Test of lepton universality in rare beauty quark decays

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CIEMAT HEP seminar

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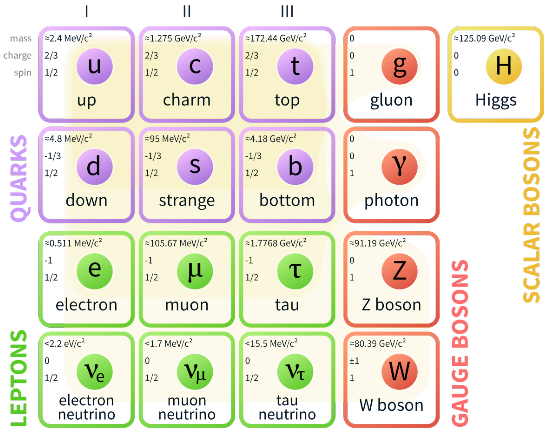
The Standard Model

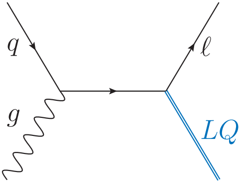


- Mathematical model that describes all fundamental particles and their interactions
- Still open questions (DM, matter-antimatter asymmetry, ...) $\Rightarrow$ SM is not the full picture

Quest for New Physics

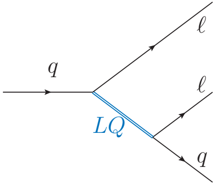
The SM is thought to be the low-energy limit of a more fundamental theory at higher energy scale with new particles and interactions.

Direct approach



- Direct production of new particles in the collision
- Easy interpretation
- Probes masses $< E_{\text{collision}}$

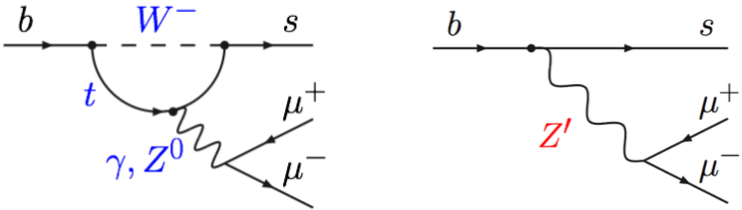
Indirect approach



- New (virtual) particles induce deviations from the SM predictions
- More difficult interpretation
- Probes very-high mass scales

Rare beautiful decays

- Decays involving $b \to s(d)l^+l^-$ transitions (FCNC)
  - forbiden at tree level in the SM



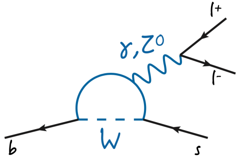
Strongly suppressed in the SM, but **not necessarily beyond the SM!**

Flavour anomalies

In recent years, we have observed an interesting set of tensions with the SM predictions

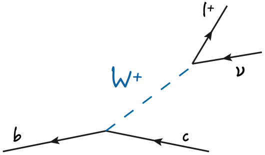
A) **In $b \to s\ell^+\ell^-$ transitions (FCNC)**

- **Branching fractions** of $b \to s\mu^+\mu^-$ decays
- **Angular observables** in $b \to s\mu^+\mu^-$ decays
- **Lepton Flavour Universality tests** in μ/e ratios



B) In $b \to c\ell\nu$ transitions (tree-level)

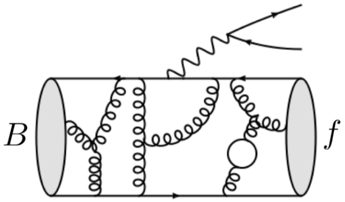
- Lepton Flavour Universality tests in μ/τ ratios



Theory uncertainties: Exclusive decays

Unfortunately, we do not observe the quark-transition, but the hadron decay
$\Rightarrow$ We need to compute hadronic matrix elements (form-factors and decay constants)

$$b \to s\mu\mu \quad \Longrightarrow \quad B^+ \to K^+\mu^+\mu^-,\ B^0 \to K^{*0}\mu^+\mu^-,\ B_s \to \phi\mu^+\mu^- ...$$



e.g. semileptonic decay

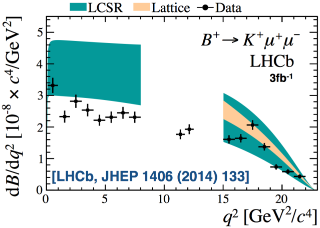
$\rightarrow$ Non-pertubative QCD, i.e. these are difficult to compute.

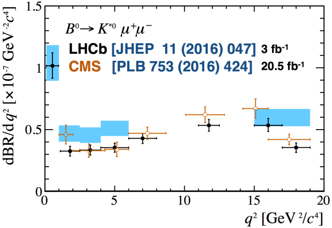
(Lattice QCD, QCD factorisation, Light-Cone sum rules...)

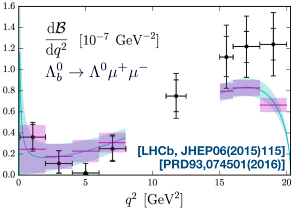
$\rightarrow$ Certain observables will profit from cancellation of these hadronic nuisances, making them more sensitive to New Physics contributions.

