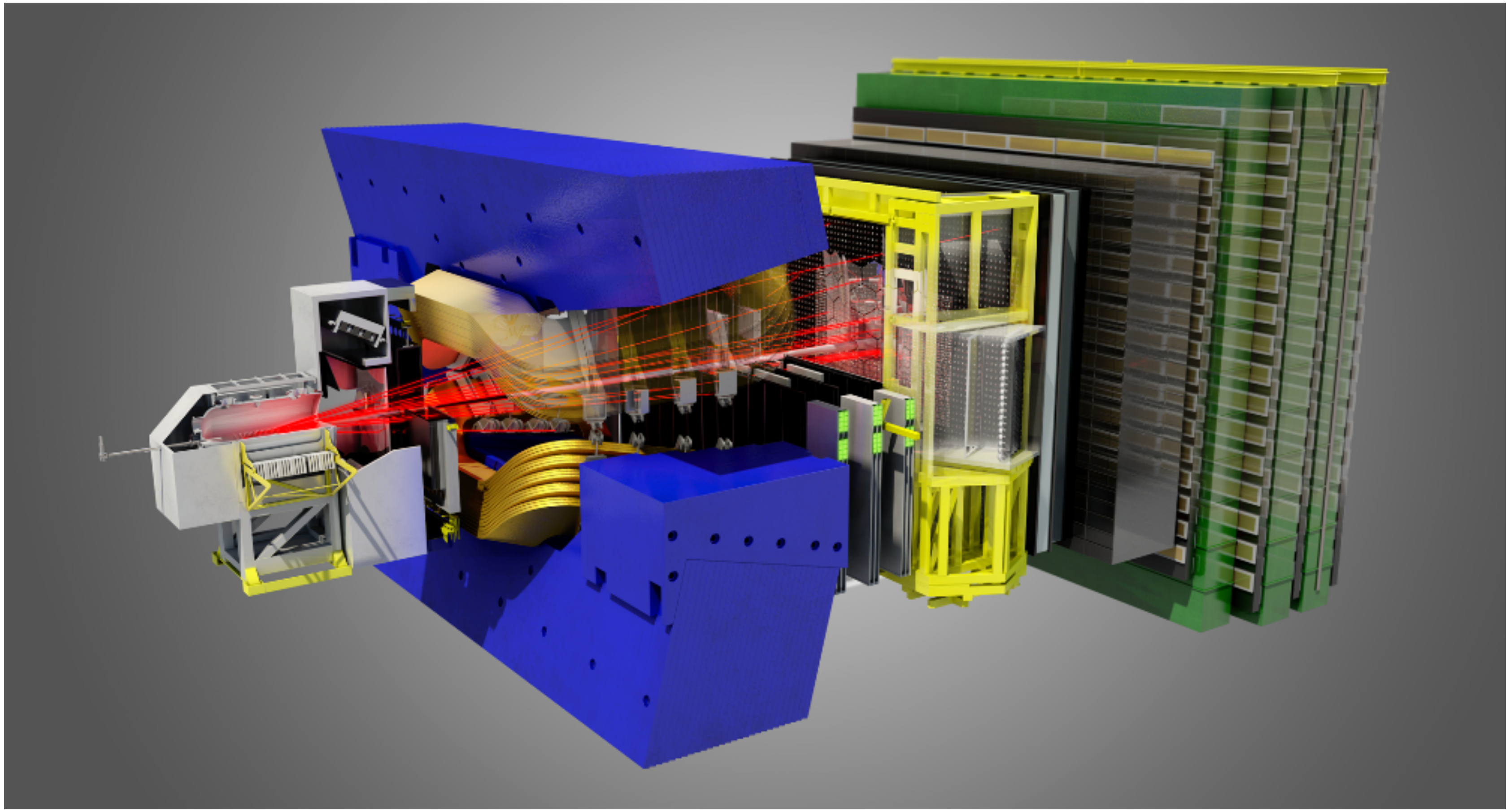
The B-anomalies



Mitesh Patel (Imperial College London)

Planck Conference, 30th June 2021

Imperial College London

LHCb

Introduction

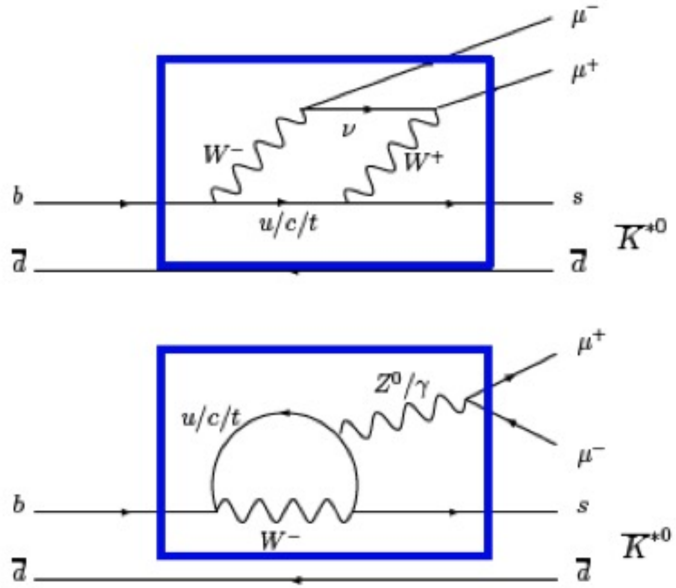
- Interesting set of anomalies have appeared in measurements of B decays :
  - Branching fractions of several $b \to (s)ll$ processes
  - Angular observables in $B^0 \to K^{*0}\mu\mu$
  - Lepton-flavour universality ratios in $b \to cl\nu$ and $b \to sll$ decays
- Extent of discrepancies depends on some theoretical issues
  - Will try and connect with these issues as I go through but details in D. Van Dyk's talk from yesterday and M.Blanke later today
- B-decays of interest when well-calculable process, sensitive to new physics can be measured…

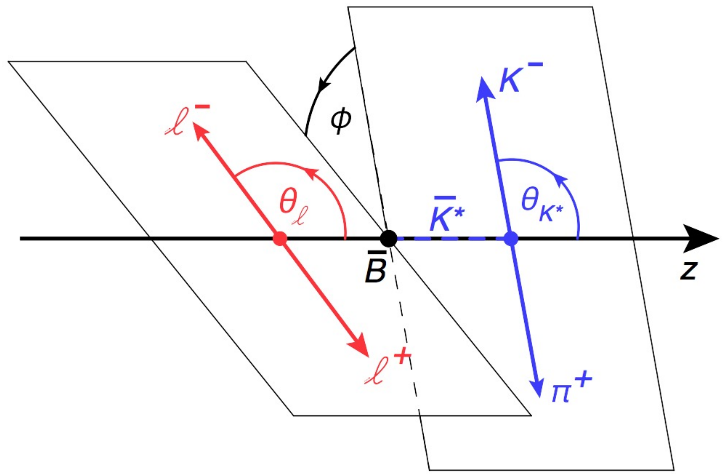
b→sll decays

- b→sll decays involve flavour changing neutral currents → loop process

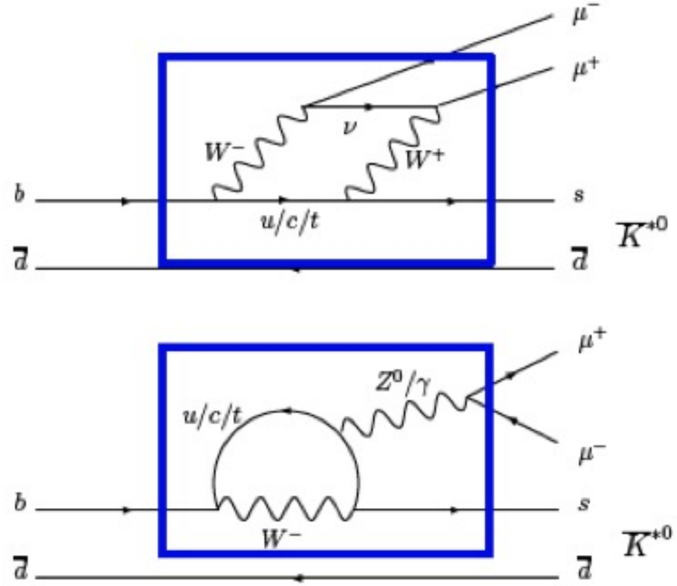
- Best studied decay $B^0 \to K^{*0}\mu\mu$

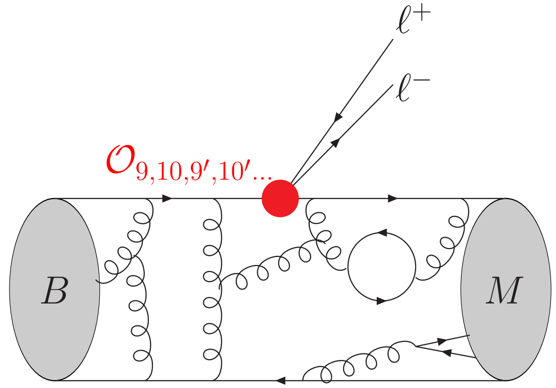
- Large number of observables: BF, A_{CP} and angular observables – dynamics can be described by three angles (θ_l, θ_K, ϕ) and di-μ invariant mass squared, q^2

