Lepton-flavour-non-universal measurements from LHCb

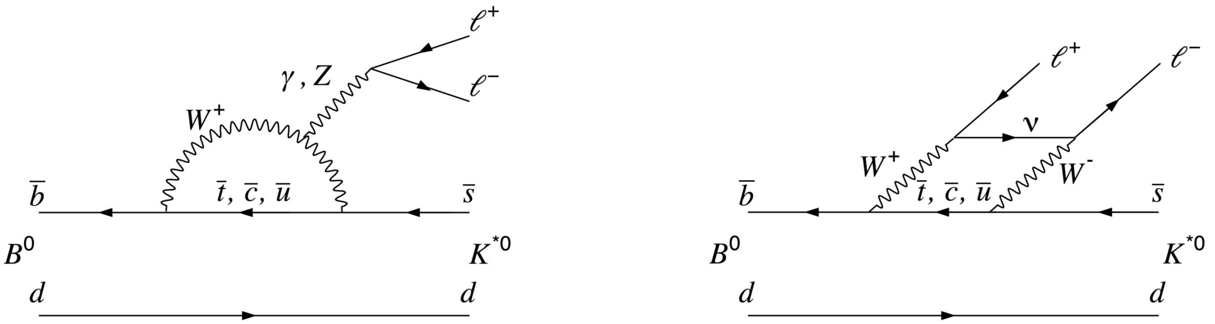
Carla Marin
on behalf of the LHCb collaboration

Lepton Photon, 11-01-2021, Manchester, UK

in $b \to s l l$ decays.
See G. Wormser talk
for $b \to c l \nu$

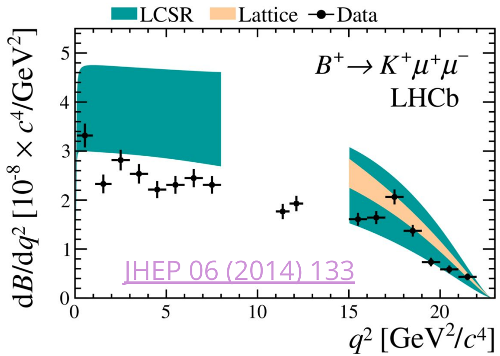
Why rare b → sll decays?

- FCNC sensitive to indirect effects of New Physics (NP) in loops
    - branching fractions, angular distributions, etc.
- Access to much larger scales than direct searches
- Tests of couplings to 3rd generation b-quarks

