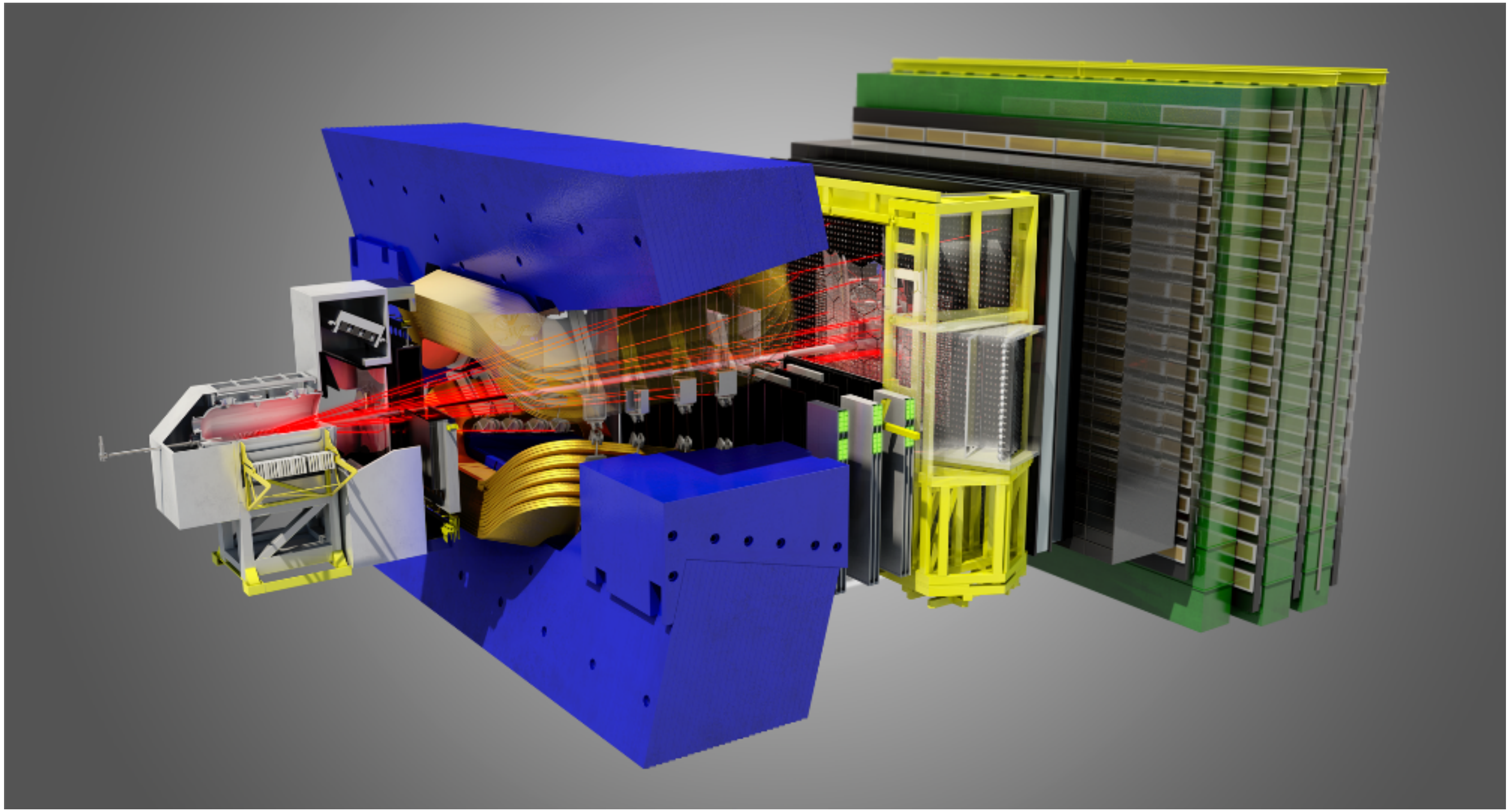
Recent results from LHCb



Mitesh Patel (Imperial College London)

Anomalies, 10th Nov 2021

Imperial College London

Introduction

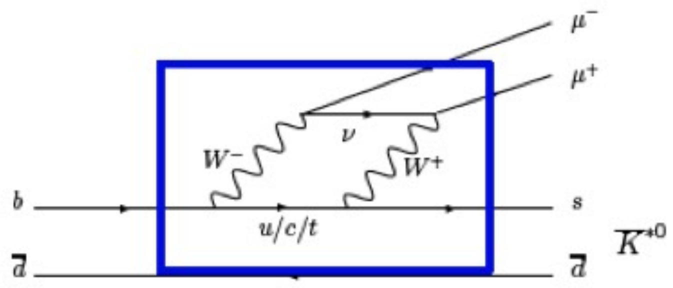
- Interesting set of anomalies have appeared in measurements of B decays :
  - Branching fractions of several $b \to sll$ processes
  - Angular observables in $B^0 \to K^{*0}\mu\mu$, $B^+ \to K^{*+}\mu\mu$
  - Lepton-flavour universality ratios $b \to sll$ and $b \to cl\nu$ decays

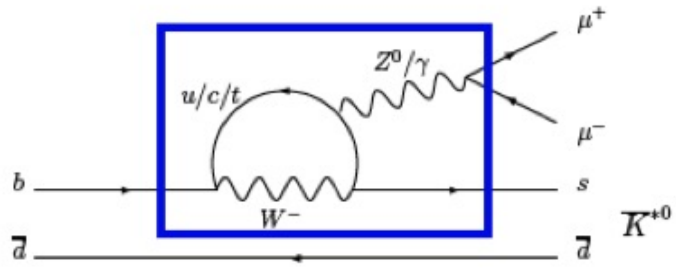
- Majority of you will be familiar with the measurements themselves – will try and remind you of:
  - the issues in each case
  - what makes us think we have good experimental control
  - what might still be wrong (from an exp'talists perspective)

  Will try and at least connect with the theory issues

b→sll decays

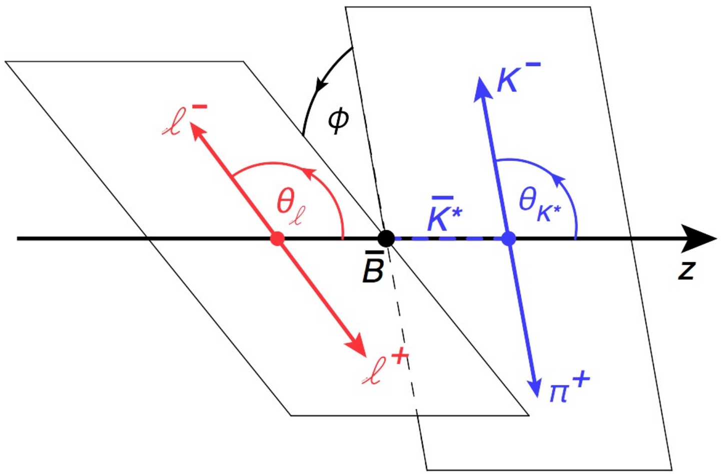
- b→sll decays involve flavour changing neutral currents → loop process



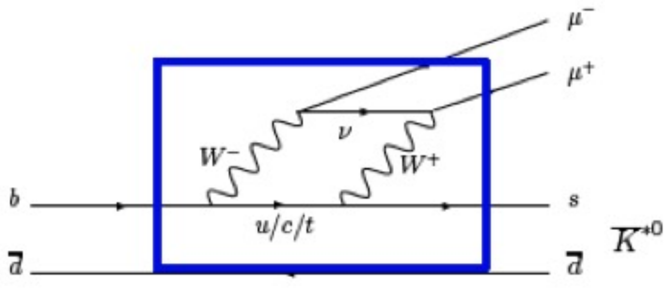


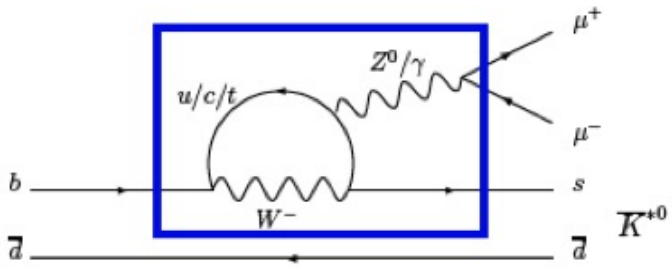
- Best studied decay at LHCb is $B^0 \to K^{*0}\mu\mu$

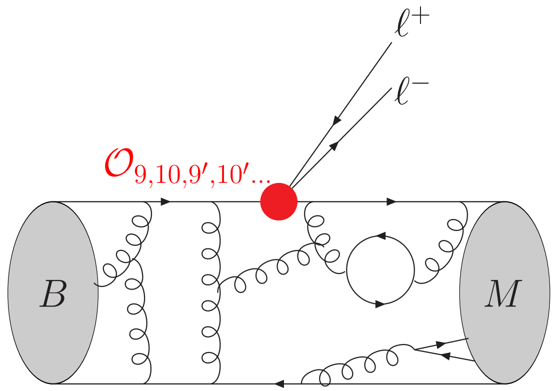
- Large number of observables: BF, A_{CP} and angular observables – dynamics can be described by three angles (θ_l, θ_K, ϕ) and di-μ invariant mass squared, q^2



