LFU in neutral current B decays

Conference on Flavor Physics and CP Violation, 7th May 2019

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on behalf of the LHCb collaboration with results
from ATLAS, BaBar, Belle and CMS

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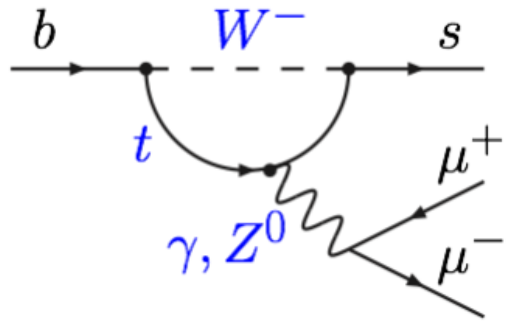
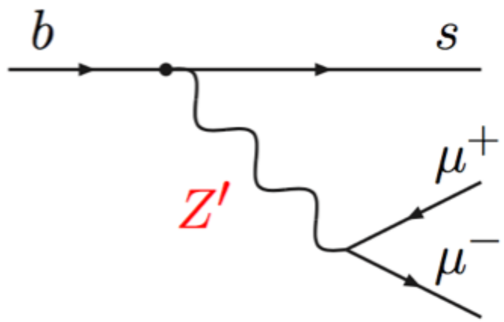
Introduction

- FCNC transitions, such as $b \to s(d)l^+l^-$ decays, are excellent candidates for indirect NP searches



- Strongly suppressed in the SM as
  - arise only at the loop level
  - quark-mixing is hierarchical (off-diagonal CKM elements $\ll$ 1)
  - GIM mechanism
  - only the left-handed chirality participates in flavour-changing interactions



- But these conditions do not necessarily apply to physics beyond the SM!

Outline

- Theoretical framework
- Status of neutral current B decay measurements
- Latest LFU measurements
- Impact on global picture
- Future prospects

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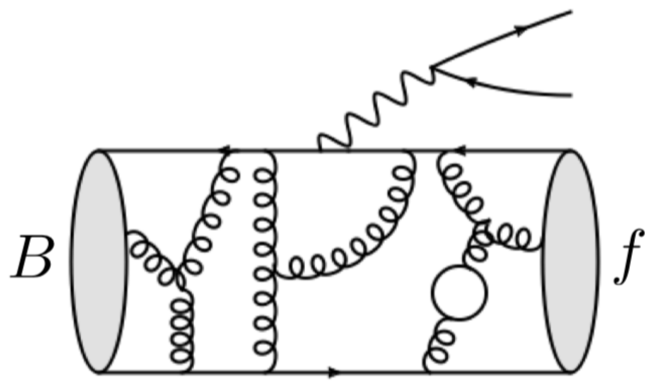
Choosing observables

- Observe hadronic decay, not the quark-level transition
  ⇒ Need to compute hadronic matrix elements (form-factors and decay constants)

- $b \to s\mu\mu$ = ⇒ $B^+ \to K^+\mu^+\mu^-$, $B^0 \to K^{*0}\mu^+\mu^-$, $B_s \to \varphi\mu^+\mu^-$...



→ Non-perturbative QCD, i.e. difficult to compute

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

- Hadronic uncertainties cancel in certain observables, making them more sensitive to New Physics

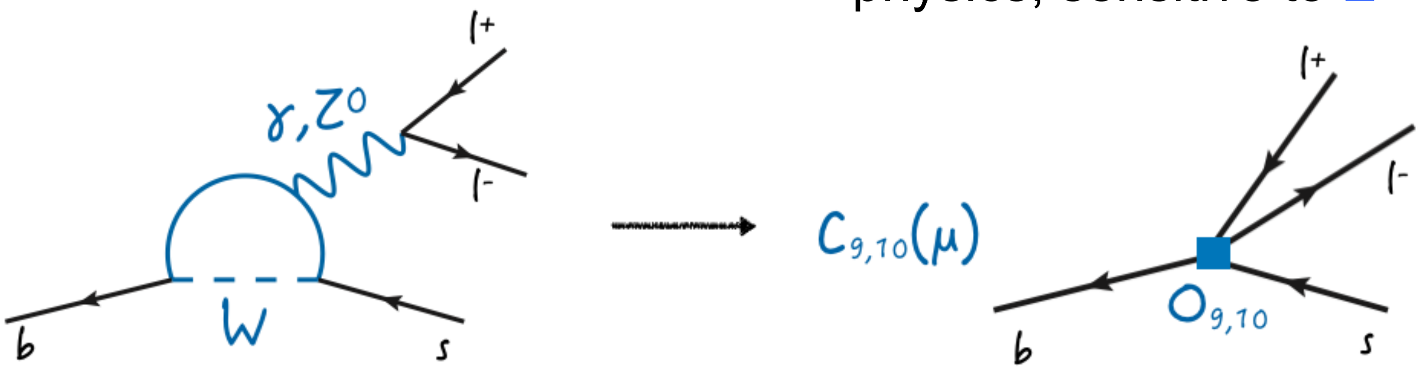
Theoretical framework

- Interactions described in terms of an effective Hamiltonian that describes the full theory at lower energies (μ)

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

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

O_i → Local operators (non-perturbative, long-distance physics, sensitive to $E < \mu$)



→ Contributions from New Physics will modify the measured values of WC's or introduce new operators

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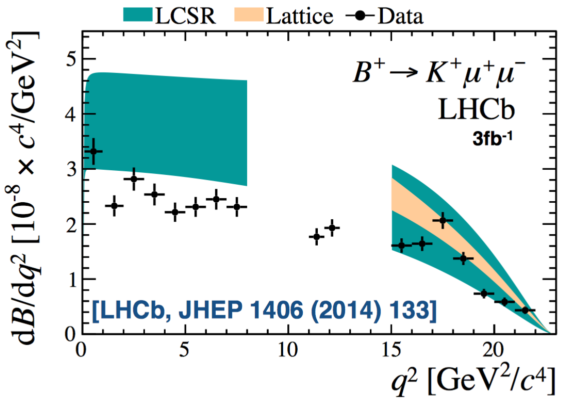
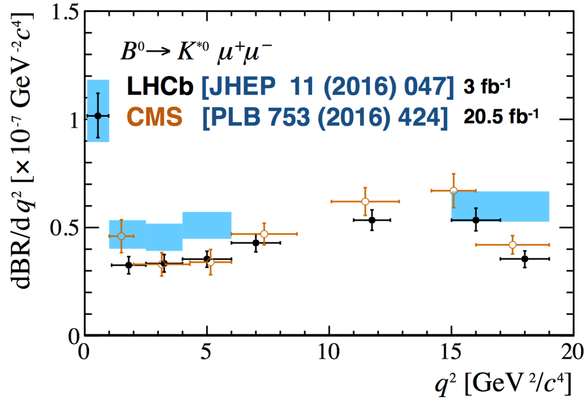
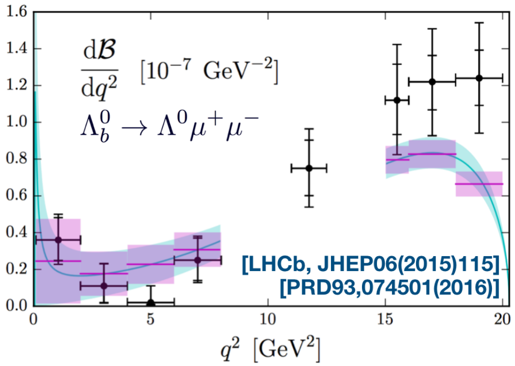
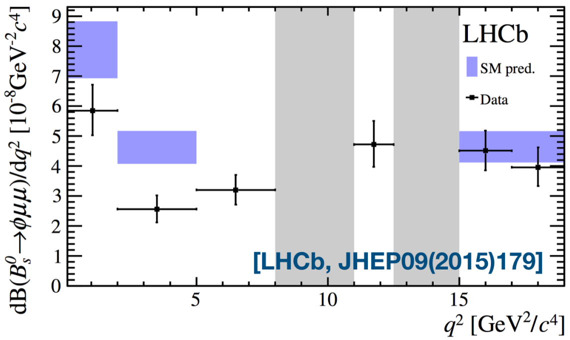
Branching fraction measurements

