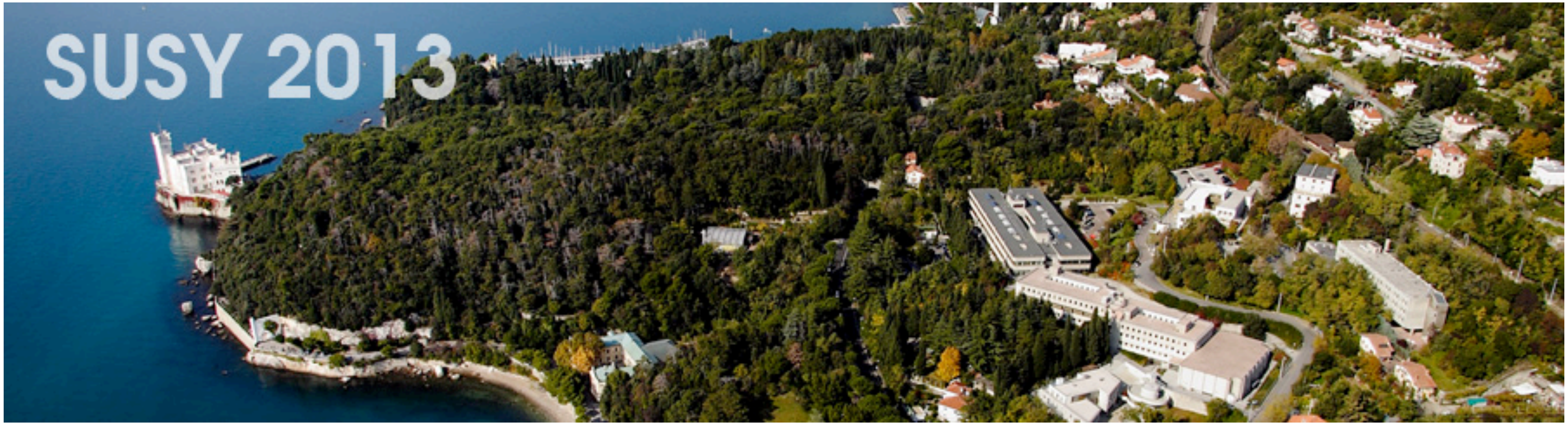

LHCb results relevant to SUSY and BSM physics

SUSY 2013, 31st August 2013

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On behalf of the LHCb Collaboration

Imperial College London

LHCb

Introduction

- The interest in B physics :
  - Virtual contributions from particles in loop processes → deviations that have often preceded the direct observation of new particles:
    - Suppression of $K^0 \to \mu\mu$ → GIM mechanism (charm quark)
    - B-$\bar{B}$ oscillations → heavy top quark
    - B($B^0 \to K^{*0}\gamma$) → indirect evidence top quark (and nothing else)
    - …

- Present interest from two sides :
  - CKM is dominant mechanism in SM but does it provide a complete description of CPV?
  - Rare decays are a window on virtual new particles beyond the energy scale accessible in direct searches

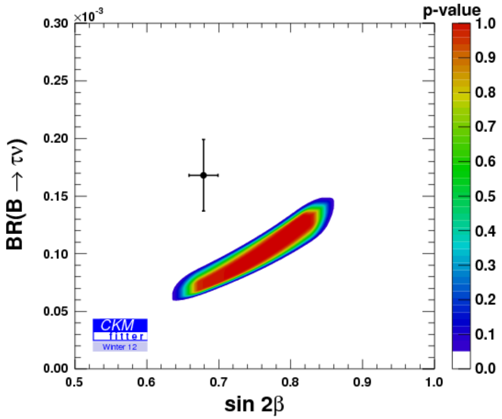
[see talks of K. Bruyn, D. Savrina, S. Coquereau, S. Tourneur]

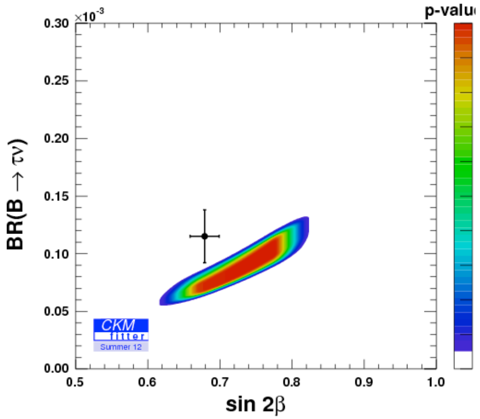
- Will select a few topics from each of these areas

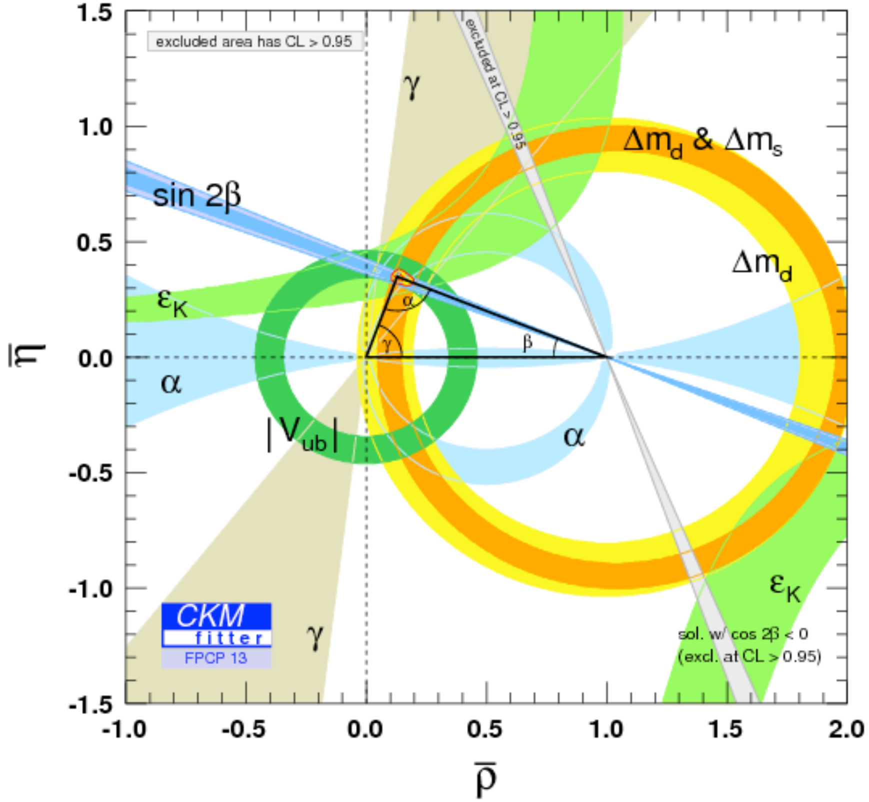
- Will also try and point out future prospects

The CKM picture

- Already last summer, residual tensions in CKM picture reduced by Belle update of B($B^+ \to \tau^+ \nu$)







- LHCb has added a large number of measurements showing that the CKM picture remains rock-solid
  - Time integrated measurements of $B \to K\pi$
  - Angle γ measurements
  - Mixing measurements

Time integrated CPV in B→Kπ

[PRL110(2013)221601]

- Recent LHCb analysis :

$A_{CP}(B_d^0 \to K^+\pi^-) = -0.080 \pm 0.007 \pm 0.003$ [world's best]

$A_{CP}(B_s^0 \to K^-\pi^+) = +0.27 \pm 0.04 \pm 0.01$ [world's first 5σ observation of CPV in B_s^0 system]

  - Det. asymm $D^*\to D(K\pi/KK)\,\pi$
  - Prod. asymm time-dep study

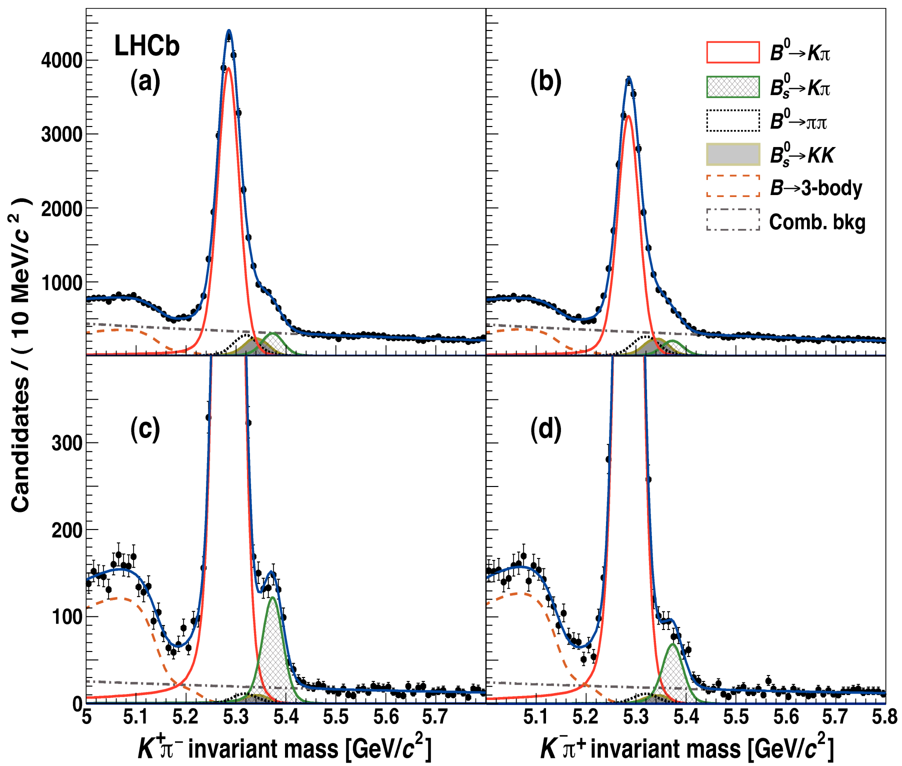
- Exploit approx. flavour symmetry to cancel unknown theory parameters and hadronic uncert.

