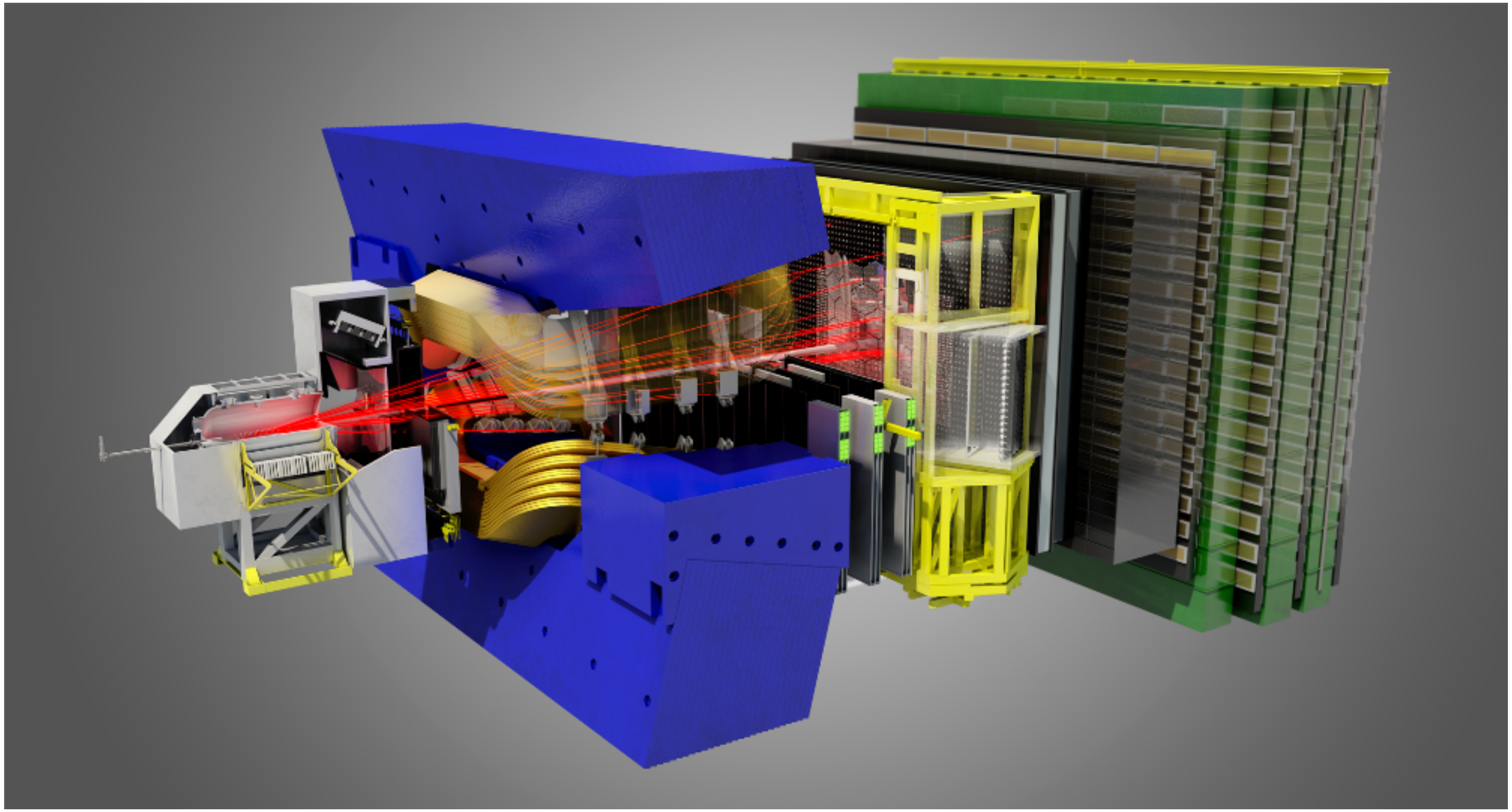
B-anomalies at LHCb



Mitesh Patel (Imperial College London)

University College London, 24th November 2017

Imperial College London

Introduction

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

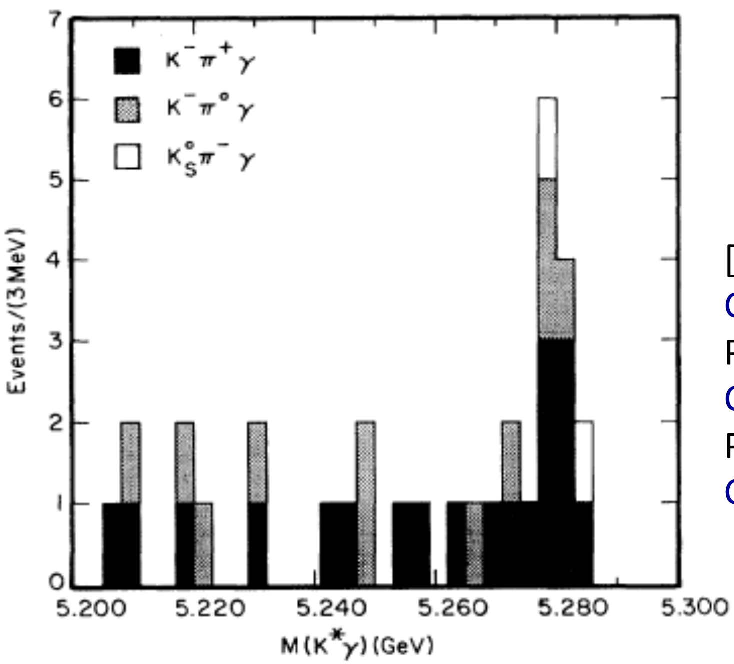
- Extent of discrepancies depends on several theoretical issues
  - will try and highlight these issues
  - point out where experiment can provide some future input

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

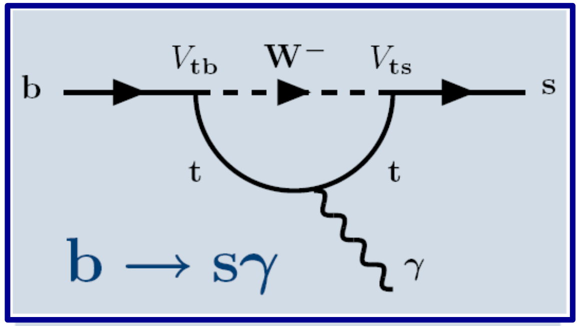
A historical example – $B_d^0 \rightarrow K^{*0}\gamma$

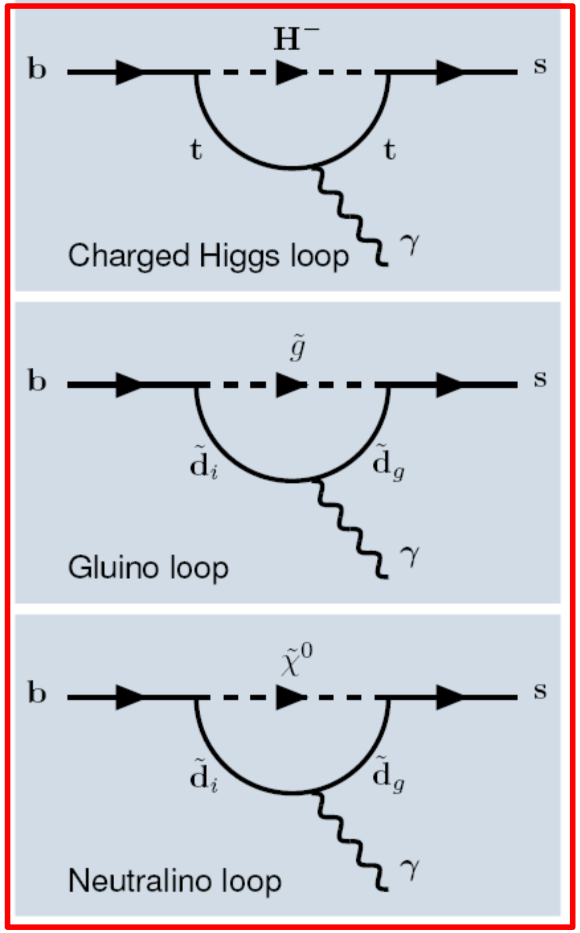
- In SM: occurs through a dominating W-t loop
- Possible NP diagrams:
- Observed by CLEO in 1993, two years before the direct observation of the top quark
  - BF was expected to be (2-4) × 10^{-4}

  → measured BF = (4.5 ± 1.7) × 10^{-4}



[Phys.Rev.Lett. 71 (1993) 674 - Cited by 678 records
Phys.Rev.Lett. 74 (1995) 2885 - Cited by 930 records
Phys.Rev.Lett. 87 (2001) 251807 Cited by 666 records]





Theoretical Foundation

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

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

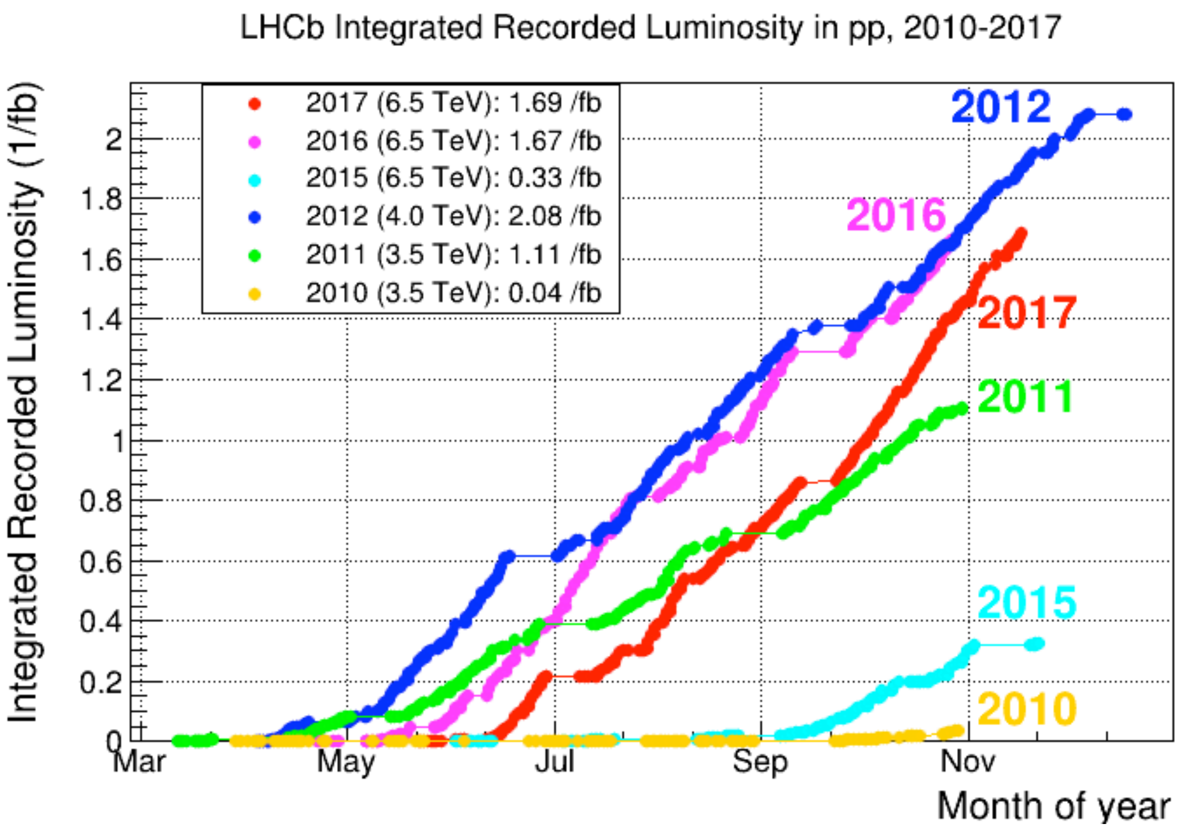
  - "Wilson Coefficients" C_i
    - Describe the short distance part, can compute perturbatively in given theory
    - Integrate out the heavy degrees of freedom that can't resolve at some scale μ
  - "Operators" O_i
    - Describe the long distance, non-perturbative part involving particles below scale 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

- 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*

LHCb data-taking



- Have analysed $3fb^{-1}$ of data taken during 2011,12
  - Analysis of further $\sim 2fb^{-1}$ (with ~1.5 cross-section) in progress
  - Have taken further $1.7fb^{-1}$ in 2017

Outline

- Angular observables in $B^0 \to K^{*0}\mu\mu$ and $b \to sll$ BFs
- Lepton-flavour universality ratios in $b \to sll$ decays
- Semileptonic $b \to cl\nu$ decays
- Some remarks about the future

