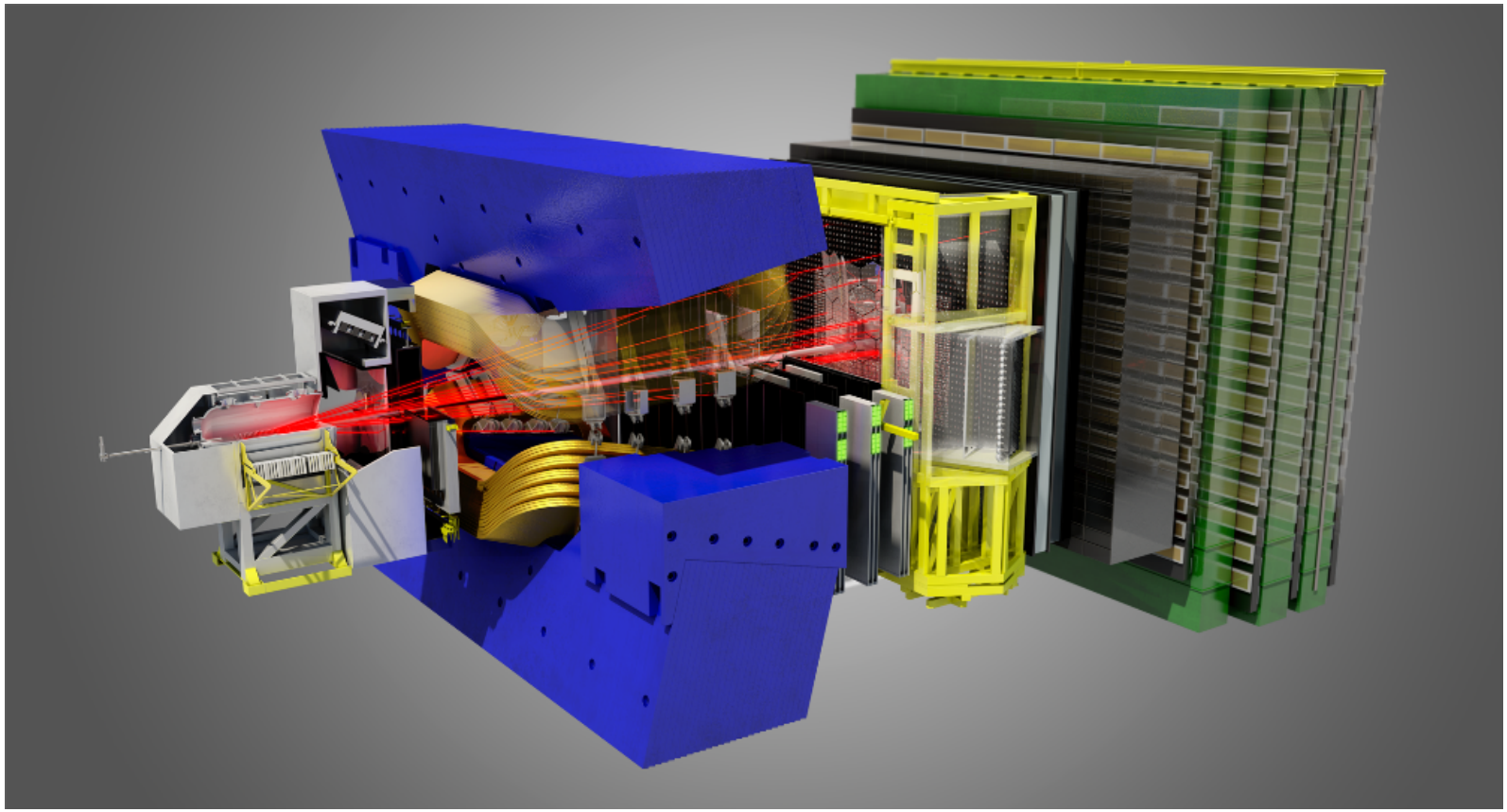
B anomalies at LHCb



Flavour and Dark Matter, 28th September 2017

Mitesh Patel (Imperial College London)
on behalf of the LHCb collaboration

Imperial College London

LHCb

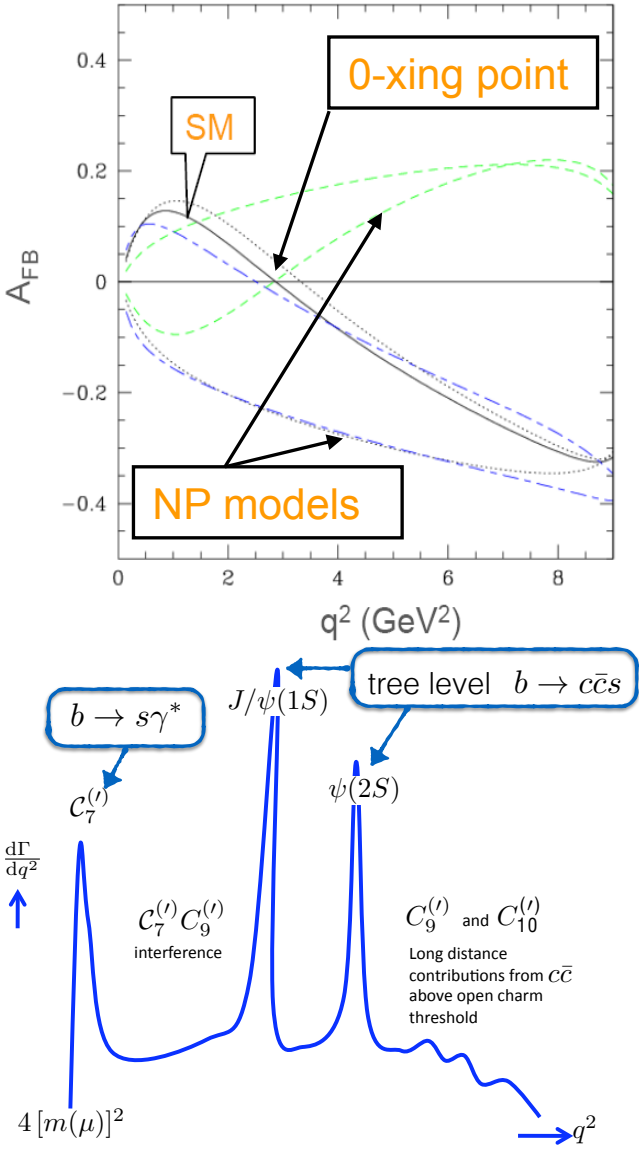
Introduction

- Interesting set of anomalies have appeared in measurements made at the LHCb experiment :
  - Angular observables in $B^0 \to K^{*0} \mu\mu$
  - Branching fractions of several $b \to s\ell\ell$ decays
  - Lepton-flavour universality in $b \to s\ell\ell$ decays
  - Lepton-flavour universality in $b \to c\ell\nu$ decays

- Extent of discrepancies depends on several theoretical issues – will try and highlight some of these

