Experimental results on b→sll decays

UK Flavour Workshop, September 2013

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On behalf of the LHCb Collaboration

Imperial College London

LHCb

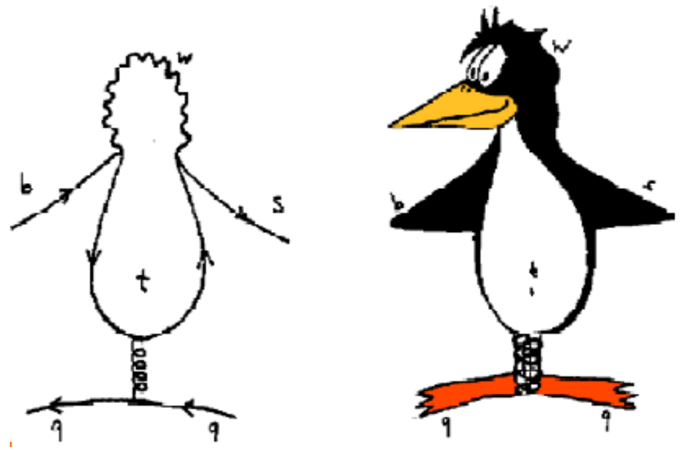
The interest in b→sll decays

- 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

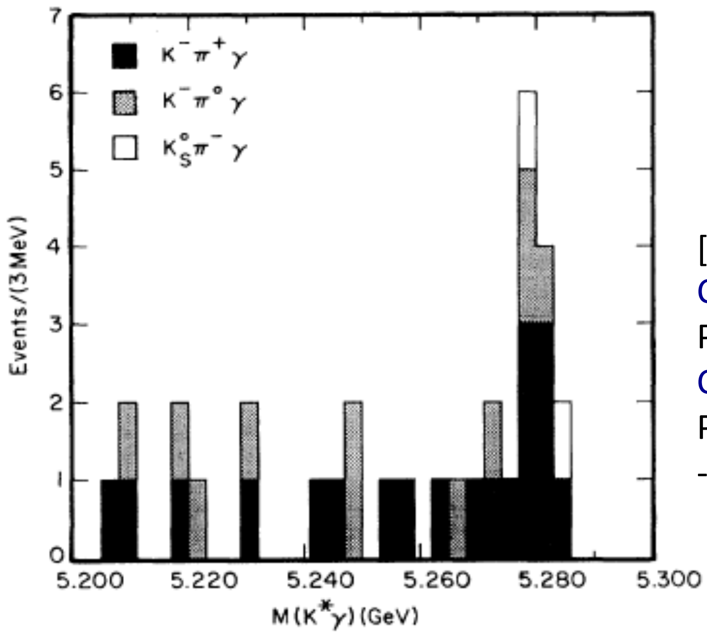
  → Probe masses > E_{CM} of the accelerator

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

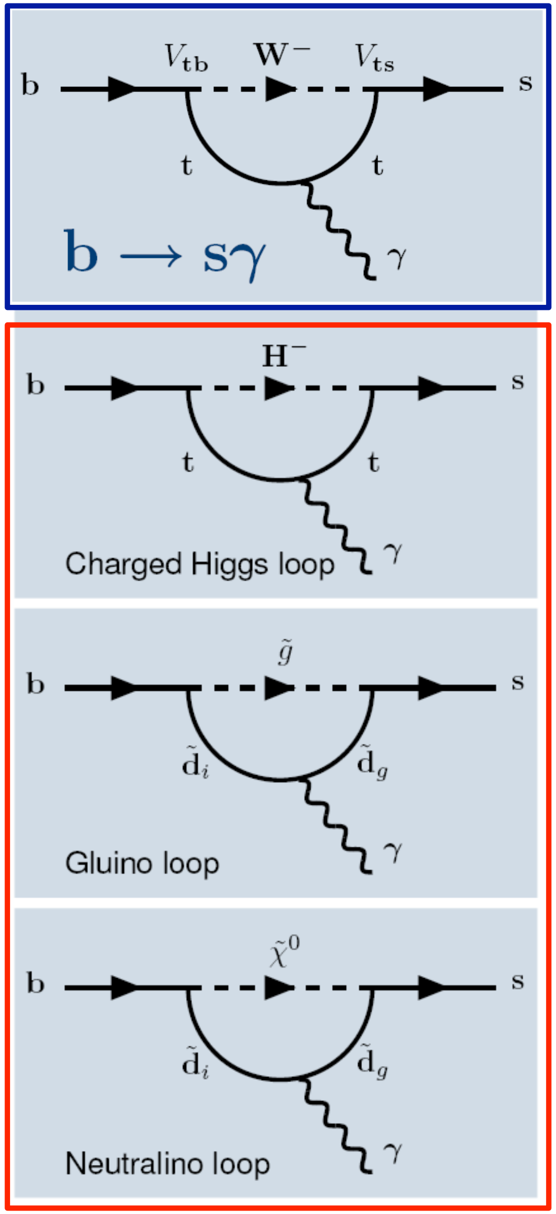


A historical example – $B_d^0 \rightarrow K^{*0}\gamma$

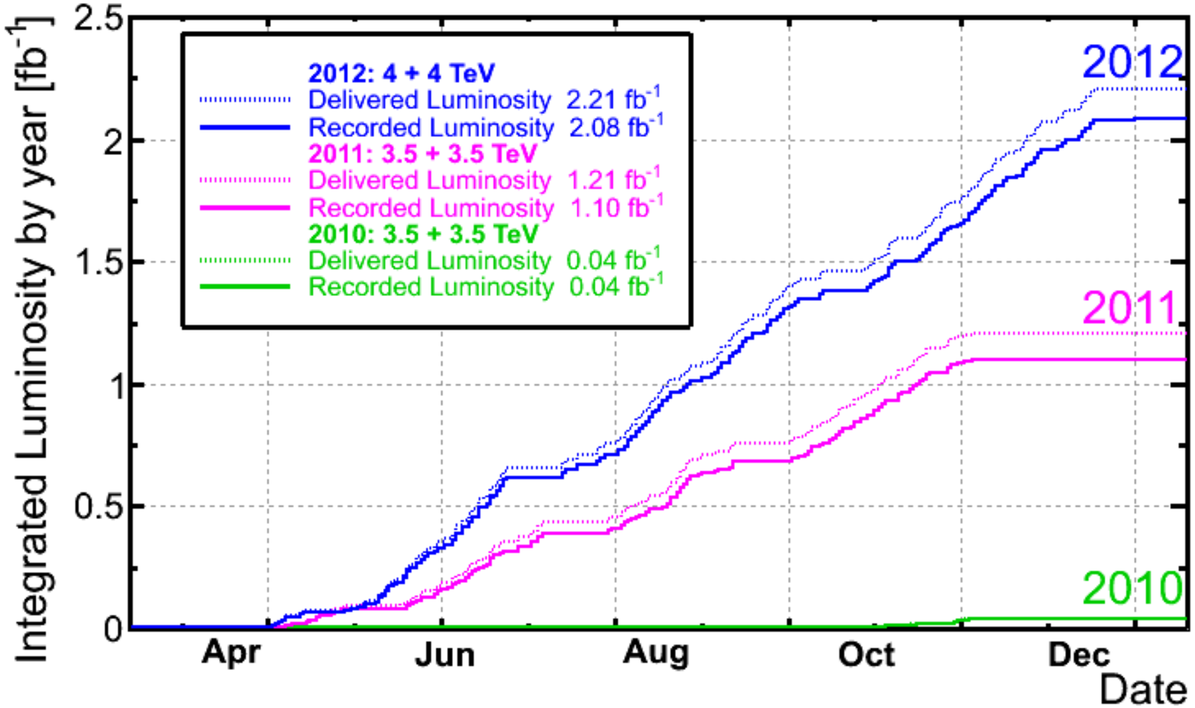
- In SM: occurs through a dominating W-t loop
- Possible NP diagrams:
- Observed by CLEO in 1993, two years before the direct observation of the top quark
  - BR was expected to be $(2\text{-}4)\times 10^{-4}$
  - $\rightarrow$ measured BR = $(4.5\pm 1.7)\times 10^{-4}$



[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]



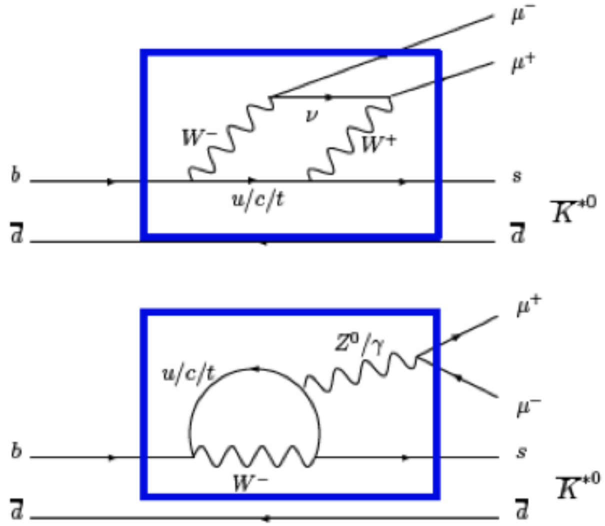
LHCb data-taking

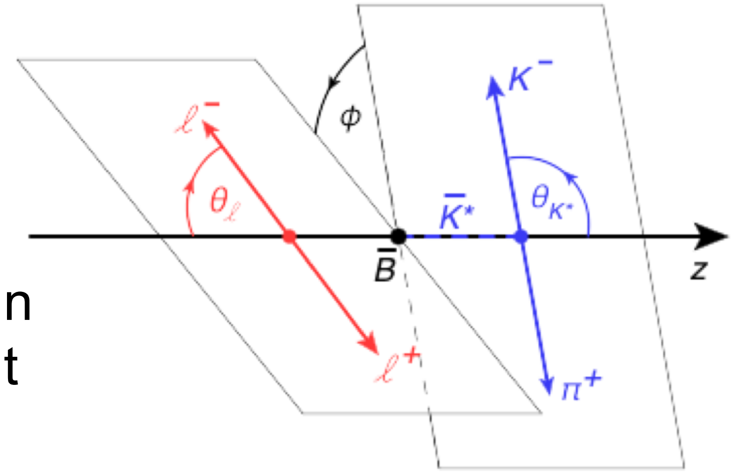


- In total have recorded 3fb^{-1} at instantaneous luminosities of up to 4×10^{32} cm^{-2}s^{-1} (twice the design value!) – results that follow from 1fb^{-1}
- While data-taking from 2015 onward will add substantial luminosity, will not be the step-change from higher $\sqrt{s}$ anticipated at the central detectors – need 2018 upgrade for that step-change