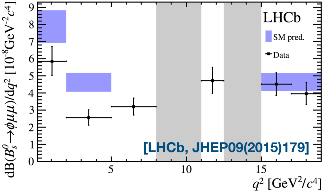
Branching fraction measurements

- Branching fractions consistently below the SM prediction at low $q^2 = [m(\ell^+\ell^-)]^2$ for many $b \to s\mu\mu$ processes (2-3σ)



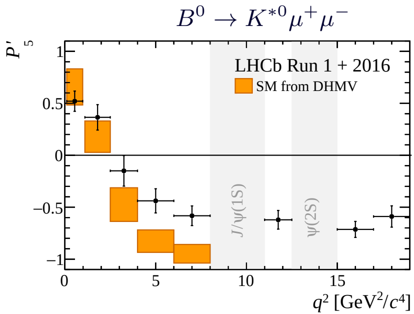


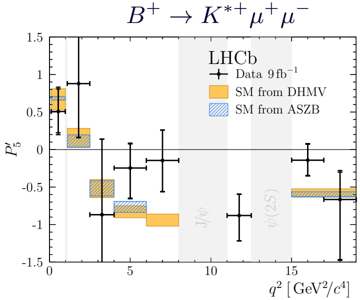




Angular observables

[LHCb, PRL 125 (2020) 011802]
[LHCb, arXiv:2012.13241]



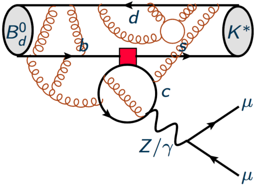


- Complementary constraints on NP & orthogonal experimental systematics compared to BR's
- Give access to observables with reduced dependence on hadronic effects [JHEP 1204 (2012) 104]
- Tension with the SM at the level of $\sim 3\sigma$

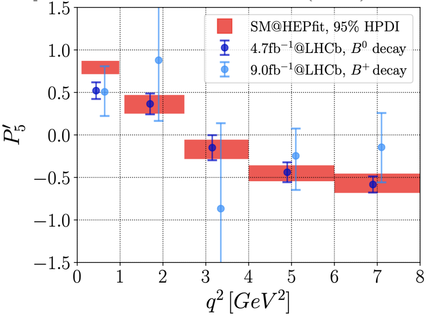
New Physics or QCD?

Debate on whether we can trust the SM predictions in these observables,

- Could unaccounted for $c\bar{c}$-loop contributions mimic a NP contribution?



[M. Ciuchini et al, PRD 103 (2021) 015030]



Lepton flavour universality tests

- In the Standard Model, couplings of the gauge bosons to leptons are independent of lepton flavour
  $\rightarrow$ branching fractions of e, μ and τ differ only by phase space and helicity-suppressed contributions

- Ratios of the form:

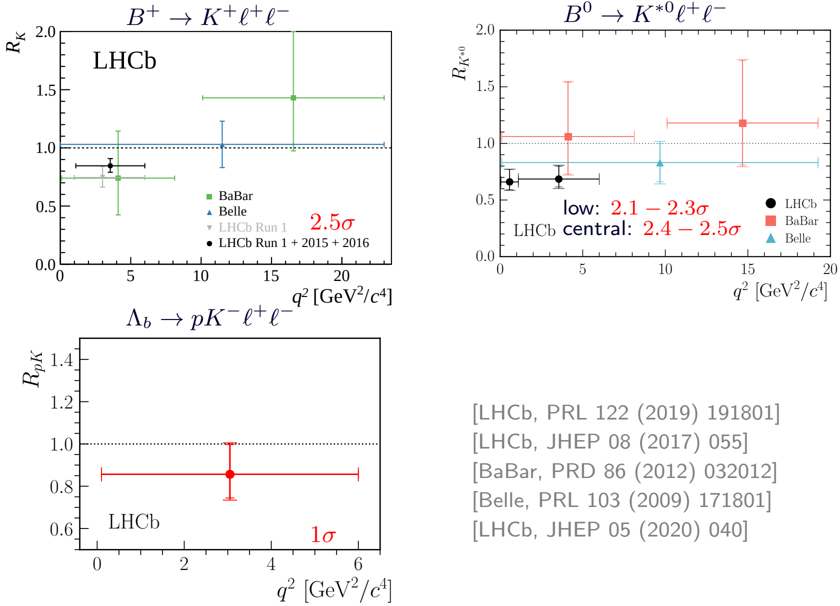
$$R_K = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)} \overset{\text{SM}}{\cong} 1$$

$\rightarrow$ **Free from QCD uncertainties that may affect other observables**
(hadronic effects cancel in the ratio, error is $\mathcal{O}(10^{-4})$ [JHEP 07 (2007) 040])

$\rightarrow$ QED corrections can be $\mathcal{O}(10^{-2})$ [EPJC 76 (2016) 8,440]

Any sign of lepton flavour non-universality would be smoking gun for New Physics

LFU ratios



[LHCb, PRL 122 (2019) 191801]
[LHCb, JHEP 08 (2017) 055]
[BaBar, PRD 86 (2012) 032012]
[Belle, PRL 103 (2009) 171801]
[LHCb, JHEP 05 (2020) 040]