Rare decays – b→sll

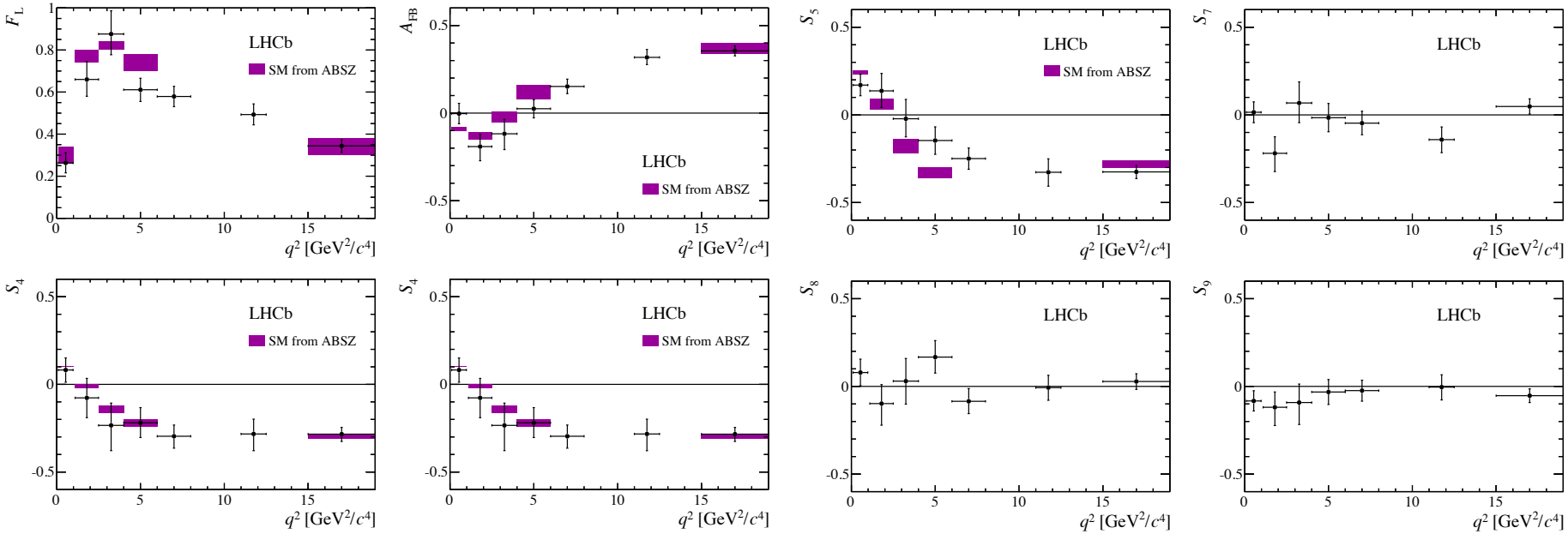
- b→sll decays involve flavour changing neutral currents → loop process
- At LHCb, best studied decay $B^0 \to K^{*0}\mu\mu$
- Large number of observables: BF, A_{CP} and angular observables – dynamics can be described by three angles (θ_l, θ_K, ϕ) and di-μ invariant mass squared, q^2
- Try to use observables where theoretical uncertainties cancel e.g. Forward-backward asymmetry A_{FB} of θ_l distribution
- Interpreted in effective field theory describing couplings (C) of photon (O_7), vector (O_9) and axial-vector (O_{10}) operators



dimuon invariant mass squared, q^2

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

- Have performed first full angular analysis [JHEP 02 (2016) 104]
  - Extract the full set of CP-averaged angular terms and their correlations
  - Determine a full set of CP-asymmetries

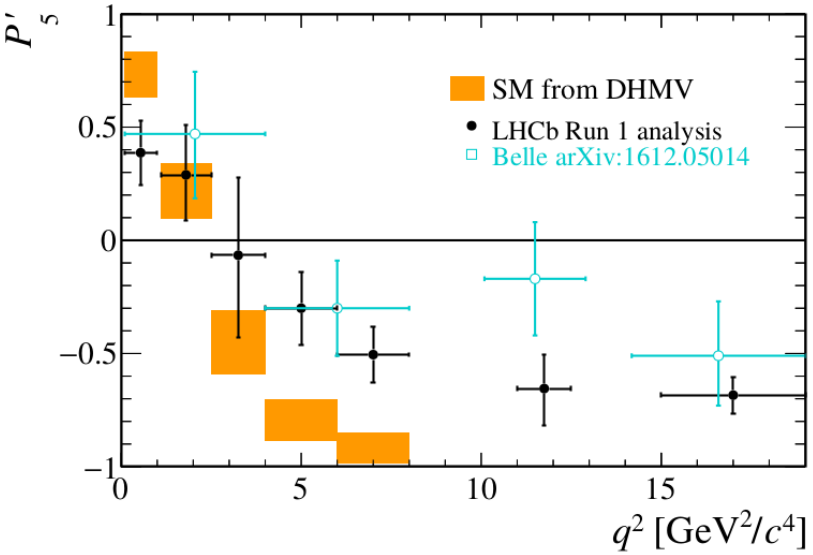


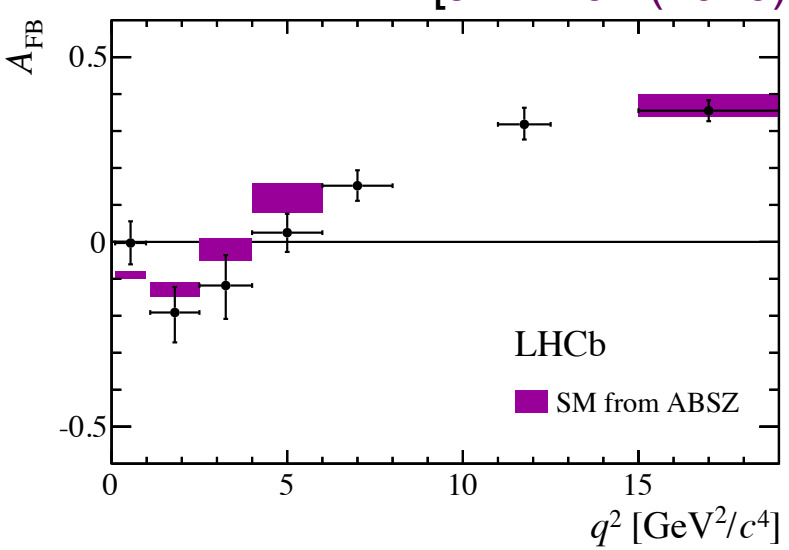
- Vast majority of observables in agreement with SM predictions, giving some confidence in theory control of relevant form-factors

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

- In SCET/QCD factorisation can reduce to just two form-factors- can then construct ratios of observables which are independent of form-factors at LO [JHEP 1204 (2012) 104]

[JHEP 02 (2016) 104]



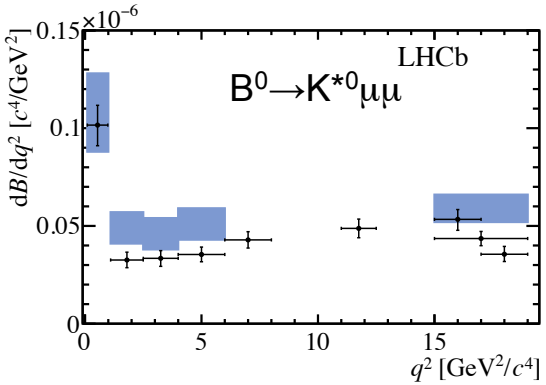


- Form-factor "independent" P_5' has a local discrepancy in two bins – (subsequently confirmed by Belle [PRL 118 (2017) 111801])
- Form-factor dependent A_{FB} hints at a trend, but is consistent with SM

