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

Stephan Escher, Christoph Langenbruch, Simon Nieswand (Aachen)

Simone Bifani, Ryan Calladine, Nigel Watson (Birmingham)

Johannes Albrecht, Julian Boelhauve, Alex Seuthe (Dortmund)

Fabrice Desse, Marie-Hélène Schune (LAL-Orsay)

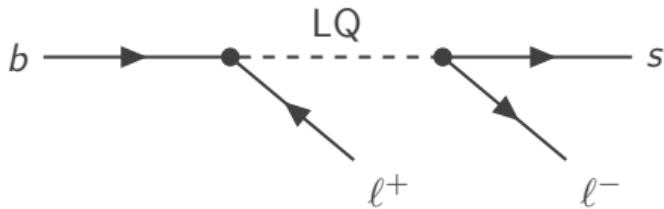
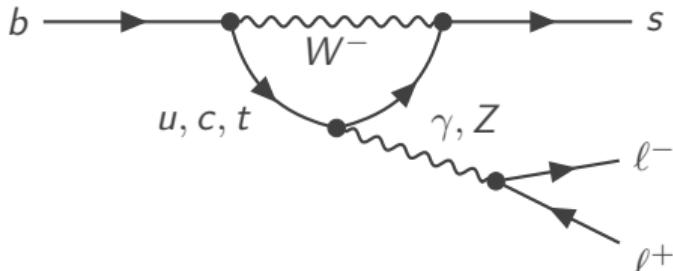
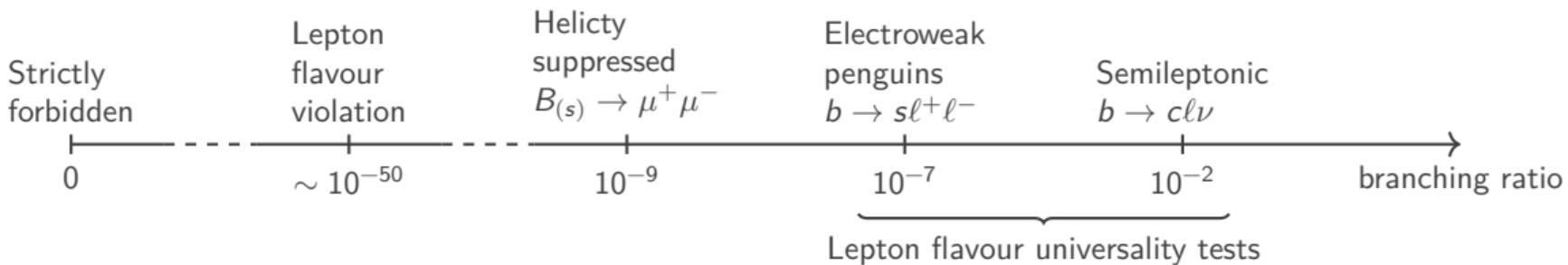
Vladimir V. Gligorov, Francesco Polci, Renato Quagliani, Da Yu Tou (LPNHE)

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Universität Rostock

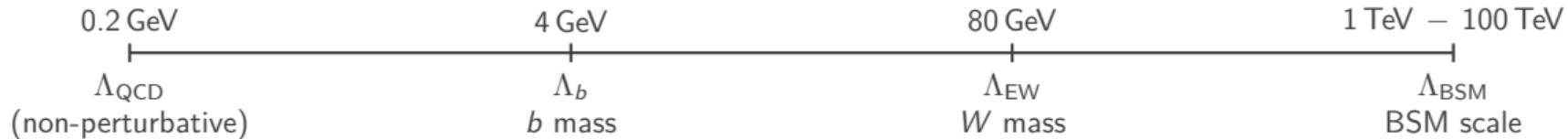
Rare decays at LHCb

- Rare decays: suppressed in the Standard Model (SM)
 - Sensitive to BSM contributions
- Flavour Changing Neutral Currents (FCNC)
 - Forbidden at tree-level
 - Further suppression due to e.g. helicity
- Probes higher mass scales than direct searches



