

Flavour Anomalies in Rare Decays at LHCb

Miguel Ramos Pernas
on behalf of the LHCb collaboration

Universidade de Santiago de Compostela

miguel.ramos.pernas@cern.ch

SUSY 2018

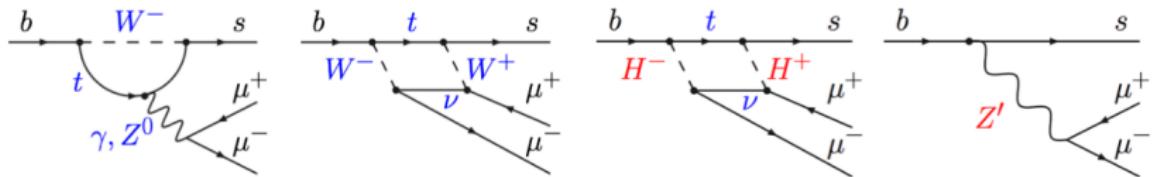
Barcelona, July 23, 2018



European Research Council
Established by the European Commission

Covered in this talk

$b \rightarrow s\ell^+\ell^-$ transitions, where only loop-level diagrams are allowed in the SM:



1) Rates and angular observables in $b \rightarrow s\mu^+\mu^-$:

$$B^0 \rightarrow K^{*0} \mu^+ \mu^-$$

$$B^+ \rightarrow K^{*+} \mu^+ \mu^-$$

$$B^0 \rightarrow K^0 \mu^+ \mu^-$$

$$B^+ \rightarrow K^+ \mu^+ \mu^-$$

$$\Lambda_b^0 \rightarrow \Lambda^0 \mu^+ \mu^-$$

$$B_s^0 \rightarrow \phi \mu^+ \mu^-$$

2) Lepton Flavour Universality (LFU) tests in μ/e ratios:

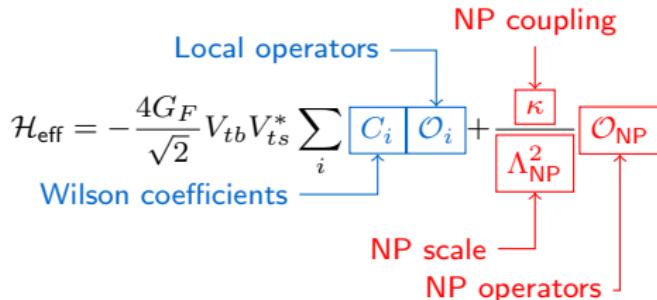
$$\bullet R_K \propto \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)}$$

$$\bullet R_{K^{*0}} \propto \frac{\mathcal{B}(B^0 \rightarrow K^{*0} \mu^+ \mu^-)}{\mathcal{B}(B^0 \rightarrow K^{*0} e^+ e^-)}$$

Most of the results were obtained with the full Run-I LHCb sample (3 fb^{-1}).

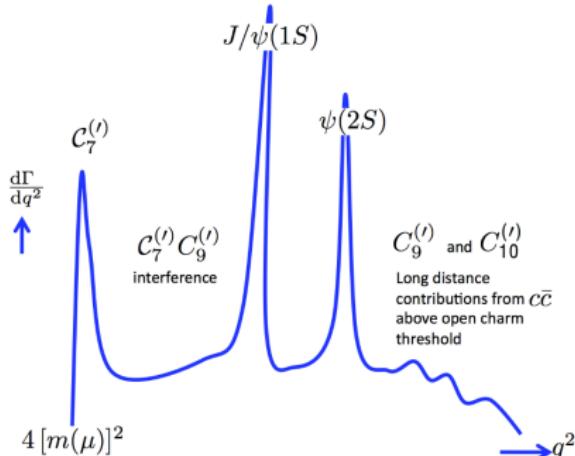
Measurements in $b \rightarrow s\ell^+\ell^-$ transitions

- Interpretation in effective field theory, in terms of



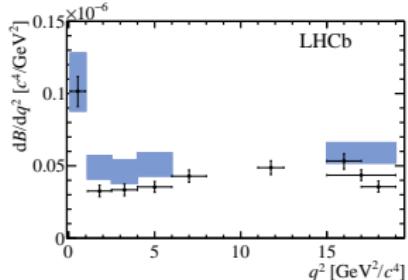
- Scape from the $c\bar{c}$ resonant region of the $\mu^+\mu^-$ spectrum, where hadronic processes dominate (non-factorizable QCD).

- Many different decay channels studied $B \rightarrow K\mu^+\mu^-$, $B \rightarrow K^*\mu^+\mu^-$, $B_s^0 \rightarrow \phi\mu^+\mu^-$ and $\Lambda_b^0 \rightarrow \Lambda^0\mu^+\mu^-$.
- Clear normalization and control channel using the J/ψ modes.
- Preference for the low q^2 region (less affected from $c\bar{c}$ resonances).