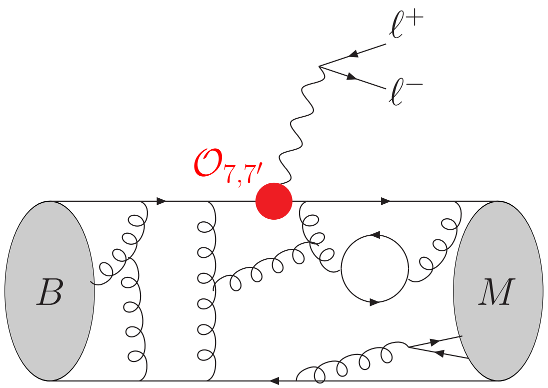
Hadronic Effects

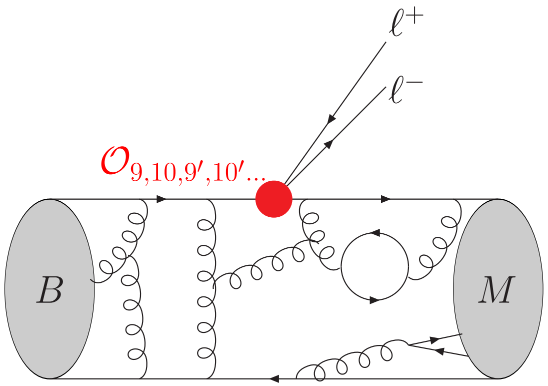


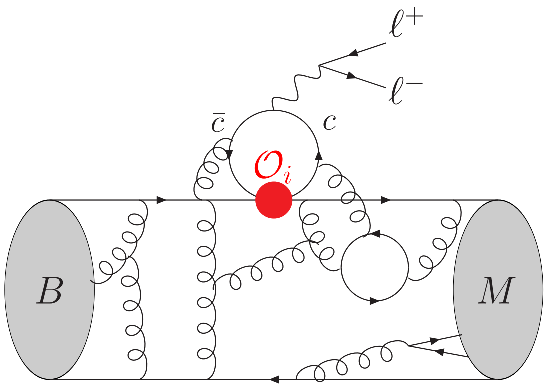




Use the **Operator Product Expansion** to handle theoretically







Form factors (local) Form factors (local)

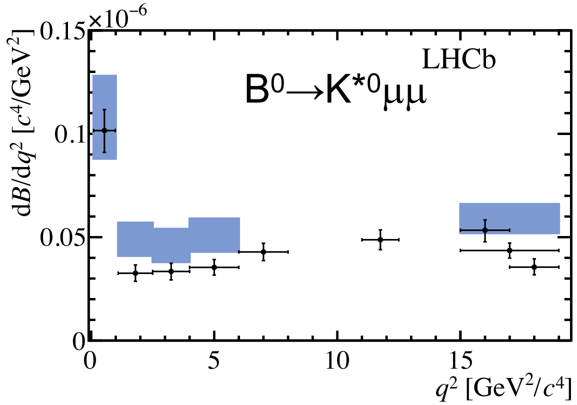
Charm loop (non-local)

→ BFs have relatively large theoretical uncertainties

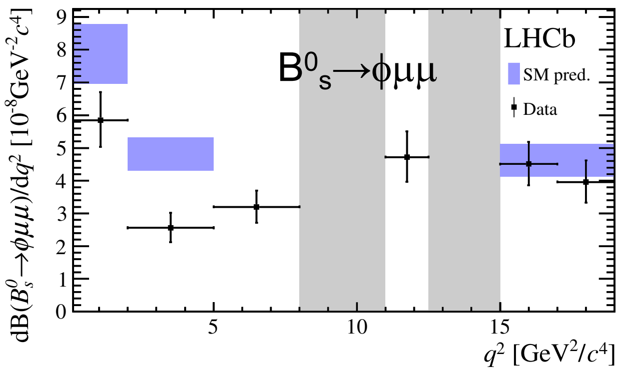
b→sll branching fractions

b→sll branching fractions

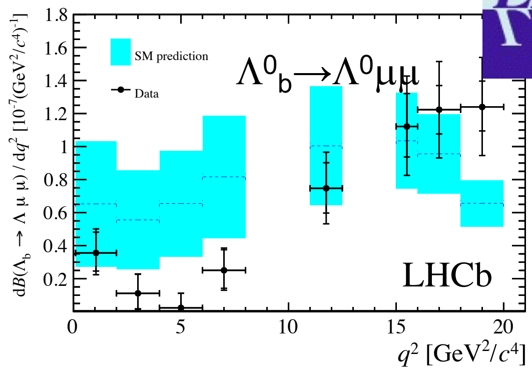
- Several b→sμμ branching fractions measured at LHCb show some tension with predictions, particularly at low q^2



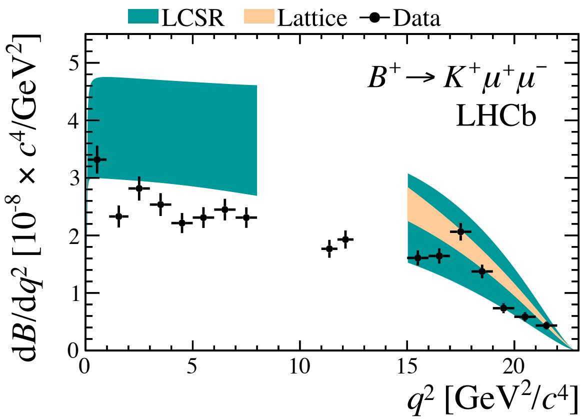
[JHEP 11 (2016) 047, JHEP 04 (2017) 142]

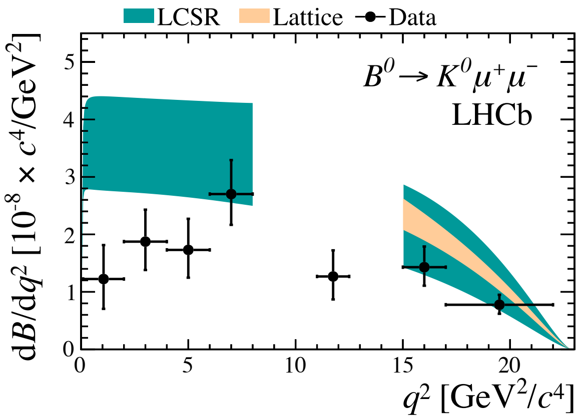


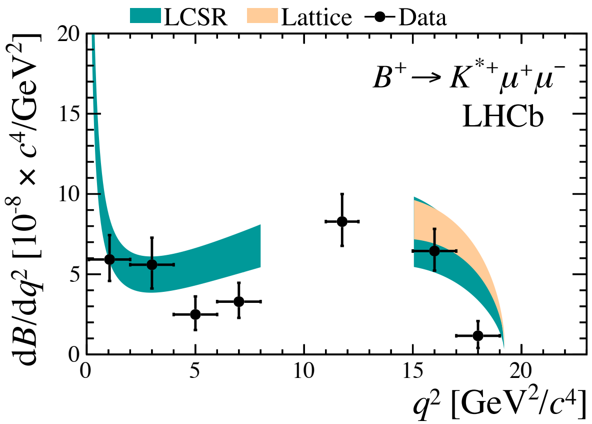
[JHEP 09 (2015) 179]



[JHEP 06 (2015) 115]



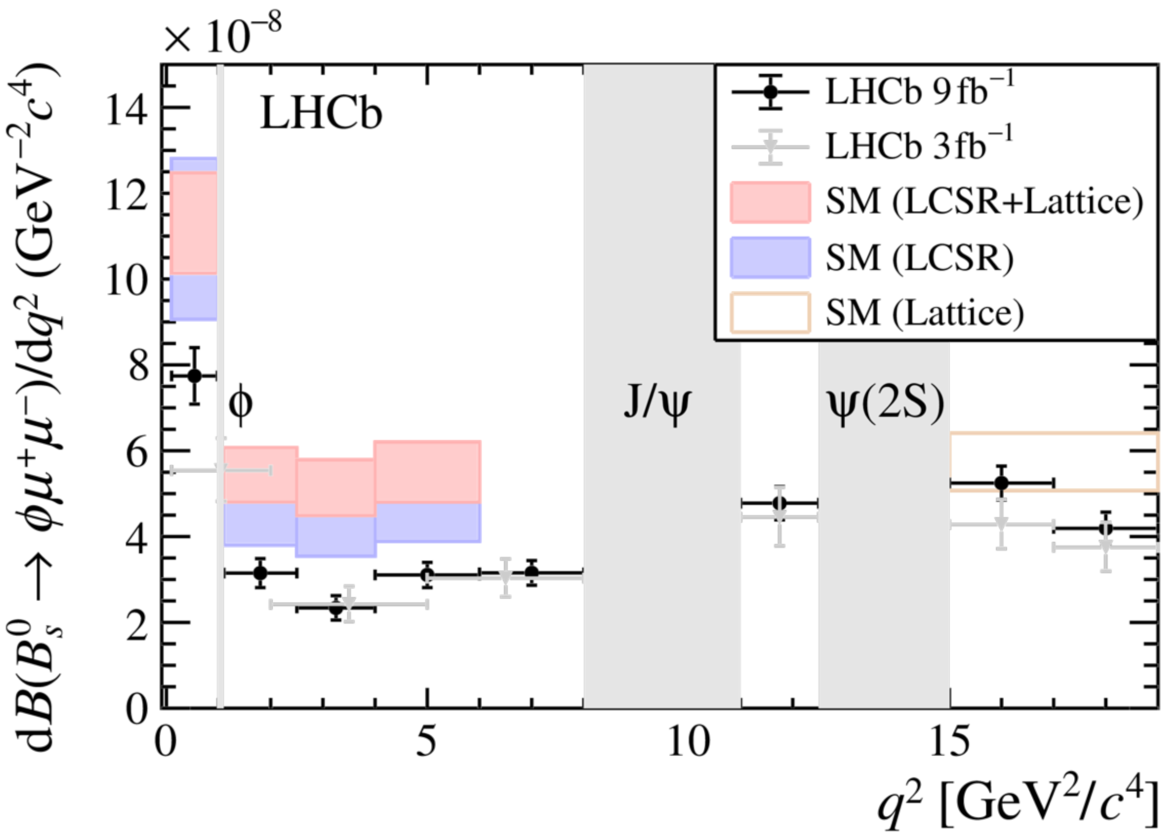




[JHEP 06 (2014) 133]

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]

