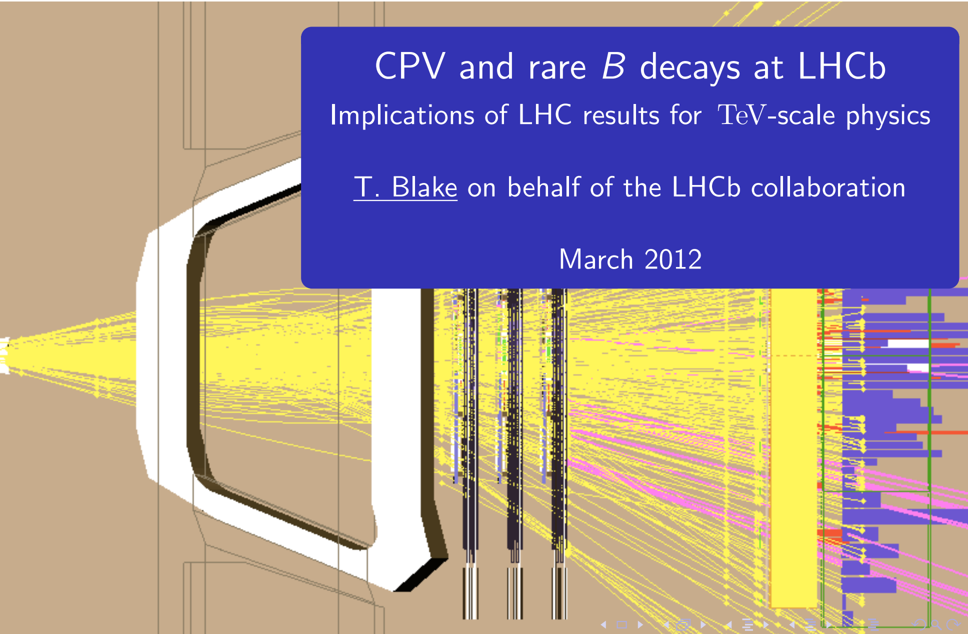
CPV and rare B decays at LHCb

Implications of LHC results for TeV-scale physics

T. Blake on behalf of the LHCb collaboration

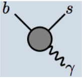
March 2012

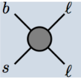


Where should we look for NP contributions in B decays?

- Flavour changing neutral currents ($\Delta F = 1$ or $\Delta F = 2$) which are suppressed in the SM (only occur at loop-order) are a promising place to search for NP:
  - B_d and B_s mixing (Δm_d, Δm_s, $S_{J/\psi K^0_S}$ and $S_{J/\psi \phi}$).
  - Rare $b \to s\ell^+\ell^-$ and $b \to s\gamma$ processes ($B_d \to K^{*0}\gamma$, $B_d \to K^{*0}\mu^+\mu^-$, $B_s \to \mu^+\mu^-$).
- Can also explore the CKM picture at loop and tree-order (more later).

Sensitivity to NP through rare decays





Operator $\mathcal{O}_i$	$B \to K^{*0}\gamma$	$B \to K^{*0}\mu^+\mu^-$	$B \to \mu^+\mu^-$
$\mathcal{O}_7 \sim m_b(\bar{s}_L\sigma_{\mu\nu}b_R)F_{\mu\nu}$	✓	✓	
$\mathcal{O}_9 \sim (\bar{s}b)_{V-A}(\bar{\ell}\ell)_V$		✓	
$\mathcal{O}_{10} \sim (\bar{s}b)_{V-A}(\bar{\ell}\ell)_A$		✓	✓
$\mathcal{O}_{S,P} \sim (\bar{s}b)_{S+P}(\bar{\ell}\ell)_{S,P}$			✓

In the SM:

- $\mathcal{C}_{S,P} \propto m_\ell m_b/m_W^2 \sim 0$.
- Helicity flipped operators $(\mathcal{C}_i'\mathcal{O}_i')$ suppressed by m_s/m_b.

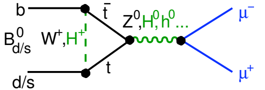
$$B^0_{(d,s)} \to \mu^+\mu^-$$

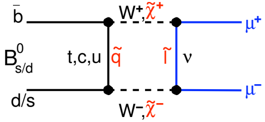
$B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$

- Sensitive to contributions from scalar + pseudo-scalar sector.
  - $\to$ Interesting to probe NP models with extended Higgs sector, e.g. MSSM, 2HDM, ...

e.g. in MSSM, branching fraction scales approximately as $\tan^6\beta/M_A^4$

- More generally:

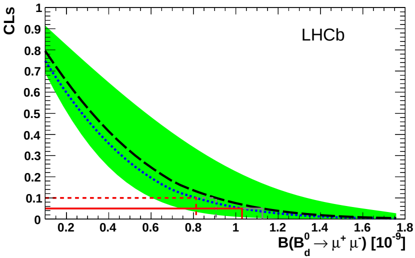




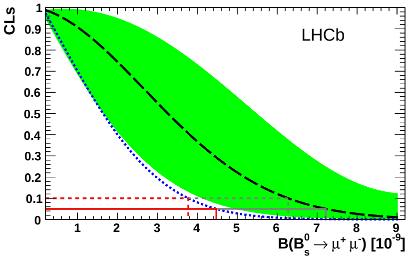
$$\mathcal{B}(B_q^0 \to \mu^+\mu^-) \simeq \frac{G_F \alpha^2 M^3_{B_q^0} f^2_{B_q^0} \tau_{B_q^0}}{64\pi^3 \sin^4\theta_W} |V_{tb}V^*_{tq}|^2 \left(1 - \frac{4m_\mu^2}{M^2_{B_q^0}}\right)^{1/2} \times$$
$$\left[M^2_{B_q^0}\left(1 - \frac{4m_\mu^2}{M^2_{B_q^0}}\right) |\mathcal{C}_S|^2 + \left(M_{B_q^0}\,\mathcal{C}_P + \frac{2m_\mu}{M_{B_q^0}}\,\mathcal{C}_{10} + \frac{2m_\mu}{M_{B_q^0}}\,\mathcal{C}'_{10}\right)^2 \right]$$

- Set limit on the branching fraction using the CLs technique, dividing data into bins of BDT response and mass.
- BDT response and mass line-shape of the signal calibrated from data using $B \to hh'$ and $J/\psi/\psi(2S)/\Upsilon(1S) \to \mu^+\mu^-$ decays.
- Expected limit $\mathcal{B}(B_s \to \mu^+\mu^-) < 7.2 \times 10^{-9}$ (bkg + SM at 95% C.L.)

$\mathcal{B}(B_d \to \mu^+\mu^-) < 1.0 \times 10^{-9}$ (95% C.L.)



$\mathcal{B}(B_s \to \mu^+\mu^-) < 4.5 \times 10^{-9}$ (95% C.L.)



c.f. $\mathcal{B}(B_s \to \mu^+\mu^-) < 22 \times 10^{-9}$ [ATLAS-CONF-2012-010]

$\mathcal{B}(B_s \to \mu^+\mu^-) < 7.7 \times 10^{-9}$ [CMS-BPH-11-020]

- LHCb sets a limit for $\mathcal{B}(B_s \to \mu^+\mu^-) < 4.5 \times 10^{-9}$ (95% C.L.)

