Lepton Flavour Universality in $b \to s\ell\ell$ Decays at LHCb

Lake Louise Winter Conference (Fairmont Chateau, Lake Louise, AB)

Sam Maddrell-Mander [1,2]

February 11 2020

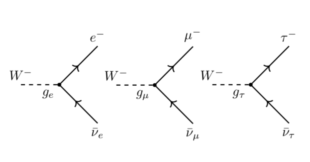
[1]University of Bristol on behalf of the [2]LHCb Collaboration

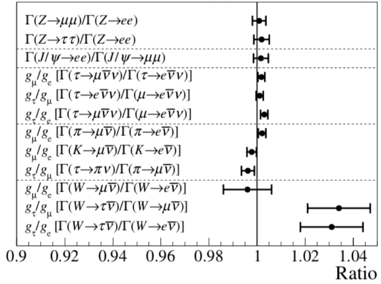
SM couplings of charged leptons to gauge bosons are identical

- Extensively probed with $Z \to \ell^+\ell^-$, $J/\Psi \to \ell^+\ell^-$ to sub percent level

Lepton universality test in rare loop-level decays

- $b \to s\ell\ell$ are Flavour Changing Neutral Currents
- Exist only at loop level in the SM
- $\mathrm{BF}(b \to s\ell\ell)$ decays $< 10^{-6}$
- Sensitive to NP contributions
- Compare observed rates in μ mode with e mode



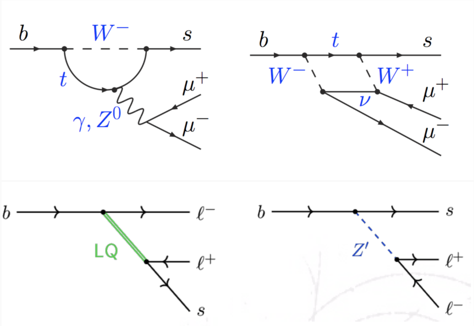


SM couplings of charged leptons to gauge bosons are identical

- Extensively probed with $Z \to \ell^+\ell^-$, $J/\Psi \to \ell^+\ell^-$ to sub percent level

Lepton universality test in rare loop-level decays

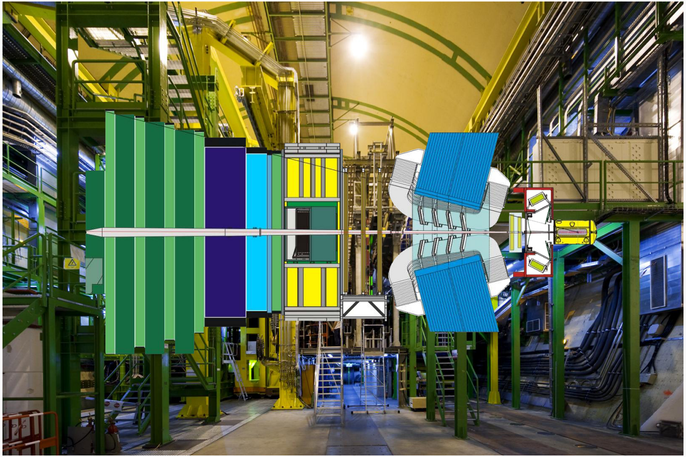
- $b \to s\ell\ell$ are Flavour Changing Neutral Currents
- Exist only at loop level in the SM
- BF($b \to s\ell\ell$) decays $< 10^{-6}$
- Sensitive to NP contributions
- Compare observed rates in μ mode with e mode



The LHCb Detector

Designed for the study of b-mesons

- Operates at lower intensity the general purpose experiments
- Very high momentum resolution
- Excellent particle identification of stable charged particles (π, K, p, μ, e)
- B lifetime $\rightarrow$ displaced decay vertex from pp collision



[Int. J. Mod. Phys. A 30, 1530022 (2015)]

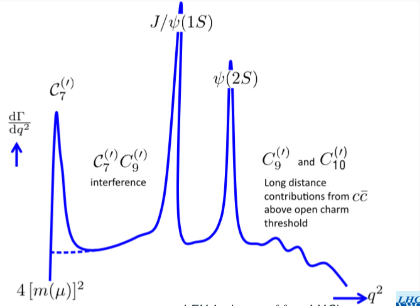
Effective Field Theory (EFT)