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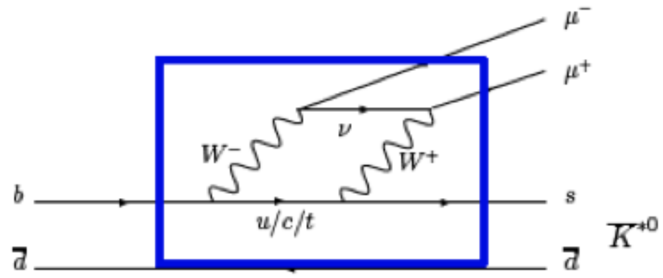
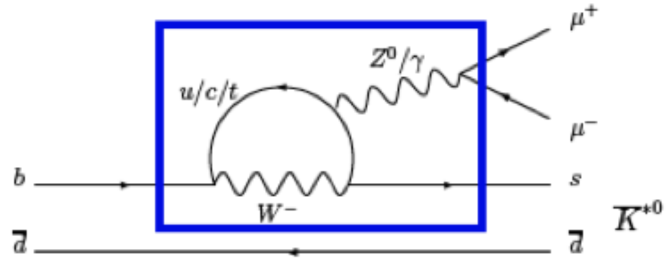
b→sll decays

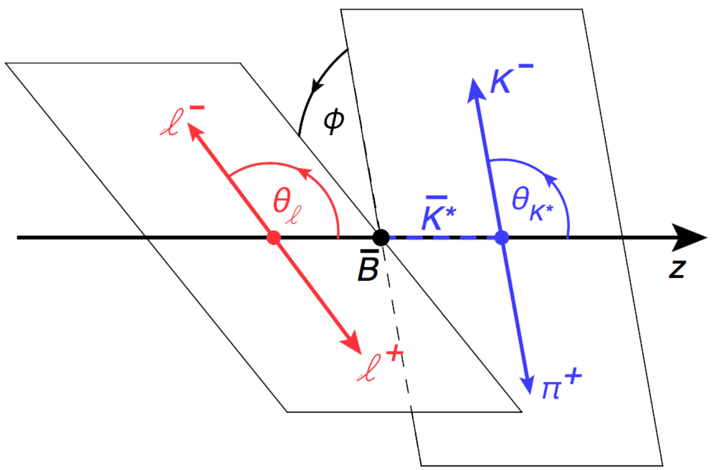
- b→sll decays involve flavour changing neutral currents → loop process

- 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







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

- Amplitudes that describe the $B_d^0 \to K^{*0}\mu\mu$ 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

$$A_\perp^{L(R)} = N\sqrt{2\lambda}\left\{\left[(\mathbf{C}_9^{\mathrm{eff}} + \mathbf{C}_9'^{\mathrm{eff}}) \mp (\mathbf{C}_{10}^{\mathrm{eff}} + \mathbf{C}_{10}'^{\mathrm{eff}})\right]\frac{\mathbf{V}(\mathbf{q}^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2}(\mathbf{C}_7^{\mathrm{eff}} + \mathbf{C}_7'^{\mathrm{eff}})\mathbf{T}_1(\mathbf{q}^2)\right\}$$

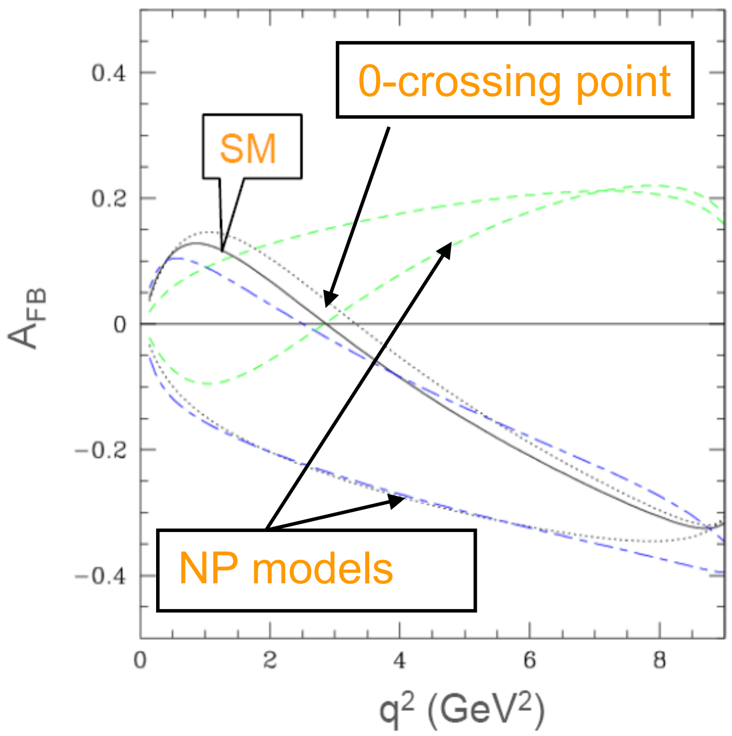
$$A_\parallel^{L(R)} = -N\sqrt{2}(m_B^2 - m_{K^*}^2)\left\{\left[(\mathbf{C}_9^{\mathrm{eff}} - \mathbf{C}_9'^{\mathrm{eff}}) \mp (\mathbf{C}_{10}^{\mathrm{eff}} - \mathbf{C}_{10}'^{\mathrm{eff}})\right]\frac{\mathbf{A}_1(\mathbf{q}^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2}(\mathbf{C}_7^{\mathrm{eff}} - \mathbf{C}_7'^{\mathrm{eff}})\mathbf{T}_2(\mathbf{q}^2)\right\}$$

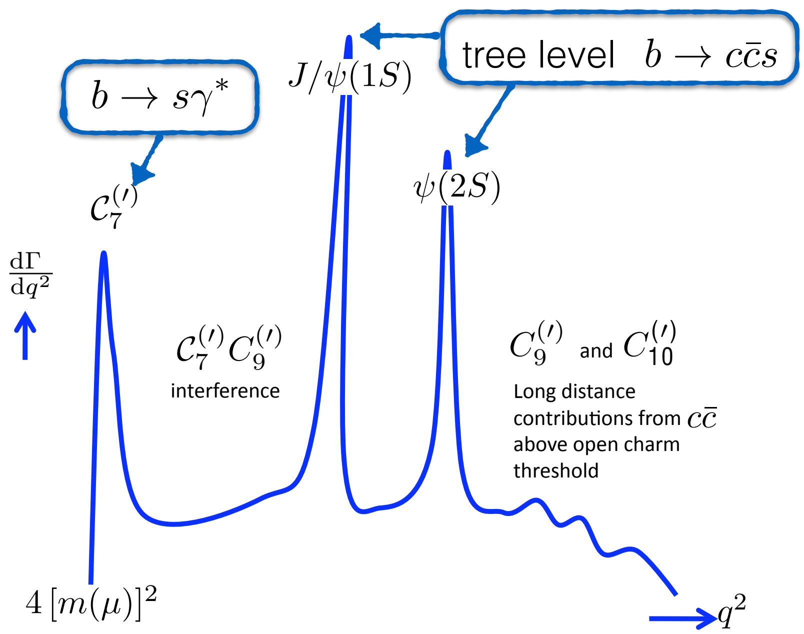
$$A_0^{L(R)} = -\frac{N}{2m_{K^*}\sqrt{q^2}}\left\{\left[(\mathbf{C}_9^{\mathrm{eff}} - \mathbf{C}_9'^{\mathrm{eff}}) \mp (\mathbf{C}_{10}^{\mathrm{eff}} - \mathbf{C}_{10}'^{\mathrm{eff}})\right]\left[(m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*})\mathbf{A}_1(\mathbf{q}^2) - \lambda\frac{\mathbf{A}_2(\mathbf{q}^2)}{m_B + m_{K^*}}\right]\right.$$
$$\left. + 2m_b(\mathbf{C}_7^{\mathrm{eff}} - \mathbf{C}_7'^{\mathrm{eff}})\left[(m_B^2 + 3m_{K^*} - q^2)\mathbf{T}_2(\mathbf{q}^2) - \frac{\lambda}{m_B^2 - m_{K^*}^2}\mathbf{T}_3(\mathbf{q}^2)\right]\right\}$$

→ BFs have relatively large theoretical uncertainties

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

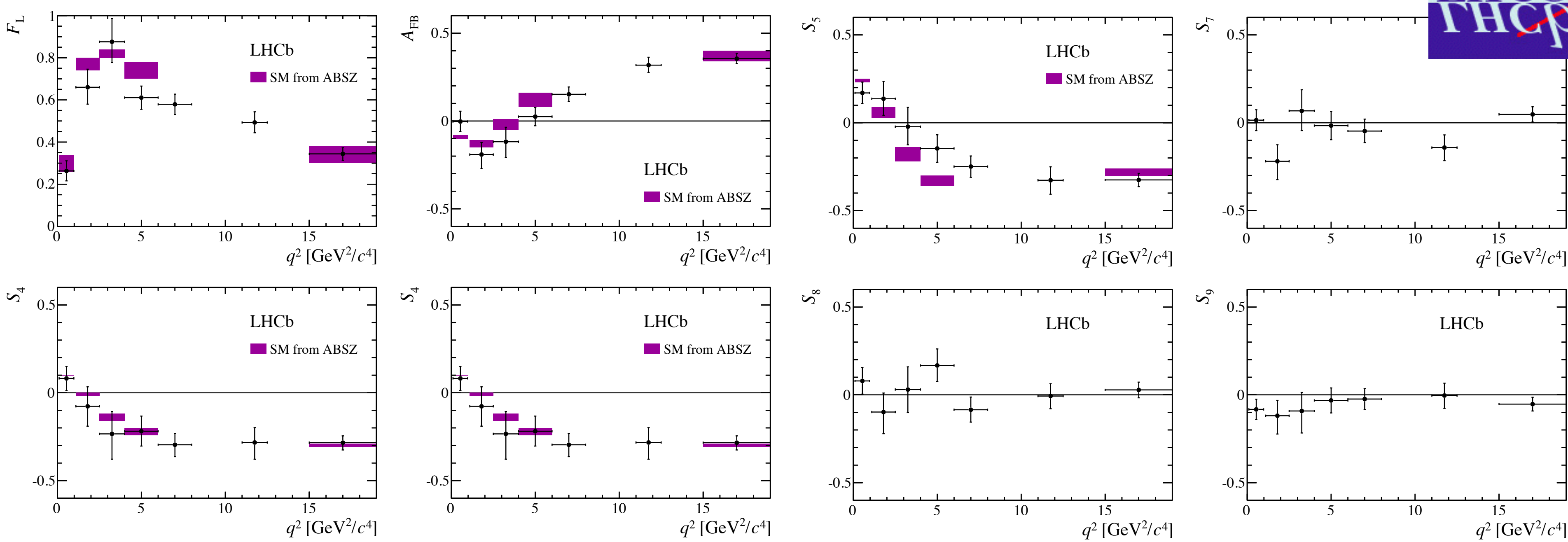
- Try to use observables where theoretical uncertainties cancel e.g. Forward-backward asymmetry A_{FB} of θ_l distn





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

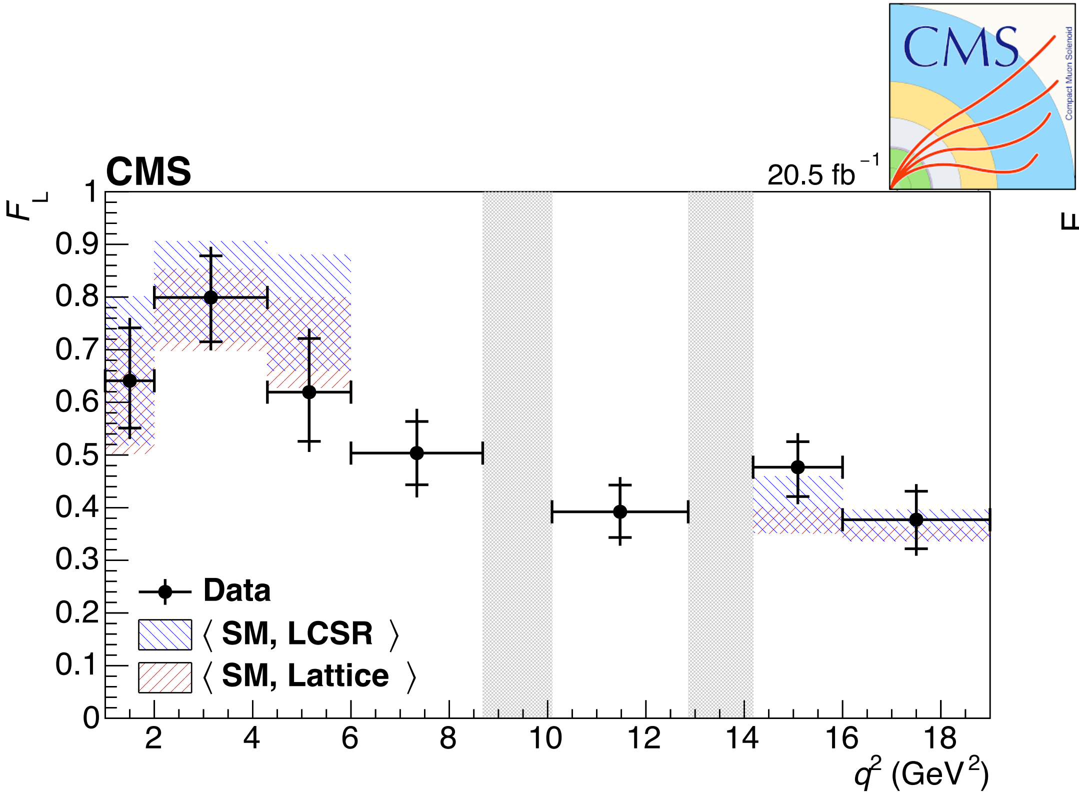
- LHCb performed first full angular analysis [JHEP 02 (2016) 104]
  - Extracted the full set of CP-avg'd angular terms and correlations
  - Determined full set of CP-asymmetries