Theoretical description of FCNC decays

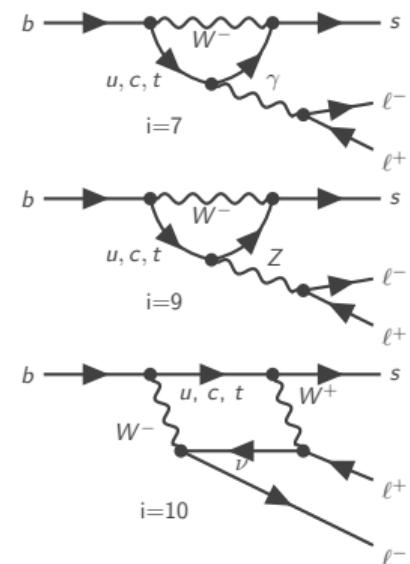
- Processes at many different energy scales



- Described by effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \left[\underbrace{\mathcal{C}_i(\mu) \mathcal{O}_i(\mu)}_{\text{Left handed}} + \underbrace{\mathcal{C}'_i(\mu) \mathcal{O}'_i(\mu)}_{\text{Right handed}} \right] + \text{h.c.}$$

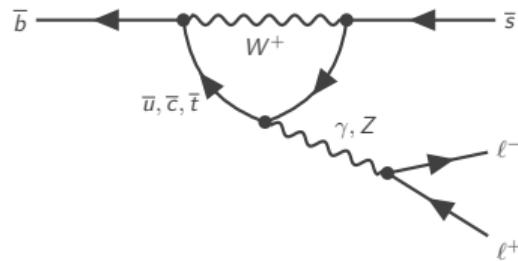
- \mathcal{O}_i (Operators): long distance, non-perturbative physics
- \mathcal{C}_i (Wilson coefficients): short distance, high energy physics
 - BSM processes may modify these coefficients



Tests of lepton flavour universality (LFU)

- SM: leptons couple equally to weak gauge bosons, well tested by LEP at tree level
- Now: Test of lepton flavour universality in loop processes

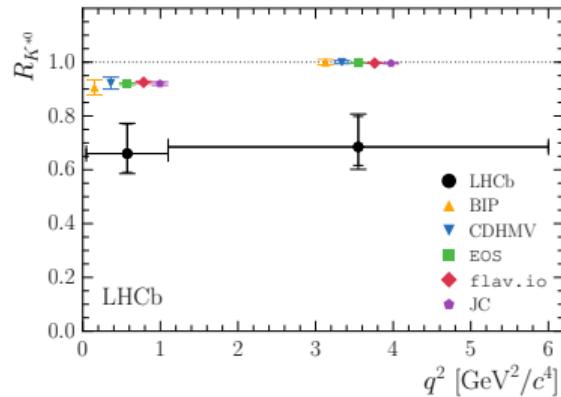
u, d —————→ u, d



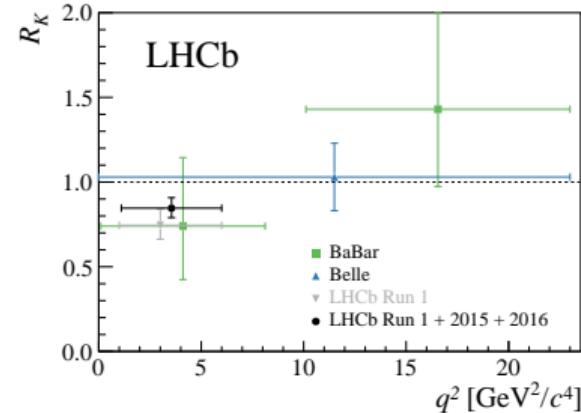
$$R_H = \frac{\int_{q_{\min}^2}^{q_{\max}^2} \frac{d\mathcal{B}(B \rightarrow H\mu^+\mu^-)}{dq^2} dq^2}{\int_{q_{\min}^2}^{q_{\max}^2} \frac{d\mathcal{B}(B \rightarrow He^+e^-)}{dq^2} dq^2}$$