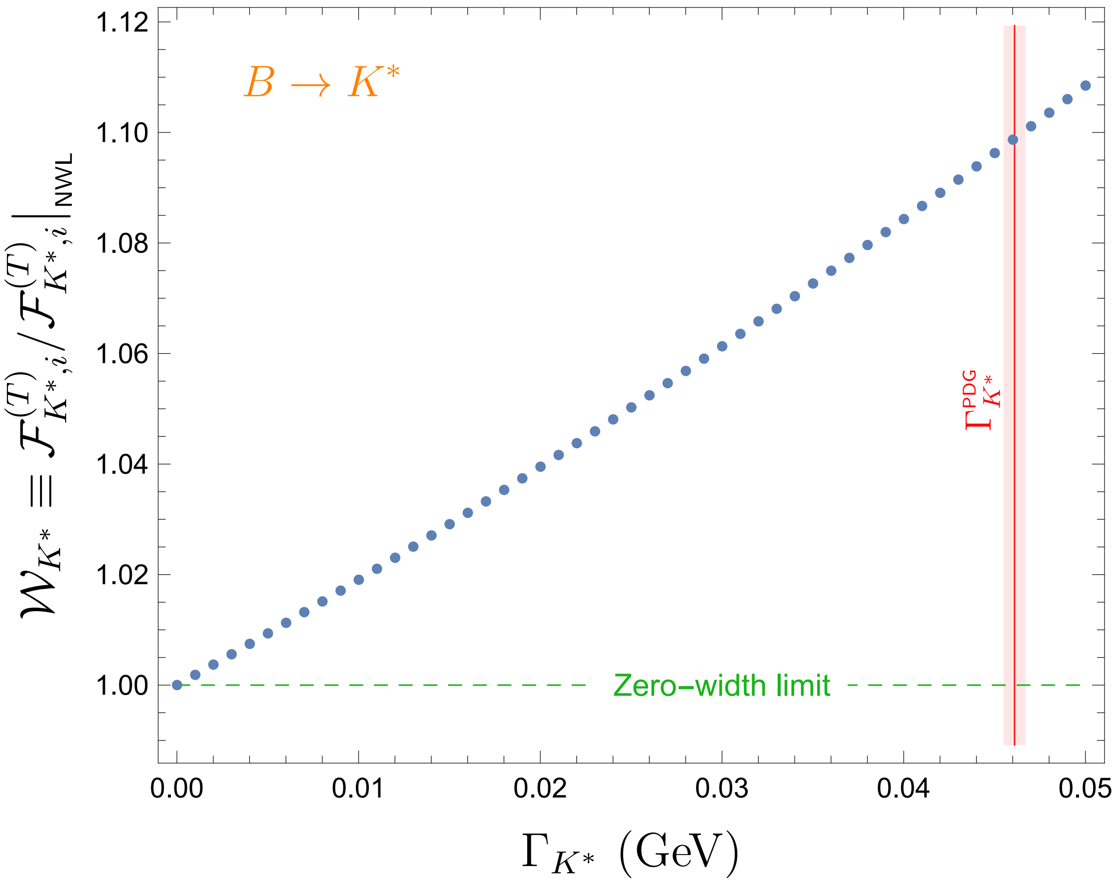
SM LCSR+Lattice:

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

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

- This 3.6σ tension with SM further inflates tensions noted by some 'global' fitting groups

BF($B^0 \to K^{*0}\mu\mu$) and the narrow width approximation



[arXiv:1908.02267]

Crucial input: $\tau \to K\pi\nu$

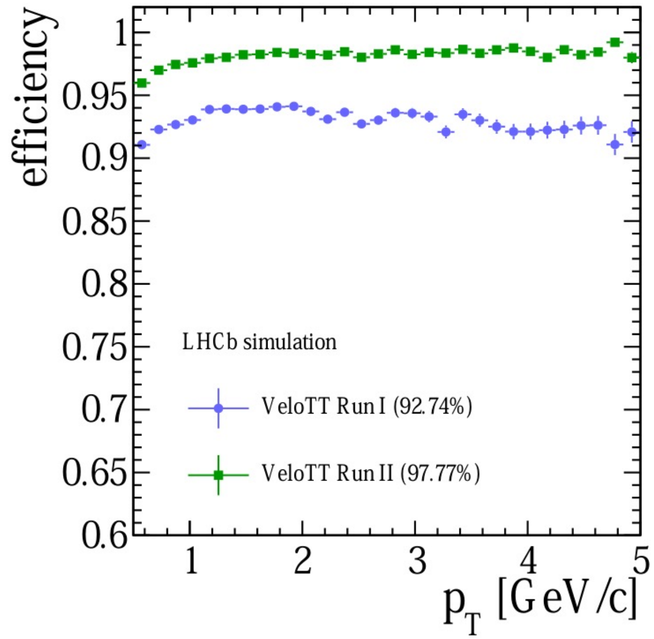
$$\mathcal{W}_{K^*} \simeq 1 + 1.9\,\frac{\Gamma_{K^*}}{m_{K^*}}$$

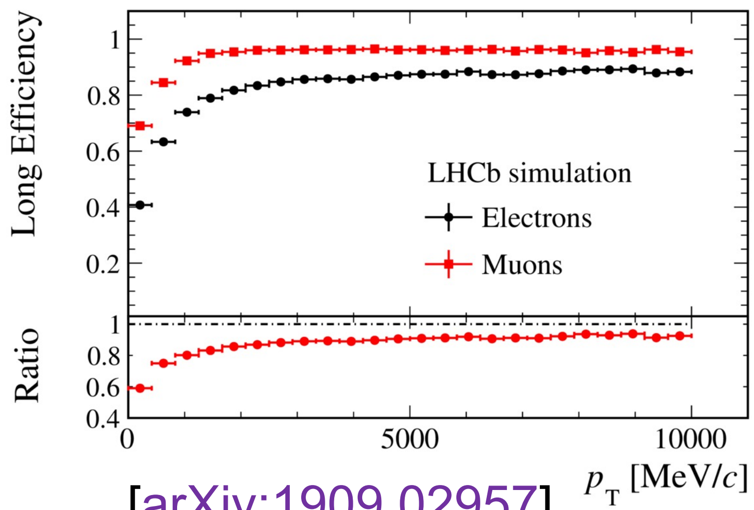
$$\mathcal{W}_{K^*} = 1.09 \pm 0.01$$

$\Rightarrow$ BRs are corrected by a factor $|\mathcal{W}_{K^*}|^2 \simeq 1.2$ (increasing anomalies)

Could something have gone wrong?

- [On the experimental side…]
- Would need muon efficiency to be wrong (only) at low q^2
- Detector performance doesn't depend directly on q^2, depends on momenta, spatial position of tracks
  - Why only at low q^2?
  - Performance calibrated with data
  - Have plenty of decays with muons where we are not seeing any NP effects
  - How to triple check?



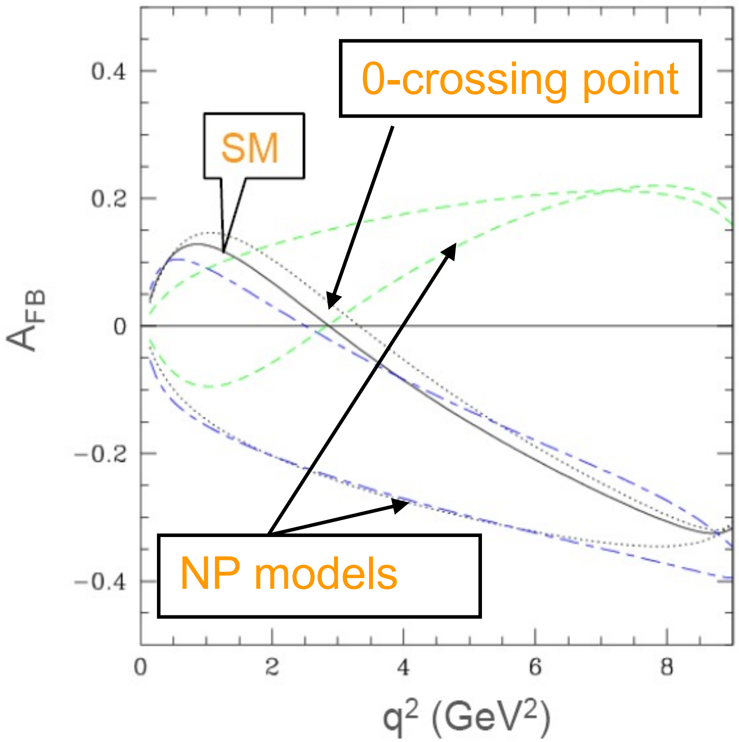


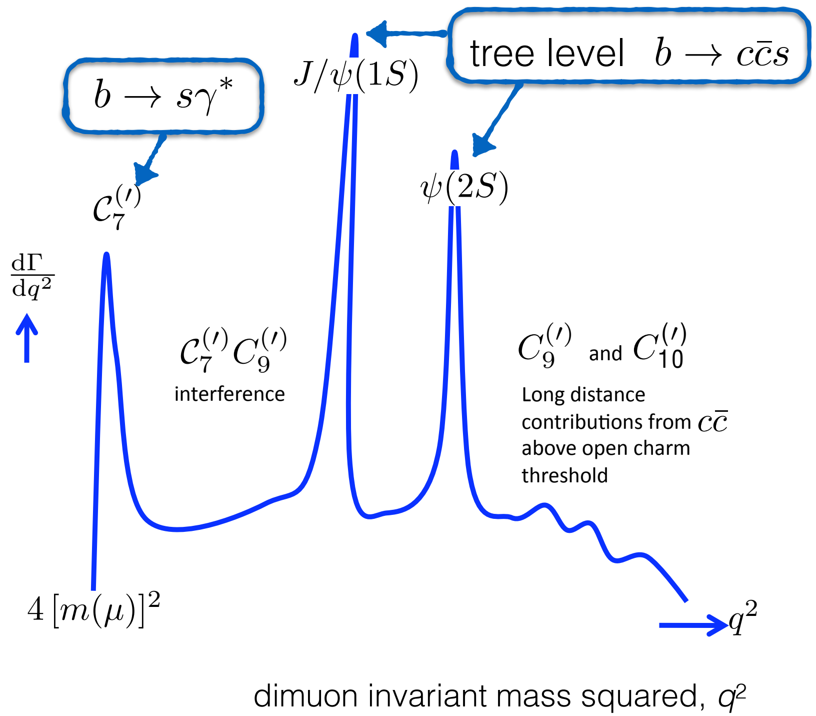
[arXiv:1909.02957]