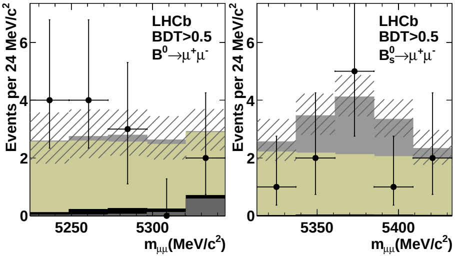
c.f. SM expectation of $(3.2 \pm 0.2) \times 10^{-9}$.

- Best fit branching fraction estimated to be:

$$\mathcal{B}(B_s \to \mu^+\mu^-) = (0.8\ {}^{+1.8}_{-1.3}) \times 10^{-9}$$

using a simultaneous maximumum likelihood fit to the $\mu^+\mu^-$ mass distribution in the 8 BDT bins.

signal
cross-feed
background
$B \to hh'$

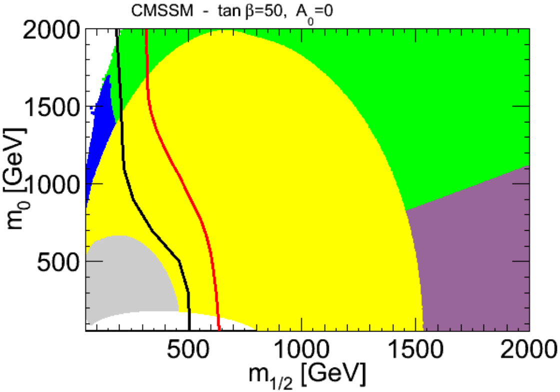


- CDF Preliminary ($9.6\,\text{fb}^{-1}$), $\mathcal{B}(B_s \to \mu^+\mu^-) = (13\ {}^{+9}_{-7}) \times 10^{-9}$.

- Strong constraints from $\mathcal{B}(B_s \to \mu^+\mu^-)$ at high-tan β.
- TeV-scale CMSSM at high-tan β largely excluded.

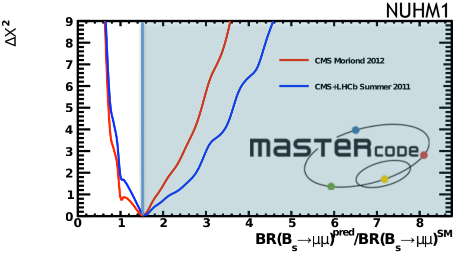
Direct search results from CMS ($5\,\mathrm{fb}^{-1}$)
Allowed region
Charged LSP
$B \to \tau\nu$
$B_s \to \mu^+\mu^-$

N. Mahmoudi, Moriond QCD 2012

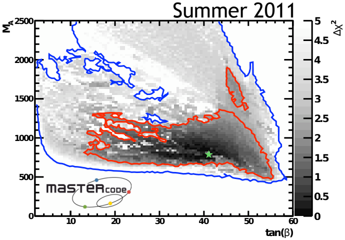


Mastercode [arXiv:1112.3564]

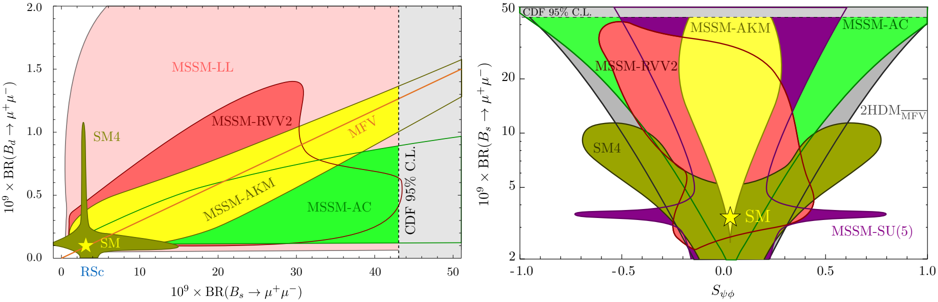
- $\mathcal{B}(B_s \to \mu^+\mu^-)$ is one of a number of strong constraints on NP models. Expect large impact from updated limit from LHCb.



LHCb $1\,\mathrm{fb}^{-1}$ (95% C.L.)



D. Straub [arXiv:1107.0266v1] (at the end of 2010)



- Ratio of $B_s \to \mu^+\mu^-$ to $B_d \to \mu^+\mu^-$ is a test of MFV.
  $\mathcal{B}(B_d \to \mu^+\mu^-)/\mathcal{B}(B_s \to \mu^+\mu^-) \neq$ SM
  implies FCNC independent of CKM structure.

$B_s \to \mu^+\mu^-$, $B_d \to \mu^+\mu^-$ and $S_{J/\psi\,\phi}$

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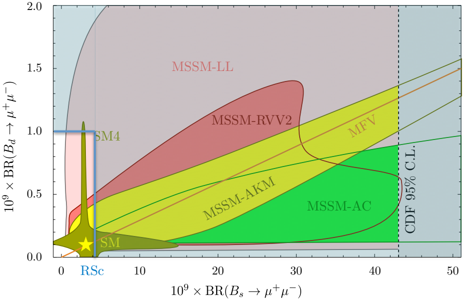
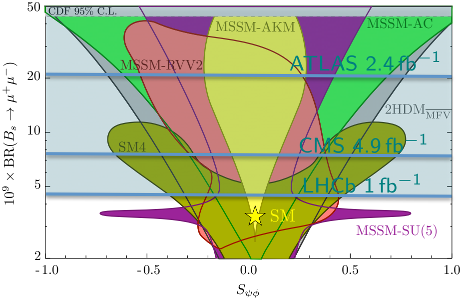
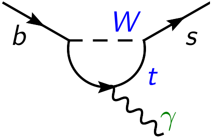




LHCb 95% C.L. on $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$ ($1\,\mathrm{fb}^{-1}$)

- Ratio of $B_s \to \mu^+\mu^-$ to $B_d \to \mu^+\mu^-$ is a test of MFV.
  $\mathcal{B}(B_d \to \mu^+\mu^-)/\mathcal{B}(B_s \to \mu^+\mu^-) \neq$ SM
  implies FCNC independent of CKM structure.

