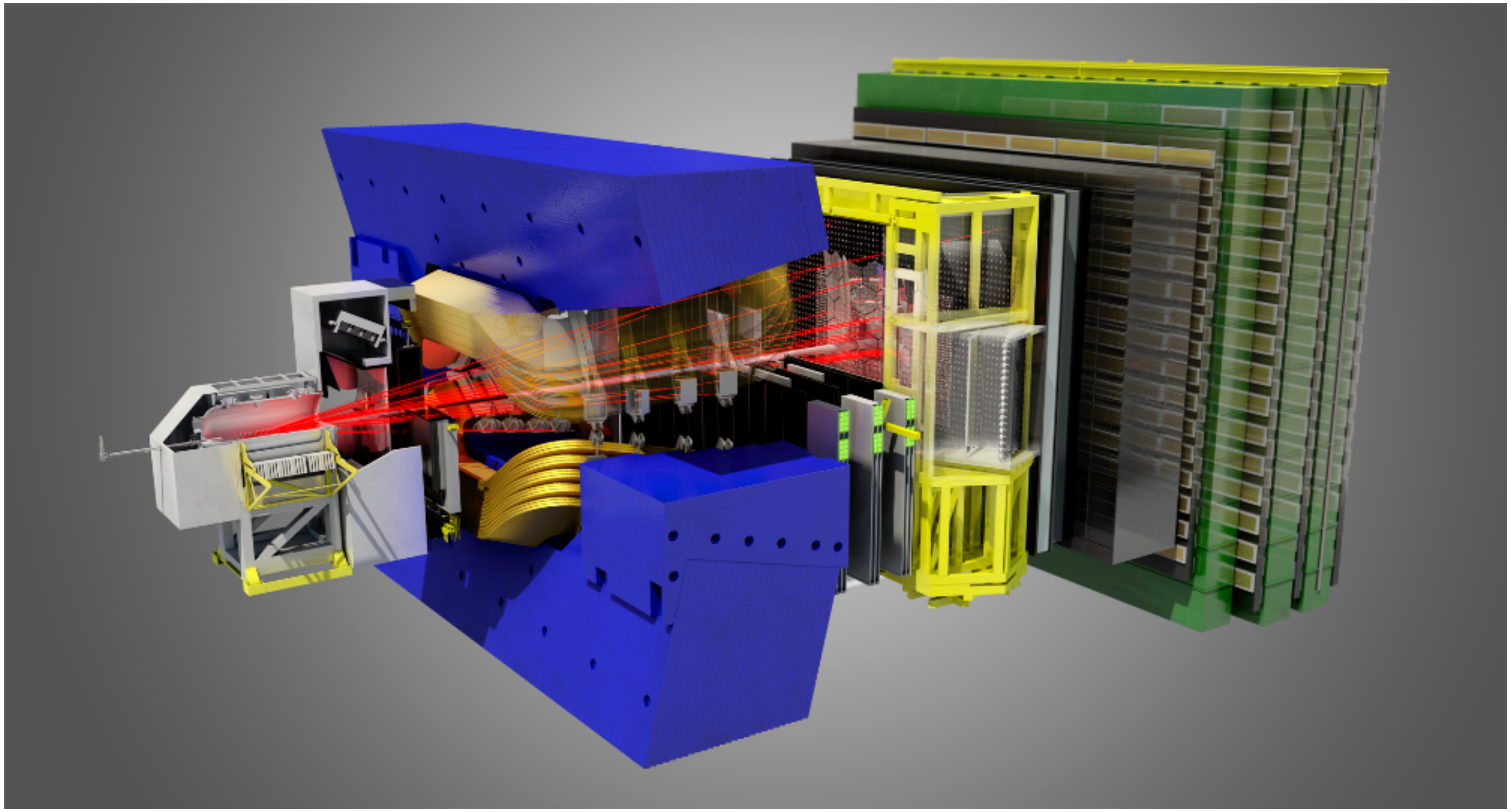
Highlights from LHCb



Mitesh Patel (Imperial College London)

HEFT 2016 Copenhagen, 26th Oct 2016

Imperial College London

The interest in flavour

- Standard Model has no tree-level Flavour Changing Neutral Currents (FCNC)

- FCNC only occur as loop processes, proceed via penguin or box diagrams – sensitive to contributions from new (virtual) particles

  → Probe particle masses > E_{CM} of the accelerator

- Exploration of flavour processes has played a central role in the development of the SM
  - c-quark inferred from measured suppression of $K^0 \rightarrow \mu^+\mu^-$ cf $K^+ \rightarrow \mu^+\nu$ (GIM, 1970) ; J/ψ discovered in 1974
  - t-quark mass from B^0 mixing (ARGUS, 1987); discovered D0, CDF 1995
  - t, b-quarks inferred from CP violation in K sector (KM of CKM 1973)

- Will argue that flavour still has discovery potential in the LHC era

Outline

- Theoretical foundation and LHCb data-taking
- Measurements of $b \to sll$ decays
- $B^0 \to \mu^+\mu^-$ branching fraction measurements
- A critical look at the theory predictions
- Theoretically pristine observables
- Future outlook

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Theoretical Foundation

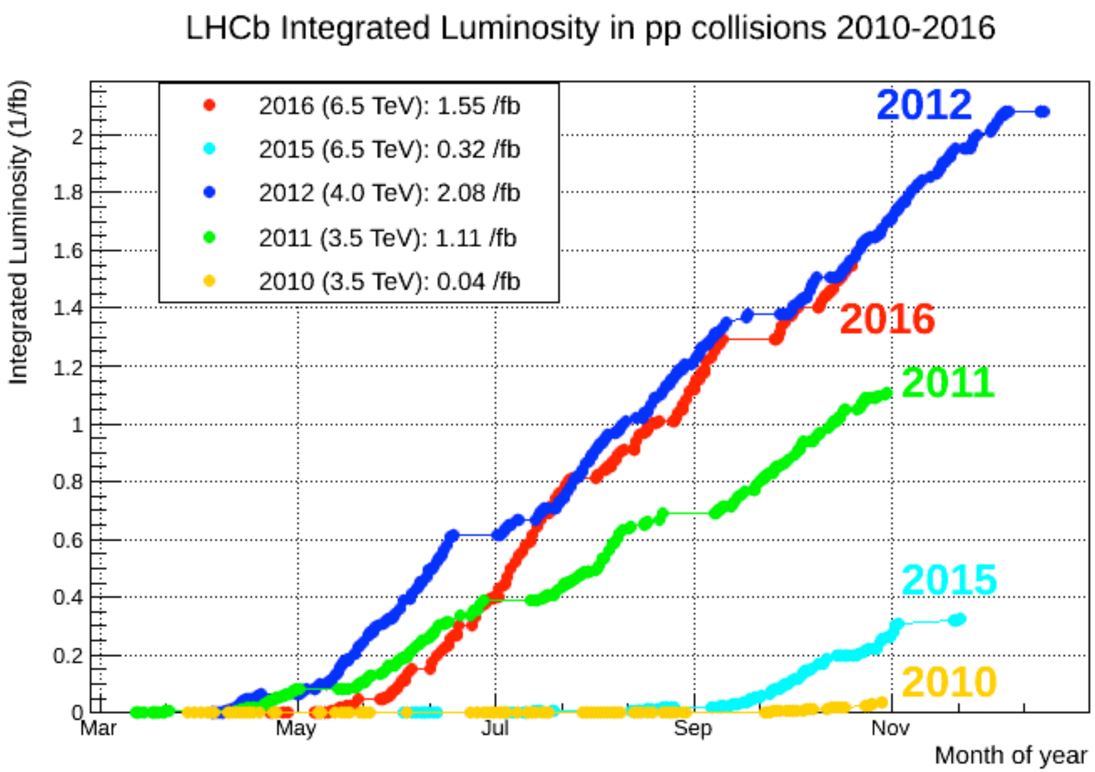
- The **Operator Product Expansion** is the theoretical tool that underpins rare decay measurements – rewrite SM Lagrangian as :

