Rare Decays

31st Rencontres de Blois on Particle Physics and Cosmology

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

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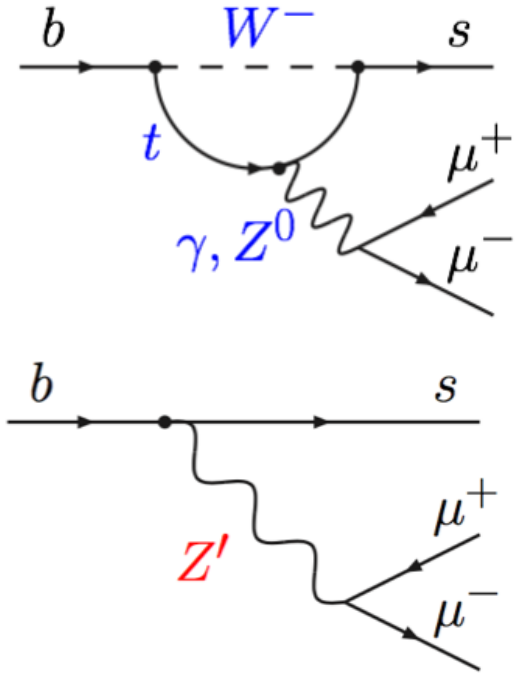
Introduction

- Rare decays are excellent candidates for indirect searches for new physics (NP) *e.g.* $b \to s l^+ l^-$ decays

- Strongly suppressed in the SM as
  - involve Flavour Changing Neutral Currents (FCNC) - 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 rare decay measurements
- Impact on global picture and connection to other processes
- Future prospects and conclusions

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- **Theoretical framework**
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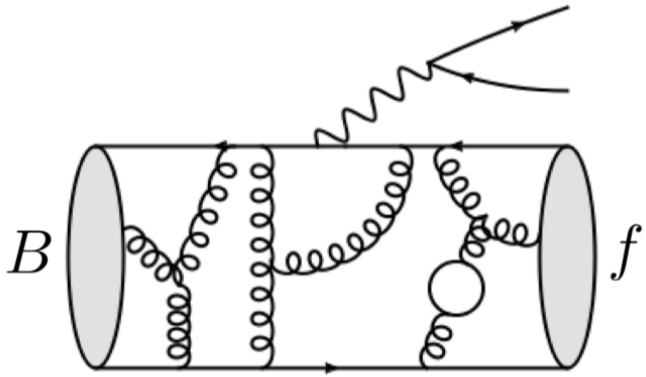
Choosing observables

- 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

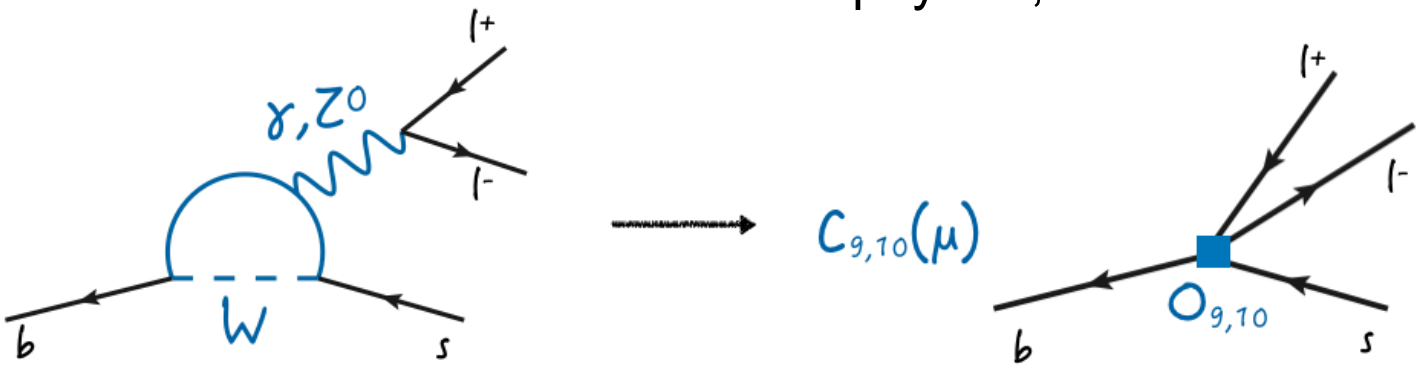
Theoretical framework

- 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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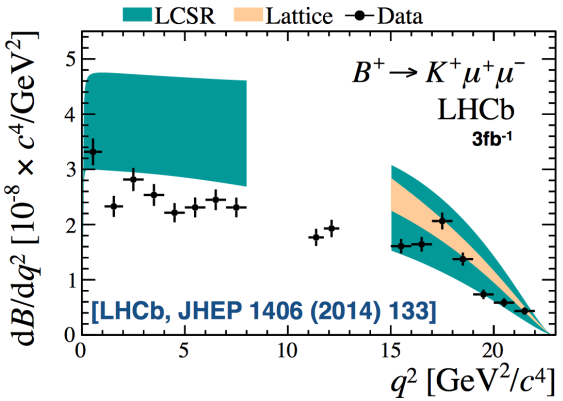
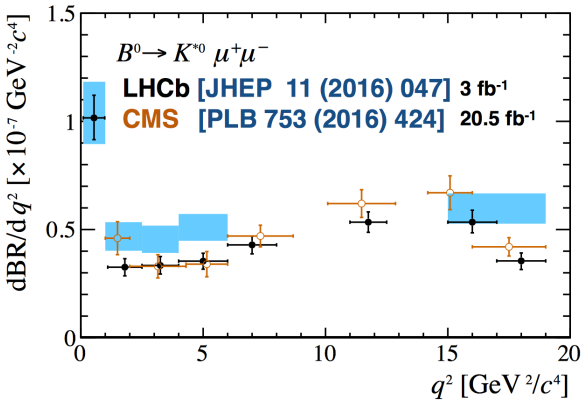
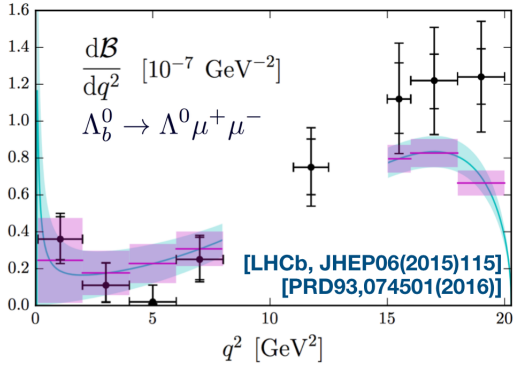
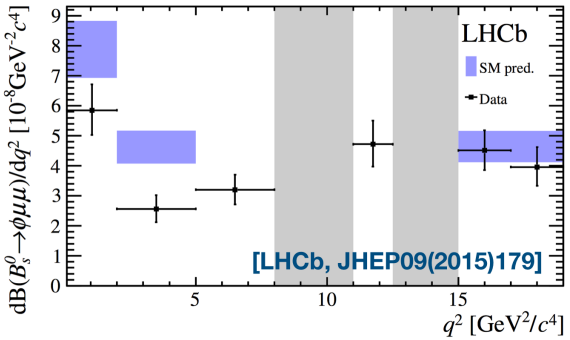
Branching fraction measurements