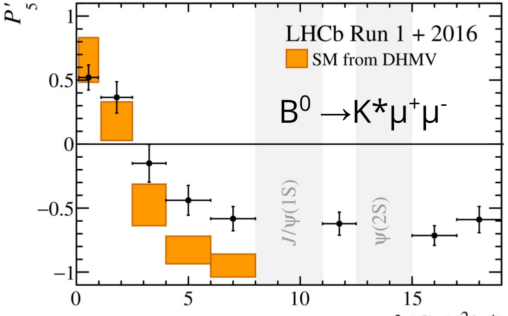


Intriguing deviations in rare b ⟶ sll decays

Differential BR and angular distributions

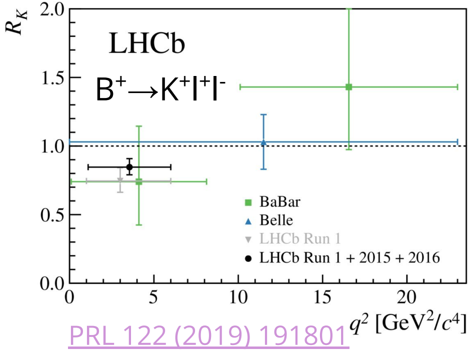


JHEP 06 (2014) 133

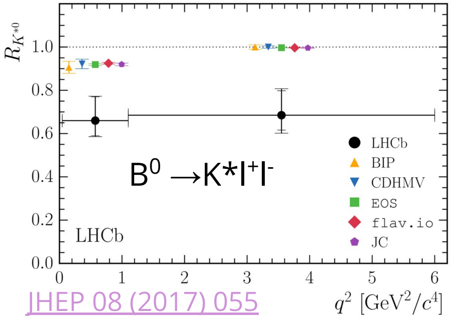


PRL 125 (2020) 011802

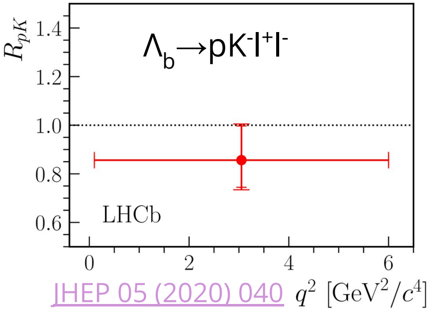
Lepton Flavour Universality tests



PRL 122 (2019) 191801



JHEP 08 (2017) 055



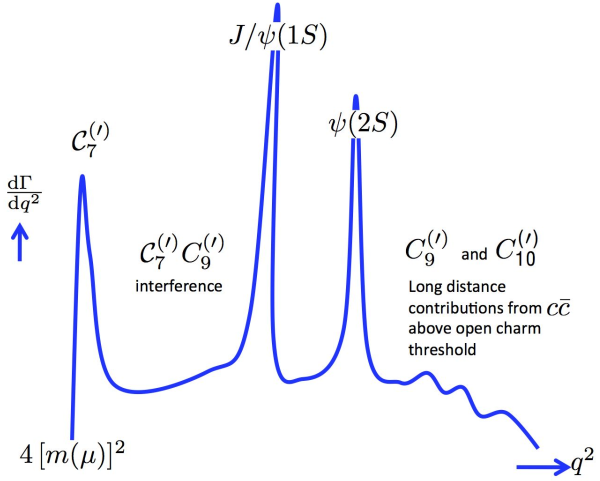
JHEP 05 (2020) 040

Effective Hamiltonian

Model independent description in effective field theory [Buchalla et al.]. Complete basis of 4-body operators contributing to different final states:

$$H_{eff} \propto V_{tb} V_{ts}^{*} \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right)$$

$$O_7^{(\prime)} \propto (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$$
$$O_9^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{l}\gamma_\mu l)$$
$$O_{10}^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{l}\gamma_\mu \gamma_5 l)$$
$$O_S^{(\prime)} \propto (\bar{s} P_{L(R)} b)(\bar{l} l)$$
$$O_P^{(\prime)} \propto (\bar{s} P_{L(R)} b)(\bar{l}\gamma_5 l)$$



Lepton Universality tests

Leptons of different species couple identically to electroweak bosons in SM
→ Lepton Flavour Universality (LFU)

Measure ratio of same b → sll process with muons and electrons in final state:

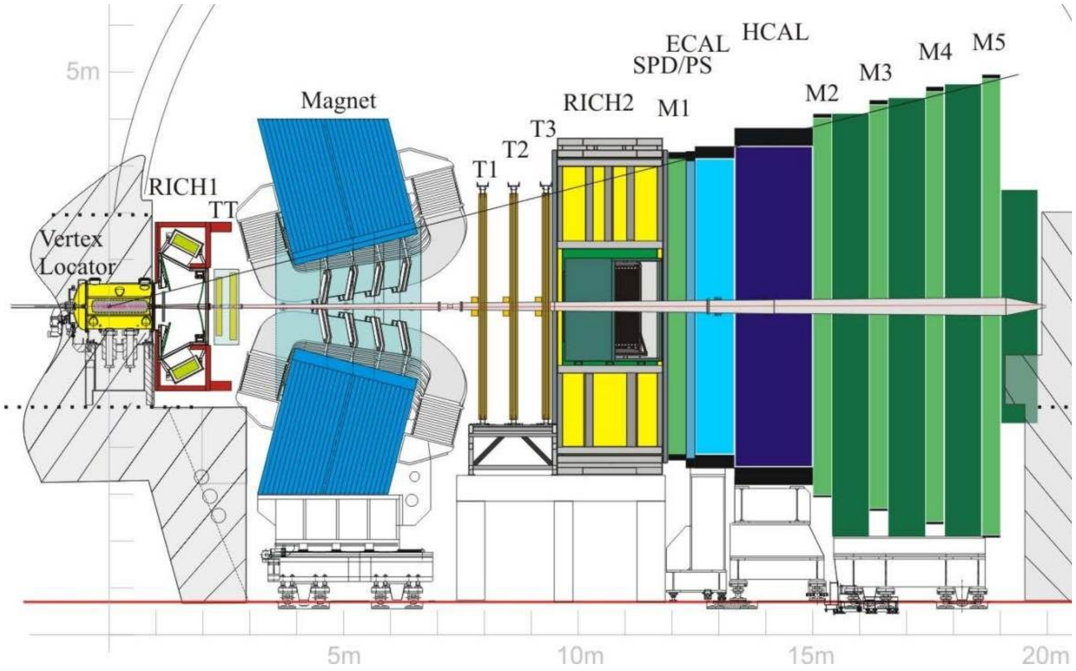
$$R_H \equiv \frac{\int \frac{d\Gamma(B \to H\mu^+\mu^-)}{dq^2} dq^2}{\int \frac{d\Gamma(B \to He^+e^-)}{dq^2} dq^2}$$

H = K^+, K^{0*}, K^0_S, K^{0+} ...