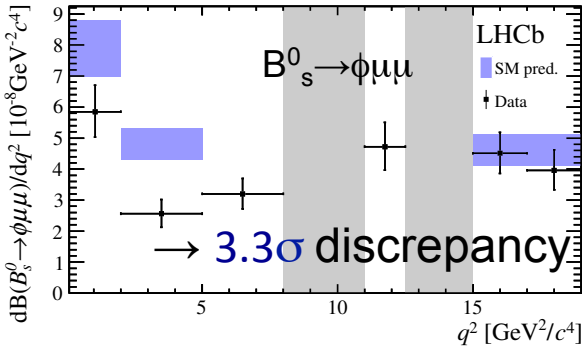
→ **3.4σ discrepancy with the vector coupling $\Delta C_9 = -1.04 \pm 0.25$**

b→sll Branching Fractions

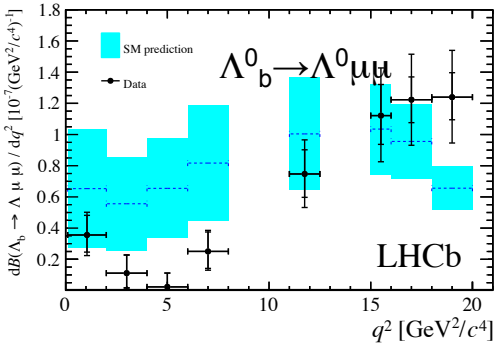
- Several b→sll branching fractions measured, show some tension with predictions, particularly at low q^2



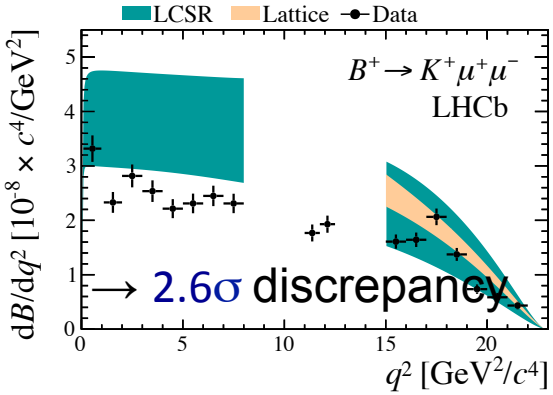
[JHEP 11 (2016) 047, JHEP 04 (2017) 142]

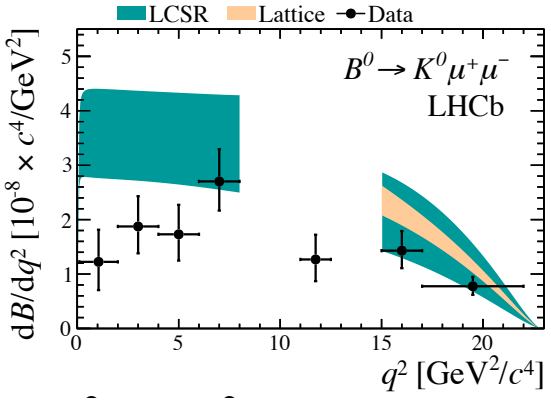


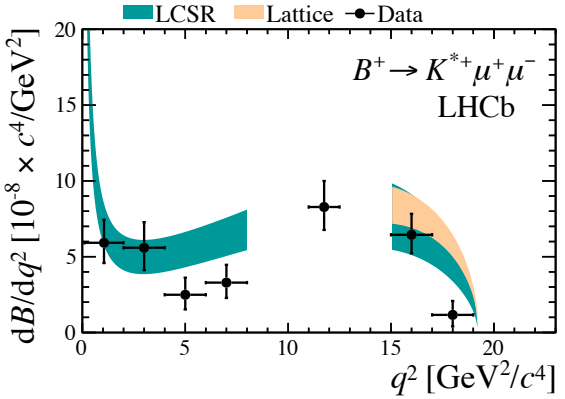
[JHEP 09 (2015) 179]



[JHEP 06 (2015) 115]



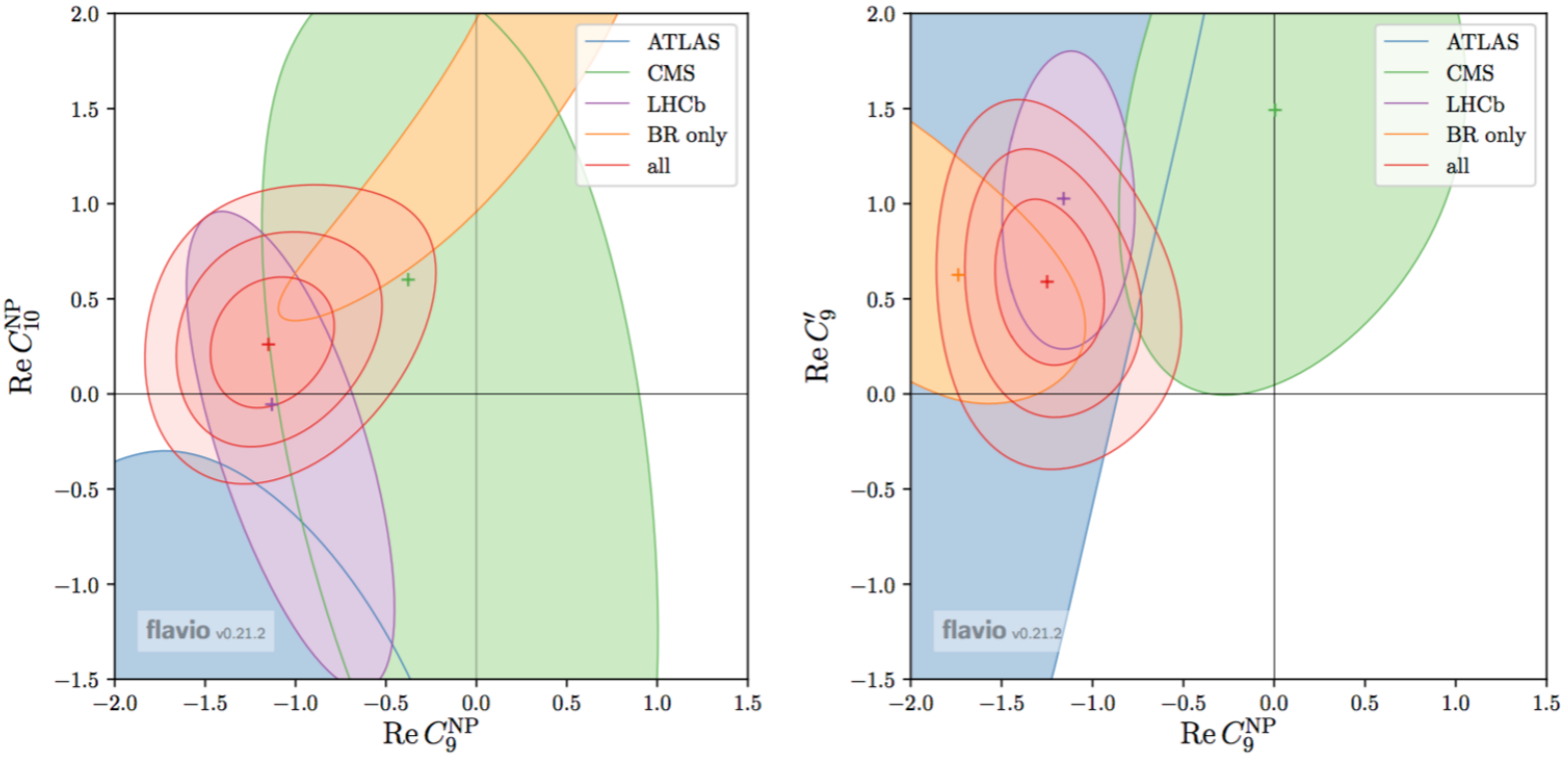




[JHEP 06 (2014) 133]

b→sll interpretation

- Several groups have interpreted results by performing global fits to b→sll data e.g. [arXiv:1704.05340, EPJC(2017)77:377]