- SM predicts

$$\Delta = \frac{A_{CP}(B^0\to K^+\pi^-)}{A_{CP}(B_s\to K^-\pi^+)} + \frac{BR(B_s\to K^-\pi^+)}{BR(B^0\to K^+\pi^-)}\frac{\tau_d}{\tau_s} = 0$$

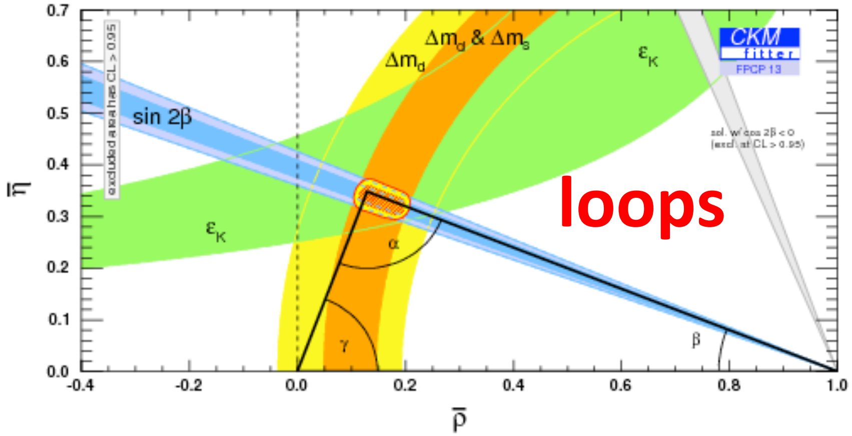
- LHCb measurement :

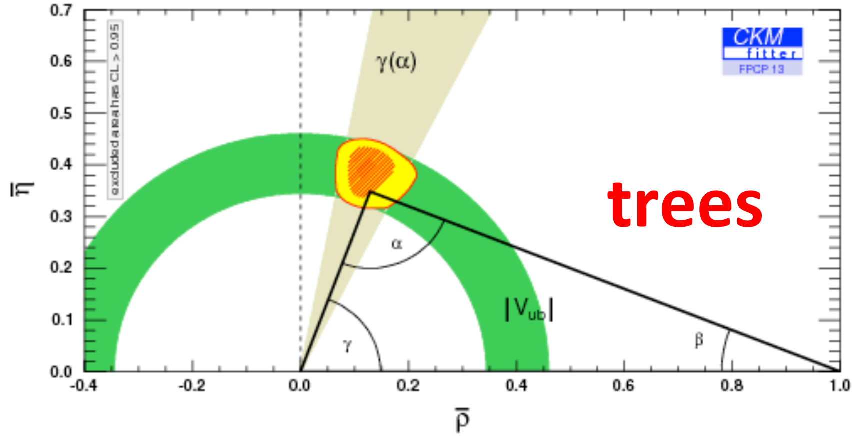
$\Delta = -0.02 \pm 0.05 \pm 0.04$



CKM angle γ

- Progress in comparison of tree and loop level constraints needs improved knowledge of angle γ
  - Direct knowledge at 12° level
  - Indirectly (i.e. NP sensitive) determination at the 4° level



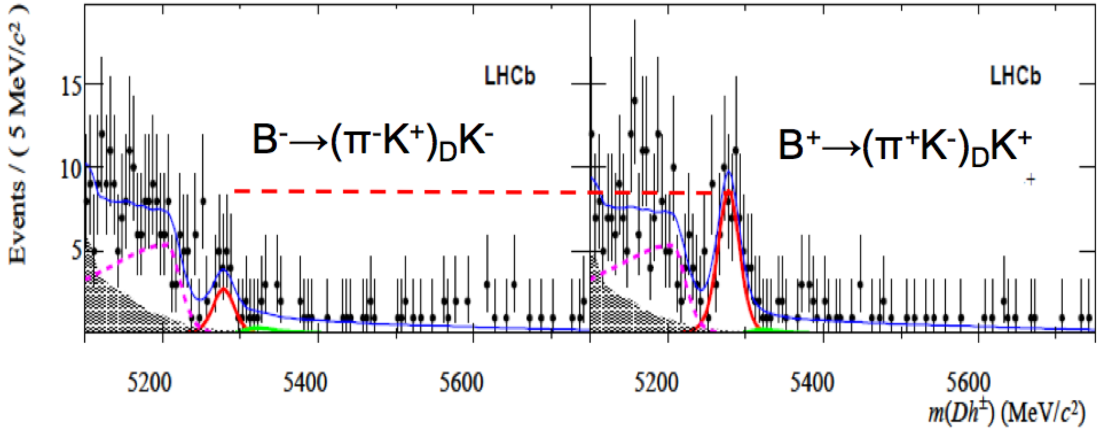


- LHCb results from a wide range of modes :
  - *B→Dh, D→πK* [ADS]
  - *B→Dh, D→KK, D→ππ* [GLW] [PLB 712 (2012) 203, 1fb^{-1}]
  - *B→Dh, D→K3π* [K3π] [PLB 723 (2013) 44, 1fb^{-1}]
  - *B→DK, D→K_S^0ππ* [GGSZ] [LHCb-CONF-2013-004, 2fb^{-1}]

γ in tree decays – ADS

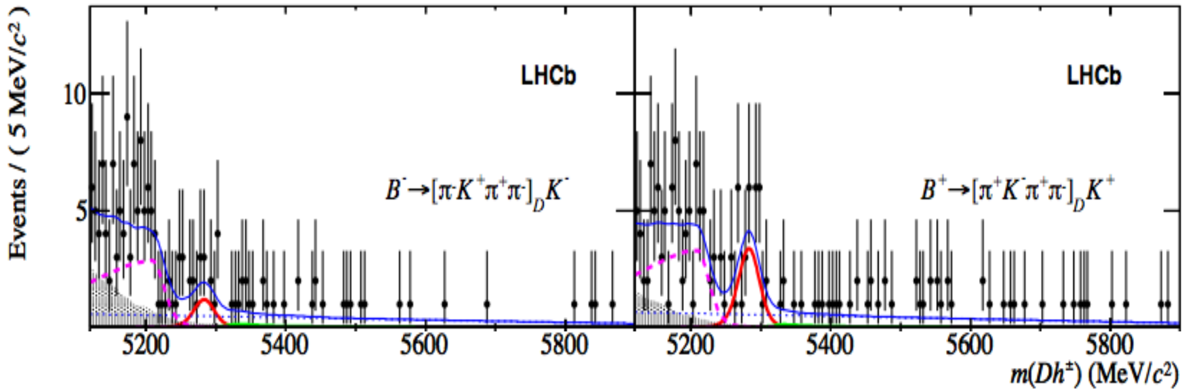
- Discovery of 'suppressed ADS' mode
  - Visible BF ~10^{-7} , large CP asymmetry gives *clean* information on γ

[PLB 712 (2012) 203]



  - Analogous method used to isolate $B^\pm \to (K\pi\pi\pi)_D K^\pm$, provides orthogonal information rather than just statistics

[PLB 723 (2013) 44]



γ in tree decays – GGSZ

[LHCb-CONF-2013-004]

- Model independent Dalitz plot analysis of $B^{\pm} \to DK^{\pm}$ with $D \to K_S^0 h^+ h^-$ ($h = \pi$, K)
  - Strong phase of D^0 decay varies across Dalitz plot – take from CLEO measurements of DD *pairs from* $\Psi(3770)$ [PRD 82 (2010) 112006]
  - Measure,

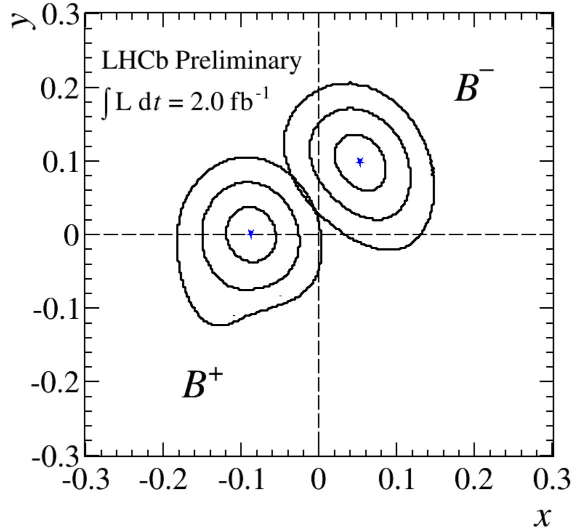
    $x_{\pm} = r_B \cos(\delta_B \pm \gamma)$

    $y_{\pm} = r_B \sin(\delta_B \pm \gamma)$
  - $3 fb^{-1}$ results:

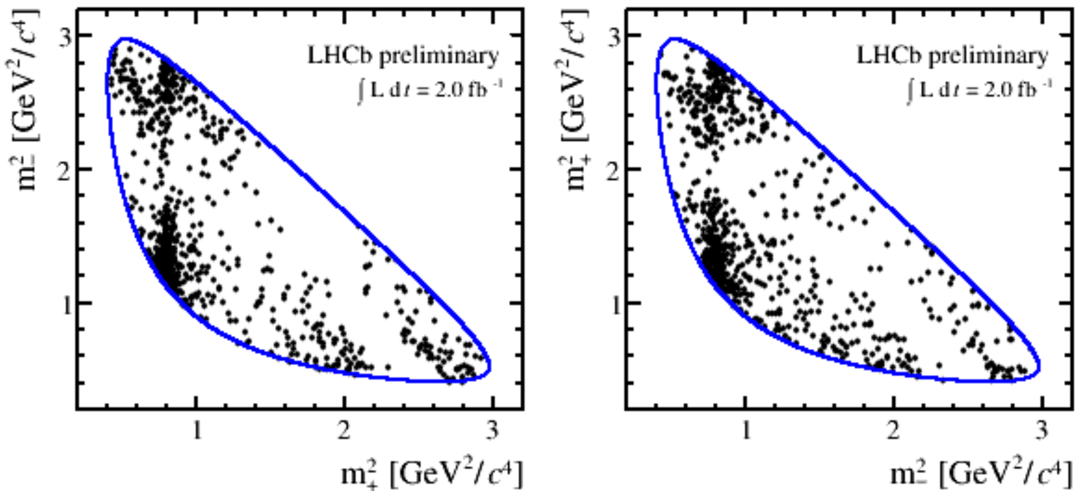
    $\gamma = (57 \pm 16)^{\circ}$

    $r_B = (8.8^{+2.3}_{-2.4}) \times 10^{-2}$

    $\delta_B = (124^{+15}_{-17})^{\circ}$



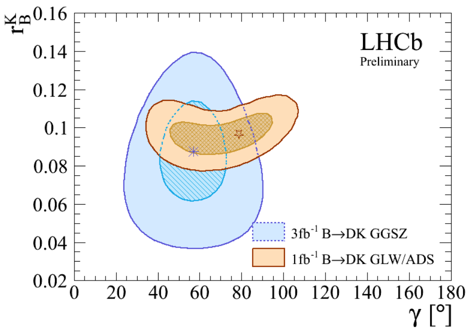
$B^{\pm} \to DK^{\pm}$ with $D \to K_S^0 \pi^+ \pi^-$

