B-flavour anomalies in $b \to s\ell\ell$ and $b \to c\ell\nu$ transitions at LHCb

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on behalf of the LHCb collaboration

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Lepton Flavour Universality

• In the SM, gauge bosons have universal coupling to leptons, independently of their family. This is called Lepton Flavour Universality (LFU).

<table>
<thead>
<tr>
<th>e^-</th>
<th>μ^-</th>
<th>τ^-</th>
</tr>
</thead>
<tbody>
<tr>
<td>ν_e</td>
<td>ν_μ</td>
<td>ν_τ</td>
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<td>u</td>
<td>c</td>
<td>t</td>
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<tr>
<td>d</td>
<td>s</td>
<td>b</td>
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</table>

• Tensions between experiments and SM predictions found in:
  • Neutral currents ($b \rightarrow s\ell\ell$).
  • Charged currents ($b \rightarrow c\ell\nu$).

• A violation of LFU would require the existence of new particles outside the SM ($H^\pm$, $Z'$, $W'^\pm$, leptoquarks...).
LHCb detector

- High b-quark production:
  - Run1 (2011-2012, 7-8 TeV):
    - $3.2 \text{ fb}^{-1}$, $\sigma_{b\bar{b}X} \approx 72 \mu\text{b}$
    - $5.9 \text{ fb}^{-1}$, $\sigma_{b\bar{b}X} \approx 144 \mu\text{b}$
- Excellent vertex and impact parameter resolution ($\sim 25 \mu\text{m}$).
- $b$-hadrons highly boosted, giving large values of the impact parameter.
- Excellent PID performance for charged particles (muon efficiency of $\sim 97\%$).
LFU tests at LHCb: neutral currents

- \( b \to s \ell^+ \ell^- \) decays:
  \[
  R(\mathcal{H}_S)[q_{\text{min}}, q_{\text{max}}] \equiv \frac{\int_{q_{\text{min}}}^{q_{\text{max}}} \frac{d\Gamma(\mathcal{H}_b \to \mathcal{H}_S \mu^+ \mu^-)}{dq^2}}{\int_{q_{\text{min}}}^{q_{\text{max}}} \frac{d\Gamma(\mathcal{H}_b \to \mathcal{H}_S e^+ e^-)}{dq^2}},
  \]
  where
  \[
  q^2 = m_{\ell \ell}^2,
  \]
  \( \mathcal{H}_b = B^0, B^+, \ldots \)
  \( \mathcal{H}_S = K, K^+, \ldots \)

- In SM: strongly suppressed. Can only happen via loops.
- Sensitivity to NP in branching fractions and in angular distributions.
- Small theoretical uncertainties.
- Partial cancelation of hadronic form factor uncertainties.

Different \( q^2 \) regions \( \rightarrow \) Contributions from different processes
Difficulties due to differences in the detection of electrons and muons:
• Electrons have a lower trigger efficiency.
• Electrons lose a large amount of energy through bremsstrahlung radiation.

Bremsstrahlung photons used to improve the reconstruction of the electron energy-momentum.

To reduce systematics, $R(H_s)$ is measured as a double ratio:

$$R(H_s) = \frac{\mathcal{B}(H_b \to H_s \mu^+ \mu^-)}{\mathcal{B}(H_b \to H_s J/\psi(\to \mu^+ \mu^-)) \mathcal{B}(H_b \to H_s e^+ e^-)}$$

(Possible since $J/\psi \to \ell^+ \ell^-$ is measured to be lepton universal)
**$R(K^{*0})$ measurement at LHCb**

(Run1 data, 3.2 fb$^{-1}$)

- Nonresonant modes: $B^0 \to K^{*0} (\to K^+\pi^-) \ell^+\ell^-$
- Resonant modes: $B^0 \to K^{*0} (\to K^+\pi^-) J/\psi (\to \ell^+\ell^-)$

Two $q^2$ bins:

- **Lower:** $0.045 < q^2 < 1.1 \text{ GeV}^2/c^4$
- **Central:** $1.1 < q^2 < 6.0 \text{ GeV}^2/c^4$

- $e^+e^-$ data divided into three categories depending on how the event was triggered.
- Neural network classifiers to separate signal from combinatorial background.
- Large background from $B^0 \to D^- (\to K^{*0} \ell^- \bar{\nu}_\ell) \ell^+ \nu_\ell$ separated using angular distribution of $\ell^+\ell^-$ pair.