$B_d^0 \rightarrow K^{*0}\mu\mu$

- Flavour changing neutral current → loop
- Sensitive to interference between $O_{7\gamma}$, $O_{9,10}$ and their primed counterparts
- Decay described by three angles, θ_l, θ_K and ϕ, and $q^2 = m^2_{\mu\mu}$, self-tagging → angular analysis allows to probe helicity
- Exclusive decay → theory uncertainty from form factors
- Theorists construct angular observables in which uncertainties cancel to some extent





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

- Full angular distribution can be simplified by applying "folding" technique: $\phi \to \phi+\pi$ for $\phi < 0$:

$$\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} \propto I_1^s\sin^2\theta_K + I_1^c\cos^2\theta_K + \left(I_2^s\sin^2\theta_K + I_2^c\cos^2\theta_K\right)\cos 2\theta_\ell$$
$$+I_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + I_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$
$$+I_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+\left(I_6^s\sin^2\theta_K + I_6^c\cos^2\theta_K\right)\cos\theta_\ell + I_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+I_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + I_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi$$

- Fitting this angular distribution allows access to angular observables where the hadronic uncertainties are under control :
  - F_L, the fraction of K^{*0} longitudinal polarisation
  - A_{FB}, the forward-backward asymmetry – and zero-crossing point
  - $S_3 \propto A^2_T(1-F_L)$, the asymmetry in K^{*0} transverse polarisation
  - A_9, a T-odd CP asymmetry

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

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  $\phi \rightarrow \phi+\pi$ for $\phi < 0$:

$$
\begin{aligned}
\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} \quad \propto \quad & F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K) + \\
& F_L\cos^2\theta_K(2\cos^2\theta_\ell) + \\
& \frac{1}{4}(1-F_L)(1-\cos^2\theta_K)(2\cos^2\theta_\ell - 1) + \\
& S_3(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\phi + \\
& \frac{4}{3}A_{FB}(1-\cos^2\theta_K)\cos\theta_\ell + \\
& A_9\,(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\phi
\end{aligned}
$$

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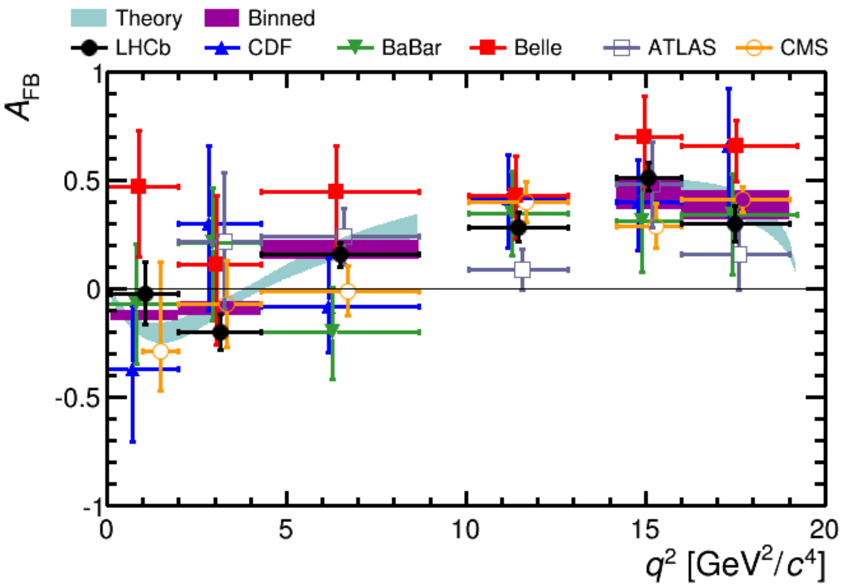
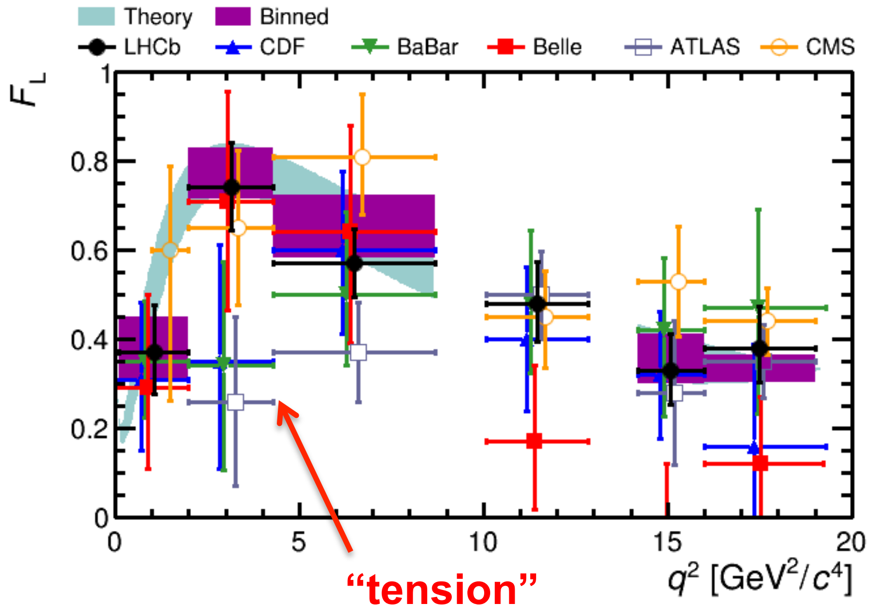
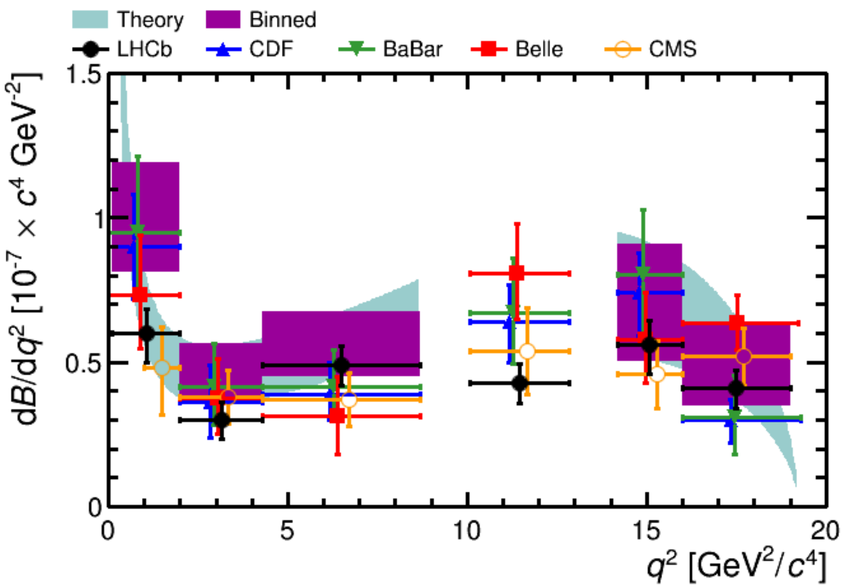
$B_d^0 \to K^{*0}\mu\mu$ – angular observables







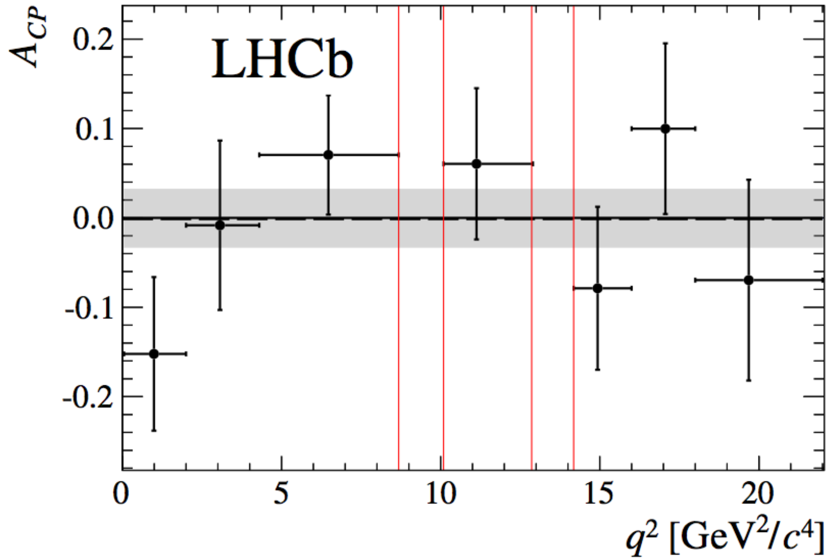
- Good agreement with SM predictions

Theory pred : C. Bobeth *etal.*, JHEP 07 (2011) 067

[CMS: CMS-PAS-BPH-11-009 (5.2 fb^{-1} ; ATLAS: ATLAS-CONF-2013-038 (4.9 fb^{-1}); BELLE: Phys. Rev. Lett. 103 (2009) 171801 (605 fb^{-1}; BABAR: Phys. Rev. D73 (2006) 092001 (208 fb^{-1}); CDF: Phys. Rev. Lett 108 (2012) 081807 (6.8 fb^{-1}) (results from CDF Public Note 10894 (9.6 fb^{-1}) not included) ; LHCb: JHEP08 (2013) 131 (1 fb^{-1})]

