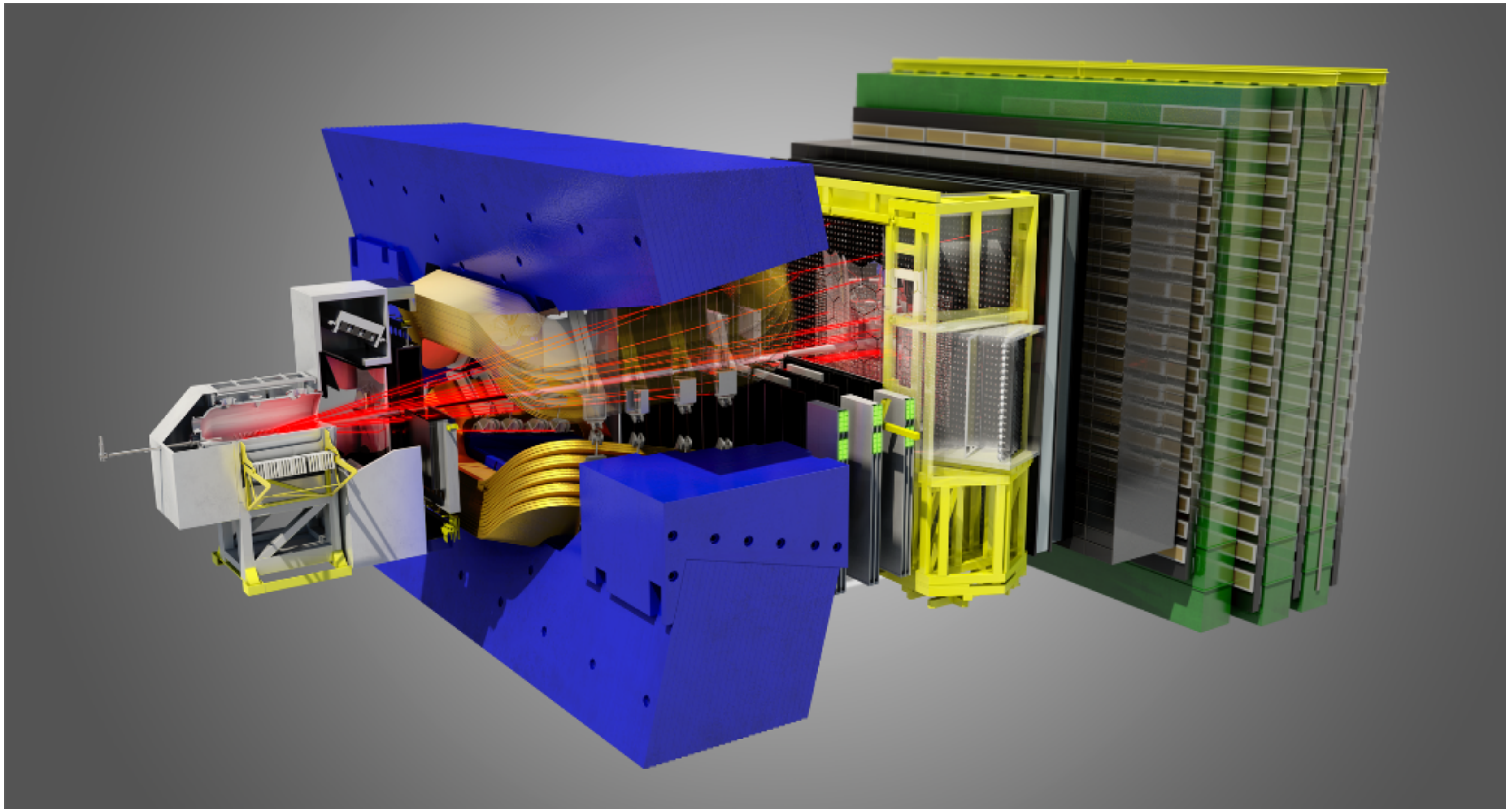
B-anomalies at LHCb



Mitesh Patel (Imperial College London)

Seminar at Helsinki Institute of Physics, 25th May 2021

Imperial College London

Introduction

- Interesting set of anomalies have appeared in measurements of B decays :
  - Branching fractions of several $b \to (s)ll$ processes [update 2weeks ago]
  - Angular observables in $B^0 \to K^{*0}\mu\mu$ [updated last year]
  - Lepton-flavour universality ratios in $b \to cl\nu$ and $b \to sll$ decays

  Latter subject of a recent update that got some attention in the community - will talk about our measurement of the LFU ratio, R_K

- Extent of discrepancies depends on theoretical issues
  - Will try and highlight these issues as go through
  - Some evolution here also

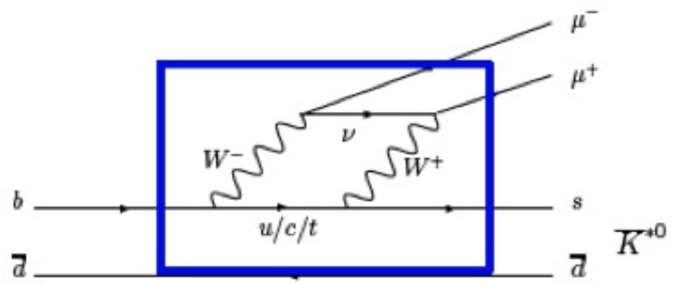
- B-decays of interest when well-calculable process, sensitive to new physics can be measured…

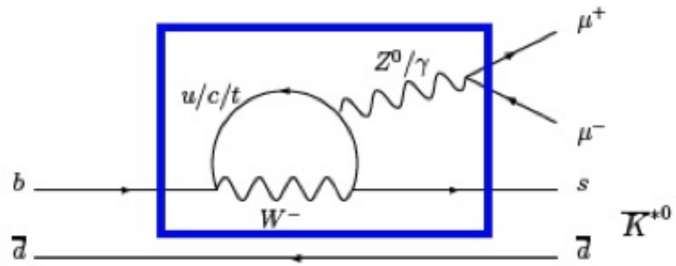
$b \to sll$ decays

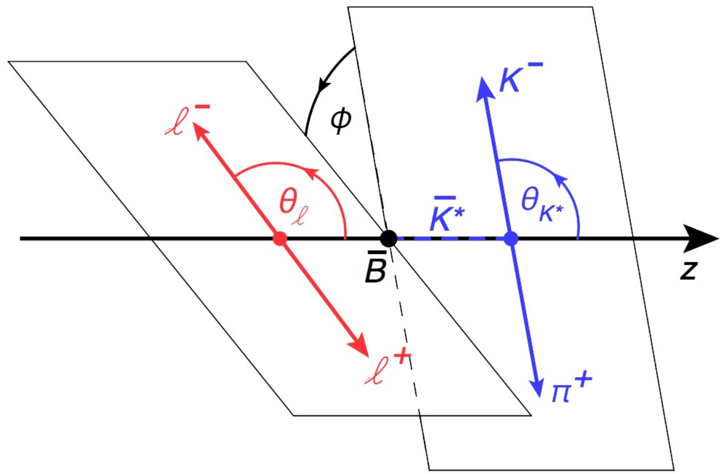
- $b \to sll$ decays involve flavour changing neutral currents → loop process

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

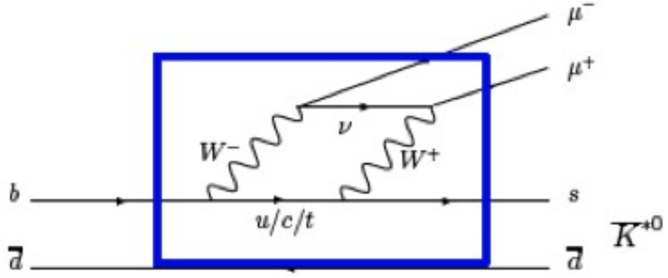
- Large number of observables: BF, A_{CP} and angular observables – dynamics can be described by three angles (θ_l, θ_K, ϕ) and di-μ invariant mass squared, q^2

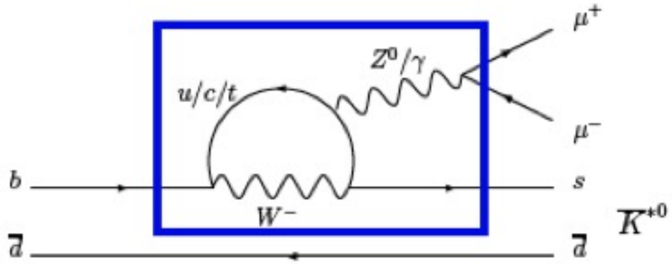


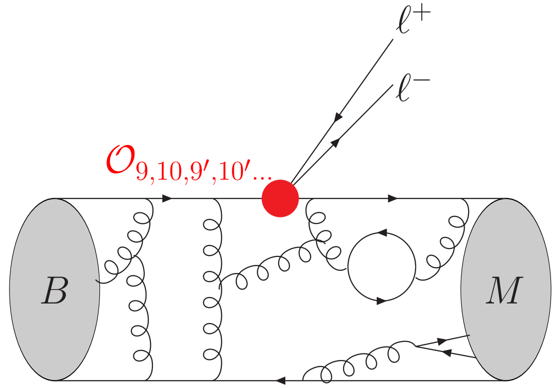


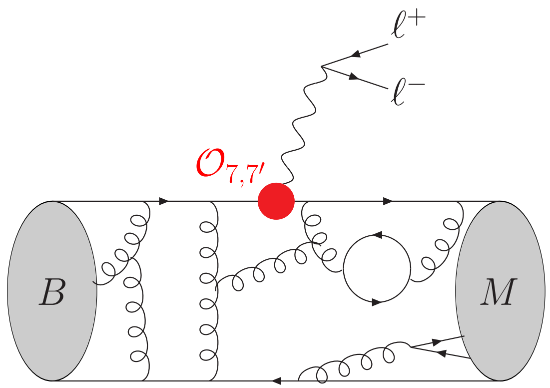


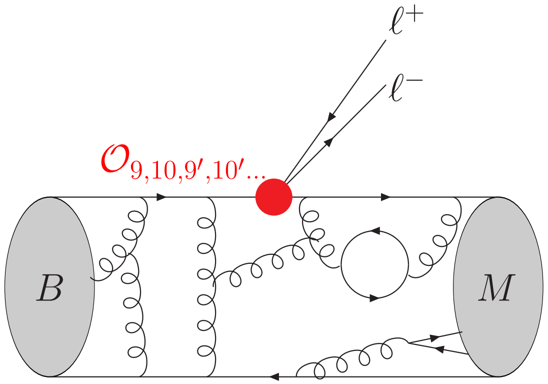
Hadronic Effects

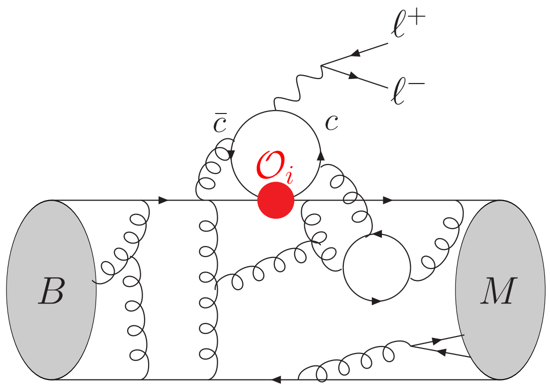












Form factors (local) Form factors (local) Charm loop

(non-local)

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 in given theory
    - Integrate out the heavy degrees of freedom that can't resolve at some scale μ
  - "Operators" O_i
    - Describe the long distance, non-perturbative part involving particles below scale μ
    - Account for effects of strong interactions and are difficult to calculate reliably

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

Theoretical Foundation

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

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

- Mixing between different operators : $C_i \rightarrow C_i^{\text{effective}}$

- In *certain* observables the uncertainties on the operators cancel out – are then free from theoretical problems and measuring the $\mathbf{C_i}$ tells us about the heavy degrees of freedom – *independent of model*

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

$$A_\perp^{L(R)} = N\sqrt{2\lambda}\left\{\left[(\mathbf{C_9^{eff}} + \mathbf{C_9'^{eff}}) \mp (\mathbf{C_{10}^{eff}} + \mathbf{C_{10}'^{eff}})\right]\frac{\mathbf{V(q^2)}}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(\mathbf{C_7^{eff}} + \mathbf{C_7'^{eff}})\mathbf{T_1(q^2)}\right\}$$

$$A_\parallel^{L(R)} = -N\sqrt{2}(m_B^2 - m_{K^*}^2)\left\{\left[(\mathbf{C_9^{eff}} - \mathbf{C_9'^{eff}}) \mp (\mathbf{C_{10}^{eff}} - \mathbf{C_{10}'^{eff}})\right]\frac{\mathbf{A_1(q^2)}}{m_B - m_{K^*}} + \frac{2m_b}{q^2}(\mathbf{C_7^{eff}} - \mathbf{C_7'^{eff}})\mathbf{T_2(q^2)}\right\}$$

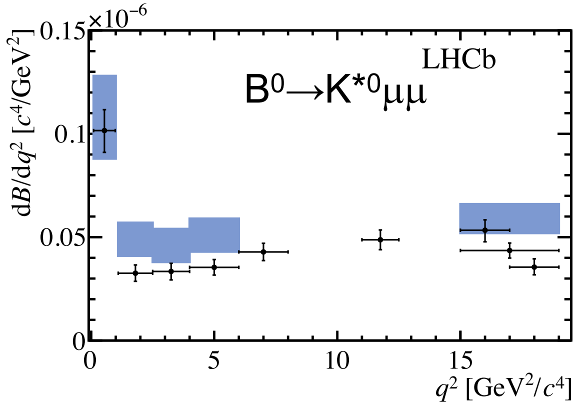
$$A_0^{L(R)} = -\frac{N}{2m_{K^*}\sqrt{q^2}}\left\{\left[(\mathbf{C_9^{eff}} - \mathbf{C_9'^{eff}}) \mp (\mathbf{C_{10}^{eff}} - \mathbf{C_{10}'^{eff}})\right]\left[(m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*})\mathbf{A_1(q^2)} - \lambda\frac{\mathbf{A_2(q^2)}}{m_B + m_{K^*}}\right]\right.$$
$$\left. + 2m_b(\mathbf{C_7^{eff}} - \mathbf{C_7'^{eff}})\left[(m_B^2 + 3m_{K^*} - q^2)\mathbf{T_2(q^2)} - \frac{\lambda}{m_B^2 - m_{K^*}^2}\mathbf{T_3(q^2)}\right]\right\}$$

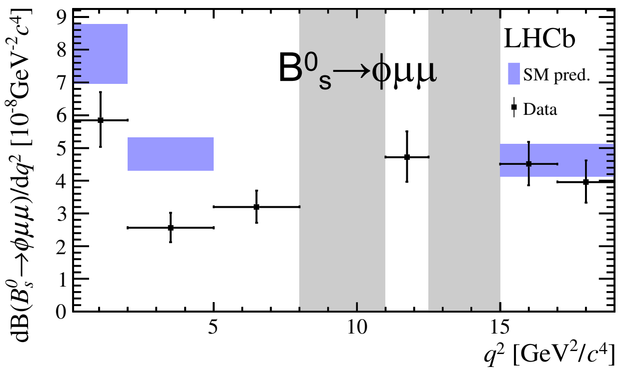
$\rightarrow$ BFs have relatively large theoretical uncertainties