- Consistent picture, tensions solved simultaneously by a modified vector coupling (ΔC_9 != 0) at >**3σ**

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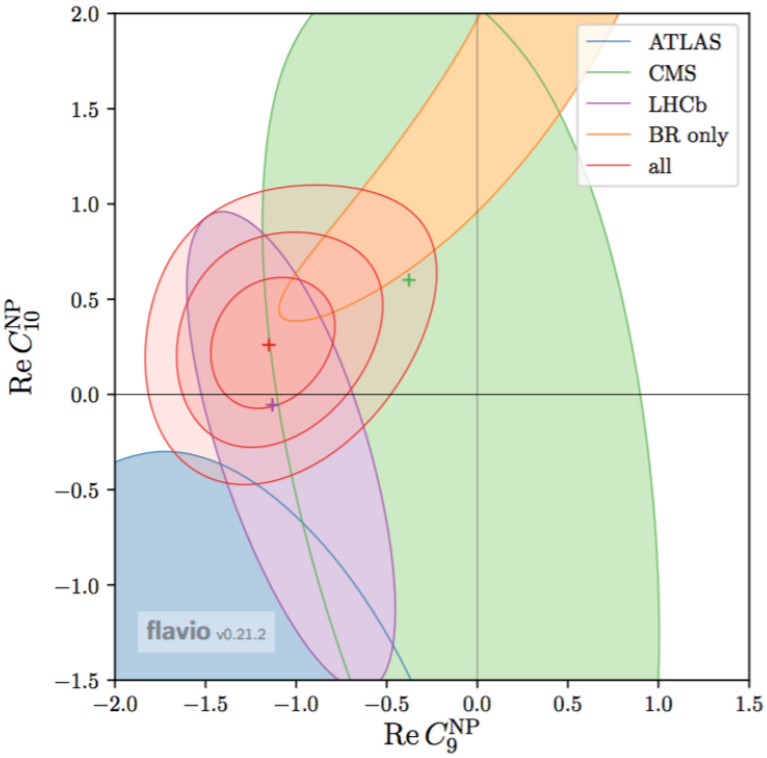
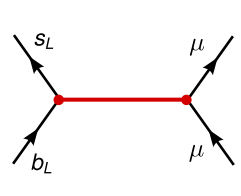
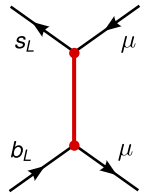


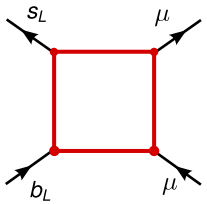
Discrepancies have got enough interest st model builders have started to step-in...



- Z'
- $SU(2)_L$ singlet or triplet



- Leptoquark
- Spin 0 or 1



- New scalars/vectors, also leptoquarks possible

For a review see, *e.g.* D.Straub @ Instant workshop on B meson anomalies

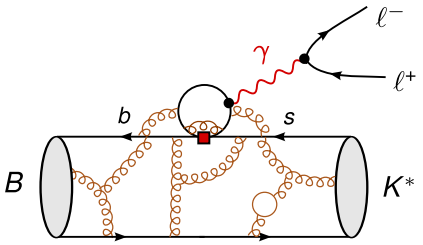
- Consistent picture, tensions solved simultaneously by a modified vector coupling (ΔC_9 != 0) at >**3σ**

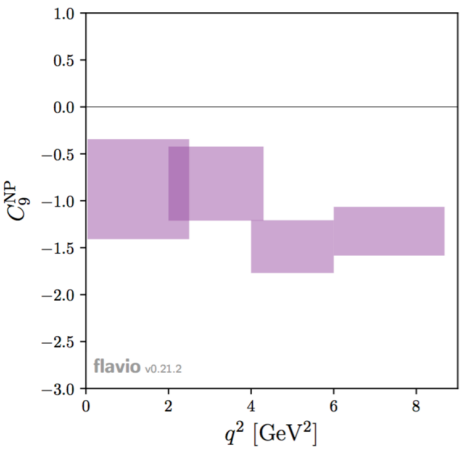
b→sll interpretation

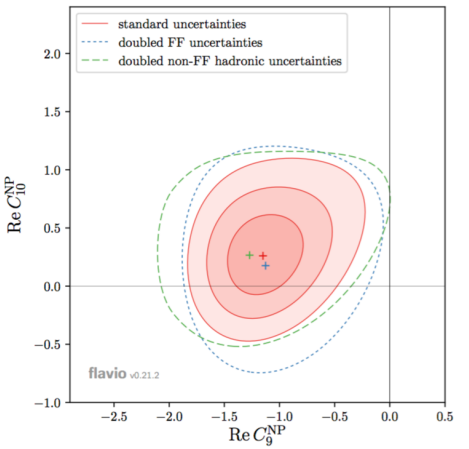
- Community have started to look critically at the theory predictions – in particular, the $O_{1,2}$ operators have a component that could mimic a NP effect in C_9 through $c\bar{c}$ loop

- Effect can be parameterised as function of three helicity amplitudes, h_{+-0} [EPJC (2017) 77: 377]
  - Absorb effect of these amplitudes into a helicity dependent shift in C_9,
    $C_9^{SM} + \Delta C_9^{+-0}(q^2)$ cf. $C_9^{SM} + \Delta C_9^{NP}$
    Look for q^2 and helicity dependence of shift in C_9
  - "The absence of a q^2 and helicity dependence is intriguing, but cannot exclude a hadronic effect as the origin of the apparent discrepancies"

- Recent 1st NLO calculation of contribution includes phases between long and short-distance amplitudes for 1st time







[JHEP04(2017)016, EPJC (2017) 77: 377]

