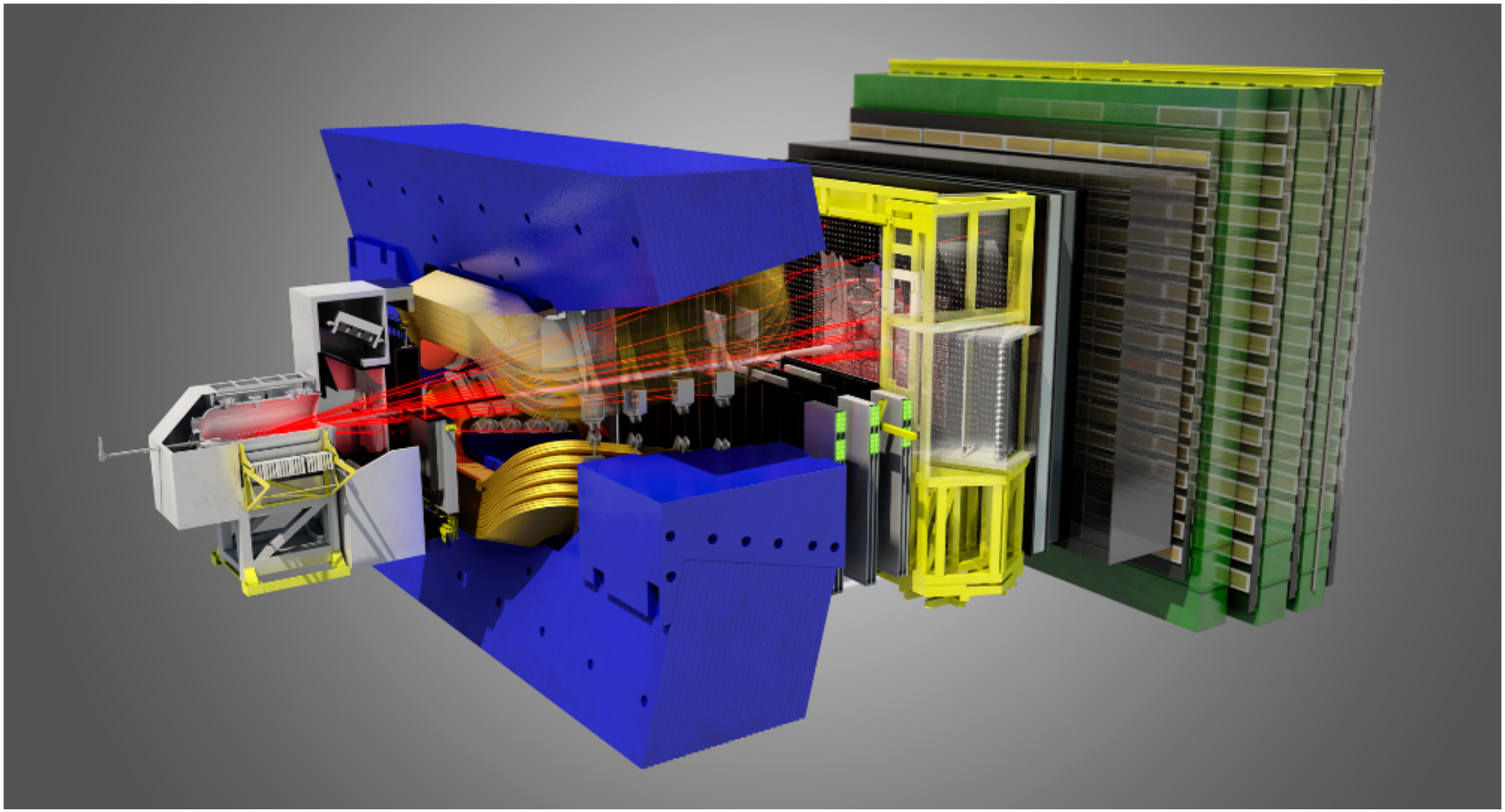
Status & Outlook for $R_D(*)$, $R_K(*)$ from LHCb



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LHCb

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

Introduction

- Interesting set of anomalies have appeared in measurements of B decays :
  - Lepton-flavour universality ratios $b \to s\ell\ell$ and $b \to c\ell\nu$ decays
  - Branching fractions of several $b \to s\ell\ell$ processes
  - Angular observables in $B^0 \to K^{*0}\mu\mu$, $B^+ \to K^{*+}\mu\mu$
- Reminder of key LFU measurements and outlook for such measurements
- Mention connection to non-LFU measurements

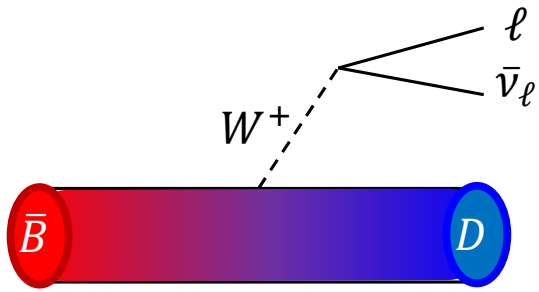
LFU in $b \to c$ decays

LFU in b→c decays

- Anomaly is seen in LFU ratios with semileptonic **b→clν** decays

- Good theoretical control due to factorisation of hadronic and leptonic parts – then theoretically pristine quantity e.g. in case of **b→clν** transition,

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

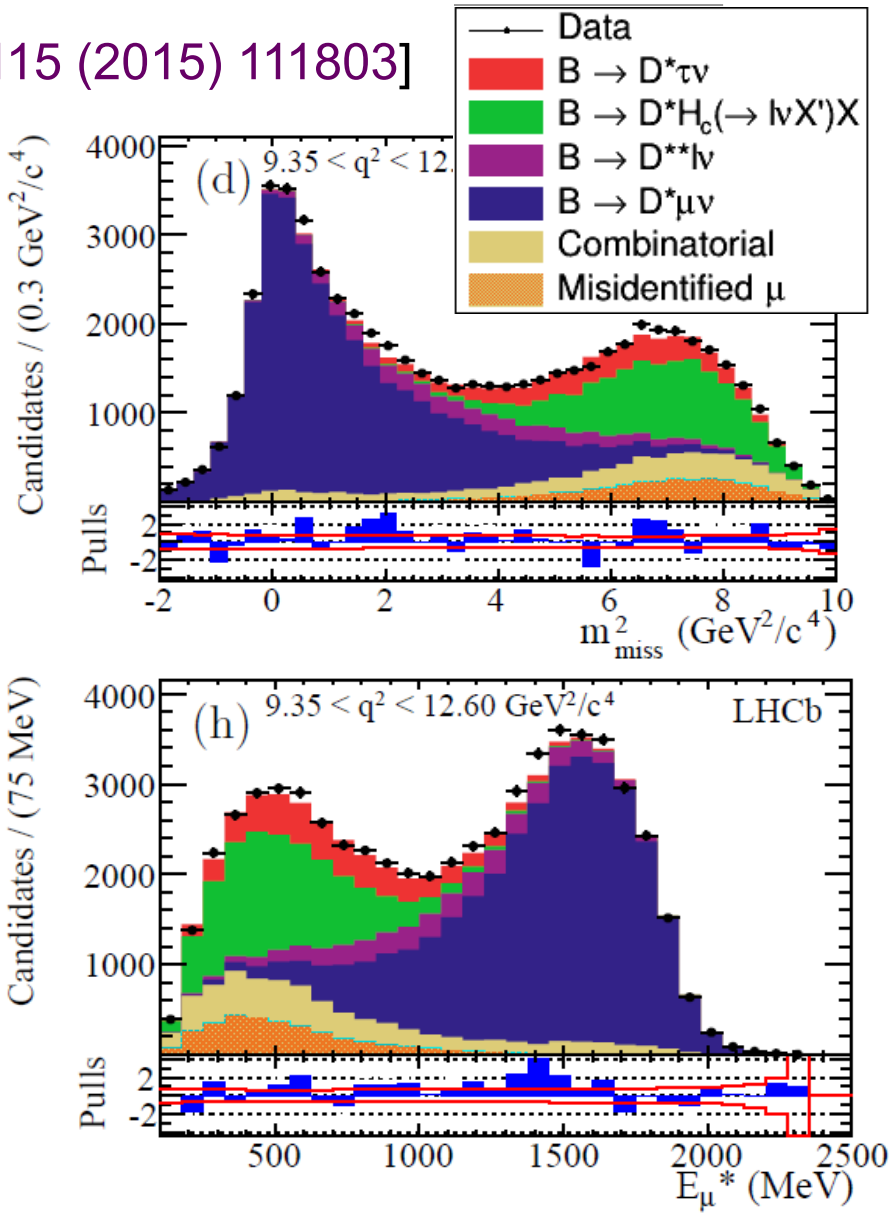


  - Tree-level processes in SM – requires a huge NP effect, comparable with the SM amplitude in order to explain data with new physics
  - Drives idea of hierarchical effect: large NP effect in τ, smaller in μ, e