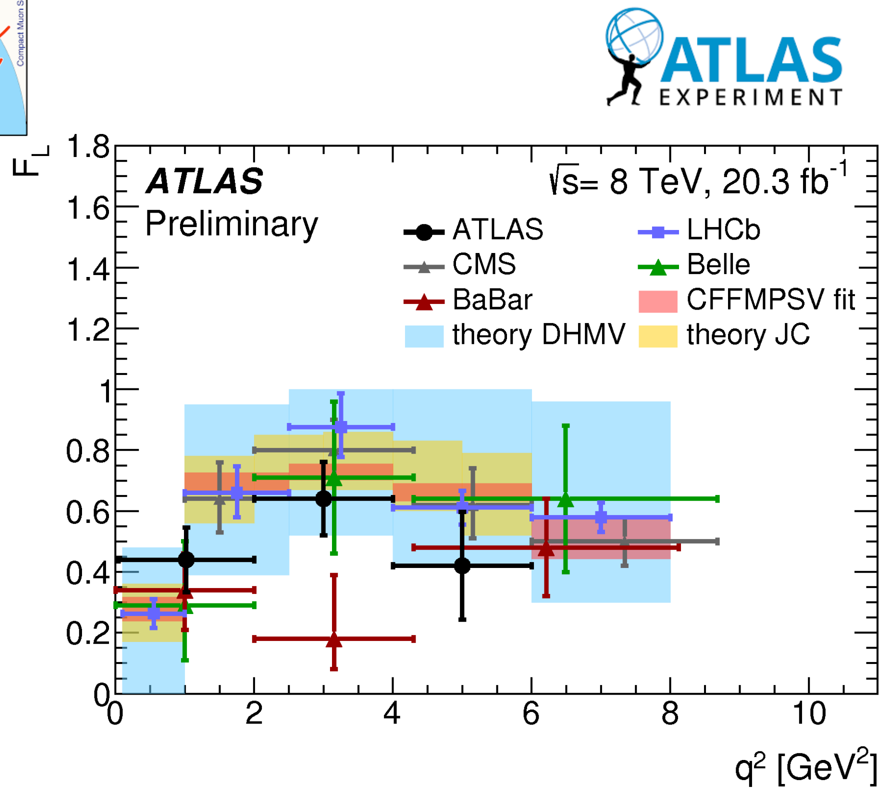
- Vast majority of observables in agreement with SM predns, giving some confidence in theory control of form-factors

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

- CMS and ATLAS confirm these findings



[Phys. Lett. B 753 (2016) 424]



[ATLAS-CONF-2017-023]

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

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

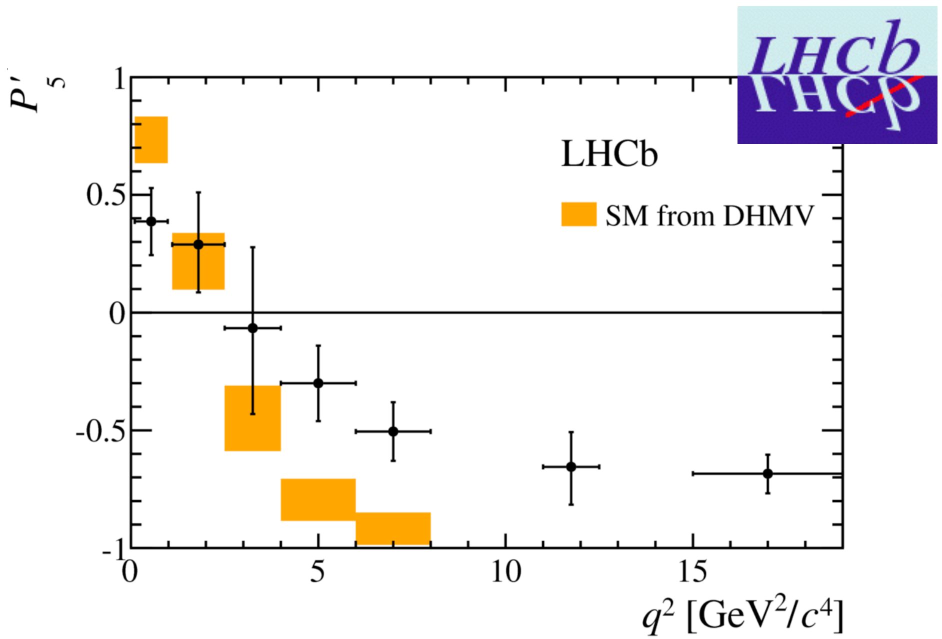
  which are form-factor independent *at leading order*

- 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})

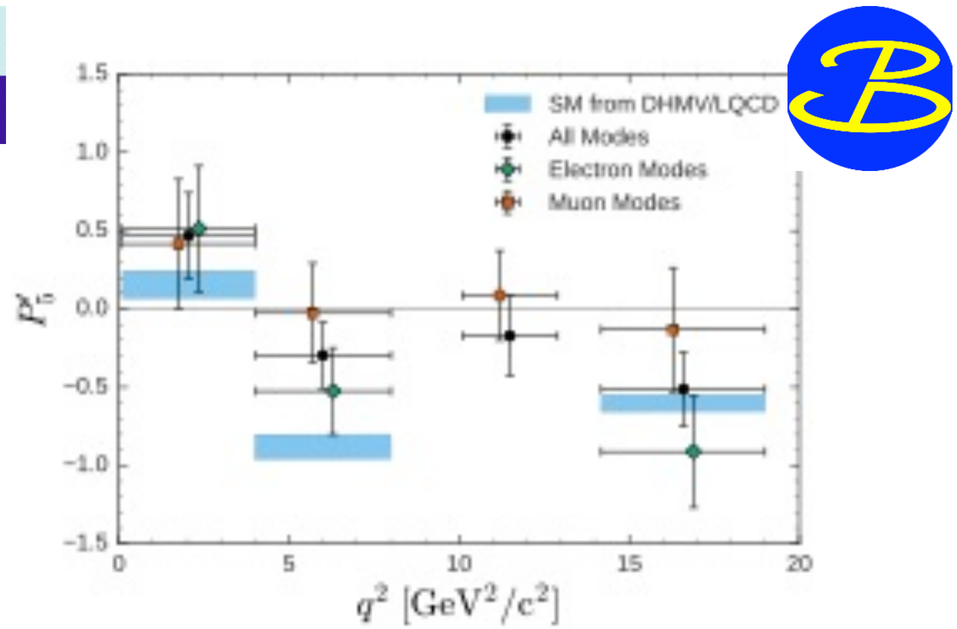
$B^0 \rightarrow K^{*0}\mu\mu$ angular analysis

- Form-factor "independent" P_5' has a local discrepancy in two bins – (subsequently confirmed by Belle)

  → **3.4σ** discrepancy with the vector coupling **ΔC_9 = −1.04±0.25**



[JHEP 02 (2016) 104]



[PRL 118 (2017) 111801]

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

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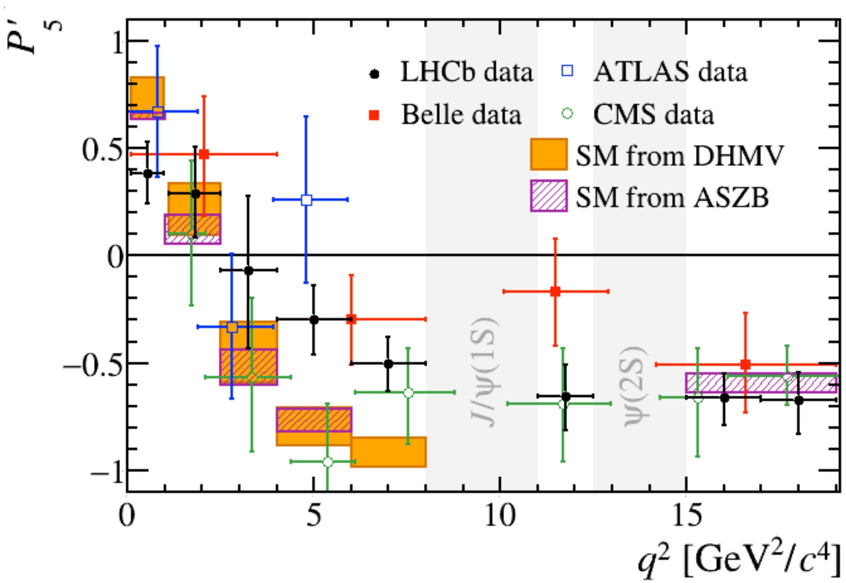


[JHEP 02 (2016) 104]

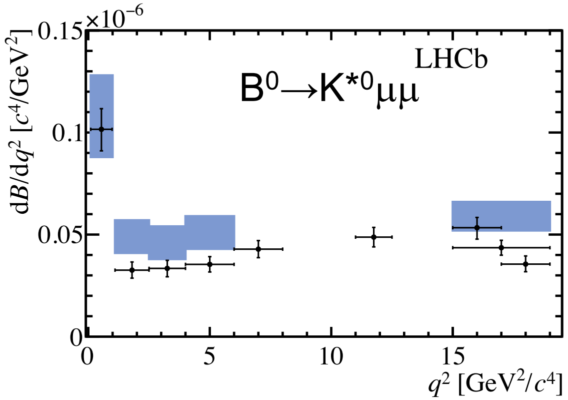
[PRL 118 (2017) 111801]

[ATLAS-CONF-2017-023]

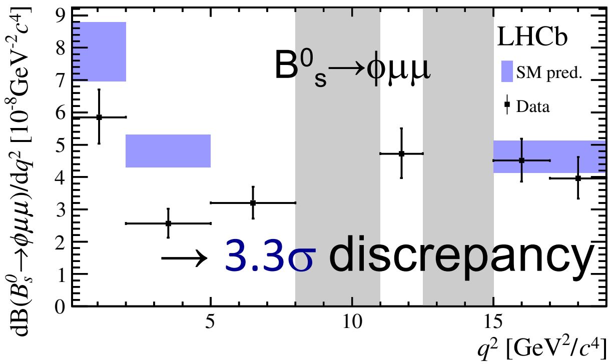
[arXiv:1710.02846]

b→sll branching fractions

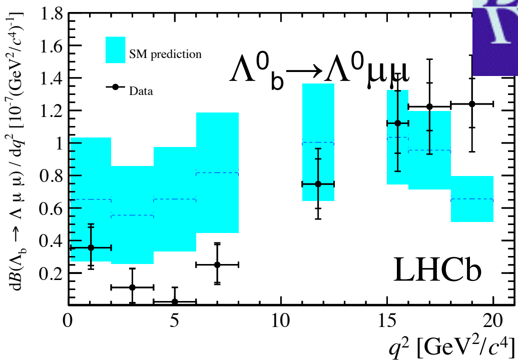
- Several b→sll branching fractions measured at LHCb show some tension with predictions, particularly at low q^2



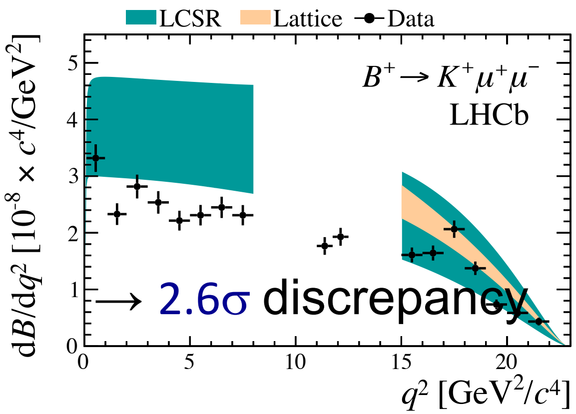
[JHEP 11 (2016) 047, JHEP 04 (2017) 142]

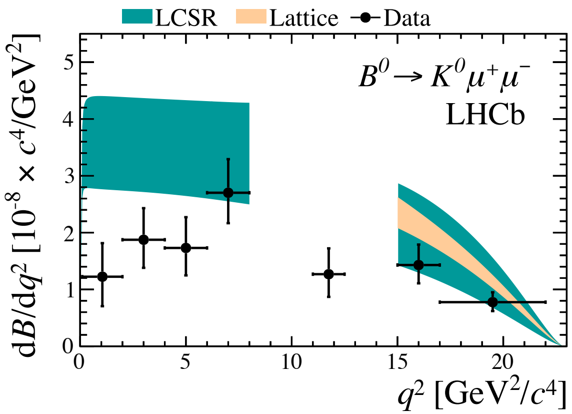


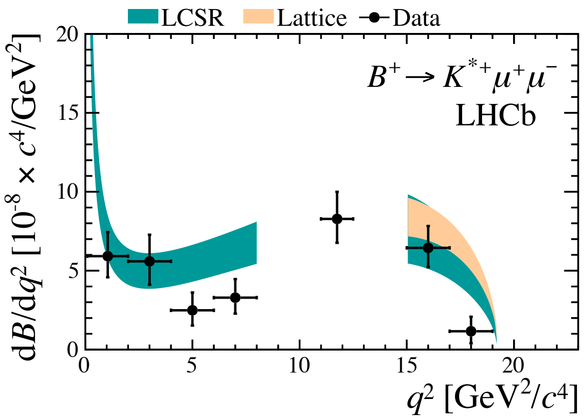
[JHEP 09 (2015) 179]