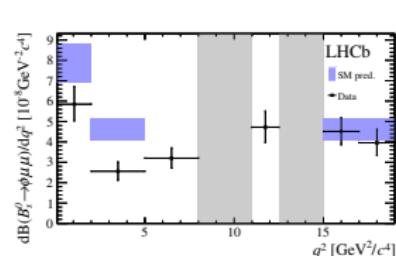


Branching fraction measurements in $b \rightarrow s\mu^+\mu^-$ transitions

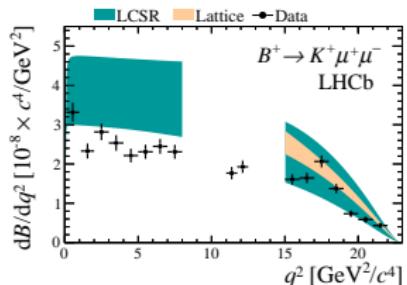
$B^0 \rightarrow K^{*0}\mu^+\mu^-$ [JHEP 1406 (2014) 133]



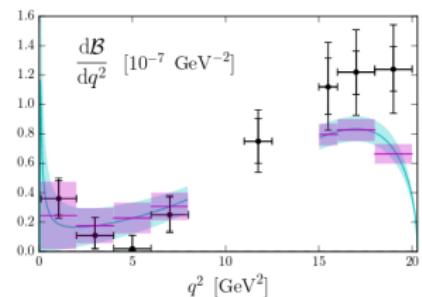
$B_s^0 \rightarrow \phi\mu^+\mu^-$ [JHEP 09 (2015) 179]



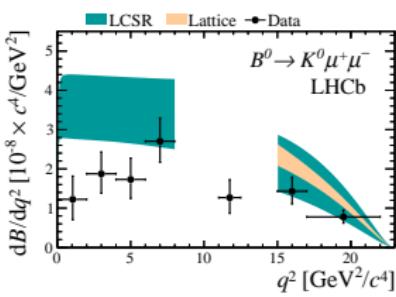
$B^+ \rightarrow K^+\mu^+\mu^-$ [JHEP 1406 (2014) 133]



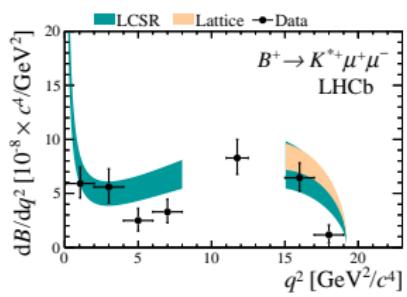
$\Lambda_b^0 \rightarrow \Lambda^0\mu^+\mu^-$ [JHEP 06 (2015) 115]
[PRD 93 (2016) 074501]



$B^0 \rightarrow K^0\mu^+\mu^-$ [JHEP 1406 (2014) 133]

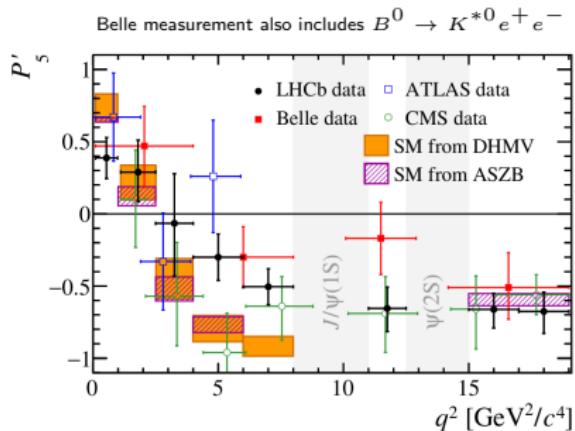
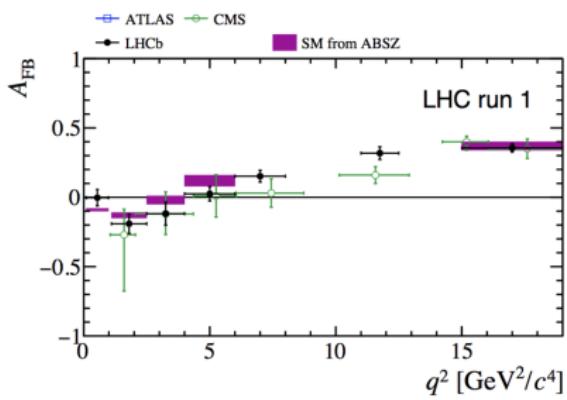


$B^+ \rightarrow K^+\mu^+\mu^-$ [JHEP 1406 (2014) 133]



- Systematically below the standard model prediction.
- Tensions at $1 - 3\sigma$, but sizeable hadronic uncertainties.

