What B physics can say about BSM models

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12 April 2016

11th Franco-Italian meeting on B physics,
Paris, LPNHE, 11 – 13 April 2016

Thanks to C. Langenbruch and G. Cowan for donating many slides

Standard Model

How Standard Model works, [YouTube demonstration]

The Standard Model A was released in 1908 with its characteristic Columbia type speed control. Standard was still in business as late as 1920, selling model A's even though an internal horn model B was introduced in 1911. The Standard Model B was not to replace the model A, but merely expand the model range. The model A has a red iridescent horn. The model A, like the model AA has a large spindle, and will only play "Standard" records.

Introduction

- In general, we search for NP indirectly in processes where SM contributions are suppressed, and so, small NP effects can become visible (or even dominant).
- Phenomenologically, we can classify potential NP contributions as
  - $\Delta F = 1$ (B decays)
    - Loop suppression (NP can enter through trees, *e.g.* FCNC)
    - Helicity suppression (Vector-mediated SM transitions are small compared to (pseudo)scalar-mediated NP).
  - $\Delta F = 2$ (neutral B mixing)
    - 2nd order weak transition in SM, can be enhanced by NP

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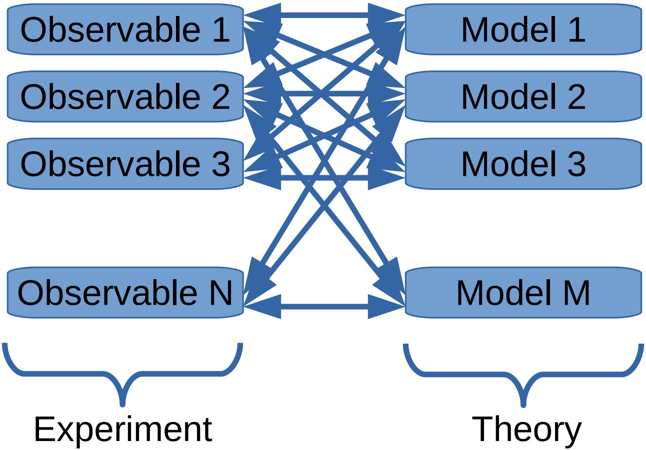
  - $\Delta F = 2$ (neutral B mixing)
    - 2nd order weak transition in SM, can be enhanced by NP
- Usually, after excitement of first data, everything is perfectly consistent with SM, so we enter the regime of precision measurement (search for NP as a small correction to SM)
  - Variation: after exciting 3-4σ tension, we enter the regime of precision measurement and the tension vanishes
  - Experimental and theoretical challenges related to precision measurements

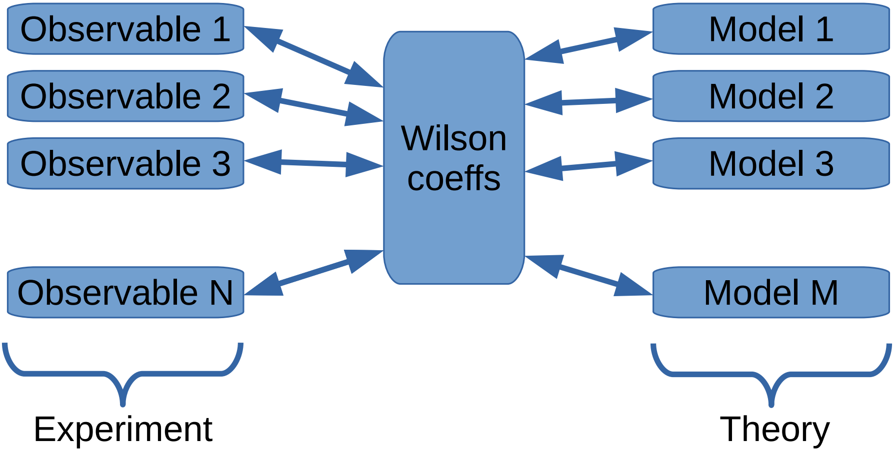
An incomplete selection of NP-sensitive measurements

- Very rare decays ($B^0_s \to \mu^+\mu^-$)
- $b \to s$ penguins ($B^0 \to K^*\mu^+\mu^-$)
- Radiative $b \to s\gamma$ decays ($B^0 \to K^*\gamma$)
- Radiative $b \to s\gamma\gamma$ decays ($B_{(s)} \to \gamma\gamma$)
- Fully leptonic decays ($B \to \tau\nu_\tau$)
- Direct CP violation
- $B_{(s)}$ mixing ($B^0 \to J/\psi\, K^0_{\rm S}$, $B^0_s \to J/\psi\,\phi$)
- Flavour-violating decays ($\tau \to 3\mu$)
- Lepton (non-)universality (R_K, $B \to D^{(*)}\tau\nu$)

} Covered this morning


Observable 1
Observable 2
Observable 3
Observable N
Model 1
Model 2
Model 3
Model M
Experiment
Theory

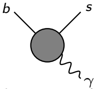
Effective field theory

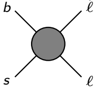


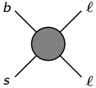
- Model-independent description in effective field theory

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{\rm tb} V^*_{\rm ts} \sum_i \underbrace{\mathcal{C}_i \mathcal{O}_i}_{\text{Left-handed}} + \underbrace{\mathcal{C}'_i \mathcal{O}'_i}_{\text{Right-handed, } \frac{m_s}{m_b} \text{ suppressed}}$$

- Wilson coefficients $\mathcal{C}_i^{(\prime)}$ encode short-distance physics, $\mathcal{O}_i^{(\prime)}$ corr. operators

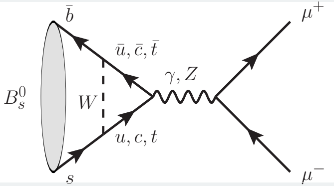






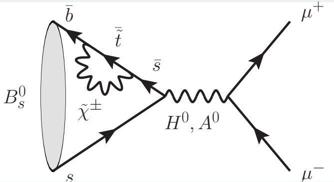
	$b \to s\gamma$	$B \to \mu\mu$	$b \to s\ell\ell$
$\mathcal{O}_7^{(\prime)}$ photon penguin	✓		✓
$\mathcal{O}_9^{(\prime)}$ vector coupling			✓
$\mathcal{O}_{10}^{(\prime)}$ axialvector coupling		✓	✓
$\mathcal{O}_{S,P}^{(\prime)}$ (pseudo)scalar penguin		✓	

SM



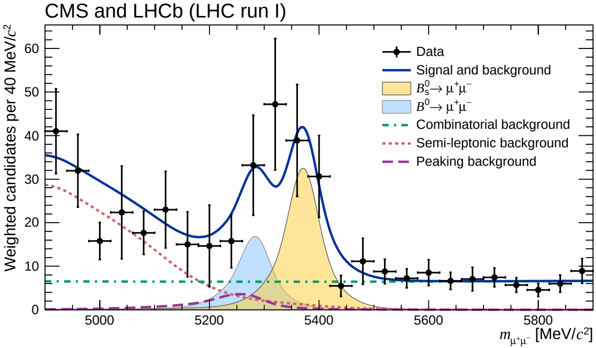
Weak suppression (2nd order)
Helicity suppression

NP



(MSSM contribution)
Extremely sensitive to scalar and pseudoscalar NP operators

Combined analysis of LHCb and CMS Run I data [Nature 522 (2015) 68-72]