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





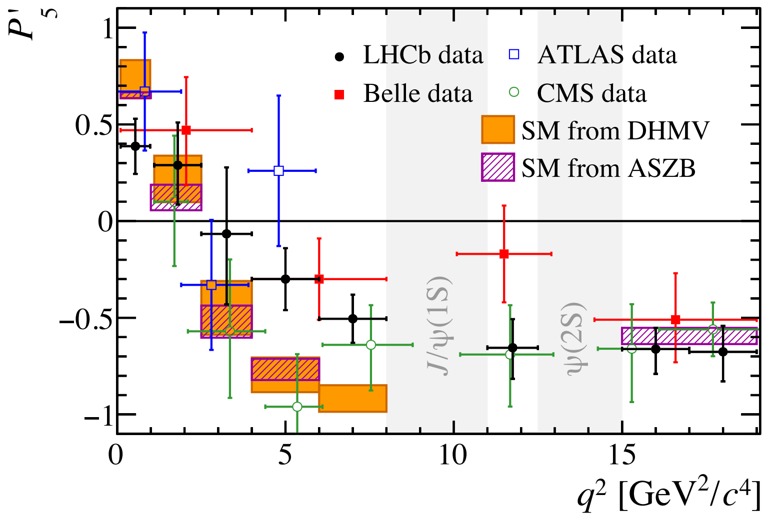




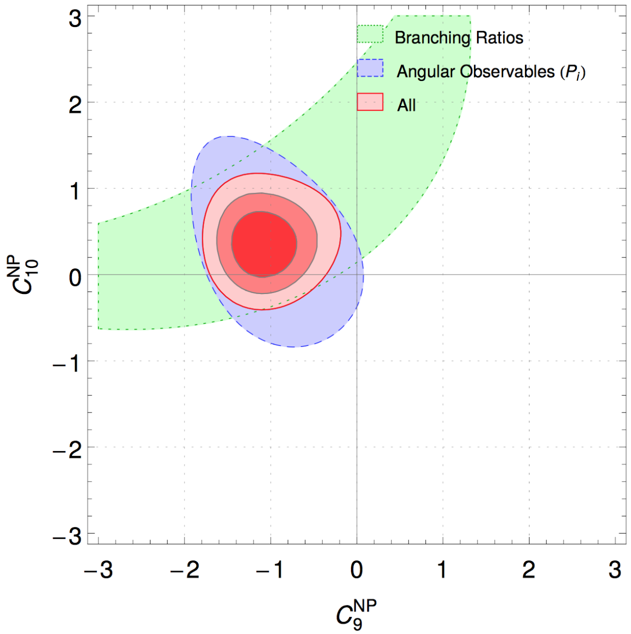
- SM predictions suffer from large uncertainties

Angular observables

- Angular observables have reduced dependence on hadronic effects and also show some tension with SM



[PLB 781 (2018) 517]
[JHEP 10 (2018) 047]
[PRL 118 (2017) 111801]
[JHEP 02 (2016) 104]



[JHEP06 (2016) 092]

- BF and angular data consistent, best fit prefers shifted vector coupling C_9 (or C_9 and axial-vector C_{10})
- … could QCD effects mimic vector-like NP ?

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Lepton flavour universality tests

- In the Standard Model, couplings of the gauge bosons to leptons are independent of lepton flavour

- Ratios of the form:

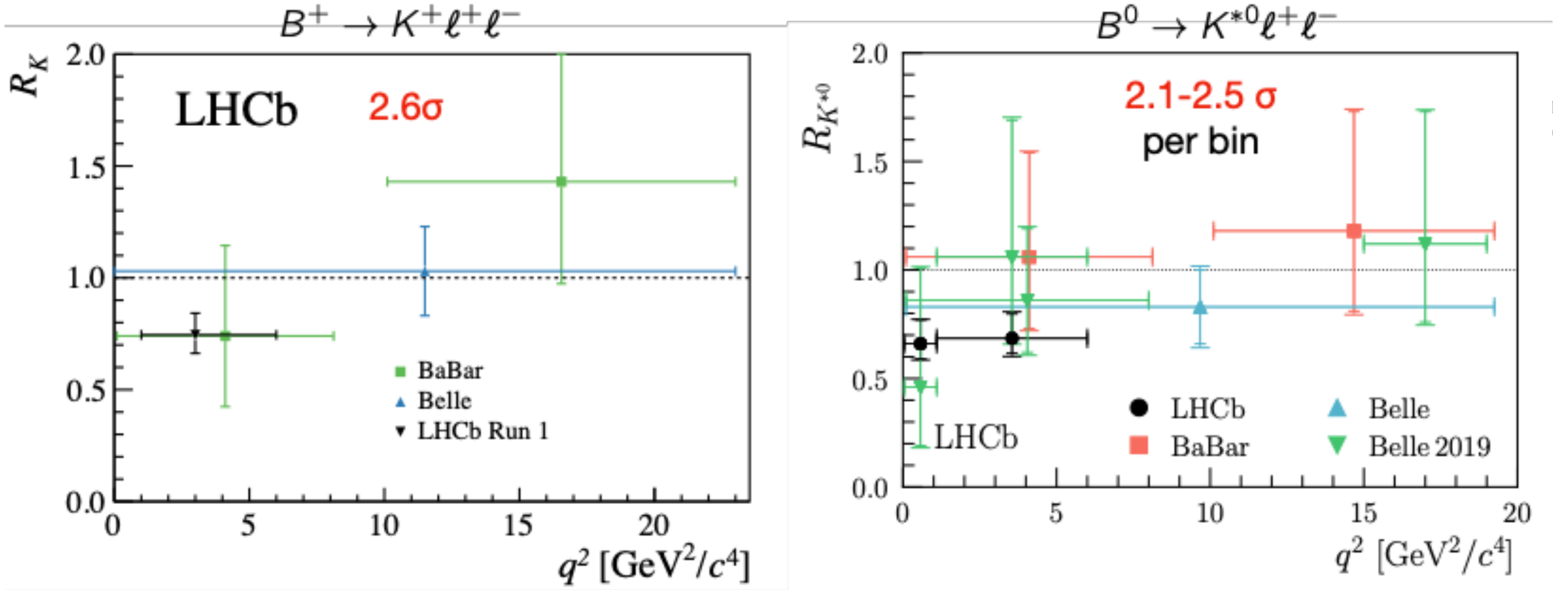
$$R_K = \frac{BR(B^+ \to K^+ \mu^+ \mu^-)}{BR(B^+ \to K^+ e^+ e^-)} \overset{\mathrm{SM}}{\cong} 1$$

  free from QCD uncertainties that affect other observables
  - hadronic effects cancel, error is $O(10^{-4})$ [JHEP 07 (2007) 040]
  - QED corrections can be $O(10^{-2})$ [EPJC 76 (2016) 440]

- Any sign of lepton flavour non-universality would be a direct sign for New Physics

Status of LFU tests

- With the Run 1 LHC data, intriguing picture:



[LHCb, PRL 113 (2014) 151601]
[LHCb, JHEP 08 (2017) 055]
[BaBar, PRD 86 (2012) 032012]
[Belle, PRL 103 (2009) 171801]
[Belle, arXiv:1904.02440]

- Both R_K and R_{K^*} results below the SM expectation, although significance low

- Tensions can be explained with anomalous $b \to s\mu\mu$ measurements in a coherent NP picture

