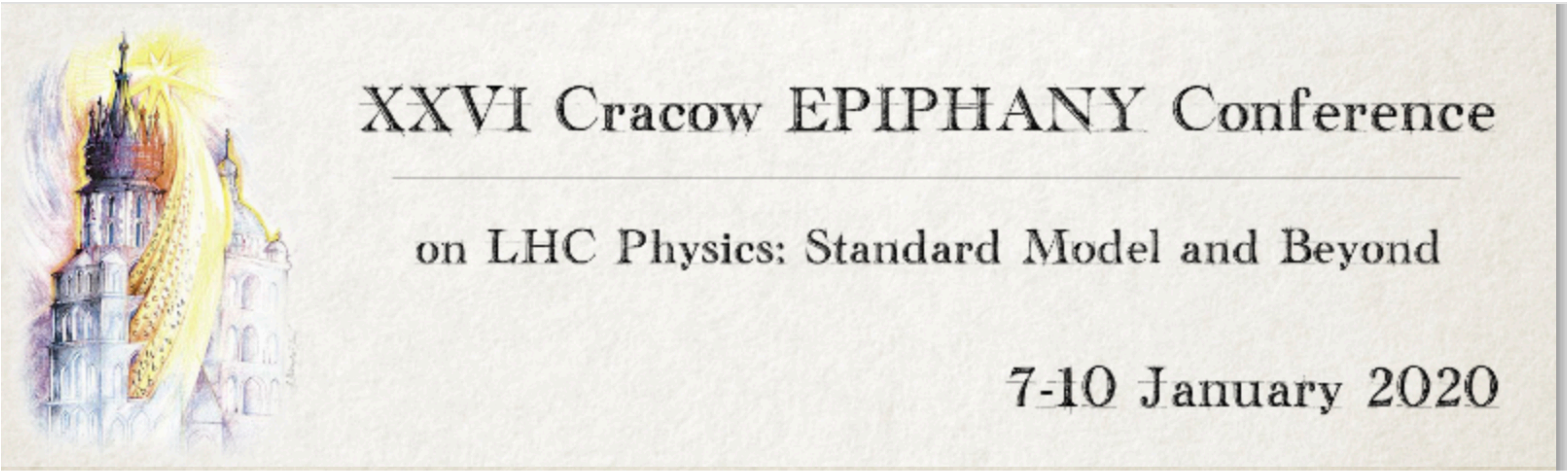
Flavour Anomalies



Cracow Epiphany Conference, 8th January 2020

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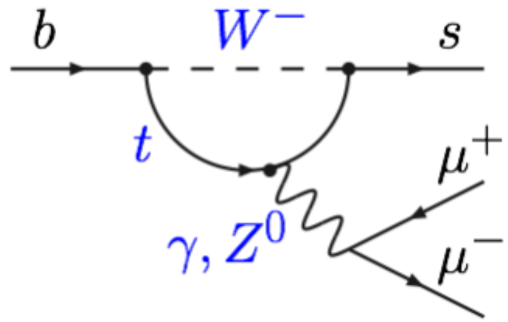
on behalf of LHCb, with material from ATLAS, CMS

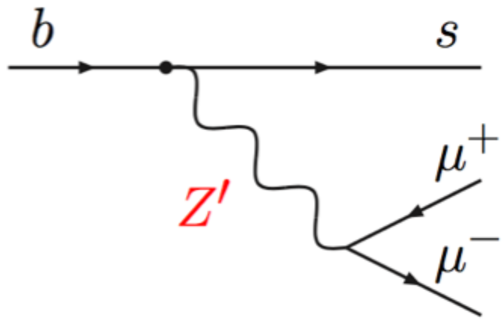
Imperial College London

LHCb

Introduction

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





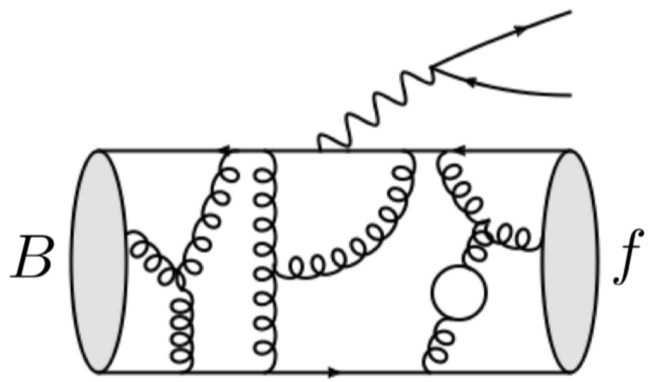
- Strongly suppressed in the SM as
  - arise only at the loop level
  - quark-mixing is hierarchical (off-diagonal CKM elements $\ll$ 1)
  - GIM mechanism
  - only the left-handed chirality participates in flavour-changing interactions

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

Choosing observables

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

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



→ 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

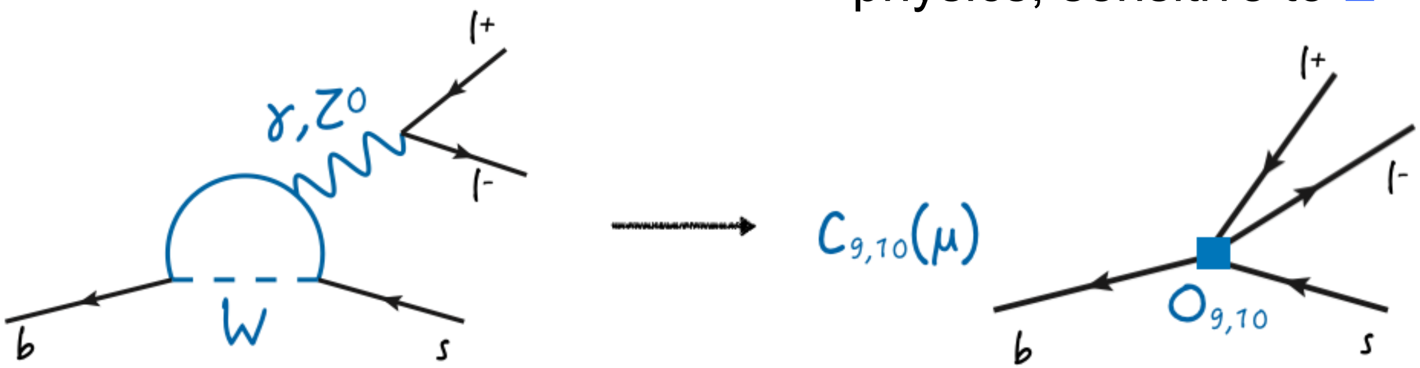
Theoretical framework

- 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 can modify the measured values of WC's and/or introduce new operators

Outline

- Status of the anomalous flavour measurements
- Global fits and model building
- Future prospects