- First obs. of $B_s^0 \to \mu^+\mu^-$ with 6.2 σ significance (expected 7.2 σ)
  $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$ compatible with SM at 1.2 σ
- First evidence for $B^0 \to \mu^+\mu^-$ with 3.0 σ significance (expected 0.8 σ)
  $\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$ compatible with SM at 2.2 σ

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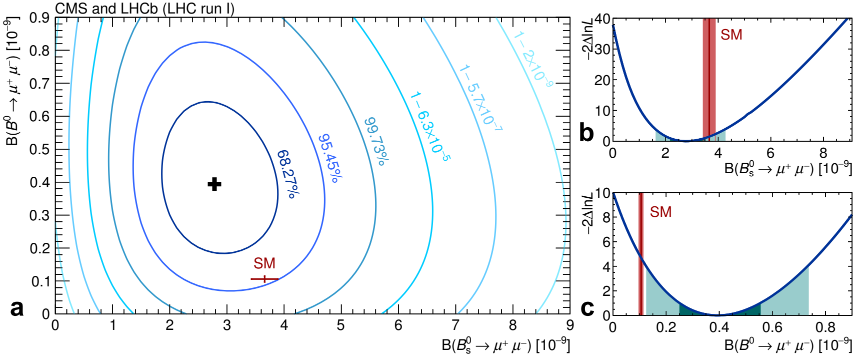

- First obs. of $B_s^0 \to \mu^+\mu^-$ with $6.2\,\sigma$ significance (expected $7.2\,\sigma$)
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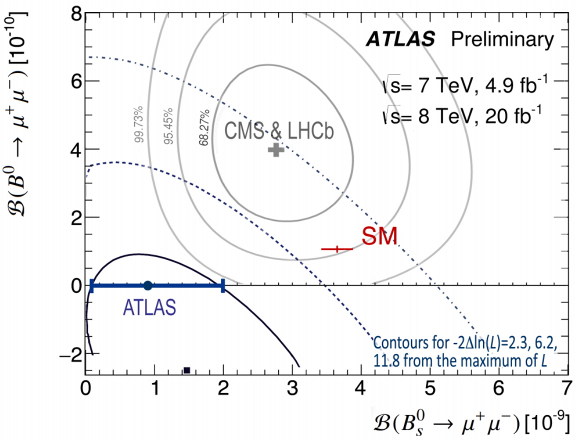
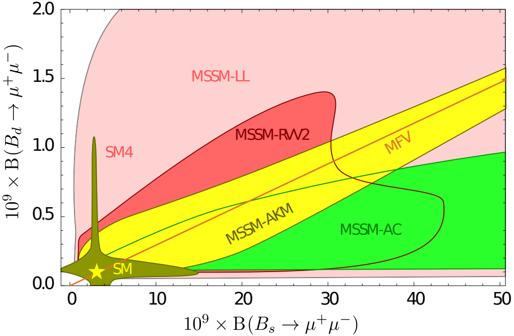
  $\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$ compatible with SM at $2.2\,\sigma$

Recent news from ATLAS collaboration [Moriond EW 2016 preliminary]



- $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (0.9^{+1.1}_{-0.8}) \times 10^{-9}$ ($< 3.0 \times 10^{-9}$ at 95% CL)
- $\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-9}$ at 95% CL
- Compatibiltiy with SM for simultaneous fit: 2.0σ

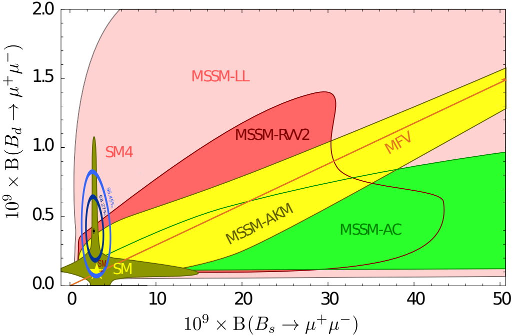


[D. Straub, arXiv:1205.6094]

$B_{(s)} \to \mu^+\mu^-$ exclude a **huge** parameter region of MSSM and 4-gen models.

[G. Hou, arXiv:1307.2448]

Fourth generation can accommodate enhanced $\mathcal{B}(B^0 \to \mu^+\mu^-)$ if it's confirmed. In addition, reduces some tensions in CKM measurements, but needs a rather conspirological explanation of SM Higgs couplings.



[D. Straub, arXiv:1205.6094]

Vote?

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"supersymmetry is dead"

Environ 1 560 résultats

"supersymmetry is not dead"

10 résultats

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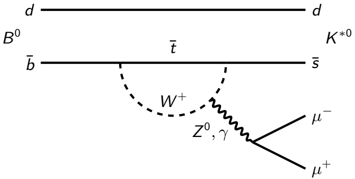
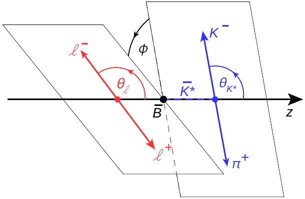
"Golden mode" $B^0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-$

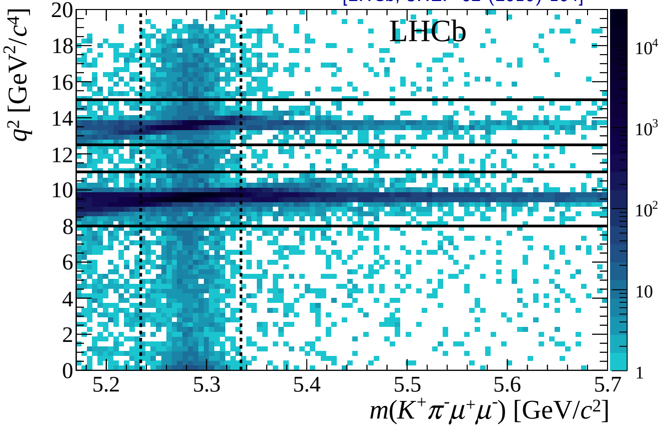




- Decay fully described by three helicity angles $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$ and $q^2 = m^2_{\mu\mu}$
- $$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ \tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$
- $F_{\mathrm{L}}, A_{\mathrm{FB}}, S_i$ combinations of K^{*0} spin amplitudes depending on Wilson coefficients $C_7^{(\prime)}$, $C_9^{(\prime)}$, $C_{10}^{(\prime)}$ and form factors
- Perform ratios of angular observables where form factors cancel at leading order
  Example: $P_5' = \frac{S_5}{\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}}$ [S. Descotes-Genon *et al.*, JHEP, 05 (2013) 137]
- Relative sign between B^0 and $\bar{B}^0$ $\to$ access to CP asymmetries $A_{3,\ldots,9}$

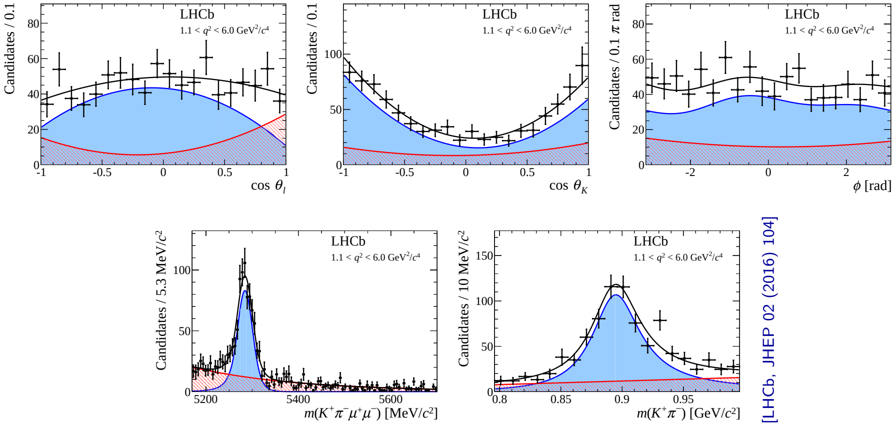
$B^0 \to K^{*0}\mu^+\mu^-$ selection

[LHCb, JHEP 02 (2016) 104]



