Lepton flavour universality tests with LHCb

Michael M^{c}Cann
On behalf of the LHCb collaboration

Imperial College London

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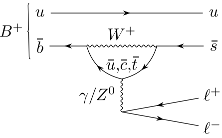
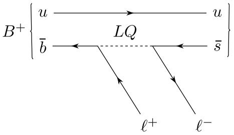
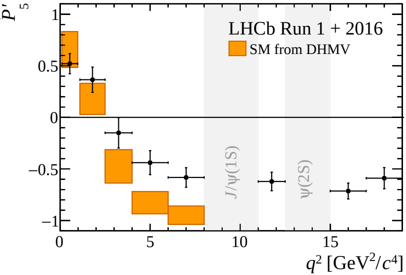
Anomalies in $b \to s\ell\ell$ transitions







Phys. Rev. Lett. 125 (2020) 011802

- Several deviations seen in branching fractions and angular observables
- Debate over the impact of hadronic uncertainties in their interpretation

Want observables with less contested theoretical interpretations

- Lepton flavour universality is built in to the SM
- Ratios between decays to different leptons very well predicted

$$R_H = \frac{\mathcal{B}(H_B \to H\mu^+\mu^-)}{\mathcal{B}(H_B \to He^+e^-)} \sim 1$$

- Deviations in LFU observables would be smoking gun of NP

Current state of LFU

Several LFU measurements have been reported previously as low

- R_{K^*} in 3 fb^{-1} ($B^0 \to K^{*0}\ell^+\ell^-$)

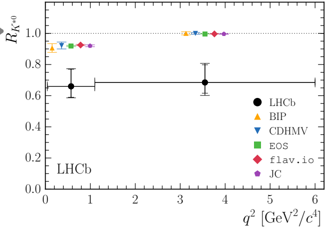
  Phys. Rev. Lett. 122 (2019) 191801

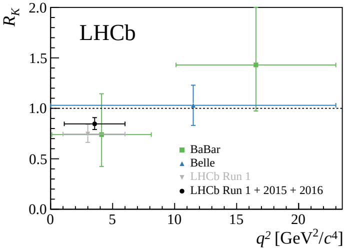
- R_{pK} in 5 fb^{-1} ($\Lambda_b \to pK\ell^+\ell^-$)

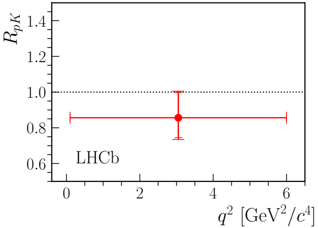
  JHEP 05 (2020) 040

- R_K in 5 fb^{-1} ($B^+ \to K^+\ell^+\ell^-$)

  Phys. Rev. Lett. 122 (2019) 191801



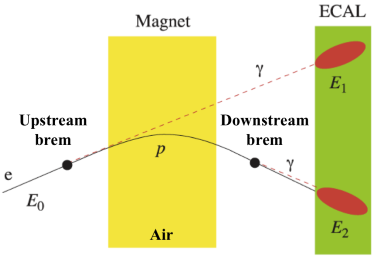




This talk will focus on the updated measurement of R_K

Challenges of LFU at LHCb

- Measuring decays with muons is relatively straightforward
- Electrons are light
  ⇒ scatter more in detector
  - Larger E loss
  - e.g Bremsstrahlung emission
- Attempt to recover the emitted photons
  - Doesn't capture all
  - Some misattributed
- Poorer mass resolutions with electrons



Can we mitigate some of these issues?

Measuring R_K

The observable we want to measure:

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}$$

- Requires excellent control of efficiencies

Measuring R_K

The observable we measure:

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} \bigg/ \frac{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)}$$

- Better control of efficiency in double ratio with control mode
- Electrons normalised to electrons, muons normalised to muons
- Control mode consistent with LFU
  (0.998 ± 0.008) Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

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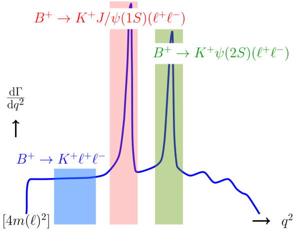
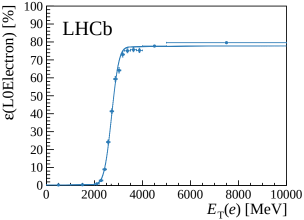
- Define 3 regions
  - Rare mode
    $(1.1 < q^2 < 6.0\ \mathrm{GeV}^2/c^4)$
  - Control mode, dominated by J/ψ resonance
  - $\psi(2S)$ mode, dominated by $\psi(2S)$ resonance



Controlling electron and muon efficiencies

Main challenge is controlling the differences between electrons and muons

- Modes inherently different in:
  - Trigger efficiency
  - Dilepton mass resolution
  - Kinematic distribution
  - Particle Identification



- Electron-mode and muon-mode efficiencies computed from simulation

- Calibrated using control mode data

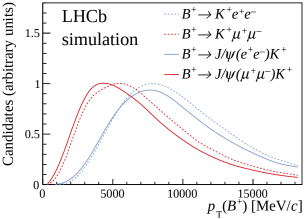
- Procedure controls efficiencies to $\sim$1%

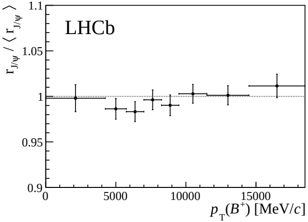
How do we validate these procedures?

