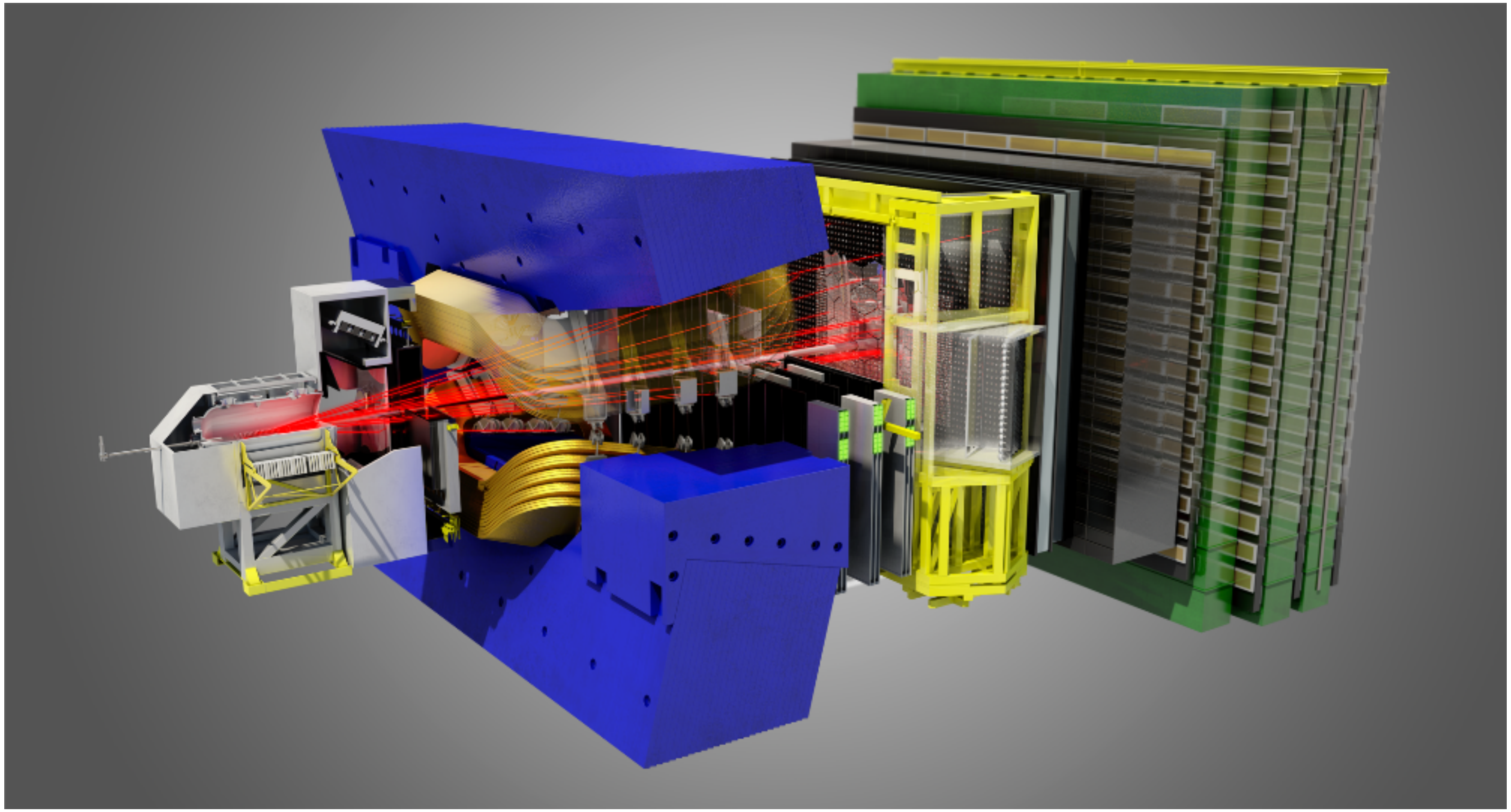
Rare Decays at LHCb



Mitesh Patel (Imperial College London)

The University of Birmingham, 2nd March 2016

Imperial College London

LHCb

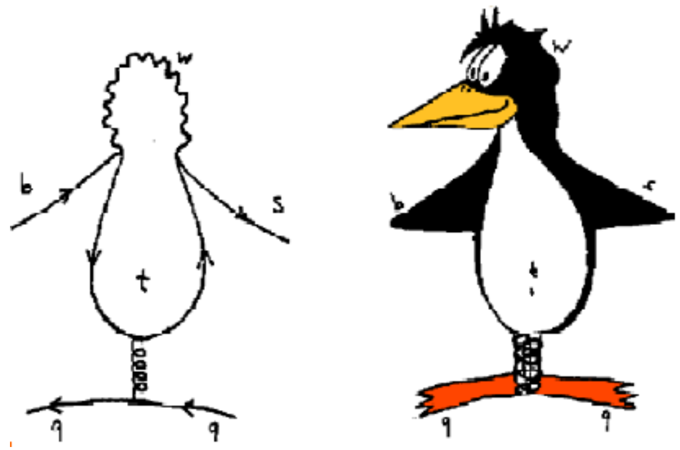
The interest in Rare Decays

- 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 which can then be at same level as SM contributions

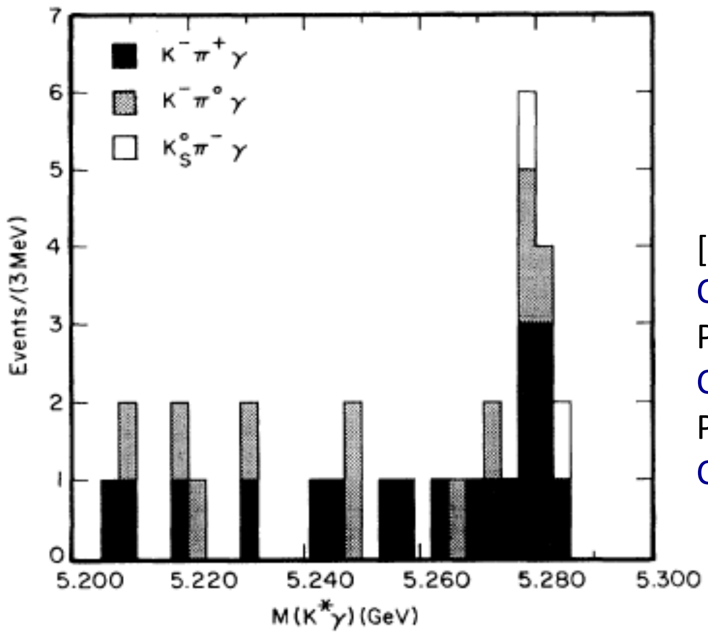
  → Probe masses > E_{CM} of the accelerator

- e.g. $B_d^0 \rightarrow K^{*0}\gamma$ decay

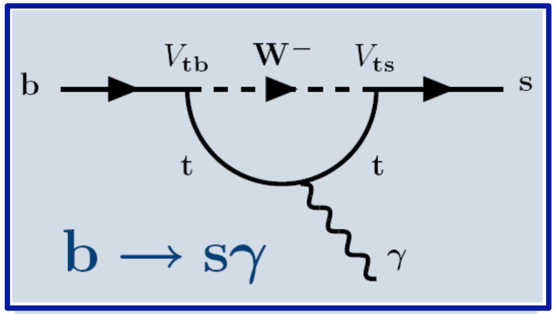


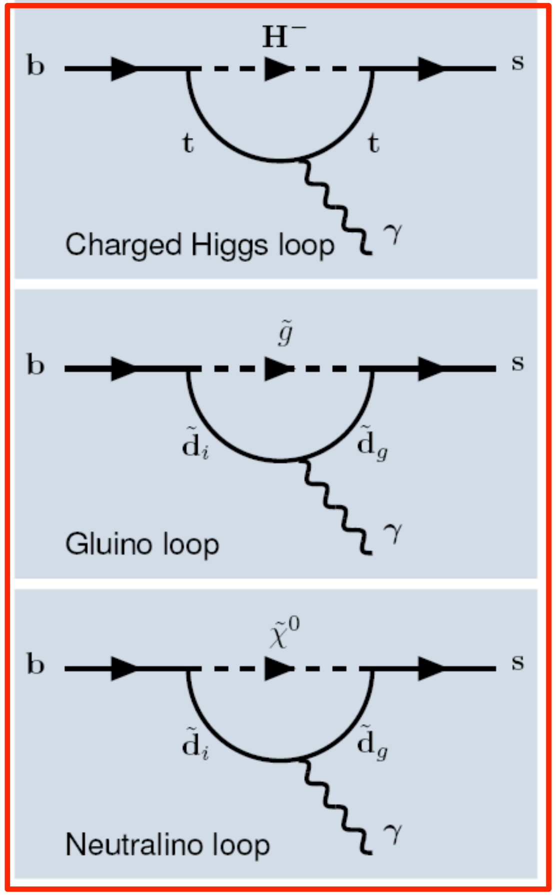
A historical example – $B_d^0 \to K^{*0}\gamma$

- 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 $(2\text{-}4)\times10^{-4}$
  - → measured BF = $(4.5\pm1.7)\times10^{-4}$



[Phys.Rev.Lett. 71 (1993) 674 - Cited by 605 records
Phys.Rev.Lett. 74 (1995) 2885 - Cited by 836 records
Phys.Rev.Lett. 87 (2001) 251807 Cited by 565 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

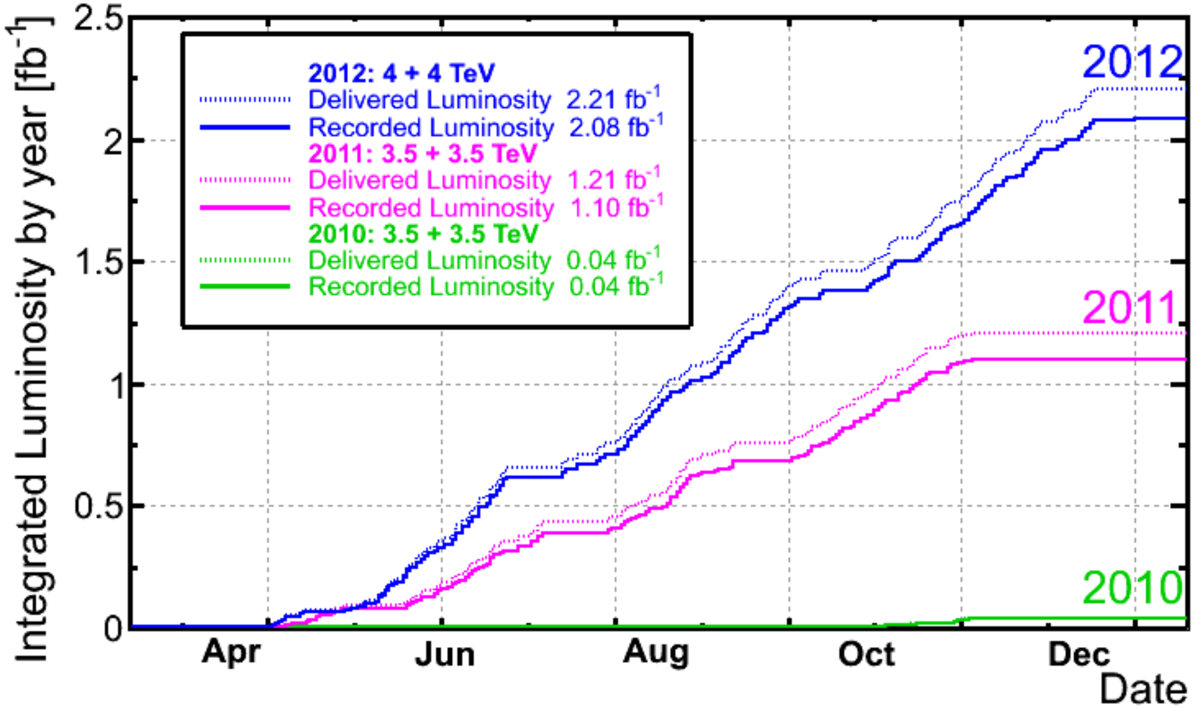
  – "Operators" O_i
    - Describe the long distance, non-perturbative part involving particles below scale μ
    - Account for effects of strong interactions and are difficult to calculate reliably

  → 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



- In total have recorded $3fb^{-1}$ at instantaneous luminosities of up to $4\times10^{32}\,cm^{-2}s^{-1}$ (twice the design value!)
- While Run-II data-taking will add substantial luminosity (so far $0.3fb^{-1}$), will not be the step-change from higher $\sqrt{s}$ anticipated at the central detectors – need 2019 upgrade for that step-change

Outline

- A tour of existing LHCb rare decay measurements
  - $B^0 \to \mu\mu$ branching fraction measurements
  - $B_d^0 \to K^{*0}\mu\mu$ angular measurements
  - Other $b \to s\mu\mu$ branching fraction measurements
  - Global fits to $b \to sll$ data
  - Mention a couple of other anomalous results
- (Very) latest $B_d^0 \to K^{*0}\mu\mu$ angular results
  - Compatibility with SM
  - Updated global fits
- Some remarks about the future

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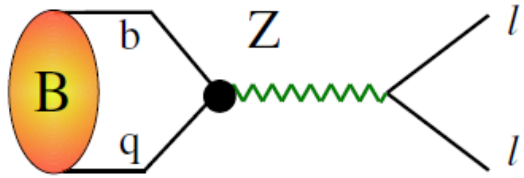
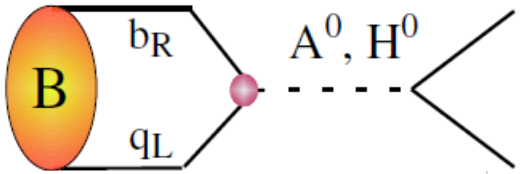
$B^0 \to \mu^+\mu^-$ – Physics Interest

- Both helicity suppressed and GIM suppressed
  - In the SM,
    - Dominant contribution from Z-penguin diagram
    - Precise predictions for BFs :
    - $B(B_s^0 \to \mu\mu) = (3.66 \pm 0.23) \times 10^{-9}$
    - $B(B_d^0 \to \mu\mu) = (1.06 \pm 0.09) \times 10^{-10}$

      [PRL 112 (2014) 101801]

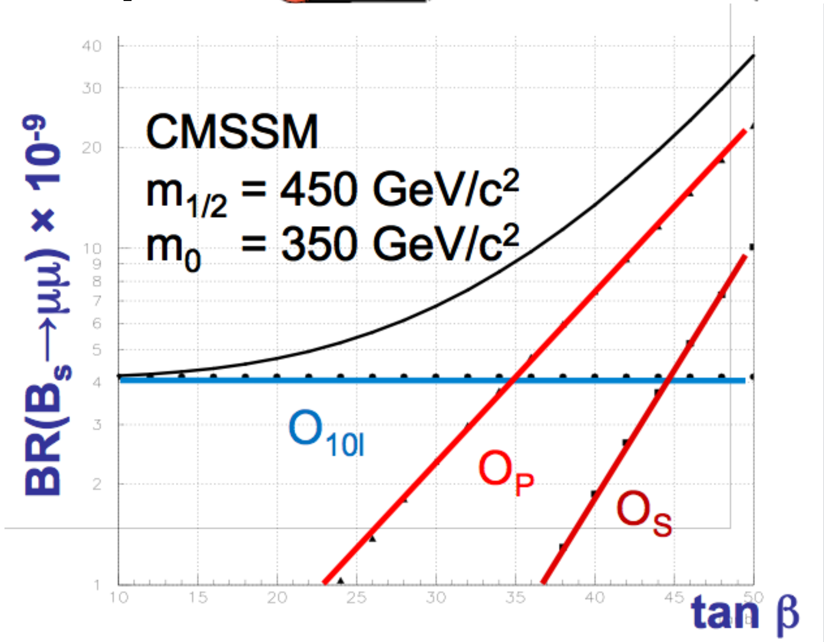




  - In NP models,
    - New scalar (O_S) or pseudoscalar (O_P) interactions can modify BF

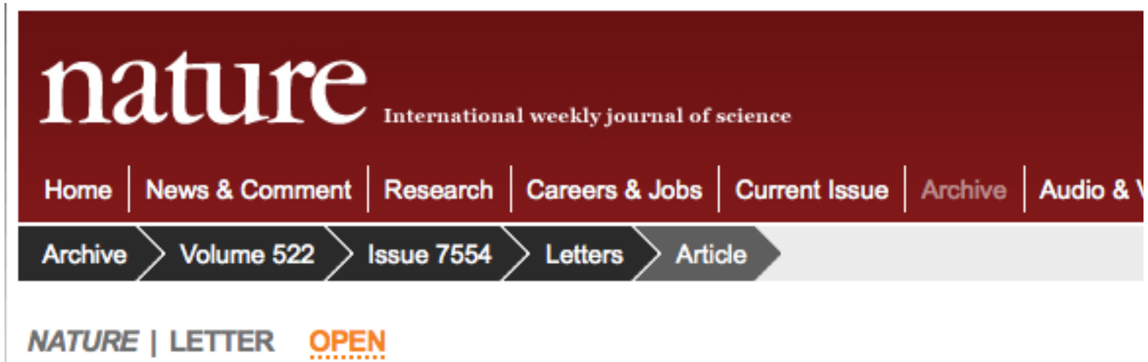
    e.g. in MSSM, extended Higgs sector gives BF that scales with $\tan^6 \beta / M_{A^0}^4$

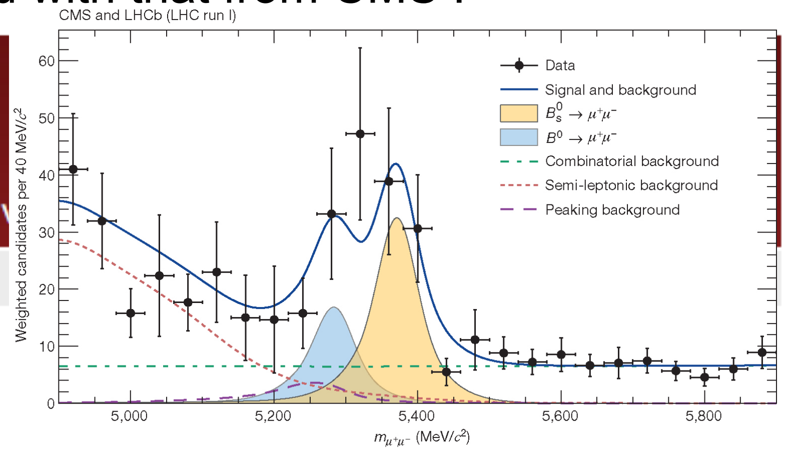
→ Extremely sensitive probe of NP!