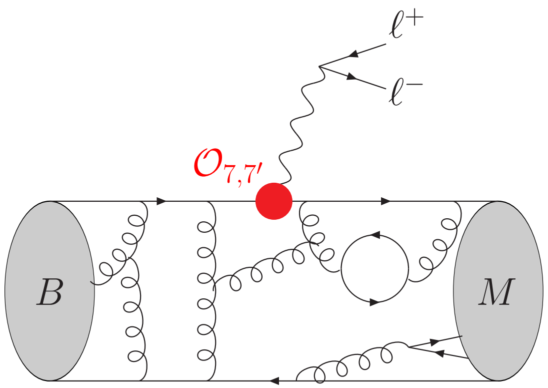


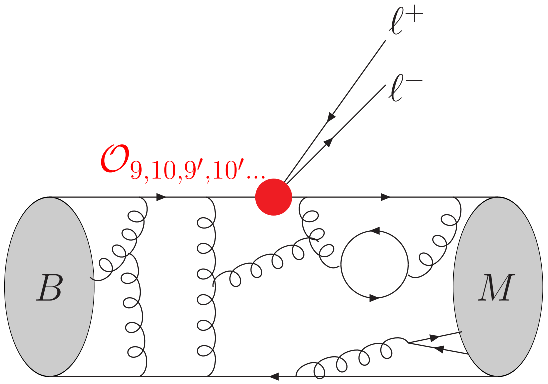


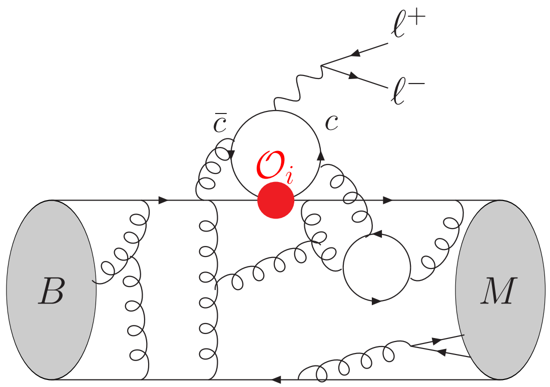
Hadronic Effects











Form factors (local) Form factors (local) (non-local) Charm loop

Theoretical Foundation

- The **Operator Product Expansion** is the theoretical tool that underpins rare decay measurements – rewrite SM Lagrangian as :

$$\mathcal{L} = \sum_i C_i O_i$$

  - "Wilson Coefficients" C_i
    - Describe the short distance part, can compute perturbatively
    - Integrate out the heavy particles that can't resolve at some scale μ
  - "Operators" O_i
    - Describe the long distance, non-perturbative part, particles below scale μ
    - Account for effects of strong interactions, difficult to calculate reliably

Form a complete basis – can put in all operators from NP/SM

$B^0 \to K^{*0}\mu\mu$ C_i and form factors

- Amplitudes that describe the **$B^0 \to K^{*0}\mu\mu$** decay involve
  - The (effective) Wilson Coefficients: C_7^{eff} (photon), C_9^{eff} (vector), C_{10}^{eff} (axial-vector)
  - Seven (!) form factors – primary origin of theoretical uncertainties

$$A_\perp^{L(R)} = N\sqrt{2\lambda}\left\{\left[(\mathbf{C}_9^{\text{eff}} + \mathbf{C}_9^{\prime\text{eff}}) \mp (\mathbf{C}_{10}^{\text{eff}} + \mathbf{C}_{10}^{\prime\text{eff}})\right]\frac{\mathbf{V}(\mathbf{q}^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(\mathbf{C}_7^{\text{eff}} + \mathbf{C}_7^{\prime\text{eff}})\mathbf{T}_1(\mathbf{q}^2)\right\}$$

$$A_\parallel^{L(R)} = -N\sqrt{2}(m_B^2 - m_{K^*}^2)\left\{\left[(\mathbf{C}_9^{\text{eff}} - \mathbf{C}_9^{\prime\text{eff}}) \mp (\mathbf{C}_{10}^{\text{eff}} - \mathbf{C}_{10}^{\prime\text{eff}})\right]\frac{\mathbf{A}_1(\mathbf{q}^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2}(\mathbf{C}_7^{\text{eff}} - \mathbf{C}_7^{\prime\text{eff}})\mathbf{T}_2(\mathbf{q}^2)\right\}$$

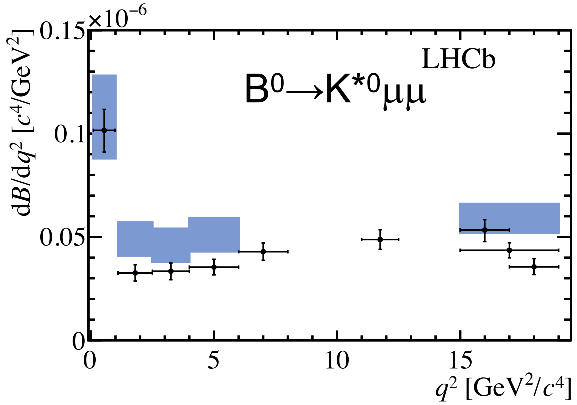
$$A_0^{L(R)} = -\frac{N}{2m_{K^*}\sqrt{q^2}}\left\{\left[(\mathbf{C}_9^{\text{eff}} - \mathbf{C}_9^{\prime\text{eff}}) \mp (\mathbf{C}_{10}^{\text{eff}} - \mathbf{C}_{10}^{\prime\text{eff}})\right]\left[(m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*})\mathbf{A}_1(\mathbf{q}^2) - \lambda\frac{\mathbf{A}_2(\mathbf{q}^2)}{m_B + m_{K^*}}\right]\right.$$
$$\left. + 2m_b(\mathbf{C}_7^{\text{eff}} - \mathbf{C}_7^{\prime\text{eff}})\left[(m_B^2 + 3m_{K^*} - q^2)\mathbf{T}_2(\mathbf{q}^2) - \frac{\lambda}{m_B^2 - m_{K^*}^2}\mathbf{T}_3(\mathbf{q}^2)\right]\right\}$$

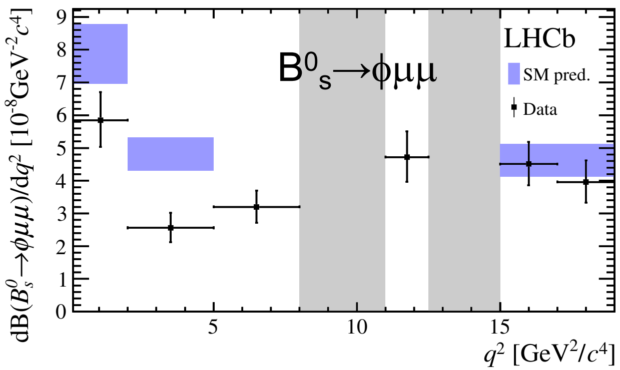
→ BFs have relatively large theoretical uncertainties

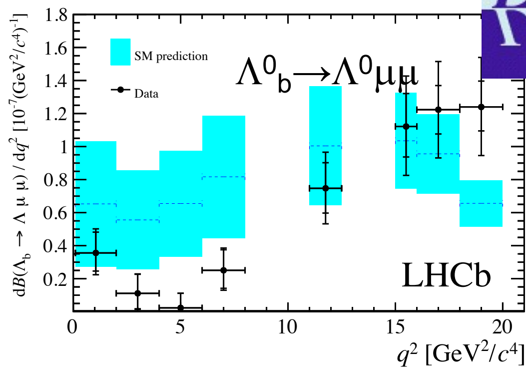
$b \to sll$ branching fractions

b→sll branching fractions

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



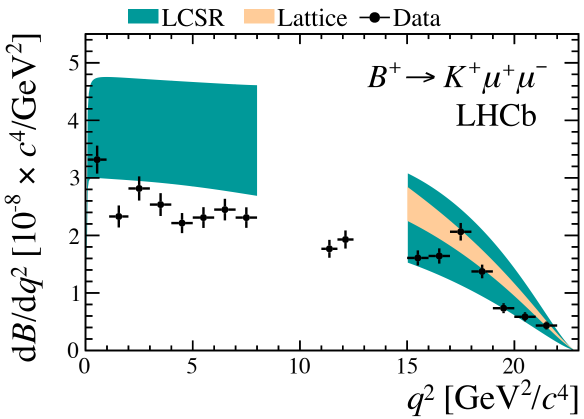


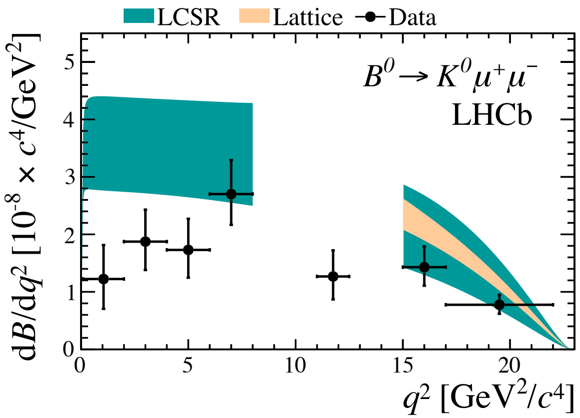


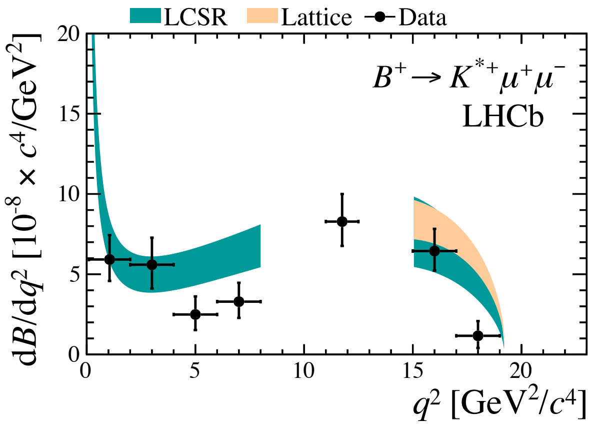
[JHEP 11 (2016) 047, JHEP 04 (2017) 142]

[JHEP 09 (2015) 179]

[JHEP 06 (2015) 115]