A_{CP} in $B_d^0 \to K^{*0}\mu\mu$

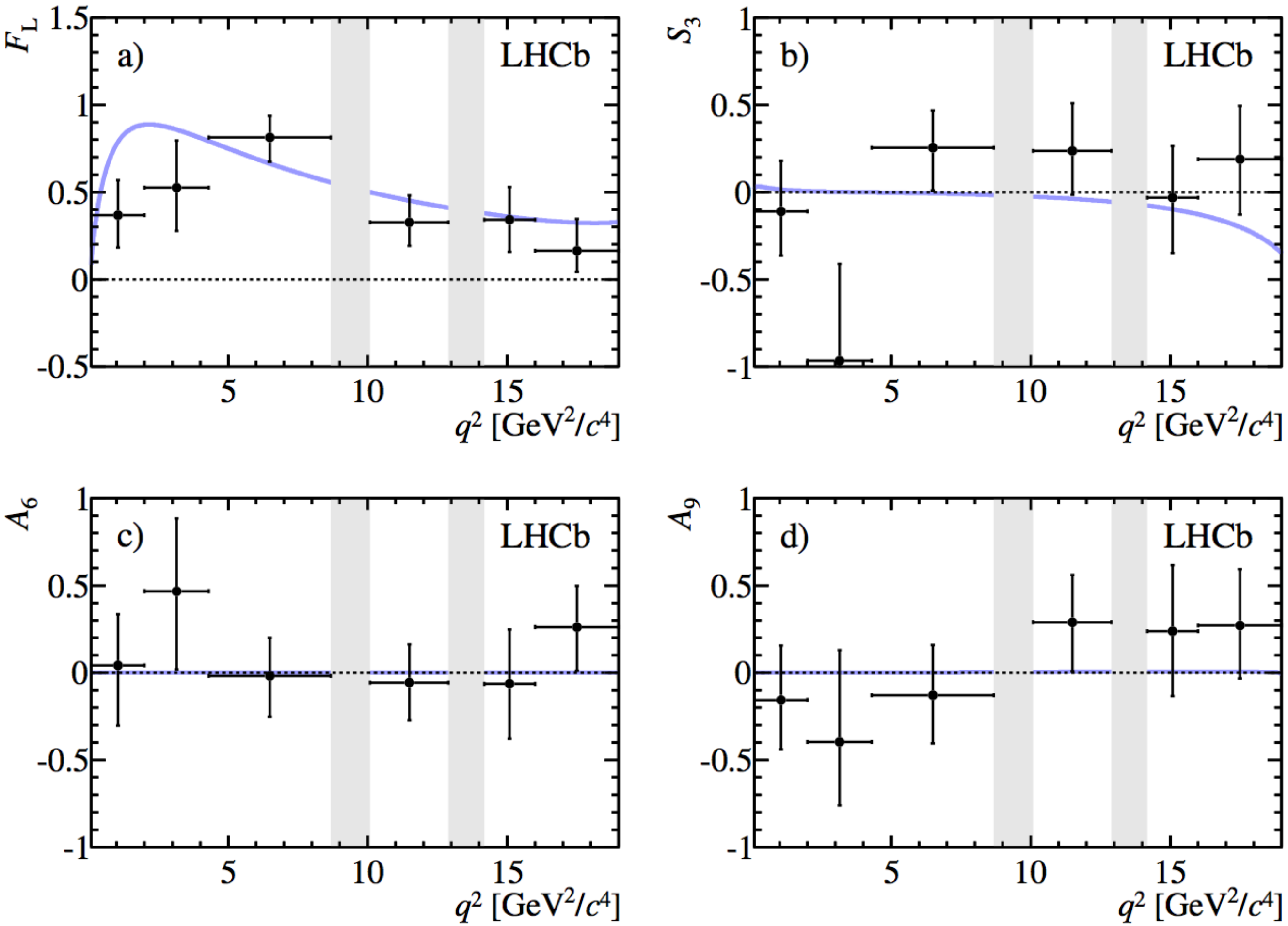
- Have also measured A_{CP} in $B_d^0 \to K^{*0}\mu\mu$
  - Use $B_d^0 \to K^{*0} J/\psi$ control channel, which has same final state, to cancel detector and production asymmetries
  - Use fits to both magnetic field polarities to reduce detector effects



- $A_{CP}(B_d^0 \to K^{*0}\mu\mu) = -0.072 \pm 0.040\ \text{(stat.)} \pm 0.005\ \text{(syst.)}$ [PRL110 (2013) 031801]
- $A_{CP}(B_d^0 \to K^{*0}\mu\mu) = 0.03 \pm 0.13\text{(stat.)} \pm 0.01\text{(syst.)}$ [PRD 86 (2012) 032012]
- $A_{CP}(B_d^0 \to K^{*0}\mu\mu) = -0.10 \pm 0.10\text{(stat.)} \pm 0.01\text{(syst.)}$ [PRL103 (2009) 171801]

$B_s^0 \to \phi\mu\mu$ angular analysis

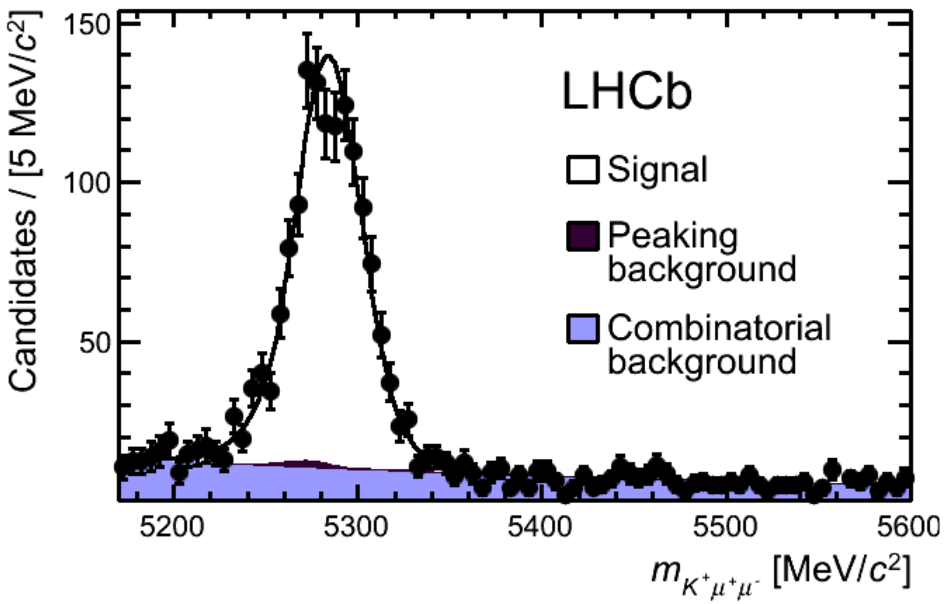
[JHEP 07 (2013) 084]

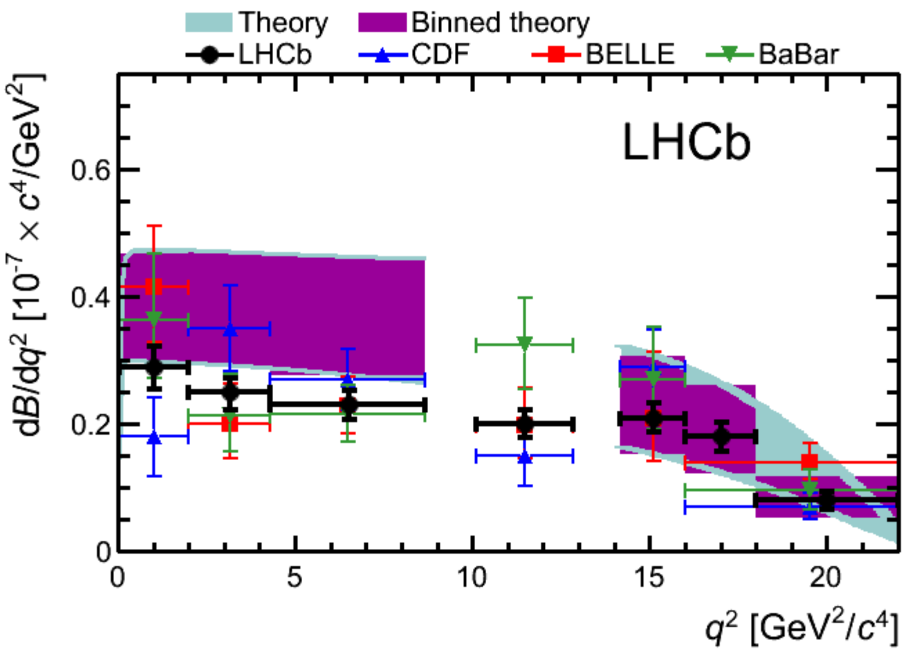


Angular distribution and BF of $B^+ \to K^+ \mu\mu$

[JHEP 02 (2013) 105]

- Have measured angular observables and differential BF in $B^+ \to K^+ \mu\mu$
- BF normalised to $B^+ \to K^+ J/\psi$,
  - $\mathcal{B}(B^+ \to K^+ \mu\mu) = (4.36 \pm 0.15 \pm 0.18) \times 10^{-7}$ cf. world average $(4.8 \pm 0.4) \times 10^{-7}$
- Differential BF :