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



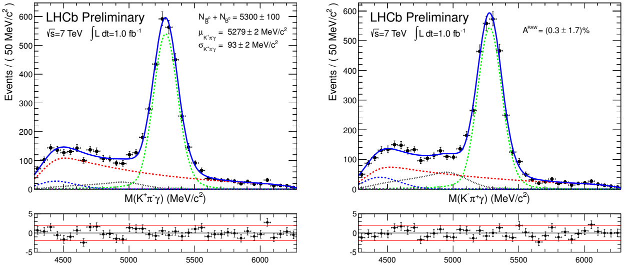
- SM prediction for CP asymmetry:

$$A_{\mathcal{CP}} = -0.006 \pm 0.004$$ [arXiv:0406055]

- Previous best measurement from *BABAR*:

$$A_{\mathcal{CP}} = -0.016 \pm 0.022 \pm 0.007$$ [PRL 103 (2009)]

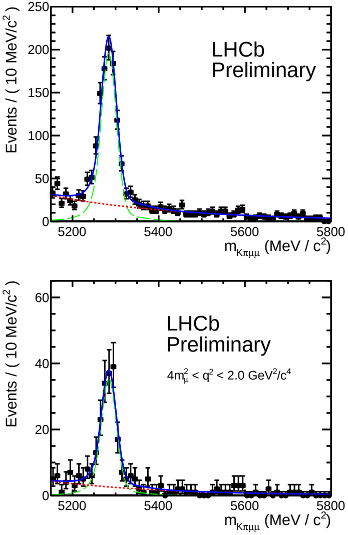
$$A_{\mathcal{CP}}(B_d \to K^{*0}\gamma) = A^{\rm RAW}_{\mathcal{CP}}(B_d \to K^{*0}\gamma) - A_{\rm prod.}(B_d) - A_{\rm det.}(K\pi)$$
$$= 0.008 \pm 0.017({\rm stat}) \pm 0.009({\rm syst}) \quad [\text{Preliminary}]$$



- Also collecting large samples of B_s decays. Observe 240 $B_s \to \phi\gamma$ candidates in $0.37\,{\rm fb}^{-1}$ [LHCb-PAPER-2011-042].

Angular analysis of $B_d \to K^{*0}\mu^+\mu^-$

- Gives access to $\mathcal{C}_7^{(\prime)}$, $\mathcal{C}_9^{(\prime)}$ and $\mathcal{C}_{10}^{(\prime)}$.
- Sensitivity through branching fraction measurements and angular observables. Angular analysis can be sensitive to the chiral structure of the NP (e.g. S_3/A_T^2).
- Decay described by three angles and dimuon invariant mass squared $(\theta_\ell, \theta_K, \phi, q^2)$.
- Analysis based on $1\,\text{fb}^{-1}$. Observe 900 candidates (c.f. *BABAR* + Belle + CDF ~ 600).



$B_d \to K^{*0}\mu^+\mu^-$ angular distribution after folding

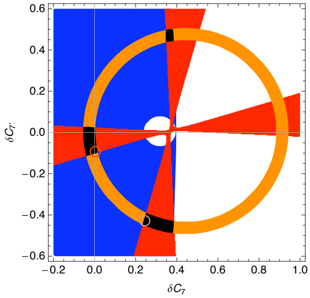
- Take advantage of a symmetry of the system, by folding the distribution in ϕ, to reduce the number of free parameters.
- $\hat{\phi} = \phi + \pi$ if $\phi < 0$ and $\hat{\phi} = \phi$ if $\phi > 0$, leading to:

$$
\begin{aligned}
\frac{1}{\Gamma}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\hat{\phi}\,\mathrm{d}q^2} = \frac{9}{16\pi}\Big[\; & F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K) \;+ \\
& F_L\cos^2\theta_K(2\cos^2\theta_\ell - 1) \;+ \\
& \frac{1}{4}(1-F_L)(1-\cos^2\theta_K)(2\cos^2\theta_\ell - 1) \;+ \\
& S_3(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\hat{\phi} \;+ \\
& \frac{4}{3}A_{FB}(1-\cos^2\theta_K)\cos\theta_\ell \;+ \\
& A_{Im}(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\hat{\phi} \;\Big]
\end{aligned}
$$

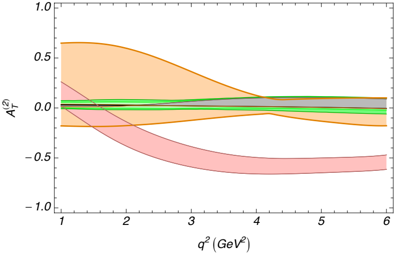
New physics sensitivity to $\mathcal{C}_7^{(\prime)}$

- $\mathcal{C}_7$ and $\mathcal{C}_7'$ are constrained by $b \to s\gamma$ processes. Even in the SM-like allowed region can still have large sensitivity to $\mathcal{C}_7'$ through A_T^2.
- Where S_3 is related to theoretically clean observable A_T^2 through $S_3 = \frac{1}{2}(1 - F_L)A_T^2$.

S. Descotes-Genon et. al. [arXiv:1104.334]



$A_I(K^{*0}\gamma)$, $S_{K^{*0}\gamma}$, $\mathcal{B}(b \to s\gamma)$



Non-SM like region

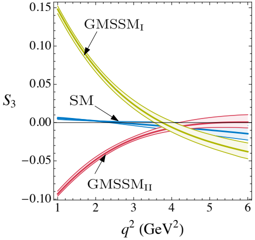
SM-like region

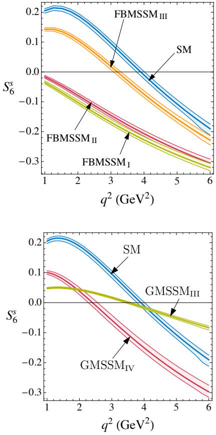
- Can be highly sensitive to NP contributions to $\mathcal{C}_7^{(\prime)}$, $\mathcal{C}_9^{(\prime)}$ and $\mathcal{C}_{10}^{(\prime)}$.

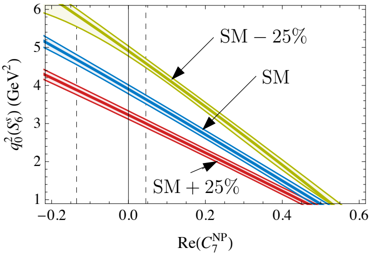
e.g. W. Almannshofer et. al. [arXiv:0801.1214v5] , where $S_6 = -\frac{4}{3}A_{FB}$.

Generic MSSM

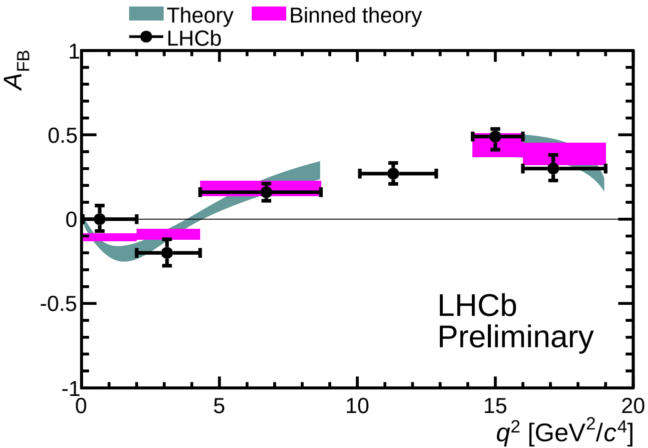
Flavour blind MSSM



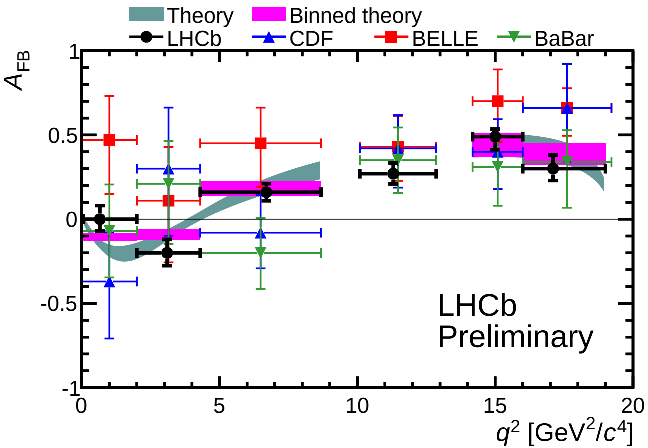




SM ±25% refers to a 25% change in $\mathcal{C}_9$.