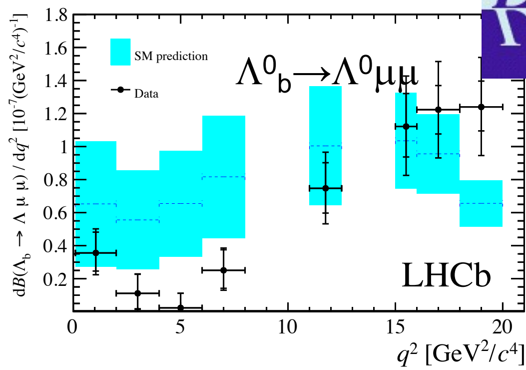
b→sll branching fractions

b→sll branching fractions

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



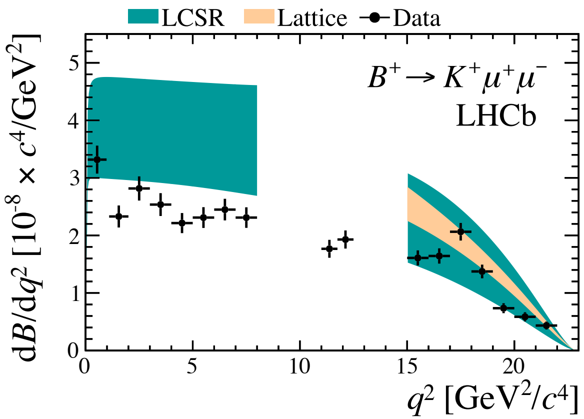


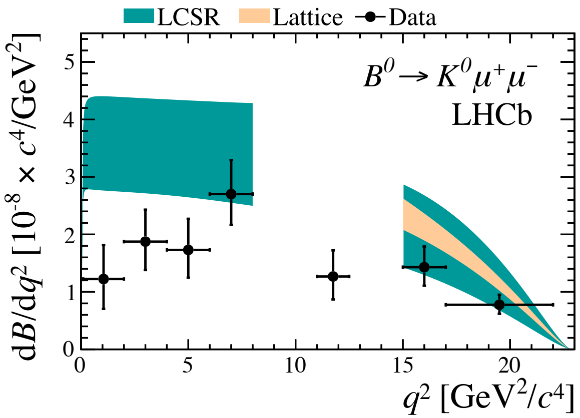


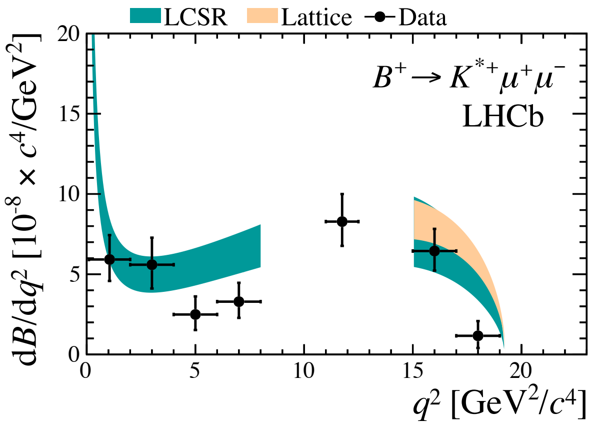
[JHEP 11 (2016) 047, JHEP 04 (2017) 142]

[JHEP 09 (2015) 179]

[JHEP 06 (2015) 115]



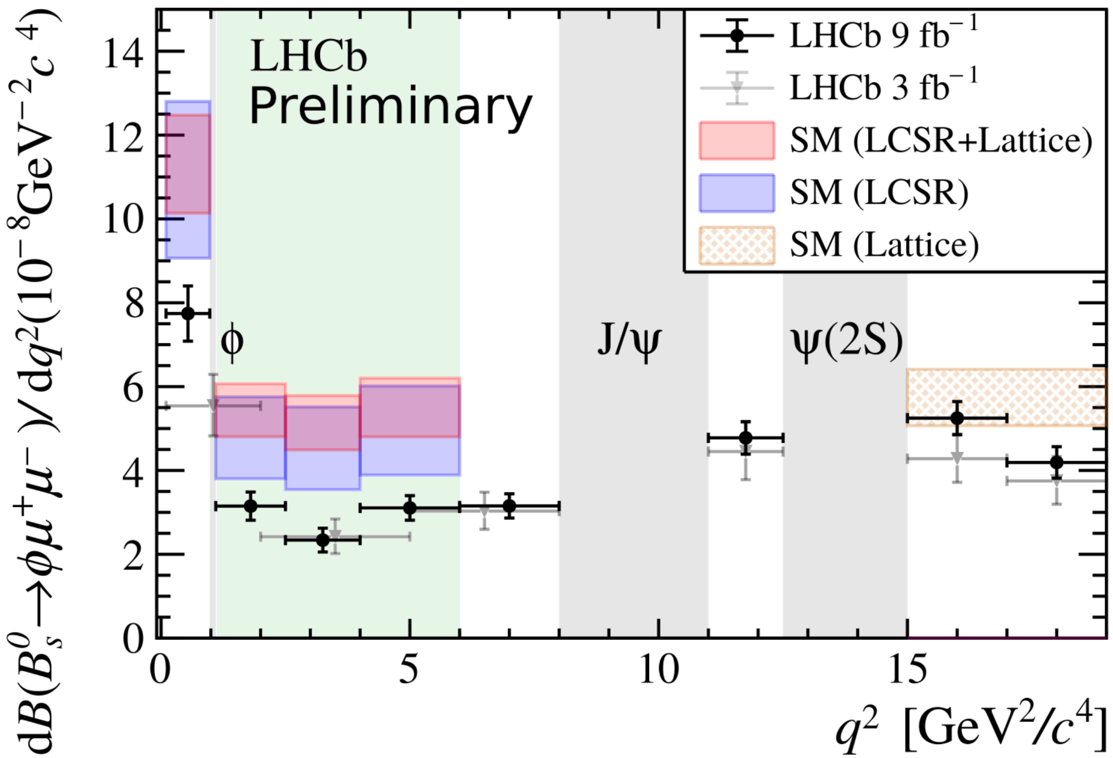




[JHEP 06 (2014) 133]

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

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



[LHCB-PAPER-2021-014, in prepn]

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:

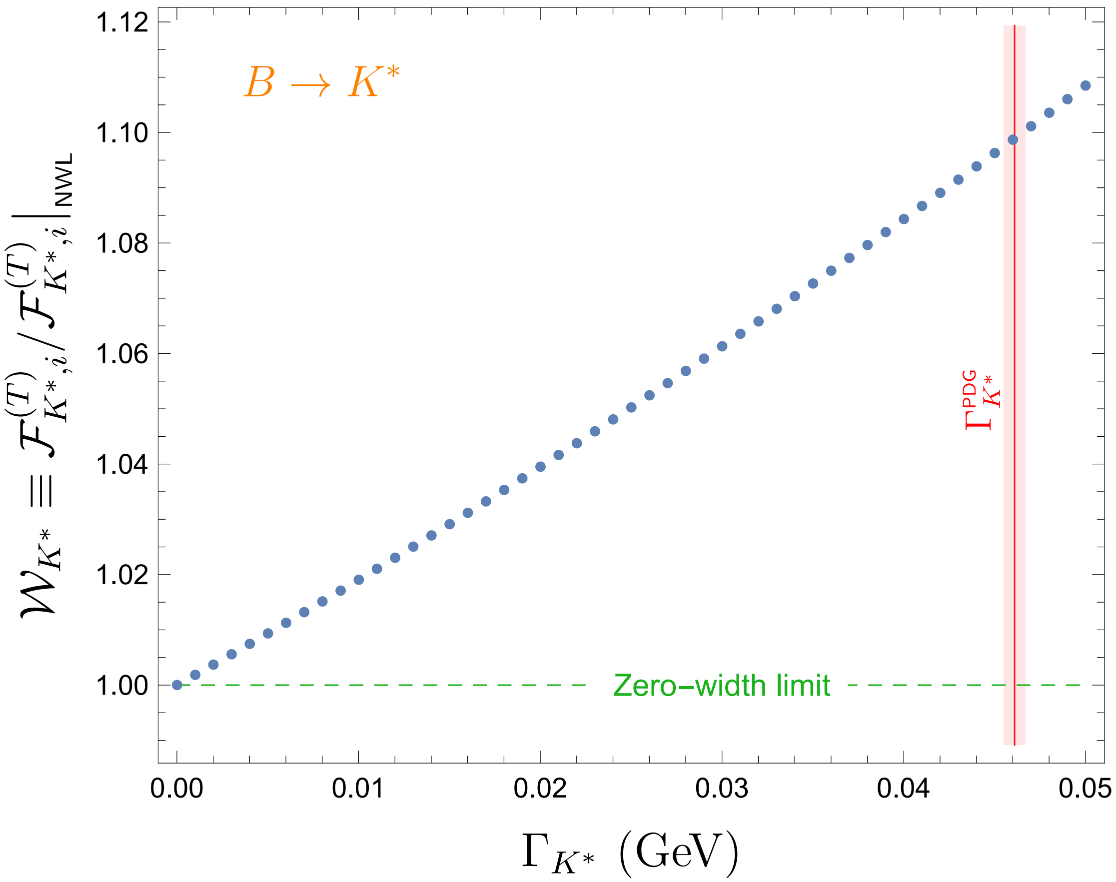
+[Horgan et al., PRL 112 (2014) 212003],

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

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

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

- Also not yet taken into account in such fits :



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

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

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

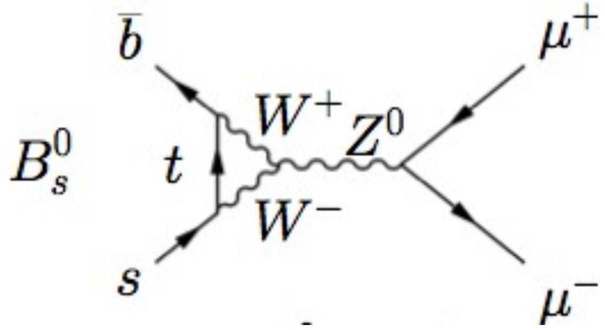
$\Rightarrow$ BRs are corrected by a factor $|\mathcal{W}_{K^*}|^2 \simeq 1.2$ (increasing anomalies)

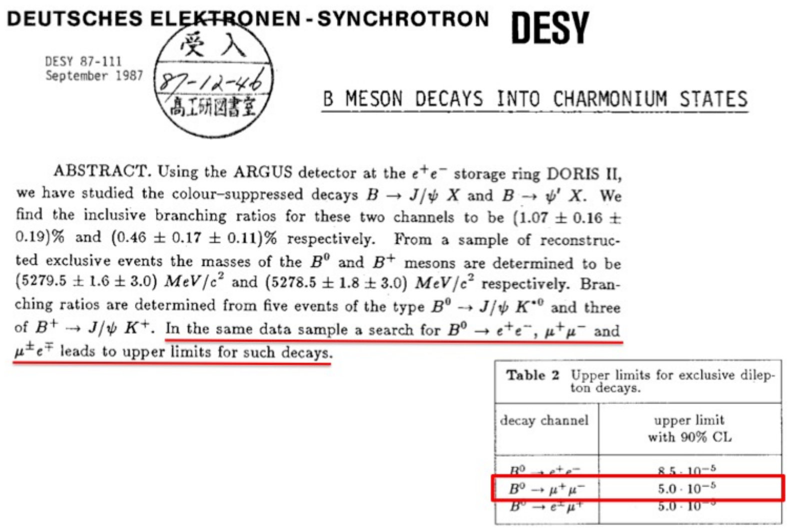
Measuring $B^0 \to \mu^+\mu^-$

- Potential of $B^0 \to \mu^+\mu^-$ decays as clean probe of NP well known for more than 30 years :
  - Dominant contribution from Z-penguin diagram, helicity and GIM suppressed
  - Can get bag-factor that would otherwise dominant theory uncertainty from data
  - Theoretically pristine, precise predictions for BFs :

    $\mathrm{BF}(B_s^0 \to \mu\mu) = (3.66 \pm 0.23) \times 10^{-9}$

    $\mathrm{BF}(B_d^0 \to \mu\mu) = (1.06 \pm 0.09) \times 10^{-10}$
  - BF can be altered by modification of $\mathbf{C_{10}}$ or new scalar or pseudoscalar contribution ($\mathbf{C_{S,P}}$)
  - Major constraint on high tan β SUSY

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DESY 87-111
September 1987

B MESON DECAYS INTO CHARMONIUM STATES

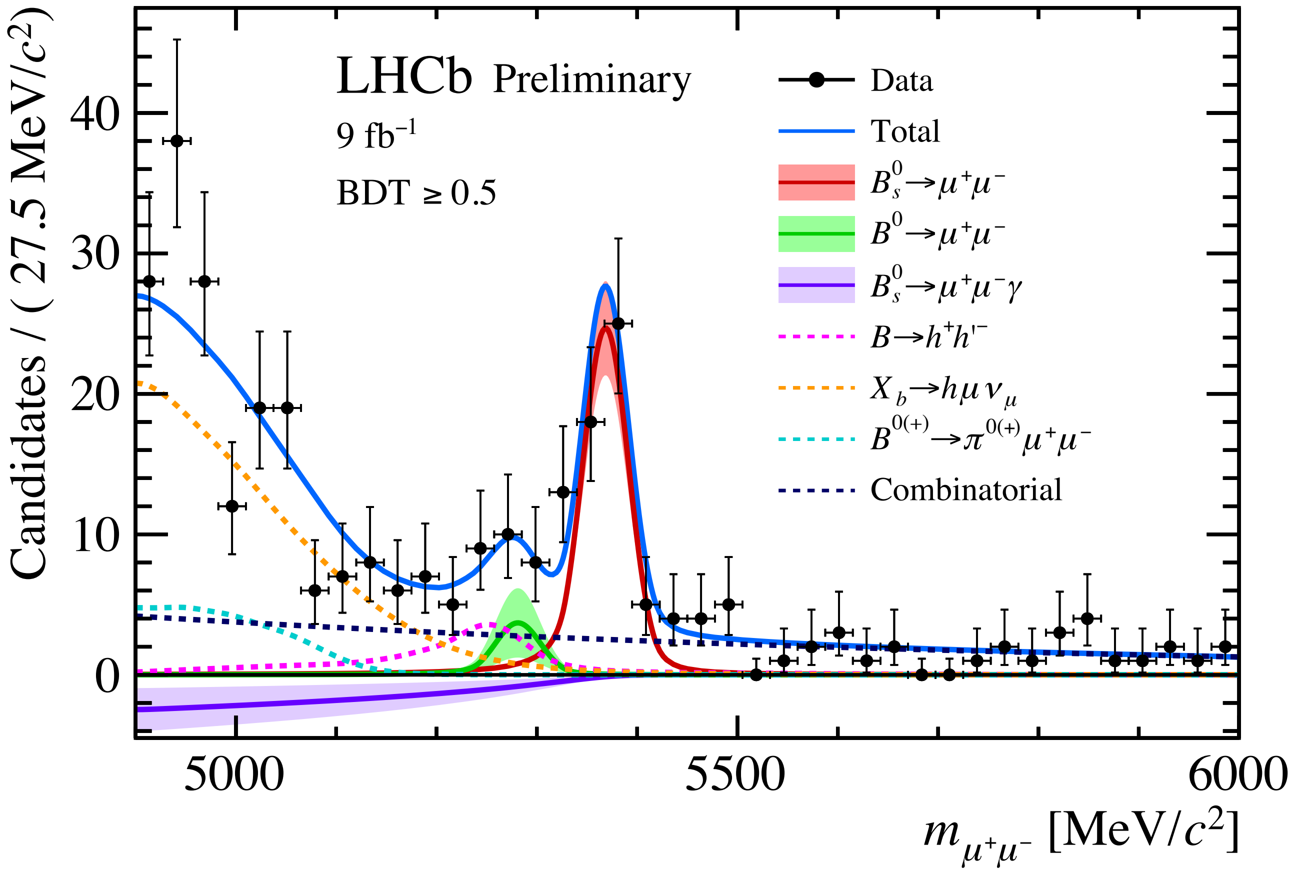
ABSTRACT. Using the ARGUS detector at the e^+e^- storage ring DORIS II, we have studied the colour–suppressed decays $B \to J/\psi\ X$ and $B \to \psi'\ X$. We find the inclusive branching ratios for these two channels to be $(1.07 \pm 0.16 \pm 0.19)\%$ and $(0.46 \pm 0.17 \pm 0.11)\%$ respectively. From a sample of reconstructed exclusive events the masses of the B^0 and B^+ mesons are determined to be $(5279.5 \pm 1.6 \pm 3.0)\ MeV/c^2$ and $(5278.5 \pm 1.8 \pm 3.0)\ MeV/c^2$ respectively. Branching ratios are determined from five events of the type $B^0 \to J/\psi\ K^{*0}$ and three of $B^+ \to J/\psi\ K^+$. In the same data sample a search for $B^0 \to e^+e^-$, $\mu^+\mu^-$ and $\mu^\pm e^\mp$ leads to upper limits for such decays.