- Ratio tests should only differ by phase space from unity
- Hadronic uncertainties cancel in the ratio: Theoretically very clean
- **This analysis:** $R_X = \frac{\mathcal{B}(B \rightarrow X\mu^+\mu^-)}{\mathcal{B}(B \rightarrow Xe^+e^-)}$, with $X = K^{*0}, K^+$

LHCb results



$R_{K^{*0}}$: Run 1 data (3 fb^{-1}) shows $2.4 - 2.5\sigma$ tension with SM [JHEP08(2017)055]

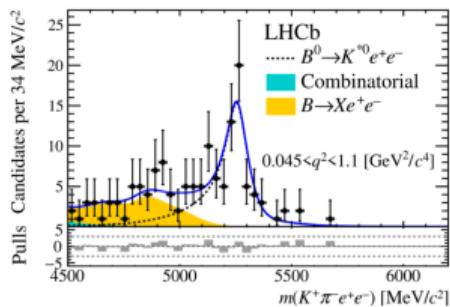


R_K : Run 1, 2015, 2016 data (5 fb^{-1}) shows 2.5σ tension with SM [PRL122(2019)191801]

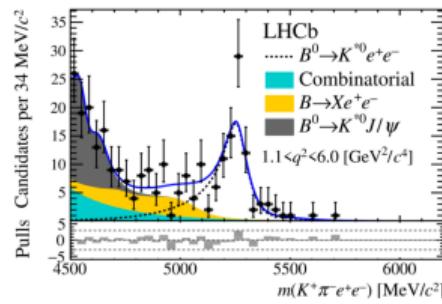
Choice of q^2 bins

Align q^2 binning for R_K and $R_{K^{*0}}$

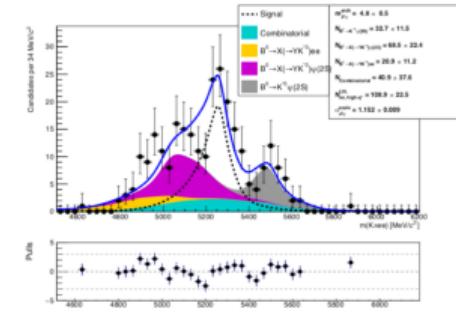
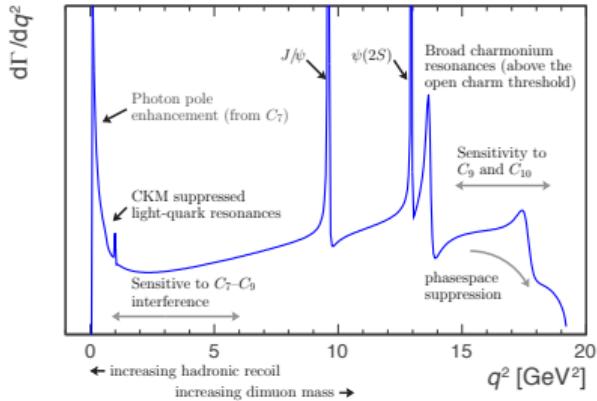
- Low q^2 threshold increased to [0.1, 1.1] to reduce uncertainty from $\gamma \rightarrow ee$ pole
- Central q^2 bin kept as [1.1, 6.0]
- High q^2 bin needs special care, considerably worse separation of signal and background



Fit to low q^2 (2017 Analysis)



Fit to central q^2 (2017 Analysis)