EFT is a model independent general description

- Wilson coefficients ($\mathcal{C}_i$) describe short range effects
- Operators ($\mathcal{O}_i$) describe long range QCD effects
- Different regions in $q^2 = m^2(\ell\ell)$ are sensitive to different operator combinations

$$\mathcal{H}_{eff}^{b\to s\ell\ell} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \left(\mathcal{C}_i \mathcal{O}_i + \mathcal{C}_i' \mathcal{O}_i'\right)$$

Wilson Coefficient		Operator
γ-penguin	$\mathcal{C}_7^{(')}$	$(\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu}$
vector	$\mathcal{C}_9^{(')}$	$(\bar{s}\gamma_\mu P_{R(L)}b)\bar{\mu}\gamma^\mu\mu$
axial-vector	$\mathcal{C}_{10}^{(')}$	$(\bar{s}\gamma_\mu P_{R(L)}b)\bar{\mu}\gamma^\mu\gamma_5\mu$
scalar	$\mathcal{C}_S^{(')}$	$\bar{s}P_{R(L)}b\bar{\mu}\mu$
pseudo-scalar	$\mathcal{C}_P^{(')}$	$\bar{s}P_{R(L)}b\bar{\mu}\gamma_5\mu$



Double Ratio - exploits cancellation of systematic effects

Double ratio normalises the rare BF ratio with a control BF ratio

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

$$= \frac{N_{B\to K^{(*)}\mu^+\mu^-}}{N_{B\to K^{(*)}J/\psi(\to\mu^+\mu^-)}} \times \frac{\epsilon_{B\to K^{(*)}J/\psi(\to\mu^+\mu^-)}}{\epsilon_{B\to K^{(*)}\mu^+\mu^-}} \times \frac{N_{B\to K^{(*)}e^+e^-}}{N_{B\to K^{(*)}J/\psi(\to e^+e^-)}} \times \frac{\epsilon_{B\to K^{(*)}J/\psi(\to e^+e^-)}}{\epsilon_{B\to K^{(*)}e^+e^-}}$$

$$= 1 \pm \mathcal{O}(10^{-3})$$

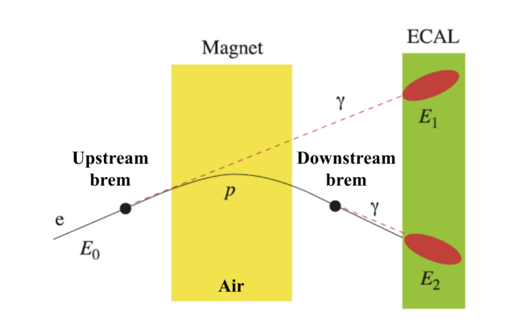
- The J/Ψ sits in a different q^2 region, but is otherwise identical
- The limiting factor in the measurement is rare mode (electron specifically) statistics
- Experimentally clean: Most systematic uncertainties cancel due to double ratio, but controlling efficiencies is vitally important
- Theoretically clean: Hadronic uncertainties cancel + QED effects are small

Bremsstrahlung

- Electrons suffer heavy losses from bremsstrahlung radiation (compared to μ)

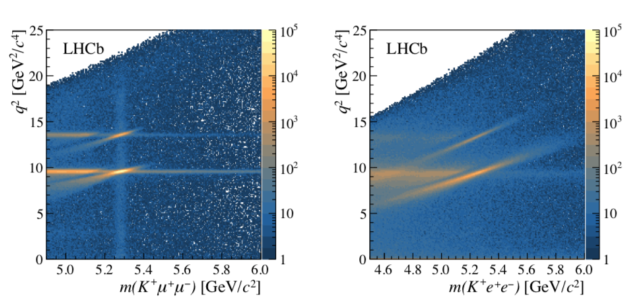
  $\rightarrow$ Leads to significantly broader resolution for e modes
- Electrons have their momentum corrected by combining energy deposits from photons

  $\rightarrow$ Originating from small projected region in the ECAL



Bremsstrahlung

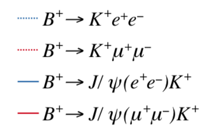
- Electrons suffer heavy losses from bremsstrahlung radiation (compared to μ)
  $\rightarrow$ Leads to significantly broader resolution for e modes
- Electrons have their momentum corrected by combining energy deposits from photons
  $\rightarrow$ Originating from small projected region in the ECAL