Measuring R_K

- LHCb collaboration recently updated R_K measurement

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

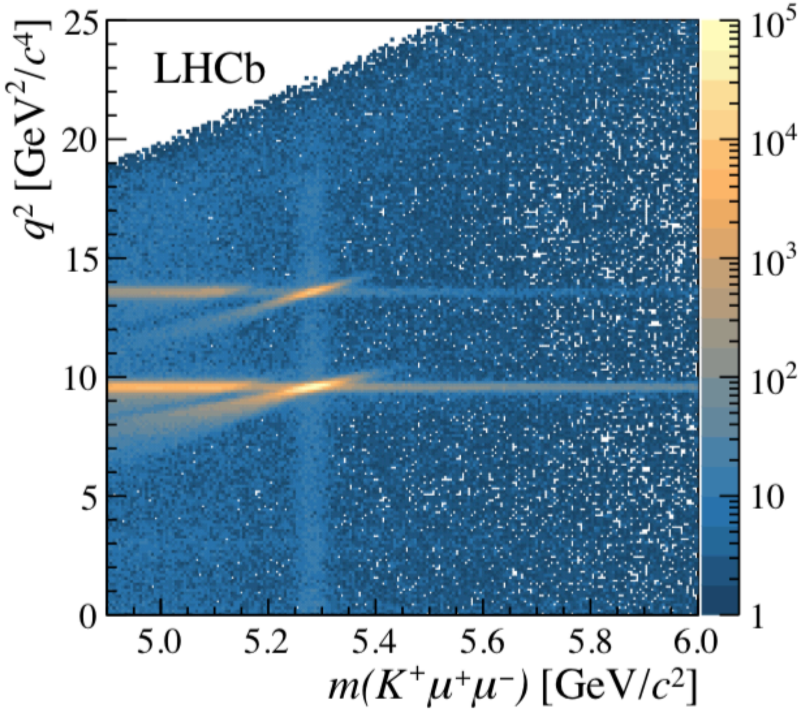
- Measurement performed in $1.1 < q^2 < 6.0\ \mathrm{GeV}^2/c^4$ on :
  - Reanalysed 2011 & 2012 data (3 fb^{-1}),
    → Improved reconstruction and re-optimised analysis strategy
  - Added 2015 and 2016 datasets (2 fb^{-1})
    → Larger $b\bar{b}$ cross-section due to higher $\sqrt{s}$

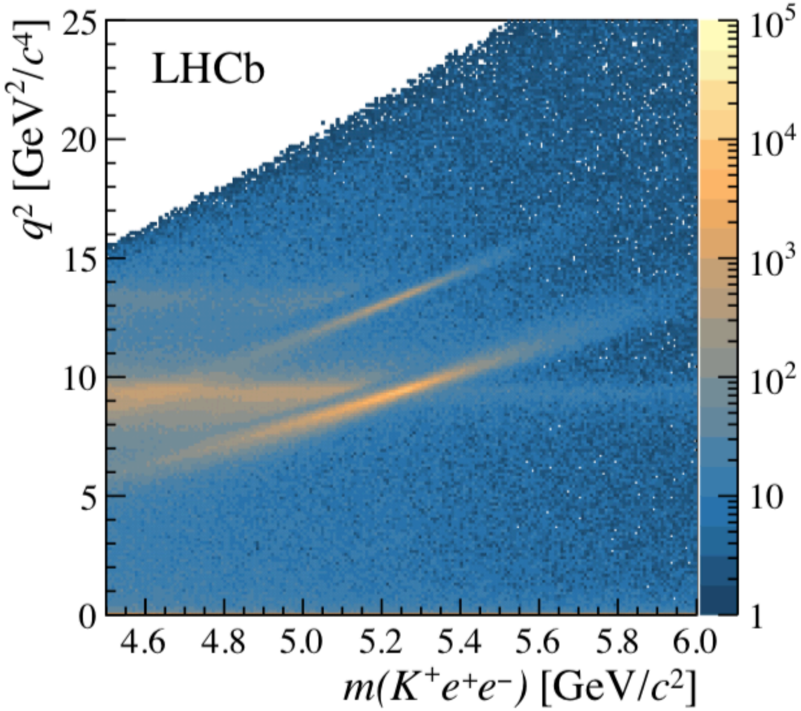
- In total, ~twice as many B's as previous analysis

The Experimental Challenge

- Electrons and muons behave very differently in LHCb due to larger Bremsstrahlung radiation for the electrons
  - Worse mass and q^2 resolution
  - Lower reconstruction efficiency

[LHCb-PAPER-2019-009]





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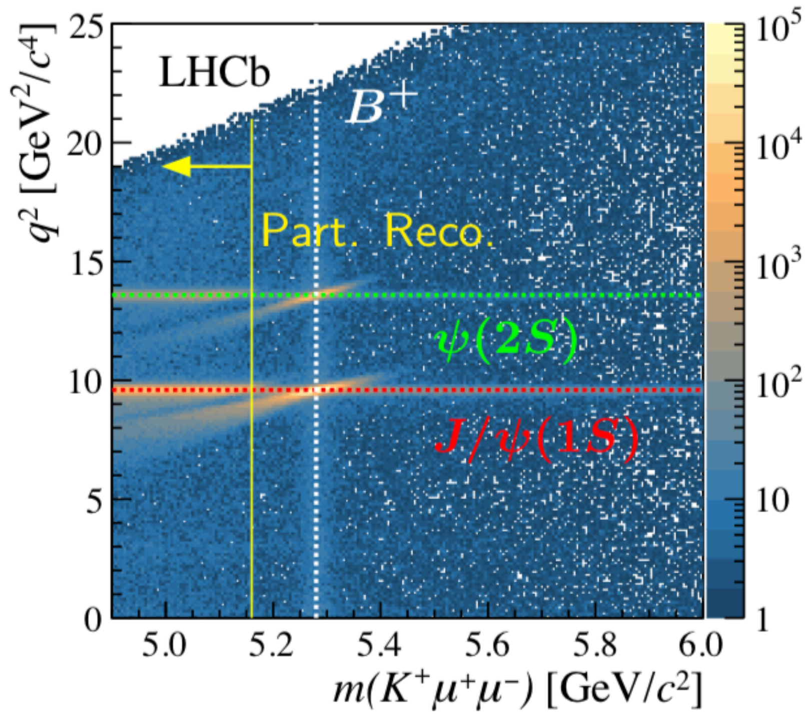
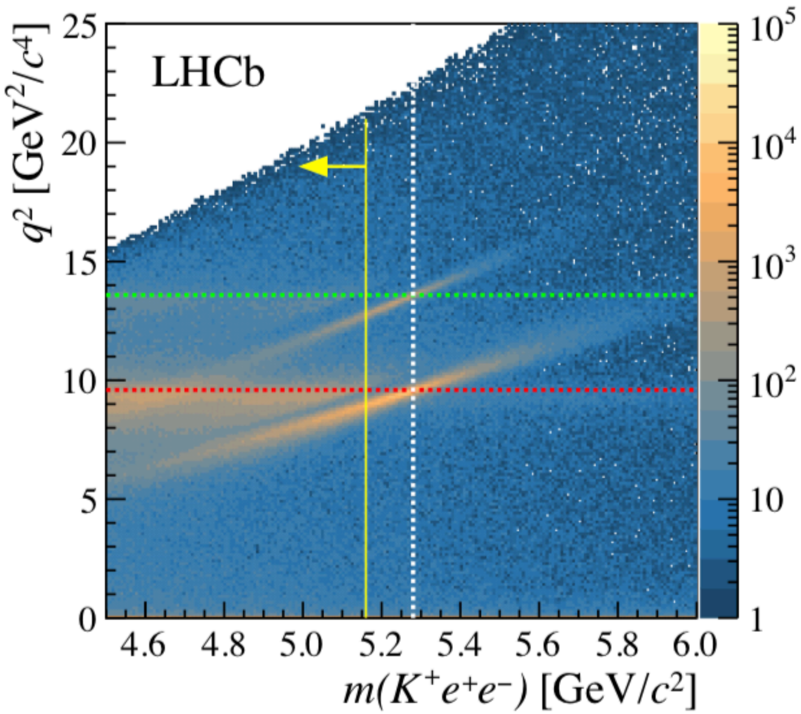