Hadronic uncertainties cancel in ratio → very clean theory prediction

JINST 3 (2008) S08005

Experimental setup



$\Delta p / p = 0.5 - 1.0\%$
$\Delta IP = (15 + 29/p_T[GeV])\ \mu m$

$\Delta E/E_{ECAL} = 1\% + 10\% / \sqrt{(E[GeV])}$

Electron ID ~90% for ~5% $h \rightarrow e^{\pm}$ mis-id probability

Muon ID ~ 97% for 1-3% $\pi \rightarrow \mu$ mis-id probability

How do we measure LFU at LHCb?

In the SM:

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

H = K^+, K^{0*}, K^0_S, K^{0+} ...

Experimentally:

$$R_H = \boxed{\frac{N(B\to H\mu^+\mu^-)}{N(B\to He^+e^-)}} \times \boxed{\frac{\epsilon(B\to He^+e^-)}{\epsilon(B\to H\mu^+\mu^-)}}$$

from mass fit

from MC and calibration samples

Exploit the well tested LFU in J/ψ modes

$$r_{J/\psi} = \frac{BR(B\to HJ/\psi(\mu^+\mu^-))}{BR(B\to HJ/\psi(e^+e^-))} = 1$$

- as stringent cross-check
- to build double ratio at LHCb → cancel systematic effects

$$R_H = \frac{\frac{N(B\to H\mu^+\mu^-)}{N(B\to HJ/\psi(\mu^+\mu^-))}}{\frac{N(B\to He^+e^-)}{N(B\to HJ/\psi(e^+e^-))}} \times \frac{\frac{\epsilon(B\to He^+e^-)}{\epsilon(B\to HJ/\psi(e^+e^-))}}{\frac{\epsilon(B\to H\mu^+\mu^-)}{\epsilon(B\to HJ/\psi(\mu^+\mu^-))}}$$

$b \to sll$ with electrons at LHCb

Hardware trigger

Larger ECAL occupancy → tighter thresholds for electrons than muons:

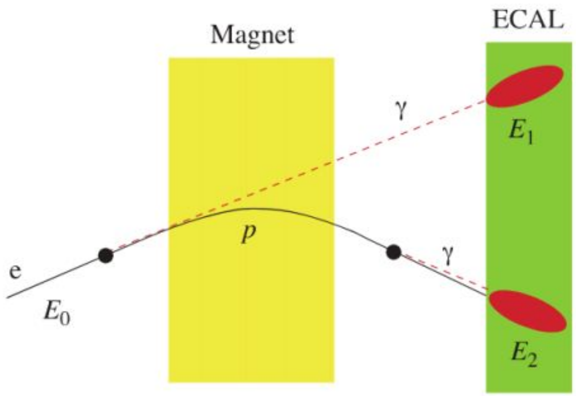
- e p_T > 2400 (2700) MeV in 2016 (2012)
- μ p_T > 1800 (1700) MeV in 2016 (2012)

[LHCb-PUB-2014-046, 2019 JINST 14 P04013]

Interaction with detector material

Electrons radiate much more Bremsstrahlung

Recovery procedure in place



- miss some photons and add fake ones
- ECAL resolution worse than tracking

→ worse mass resolution for electron modes

arXiv:2103.11769

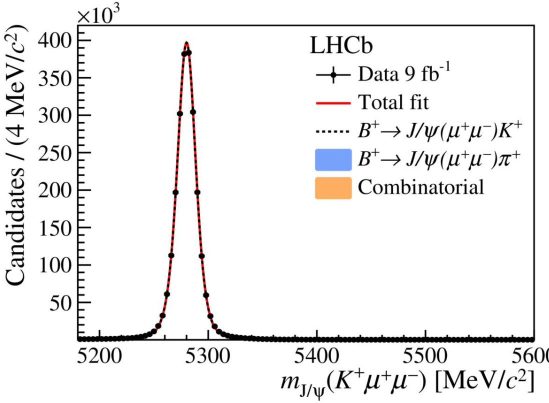
R_K with full LHCb data

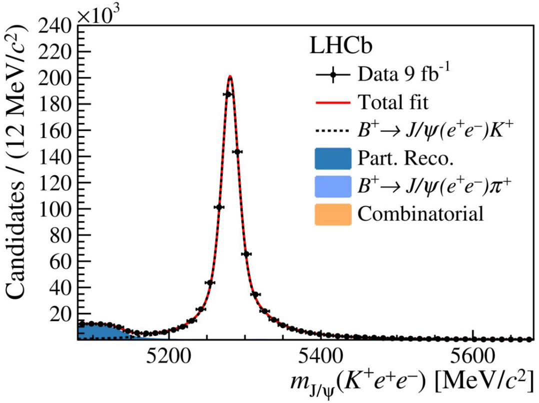
Stringent cross-checks with $B^+ \to J/\psi K^+$ and $B^+ \to \psi(2S) K^+$ decays

