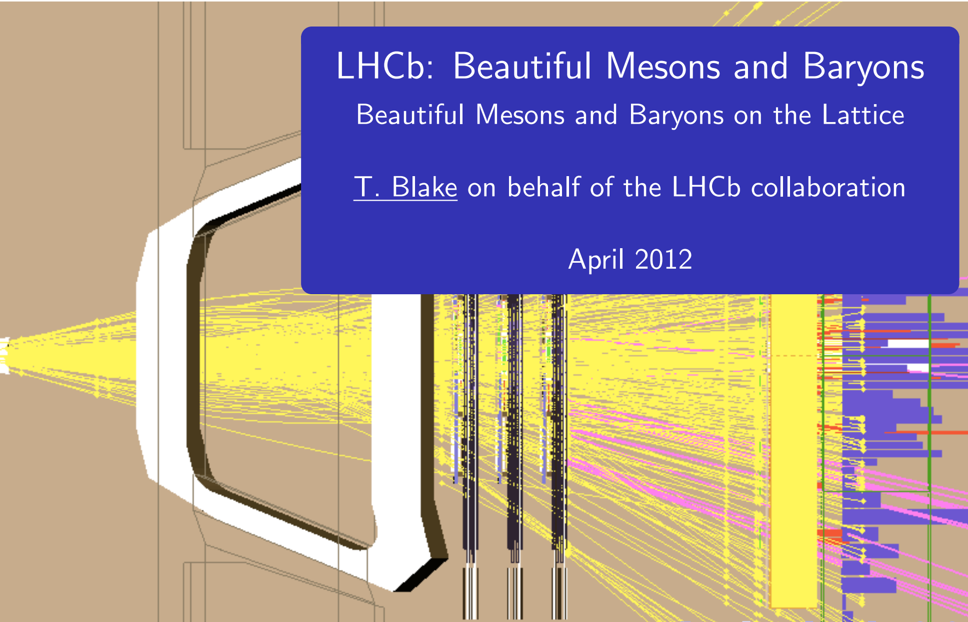
LHCb: Beautiful Mesons and Baryons

Beautiful Mesons and Baryons on the Lattice

T. Blake on behalf of the LHCb collaboration

April 2012



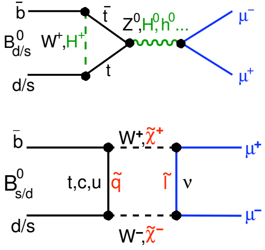
Introduction

- Will try to discuss briefly recent LHCb results for:
  1. Rare decay processes.
  2. B_s mixing observables.
  3. Mass measurements and spectroscopy.

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

- Sensitive to contributions from scalar + pseudo-scalar sector.
  - $\rightarrow$ 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:

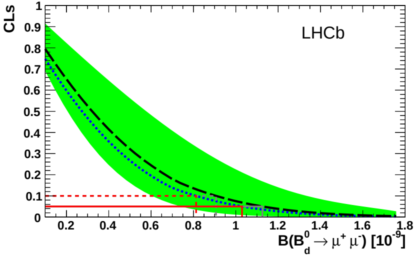
$$\mathcal{B}(B^0_q \to \mu^+\mu^-) \simeq \frac{G_F \alpha^2 M^3_{B^0_q} f^2_{B^0_q} \tau_{B^0_q}}{64\pi^3 \sin^4\theta_W} |V_{tb}V^*_{tq}|^2 \left(1 - \frac{4m^2_\mu}{M^2_{B^0_q}}\right)^{1/2} \times$$

$$\left[M^2_{B^0_q}\left(1 - \frac{4m^2_\mu}{M^2_{B^0_q}}\right)|\mathcal{C}_S|^2 + \left(M_{B^0_q}\,\mathcal{C}_P + \frac{2m_\mu}{M_{B^0_q}}\,\mathcal{C}_{10} + \frac{2m_\mu}{M_{B^0_q}}\,\mathcal{C}'_{10}\right)^2\right]$$

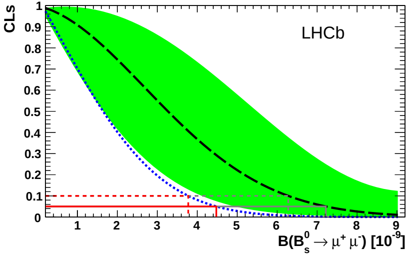
$B^0_{(d,s)} \to \mu^+\mu^-$ [LHCb-PAPER-2012-007]

- 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.

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



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



- Expected limit $\mathcal{B}(B_s \to \mu^+\mu^-) < 7.2 \times 10^{-9}$ (bkg + SM)

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.)