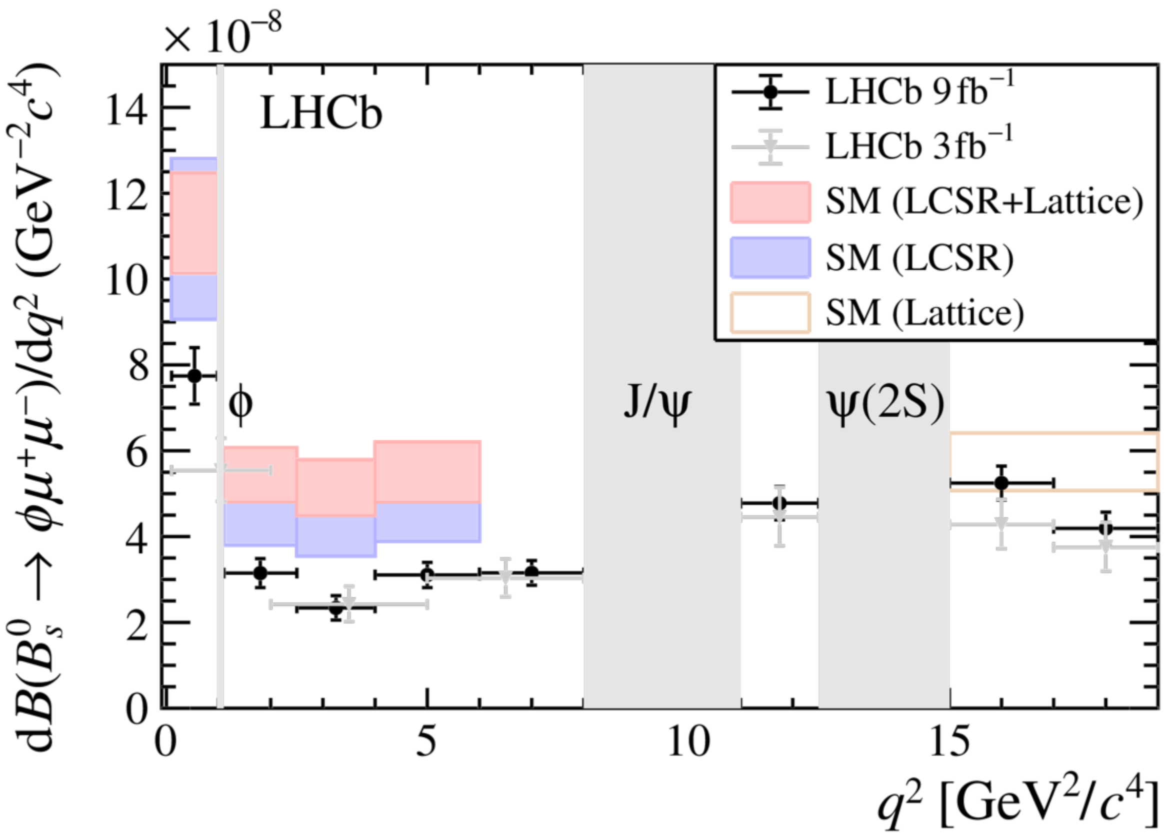




[JHEP 06 (2014) 133]

New BF($B_s \to \phi\mu\mu$) update

- LHCb recently presented updated results for BF($B_s \to \phi\mu\mu$) :



[arXiv:2105.14007]

Run 1 result:

[JHEP 09 (2015) 179], [arXiv:2103.06810]

SM LCSR:

[Bharucha et al., JHEP 08 (2016) 098],

[Altmannshofer et al., EPJ C 75 (2015) 382],

[Straub, arXiv:1810.08132]

SM LCSR+Lattice:

+[Horgan et al., PRL 112 (2014) 212003],

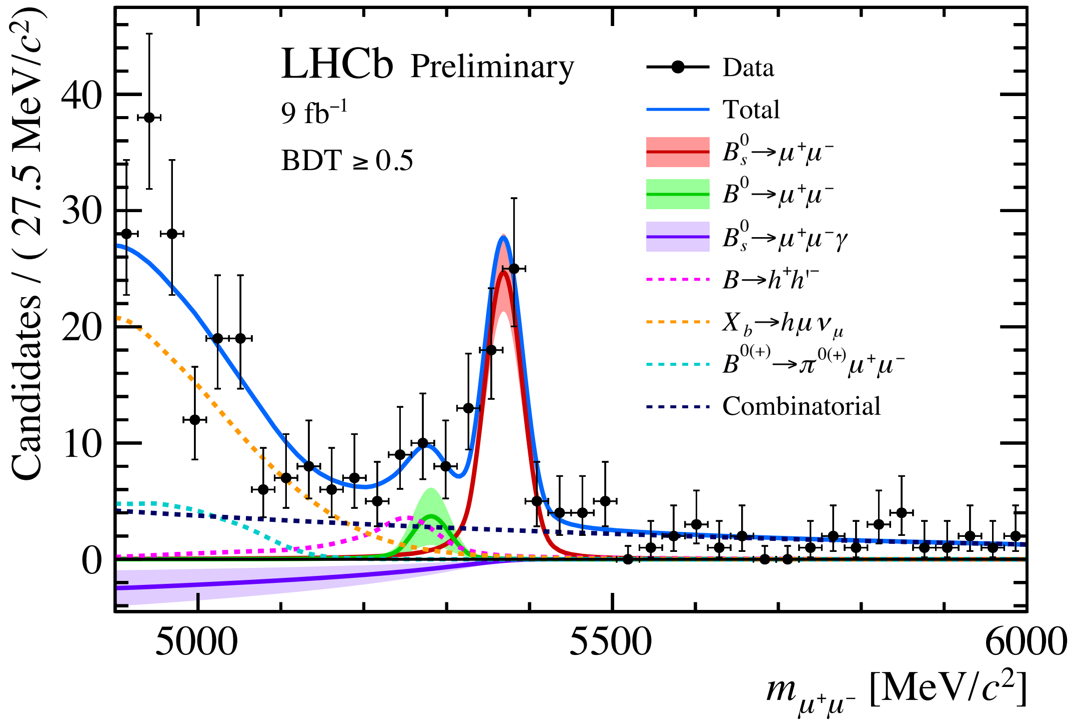
+[Horgan et al., PoS LATTICE2014 (2015) 372]

- This 3.6σ tension with SM is not yet in the global fits to the anomalies

New $B^0 \to \mu^+\mu^-$ measurement

[LHCb-PAPER-2021-007,8]

- LHCb search for with full Run 2 data released in March :



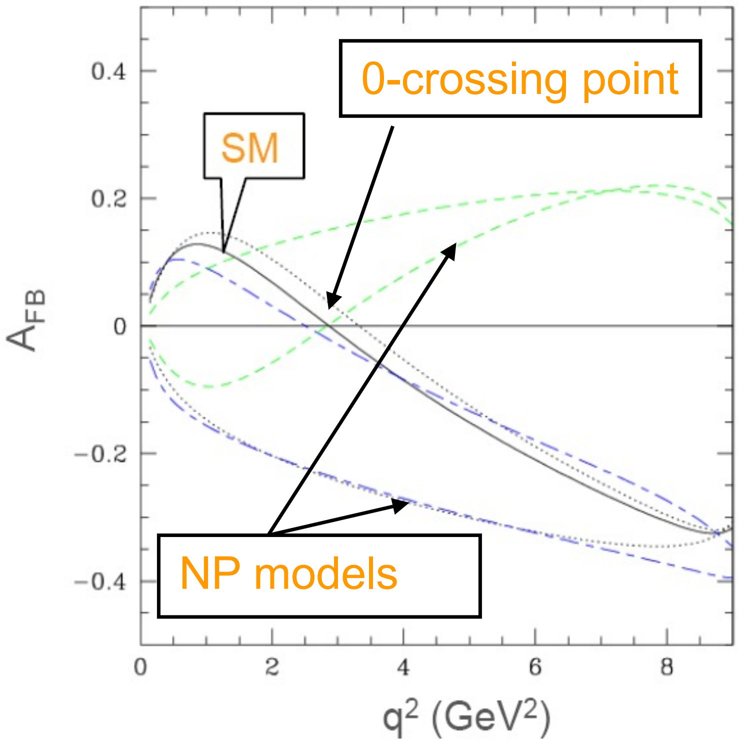
- $\mathscr{B}(B_s^0 \to \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$
  - $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-\gamma$ compatible with background only at 1.7σ and 1.5σ

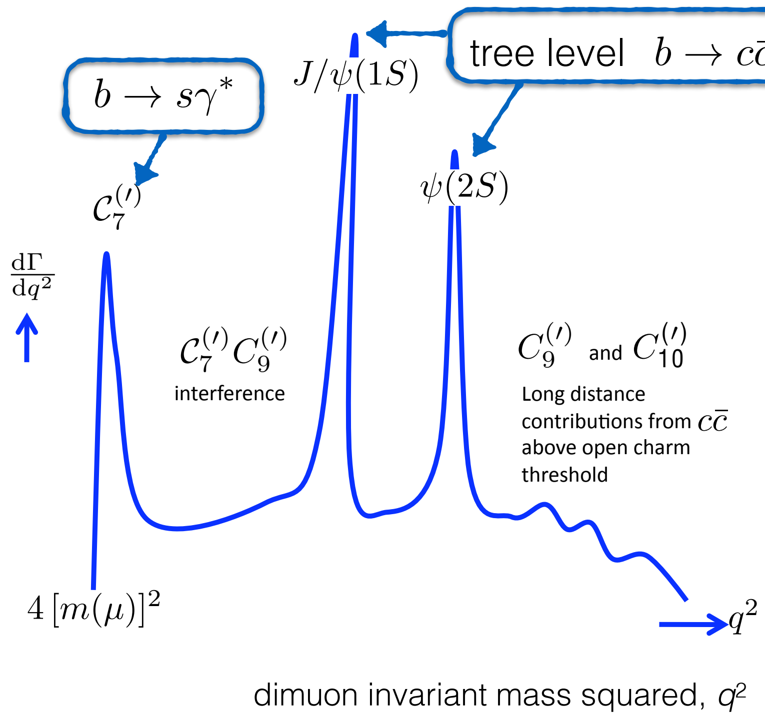
- Combine with ATLAS, CMS data- compatible with SM at 2σ

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

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

- Try to use observables where theoretical uncertainties cancel e.g. Forward-backward asymmetry A_{FB} of θ_l distn

