Lepton Flavour Universality tests with B decays at LHCb

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On behalf of LHCb Collaboration

See also the talk of Marc-Olivier Bettler
Lepton Flavour Universality tests with B decays

In the SM:

\[ W^+ \rightarrow \ell^+ \nu \ell \]

\[ Z^0 \rightarrow \ell^- \ell^+ \]

\[ \ell = e, \mu, \tau \]

\[ \ldots \rightarrow R(D^*) \] and \[ R(K) \]

\[ R(D^*) = \frac{B \rightarrow D^* \tau \nu}{B \rightarrow D^* \mu \nu} \]

\[ R(D^*) = 0.252 \pm 0.003 \]

\[ R(K) = \frac{B \rightarrow K \mu \mu}{B \rightarrow K e e} \]

\[ R = 1 \text{ (at } 10^{-3} \text{ ) in the SM} \]

Practical considerations

Extremely challenging analyses:

**R(D*)**
- Neutrinos in the final state
- Trigger background levels

**R(K*)**
- Rare decays
- Differences between $\mu$ and $e$
- Bremsstrahlung
- Reconstruction
- Trigger

Analyses presented today based on the Run 1 dataset
\[ R(D^*) \equiv \frac{\mathcal{B}(B \rightarrow D^*\tau\nu)}{\mathcal{B}(B \rightarrow D^*\mu\nu)} \]

BR(\(\tau \rightarrow \mu\nu\nu\)) ~ 17 %

Identical final states

No sharp peak
Background from partially reconstructed B decay

Signal

Known B flight direction, approximate the B momentum

\((\gamma \beta_z)_{B^0} \equiv (\gamma \beta_z)_{D^*\mu}\)

Large statistics:

\[ N(B^0 \rightarrow D^{*+}\mu^-\bar{\nu}_\mu) = 363000 \]

\[ \frac{N(B^0 \rightarrow D^{*+}\tau^-\bar{\nu}_\tau)}{N(B^0 \rightarrow D^{*+}\mu^-\bar{\nu}_\mu)} = (4.54 \pm 0.46) \times 10^{-2} \]
R(D*)

3 discriminating variables (B rest frame)

- \( q^2 = |p_B - p_D|^2 \)
- \( m_{\text{miss}}^2 = |p_B - p_D - p_\mu|^2 \)
- \( E_\mu^* \)

MC truth

Reconstructed

Form factor uncertainties folded in the fit


Templated fit in 4 bins of \( q^2 \) (with different S/B)
$\mathcal{R}(D^*) = 0.336 \pm 0.027\,\text{(stat)} \pm 0.030\,\text{(syst)}$

In agreement with other measurements and 2.1 $\sigma$ away from the SM

In total $\sim 3.9\,\sigma$ away from the SM
R(D*) : what's next?

Increase the statistics by using hadronic tau decays (BR(τ → 3 prongs ~ 15%))

Very different backgrounds:
D*3πX
Double charm decays

→ LHCb precise vertex reconstruction
→ Measurement of the background levels on data
→ Use D* D_s(3π) control channel to monitor the background

as well as R(D), R(Λ_c)
Experimentally, use a double ratio to cancel systematics

\[ R_K = \frac{\int_{q_{\text{min}}^2}^{q_{\text{max}}^2} d\Gamma[B^+ \to K^+ \mu^+ \mu^-] dq^2}{\int_{q_{\text{min}}^2}^{q_{\text{max}}^2} d\Gamma[B^+ \to K^+ e^+ e^-] dq^2} \]

\[ R_K = \left( \frac{N_{K^+ \mu^+ \mu^-}}{N_{K^+ e^+ e^-}} \right) \left( \frac{N_{J/\psi(e^+ e^-) K^+}}{N_{J/\psi(\mu^+ \mu^-) K^+}} \right) \left( \frac{\epsilon_{K^+ e^+ e^-}}{\epsilon_{K^+ \mu^+ \mu^-}} \right) \left( \frac{\epsilon_{J/\psi(\mu^+ \mu^-) K^+}}{\epsilon_{J/\psi(e^+ e^-) K^+}} \right) \]