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**Figure:**

- Scatter plots of $m(K^+\pi^-\mu^+\mu^-)$ vs. $q^2$ for $B^0 \to K^{*0} (\to K^+\pi^-) \ell^+\ell^-$.
- Two bins: Lower and Central.

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Signal yields obtained from fits to $m(K^+\pi^-\ell^+\ell^-)$ distributions for each $q^2$ bin and lepton type. Simultaneous fits on resonant and nonresonant modes, with shared parameters. In the electron channels, separate model for each trigger category.
$R(K^{*0})$ measurement at LHCb

$0.045 < q^2 < 1.1$ GeV$^2/c^4$ : $R(K^{*0}) = 0.66^{+0.11}_{-0.07} \pm 0.03 \sim 2.1-2.3\sigma$ below SM predictions

$1.1 < q^2 < 6.0$ GeV$^2/c^4$ : $R(K^{*0}) = 0.69^{+0.11}_{-0.07} \pm 0.05 \sim 2.4-2.5\sigma$ below SM predictions

BaBar: [PRD 86 (2012) 032012]
Belle: [PRL 103 (2009) 171801]
Belle 2019: [arXiv:1904.02440]
**$R(K)$ measurement at LHCb**

(Adapted from PRL 122 (2019) 191801)

Nonresonant modes: $B^+ \to K^+ \ell^+ \ell^-$

Resonant modes: $B^+ \to K^+ J/\psi (\to \ell^+ \ell^-)$

$q^2$ range: $1.1 < q^2 < 6.0 \text{ GeV}^2/\text{c}^4$

BDTs reduce combinatorial background and select resonant decays.

Resonant mode yields obtained from separate fits to $m_{J/\psi}(K^+ \ell^+ \ell^-)$, and used as constraints in the fit to $m(K^+ \ell^+ \ell^-)$, with $R(K)$ as a free parameter.
$R(\bar{K})$ measurement at LHCb

$1.1 < q^2 < 6.0 \text{ GeV}^2/c^4$ : 

$R(\bar{K}) = 0.846^{+0.060 +0.016}_{-0.054 -0.014}$

$\sim 2.5\sigma$ below SM predictions

Separate fits just to Run1 and Run2 data:

$R(\bar{K})_{7-8\text{ TeV}} = 0.717^{+0.083}_{-0.071} +0.017$

$R(\bar{K})_{13\text{ TeV}} = 0.928^{+0.089}_{-0.076} +0.020$

Previous LHCb measurement with Run1 data:

$1.0 < q^2 < 6.0 \text{ GeV}^2/c^4$ : 

$R(\bar{K}) = 0.745^{+0.090}_{-0.074} \pm 0.036$

$[\text{PRL 113,151601 (2014)}] \sim 2.6\sigma$ below SM predictions

Both measurements compatible within $1\sigma$. 

[PRD 86 (2012) 032012]
[Belle: [PRL 103 (2009) 171801]
LFU tests at LHCb: charged currents

- $b \rightarrow c \ell^- \bar{\nu}_\ell$ decays:

$$R(H_c) \equiv \frac{\mathcal{B}(H_b \rightarrow H_c \tau^- \bar{\nu}_\tau)}{\mathcal{B}(H_b \rightarrow H_c \mu^- \bar{\nu}_\mu)},$$

where

$$H_b = B^0, B^+, B_s^0, \Lambda_b^0 ...$$
$$H_c = D^{(*)0}, D^{(*)+}, D_s^+, \Lambda_c^+, J/\psi ...$$

- In SM: tree-level decays mediated by a $W$ boson.
- Sensitivity to NP contributions at tree level.
- Partial cancelation of hadronic form factor uncertainties.
- High rate of charged current decays: $\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau) \approx 1.2\%$.