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

LHCb's $B^0 \to \mu^+\mu^-$ analysis has now been combined with that from CMS :

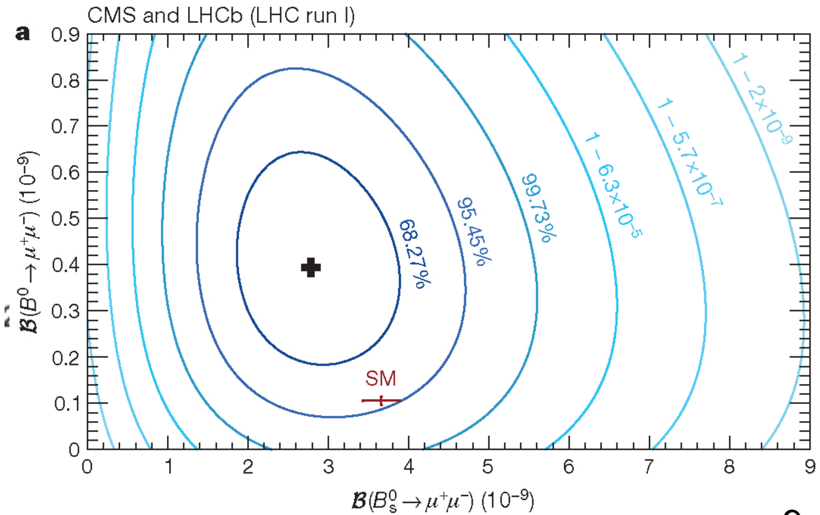




- Measure
  - $B(B_s^0 \to \mu^+\mu^-) = (\,2.8^{+0.7}_{-0.6}\,) \times 10^{-9}$
  - $B(B_d^0 \to \mu^+\mu^-) = (\,3.9^{+1.6}_{-1.4}\,) \times 10^{-9}$

  in good agreement with SM predictions

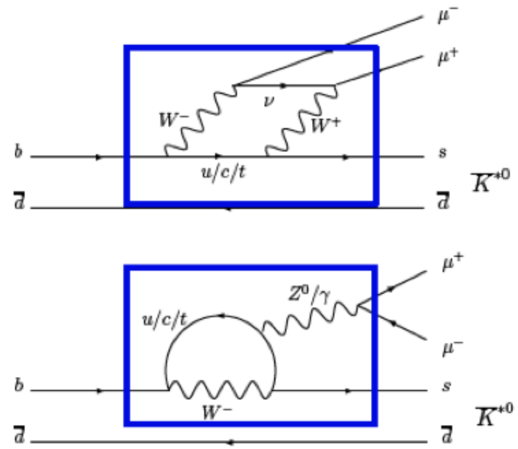
→ No evidence of NP contributions to C_S and C_P

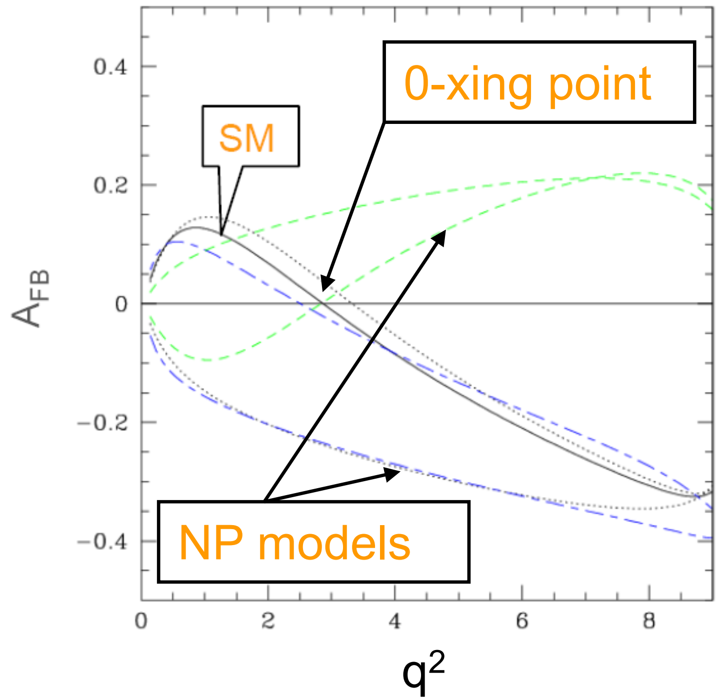


$B_d^0 \rightarrow K^{*0}\mu\mu$ – Physics Interest

- Flavour changing neutral current → loop process (→ sensitive to NP)
- Decay described by three angles (θ_l, ϕ, θ_K) and di-μ invariant mass q^2
- Try to use observables where theoretical uncertainties cancel

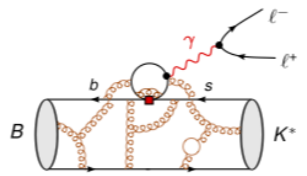
  e.g. Forward-backward asymmetry A_{FB} of θ_l distribution
- Zero-crossing point: ±6% uncertainty





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



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

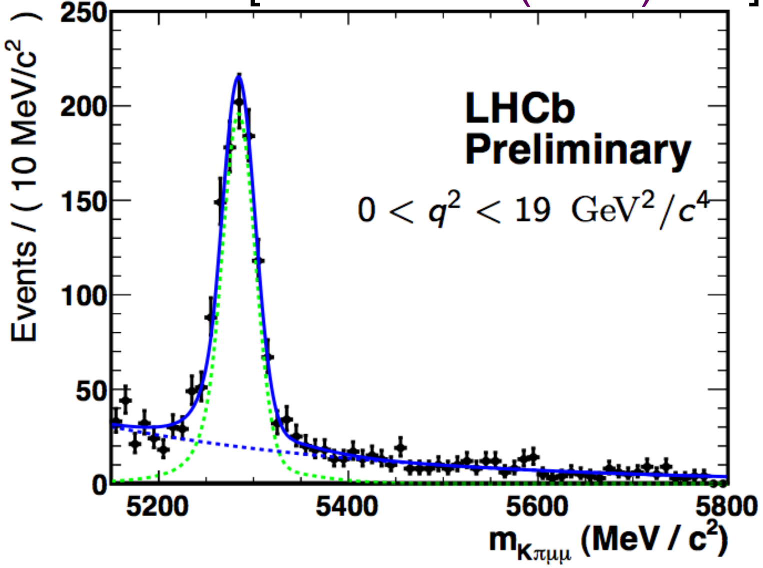
$$A_{\parallel}^{L(R)} = -N\sqrt{2}(m_B^2 - m_{K^*}^2)\left\{\left[(\mathbf{C_9^{eff}} - \mathbf{C_9^{\prime eff}}) \mp (\mathbf{C_{10}^{eff}} - \mathbf{C_{10}^{\prime eff}})\right]\frac{\mathbf{A_1(q^2)}}{m_B - m_{K^*}} + \frac{2m_b}{q^2}(\mathbf{C_7^{eff}} - \mathbf{C_7^{\prime eff}})\mathbf{T_2(q^2)}\right\}$$

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

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

1^{st} generation measurements

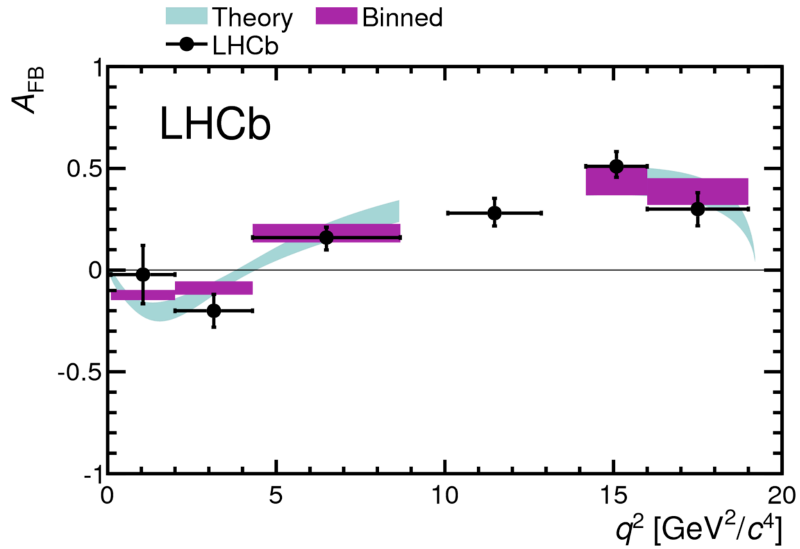
[JHEP 1308 (2013) 131]



- With 2011 data found 900±34 signal events (BaBar + Belle + CDF ~ 600)
- B/S≈0.25
- World's most precise measurements of angular observables
- The world's 1^{st} measurement of zero-crossing point at $4.9^{+1.1}_{-1.3}$ GeV^2/c^4

  → "a textbook confirmation of the SM"

- Seems theorists have good control of form factor uncertainties



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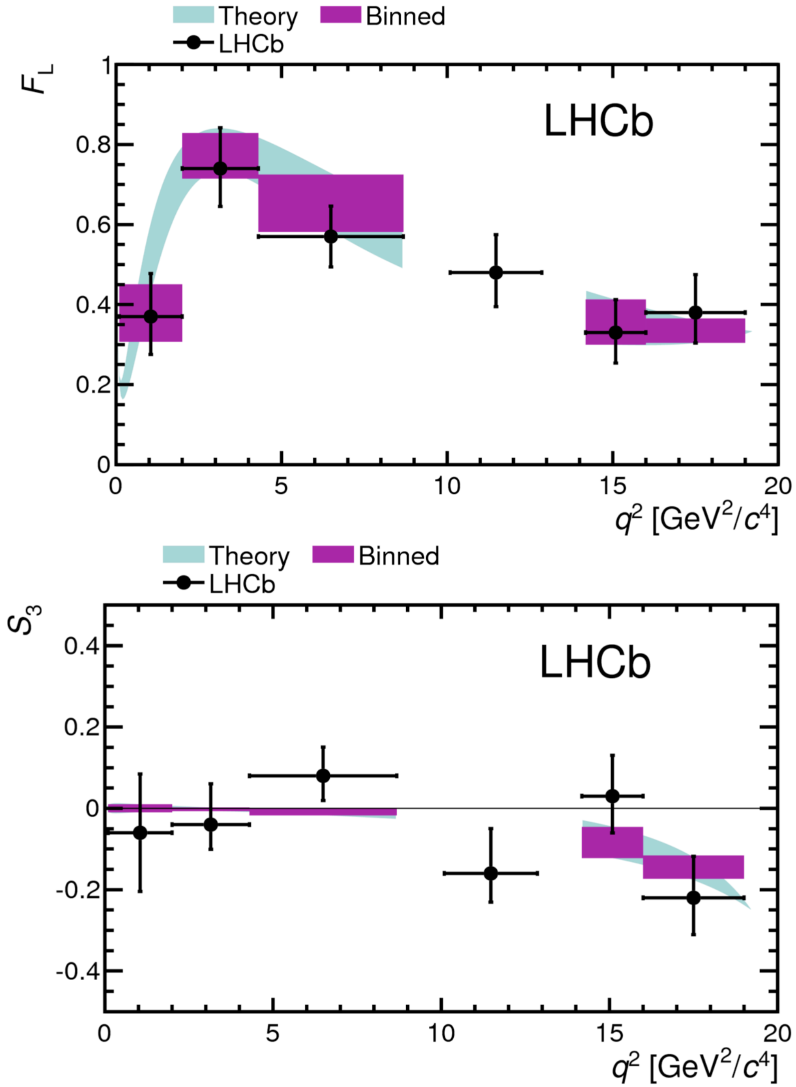
[JHEP 1308 (2013) 131]



Form-factor independent obs.