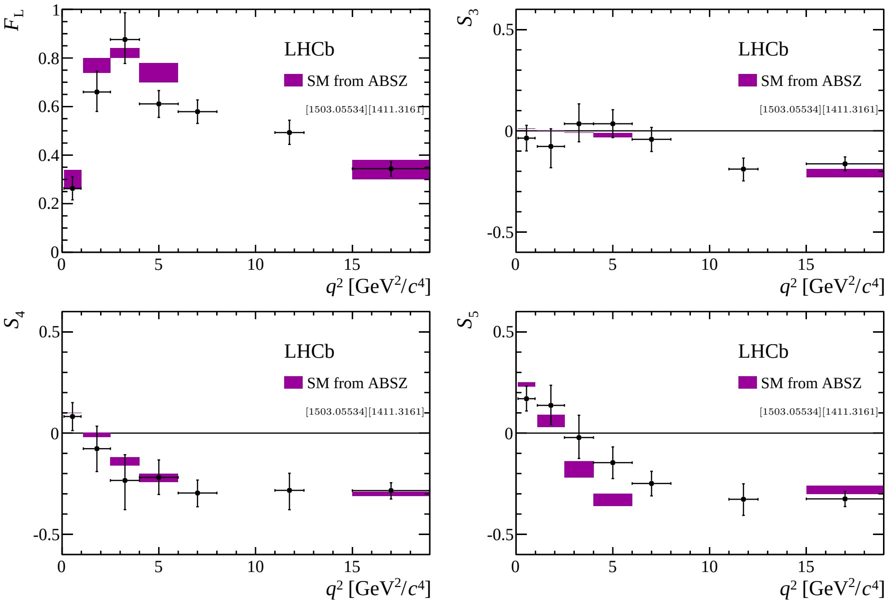
- BDT to suppress combinatorial background
  Input variables: PID, kinematic and geometric quantities, isolation variables
- Veto of $B^0 \to J/\psi\, K^{*0}$ and $B^0 \to \psi(2S) K^{*0}$ (important control decays) and peaking backgrounds using kinematic variables and PID
- Signal clearly visible as vertical band after the full selection

$B^0 \to K^{*0}\mu^+\mu^-$ likelihood projections $[1.1, 6.0]\,\mathrm{GeV}^2/c^4$



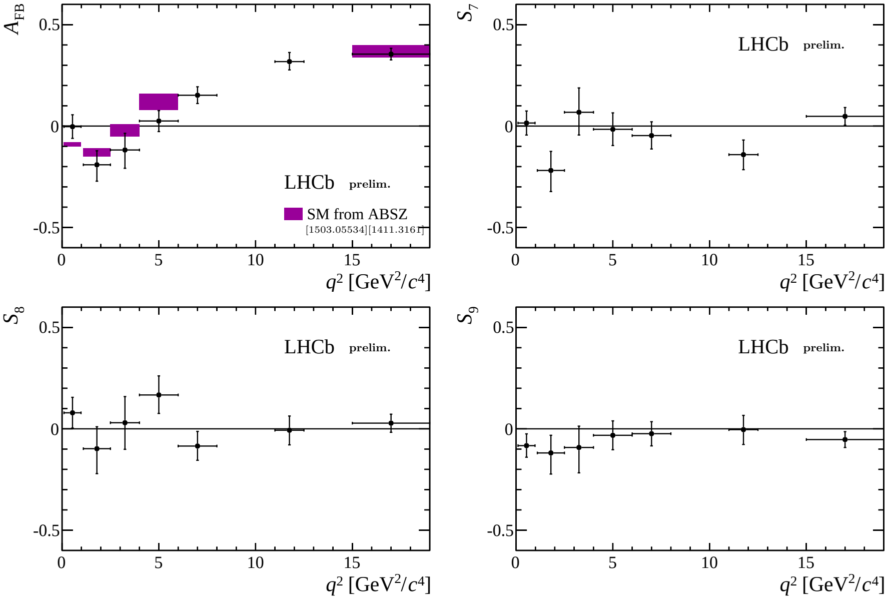
[LHCb, JHEP 02 (2016) 104]

- Use $B^0 \to J/\psi\, K^*$ as control channel
- Efficiency corrected distributions show good agreement with overlaid projections of the probability density function



[LHCb, JHEP 02 (2016) 104]

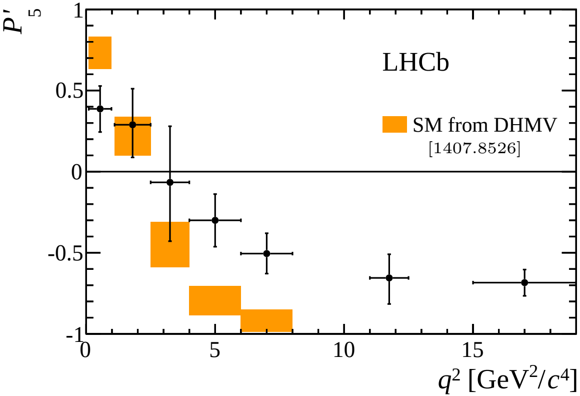
$B^0 \to K^{*0}\mu^+\mu^-$ Results: $A_{\rm FB}$, S_7, S_8, S_9



[LHCb, JHEP 02 (2016) 104]

$B^0 \to K^{*0}\mu^+\mu^-$: P'_5

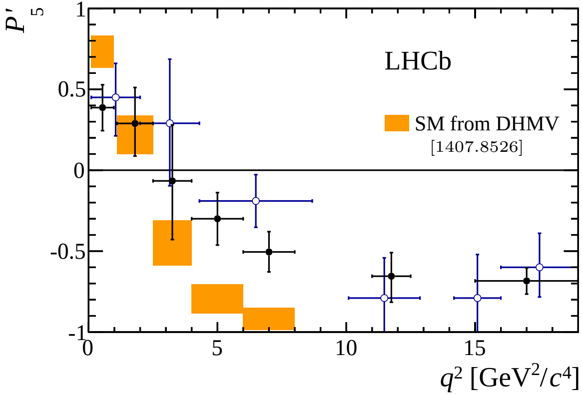
[LHCb, JHEP 02 (2016) 104]



- $[4.0, 6.0]$ and $[6.0, 8.0]\,\mathrm{GeV}^2/c^4$ local deviations of 2.8σ and 3.0σ

$B^0 \to K^{*0}\mu^+\mu^-$: P_5'

[LHCb, JHEP 02 (2016) 104]