LHCb R_D* result – leptonic τ

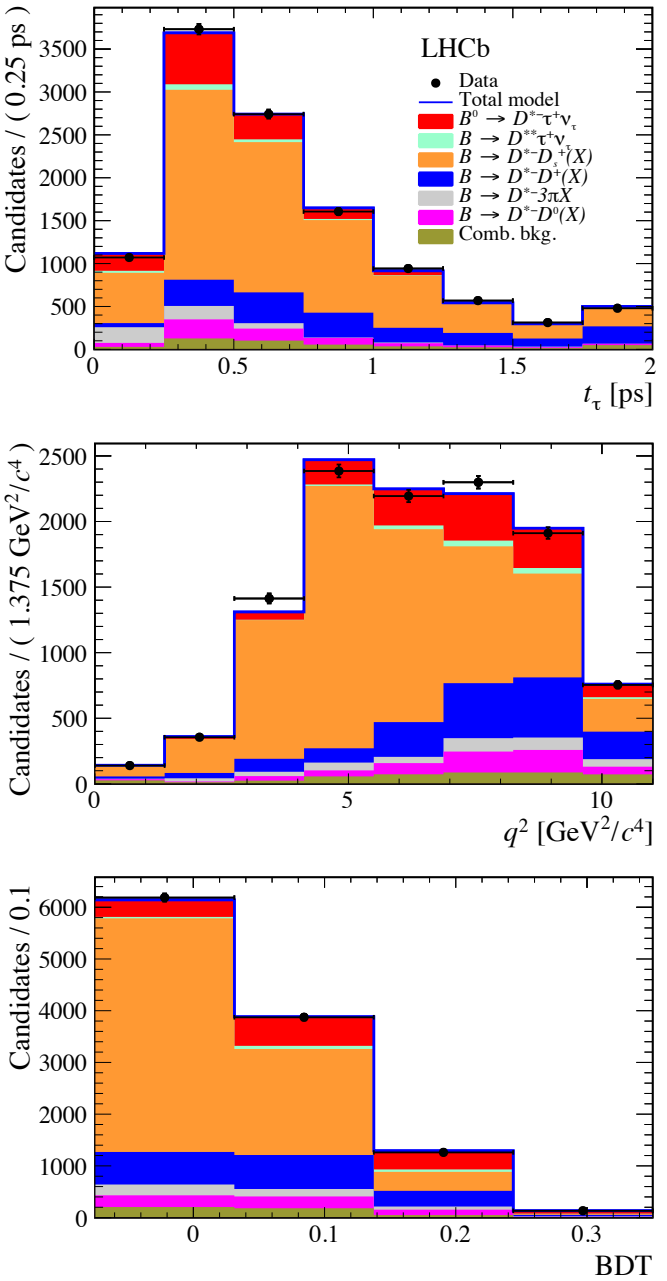
[PRL 115 (2015) 111803]

- Very challenging analyses in our environment at LHCb
- 3D fit to (m_{miss}^2, E_μ*,q^2)
- R(D*) = 0.336±0.027±0.030
- **2.1σ** above SM prediction



LHCb R_D* result – 3-prong τ

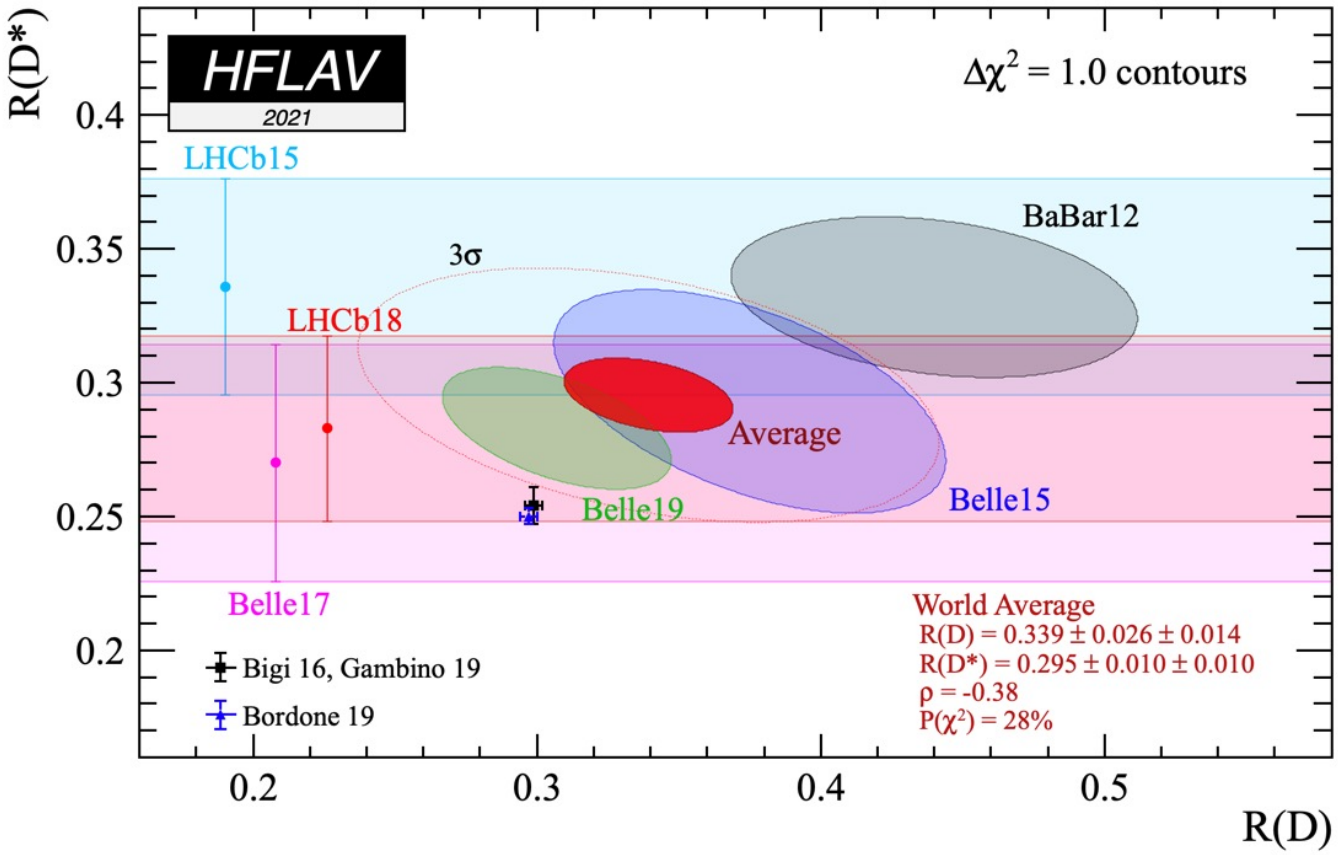
- Largest residual background $B \to D^* D_S[\to 3\pi X]$
- Train BDT to separate from signal using 3π dynamics, visible mass, momenta etc.
- 3D fit to (BDT, τ_τ, q^2)
- R(D*) = 0.286±0.019±0.025±0.021
  - 3rd uncertainty from B($B^0 \to D^{*-}\pi^+\pi^-\pi^+$) and B($B^0 \to D^{*-}\mu^+\nu$)
- **0.9σ** above SM prediction



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

Fit to $b \to c l \nu$ LFU ratios

- Combination of these results with those from Babar/Belle
- World average value SM predictions shows a 3σ tension
  - Key theory inputs from lattice give confidence in SM predn.



LHCb $R_{J/\psi}$ result

[PRL 120 (2018) 121801]

- Have made analogous measurement to R_{D^*} with B_c^+ mesons

$$R(J/\psi) \equiv \frac{\mathcal{B}(B_c^+ \to J/\psi\tau\nu)}{\mathcal{B}(B_c^+ \to J/\psi\mu\nu)} = 0.71 \pm 0.17 \pm 0.18$$

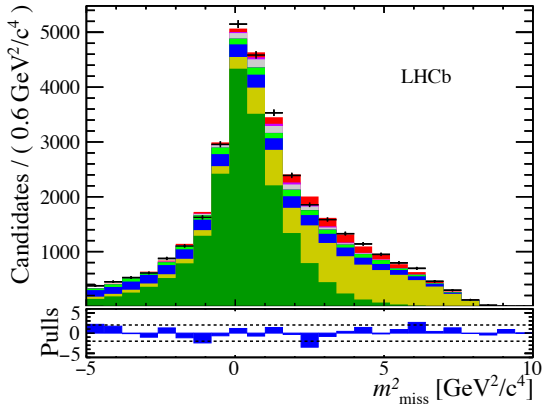
- Reconstruct J/ψ→μμ final state, giving a striking signal signature
  - But production of B_c^+ mesons

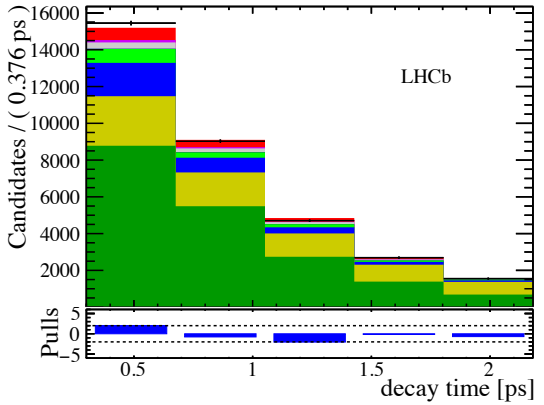
- Improvements in lattice mean this is result also of increased interest :