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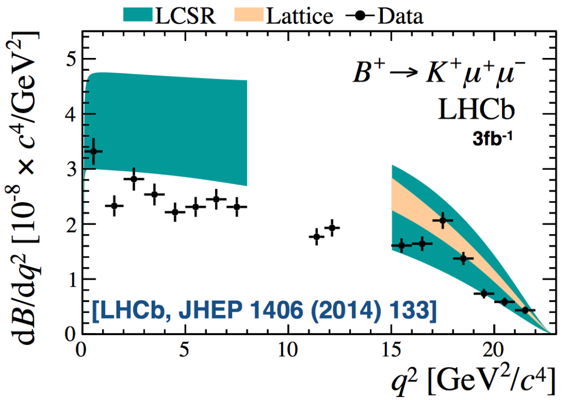
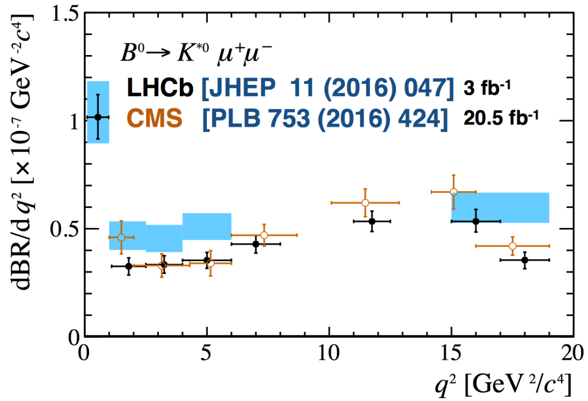
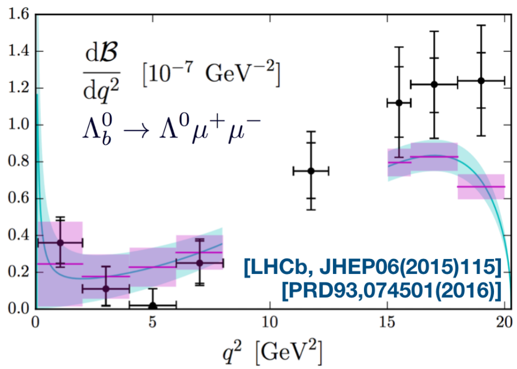
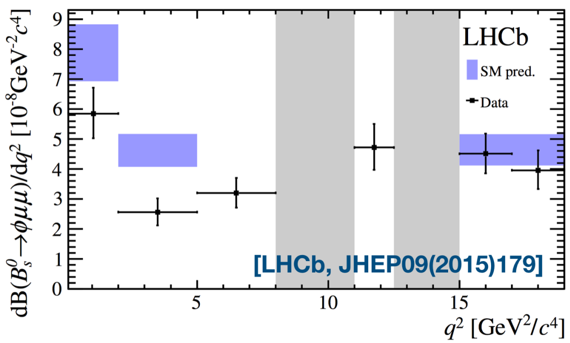
Branching fraction measurements

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









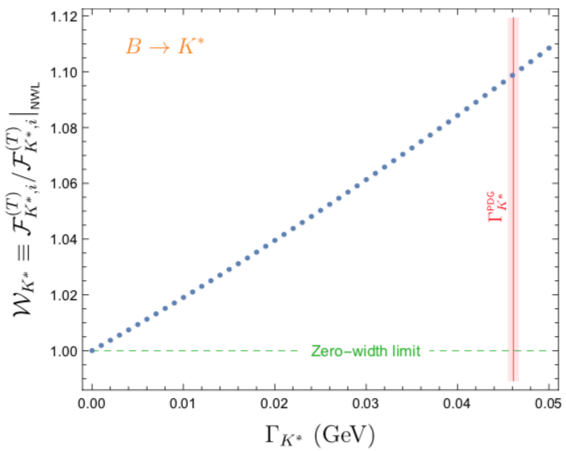
- SM predictions suffer from large uncertainties

BF – theory progress

- Width of the K* difficult to treat, calculations have thus far used the "narrow width" approximation
- First calculations of the effect of a wide K* appearing :

Beyond the narrow-width approximation for K^*

LCSR with K^* only: $\mathcal{F}^{(T)}_{K^*,i}(q^2)\, d^{(T)}_{K^*,i}\, I_{K^*}(s_0, M^2) = \mathcal{P}_i^{(T)\mathrm{OPE}}(q^2, \sigma_0, M^2)$.



Width induces universal shift in normalisation from overlap integral I_{K^*}

(effect depending mainly on s_0, M^2 and Γ_{K^*})

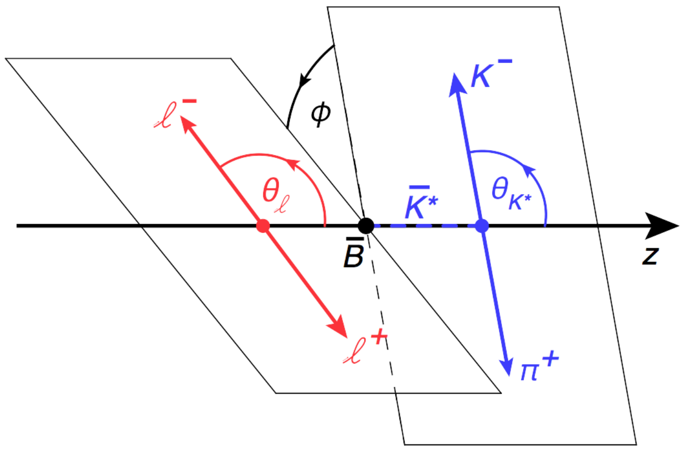
$$\mathcal{W}_{K^*} \equiv \frac{\mathcal{F}^{(T)}_{K^*,i}(q^2)}{\mathcal{F}^{(T)}_{K^*,i}(q^2)_{\mathrm{NWL}}} = \frac{I_{K^*}(s_0, M^2)|_{\Gamma_{K^*} \to 0}}{I_{K^*}(s_0, M^2)} \simeq 1 + 1.9\, \frac{\Gamma_{K^*}}{m_{K^*}}$$

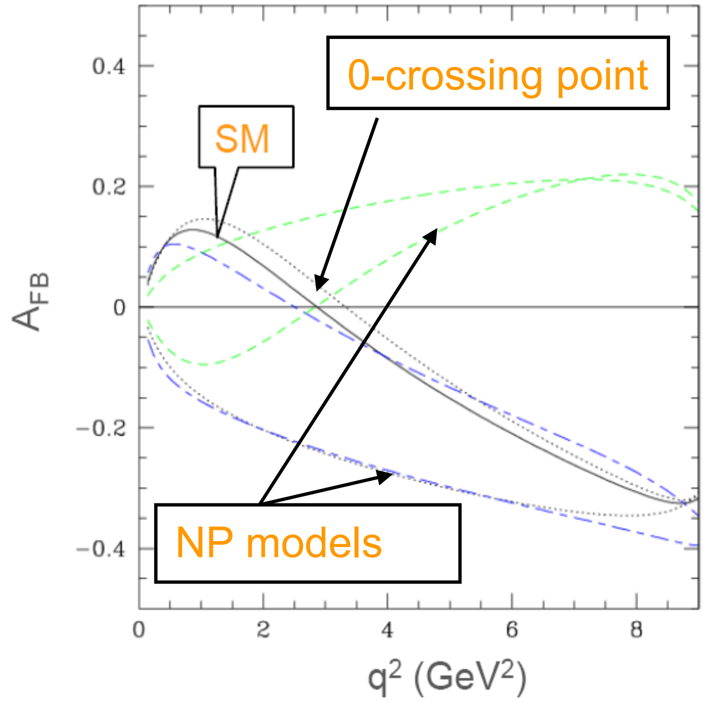
Correction $\simeq$ 10 % (increasing the discrepancy data-SM for $B \to K^* \mu\mu$)