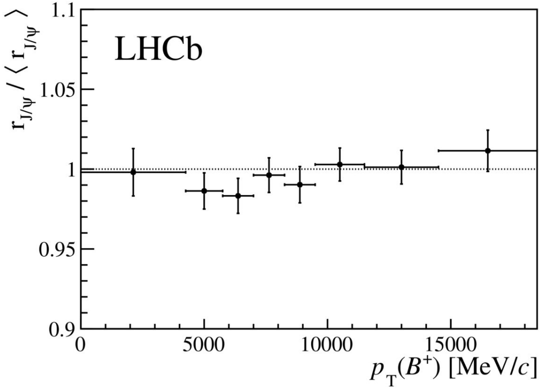
- shows that even absolute electron and muon efficiencies are understood

$$r_{J/\psi} = 0.981 \pm 0.020$$

$$R_{\psi(2S)} = 0.997 \pm 0.011$$ (double-ratio)







constraint m(ll) to J/ψ mass → strong improvement of mass resolution

arXiv:2103.11769

R_K with full LHCb data

Detailed study of systematic uncertainties:

Fit model	1%
Calibration sample size	1%
Trigger, PID and B kinematics calibration	< 0.1%
q^2 distribution and resolution	negligible

Effect of simulation corrections is small thanks to the double ratio:

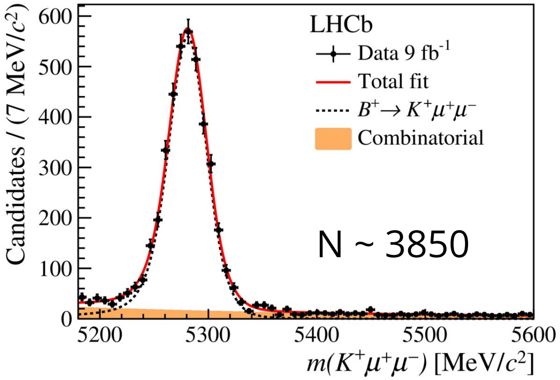
- R_K: (+3 ± 1)%
- $R_{J/\psi}$: 20%

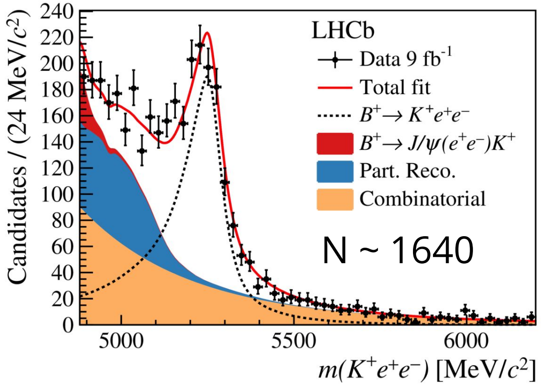
arXiv:2103.11769

R_K with full LHCb data

Measurement in $1.1 < q^2 < 6.0$ GeV^2 with Run 1+2 datasets → x2 b decays

R_K from simultaneous fit to $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$ candidates





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

most precise R_K measurement !

Consistent with SM at 0.10% (3.1σ) → evidence for the breaking of LU in b → sll decays

arXiv:2110.09501

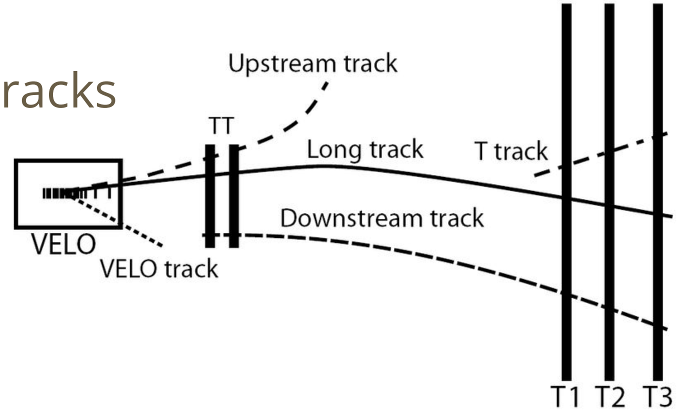
R_K and R_{K^*} with neutral Kaons

Recent measurement of isospin partners $B^0 \to K^0_S\, l^+ l^-$ and $B^+ \to K^{*+}\, l^+ l^-$

- only explored by Belle/BaBar so far, more challenging at LHCb
- no unambiguous observation of electron modes by any experiment

Use full dataset and follow R_K strategy, with some particularities:

- reconstruct $K^0_S \to \pi^+\pi^-$ and $K^{*+} \to K^0_S\pi^+$
- reconstruct K^0_s from long and downstream tracks
- still smaller yields due to long-lived K^0_S