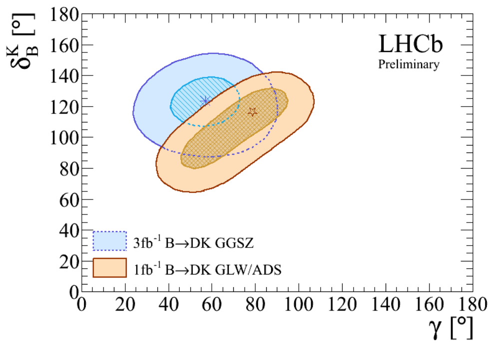


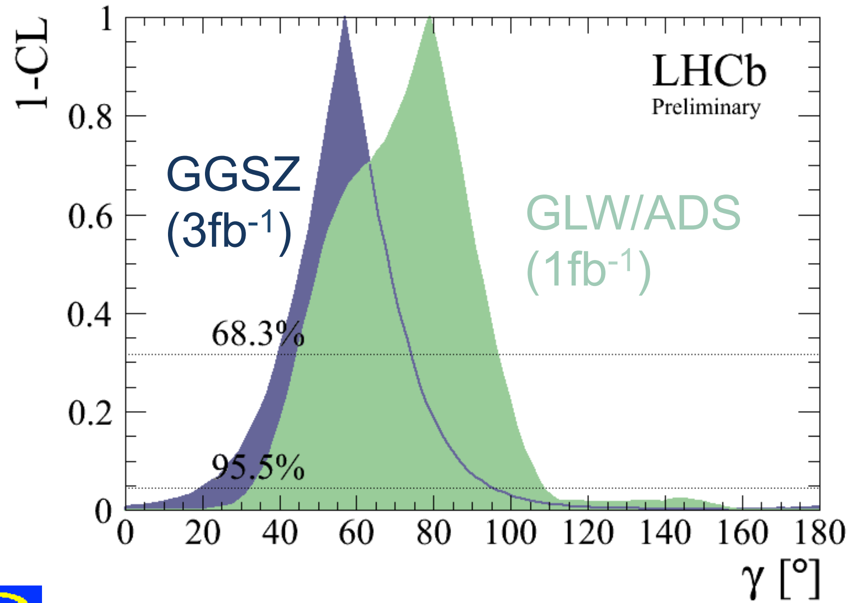
γ in tree decays – combination

[LHCb-CONF-2013-006]

- Channels combined to give overall LHCb result for γ







LHCb

$\gamma = (67 \pm 12)^\circ$

$r_B = (9.2 \pm 0.8) \times 10^{-2}$

$\delta_B = (114^{+12}_{-13})^\circ$

cf. BELLE BABAR

$(68^{+15}_{-14})^\circ$ [arXiv:1301.2033]

$(69^{+17}_{-16})^\circ$ [PRD 87 (2013) 052015]

predictions:

$(68.6 \pm 3.6)^\circ$ [UTFit]

$(68.6^{+4.1}_{-4.6})^\circ$ [CKMFitter]

→ Very good agreement between direct measurements and fit

- 3fb^{-1} updates to ADS/GLW methods will improve precision further

Mixing induced CPV in B_s^0 system

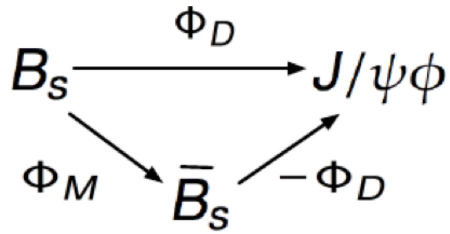
- Interference between *decay* or *mixing and then decay* results in CP-violating phase:
  - $\phi_S = \phi_M - 2\phi_D$

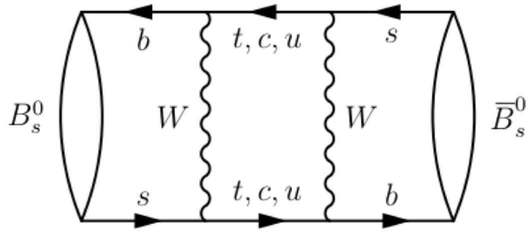
  can be precisely predicted in SM, new physics could change phase

- Mass eigenstates ≠ weak eigenstates: system described by: m, Γ, $\Delta\Gamma_s$, Δm_s, ϕ_S
  - CPV modulated by high Δm_s

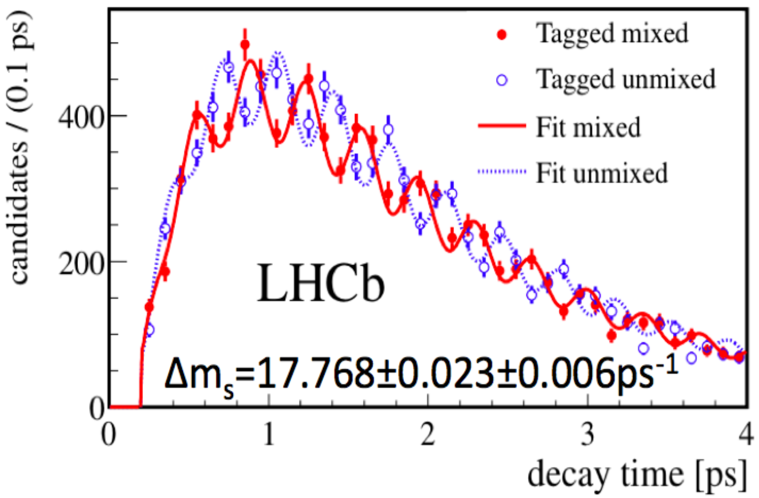
- $J/\psi\phi(K^+K^-)$ decays – high BF, mixture CP-even/odd → angular analysis to disentangle
- $J/\psi f_0(\pi^+\pi^-)$ decays – smaller yield but pure CP-odd

- $m(K^+K^-)$ dependence allows to resolve two-fold ambiguity [PRL 108 (2012) 241801]
- S-wave contribution : 4±2%

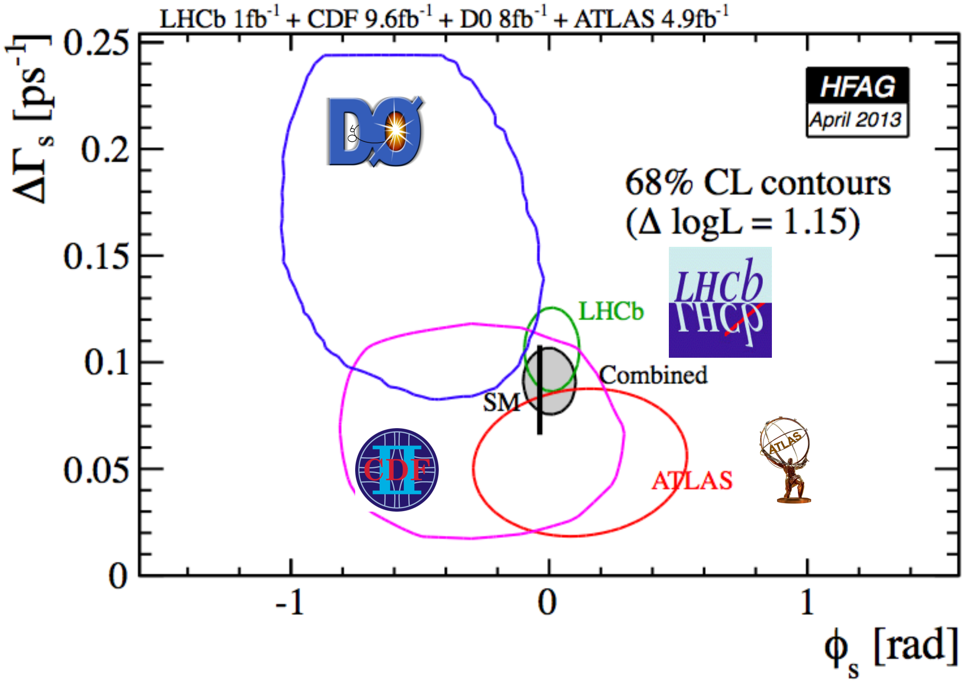




[New J Phys 15 (2013) 053021]



Mixing induced CPV in B_s^0 system



	CDF	D0	LHCb	ATLAS	CMS*)
$\int \mathcal{L}$ [fb^{-1}]	9.6	8.0	1.0	4.9	5.0
# $B_s \to J/\psi KK(f_0)$	11k	5.6k	27.6k (7.4k)	22.7k	14.5k
ϵD^2 OS [%]	1.39 ± 0.05	2.48 ± 0.22	2.29±0.22	1.45±0.05	-
ϵD^2 SS [%]	3.5±1.4	-	0.89±0.18	-	-
σ_t [fs]	100	100	48	100	-
Reference	PRL 109(2012) 171802	PRD85(2012) 032006	PRD87(2013) 112010	ATLAS-CONF-2013.029	CMS-PAS BPH-11-006

* CMS: $\Delta\Gamma$ only: 0.048±0.024±0.003 ps^{-1}

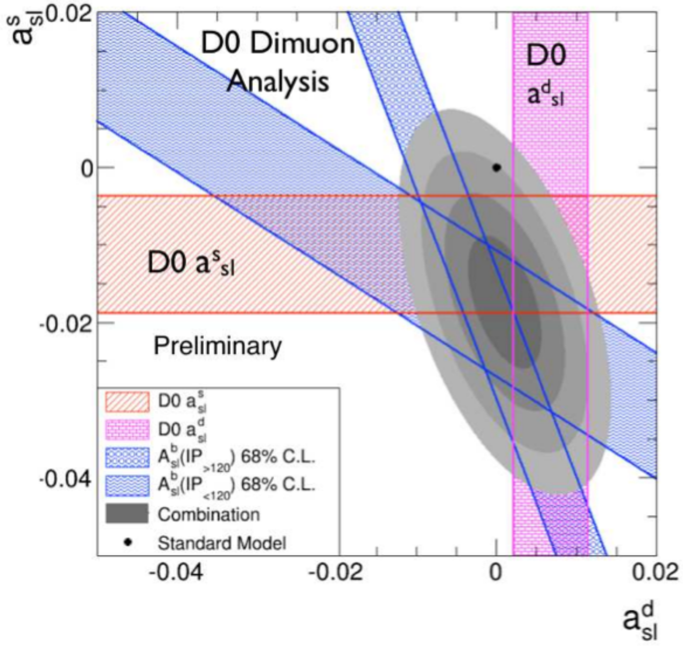
Semileptonic asymmetries

- Another way of probing mixing - semileptonic asymmetries :

$$a^s_{sl} \propto \frac{N(\mu^+ D_s^{(*)-}) - N(\mu^- D_s^{(*)+})}{N(\mu^+ D_s^{(*)-}) + N(\mu^- D_s^{(*)+})}$$

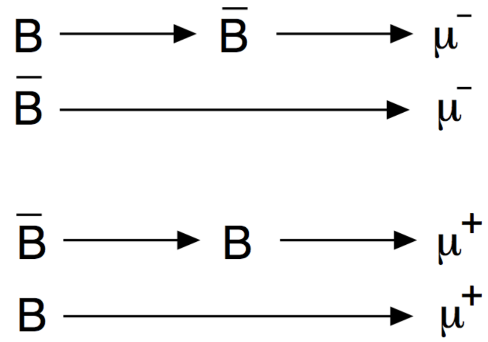
$$a^d_{sl} \propto \frac{N(\mu^+ D^{(*)-}) - N(\mu^- D^{(*)+})}{N(\mu^+ D^{(*)-}) + N(\mu^- D^{(*)+})}$$

sensitive probes of NP as expected to be small in SM ($\sim 10^{-5}$ (10^{-4}) for B^0_s (B^0))



- D0 experiment measured dimuon asymmetry :

$$A = \frac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)}$$



A_{CP} = (-0.276 ± 0.067 ± 0.063)% (9.0 fb^{-1})