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

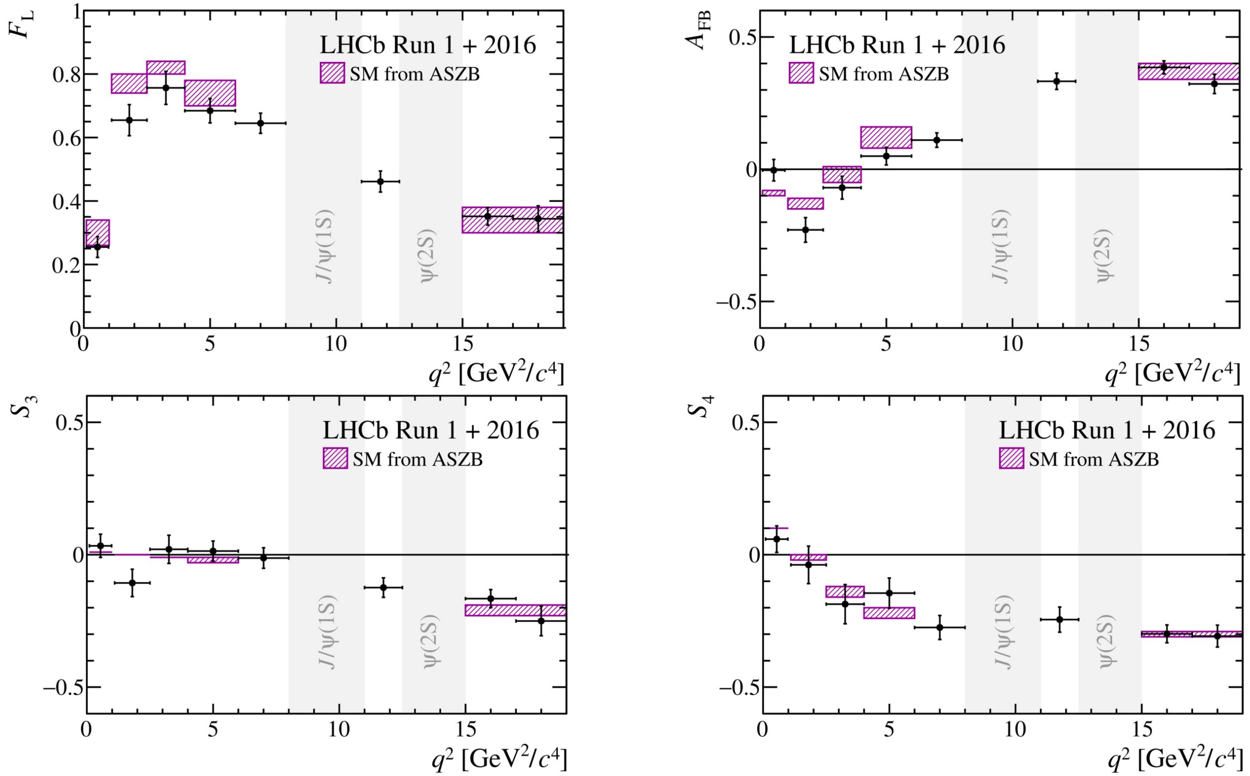




$B^0 \to K^{*0}\mu\mu$ angular analysis

- LHCb angular analysis of 2016 and Run I data

[PRL 125 (2020) 011802]

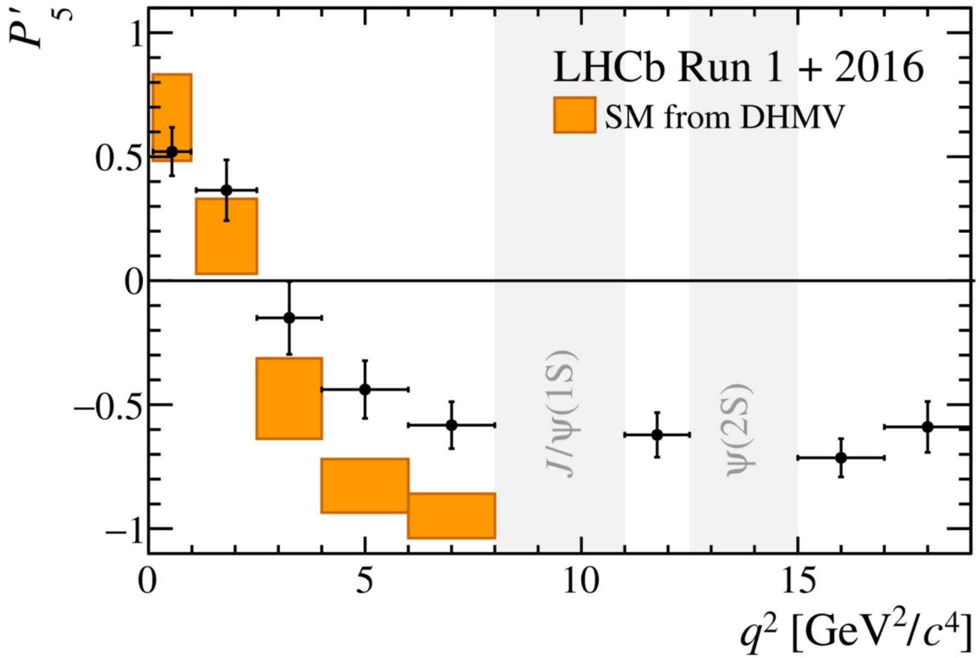


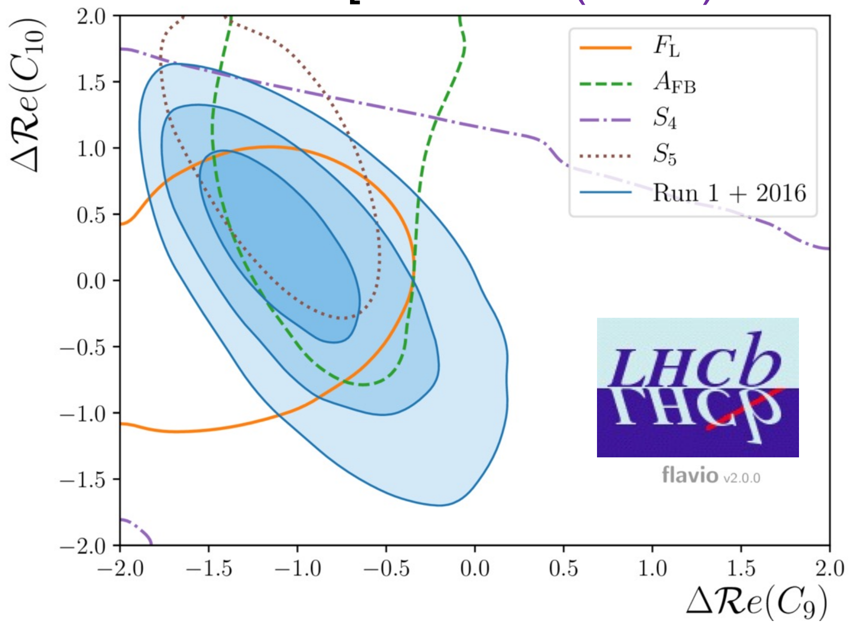
- Vast majority of observables in agreement with SM predns, giving some confidence in theory control of form-factors

$B^0 \to K^{*0}\mu\mu$ 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]

