New results on theoretically clean observables in rare $B$-meson decays from LHCb

2. Test of Lepton Flavour Universality in $B^+ \rightarrow K^+ \ell^+\ell^-$ decays

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$B^+ \rightarrow K^+ \ell^+ \ell^-$ and related decays

- Occur through $b \rightarrow s \ell^+ \ell^-$ transition but in contrast to $B_s^0 \rightarrow \ell^+ \ell^-$, contain a hadron in the final state.
  e.g $B^+ \rightarrow K^+ \ell^+ \ell^-$, $B^0 \rightarrow K^{*0} \ell^+ \ell^-$, $B_s \rightarrow \phi \mu^+ \mu^-$, $\Lambda_b \rightarrow \Lambda^* \ell^+ \ell^- \ldots$

- Offer multitude of observables complementary to $B_s^0 \rightarrow \ell^+ \ell^-$ measurements.
Flavour Anomalies

Over the past decade we have observed a coherent set of tensions with SM predictions

In $b \rightarrow s \ell^+ \ell^-$ transitions (FCNC)

1. **Branching Fractions**
   $$B \rightarrow K^{(*)} \mu^+ \mu^-, B_s \rightarrow \phi \mu^+ \mu^-, \Lambda_b \rightarrow \Lambda \mu^+ \mu^-$$

2. **Angular analyses**
   $$B \rightarrow K^{(*)} \mu^+ \mu^-, \Lambda_b \rightarrow \Lambda \mu^+ \mu^-$$

3. **Lepton Flavour Universality involving $\mu/e$ ratios**
   $$B^0 \rightarrow K^{*0} \ell^+ \ell^-, B^+ \rightarrow K^+ \ell^+ \ell^-$$
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   $B^0 \rightarrow K^{*0} \ell^+ \ell^-$, $B^+ \rightarrow K^+ \ell^+ \ell^-$
Lepton Flavour Universality tests (I)

- In the SM couplings of gauge bosons to leptons are independent of lepton flavour.
  - Branching fractions differ only by phase space and helicity-suppressed contributions.

- Ratios of the form:

  \[ R_{K^(*)} := \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \overset{\text{SM}}{\approx} 1 \]

- In SM free from QCD uncertainties affecting other observables.
  - \( \mathcal{O}(10^{-4}) \) uncertainty [JHEP07(2007)040]
  - Up to \( \mathcal{O}(1\%) \) QED corrections [EPJC76(2016)8,440]

  → Any significant deviation is a smoking gun for New Physics.
Lepton Flavour Universality tests (II)

Left: $B^0 \rightarrow K^{*0} \ell^+ \ell^−$ $R_{K^*}$ 3 fb$^{-1}$ [JHEP08(2017)055]

Right: $B^+ \rightarrow K^+ \ell^+ \ell^−$ $R_K$ 5 fb$^{-1}$ [PRL122(2019)191801]

Bottom: $\Lambda_b \rightarrow pK \ell^+ \ell^−$ $R_{pK}$ 4.7 fb$^{-1}$ [JHEP05(2020)040]

$(q^2 \equiv$ dilepton invariant mass squared)
Global fits

- Combination all $b \to s \ell^+ \ell^-$ measurements
- Measurements point to new vector coupling ($C_9^\mu$)
- $B_s \to \mu^+ \mu^-$ and LFU observables have very clean theory predictions.

- $B \to K^{(*)} \mu^+ \mu^-$ BF and angular observables potentially suffer from underestimated hadronic uncertainties.