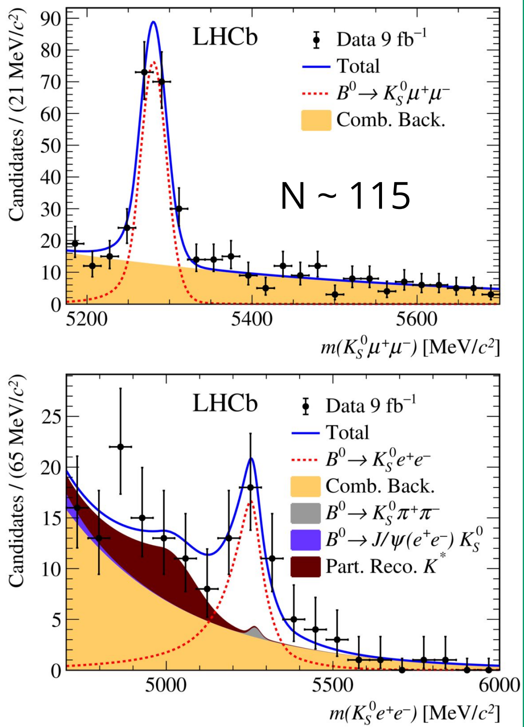


See CERN seminar for further details

arXiv:2110.09501

R_K and R_{K^*} with neutral Kaons

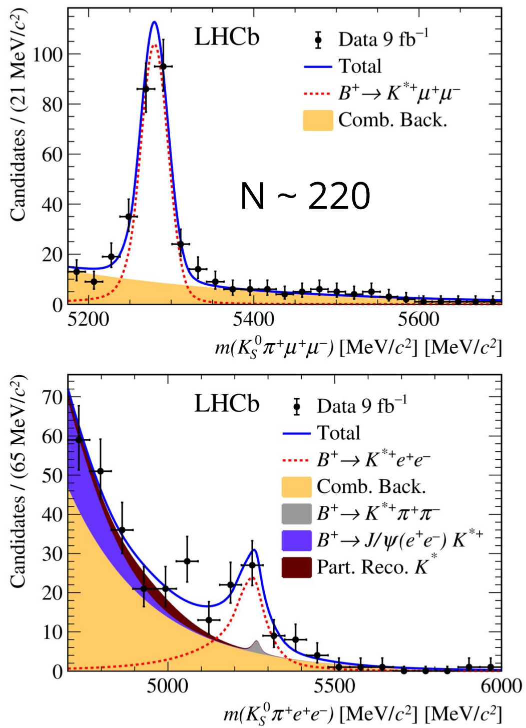
Separate fits to B^0 and B^+ decays, simultaneous for muons and electrons



$$R_{K^0_S} = 0.66\,^{+0.20}_{-0.14}\,(\text{stat.})\,^{+0.02}_{-0.04}\,(\text{syst.})$$

$$R_{K^{*+}} = 0.70\,^{+0.18}_{-0.13}\,(\text{stat.})\,^{+0.03}_{-0.04}\,(\text{syst.})$$

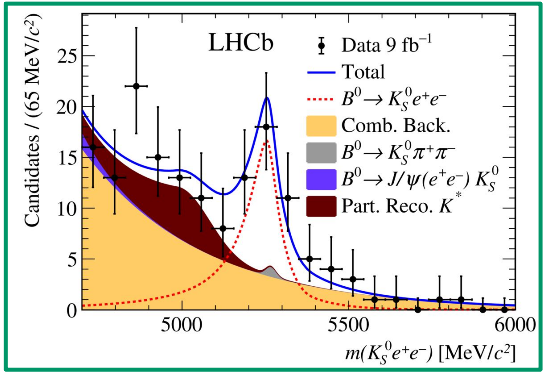
Most precise results and consistent with SM at 1.5 and 1.4σ



arXiv:2110.09501

R_K and R_{K^*} with neutral Kaons

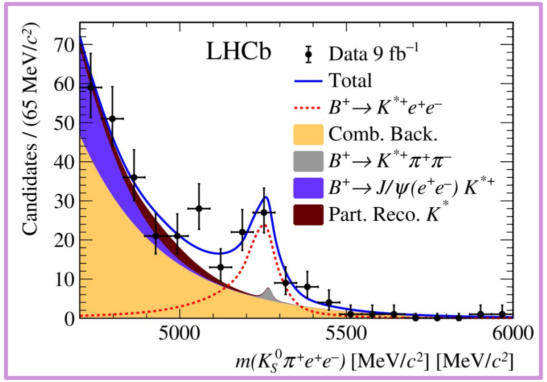
Separate fits to B^0 and B^+ decays, simultaneous for muons and electrons



Electron mode significance of 5.3 and 6.0σ → 1st observation

$e^{\pm}$ misId backgrounds are included in the fits

dB/dq^2 measured for first time in electron modes, in q^2 bins [1.1, 6.0] and [0.045, 6.0] GeV^2/c^4