**B → K \mu\mu**  
~1200 signal events

**B → K e\e**  
~250 signal events

<table>
<thead>
<tr>
<th>Electron trigger</th>
<th>Hadron trigger</th>
<th>OtherB trigger</th>
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<tbody>
<tr>
<td><img src="image1" alt="Electron trigger graph" /></td>
<td><img src="image2" alt="Hadron trigger graph" /></td>
<td><img src="image3" alt="OtherB trigger graph" /></td>
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$R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$

Tension with the SM at 2.6 $\sigma$
LFU tests in $b \rightarrow s ll$ : what’s next ?

Test more :

$$R(K^*) = \frac{B \rightarrow K^* \mu \mu}{B \rightarrow K^* e e} \quad R(\phi) = \frac{B_S \rightarrow \phi \mu \mu}{B_S \rightarrow \phi e e}$$

- more $q^2$ bins

Test of LFU with $B^0 \rightarrow K^0 \mu \mu$ and $B^0 \rightarrow K^0 e e$
LFU tests in $b \rightarrow sll$ transitions: what’s next?

LHCb: 2.8 and 3.0 $\sigma$ from SM

$B^0 \rightarrow K^* \mu\mu$ angular analysis

LHCb JHEP 02(2016) 104

Belle PRL118, 111801 (2017)

ATLAS, preliminary Moriond EW

CMS, preliminary Moriond EW

$K^{(*)}$ ee angular analyses in the same $q^2$ region 1-6 GeV$^2$/c$^4$?
Summary

- In the SM observables to test Lepton Flavour Universality can be precisely predicted
- Experimentally challenging
- Stay tuned!

Increase of energy (cross-section) and collected data (~5 fb⁻¹ expected in LHCb) in Run 2
Backup slides
Angular Analyses

- Results consistent with SM predictions

\[ \text{B}^0 \rightarrow \text{K}^*0 \text{ee} \]

\[ F_L = 0.16 \pm 0.06 \pm 0.03 \]
\[ A_T^{\text{Re}} = 0.10 \pm 0.18 \pm 0.05 \]
\[ A_T^{(2)} = -0.23 \pm 0.23 \pm 0.05 \]
\[ A_T^{\text{Im}} = 0.14 \pm 0.22 \pm 0.05 \]

\[ \Lambda_{b} \rightarrow \Lambda \mu \mu \]

- Low-\( q^2 \): 0.0004–1 GeV\(^2\)
- Challenging due to Bremsstrahlung
- Sensitive to photon polarisation

- \( \Lambda_{b} \): gives access to different combinations of Wilson coefficients

\[ \text{JHEP 06 (2015) 115} \]

\[ \text{JHEP 04 (2105) 064} \]

\[ \text{JHEP 09 (2015) 179} \]
Differential Branching Fractions

- Results **consistently lower than SM predictions** despite large theory uncertainties from form-factors

\[ B^+ \rightarrow K^+ \mu^+ \mu^- \quad \text{LHCb} \]

\[ B^0 \rightarrow K^0 \mu^+ \mu^- \quad \text{LHCb} \]

\[ B_s \rightarrow \phi \mu \mu \quad \text{JHEP 09 (2015) 179} \]

\[ \Lambda_b \rightarrow \Lambda \mu \mu \quad \text{LHCb} \]

\[ JHEP 06 (2014) 133 \]

\[ JHEP 06 (2015) 115 \]
Global Fits

• Several attempts to interpret results by performing global fits to $b \rightarrow s$ data (e.g. arXiv:1503.06199, arXiv:1510.04239 and arXiv:1512.07157)

• Take into account $\sim 80$ observables from 6 experiments including $b \rightarrow \mu\mu$, $b \rightarrow sll$ and $b \rightarrow s\gamma$ transitions

• All global fits require an additional contribution with respect to the SM to accommodate the data, with a preference for NP in $C_9$ at $\sim 4\sigma$

• Or is this a problem with our understanding of QCD? (e.g. are we correctly estimating the contribution for charm loops?)