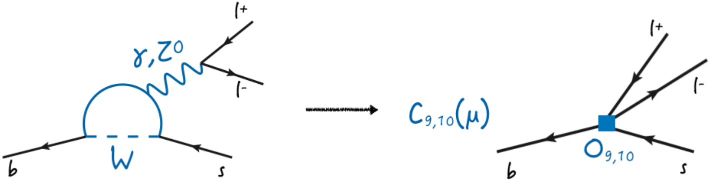
Theoretical framework - Effective theory

- Can describe these interactions in terms of an effective Hamiltonian that describes the full theory at lower energies (μ)

$$\mathcal{H}_{\text{eff}} \sim \sum_i C_i(\mu)\mathcal{O}_i(\mu)$$

$C_i(\mu) \rightarrow$ Wilson coefficient
(perturbative, short-distance physics, sensitive to $E > \mu$)

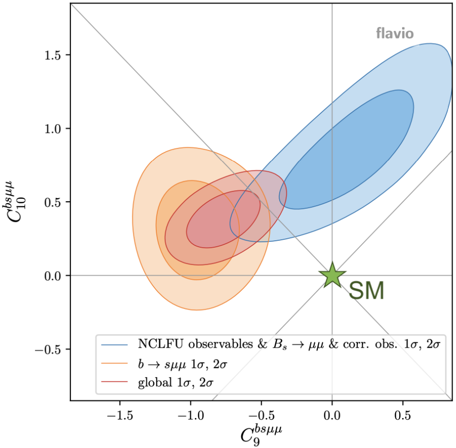
$\mathcal{O}_i \rightarrow$ Local operators
(non-perturbative, long-distance physics, sensitive to $E < \mu$)



$\rightarrow$ Contributions from New Physics will modify the measured value of the Wilson coefficients present in the SM or introduce new operators

Global fits to $b \to s\ell^+\ell^-$ observables

[P. Stangl, La Thuile 2021]



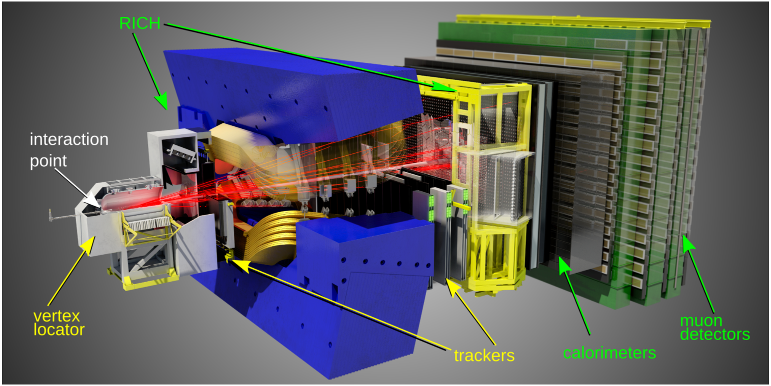
Best fit prefers shifted muon vector coupling $C_9^{\mu\mu}$ (or a combination $C_9^{\mu\mu}$ and axial-vector $C_{10}^{\mu\mu}$)

- LFU observables and $B_s^0 \to \mu^+\mu^-$ [theoretically clean]
- Angular observables and BR's [considerable hadronic uncertainties]

Critical to improve precision in theoretically clean observables

[similar fits by Aebischer et al. arXiv:1903.10434, Algueró et al., arXiv:1903.09578, Kowalska et al. arXiv:1903.10932, Ciuchini et al. arXiv:2011.01212, Datta et al. arXiv:1903.10086, Arbey et al. arXiv:1904.08399]

The LHCb detector



- Forward spectrometer to study b- and c-hadron decays ($2 < \eta < 5$) @ LHC
  - Good vertex and impact parameter resolution ($\sigma(IP) = 15 + 29/p_T)\mu m$)
  - Excellent momentum resolution ($\sigma(m_B) \sim 25\,\mathrm{MeV}/c^2$ for 2-body decays)
  - Excellent particle ID (μ ID 97% for ($\pi \to \mu$) misID of 1-3%)
  - Versatile & efficient trigger

JINST 3 (2008) S080005

Int. J. Mod. Phys. A 30 (2015) 1530022

New R_K measurement: LFU in $B^+ \to K^+\ell^+\ell^-$

$$R_K = \frac{\int_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+\to K^+\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+\to K^+e^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2}$$

Measurement performed on full LHCb dataset, $\sim$**twice as many B's as previous analysis**

- Previously analised Run1 and 2015+2016 data ($5\,\mathrm{fb}^{-1}$)
- Added 2017 and 2018 datasets ($4\,\mathrm{fb}^{-1}$)

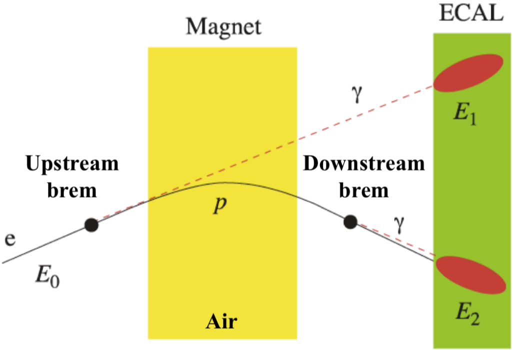
Similar strategy to previous measurement [LHCb, PRL 122 (2019) 191801]