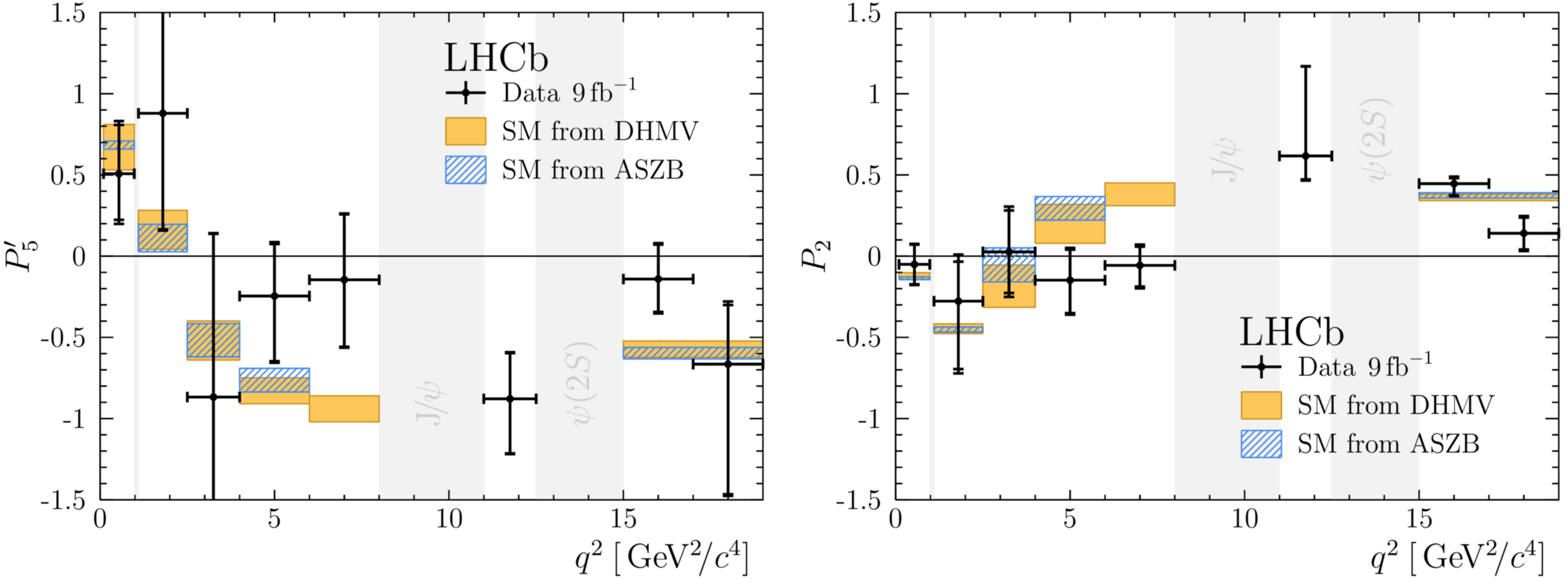




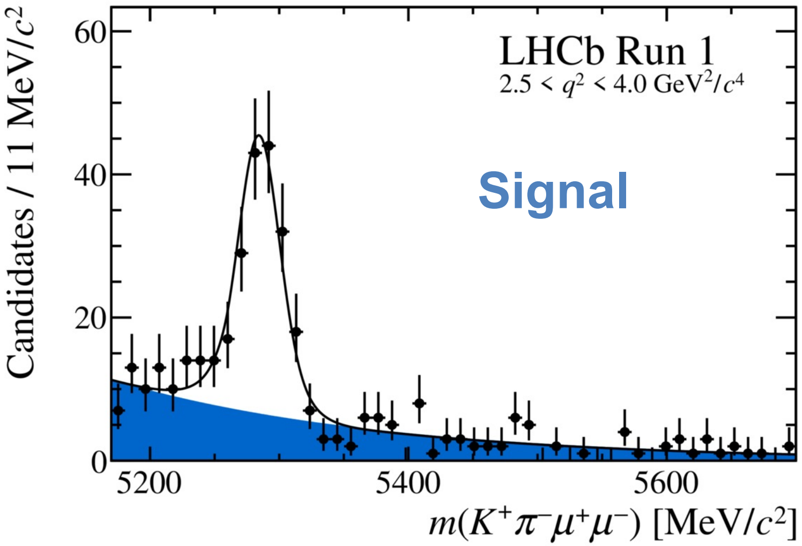
$B^+ \to K^{*+}\mu\mu$ angular analysis

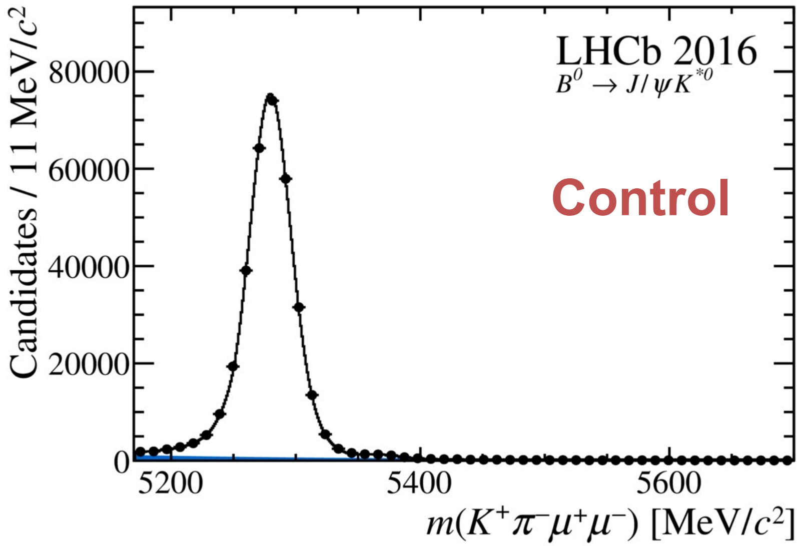
- Most recently angular analysis performed for analogous K^{*+} decay mode with $K^{*+} \to K_S^0\pi^+$
- Lower statistics but message is identical – in this decay tension with SM is 3.1σ

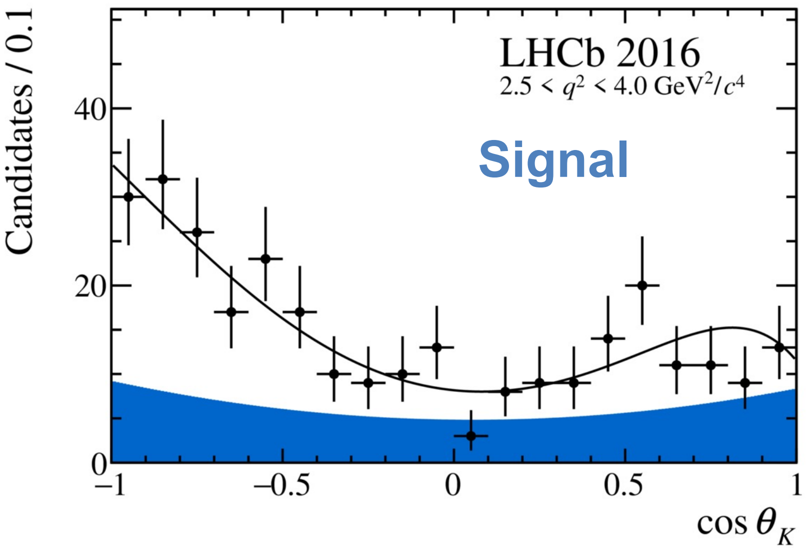
[PRL 126 (2021) 0161802]

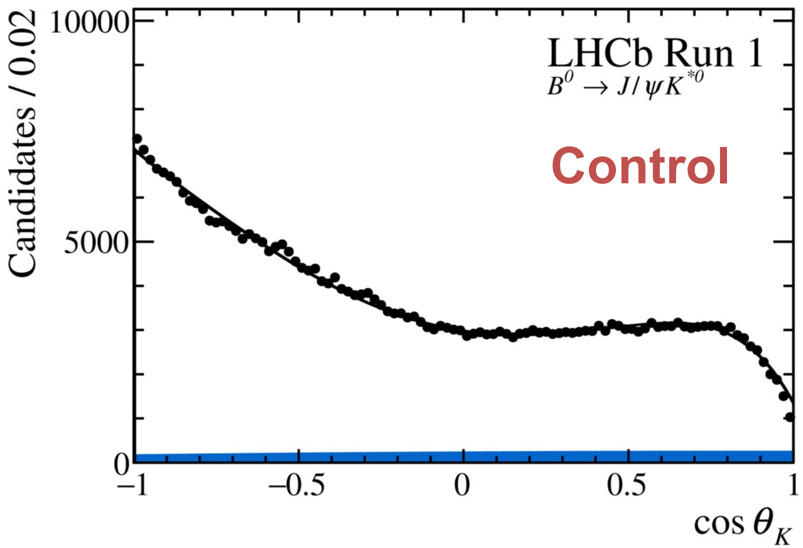


Control channel angular analysis









Could something have gone wrong?

- [On the experimental side…]
- Angular anomaly looks very compatible with branching fraction anomaly but very different analysis
- Even at low q^2, majority of observables agree with SM prediction
- Control channel analysis gives confidence
- These are not angles in lab frame … difficult to see how to build a connection to any detector effect
- IMO electron angular analysis could end the debate

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

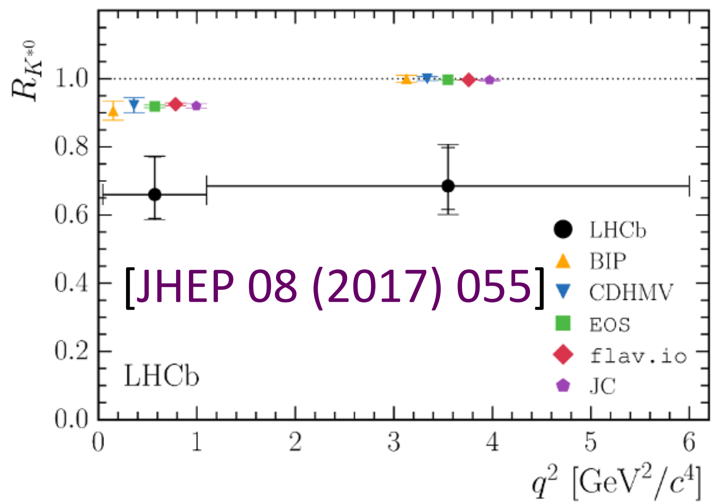
- Ratios of the form: $$R_{K^{(*)}} := \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \overset{\text{SM}}{\cong} 1$$

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

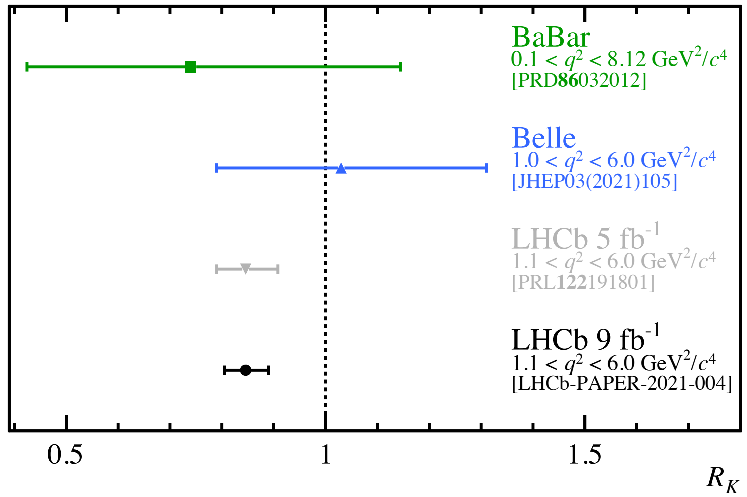
→ Any significant deviation is a smoking gun for New Physics