Improving experimental precision of LFU observables is critical.
Today: $R_K$ with the full LHCb dataset

$$R_K = \frac{\int_{6.0 \text{ GeV}^2}^{1.1 \text{ GeV}^2} d\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-) dq^2}{\int_{6.0 \text{ GeV}^2}^{1.1 \text{ GeV}^2} d\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-) dq^2}$$

Measurement performed in $1.1 < q^2 < 6.0 \text{ GeV}^2/c^4$

- Previous measurement [PRL122(2019)191801] used 5 fb$^{-1}$ of data.
  - 3 fb$^{-1}$ of Run1
  - 2 fb$^{-1}$ of Run2 in 2015 and 2016
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- This update:
  - Add remaining $4 \text{ fb}^{-1}$ of Run2 in 2017 and 2018.
  - $9 \text{ fb}^{-1}$ in total.
  - Doubling the number of $B$’s as previous analysis.
Today: $R_K$ with the full LHCb dataset

\[
R_K = \frac{\int_{6.0 \text{ GeV}^2}^{1.1 \text{ GeV}^2} dB(B^+ \rightarrow K^+\mu^+\mu^-) \, dq^2}{\int_{1.1 \text{ GeV}^2}^{6.0 \text{ GeV}^2} dB(B^+ \rightarrow K^+e^+e^-) \, dq^2} \frac{dq^2}{dq^2}
\]

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- This update:
  - Add remaining $4 \text{ fb}^{-1}$ of Run2 in 2017 and 2018.
  - $9 \text{ fb}^{-1}$ in total.
  - Doubling the number of $B$’s as previous analysis.
- Follow the same analysis strategy as our previous measurement.
Electrons vs muons (I)

- Electrons lose a large fraction of their energy through Bremsstrahlung in detector material.

- Most electrons will emit one energetic photon the before magnet.
  → Look for photon clusters in the calorimeter ($E_T > 75\,\text{MeV}$) compatible with electron direction before magnet.
  → Recover brems energy loss by “adding” the cluster energy back to the electron momentum.
Electrons vs muons (II)

- Even after the Bremsstrahlung recovery electrons still have degraded mass and $q^2$ resolution

From previous result, LHCb [PRL122(2019)191801]

![Graphs showing particle distributions](image)

- L0 calorimeter trigger requires higher thresholds, than L0 muon trigger, due to high occupancy.
  - Use 3 exclusive trigger categories for $e^+e^-$ final states
    1. $e^\pm$ from signal-$B$
    2. $K^{\pm}$ from signal-$B$
    3. rest of event

- Particle ID and tracking efficiency larger for muons than electrons
Electrons vs muons (II)

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From previous result, LHCb [PRL122(2019)191801]

Controlling the differences between electron and muon efficiencies lies at the heart of the analysis strategy.

- L0 calorimeter trigger requires higher thresholds, than L0 muon trigger, due to high occupancy.

  → Use 3 exclusive trigger categories for $e^+e^-$ final states

  1. $e^\pm$ from signal-$B$; 2. $K^\pm$ from signal-$B$; 3. rest of event

- Particle ID and tracking efficiency larger for muons than electrons.
Measurement Strategy

\[ R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+ \mu^-))} / \frac{\mathcal{B}(B^+ \to K^+ e^+ e^-)}{\mathcal{B}(B^+ \to K^+ J/\psi(e^+ e^-))} = \frac{N_{rare}^{\mu^+ \mu^-} \varepsilon_{J/\psi}^{J/\psi} \mu^+ \mu^-}{N_{J/\psi}^{\mu^+ \mu^-} \varepsilon_{rare}^{\mu^+ \mu^-}} \times \frac{N_{rare}^{e^+ e^-} \varepsilon_{J/\psi}^{J/\psi} e^+ e^-}{N_{rare}^{e^+ e^-} \varepsilon_{J/\psi}^{J/\psi} e^+ e^-} \]

→ \( R_K \) is measured as a **double ratio** to cancel out most systematics

- Rare and \( J/\psi \) modes share identical selections apart from cut on \( q^2 \)
- Yields determined from a fit to the invariant mass of the final state particles
- Efficiencies computed using simulation that is calibrated with control channels in data

\( q^2 \equiv \text{dilepton invariant mass squared} \)
Selection and backgrounds

- As in our previous measurement, use particle ID requirements and mass vetoes to suppress peaking backgrounds from exclusive $B$-decays to negligible levels
  - Backgrounds of e.g. $B^+ \rightarrow D^0(\rightarrow K^+e^-\nu)e^+\bar{\nu}$: cut on $m_{K^+e^-} > m_{D^0}$
  - Mis-ID backgrounds, e.g. $B \rightarrow K\pi^+\pi^-\pi^-\rightarrow e^-\pi^-$: cut on electron PID
- Multivariate selection to reduce combinatorial background and improve signal significance (BDT)