3.9σ ≡ 0.33% compatible with SM

Semileptonic asymmetries

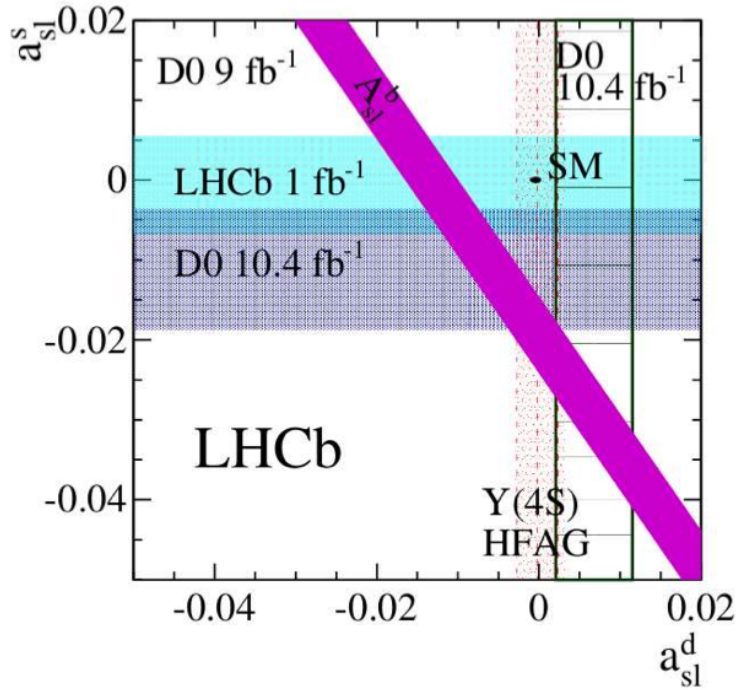
- At LHC, collide pp → production asymmetry
  - Measurements sensitive to production and detection asymmetries

$$A_{meas} = \frac{N(D_q^- \mu^+) - N(D_q^+ \mu^-)}{N(D_q^- \mu^+) + N(D_q^+ \mu^-)} = \frac{a_{sl}^q}{2} + \left[a_{prod} - \frac{a_{sl}^q}{2}\right]\kappa_q$$

  - fast B_s^0 oscillations → time integrated a_{sl}^s measurement possible (κ_s=0.2%)
  - slow B_d^0 oscillations → time dependent analysis required to get a_{sl}^d (κ_d=30%)

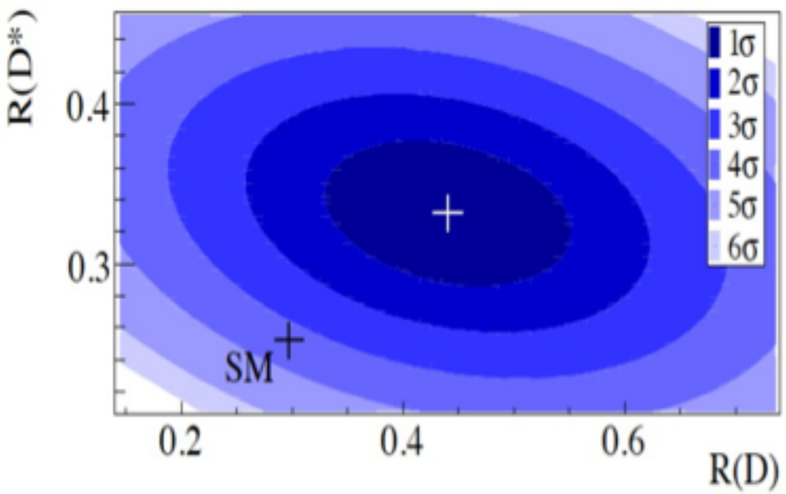
- LHCb measurement of a_{sl}^s with 1fb^{-1}
  - a_{sl}^s = (-0.06 ± 0.50 ± 0.36)%
    [arXiv:1308.1048]
  - This result and B-factory average for a_{sl}^d in good agreement with SM

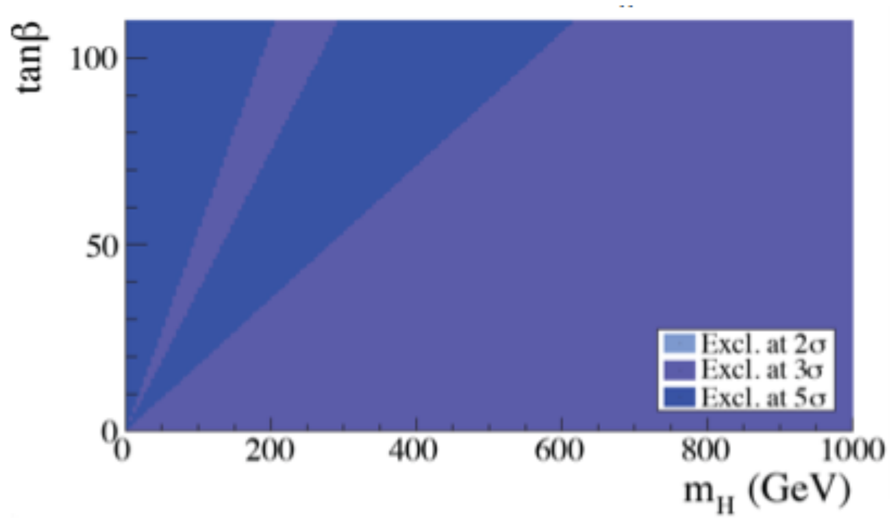
- LHCb has demonstrated ability to reconstruct semileptonic states…



B→D(*)τν

- Measurements of $R(D^{(*)}) = \frac{\Gamma(B \to D^{(*)}\tau\nu_\tau)}{\Gamma(B \to D^{(*)}\ell\nu_\ell)_{\ell=e,\mu}}$





- BABAR 3.4σ from SM
- "excess cannot be explained by a charged Higgs boson in the type II two-Higgs-doublet model"

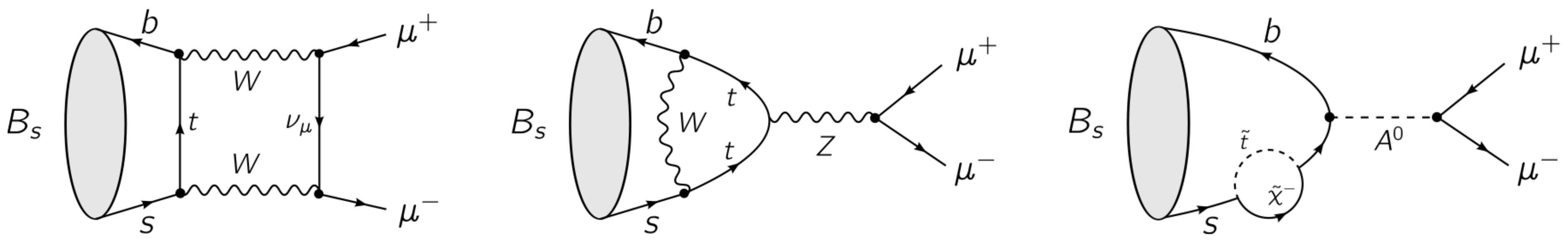
- BELLE 3.3σ from SM

[PRL109,101802 (2012), arXiv:1303.0571]
[see talk of A. Oyanguren]

- Combined BABAR+BELLE: 4.8σ from SM, await Belle update with interest – would be interesting if LHCb can also contribute here

The decays $B_d^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-$

- The branching ratios of the decays $B_d^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-$ allow the parameters of any extended Higgs sector to be probed



- The decays are doubly suppressed in the SM
  - Flavour Changing Neutral Currents
  - Helicity suppression

However, rates well calculable – in the SM,

$B(B_s^0 \to \mu^+\mu^-) = 1.1\times(3.2\pm0.2)\times10^{-9}$

time integrated BF taking into account $\Delta\Gamma_s \neq 0$

[*Buras et al., arXiv:1007.5291*
De Bruyin et al., *arXiv:*1204.1735]

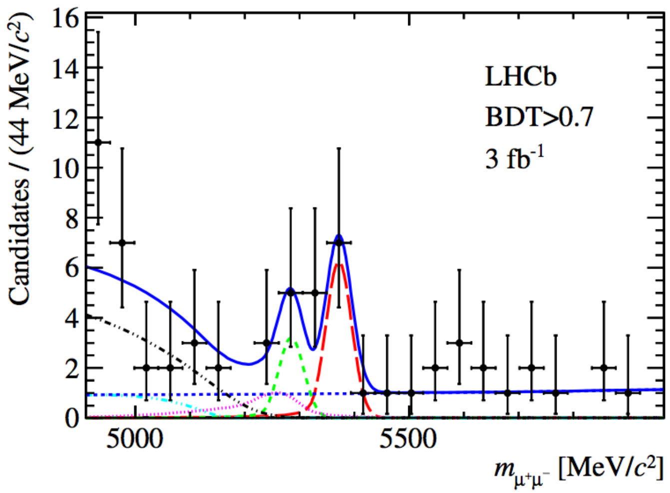
- Sensitive to NP contributions in the scalar/pseudo-scalar sector:

$$(c_{S,P}^{MSSM})^2 \propto \left(\frac{m_b m_\mu \tan^3\beta}{M_A^2} \right)^2$$

MSSM, large tanβ approximation

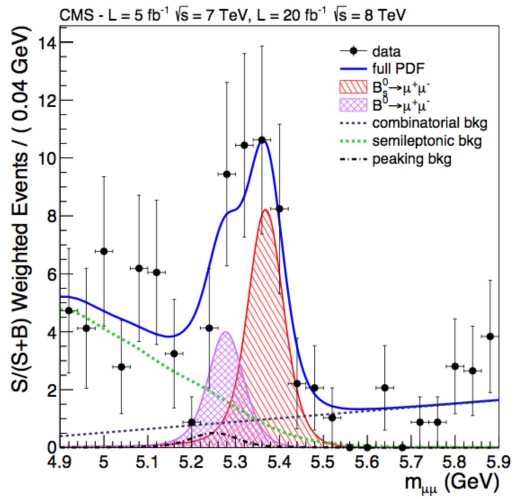
[arXiv:1307.5024] [arXiv:1307.5025]

- LHCb update at EPS:
  - $2.1 fb^{-1} \rightarrow 3.0 fb^{-1}$
  - Improved reconstruction
  - Additional variables added to BDT
  - Expected sensitivity: $3.7 \rightarrow 5.0\sigma$



- B ($B_s^0 \rightarrow \mu^+\mu^-$) = $(2.9^{+1.1}_{-1.0}(stat)^{+0.3}_{-0.1}(syst)) \times 10^{-9}$ $\rightarrow 4\sigma$
- B ($B^0 \rightarrow \mu^+\mu^-$) = $(3.7^{+2.4}_{-2.1}(stat)^{+0.6}_{-0.4}(syst)) \times 10^{-10}$ $\rightarrow 2.0\sigma$ [$<7.4 \times 10^{-10}$ at 95% CL]

- CMS update at EPS
  - $5 fb^{-1} \rightarrow 25 fb^{-1}$
  - Cut-based selection → BDT
  - New and improved variables
  - Expected sensitivity: 4.8σ



- B ($B_s^0 \rightarrow \mu^+\mu^-$) = $(3.0^{+1.0}_{-0.9}) \times 10^{-9}$ $\rightarrow 4.3\sigma$
- B ($B^0 \rightarrow \mu^+\mu^-$) = $(3.5^{+2.1}_{-1.8}) \times 10^{-10}$ $\rightarrow 2.0\sigma$ [$<11.0 \times 10^{-10}$ at 95% CL]