- Muonic channel: $\mathcal{B}(\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau) \approx 17.39\%$
- Hadronic channel: $\mathcal{B}(\tau^- \rightarrow \pi^- \pi^+ \pi^- (\pi^0) \nu_\tau) \approx 13.81\%$

- Systematic uncertainties cancel in the ratio $R(H_c)$.
- Presence of inclusive $H_b \rightarrow H_c \mu^- \bar{\nu}_\mu (X)$ decays.
- Only one neutrino.
- $\tau$ vertex reconstruction.

\[ \begin{array}{c}
\tau^-
\downarrow
\mu^-
\downarrow
\bar{\nu}_\mu
\downarrow
\nu_\tau
\downarrow
\pi^-
\downarrow
\pi^+
\downarrow
\pi^0
\downarrow
\end{array} \]
$R(D^*)$ muonic

$$R(D^*) = \frac{B(B^0 \rightarrow D^{*+}\tau^–\bar{\nu}_\tau)}{B(B^0 \rightarrow D^{*+}\mu^–\bar{\nu}_\mu)}$$

Both channels selected, and then disentangled using a multidimensional fit to:

$$\rho_B = \frac{m_B}{m_{reco}}(p_{reco})_z$$

- $E^*_\mu$ (B rest frame)
- $m_{\text{miss}}^2 = (p_B - p_{D^*} - p_\mu)^2$
- $q^2 = (p_B - p_{D^*})^2$

$$R(D^*)_{\text{muonic}} = 0.336 \pm 0.027 \pm 0.030$$

2.1σ above SM prediction

$R(D^*)_{\text{SM}} = 0.252 \pm 0.003$

(Run1 data, 3.2 fb⁻¹)
$R(J/\psi)$ muonic

\[ R(J/\psi) = \frac{\mathcal{B}(B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)} \]

Similar to $R(D^*)$ analysis, fit using:
- $m_{\text{miss}}^2 = (p_B - p_{J/\psi} - p_\mu)^2$
- $q^2 = \left(p_B - p_{J/\psi}\right)^2$
- $E_\mu^* (B \text{ rest frame})$
- $B_c$ decay time

\[ R(J/\psi)_{\text{muonic}}^{(\text{raw})} = \frac{N(B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau)}{N(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)} \frac{1}{\mathcal{B}(\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau)} \frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}} \]

+Systematic bias in the fit

$R(J/\psi)_{\text{muonic}} = 0.71 \pm 0.17 \pm 0.18$

$2\sigma$ above SM prediction
$R(J/\psi)_{\text{SM}} \in [0.25, 0.28]$
$R(D^*)$ hadronic

$$\mathcal{K}(D^{*-}) \equiv \frac{B(B^0 \to D^{*-}\tau^+\nu_{\tau})}{B(B^0 \to D^{*-}\pi^-\pi^+\pi^+)} = \frac{N_{\text{sig}} \varepsilon_{\text{norm}}}{N_{\text{norm}} \varepsilon_{\text{sig}}} \frac{1}{B(\tau^+ \to \pi^+\pi^-\pi^+\pi^0\bar{\nu}_{\tau})}$$

$$R(D^{*-})_{\text{had}} = \frac{B(B^0 \to D^{*-}\pi^-\pi^+\pi^+)}{B(B^0 \to D^{*-}\mu^+\nu_{\mu})} \mathcal{K}(D^{*-})$$

The presence of only one neutrino allows the $\tau$ and $B^0$ momenta to be determined up to a two-fold ambiguity.

$N_{\text{sig}}$ obtained from a binned fit in these variables:
- Squared transferred momentum, $q^2$.
- $\tau$ decay time, $t_{\tau}$.
- Output of a BDT, which takes as input 18 variables (kinematic variables of the decay chain and neutral isolation properties).