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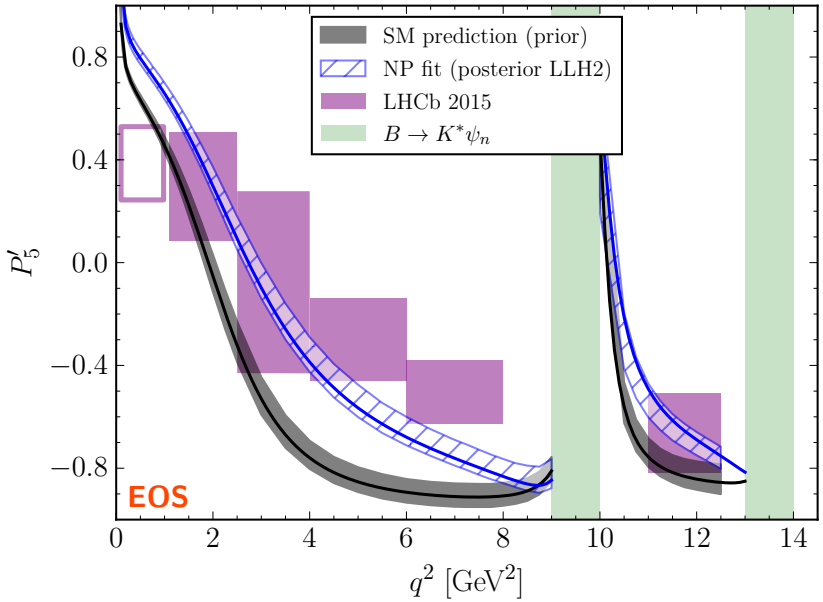
[arXiv:1707.07305]



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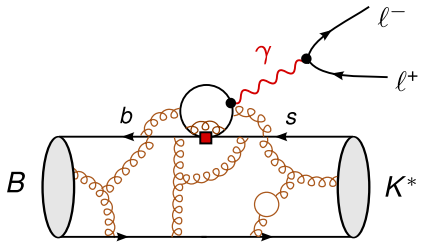
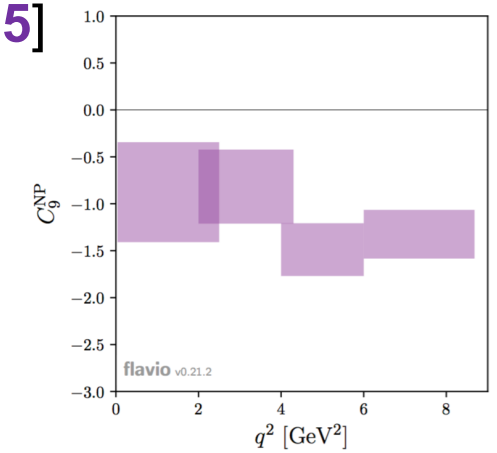
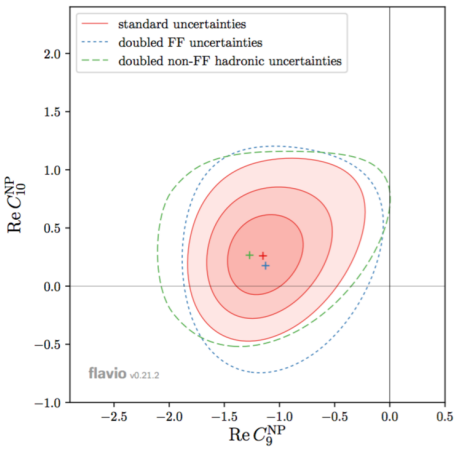






[JHEP04(2017)016, EPJC (2017) 77: 377]

Lepton universality with loop decays

[JHEP 08 (2017) 055]

- Whatever hadronic uncertainties affect $b \to s\ell\ell$ decays, they should cancel in the ratio of branching fractions

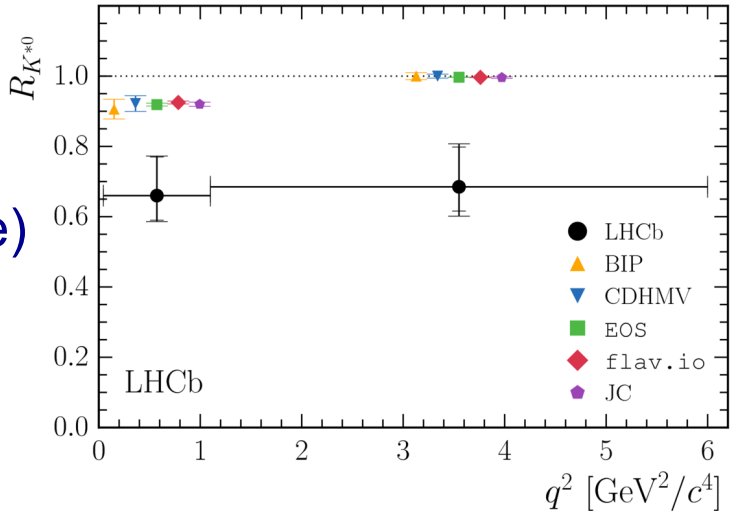
  $R_{K^{*0},K} = B(B^{0,+} \to K^{*0,+}\mu\mu) / B(B^{0,+} \to K^{*0,+}ee)$

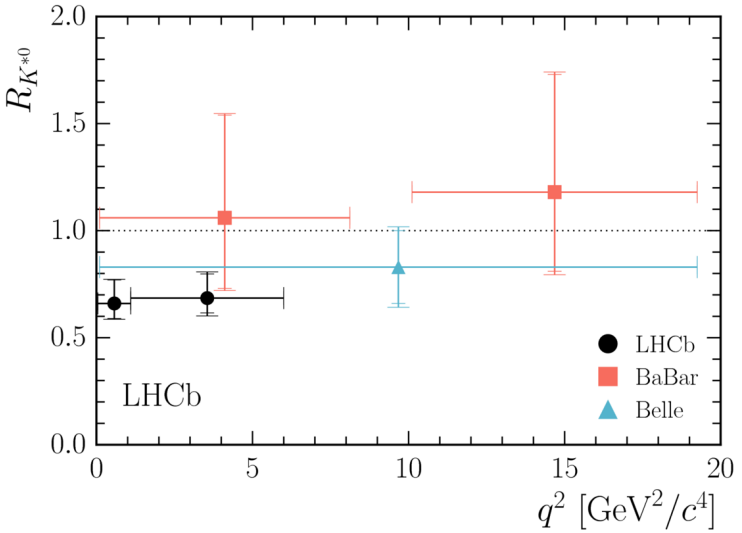
- LHCb measurement of $\mathbf{R_K}$ is 2.6σ below SM prediction [PRL 113 (2014) 151601] and consistent with $\Delta C_9^{ee}=0$, $\Delta C_9^{\mu\mu}=-1$

- Recent $\mathbf{R_{K^*}}$ measurement
  - low q^2 : 2.1-2.3σ below SM prediction
  - Central q^2 : 2.4-2.5σ below SM prediction