[JHEP 06 (2015) 115]





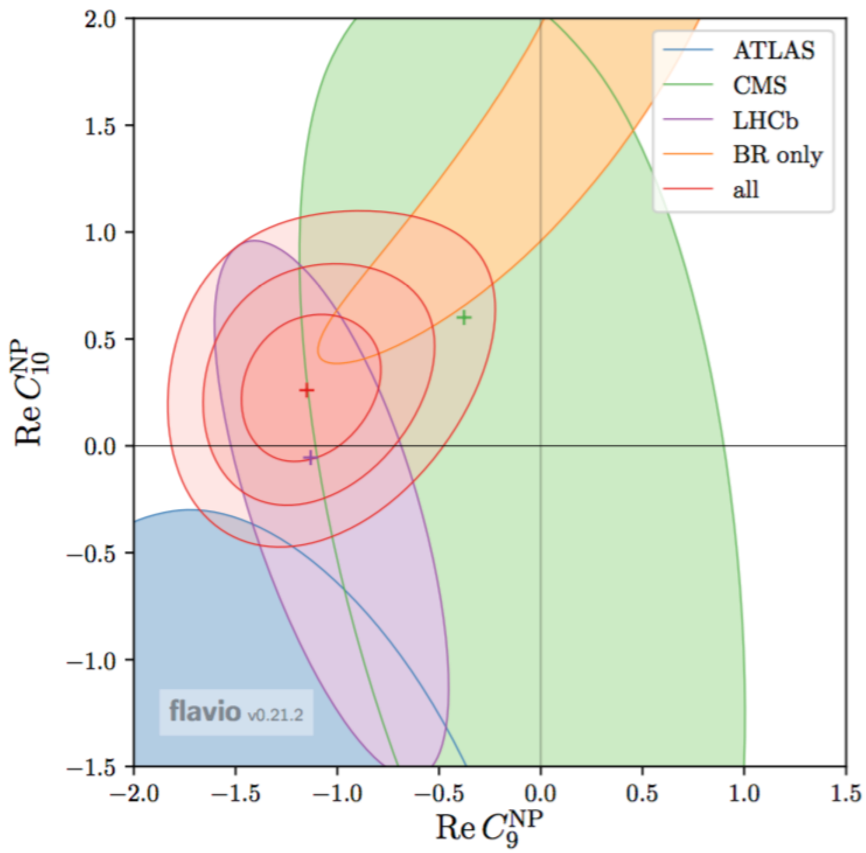


[JHEP 06 (2014) 133]

Global fits

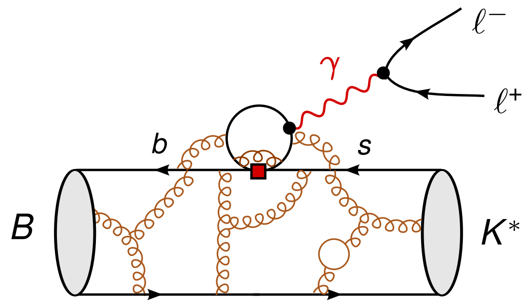
- Several theory groups have interpreted results by performing global fits to $b\rightarrow sll$ data e.g. [arXiv:1704.05340, EPJC(2017)77:377]

- Consistent picture, tensions solved simultaneously by a modified vector coupling (ΔC_9 != 0) at >**3σ** but discussion of residual hadronic uncertainties (…)



Could the SM predn be wrong?

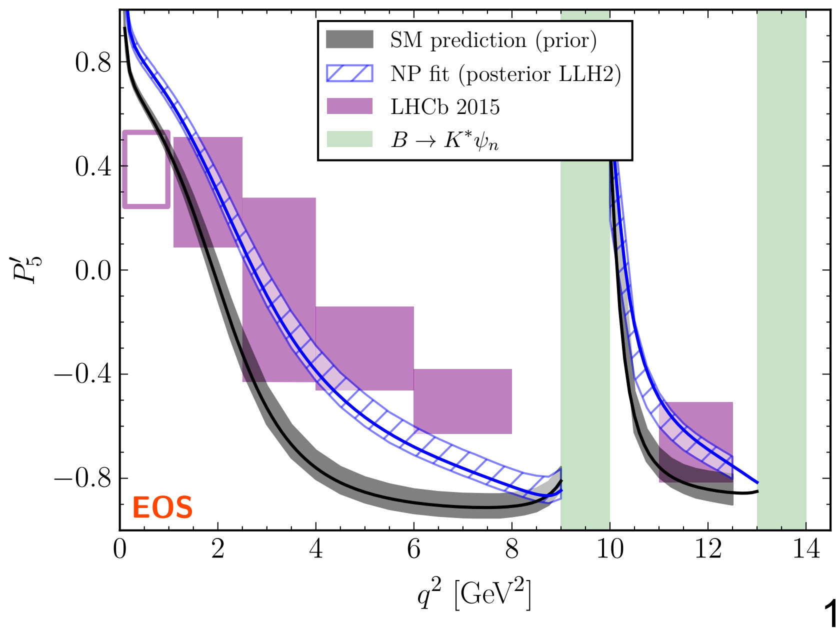
- Largest individual uncertainty on P_5' from $c\bar{c}$-loop effects



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

- Recent paper fits parameterisation to theory and auxiliary data to try and determine $c\bar{c}$ effect

[arXiv:1707.07305]



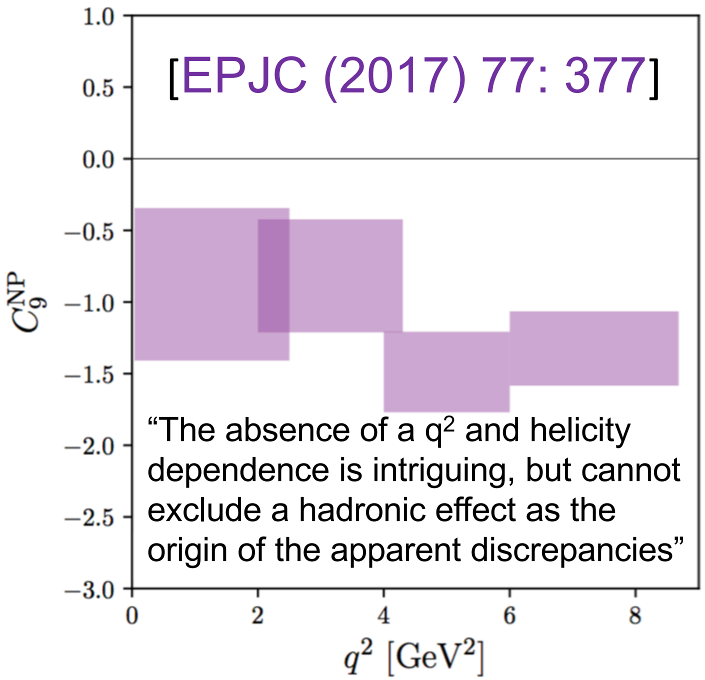
Could the SM predn be wrong?

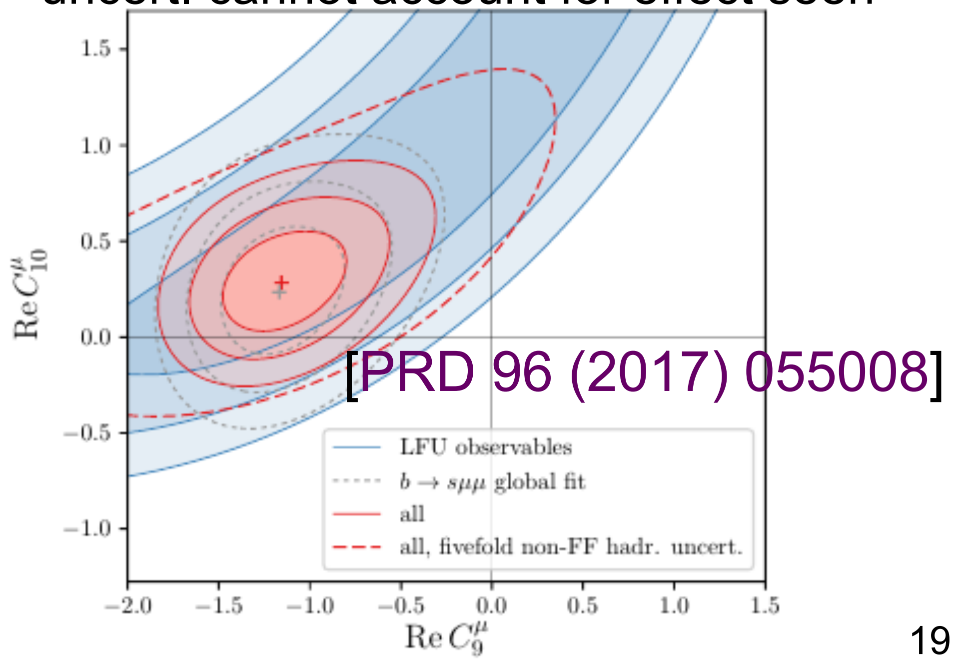
- Effect can be parameterised as function of three helicity amplitudes, $\mathbf{h_{+-0}}$
  - Absorb effect of these amplitudes into a helicity dependent shift in $\mathbf{C_9}$

    $\mathbf{C_9^{SM} + \Delta C_9^{+-0}(q^2)}$ cf. $\mathbf{C_9^{SM} + \Delta C_9^{NP}}$

    → Look for $\mathbf{q^2}$ and helicity dependence of shift in $\mathbf{C_9}$

Factor 5 increase in non-FF hadronic uncert. cannot account for effect seen





Could the SM predn be wrong?

- What about the form factors, could they be wrong?
  - Would give a correlated effect in other observables
  - Even if double errors, don't get close to explaining anomalies

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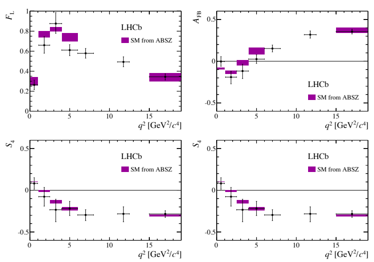
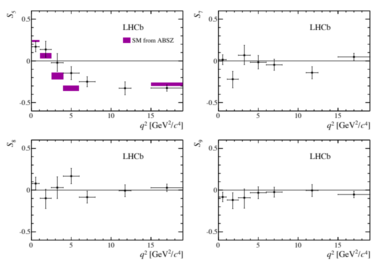
- An experimental problem?





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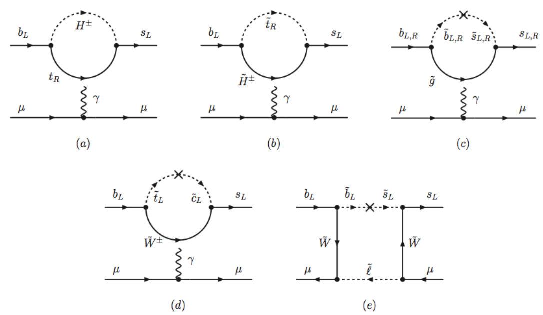
What if SM predn are correct?

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

- Very 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*"

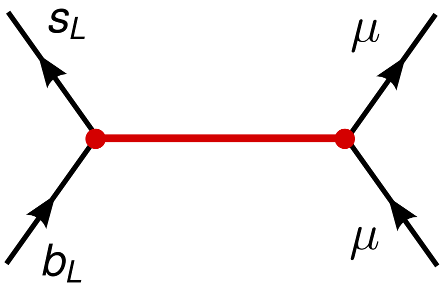


- Models with composite Higgs/UED have same problem

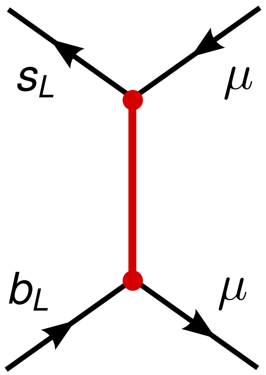
- **Could generate observed deviation with a Z' or LQ**

What if SM predn are correct?