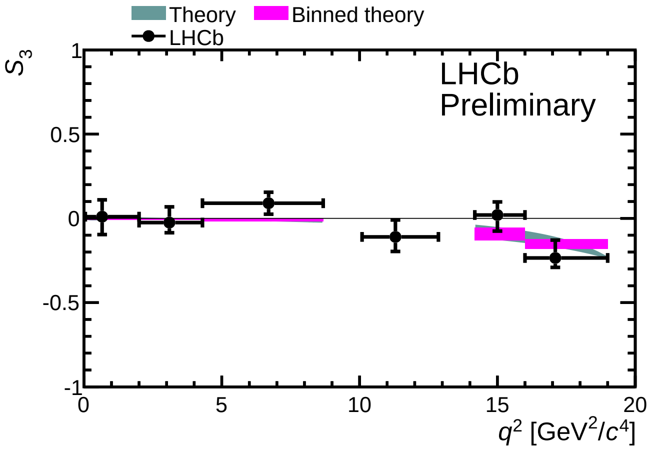


Theory prediction from C. Bobeth et al. [arXiv:1105.0376] (and references therein)

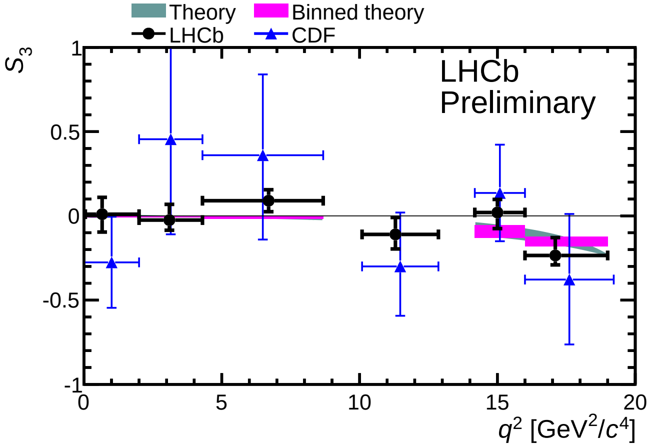


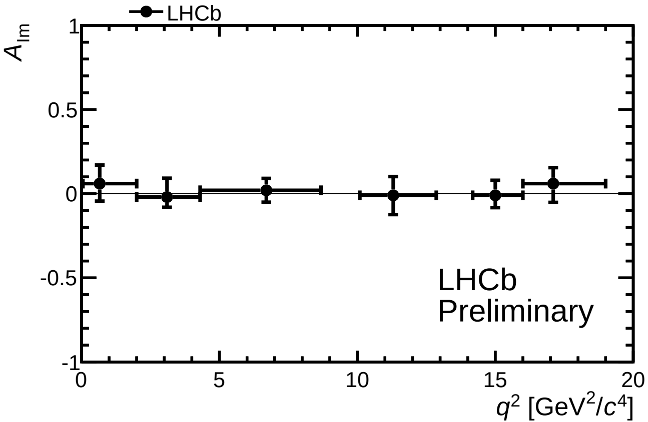
CDF, PRL 108 (2012) Belle, PRL 103 (2009) BaBar prelim., Lake Louise 2012

$B_d \to K^{*0}\mu^+\mu^-$ transverse asymmetry



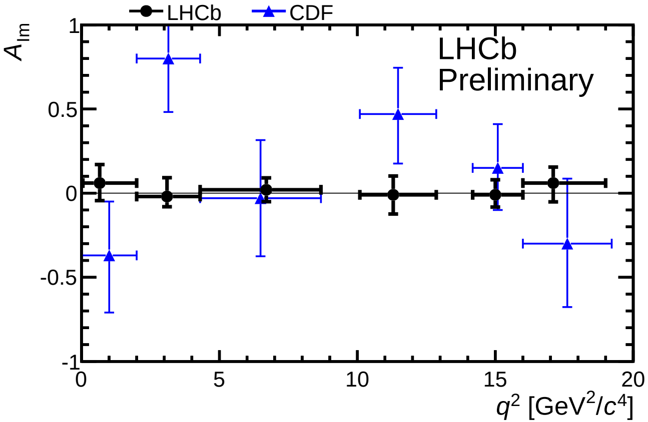
$B_d \to K^{*0}\mu^+\mu^-$ transverse asymmetry





A_{Im} expected to be $\mathcal{O}(10^{-3})$ in the SM

$B_d \to K^{*0}\mu^+\mu^-$ T-odd CP asymmetry

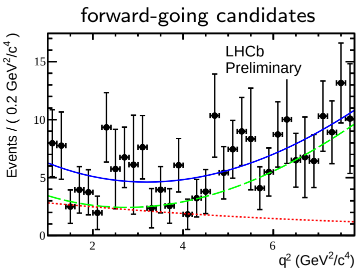


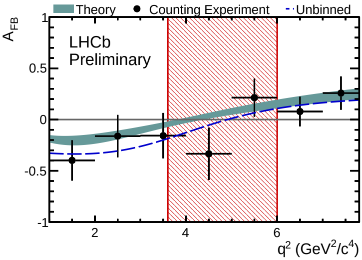
Zero-crossing point of the forward-backward asymmetry

- In the SM, A_{FB} varies with q^2 and changes sign at a well defined point where leading uncertainties from the $B \to K^{*0}$ form-factors cancel.
- Estimate zero-crossing point by fitting forward- and backward-going events separately.
- Gives: $q_0^2 = 4.9\ ^{+1.3}_{-1.1}\,\mathrm{GeV}^2/c^4$

(LHCb preliminary)

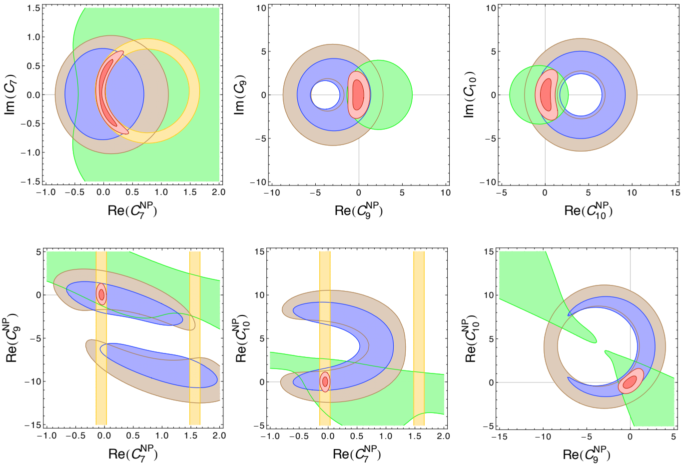
c.f. SM predictions in the range 3.9 - 4.3 GeV^2/c^4.