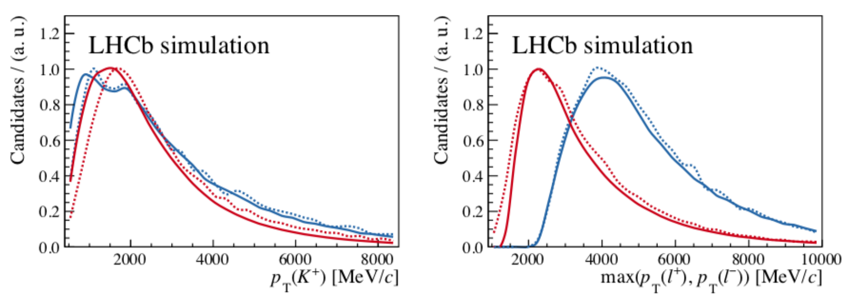


[PRL. 122, 191801]

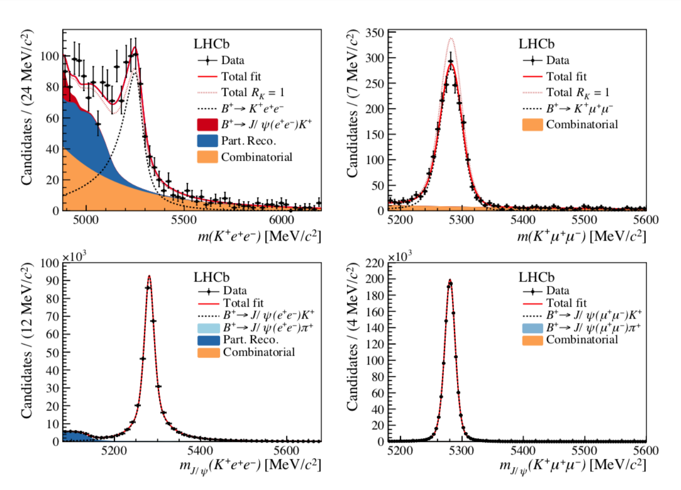
Efficiencies corrected and controlled using data

- Trigger ϵ obtained from control mode data
- PID efficiency from high stat. sample
- Kinematics / mass resolution taken from control mode
- Highly boosted nature of LHCb - the rare and control very similar



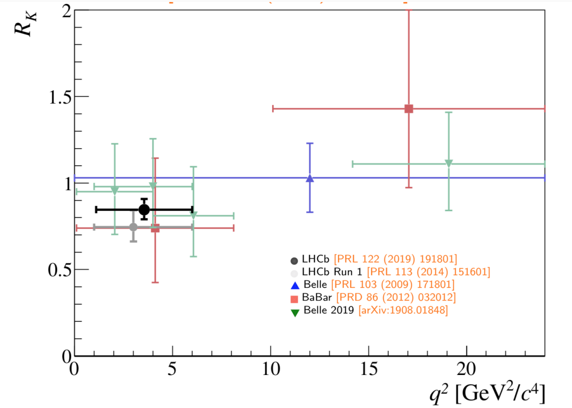


Yields $B^+ \to K^+\ell\ell$



- $N(B^+ \to K^+J/\Psi(\to e^+e^-)) = 344100 \pm 610$
- $N(B^+ \to K^+J/\Psi(\to \mu^+\mu^-)) = 1161800 \pm 1100$
- $N(B^+ \to K^+e^+e^-) = 766 \pm 48$
- $N(B^+ \to K^+\mu^+\mu^-) = 1943 \pm 49$