- Branching fractions for several b→sμμ processes are below the SM prediction at low $q^2 = [m(l^+l^-)]^2$





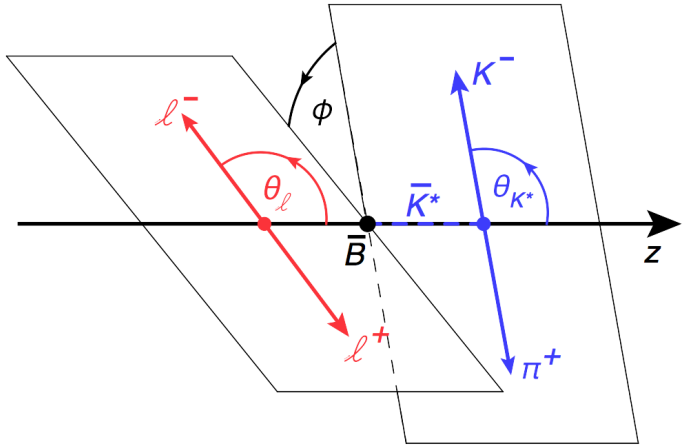


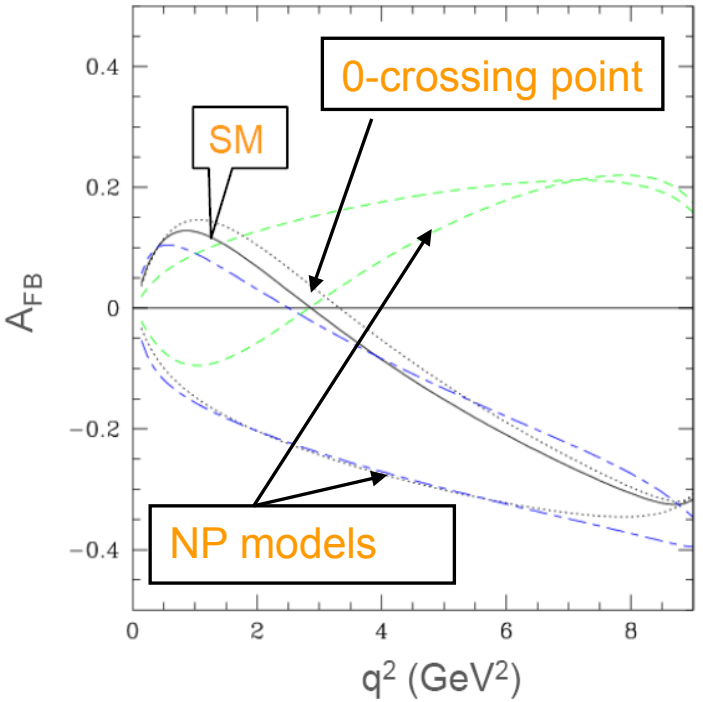


- SM predictions suffer from large uncertainties

Angular observables

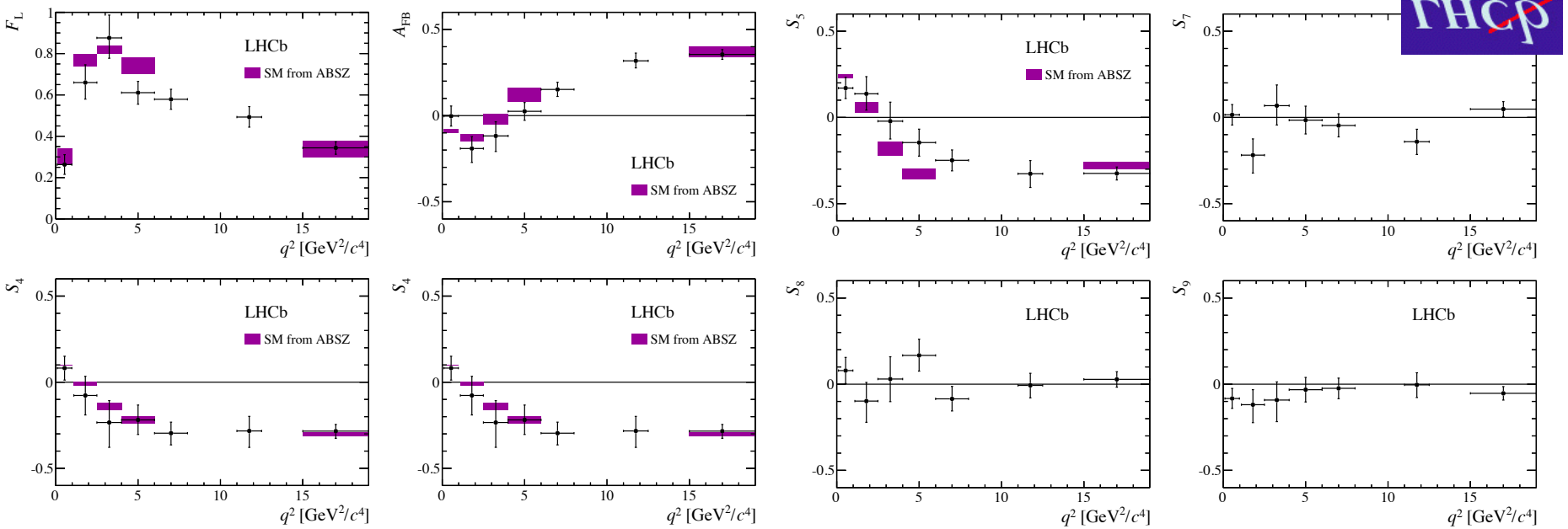
- Angular observables have reduced dependence on hadronic effects
- Best studied decay $B^0 \to K^{*0}\mu\mu$
  - Dynamics can be described by three angles (θ_l, θ_K, ϕ) and di-μ invariant mass squared, q^2
- Large number of observables where theoretical uncertainties cancel to some extent *e.g.* Forward-backward asymmetry A_{FB} of θ_l distn