Table 2 Upper limits for exclusive dilepton decays.

decay channel	upper limit with 90% CL
$B^0 \to e^+e^-$	$8.5 \cdot 10^{-5}$
$B^0 \to \mu^+\mu^-$	$5.0 \cdot 10^{-5}$
$B^0 \to e^\pm\mu^\mp$	$5.0 \cdot 10^{-5}$

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

- LHCb search for with full Run 2 data released 23rd March :

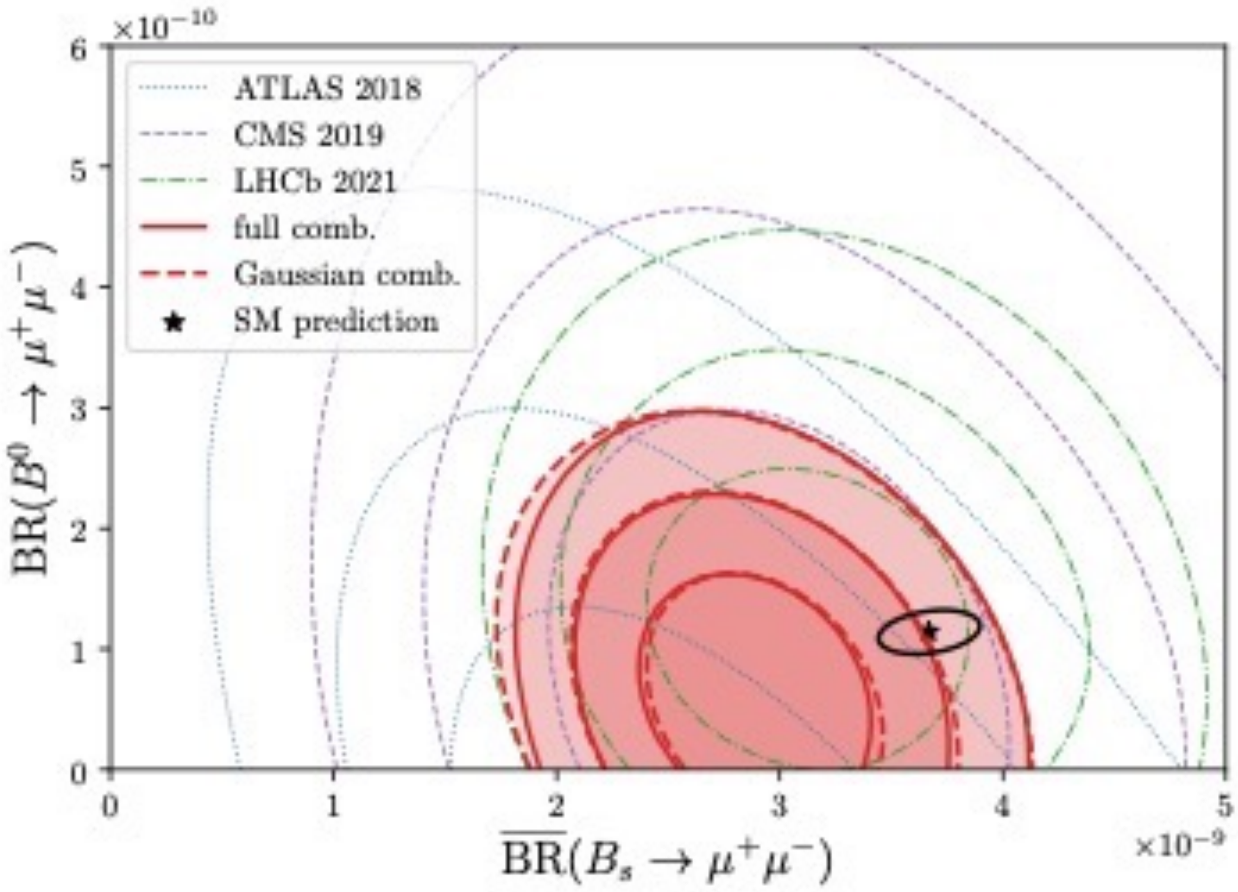


- $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$

- $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-\gamma$ compatible with background only at 1.7σ and 1.5σ

Search for $B^0 \rightarrow \mu\mu$

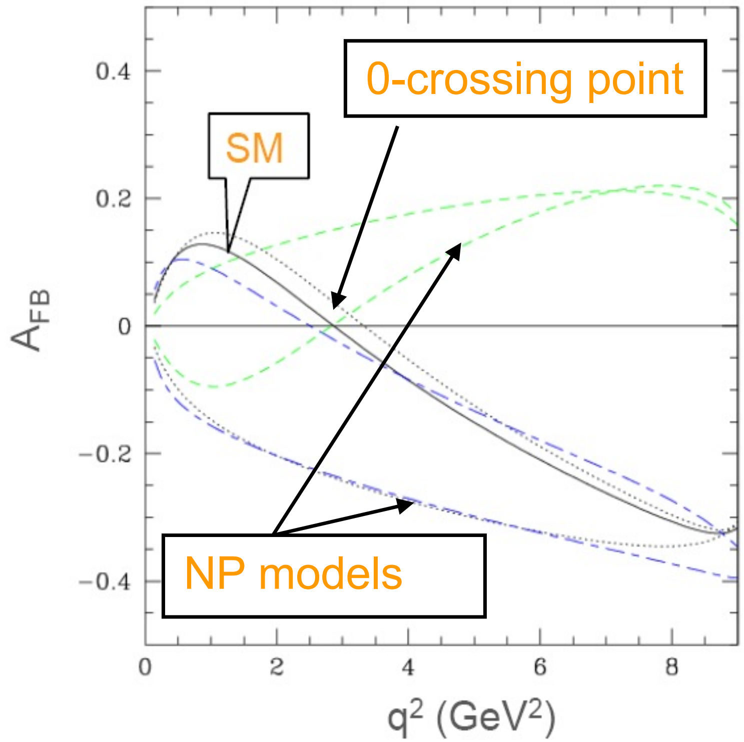
- Combined with results from ATLAS (2018) and CMS (2019)
- Results compatible with SM at 2σ level [arXiv:2103.13370]

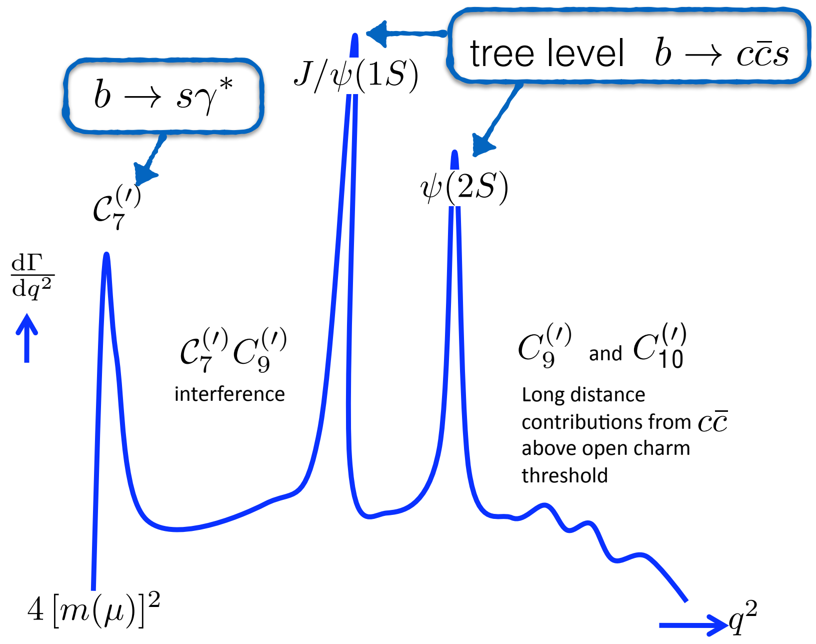


$B^0 \rightarrow K^{*0} \mu\mu$ angular analysis

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

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





dimuon invariant mass squared, q^2

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

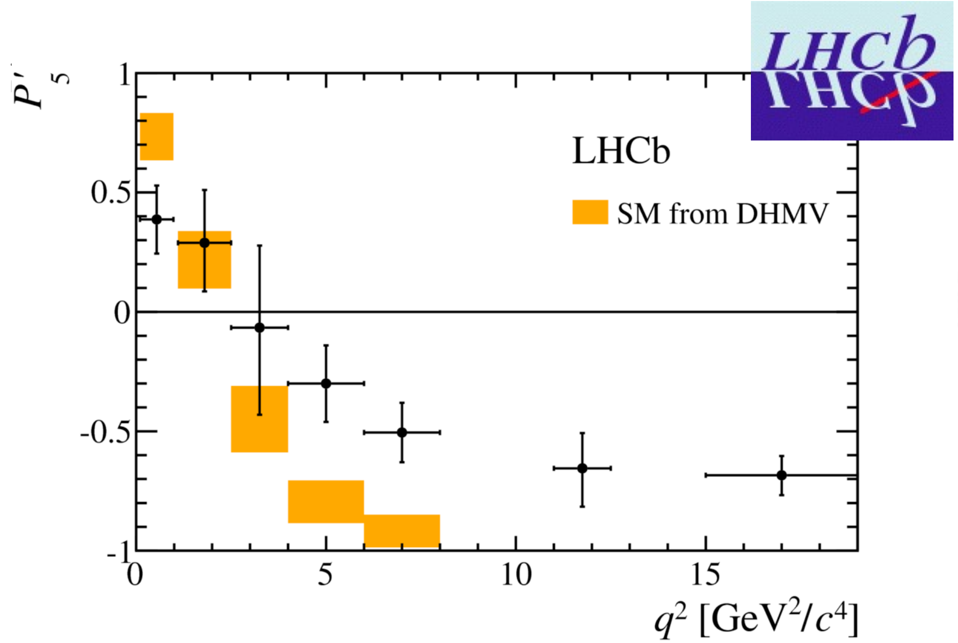
$$P'_5 \sim \frac{Re(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*})}{\sqrt{(|A_0^L|^2+|A_0^R|^2)(|A_\perp^L|^2+|A_\perp^R|^2+|A_\parallel^L|^2+|A_\parallel^R|^2)}}$$

  which are form-factor independent *at leading order*

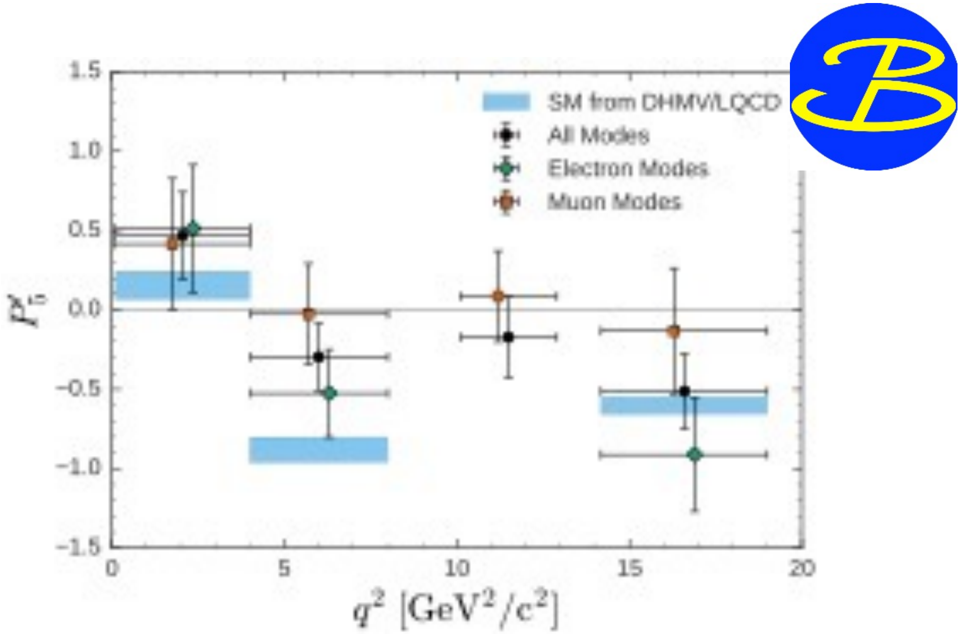
- In fact, can form a complete basis ($P^{(')}$ series) in which there are six form-factor independent and two form-factor dependent observables (F_L and A_{FB})

The P_5' anomaly

- Run 1 data showed form-factor "independent" P_5' observable has a local discrepancy in two bins – (subsequently confirmed by Belle)



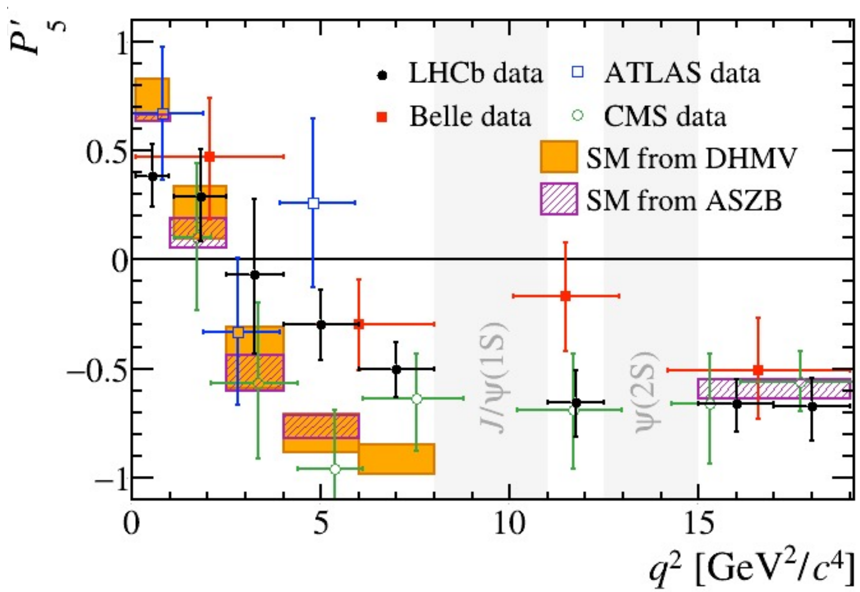
[JHEP 02 (2016) 104]



[PRL 118 (2017) 111801]