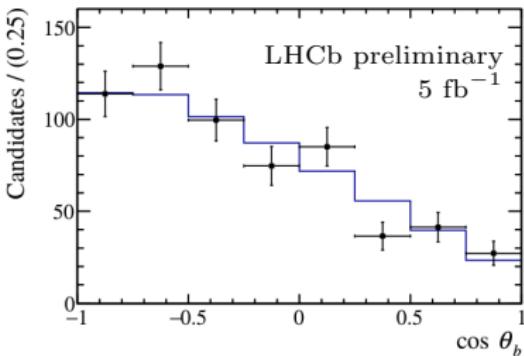
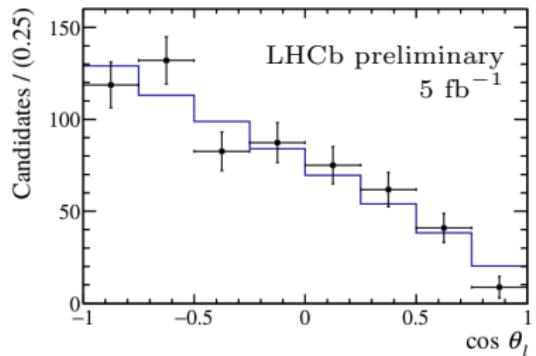
Angular observables in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$



- Rich angular structure in $b \rightarrow s\ell^+\ell^-$ transitions.
- Interest on quantities less dependent on the form-factors, like $P'_5 \equiv S_5 / \sqrt{F_L(1 - F_L)}$.
- Good agreement with the SM in many of the observables.
- Deviations in P'_5 (3.4σ LHCb only), where the sensitivity is dominated by LHCb.
- Measurements by LHCb [[JHEP 02 \(2016\) 104](#)], Belle [[arXiv:1612.05014 \(submitted to PRL\)](#)], CMS [[CMS-PAS-BPH-15-008](#)] and ATLAS [[arXiv:1805.04000](#)], affected by different systematics.

Other angular analyses in $b \rightarrow s\mu^+\mu^-$ decays

- $B_s^0 \rightarrow \phi\mu^+\mu^-$
 - Angular observables in agreement with the SM [[JHEP 09 \(2015\) 179](#)].
 - P'_5 can not be calculated (not self-tagged).
- $\Lambda_b^0 \rightarrow \Lambda^0\mu^+\mu^-$



[LHCb-PAPER-2018-029]

Asymmetries (preliminary results, erratum for [[JHEP 06 \(2015\) 115](#)]):

$$A_{FB}^\ell = -0.39 \pm 0.04 \text{ (stat)} \pm 0.01 \text{ (syst)}$$

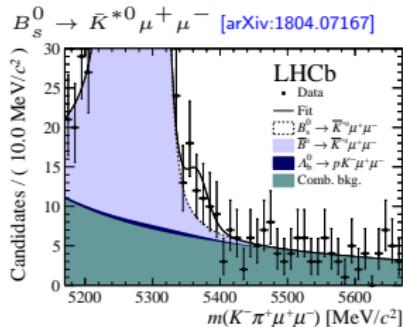
$$A_{FB}^h = -0.30 \pm 0.05 \text{ (stat)} \pm 0.02 \text{ (syst)}$$

$$A_{FB}^{\ell h} = +0.25 \pm 0.04 \text{ (stat)} \pm 0.01 \text{ (syst)}$$

Small difference with the standard model $\sim 2\sigma$

Results on $b \rightarrow d\ell^+\ell^-$

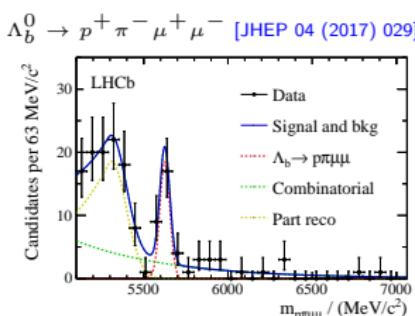
- If no distinction is done by the NP particles between s and d quarks, we must see deviations in $b \rightarrow d\ell^+\ell^-$ transitions too.
- Cabibbo suppressed mode, ~ 25 times smaller BR than $b \rightarrow s\ell^+\ell^-$ transitions.
- Allows for measuring V_{td}/V_{ts} , to constrain the Minimal Flavour Violation hypothesis.



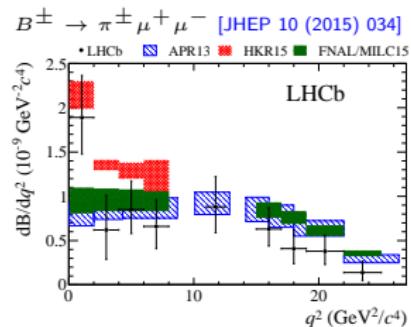
Equivalent to $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