S. Descotes-Genon (LPT-Orsay) | $B \to K\pi$ form factors | $b \to s\ell\ell$2019 (4/9/19) | 13

Angular observables

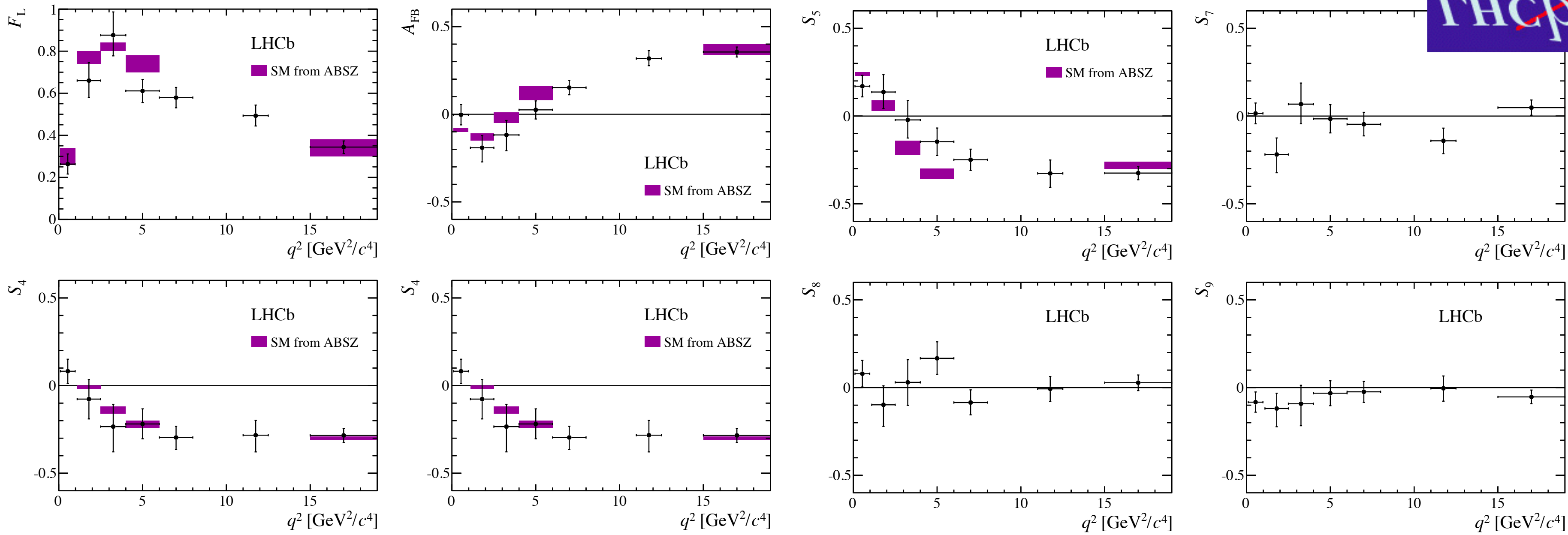
- Angular observables have reduced dependence on hadronic effects
- Best studied decay $B^0 \rightarrow K^{*0}\mu\mu$
  - Dynamics can be described by three angles (θ_l, θ_K, ϕ) and di-μ invariant mass squared, q^2
- Large number of observables where theoretical uncertainties cancel to some extent *e.g.*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





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

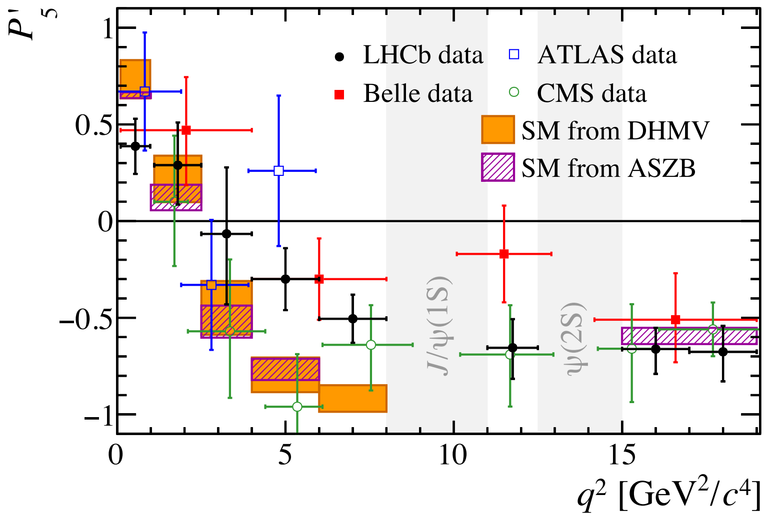
- LHCb performed first full angular analysis [JHEP 02 (2016) 104]
  - Extracted the full set of CP-avg'd angular terms and correlations
  - Determined full set of CP-asymmetries



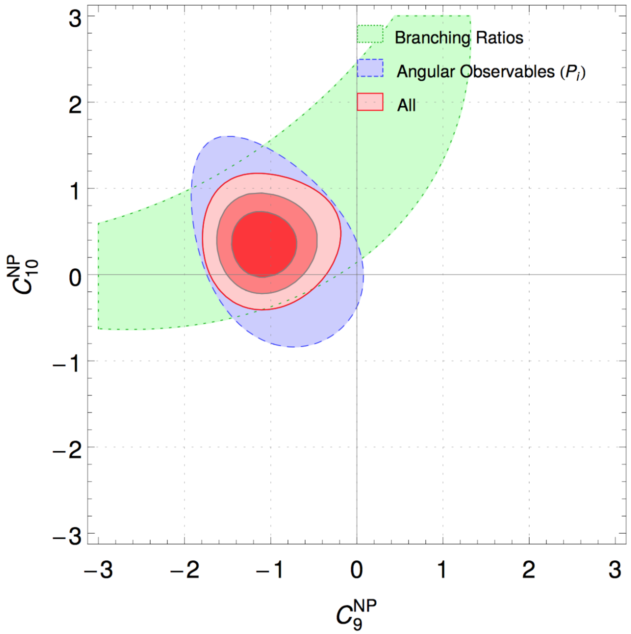
- Vast majority of observables in agreement with SM predns, giving some confidence in theory control of form-factors

Angular observables

- Some angular observables have reduced dependence on hadronic effects and show some tension with SM



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



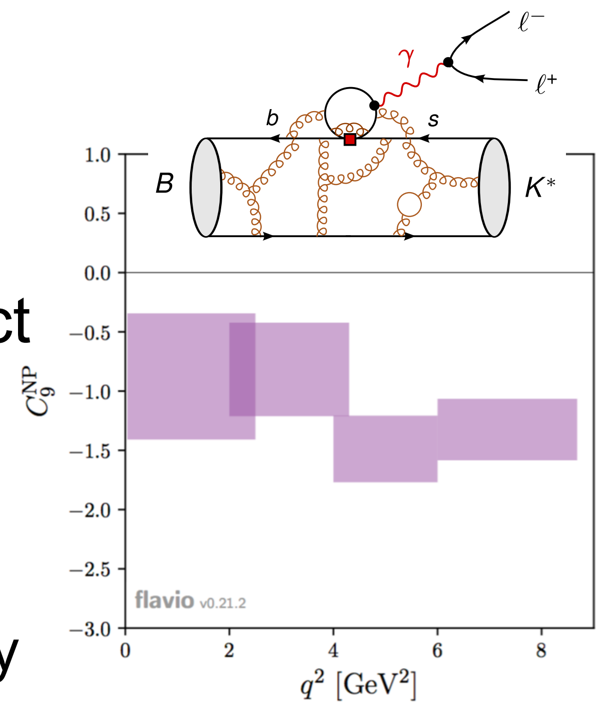
[JHEP06 (2016) 092]