- At low and high q^2, there are relations between the various form factors (at leading order) that allow a number of form-factor independent observables to be constructed

- E.g. in the region $1<q^2<6\ \text{GeV}^2$, 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*

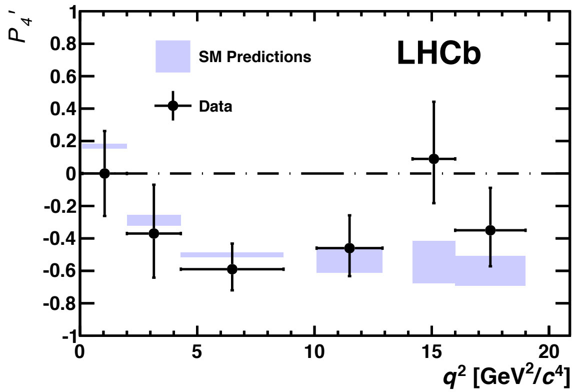
- In fact can form a complete basis ($P^{(')}$ series) in which there are six form-factor independent and two form-factor dependent observables (F_L and A_{FB})

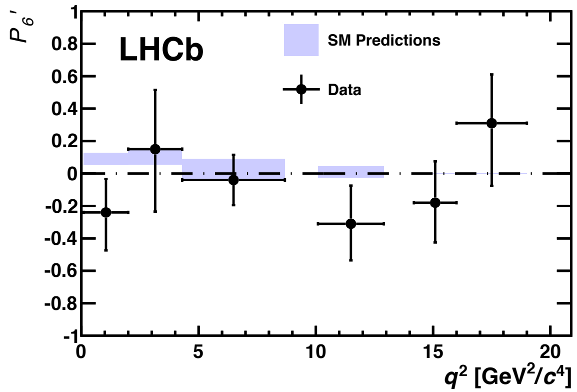
- Updated analysis measuring P(') series of observables gave a surprise…

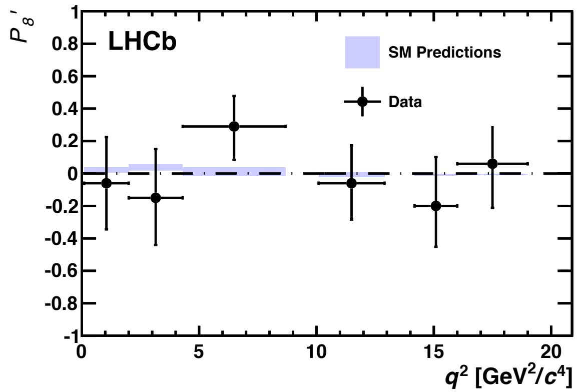
$B_d^0 \to K^{*0}\mu^+\mu^-$ – P(') series

[Phys. Rev. Lett. 111 (2013) 191801]

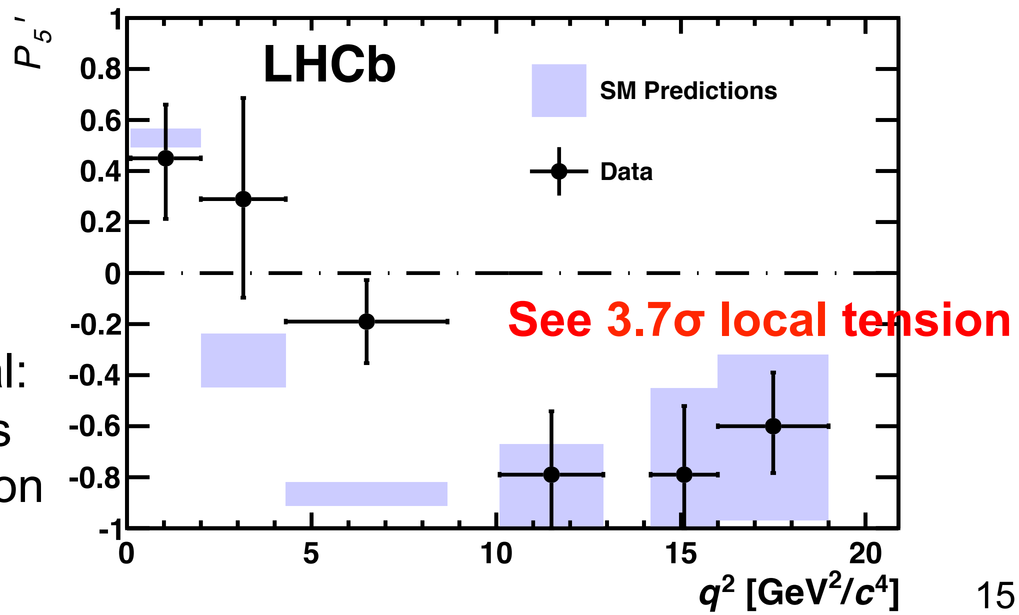
- Good agreement with predictions for P_4', P_6', P_8' observables







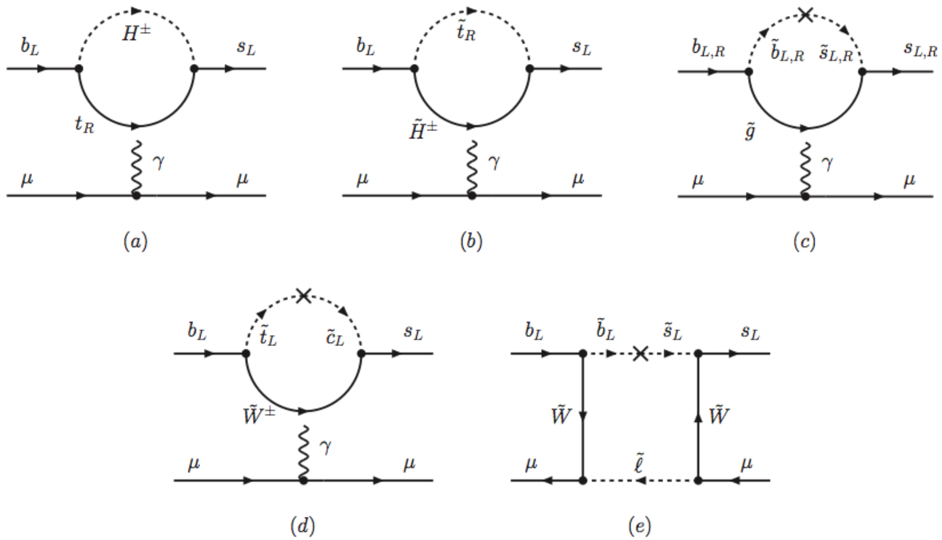
- 0.5% probability to see such a deviation with 24 independent measurements
- Finding a consistent NP explanation looks highly non-trivial: prev. $B_d^0 \to K^{*0}\mu\mu$ observables plus $B^0 \to \mu\mu$, $B \to K\mu\mu$, $B \to X_s\gamma$ depend on same short-distance physics



$B_d^0 \to K^{*0}\mu\mu$ – 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'**

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

- Theoretical analyses conclude deviation observed does ***not*** create any tension with other flavour observables

- e.g. [arXiv:1307.5683] consistent with negative NP contribution to C_9 : **$\Delta C_9 \sim -1$**

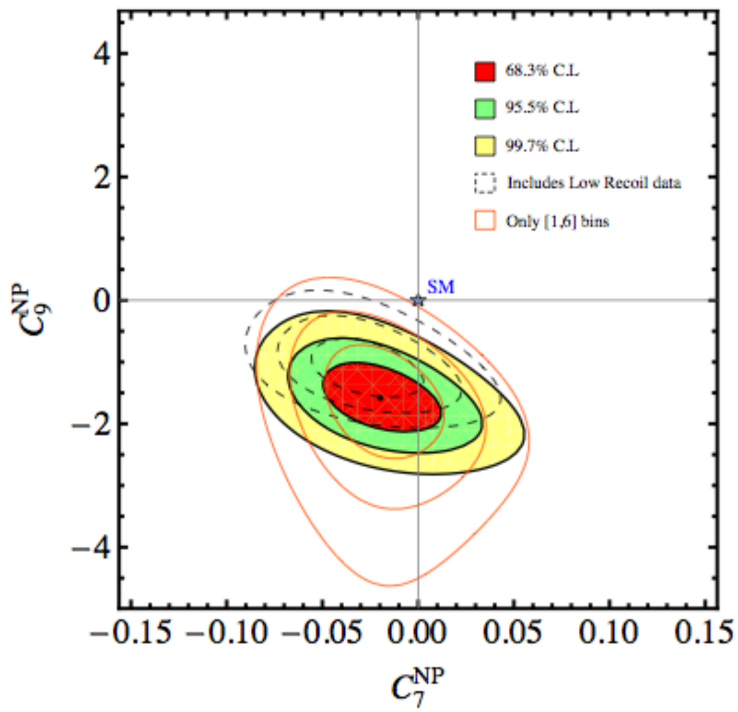
- Preferred value of C_9 can be translated into NP scale in a model independent way but the answer depends on what else is considered in the fit e.g.

$M_{Z'} \in [5.7, 6.9]$ TeV [arXiv:1310.1082]

$$\Lambda_{9^{(\prime)}} \simeq (35\ \text{TeV}) \left(\frac{1.0}{|C_9^{(\prime)}|}\right)^{1/2}$$

$$\Lambda_{9^{(\prime)}}^{\text{loop}} \simeq (2.8\ \text{TeV}) \left(\frac{1.0}{|C_9^{(\prime)}|}\right)^{1/2}$$

[arXiv:1308.1501]



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

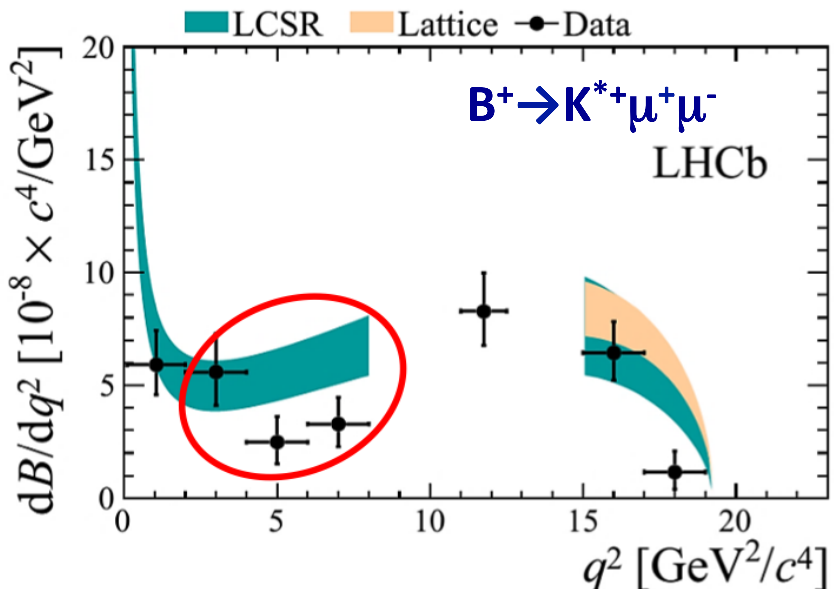
- While some theorists are very excited, some are less keen…

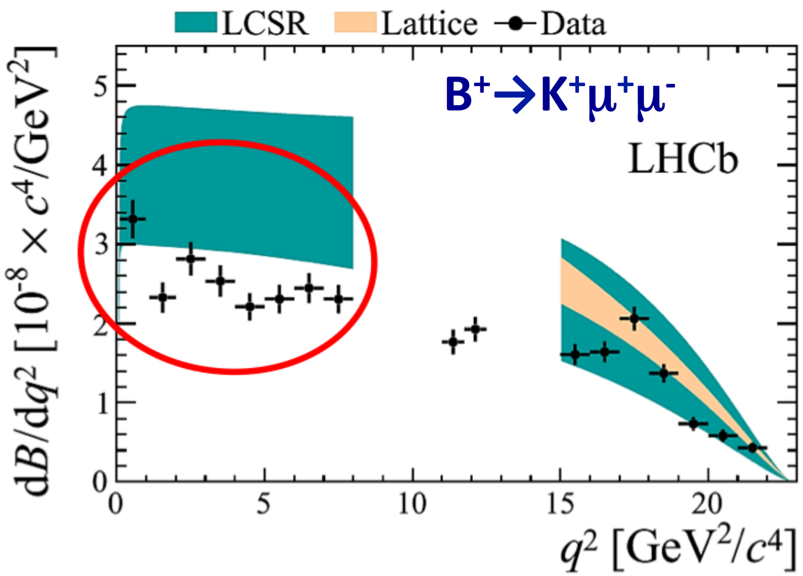
Ugly face of $B \to K^* \mu^+ \mu^-$

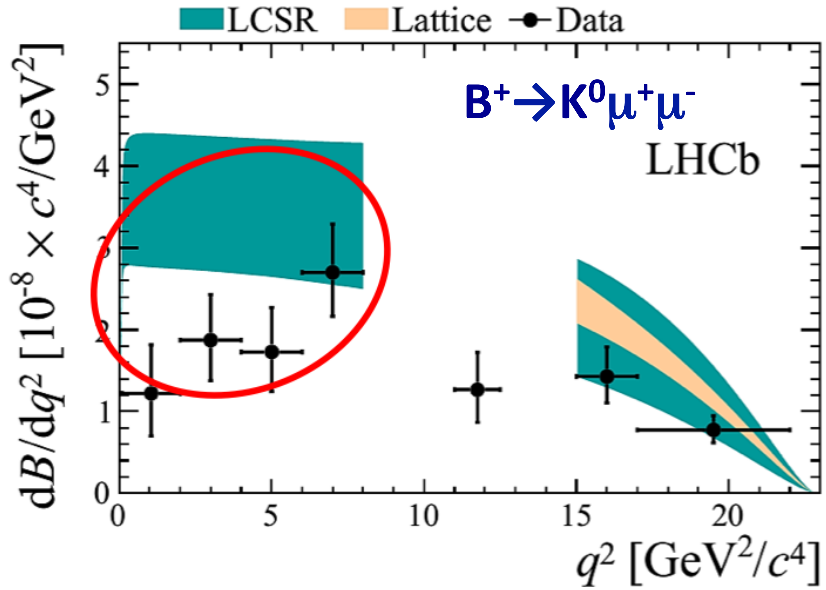
Adding the branching fractions...

- If we did have such a vector contribution we'd expect low branching fractions for other b→sμμ decays with different spectator quark

[JHEP 06 (2014) 133]