$B^0 \to K^{*0} \mu\mu$ angular analysis

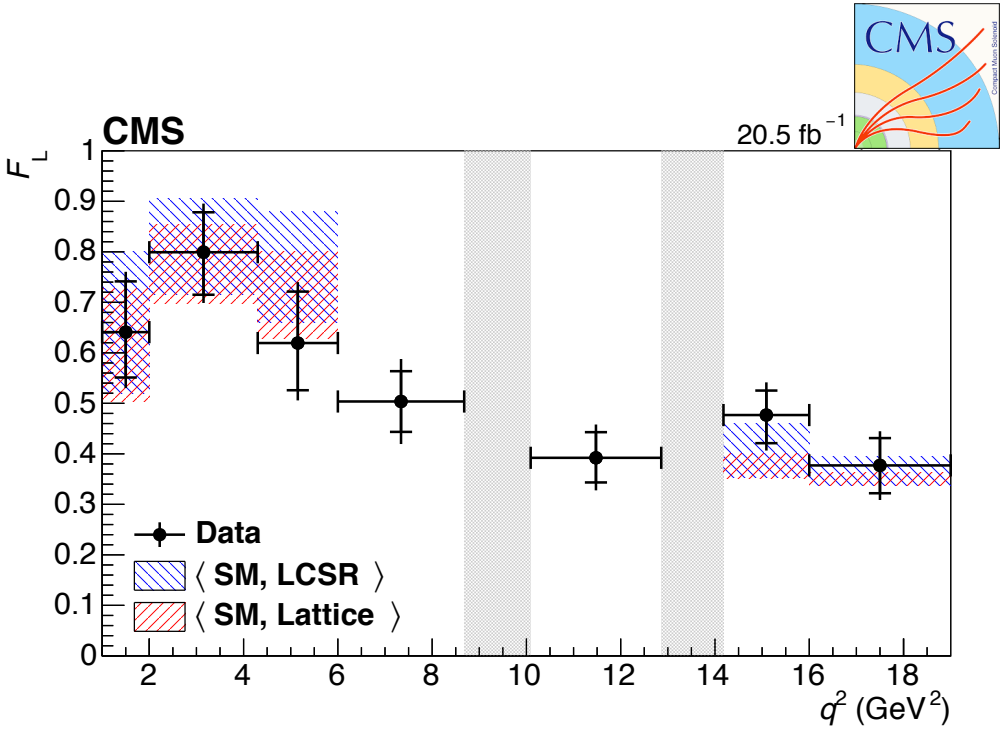
- LHCb performed first full angular analysis [JHEP 02 (2016) 104]
  - Extracted the full set of CP-avg'd angular terms and correlations
  - Determined full set of CP-asymmetries



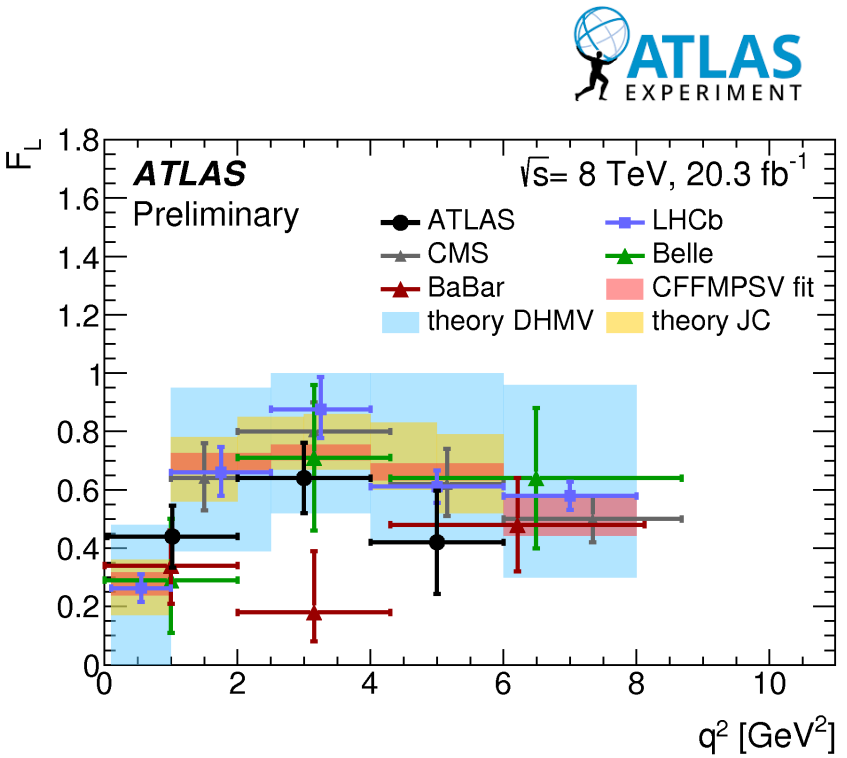
- Vast majority of observables in agreement with SM predns, giving some confidence in theory control of form-factors

$B^0 \to K^{*0} \mu\mu$ angular analysis

- CMS and ATLAS confirm these findings



[PLB 753 (2016) 31]



[JHEP 10 (2018) 047]

Form-factor independent obs.

- At low and high q^2, (leading order) relations between the various form factors allow a number of form-factor "independent" observables to be constructed

- In the region $1<q^2<6$ GeV^2, relations reduce the seven $B^0 \to K^{*0}\mu\mu$ form-factors to just two – allows to form *e.g.*

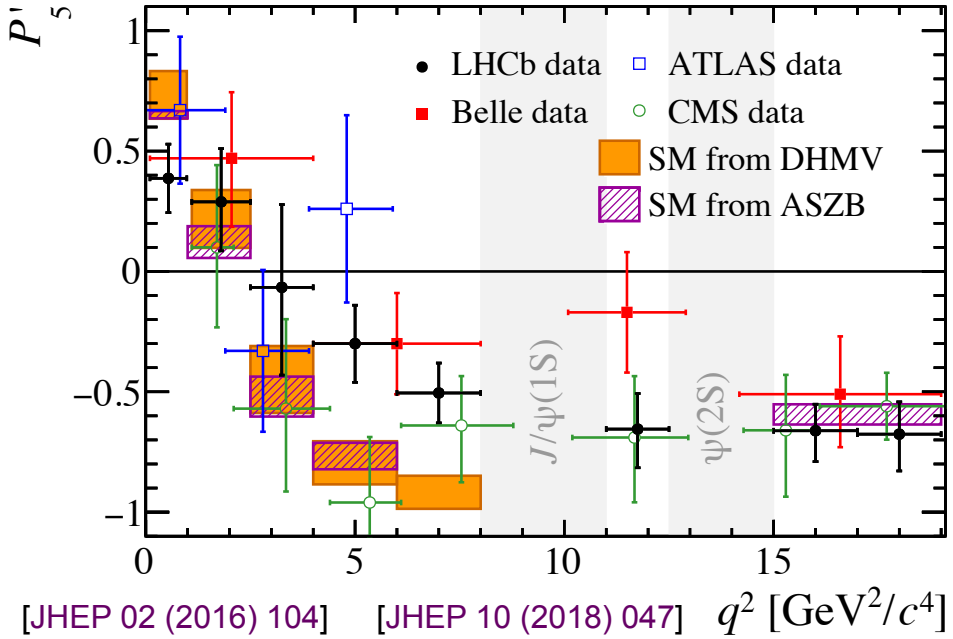
$$P_5' \sim \frac{Re(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*})}{\sqrt{(|A_0^L|^2+|A_0^R|^2)(|A_\perp^L|^2+|A_\perp^R|^2+|A_\parallel^L|^2+|A_\parallel^R|^2)}}$$