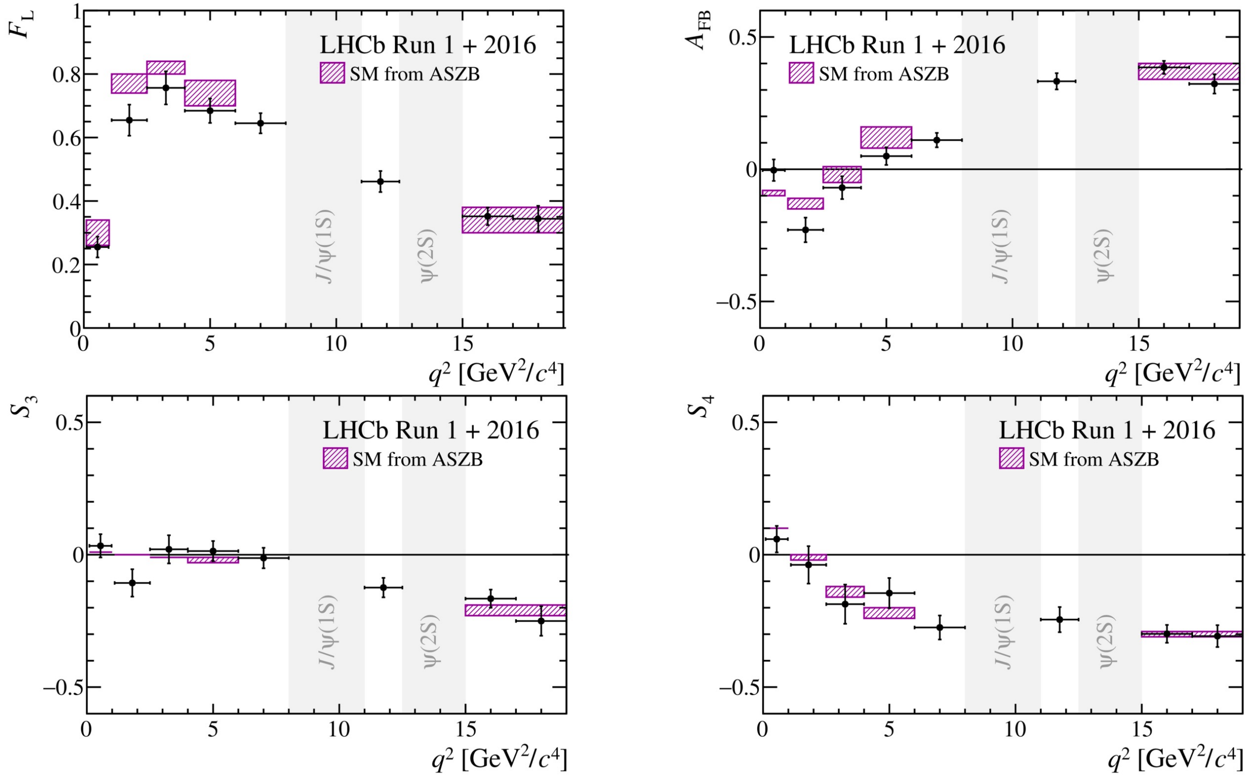




$B^0 \rightarrow K^{*0} \mu\mu$ angular analysis

- LHCb angular analysis of 2016 and Run I data

[PRL 125 (2020) 011802]



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

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
- E.g. in the region $1<q^2<6$ GeV^2, relations reduce the seven form-factors to just two – allows to form quantities like

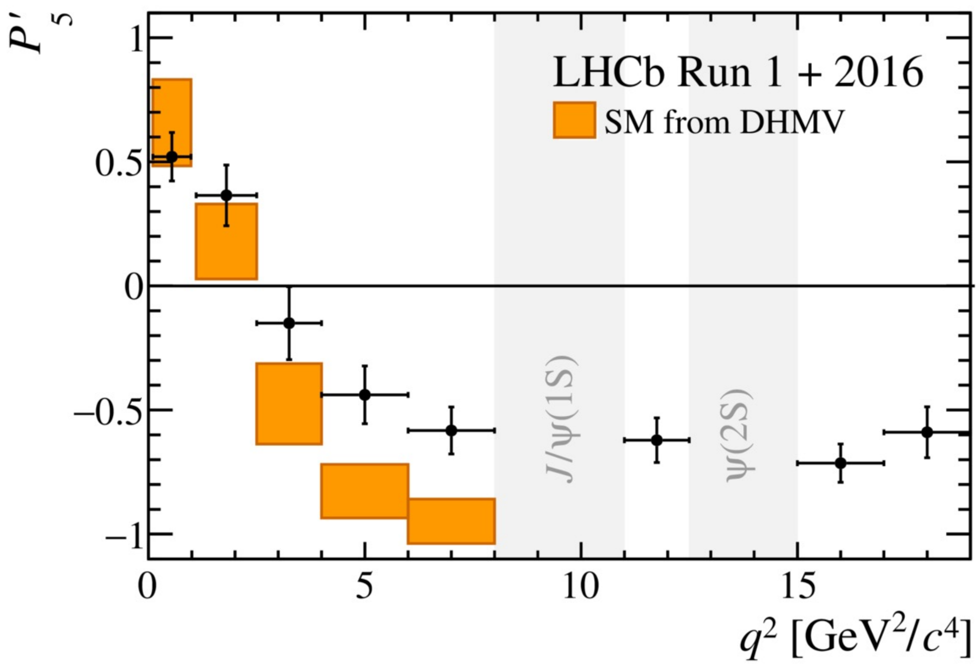
$$P_5' \sim \frac{Re(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*})}{\sqrt{(|A_0^L|^2+|A_0^R|^2)(|A_\perp^L|^2+|A_\perp^R|^2+|A_\parallel^L|^2+|A_\parallel^R|^2)}}$$

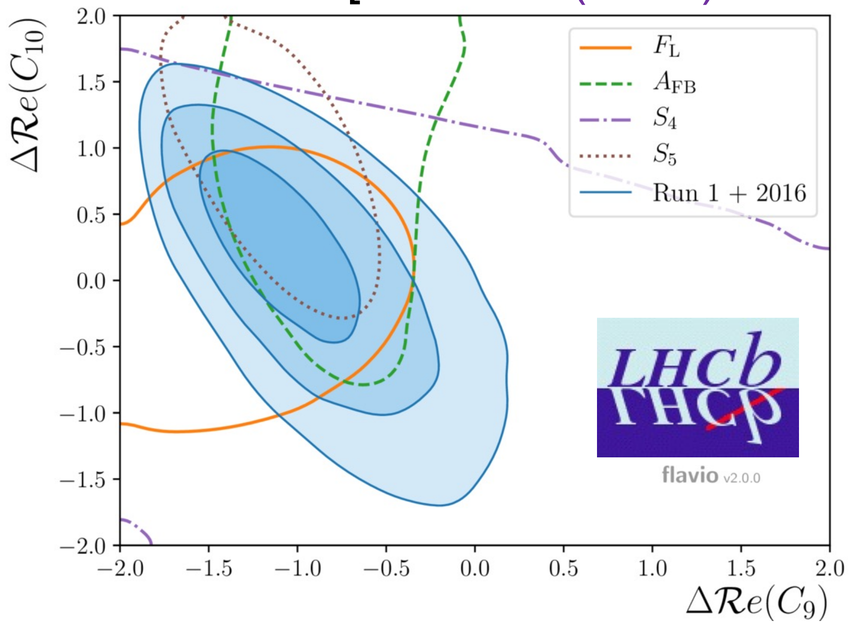
  which are form-factor independent *at leading order*
- In fact, can form a complete basis ($P^{(\prime)}$ series) in which there are six form-factor independent and two form-factor dependent observables (F_L and A_{FB})

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

- P_5' shows significant discrepancy wrt SM prediction
- Good coherence between observables
- Tension with SM in angular analysis alone 3.3σ … but theory treatment of intractable $c\bar{c}$ contribution?

[PRL 125 (2020) 011802]