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

  - "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
    - Mixing between different operators : $C_i \rightarrow C_i^{\text{effective}}$
  - "Operators" O_i
    - Describe the long distance, non-perturbative part involving particles below μ
    - Account for effects of strong interactions and are difficult to calculate reliably

- The challenge : measure those observables where 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

LHCb data-taking



- Results in this talk from Run-I data – recorded 3.0 fb^{-1} at instantaneous luminosities up to twice the design value
- Start of Run-II has been spectacular, have 1.5 fb^{-1} on-tape, but collision energy means nearly twice the cross-section for $b\bar{b}$ production

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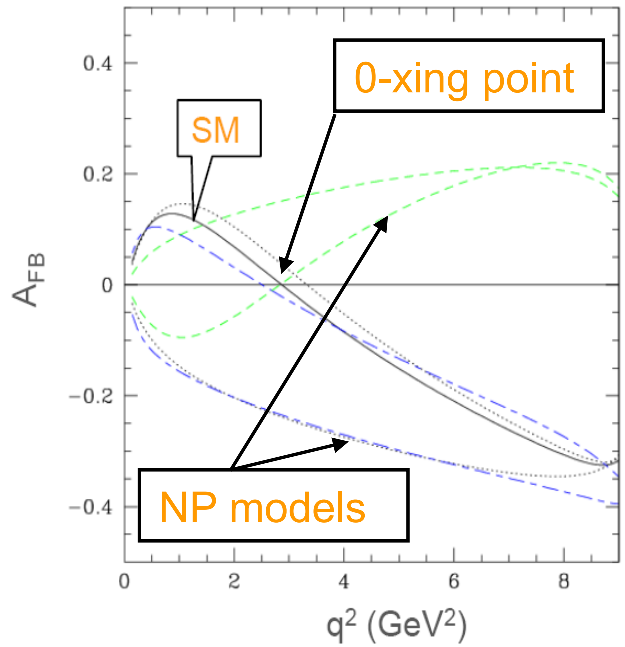
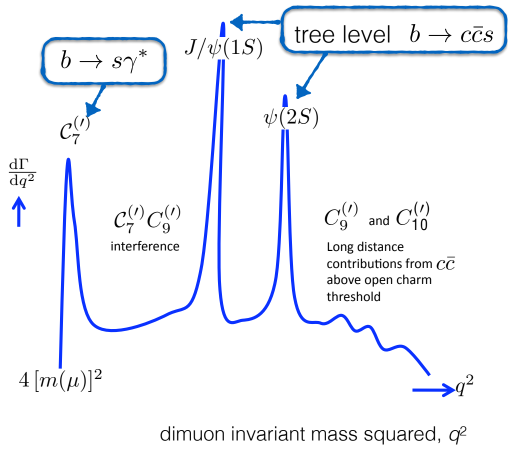
Rare decays – b→sll

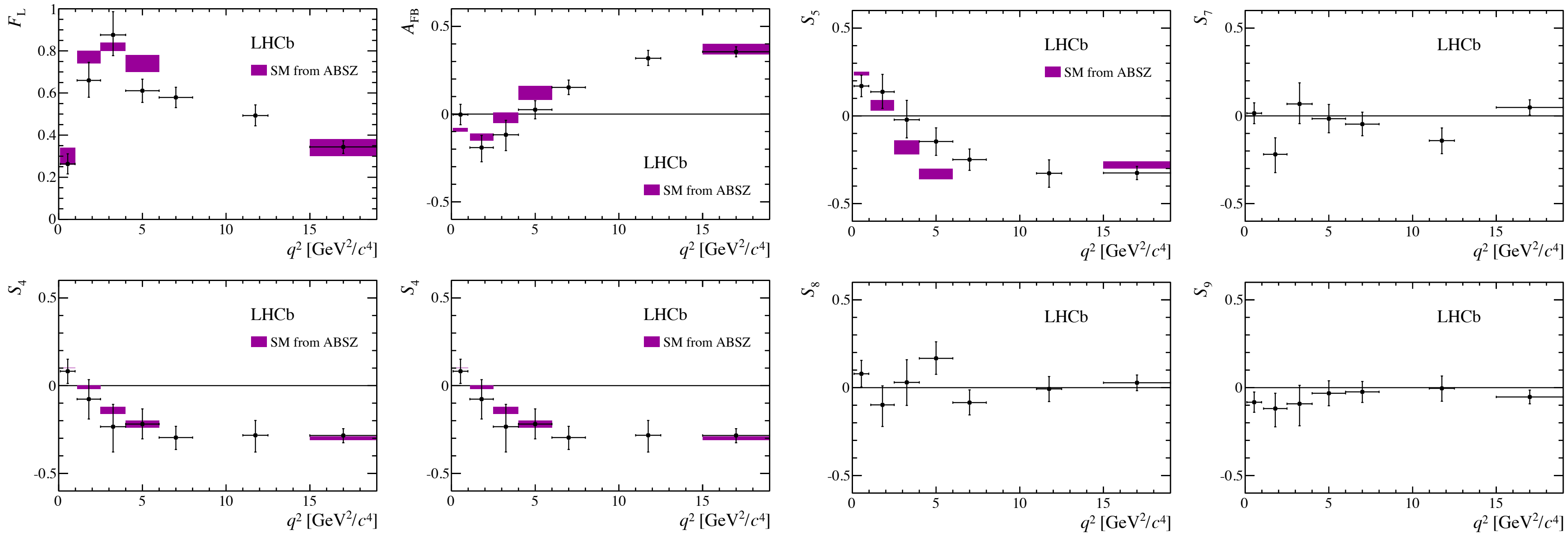
- b→sll decays involve flavour changing neutral currents → loop process
- At LHCb, best studied decay $B^0 \to K^{*0}\mu\mu$
- Large number of observables: BF, A_{CP} and angular observables – dynamics can be described by three angles (θ_l, θ_K, ϕ) and di-μ invariant mass q^2
- Try to use observables where theoretical uncertainties cancel e.g. Forward-backward asymmetry A_{FB} of θ_l distribution
- Interpreted in effective field theory describing couplings (C) of photon (O_7), vector (O_9) and axial-vector (O_{10}) operators





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

- Have performed first full angular analysis [JHEP 02 (2016) 104]
  - Extract the full set of CP-averaged angular terms and their correlations
  - Determine a full set of CP-asymmetries