  which is form-factor independent *at leading order*

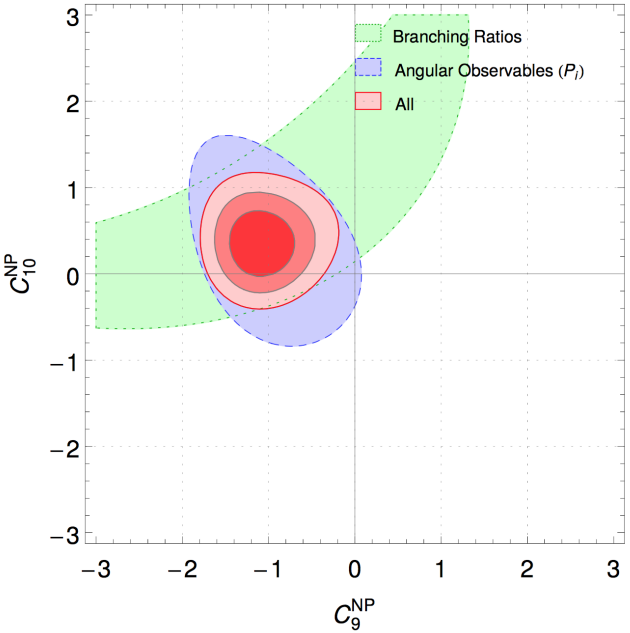
- In fact, can form a complete basis ($P^{(\prime)}$ series) in which there are six form-factor independent and two form-factor dependent observables (F_L and A_{FB})

Angular observables

- Form-factor "independent" P_5' has a local discrepancy in two bins



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

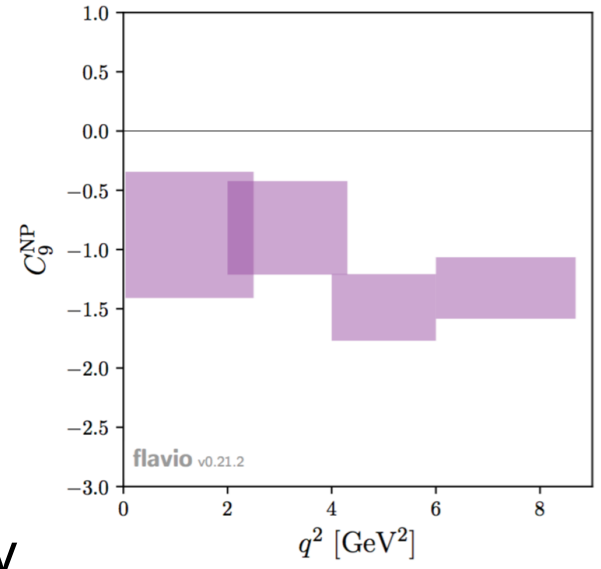


[JHEP06 (2016) 092]

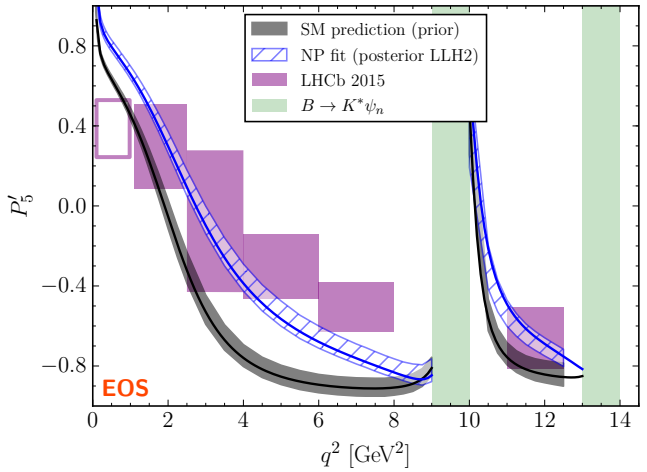
- BF and angular data consistent, best fit prefers shifted vector coupling C_9 (or C_9 and axial-vector C_{10})

Could the SM predn be wrong?

- Theorists have started to look critically at their predictions – $O_{1,2}$ operators have a component that could mimic a NP effect in C_9 through $c\bar{c}$ loop
  - Look for q^2 dependence of C_9 shift [EPJC 77 (2017) 377]
  - Parameterisation to theory and auxiliary data to try and determine $c\bar{c}$ effect [EPJC 78 (2018) 451]