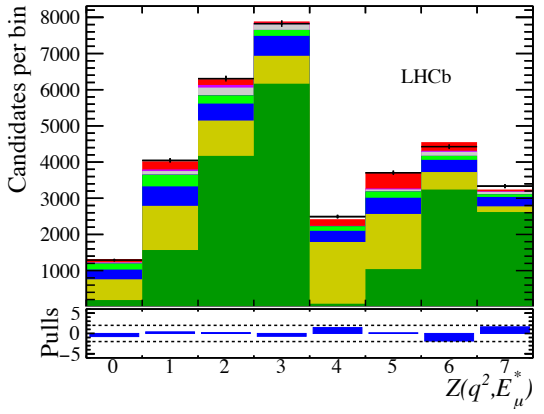
	Lattice only	Lattice+Exp[6]	Experiment	Tension
$R(D)$	0.293(4)[7]	0.299(3)	0.340(30)	1.4σ
$R(D^*)$	0.265(13)	0.2483(13)	0.295(14)	3.3σ
$R(D_s)$	0.299(5)	–	–	–
$R(D_s^*)$	0.244(8)	–	–	–
$R(J/\psi)$	0.258(4)	–	0.71(25)[8]	1.8σ

HFLAV average, Fermilab-MILC, HPQCD.

[arXiv:2111.06782]

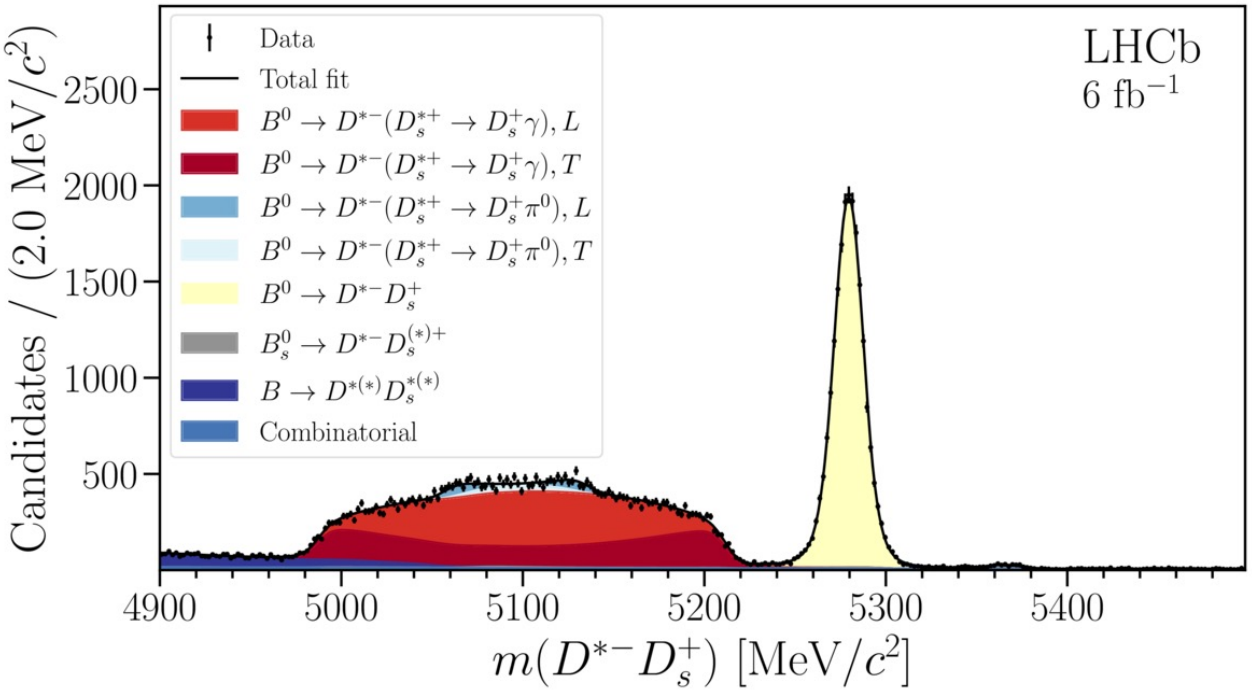


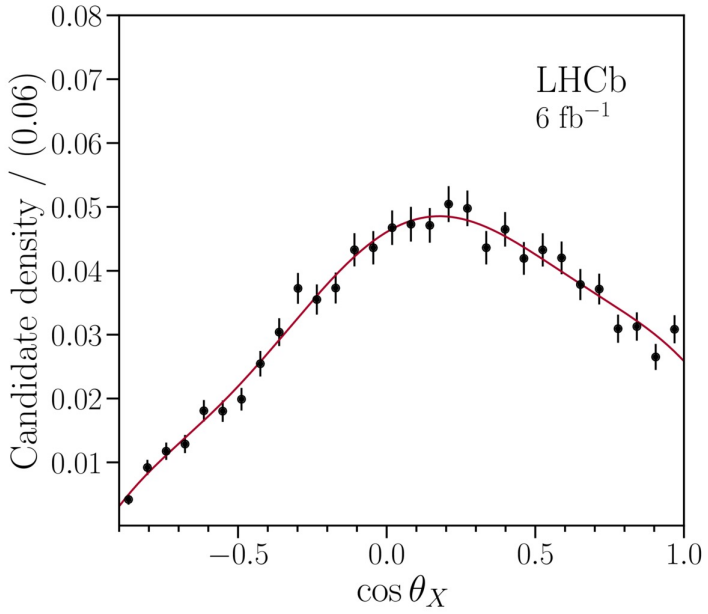




LFU in b→c decays – Outlook

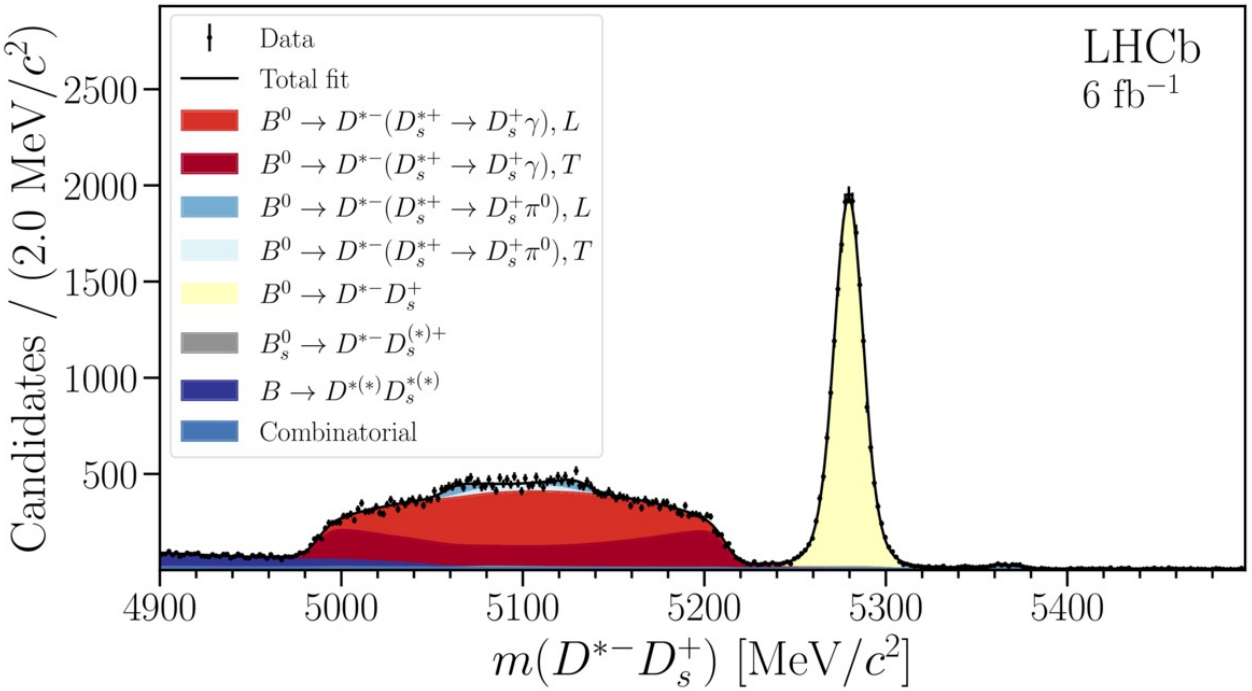
- Largest systematic uncertainty on R_D^* result is from simulation statistics
  - Fast simulation developments will address this for future measurements [EPJC 79 (2018) 1009]
  - Other major uncertainty from double charm - can improve with more data and additional external measurements