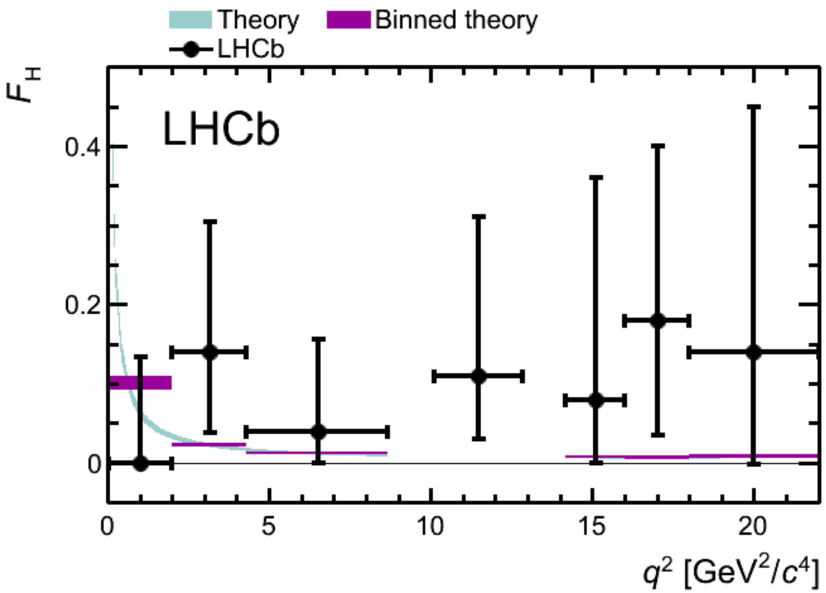
Angular distribution and BF of $B^+ \to K^+\mu\mu$

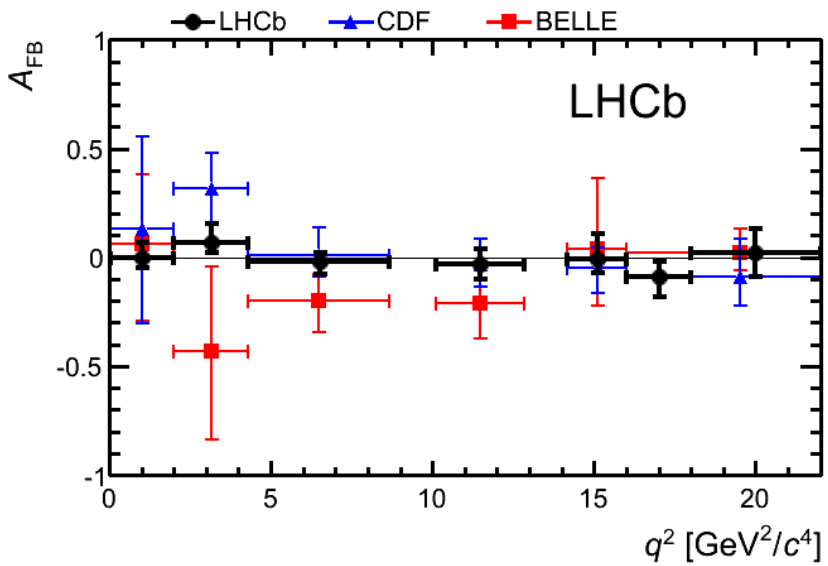
[JHEP 02 (2013) 105]

- Angular distribution is governed by a single angle, described by

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma[B^+ \to K^+\mu^+\mu^-]}{\mathrm{d}\cos\theta_l} = \frac{3}{4}(1-F_{\rm H})(1-\cos^2\theta_l) + \frac{1}{2}F_{\rm H} + A_{\rm FB}\cos\theta_l$$

- Fit for F_H and the dimuon system forward-backward asymmetry A_{FB}
- In SM, $A_{FB}=0$ and $F_H\sim0$
- Measured $A_{CP}= 0.000\pm0.033(\text{stat.})\pm0.005(\text{syst.})\pm0.007(K^+J/\psi)$ [arXiv:1308.1340]

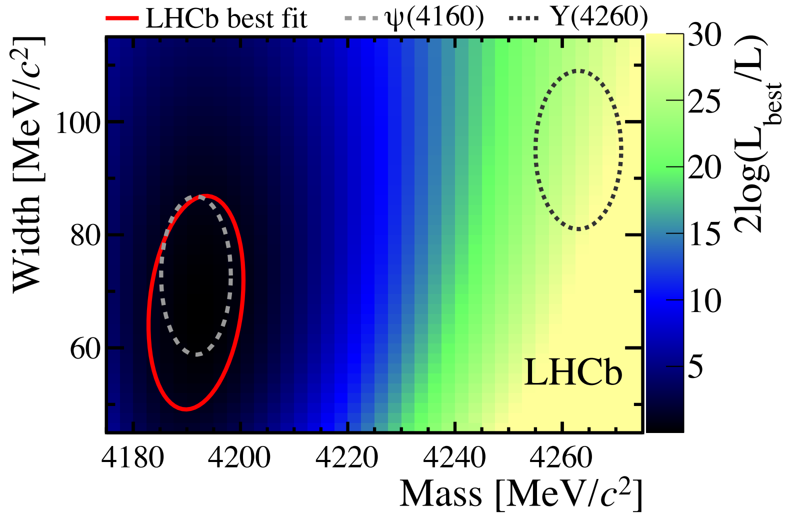


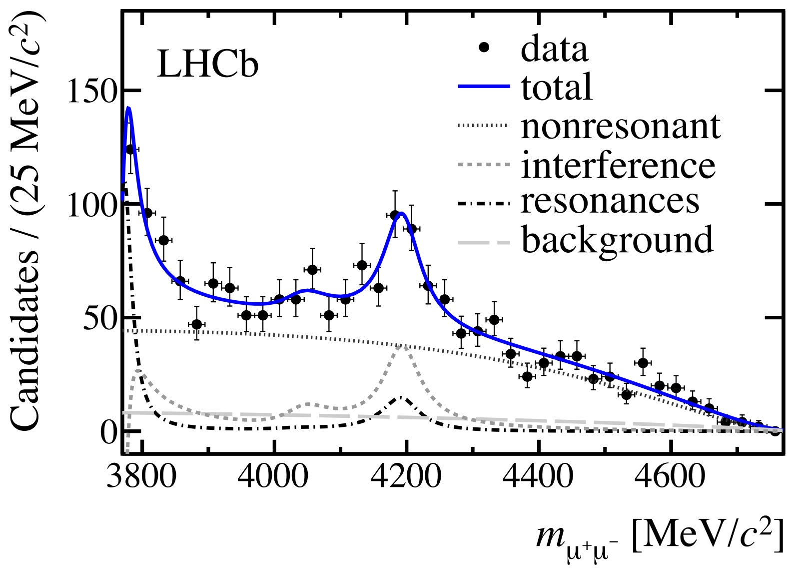


Di-μ resonance in $B^+ \to K^+\mu\mu$

[arXiv:1307.7595]

- Resonance in di-μ system observed at high q^2 in $B^+ \to K^+\mu\mu$ above open charm threshold ($3fb^{-1}$)
- Little known about these resonances – info from BES [PLB660 (2008) 315]
- Unconstrained fit → resonance matches measurements of $\psi(4160)$
- Fit allowing parameters to float within Gaussian uncertainties of BES
- First observation of $\psi(4160) \to \mu\mu$

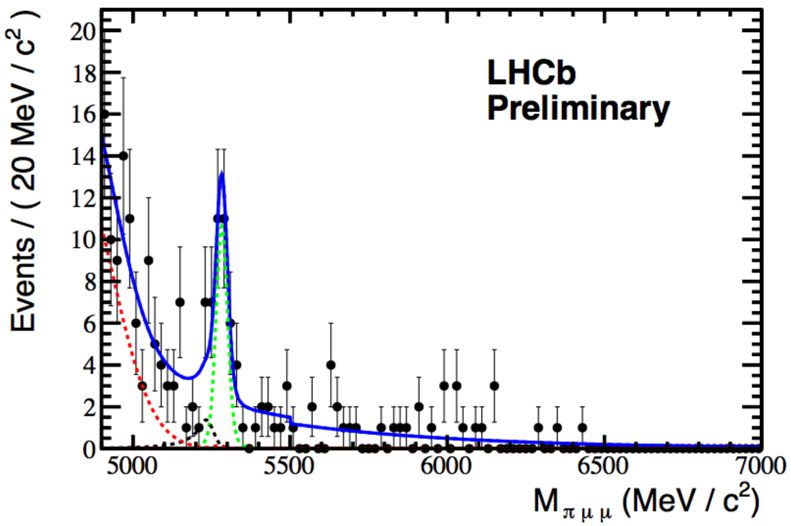


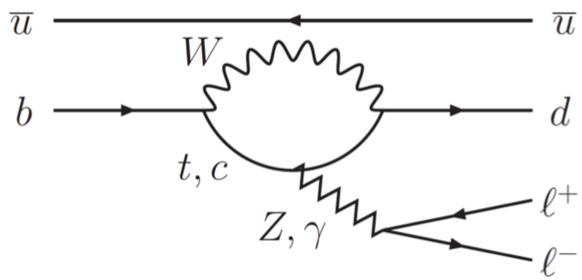


BF of $B^+ \to \pi^+\mu^+\mu^-$

[JHEP 12 (2012) 125]

- The $B^+ \to \pi^+\mu^+\mu^-$ decay is $b \to d$ process cf. $b \to s$ decay $B^+ \to K^+\mu^+\mu^-$
- In SM, BF suppressed by $|V_{ts}/V_{td}|^2$
- With 1.0 fb^{-1} LHCb finds $25.3^{+6.7}_{-6.4}$ $B^+ \to \pi^+\mu^+\mu^-$ signal events
  - 5.2σ excess above background





- $B(B^+ \to \pi^+\mu^+\mu^-) = (2.3 \pm 0.6(\text{stat}) \pm 0.1(\text{syst})) \times 10^{-8}$, within 1σ of SM pred.