Residual backgrounds suppressed by choice of $m(K^+\ell^+\ell^-)$ window

- $B^+ \rightarrow K^+J/\psi(e^+e^-)$
- Partially reconstructed dominated by $B \rightarrow K^+\pi^-e^+e^-$ decays
- Model in fit by constraining their fractions between trigger categories and calibrating simulated templates from data.

Cross-check our estimates using control regions in data and changing $m(K^+\ell^+\ell^-)$ window in fit
Efficiency calibration

Following identical procedure to our previous measurement, the simulation is calibrated based on control data for the following quantities:

- Trigger efficiency.
- Particle identification efficiency.
- $B^+$ kinematics.
- Resolutions of $q^2$ and $m(K^+ e^+ e^-)$.

Verify procedure through host of cross-checks.
Cross-check: Measurement of $r_{J/\psi}$

To ensure that the efficiencies are under control, check

$$r_{J/\psi} = \frac{\mathcal{B}(B^+ \rightarrow K^+ J/\psi(\mu^+ \mu^-))}{\mathcal{B}(B^+ \rightarrow K^+ J/\psi(e^+ e^-))} = 1,$$

known to be true within 0.4% [Particle Data Group].

→ Very stringent check, as it requires direct control of muons vs electrons.

Result:

$$r_{J/\psi} = 0.981 \pm 0.020 \text{ (stat + syst)}$$

→ Checked that the value of $r_{J/\psi}$ is compatible with unity for new and previous datasets and in all trigger samples.
Cross-check: $r_{J/\psi}$ as a function of kinematics

Test efficiencies are understood in all kinematic regions by checking $r_{J/\psi}$ is flat in all variables examined.

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

Flatness of $r_{J/\psi}$ 2D plots gives confidence that efficiencies are understood across entire decay phase-space.

→ If take departure from flatness as genuine rather than fluctuations (accounting for rare-mode kinematics) bias expected on $R_K$ is 0.1%
Cross-check: Measurement of $R_{\psi(2S)}$

Measurement of the double ratio

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

- Independent validation of double-ratio procedure at $q^2$ away from $J/\psi$

- Result well compatible with unity:

\[
R_{\psi(2S)} = 0.997 \pm 0.011 \text{ (stat + syst)}
\]

→ can be interpreted as world’s best LFU test in $\psi(2S) \to \ell^+\ell^-$
Systematic uncertainties

Dominant sources: $\sim 1\%$

- Choice of fit model
  - Associated signal and partially reconstructed background shape
- Statistics of calibration samples
  - Bootstrapping method that takes into account correlations between calibration samples and final measurement

Sub-dominant sources: $\sim 1\%$

- Efficiency calibration
  - Dependence on tag definition and trigger biases
  - Precision of the $q^2$ and $m(K^+ e^+ e^-)$ smearing factors
  - Inaccuracies in material description in simulation

Total relative systematic of 1.5% in the final $R_K$ measurement

Expected to be statistically dominated
Measuring $R_K$

$R_K$ is extracted as a parameter from an unbinned maximum likelihood fit to $m(K^+\mu^+\mu^-)$ and $m(K^+e^+e^-)$ distributions in $B^+ \rightarrow K^+\ell^+\ell^-$ and $B^+ \rightarrow J/\psi(\ell^+\ell^-)K^+$ decays.

- Correlated uncertainties on efficiency ratios included as multivariate constraint in likelihood.
$R_K = 0.846^{+0.042}_{-0.039} \, \text{(stat)}^{+0.013}_{-0.012} \, \text{(syst)}$

- $p$-value under SM hypothesis: 0.0010
  → Evidence of LFU violation at 3.1σ

- Compatibility with the SM obtained by integrating the profiled likelihood as a function of $R_K$ above 1
  ▶ Taking into account the 1% theory uncertainty on $R_K$ [EPJC76(2016)8,440]
$R_K$ with full Run1 and Run2 dataset

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

- $p$-value under SM hypothesis: 0.0010
  → Evidence of LFU violation at 3.1$\sigma$

- Using $R_K$ and previous measurement of $\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)$ [JHEP06(2014)133] determine $\mathcal{B}(B^+ \to K^+ e^+ e^-)$.