Strategy

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

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

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

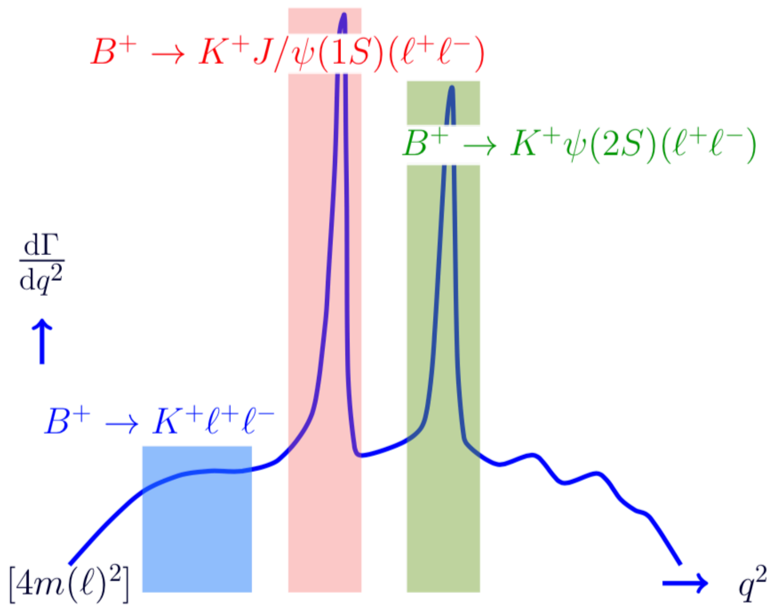
$$\times \frac{N(B^+ \to K^+J/\psi(e^+e^-))}{N(B^+ \to K^+e^+e^-)} \times \frac{\varepsilon_{B^+\to K^+e^+e^-}}{\varepsilon_{B^+\to K^+J/\psi(e^+e^-)}}$$

- 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

Calibrating the efficiencies

- Resonant and nonresonant decays are separated in q^2
  → However, good overlap between these decays in the variables relevant to the detector response

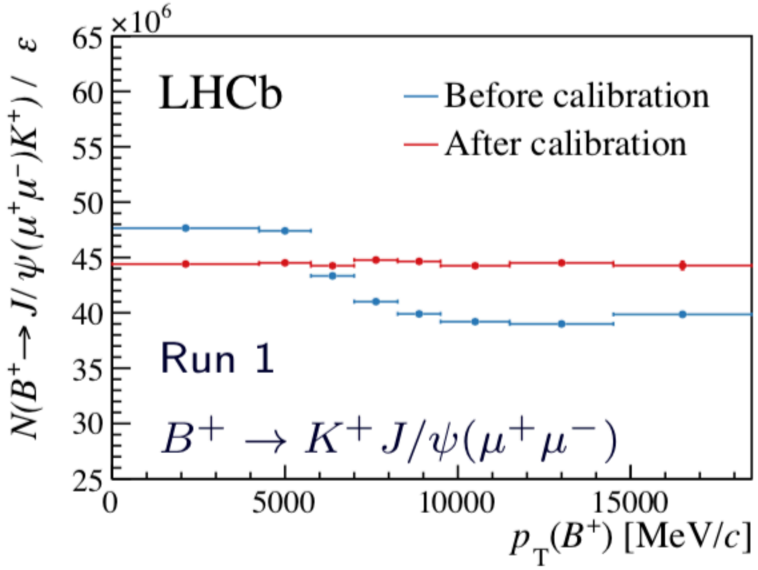
- Calibration makes extensive use of $B^+ \to K^+ J/\psi(l^+l^-)$ and $B^+ \to K^+\psi(2S)(l^+l^-)$

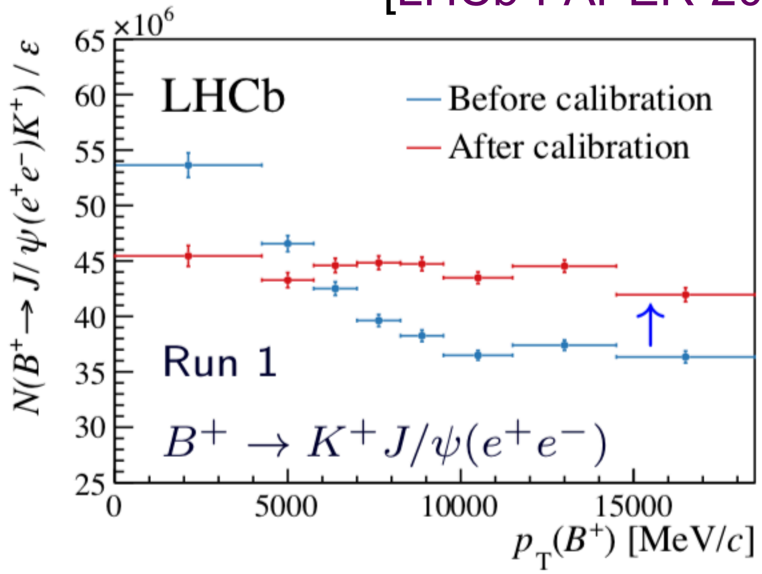


Calibrating the efficiencies

- After calibration, very good data/simulation agreement in all key observables

[LHCb-PAPER-2019-009]





Cross-checks: Measurement of $r_{J/\psi}$

- 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: [LHCb-PAPER-2019-009]

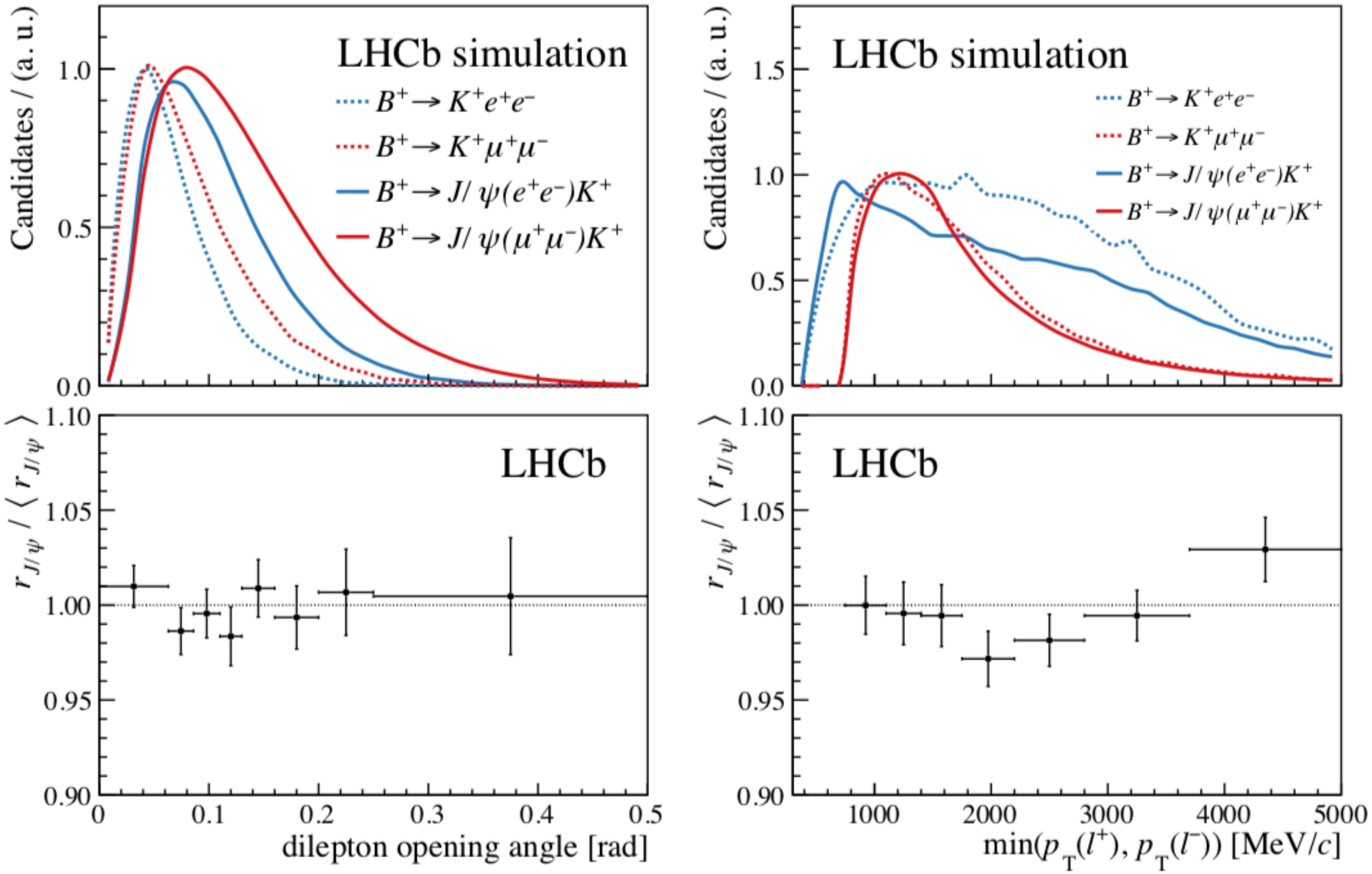
$$r_{J/\psi} = 1.014 \pm 0.035 \;(\mathrm{stat} + \mathrm{syst})$$

