **1960’s**: Predicting charm to make GIM work and explain missing FCNC.
  - **1970’s**: Predict lower bounds on Z and W masses from muon lifetime (motivate SPS)
  - **2010’s**: Lepton Flavour Universality Violation? Z’? Leptoquarks?

..and MFV NP affecting the B decays would be \( \sim O(1) \) below the current limits on Kaon decays
A. Crivellin et al, arXiv:1601.00970v3
LHCb’s schedule is busy…

- LHCb has collected **additional 1.32 fb⁻¹ at 13 TeV**
- Presented analysis will be **updated (some very soon!)**

- Many **new analysis** ongoing/foreseen at LHCb:
  - $R(K^*)$ with $B^0 \rightarrow K^* l^+ l^-$ and larger $q^2$ range
  - Electron-muon asymmetry in $P'\ _5$
  - Upcoming rare strange programme
  - $R(D^*)$ using hadronic $\tau$-decays
  - $R(D)$ measurement
  - Extend $R$ to other mesons/baryons: $R(D_s)$, $R(\Lambda_c)$, $R(\Lambda_c^*)$

...very interesting year (not years) ahead.