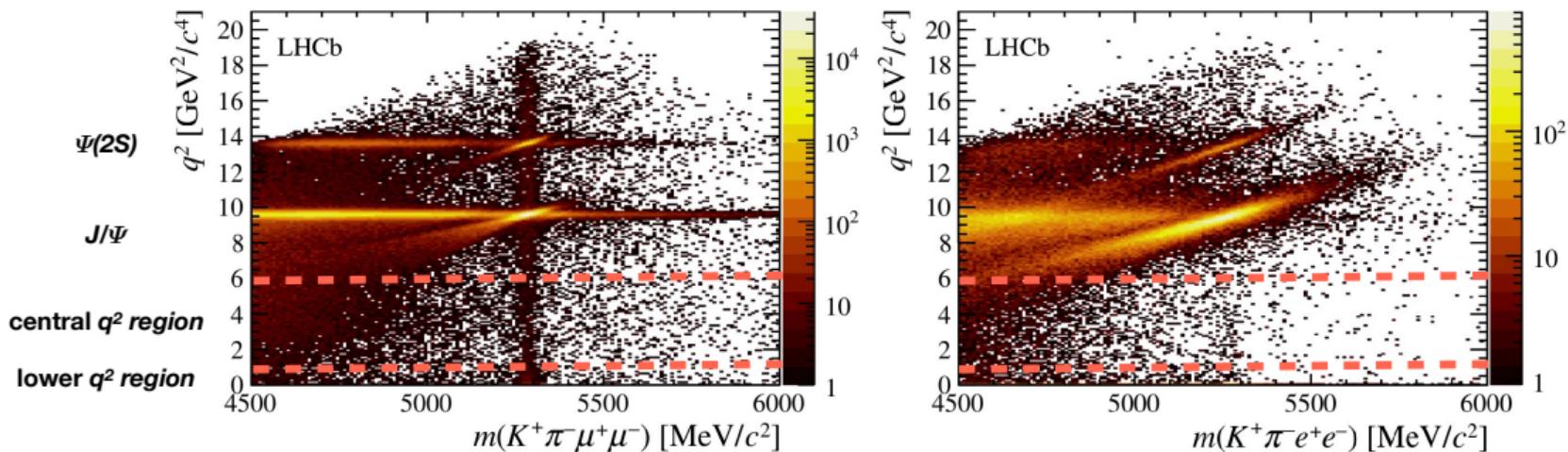


Fit to high q^2 (2017 Analysis)

Main experimental challenges

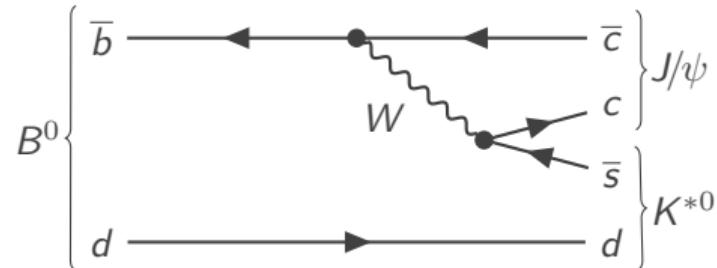
- Very different signature of electrons and muons in the LHCb detector
 - Bremsstrahlung, Trigger, Tracking, ...
- Backgrounds
 - Combinatorial, misidentifications, partially reconstructed
- Tuning of simulation to properly describe data

JHEP 08 (2017) 055



$R(X)$ measurement strategy

- Analysis of the full LHCb dataset
- Simultaneous measurement of $R_{K^{*0}}$ and R_K
 - Simulation corrections from resonant B^+ and B^0 modes enable cross-validations
 - Constrain cross feed in fits to data
- Measurement as a double ratio with tree-level decays
 $B \rightarrow X J/\psi (\rightarrow \ell^+ \ell^-)$ as normalization channels
- Many systematic uncertainties cancel out