The P_5' anomaly

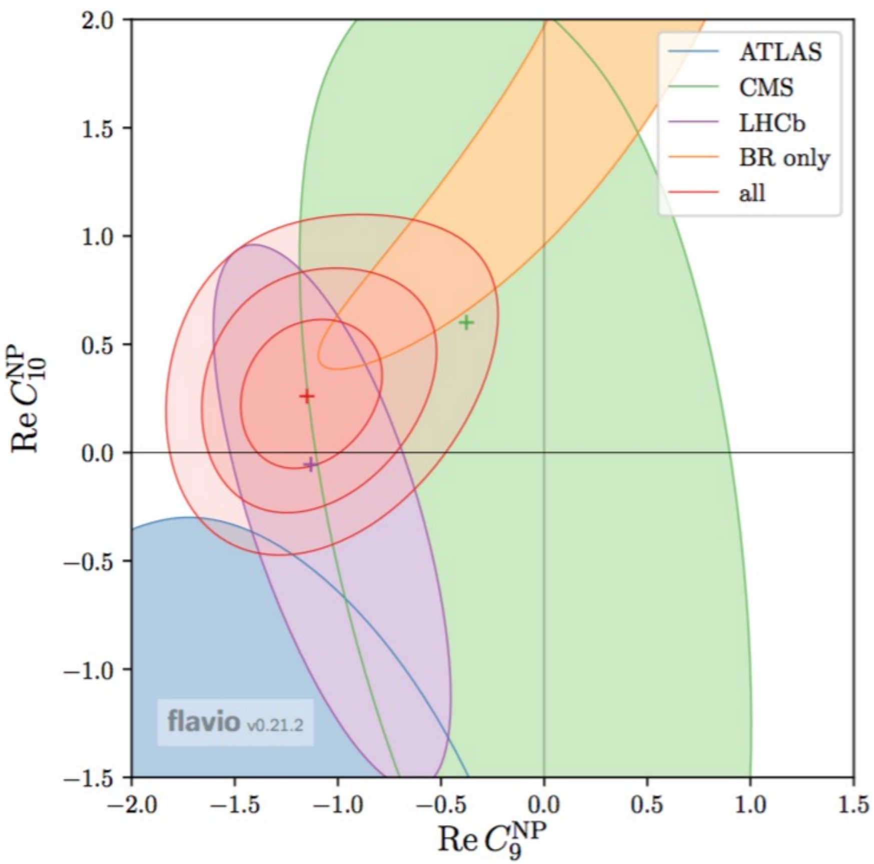
- Run 1 data showed form-factor "independent" P_5' observable has a local discrepancy in two bins – (subsequently confirmed by Belle)
- Also measurements by ATLAS and CMS



[JHEP 02 (2016) 104]
[PRL 118 (2017) 111801]
[ATLAS-CONF-2017-023]
[arXiv:1710.02846]

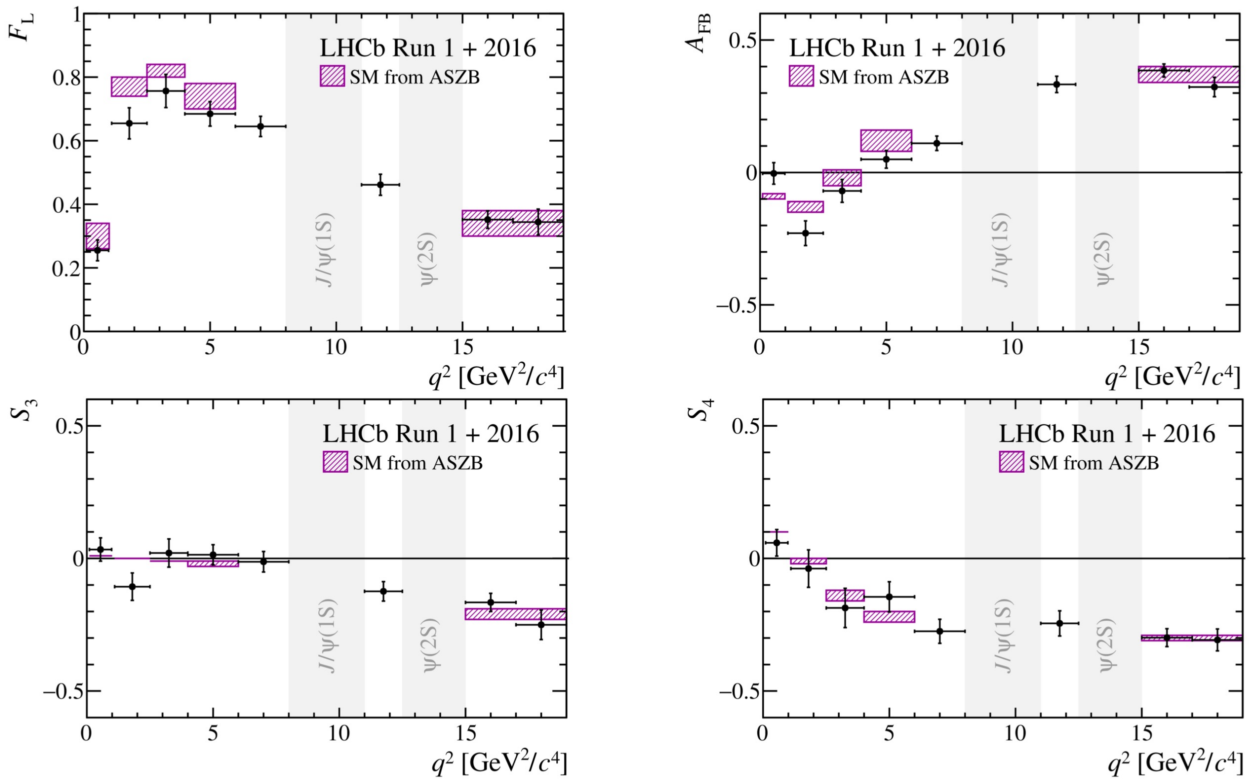
“Global” fits

- Several 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 (…)



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

- Published updated analysis adding 2016 data to Run I ana.
  - Double dataset cf previous analysis [PRL 125 (2020) 011802]
  - Analysis of remaining Run II data in progress (further doubling)

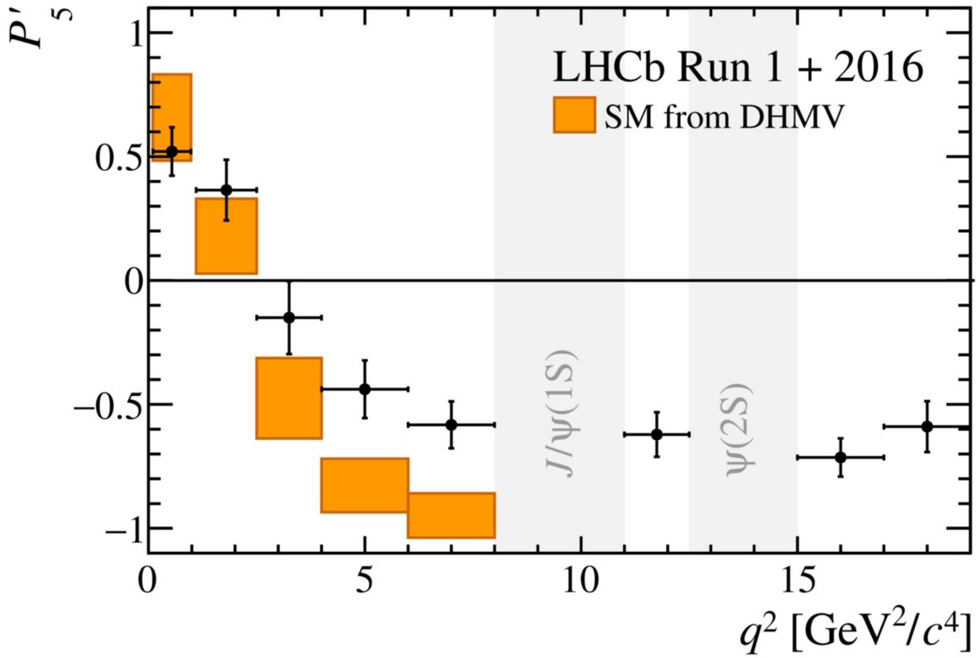


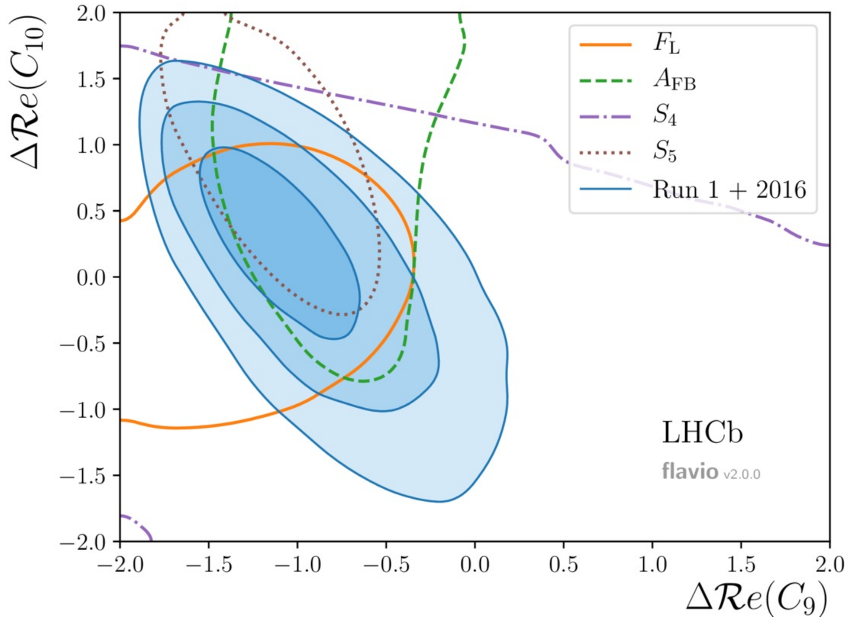
- Vast majority of observables in agreement with SM predns, giving some confidence in theory control of form-factors

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

[PRL 125 (2020) 011802]

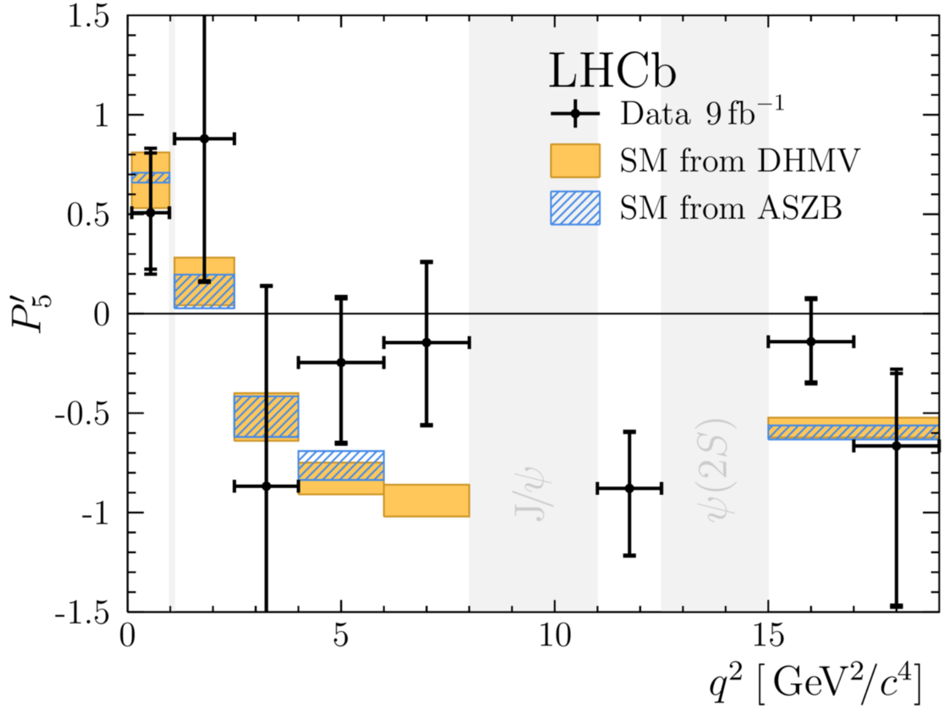
- P_5' continues to show significant discrepancy wrt SM prediction
- Coherence between observables improved cf Run I analysis – tension with SM in angular analysis alone 3.3σ

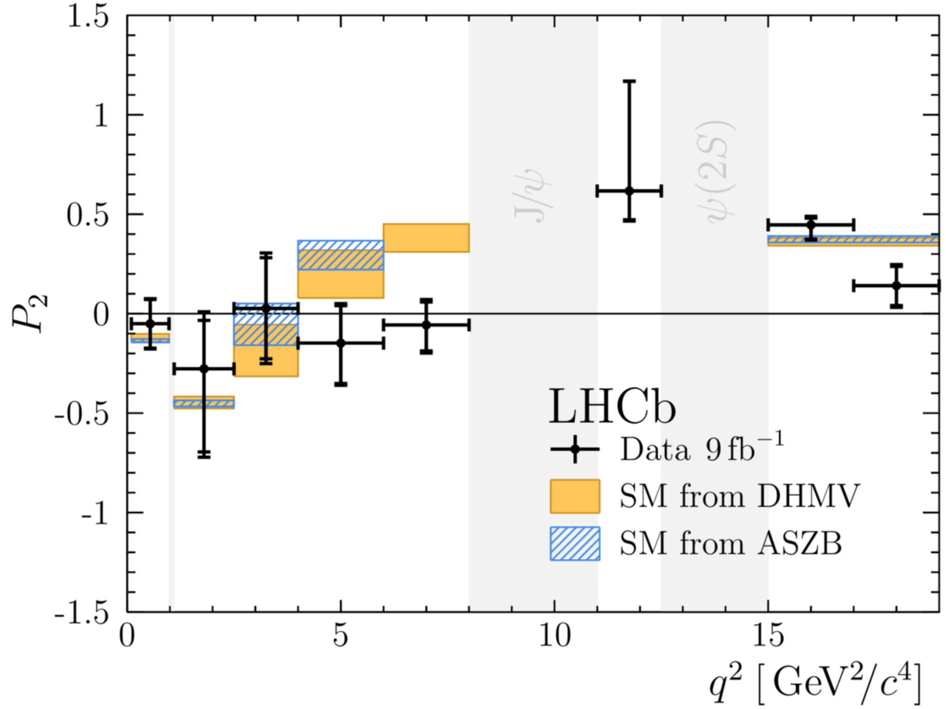




$B^+ \to K^{*+}\mu\mu$ angular analysis

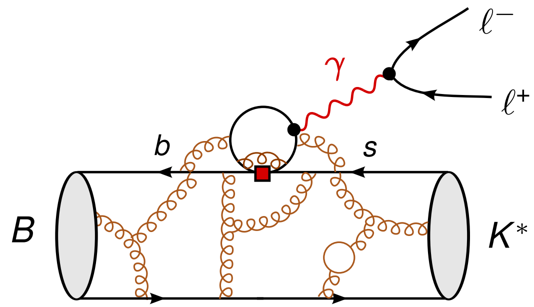
- Angular analysis now performed for analogous K^{*+} decay mode with $K^{*+} \to K_S^0 \pi^+$
- Lower statistics but message is identical – in this decay tension with SM is 3.1σ





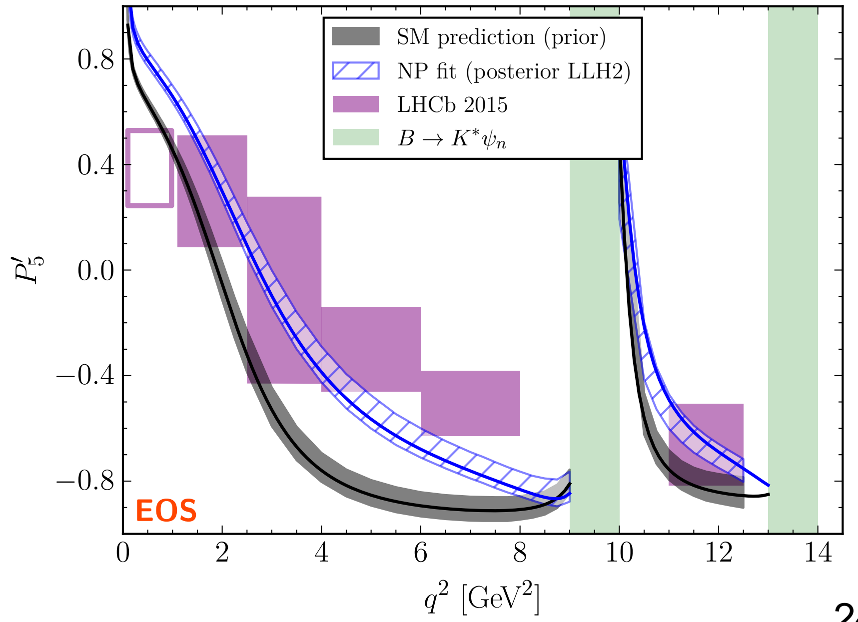
Could the SM predn be wrong?