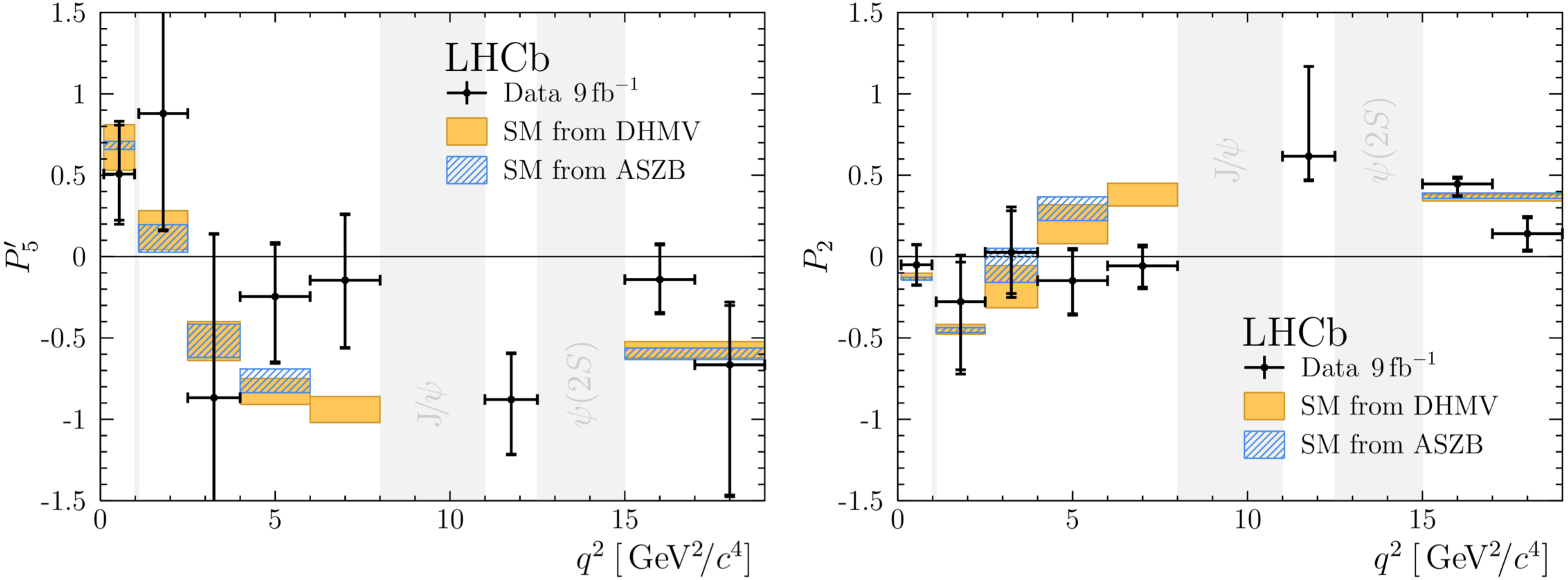




$B^+ \to K^{*+}\mu\mu$ angular analysis

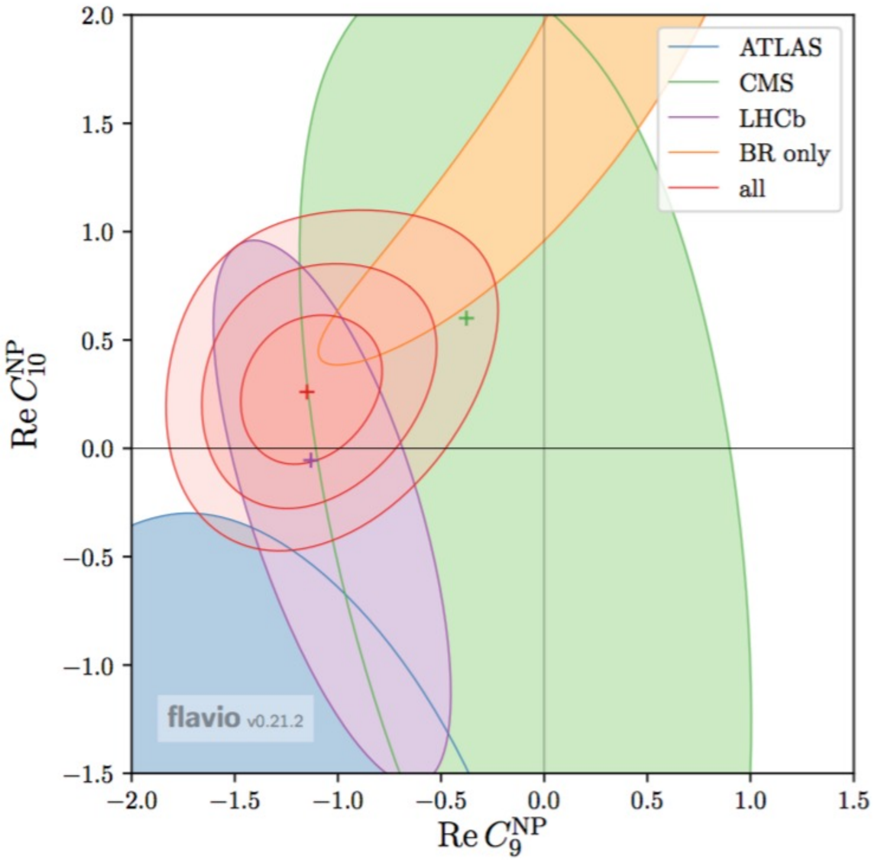
- Angular analysis now performed for analogous K^{*+} decay mode with $K^{*+} \to K_S^0 \pi^+$
- Lower statistics but message is identical – in this decay tension with SM is 3.1σ

[PRL 126 (2021) 0161802]



“Global” fits

- *Many* theory groups have interpreted results by performing fits to $b \to s\mu\mu$ data
- Consistent picture, tensions solved simultaneously by a modified vector coupling (ΔC_9 != 0) at >**3σ** but discussion of residual hadronic uncertainties (…)



Lepton Universality Ratios

Lepton Universality Ratios

- In the SM couplings of gauge bosons to leptons are independent of lepton flavour

- Branching fractions of processes with different leptons differ only by phase space and helicity-suppressed contributions

- Ratios of the form: $$R_{K^{(*)}} := \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \overset{\mathrm{SM}}{\cong} 1$$

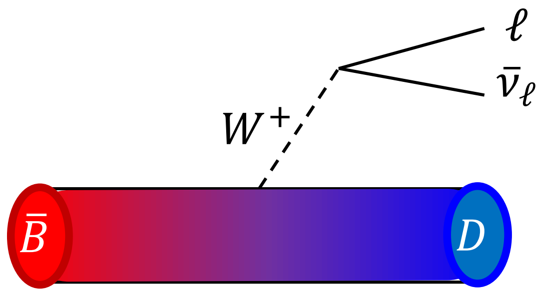
  - free from QCD uncertainties affecting other observables $\rightarrow$ $O(10^{-4})$ uncertainty [JHEP07 (2007) 040]
  - Up to O(1%) QED corrections [EPJC76 (2016) 8,440]

$\rightarrow$ Any significant deviation is a smoking gun for New Physics

b→clν LFU ratios

- A further anomaly is seen in LFU ratios in **b→clν** decays
  - Good theoretical control due to factorisation of hadronic and leptonic parts – then theoretically pristine e.g.

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



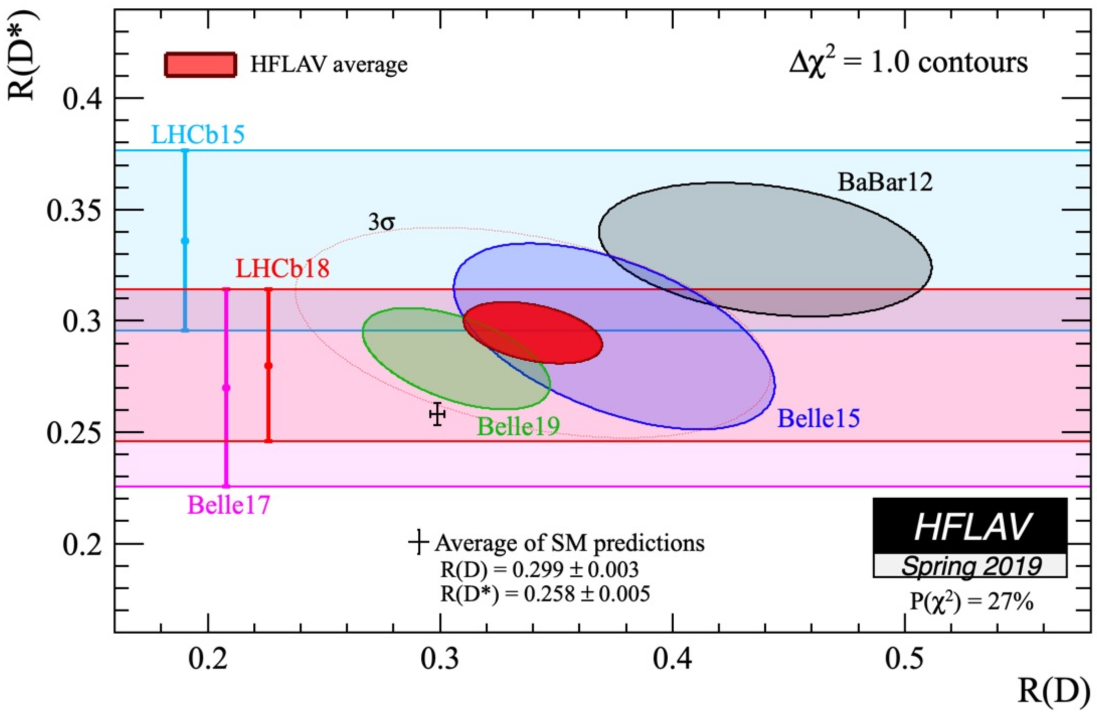
  - Tree-level processes in SM – requires a *huge* NP effect, comparable with the SM amplitude
  - Drives idea of hierarchical effect: large NP effect in **τ**; smaller in **μ**, where have measured **b→sμμ decays**, and little/no effect in **e** modes

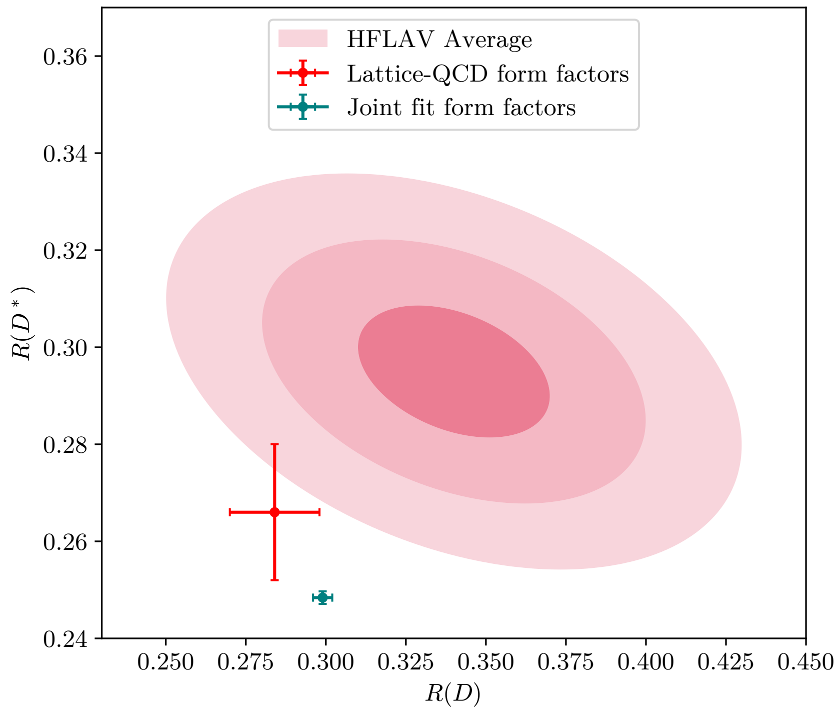
- Possible to make a NP explanation, coherent with **b→sμμ**
  - Most discussed NP models involve Leptoquarks or Z'

Fit to b→clν LFU ratios

- Combination of LHCb results with those from Babar/Belle
- World average value shows a **3.1σ** tension with SM prediction but very recent updates to SM theory from lattice

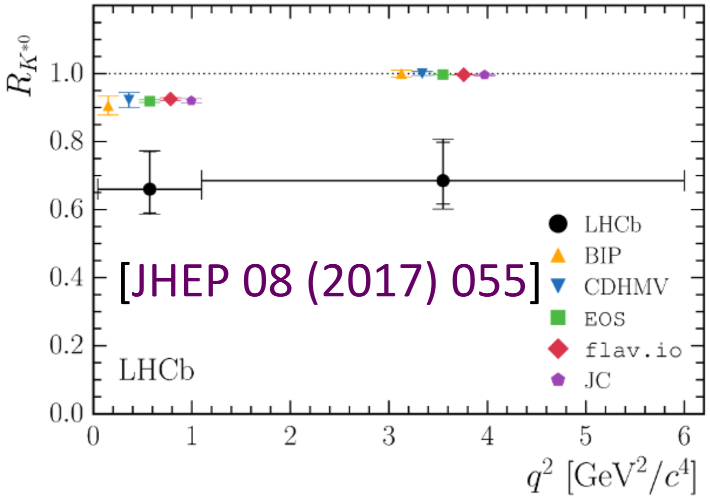
[arxiv:2105.14019]