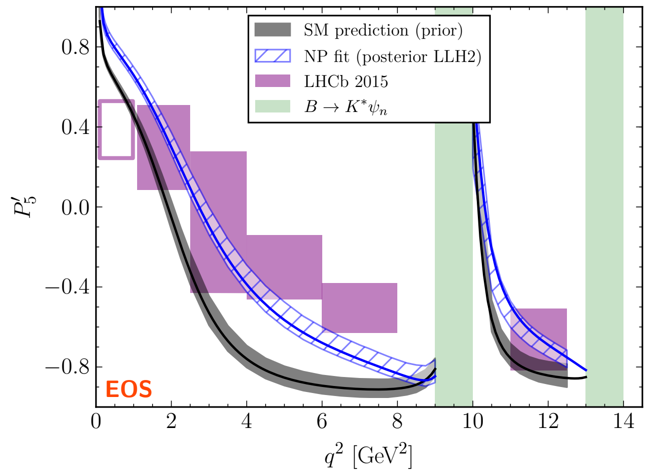
- BF and angular data consistent, best fit prefers shifted vector coupling C_9 (or C_9 and axial-vector C_{10})
- … could QCD effects mimic vector-like NP ?

Could the SM predn be wrong?

- Theorists have looked critically at their predictions – $\mathbf{O_{1,2}}$ operators have a component that could mimic a NP effect in $\mathbf{C_9}$ through $c\bar{c}$ loop
  - Look for $\mathbf{q^2}$ dependence of $\mathbf{C_9}$ 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





$c\bar{c}$ loops – theory progress

- Calculation of hadronic matrix element for $c\bar{c}$ effect
  - Factor 200 ***smaller*** than before… !

Preliminary results and comparison

17/19

$\Delta C9(q^2)$		KMPW2010	GvDV2019
factorizable contr.		0.27	0.27
$B \to Kll$	$\tilde{\mathcal{A}}(q^2 = 1)$	$-0.09^{+0.06}_{-0.07}$	$(1.9^{+0.6}_{-0.6}) \cdot 10^{-4}$
	$\tilde{\mathcal{V}}_1(q^2 = 1)$	$0.6^{+0.7}_{-0.5}$	$(1.2^{+0.4}_{-0.4}) \cdot 10^{-3}$
$B \to K^*ll$	$\tilde{\mathcal{V}}_2(q^2 = 1)$	$0.6^{+0.7}_{-0.5}$	$(2.1^{+0.7}_{-0.7}) \cdot 10^{-3}$
	$\tilde{\mathcal{V}}_3(q^2 = 1)$	$1.0^{+1.6}_{-0.8}$	$(3.0^{+1.0}_{-1.0}) \cdot 10^{-3}$
$B_s \to \phi ll$	...	-	???

[q^2 is the dilepton mass square]

results represented as a q^2 dependent correction to $C9$
we fully reproduce the results given in KMWP2010

matrix elements parametrized analogously to the form factors:

$$\langle K(k)|\tilde{O}_\mu(0,x)|B(q+k)\rangle = \left((k\cdot q)q_\mu - q^2 k_\nu\right)\tilde{\mathcal{A}}(q^2) + \dots$$

$$\langle K^*(k,\eta)|\tilde{O}_\mu(0,x)|B(q+k)\rangle = \epsilon_{\mu\alpha\beta\gamma}\eta^{*\alpha}q^\beta k^\gamma\,\tilde{\mathcal{V}}_1(q^2) + i\left((m_B^2 - m_{K^*}^2)\eta^*_\mu - (\eta^*\cdot k)(2k+q)_\mu\right)\tilde{\mathcal{V}}_2(q^2)$$
$$+ i(\eta^*\cdot q)\left(q_\mu - \frac{q^2}{m_B^2 - m_{K^*}^2}(2k+q)_\mu\right)\tilde{\mathcal{V}}_3(q^2) + \dots$$

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 a direct sign for New Physics

LFU in charged-current decays

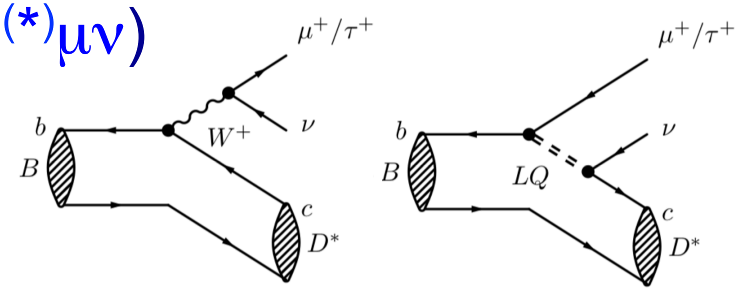
- An anomalous effect is seen in the ratio of **tree-level** branching fractions

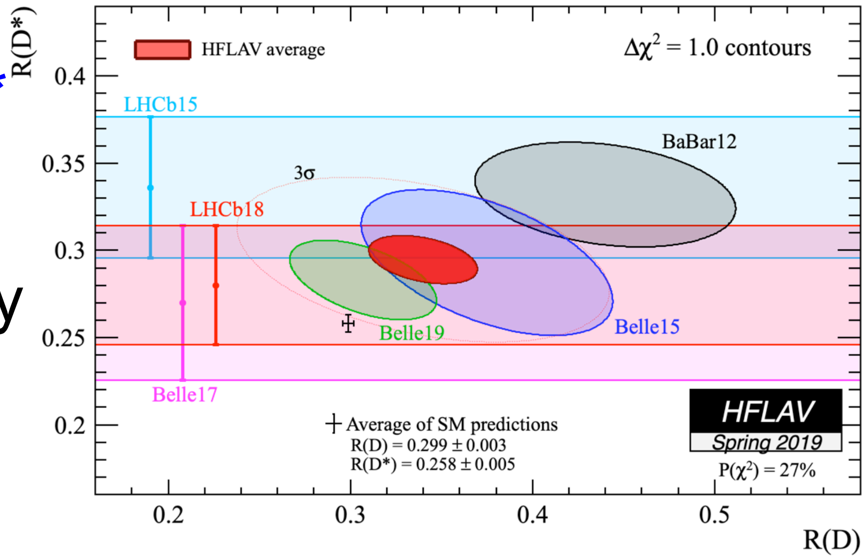
  $R_D^{(*)} = B(B^0 \to D^{(*)}\tau\nu)/B(B^0 \to D^{(*)}\mu\nu)$

- Not at all rare: $B(B^0 \to D^*\tau\nu)$ ~1%, problem is the bkgrd

- Measurements of R_D and $R_D{}^*$ by BaBar, Belle and LHCb

- Average shows a discrepancy with the SM of 3.1σ (HFLAV); recent claim that updated form factors make this 3.9σ [see here]