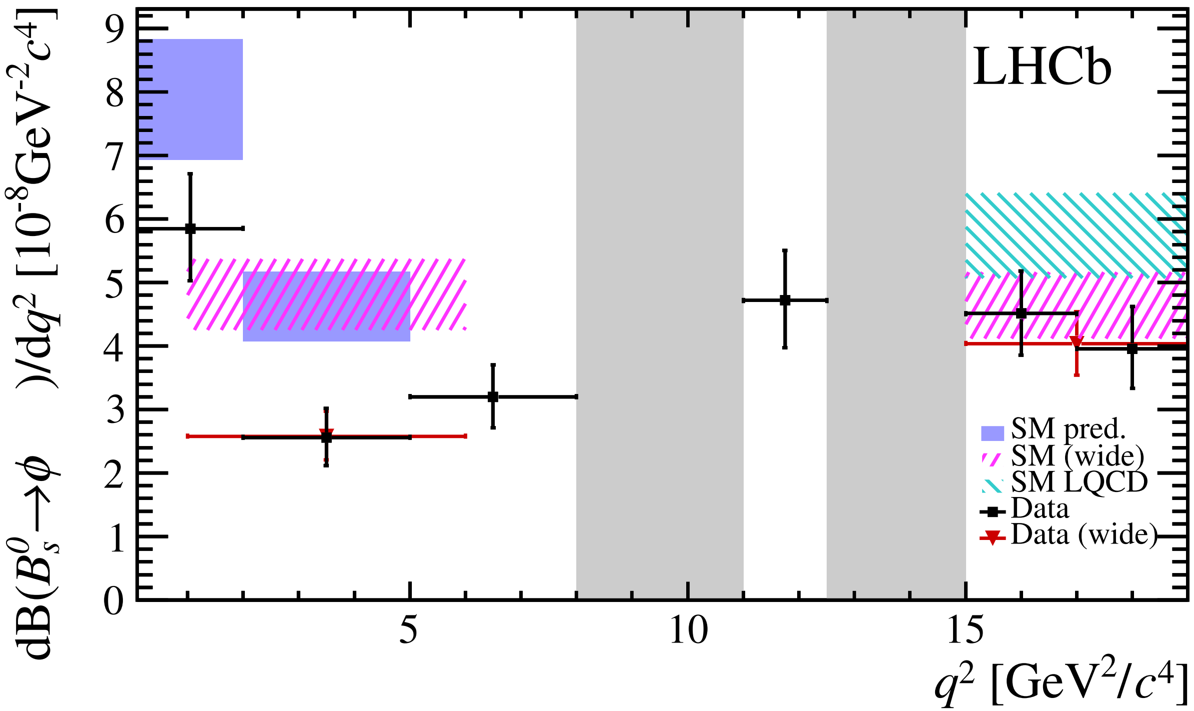




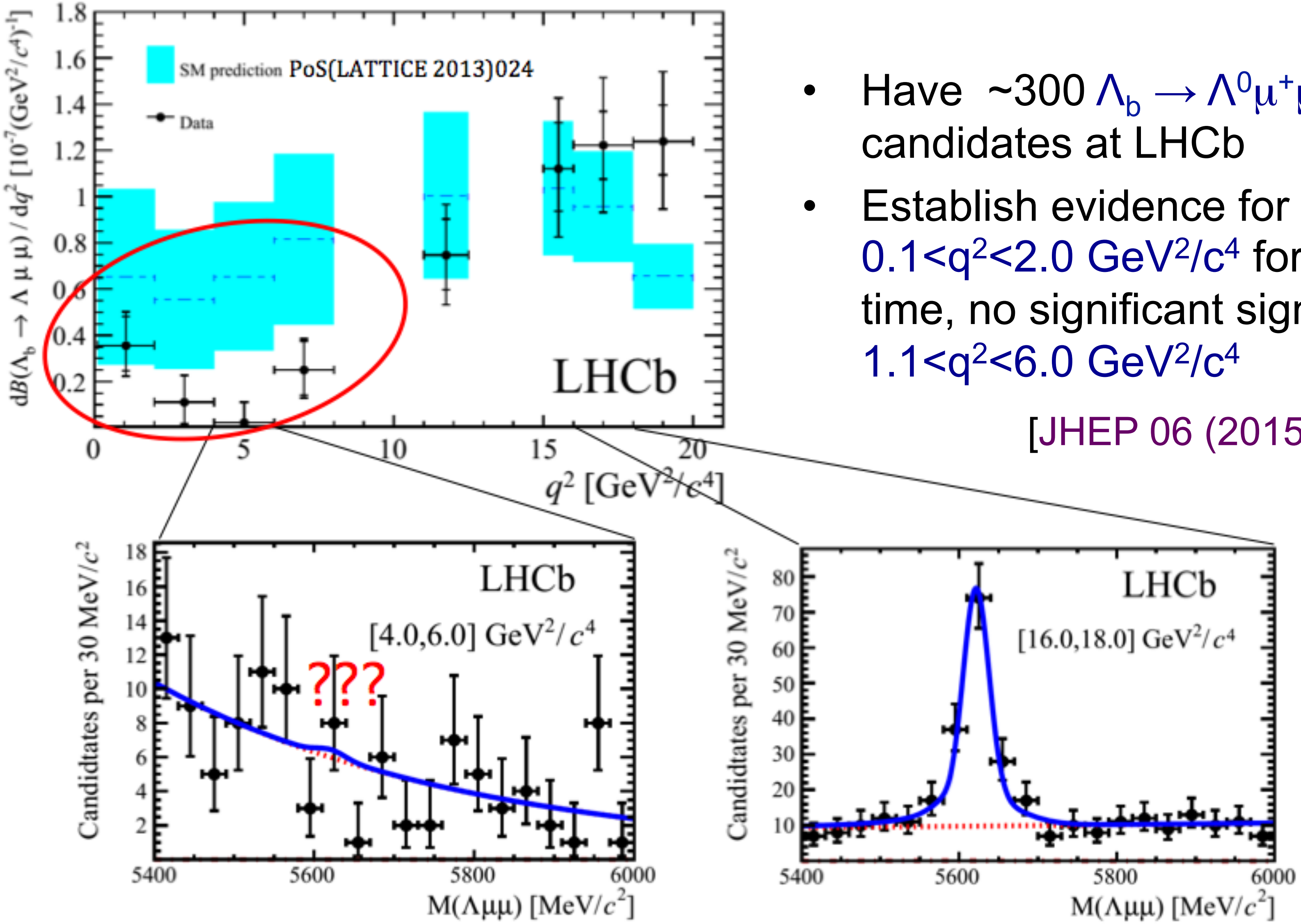
$B^0_s \to \phi\mu^+\mu^-$

- Measurements of $B^0_s \to \phi\mu^+\mu^-$ show a similar trend in the low q^2 region
  - Narrow ϕ resonance gives clean signal
  - This measurement alone is 3.3σ from SM prediction in $1.0<q^2<6.0$ GeV^2

[JHEP09 (2015) 179]



$\Lambda_b \rightarrow \Lambda^0\mu^+\mu^-$



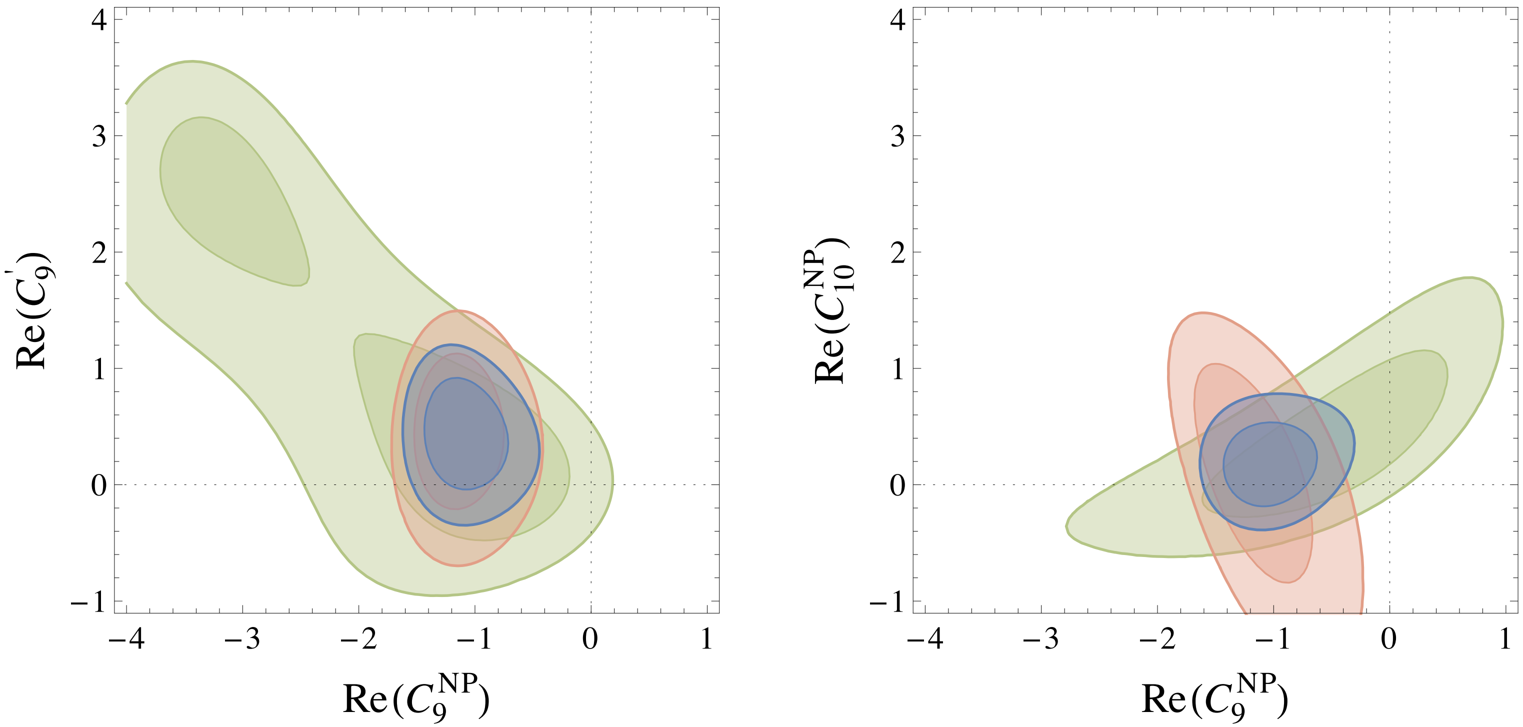
- Have ~300 $\Lambda_b \rightarrow \Lambda^0\mu^+\mu^-$ candidates at LHCb
- Establish evidence for signal $0.1<q^2<2.0$ GeV^2/c^4 for 1st time, no significant signal in $1.1<q^2<6.0$ GeV^2/c^4

[JHEP 06 (2015) 115]

Global fit to angular and BF data

- Fit the **angular** and **branching fraction** data :

[arXiv:1405.5182]



→ **BF data also favours same NP solution : $\Delta C_9 \sim -1$;**

Can't tell if a two C_i solution preferred (e.g. V-A, impact $B^0 \to \mu^+\mu^-$)

The plot thickens: R_K

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

  $R_K = B(B^+ \to K^+\mu^+\mu^-) \,/\, B(B^+ \to K^+e^+e^-)$

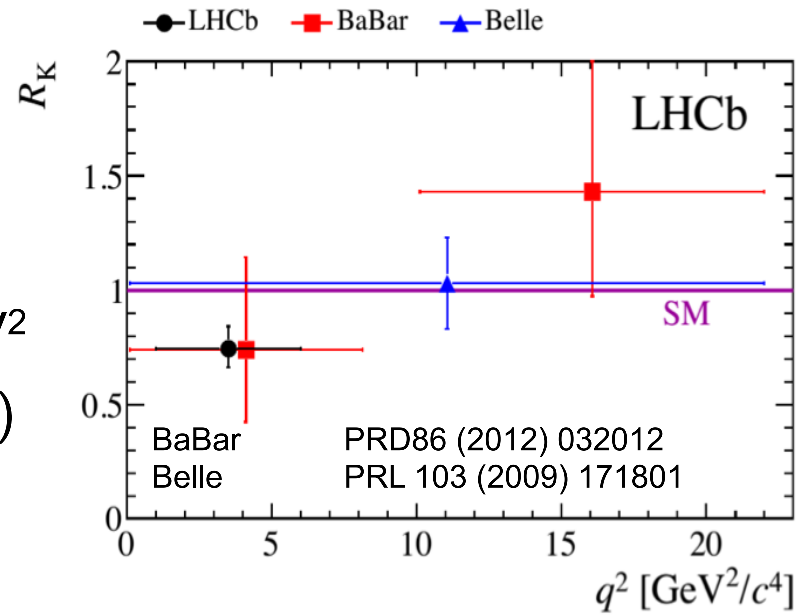
- Precisely predicted in SM,

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

- LHCb measurement in $1.0 < q^2 < 6.0\ \mathrm{GeV}^2$

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

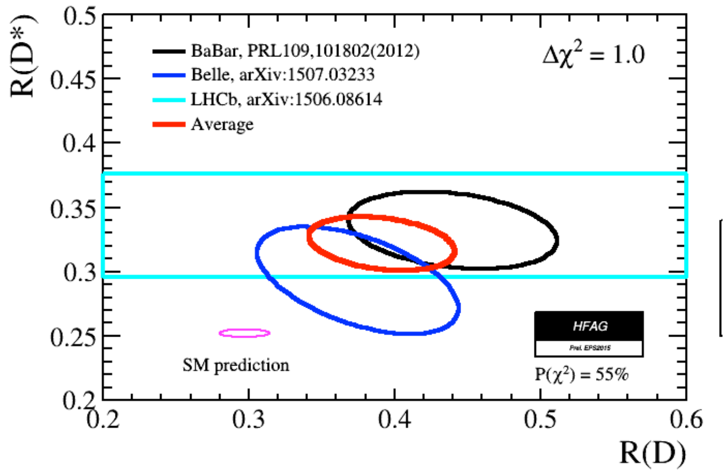
  → 2.6σ from SM prediction



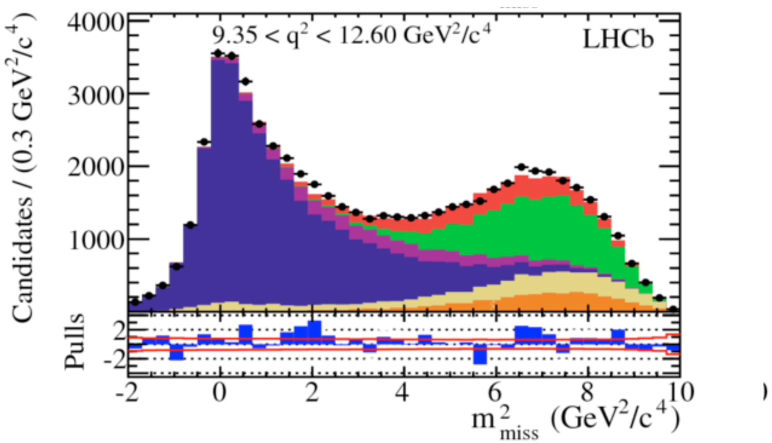
- Large number of theory models on the market pointing out this is consistent with $\Delta C_9^{ee}=0$, $\Delta C_9^{\mu\mu}=-1$ (latter consistent with $B_d^0 \to K^{*0}\mu\mu$)

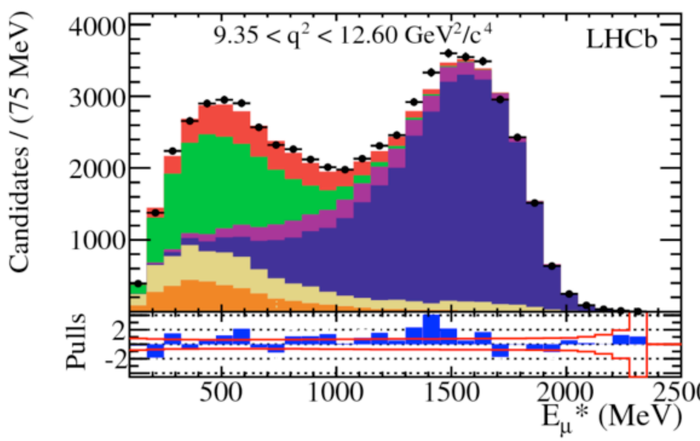
A short aside : R_D*

- Note we also see an anomalous effect in the ratio of **tree-level** branching fractions $R_D* = B(B_d^0 \to D^{*+}\tau\nu)/B(B_d^0 \to D^{*+}\mu\nu)$
- 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, combined significance 3.9σ



[Phys.Rev.Lett. 115(2015)112001]





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  - compatibility with SM
  - Updated global fits

- Some remarks about the future

Full Run-I $B_d^0 \to K^{*0}\mu\mu$ update

- Our full run-I $B_d^0 \to K^{*0}\mu\mu$ update recently published [JHEP 02 (2016) 104], dataset 3× larger than previous analysis
- For first time made full angular fit involving all angular terms → **complete set observables (and correlations)**
- Finer q^2 binning → more shape information(*), cross-check with a second (less precise) method
- First measurement of CP asymmetries, measurements of zero-crossing points by determining amplitudes as fn q^2
- Will try and give a feeling for how the measurement is made…

(*) As well as low branching fractions, $\boldsymbol{\Delta C_9 \sim -1}$ would give a shift in $\boldsymbol{A_{FB}}$

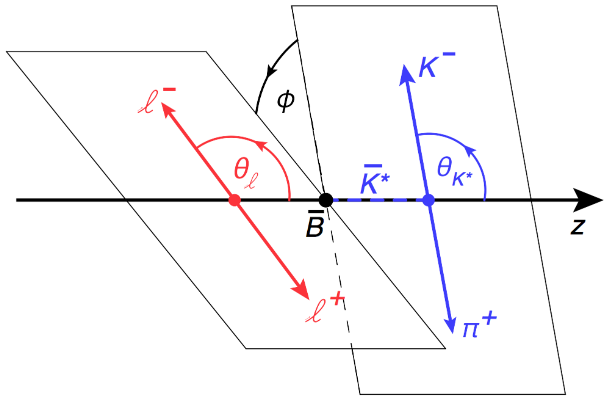
Differential decay rate

- Decay described by di-μ invariant mass q^2 and three decay angles $\vec{\Omega} = (\cos\theta_l, \cos\theta_K, \phi)$

- Differential decay rate given

$$\frac{d^4\Gamma[\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi} \sum_j I_j(q^2) f_j(\vec{\Omega})$$

$$\frac{d^4\bar{\Gamma}[B^0 \to K^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi} \sum_j \bar{I}_j(q^2) f_j(\vec{\Omega})$$



- I_j terms – eleven q^2 dependent angular observables
  Can be expressed as bi-linear combinations of six complex decay amplitudes $\mathcal{A}_{0,\|,\perp}^{L,R}$

- $f_j(\vec{\Omega})$ terms – combinations of spherical harmonics

Angular observables

- Can define CP-averaged and CP-asymmetric observables

$$S_j = (I_j + \bar{I}_j) \Big/ \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} + \frac{\mathrm{d}\bar{\Gamma}}{\mathrm{d}q^2}\right)$$

$$A_j = (I_j - \bar{I}_j) \Big/ \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} + \frac{\mathrm{d}\bar{\Gamma}}{\mathrm{d}q^2}\right)$$

- Additional suffix s/c sometimes added to indicate $\sin^2\theta_K$ or $\cos^2\theta_K$ dependence; $S_{1c} = F_L$; $\frac{3}{4}S_{6s} = A_{FB}$

- For large q^2, μ's effectively massless – relations between different S_j terms, 11 $\rightarrow$ 8 CP-averaged observables

- Further observables, optimised to reduce FF uncertainties, can be built from F_L, S_3-S_9 e.g. $P_5' = S_5/\sqrt{F_L(1-F_L)}$

CP-averaged angular distn

- CP-averaged angular distribution then given

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

(!)

- For the 1st time, account for the effect of the $K\pi$ system being in an S-wave configuration rather than K^{*0} P-wave

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{S+P}} = (1-F_{\mathrm{S}})\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{P}}$$
$$+\frac{3}{16\pi}F_{\mathrm{S}}\sin^2\theta_\ell$$
$$+\frac{9}{32\pi}(S_{11}+S_{13}\cos 2\theta_\ell)\cos\theta_K$$
$$+\frac{9}{32\pi}(S_{14}\sin 2\theta_\ell + S_{15}\sin\theta_\ell)\sin\theta_K\cos\phi$$
$$+\frac{9}{32\pi}(S_{16}\sin\theta_\ell + S_{17}\sin 2\theta_\ell)\sin\theta_K\sin\phi$$

(!!)