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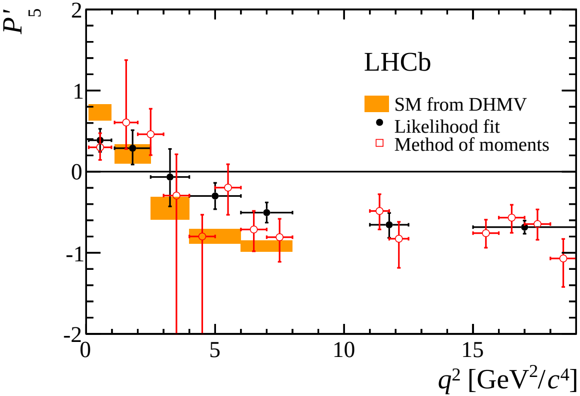
- Tension seen in P_5' in [PRL 111, 191801 (2013)] confirmed
- Compatible with $1\,\mathrm{fb}^{-1}$ measurement

$B^0 \to K^{*0}\mu^+\mu^-$: P_5'

[LHCb, JHEP 02 (2016) 104]



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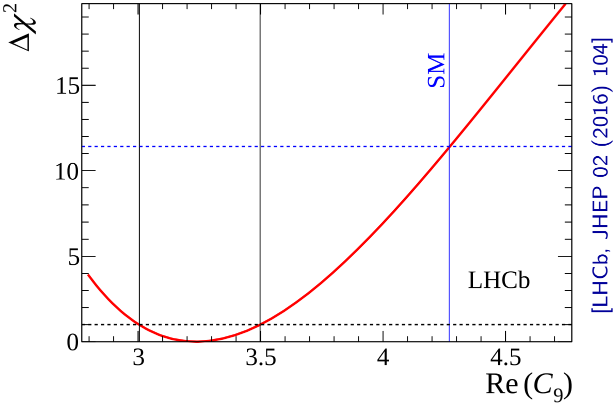
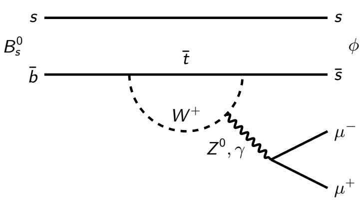
- Compatible with $1\,\mathrm{fb}^{-1}$ measurement
- Moments analysis: 10-30% less sensitive than Maximum Likelihood fit [F. Beaujean *et al.*, PRD 91 (2015) 114012] but allows narrow $1\,\mathrm{GeV}^2/c^4$ wide q^2 bins

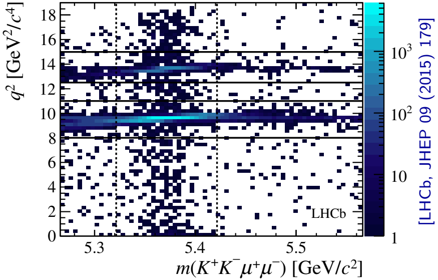
$B^0 \to K^{*0}\mu^+\mu^-$: Compatibility with the SM



- Perform χ^2 fit of measured S_i observables using [EOS] software
- Varying $\mathrm{Re}(\mathcal{C}_9)$ and incl. nuisances according [F. Beaujean *et al.*, EPJC 74 (2014) 2897]
- $\Delta\mathrm{Re}(\mathcal{C}_9) = -1.04 \pm 0.25$ with global significance of $3.4\,\sigma$

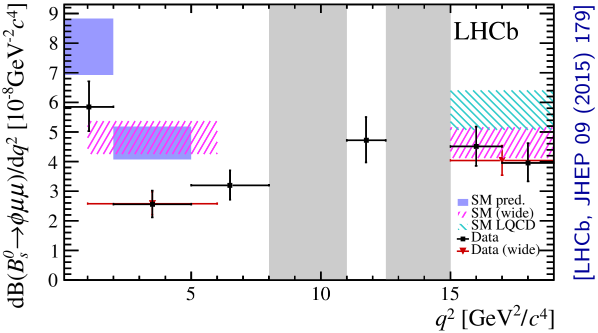
The rare decay $B_s^0 \to \phi[\to K^+K^-]\mu^+\mu^-$





- Dominant $b \to s\mu^+\mu^-$ decay for B_s^0, analogous to $B^0 \to K^{*0}\mu^+\mu^-$
- $K^+K^-\mu^+\mu^-$ final state not self-tagging
  $\to$ reduced number of angular observables: F_{L}, $S_{3,4,7}$, $A_{5,6,8,9}$
- Signal yield lower due to $\frac{f_s}{f_d} \sim \frac{1}{4}$, $\frac{\mathcal{B}(\phi\to K^+K^-)}{\mathcal{B}(K^{*0}\to K^+\pi^-)} = \frac{3}{4}$
- Clean selection due to narrow ϕ resonance, S-wave negligible

$B_s^0 \to \phi\mu^+\mu^-$ differential branching fraction



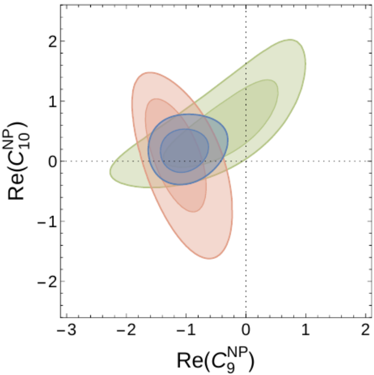
- In $1 < q^2 < 6\,\mathrm{GeV}^2/c^4$ diff. $\mathcal{B}$ more than $3\,\sigma$ below SM prediction
- Confirming deviation seen in $1\,\mathrm{fb}^{-1}$ analysis [LHCb, JHEP 07 (2013) 084]
- Most precise measurement of relative and total branching fraction

$$\frac{\mathcal{B}(B_s^0\to\phi\mu^+\mu^-)}{\mathcal{B}(B_s^0\to J/\psi\,\phi)} = (7.41^{+0.42}_{-0.40} \pm 0.20 \pm 0.21)\times 10^{-4},$$

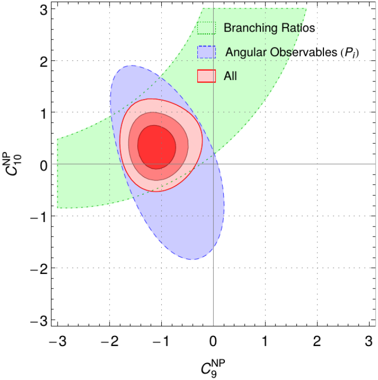
$$\mathcal{B}(B_s^0\to\phi\mu^+\mu^-) = (7.97^{+0.45}_{-0.43} \pm 0.22 \pm 0.23 \pm 0.60)\times 10^{-7},$$

Global fits to $b \to s$ data

[W. Altmannshofer *et al.*, EPJC 75 (2015) 382]



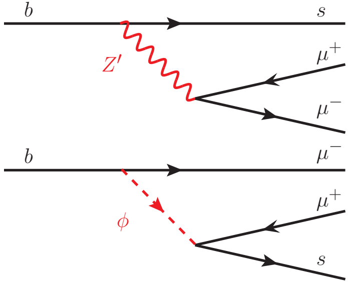
[S. Descotes-Genon *et al.*, arXiv:1510.04239]

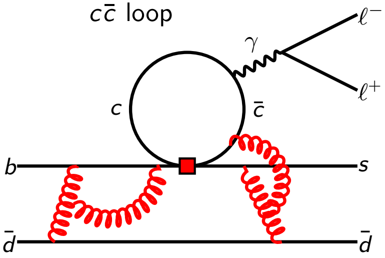


- Using input from $B_s^0 \to \mu^+\mu^-$, $B^0 \to K^{*0}\mu^+\mu^-$, $B_s^0 \to \phi\mu^+\mu^-$; angular and differential $\mathcal{B}$ measurements
- Tension can be reduced with $\Delta\mathrm{Re}(\mathcal{C}_9) \sim -1$, significances around $4\,\sigma$
- Consistency between angular observables and branching fractions

NP or hadronic effect?

