Test of lepton flavour universality in $b \rightarrow s \ell^+\ell^-$ decays at LHCb

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Lepton Flavour Universality (LFU) & rare decays

Standard Model (SM) couplings of leptons to vector bosons are flavour-independent.

- any sign of lepton flavour non-universality would indicate new physics (NP)

Decays of $b$-quarks are sensitive to LFU.

- example: the rare process $b \rightarrow s\ell^+\ell^-$ — flavour-changing neutral current (FCNC)

- SM only allows FCNCs through loop, but NP can enter at tree level or contribute to the loop (even at high mass scales) $\Rightarrow$ potential LFU violation
Anomalous flavour observables

A pattern of interlinked anomalies has emerged in studies of $b \to s \ell^+ \ell^-$ processes.

- branching fractions of e.g.
  - $B_s \to \mu^+ \mu^-$ (see Flavio’s talk)
  - $B \to K(\ast)\mu^+ \mu^-$ \cite{JHEP 06 (2014) 133}

- angular observables in e.g. $B^0 \to K^{*0}\mu^+ \mu^-$ \cite{PRL 125 (2020) 011802}

- ratios of branching fractions, such as $R_{K^{*0}}$ \cite{JHEP 08 (2017) 055}
The observable $R_K$

One of the anomalous LFU observables is:

$$R_K = \frac{\int_{1.1 \text{ GeV}^2}^{6.0 \text{ GeV}^2} dB(B^+ \rightarrow K^+ \mu^+ \mu^-) dq^2}{\int_{1.1 \text{ GeV}^2}^{6.0 \text{ GeV}^2} dB(B^+ \rightarrow K^+ e^+ e^-) dq^2} \equiv 1 \pm O(10^{-2}) \text{ EM correction}^1$$

Previous LHCb measurement is in tension with SM prediction at level of 2.5 $\sigma$ [PRL 122 (2019) 191801].

- obtained using data collected up until 2016
- subject of this talk: update of the previous measurement, with full Run 1 and Run 2 data
  - adding 2017 & 2018 data effectively doubles the dataset
  - following essentially identical procedure

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Challenge: muons vs. electrons at LHCb

Bulk of the analysis is dedicated to getting differences between electron and muon detection under control.

- different trigger and particle identification strategies
- electrons lose significant portions of energy to bremsstrahlung radiation
  - worse mass resolution and reconstruction efficiency
  - cf. muons
- mitigated by e.g. recovery algorithm (look for photon clusters in calorimeter that are compatible with electron trajectory)
Measuring $R_K$

$$R_K = \left( \frac{N_{\mu\mu}^{\text{rare}}}{\varepsilon_{\mu\mu}^{\text{rare}}} \bigg/ \frac{N_{ee}^{\text{rare}}}{\varepsilon_{ee}^{\text{rare}}} \right)$$

Five main steps:
1. Obtain electron and muon data through tailored selection
2. Calibration of simulation $\rightarrow$ Efficiency calculation
3. Estimation of systematic uncertainties
4. Conduct cross-checks, such as $r_J/\psi$ (known LFU)
5. Fit rare data $\rightarrow$ Extraction of $R_K$
Measuring $R_K$

Control electron-muon differences through double ratio between rare $B^+ \rightarrow K^+ \ell^+ \ell^-$ modes and control $B^+ \rightarrow K^+ J/\psi (\ell^+ \ell^-)$ channels:

$$R_K = \left( \frac{N_{\mu\mu}^{\text{rare}}}{\varepsilon_{\mu\mu}^{\text{rare}}} \frac{N_{ee}^{\text{rare}}}{\varepsilon_{ee}^{\text{rare}}} \right) / \left( \frac{N_{\mu\mu}^{\text{control}}}{\varepsilon_{\mu\mu}^{\text{control}}} \frac{N_{ee}^{\text{control}}}{\varepsilon_{ee}^{\text{control}}} \right) \cdot r_{J/\psi}$$
Measuring $R_K$