$$\begin{aligned} R_X &= \frac{\mathcal{B}(B \rightarrow X \mu^+ \mu^-)}{\mathcal{B}(B \rightarrow X e^+ e^-)} \times \frac{\mathcal{B}(B \rightarrow X J/\psi (\rightarrow e^+ e^-))}{\mathcal{B}(B \rightarrow X J/\psi (\rightarrow \mu^+ \mu^-))} \\ &= \underbrace{\left(\frac{\mathcal{N}_{X \mu^+ \mu^-}}{\mathcal{N}_{X e^+ e^-}} \right) \left(\frac{\mathcal{N}_{X J/\psi (\rightarrow e^+ e^-)}}{\mathcal{N}_{X J/\psi (\rightarrow \mu^+ \mu^-)}} \right)}_{\text{Mass fits}} \times \underbrace{\left(\frac{\epsilon_{X e^+ e^-}}{\epsilon_{X \mu^+ \mu^-}} \right) \left(\frac{\epsilon_{X J/\psi (\rightarrow \mu^+ \mu^-)}}{\epsilon_{X J/\psi (\rightarrow e^+ e^-)}} \right)}_{\text{Corrected simulation}} \end{aligned}$$

Main cross-checks

- Measure the ratio of the branching fractions of the muon and electron resonant channels $r_{J/\psi}$

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

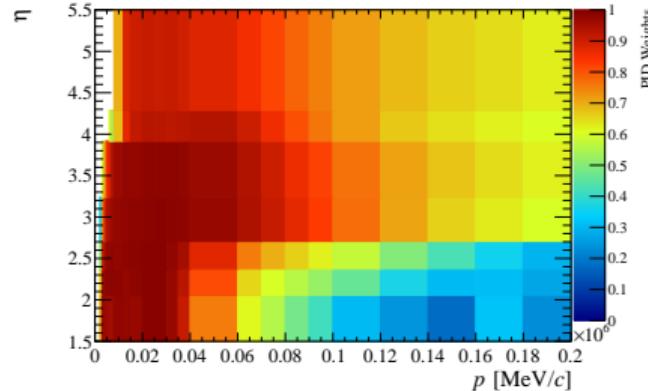
- Compatibility with unity validates measurement
- In contrast to the ratio R_X no cancellation of experimental uncertainties: Extremely stringent check
- Extent of cancellation of residual systematics is verified by measuring the ratio $R_{\psi(2S)}$

$$R_{\psi(2S)} = \frac{\mathcal{B}(B \rightarrow X \psi(2S) (\rightarrow \mu^+ \mu^-))}{\mathcal{B}(B \rightarrow X \psi(2S) (\rightarrow e^+ e^-))}$$

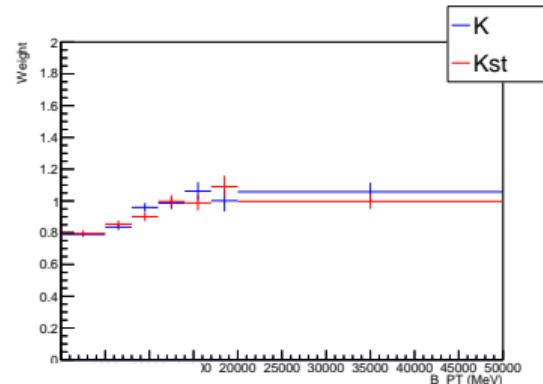
Corrections to simulation

- PID corrections
 - Using high purity calibration data
 - Constantly developing LHCb tools
- B kinematics and multiplicity
 - Correcting with high statistics channels
 - Using BDT reweighting
- L0 corrections
 - TISTOS method uses data/simulation ratios for corrections
 - Corrections in trigger categories
- HLT corrections
 - Good agreement with data found
 - No corrections applied