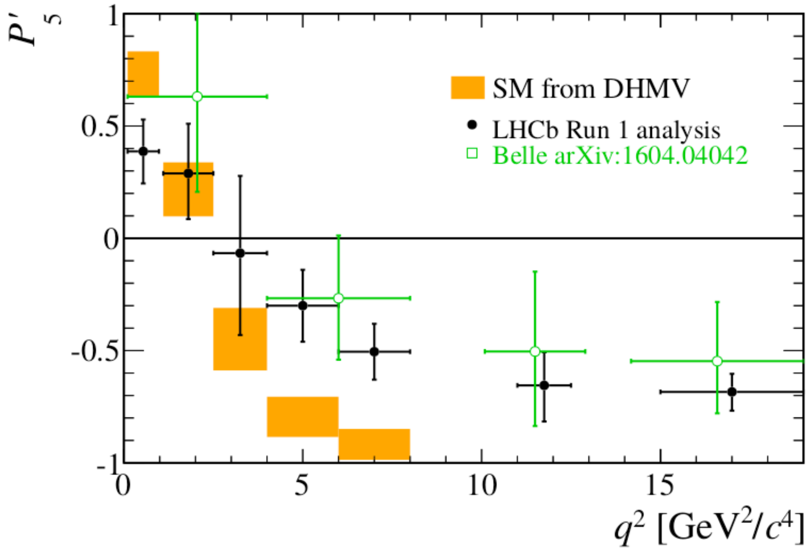


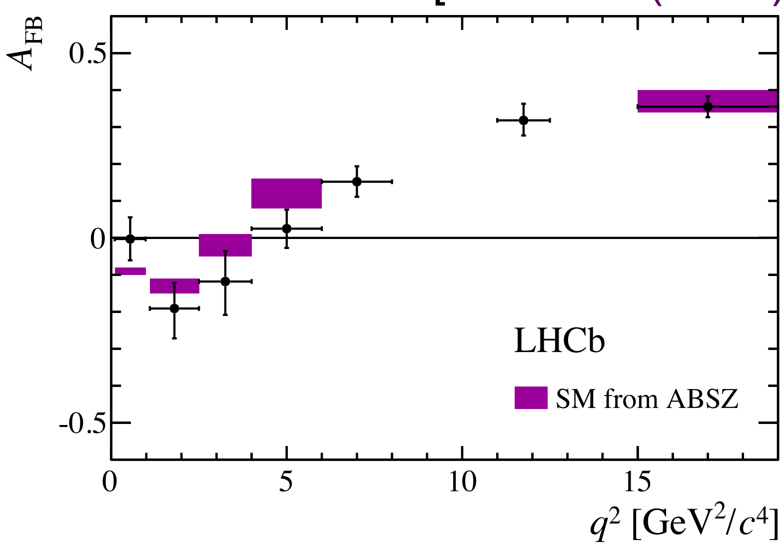
- Vast majority of observables in agreement with SM predictions, giving some confidence in theory control of relevant form-factors

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

- In SCET/QCD factorisation can reduce to just two form-factors- can then construct ratios of observables which are independent of form-factors at LO [JHEP 1204 (2012) 104]

[JHEP 02 (2016) 104]



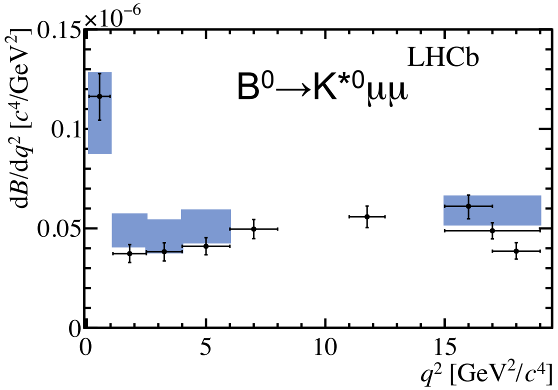


- Form-factor "independent" P_5' has a local discrepancy in two bins – (subsequently confirmed by Belle [arxiv:1604.04042])
- Form-factor dependent A_{FB} hints at a trend, but is consistent with SM

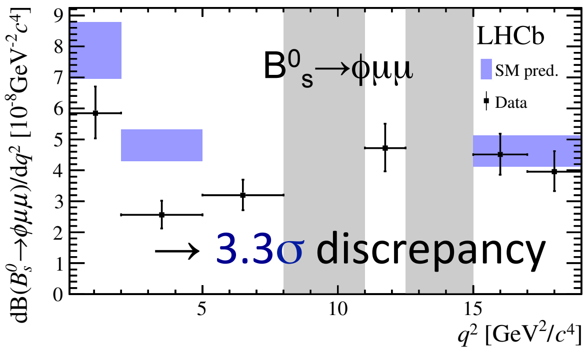
→ **3.4σ** discrepancy with the vector coupling **$\Delta C_9 = -1.04 \pm 0.25$**

b→sll Branching Fractions

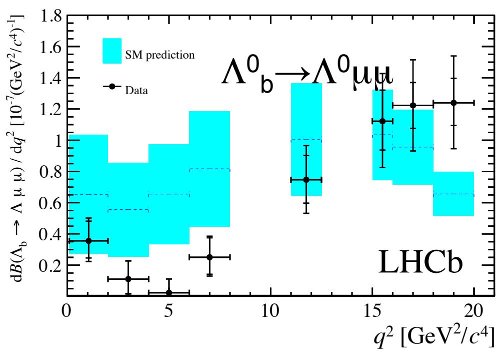
- Several b→sll branching fractions measured, show some tension with predictions, particular at low q^2



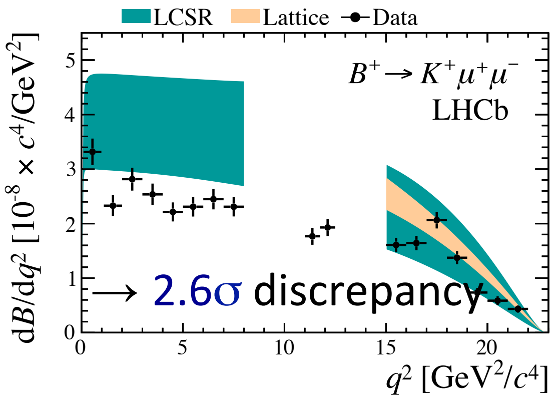
[arXiv:1606.04731]

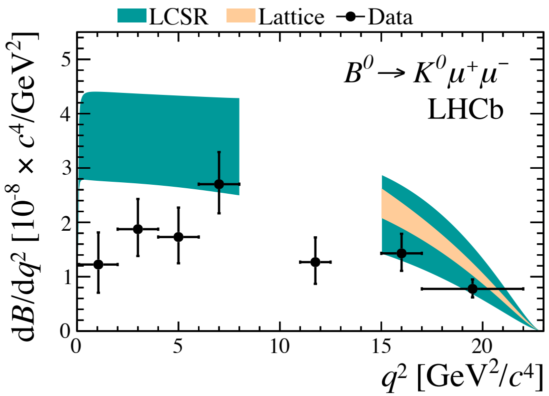


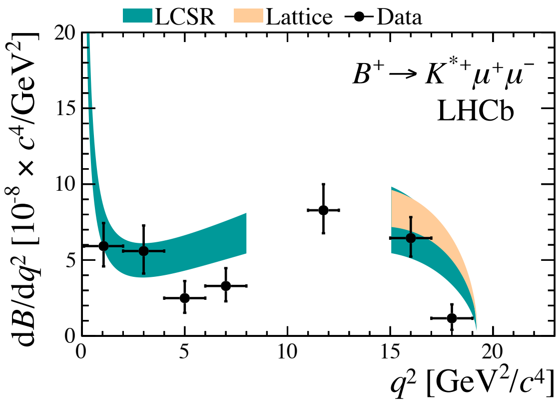
[JHEP 09 (2015) 179]



[JHEP 06 (2015) 115]