- Suggests electrons are more SM-like than muons.

\[
\frac{d\mathcal{B}(B^+ \to K^+ e^+ e^-)}{dq^2} = (28.6^{+1.5}_{-1.4} \text{ (stat)} \pm 1.4 \text{ (syst)}) \times 10^{-9} \frac{c^4}{\text{GeV}^2}.
\]
Conclusions

Using the full LHCb dataset to date, presented:

1. Single most precise measurement of $\mathcal{B}(B^0_s \to \mu^+ \mu^-)$, improved precision on $\tau_{\mu^+ \mu^-}$ and first every limit on $B^0_s \to \mu^+ \mu^- \gamma$
2. Updated $R_K$ measurement $\to 3.1\sigma$ departure from LFU!
   $\to$ Reframing discussion on flavour anomalies

Complementarity between $R_K$ and $\mathcal{B}(B^0_s \to \mu^+ \mu^+)$ measurements crucial moving forward.

“...perhaps the end of the beginning.”
Outlook

Many more measurements underway with full LHCb dataset

- \( R_{K^*}, R_{pK} \) update, \( R_{\phi}, R_{K^*+} \)...
- \( R_K \) and \( R_{K^*} \) at high \( q^2 \).
- Angular analyses of \( B \to K(\ast)e^+e^- \) and \( B \to K(\ast)\mu^+\mu^- \) decays.
- Further validation of our understanding of reconstruction effects at low \( q^2 \).
- \( b \to s\tau\tau \) and LFV measurements with \( \tau \)'s
- ...

\[ \text{Current dataset will offer clearer picture} \]

For a definitive understanding, Run3 is imperative.

Input from our LHC and Belle2 colleagues is important.
1. Decay Rates

▶ Measurements consistently below theory predictions at low $q^2 \equiv m_{\ell\ell}^2$ for many $b \to s\mu^+\mu^-$ decays

[10^2 GeV^2/c^4]

$B^+ \to K^*\mu^+\mu^-$ [JHEP11(2016)047], $\Lambda_b \to \Lambda\mu^+\mu^-$ [JHEP06(2015)115] $B_s \to \phi\mu^+\mu^-$ [JHEP09(2015)179]

▶ SM predictions suffer from large hadronic uncertainties
2. Angular analyses of $B \rightarrow K^{*}\mu^{+}\mu^{-}$

- Large number of observables offering complementary constraints on NP compared to BF’s
- Orthogonal experimental systematics and more precise theory predictions

Left: $B^0 \rightarrow K^{*0}\mu^{+}\mu^{-}$ [PRL125011802(2020)], Right: $B^+ \rightarrow K^{*+}\mu^{+}\mu^{-}$ [arXiv:2012.13241]

- Combination of all angular observables suggests $\sim 3\sigma$ tension with SM predictions in each channel
Control mode fits

[PDF: LHCb-PAPER-2021-004]

Previous data

New data

Total data

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Signal Lineshape

- The \( m(K^+\ell^+\ell^-) \) distributions of the rare mode are obtained from simulated decays, calibrating the peak and width of the distribution using \( B^+ \rightarrow J/\psi(\ell^+\ell^-)K^+ \) data.

- In the subsequent fit to the rare mode the \( m(K^+\ell^+\ell^-) \) lineshape is fixed.