Constraints on NP contributions to operators

D. Straub et al. [arXiv:1111.1257] using previous LHCb result with $0.37\,\text{fb}^{-1}$.



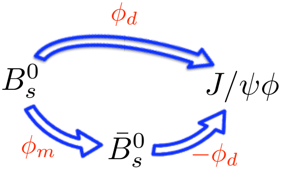
$\text{BR}(B \to X_s \ell^+ \ell^-)$ $\text{BR}(B \to X_s \gamma)$ $\text{BR}(B \to K^* \mu^+ \mu^-)$ $A_{\text{FB}}(B \to K^* \mu^+ \mu^-)$

ϕ_s from $B_s \to J/\psi\,\phi$ and $B_s \to J/\psi\,\pi^+\pi^-$

- Interference between mixing and decay gives rise to a $\mathcal{CP}$ phase: $\phi_s = \phi_m - 2\phi_d$.

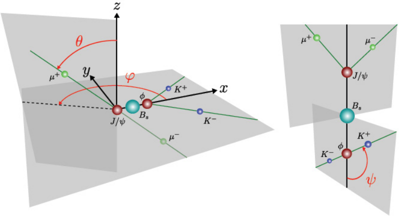
$$\phi_s^{\rm SM} = -2arg\left(\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = 0.036 \pm 0.002\,\mathrm{rad}$$

Charles et al. [Phys. Rev. D84 (2011) 033005]



$B_s \to J/\psi\,\phi$:

- Mixture of $\mathcal{CP}$-odd and $\mathcal{CP}$-even final state.
- Need to perform a time dependent angular analysis to separate $\mathcal{CP}$ states and measure ϕ_s.



$$S(\vec{\lambda}, t, \vec{\Omega}) = \epsilon(t, \vec{\Omega}) \times \left(\frac{1+qD}{2} s(\vec{\lambda}, t, \vec{\Omega}) + \frac{1-qD}{2} \overline{s}(\vec{\lambda}, t, \vec{\Omega}) \right) \otimes R_t$$

acceptance — flavour tagging — time resolution

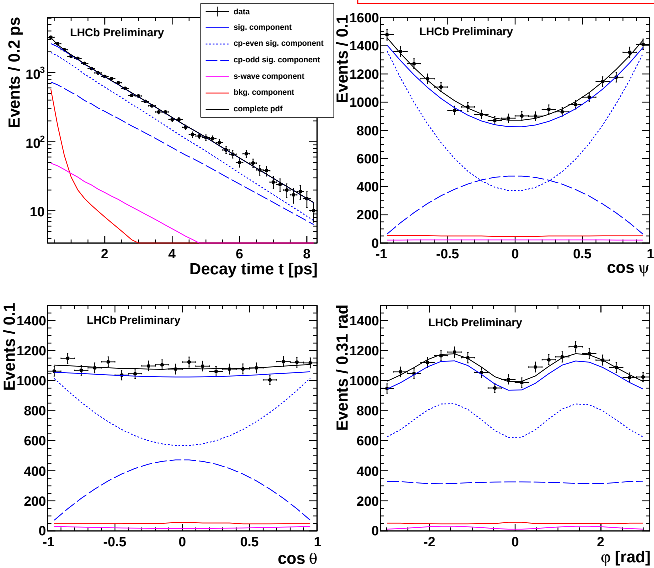
$$\vec{\lambda} = (\Gamma_s, \Delta\Gamma_s, \Delta m_s, \phi_s, |A_0|^2, |A_\perp|^2, \delta_\parallel, \delta_\perp, |A_S|^2, \delta_S)$$

$B_s \to J/\psi\,\pi^+\pi^-$:

- Region of $\pi^+\ \pi^-$ mass around the f_0 gives a $\mathcal{CP}$-odd final state. Can measure ϕ_s from fits to the B_s and $\overline{B}_s$ lifetime.

Measuring ϕ_s with $B_s \to J/\psi\,\phi$

21k signal candidates with $\tau > 0.3\,\mathrm{ps}$

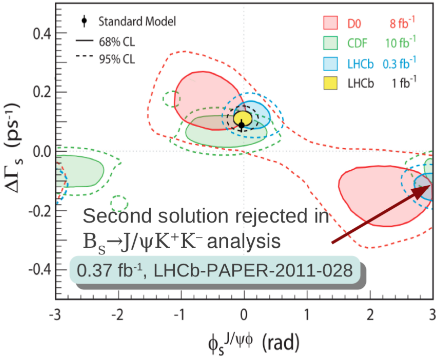


- $B_s \to J/\psi\,\phi$:

  $\phi_s = 0.00 \pm 0.10 \pm 0.03\,\mathrm{rad}$
  $\Delta\Gamma_s = 0.12 \pm 0.02 \pm 0.01\ \ \mathrm{ps}^{-1}$
  (Preliminary)
  [LHCb-CONF-2012-002]

- $B_s \to J/\psi\,\pi^+\pi^-$:

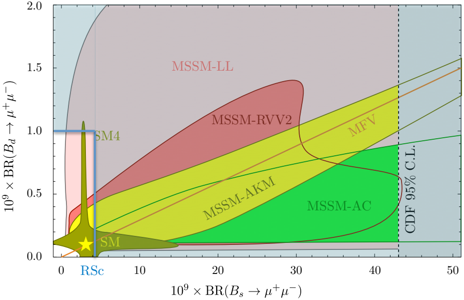
  $\phi_s = -0.02 \pm 0.17 \pm 0.02\,\mathrm{rad}$
  [LHCb-PAPER-2012-006]



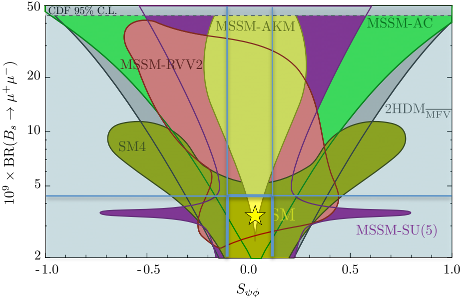
Combination $\phi_s = 0.00 \pm 0.08 \pm 0.03\,\mathrm{rad}$ (LHCb Preliminary)

- Two-fold ambiguity $\Delta\Gamma_s \to -\Delta\Gamma_s$ and $\phi_s \to \phi_s + \pi$ resolved using $B_s \to J/\psi\,K^+K^-$ and S-wave interference. [LHCb-PAPER-2011-028]

D. Straub [arXiv:1107.0266v1] (at the end of 2010)



LHCb 95% C.L. ($1\,\mathrm{fb}^{-1}$)



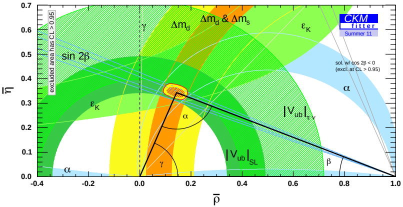
LHCb ϕ_s 68% C.L ($1\,\mathrm{fb}^{-1}$)

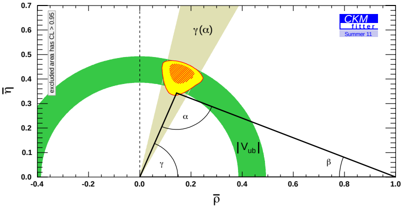
Towards a measurement of γ

CKM picture

- CKM picture seems to describe nature remarkably well.