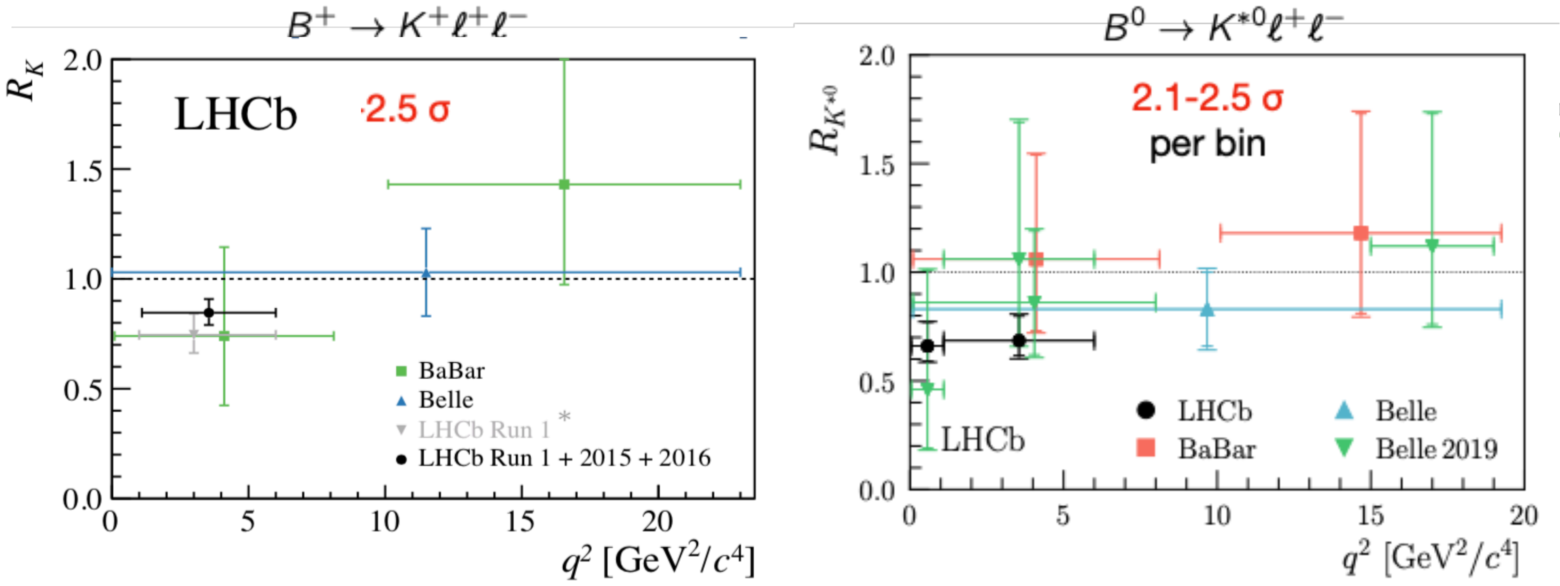




[arXiv:1904.08794, arXiv:1506.08614, arXiv:1711.02505, arXiv:1708.08856, arXiv:1607.07923, arXiv:1205.5442, arXiv:1303.0571, arXiv:1612.00529, arXiv:1709.00129]

LFU in neutral-current decays

- Equally intriguing picture in b→sll neutral-current decays:



[LHCb, PRL 113 (2014) 151601]
[LHCb, JHEP 08 (2017) 055]
[BaBar, PRD 86 (2012) 032012]
[LHCb, PRL 122 (2019) 191801]
[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→sμμ measurements in a coherent NP picture

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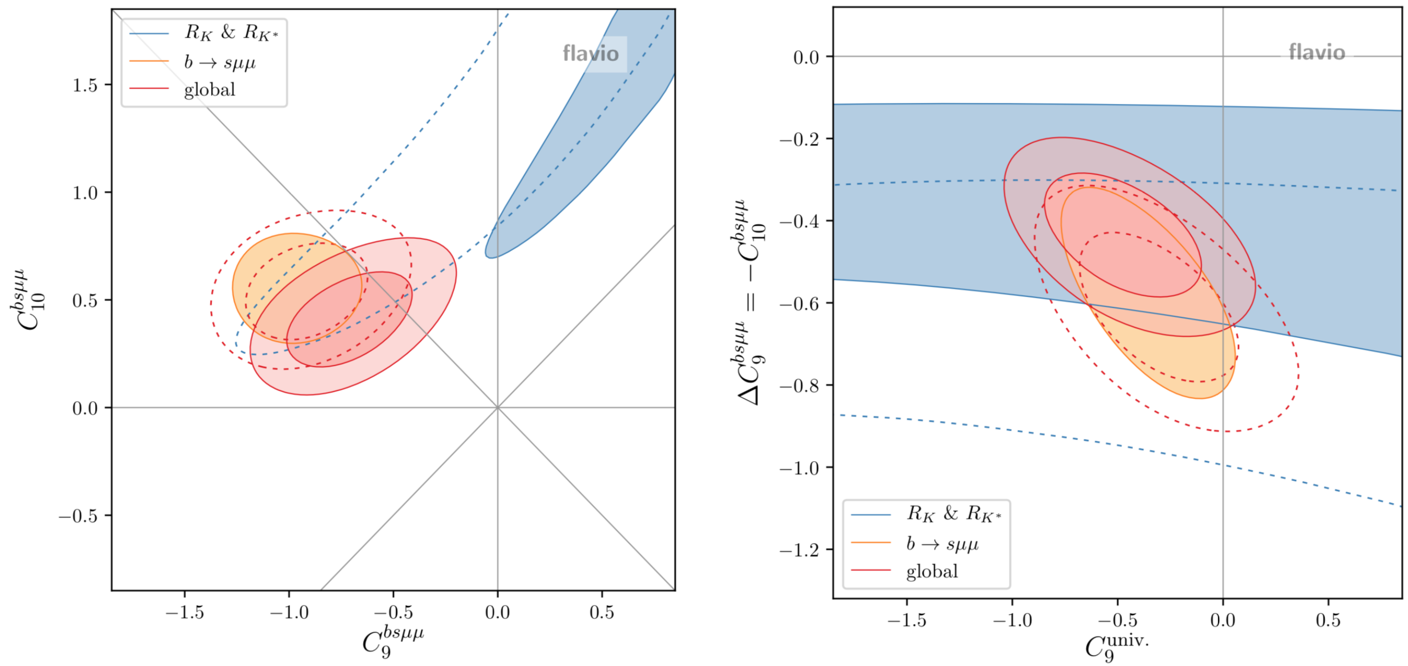
Global fit including LFU obs.