- The \( q^2 \) scale/resolution in the simulation is corrected using the same procedure
  → the efficiency of the \( q^2 \) cut is calibrated from the data
Trigger strategy

Same approach as in the previous analysis:

- for $\mu\mu$ channels, trigger on muons: $L0\text{Muon}$
- for $ee$ channels, use three exclusive trigger categories: $L0\text{Electron}$, $L0\text{Hadron}$, $L0\text{TIS}$
- systematics calculated and cross-checks performed for each trigger individually

[Credit: Dan Moise]
$B^+ \rightarrow K^+\ell^+\ell^-$
Semileptonic vetos

The figure shows the normalized distribution of the invariant mass of the system $K^+e^-$ for the decay $B^+ \to K^+e^+\nu_e$. The LHCb simulation includes events of the form $B^+ \to D^0(\to K^+e^-\nu_e)e^+\nu_e$ and $B^+ \to D^0(\to K^+e^-\nu_e)\pi^+\to e^+\nu_e$, with a background veto applied. This removes transitions of the form $\nu_e \to \nu_\tau$, ensuring the consistency of the LFU test at LHCb.

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Test of LFU at LHCb
March 2021
Parameter overlap (I)

\[
\begin{align*}
&\text{Candidates / (a. u.)} \\
&\alpha(l^+, l^-) \text{ [rad]} \\
\end{align*}
\]

\[
\begin{align*}
&\text{Candidates / (a. u.)} \\
&\alpha(K^+, l^-) \text{ [rad]} \\
\end{align*}
\]

\[
\begin{align*}
&\text{Candidates / (a. u.)} \\
&p_T(K^+) \text{ [MeV/c]} \\
\end{align*}
\]

\[
\begin{align*}
&\text{Candidates / (a. u.)} \\
&\max(p_T(l^+), p_T(l^-)) \text{ [MeV/c]} \\
\end{align*}
\]
Parameter overlap (II)

Distributions of rare & control samples (II)

\[ K(\eta_{2 3 4 5}) \]

\[ \text{Candidates / (a. u.)} \]

0.0 0.2 0.4 0.6 0.8 1.0 1.2

LHCb simulation

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LHCb simulation

\[ B^+ \rightarrow K^+ e^+ e^- \]

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

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

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

Ratio of efficiencies determined with simulation carefully calibrated using control channels selected from data:

- **Particle ID calibration**
  - Tune particle ID variables for different particle species using kinematically selected calibration samples \( D^{*+} \rightarrow D^0(K^\pi^+)\pi^+ \ldots \) [EPJ T&I(2019)6:1]

- **Calibration of \( q^2 \) and \( m(K^+e^+e^-) \) resolutions**
  - Use fit to \( m(J/\psi) \) to smear \( q^2 \) in simulation to match that in data

- **Calibration of \( B^+ \) kinematics**

- **Trigger efficiency calibration**
Calibration of $B^+$ kinematics

- Calibrate the simulation so that it describes correctly the kinematics of the $B^+$'s produced at LHCb.
- Compare distributions in data and simulation using $B^+ \rightarrow K^+ J/\psi (\ell^+ \ell^-)$ candidates.
- Iterative reweighing of $p_T(B^+) \times \eta(B^+)$, but also the vertex quality and the significance of the $B^+$ displacement.

none

µµ L0Muon, nominal

µµ LOTIS

ee L0Electron

$VTX \chi^2$: ee L0Electron, $p_T(B) \times \eta(B)$, $IP \chi^2$: µµ L0Muon

→ Systematic uncertainty from RMS between all these weights
Trigger efficiency

The trigger efficiency is computed in data using $B^+ \rightarrow K^+ J/\psi (\ell^+ \ell^-)$ decays through a tag-and-probe method.

Especially for the electron samples, need to take into consideration some subtleties:

- dependence on how the calibration sample is selected,
- correlation between the two leptons in the signal.

Repeat calibration with different samples/different requirements on the accompanying lepton

→ Associated systematic in the ratio of efficiencies is small
Efficiency calibration summary

- After calibration, very good data/MC agreement in all key observables

Maximal effect of turning off corrections results in relative shift $R_K (+3 \pm 1)\%$ compared to 20\% in $r_{J/\psi}$.

**Demonstrates the robustness of the double-ratio method in suppressing systematic biases that affect the resonant and nonresonant decay modes similarly.**