First evidence 3.4σ with 5 fb^{-1}

$$\mathcal{B} = (2.9 \pm 1.0 \pm 0.2 \pm 0.3) \times 10^{-8}$$

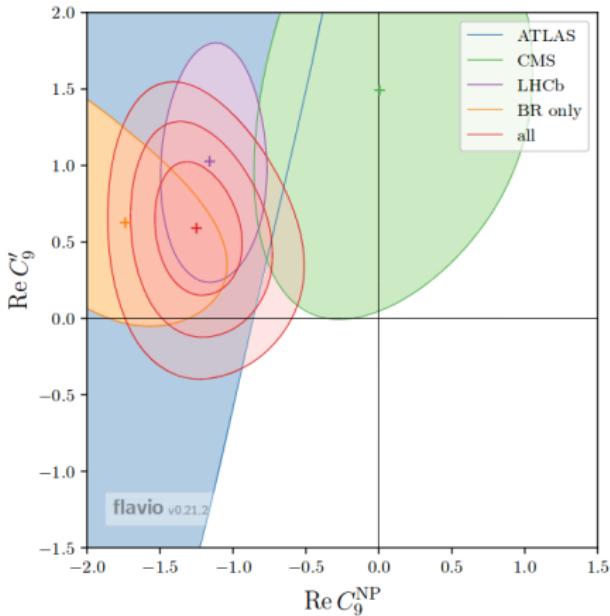
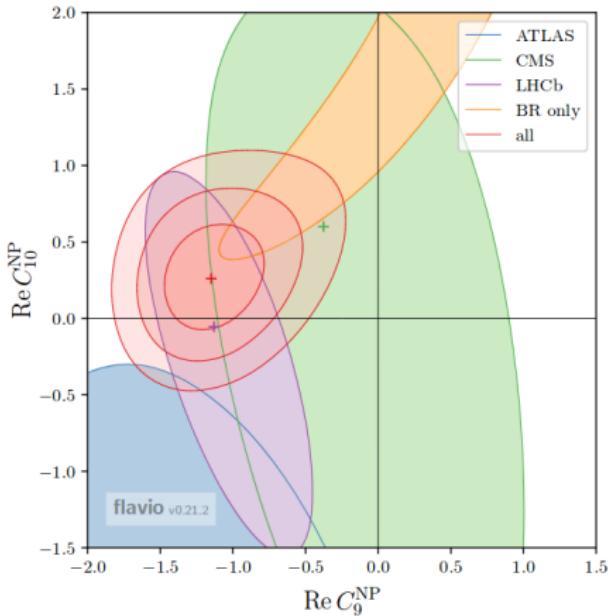


$$\mathcal{B} = (6.9 \pm 1.9 \pm 1.1 \pm 1.3) \times 10^{-8}$$



$$\mathcal{B} = (1.83 \pm 0.24 \pm 0.05) \times 10^{-8}$$

The global fit to the $b \rightarrow s\mu^+\mu^-$ observables



[EPJC 77 (2017) 377]

- Consistency between the measurements of branching fractions and angular observables.
- Best fit preferring a shift in C_9^{NP} or $C_9^{\text{NP}} = -C_{10}^{\text{NP}}$.

LFU in $R_{K^{*0}/K}$

Motivation:

- Universal coupling of the gauge bosons to leptons in the SM.
- In the SM, branching fractions in $b \rightarrow q\ell^+\ell^-$ transitions differ depending on the lepton mass (affecting phase-space and helicity).
- Any sign of lepton flavour non-universality would be a direct sign of NP.

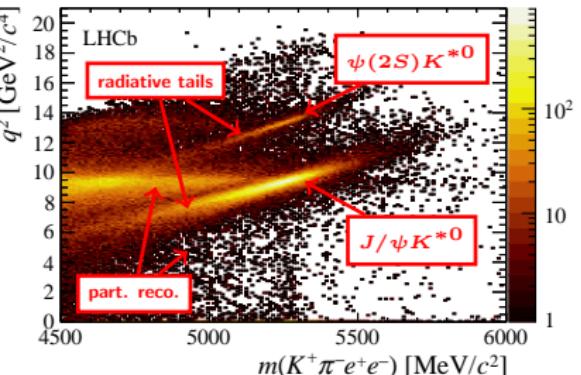
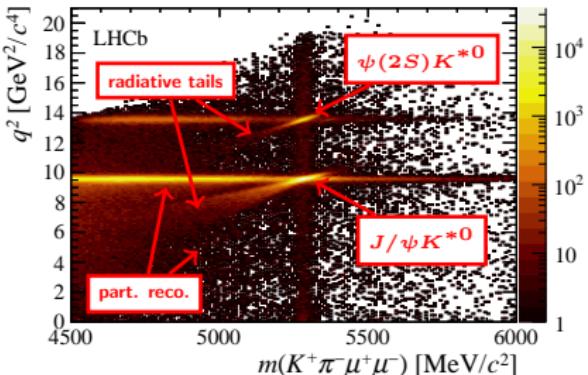
Aim to study the double ratios:

$$R_{K^{*0}} \equiv \frac{\mathcal{B}(B^0 \rightarrow K^{*0}\mu^+\mu^-) / \mathcal{B}(B^0 \rightarrow K^{*0}J/\psi(\rightarrow \mu^+\mu^-))}{\mathcal{B}(B^0 \rightarrow K^{*0}e^+e^-) / \mathcal{B}(B^0 \rightarrow K^{*0}J/\psi(\rightarrow e^+e^-))}$$
$$R_K \equiv \frac{\mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-) / \mathcal{B}(B^+ \rightarrow K^+J/\psi(\rightarrow \mu^+\mu^-))}{\mathcal{B}(B^+ \rightarrow K^+e^+e^-) / \mathcal{B}(B^+ \rightarrow K^+J/\psi(\rightarrow e^+e^-))}$$