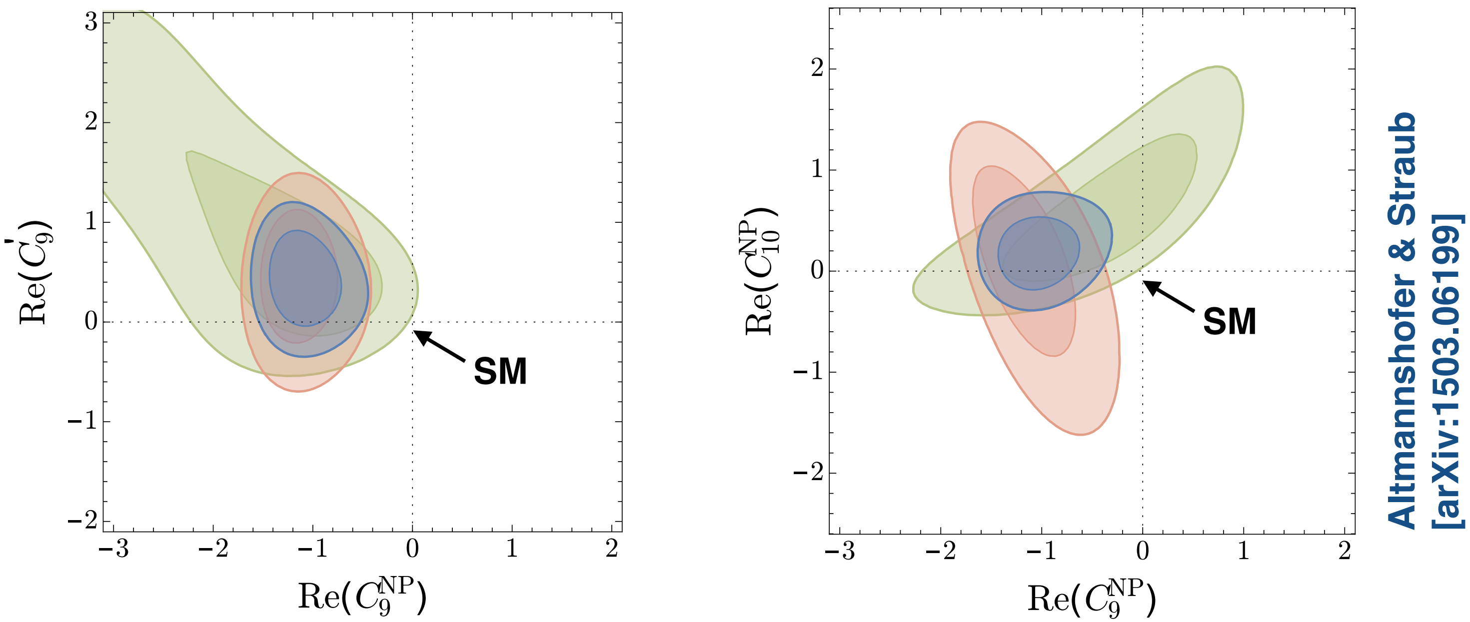




[JHEP 06 (2014) 133]

b→sll interpretation

- Several groups have interpreted LHCb results by performing global fits to b→sll data e.g. [arXiv:1503.06199,1510.04239,1512.07157,1603.00865]



branching fractions, angular observables and combination

- Consistent picture, tensions solved simultaneously by a modified vector coupling (ΔC_9 != 0) at **3-4σ**

b→sll interpretation

- Observe significant tension in b→sll processes, a consistent theory interpretation is *possible*, but is it correct?

- Community have started to critically look at the theory predictions
  - Problem with B→K* form factors?
  - Charm loop contribution?

  [With thanks to D.Straub @ LHCb implications workshop]

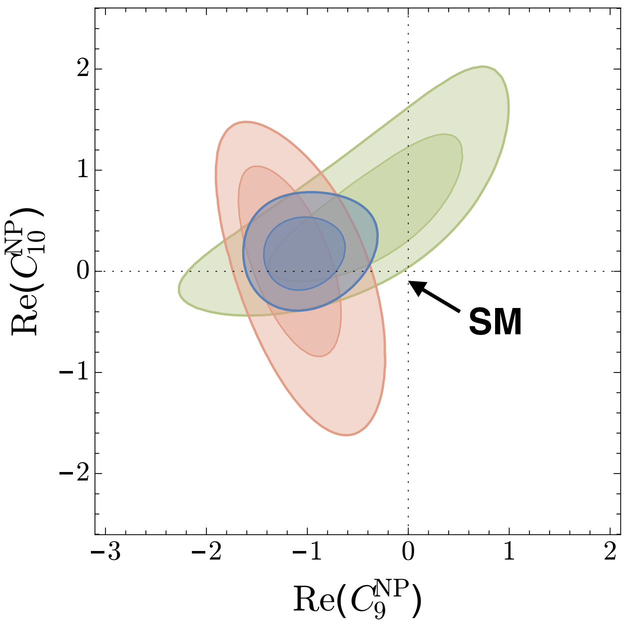
- Before addressing these – effect could be substantiated in another way…

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

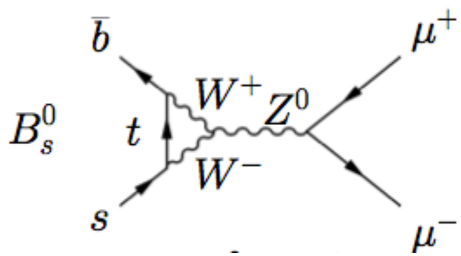
- Single-particle explanations of all anomalies predict $\mathbf{C_9^{NP} = -C_{10}^{NP}}$
- Data are clearly still compatible with such a solution
- If this were the case would expect to see effect in $B^0 \to \mu^+\mu^-$ decays
  - Helicity and GIM suppressed
  - Dominant contribution from Z-penguin diagram
  - Precise predictions for BFs :

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

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



Altmannshofer & Straub [arXiv:1503.06199]

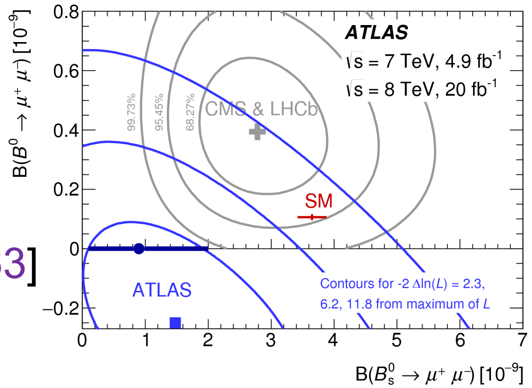


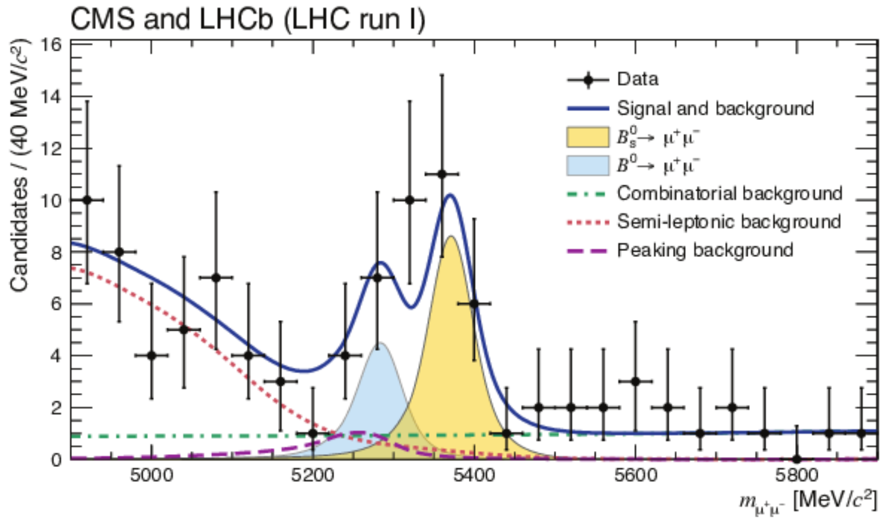
$B^0 \to \mu^+\mu^-$ analysis

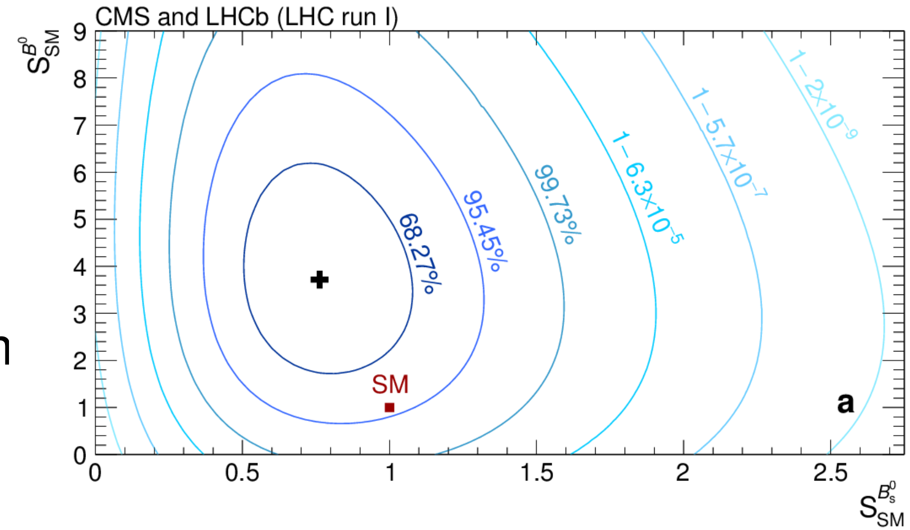
- LHCb and CMS measurements combined [Nature 522 (2015) 68]
  - $B_s^0 \to \mu^+\mu^-$ established at 6.2σ
  - $B_d^0 \to \mu^+\mu^-$ evidence at 3.2σ