- ATLAS also gave an update at EPS : B ($B_s^0 \rightarrow \mu^+\mu^-$) $<1.5 \times 10^{-8}$ at 95% CL

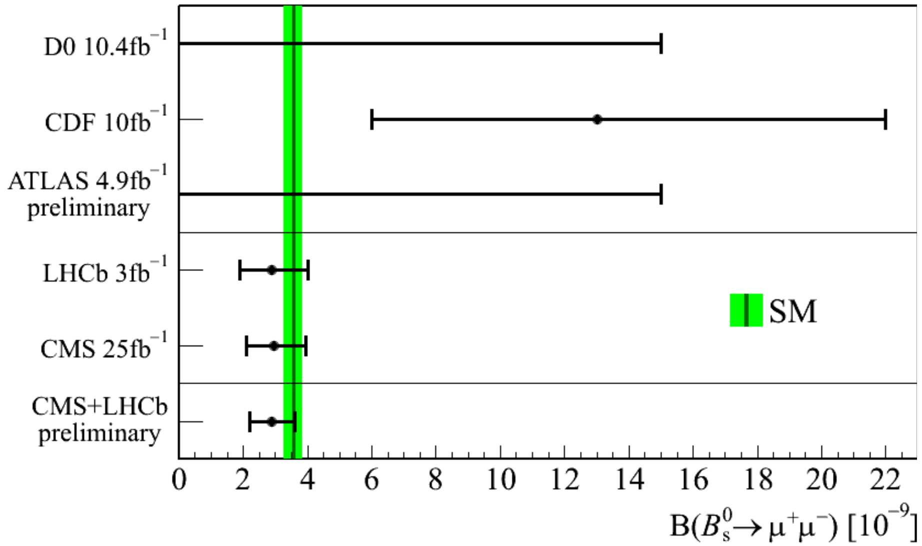
Combined LHCb, CMS result

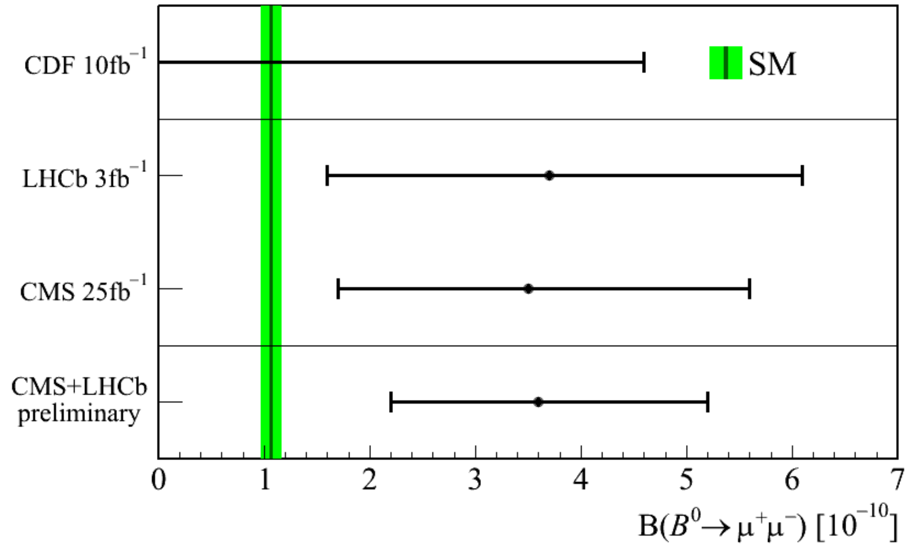
- The LHCb and CMS results have been combined

[LHCb-CONF-2013-012]
[CMS-PAS-BPH-13-007]

$B\,(B_s^0 \to \mu^+\mu^-) \quad = \quad (2.9 \pm 0.7)\times 10^{-9}$ (First observation)

$B\,(B^0 \to \mu^+\mu^-) \quad = \quad (3.6^{+1.6}_{-1.4})\times 10^{-10}$

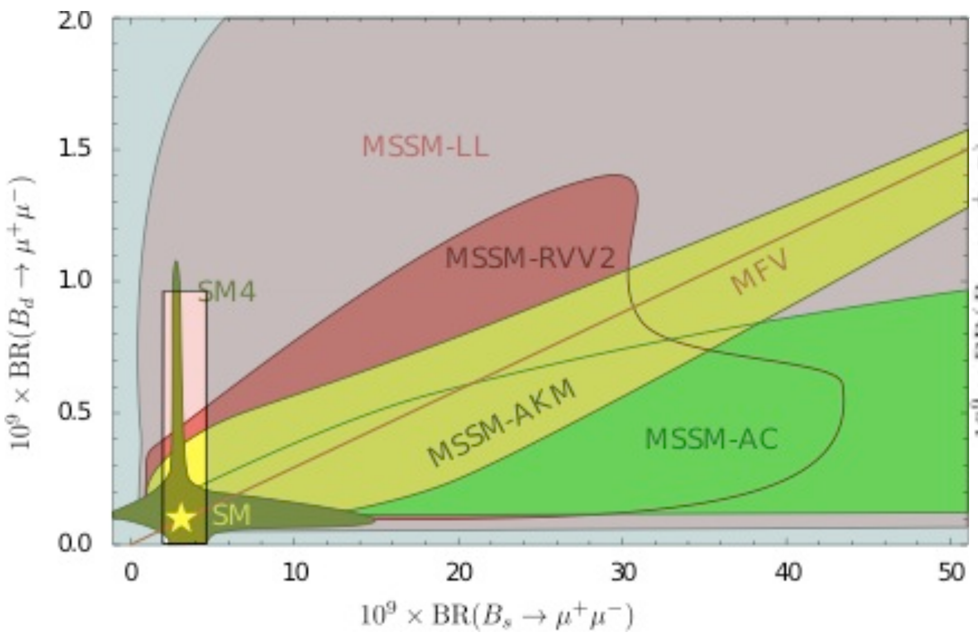


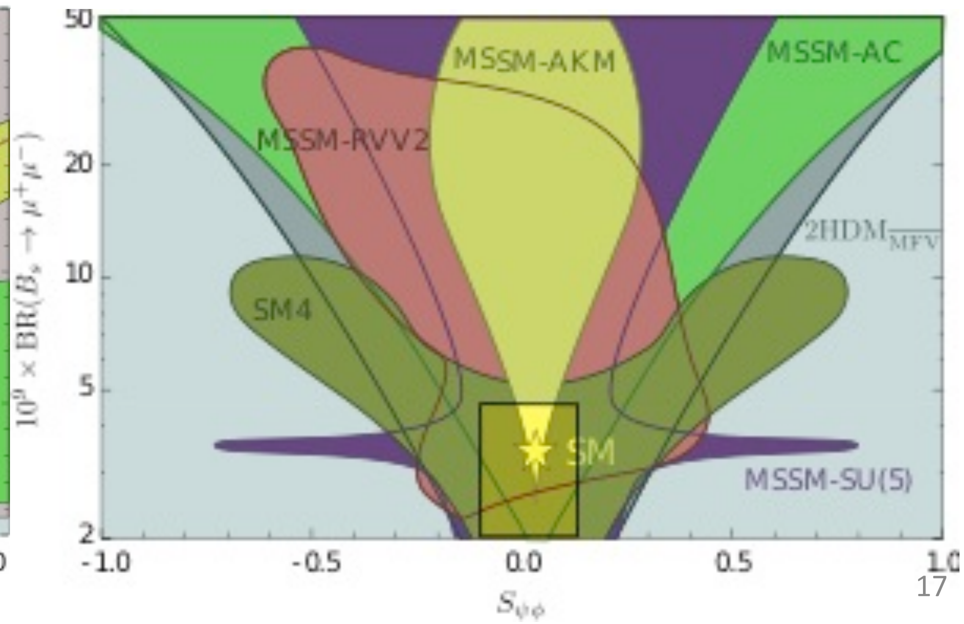


- Good agreement with SM predictions

$B^0_{(s)} \to \mu^+\mu^-$ – future

- Interest for the future will be measuring the ratio $B(B_d^0 \to \mu^+\mu^-)/B(B_s^0 \to \mu^+\mu^-)$
  - In SM, given by $|V_{td}/V_{ts}|^2$ → 5% theory precision
  - Major issue double decay in flight with $B_d^0 \to \pi^+\pi^-$ decays
  - With LHCb upgrade (50fb^{-1}) could measure ratio to ~35%





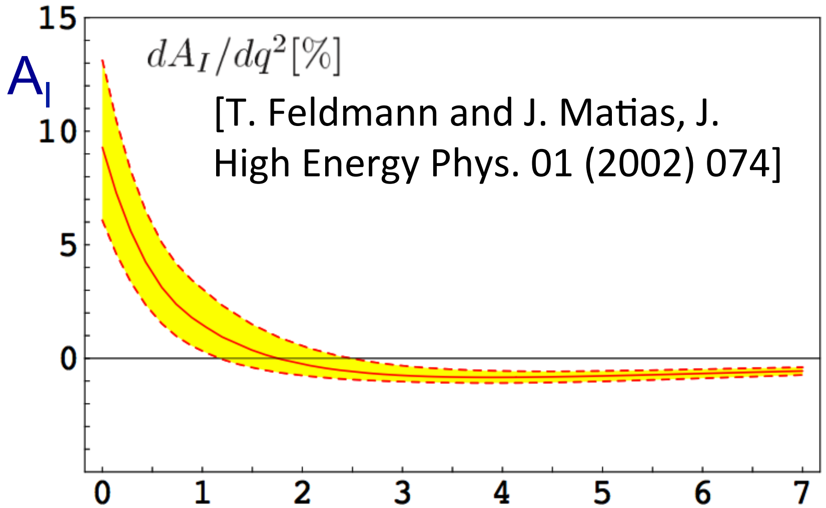
Isospin Asymmetry in $B \to K^{(*)}\mu^+\mu^-$

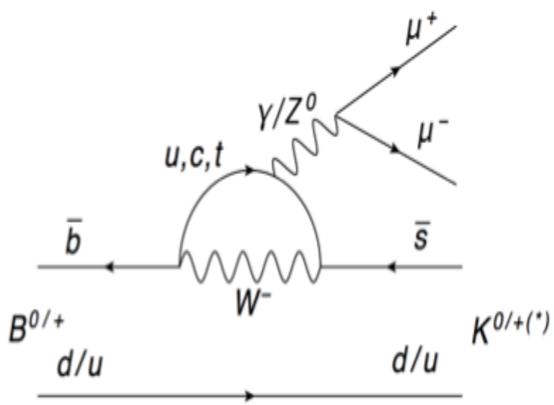
- The isospin asymmetry of $B \to K^{(*)}\mu^+\mu^-$, A_I is defined as:

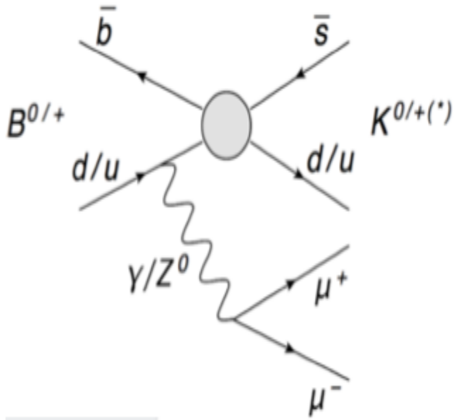
$$A_I = \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - \frac{\tau_0}{\tau_+}\mathcal{B}(B^\pm \to K^{(*)\pm}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + \frac{\tau_0}{\tau_+}\mathcal{B}(B^\pm \to K^{(*)\pm}\mu^+\mu^-)}$$

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

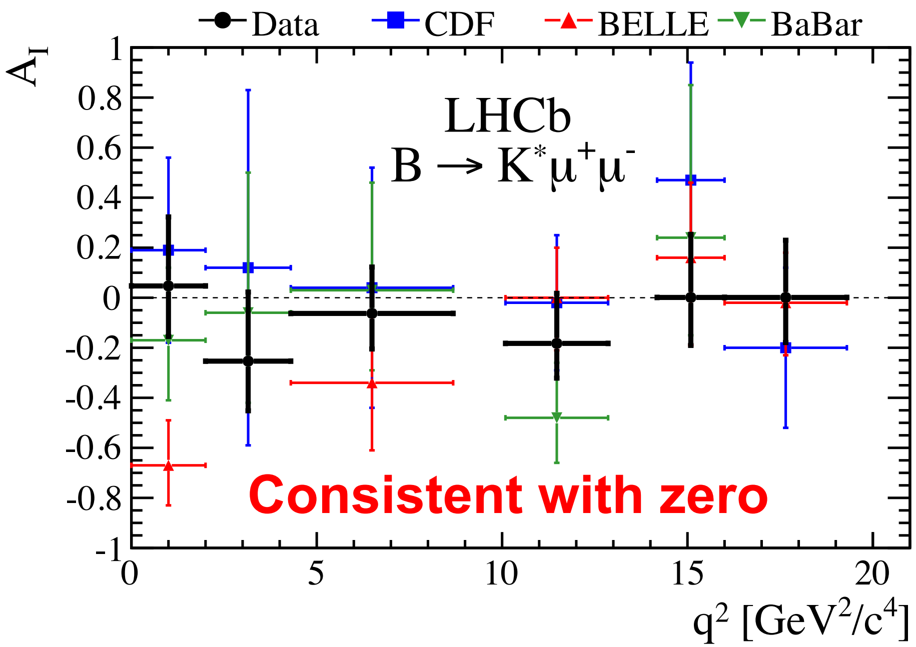
- The isospin asymmetry of $B \to K^{(*)}\mu^+\mu^-$, A_I is defined as:

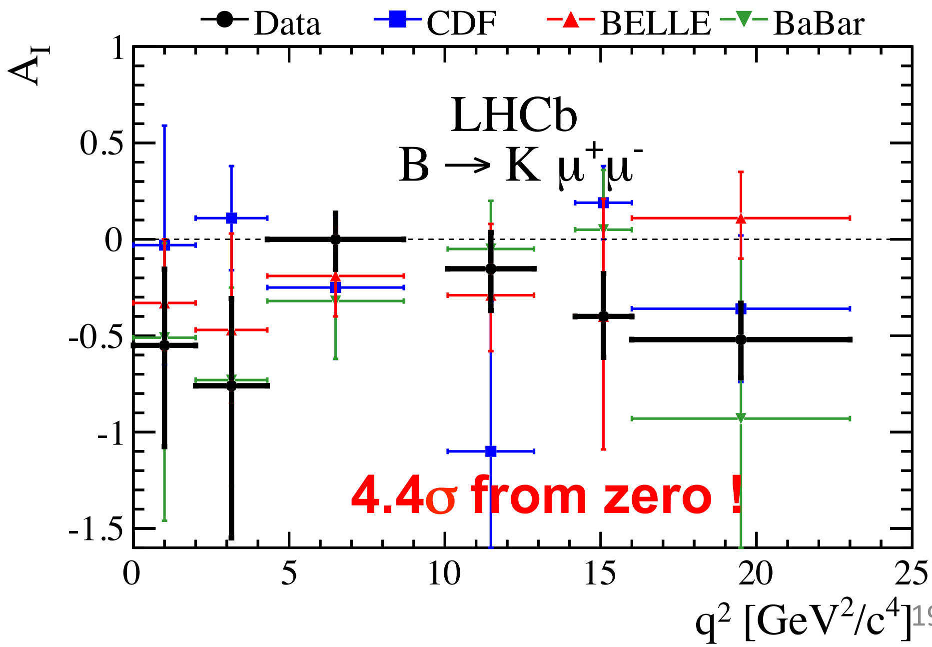
$$A_I = \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - \frac{\tau_0}{\tau_+}\mathcal{B}(B^\pm \to K^{(*)\pm}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + \frac{\tau_0}{\tau_+}\mathcal{B}(B^\pm \to K^{(*)\pm}\mu^+\mu^-)}$$

can be more precisely predicted than the branching fractions

- LHCb measurement from 1fb^{-1} : (will soon be updated)

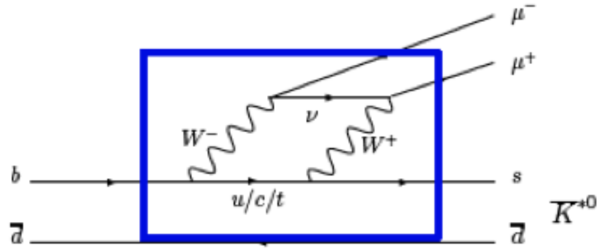
[JHEP 07 (2012) 133]

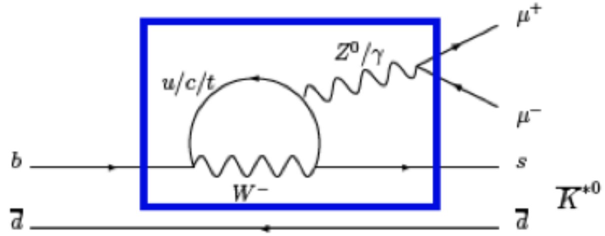


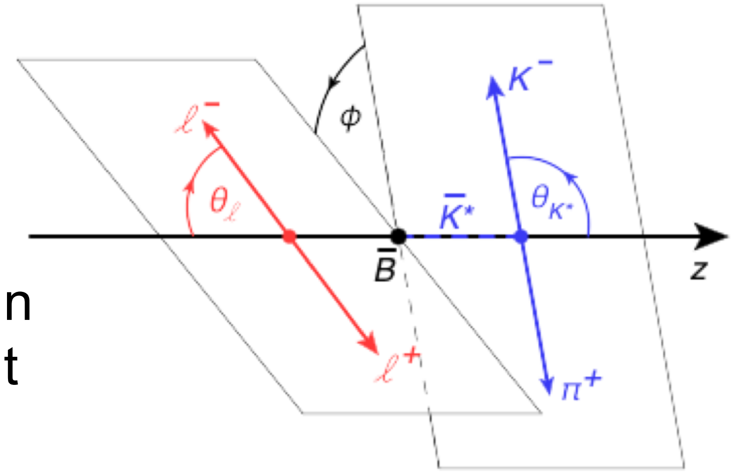


$B_d^0 \rightarrow K^{*0}\mu\mu$

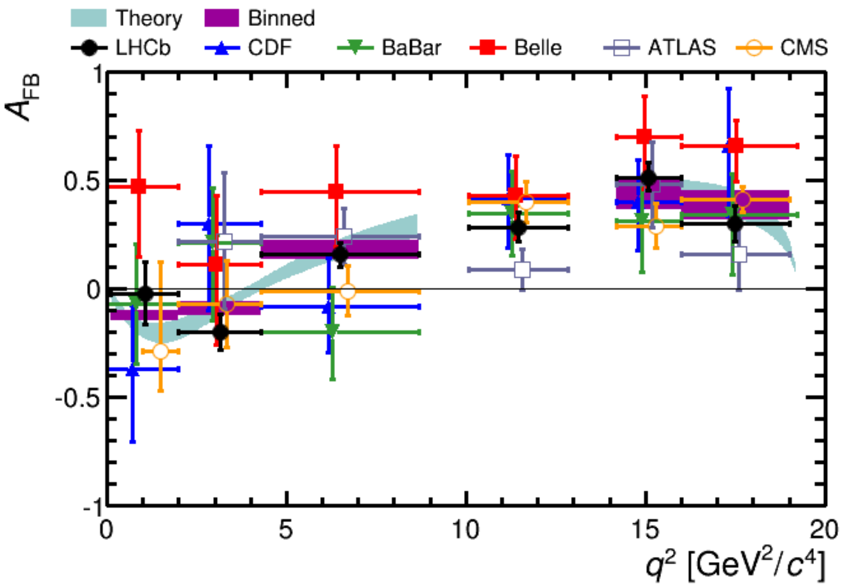
- Flavour changing neutral current → loop
- Sensitive to interference between $O_{7\gamma}$, $O_{9,10}$ and their primed counterparts
- Decay described by three angles, θ_l, θ_K and ϕ, and $q^2 = m^2_{\mu\mu}$, self-tagging → angular analysis allows to probe helicity
- Exclusive decay → theory uncertainty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