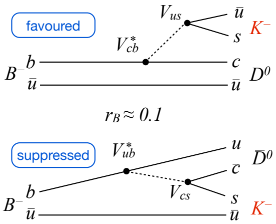
But Have just been discussing the possible effects from NP to loop-order processes. The picture from tree-level is much less complete ...





How can we access γ

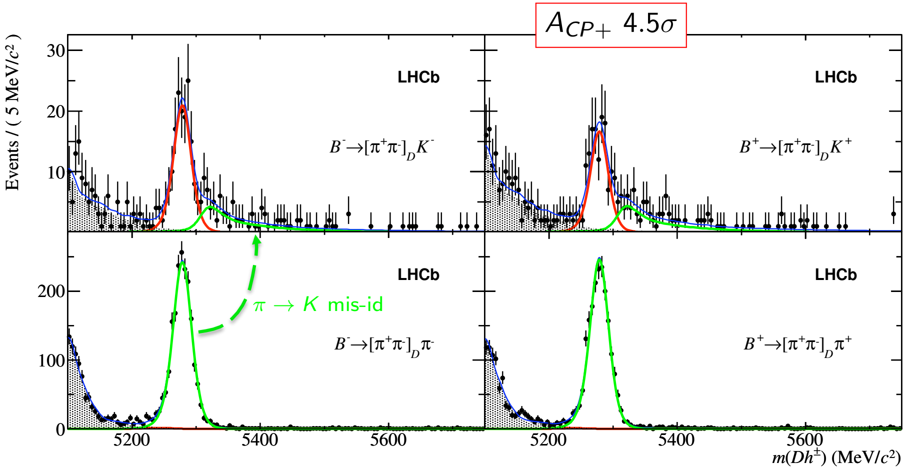
- Access CKM phase γ through interference of $b \to u$ and $b \to c$ transitions in decays with a common final state.
- One way is through $B^{\pm} \to DK^{\pm}$ decays, where the D^0 and $\bar{D}^0$ decay to common final states:
  - $D^0, \bar{D}^0 \to \pi^+\pi^-$ or K^+K^- (GLW) see e.g. [PLB 265 (1991)]
  - $D^0, \bar{D}^0 \to K^+\pi^-$ (ADS) [PRL 78 (1997)]



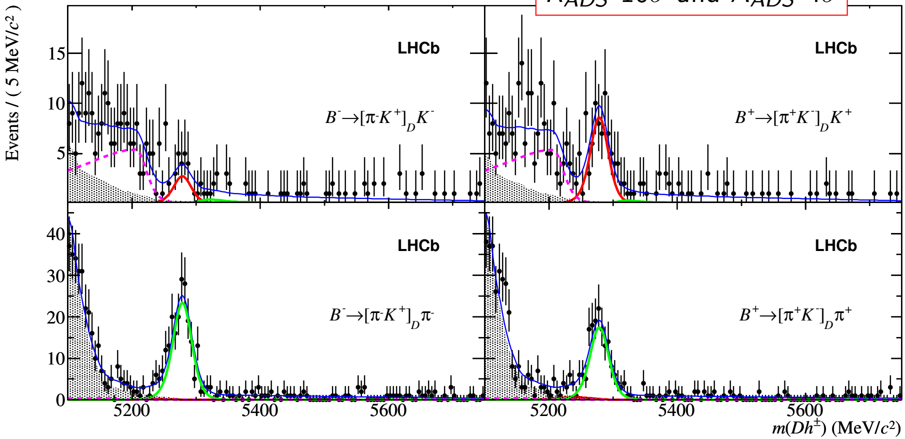
- ADS mode is experimentally challenging:
  - It's a fully hadronic B decay with an effective branching fraction of 2×10^{-7}!

CP mode with $D \to \pi^+\pi^-$

[LHCb-PAPER-2012-001]



R_{ADS} 10σ and A_{ADS} 4σ



First observation of the ADS mode

- What do A_{ADS} and A_{CP+} tell us about γ?

$$
\begin{aligned}
A_{CP+} &= \frac{2r_B \sin\delta_B \sin\gamma}{1 + r_B^2 \pm 2r_B \cos\delta_B \cos\gamma} = 0.145 \pm 0.032 \pm 0.010, \\
A_{ADS} &= \frac{2r_B r_D \sin(\delta_B + \delta_D) \sin\gamma}{r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D) \cos\gamma} = -0.52 \pm 0.15 \pm 0.02, \\
R_{CP+} &= 1 + r_B^2 + 2r_B \cos\delta_B \cos\gamma = 1.007 \pm 0.038 \pm 0.012, \\
R_{ADS} &= \frac{r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D) \cos\gamma}{1 + r_B^2 r_D^2 \cos(\delta_B - \delta_D) \cos\gamma} = 0.0152 \pm 0.0020 \pm 0.0004
\end{aligned}
$$

(LHCb Preliminary)

- Combine with GGSZ modes ($B^- \to DK^-$, $D \to K_S^0 \pi^+ \pi^-$) to estimate γ.

- The LHCb physics programme is very broad. I've only had time to cover some of the recent results from our benchmark channels.
- For more details on B CPV and rare decay measurements at LHCb, please go to see the talks on:
  - "Rare decays at LHCb" by G. Ciezarek
  - "CP violation at LHCb" by C. Linn.

  in Friday's parallel session.
- Next up "Charm physics at LHCb" .

Summary

Excellent performance from LHC and LHCb in 2011.

Flavour physics can provide strong constraints on NP physics at the TeV-scale.

Large number of new heavy flavour results presented this year. More to come at the Spring & Summer conferences.

Backup

The flavour problem?

[from an experimentalists perspective]

- New physics on the TeV scale
  - $\rightarrow$ contributions from new virtual particles to loop-order processes
    - $\rightarrow$ we should expect to see deviations from SM predictions in flavour obsevables.