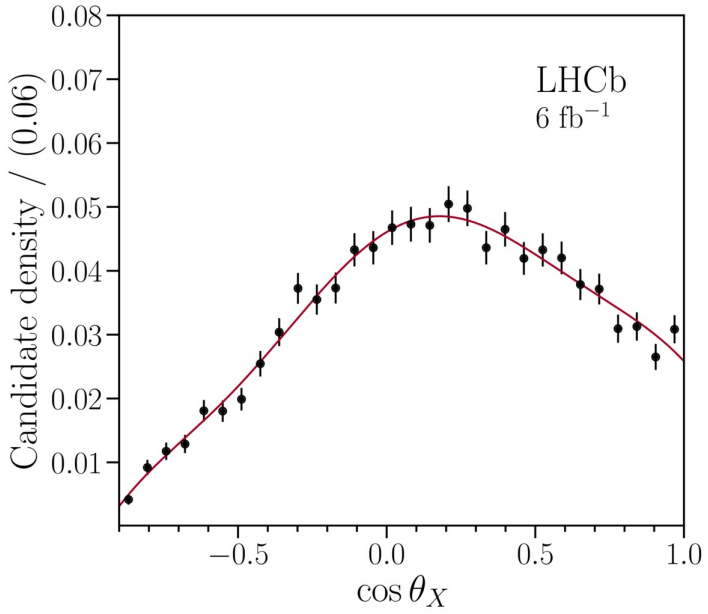




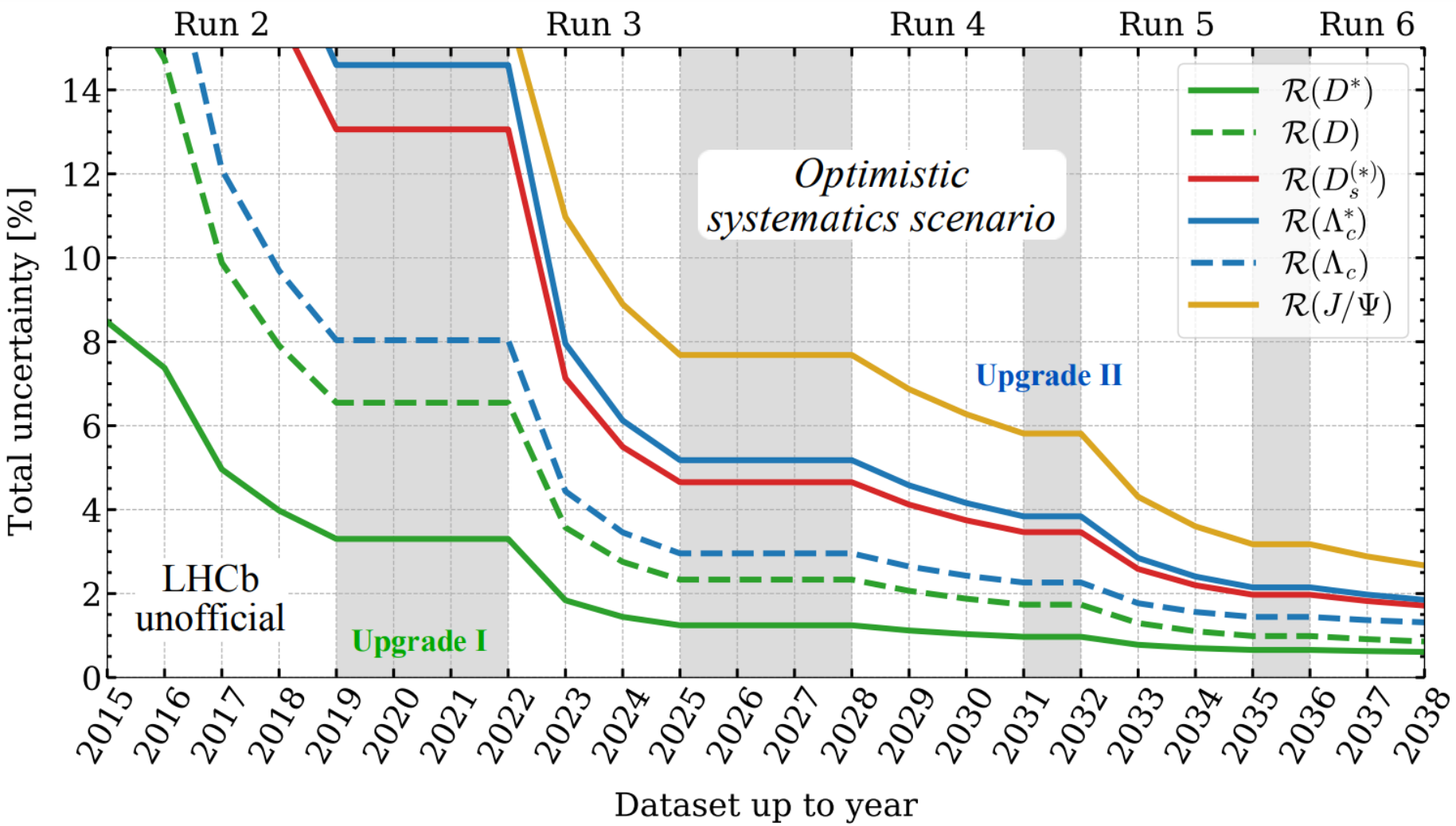
LFU in b→c decays – Outlook

- Will make a simultaneous measurement of R_D,R_{D^*} with full Run2 dataset
- In addition, many additional measurements in progress :
  - R_{D+}, $R_{\Lambda c+}$ R_{Ds+}
- Update $R_{J/\psi}$ to using Run 2 data and add hadronic τ's





LFU in b→c decays – Outlook



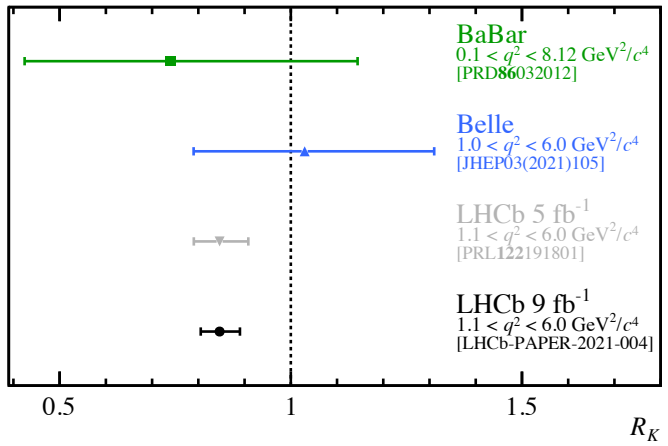
- If we can continue to control the systematics a further LHCb-upgrade could give access to %-level uncertainties