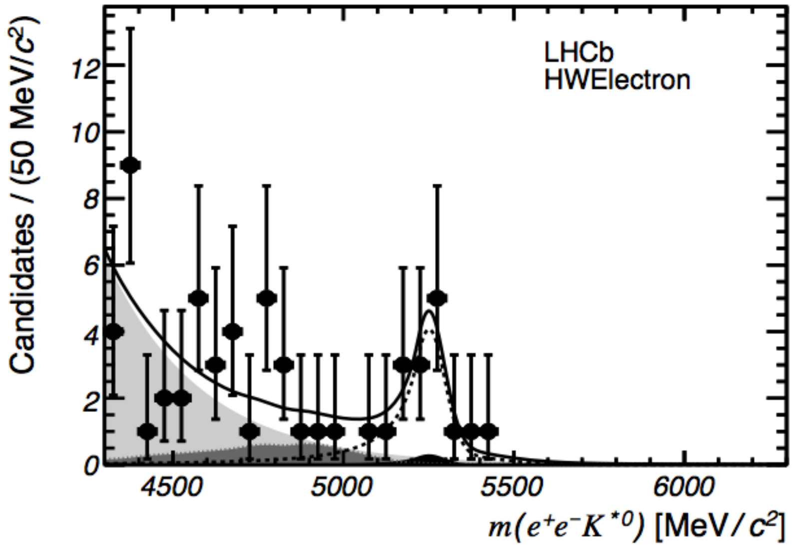
$B_d^0 \to K^{*0} e^+ e^-$

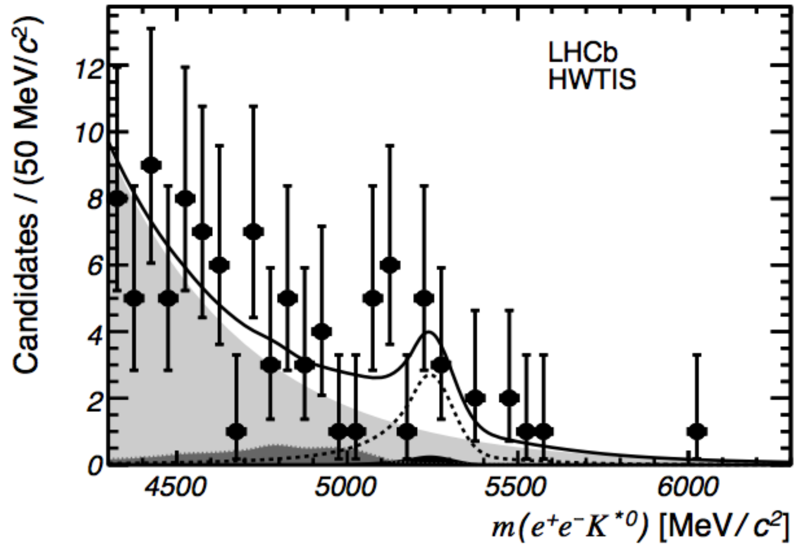
[arXiv:1304.3035]

- Although $B(B_d^0 \to K^{*0}\gamma)$ in agreement with SM prediction there could still NP contributions giving e.g. contribution from right-handed γ
- Can explore this through angular analysis of low q^2 region- electron modes allows to go lower than muon equivalent with no complications from mass terms
- At present have just measured branching fraction:

$$B(B_d^0 \to K^{*0} e^+ e^-)_{30-1000\ \mathrm{MeV}/c^2} = (3.1^{+0.9}_{-0.8}) \times 10^{-7}$$

- Longer term will be able to measure the ratio between the electron and muon modes, R_K, sensitive to e.g. Higgs contributions

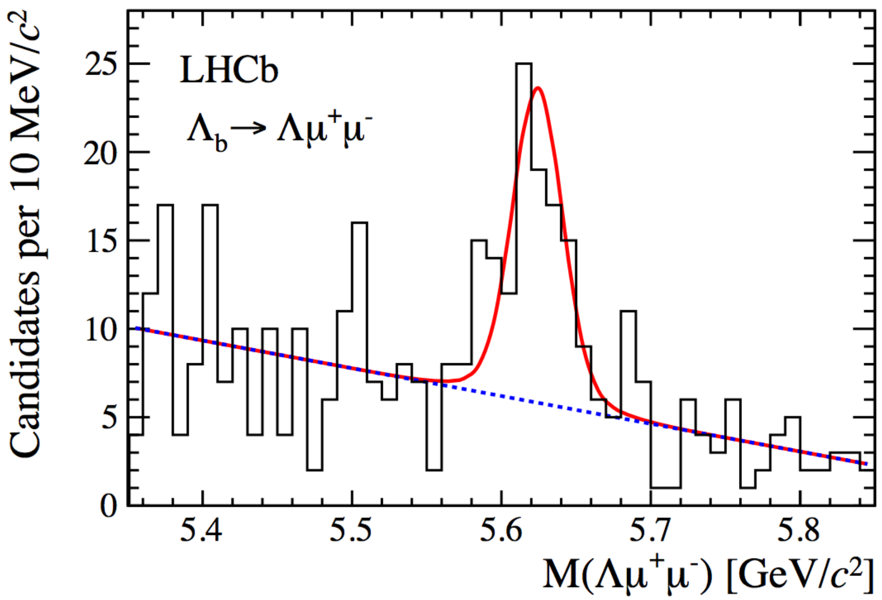


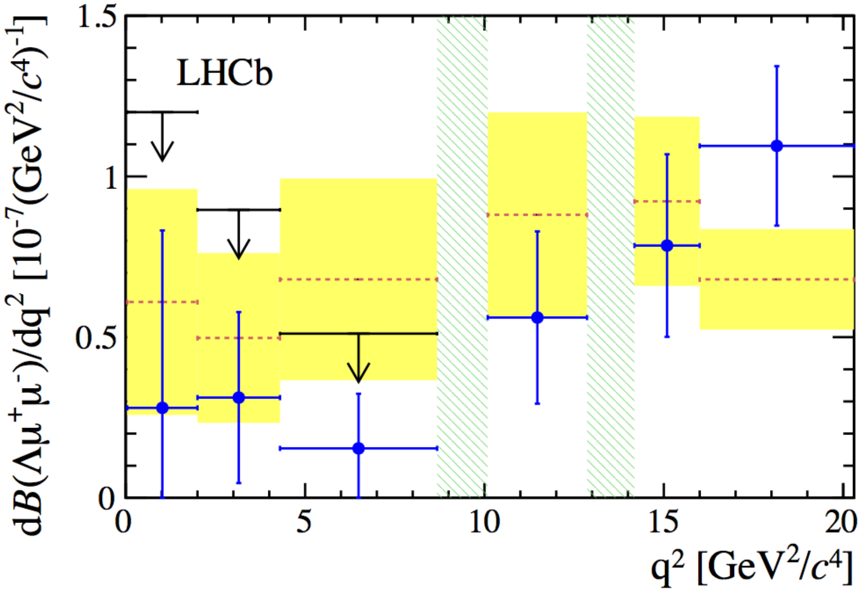


$\Lambda_B^0 \rightarrow \Lambda^0 \mu\mu$

[arXiv:1306.2577]

- Λ_B^0 has non-zero spin → can allow a different probe of the helicity structure of the $b \rightarrow s$ transition
- Observe 78±12 $\Lambda_B^0 \rightarrow \Lambda^0 \mu\mu$ decays
- Significant signal is found in the q^2 region above the J/ψ resonance → measure branching fraction
- At lower-q^2 values upper limits are set on the differential branching fraction





The picture from b→sll decays

- b→sll results are in excellent agreement with SM predictions
  - $B_d^0 \to K^{*0}\mu\mu$ angular analysis
  - Same techniques used for other electroweak penguin measurements – A_{CP} in $B_d^0 \to K^{*0}\mu\mu$ and $B^+ \to K^+\mu\mu$, angular analysis of $B_s^0 \to \phi\mu\mu$ and $B^+ \to K^+\mu\mu$ all also show excellent agreement with SM

  → Experimental methodology well-validated- no surprises across a range of observables and channels

[G. Isidori *etal.*]

- From $\Delta F=2$ (mixing) processes:

$$M(B_d\text{–}\bar{B}_d) \sim \frac{(y_t^2 V_{tb}^* V_{td})^2}{16\pi^2 m_t^2} + c_{NP}\frac{1}{\Lambda^2}$$

c_{NP}:

- $\sim 1 \xrightarrow{\text{tree/strong + generic flavor}} \Lambda \gtrsim 2\times10^4$ TeV [K]
- $\sim 1/(16\pi^2) \xrightarrow{\text{loop + generic flavor}} \Lambda \gtrsim 2\times10^3$ TeV [K]
- $\sim (y_t V_{ti}^* V_{tj})^2 \xrightarrow{\text{tree/strong + “alignment”}} \Lambda \gtrsim 5$ TeV [K & B]
- $\sim (y_t V_{ti}^* V_{tj})^2/(16\pi^2) \xrightarrow{\text{loop + “alignment”}} \Lambda \gtrsim 0.5$ TeV [K & B]

- Number of theory analyses use e.g. $B_d^0 \to K^{*0}\mu\mu$ angular observable measurements to place constraints on scale of new physics, depending on assumptions about coupling strength […]