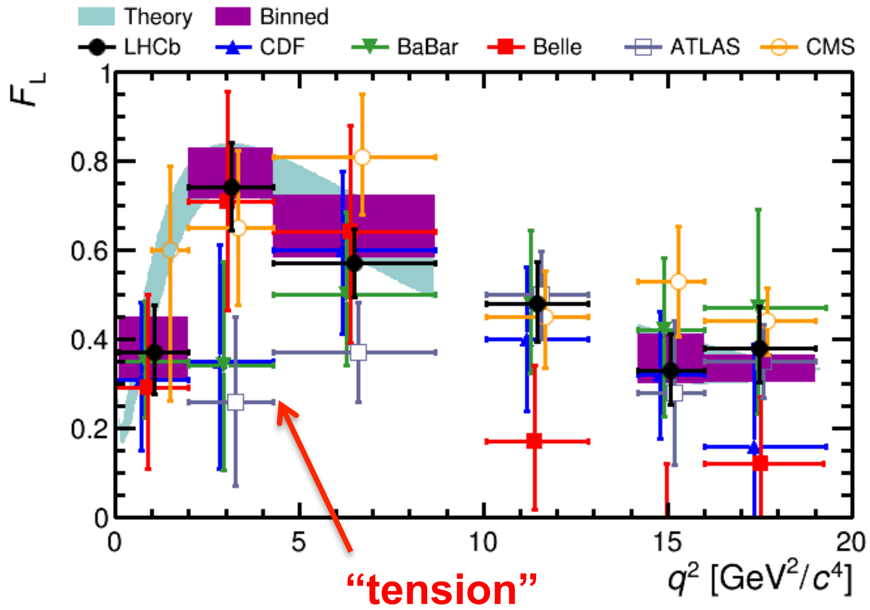


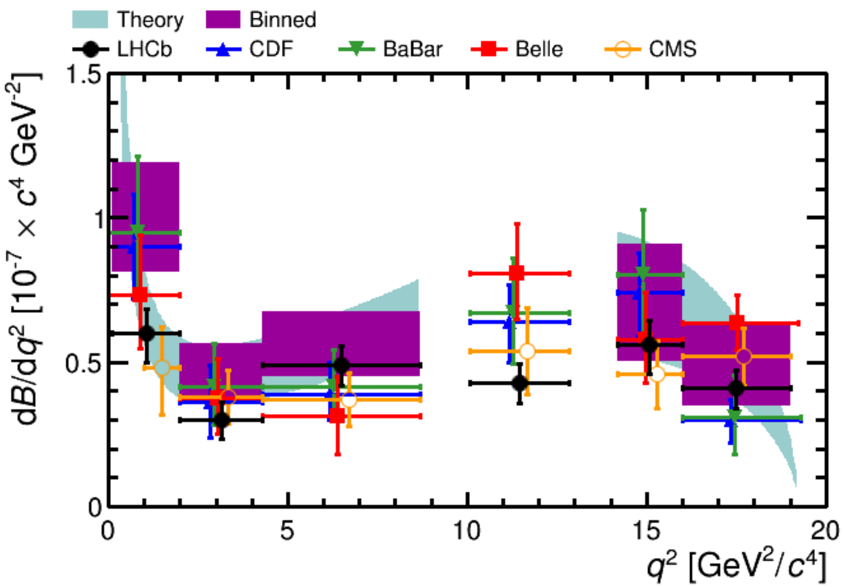




$B_d^0 \to K^{*0}\mu\mu$ – angular observables







- Good agreement with SM predictions
- Analysis for $B_s^0 \to \phi\mu\mu$, $B^+ \to K^+\mu\mu$ also give results consistent with SM

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: arXiv: 1304.6325 (1 fb^{-1})]

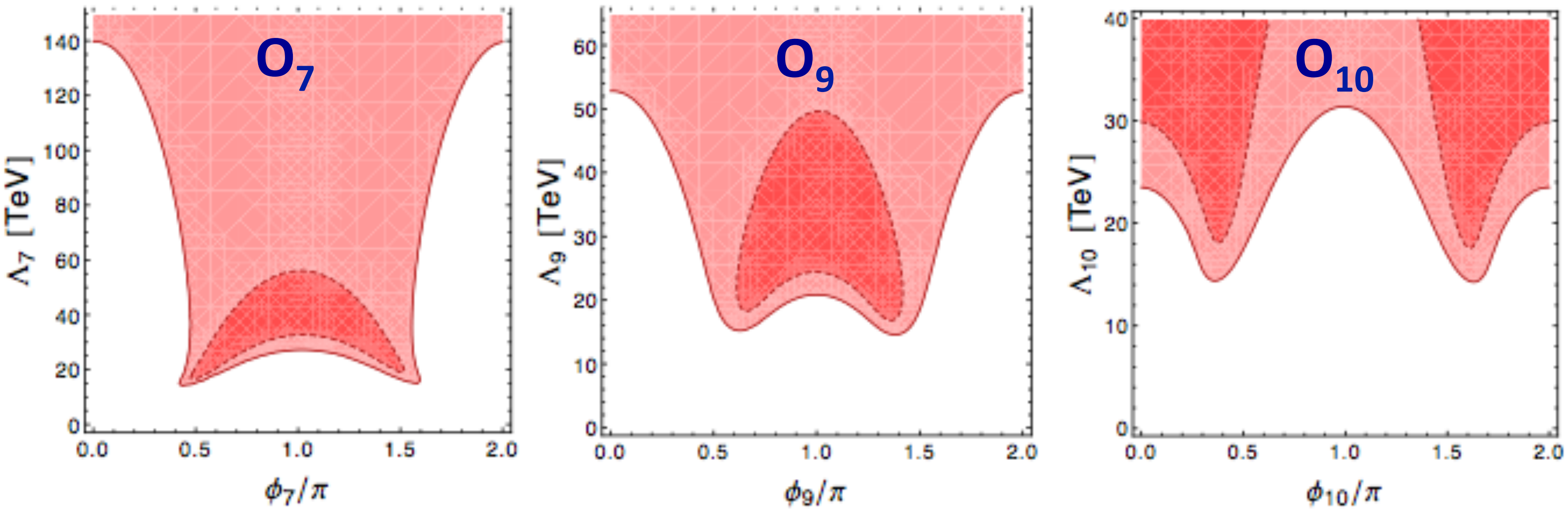
Impact – with tree level FV

[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):

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

~tree level generic flavour violation



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

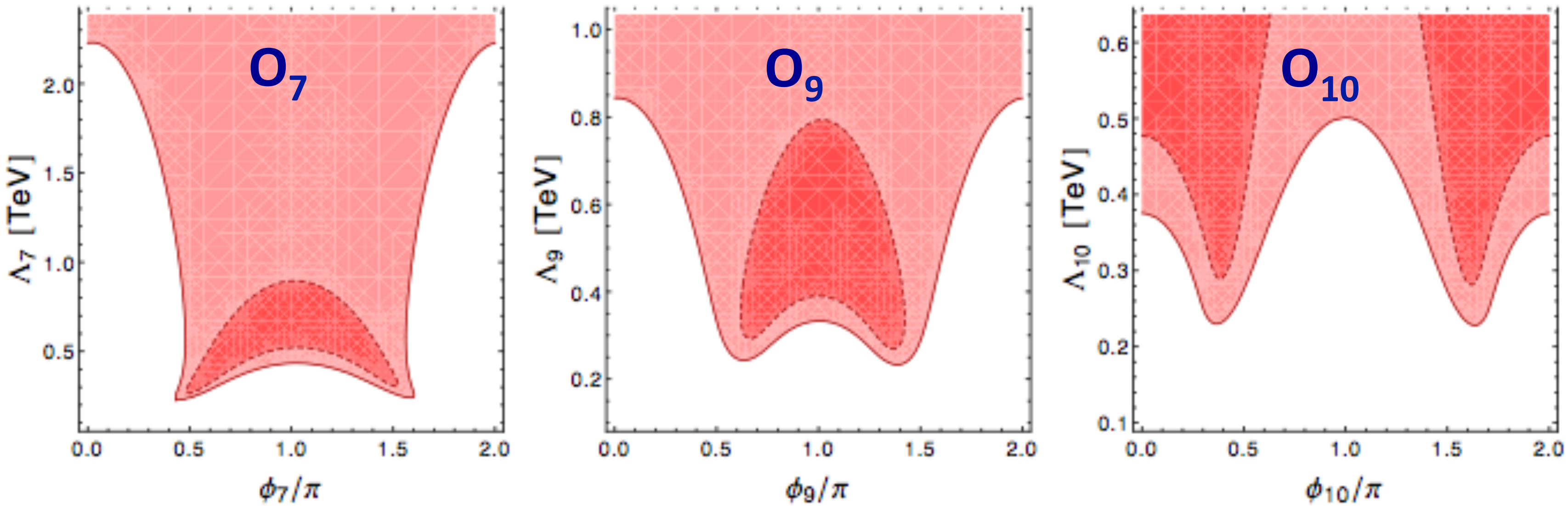
Impact – with loop CKM-like FV

[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):

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

~loop level CKM-like flavour violation

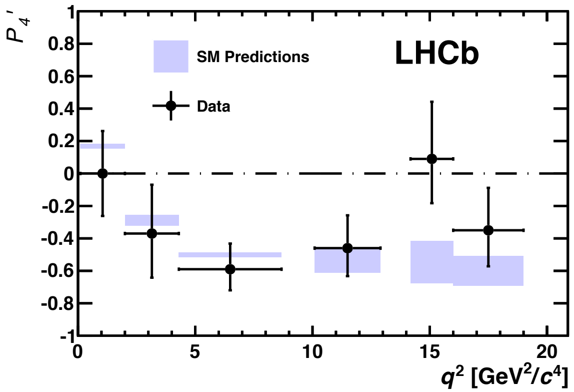


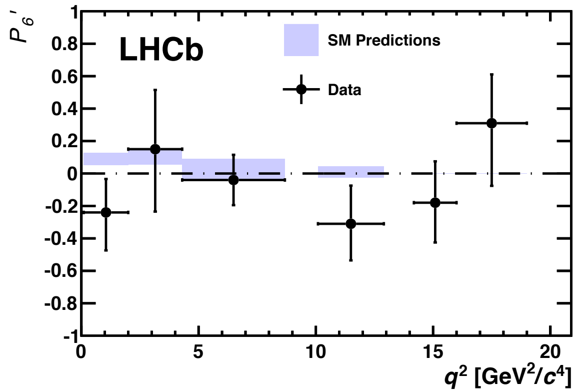
→ NP > 10TeV or NP mimics Yukawa couplings (MFV)

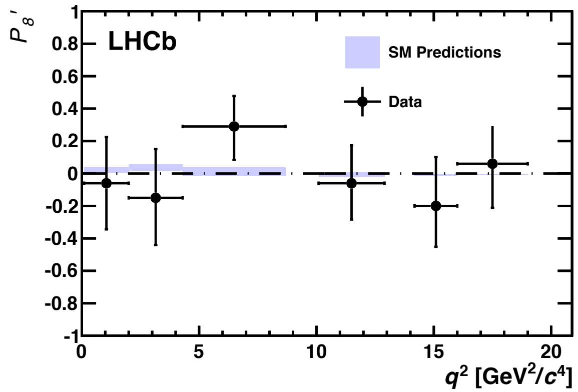
$B_d^0 \to K^{*0}\mu\mu$ – new observables

[arXiv:1308.1707]

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

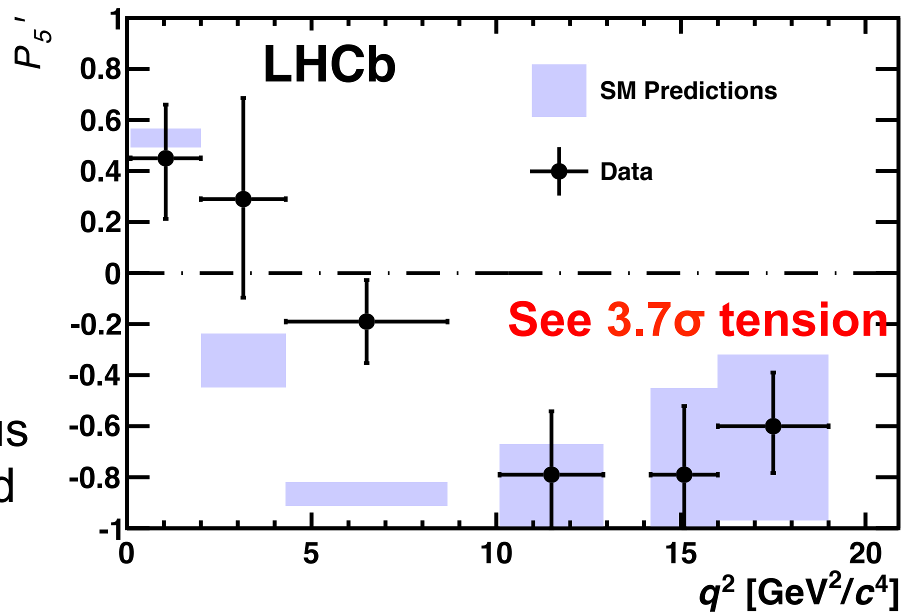






- 0.5% probability to see such a deviation with 24 independent measurements

- 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



See 3.7σ tension in P_5'