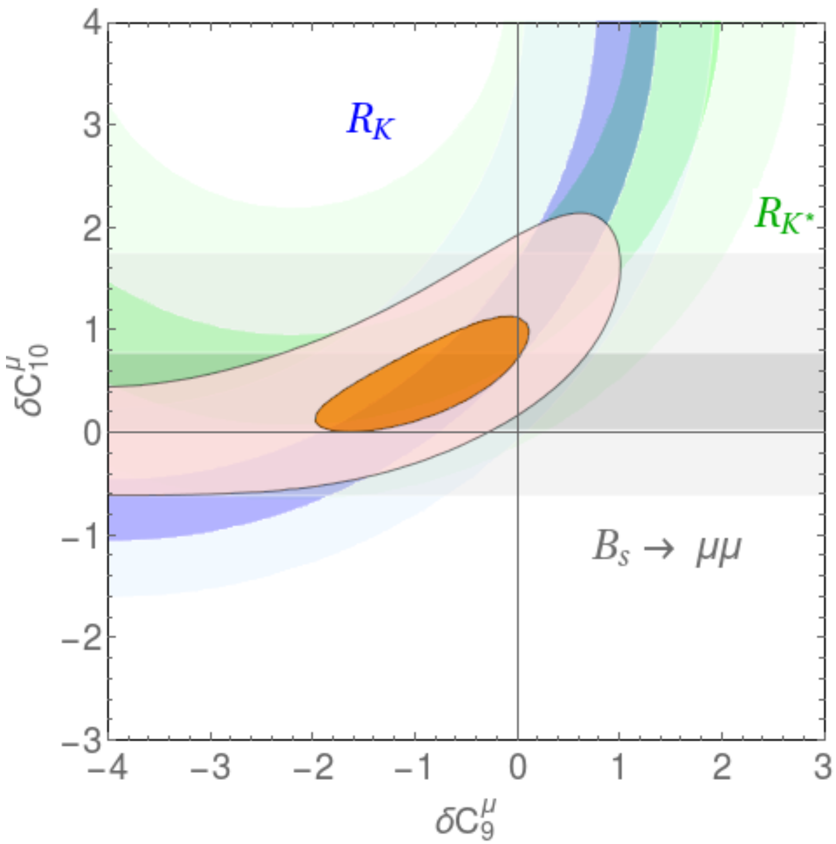


[arXiv:1903.10434]

- Best fit point in significant tension with the SM
- Muonic NP: $C_9 = -C_{10}$ 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]

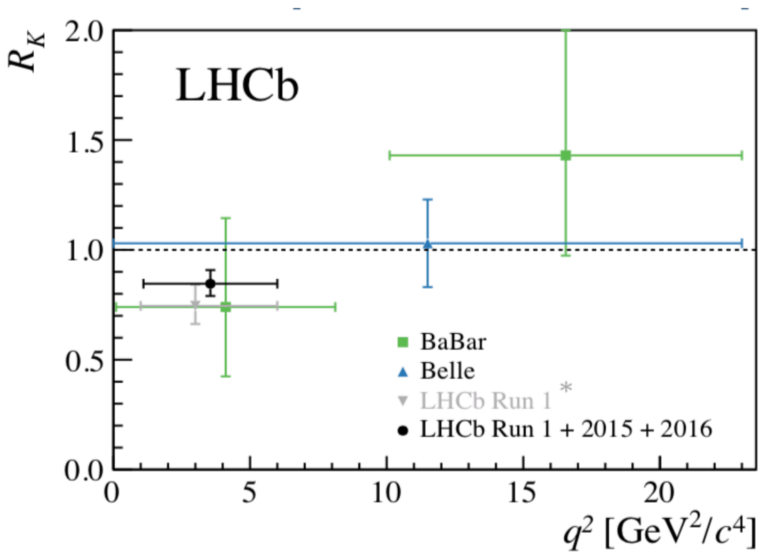
Global fit with just ‘clean’ obs.

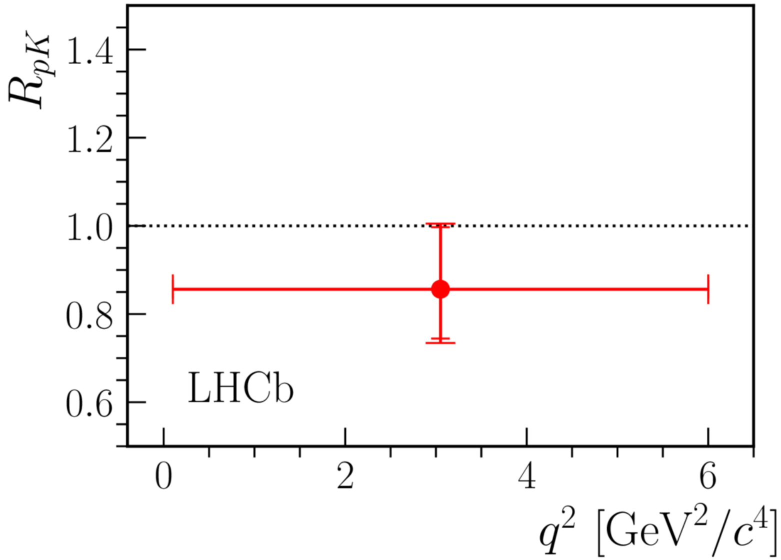


- Using *just* theoretically clean observables, R_K, R_{K^*} and BF($B \to \mu\mu$), can exclude SM at **3.6σ** level

LFU in neutral-current decays

- Recent LHCb measurement of a further LFU ratio, R_{pK}
  - Submitted to JHEP [arXiv:1912.08139]



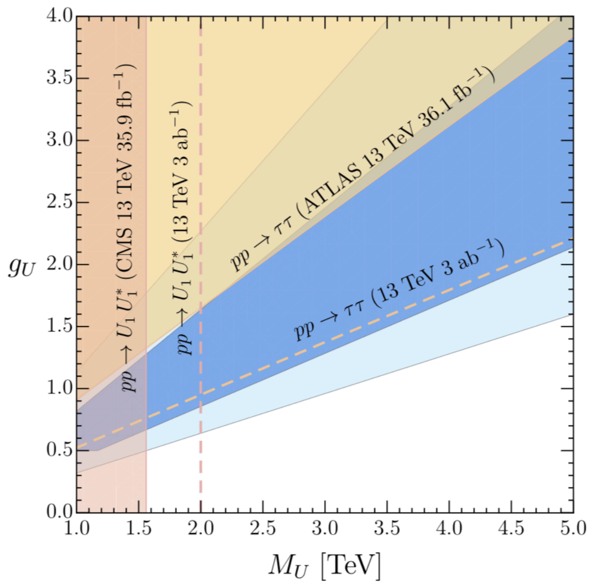


$$R_K = 0.846\,^{+0.060}_{-0.054}\,(\text{stat})\,^{+0.014}_{-0.016}\,(\text{syst})$$

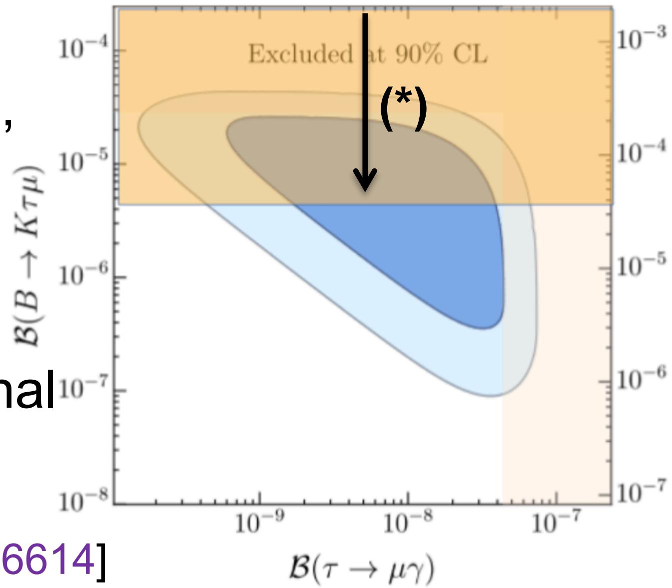
$$R_{pK}|_{0.1<q^2<6\,\text{GeV}^2/c^4} = 0.86\,^{+0.14}_{-0.11} \pm 0.05$$