- Same q^2 region: **[1.1, 6.0]** GeV^2/c^4

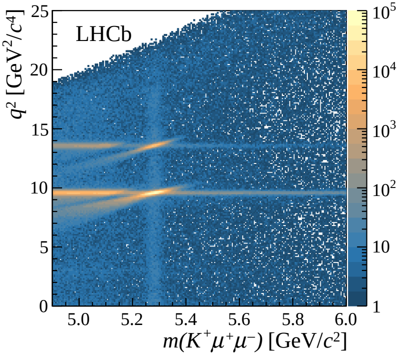
Electron Bremsstrahlung

Electrons lose a large fraction of their energy through Bremsstrahlung radiation

Bremsstrahlung recovery procedure to improve momentum measurement for electrons
$\rightarrow$ Add photon clusters in the calorimeter ($E_T > 75\,\mathrm{MeV}$) compatible with electron direction before magnet



1. Even after Bremsstrahlung recovery, electrons still have degraded momentum, and mass/q^2 resolution



Electrons VS Muons

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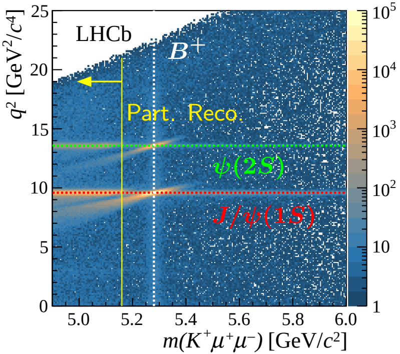
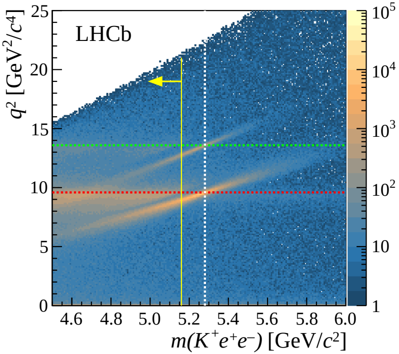
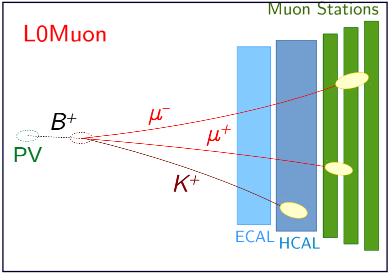
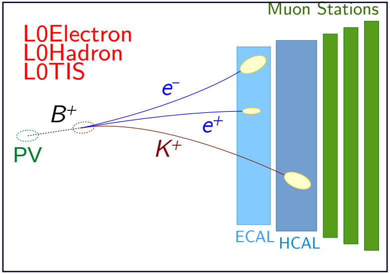




Electrons VS Muons

1. Even after Bremsstrahlung recovery, electrons still have degraded momentum, and mass/q^2 resolution
2. Very different trigger signatures: Lower trigger efficiency for electrons
   - Muons identified by Muon stations
   - Electrons rely on signal in the Calorimeter (higher occupancy $\Rightarrow$ higher trigger thresholds)





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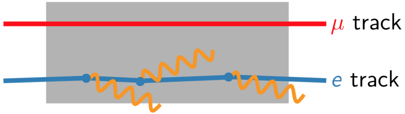
3. Particle ID and track reconstruction efficiencies also larger for muons than for electrons



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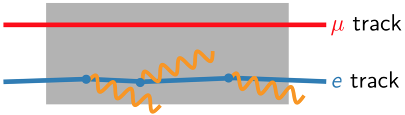


$\rightarrow$ **Critical aspect of the analysis: Get the differences between electron and muon efficiencies fully under control**

Analysis strategy

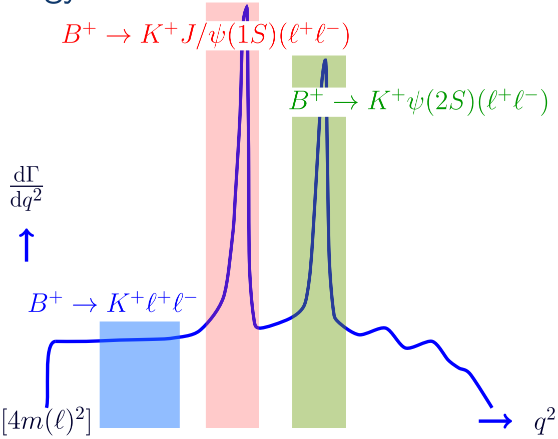
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))}$$

$$= \frac{N(B^+ \to K^+\mu^+\mu^-)}{N(B^+ \to K^+J/\psi(\mu^+\mu^-))} \times \frac{\varepsilon_{B^+\to K^+J/\psi(\mu^+\mu^-)}}{\varepsilon_{B^+\to K^+\mu^+\mu^-}}$$

$$\times \frac{N(B^+ \to K^+J/\psi(e^+e^-))}{N(B^+ \to K^+e^+e^-)} \times \frac{\varepsilon_{B^+\to K^+e^+e^-}}{\varepsilon_{B^+\to K^+J/\psi(e^+e^-)}}$$

- R_K is measured as a **double ratio** to cancel out most systematics
  $\to$ $B^+ \to K^+J/\psi(\ell^+\ell^-)$ measured to be LF-universal within 0.4%
- 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