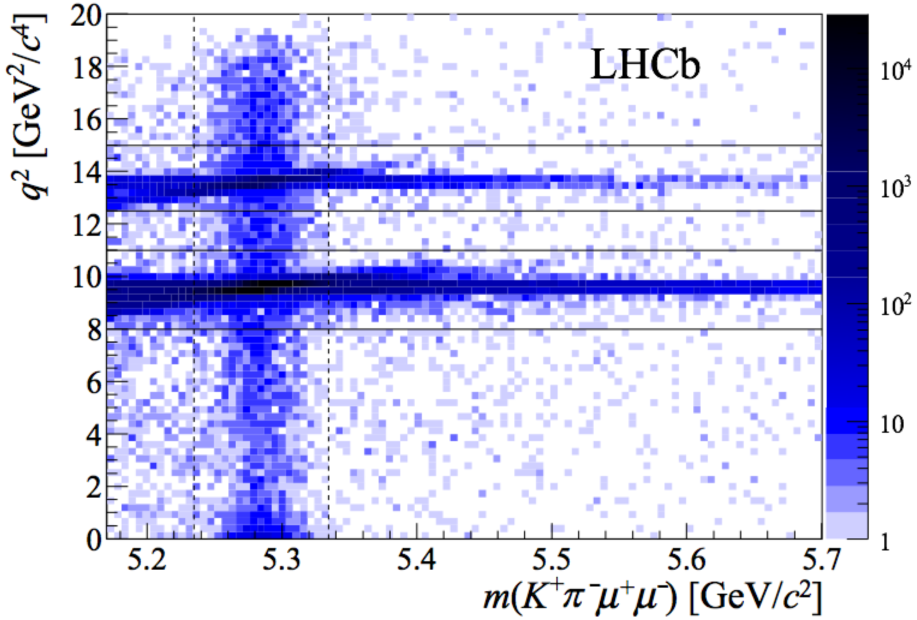
Determine A_i by flipping the sign in front of the corresponding angular terms for B^0 decays while leaving unchanged for $\bar{B}^0$ decays

→ two new amplitudes and six additional angular terms (explicitly included as nuisance parameters)

$B^0 \to K^{*0}\mu^+\mu^-$ signal selection

- Selection uses range of PID, kinematic and isolation quantities in a Boosted Decision Tree

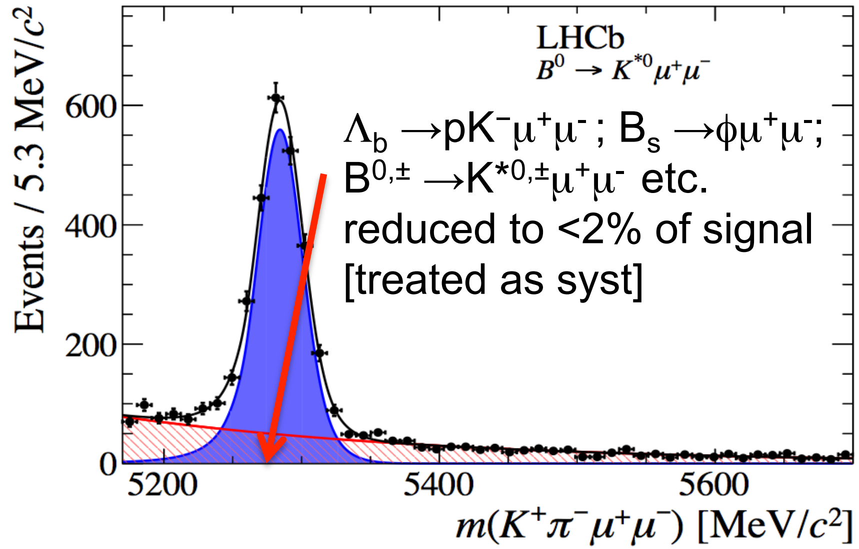
- Veto $B^0 \to K^{*0} J/\psi$ and $B^0 \to K^{*0}\psi(2S)$ decays, as well as a number of peaking backgrounds :
  - evidence for $\phi(1020)$ at low q^2 → exclude $0.98, < q^2 < 1.1$ GeV^2
  - Consider e.g. $\Lambda_b \to pK^-\mu^+\mu^-$; $B_s \to \phi\mu^+\mu^-$; $B^{0,+} \to K^{*0,+}\mu^+\mu^-$ …



- After selection, signal clearly visible as vertical band Clean enough to allow finer q^2 binning than for 1 fb^{-1}

$B^0 \to K^{*0}\mu^+\mu^-$ signal selection

- Signal $K\pi\mu\mu$ mass model
  - sum of two Gaussians with power law tail on low mass-side
  - defined using $B^0 \to K^{*0} J/\psi$ control channel (correct for q^2 dependence using simulation)
  - Combinatorial background modelled with falling exponential
- $K\pi$ mass model :
  - Rel. Breit Wigner for P-wave
  - LASS for S-wave
  - Linear model for bkgrd

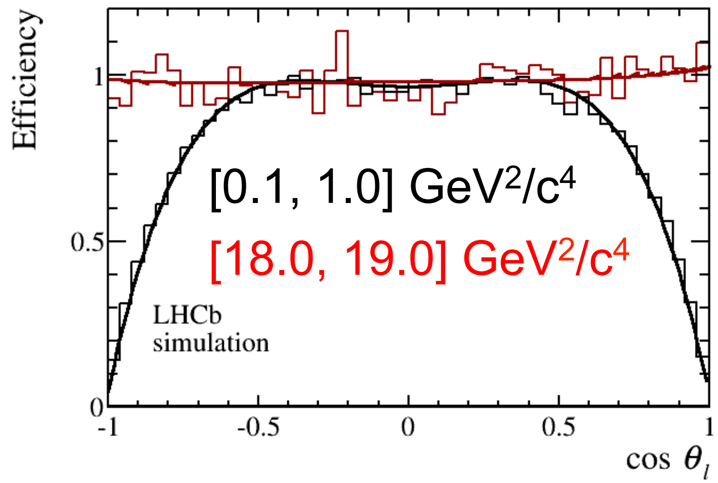


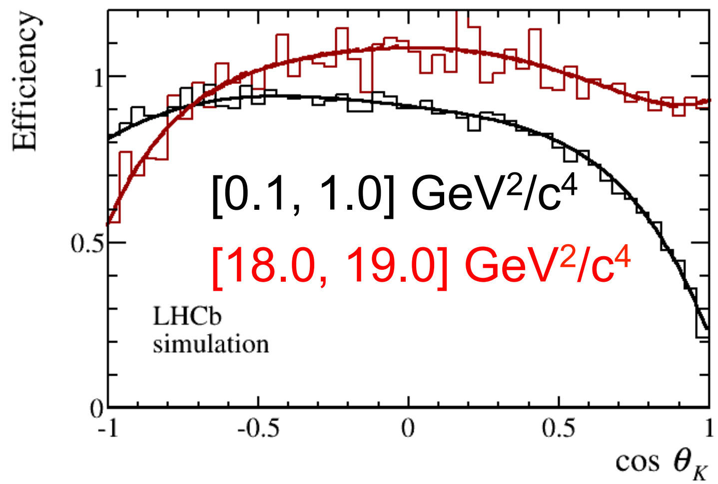
- Find 2398±57 signal events in $0.1<q^2<19.0$ GeV^2/c^4 (624±30 events in $1.1<q^2<6.0$ GeV^2/c^4)

Correcting for the efficiency

- Detector and selection distort the angular and q^2 distribution
  - Momentum/IP requirements
- Compute 4D efficiency function, ε, using simulated events

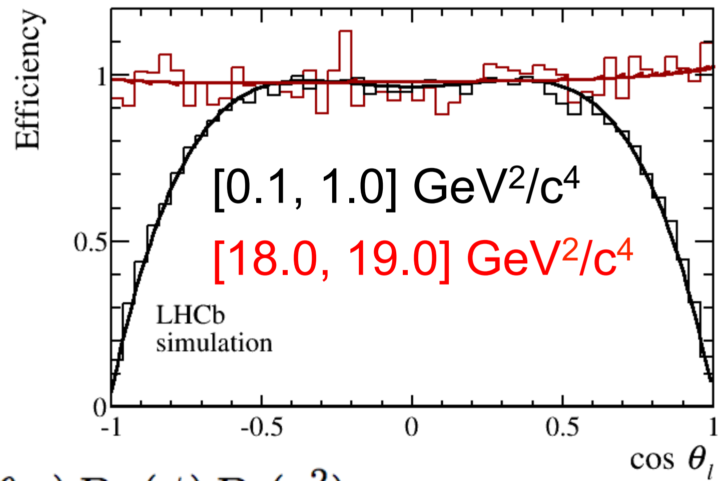
  $\varepsilon(\cos\theta_l, \cos\theta_K, \phi, q^2)$
- Function of all underlying variables → can determine with a phase-space simulation





Correcting for the efficiency

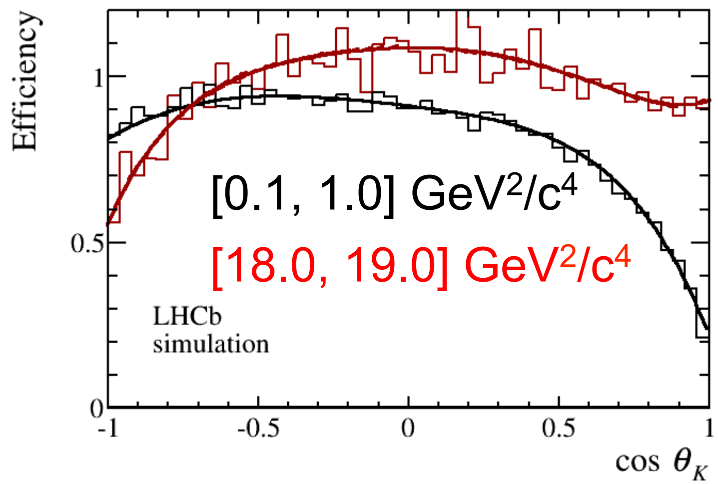
- Acceptance is **not** assumed to factorise in the decay angles



- Parameterised,

$$\varepsilon(\cos\theta_l, \cos\theta_K, \phi, q^2) = \sum_{klmn} c_{klmn} P_k(\cos\theta_l) P_l(\cos\theta_K) P_m(\phi) P_n(q^2)$$

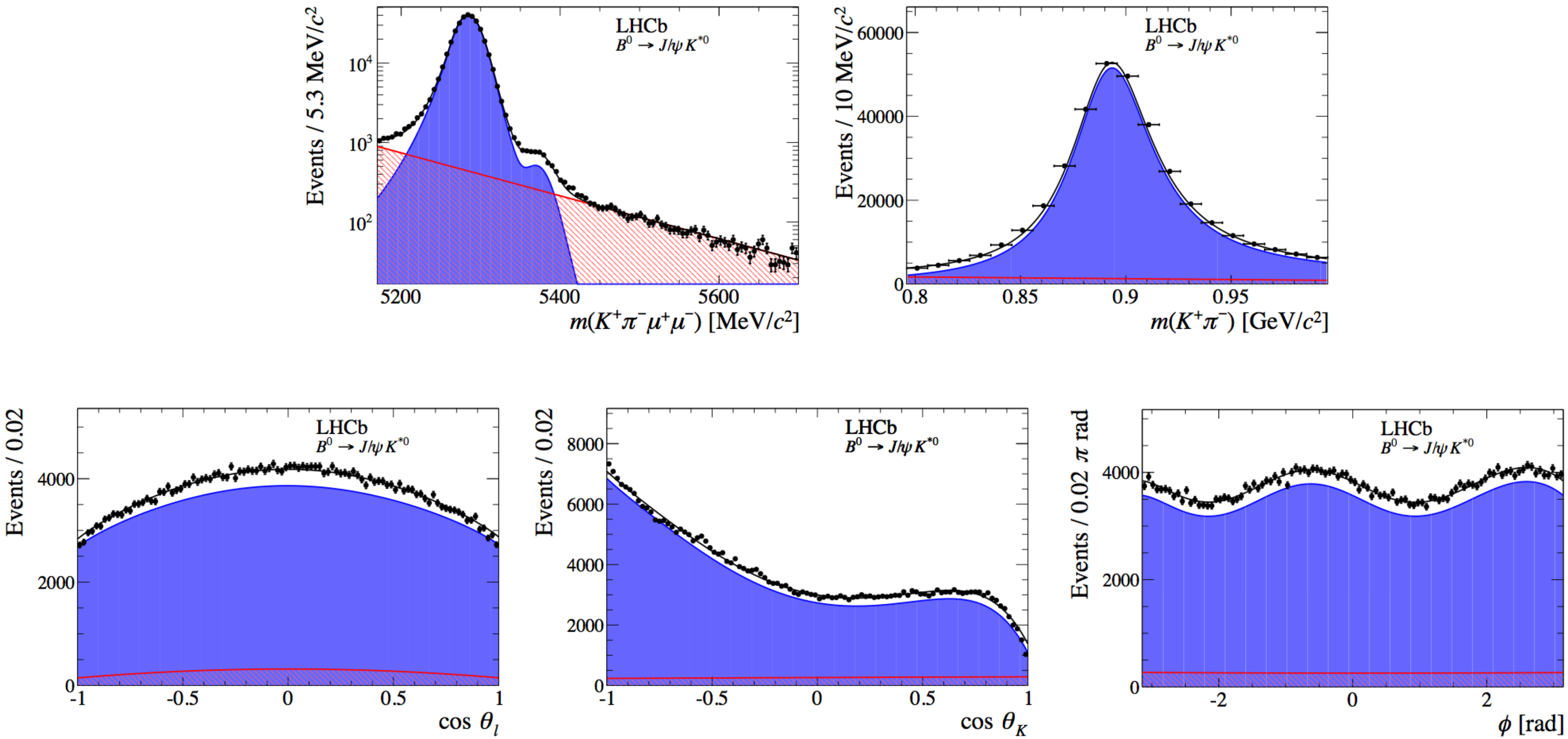
  - $P_i(x)$ are Legendre polynomials of order i (x rescaled -1→1)
  - For **cos θ_l, cos θ_K, ϕ, q^2** use up-to and including 4th,5th,6th, 5th order polynomials



- Coeff $\mathbf{c_{klmn}}$ determined using a principal moments analysis

$B^0 \to K^{*0} J/\psi$ angular fit

- Reproduce angular observables measured elsewhere
  [PRD 88 (2013) 052002]



Likelihood fit

- In each q^2 bin, unbinned maximum likelihood fit to $m_{K\pi\mu\mu}$ and three decay angles, plus a simultaneous fit to $m_{K\pi}$
- Angular distribution
  - Signal – large expression showed before
  - Bkgrd – second order polynomials in **$\cos\theta_l$, $\cos\theta_K$, ϕ**
- Application of acceptance, ε
  - Narrow q^2 bins, multiply angular pdf by acceptance at bin centre [syst.]
  - Wide $1.1<q^2<6.0$ GeV^2 and $15.0<q^2<19.0$ GeV^2 bins – ε varies significantly across bin, weight candidates by ε^{-1}, correct for coverage
- Feldman-Cousins used to determine parameter uncertainties
  - Nuisance parameters (e.g. other angular parameters, signal fraction, background parameters…) treated with plug-in method