The $R_{K^{*0}/K}$ measurements profit from:

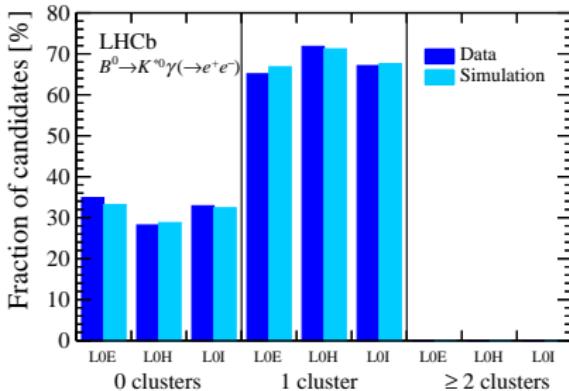
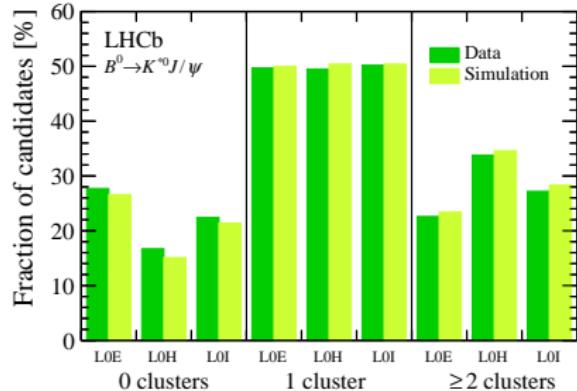
- ① Double ratio μ/e allows to get rid of QCD uncertainties and some experimental systematics.
- ② Sensitivity to high masses of NP particles (indirect search).
- ③ $B^0 \rightarrow K^{*0}J/\psi$ and $B^+ \rightarrow K^+J/\psi$ serve as normalization and control modes.

Electrons, the experimental challenge



[JHEP 08 (2017) 055]

- Big differences between electrons and muons.
- Bremsstrahlung strongly affects the resolution.
- Less efficient trigger for electrons.
- Use as control channels modes involving J/ψ , $\psi(2S)$ and γ .



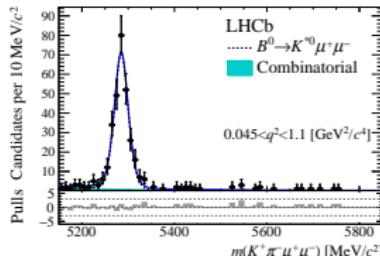
- Use $B^0 \rightarrow K^{*0} J/\psi(\rightarrow e^+ e^-)$ and $B^0 \rightarrow K^{*0} \gamma(\rightarrow e^+ e^-)$ to calculate efficiency corrections.
- Crosschecks with $R_{J/\psi}$ and $R_{\psi(2S)}$ compatible with unity:

$$R_{J/\psi} \equiv \frac{\mathcal{B}(B^0 \rightarrow K^{*0} J/\psi(\rightarrow \mu^+ \mu^-))}{\mathcal{B}(B^0 \rightarrow K^{*0} J/\psi(\rightarrow e^+ e^-))}$$

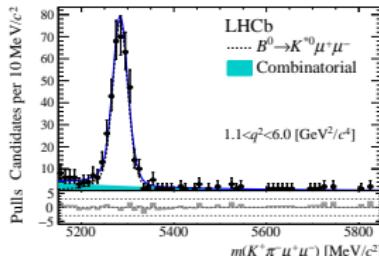
$$R_{\psi(2S)} \equiv \frac{\mathcal{B}(B^0 \rightarrow K^{*0} \psi(2S)(\rightarrow \mu^+ \mu^-)) / \mathcal{B}(B^0 \rightarrow K^{*0} J/\psi(\rightarrow \mu^+ \mu^-))}{\mathcal{B}(B^0 \rightarrow K^{*0} \psi(2S)(\rightarrow e^+ e^-)) / \mathcal{B}(B^0 \rightarrow K^{*0} J/\psi(\rightarrow e^+ e^-))}$$

$B^0 \rightarrow K^{*0} \ell^+ \ell^-$ mass fits

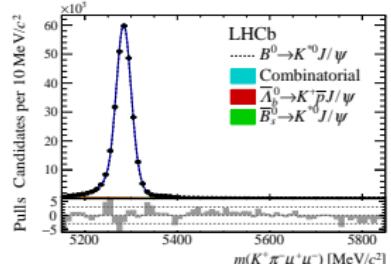
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$