Analysis strategy

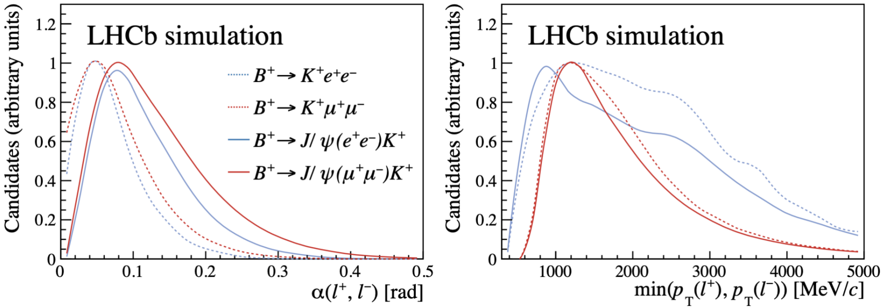


Resonant and nonresonant are separated in q^2

$\rightarrow$ However, good overlap between $B^+ \to K^+\ell^+\ell^-$ and $B^+ \to K^+ J/\psi(\ell^+\ell^-)$ in the variables relevant to the detector response

Analysis strategy

[LHCb-PAPER-2021-004]



Resonant (——) and nonresonant (- - -) are separated in q^2

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Selection & backgrounds

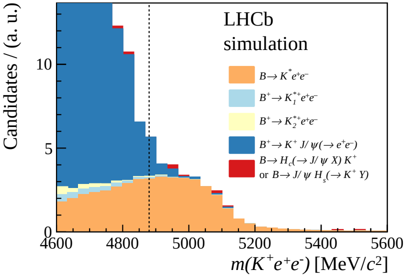
[LHCb, PRL 122 (2019) 191801]

Identical selection between resonant and rare modes (except q^2 and $m(K\ell\ell)$)

- Use particle ID requirements and mass vetoes to suppress exclusive B-decays to negligible levels
  - Backgrounds from e.g. $B \to \bar{D}^0(K\ell\nu)\ell\nu$, with $m(K\ell) > m_{D^0}$
  - Mis-ID backgrounds, e.g. $B \to K\pi^+_{(\to e^+)}\pi^-_{(\to e^-)}$, with electron ID
- Multivariate selection to reduce combinatorial background (BDT)

Remaining backgrounds suppressed by choice of $m(K\ell\ell)$ window

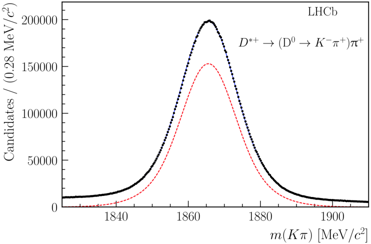
- $B^+ \to K^+ J/\psi(e^+e^-)$
- Partially reconstructed $B \to KX\,\ell\ell$ decays
- Modelled in fit by constraining their fractions between trigger categories and calibrating simulated templates from data.
- Cross-check our estimates using control regions in data and changing $m(K\ell\ell)$ window in fit



Efficiency calibration

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

- Particle ID calibration
  - Tune particle ID variables for diff. particle species using kinematically selected calibration samples ($D^{*+} \to D^0(K^-\pi^+)\pi^+ ...$) [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

[LHCb, PRL 122 (2019) 191801]

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

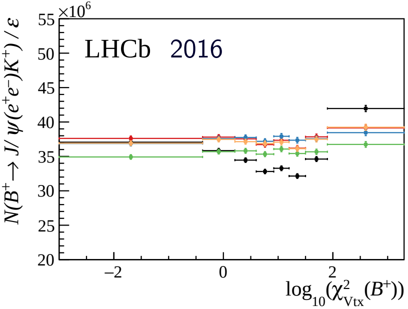
none

$\mu\mu$ `L0Muon, nominal`

$\mu\mu$ `L0TIS`

ee `L0Electron`

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



$\rightarrow$ Systematic uncertainty from RMS between all these weights

Cross-check: Measurement of $r_{J/\psi}$ [LHCb-PAPER-2021-004]

- To ensure that the efficiencies are under control, check

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

known to be true within 0.4%.

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

- Result:

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

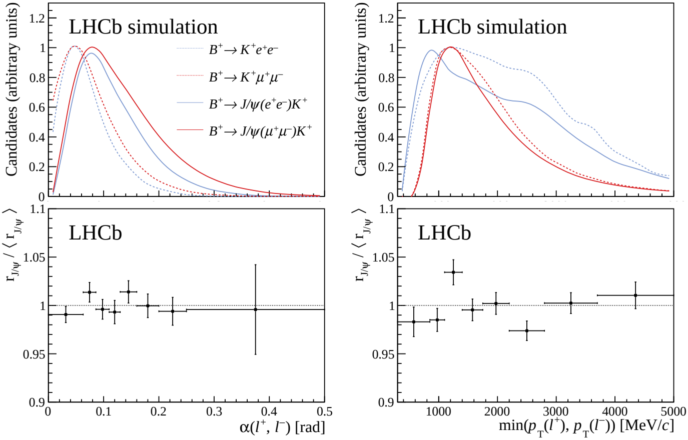
- Checked that the value of $r_{J/\psi}$ is compatible with unity for all periods and in all trigger samples.