$N_{\text{norm}}$ obtained by fitting the invariant mass distribution of the $D^{*-}3\pi$ system around the $B^0$ mass.
$R(D^*)$ hadronic

$$N_{norm} = 17808 \pm 143$$

$$N_{sig} = 1296 \pm 86$$

$K(D^{*-}) = 1.97 \pm 0.13\text{(stat)} \pm 0.18\text{(syst)}$

$R(D^{*-})_{had} = 0.291 \pm 0.019 \pm 0.029$

1.1$\sigma$ higher than SM prediction

$R(D^*)_{SM} = 0.252 \pm 0.003$
With the new Belle preliminary result, global averages are at 1.4\(\sigma\) difference in \(R(D)\), 2.5\(\sigma\) in \(R(D^*)\) and 3.08\(\sigma\) combined.
Prospects

Run1+Run2: ~4 times as many $b\bar{b}$ pairs as in Run1

Ongoing and future analyses:

- Simultaneous measurement of $R(D^0)$ and $R(D^*)$ via three-prong and muonic tau decays (Run2).
- Simultaneous measurement of $R(D^+)$ and $R(D^{*+})$ via three-prong and muonic tau decays (Run2).
- Updated results for $R(K)$, $R(K^*)$, $R(D^*)$, $R(J/\psi)$...
- Measurement of new ratios $R(\phi)$, $R(\Lambda_c)$, $R(D_s)$...
Conclusions

- Intriguing tensions with SM in ratios of branching fractions in
  - $b \to s \ell \ell$ decays
  - $b \to c \ell \nu$ decays

- Potential for NP? We need smaller uncertainties!

- LHCb Run2 data will provide significant improvements and new measurements.

Stay tuned!
Thank you!
Effective Hamiltonian

\[ \mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}}V_{tb}V_{ts}^* \frac{e^2}{16\pi^2} \sum_i C_i \mathcal{O}_i \]

\( C_i \): Wilson coefficients, effective coupling (short-distance).
\( \mathcal{O}_i \): Local operators (long-distance).

Global fits performed to constrain the value of \( C_i^{NP} \)
Angular analysis in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

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

\[ F_L, A_{FB}, S_i \] are combinations of angular amplitudes and depend on Wilson coefficients and on form factors.

Optimised observables where form factor uncertainties cancel, like $P'_5 \equiv \frac{S_5}{\sqrt{F_L(1-F_L)}}$

3.4σ difference with SM
Trigger categories

$B^0$ mass resolution and signal/background contributions depend on the way the event is triggered.

Data sample divided in three categories, by order of precedence:
• L0E: one of the electrons satisfies the hardware electron trigger.
• L0H: one of the hadrons satisfies the hardware hadron trigger.
• L0I: candidates triggered by non-signal particles.

$B^0 \rightarrow K^{*0}(\rightarrow K^+\pi^-)e^+e^-$

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<th>L0E</th>
<th>L0H</th>
<th>L0I</th>
<th>L0E</th>
<th>L0H</th>
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<td>5.5</td>
<td>6.4</td>
<td>7.5</td>
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</table>
$R(D^*)$ muonic: signal discrimination

- $\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu$
- $\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau$
Fits to simulated data reveal a systematic bias, thus the raw $R(J/\psi)$ result needs to be corrected:
### Source of uncertainty

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<th>Source of uncertainty</th>
<th>Size ($\times 10^{-2}$)</th>
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<td>Limited size of simulation samples</td>
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<td>$B_c^+ \rightarrow J/\psi$ form factors</td>
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<td><strong>Statistical uncertainty</strong></td>
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$R(D^*)$ hadronic: detached vertex cut

Prompt background reduced by three orders of magnitude
40% of signal retained
$R(D^*)$ hadronic: BDT
With LHC Upgrade II, we will be able to discriminate between different NP scenarios:

\[ \begin{array}{c|cccc} \text{scenario} & C_9^{\text{NP}} & C_{10}^{\text{NP}} & C_9' & C_{10}' \\ \hline \text{I} & -1.4 & 0 & 0 & 0 \\ \text{II} & -0.7 & 0.7 & 0 & 0 \\ \text{III} & 0 & 0 & 0.3 & 0.3 \\ \text{IV} & 0 & 0 & 0.3 & -0.3 \end{array} \]