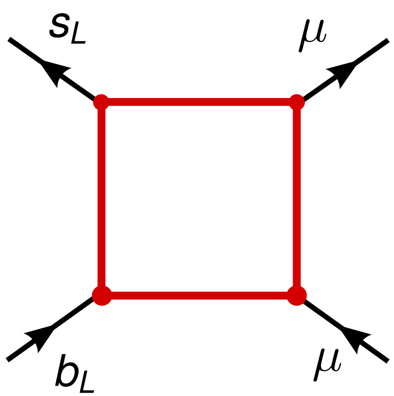
- Discrepancies have got enough interest st model builders have started to step-in



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



- Leptoquark
- Spin 0 or 1



- New scalars/vectors, also leptoquarks possible

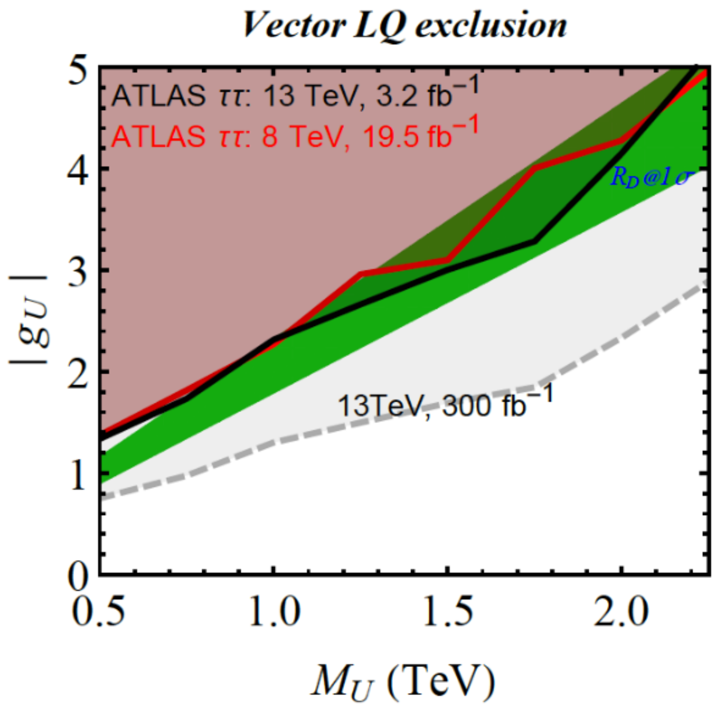
- For a review see, *e.g.* D.Straub @ Instant workshop on B meson anomalies

Direct searches

- Measurements give constraints on mass, coupling plane – in order to understand how heavy e.g. LQ might be, need a model for couplings
  - Couple only to b-s (and hence avoid lots of other expt'al constraints)?

    → LQ can be ~TeV but then very difficult to measure directly
  - Invent full model with coupling to other quarks?

    → LQ can then be ~30TeV and even a 100TeV future collider might not be able to do the job (!)

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Science
Life and Physics

Anomalous bottoms at Cern and the case for a new collider

Particles known as "bottom mesons" are not decaying in the way the Standard Model of particle physics says they should, and it's causing some excitement

Outline

- Angular observables in $B^0 \to K^{*0}\mu\mu$ and $b \to sll$ BFs
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The plot thickens: R_K

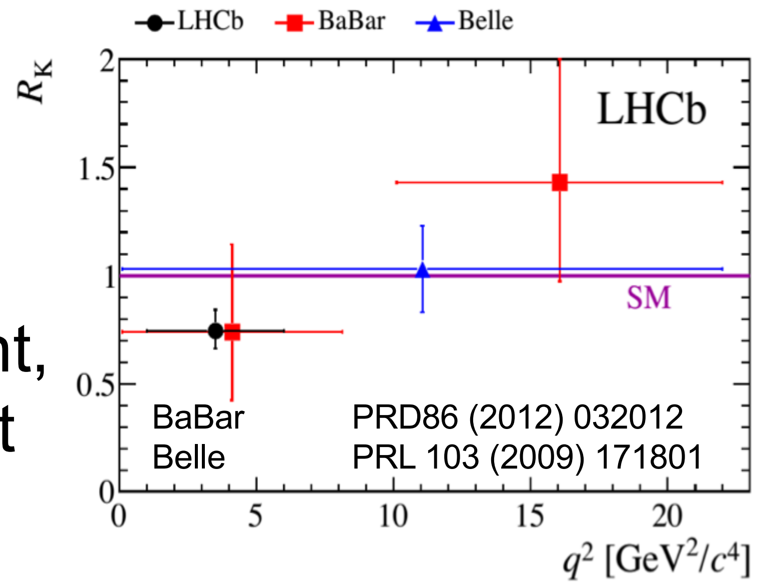
- The ratio of $b \to s\mu\mu$ and $b \to see$ branching fractions, **R**, is a theoretically pristine quantity, precisely predicted in the SM
  $R_{K^{*0},K} = BF(B^{0,+} \to K^{*0,+}\mu\mu) / BF(B^{0,+} \to K^{*0,+}ee)$

- Whatever hadronic uncertainties affect $b \to sll$ decays, they should cancel in this ratio

- 2014 LHCb measurement of $\mathbf{R_K}$,

  $$\mathbf{R_K} = 0.745^{+0.090}_{-0.074}(\text{stat})^{+0.036}_{-0.036}(\text{syst})$$

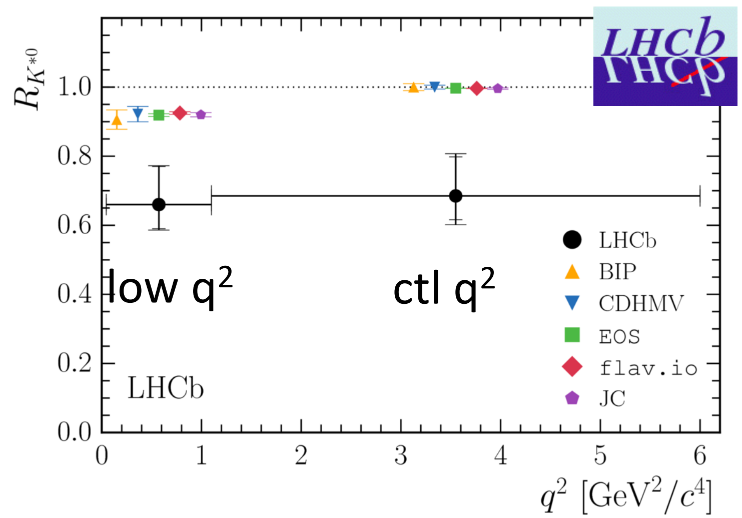
  already generated some excitement, despite being consistent with SM at 2.6σ level



  - Measured value is what would result from $\Delta C_9^{ee}=0$, $\Delta C_9^{\mu\mu}=-1$ i.e. could account for angular data, BFs and this R_K ratio by changing only $C_9^{\mu\mu}$

Lepton universality measurements

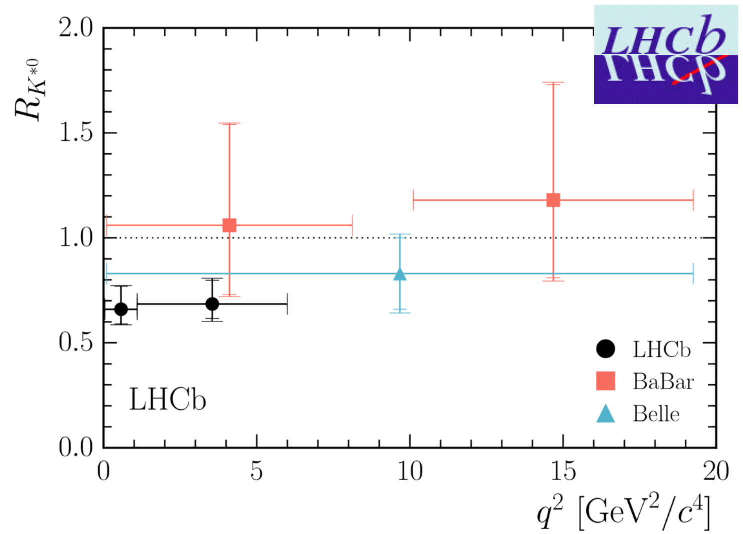
[JHEP 08 (2017) 055]



- Have recently added analogous measurement using **$K^{*0}ll$** instead of **$K^{+}ll$ → $R_{K^{*0}}$**

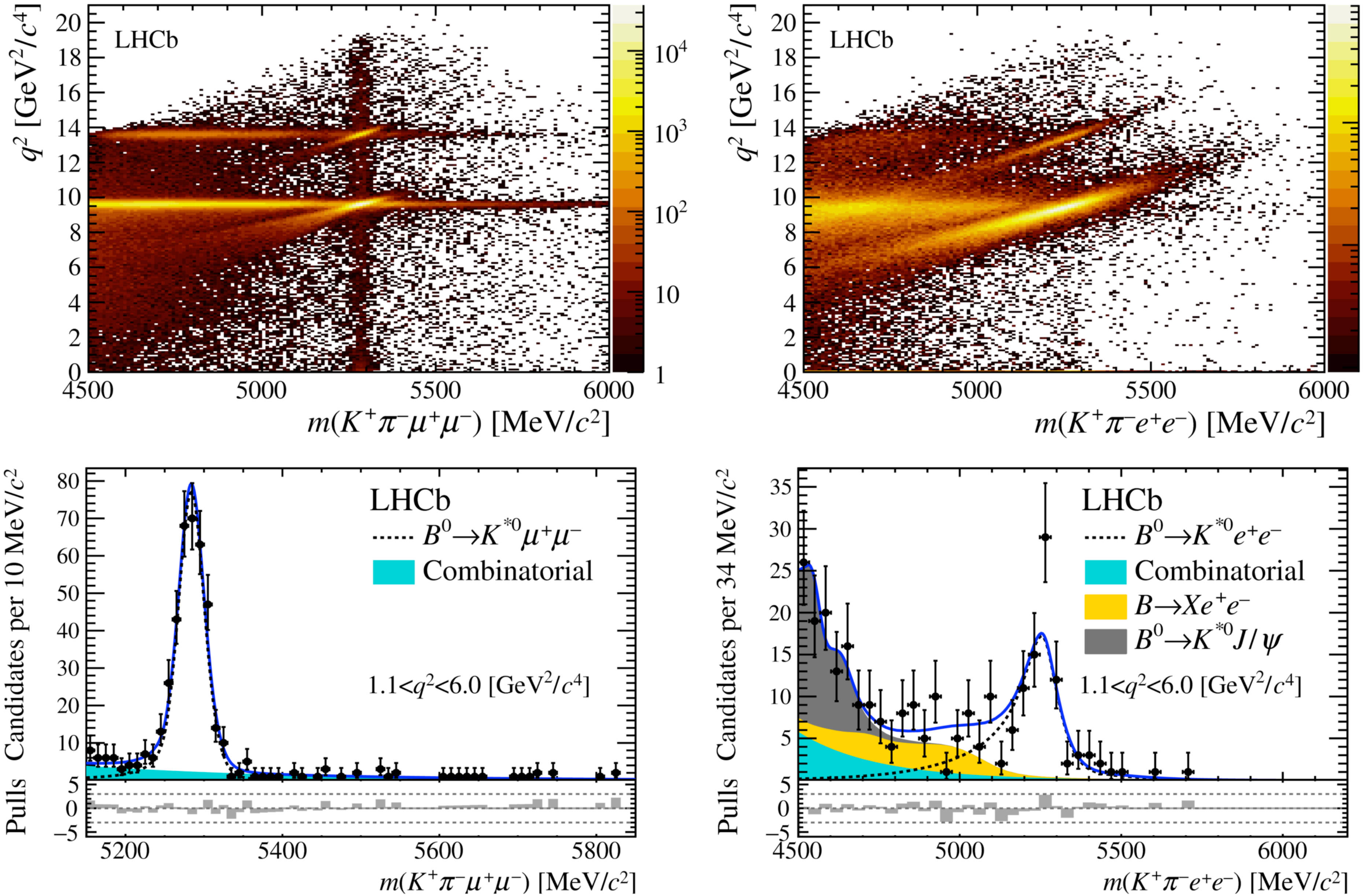
- Find,
  - low q^2: 2.1-2.3σ below SM predn
  - ctl q^2: 2.4-2.5σ below SM predn

  [JHEP 08 (2017) 055]



- Cue a new wave of global fits (…)

$R_{K^{*0}}$ – experimental issues



Cross-checking R ratios

- R_X measurements made exploiting double ratio wrt equivalent J/ψ decay modes in order to cancel experimental systematic uncertainties

$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

- Need observed yield of each decay mode and (ratio of) selection efficiencies
  - Bremsstrahlung and trigger give main differences between
  - Cancel effect by comparing to J/ψ modes with similar issues