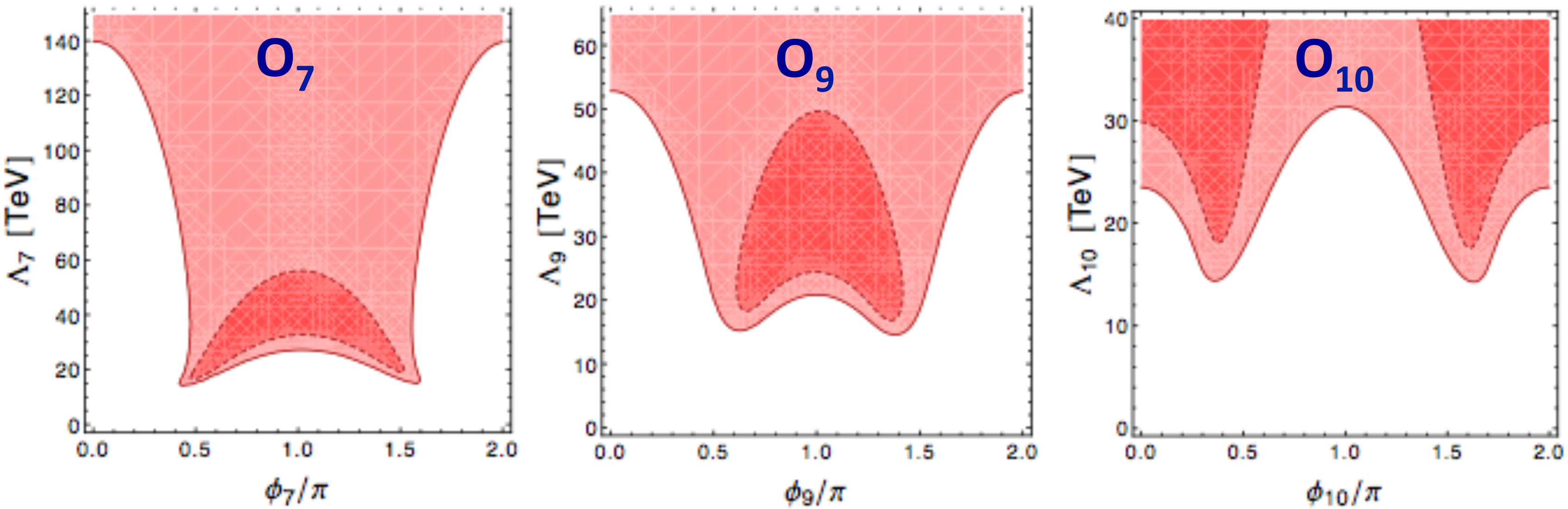
Impact – with tree level FV

[Altmannshofer *etal.*, arXiv:1111.1257, JHEP 1202:106]

- Together with other EW penguin measurements, these results confirm in $\Delta F=1$ transitions the picture we have from $\Delta F=2$ (mixing):

$$\mathscr{L} = \mathscr{L}_{SM} + \sum_{j=7,9,10} \frac{e^{i\phi_j}}{\Lambda_j^2} \mathcal{O}_j$$

~tree level generic flavour violation



(Analysis doesn't include $A_{CP}(B_d^0 \to K^{*0}\mu\mu)$, $B^+ \to K^+\mu\mu$, $B_s^0 \to \phi\mu\mu$, ...)

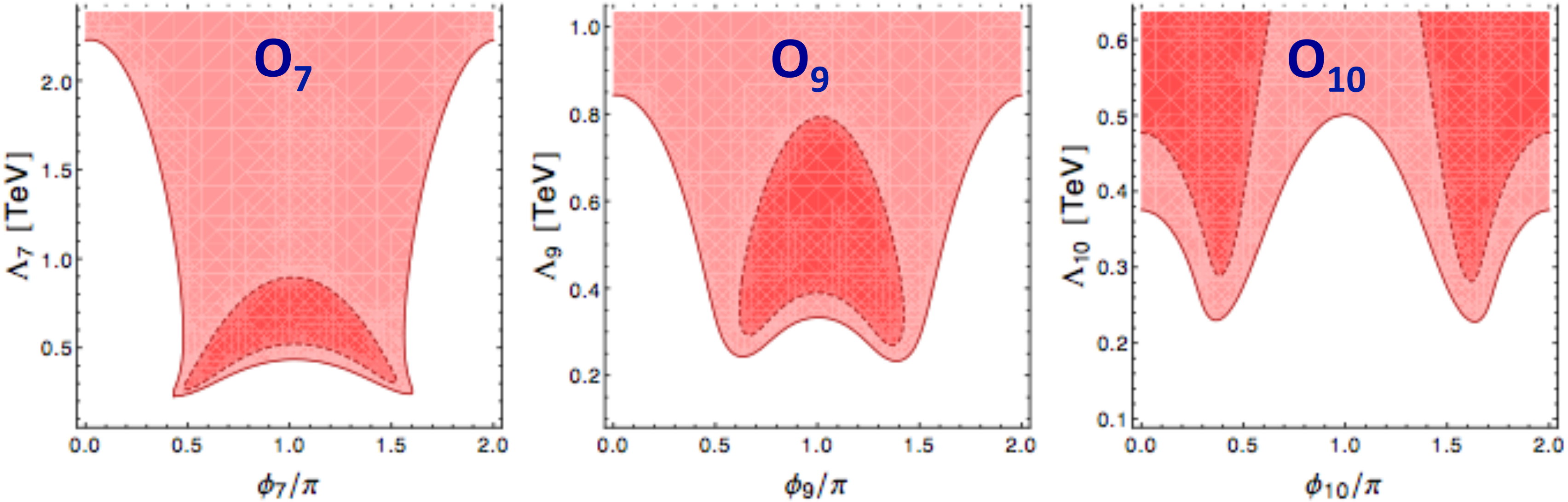
Impact – with loop CKM-like FV

[Altmannshofer *etal.*, arXiv:1111.1257, JHEP 1202:106]

- Together with other EW penguin measurements, these results confirm in $\Delta F=1$ transitions the picture we have from $\Delta F=2$ (mixing):

$$\mathcal{L} = \mathcal{L}_{SM} - \sum_{j=7,9,10} \frac{V_{tb}V_{ts}^*}{16\pi^2} \frac{e^{i\phi_j}}{\Lambda_j^2} \mathcal{O}_j$$

~loop level CKM-like flavour violation



→ NP > 10TeV or NP mimics Yukawa couplings (MFV)

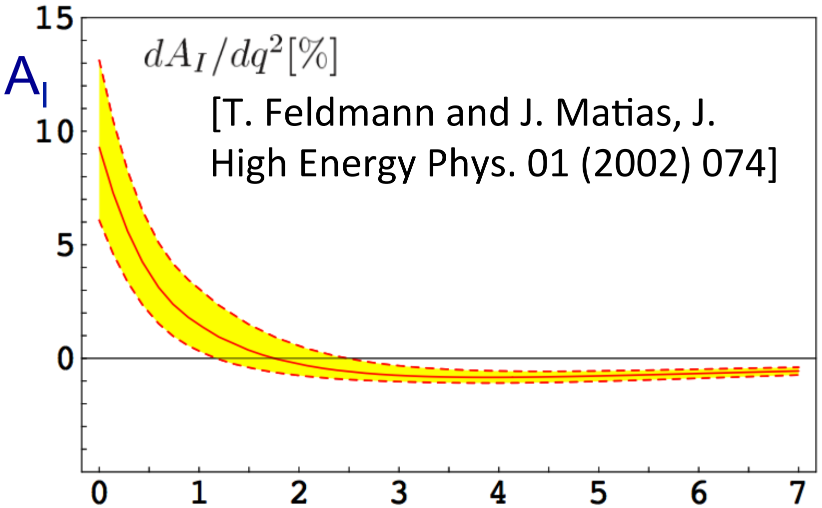
Isospin Asymmetry in $B \to K^{(*)}\mu^+\mu^-$

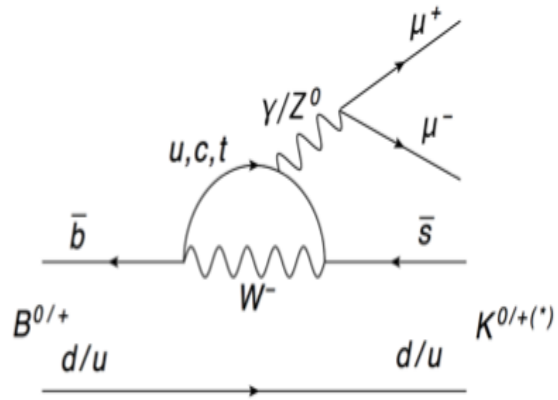
- The isospin asymmetry of $B \to K^{(*)}\mu^+\mu^-$, A_I is defined as:

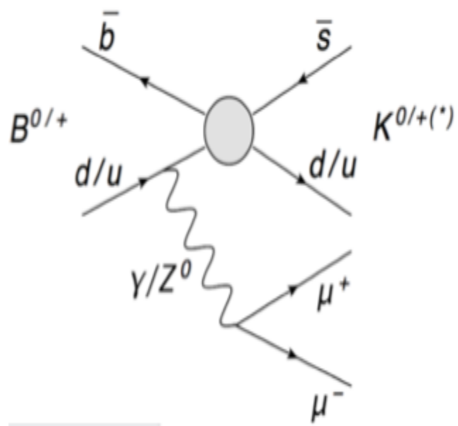
$$A_I = \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - \frac{\tau_0}{\tau_+}\mathcal{B}(B^\pm \to K^{(*)\pm}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + \frac{\tau_0}{\tau_+}\mathcal{B}(B^\pm \to K^{(*)\pm}\mu^+\mu^-)}$$

can be more precisely predicted than the branching fractions

- A_I is expected to be very close to zero in the SM e.g. for $B \to K^*\mu^+\mu^-$:







- A_I=(5.2±2.6)% has been measured in $K^*\gamma$ decay modes, agrees with SM

Isospin Asymmetry in $B \to K^{(*)}\mu^+\mu^-$

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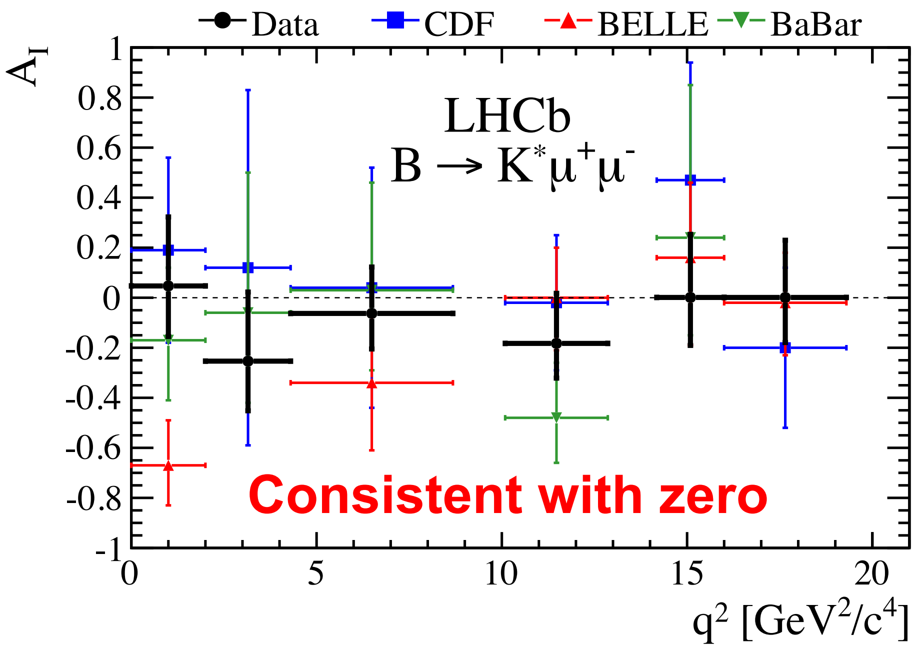
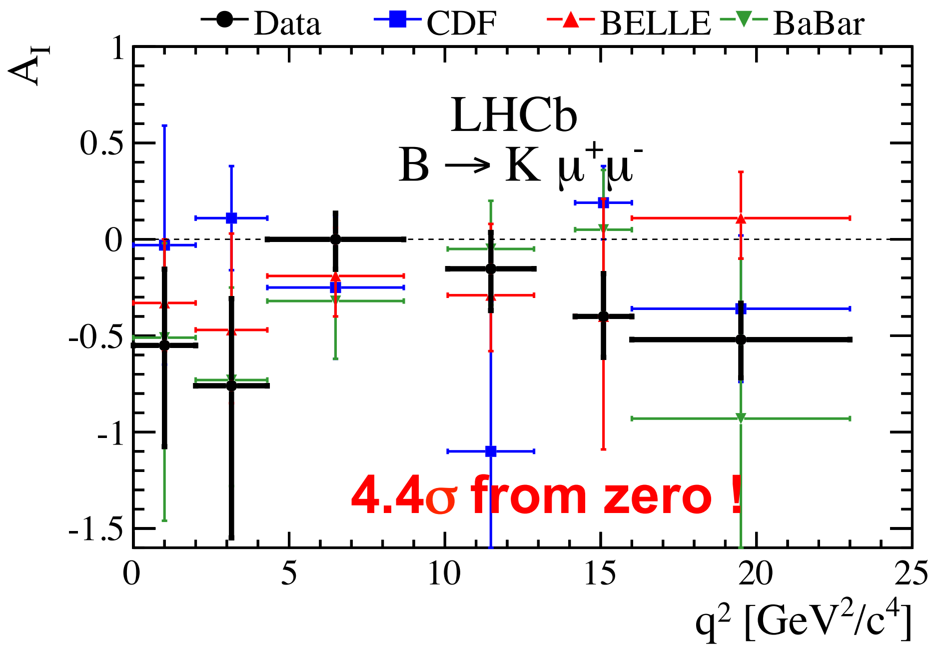
can be more precisely predicted than the branching fractions

- 2012 LHCb data should allow errors to be halved

[JHEP 07 (2012) 133]





$B_d^0 \rightarrow K^{*0}\mu\mu$ – new observables

- Can make alternative transformations of full angular distribution in order to access other (form-factor insensitive) observables

  e.g. $\phi \rightarrow -\phi$ (if $\phi<0$) and $\theta_l \rightarrow \pi-\theta_l$ (if $\theta_l < \pi/2$) gives access to P_5' (or S_5)

$$\frac{1}{\Gamma}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi} = \frac{9}{8\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell -$$
$$F_L\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi +$$
$$\sqrt{F_L(1-F_L)}P_5'\sin 2\theta_K\sin\theta_\ell\cos\phi\Big]$$

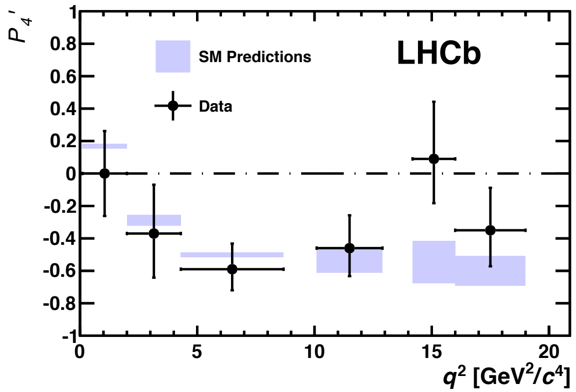
- Other transformations give access to $P_{4,6,8}'$

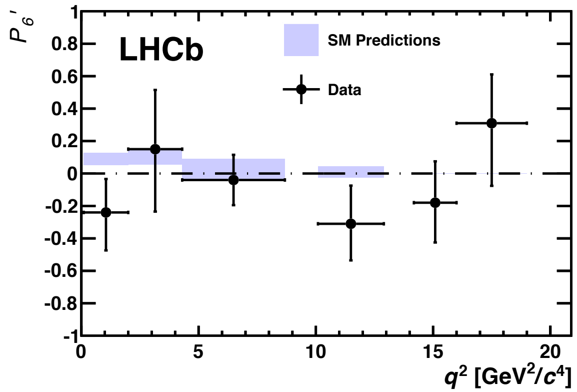
- Intriguing results from $1fb^{-1}$ measurements of these observables…

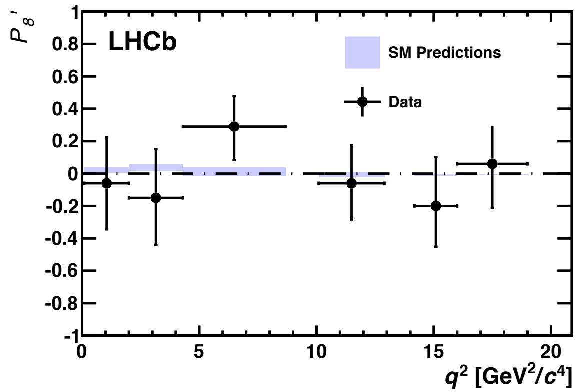
$B_d^0 \to K^{*0}\mu\mu$ – new observables

[arXiv:1308.1707]

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

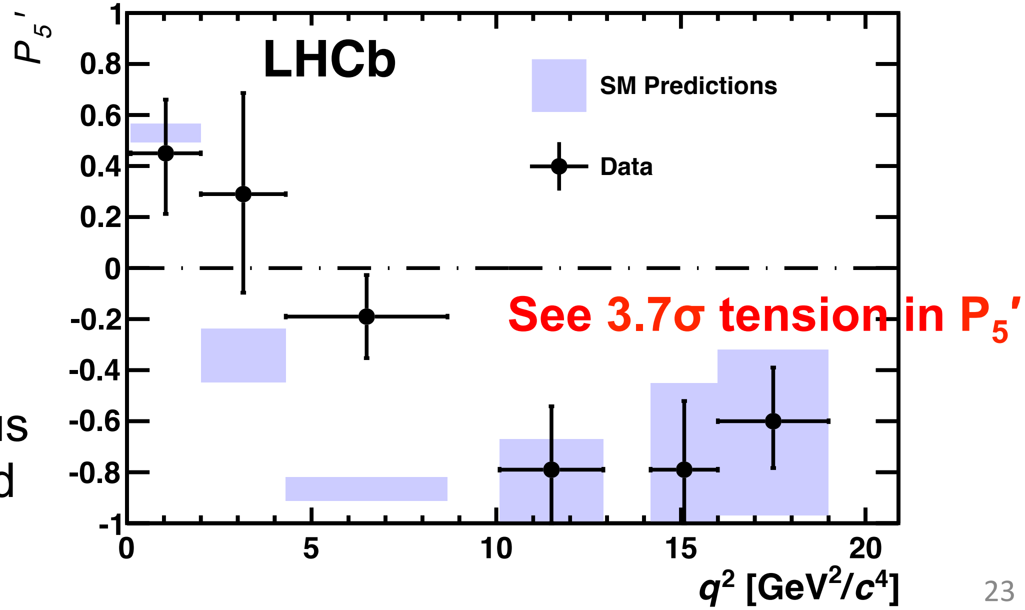






- 0.5% probability to see such a deviation with 24 independent measurements

- Finding a consistent NP explanation is highly non-trivial: prev. $B_d^0 \to K^{*0}\mu\mu$ observables plus $B_S^0 \to \mu\mu$, $B \to K\mu\mu$, $B \to X_s\gamma$ depend on same short-distance physics



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

- Descotes-Genon *etal*. combine the LHCb measurements with constraints from $B \to X_s\gamma$, $B \to X_s\mu^+\mu^-$, $B \to K^*\gamma$, $B_s^0 \to \mu^+\mu^-$ [arXiv:1307.5683]

- Consistent with negative NP contribution to C_9 (4.5σ from SM using low q^2 data (3.7σ using both high and low q^2 data))

- Conclude deviation observed does not create any tension with other flavour observables

- Suggest could be generated by Z'