- ATLAS have also made a search

[arXiv: 1604.04263]







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

- LHCb update in progress, CMS should also be v. competitive here

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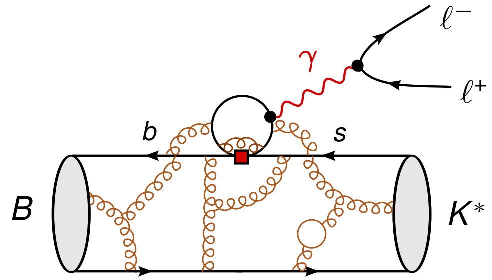
Problem with B→K* form factors?

- Form factor calculations made using both LCSR and LQCD techniques [arXiv: 1503.05534, 1501.00367]
  - These show good agreement
- Some analysts prefer to use form factors evaluated in heavy quark limit (so-called "soft" form factors) rather than full [arXiv:1510.04239]
  - Again, these show good agreement
  - Vigorous debate about how to quantify (power) corrections without using info from LCSR or LQCD [arXiv:1407.8526, 1412.3183]
- Branching fractions less theoretically clean than angular observables – LHCb's updated $B^0 \to K^{*0}\mu\mu$ angular analysis will be important!

Charm loop contribution?

- The $O_{1,2}$ operator has a component that could mimic a new physics effect in C_9 through $c\bar{c}$ loop

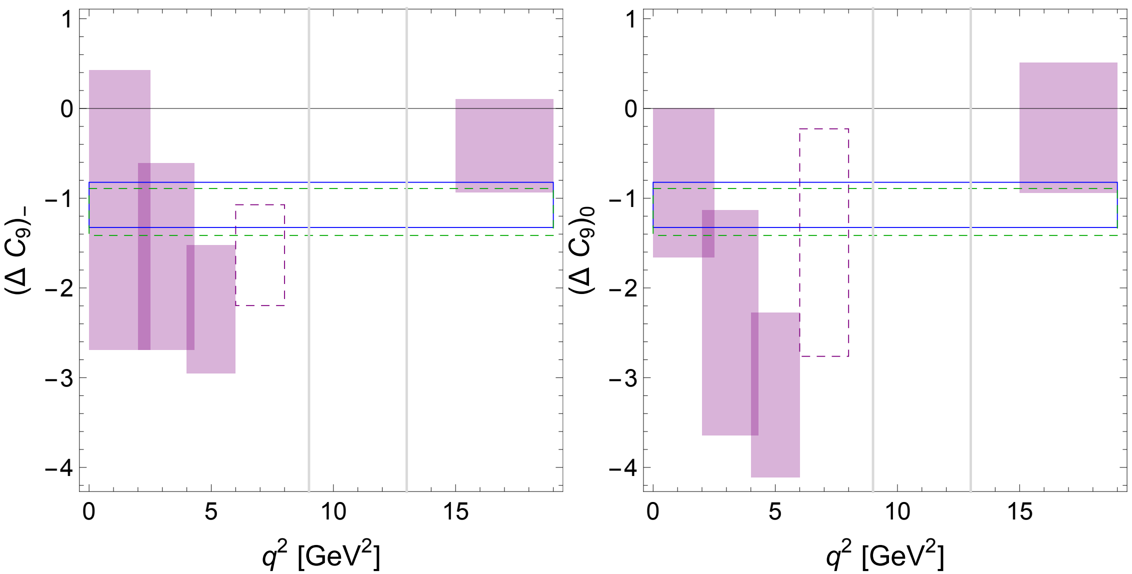


- Effect can be parameterised as function of three helicity amplitudes h_{+-0}

- Absorb effect of these amplitudes into a helicity dependent shift in C_9,

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

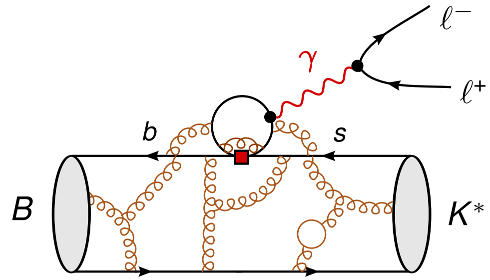
  Look for q^2 and helicity dependence of apparent shift in C_9



[arXiv:1503.06199]

Boxes are the 1σ errors

Charm loop contribution?