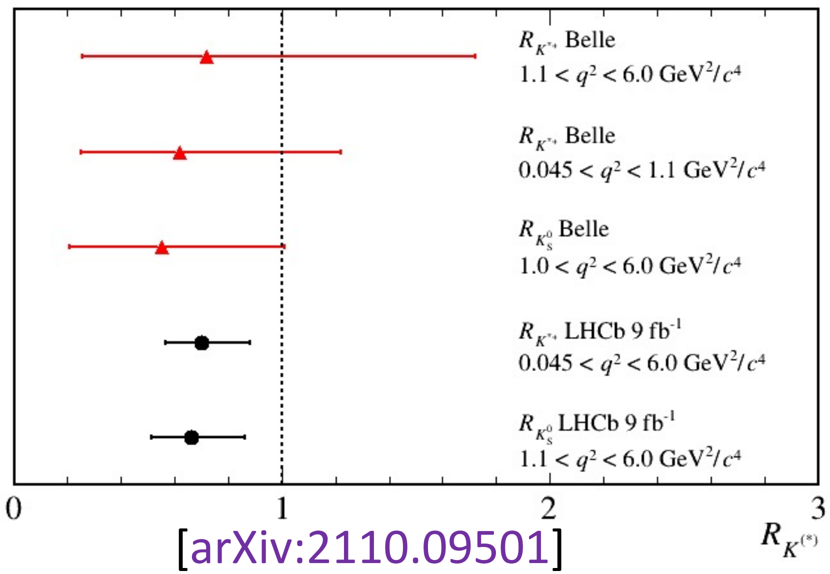
b→sll LFU ratios

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



$B^+ \to K^+\ell^+\ell^-$ R_K [arXiv:2103.11769]





[arXiv:2110.09501]

- Recent $R_{K^{*+}}$, R_{K0} measurements ~2σ consistency with SM, compatible with R_K, which is 3σ from SM
  - Can accommodate branching fraction, angular data and R_K with vector NP contribution
  - Possible LFU NP contribution?
  - Possible RH contribution?

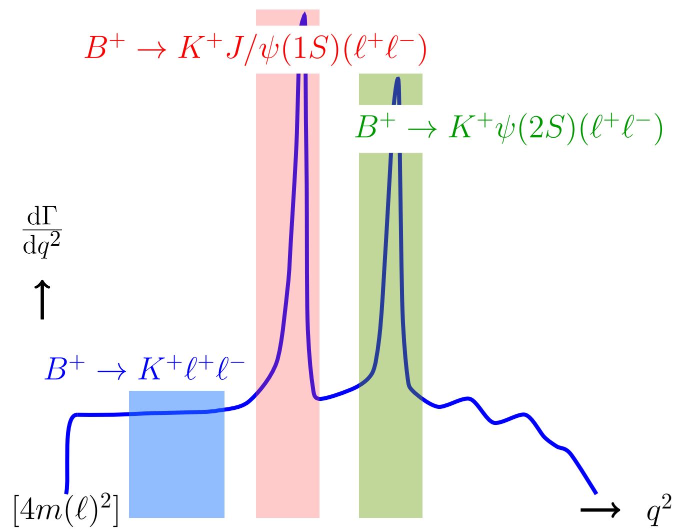
R_K Analysis Strategy

[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

Could something have gone wrong?

[arXiv:2103.11769]

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

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

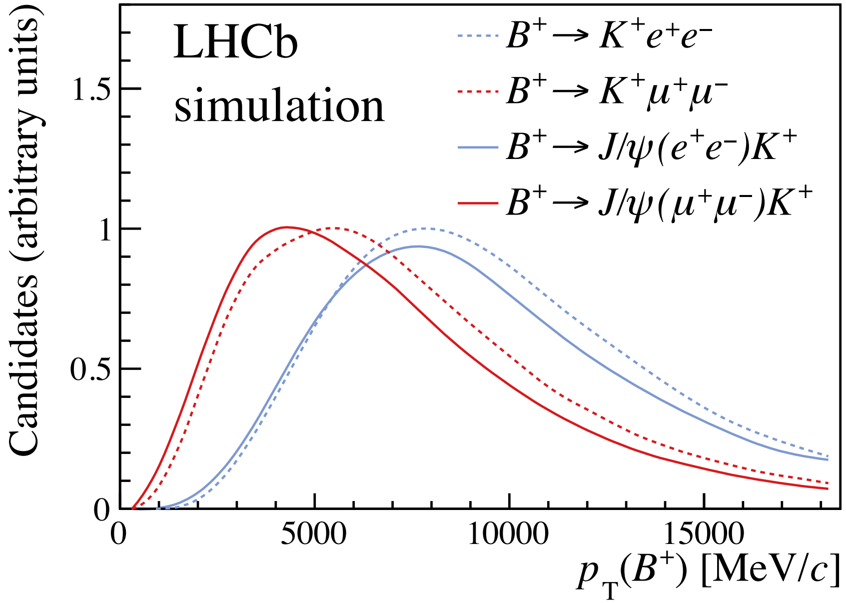
  where we do not benefit from the double ratio cancellation

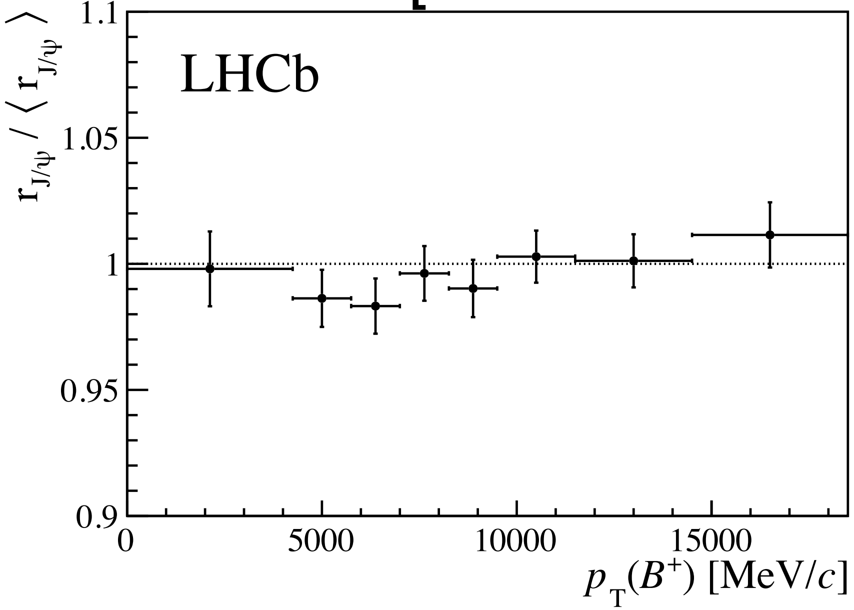
- $r_{J/\psi}$ measured to be lepton universal at 0.4% level

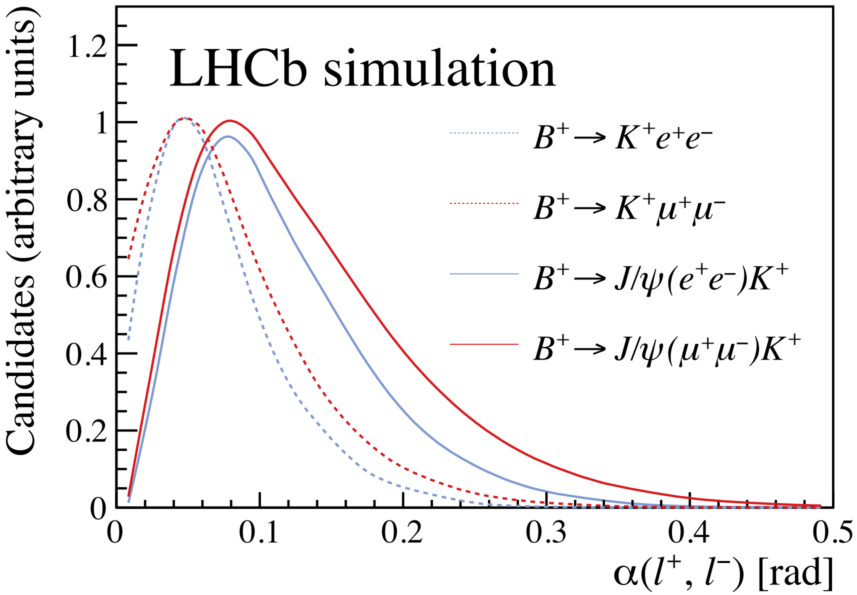
- Measure $r_{J/\psi} = 0.981 \pm 0.020$ (stat+syst)
  - compatible with unity for new and previous datasets and in all trigger samples
  - result is independent of the decay kinematics
  - binning in quantities that would expect bremsstrahlung and trigger to depend on see completely uniform result

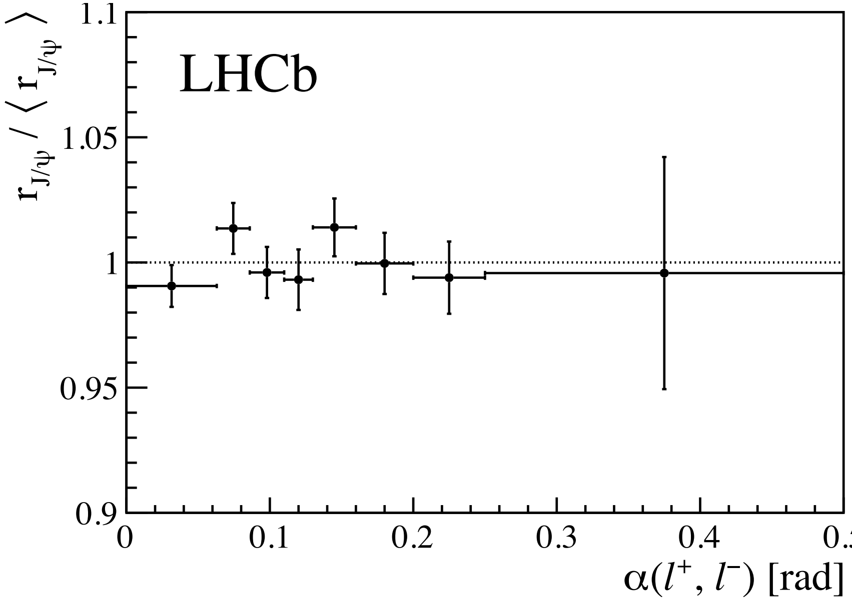
Could something have gone wrong?