Cross-checking R ratios

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

$$r_{J/\psi} = \frac{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))}$$

  where we do not benefit from this cancellation

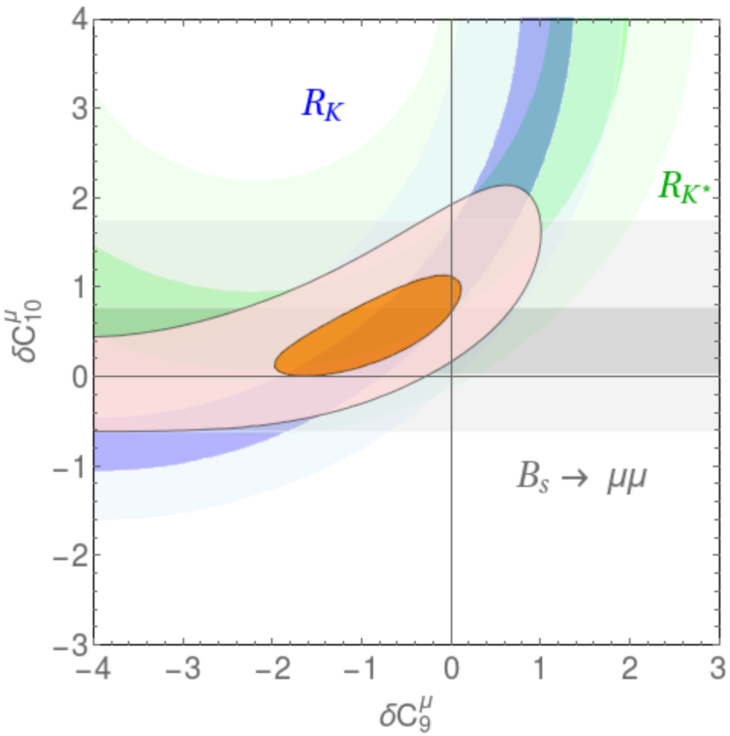
- $r_{J/\psi}$ known to be lepton universal at ~% level
- Measure $r_{J/\psi}$ = 1.043±0.006 (stat) ±0.045 (syst), result is independent of the decay kinematics, binning in quantities that would expect bremsstrahlung and trigger to depend on see completely uniform result

Cross-checking R ratios

- Extent of the cancellation of residual systematics verified by measuring the double ratio, $R_{\psi(2S)}$, where $B^0 \rightarrow K^{*0}\psi(2S)(\rightarrow l^+l^-)$ decays used in place of $B^0 \rightarrow K^{*0}l^+l^-$
- Find compatible with unity, σ_{stat}~2%
- Further check at low q^2 : measure BF($B^0 \rightarrow K^{*0}\gamma$) where γ converts to e^+e^-, again result compatible with PDG
- Various data-driven adjustments made to simulation in order to reproduce trigger-, PID-, tracking- efficiencies observed with data control channels, even if turn these off completely, result shifts by <5%

Global fits revisited

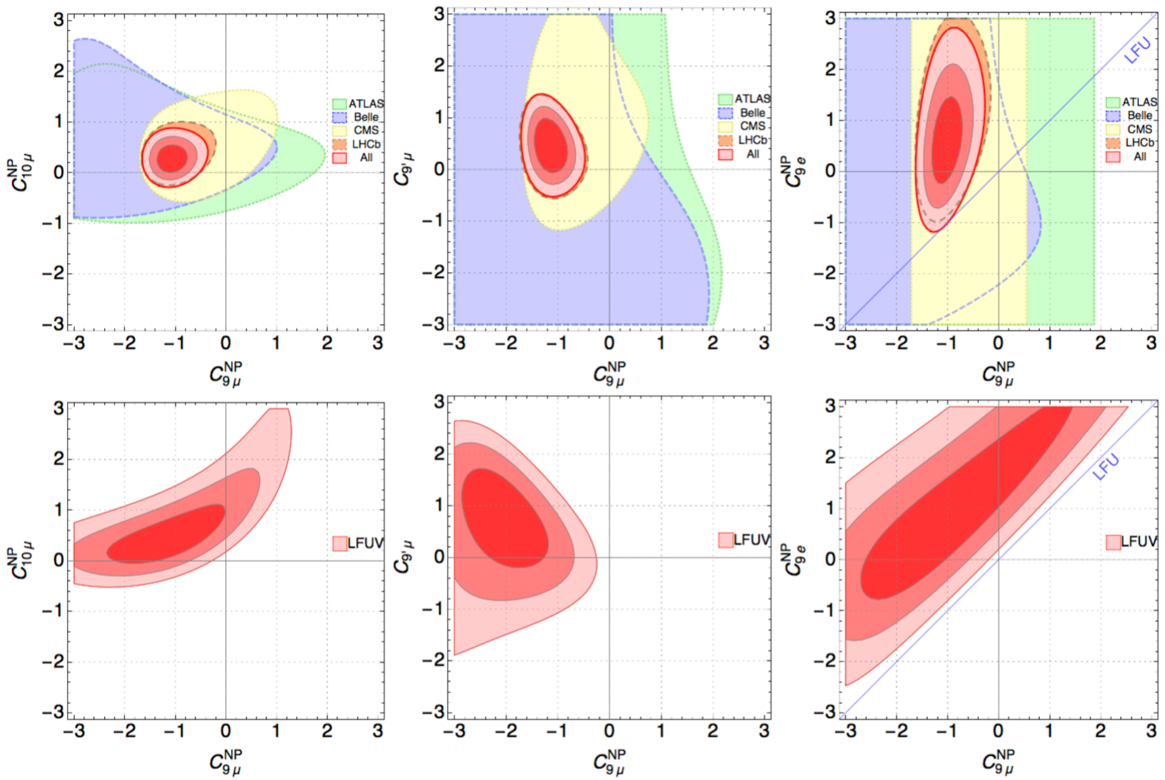
- Using *just* the theoretically clean observables, R_K, R_{K^*} and BF($B \rightarrow \mu\mu$), fits exclude SM at **3.6σ** level



- NB: have more than twice data again in-hand

Global fits revisited

- Adding the angular and branching fractions observables to the LFU ratios, the size of the discrepancy → >5σ [see e.g. arXiv:1704.05340]



… but community understandably still reluctant to call this NP

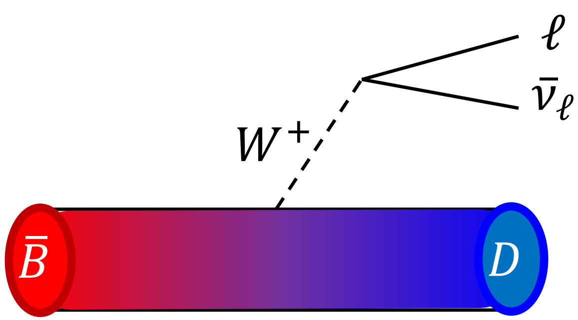
Outline

- Angular observables in $B^0 \to K^{*0} \mu\mu$ and $b \to sll$ BFs
- Lepton-flavour universality ratios in $b \to sll$ decays
- Semileptonic $b \to cl\nu$ decays
- Some remarks about the future

Semileptonic anomaly

- A further anomaly is seen in semileptonic B decays
  - Tree-level process in SM
  - Good theoretical control due to factorisation of hadronic and leptonic parts but again use lepton universality ratio to access theoretically pristine quantity e.g. in case of **b→clν** transition,

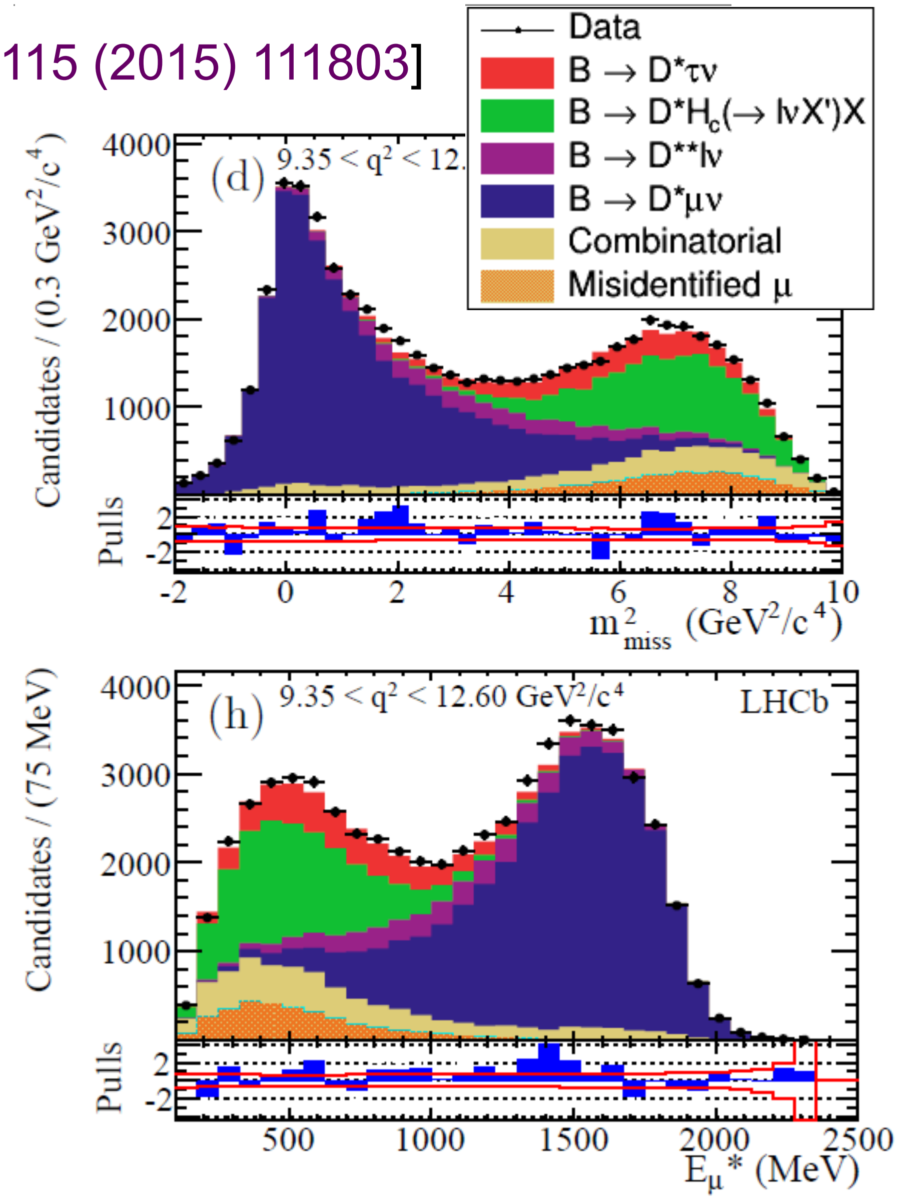
$$R\left(D^{(*)}\right) \equiv \frac{\mathcal{B}\left(\bar{B}^0 \to D^{(*)}\tau^-\bar{\nu}_\tau\right)}{\mathcal{B}\left(\bar{B}^0 \to D^{(*)}\ell^-\bar{\nu}_\ell\right)}$$



  - SM predictions
    - R(D) = 0.300(8) [EPJ C77 (2017)112]
    - R(D*)=0.252(3) [PRD 85 (2012) 094025]
  - Recent updates take into account alternative extrapolation for form-factors and differential distributions from Belle data,
    - R(D)=0.258(5) [arXiv:1707.09977]
    - R(D*)=0.260(8) [arXiv:1707.09509]

LHCb result – leptonic τ

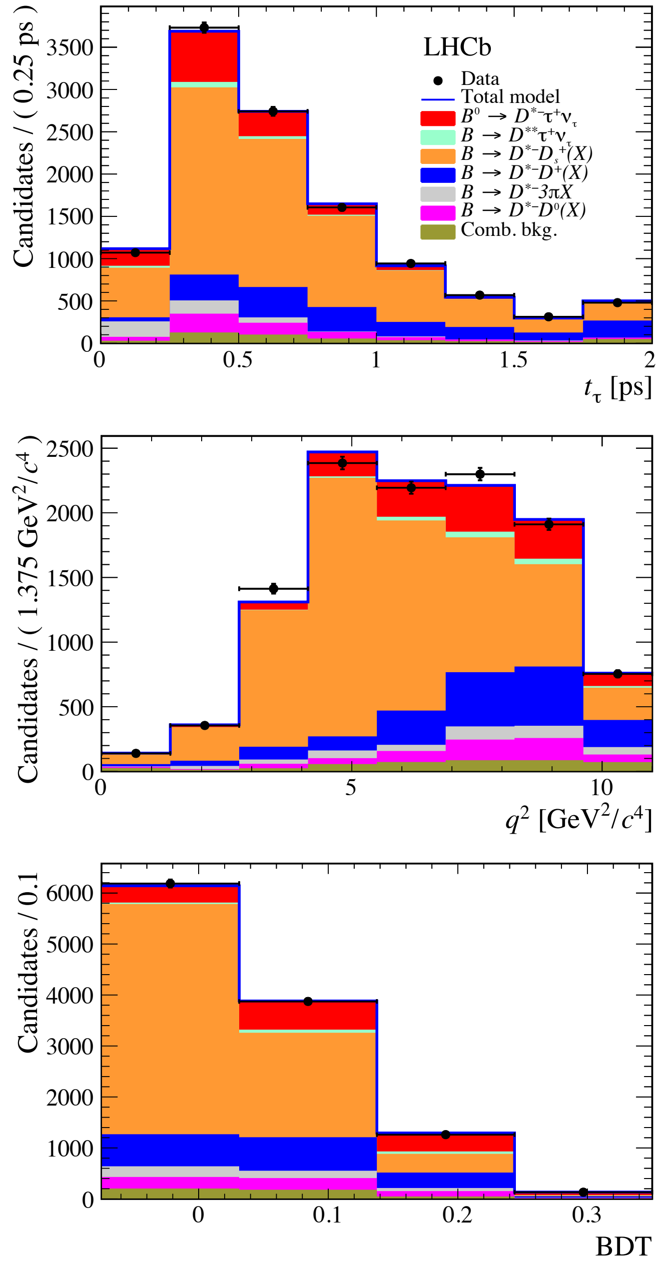
[PRL 115 (2015) 111803]