  Checked that the value of $r_{J/\psi}$ is compatible with unity for both Run 1 and Run 2 datasets, and in all trigger samples

Cross-checks: differential $r_{J/\psi}$

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

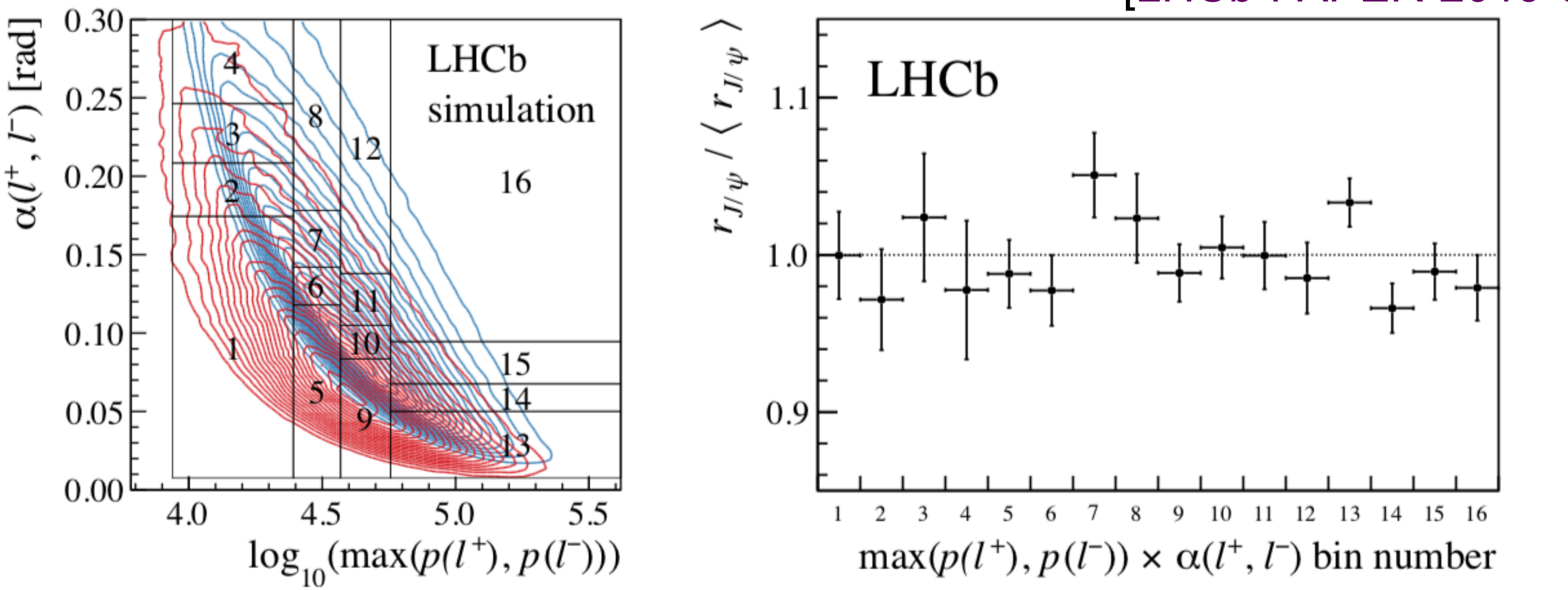
[LHCb-PAPER-2019-009]



Cross-checks: $r_{J/\psi}$ in 2d

- Repeat the exercise in 2D, to check for correlated effects
  - Choose q^2-dependent variables relevant for the detector response
  - Select $B^+ \to K^+ J/\psi(l^+l^-)$ events in bins of this 2D space and compute $r_{J/\psi}$ in each of them

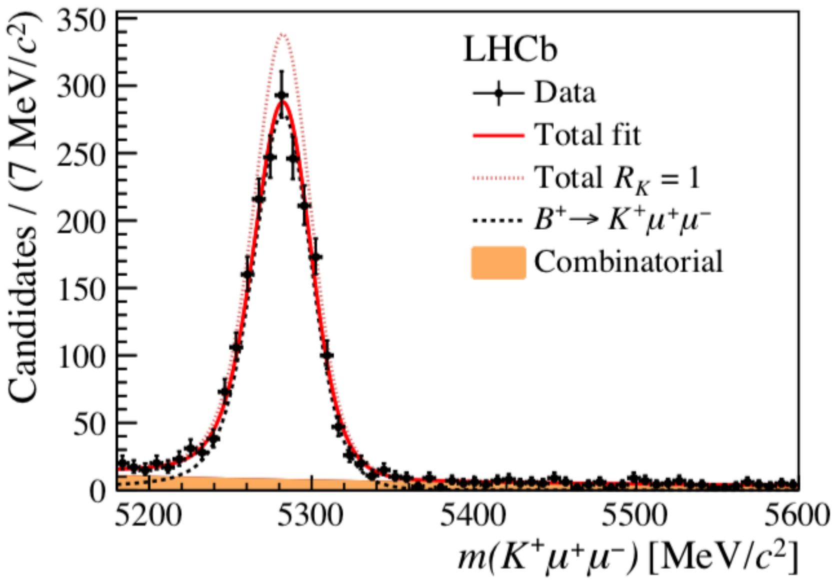
[LHCb-PAPER-2019-009]

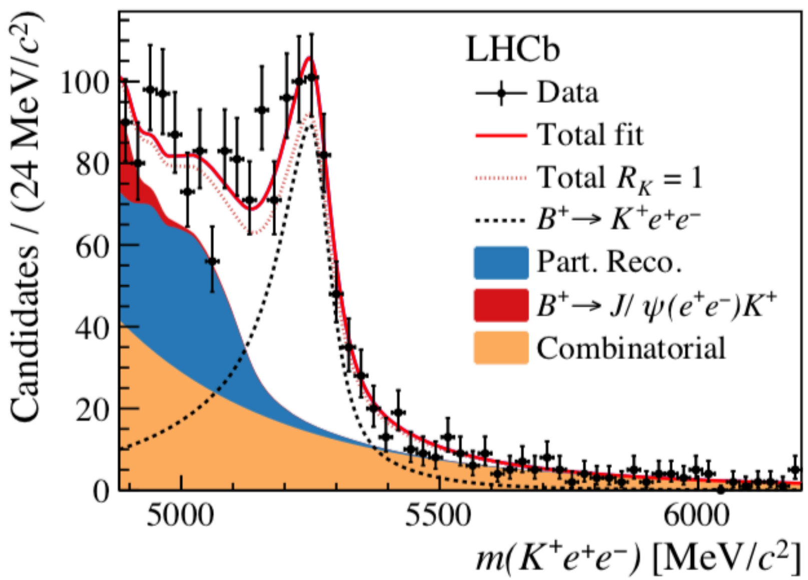


- Flatness gives confidence that understand efficiencies over entire phase space

R_K simultaneous fit

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





[LHCb-PAPER-2019-009]