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 *e.g.* pp→ττ
  - Expect effects in *e.g.* B→τμ, B→Kττ *etc.*, which can be huge
  - While need LFUV, LFV is not mandatory [arXiv:1505.05164]
  - UV complete models give rise to additional particles



[arXiv:1903.11517]



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

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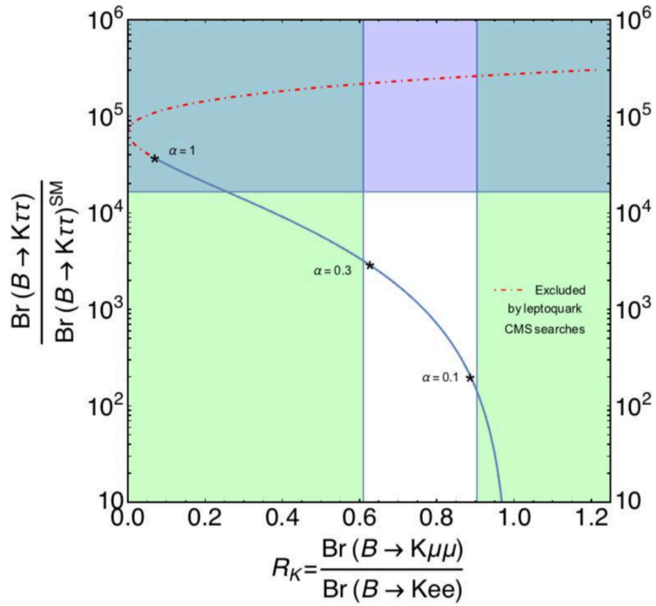
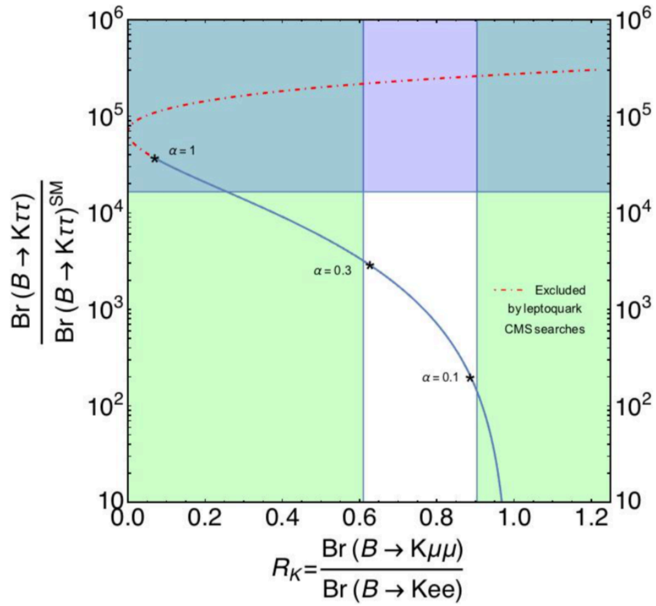


[arXiv:1505.05164]

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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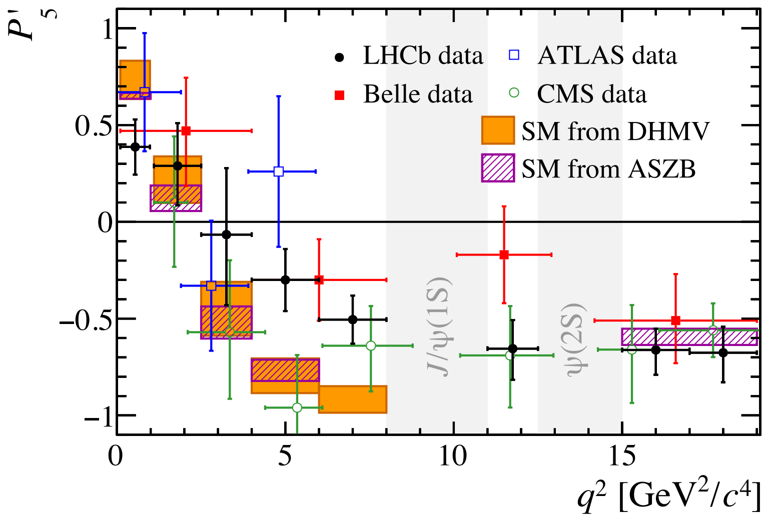
Future measurements

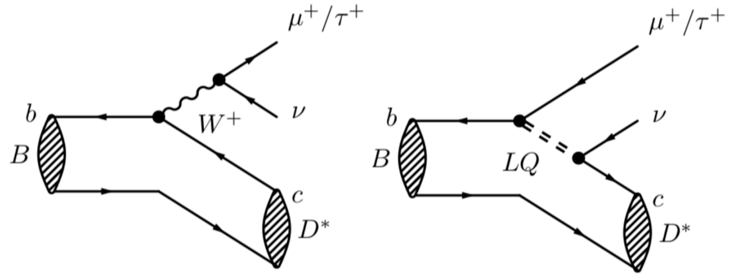
- BFs already limited by precision of theory predictions
- Expect substantial gains from updated angular analysis
  - In short term, expect factor ~2 increase in $B^0 \rightarrow K^{*0}\mu\mu$ precision from analysis of 2016 LHCb data
  - Further factor ~2 improvement in precision from 2017,18 data
  - Will take time to do precise job but e.g. P_5' in electron modes looking SM-like would be compelling

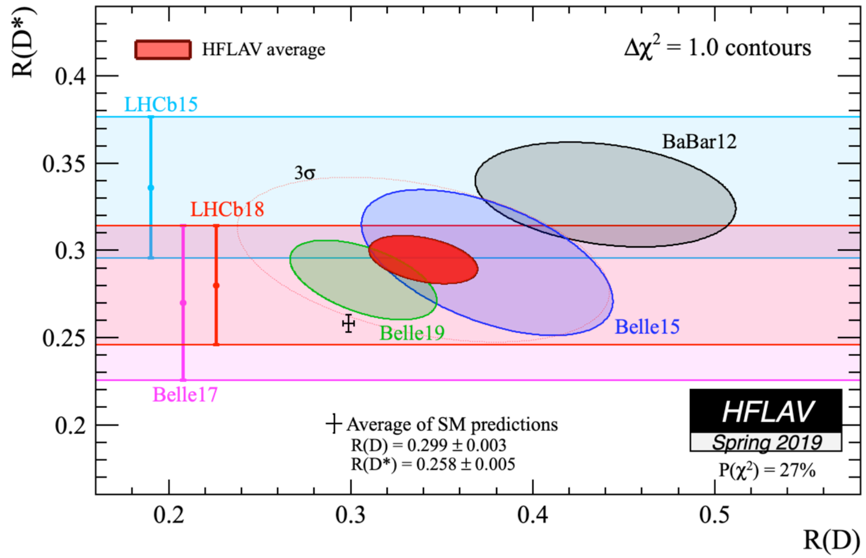


[PLB 781 (2018) 517]
[JHEP 10 (2018) 047]
[PRL 118 (2017) 111801]
[JHEP 02 (2016) 104]