- No consensus in theory community about the size of such effects



Lepton flavour universality tests

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

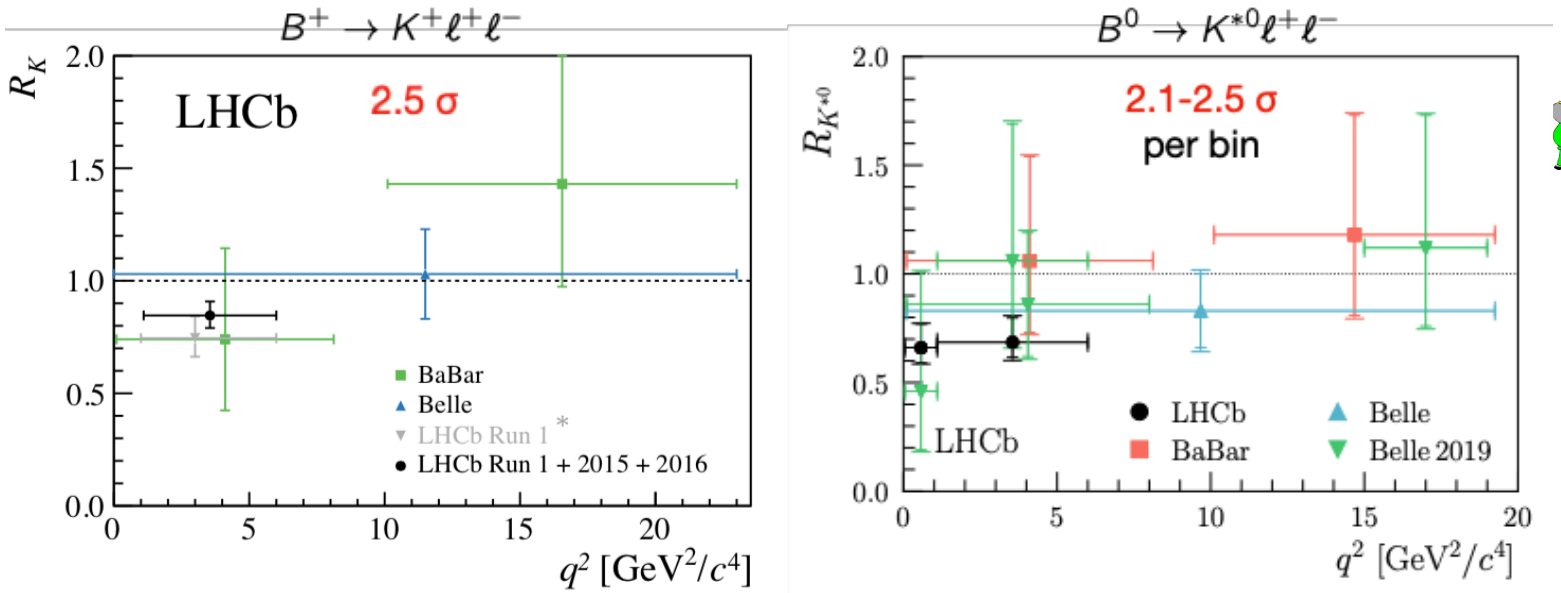
- Ratios of the form:

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

  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]

- [Theorists in unison:] Any sign of lepton flavour non-universality would be an unambiguous sign for New Physics

Status of LFU tests



[LHCb, PRL 113 (2014) 151601]
[LHCb, JHEP 08 (2017) 055]
[LHCb, PRL 122 (2019) 191801]

[BaBar, PRD 86 (2012) 032012]

[Belle, PRL 103 (2009) 171801]
[Belle, arXiv:1904.02440]

- Intriguing picture : both R_K and R_{K^*} results below the SM expectation, although significance low
- Tensions can be explained with anomalous b→sμμ measurements in a coherent NP picture

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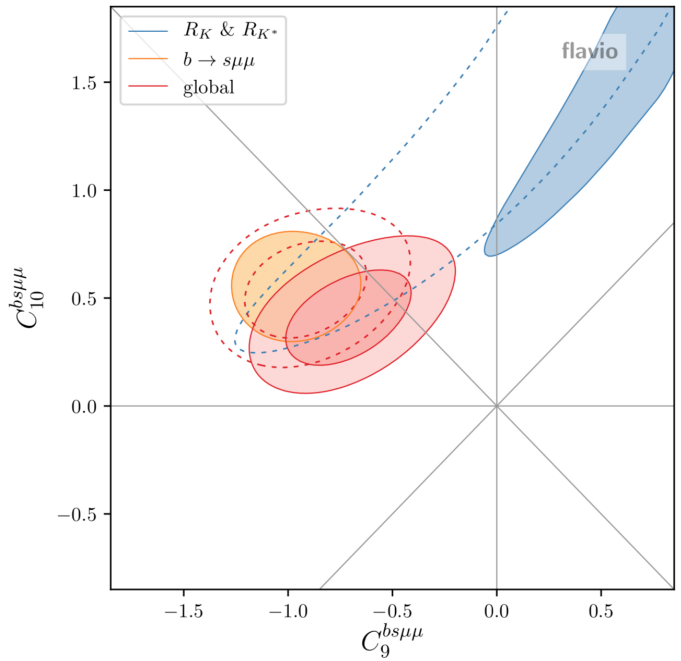
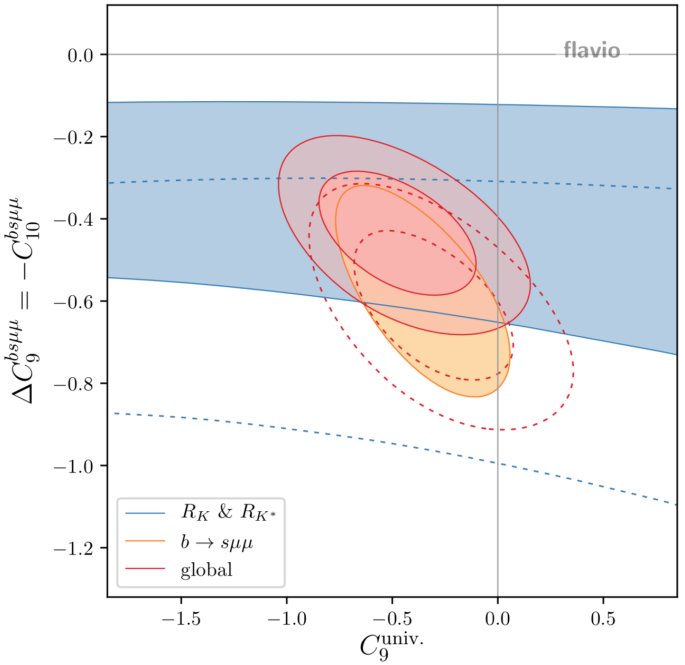
Impact on global fits





[arXiv:1903.10434]

- Best fit point still in tension with the SM
- Muonic NP: best fit closer to the SM, $C_9 = -C_{10}$ still preferred
- Allowing 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]