- Largest individual uncertainty on P_5' from $c\bar{c}$-loop effects



- 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

- Parameterisation to theory and auxiliary data to try and determine $c\bar{c}$ effect



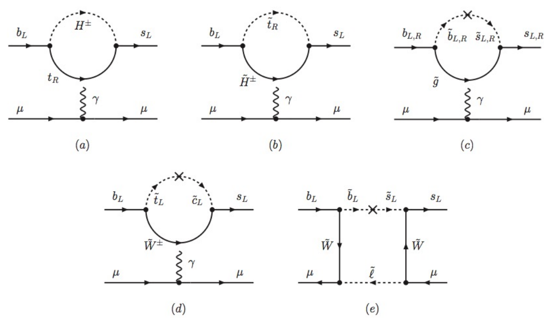
What if SM predn are correct?

- Need a new vector contribution → adjusts C_9 Wilson Coefficient; $C_9^{NP} = -C_{10}^{NP}$ (V-A) also considered (…)

- Difficult to generate in SUSY models :

[arXiv:1308.1501]

"[C_9 remains] *SM-like throughout the viable MSSM parameter space, even if we allow for completely generic flavour mixing in the squark section*"



(but recent publicity has seen some resurrection)

- Models with composite Higgs/UED have same problem

- **Could generate observed deviation with a Z' or LQ**

Lepton Universality Ratios

Lepton Universality Ratios

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

- Branching fractions differ only by phase space and helicity-suppressed contributions

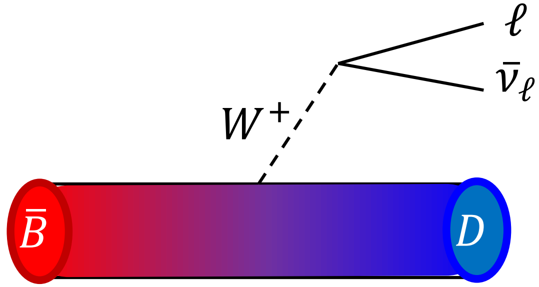
- Ratios of the form: $$R_{K^{(*)}} := \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \overset{\text{SM}}{\cong} 1$$
  - free from QCD uncertainties affecting other observables
    $\rightarrow$ O(10^{-4}) uncertainty [JHEP07 (2007) 040]
  - Up to O(1%) QED corrections [EPJC76 (2016) 8,440]

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

b→clν LFU ratios

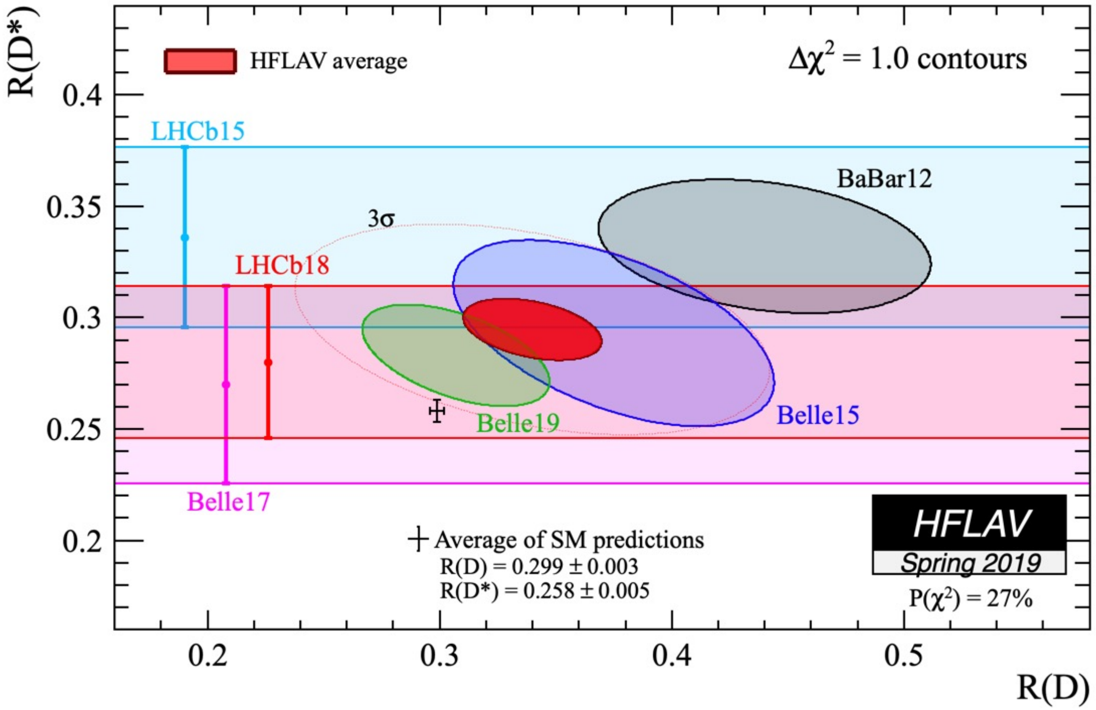
- A further anomaly is seen in LFU ratios with semileptonic **b→clν** decays
  - Tree-level processes in SM – requires a huge NP effect, comparable with the SM amplitude
  - Drives idea of hierarchical effect: large NP effect in τ, smaller in μ where have measured **b→sμμ** decays and little/no effect in e modes
  - Theorists claim it is possible to make a NP explanation, coherent with **b→sμμ**
  - Good theoretical control due to factorisation of hadronic and leptonic parts – then theoretically pristine quantity e.g. in case of **b→clν** transition,

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



Fit to b→clν LFU ratios

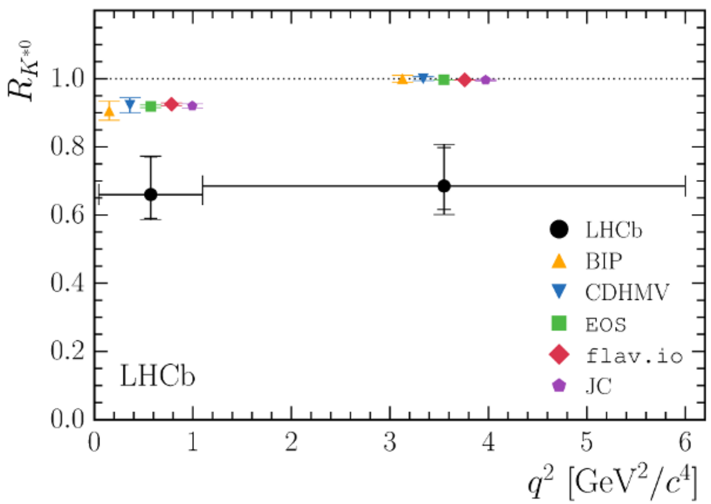
- Combination of LHCb results with those from Babar/Belle
- World average value SM predictions shows a **3.1σ** tension – very recent updates to SM theory from lattice



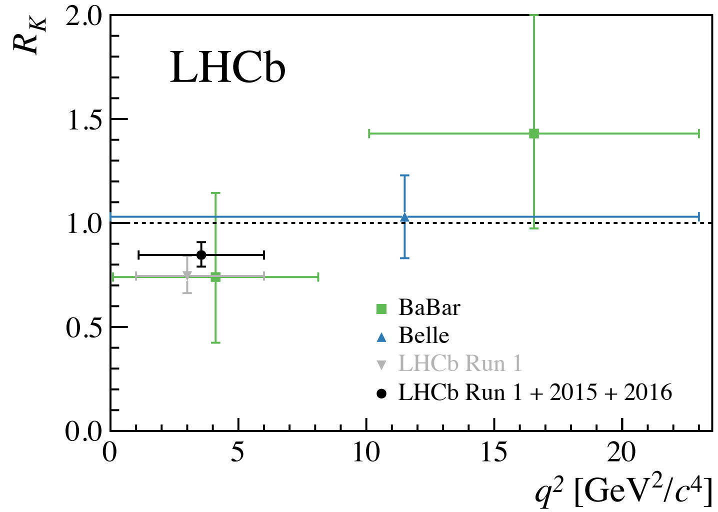
- (R_D,R_{D^*}) update from LHCb coming; CMS... ?

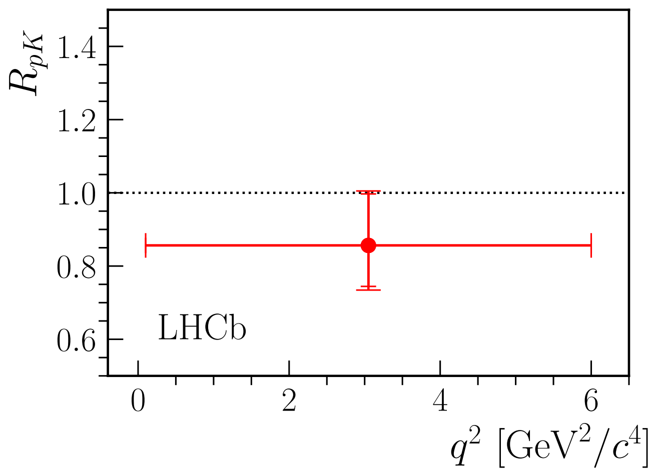
b→sll LFU ratios

$B^0 \to K^{*0}\ell^+\ell^-$ 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

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

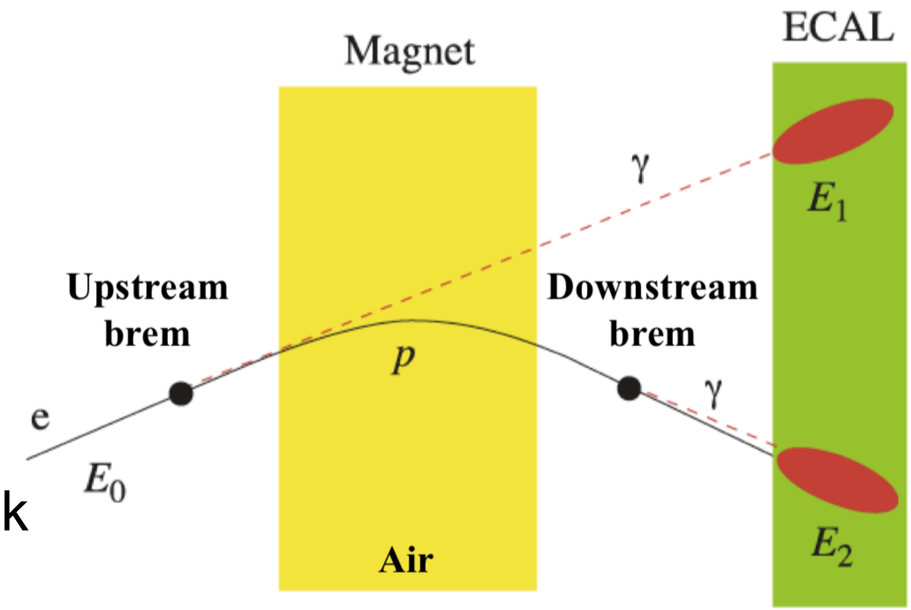
$$R_K = \frac{\int_{1.1\ \mathrm{GeV}^2}^{6.0\,\mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+\to K^+\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{1.1\,\mathrm{GeV}^2}^{6.0\,\mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+\to K^+e^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2}$$

- Previous measurement used 5fb^{-1} data from Run1, 2015,16
- Update adds 4fb^{-1} from 2017 and 2018, given cross-section difference effectively doubles number of B decays
- Measurement strategy identical to our previous analysis

R_K Experimental challenge

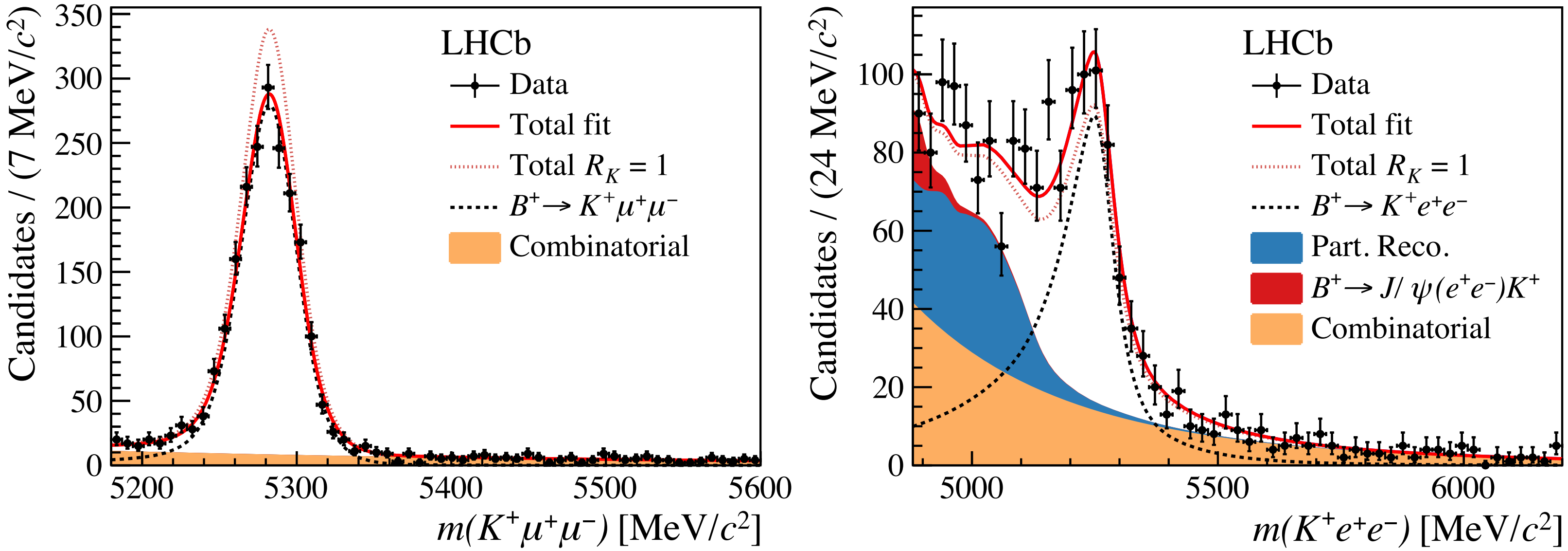
- Primary difficult of analysis, controlling the differences between the electron and muon efficiencies

- Electrons lose a large fraction of their energy through Bremsstrahlung in detector material
  - Most $e^{\pm}$ will emit one energetic photon before magnet
    $\rightarrow$ Look for photon clusters in the calorimeter (E_T > 75 MeV) compatible with $e^{\pm}$ direction before magnet
  - Recover brem. energy loss by "adding" the cluster energy back to the $e^{\pm}$ momentum



R_K Experimental challenge

- Even after the Bremsstrahlung recovery electrons still have degraded mass and q^2 resolution



- L0 calorimeter trigger requires higher thresholds than L0 muon trigger, due to high occupancy
  - Use three exclusive trigger categories for e+e− final states: $e^{\pm}$ from signal-B; $K^{\pm}$ from signal-B; rest of event