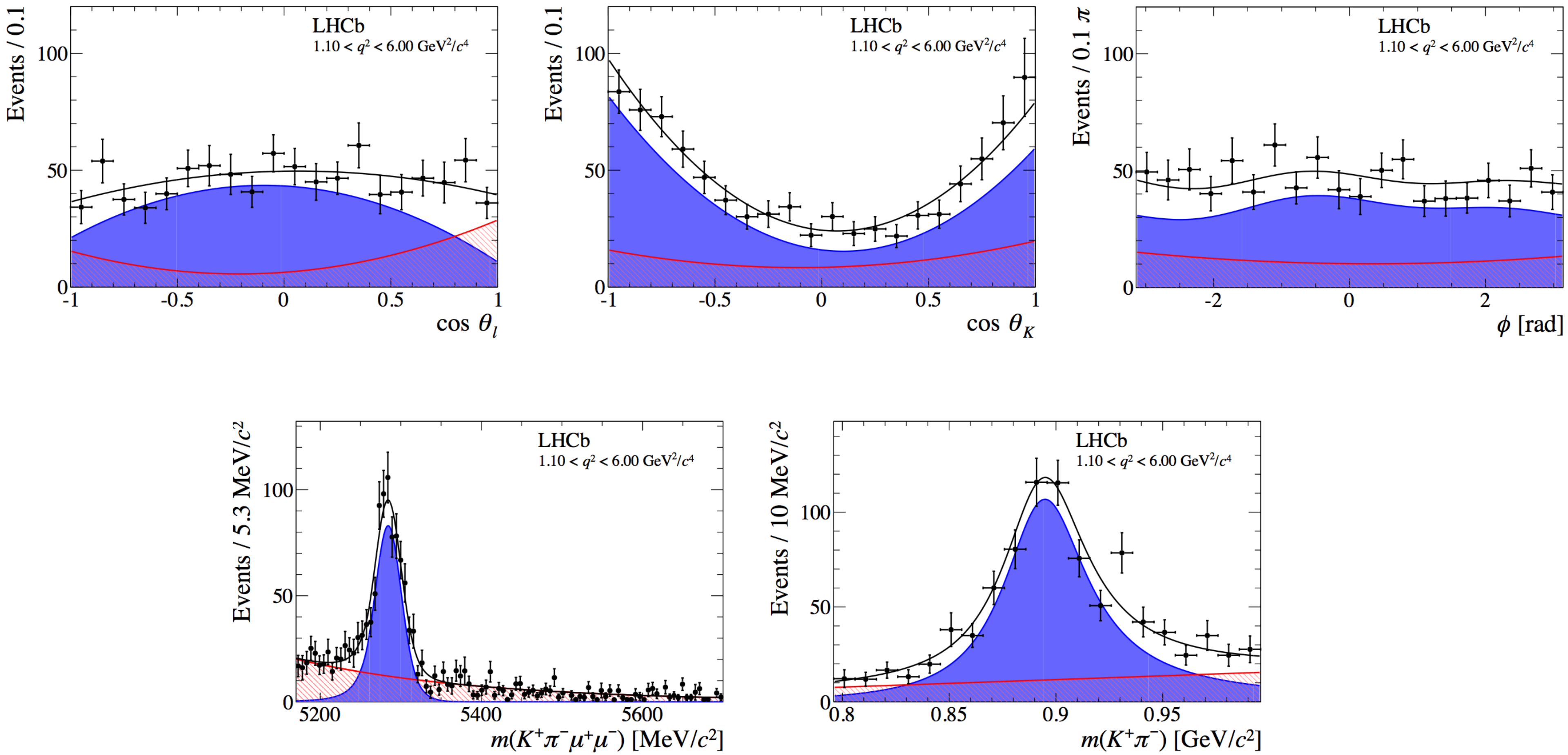
Systematics

- Evaluated using high statistics pseudoexpts where vary approach and look at difference in angular observables
- Signal – main effects from angular acceptance :
  - Statistical uncert. from simulation [re-evaluate using cov.]
  - Residual data-simulation differences [reweight for diffs,re-eval.]
  - Uncert. associated with parameterisation [increase order polyn.]
  - Uncertainty from evaluating acceptance at fixed q^2 point [alter point used]
- Background
  - Angular model [increase order polyn.]
- Bias from higher K* states negligible

Systematics

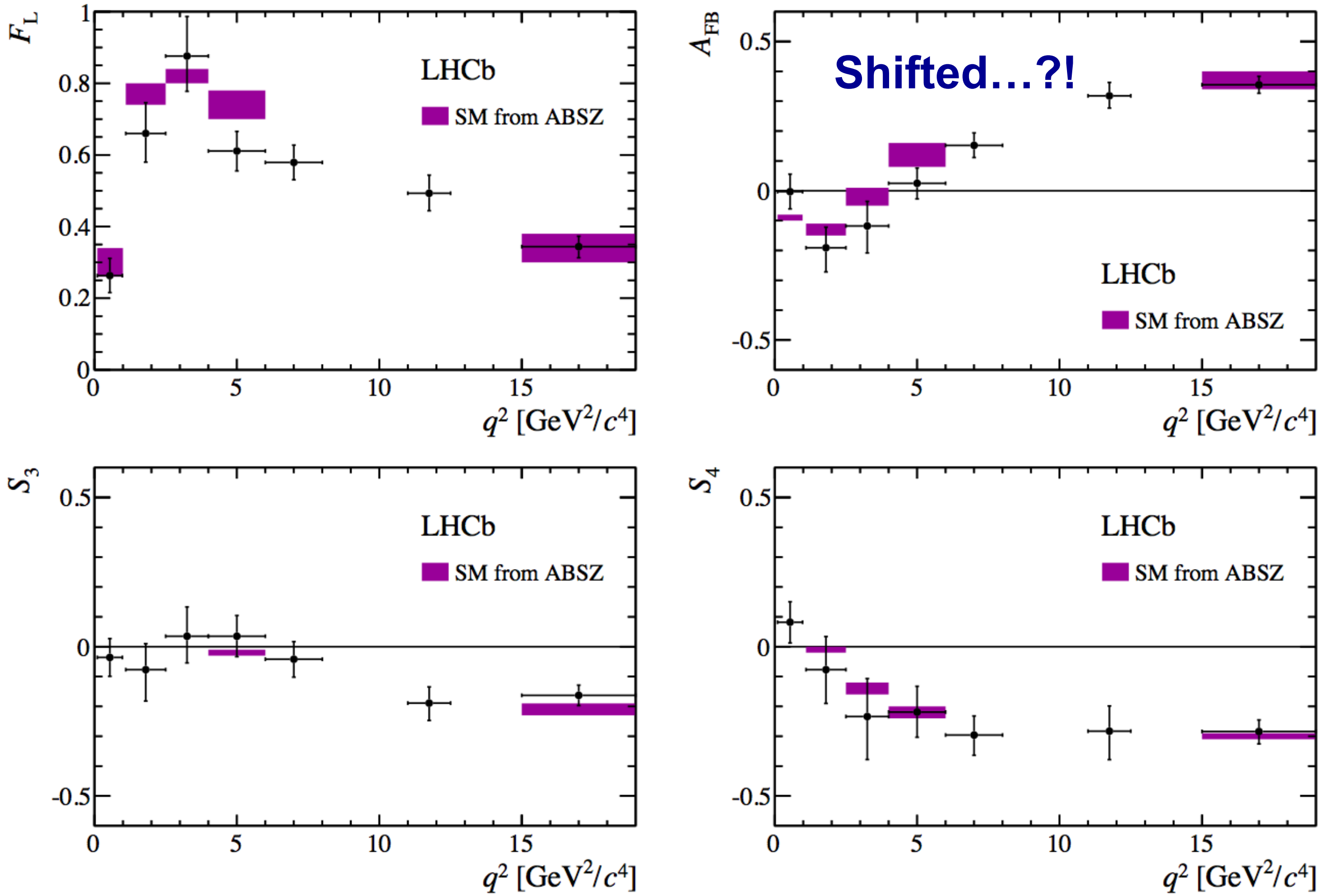
- Include angular distribution of residual peaking bkgrds
- Mass modelling
  - $m_{K\pi\mu\mu}$ – drop power law tails
  - $m_{K\pi}$ – radius used in Breit Wigner for P-wave; LASS → isobar
- [For amplitude fit] S-wave amplitudes constant with q^2 → assume same q^2 dependence as long. P-wave amplitude
- Production/detection asymmetries give negligible contribution to A_i's
- In general, syst. significantly smaller than stat.
  - e.g. F_L(A_{FB}) – syst 30 (20)% of stat. [largest p_π mismatch]

Fit projection $1.1<q^2<6.0\ \mathrm{GeV}^2/c^4$

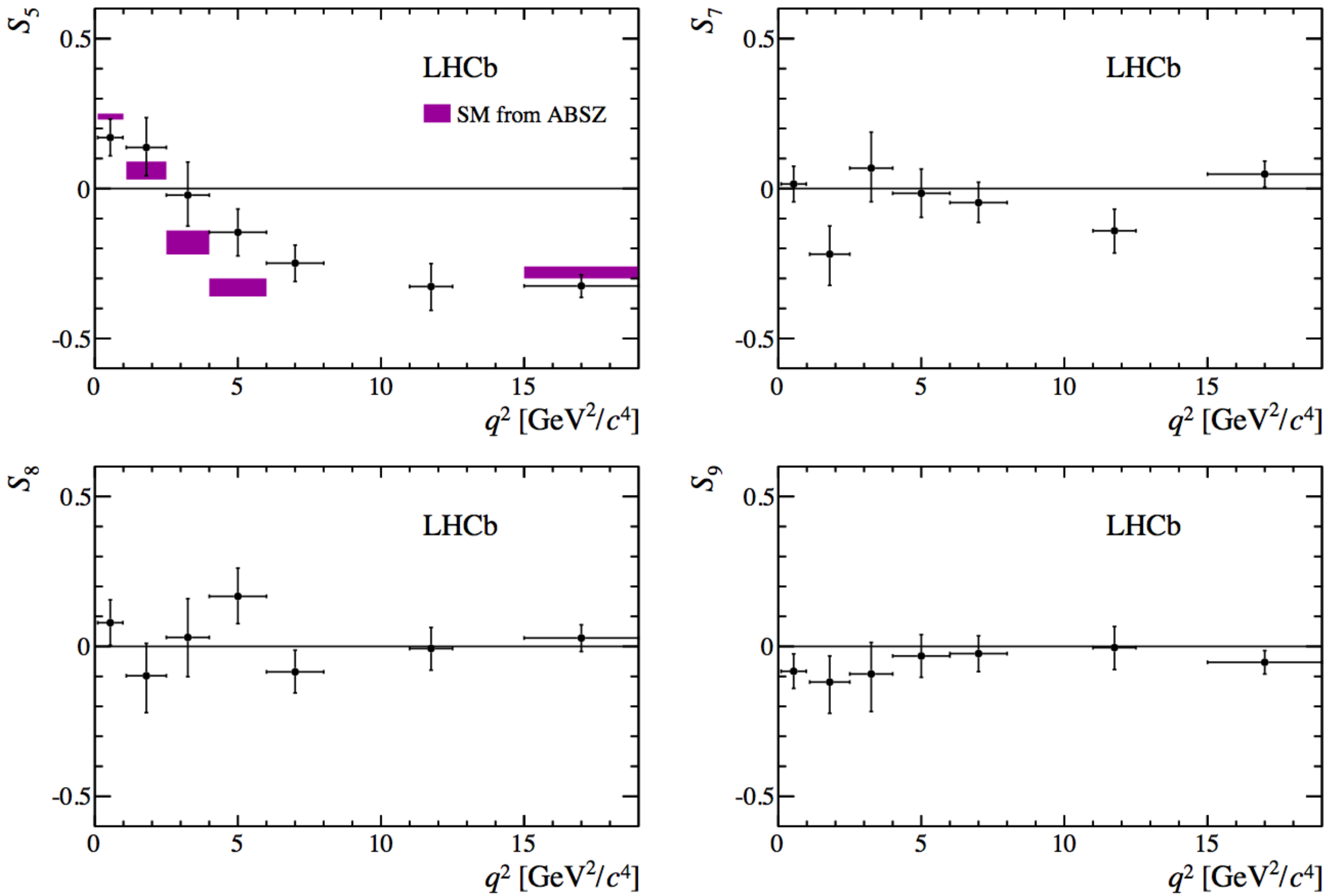


NB: weighted candidates

Results: Likelihood, CP-avgd

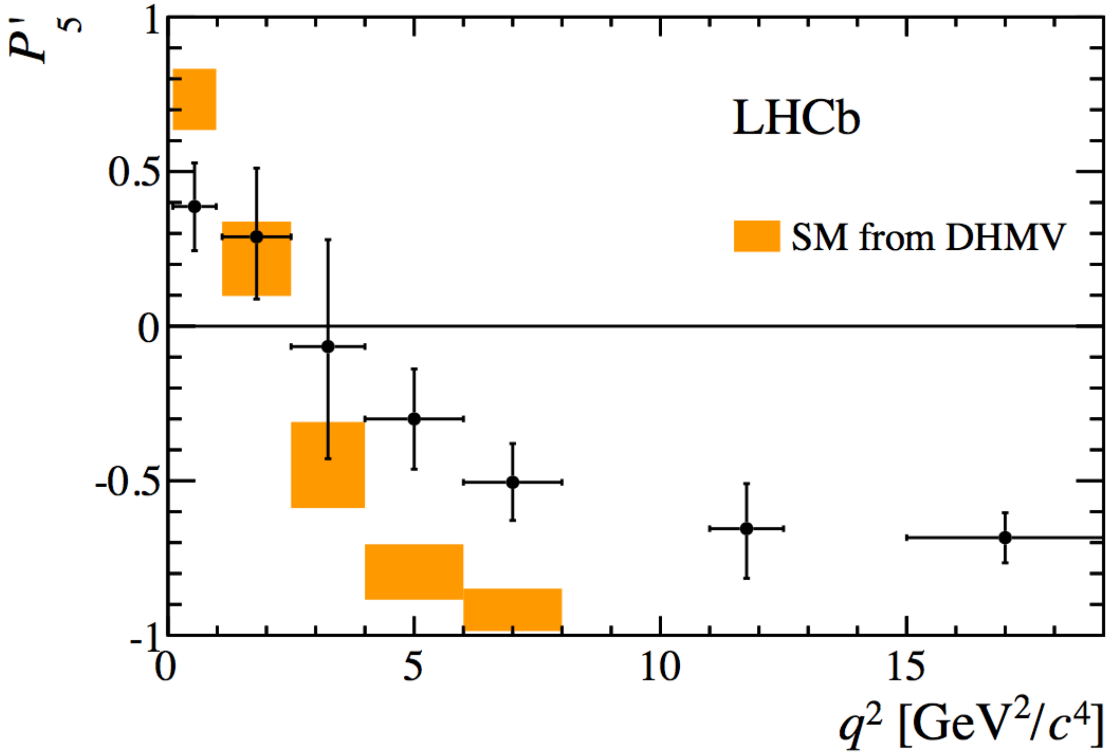


Results: Likelihood, CP-avgd



Results: Likelihood, CP-avgd

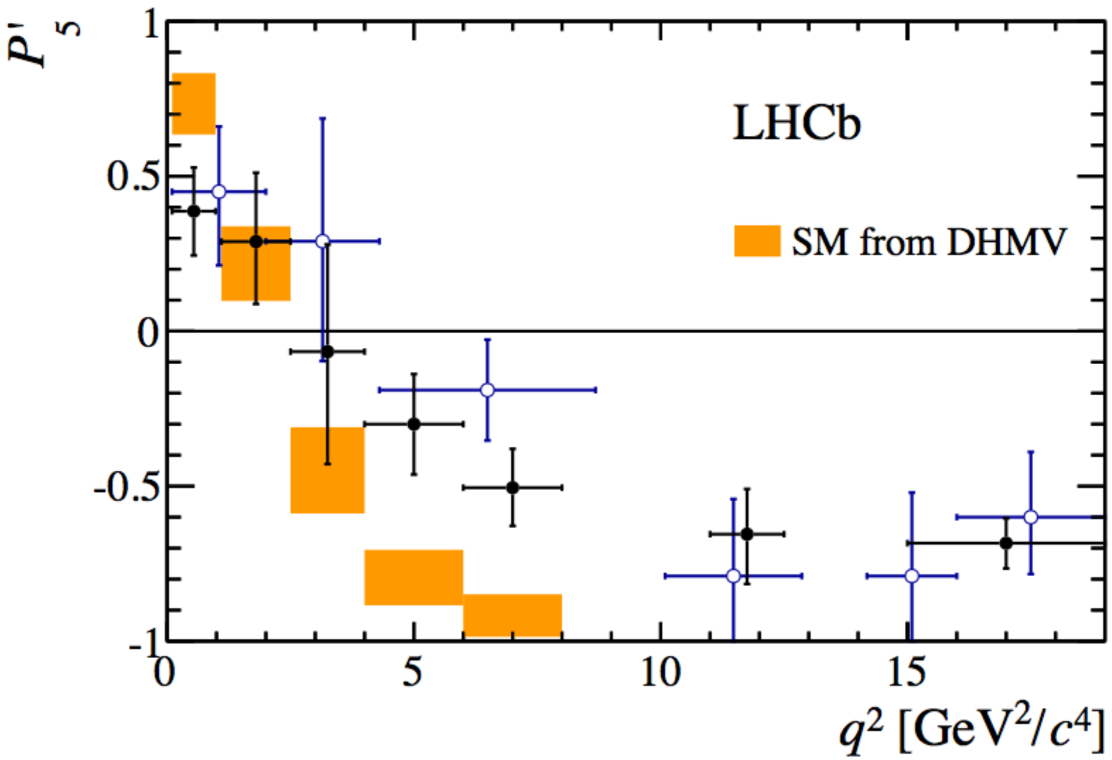
- Tension seen in P_5' in $1 fb^{-1}$ data confirmed with $3 fb^{-1}$:



- $4.0<q^2<6.0$ and $6.0<q^2<8.0$ GeV^2/c^4 bins each show deviations of 2.8σ and 3.0σ respectively

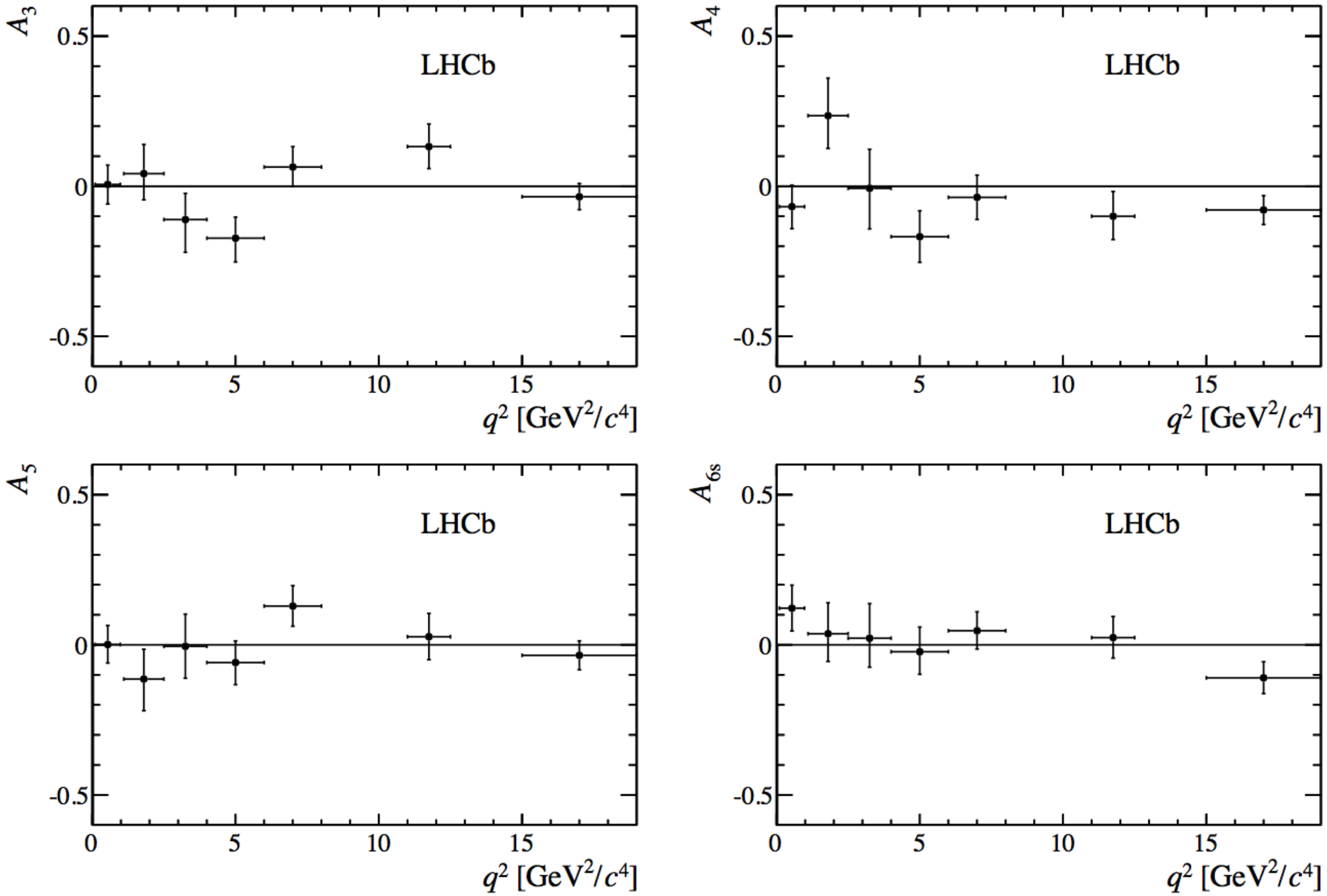
Results: Likelihood, CP-avgd

- Tension seen in P_5' in 1fb^{-1} data confirmed with 3 fb^{-1}:

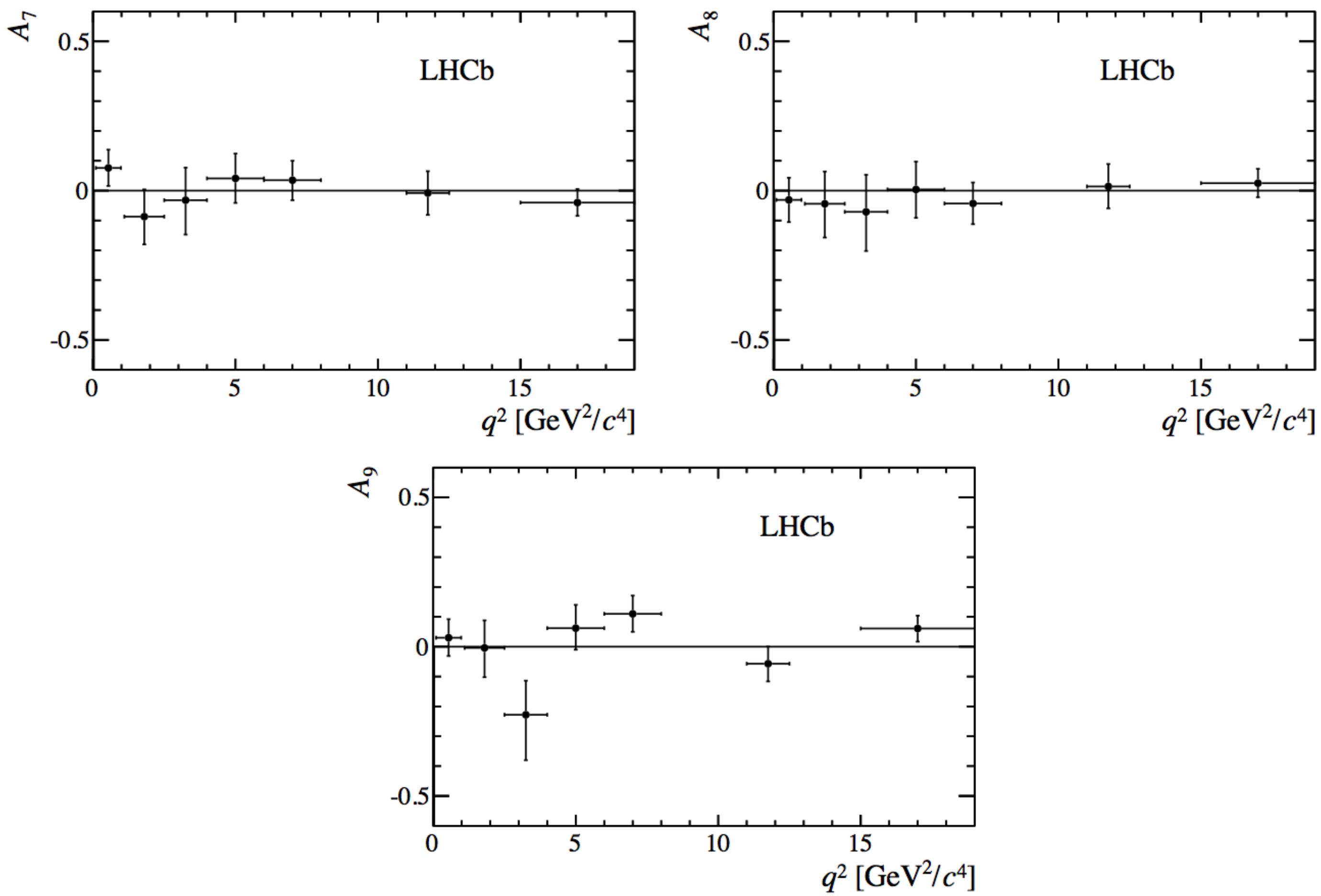


- 4.0<q^2<6.0 and 6.0<q^2<8.0 GeV^2/c^4 bins each show deviations of 2.8σ and 3.0σ respectively

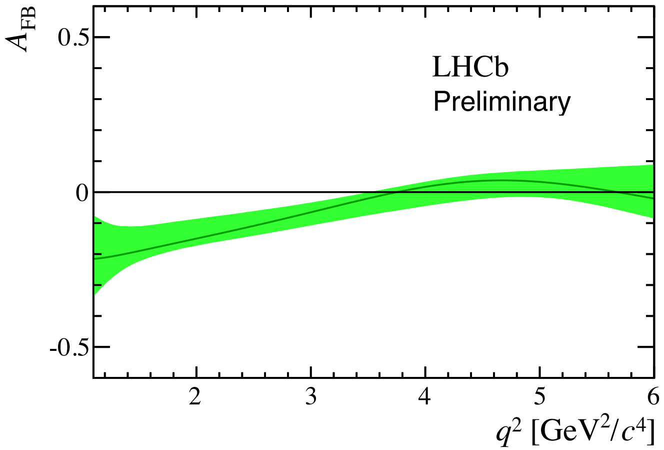
Results: Likelihood, CP-asymm

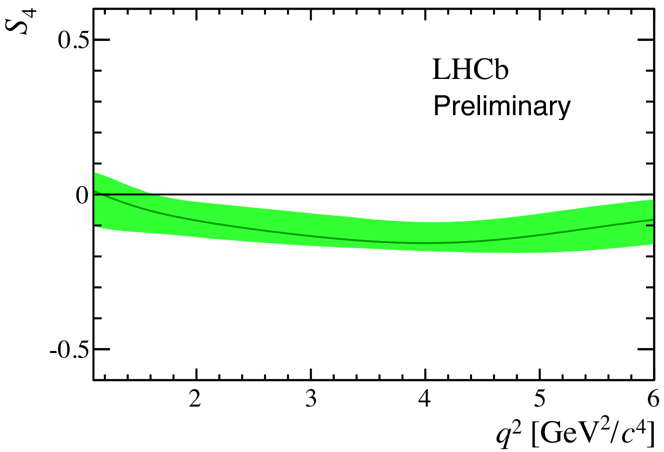


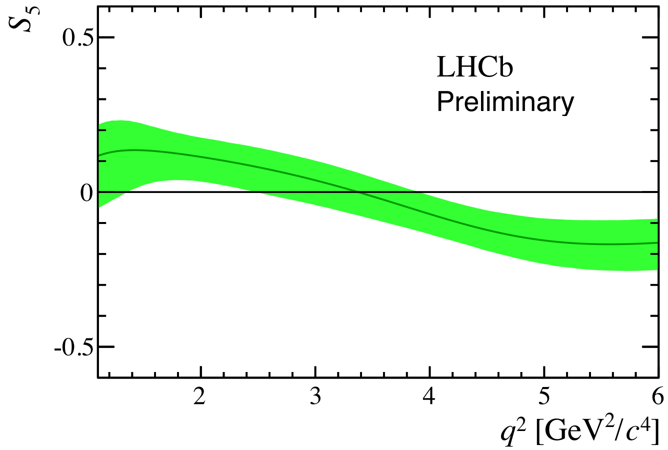
Results: Likelihood, CP-asymm



Zero-crossing points







Zero crossing points:

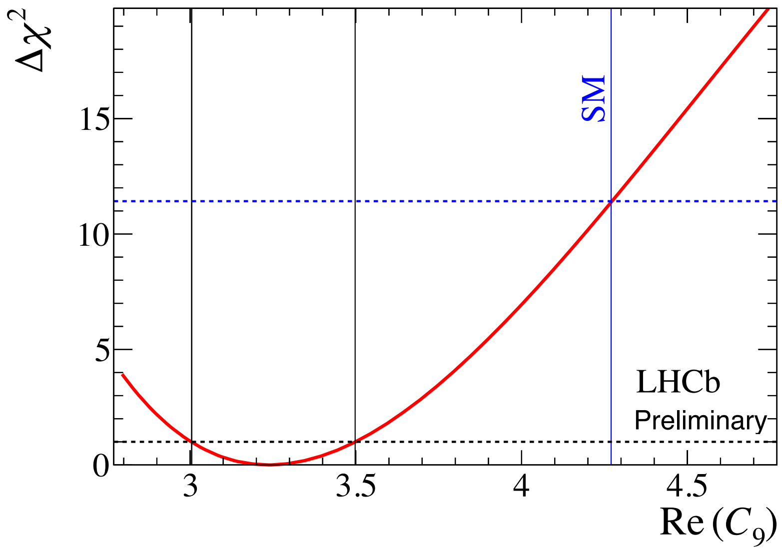
$q_0^2(S_4) < 2.65\,\mathrm{GeV}^2/c^4$ @ 95% CL

$q_0^2(S_5) \in [2.49, 3.95]\,\mathrm{GeV}^2/c^4$ @ 68% CL

$q_0^2(A_{\mathrm{FB}}) \in [3.40, 4.87]\,\mathrm{GeV}^2/c^4$ @ 68% CL

Compatibility with the SM

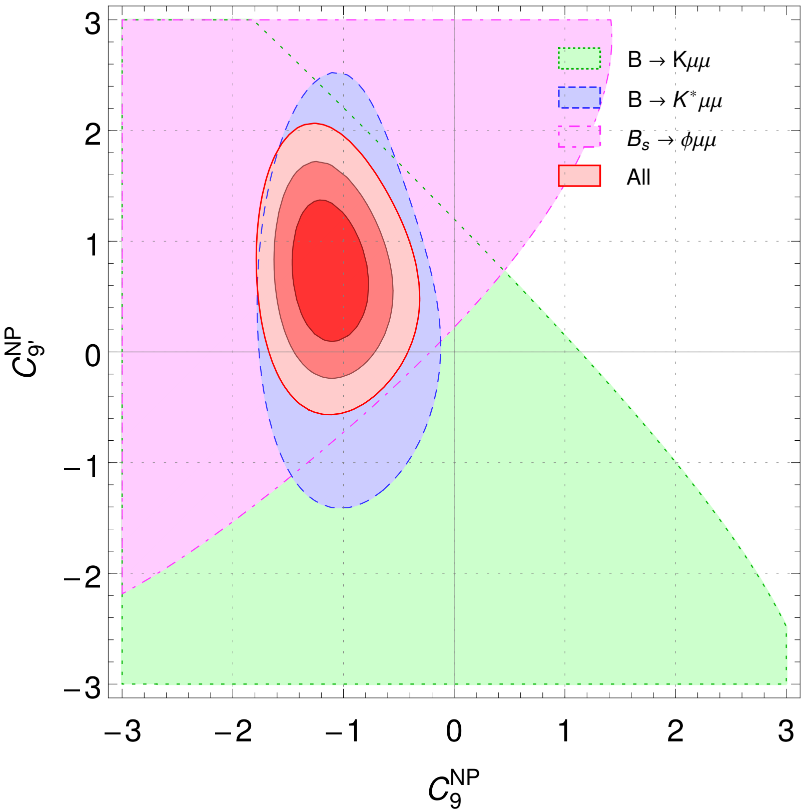
- Use EOS software to check compatibility of CP-averaged angular measurements with SM
- Make χ^2 fit to F_L, A_{FB} and S_3-S_9 in q^2 range <8.0 GeV^2 and in wide bin 15.0<q^2<19.0 GeV^2
- Consider only modification to $Re(C_9^{eff})$
- Find LHCb **CP-averaged angular data *alone*** 3.4σ from SM predictions