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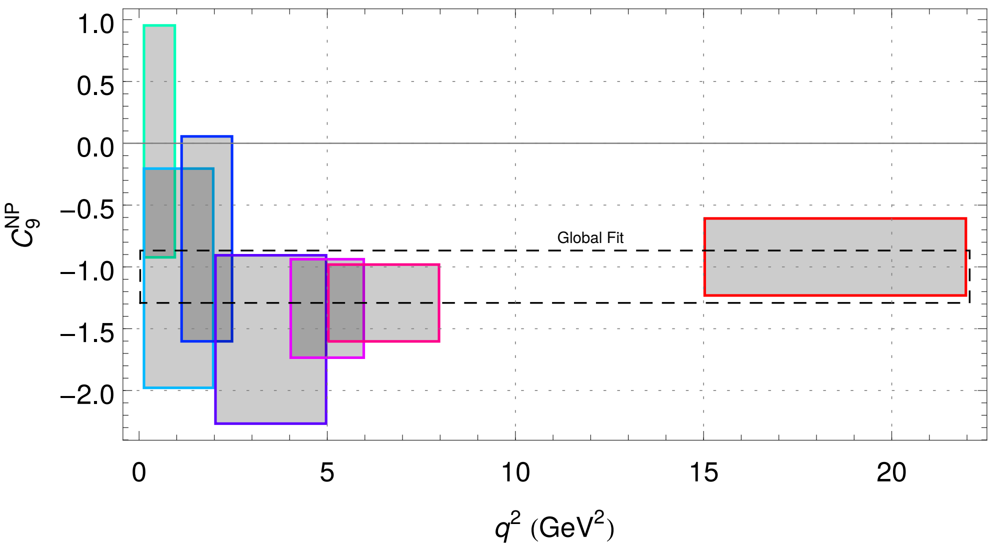
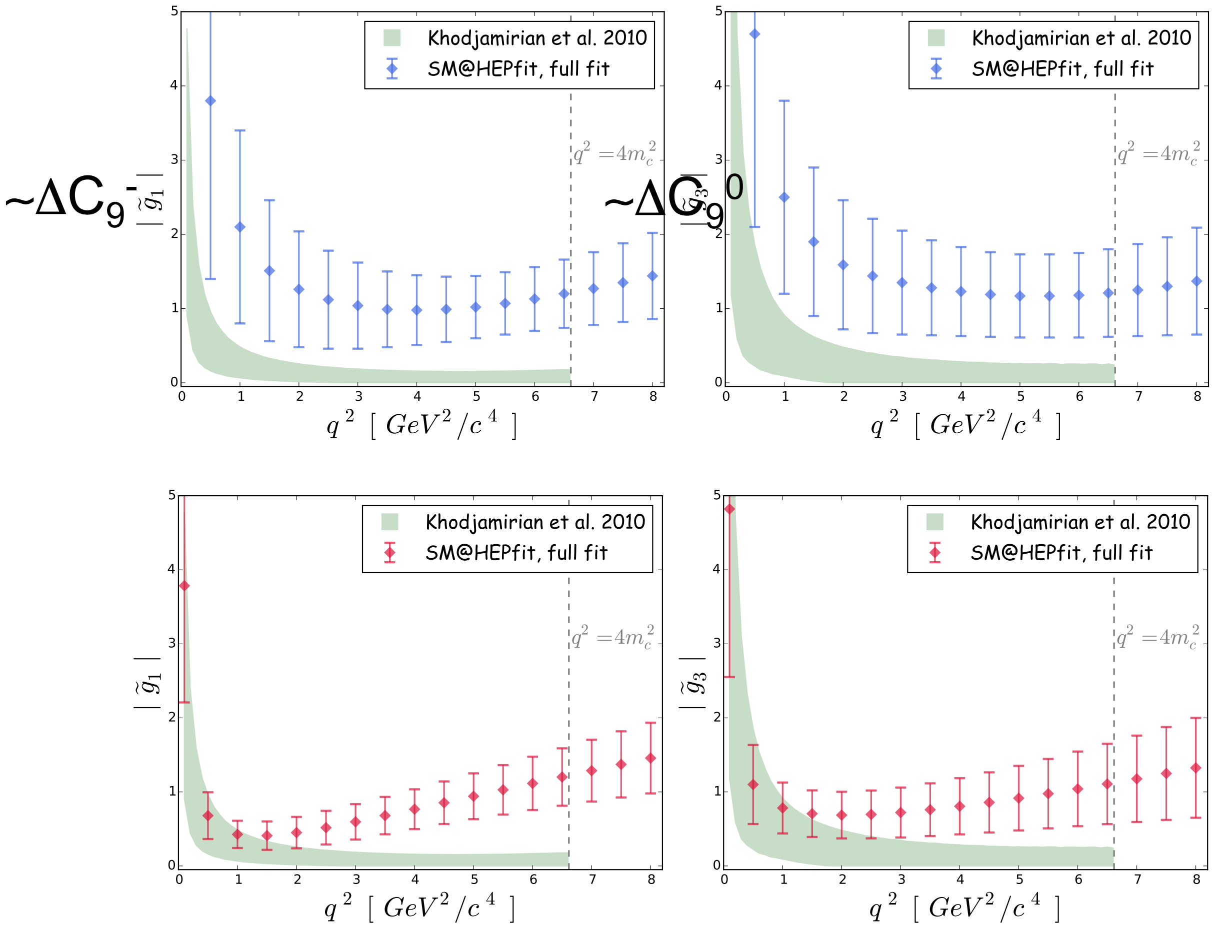


[arXiv:1510.04239]

Boxes are the 1σ errors

Charm loop contribution?

- Bayesian fit assuming polynomial form for $\mathbf{h_{+-0}}$ [arXiv:1512.07157]



- Assumes small ΔC_9^x for small q^2 – true in SM, but not for NP

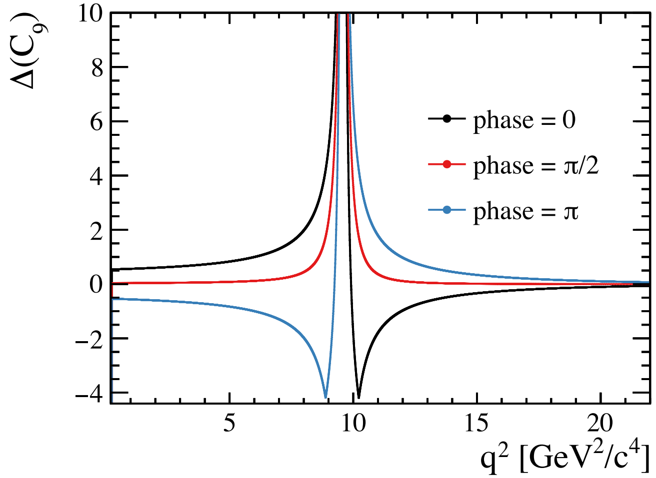
Charm loop contribution?

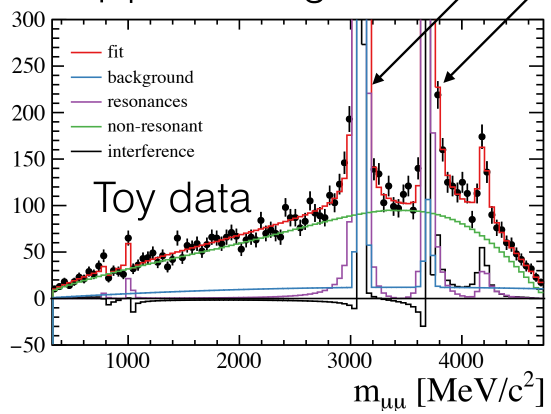
- q^2 dependence is compatible with both SM and NP

  → need to analyse the Run-II data and improve the precision!

- No way for charm loop effects to give a contribution to C_{10} – evidence of a V-A effect in $b \to sll$, or anomaly in $B^0 \to \mu^+\mu^-$, would be a game-changer

- At low q^2, $\Delta C_9^{+-0}(q^2)$ term arises mainly from interference penguin decay and J/ψ
  – Measure phase of interference by fitting differential rate – results for $B^+ \to K^+\mu^+\mu^-$ imminent





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Lepton universality with loop decays

- The ratio of $b \to s\mu\mu$ and $b \to see$ branching fractions, R_K, is a theoretically pristine quantity

  $R_K = B(B^+ \to K^+\mu\mu) / B(B^+ \to K^+ee)$

- Precisely predicted in SM,

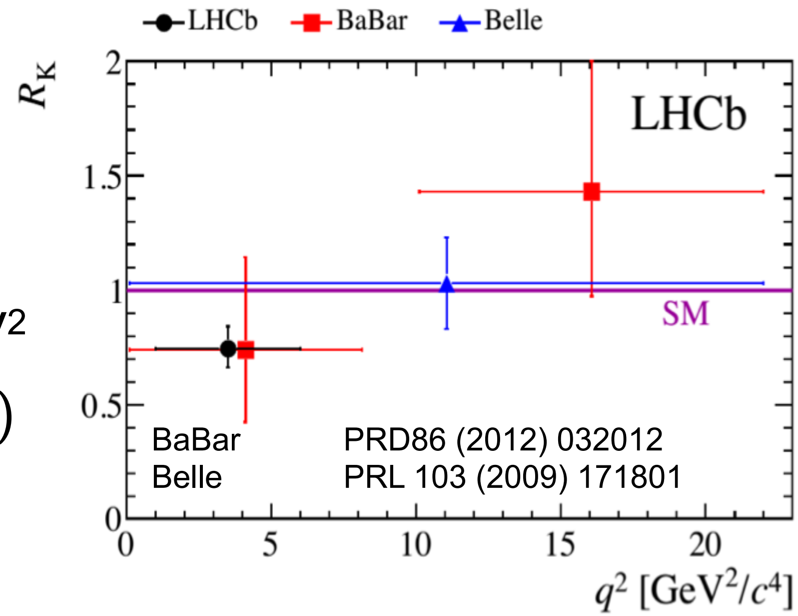
  $R_K = 1.00030^{+0.00010}_{-0.00007}$

- LHCb measurement in $1.0<q^2<6.0$ GeV^2

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

  $\to$ **2.6σ from SM prediction**

[Phys. Rev. Lett. 113 (2014) 151601]