- Particle ID and tracking efficiency larger for $\mu^{\pm}$ than $e^{\pm}$

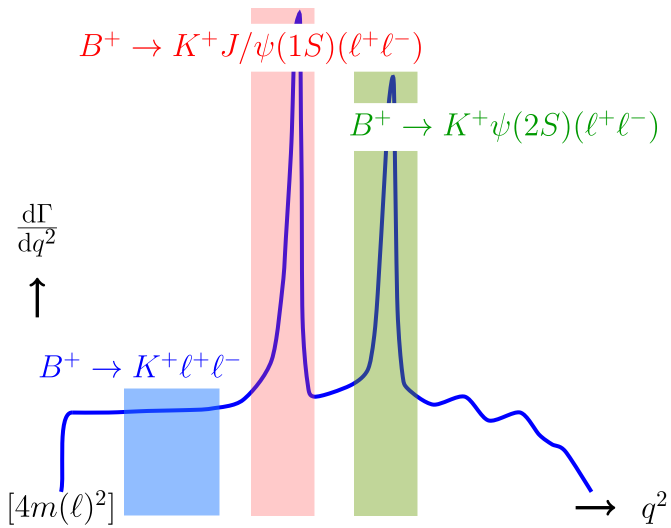
R_K Analysis Strategy

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

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

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

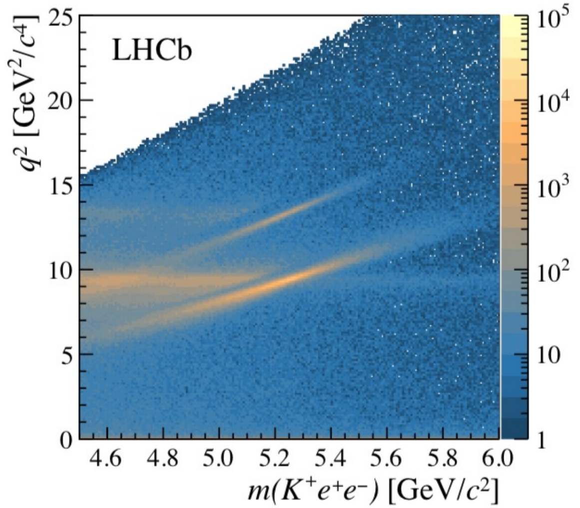
  - Measurement then statistically dominated
  - Rare and J/ψ modes share identical selections apart from cut on q^2
  - Yields determined from a fit to the invariant mass of the final state particles
  - Efficiencies computed using simulation that is calibrated with control channels in data



R_K selection and backgrounds

- Particle ID and mass vetoes used to suppress peaking bkgrds from exclusive B-decays to negligible levels e.g.
  - $B^+ \to D^0(\to K^+e^-\nu)e^+\nu$: cut on $m_{K+e-} > m_{D0}$
  - $B \to K\pi^+(\to e^+)\pi^-(\to e^-)$: cut on electron PID
- BDT to reduce combinatorial bkgrds
- Residual bkgrds suppressed by choice of $m(K^+l^+l^-)$ window
  - $B^+ \to K^+J/\psi(e^+e^-)$
  - Partially reconstructed dominated by $B \to K^+\pi^-e^+e^-$ decays

  Constrain fractions between trigger categories and calibrate simulated templates using data



- Check estimates using data control regions, altering fitted regions

Efficiency calibration

- Simulation is calibrated based on control data for the following quantities:
  - 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

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

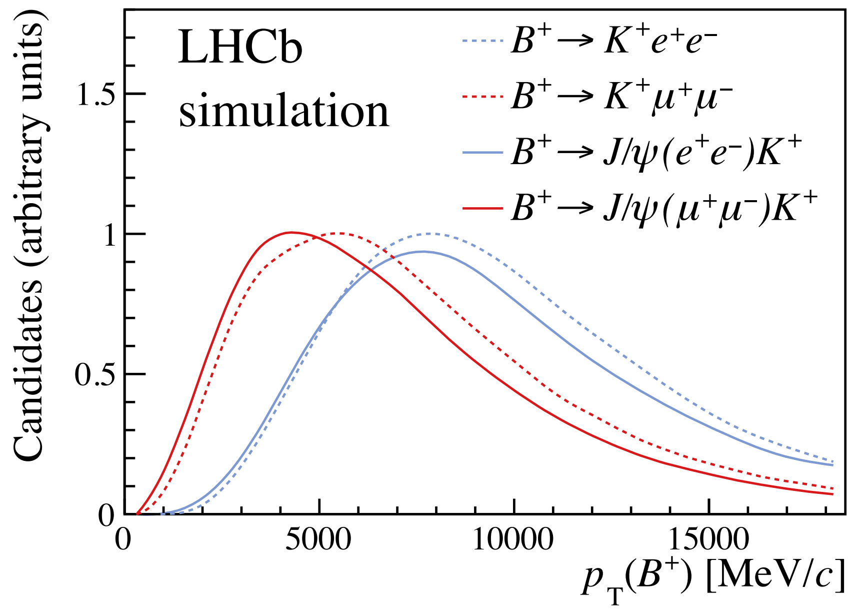
$$r_{J/\psi} = \frac{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+ J/\psi(e^+e^-))}$$

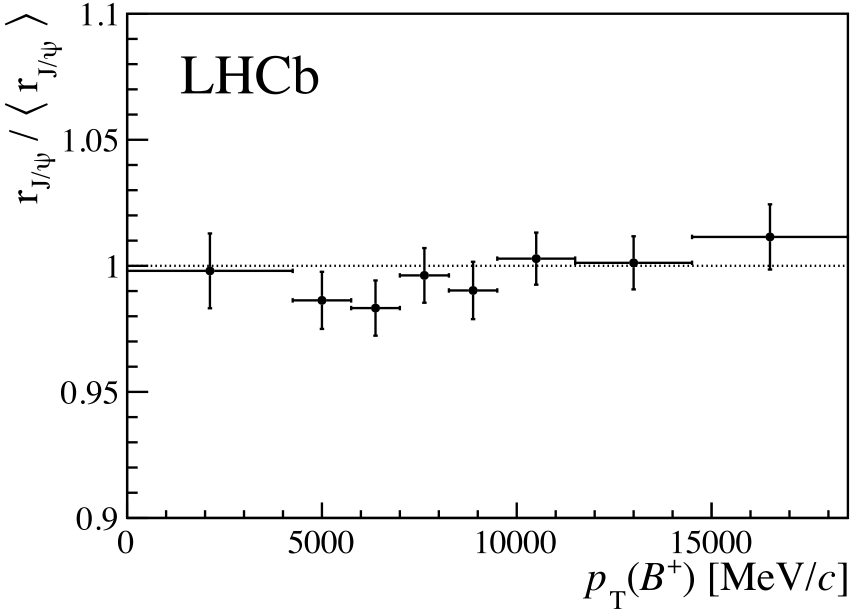
  where we do not benefit from the double ratio cancellation

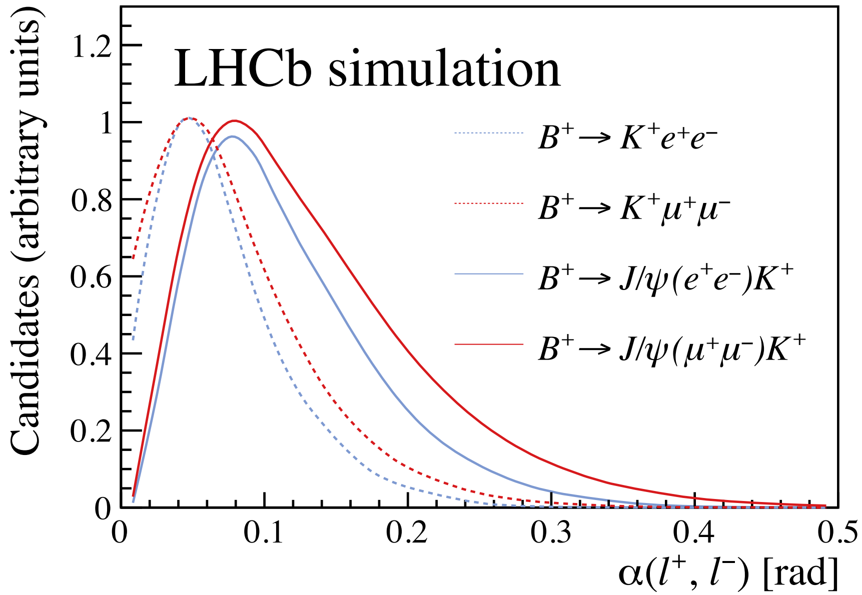
- $r_{J/\psi}$ measured to be lepton universal at 0.4% level

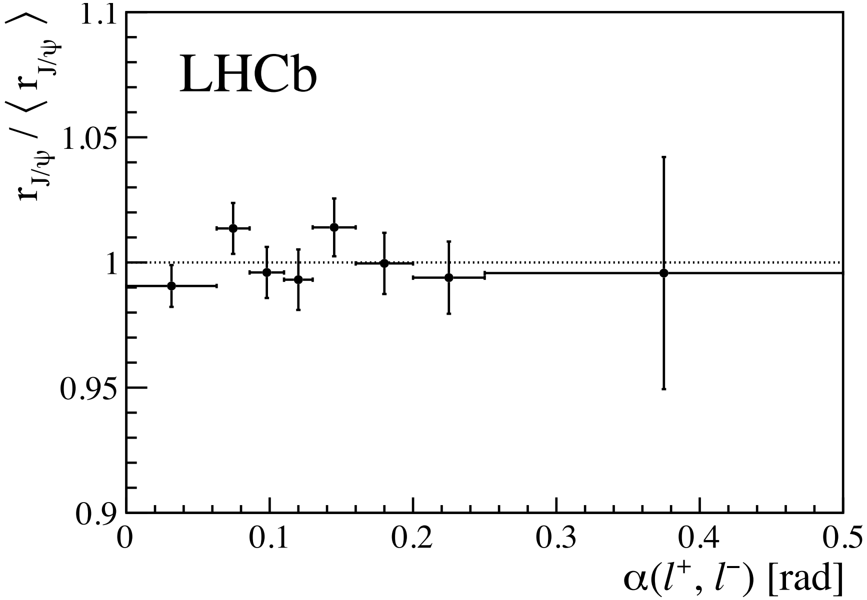
- Measure $r_{J/\psi}$ = 0.981±0.020 (stat+syst)
  - compatible with unity for new and previous datasets and in all trigger samples
  - result is independent of the decay kinematics
  - binning in quantities that would expect bremsstrahlung and trigger to depend on see completely uniform result

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



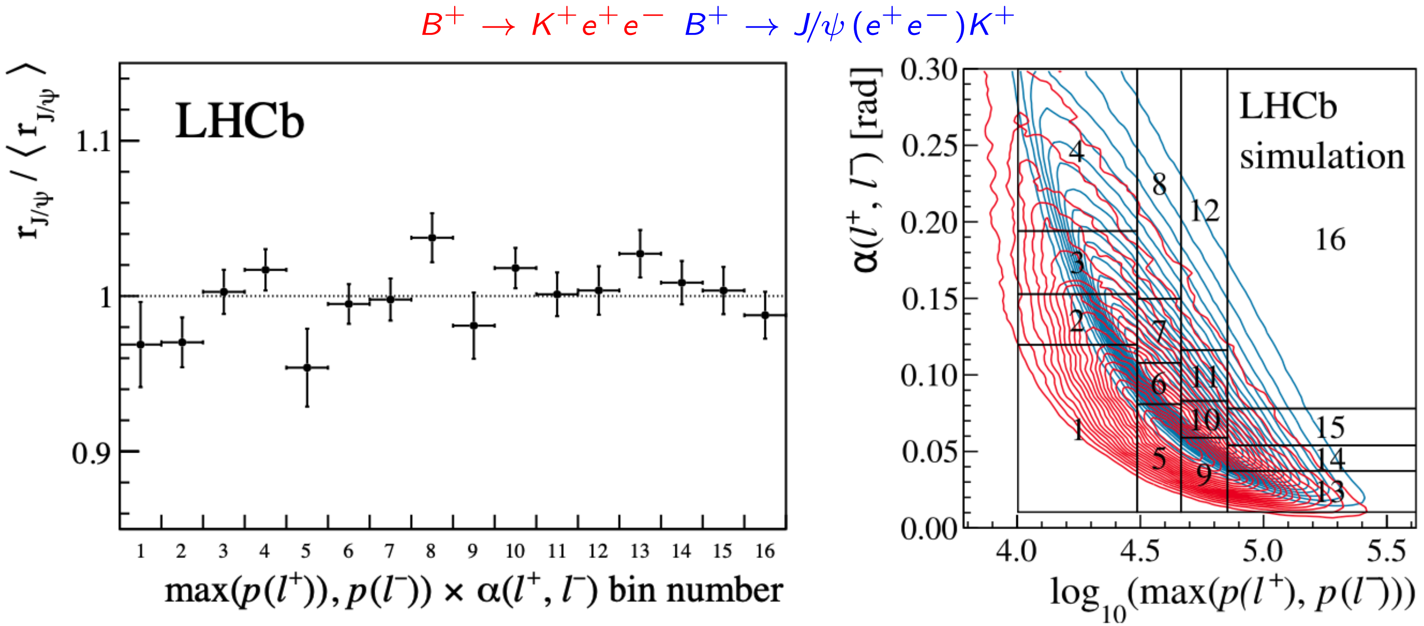






Differential $r_{J/\psi}$ cross-check

- Also test $r_{J/\psi}$ in 2D bins



- Flatness of 2D $r_{J/\psi}$ plots gives confidence that efficiencies understood across entire phase-space

- If take departure from flatness as genuine rather than fluctuations bias expected on R_K is 0.1%

Systematic uncertainties

- Dominant sources: ~ 1%
  - Choice of fit model
    - Associated signal and partially reconstructed background shape
  - Statistics of calibration samples
    - Bootstrapping method that takes into account correlations between calibration samples and final measurement

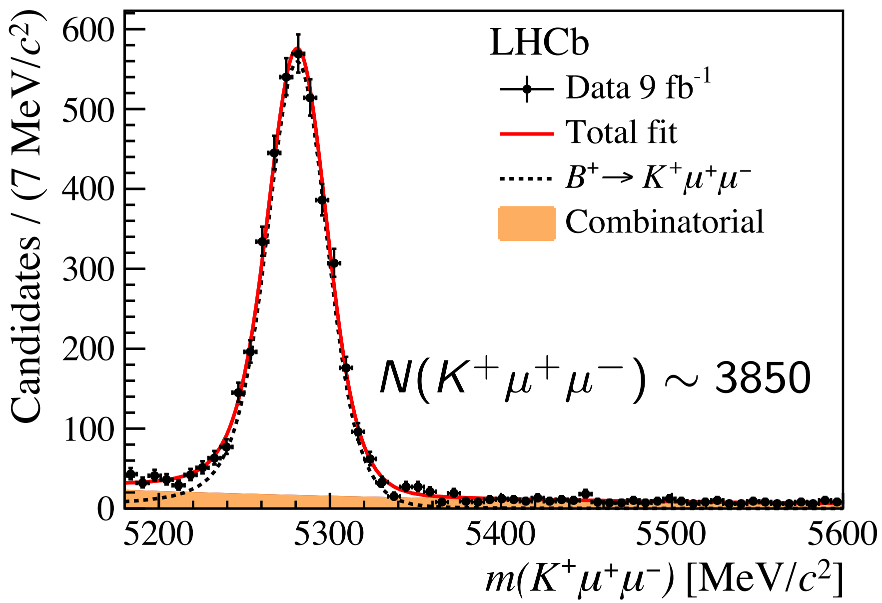
- Sub-dominant sources: ~ 0.1%
  - Efficiency calibration
    - Dependence on tag definition and trigger biases
    - Precision of the q^2 and $m(K^+e^+e^-)$ smearing factors
    - Inaccuracies in material description in simulation

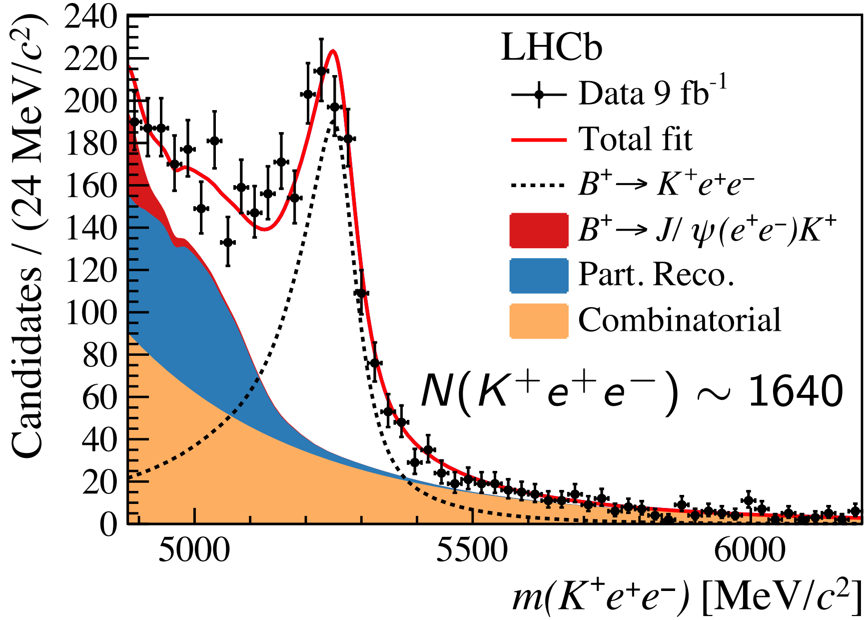
      ...