[arXiv:2103.11769]









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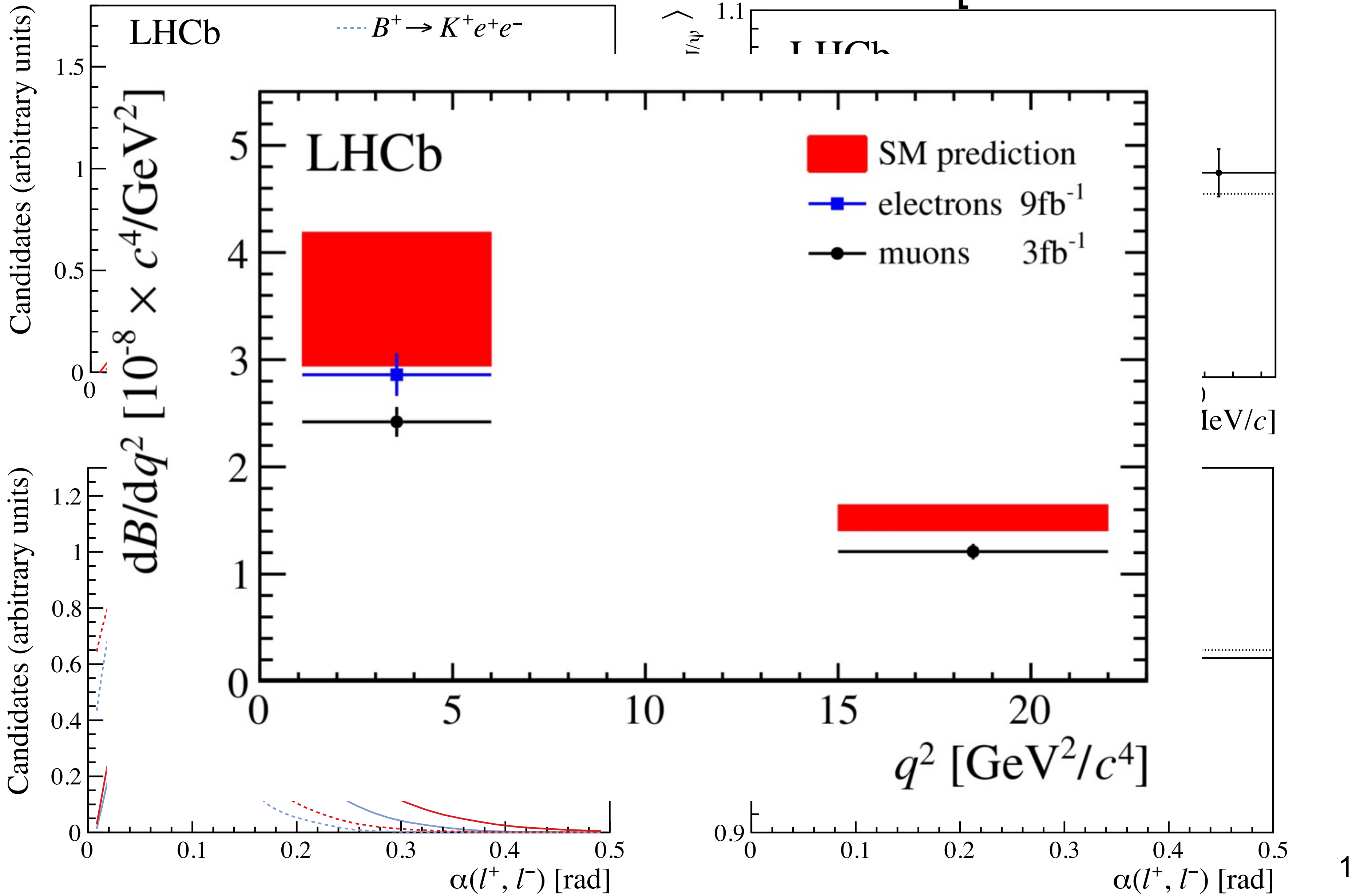
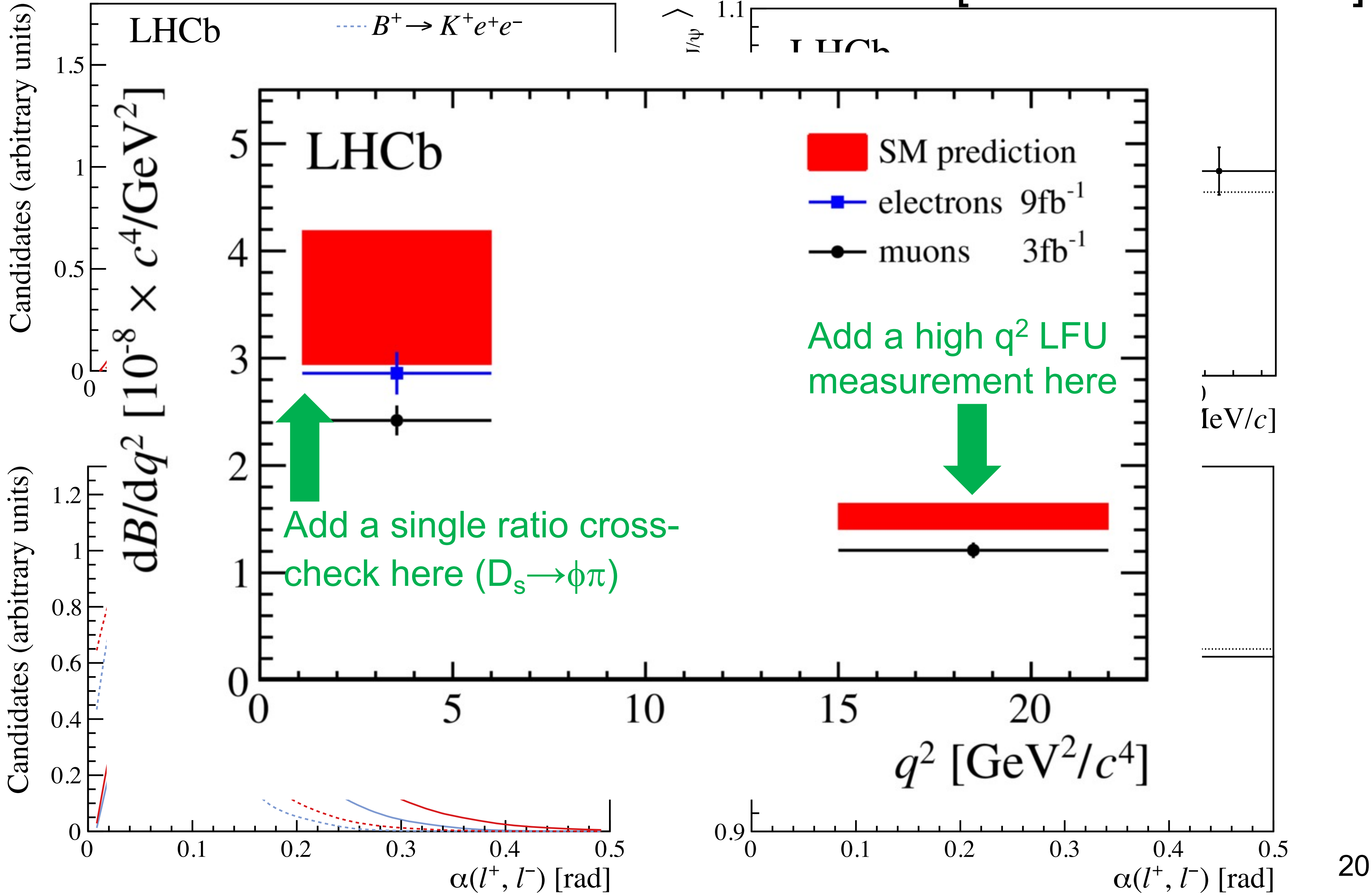


Ending the (expt'al) debate

[arXiv:2103.11769]



The broader landscape

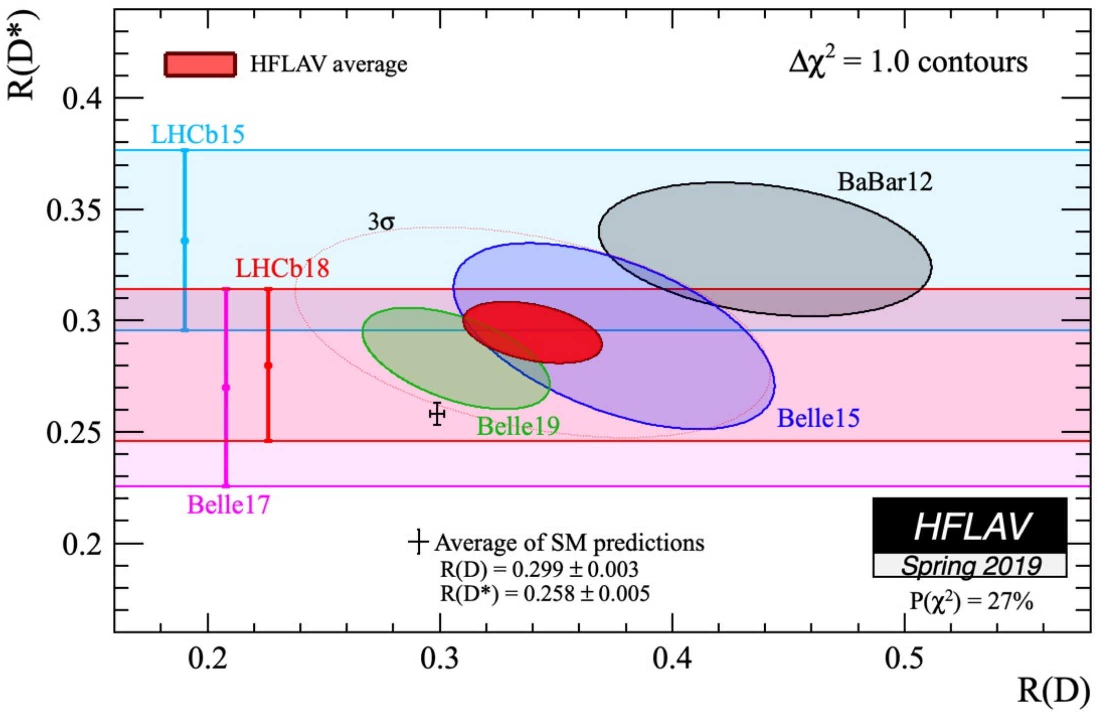
- A further anomaly is seen in LFU ratios in **$b \to c l \nu$** decays
  - Good theoretical control due to factorisation of hadronic and leptonic parts – again very clean
  - Tree-level processes in SM – requires a *huge* NP effect, comparable with the SM amplitude
  - Drives idea of hierarchical effect: large NP effect in τ; smaller in μ, where have measured **$b \to s\mu\mu$** decays, and little/no effect in **e** modes