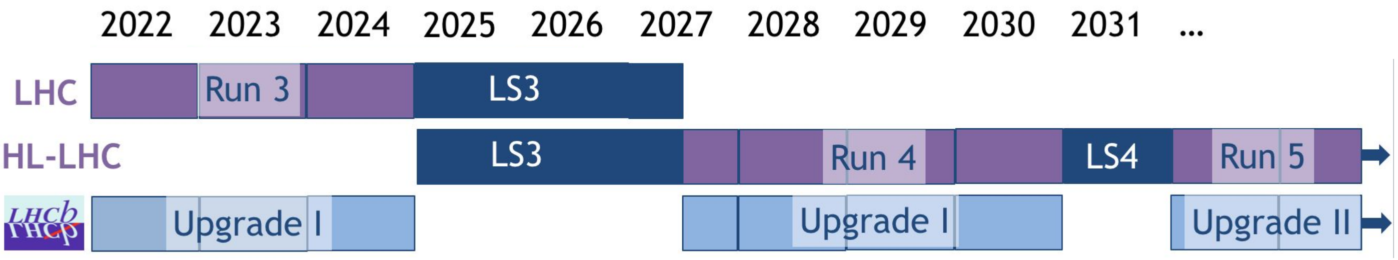


$$\frac{d\mathcal{B}\,(B^0 \to K^0 e^+ e^-)}{dq^2} = (2.6 \pm 0.6\,(\text{stat.}) \pm 0.1\,(\text{syst.})) \times 10^{-8}\ \text{GeV}^{-2} c^4$$

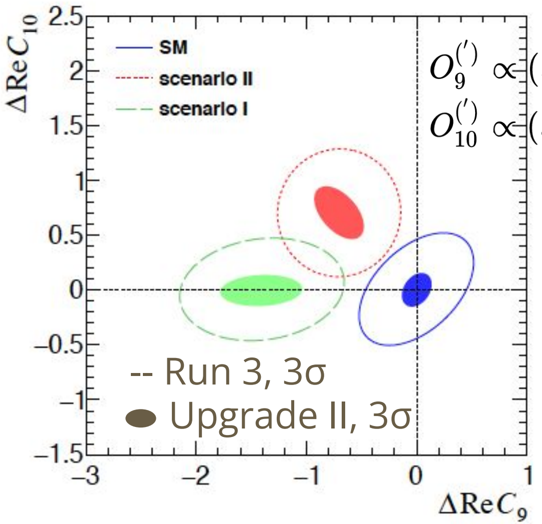
$$\frac{d\mathcal{B}\,(B^+ \to K^{*+} e^+ e^-)}{dq^2} = \left(9.2\,^{+1.9}_{-1.8}\,(\text{stat.})^{+0.8}_{-0.6}\,(\text{syst.})\right) \times 10^{-8}\ \text{GeV}^{-2} c^4$$

LHCB-PUB-2018-009

Future prospects for LFU tests at LHCb



		Run 3	Run 4	Upgrade II
R_X precision	$9\,\text{fb}^{-1}$	$23\,\text{fb}^{-1}$	$50\,\text{fb}^{-1}$	$300\,\text{fb}^{-1}$
R_K	0.043	0.025	0.017	0.007
$R_{K^{*0}}$	0.052	0.031	0.020	0.008
R_ϕ	0.130	0.076	0.050	0.020
R_{pK}	0.105	0.061	0.041	0.016
R_π	0.302	0.176	0.117	0.047



$$O_9^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{l}\gamma_\mu l)$$

$$O_{10}^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{l}\gamma_\mu \gamma_5 l)$$