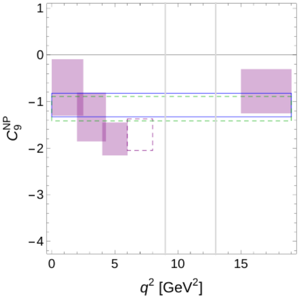
New physics





- Possible explanations for shift in $\mathcal{C}_9$
  - NP *e.g.* Z' [Gauld et al.] [Buras et al.] [Altmannshofer et al.] [Crivellin et al.] Leptoquarks [Hiller et al.] [Biswas et al.] [Buras et al.] [Gripaios et al.]
  - hadronic charm loop contributions

[W. Altmannshofer *et al.*, arXiv:1503.06199]



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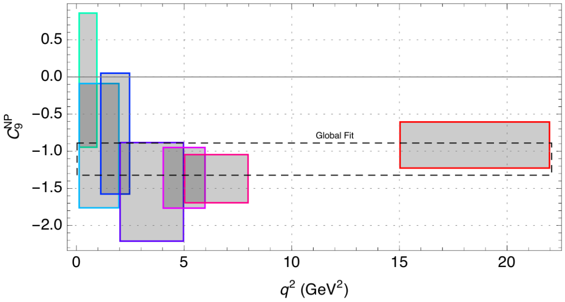

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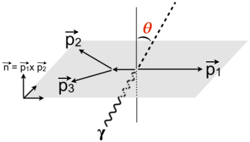
  - hadronic charm loop contributions
- q^2 dependence: $c\bar{c}$ loops rise towards J/ψ, NP q^2-independent

- $b \to s\gamma$ is dominated by radiative penguin in the SM. High-E_T photon in the final state.
- In the SM, the photon is left-handed ($|c_L|^2 \gg |c_R|^2$)

$$\lambda_\gamma = \frac{|c_R|^2 - |c_L|^2}{|c_R|^2 + |c_L|^2}$$

$\lambda_\gamma = -1$ for b and $+1$ for $\bar{b}$.

- Significant right-handed component would indicate New Physics (C_7').

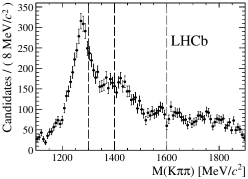


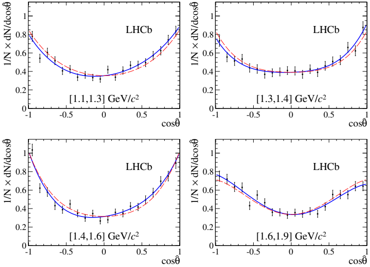
- Decays like $B \to K^*(K\pi)\gamma$ are insensitive to γ polarisation.
- Need a four-body decay: $B^+ \to K^+\pi^+\pi^-\gamma$
- Up-down asymmetry:

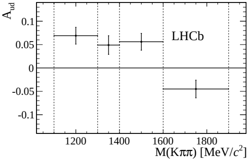
$$A_{UD}^{\pm} = \pm \frac{\int_0^1 d\cos\theta \frac{d\Gamma}{d\cos\theta} - \int_{-1}^0 d\cos\theta \frac{d\Gamma}{d\cos\theta}}{\int_{-1}^1 d\cos\theta \frac{d\Gamma}{d\cos\theta}}$$

is proportional to λ_γ

[PRL 112, 161801 (2014)]

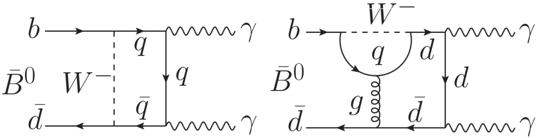






- Signal yield $N_{K\pi\pi\gamma} = 13\,876 \pm 153$
- Perform angular fit of $\cos\theta$ distribution to determine $\mathcal{A}_{\rm ud}$ in 4 bins of $M(M\pi\pi)$
- First observation of non-zero photon polarisation at $5.2\,\sigma$ in combination
- To determine precise value for λ_γ, resonance structure of final state needs to be resolved

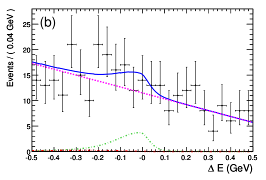
Radiative penguin decays
SM expectations:
$\mathcal{B}(B^0 \to \gamma\gamma) = (1.5 - 10) \times 10^{-8}$
$\mathcal{B}(B_s^0 \to \gamma\gamma) = (0.5 - 1) \times 10^{-6}$



Some SUSY models can enhance it by an order of maginutude (2HDM, RPV).

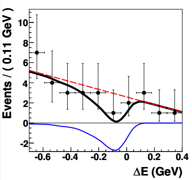
[PRD 58 (1998) 095014], [PRD 70 (2004) 035008],

$B^0 \to \gamma\gamma$ [BaBar, PRD 83:032006 (2011)]



$\mathcal{B}(B^0 \to \gamma\gamma) < 3.3 \times 10^{-7}$

$B_s^0 \to \gamma\gamma$ [Belle, PRL 100:121801 (2008)]



$\mathcal{B}(B_s^0 \to \gamma\gamma) < 8.7 \times 10^{-6}$

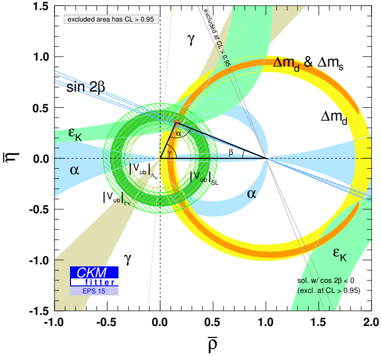
Belle II expected precision for $B_s^0 \to \gamma\gamma$: 0.3×10^{-6} (so, SM rate could be visible).
Seems hard for LHCb, but not hopeless? Two hard photons, no missing particles...

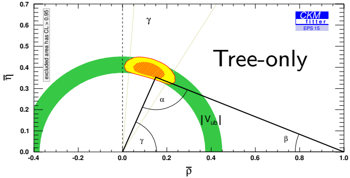
Unitarity Triangle measurements

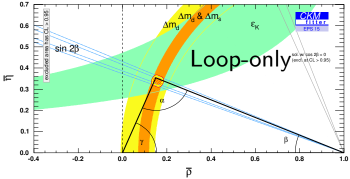
Cabibbo-Kobayashi-Maskawa matrix

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Sensitivity to NP comes from the global consistency of various measurements







Unitarity Triangle measurements

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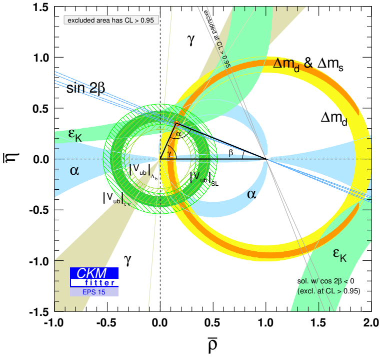
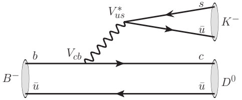
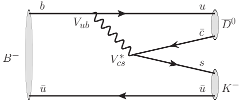