Crosscheck using control mode: $r_{J/\psi}$

$$r_{J/\psi} = \frac{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)} = \frac{\mathcal{N}(\mu^+\mu^-)}{\varepsilon(\mu^+\mu^-)} \Bigg/ \frac{\mathcal{N}(e^+e^-)}{\varepsilon(e^+e^-)}$$

- Ratio in q^2 region dominated by J/ψ
- No expected LFU violation effects
- Tests control of electron vs muon effs
- $r_{J/\psi} = 0.981 \pm 0.020$
- Checked in 1D and 2D as function of kinematic variables



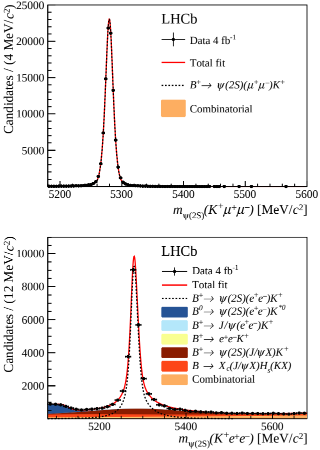


Crosscheck at independent q^2 region: $R_{\psi(2S)}$

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

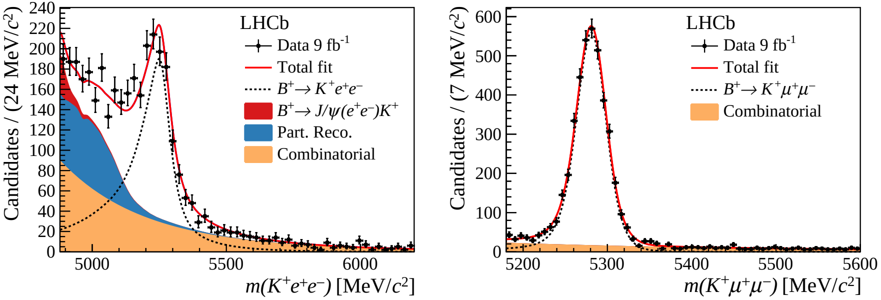
(2017 & 2018 only)

- Use full procedure on q^2 region dominated by $\psi(2S)$
- No expected LFU violation effects
- $R_{\psi(2S)} = 0.997 \pm 0.011$
- Strongly validates procedure
- Also best test of LFU for $\psi(2S)$



Fits to the rare mode

R_K extracted as a fit parameter



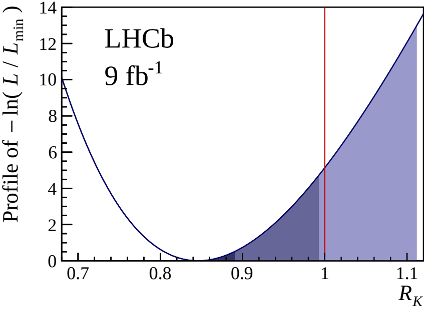
- Relative efficiencies gaussianly constrained in fit
- Fit model dominant systematics ($\sim 1\%$)

Updated value of R_K with 9 fb^{-1}

$$R_K(1.1 < q^2 < 6.0 \text{ GeV}^2/c^4) = 0.846\,^{+0.042}_{-0.039}\,(\text{stat.})\,^{+0.013}_{-0.012}\,(\text{syst.})$$

arXiv:2103.11769

- Cf. SM prediction:
  $R_K = 1.00 \pm 0.01$
  JHEP 06 (2016) 092, JHEP 07 (2007) 040, EPJC 76 (2016) 440, PRD 69 (2004) 074020, PRD 68 (2003) 094016, EOS, flavio
- p-value wrt. SM: 0.1%
- Significance: 3.1σ



0–1σ 1–3σ 3–5σ

Evidence of LFU violation in $B^+ \to K^+\ell^+\ell^-$ decays

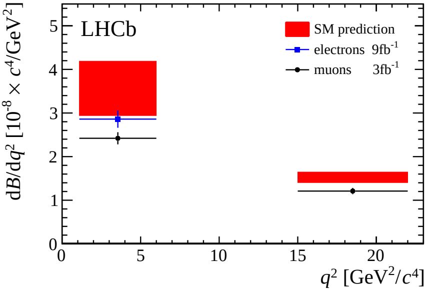
Branching ratios

Combining with muon-mode branching fraction (JHEP 06 (2014) 133):

$$\frac{d\mathcal{B}}{dq^2}(B^\pm \to K^\pm e^+ e^-) = 28.6\,^{+1.5}_{-1.4} \pm 1.3 \times 10^{-9} c^4/\mathrm{GeV}^2$$

in $(1.1 < q^2 < 6.0\ \mathrm{GeV}^2/c^4)$

- Electron BF more consistent with SM prediction
    - NB muon BF systematically limited