Cross-check: $r_{J/\psi}$ as a function of kinematics

Check that efficiencies are understood in all kinematic regions $\rightarrow$ $r_{J/\psi}$ is flat for all variables examined

$\rightarrow$ e.g. given expected $\min(p_T(\ell^+), p_T(\ell^-))$ spectra, bias expected on R_K if deviations are genuine rather than fluctuations is 0.1%

[LHCb-PAPER-2021-004]



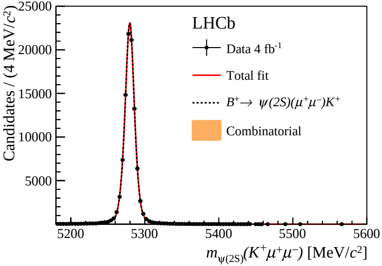
Cross-check: Measurement of $R_{\psi(2S)}$ [LHCb-PAPER-2021-004]

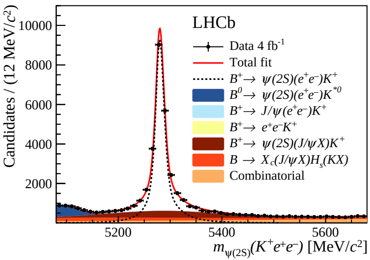
- Measurement of the double ratio

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

Result well compatible with unity:

$$R_{\psi(2S)} = 0.997 \pm 0.011\ (\mathrm{stat+syst})$$





Systematics uncertainties

Dominant sources ($\sim 1\%$)

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

Sub-dominant sources ($\sim 1‰$)

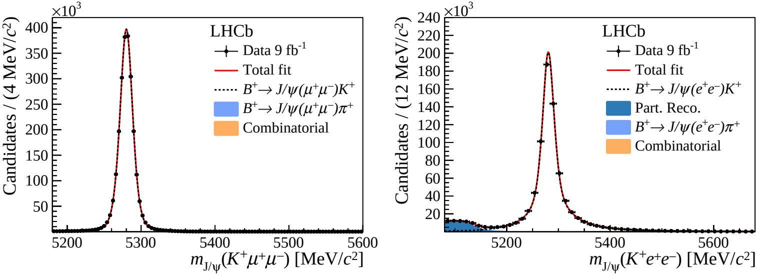
- Efficiency calibration
  - Dependence with tag, in tag-and-probe determinations;
  - Parameterisation bias (e.g. factorisation of PID efficiencies for kaons and electrons) tag and trigger bias;
  - Dependence of q^2 and $m(K^+e^+e^-)$ resolution with q^2
  - Inaccuracies in material description in simulation (tracking efficiency)
  - ...

$\rightarrow$ Total relative systematic of 1.5% in the final R_K measurement $\Rightarrow$ Expected to be statistically dominated

Fit to the resonant modes

[LHCb-PAPER-2021-004]

Yields for $B^+ \to K^+ J/\psi(\ell^+\ell^-)$, used as input for cross-checks and final determination of R_K, obtained from a fit to the J/ψ-constrained B mass



- Signal and background shapes determined from calibrated simulation
- Allow for a shift in the position in the signal peak and a scale factor to the resolution to float in the fit
- Results cross-checked with a fit to the unconstrained $m(K\ell\ell)$

Simultaneous fit to extract R_K

- Get R_K directly as a parameter of the fit
- Perform simultaneous fit to $m(K^+e^+e^-)$ and $m(K^+\mu^+\mu^-)$ distributions

$$R_K = \frac{N^r_{K\mu\mu}}{N^{rt}_{Kee}} \cdot \frac{N^{rt}_{J/\psi ee}}{N^r_{J/\psi\mu\mu}} \cdot \frac{\varepsilon^{rt}_{Kee}}{\varepsilon^r_{K\mu\mu}} \cdot \frac{\varepsilon^r_{J/\psi\mu\mu}}{\varepsilon^{rt}_{J/\psi ee}}$$

$$= \frac{N^r_{K\mu\mu}}{N^{rt}_{Kee}} \cdot c^{rt}_K,$$

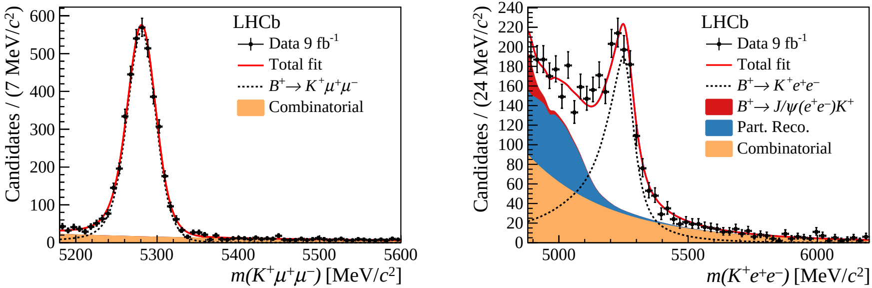
for $r =$Run 1, Run 2 and $t =$L0Electron, L0Hadron, L0TIS.