Future measurements – CC

- For the charged-current decays – a simultaneous measurement of $R_D, R_D{}^*$ is in progress at LHCb
  - IMO not obvious this will have the precision to change the picture definitively
  - Analysis of equivalent ratio in $\Lambda_b \rightarrow \Lambda_c l \nu$ decays, $R(\Lambda_c)$ is also well-advanced





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Future measurements – NC

- R_K update with 2017, 2018 data will effectively double the existing dataset
  - Try to minimise changes to technique; enable smoother review
  - Nonetheless, expect result to receive intense internal scrutiny
  - NB – present R_K result separated into different data-taking periods:

$$R_K^{7\,\mathrm{and}\,8\,\mathrm{TeV}} = 0.717\,^{+\,0.083}_{-\,0.071}\,^{+\,0.017}_{-\,0.016}\,,$$
$$R_K^{13\,\mathrm{TeV}} = 0.928\,^{+\,0.089}_{-\,0.076}\,^{+\,0.020}_{-\,0.017}\,,$$

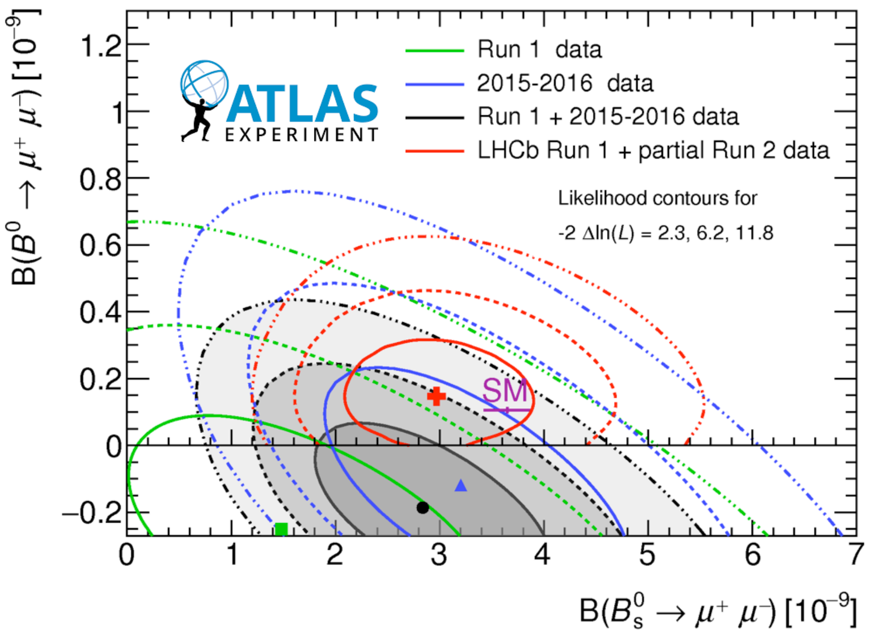
  - Compatibility (1.9σ) checked while result still blind
  - In several *years* of study have found no feature that suggests any unaccounted for difference in performance between run1, 2
  - Trend in remainder of run2 data will clearly be of interest

- Other decay modes – R_{K^*} for model discrimination; R_ϕ to check bkgrd control; $D_s \to \phi(ee)\pi$ to check low q^2; high q^2 analyses

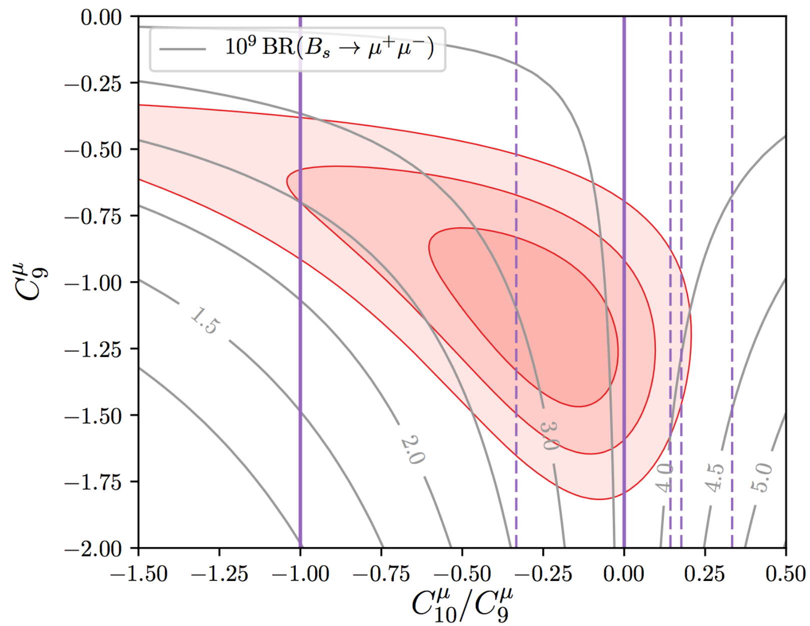
Future measurements – NC

- With $C_9^{NP} = -C_{10}^{NP}$ would eventually expect to see an effect in $B(B^0_s \to \mu^+\mu^-)$ decays

- Also expect to see a different pattern in $B^0 \to K^{*0}\mu^+\mu^-$ angular analysis



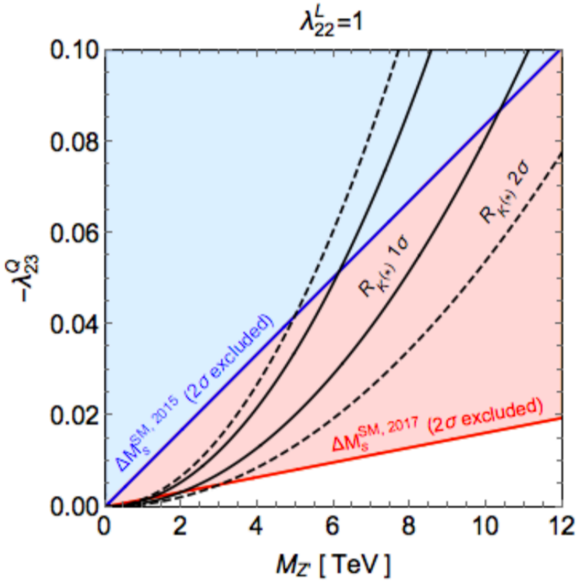
[JHEP 04 (2019) 098]

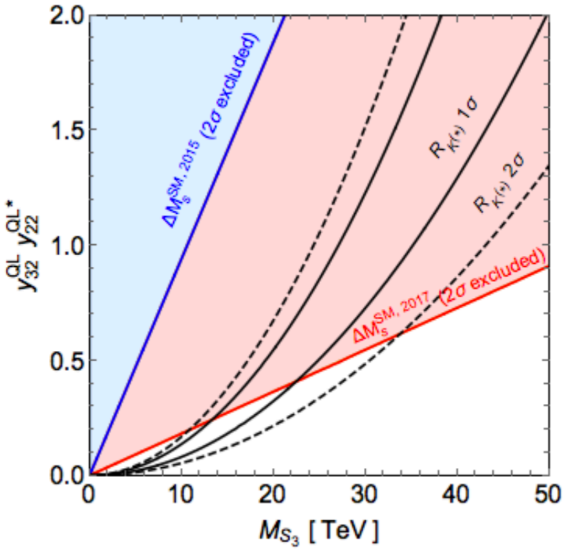


[PRD 96 (2017) 055008]

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 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