R_K simultaneous fit

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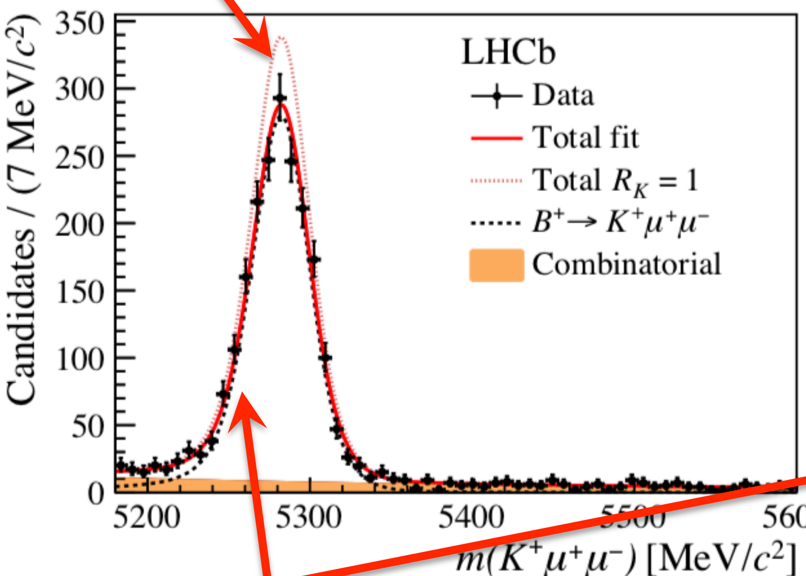
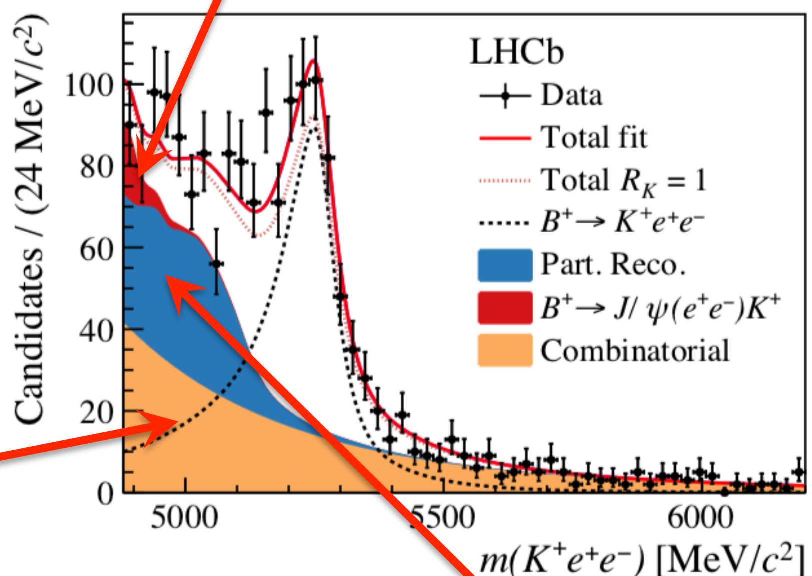
Expectation from observed $B^+\to K^+e^+e^-$ yield & R_K=1

Leakage from $B\to K^+J/\psi(ee)$ constrained from the fit to the resonant mode





[LHCb-PAPER-2019-009]

Different signal shape between muons and electrons:
- worse mass resolution (recovered γ)
- longer radiative tail (more Bremsstrahlung)

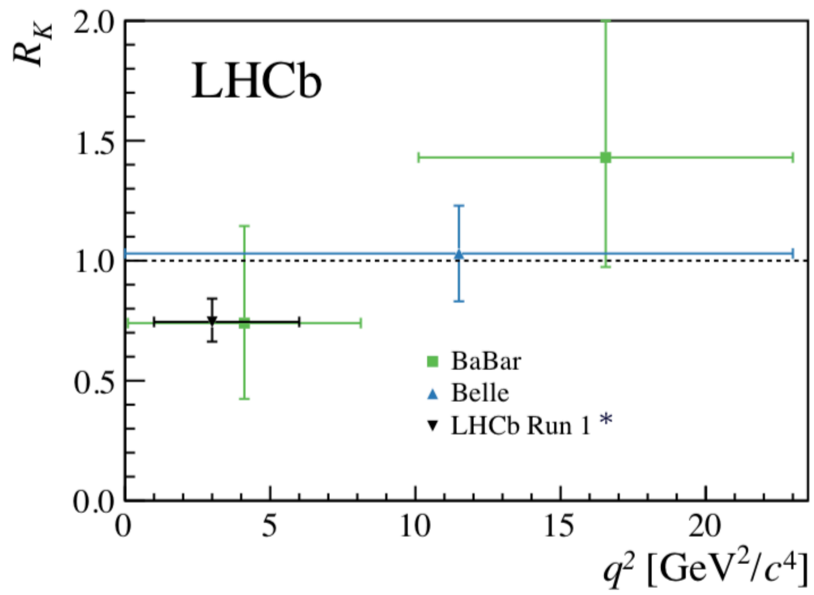
Partially reconstructed background, mainly $B^0\to K^{*0}e^+e^-$

Updated R_K measurement

- Using 2011 and 2012 data:

$$R_K = 0.745 \,^{+0.090}_{-0.074}\,(\text{stat}) \,\pm 0.036\,(\text{syst})$$

compatible with the SM expectation at 2.6σ



[LHCb, PRL 113 (2014) 151601]
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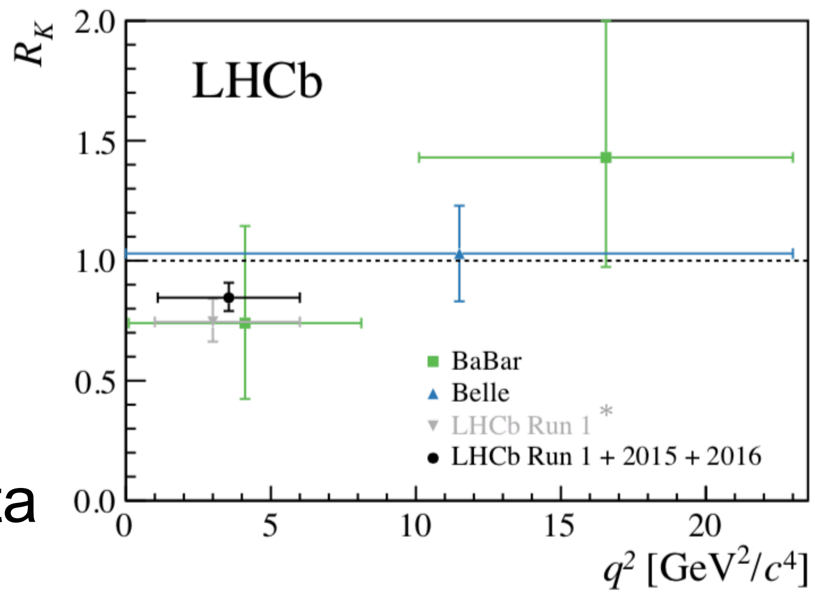
$$R_K = 0.745\ ^{+0.090}_{-0.074}\ (\text{stat})\ \pm 0.036\ (\text{syst})$$

compatible with the SM expectation at 2.6σ

- Reanalysing the 2011-2012 data and adding 2015 and 2016,

$$R_K = 0.846\ ^{+0.060}_{-0.054}\ (\text{stat})\ ^{+0.014}_{-0.016}\ (\text{syst})$$