- Several theorists have pointed out this is consistent with $\Delta C_9^{ee}=0$, $\Delta C_9^{\mu\mu}=-1$ (latter consistent with $B^0 \to K^{*0}\mu\mu$) – work on-going to add range of other measurements e.g. R_{K^*}, R_ϕ,.. angular analysis $K^{*0}ee$

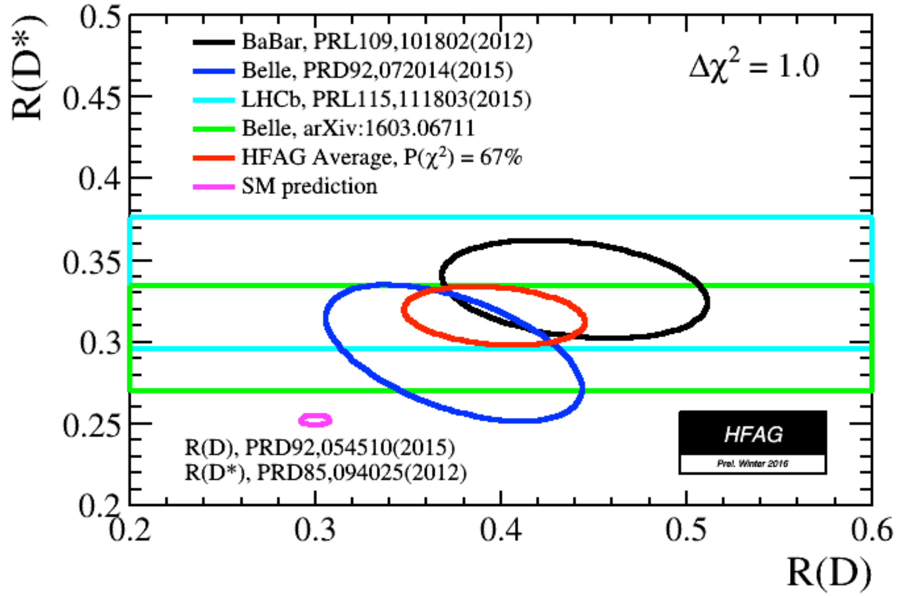
Lepton universality with tree decays

- An anomalous effect is seen in the ratio of **tree-level** branching fractions

  $R_{D^*} = B(B^0 \to D^{*+}\tau\nu)/B(B^0 \to D^{*+}\mu\nu)$

- At LHCb reconstruct the tauonic decay through $\tau \to \mu\nu\nu$, final state has three neutrinos!

- Confirms effect seen in R_D, R_{D^*} at BaBar/Belle, including latest Belle hadronic result from ICHEP combined significance now 4σ



- LHCb measurement of (R_D, R_{D^*}) in preparation. Also working on hadronic τ decay. Will also perform measurements with other b-hadrons e.g. B_s, B_c and Λ_b

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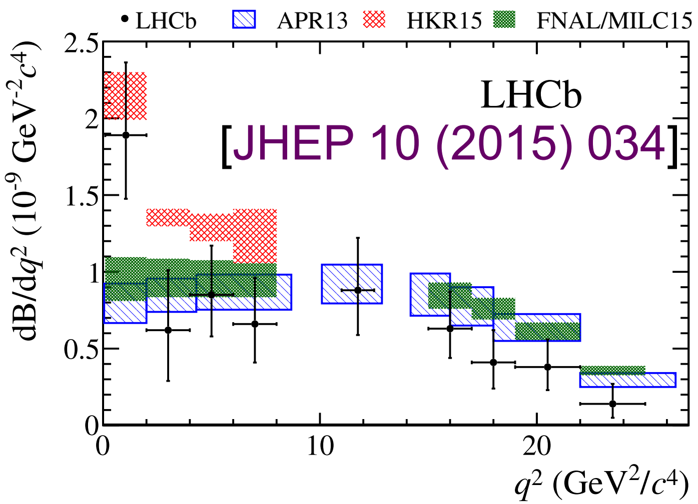
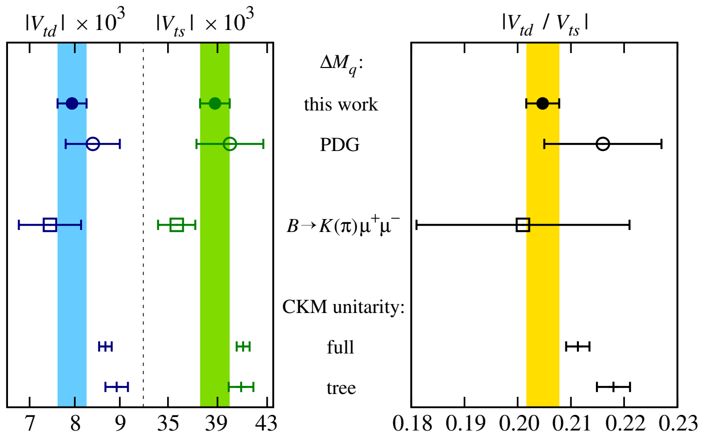
Future Outlook

- LHCb will upgrade detector in LS2 (2019-20) then take **~50 fb^{-1}** during Run 3 (2021-23) and Run 4 (2027-29)
- Expect approximately linear increase in rare muon decays such as $B^0 \to K^{*0}\mu\mu$
- Have talked about $b \to s$ decays, will then be able to make comparable tests for (CKM suppressed) $b \to d$ decays
  - E.g. $B^+ \to \pi^+\mu^+\mu^-$ differential BF → test of MFV hypothesis



[JHEP 10 (2015) 034]



[arXiv:1602.03560, PRD93 (2016) 034005]

Conclusions

- A number of discrepancies seen wrt Standard Model predictions –
  - $b \rightarrow sll$ decays angular observables and branching fractions
  - Lepton universality tests in both loop and tree decays

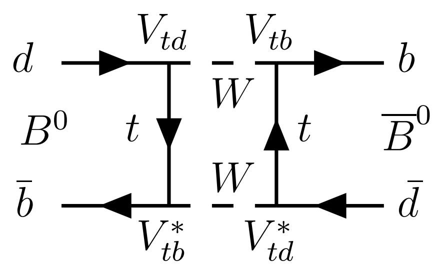
  will be interesting to add Run-II data to try and clarify the picture

- Beyond this working on LHCb upgrade to secure the next generation of measurements

Backup

Δm_d with $B^0 \rightarrow D^{(*)}\mu\nu X$

- In the SM, the B^0 oscillation frequency $\Delta m_d \sim V_{tb}V_{td}$



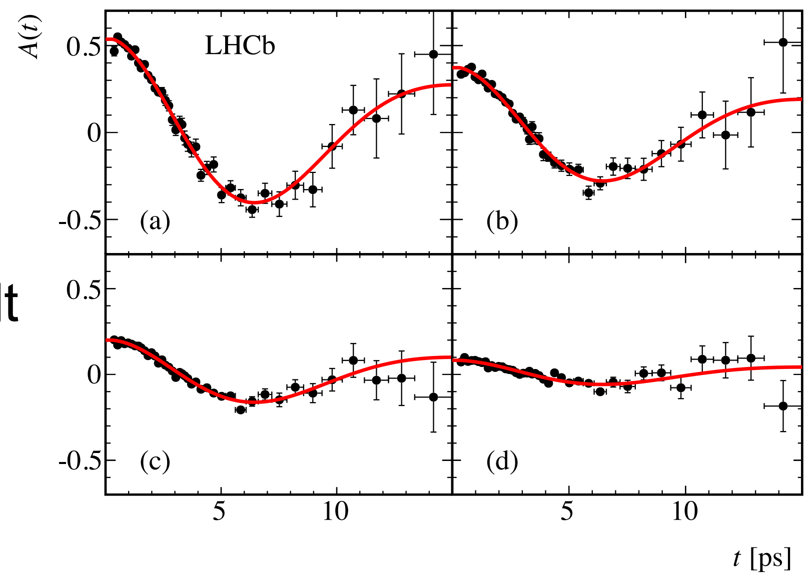
- Measure using $B^0 \rightarrow D^{(*)-}\mu^+ \nu X$ decays with 6.7×10^6 $D^- \rightarrow K^+\pi^-\pi^-$ and 8.3×10^5 $D^{*-} \rightarrow D^0(K^+\pi^-)\pi^-$