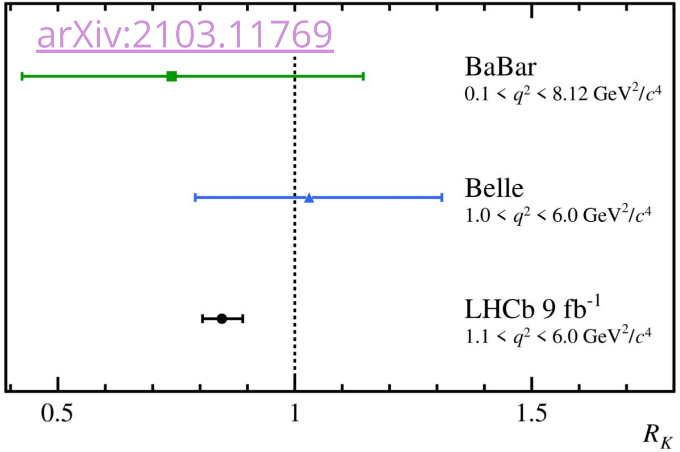
Summary & conclusions

See talk by D. van Dyk and recent Anomaly WS for interpretation of results

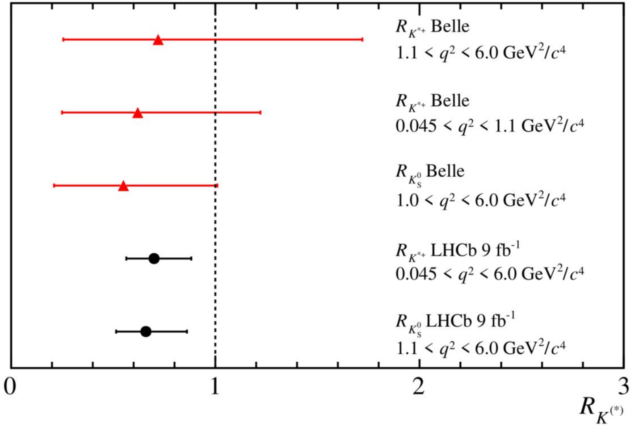
Rare b → sll decays provide stringent tests of NP

Recent results hint at breaking of LFU in b → sll

arXiv:2103.11769



arXiv:2110.09501



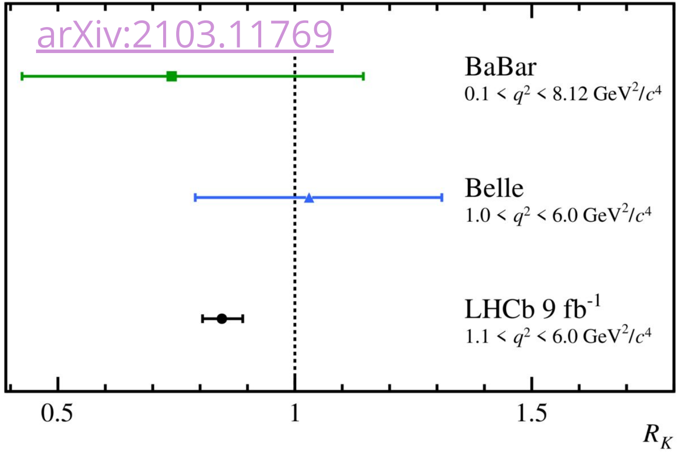
Summary & conclusions

See talk by D. van Dyk and recent Anomaly WS for interpretation of results

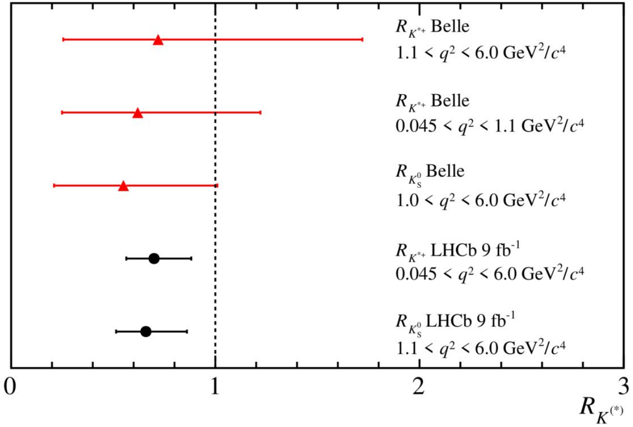
Rare b → sll decays provide stringent tests of NP

Recent results hint at breaking of LFU in b → sll

arXiv:2103.11769



arXiv:2110.09501



Stay tuned!

Thanks for the attention

BACK-UP

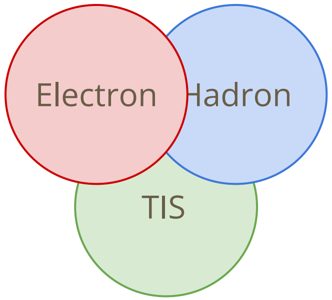
LHCb hardware trigger for electrons

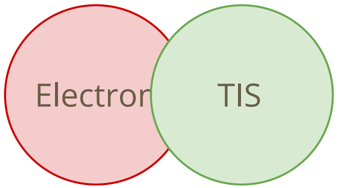
Larger ECAL occupancy → tighter thresholds for electrons:

- e p_T > 2700/2400 MeV in 2012/2016
- μ p_T > 1700/1800 MeV in 2012/2016

[LHCb-PUB-2014-046, 2019 JINST 14 P04013]

Mitigate including hadron trigger and events Triggered Independently of the Signal (TIS)