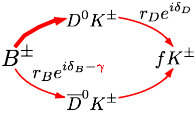
Some UT measurements potentially affected by NP:

- γ from trees vs. γ from loops
- γ vs. Δm_s
- $\sin 2\beta$ vs. V_{ub} from $B \to \tau\nu$
- V_{ub} from SL vs. V_{ub} from $B \to \tau\nu$
- $\sin 2\beta$ from $B \to J/\psi K^0_S$ vs. $\sin 2\beta_{\text{eff}}$ from *e.g.* $b \to sq\bar{q}$

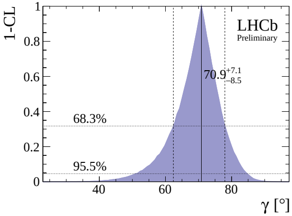
- Measured entirely from tree decays.
- All hadronic parameters can be constrained from experiment $\Rightarrow$ theoretically very clean (uncertainty $< 10^{-7}$[Brod, Zupan, JHEP 1401 (2014) 051])





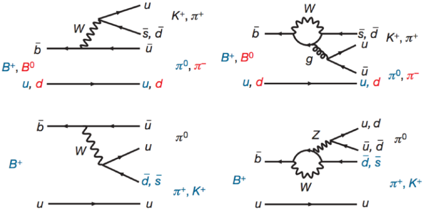


- Combination of many different modes:
  - Time-integrated asymmetries in $B \to DK$, $B \to DK^*$, $B \to DK\pi$ with $D \to hh, hhhh$
  - Dalitz-plot analysis of $D^0 \to K^0_S h^+ h^-$ from $B \to DK$, $B \to DK^*$
  - Time-dependent analysis of $B_s \to D_s K$
- Experimentally, just entering precision measurement regime ($< 10\%$)

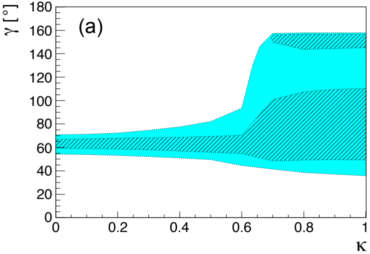


[LHCb-CONF-2016-001]

- As in $B \to DK$, interference of several diagrams, with or without $V_{ub} \Rightarrow$ CP violation, phase γ
- Loop diagrams: NP can affect γ extraction from these modes.



Extraction of γ from time-dependent asymmetries of $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ and U-spin symmetry



$\gamma = (63.5^{+7.2}_{6.7})^\circ$ (U-breaking up to 50%)

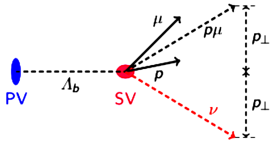
Large CPV effects seen in other charmless modes (*e.g.* $B \to hhh$), but interpretation in terms of γ needs more work

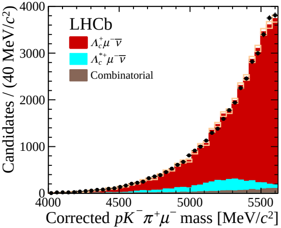
[LHCb, PLB 741 (2015) 1]

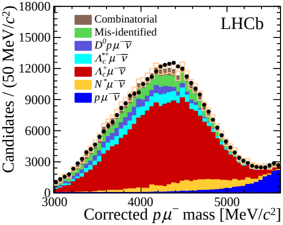
SM reference CKM measurements: $|V_{ub}|$ from semileptonic decays

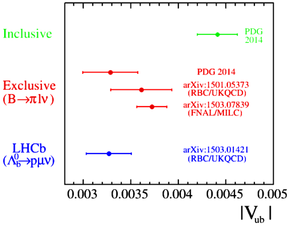
[LHCb, Nature Phys. 11 (2015) 743]

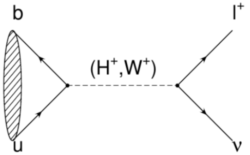
- Use Λ_b^0 sample for $|V_{ub}|$ measurement, cleaner final state
- Measure $|V_{ub}|/|V_{cb}|$ from
  $$|V_{ub}/V_{cb}|^2 = \frac{\mathcal{B}(\Lambda_b^0 \to p\mu\nu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu\nu)} R_{FF}$$
- Fit corrected mass $M_{\text{corr}} = \sqrt{p_T^2 + M_{p\mu}^2} + p_T$
- $|V_{ub}| = [3.27 \pm 0.15 \pm 0.16(\text{LQCD}) \pm 0.06(V_{cb})] \times 10^{-3}$











SM transition can be modified at tree level by charged Higgs or leptoquarks

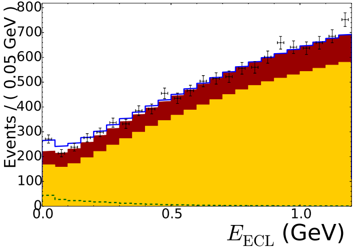
$$\mathcal{B}(B^+ \to \tau^+\nu_\tau)_{\rm SM} = \frac{G_F m_B m_\tau^2}{8\pi}\left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 |V_{ub}|^2 \tau_B$$

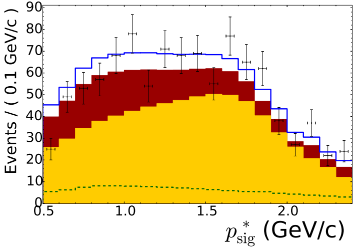
$$\mathcal{B}(B^+ \to \tau^+\nu_\tau)_{\rm SM} = (0.75^{+0.10}_{-0.05}) \times 10^{-4}$$

[Belle, PRL 110 131801 (2013)], [PRD 92 051102 (2015)]

[BaBar, PRD 88 031102 (2013)], [PRD 81 051101 (R) (2010)]

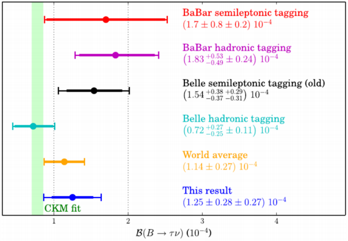
Measured with tagged B (SL or hadronic), main signature is absence of extra activity in EM calorimeter

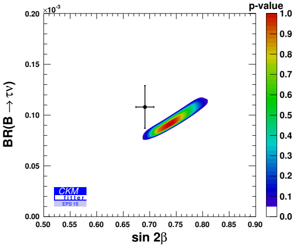




Potential NP measurement: $B \to \tau\nu_\tau$

$\mathcal{B}(B^+ \to \tau\nu) = (1.14 \pm 0.27) \times 10^{-4}$ (PDG average)



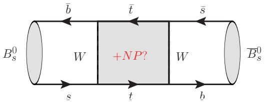


[Belle, PRD 92 051102 (2015)]

Belle II is in a good position to measure it with $\sim 5\%$ precision ($50\ \text{ab}^{-1}$).

[Physics at Super B Factory, arXiv:1002.5012]

LHCb unlikely to contribute, but could probe the similar transitions with muons, *e.g.* $B \to \mu^+\mu^-\mu^+\nu_\mu$ ("only" one neutrino in the final state, three tracks making a vertex)



Evolution of $B^0_{(s)}$ system is described by $H = M - i\Gamma/2$
Off-diagonal terms M_{12}, Γ_{12} responsible for oscillations.