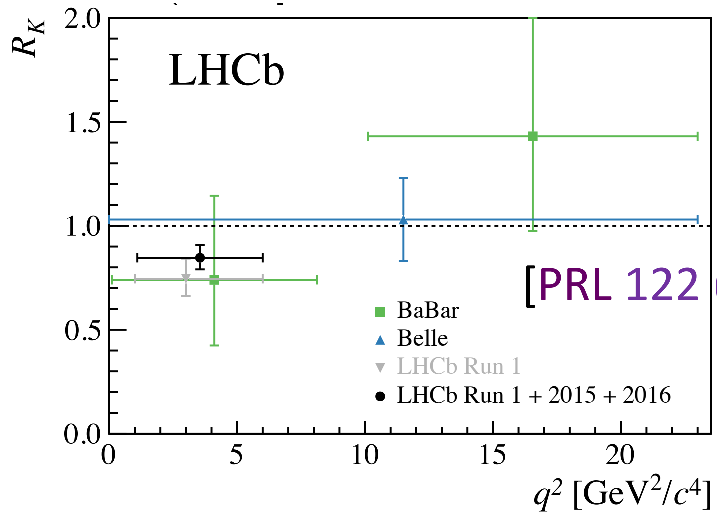


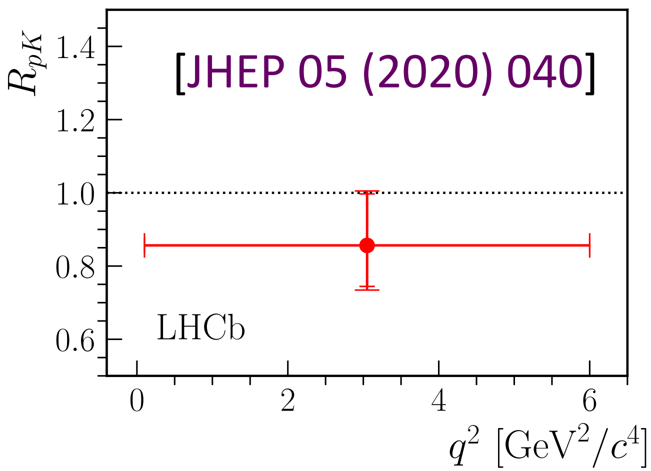
b→sll LFU ratios

$B^0 \to K^{*0}\ell^+\ell^-$ R_{K^*} 3fb^{-1}



$B^+ \to K^+\ell^+\ell^-$ R_K 5fb^{-1}





- Despite ~2.5σ consistency with SM, measured values have generated some excitement – are precisely what would result from $\Delta C_9^e=0, \Delta C_9^\mu= -1$
i.e. could account for angular data, BFs and $R_{K(*)}$ ratios by changing only C_9^μ

R_K LFU ratio update

[arXiv:2103.11769]

- Recently updated R_K measurement in $1.1<q^2<6.0\ \mathrm{GeV}^2/c^4$ region,

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

- Update effectively doubles number of B decays cf previous measurement

- Measurement strategy identical to our previous analysis

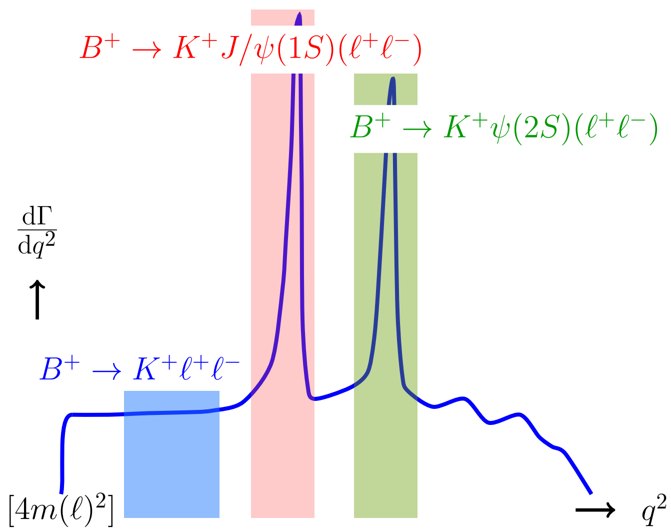
R_K Analysis Strategy

[arXiv:2103.11769]

- Exploit double ratio wrt equivalent J/ψ decay modes in order to cancel experimental systematic uncertainties

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

$$= \frac{N^{\mathrm{rare}}_{\mu^+\mu^-}\ \varepsilon^{J/\psi}_{\mu^+\mu^-}}{N^{J/\psi}_{\mu^+\mu^-}\ \varepsilon^{\mathrm{rare}}_{\mu^+\mu^-}} \times \frac{N^{J/\psi}_{e^+e^-}\ \varepsilon^{\mathrm{rare}}_{e^+e^-}}{N^{\mathrm{rare}}_{e^+e^-}\ \varepsilon^{J/\psi}_{e^+e^-}}$$



- Measurement then statistically dominated

Efficiency calibration

[arXiv:2103.11769]

- Efficiencies computed using simulation that is calibrated with control channels in data
  - Trigger efficiency
  - Particle identification efficiency
  - B^+ kinematics
  - Resolutions of q^2 and $m(K^+e^+e^-)$

  Verify procedure through host of cross-checks

- Overall effect of these calibrations is a relative shift of the R_K result by $(+3\pm1)\%$

  [would be 20% without the double ratio method]

$r_{J/\psi}$ cross-check

[arXiv:2103.11769]

- Test control of the absolute scale of the efficiencies by instead measuring the single ratio,

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

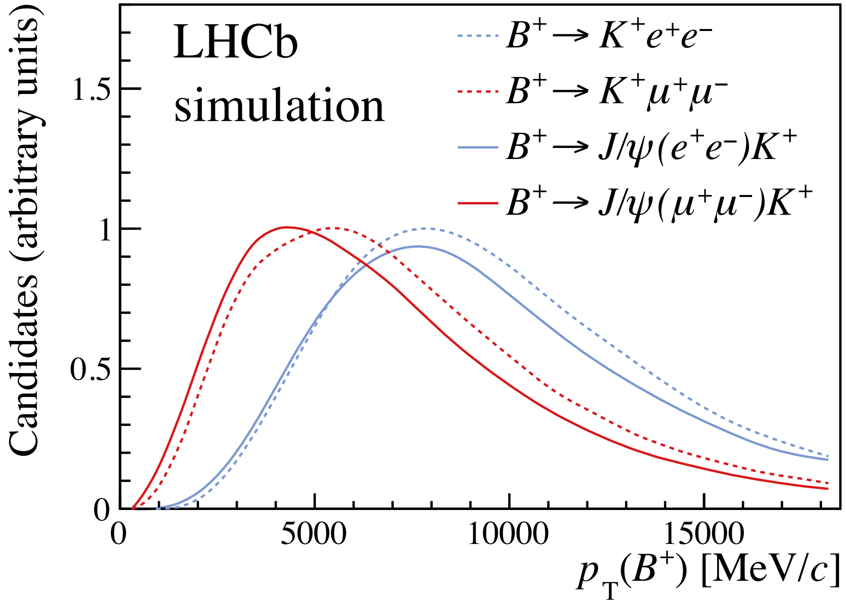
  where we do not benefit from the double ratio cancellation

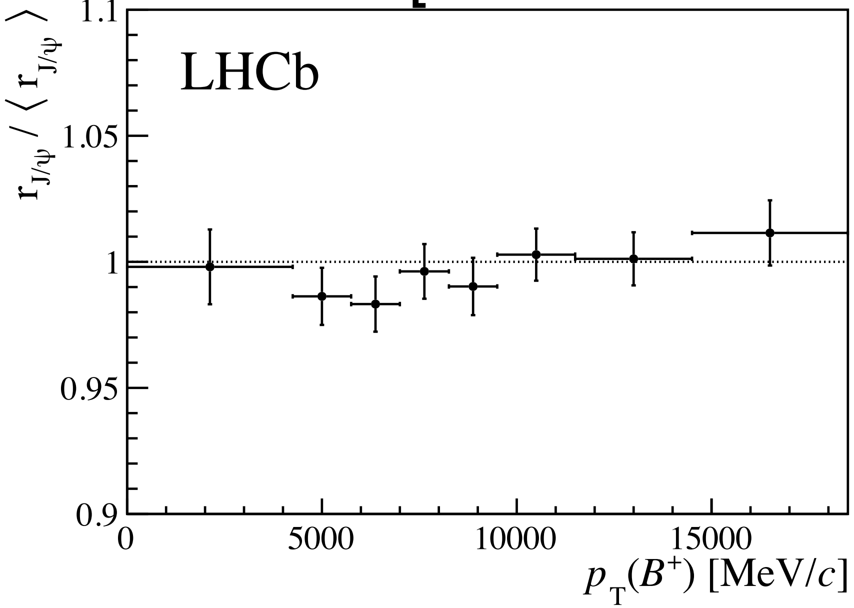
- $r_{J/\psi}$ measured to be lepton universal at 0.4% level

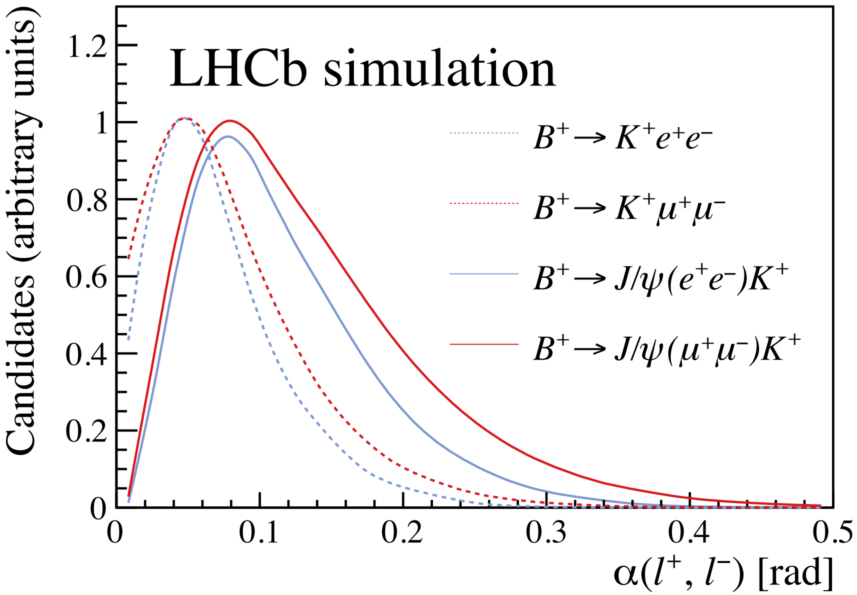
- Measure $r_{J/\psi}$ = 0.981±0.020 (stat+syst)
  - compatible with unity for new and previous datasets and in all trigger samples
  - result is independent of the decay kinematics
  - binning in quantities that would expect bremsstrahlung and trigger to depend on see completely uniform result