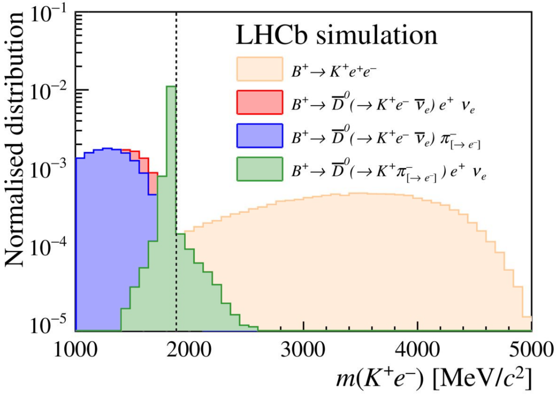


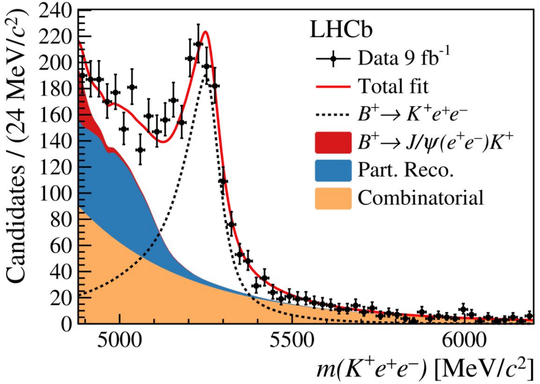


arXiv:2103.11769

R_K with full LHCb data

Cannot apply J/ψ mass constraint to rare mode → worse resolution → larger backgrounds for electron mode. Dedicated vetoes to minimise them.



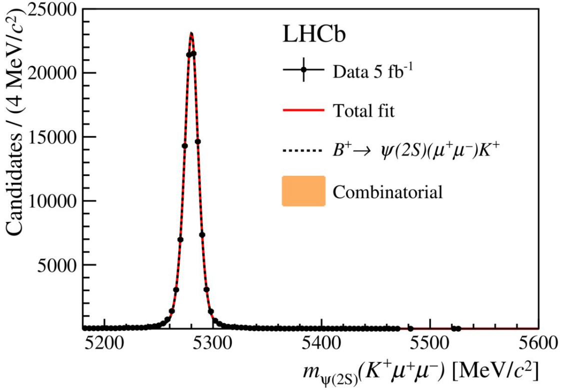


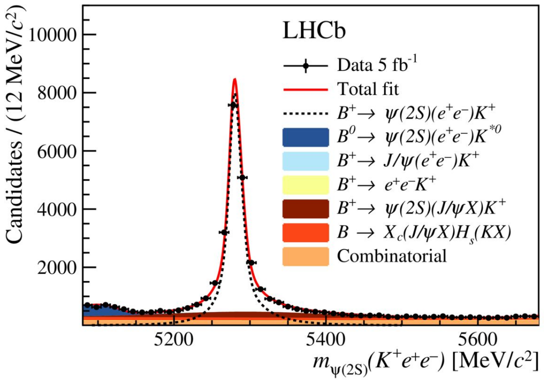
arXiv:2103.11769

$R_{\psi(2S)}$ cross-check

Stringent cross-checks with $B^+ \to J/\psi\, K^+$ and $B^+ \to \psi(2S)\, K^+$ decays

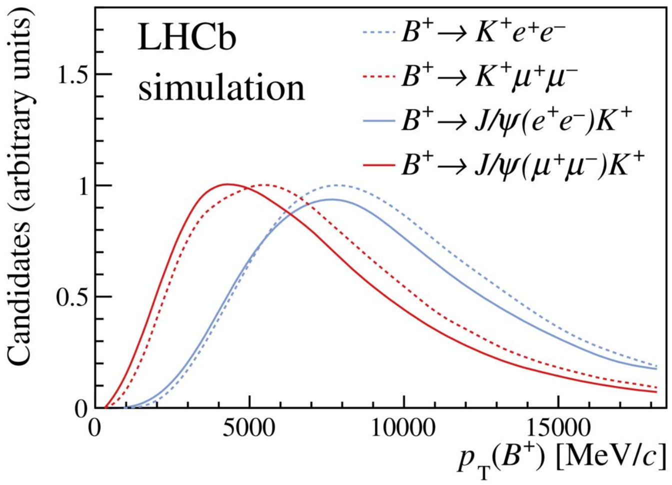
$$R_{\psi(2S)} = 0.997 \pm 0.011$$ (double-ratio)

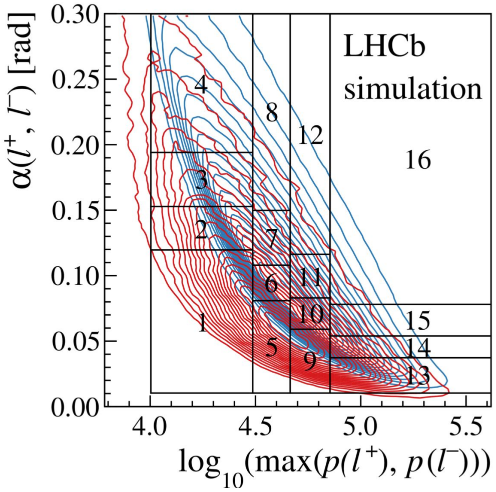




Constraint m(ll) to J/ψ or ψ(2S) mass → strong improvement of mass resolution

R_K: $r_{J/\psi}$ cross-checks





R_K: significance