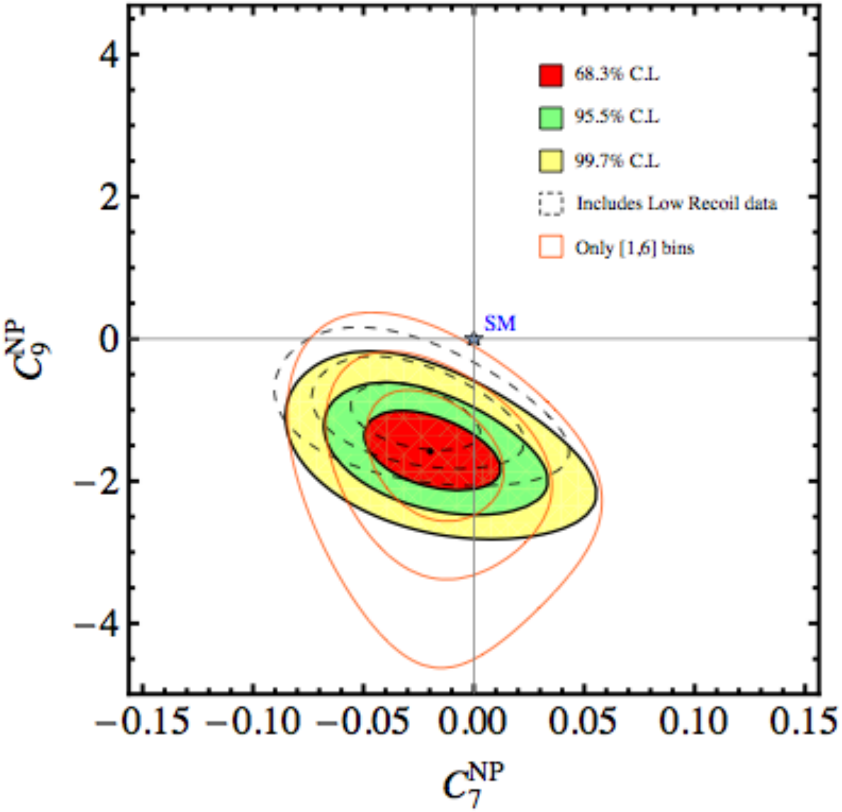
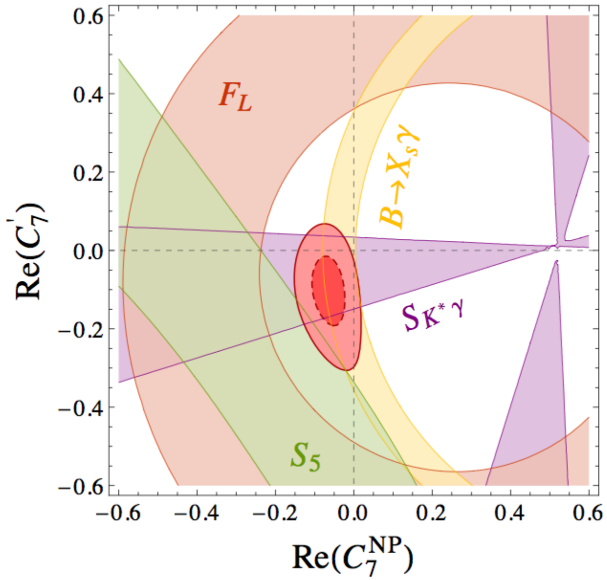
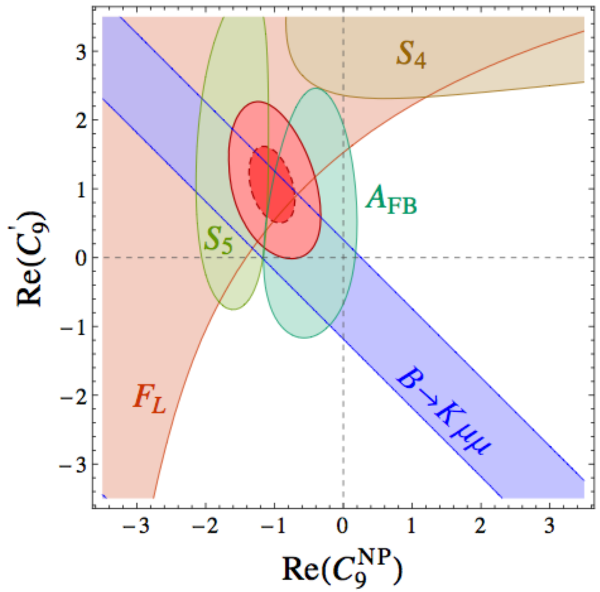


FIG. 1: Fit to $(\mathcal{C}_7^{\rm NP}, \mathcal{C}_9^{\rm NP})$, using the three large-recoil bins for $B \to K^*\mu^+\mu^-$ observables, together with $B \to X_s\gamma$, $B \to X_s\mu^+\mu^-$, $B \to K^*\gamma$ and $B_s \to \mu^+\mu^-$. The dashed contours include both large- and low-recoil bins, whereas the orange (solid) ones use only the 1-6 GeV^2 bin for $B \to K^*\mu^+\mu^-$ observables. The origin $\mathcal{C}_{7,9}^{\rm NP} = (0,0)$ corresponds to the SM values for the Wilson coefficients $\mathcal{C}_{7\rm eff,9}^{\rm SM} = (-0.29, 4.07)$ at $\mu_b = 4.8$ GeV.

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

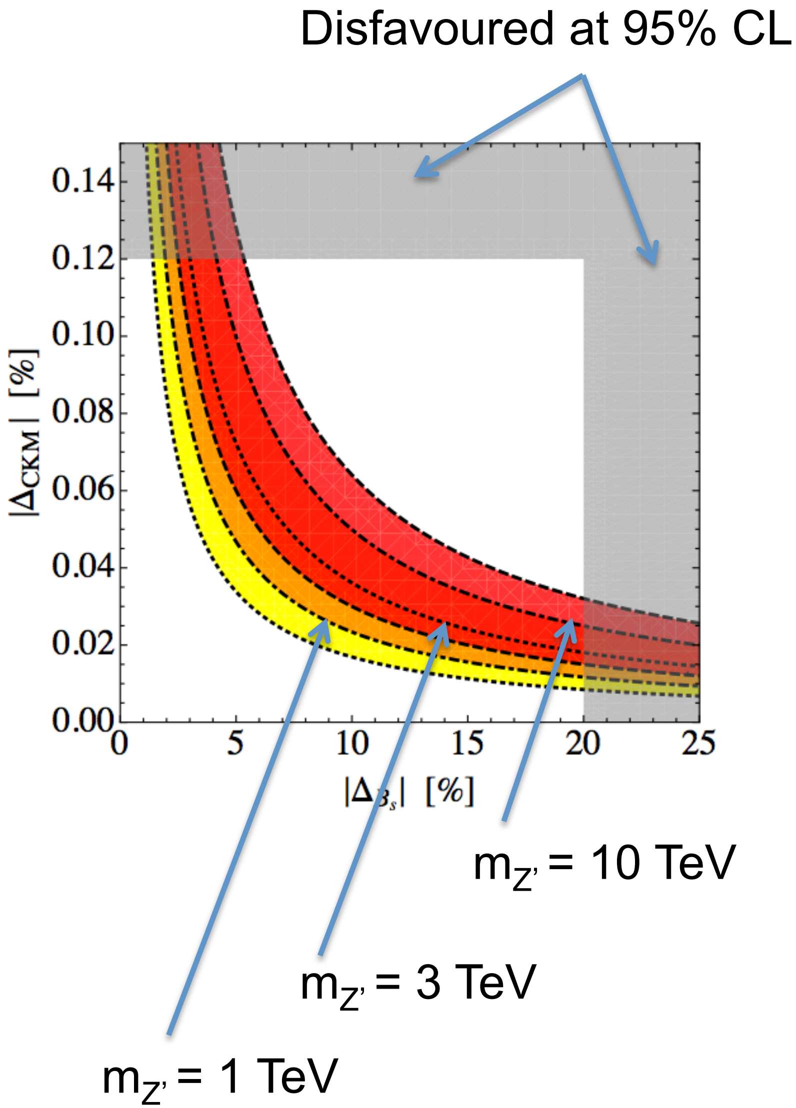
- Altmannshofer, Straub [arXiv:1308.1501] :
  - Use all angular analysis results
  - Constraints from $B(B \to X_s\gamma)$ and the A_{CP} in $B \to K^*\gamma$ prevent NP contribution to C_7, C_7'
  - Similarly, C_9, C_9' limited by A_{FB} and $B(B \to K\mu\mu)$
  - $\to$ Best fit with modification of C_9, C_9' or C_9, C_{10}'
- Also suggest Z' explanation consistent
- MSSM
  - In large regions of parameter space easy to get large NP contributions to C_7, C_7'
  - Hard to get SUSY contributions to C_9, C_9' :
    "*remain to a good approximation 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





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

- arXiv:1308.1959, Gauld *etal.*
  - Most minimal Z′ model that can address the observed anomaly → a model-independent triple-correlation between NP in $B_d^0 \to K^{*0}\mu\mu$, B^0_s-mixing, and "first-row" CKM unitarity



Conclusions

- LHCb measurements in wide-range of b→sll decays in good agreement with SM predictions
  - A_{FB}, F_L, S_3, A_T^2, A_T^{Re}, A_{CP}, $P_{4,6,8}$' in $B_d^0 \rightarrow K^{*0}\mu\mu$
  - Angular observables in $B^+ \rightarrow K^+\mu\mu$, BF of $B^+ \rightarrow \pi^+\mu\mu$
  - $B_s^0 \rightarrow \phi\mu\mu$
  - …

- Intriguing hints to explore with 3fb^{-1} data
  - Isospin asymmetry in $B \rightarrow K^{(*)}\mu^+\mu^-$
  - P_5' in $B_d^0 \rightarrow K^{*0}\mu\mu$

which raise some interesting experimental issues for next generation analysis

→ see talk of K. Petridis