- Limiting factor is electron rare mode yield

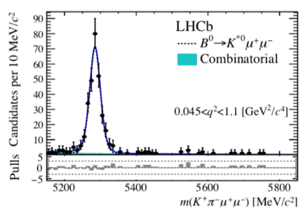


R_K measured in $1.1 < q^2 < 6.0$ GeV^2

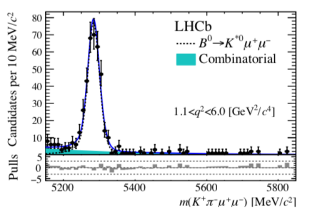
- (Run1) $R_K(1 < q^2 < 6.0\mathrm{GeV}^2) = 0.745^{+0.090}_{-0.075} \pm 0.036$
- $R_K(1 < q^2 < 6.0\mathrm{GeV}^2) = 0.846^{+0.060}_{-0.054}{}^{+0.016}_{-0.014}$
- 2.5σ tension with the SM
- Belle 2019 update → 1904.02440

Three q^2 regions (low, central, J/Ψ) - for $B^0 \to K^{*0}ee$ and $B^0 \to K^{*0}\mu\mu$

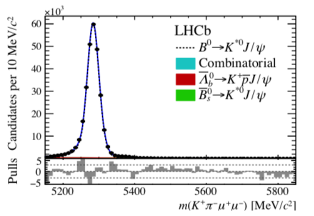
[low q^2 : 285 ± 18]



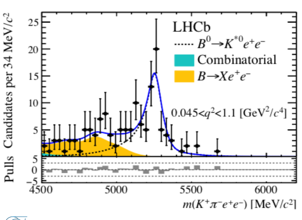
[Central q^2 : 353 ± 21]



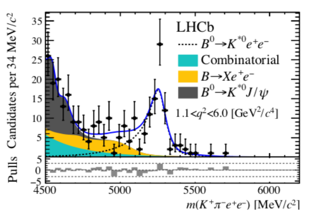
[J/Ψ q^2 : 274k]



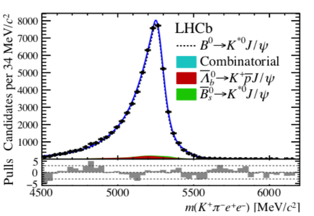
low q^2 : 89 ± 11

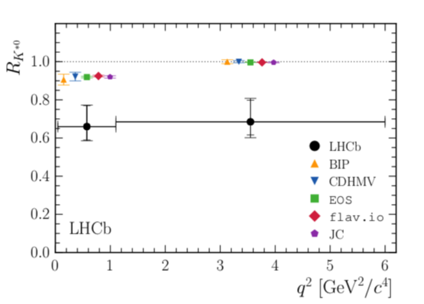


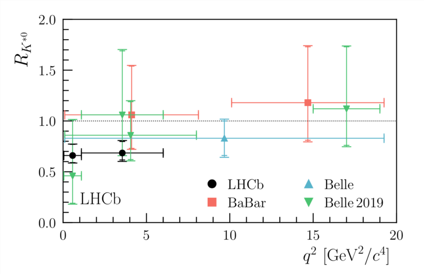
[Central q^2 : 111 ± 14]



J/Ψ q^2 : 58k







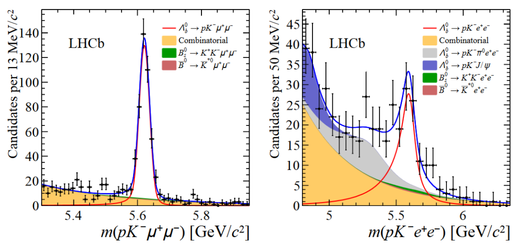
SM compatibility: $\sim 2.2\sigma$ in low q^2, $\sim 2.5\sigma$ in central q^2

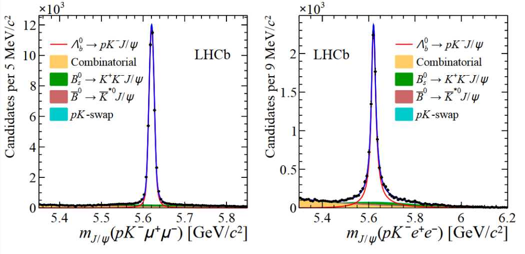
- $R_{K^*}(0.045 < q^2 < 1.1\mathrm{GeV}^2) = 0.66^{+0.11}_{-0.07} \pm 0.03$
- $R_{K^*}(1.1 < q^2 < 6.0\mathrm{GeV}^2) = 0.69^{+0.11}_{-0.07} \pm 0.05$
- Compatible with Babar and Belle - tighter uncertainty ranges Belle 2019 update $\rightarrow$ 1904.02440

First LFU measurement using B-bayrons and first observation of $\Lambda_b \to pK^-\ell\ell$ - sensitive to different exp. uncertainties than B-meson LFU measurement $\to$ highly complimentary .