Low q^2 : 285 ± 18

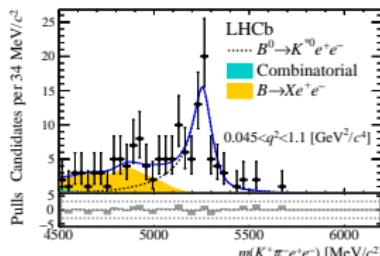


Central q^2 : 353 ± 21

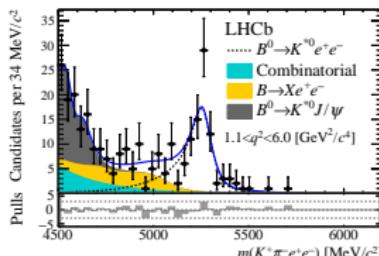


J/ψ : $274k$

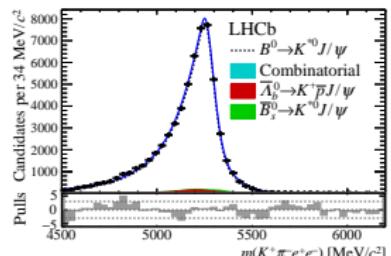
$B^0 \rightarrow K^{*0} e^+ e^-$



Low q^2 : 89 ± 11



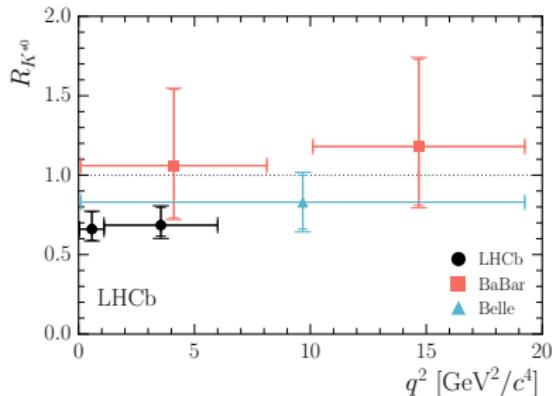
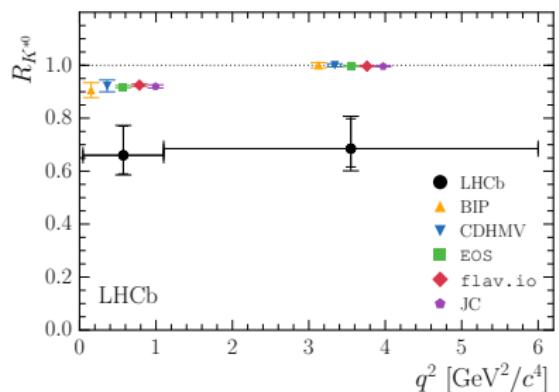
Central q^2 : 111 ± 14



J/ψ : $58k$

[JHEP 08 (2017) 055]

$B^0 \rightarrow K^{*0} \ell^+ \ell^-$, the anomaly

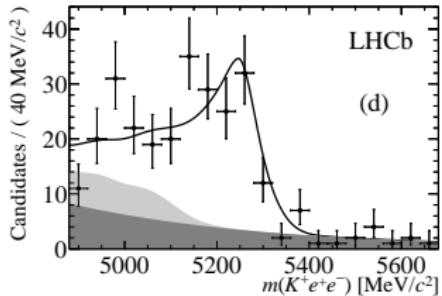
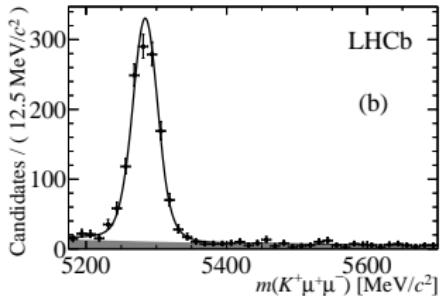


$$R_{K^{*0}} = \begin{cases} 0.66_{-0.07}^{+0.11}(\text{stat}) \pm 0.03(\text{syst}) & \text{for } 0.045 < q^2 < 1.1 \text{ GeV}^2/c^4 \\ 0.69_{-0.07}^{+0.11}(\text{stat}) \pm 0.05(\text{syst}) & \text{for } 1.1 < q^2 < 6.0 \text{ GeV}^2/c^4 \end{cases}$$

- Systematically $\sim 2\sigma$ below predictions.
- Largest theoretical uncertainty coming from QED corrections $\sim 1\%$ [[EPJC 76 \(2016\) 8,440](#)].
- Low- q^2 bin is slightly inconsistent with most popular NP scenarios.
- Compatible with BaBar [[PRD 86 \(2012\) 032012](#)] and Belle [[PRL 103 \(2009\) 171801](#)] measurements.

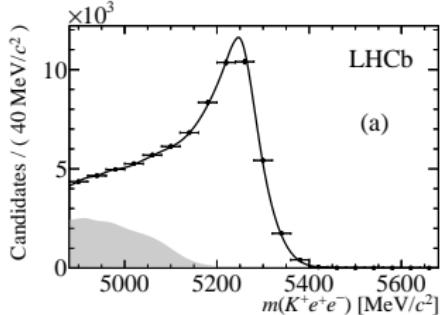
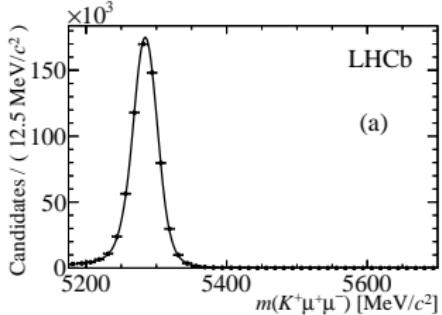
$B^+ \rightarrow K^+ \ell^+ \ell^-$

- Earlier measurement of R_K for $1 < q^2 < 6 \text{ GeV}^2/c^4$.