- Total relative systematic of 1.5% in the final R_K measurement $\rightarrow$ uncert. stat. dominated by factor ~3

Extracting R_K

- R_K is extracted as a parameter from an unbinned maximum likelihood fit to $m(K^+\mu^+\mu^-)$ and $m(K^+e^+e^-)$ distributions in $B^+ \to K^+l^+l^-$ and $B^+ \to J/\psi(l^+l^-)K^+$ decays



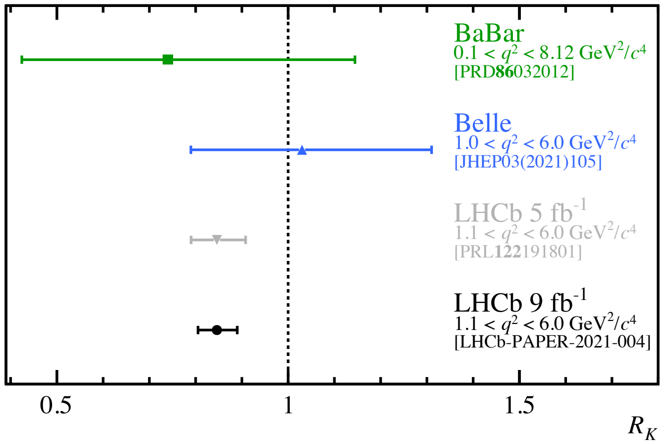


- Correlated uncertainties on efficiency ratios included as multivariate constraint in likelihood

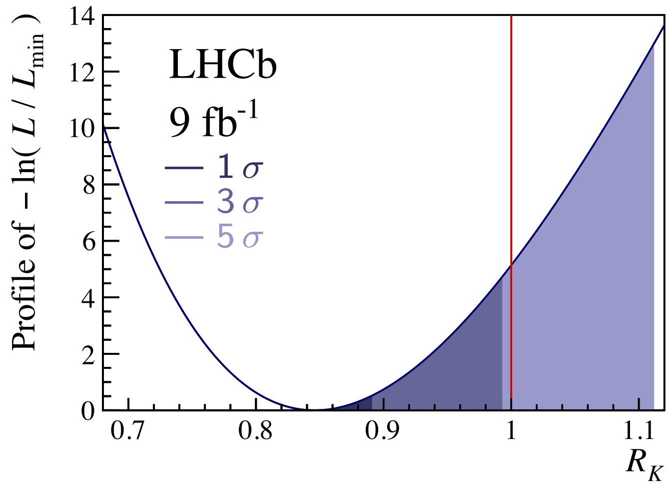
R_K result

- R_K with full Run1 and Run2 dataset

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



- 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

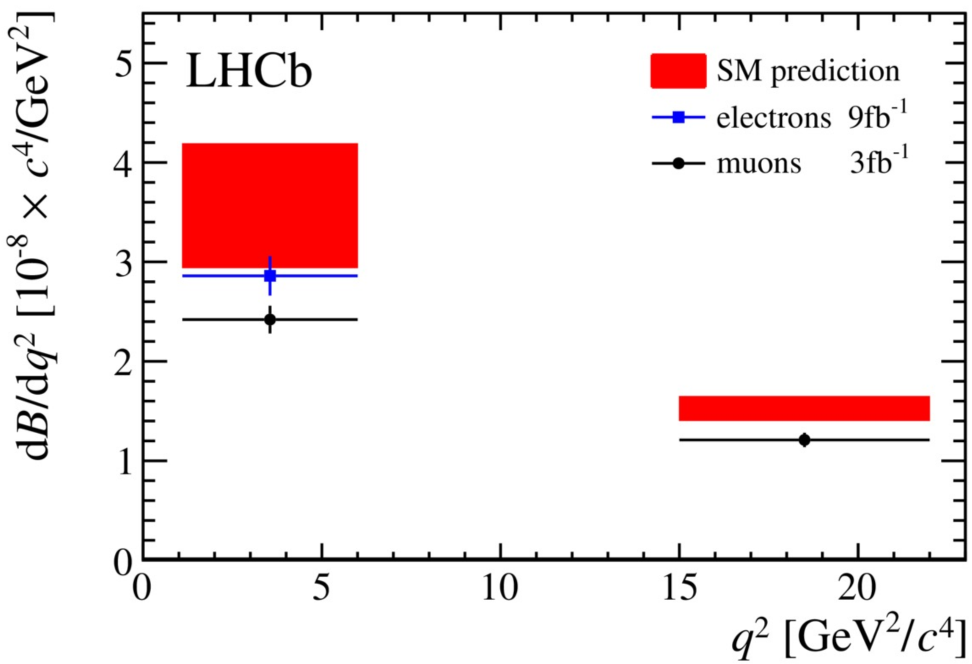
- Paper submitted to Nature Physics

Derived quantities

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

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

- As previously, suggests electrons are more SM-like than muons – plays into hierarchical idea favoured by theory community

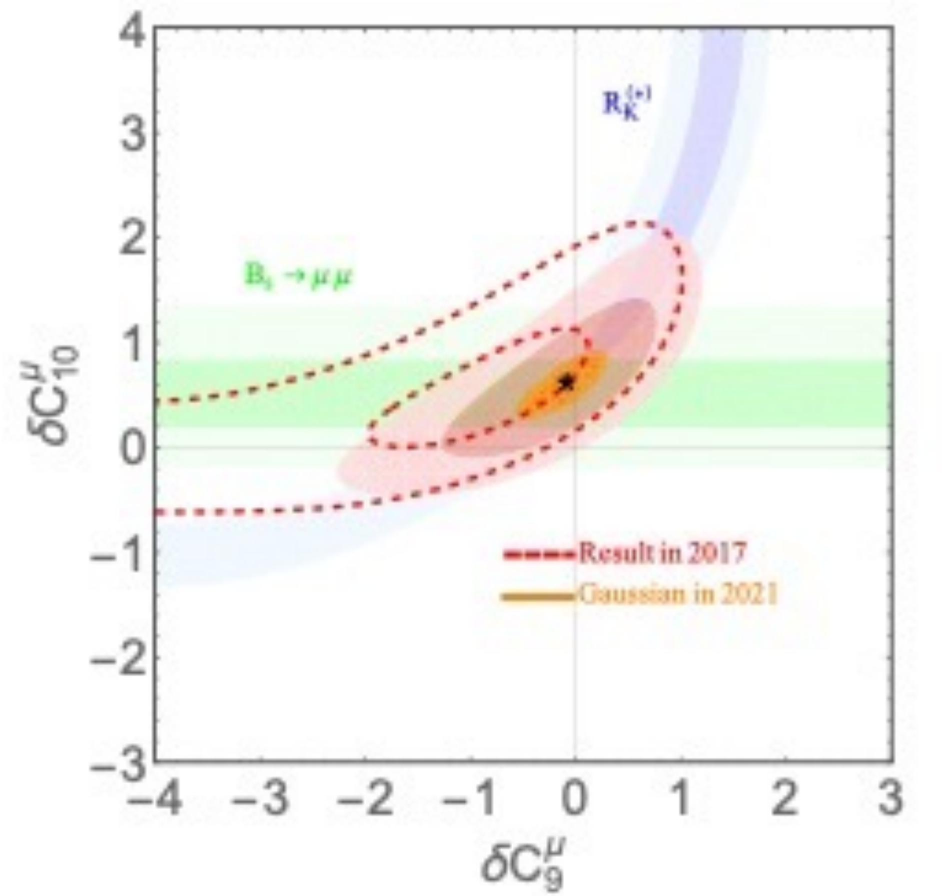


Global fits revisited

Global fits revisited

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

[arXiv:2103.12738]



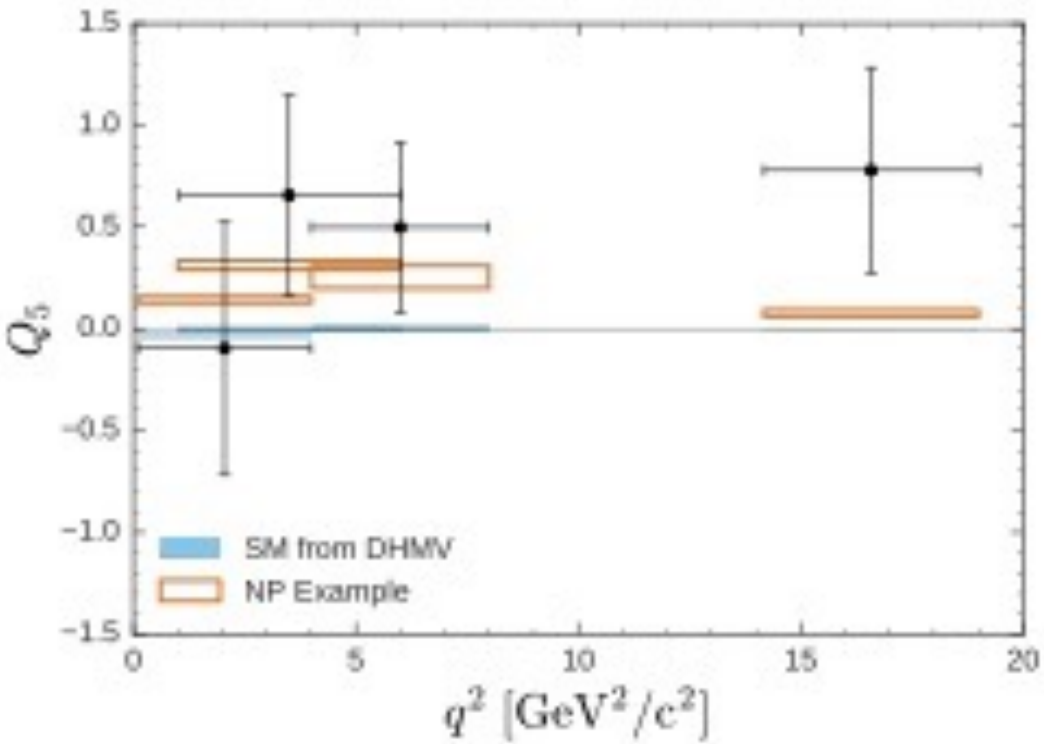
Many, many alternative fits on market e.g. [arXiv:2104.0892, arXiv:2103.13370 …]

A glimpse of the future

A glimpse of the future – P_5'

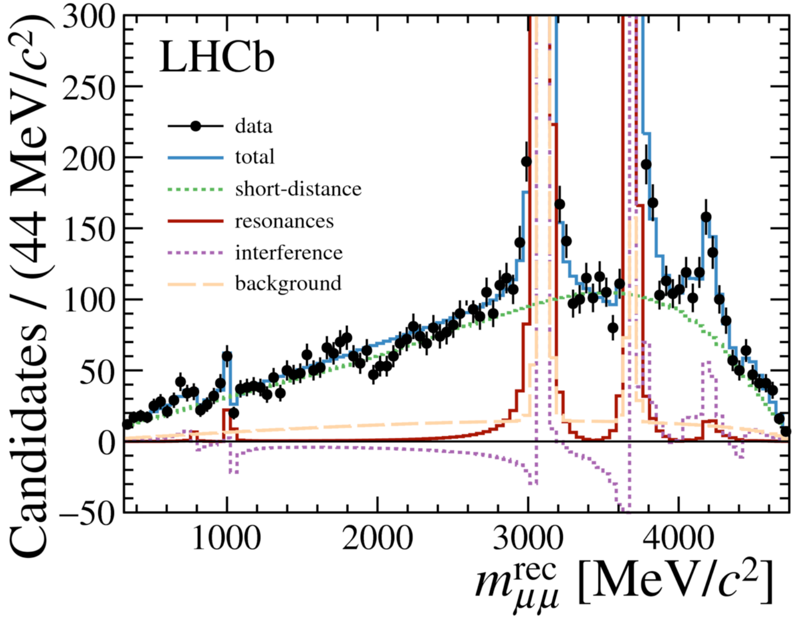
- Can make ratio of $P_5'(e)$ and $P_5'(\mu)$ $\rightarrow$ Q_5

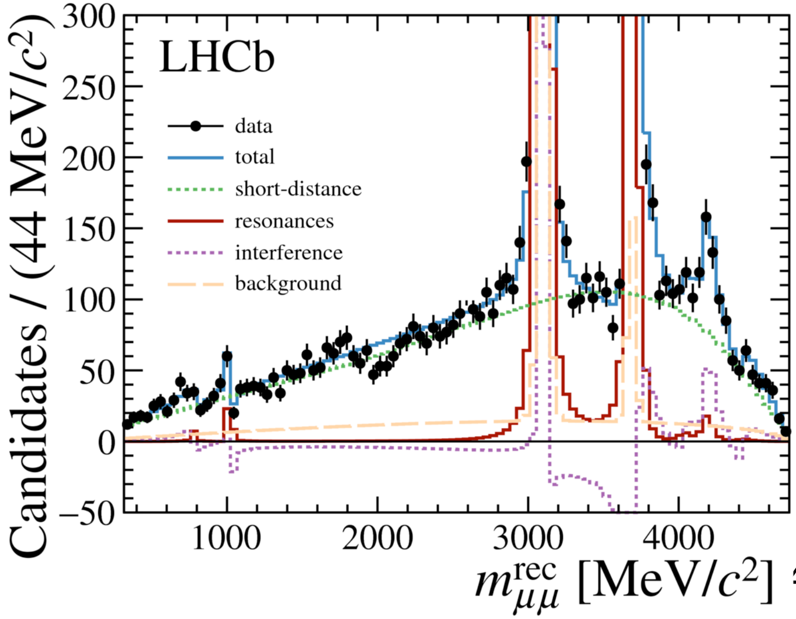
- Thus far, only done by Belle – full angular analysis of $B^0 \rightarrow K^{*0}ee$ in progress at LHCb



A glimpse of the future – $B^0 \to K^{*0}\mu\mu$

- *Measure* the effect of $c\bar{c}$ loops
- At low q^2, $\Delta C_9(q^2)$ term arises mainly from interference rare decay and J/ψ
- Measure phase of interference by fitting differential rate (and angles)
- LHCb has performed such a fit 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