Experimental observables:

- $|\Delta M| \simeq 2|M_{12}|$ — defines oscillation frequency
- $|\Delta\Gamma| \simeq 2|\Gamma_{12}| \cos\phi$ (where $\phi = \arg(-M_{12}/\Gamma_{12})$) — lifetime difference
- $a_{SL} = \mathrm{Im}(\Gamma_{12}/M_{12})$ — flavour-specific asymmetry
- Mixing-induced CP asymmetry (interference between $B \to f$ and $B \to \overline{B} \to f$)

NP mostly enters M_{12} as it is determined by box diagram.
$M_{12} = M_{12}^{SM} \cdot \Delta$, where $\Delta = |\Delta| \exp^{i\phi^{\Delta}}$ [A. Lenz, U. Nierste, PRD 83, 036004 (2011)]
Observables affected by NP ($\Delta \neq 1$):

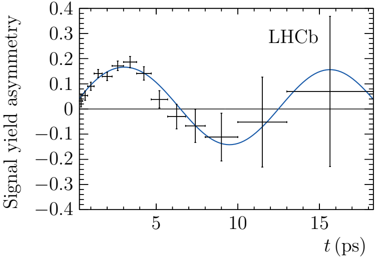
- Oscillation frequency ΔM
- Mixing-induced CPV phases 2β (B^0), ϕ_s (B^0_s)
- Semileptonic asymmetries a_{SL} and dimuon asymmetry A_{SL}

"Golden mode" at B-factories, but LHCb provides competitive measurement after recent flavour-tagging improvements.
Time-dependent asymmetry:

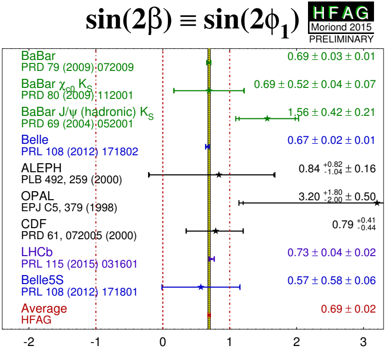
$$A(t) = \frac{S\sin(\Delta m t) + C\cos(\Delta m t)}{\cosh(\Delta\Gamma t/2) + A_{\Delta\Gamma}\sinh(\Delta\Gamma t/2)}; S = \sin 2\beta$$

[LHCb, PRL 115, 031601 (2015)]

Effective tagging power
$\varepsilon_{\rm tag}(1-2\omega) = 3.02\%$



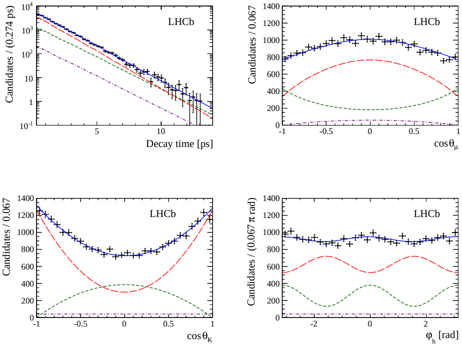
$\sin 2\beta = 0.731 \pm 0.035 \pm 0.020$



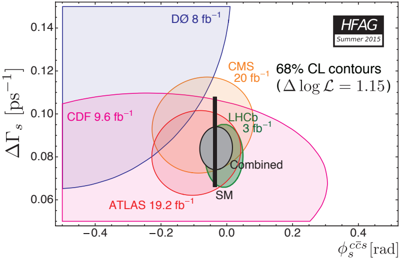
[LHCb, PRD 87 (2013) 112010]

- K^+K^- can be in P wave (ϕ) or S wave
- 3 P waves ($\mathcal{CP}$-odd or $\mathcal{CP}$-even), angular analysis to distinguish them
- Ambiguity $\varphi_s \leftrightarrow \pi - \varphi_s$ is resolved by measuring the P wave strong phase as a function of m_{KK}.
- Combined with $B_s^0 \to J/\psi \pi^+\pi^-$

Decay time and helicity distributions:



$$\phi_s = 0.01 \pm 0.07 \pm 0.01$$
$$\Gamma_s = 0.661 \pm 0.004 \pm 0.006$$
$$\Delta\Gamma_s = 0.106 \pm 0.011 \pm 0.007$$



[LHCb, PRL 114 (2015) 041601]

Use semileptonic $B^0_{(s)}$ decays.

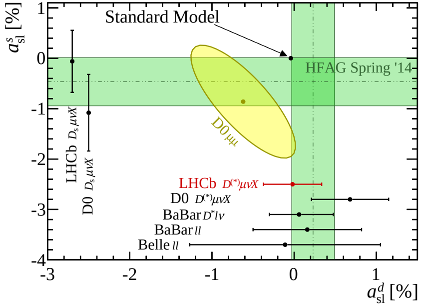
$$A_{CP} \equiv a_{SL} = \frac{\Gamma(\overline{B} \to B \to f) - \Gamma(B \to \overline{B} \to \overline{f})}{\Gamma(\overline{B} \to B \to f) - \Gamma(B \to \overline{B} \to \overline{f})}$$

$$A_{meas}(t) = \frac{a_{SL}}{2}\left(1 - \frac{\cos(\Delta m t)}{\cosh(\Delta\Gamma t/2)}\right)$$

Standard Model predictions:

[A. Lenz, arXiv:1205.1444]

$a^d_{SL} = (-4.1 \pm 0.6) \times 10^{-4}$
$a^s_{SL} = (+1.9 \pm 0.3) \times 10^{-5}$

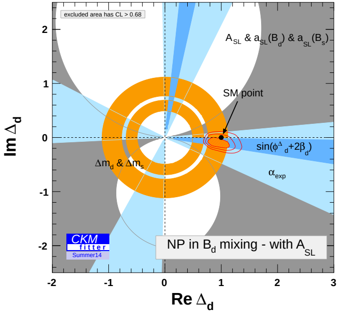


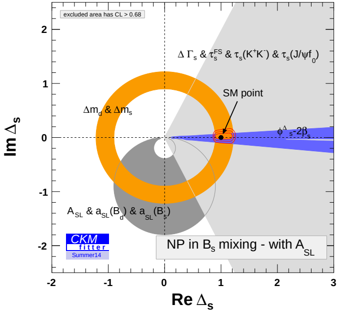
- No tagging needed. Time-dependent (B^0) or time-independent (B^0_s) SL asymmetry measurement
- 3σ tension coming from D0 dimuon asymmetry measurement

$B^0_{(s)}$ mixing

$$M_{12} = M_{12}^{SM} \cdot \Delta,\ \Delta = |\Delta| \exp^{i\phi^{\Delta}}$$

[J. Charles et al., PRD 91, 073007 (2015)]





[J. Charles et al., PRD 89, 033016 (2014)]

If the NP CKM structure is the same as SM, by the end of LHCb upgraded phase and Belle II, $B_{(s)}$ mixing probes $\Delta F = 2$ NP up to

- $\sim 20\,\mathrm{TeV}$ for tree-level NP
- $\sim 2\,\mathrm{TeV}$ for single-loop NP