LFU in b→s decays

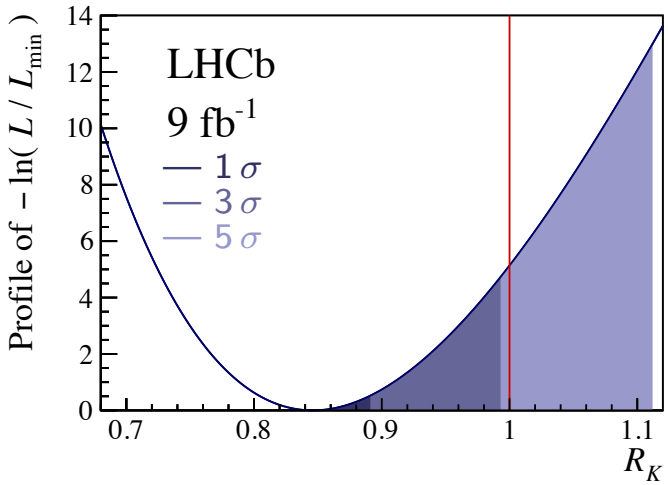
LHCb R_K result

- 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

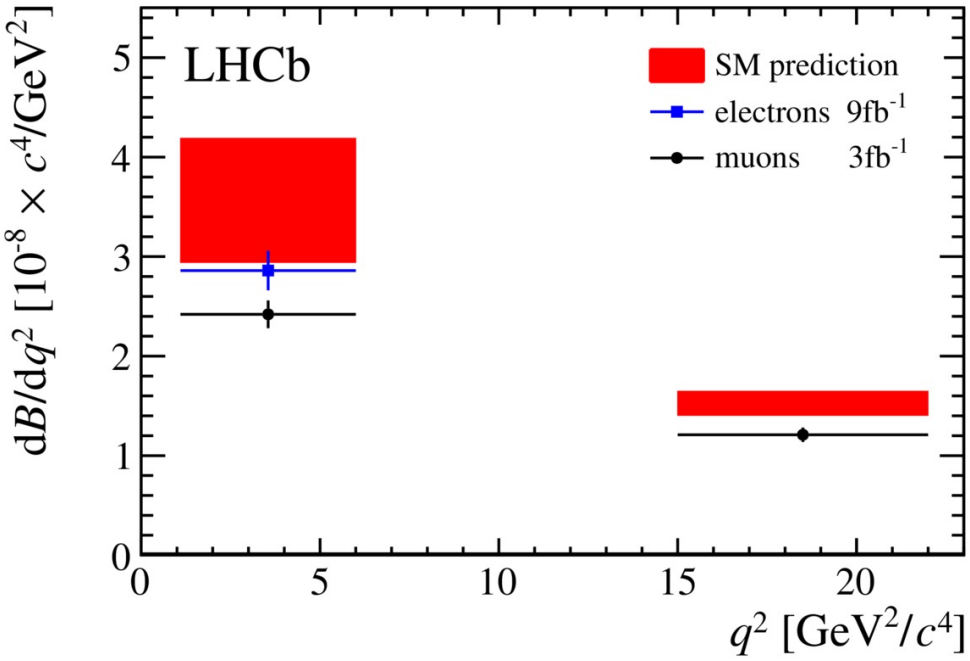
- Paper accepted by Nature Physics

Derived quantities

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

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

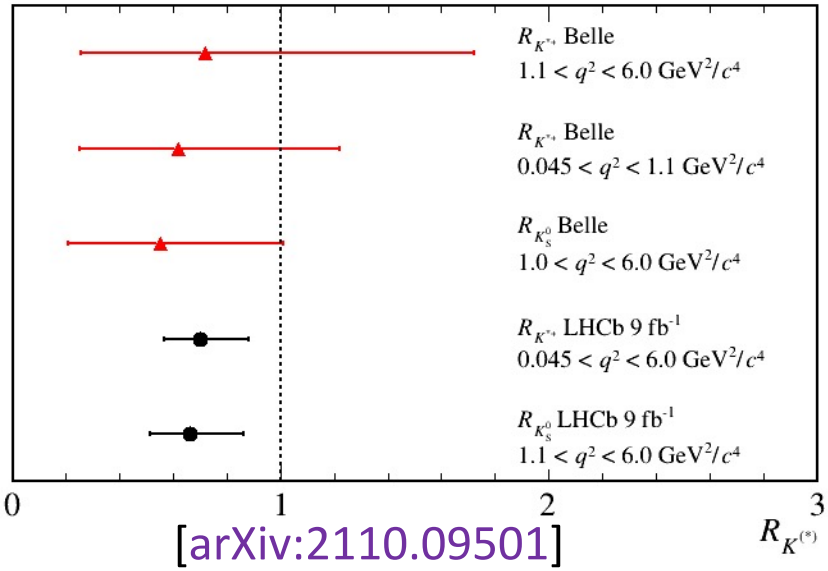
- Electrons more SM-like than muons ??? Again, hierarchical idea …



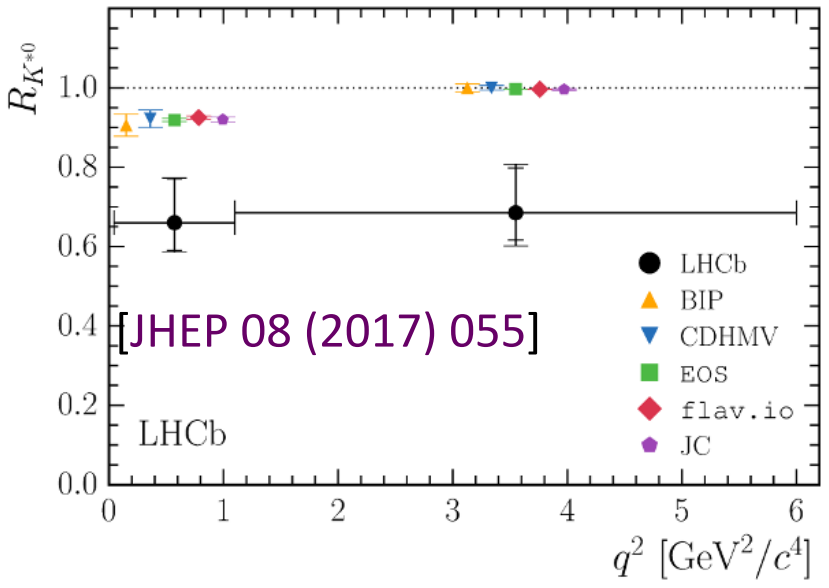
Further b→s LFU results

- Recent $R_{K^{*+}}$, R_{K^0} results ~2σ consistency with SM
  - Can accommodate these results and other b→s measurements with vector NP contribution
  - Possible LFU NP contribution?
  - Possible RH contribution?

- Older R_{K^*} result also below SM prediction



[arXiv:2110.09501]



[JHEP 08 (2017) 055]

LFU in $b \to s$ decays – outlook

Analysis Strategy

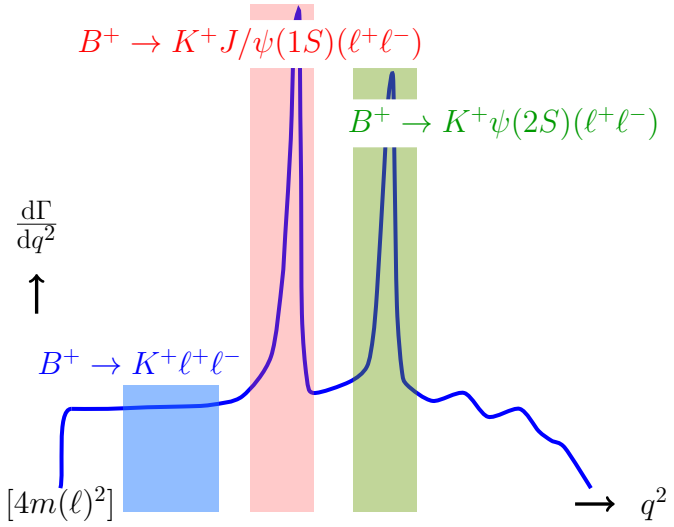
[arXiv:2103.11769]

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

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

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

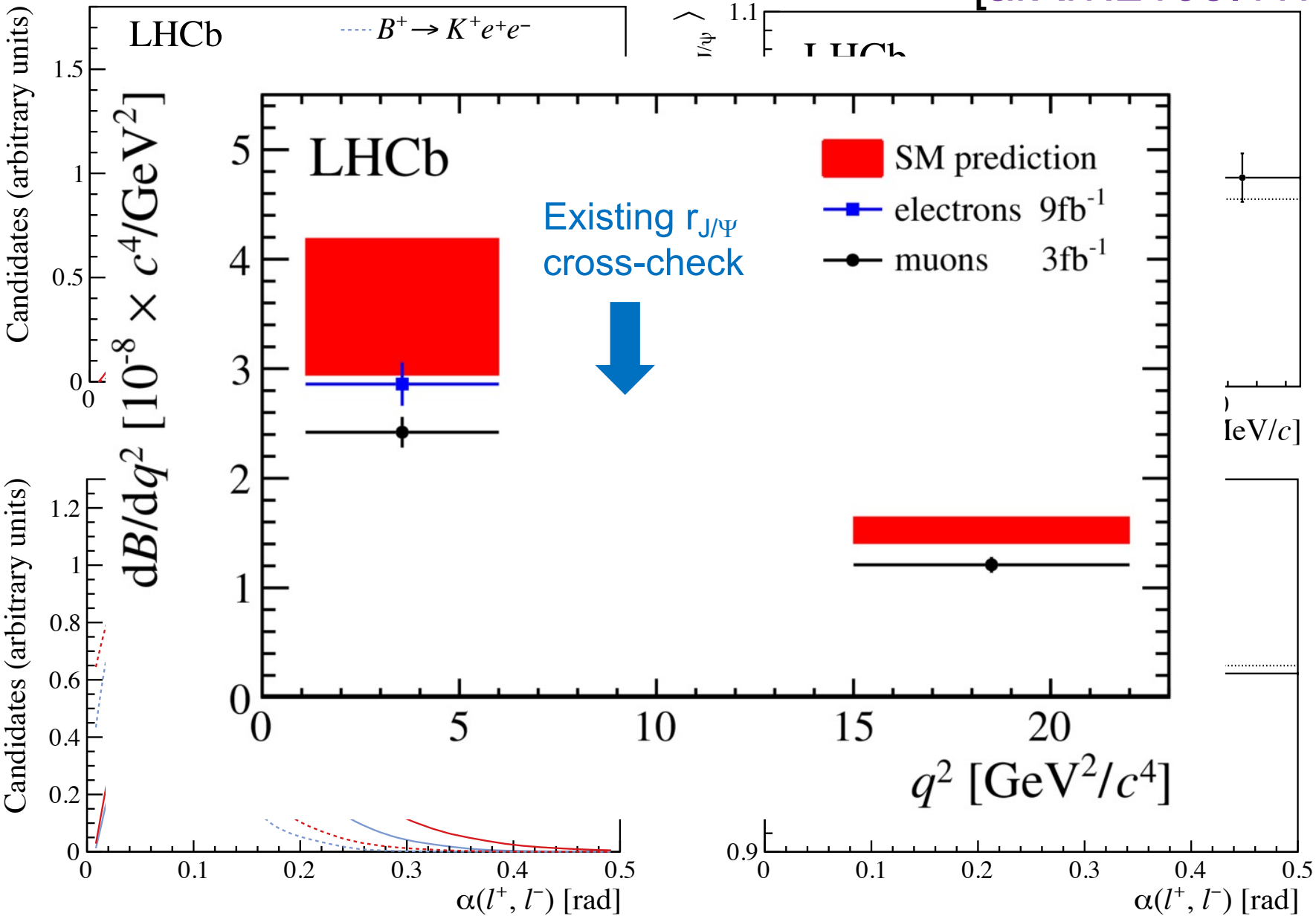
- Measurement then statistically dominated



- Test control of the absolute scale of the efficiencies by instead measuring the single ratio $r_{J/\psi}$ - compatible with 1