  (depending on theory prediction used) – further increases discrepancy

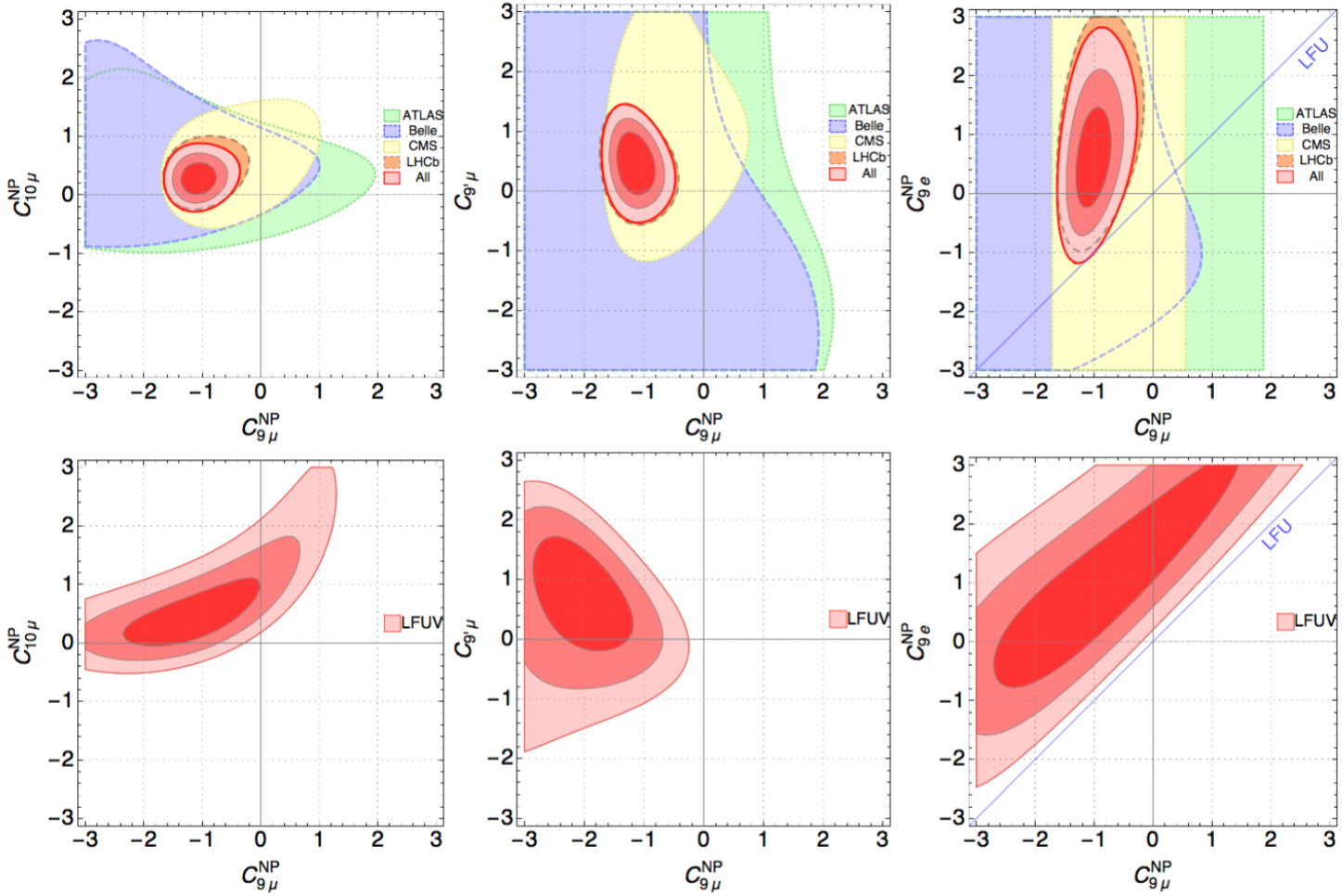
  [JHEP 08 (2017) 055]





b→sll interpretation

- Adding the LFU measurements in, the size of the discrepancy → 5σ but community still reluctant to call this NP [arXiv:1704.05340]

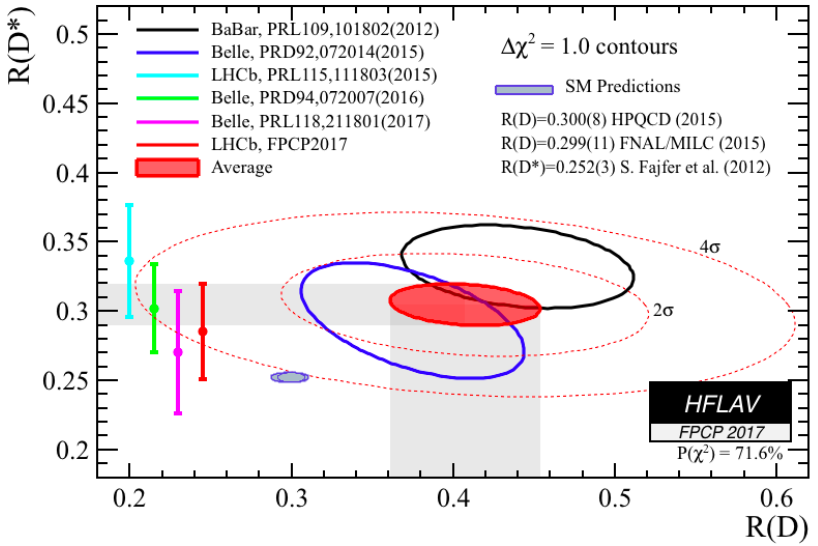


Lepton universality with tree decays

- An anomalous effect is also seen in the ratio of **tree-level** BF
  $R_D^* = B(B^0 \to D^{*+}\tau\nu)/B(B^0 \to D^{*+}\mu\nu)$

- LHCb analyses reconstruct the tau using $\tau \to \mu\nu\nu$ decays [PRL115 (2015) 111803] and $\tau \to 3\pi\nu$ decays [arXiv: 1708.08856]

- Confirms effect seen in R_D,R_{D^*} at BaBar/Belle, HFLAV combined significance now 4.1σ

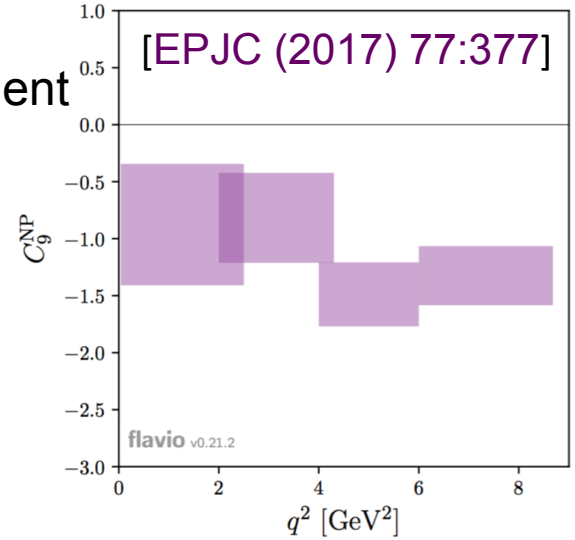


- LQ models exist that are able to explain R_K, R_{D^*} (and $(g-2)_\mu$) [PRL 116 (2016) 141802]

Ideas for the future

Near term prospects

- All of the measurements discussed will be updated with the first part of the Run II dataset (2015, 16 data)
  - $B^0 \to K^{*0}\mu\mu$ angular analysis: expect ~$\sqrt{2}$ improvement in precision
  - R_K : expect factor ~1.8 improvement in precision
  - R_{K^*} : expect factor ~1.5 improvement in precision