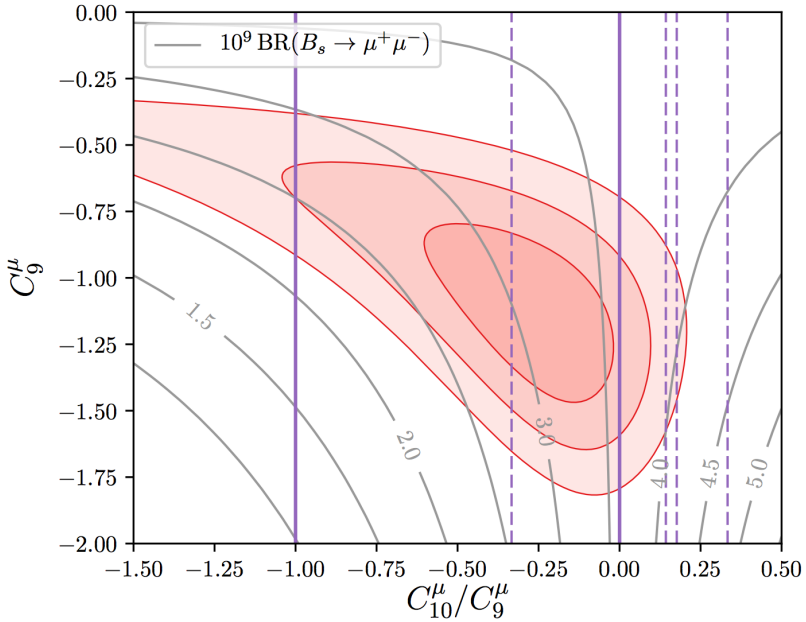
Leptonic decays - $B^0 \to \mu^+\mu^-$

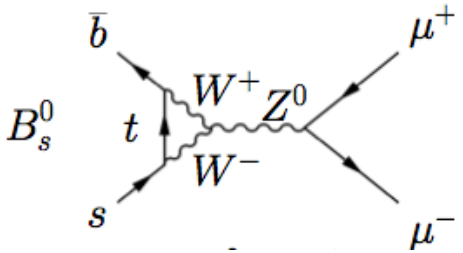
- Many single-particle explanations of anomalies predict $C_9^{NP} = -C_{10}^{NP}$ (data still compatible with such a soln)

- If this were the case would expect to see effect in $B^0 \to \mu^+\mu^-$ decays
  - Dominant contribution from Z-penguin diagram
  - Precise predictions for BFs :

    $B(B_s^0 \to \mu\mu) = (3.66 \pm 0.23) \times 10^{-9}$

    $B(B_d^0 \to \mu\mu) = (1.06 \pm 0.09) \times 10^{-10}$
  - Can be altered by modified C_{10} or new scalar/pseudoscalar ($C_{S,P}$) [high tan β SUSY]





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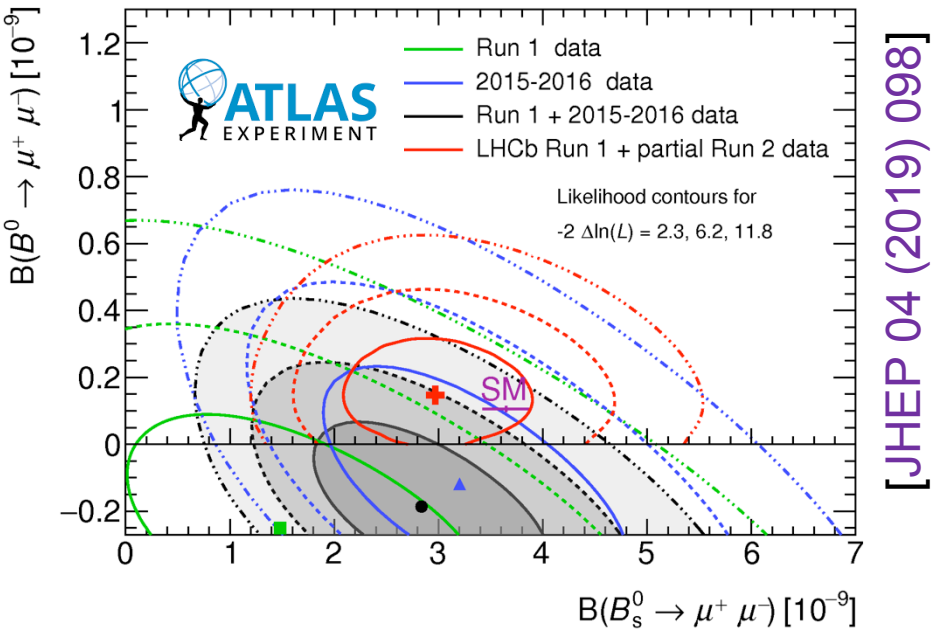
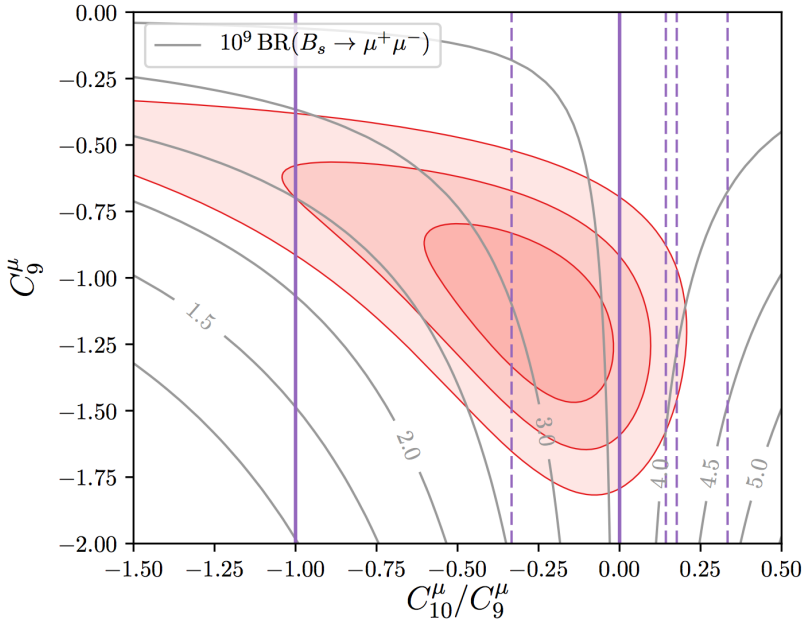
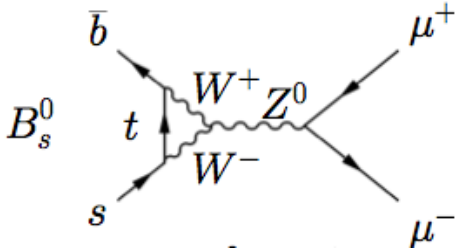


[JHEP 04 (2019) 098]



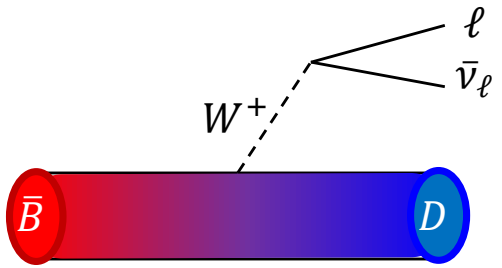
- No evidence for any deviation from SM so far…