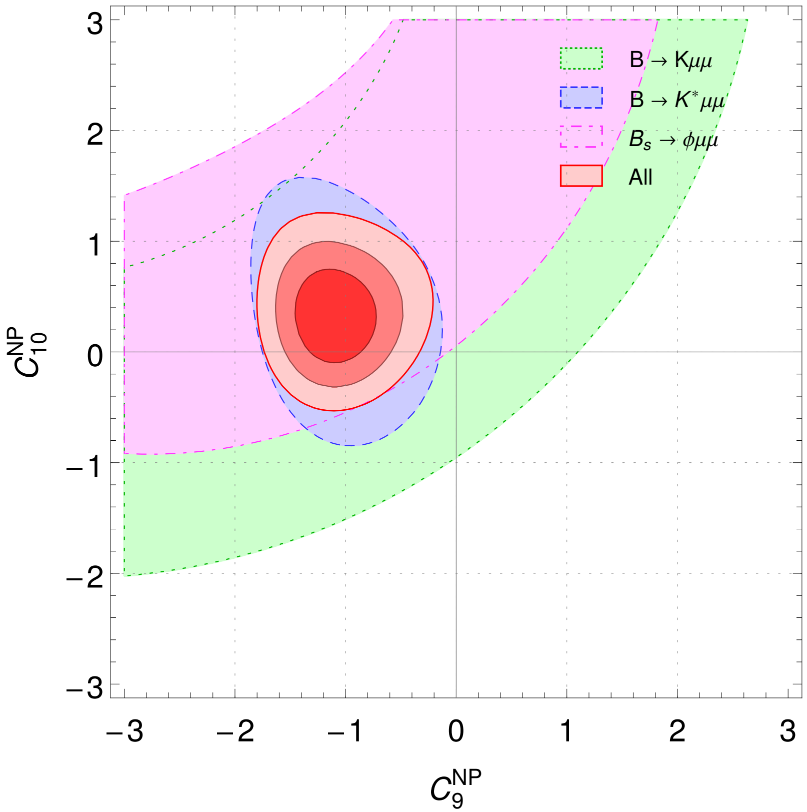


A global fit to all the b→sμμ data

- Global fit to all the (preliminary, Moriond) b→sμμ data gives a solution **4.5σ from SM … !**

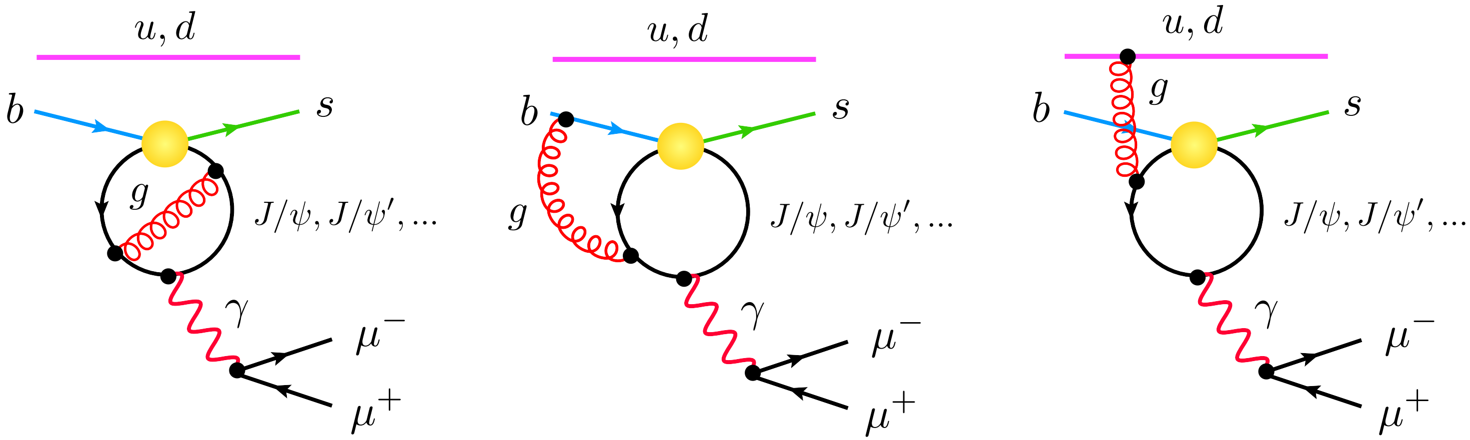
[arXiv:1510.04239]



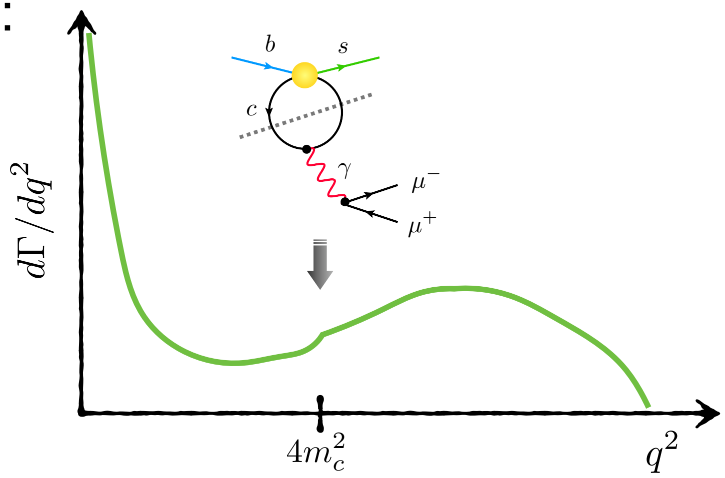


Could the SM errors be wrong?

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



- In an ideal world:



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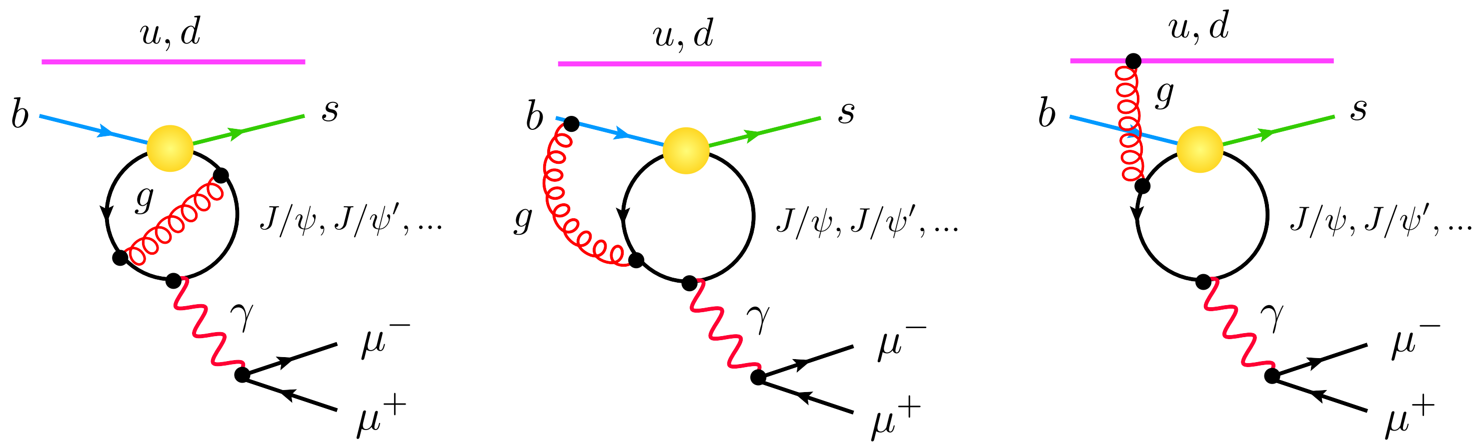
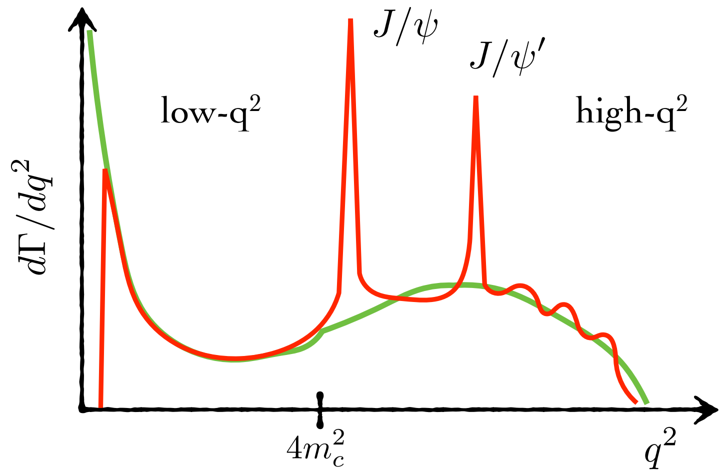


- But in reality:

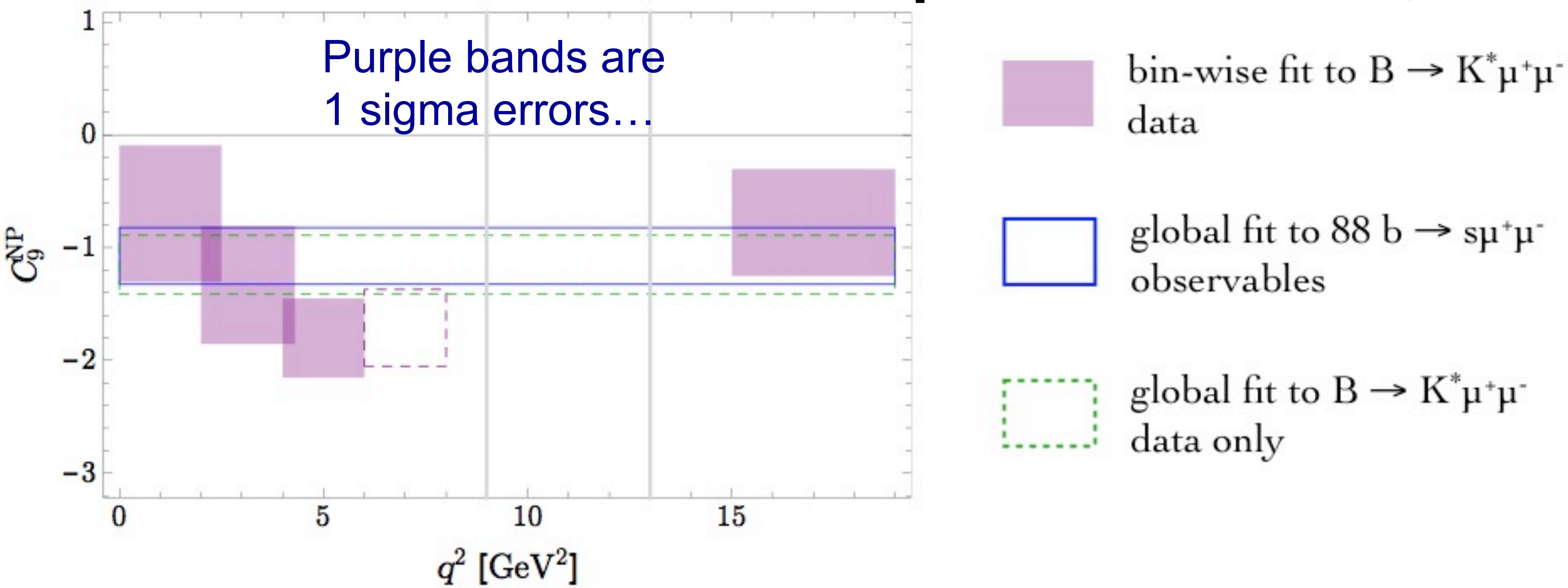


Note however that can't just effect P_5'- would see correlated effect in other observables

Could the SM errors be wrong?

- Try and test for this :
  - If anomalies are due to NP then would expect best-fit values for C_9 to be q^2 independent
  - If instead effect grows towards resonance, could be a $c\bar{c}$ effect

[Altmannshofer & Straub, 1503.06199]



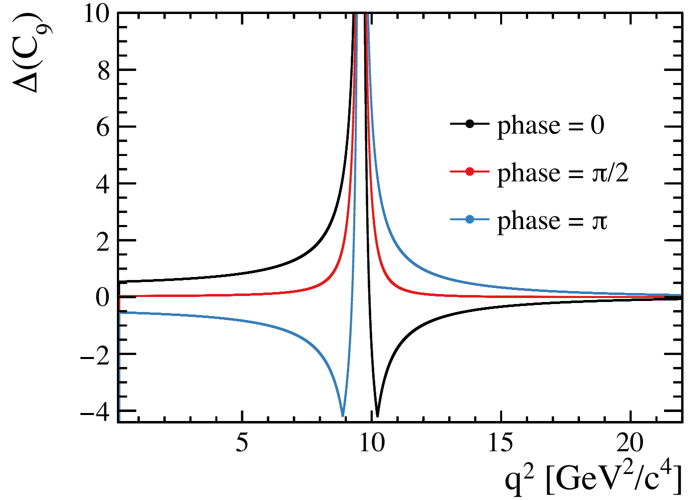
- If is to be explained by $c\bar{c}$, effect needs to “unexpectedly large”

Outline

- A tour of existing LHCb rare decay measurements
  - $B^0 \to \mu\mu$ branching fraction measurements
  - $B_d^0 \to K^{*0}\mu\mu$ angular measurements
  - Other $b \to s\mu\mu$ branching fraction measurements
  - Global fits to $b \to sll$ data
  - Mention a couple of other anomalous results
- (Very) latest $B_d^0 \to K^{*0}\mu\mu$ angular results
  - compatibility with SM
  - Updated global fits
- Some remarks about the future

The future

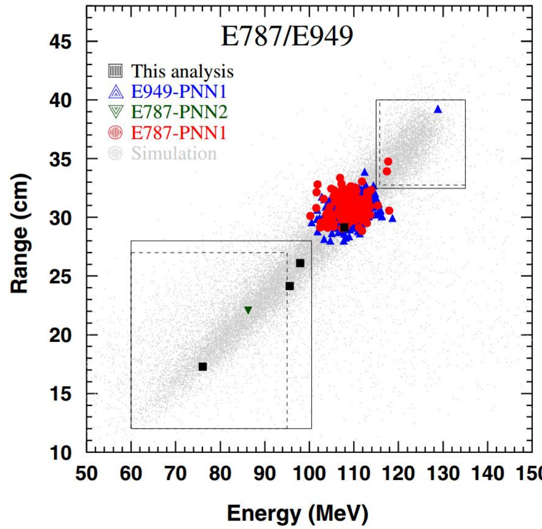
- Will improve the precision of all existing measurements with the Run-II data!
- Can also add new LHCb measurements
  - Add R_{K^*}, R_ϕ, R_Λ (for $b \to c$ equivalent R_D, R_Λ, …), and also the $(K^*, \phi, \Lambda)ee$ angular analyses
  - Can we measure the interference with the J/ψ ?
    - Introduce relevant resonances and try and fit the $m_{\mu\mu}$ distribution – requires very good control of resolution



- Elsewhere:
  - Cleaner EW penguin $B^0 \to K^{*0}\nu\nu$ will be measured at Belle2 – would expect a substantial enhancement from a Z'
  - $K^+ \to \pi^+\nu\nu$ will be measured to 10% at NA62

$B(K^+ \to \pi^+\nu\nu)$ SM pred. $= (9.11 \pm 0.72) \times 10^{-11}$

$B(K^+ \to \pi^+\nu\nu)$ measured. E787/E949 $= (17.30 \pm 11.0) \times 10^{-11}$



Conclusions

The LHCb Experiment: First Results and Prospects

Mitesh Patel (Imperial College London)
The University of Birmingham, 4th May 2011

Outline

- An extended Higgs sector? ($B_d \to \mu^+\mu^-$ and $B_s \to \mu^+\mu^-$)
- New CP violating phases in B_s mixing? (ϕ_s from $B_s \to J/\psi\phi$)
- New particles, couplings? (angular observables in $B_d \to K^*\mu\mu$)
- A whistlestop tour…
- Will try and give you a feel for the prospects in each of these areas
  - Results from 2010 data ~36 pb^{-1}
  - As of yesterday, ~80 pb^{-1} on tape, expectation is ~200 pb^{-1} for summer conferences, ~1 fb^{-1} by the end of the year

2

- The LHCb data has shown up some intriguing anomalies that warrant further experimental and theoretical exploration
- We are eagerly awaiting the Run-II data