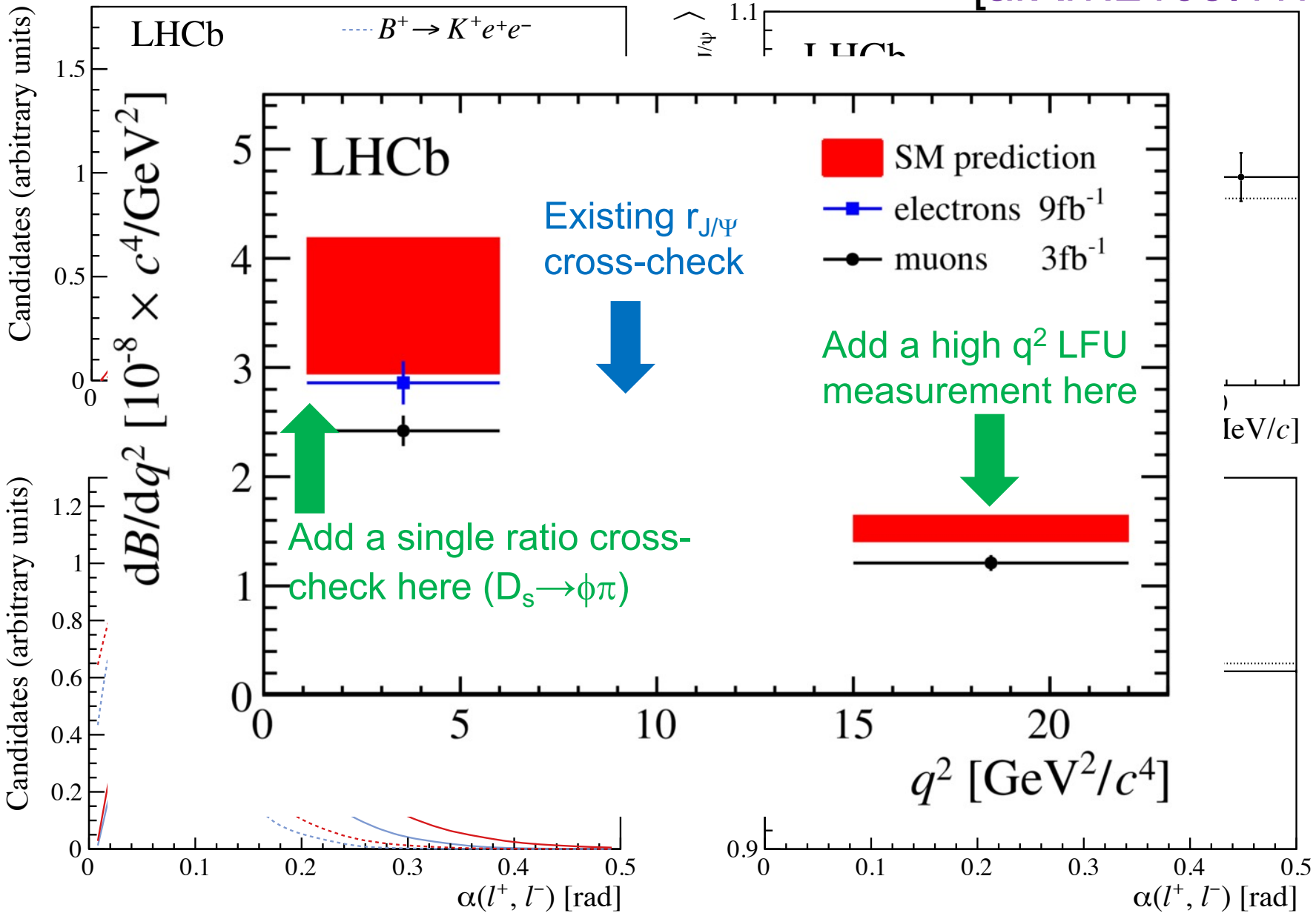
LFU in b→s decays – outlook

[arXiv:2103.11769]



LFU in b→s decays – outlook

[arXiv:2103.11769]

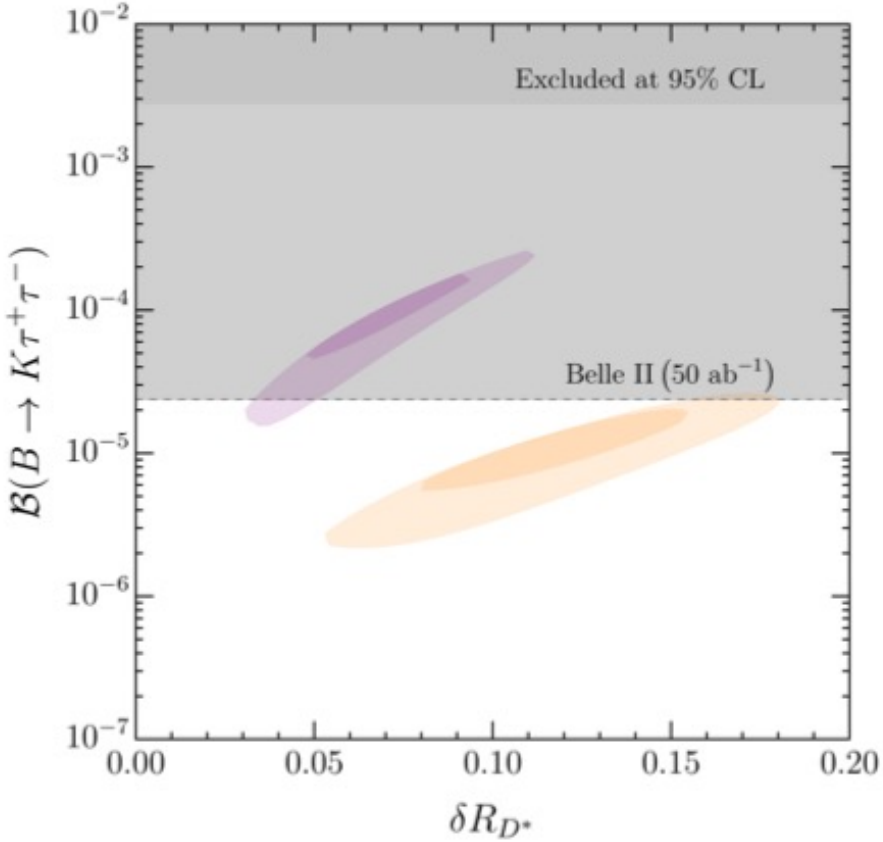


LFU in b→s decays – outlook

- New physics models that can explain the anomalies predict collosal effects in b→sττ processes

- Major new front in LFU measurements at LHCb will be trying to improve existing limits on such decays…

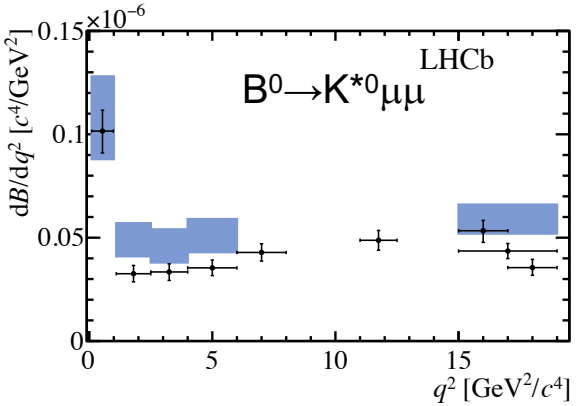
[arXiv:2101.11626]



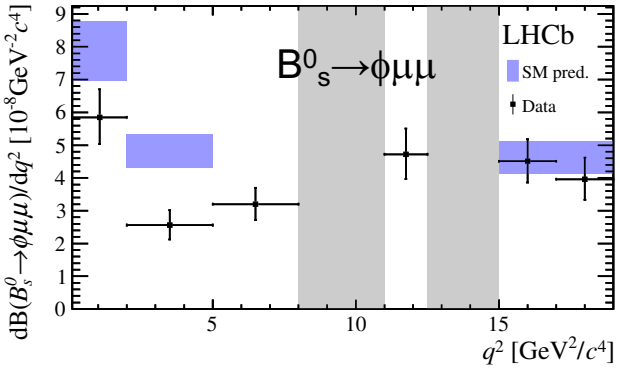
Connecting to other measurements

b→sll branching fractions

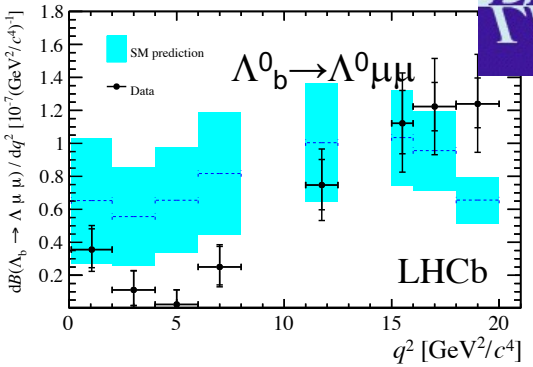
- Several b→sμμ branching fractions measured at LHCb show some tension with predictions, particularly at low q^2