- 3D fit to (m_{miss}^2, E_μ*, q^2)
- R(D*) = 0.336±0.027±0.030
- **2.1σ** above SM prediction
- Dominant systematics from MC statistical uncertainty and background from hadrons misidentified as muons

LHCb result – 3-prong τ

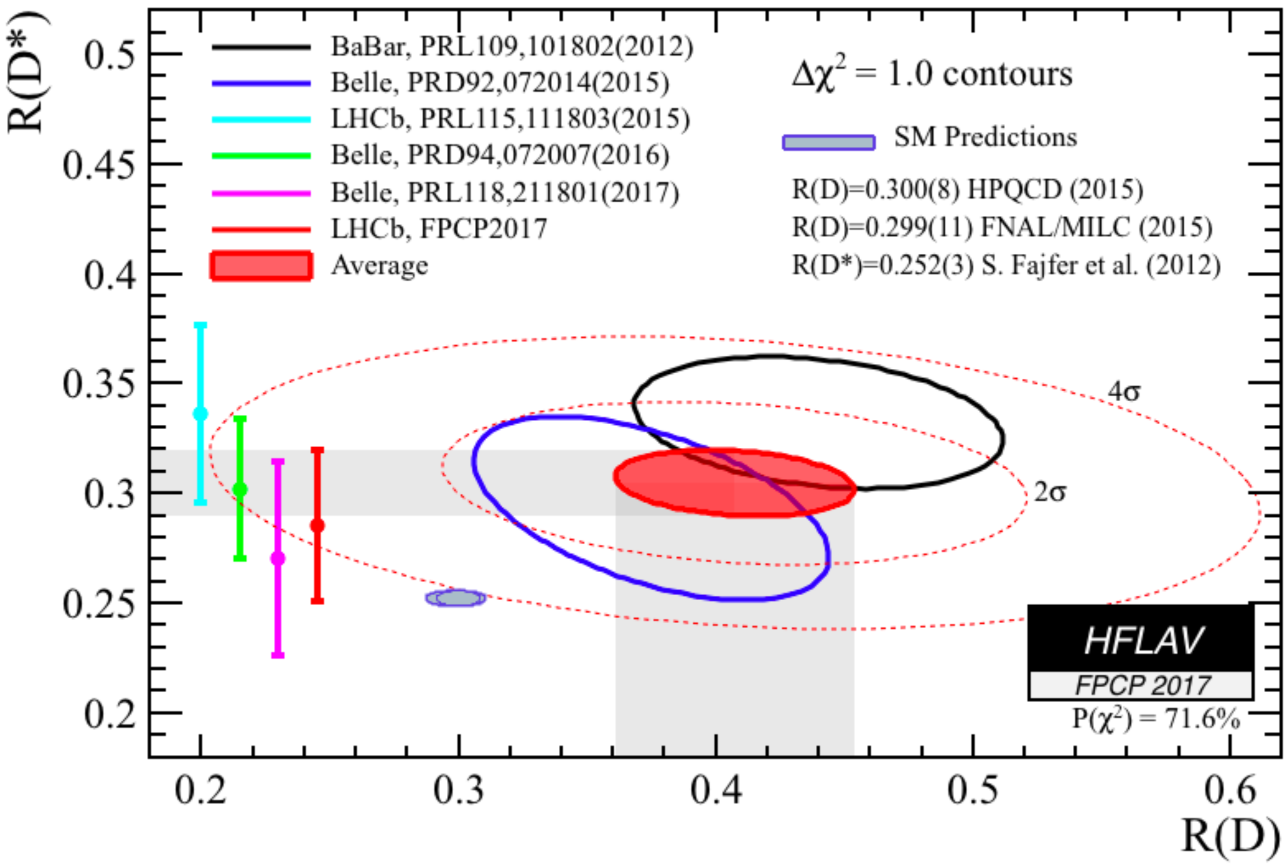
- Largest residual background $B \to D^* D_S[\to 3\pi X]$
- Train BDT to separate from signal using 3π dynamics, visible mass, momenta etc.
- 3D fit to (BDT, τ_τ, q^2)
- $R(D^*) = 0.286 \pm 0.019 \pm 0.025 \pm 0.021$
  - 3rd uncertainty from $B(B^0 \to D^{*-}\pi^+\pi^-\pi^+)$ and $B(B^0 \to D^{*-}\mu^+\nu)$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



[arXiv: 1711.02505]

Global fit to semileptonic decays

- Combination of results with those from Babar/Belle shows excellent agreement
- World average value SM predictions shows a **4.1σ** tension – updated theory can change this by ~**0.5σ**



Simultaneous explanation of the anomalies?

- Number of theory papers try and find a simultaneous explanation for the R_D and $b \to sll$ anomalies
  - Possible with both tree level mediator and with tree- and loop-level mediators
  - Reduces the NP scale of $b \to s\mu\mu$ to <9 TeV
  - Options include scalar and vector LQ and some colourless vector
  - Constraints from B-mixing, limits on $B \to K\nu\nu$ important

MITP/15-100
November 9, 2015

One Leptoquark to Rule Them All:
A Minimal Explanation for $R_{D^{(*)}}$, R_K and $(g-2)_\mu$

Martin Bauer[a] and Matthias Neubert[b,c]
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[b] *PRISMA Cluster of Excellence & MITP, Johannes Gutenberg University, 55099 Mainz, Germany*
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We show that by adding a single new scalar particle to the Standard Model, a TeV-scale leptoquark with the quantum numbers of a right-handed down quark, one can explain in a natural way three of the most striking anomalies of particle physics: the violation of lepton universality in $\bar{B} \to \bar{K}\ell^+\ell^-$ decays, the enhanced $\bar{B} \to D^{(*)}\tau\bar{\nu}$ decay rates, and the anomalous magnetic moment of the muon. Constraints from other precision measurements in the flavor sector can be satisfied without fine-tuning. Our model predicts enhanced $\bar{B} \to \bar{K}^{(*)}\nu\bar{\nu}$ decay rates and a new-physics contribution to $B_s - \bar{B}_s$ mixing close to the current central fit value.

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Outline

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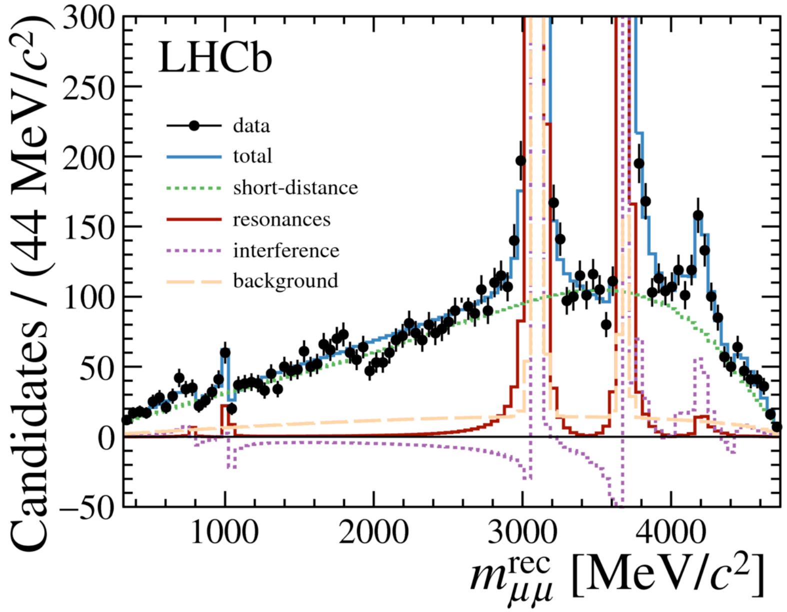
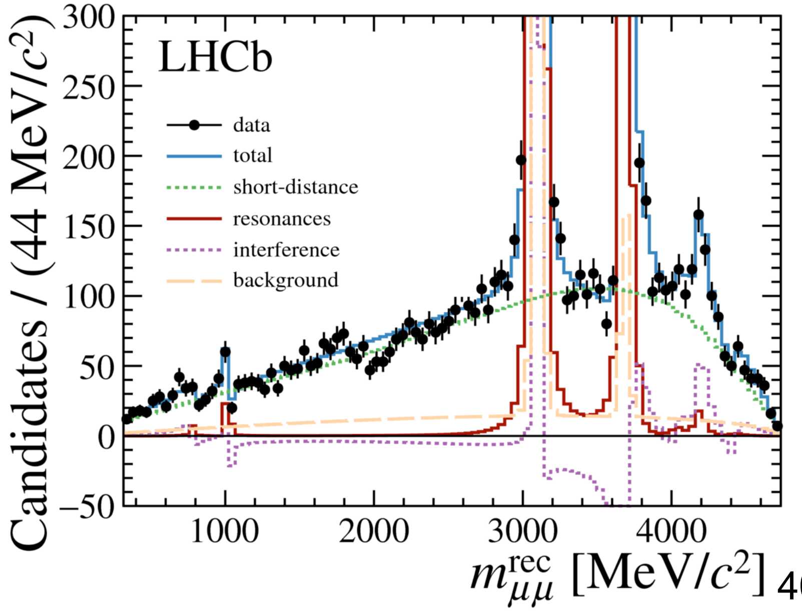
A glimpse of the future – $B_d^0 \rightarrow K^{*0}\mu\mu$

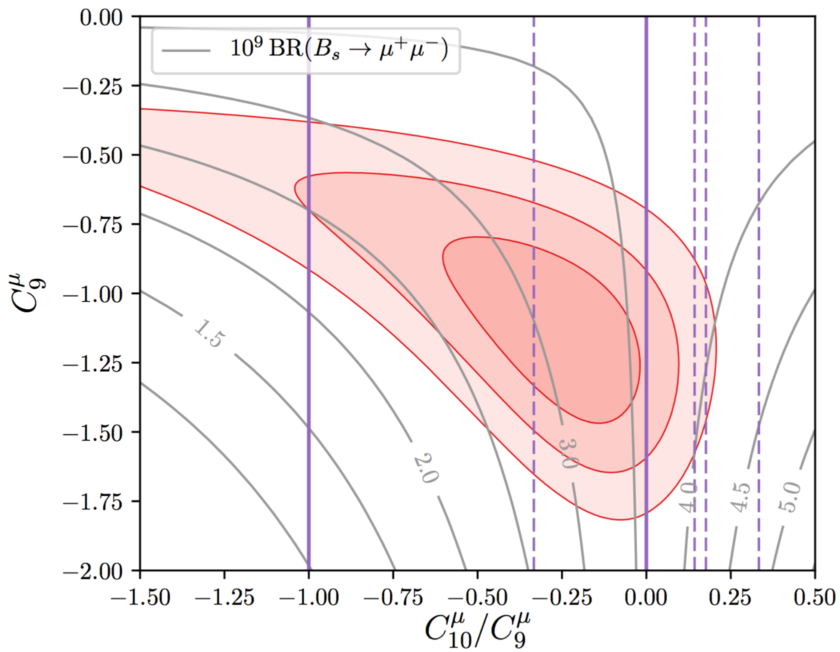
- *Measure* the effect of $c\bar{c}$ loops
- At low q^2, $\Delta C_9^{+-0}(q^2)$ term arises mainly from interference rare decay and J/ψ
- Measure phase of interference by fitting differential rate (and angles)
- LHCb has performed such a fit for $B^+ \rightarrow K^+\mu^+\mu^-$ [EJPC (2017) 77:161], considerably more complex for $B^0 \rightarrow K^{*0}\mu\mu$ but principle the same





A glimpse of the future – $B^0 \to \mu^+\mu^-$

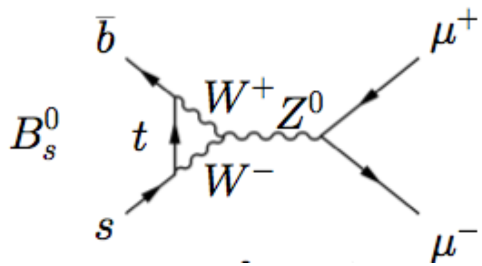
- Many single-particle explanations of anomalies predict $C_9^{NP} = -C_{10}^{NP}$ (data still compatible with such a soln)



- If this were the case would expect to see effect in $B^0 \to \mu^+\mu^-$ decays
  - Helicity and GIM suppressed
  - Dominant contribution from Z-penguin diagram
  - Precise predictions for BFs :

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

    $B(B_d^0 \to \mu\mu) = (1.06 \pm 0.09) \times 10^{-10}$
  - Can be altered by modified C_{10} or new scalar/pseudoscalar