compatible with the SM expectation at 2.5σ

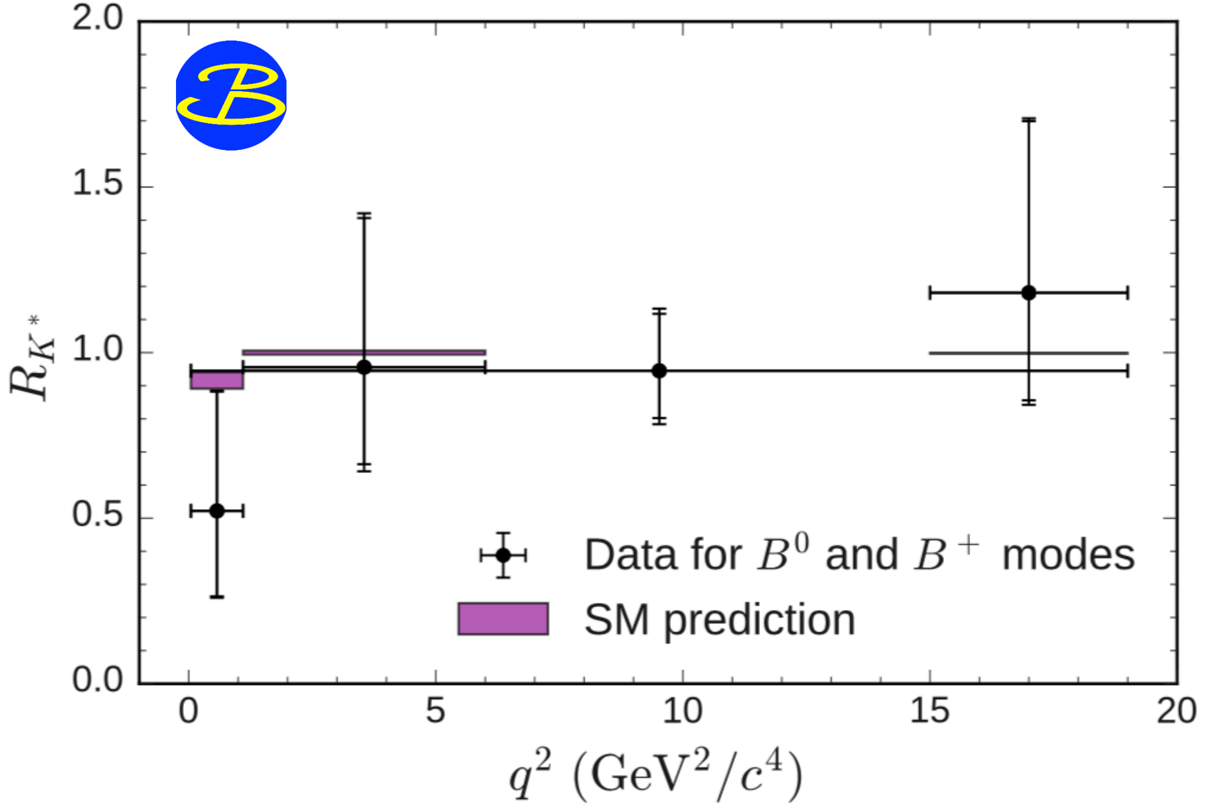


[LHCb-PAPER-2019-009]
[LHCb, PRL 113 (2014) 151601]
[BaBar, PRD 86 (2012) 032012]
[Belle, PRL 103 (2009) 171801]

Belle R_{K^*} measurement

- Belle recently updated the measurement of R_{K^*}

[arXiv:1904.02440]



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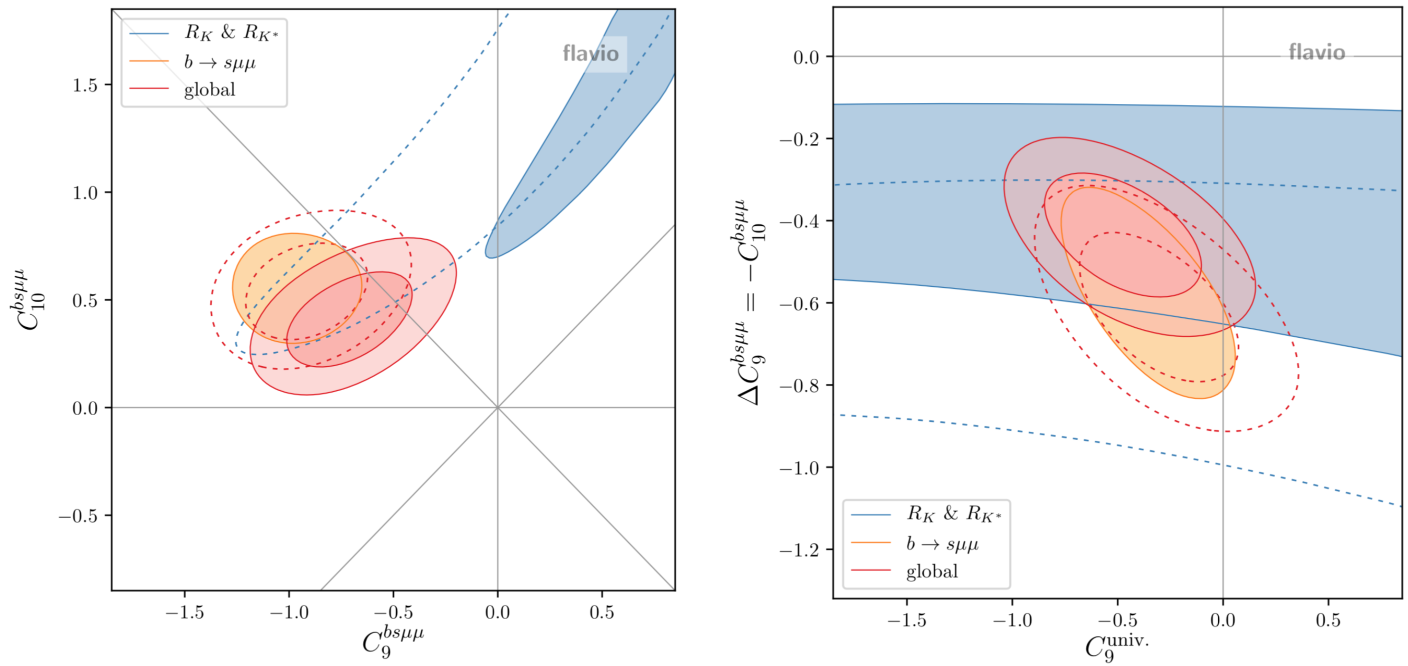
- **Impact on global picture**
- Future prospects

Impact on global fits



[arXiv:1903.10434]

- Best fit point still in tension with the SM
  Compatibility between $R_K^{(*)}$, $b \to s\mu^+\mu^-$ observables worse
- Muonic NP: best fit closer to the SM, $C_9 = -C_{10}$ still preferred
- Adding LFU NP: Slight preference for universal shift in C_9

[M. Alguero et al., arXiv:1903.09578, A. K. Alok et al., arXiv:1903.09617, M. Ciuchini et al., arXiv:1903.09632, Guido D'Amico et al., arXiv:1704.05438]

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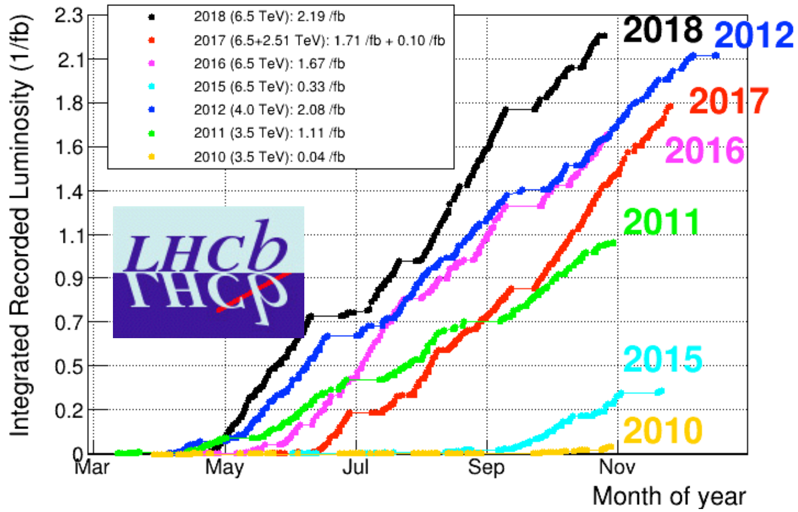
Future experimental input

- LHCb data from 2017,18 will effectively double the existing dataset
  - Improved and additional LFU analyses
  - Updated angular observables



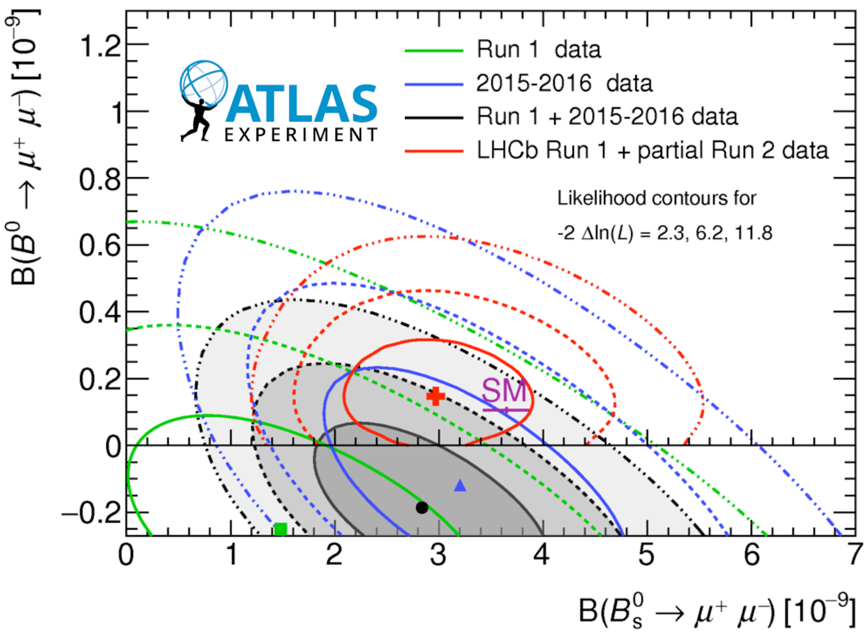
- CMS has collected a sample of 10^{10} B decays
  - With an effective low p_T electron reconstruction, should get a very competitive number of e.g. $B^+ \to K^+e^+e^-$ signal candidates
  - Expect systematics will be very different to those at LHCb e.g. no trigger effect and very different material distribution