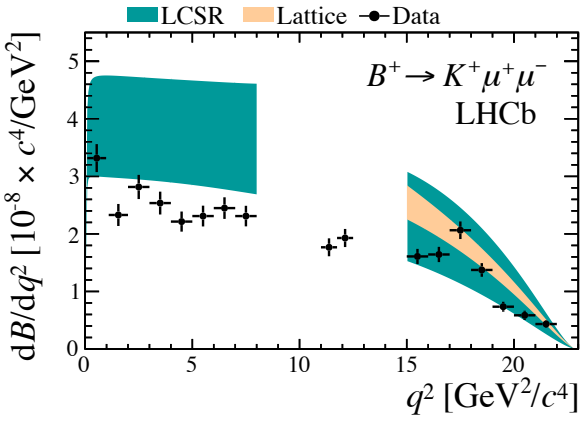
[JHEP 11 (2016) 047, JHEP 04 (2017) 142]

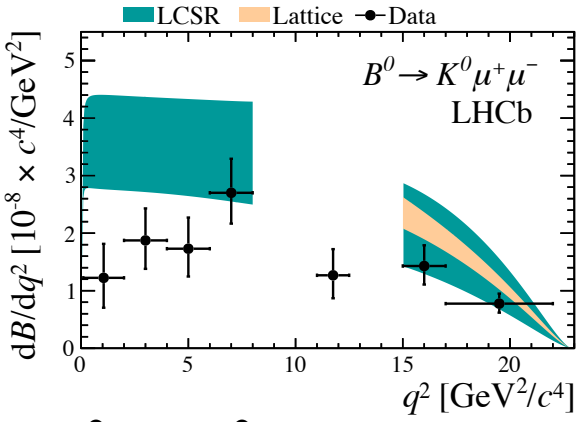


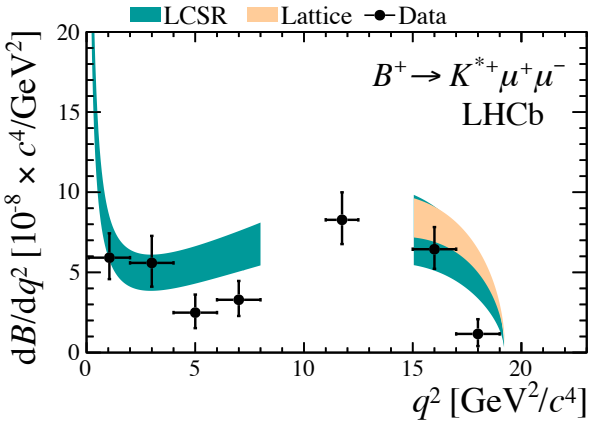
[JHEP 09 (2015) 179]



[JHEP 06 (2015) 115]



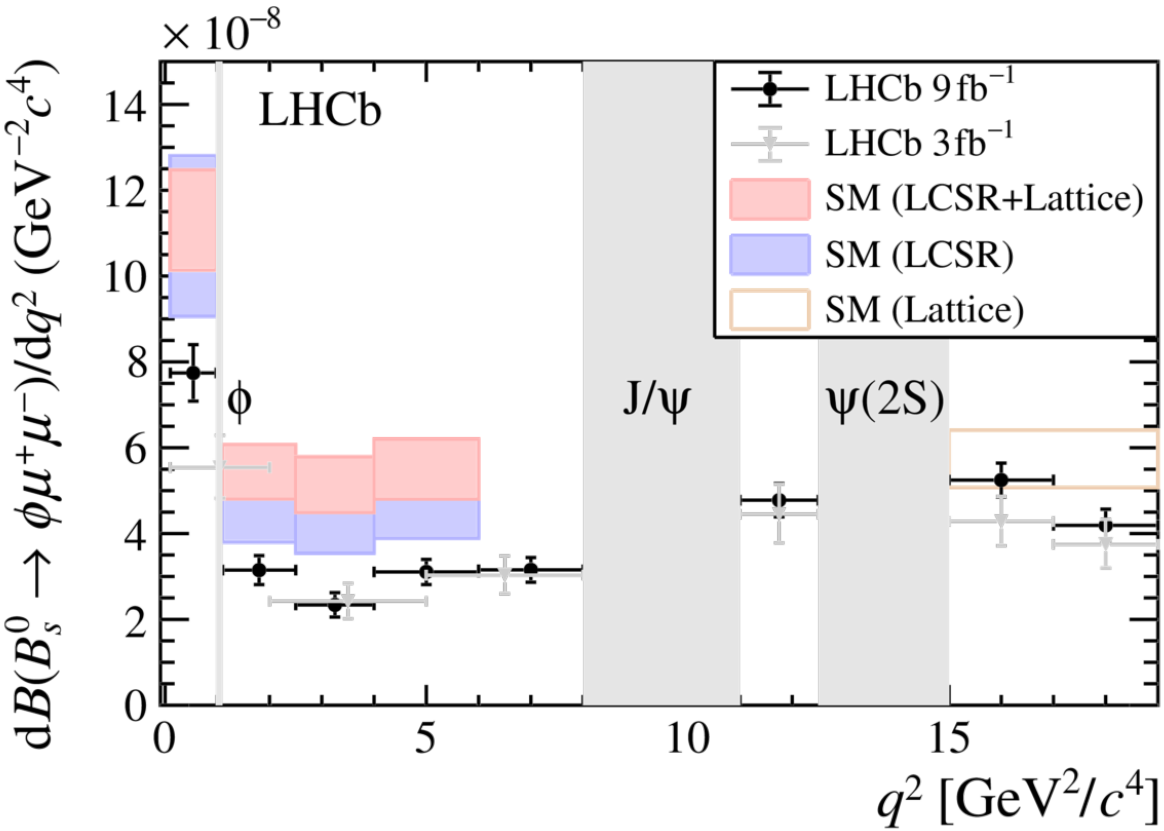




[JHEP 06 (2014) 133]

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],

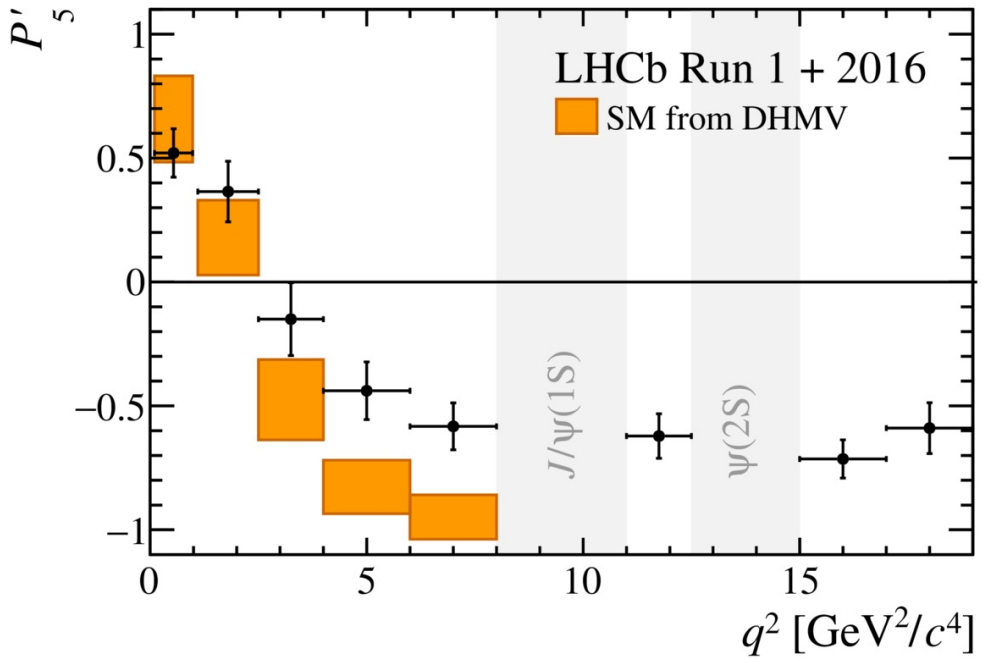
+[Horgan et al., PoS LATTICE2014 (2015) 372]

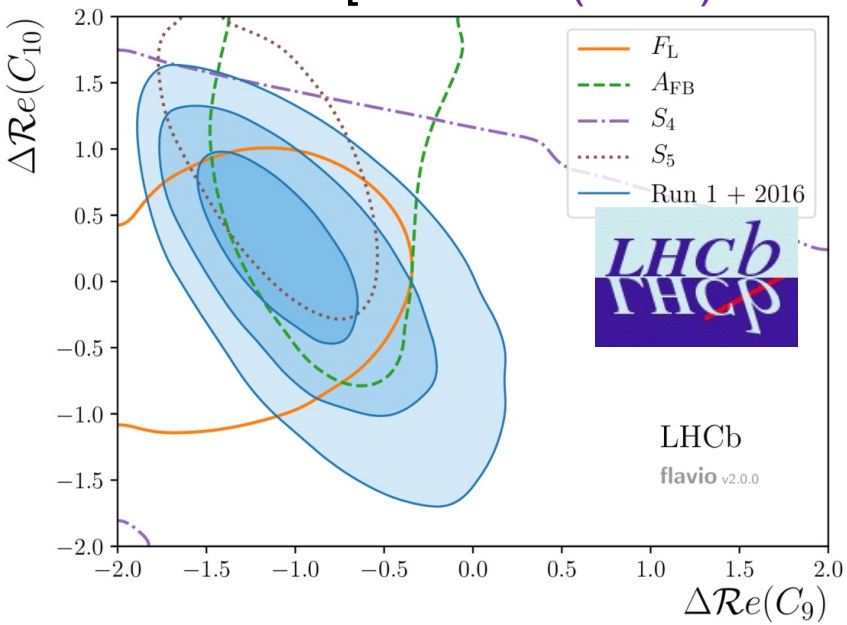
- This 3.6σ tension with SM further inflates tensions noted by some 'global' fitting groups