But we don't see large deviations:

1. Masses of particles are large $\mathcal{O}(10 - 100\,\mathrm{TeV})$ . . .
2. Couplings are small . . .

Sensitivity to $\mathcal{C}_i$

$\mathcal{C}_7^{(\prime)}$	$\mathcal{B}(B \to X_s\gamma)$, $\mathcal{B}(B \to X_s\mu^+\mu^-)$, F_L, A_{FB}, S_3
$\mathcal{C}_9^{(\prime)}$, $\mathcal{C}_{10}^{(\prime)}$	$\mathcal{B}(B \to X_s\mu^+\mu^-)$, F_L, A_{FB}, S_3
$\mathcal{C}_S^{(\prime)}$	$\mathcal{B}(B_s \to \mu^+\mu^-)$ and some sensitivity from A_{FB}
$\mathcal{C}_P^{(\prime)}$	$\mathcal{B}(B_s \to \mu^+\mu^-)$ and some sensitivity from F_L

Signal selection

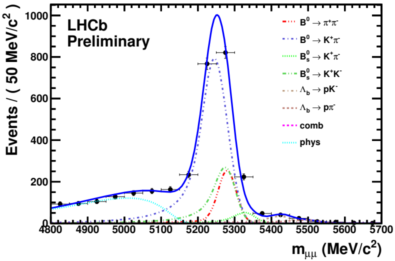
Backgrounds:

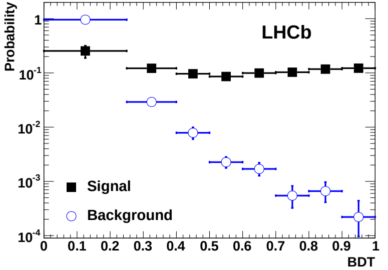
- Predominantly combinatorial $b\bar{b} \to \mu^+\mu^- + X$.
- Peaking contributions from $B \to hh'$ with $h \to \mu$, $\varepsilon_{hh' \to \mu^+\mu^-} \sim 1.5 \times 10^{-5}$
- Elastic $\gamma\gamma \to \mu^+\mu^-$ (reduced by $p_T(B) > 500\,\mathrm{MeV}/c$).

MVA classifier:

- Use a multivariate discriminant (BDT) to separate S+B.
- Trained on MC, but signal and background shapes are taken from data.

$0.8 < BDT < 0.9$





Normalisation

- Branching fraction normalised to: $B^+ \to J/\psi K^+$, $B_s \to J/\psi\,\phi$ and $B \to hh'$

$$\mathcal{B}(B_q^0 \to \mu^+\mu^-) = \mathcal{B}_{\rm norm.} \times \frac{\varepsilon_{\rm norm.}}{\varepsilon_{B_q^0\to\mu^+\mu^-}} \times \frac{f_{\rm norm.}}{f_q} \times \frac{N_{B_q^0\to\mu^+\mu^-}}{N_{\rm norm.}}$$

- Accounting for production ratios of B_s to B_d (B^+):

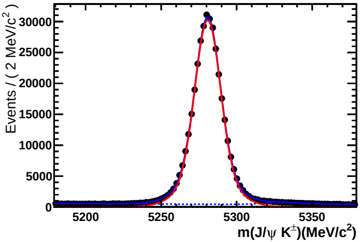
$$f_s/f_d = 0.267 \; {}^{+0.021}_{-0.020}$$

PRL 107 (2011) [arXiv:1106.4435]

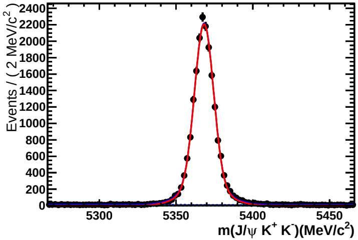
- Gives single event sensitivities:

$$\alpha_{B_s\to\mu^+\mu^-} = (3.2 \pm 0.3) \times 10^{-10}$$
$$\alpha_{B_d\to\mu^+\mu^-} = (8.4 \pm 0.4) \times 10^{-11}$$

340k $B^+ \to J/\psi\,K^+$



19k $B_s \to J/\psi\,\phi$



What does $\mathcal{B}(B_s \to \mu^+\mu^-)$ mean?

- Looking further ahead, what could a measurement of $\mathcal{B}(B_s \to \mu^+\mu^-)$ mean?

Scenario	Points to ?
$\mathcal{B}(B_s \to \mu^+\mu^-) \gg SM$	Large enhancement from NP in scalar sector, e.g. SUSY at high-tan β
$\mathcal{B}(B_s \to \mu^+\mu^-) \neq SM$	SUSY (to $\mathcal{C}_S$/ $\mathcal{C}_P$), UED, LHT, TC2 ($\mathcal{C}_{10}$) ...
$\mathcal{B}(B_s \to \mu^+\mu^-) \sim SM$	Almost any NP model, but can rule out large regions of parameter space
$\mathcal{B}(B_s \to \mu^+\mu^-) \ll SM$	NP in scalar sector. NSSM a good candidate.

- Ratio of B_d to B_s decay is also interesting as a probe of MFV:

Scenario	Points to ?
$\mathcal{B}(B_s \to \mu^+\mu^-)/\mathcal{B}(B_d \to \mu^+\mu^-) \neq SM$	CMFV ruled out. Need new source of FCNC independent of CKM matrix.

Angular basis for $B_d \to K^{*0}\mu^+\mu^-$

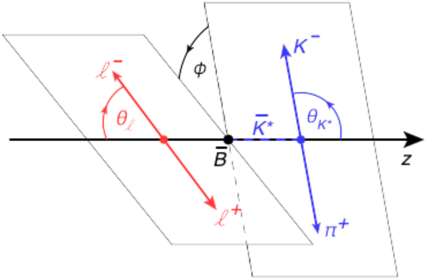
q^2 Invariant mass squared of the dimuon system $q^2 = m^2_{\mu^+\mu^-}$.

θ_ℓ Angle between the direction of the μ^- in the $\mu^+\mu^-$ rest frame and the direction of the $\mu^+\mu^-$ in the $\overline{B}_d$ rest frame.

θ_K Angle between the kaon in the $\overline{K}^{*0}$ rest frame and the $\overline{K}^{*0}$ in the $\overline{B}_d$ rest frame.

ϕ Angle between planes defined by μ^- μ^+ and the $K\pi$ in the $\overline{B}_d$ frame.

$\overline{B}_d \to \overline{K}^{*0}\ell^+\ell^-$ angular definition



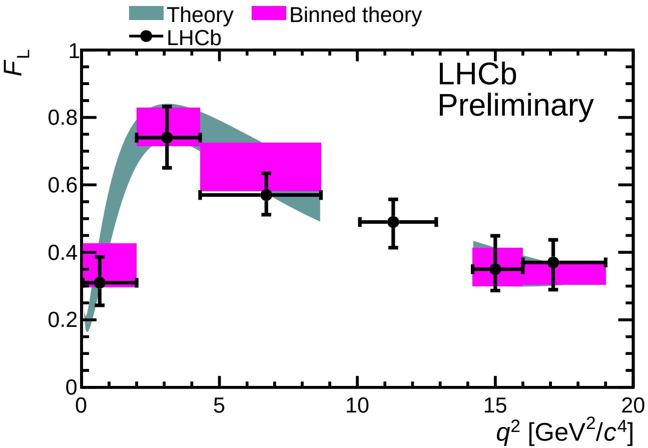
- Folding the ϕ angle such that $\phi \to \phi + \pi$ if $\phi < 0$:

$$\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} \propto \Big[J_1^s + J_1^c + (J_2^s + J_2^c)\cos 2\theta_\ell + J_3 \sin^2\theta_\ell \cos 2\phi + \cancel{J_4 \sin 2\theta_\ell \cos\phi} + \cancel{J_5 \sin\theta_\ell \cos\phi} + J_6 \cos\theta_\ell + \cancel{J_7 \sin\theta_\ell \sin\phi} + \cancel{J_8 \sin 2\theta_\ell \sin\phi} + J_9 \sin^2\theta_\ell \sin 2\phi \Big]$$