A glimpse of the future – $B^0 \to \mu^+\mu^-$

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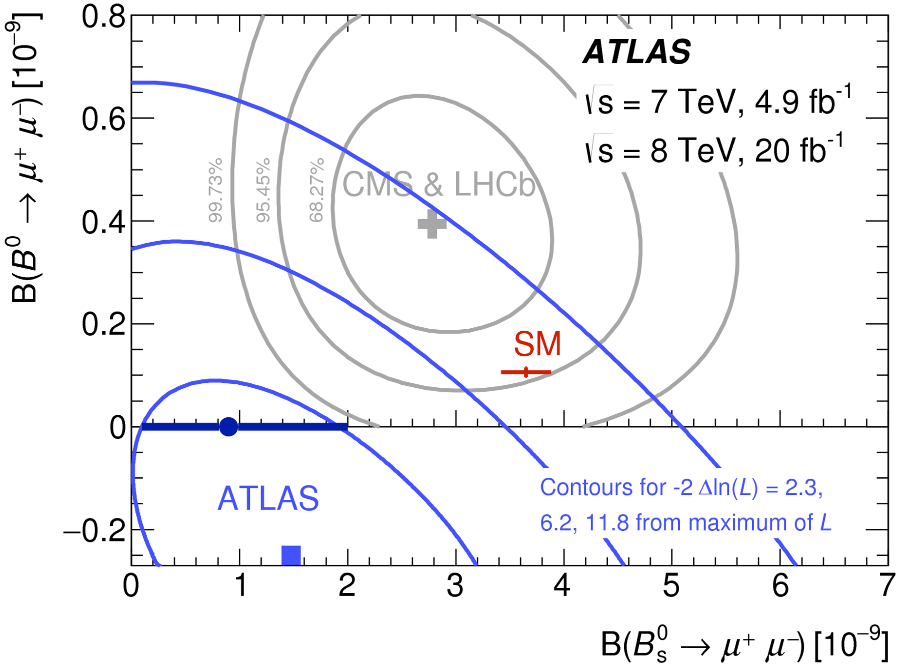
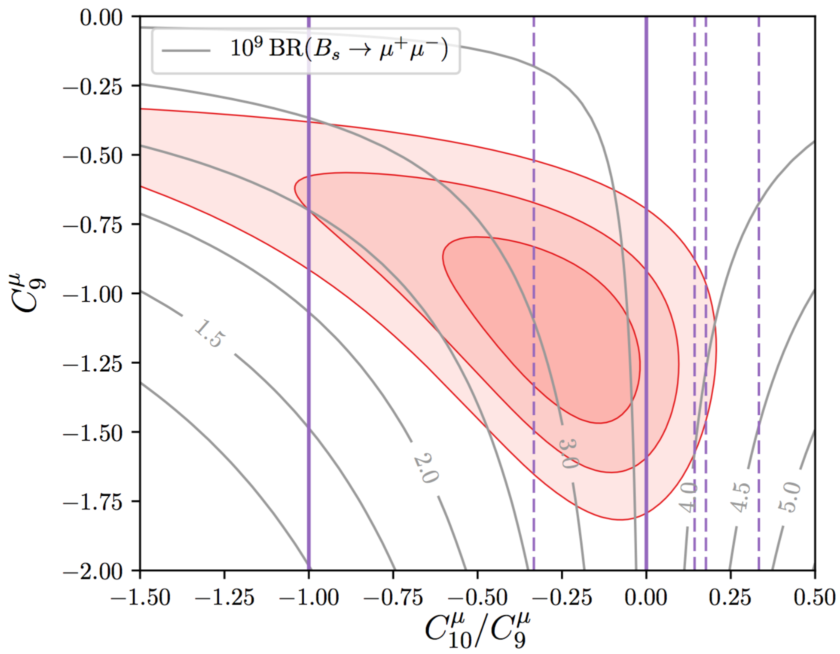
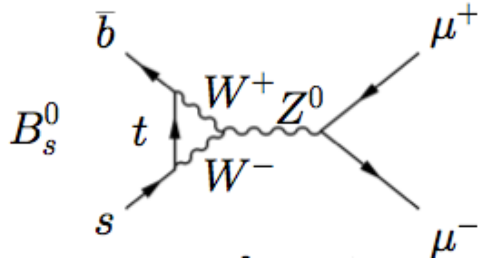




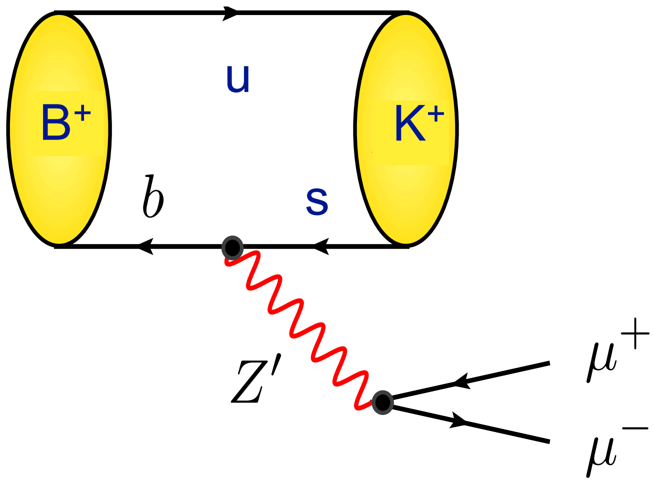
- No evidence for any deviation from SM so far… but this measurement will be important for the future!

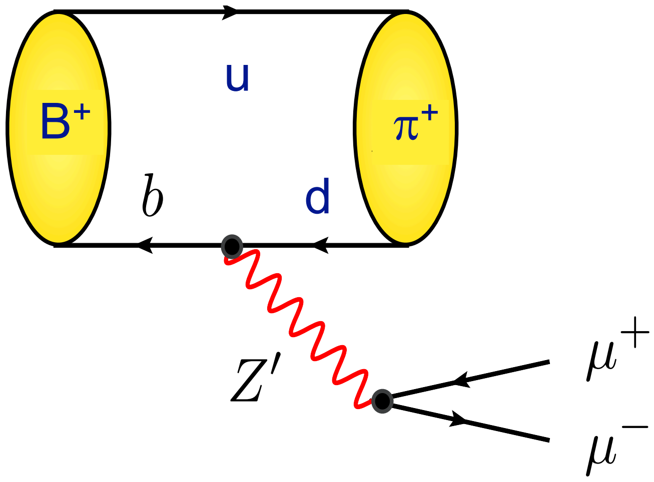


A glimpse of the future – R_X

- Programme of additional **R_X** measurements just starting :
  - Update R_K and R_{K^*} – with new data
  - Add high q^2 regions
  - Add new measurements $R(\phi)$, $R(K\pi\pi)$, $R(\Lambda)$...
  - Add CKM-suppressed decays e.g. $R(\pi)$

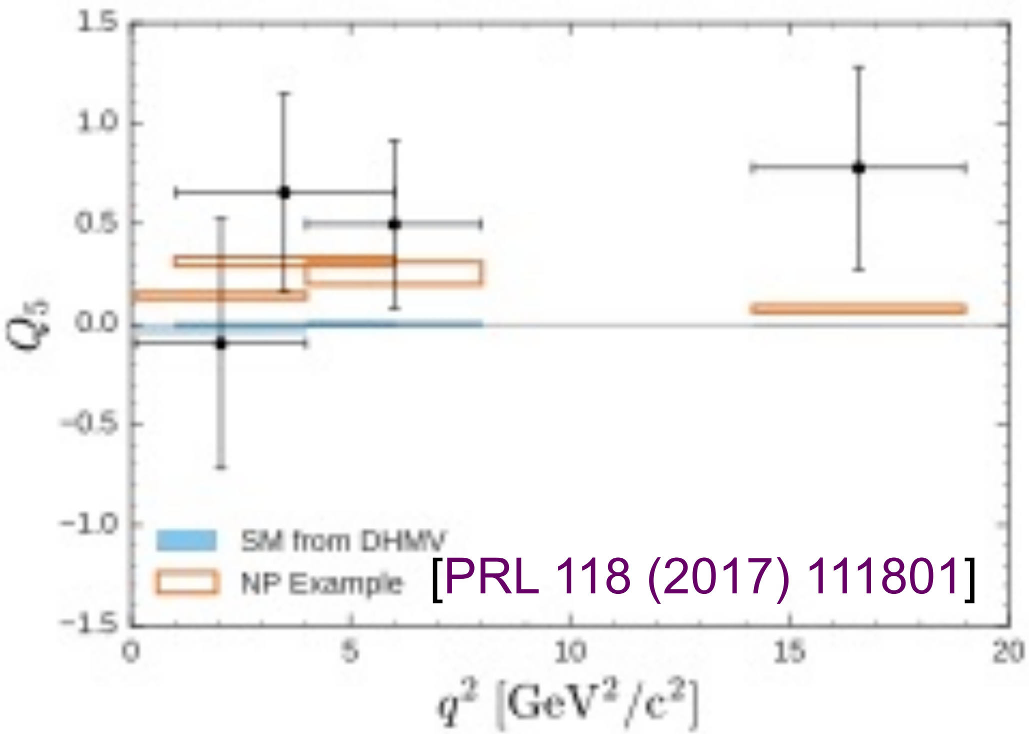
- Can also widen search for lepton-flavour violating decays e.g. **ll', Kll'** expected for **LQ** models





A glimpse of the future – P_5'

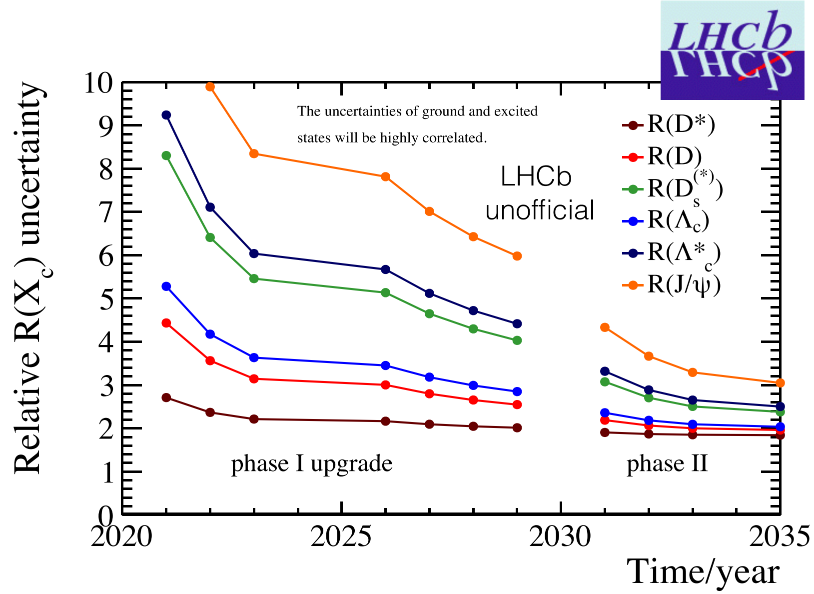
- Can make ratio of $P_5'(e)$ and $P_5'(\mu)$ $\rightarrow$ Q_5
- Thus far, only done by Belle – full angular analysis of $B^0 \rightarrow K^{*0} ee$ in progress at LHCb



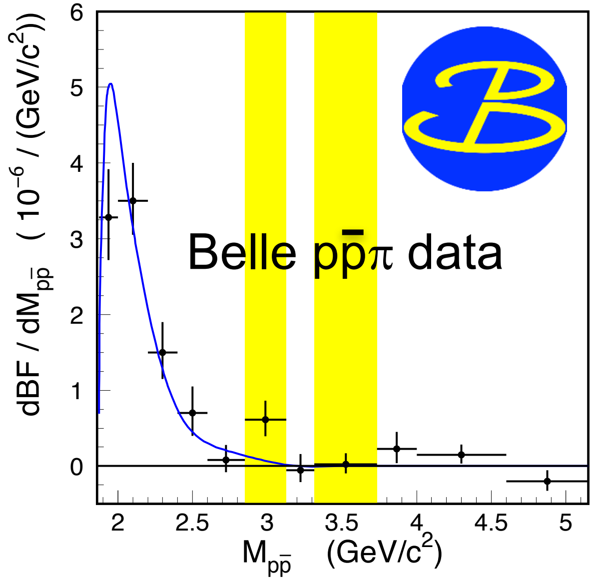
[PRL 118 (2017) 111801]

A glimpse of the future – semilep.

- Working on a simultaneous measurement of **R(D)**, **R(D*)**, as well as **R(D$^+$)**, **R(Λ_c)** in both leptonic and 3-prong cases



- Cabibbo suppressed decay **$\Lambda_B \to p l \nu$** experimentally difficult at LHCb, as no vertex to give B decay point that is needed for **τ** reconstruction
  - **$B^+ \to p\bar{p} l \nu$** an experimentally viable alternative



Conclusions

Conclusions

- Interesting set of anomalies observed in B decays – given experimental precision and theoretical uncertainties, none of them are yet compelling
- 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, full Run-2 dataset will give factor ~4 more data than Run-I on timescale that Belle-2 will start running