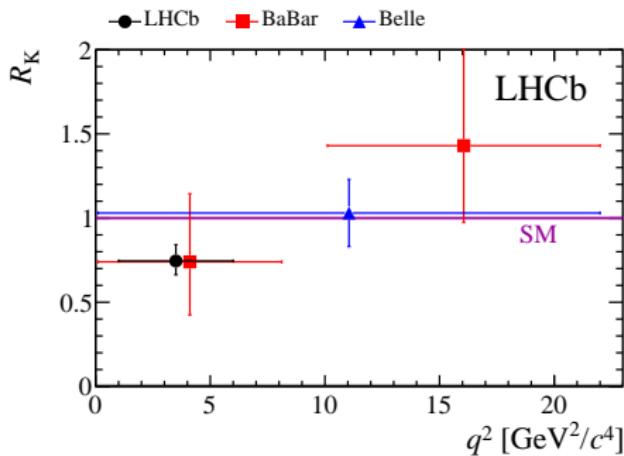
[PRL 113 (2014) 151601]

- Similar to $R_{K^{*0}}$, using $B^+ \rightarrow K^+ J/\psi$ as normalization and control channel.



[PRL 113 (2014) 151601]

$B^+ \rightarrow K^+ \ell^+ \ell^-$, the anomaly



LHCb: [PRL 113 (2014) 151601]

BaBar: [PRD 86 (2012) 032012]

Belle: [PRL 103 (2009) 171801]

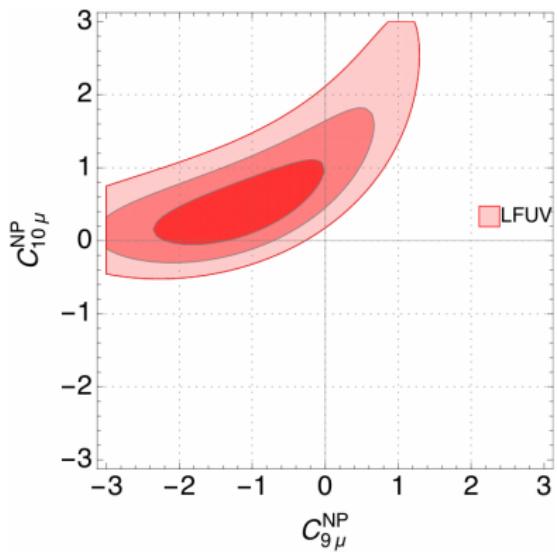
- Most precise measurement to date [PRL 113 (2014) 151601]:

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

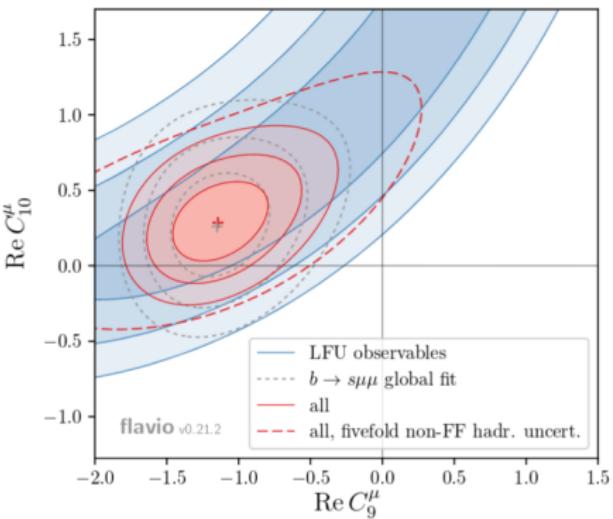
- 2.6σ below SM prediction $R_K^{\text{SM}} = 1 \pm \mathcal{O}(10^{-2})$ (QED corrections) [JHEP 12 (2007) 040] [PRL 11 (2013) 162002] [EPJC 76 (2016) 8,440]

Global fits with the LFU observables

[JHEP 01 (2018) 093]



[PRD 96 (2017) 055008]



Combination of LFU observables $R_{K^{*0}/K}$, and lepton-flavour-dependent angular analysis of $B \rightarrow K^{*}\ell^+\ell^-$ done by Belle [arXiv:1612.05014 (submitted to PRL)] shows tension with the SM at about 4σ .