$N(\Lambda_b \to pK^-ee) = 122 \pm 17$

$N(\Lambda_b \to pK^-\mu\mu) = 444 \pm 23$



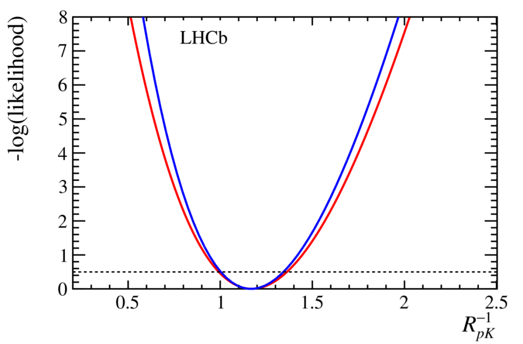


R_{pK} Results

arXiv:1912.08139

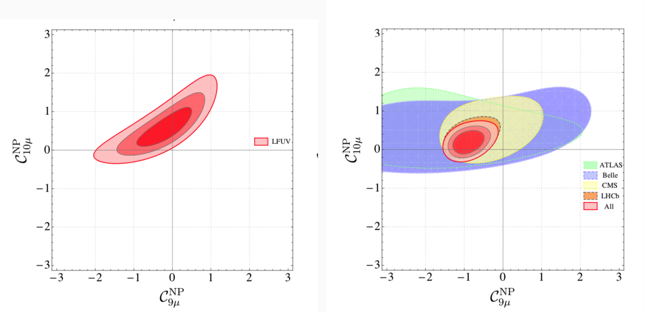
- Measured R_{pK}^{-1} to obtain more symetric errors

- $R_{pK}^{-1} = 1.17^{+0.18}_{-0.16} \pm 0.07$
- $R_{pK} = 0.86^{+0.14}_{-0.11} \pm 0.05$
- Result compatible with the SM to one standard deviation
- Also in agreement with R_K and R_K^* where μ modes occur at lower rates than e modes



(statistical and total uncertainty)

Alguero et al., EPJC 79 (2019) 8:714



Use EFT framework to obtain Wilson coefficients (C_9 Vector, C_{10} Axial-Vector)

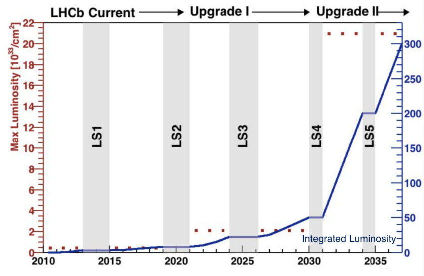
- Combination of R_K and R^*_K have a tension with SM at 3-4σ (Note: r_{pK} not yet included)
- Importantly all tensions pulling in the same direction
- All other contributions from $b \to s\ell\ell$ lead to $> 5\sigma$

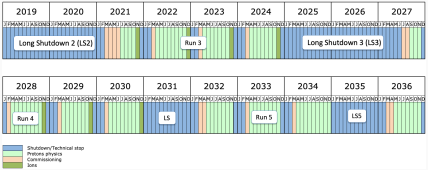
Future prospects at LHCb

It is imperative that these anomalies are resolved

- Updates to the R_K and R_{K^*} analyses are ongoing
- R_K will be updated with double the statistics and R_{K^*} with quadruple the statistics
- $b \to s$ angular analyses are also ongoing
- $50\mathrm{fb}^{-1}$ integrated luminosity expected after LS2 LHCb-TDR
- $300\mathrm{fb}^{-1}$ expected after Upgrade II

arxiv:1808.08865





LHC-Comissioning

Conclusions

- LFU tests in $b \to s\ell\ell$ channels show tensions with SM
- R_K and R_{K^*} each independently $\sim 2.5\sigma$
- Combined tension roughly $3 - 4\sigma$
- Many corroborating anomalies in BFs and angular observables

  $\to$ All point in the same general direction (shift in C_9 Wilson)
- Full Run2 datasets are being analysed in earnest to clarify the picture
- Watch this space!

Questions?