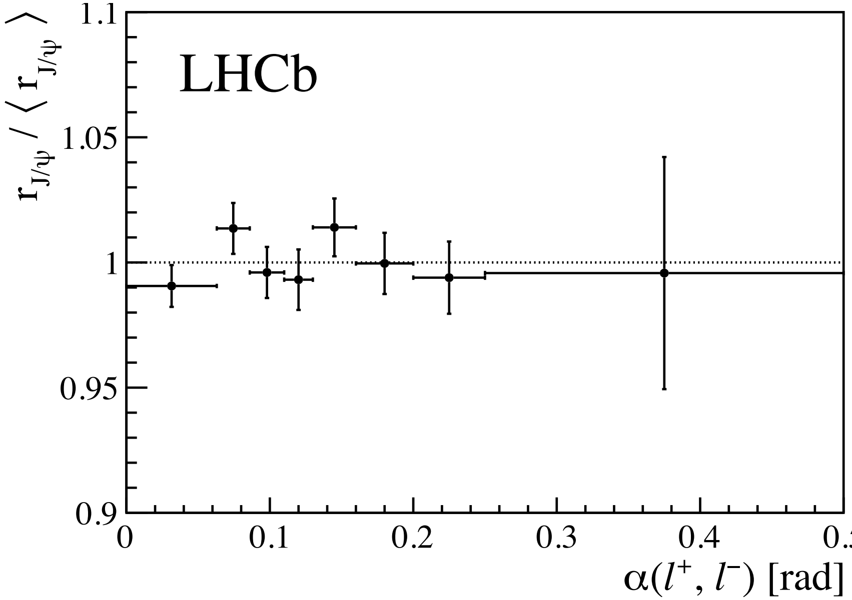
Differential $r_{J/\psi}$ cross-check

[arXiv:2103.11769]







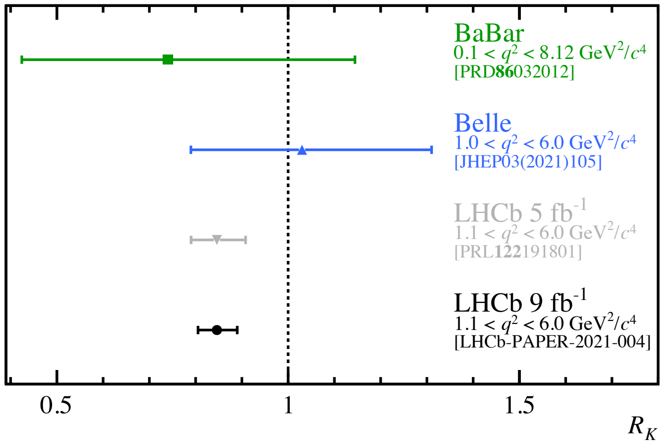


R_K result

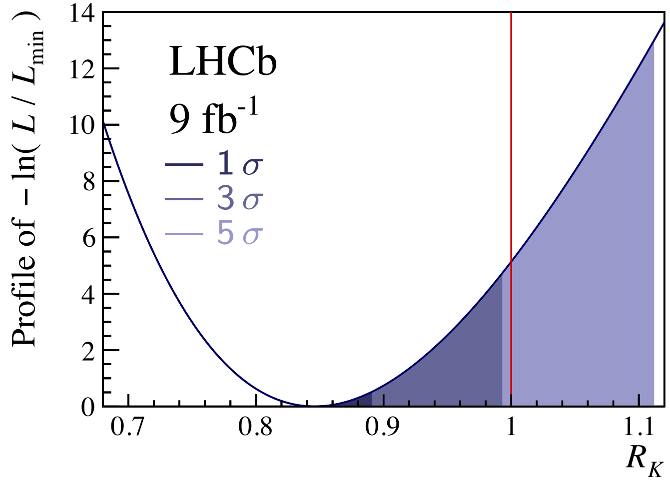
[arXiv:2103.11769]

- R_K with full Run1 and Run2 dataset

$$R_K = 0.846\ ^{+0.042}_{-0.039}\ (\text{stat})\ ^{+0.013}_{-0.012}\ (\text{syst})$$



- Compatibility with the SM obtained by integrating the profiled likelihood as a function of R_K above 1



- p-value under SM hypothesis: 0.0010
  → Evidence of LFU violation at 3.1σ

- Paper submitted to Nature Physics

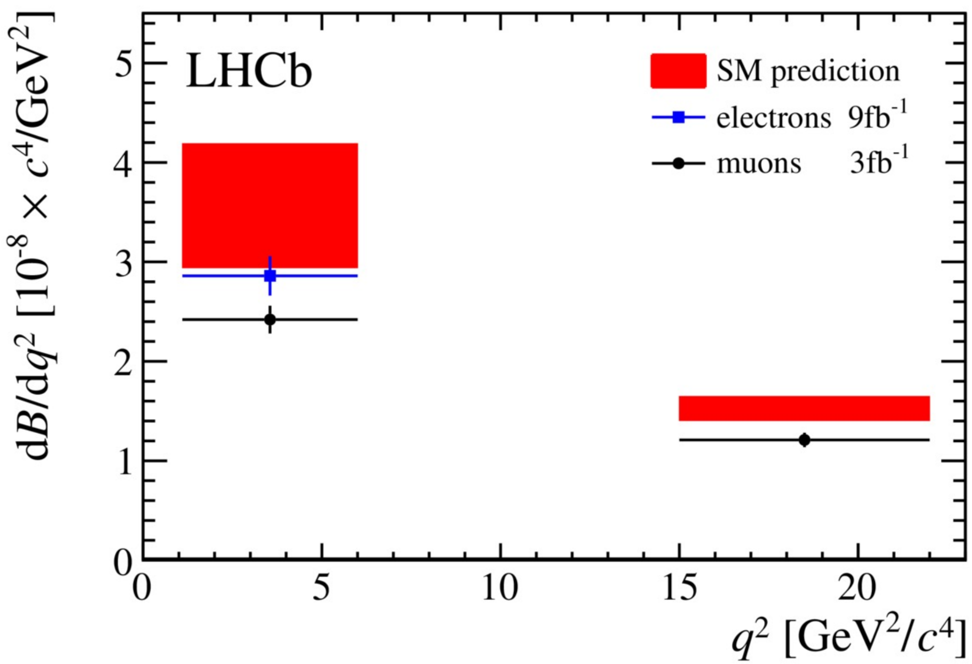
Derived quantities

[arXiv:2103.11769]

- Use R_K and previous measurement of $B(B^+ \to K^+ \mu^+ \mu^-)$ [JHEP06(2014)133] to determine $B(B^+ \to K^+ e^+ e^-)$

$$\frac{d\mathcal{B}(B^+ \to K^+ e^+ e^-)}{dq^2} = (28.6\ ^{+1.5}_{-1.4}(\text{stat})\ \pm 1.4(\text{syst})) \times 10^{-9}\ c^4/\,\text{GeV}^2.$$

- As previously, suggests electrons are more SM-like than muons – plays into hierarchical idea that theory community find appealing

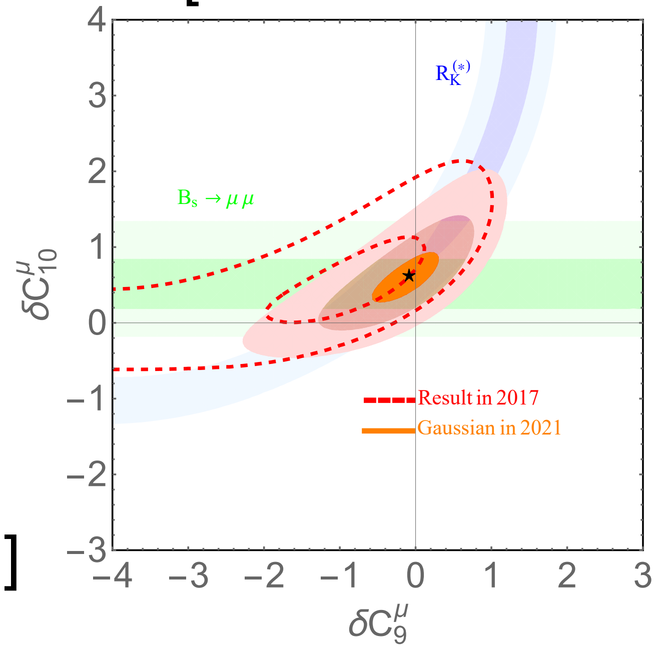


Global fits revisited

Global fits revisited

- Using *just* the theoretically pristine observables, R_K, R_{K^*} and BF($B\rightarrow\mu\mu$), that no one argues about predictions for, exclude SM at **4σ** level

[arXiv:2103.12738]



[arXiv:2104.08921]

- Updated 2D W.C. fits now have:
  - No evidence for axialvector NP ($C_{10\mu}^{NP}$ compatible with zero)
  - Some evidence for right-handed contribution ($C_{9\mu}^{NP}$, $C_{10'\mu}^{NP}$),($C_{9\mu}^{NP}$, $C_{9'\mu}^{NP}= -C_{10'\mu}^{NP}$)
  - Potential LFU NP contribution

Many, many alternative fits on the market …
[arXiv:2012.12207, 2011.01212, 1904.08399, 1903.09578, 1903.10086, …1903.10932…]

Global fits and LEE

- The significance quoted for the many global fits on the market hold for specific (well-motivated) NP hypotheses, but made a posteriori (after looking at the data) → local significance