Prospects

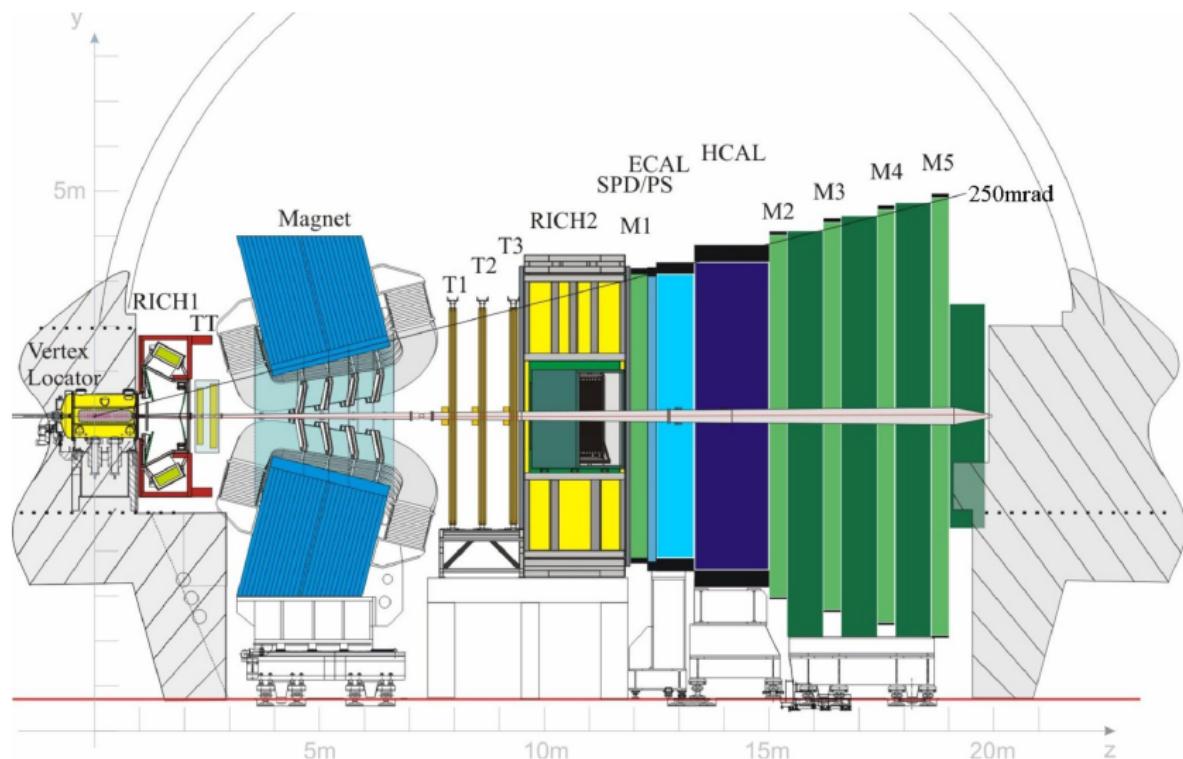
- Updates on existing measurements:
 - $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ angular analysis
 - Update on $R_{K^{*0}/K}$ with a 1.5 – 1.8 improved precision with Run-I + 1/2 Run-II
 - New ratios to be measured R_ϕ , $R_{K\pi\pi}$, ...
 - Angular analysis of $B^0 \rightarrow K^{*0} e^+ e^-$
- Amplitude fit to $B^0 \rightarrow K^{*0} \ell^+ \ell^-$, combining all the observables \mathcal{B} , $R_{K^{*0}}$, angular analysis ...
- Growing interest on electron modes at LHCb:
 - ① Pushing towards improvements in electron reconstruction, PID, ...
 - ② Increase on the amount of electron triggers in the Run-II.
 - ③ Reallocation of manpower to study R measurements.

Conclusions

- Interesting set of anomalies observed in $b \rightarrow s\ell^+\ell^-$ decays, coherently away from the SM predictions.
- In $b \rightarrow s\mu^+\mu^-$ branching fractions and angular observables... New Physics or theoretical limitations?
- Need of more data to further improve the measurements.
- LHCb Run-II data and upcoming contributions from Belle-II will probably serve for clarification.
- Updates ($R_{K^{*0}/K}$) and new measurements (R_ϕ , $B^0 \rightarrow K^{*0}e^+e^-$ angular analysis) using new strategies for the near future.

BACKUP

The LHCb detector



[JINST3 (2008) S08005] [Int. J. Mod. Phys. A30 (2015) 1530022]

$\Lambda_b^0 \rightarrow \Lambda^0 \mu^+ \mu^-$ angular analysis erratum

In the previous paper [JHEP 06 (2015) 115], A_{FB}^ℓ was referring to the asymmetry between Λ_b^0 and $\bar{\Lambda}_b^0$ instead of the combined value from both baryon and anti-baryon decays. In absence of CP violation, this quantity is expected to be zero.

Previous results [JHEP 06 (2015) 115]:

$$A_{\text{FB}}^\ell = -0.05 \pm 0.09 \text{ (stat)} \pm 0.03 \text{ (syst)}$$

$$A_{\text{FB}}^h = -0.29 \pm 0.07 \text{ (stat)} \pm 0.03 \text{ (syst)}$$

New results [LHCb-PAPER-2018-029] (see slide 5):

$$A_{\text{FB}}^\ell = -0.39 \pm 0.04 \text{ (stat)} \pm 0.01 \text{ (syst)}$$

$$A_{\text{FB}}^h = -0.30 \pm 0.05 \text{ (stat)} \pm 0.02 \text{ (syst)}$$