$B^0 \to K^{*0} \mu\mu$ 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?
- Key future (LFU) measurement : P_5' in the $B^0 \to K^{*0} ee$ mode

[PRL 125 (2020) 011802]





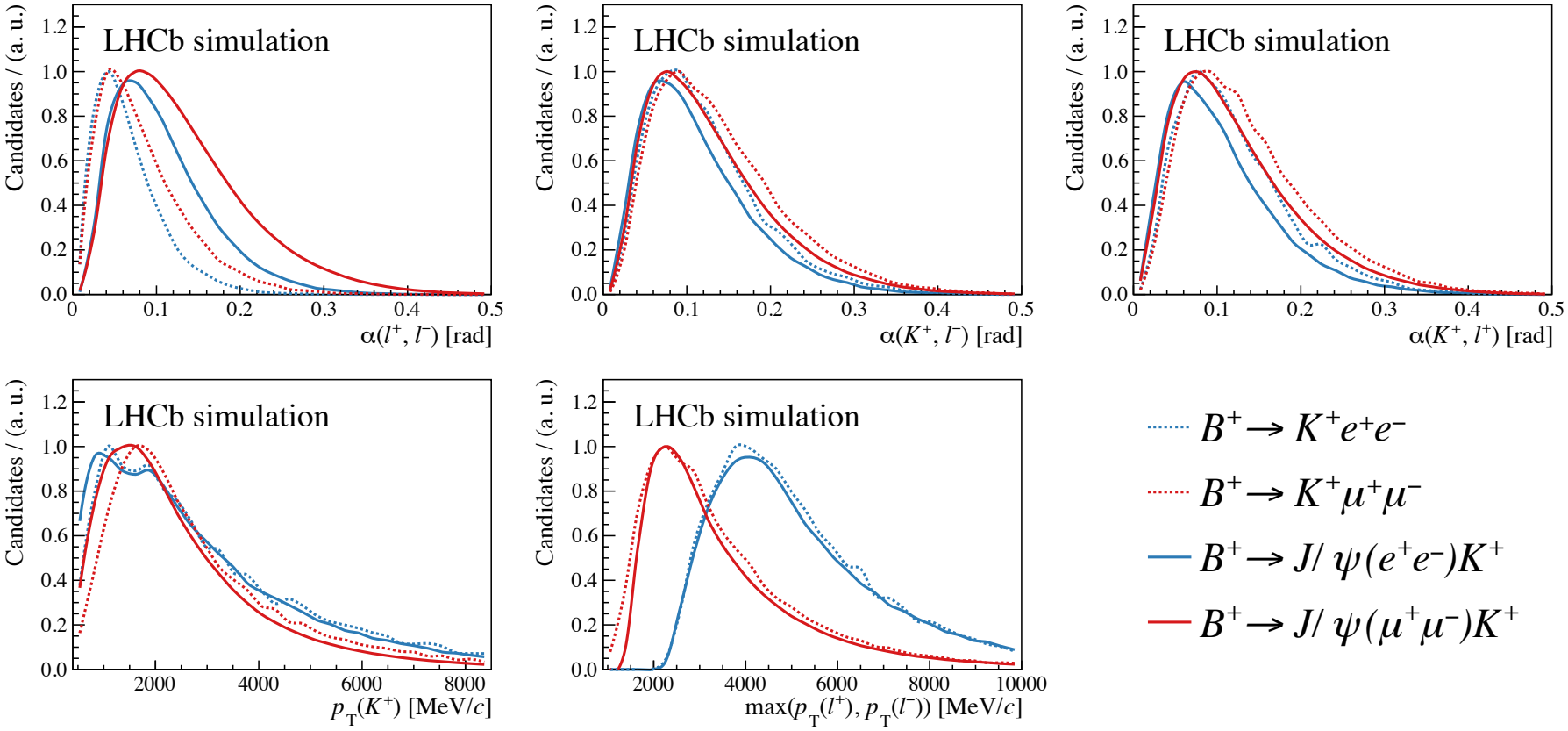
Conclusions

Conclusions

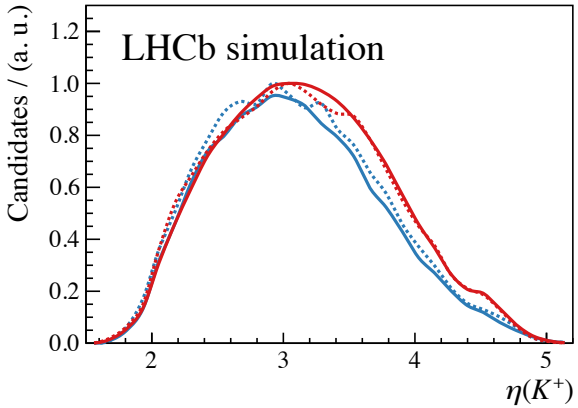
- Interesting set of anomalies observed in **$b \to c l \nu$** and **$b \to s l l$** decays

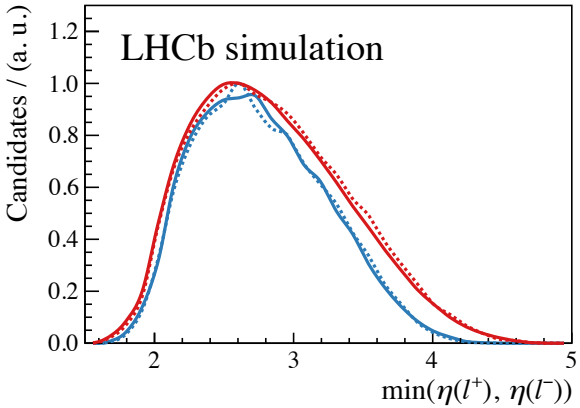
- Upcoming suite of measurements will help us get clarity
  - Increased precision with the LHCb-upgrade and further measurements with Run1+2 data
  - New decays and techniques to help address some of the underlying experimental and theoretical issues

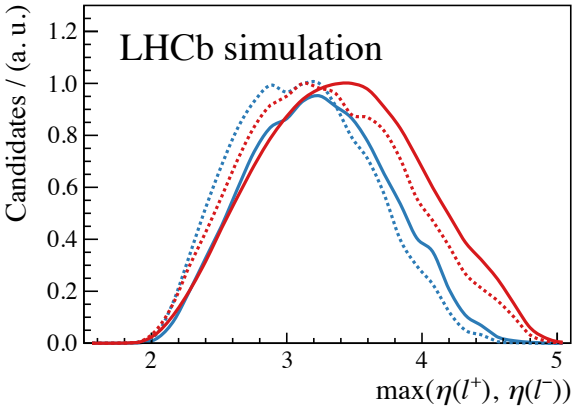
R_K Parameter overlap

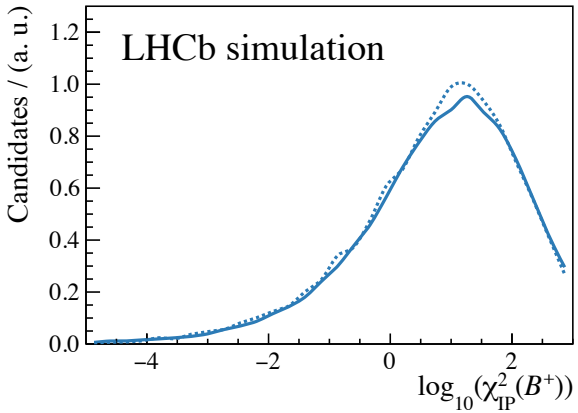


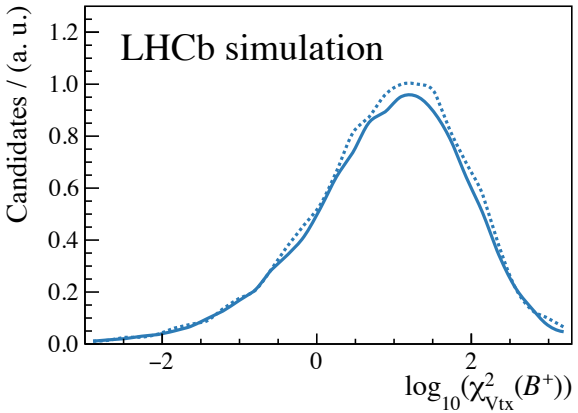
R_K Parameter overlap











$B^+ \to K^+ e^+ e^-$

$B^+ \to K^+ \mu^+ \mu^-$

$B^+ \to J/\psi(e^+ e^-) K^+$

$B^+ \to J/\psi(\mu^+ \mu^-) K^+$