Example PID corrections



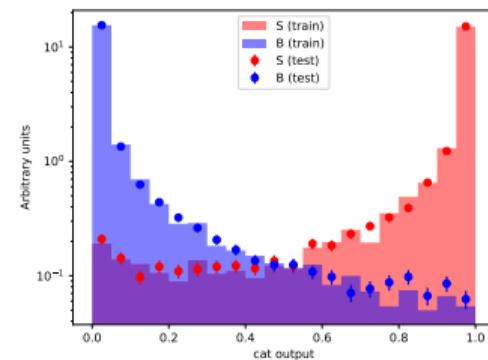
Example L0 trigger corrections



Selection

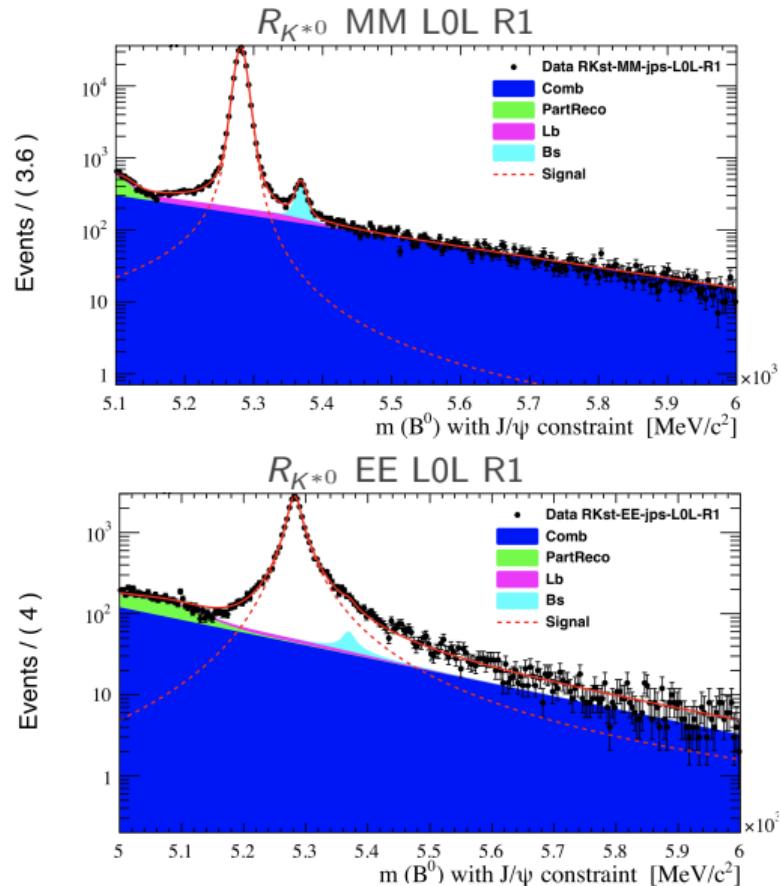
- Run 1 $R_{K^{*0}}$ result at central q^2 had 5% systematic uncertainty due to residual background
→ improved exclusive background vetos
- New MVA approach:
separate MVAs against combinatorial **and** partially reconstructed backgrounds
- Combinatorial background
 - Signal proxy: rare mode signal simulation
 - Background proxy: upper-mass sideband from data
- Partially reconstructed background
 - Signal proxy: rare mode signal simulation
 - Background proxy: non resonant $B^+ \rightarrow K\pi\pi ee$ ($R_{K^{*0}}$) and $B^0 \rightarrow K^{*0}ee$ (R_K) simulation
- Separately for B^0 , B^+ , $\mu\mu$, ee , and years

Combinatorial BDT RK MM Run 1



Fits

- Simultaneous fits to all:
 - Samples: B^0 , B^+ , $\mu\mu$, and ee
 - q^2 bins: low, central
 - L0 categories
 - Runs: Full LHCb dataset (2011-2018)
 - But cross checks and measurement in rare mode are done separately
- Gaussian constraints on data/simulation shape-difference parameters from resonant modes (ee only)
- Measure ratios directly by incorporating the efficiencies in with Gaussian constraints (e.g. $r_{J/\psi}$, $R_{\psi(2S)}$, $R_{K^{*0}}$, R_K)



Summary and outlook

- Test of Lepton flavour universality is a very stringent test of the Standard Model
- Long awaited new results can shed light onto anomalies observed during the last years
- Full LHCb dataset in the pipeline
- Full simultaneous measurement of $R_{K^{*0}}$ and R_K
- Integration of other decay modes in preparation
- Status: currently integrating new simulation samples for 2017 and 2018
- Analysis note will be circulated soon!