Control electron-muon differences through double ratio between rare $B^+ \rightarrow K^+\ell^+\ell^-$ modes and control $B^+ \rightarrow K^+J/\psi(\ell^+\ell^-)$ channels:

$$R_K = \left( \frac{N_{\mu\mu}^{\text{rare}}}{\varepsilon_{\mu\mu}^{\text{rare}}} \right) \cdot \frac{N_{ee}^{\text{control}}}{N_{\ell\ell}^{\text{control}}} = \left( \frac{N_{\mu\mu}^{\text{rare}}}{\varepsilon_{\mu\mu}^{\text{rare}}} \right) \cdot \frac{N_{ee}^{\text{control}}}{N_{\ell\ell}^{\text{control}}}$$

Five main steps:
1. obtain electron and muon data through tailored selection
2. calibration of simulation $\rightarrow$ efficiency calculation
3. estimation of systematic uncertainties
4. conduct cross-checks, such as $r_{J/\psi}$ (known LFU)
5. fit rare data $\rightarrow$ extraction of $R_K$
Efficiency calculation and corrections to simulation

Efficiencies estimated from simulated samples, which are calibrated using control data. Calibration procedure is the same as in [PRL 122 (2019) 191801], and it covers:

- trigger performance;
- particle identification efficiency;
  - method described in [EPJ T&I (2019) 6:1]]
- $B^+$ kinematics;
- resolutions of $q^2$ and $m(K^+e^+e^-)$.

This leads to %-level control of efficiency ratios.

- verified through a host of cross-checks

Example measurement of electron trigger performance
Cross-check example: the single ratio $r_{J/\psi}$

$$r_{J/\psi} = \frac{B(B^+ \to K^+ J/\psi(\mu^+ \mu^-))}{B(B^+ \to K^+ J/\psi(e^+ e^-))} = \frac{N_{\mu\mu}^{\text{control}}}{e_{\mu\mu}^{\text{control}}} / \frac{N_{ee}^{\text{control}}}{e_{ee}^{\text{control}}}$$

Single ratio requires control of electrons with respect to muons.
- stringent cross-check of efficiencies & yields

Result: $r_{J/\psi} = 0.981 \pm 0.020$ (stat. & syst.)

Also compute $r_{J/\psi}$ in bins of variables relevant to detector response (1D $r_{J/\psi}$)
- if deviations from flatness are genuine, impact on $R_K$ is within estimated systematic uncertainty
Cross-check: the double ratio $R_{\psi(2S)}$

Select data at $\psi(2S)$ resonance and evaluate:

$$R_{\psi(2S)} = \frac{B(B^+ \to K^+\psi(2S)(\mu^+\mu^-)) / B(B^+ \to K^+J/\psi(\mu^+\mu^-))}{B(B^+ \to K^+\psi(2S)(e^+e^-)) / B(B^+ \to K^+J/\psi(e^+e^-))}$$

- expected close to unity
- test efficiency corrections at $q^2$ away from $J/\psi$
- independent validation of double ratio

Result: $R_{\psi(2S)} = 0.997 \pm 0.011$ (stat. & syst.)
Fits to $B^+ \rightarrow K^+\ell^+\ell^-$ data

$R_K$ is extracted as a parameter of a simultaneous fit to all $B^+ \rightarrow K^+\ell^+\ell^-$ data.

- correlations between selection efficiencies taken into account
- shape parameters derived from calibrated simulation
- systematic effect of chosen signal & background models is $\sim 1\%$
Fits to $B^+ \to K^+ \ell^+ \ell^-$ data

$R_K$ is extracted as a parameter of a simultaneous fit to all $B^+ \to K^+ \ell^+ \ell^-$ data.

- correlations between selection efficiencies taken into account
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$R_K$ with full Run 1 and Run 2 LHCb data

The measured value of $R_K$ is:

$$R_K = 0.846^{+0.042}_{-0.039} \text{ (stat.)}^{+0.013}_{-0.012} \text{ (syst.)}$$

- dominant systematic effect: fit model
  - effects such as calibration of trigger & kinematics are at permille-level