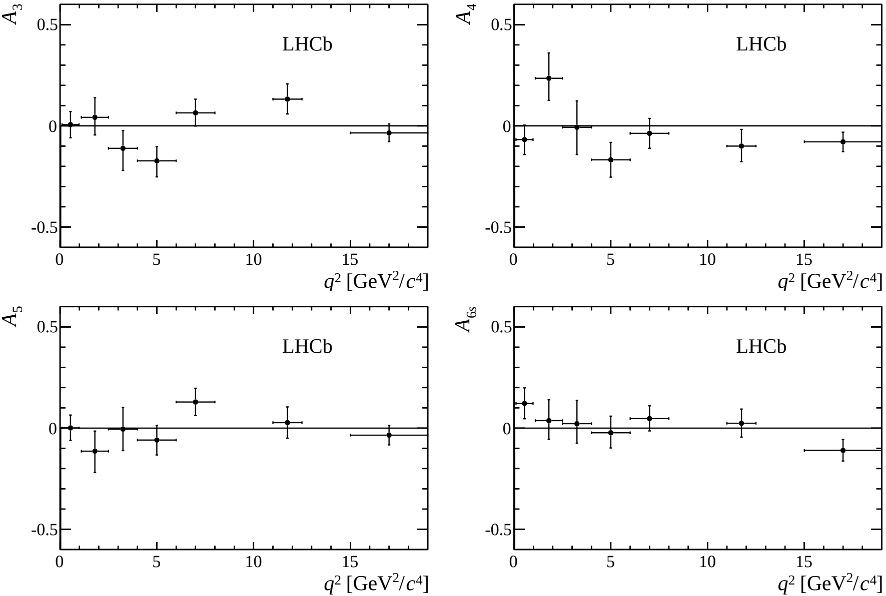
Summary

- New Physics may manifest itself in B physics in many ways:
  - Processes involving loops and even trees
  - Large enhancements of rare processes and small inconsistencies in precision measurements
  - $\Delta F = 1$ (B decays) and $\Delta F = 2$ (oscillation)
- There is a number of small tensions which seem exciting
  - Enhanced $B^0 \to \mu^+\mu^-$
  - P_5' and a number of other inconsistencies in $b \to sll$
  - R_K, $B \to D\tau\nu$ (not covered here)
  - V_{ub} from $B \to \tau\nu$
  - "$K\pi$ puzzle"

  But the number of observables is large, so look-elsewhere effect should not be neglected. Hadronic effects to be taken into account as well.

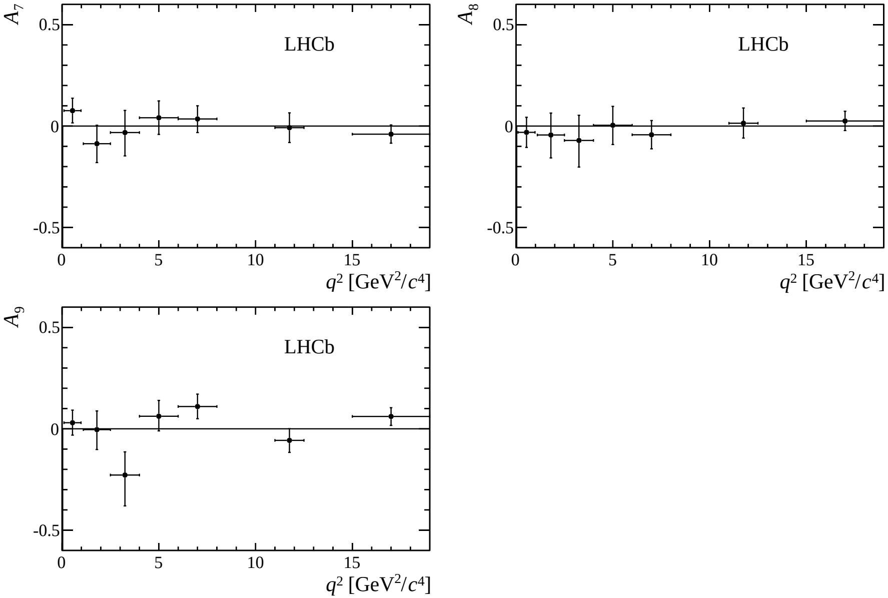
Backup

$B^0 \to K^{*0}\mu^+\mu^-$ *CP* asymmetries: A_3, A_4, A_5, A_{6s}



[LHCb, JHEP 02 (2016) 104]

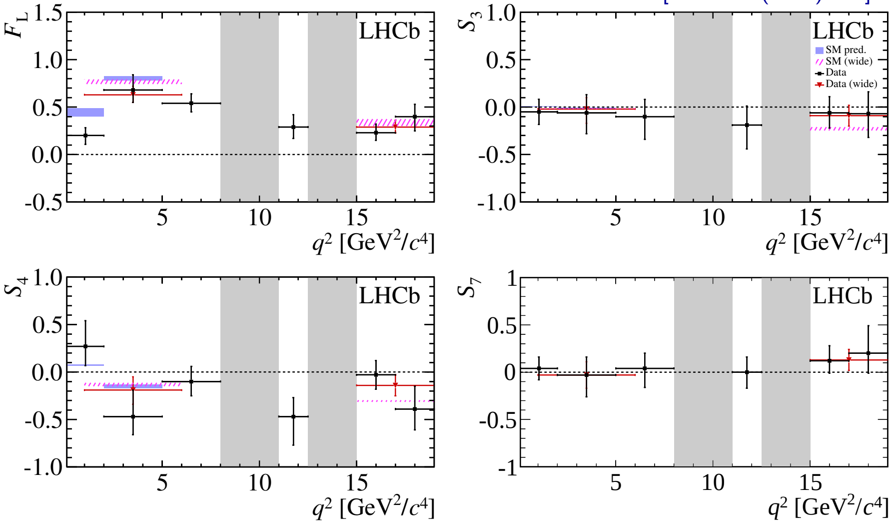
$B^0 \to K^{*0}\mu^+\mu^-$ CP asymmetries: A_7, A_8, A_9



[LHCb, JHEP 02 (2016) 104]

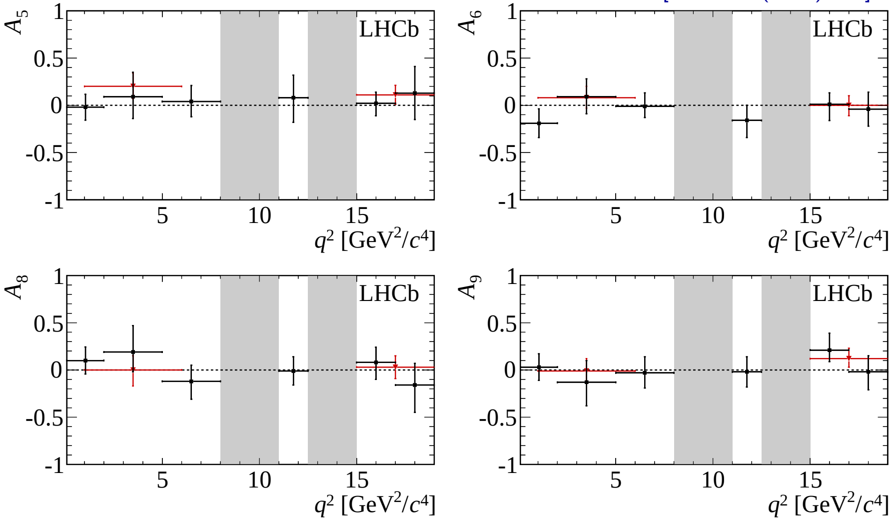
$B_s^0 \to \phi\mu^+\mu^-$ angular analysis

[JHEP 09 (2015) 179]



- Good agreement of angular obs. with SM predictions

[JHEP 09 (2015) 179]



- Good agreement of angular obs. with SM predictions