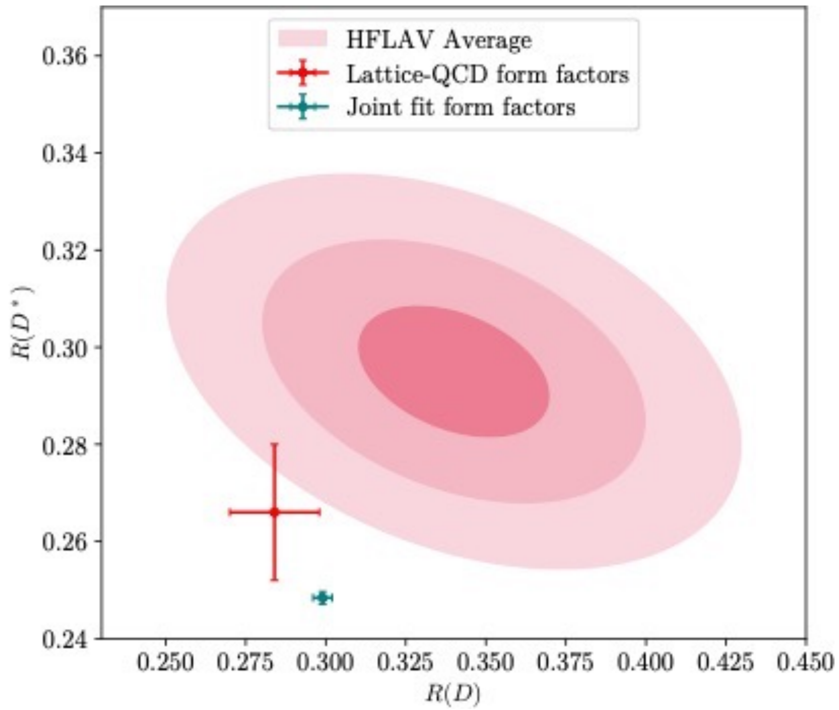
- Possible to make a NP explanation, coherent with **$b \to s\mu\mu$**
  - Most discussed NP models involve Leptoquarks or Z'
  - Difficult to connect **$b \to c l \nu$** anomaly and **g-2** anomaly, but is possible to connect **$b \to s l l$** anomalies and **g-2**

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 (recent updates to SM theory from lattice)

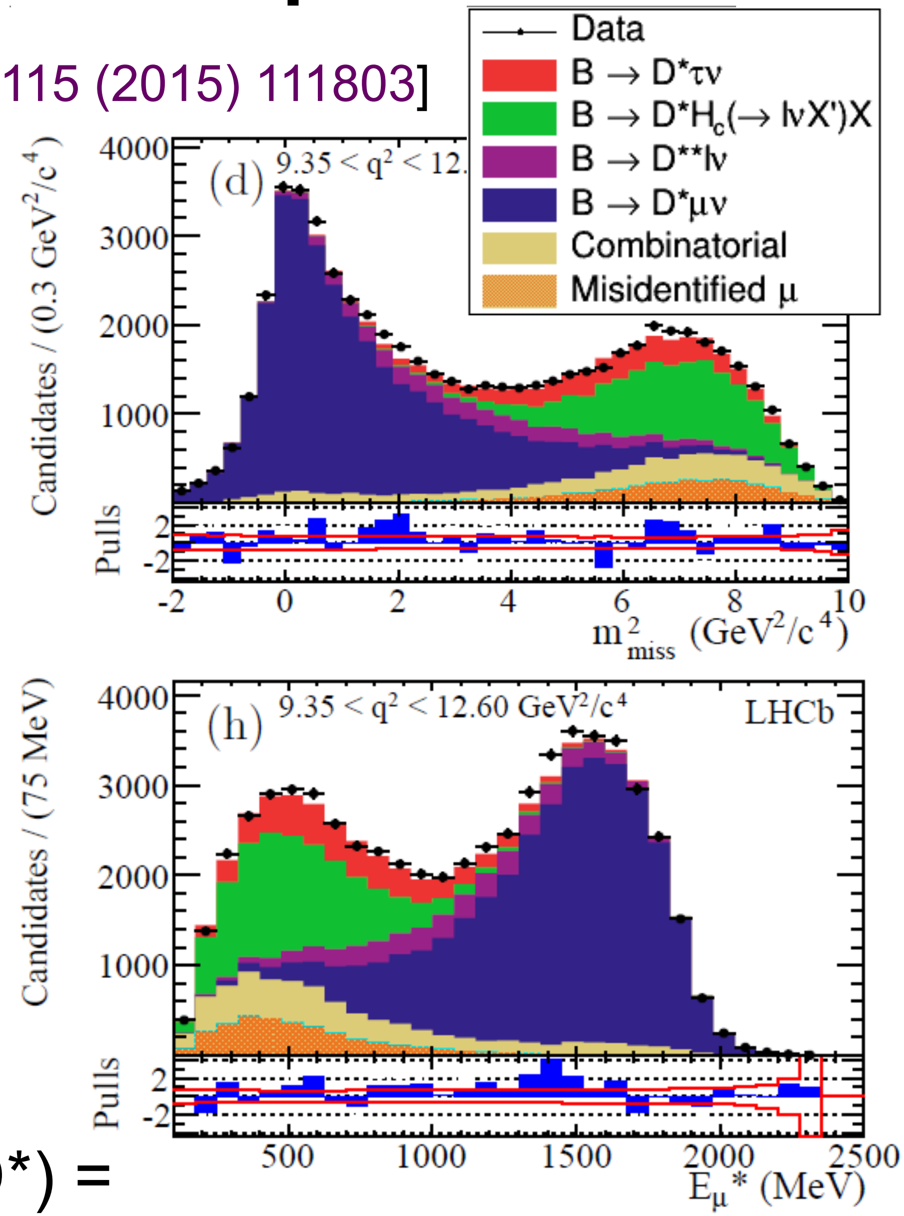
[arxiv:2105.14019]





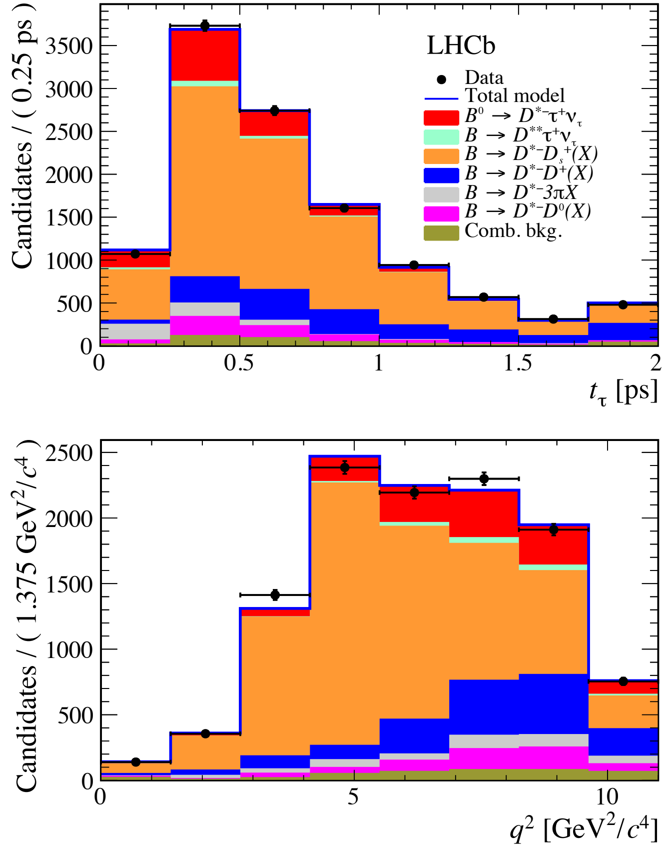
leptonic τ

[PRL 115 (2015) 111803]



R(D*) = 0.336±0.027±0.030 (**2.1σ** above SM)

3-prong τ



[Phys. Rev. D 97 (2018) 072013]

- R(D*) = 0.286±0.019±0.025±0.021
  - 3rd uncertainty from B($B^0 \to D^{*-}\pi^+\pi^-\pi^+$, $D^{*-}\mu^+\nu$)

0.9σ above SM prediction

Conclusions

Conclusions

- Interesting set of anomalies observed in **$b \rightarrow sll$** and **$b \rightarrow cl\nu$** decays

- Would need some extraordinary effects to be able to escape data-driven calibrations and explain with ‘experimental issues’

- Some of the theoretical issues still intractable – no knockout blow on the SM… yet…