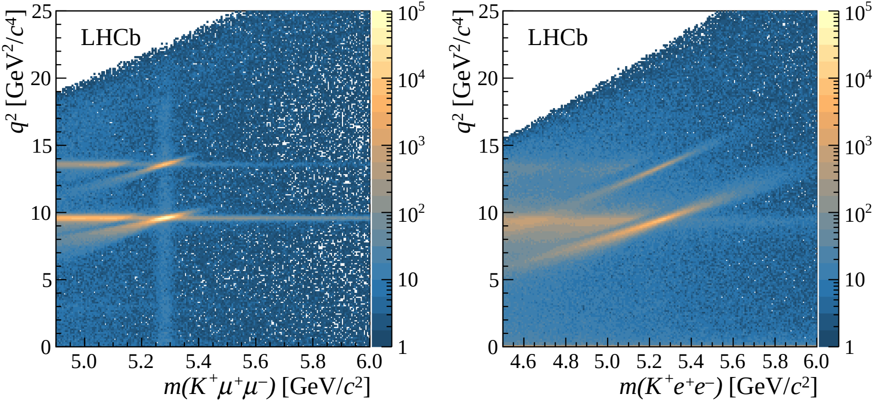


Conclusions

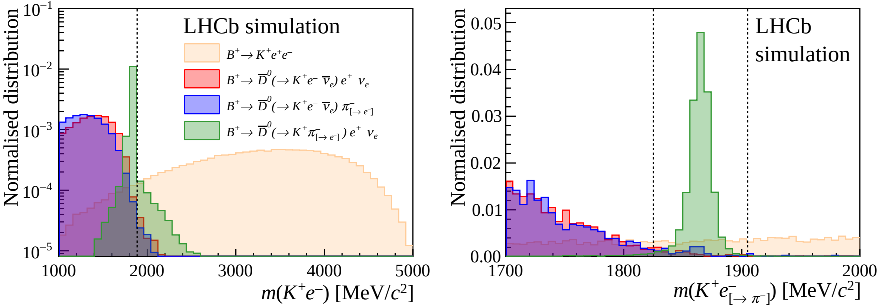
- LFU observables have potential to resolve B anomalies
- LHCb has extensive program measuring LFU observables
- Most recent measurement of R_K 3.1σ from SM
- **Evidence for LFU violation in $b \to s\ell\ell$ transistions**

Backup

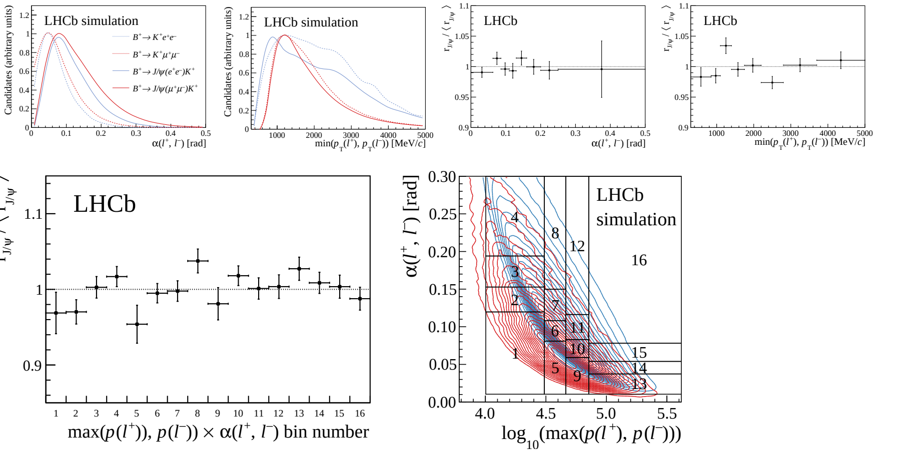
Candidate distributions



Semileptonic backgrounds



2D $r_{J/\psi}$



LHCb simulation
B+→K+e+e−
B+→K+μ+μ−
B+→J/ψ(e+e−)K+
B+→J/ψ(μ+μ−)K+
Candidates (arbitrary units)
α(l+, l−) [rad]
min(pT(l+), pT(l−)) [MeV/c]
LHCb
rJ/ψ / ⟨rJ/ψ⟩
max(p(l+)), p(l−)) × α(l+, l−) bin number
LHCb simulation
α(l+, l−) [rad]
log10(max(p(l+), p(l−)))