ATLAS pursuing similar strategy

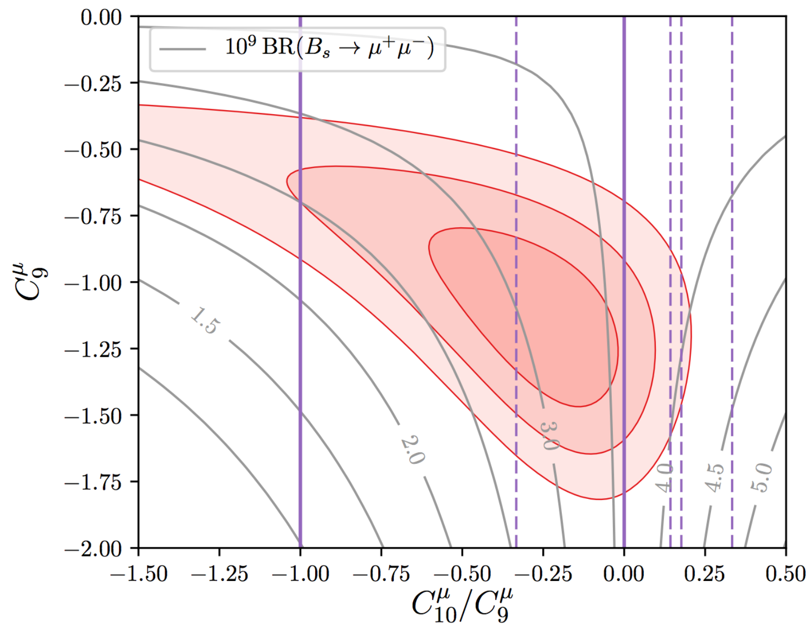
- Belle2 data-taking starting in earnest

Connection to leptonic decays

- Can explain anomalies with **$C_9^{NP} = -C_{10}^{NP}$**
- Would then expect to see an effect in $B(B^0_s \rightarrow \mu^+\mu^-)$ decays
- No evidence for any deviation from SM so far…



[JHEP 04 (2019) 098]

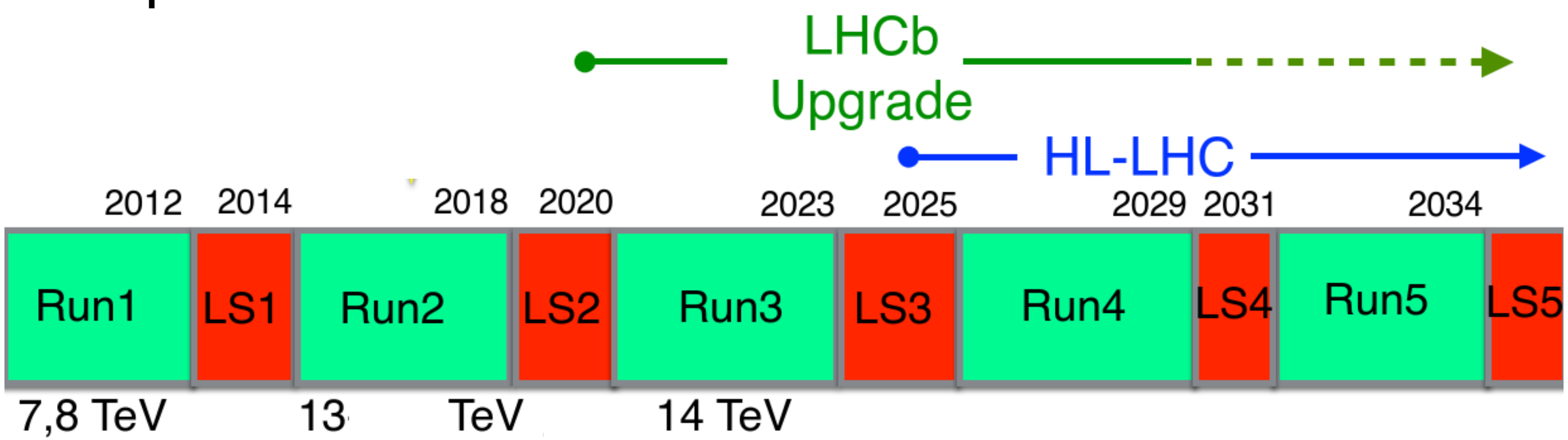


[PRD 96 (2017) 055008]

Further into the future

- Are presently installing upgraded LHCb detector which from 2021-2030 will allow ~25 fb^{-1} to be accumulated

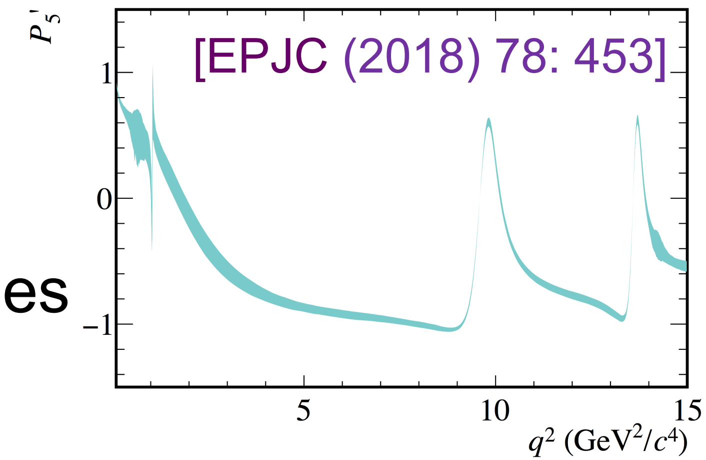
- On same timescale, Belle2 will accumulate significant sample of data



- Further "phase-II" upgrade to LHCb approved to prepare TDRs by CERN research board – target 300 fb^{-1} using $L_{inst}=2x10^{34}\ cm^{-2}s^{-1}$

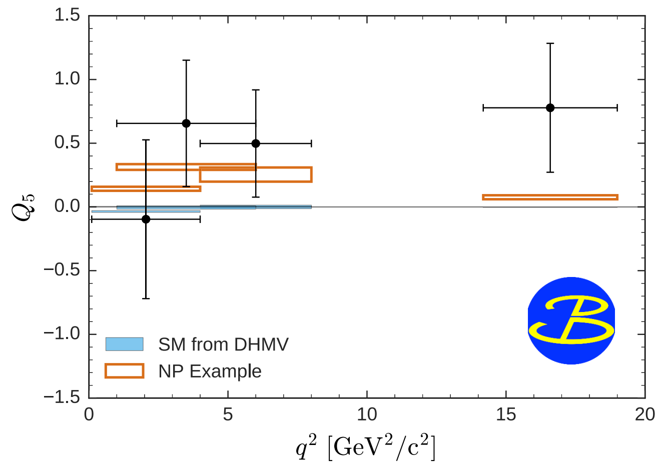
Analyses with upgrade datasets

- Parametric treatment of form-factors in angular observables



- Difference between angular observables e.g. $P_5'(\mu)$ and $P_5'(e)$ $\rightarrow$ Q_5

- Need to drive systematics in electron analyses down to ~1% level
  - Present largest systematics will scale with lumi but will need to control subdominant sources



[PRL 118 (2017) 111801]

- CKM suppressed b→d transitions in similar numbers to existing b→s samples

Conclusions

- Intriguing anomalies seen in neutral current B decays
  - Branching fractions
  - Angular observables

  but debate about control of theory uncertainties

- Lepton universality tests can give theoretically clean input
  - Latest measurements yet to provide a definitive picture

- Good prospects for resolution with new measurements