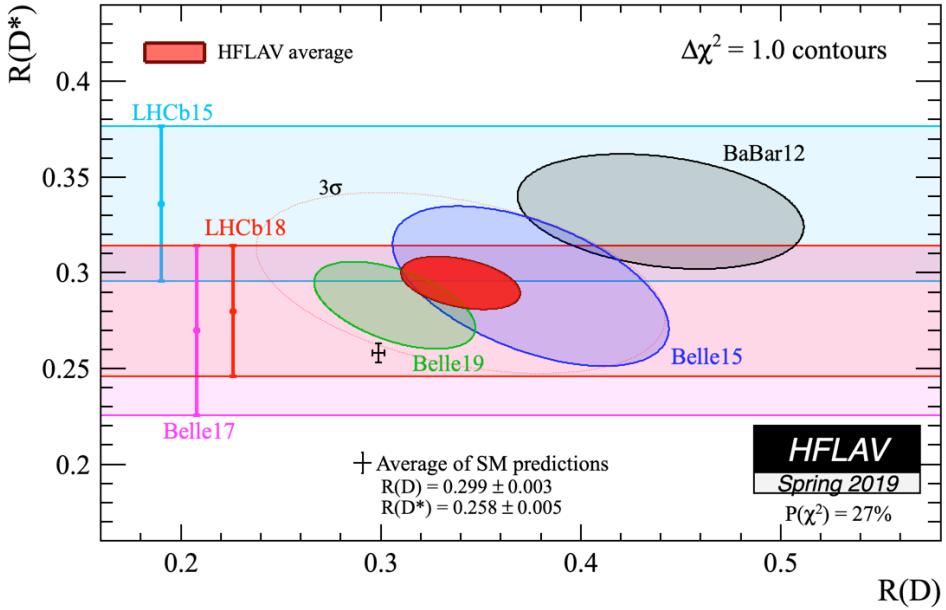


Semileptonic decays

- A ~3σ tension with SM also seen in b→c charged current processes (cf. b→s neutral current processes)
  - Tree-level processes in SM
  - Again use lepton universality ratio, R_X

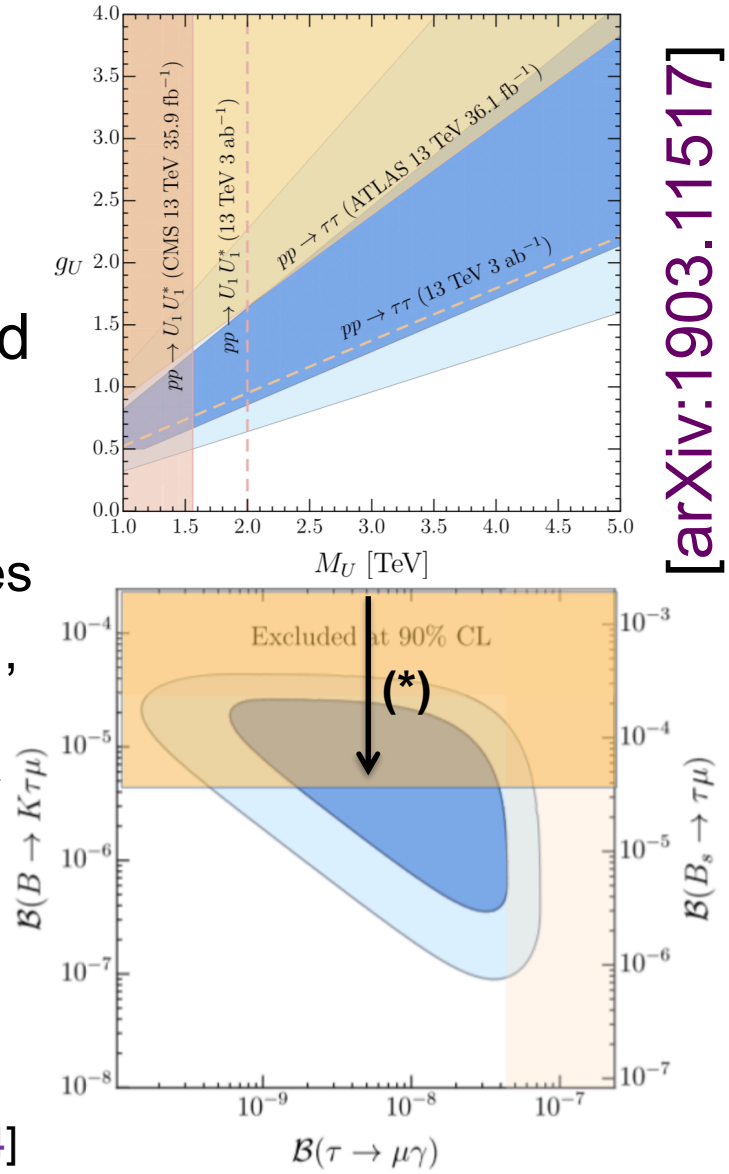
$$R\left(D^{(*)}\right) \equiv \frac{\mathcal{B}\left(\bar{B}^0 \to D^{(*)}\tau^-\bar{\nu}_\tau\right)}{\mathcal{B}\left(\bar{B}^0 \to D^{(*)}\ell^-\bar{\nu}_\ell\right)}$$





Model Building

- Can accommodate anomalies with O(TeV)-O(10TeV) new physics
- *e.g.* Vector LeptoQuark (LQ), coupled mainly to third-generation fermions, able to give pattern anomalies
  - Potentially within reach of direct searches
  - Expect effects in *e.g.* B→τμ, B→Kττ *etc.*, which can be huge
  - While need LFUV, LFV is not mandatory [arXiv:1505.05164]



[arXiv:1903.11517]

(*) Recent LHCb B→τμ result [arXiv:1905.06614]