- c^{rt}_K are included as a multidimensional Gaussian constraint, with uncertainties and correlations according to the 6×6 covariance matrix σ
- Partially reconstructed background comes essentially from $B \to K\pi e^+e^-$ and so it can be constrained using

$$\frac{N^{r,t}_{prc}}{N^{r,\mathrm{eTOS}}_{prc}} = \frac{\varepsilon^{r,t}_{trig,mass}(K\pi ee)}{\varepsilon^{r,\mathrm{eTOS}}_{trig,mass}(K\pi ee)} = r^{rt}_{prc}$$

Fit to $B^+ \to K^+\ell^+\ell^-$ candidates

[LHCb-PAPER-2021-004]



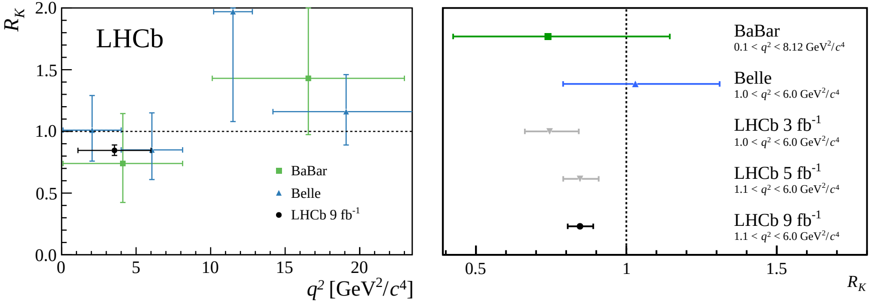
- Signal and background shapes determined from calibrated simulation.
- Mass shift and resolution scale fixed to that observed in the fit to the resonant mode.
- Leakage from $B^+ \to J/\psi(ee)K^+$ in the $B^+ \to K^+e^+e^-$ signal region $(1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4)$, constrained from the fit to the resonant mode.

R_K with full Run1 and Run2 dataset

[LHCb-PAPER-2021-004]

[Belle, JHEP 03 (2021) 105]

[BaBar, PRD 86 (2012) 032012]

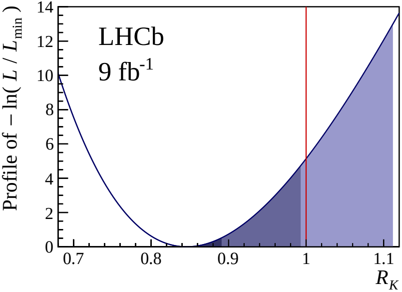


$$R_K = 0.846\ ^{+0.042}_{-0.039}\ (\mathrm{stat})\ ^{+0.013}_{-0.012}\ (\mathrm{syst})$$

Compatibility with the Standard Model

- Compatibility with the SM obtained by integrating the profiled likelihood as a function of R_K above 1
  - Taking into account the 1% theory uncertainth on R_K [EPJC76(2016)8,440]
  - p-value is converted into significance using the inverse Gaussian c.d.f. for a one-sided conversion

[LHCb-PAPER-2021-004]

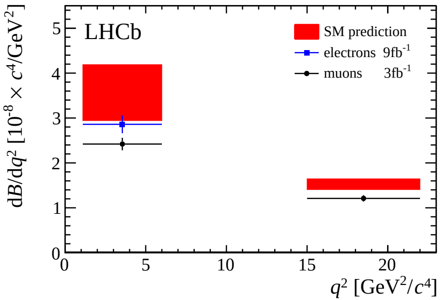


- p-value under the SM hypothesis: 0.0010

→ Evidence of LFU violation at 3.1 standard deviations

Measurement of $\mathcal{B}(B^+ \to K^+ e^+ e^-)$ [LHCb-PAPER-2021-004]

- Combining the measurement of R_K with the published value for $\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)$ [LHCb-PAPER-2014-006]



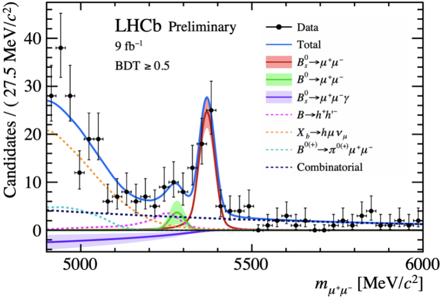
In the range $q^2 \in [1.1, 6]\,\mathrm{GeV}^2/c^4$

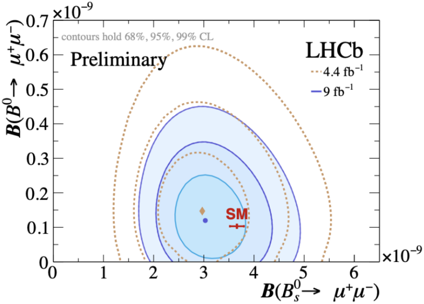
$$\frac{\mathrm{d}\mathcal{B}(B^+ \to K^+ e^+ e^-)}{\mathrm{d}q^2} = (28.6\ ^{+1.5}_{-1.4}(\mathrm{stat})\ \pm 1.4(\mathrm{syst})) \times 10^{-9}\ c^4/\,\mathrm{GeV}^2$$

$\rightarrow$ Dominant systematic comes from the $\mathcal{B}(B^+ \to K^+ J/\psi)$

$\rightarrow$ This is the most precise determination of this branching fraction to date

New measurement of $\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-)$ [LHCb-PAPER-2021-007]