$B_d^0 \to K^{*0}\mu\mu$ – 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'

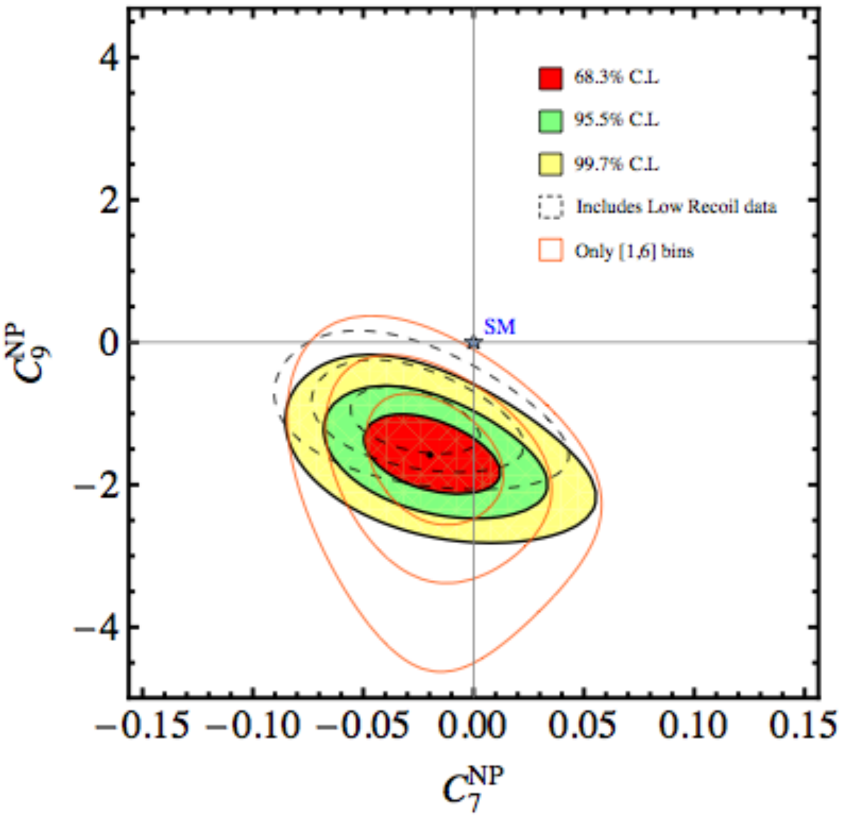
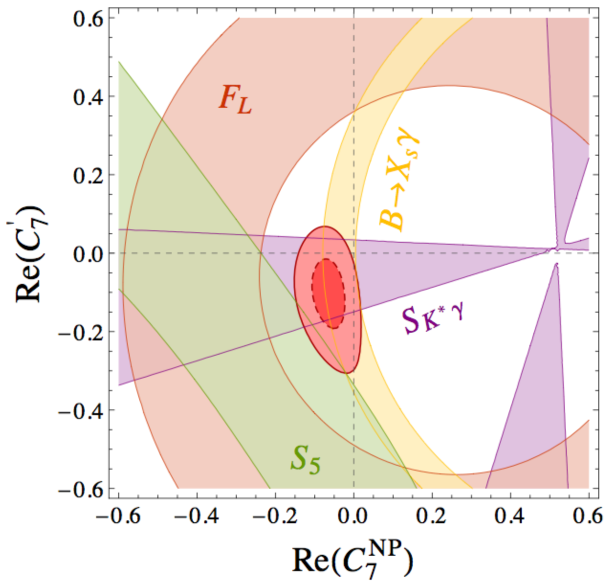
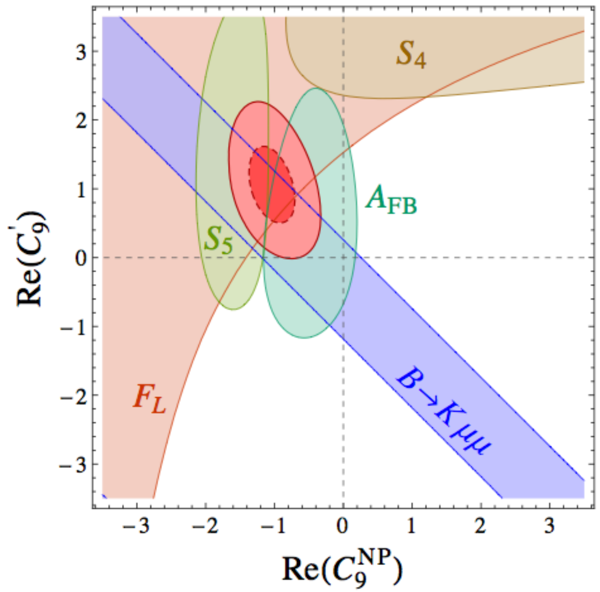


FIG. 1: Fit to $(\mathcal{C}_7^{NP}, \mathcal{C}_9^{NP})$, using the three large-recoil bins for $B \to K^*\mu^+\mu^-$ observables, together with $B \to X_s\gamma$, $B \to X_s\mu^+\mu^-$, $B \to K^*\gamma$ and $B_s \to \mu^+\mu^-$. The dashed contours include both large- and low-recoil bins, whereas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





$B_d^0 \to K^{*0}\mu\mu$ – Future

- For the full 3fb^{-1} $B_d^0 \to K^{*0}\mu\mu$ analysis, the aim is not just to increase integrated luminosity but to make a full angular fit

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\Big[J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_l$$
$$+ J_3 \sin^2\theta_K \sin^2\theta_l \cos 2\phi + J_4 \sin 2\theta_K \sin 2\theta_l \cos\phi + J_5 \sin 2\theta_K \sin\theta_l \cos\phi$$
$$+ (J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_l + J_7 \sin 2\theta_K \sin\theta_l \sin\phi + J_8 \sin 2\theta_K \sin 2\theta_l \sin\phi$$
$$+ J_9 \sin^2\theta_K \sin^2\theta_l \sin 2\phi\Big]\,, \qquad (1)$$

$$J_{1s} = \frac{(2+\beta_\ell^2)}{4}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + |A_\perp^R|^2 + |A_\parallel^R|^2\right] + \frac{4m_\ell^2}{q^2}\mathrm{Re}\left(A_\perp^L A_\perp^{R*} + A_\parallel^L A_\parallel^{R*}\right)\,,$$

$$J_{1c} = |A_0^L|^2 + |A_0^R|^2 + \frac{4m_\ell^2}{q^2}\left[|A_t|^2 + 2\mathrm{Re}(A_0^L A_0^{R*})\right] + \beta_\ell^2 |A_S|^2\,,$$

$$J_{2s} = \frac{\beta_\ell^2}{4}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + |A_\perp^R|^2 + |A_\parallel^R|^2\right]\,, \qquad J_{2c} = -\beta_\ell^2\left[|A_0^L|^2 + |A_0^R|^2\right]\,,$$

$$J_3 = \frac{1}{2}\beta_\ell^2\left[|A_\perp^L|^2 - |A_\parallel^L|^2 + |A_\perp^R|^2 - |A_\parallel^R|^2\right]\,, \qquad J_4 = \frac{1}{\sqrt{2}}\beta_\ell^2\left[\mathrm{Re}(A_0^L A_\parallel^{L*} + A_0^R A_\parallel^{R*})\right]\,,$$

$$J_5 = \sqrt{2}\beta_\ell\left[\mathrm{Re}(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*}) - \frac{m_\ell}{\sqrt{q^2}}\mathrm{Re}(A_\parallel^L A_S^* + A_\parallel^{R*} A_S)\right]\,,$$

$$J_{6s} = 2\beta_\ell\left[\mathrm{Re}(A_\parallel^L A_\perp^{L*} - A_\parallel^R A_\perp^{R*})\right]\,, \qquad J_{6c} = 4\beta_\ell \frac{m_\ell}{\sqrt{q^2}}\mathrm{Re}(A_0^L A_S^* + A_0^{R*} A_S)\,,$$

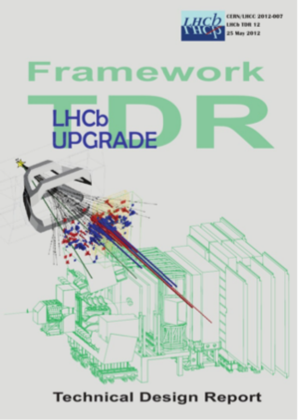
$$J_7 = \sqrt{2}\beta_\ell\left[\mathrm{Im}(A_0^L A_\parallel^{L*} - A_0^R A_\parallel^{R*}) + \frac{m_\ell}{\sqrt{q^2}}\mathrm{Im}(A_\perp^L A_S^* - A_\perp^{R*} A_S))\right]\,,$$

$$J_8 = \frac{1}{\sqrt{2}}\beta_\ell^2\left[\mathrm{Im}(A_0^L A_\perp^{L*} + A_0^R A_\perp^{R*})\right]\,, \qquad J_9 = \beta_\ell^2\left[\mathrm{Im}(A_\parallel^{L*} A_\perp^L + A_\parallel^{R*} A_\perp^R)\right]\,,$$

- J_i terms depend on the complex spin amplitudes $A_{L,R}^0$, $A_{L,R}^{//}$, $A_{L,R}$ – if it is possible to extract these
  - significantly more power for observables already determined
  - then possible to form any observable

The LHCb Upgrade

- LHCb will be upgraded during LHC's second long shutdown
- As elsewhere at the LHC, limitation for progress is in the trigger
  - The hardware trigger of LHCb at 1.1 MHz saturates for hadronic final states at luminosities above $\sim 3\times10^{32}$ $cm^{-2}s^{-1}$
  - Will remove the hardware trigger and run an entirely software-based High Level Trigger at 40 MHz, operate at 5× higher luminosity
- Planned hardware upgrades
  - Move pixel detector even closer to beam to improve light quark rejection
  - Upgrade particle identification and tracking systems to keep occupancy low
- Expect to increase data-sample collected each year by
  - Factor 20 for channels involving hadrons
  - Factor 10 for channels involving muons



[LOI, CERN-LHCC-2011-001]
[FDTR, CERN-LHCC-2012-007]

Conclusions

- Flavour physics has sensitivity to mass scales that are well above those accessible by direct production
  - Measurements I have shown are far away from systematics limits imposed by experiments or theory
  - In many cases challenge is to obtain even larger event samples
  - Look forward to more data and then upgrade of experiment
- At present, the SM comes out matching the data well
- Most significant deviation is that seen in $B_d^0 \to K^{*0}\mu\mu$ P_5'
- Are several other areas that warrant further attention in the future:
  - Update of isospin asymmetry → confirm anomaly?
  - Search for $B^0 \to \mu\mu$ → constraint on MFV
  - Measurement of $B \to D^{(*)}\tau\nu / B \to D^{(*)}\mu\nu$ → confirm $R(D^{(*)})$ anomaly (?)