- Concentrating only on the clean observables, or only on LFU ratios, neglects observables which agree with SM. Need a global significance that takes care of the Look Elsewhere Effect

- Now seeing first attempts to include all observables with sensitivity to $b \to sll$ and conservative theory errors

→ 3.9σ **global** significance with respect to any form of heavy NP

[arXiv:2104.05631]

- LHCb thinking about how to take this forward

A glimpse of the future

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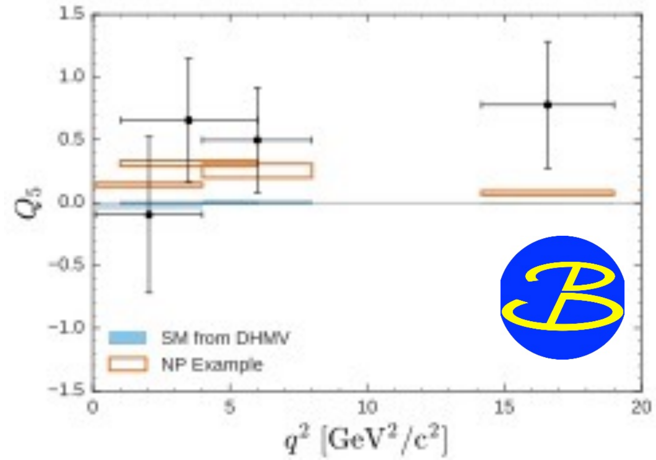
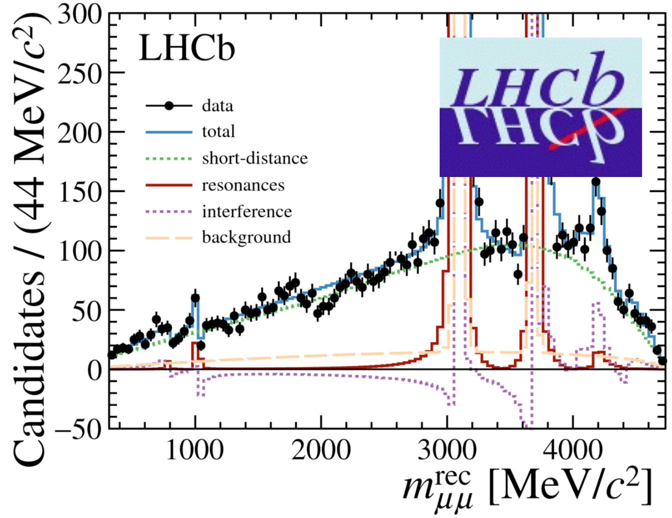
- (R_D,R_{D^*}) update from LHCb coming; CMS... ?
- Make ratio of $P_5'(e)$ and $P_5'(\mu)$ → Q_5
    - Full angular analysis of $B^0 \to K^{*0}ee$ in progress at LHCb
- *Measure* the effect of $c\bar{c}$ loops, as have already done for $B^+ \to K^+\mu^+\mu^-$
- Search for the huge effects expected in $b \to s\tau\tau$ and possibility of $b \to s\tau\mu$

[PRL 126 (2021) 161801]



[EJPC (2017) 77:161]



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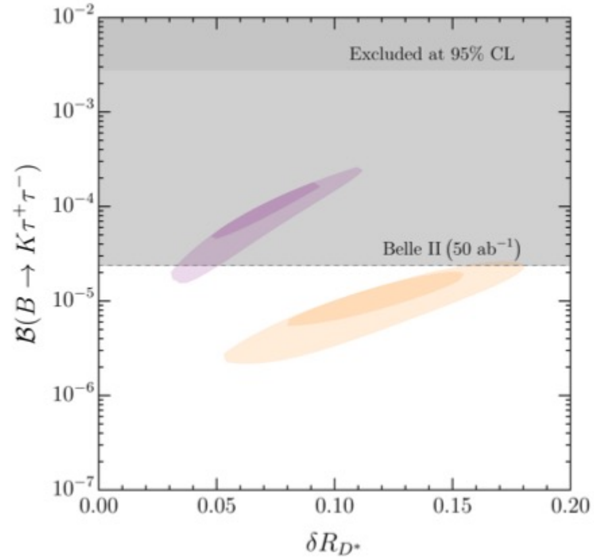
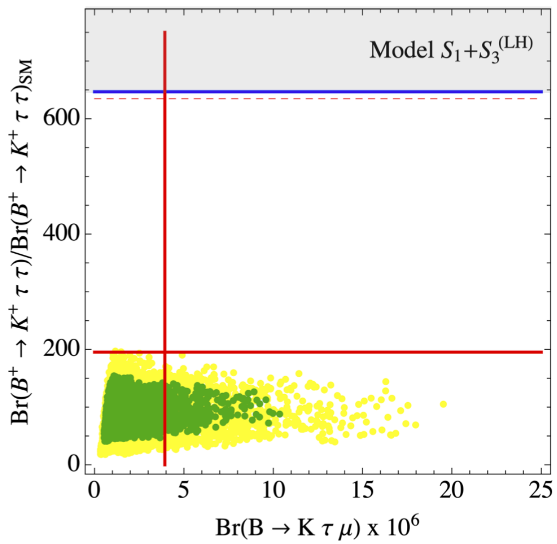


[CC, Fuentes-Martin, Faroughy, Isidori, Neubert, 2101.11626]

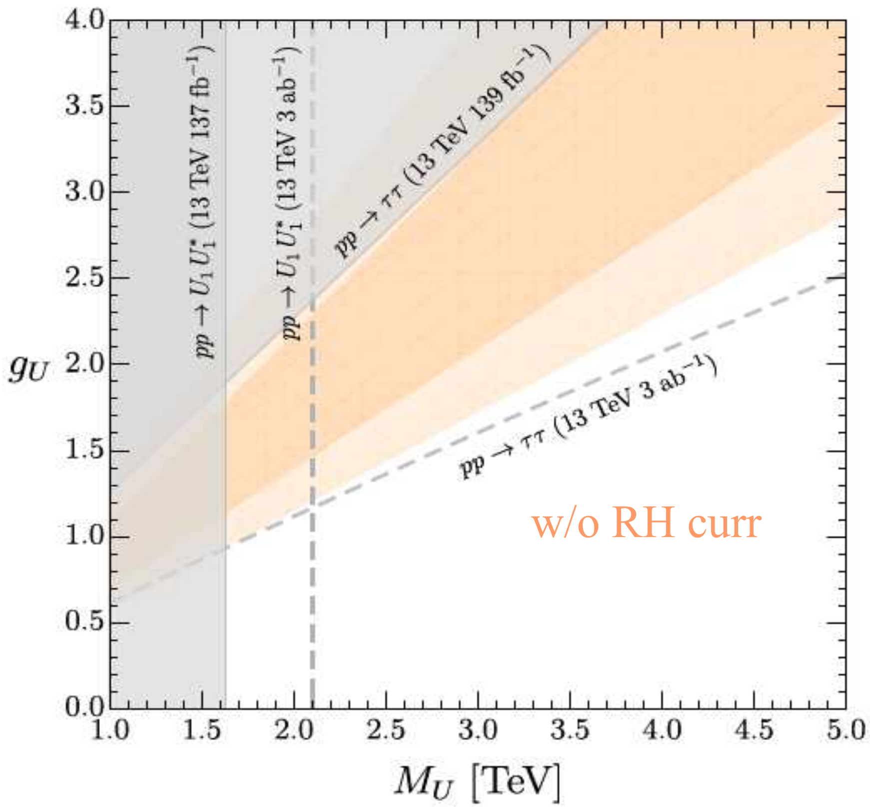


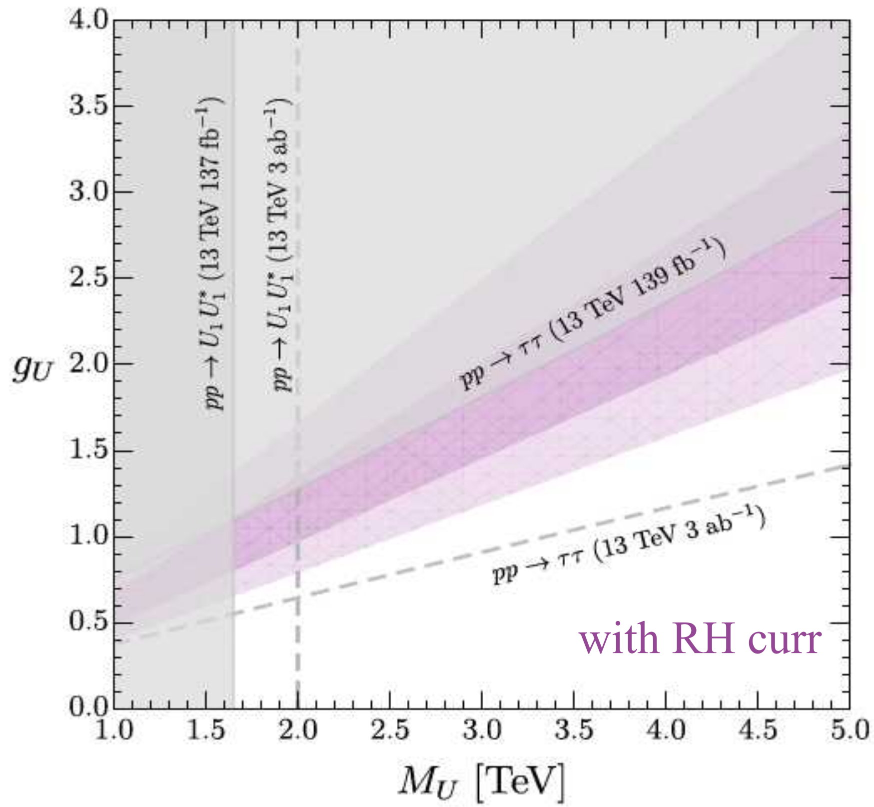
[Gherardi, Marzocca, Venturini 2008.09548]

A glimpse of the future

- Need a model of flavour to understand implications for direct searches but some analyses suggest that e.g. LQ could be within the reach of HL-LHC

[arxiv:2101.11626]





Conclusions

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- Interesting set of anomalies observed in B decays
- Near-term updates should clarify the situation and can help constrain some of the theoretical issues
- Wide range of new measurements will be added to broaden the constraints on the underlying physics