- $p$-value under SM hypothesis: 0.0010

- significance: $3.1 \sigma$ (evidence for LFU violation in $B^+ \rightarrow K^+\ell^+\ell^-$ decays)
Combining measured $R_K$ value with $\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)$ result from [JHEP 06 (2014) 133] gives:

$$\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-) = (28.6^{+1.5}_{-1.4}^{\text{(stat.)}} \pm 1.3^{\text{(syst.)}}) \times 10^{-9}$$

in the range $q^2 \in [1.1, 6.0]$ GeV$^2$/c$^4$. 
Summary

- performed most precise measurement of the LFU ratio $R_K$ using full LHCb Run 1 and Run 2 data

- gained factor $\sim 2$ statistics cf. previous result [PRL 122 (2019) 191801]

- $3.1\,\sigma$ tension with SM prediction\(^1\)
  - evidence for violation of LFU in $B^+ \rightarrow K^+ \ell^+ \ell^-$ decays

- LHCb will continue to study flavour anomalies, including LFU-sensitive observables

- paper submitted to Nature Physics [LHCb-PAPER-2021-004]

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\(^1\) [JHEP 06 (2016) 092] [JHEP 07 (2007) 040] [EPJC 76 (2016) 440] [PRD 69 (2004) 074020] [PRD 68 (2003) 094016] [EOS] [flavio]
$K^+\ell^+\ell^-$ final states at LHCb
Backgrounds coming from $b \rightarrow c \ell^- \bar{\nu}_\ell$ transitions removed by mass vetoes.
Trigger strategy

Same approach as in the previous analysis:

- for $\mu\mu$ channels, trigger on muons: L0Muon
- for $ee$ channels, use three exclusive trigger categories: L0Electron, L0Hadron, L0TIS
- systematics calculated and cross-checks performed for each trigger individually
Fits to control data: muons

Previous data

New data

[LCb-PAPER-2021-004]
Fits to control data: electrons

Electron trigger

Hadron trigger

[\textit{LHCb-PAPER-2021-004}]

Independent trigger
Cross-check: 2D $r_{J/\psi}$

The 1D $r_{J/\psi}$ cross-check is extended to two variables:

- deviations from flatness again covered by systematic uncertainty on $R_K$
- $r_{J/\psi}$ tests show efficiencies understood across phase space

2D $r_{J/\psi}$, binned in max lepton momentum and angle between leptons
Additional $r_{J/\psi}$ checks

LHCb simulation

Candidates (arbitrary units)

min($p_T(l'), p_T(l)')$ [MeV/$c$]

LHCb simulation

Candidates (arbitrary units)

$\alpha(l'^*, l')$ [rad]

LHCb

$r_{J/\psi} / \langle r_{J/\psi} \rangle$

min($p_T(l'), p_T(l)')$ [MeV/$c$]

LHCb

$r_{J/\psi} / \langle r_{J/\psi} \rangle$

$\alpha(l'^*, l')$ [rad]

[LHCb-PAPER-2021-004]

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Test of LFU at LHCb

23rd March 2021
Distributions of rare & control samples (I)

LHCb simulation

Candidates / (a. u.)

$\alpha(I^+, \Gamma)$ [rad]

$LHCb$ simulation

Candidates / (a. u.)

$\alpha(K^+, \Gamma)$ [rad]

LHCb simulation

Candidates / (a. u.)

$\alpha(K^+, I^+)$ [rad]

Candidates / (a. u.)

$p_T(K^+)$ [MeV/c]

$\max(p_T(I^+), p_T(\Gamma))$ [MeV/c]

$B^+ \to K^+e^+e^-$

$B^+ \to K^+\mu^+\mu^-$

$B^+ \to J/\psi(e^+e^-)K^+$

$B^+ \to J/\psi(\mu^+\mu^-)K^+$

[PRL 122 (2019) 191801]
Distributions of rare & control samples (II)

\[ \chi^2(B^+) = 10 \log \left( \chi^2_{\text{IP}}(B^+) \right) \]

\[ \chi^2(B^{+}) = 10 \log \left( \chi^2_{\text{vtx}}(B^{+}) \right) \]

\[ B^+ \rightarrow K^+e^+e^- \]
\[ B^+ \rightarrow K^+\mu^+\mu^- \]
\[ B^+ \rightarrow J/\psi(e^+e^-)K^+ \]
\[ B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+ \]