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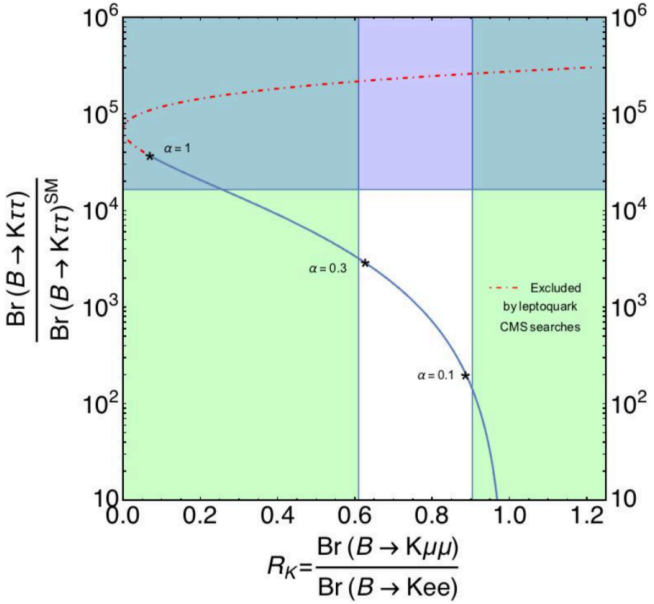
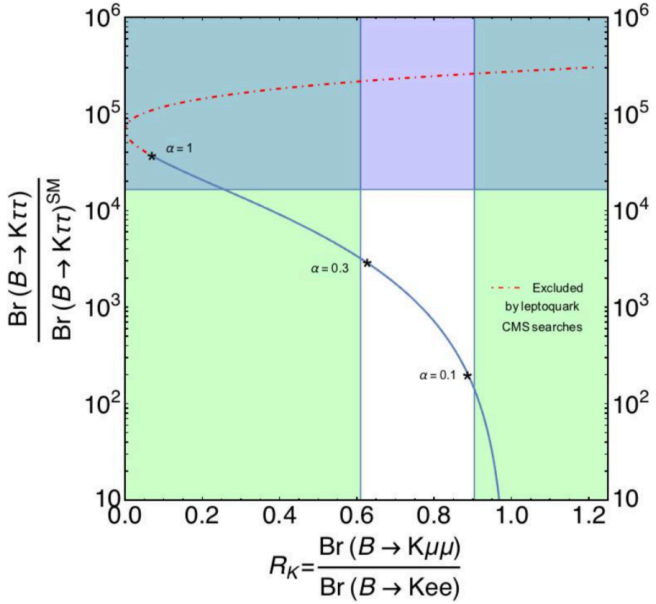


[arXiv:1505.05164]

Model Building

- Pattern of anomalies can be linked to hierarchical structure of quark and lepton mass matrices through dynamical breaking of flavour symmetry [JHEP 1810 (2018) 148]

- Can also connect to portal models of dark matter [arXiv:1503.06077, PRD 96 (2017) 075041]



[arXiv:1505.05164]

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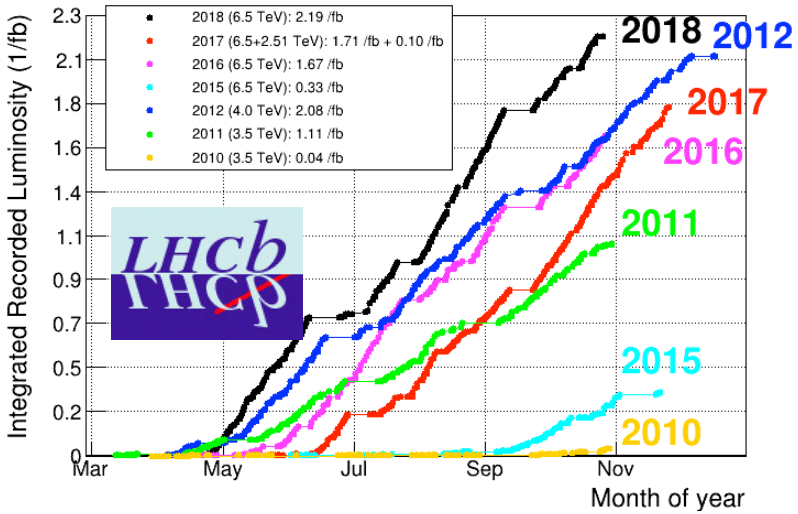
Future experimental input

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



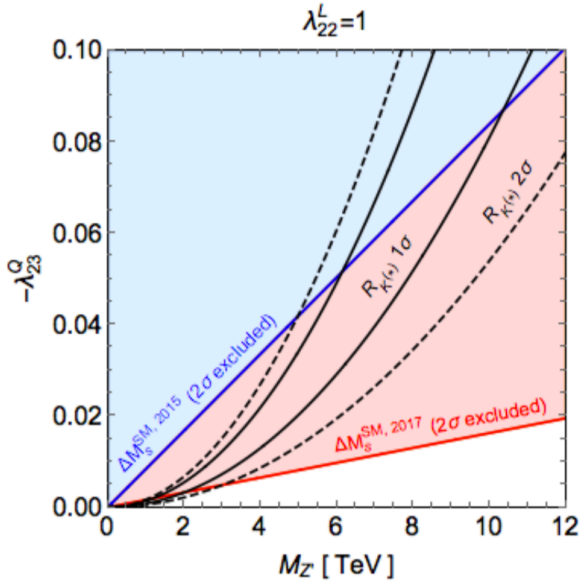
- CMS has collected a sample of 10^{10} B decays
  - With an effective low p_T electron reconstruction, should get a very competitive number of *e.g.* $B^+ \to K^+ e^+ e^-$ signal candidates
  - Expect systematics will be very different to those at LHCb *e.g.* no trigger effect and very different material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

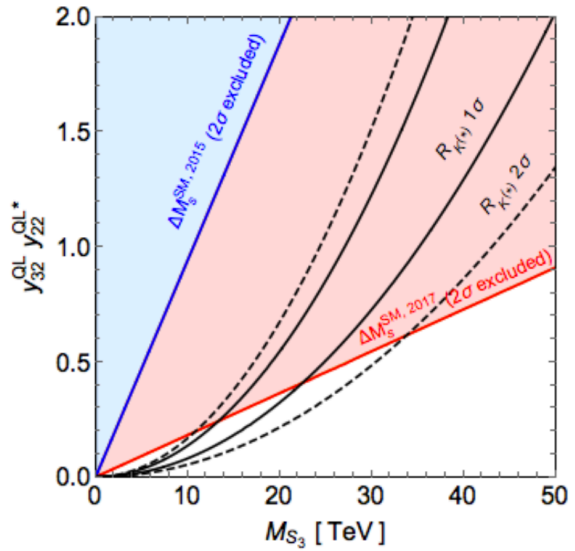
ATLAS pursuing similar strategy

- Belle2 data-taking starting in earnest

The future of direct searches

- A single rare decay measurement gives constraints on only the mass, coupling plane of any new physics
- In simple NP models, accumulation of constraints from multiple decay modes can break this degeneracy
- Could have implications for the case for a future accelerator





[PRD 97 (2018) 095035]

Conclusions

- Intriguing anomalies seen in rare B decays
  - Branching fractions
  - Angular observables

  but debate about control of theory uncertainties

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

- Good prospects for resolution with new measurements

- Should anomalies persist, expect to see correlated effects in a number of decay modes