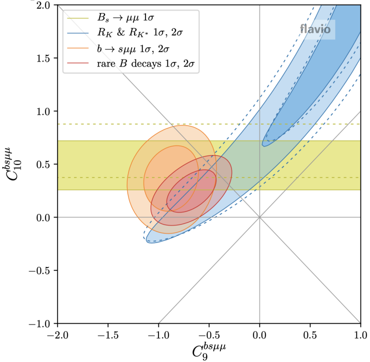


$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.09\ ^{+0.46}_{-0.43}\ ^{+0.15}_{-0.11}) \times 10^{-9}$$

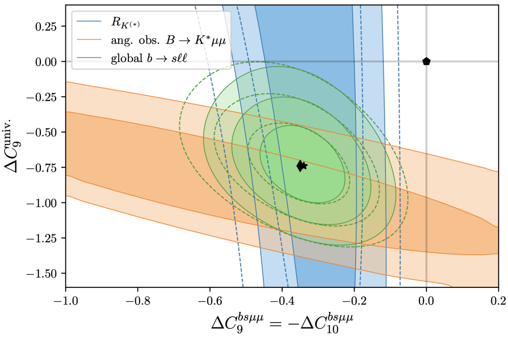
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}\ (95\%\text{CL})$$

Impact on Global Fits

[W.Altmannshofer et al., arXiv:2103.13370]



[J. Kriewald et al., arXiv:2104.00015]



- Best fit point still in tension with the SM

$\rightarrow$ Scenario with $C_9 = -C_{10}$ still good

- Tension between $R_K^{(*)}$ & $b \to s\mu^+\mu^-$ observables

$\rightarrow$ could be reduced by LFU contribution to C_9

[Similar fits by M. Algueró et al., Moriond QCD 2021,
C. Cornella et al., arXiv:2103.16558, L-G. Geng et al., arXiv:2103.12738]

Connection with charged currents?

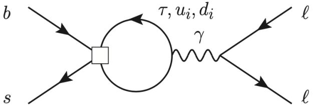
- C_9^{univ} can arise from corrections involving τ-loops

$\rightarrow$ Need to consider SMEFT (higher scale)

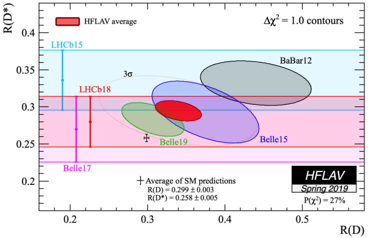
- Consider operators that can explain also anomalies in $b \rightarrow c\ell\nu$

$\rightarrow$ $R(D^{(*)}) = \mathcal{B}(B \rightarrow D^{(*)}\tau\nu)/\mathcal{B}(B \rightarrow D^{(*)}\mu\nu)$

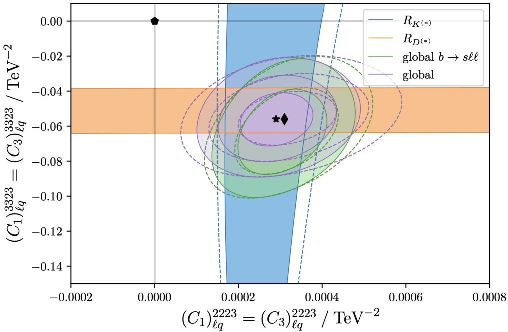
$\rightarrow$ Oversimplified scenario (need to consider real models)



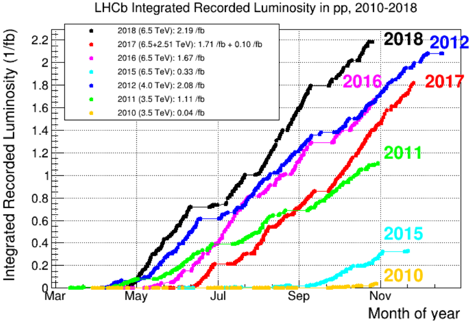
Bobeth, Haisch, arXiv:1109.1826
Crivellin, Greub, Müller, Saturnino, arXiv:1807.02068



[J. Kriewald et al., arXiv:2104.00015]



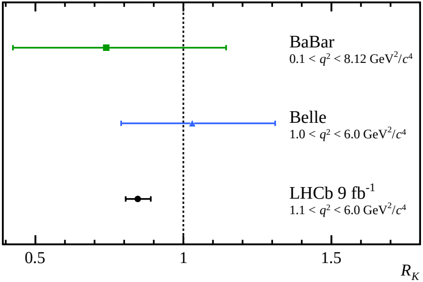
What next?



- With the LHCb dataset in hand, many interesting results still to come
  - Update of $R_{K^{*0}}$ with full Run 2 dataset
  - LFU test in different channels: R_ϕ, R_{K_S}, $R_{K^{*+}}$, $R_{K\pi\pi}\dots$
  - Update of angular observables of $b \to s\mu^+\mu^-$ decays
  - Measurements of $b \to s\tau\tau$ processes and LFV involving τ's

- For a definite answer on LFU we will need Run 3, as well as input from other LHC experiments and Belle II

Conclusions



- Performed measurement of the LFU ratio R_K using the full Run 1 and Run 2 LHCb dataset
  - Compatibility with the SM at $3.1\sigma \Rightarrow$ Evidence for LFU breaking
- Many more results on rare $b \to s\ell\ell$ decays on the pipeline
- Run 3 definitely needed to understand the full picture, as well as measurements from ATLAS, CMS and Belle II