- Tagging power 2.32–2.55% depending on mode

[Eur. Phys. J. C76 (2016) 412]

- LHCb measurement :

  $\Delta m_d = \quad (505.0\pm2.1\pm1.0)\ \text{ns}^{-1}$



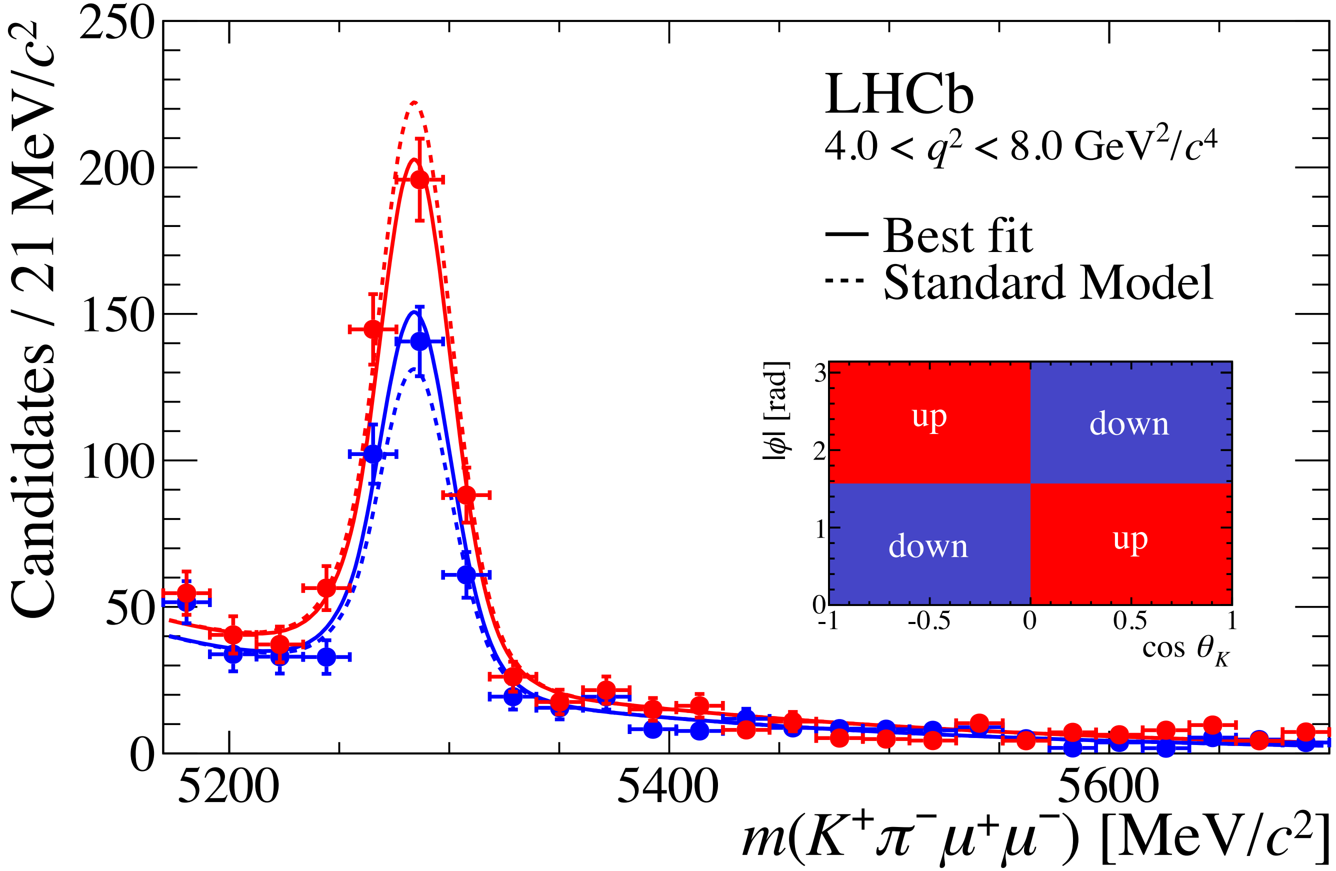
- World average [HFAG]

  $\Delta m_d = \quad (509.8\pm3.5)\ \text{ns}^{-1}$ w/o this result

  $(506.4\pm1.9)\ \text{ns}^{-1}$ w/ this result

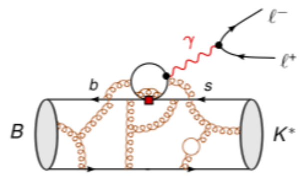
  i.e. improvement of factor 1.8 in the uncertainty

b→sll interpretation



$B^0 \to K^{*0}\mu\mu$ 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) and their right-handed (’) counterparts
  - Seven (!) form factors – these are the origin of the primary theoretical uncertainties



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

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

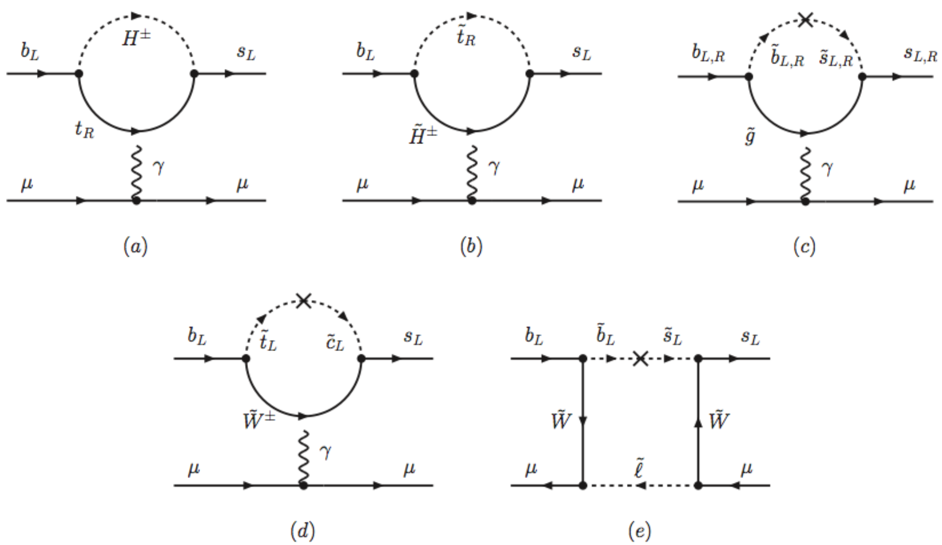
$$A_0^{L(R)} = -\frac{N}{2m_{K^*}\sqrt{q^2}}\left\{\left[(\mathbf{C_9^{eff}} - \mathbf{C_9'^{eff}}) \mp (\mathbf{C_{10}^{eff}} - \mathbf{C_{10}'^{eff}})\right]\left[(m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*})\mathbf{A_1(q^2)} - \lambda\frac{\mathbf{A_2(q^2)}}{m_B + m_{K^*}}\right]\right.$$
$$\left. + 2m_b(\mathbf{C_7^{eff}}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

- BFs have relatively large theoretical uncertainties from form factors
- Angular observables much smaller theory uncertainties

$B^0 \to K^{*0}\mu\mu$ – theoretical view

- Need a new vector contribution → adjusts C_9 Wilson Coefficient
- 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/extra dimensions have same problem
- **Could generate observed deviation with a Z'**