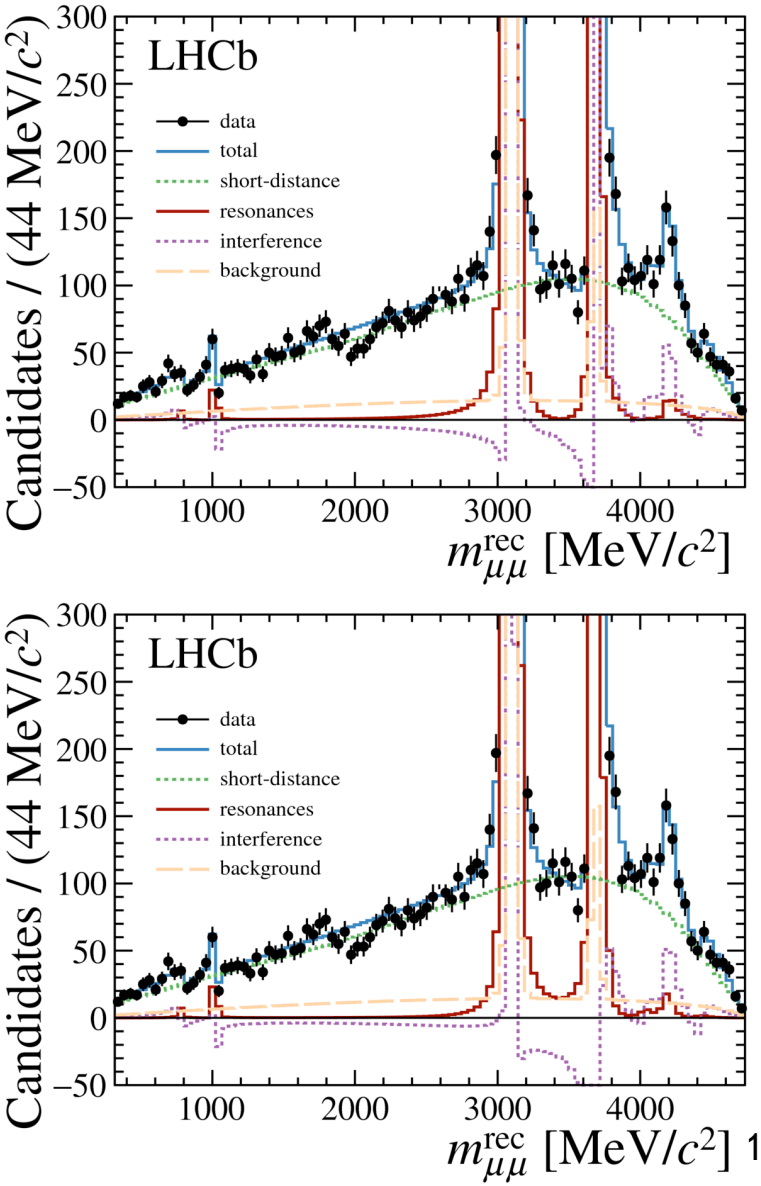
- New related measurements also in preparation:
  - R_ϕ : suppressed by f_s/f_d~0.25 and $B(\phi \to K^+K^-)$=½ but narrow mass window, absences of $\phi\pi$ resonances will reduce backgrounds
  - $K^{*0}ee$ angular analysis will enable to form ratios of angular observables

- LHCb measurement of (R_D,R_{D^*}) in preparation. Will also perform measurements with other b-hadrons e.g. B_s, B_c and Λ_b

Longer term prospects

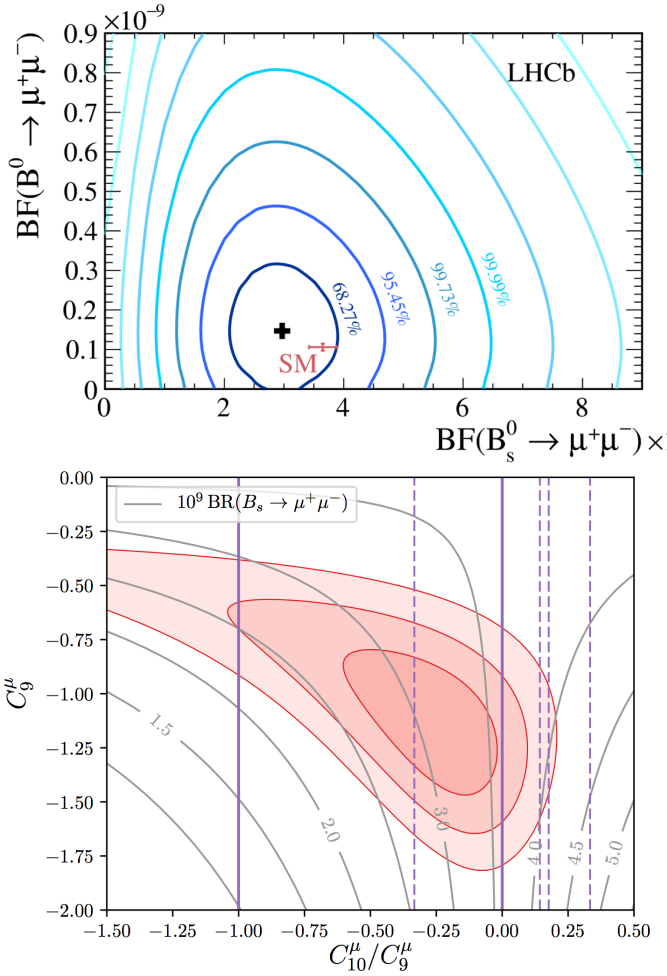
Controlling $c\bar{c}$ effects in $B^0 \to K^{*0}\mu\mu$

- At low q^2, $\Delta C_9^{+-0}(q^2)$ term arises mainly from interference penguin decay and J/ψ
  - Measure phase of interference by fitting differential rate (and angles)
- Such a fit has been performed for $B^+ \to K^+\mu^+\mu^-$ [EJPC (2017) 77:161], considerably more complex for $B^0 \to K^{*0}\mu\mu$ but principle the same
- Based on a simple model, LHCb will be able to measure the magnitude and phase of resonant contributions