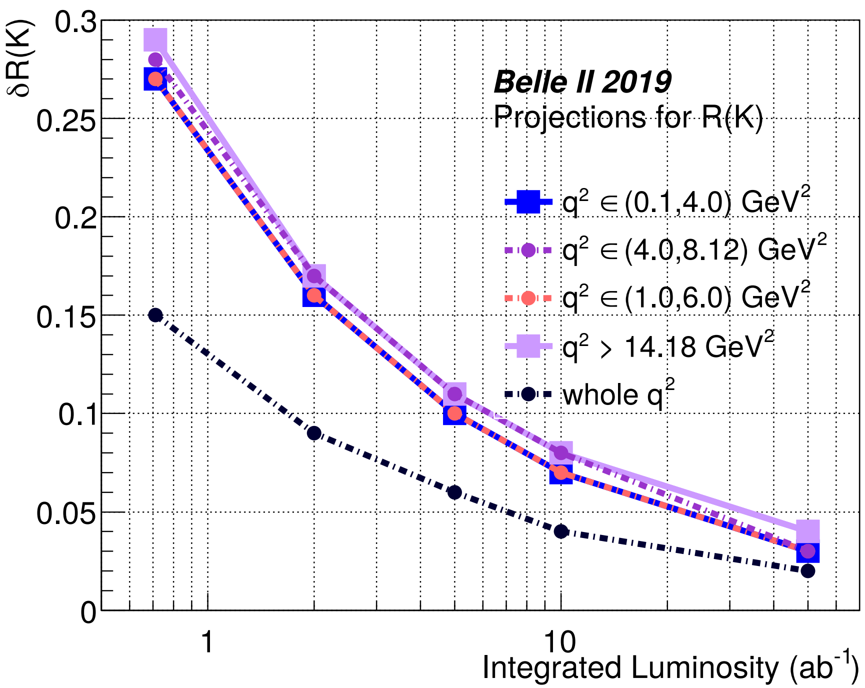
A glimpse of the future – Belle2

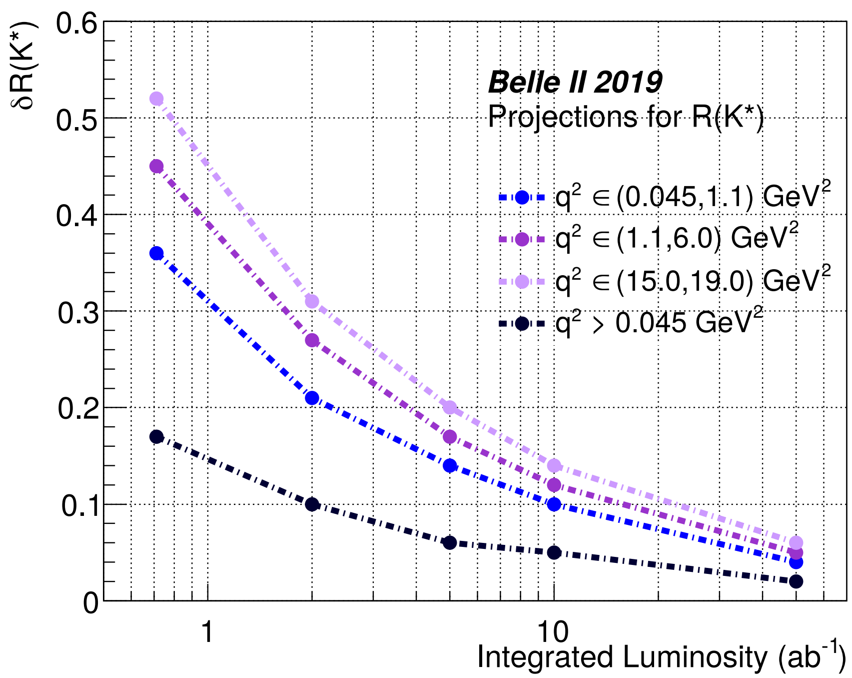
- “So when can Belle II confirm R_K?”

Belle has analysed the full dataset (R_K and R_{K^*}).

Safe answer: 20 ab^{-1} to get to the same size error bars.

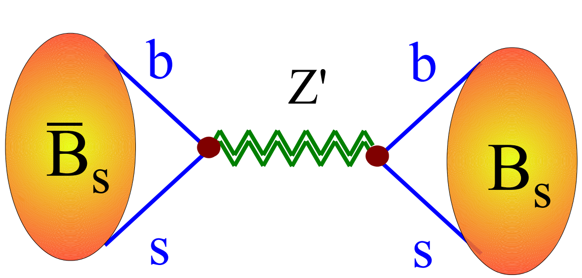
Unsafe answer: ~5 ish years.

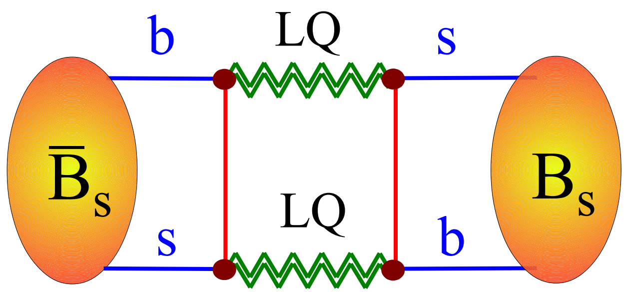




Model Building

- Anomalies can be explained by invoking Z' or LQ – majority of theorists seem to prefer LQ
  - Natural suppression of large effects on $\Delta F=2$ B-mixing



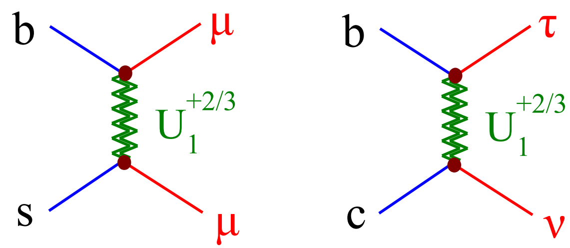


  - 3rd gen. LQ are also in better shape wrt direct searches

- Which LQ?

	Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
Scalars	$S_1 = (\mathbf{3},\mathbf{1})_{-1/3}$	✗	✓	✗
	$R_2 = (\mathbf{3},\mathbf{2})_{7/6}$	✗	✓	✗
	$\widetilde{R}_2 = (\mathbf{3},\mathbf{2})_{1/6}$	✗	✗	✗
	$S_3 = (\mathbf{3},\mathbf{3})_{-1/3}$	✓	✗	✗
Vectors	$U_1 = (\mathbf{3},\mathbf{1})_{2/3}$	✓	✓	✓
	$U_3 = (\mathbf{3},\mathbf{3})_{2/3}$	✓	✗	✗

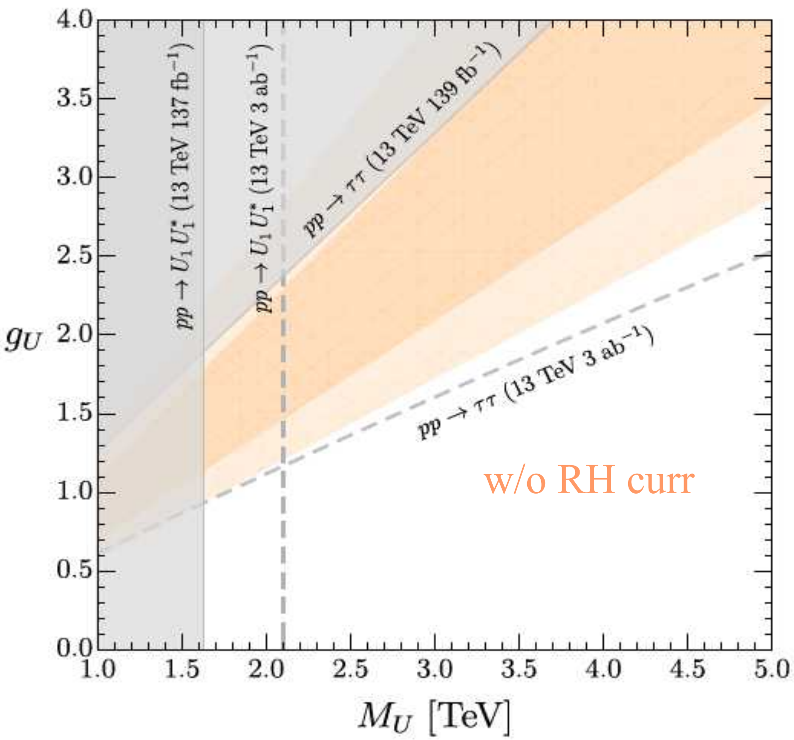
Angelescu, Becirevic, DAF, Sumensari [1808.08179]

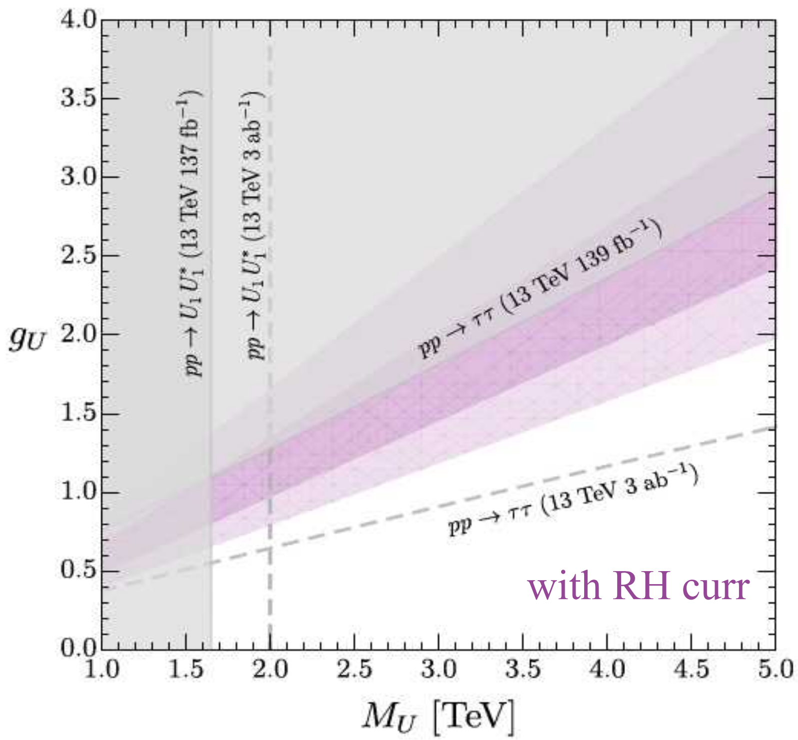


LQ of the Pati-Salam gauge group: $SU(4)\times SU(2)_L\times SU(2)_R$

Implications for direct searches

- Invoking only the LQ, U, and fitting all low-energy data enables a description of present data which is fully consistent with high-p_T searches [arxiv:2101.11626]
- LQ would then be within the reach of HL-LHC

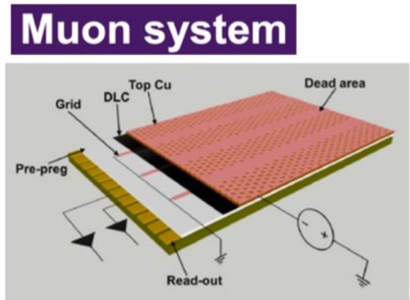


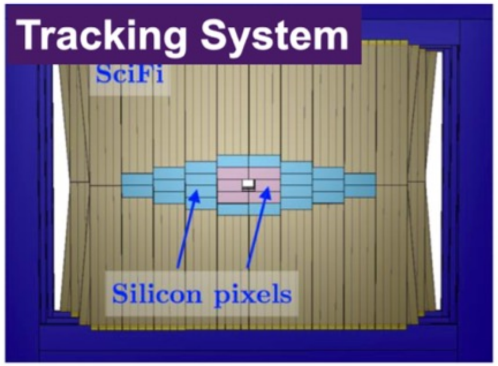


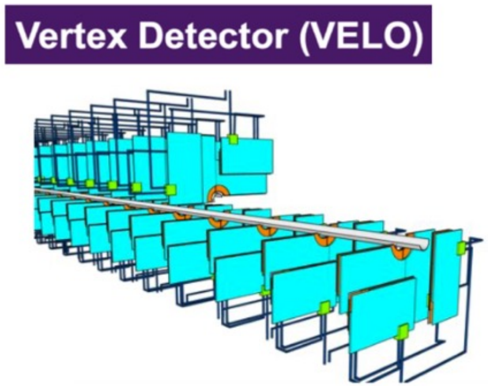
A plug…

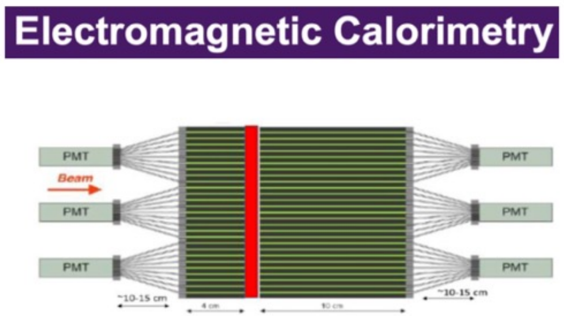
LHCb Upgrade II: R&D Progress

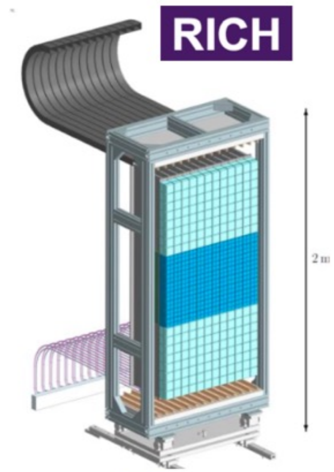
- Future **major** upgrade of the experiment, mainly for LS4 (~2030)
  - with some preparatory work in LS3 (~2025)
- Innovative Technology: precision timing, novel sensors, heterogeneous computing

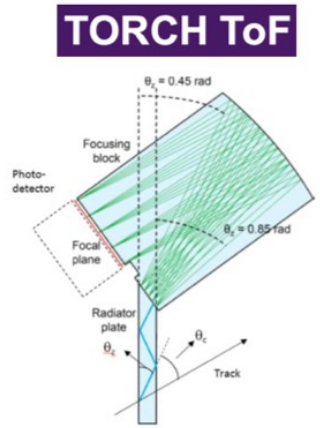


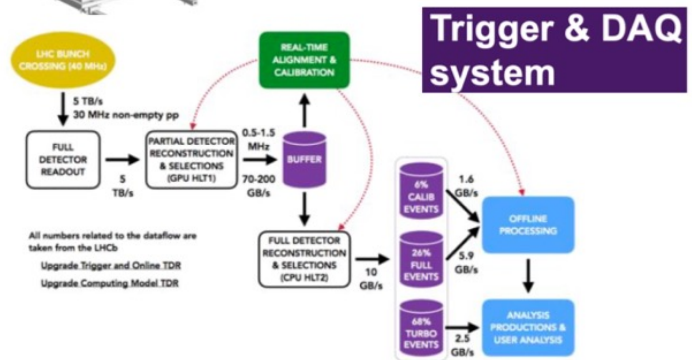








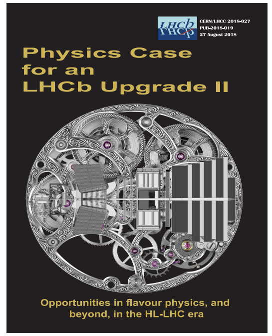




LHCb Upgrade II : Opportunities

- Strong Support
  - LHCC - Expression of interest (2017), Physics Case (2018)
  - Strong support in European Strategy (2020)
  - Framework Technical Design Report in preparation

- **Applications from new groups actively encouraged**
  - Major project after construction timescale of ATLAS/CMS/DUNE/Hyper-K
  - Technical Associate membership: physics on other experiments while pursuing R&D on LHCb
  - Synergy with future projects (EIC, FCC, CEPC…) many "firsts"



- Rad. hard CMOS detector
- Small pixel precision timing vertex detector
- ECAL with precision timing

- Hadron PID with fast timing
- Cryogenic cooled SiPMs
- GPU based triggering
- …..

Conclusions

Conclusions

- 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
- At LHCb, Run-3,4 dataset will give ~50fb^{-1} cf the 9fb^{-1} results have shown today; beyond that hope to collect 300fb^{-1} at a further LHCb upgrade