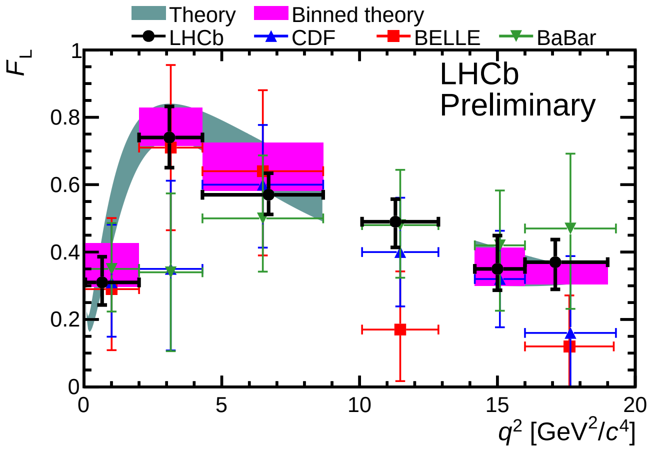
cancels terms in the angular expression with a $\sin\phi$ or $\cos\phi$ dependence.

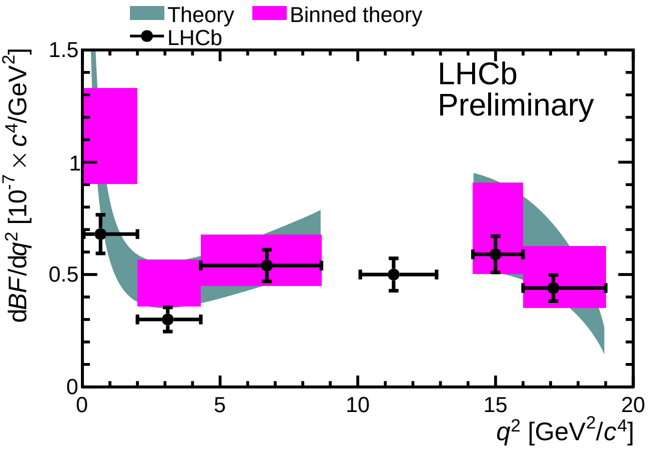
$\rightarrow$ Leaving $J_1^{s,c}$, $J_2^{s,c}$, J_3, J_6 and J_9.

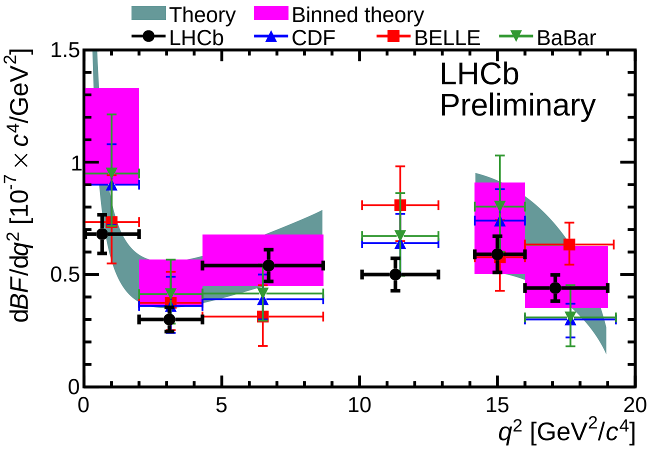
$B_d \to K^{*0}\mu^+\mu^-$ fraction of longitudinal polarisation of the K^{*0}



$B_d \to K^{*0}\mu^+\mu^-$ fraction of longitudinal polarisation of the K^{*0}




Theory
Binned theory
LHCb
LHCb
Preliminary
dBF/dq² [10⁻⁷ × c⁴/GeV²]
1.5
1
0.5
0
0
5
10
15
20
q² [GeV²/c⁴]



Theory
Binned theory
LHCb
CDF
BELLE
BaBar
LHCb
Preliminary
1.5
1
0.5
0
0
5
10
15
20
dBF/dq² [10⁻⁷ × c⁴/GeV²]
q² [GeV²/c⁴]

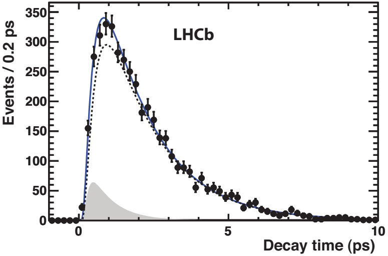
$B_d \to K^{*0}\mu^+\mu^-$ legend

■ Rate average of theory prediction over the q^2-bin.
Ref. [arXiv:1105.0376] and references therein.
Calculations use a factorisation approach at low-q^2 and operator product expansion at high-q^2.

- LHCb data, LHCb-CONF-2012-008
- CDF data, PRL 108 (2012) [arXiv:1108.0695]
- Belle data, PRL 103 (2009) [arXiv:0904.0770]
- BaBar prelim., Lake Louise 2012.

ϕ_s from $B_s \to J/\psi\, \pi^+\pi^-$

- Region around the f_0 gives a $\mathcal{CP}$-odd final state. No need to perform an angular analysis.
- Can extract ϕ_s from a tagged analysis, fitting the $B_s/\overline{B}_s$ decay rate as a function of the $B_s\overline{B}_s$ lifetime.



$$\Gamma \propto e^{-\Gamma_s} \left[e^{\Gamma_s t/2}(1+\cos\phi_s) + e^{-\Gamma_s t/2}(1-\cos\phi_s) \pm \sin\phi_s \sin(\Delta m_s t) \right]$$

- In practice measure:

$$\varepsilon(t)(1-2\omega)\sin\phi_s \sin(\Delta m_s t) \otimes R(t)$$

LHCb-PAPER-2012-006. 7400 signal candidates.

Lifetime measurements

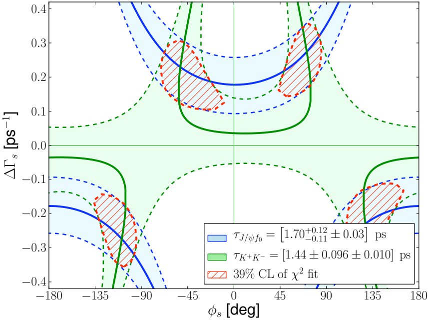
- Can also constrain $\Delta\Gamma_s$ and ϕ_s using effective lifetime measurements of:
  - $B_s \to J/\psi f_0$ (CP-odd)
  - $B_s \to K^+K^-$ (CP-even)

  with an untagged analysis.

  $\tau_{K^+K^-} = 1.44 \pm 0.10 \pm 0.01\,\mathrm{ps}$
  LHCb, PLB 707 (2012)

  $\tau_{J/\psi f_0} = 1.70\ ^{+0.12}_{-0.11} \pm 0.03\,\mathrm{ps}$
  CDF, PRD 84 (2011)

R. Fleischer et. al. [arXiv:1109.5115]



- LHCb update with $1\,\mathrm{fb}^{-1}$, using a lifetime unbiassed trigger and offline selection:

$$1.468 \pm 0.046(\mathrm{stat})\,\mathrm{ps}$$

LHCb-CONF-2012-001