$B^0 \to \mu^+\mu^-$ analysis

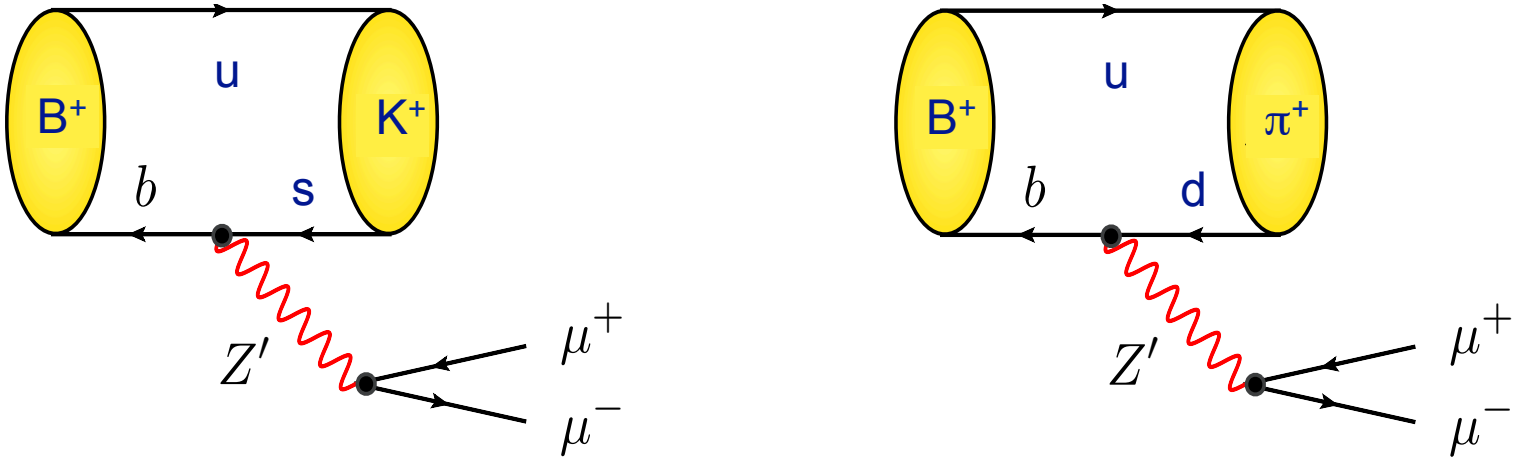
- Single-particle explanations of anomalies predict $\mathbf{C_9^{NP} = -C_{10}^{NP}}$, global fits are still compatible with such a solution
- If this were the case would expect to see effect in $B(B^0 \to \mu^+\mu^-)$ decays
- Latest LHCb measurement
  - $\mathbf{B_s^0 \to \mu^+\mu^-}$ established at 7.8σ
  - $B(\mathbf{B_d^0 \to \mu^+\mu^-}) < 3.4 \times 10^{-10}$ @ 95% CL
  - LHCb/CMS combination found $\mathbf{B_d^0 \to \mu^+\mu^-}$ evidence at 3.2σ
- No evidence for any deviation from SM so far… but this measurement will be important for the future



[PRL118(2017)191801] [DS@Instant w/shop]

LFU in suppressed decays

- Can try and compare b→s and b→d transitions e.g. to see if $R_K = R_\pi$
- Run I + Run II data set would give ~500 $\pi^+\mu^+\mu^-$ events
  → with $R_K=R_\pi$ expect 50 $\pi^+e^+e^-$ events – might be able to see decay
- With a leptoquark could presumably get NP diagram with different b→d suppression and/or different lepton flavours
- Effort starting on $(K,K^*,\phi)e\mu$ searches; even some effort on $\mu\tau$ and $\tau\tau$ modes



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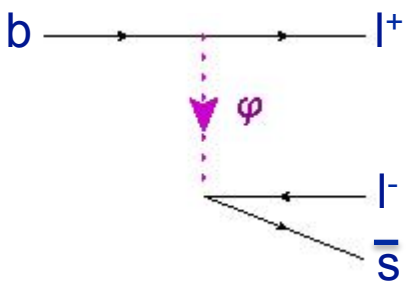
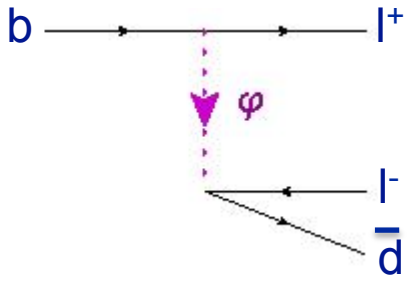




Semileptonic decays

- Most stringent tests of LFU involve only 1st-2nd generation quarks/ leptons
- Can conceive NP models where LFU is violated more in processes involving 3rd generation quarks/leptons
  - Constraints on $\Gamma(b \to c\mu\nu)/\Gamma(b \to ce\nu)$ from B-factories are relatively weak … can compete at LHCb?
  - Would expect breaking of LFU in charged currents to be universal on the quark side for $b \to c$ and $b \to u$ … can test this?

[G. Isodori @ CERN 'instant' workshop]

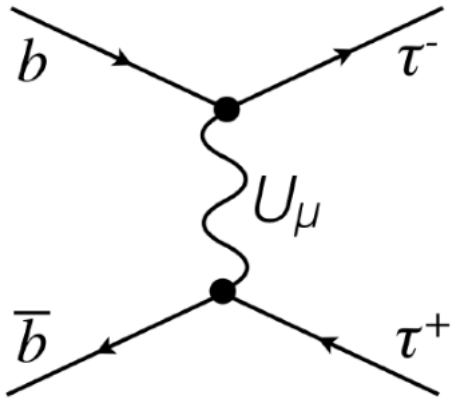
$$\mathrm{BR}(B \to D^{*}\tau\nu)/\mathrm{BR}_{SM} = \mathrm{BR}(B \to D\tau\nu)/\mathrm{BR}_{SM} = \mathrm{BR}(\Lambda_b \to \Lambda_c\tau\nu)/\mathrm{BR}_{SM} = \ldots$$
$$= \mathrm{BR}(B \to \pi\,\tau\nu)/\mathrm{BR}_{SM} = \mathrm{BR}(\Lambda_b \to p\,\tau\nu)/\mathrm{BR}_{SM} = \mathrm{BR}(B_u \to \tau\nu)/\mathrm{BR}_{SM}$$
$$= \ldots$$

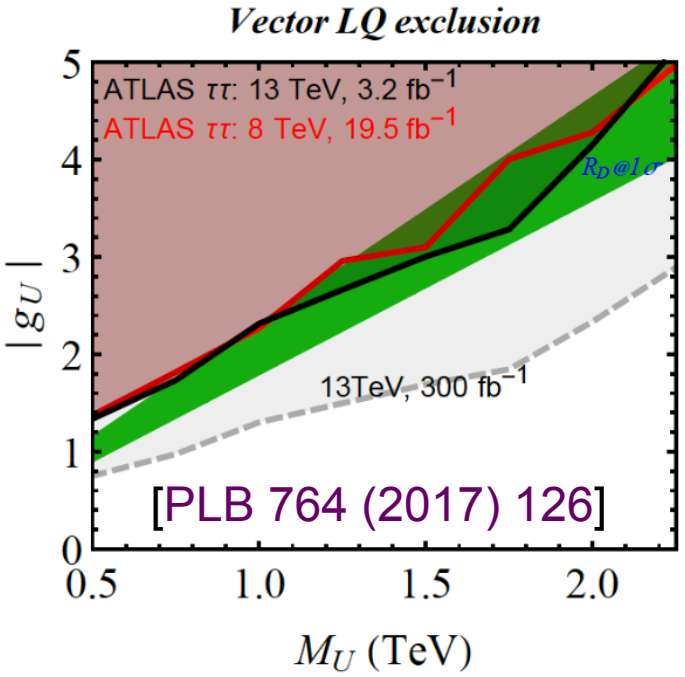
N.B.: $\mathrm{BR}(B_u \to \tau\nu)^{exp}/\mathrm{BR}_{SM} = 1.31 \pm 0.27$ UTfit. '16

Semileptonic decays

- R_D, R_{D^*} → NP scale <2TeV (or remove CKM suppression in NP)

- Given low mass-scale, direct searches will be able to search for any mediator of these anomalies e.g. ATLAS Z' →ττ search recast to look for leptoquark





Conclusions

- Interesting set of anomalies observed in B decays at LHCb – given experimental precision and theoretical uncertainties, none of them are yet compelling IMHO
- Near-term updates should clarify the experimental situation and can help constrain some of the theoretical issues
- Wide range of measurements will be added to broaden the constraints on any new physics
- Full Run-II dataset will give a factor ~5 more statistics than Run-I on timescale that Belle-2 will start physics running