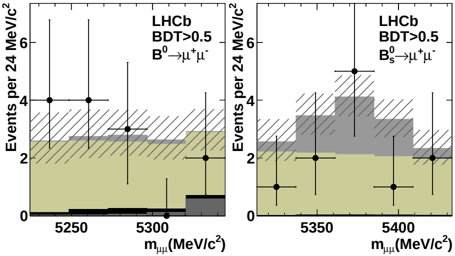
c.f. SM expectation of $(3.2 \pm 0.2) \times 10^{-9}$.

- 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: $(1.0\ ^{+0.8}_{-0.6}) \times 10^{-8}$

Experimental limits and the SM prediction

- Experimental limits are now close to the SM prediction.
- May become increasingly important to understand the uncertainty on (and the central value for) the SM prediction.
- Several predictions available:

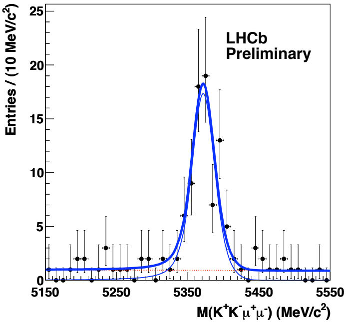
$$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9} \ (f_{B_s} = 225 \pm 4 \ \text{MeV}).$$
$$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.7 \pm 0.4) \times 10^{-9} \ (f_{B_s} = 250 \pm 12 \,\text{MeV}).$$

- For details see A. Buras [PLB 566 (2003)], with f_{B_s} from J. Laiho et al. [PRD 81 (2010)] and C. McNeile et al. [arXiv:1110.4510].

$b \to s\ell^+\ell^-$ processes

- Measure $\mathcal{B}(B_s \to \phi\mu^+\mu^-)$ normalised using $B_s \to J/\psi\,\phi$ decays.
- With simple cut based analysis and strong PID requirements, observe:

  77 ± 10 $B_s \to \phi\mu^+\mu^-$ candidates.
- Giving:



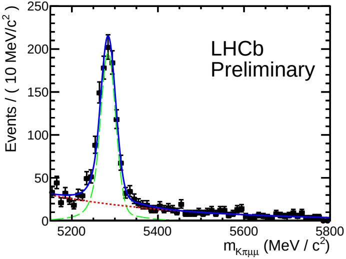
$$\mathcal{B}(B_s \to \phi\mu^+\mu^-) = (0.78 \pm 0.10(\text{stat}) \pm 0.06(\text{syst}) \pm 0.28(\mathcal{B})) \times 10^{-6}$$

(LHCb Preliminary)

- Lower than but still statistically compatible with the CDF result [PRL 107 (2011)].

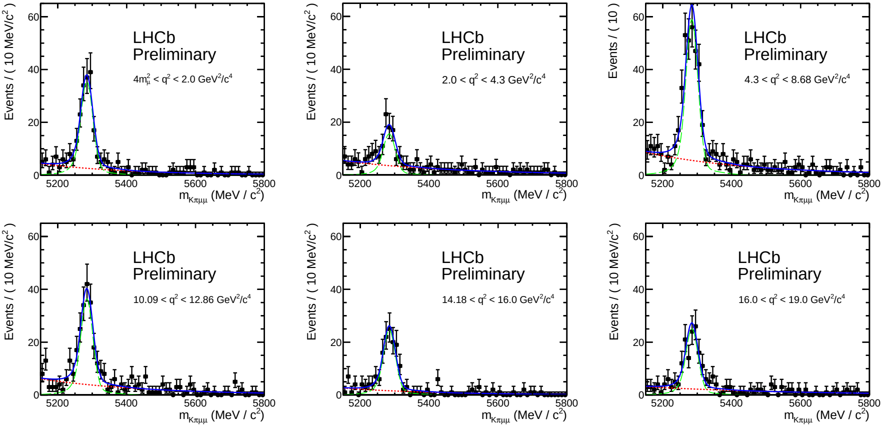
NB Can get to $\sim 10\%$ normalising to B_d modes.

- 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 (*BABAR* + Belle + CDF $\sim$ 600).

Yield in q^2-bins



Anatomy of the $B_d \to K^{*0}\mu^+\mu^-$ decay

- Anatomy of the decay was explained in detail by Christoph yesterday. Described by 12 angular terms:

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

- By folding in ϕ can cancel terms in the angular expression:
  $\to$ Leaving $J_1^{s,c}$, $J_2^{s,c}$, J_3, J_6 and J_9.
- Relate $J_1^{s,c}$ & $J_2^{s,c}$ to F_L and $F_T = 1 - F_L$ in the massless case.
- Some possibility to access J_4, J_5, J_7 and J_8 using other folding techniques. See A. Bharucha & W. Reece [arXiv:1002.4310].

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

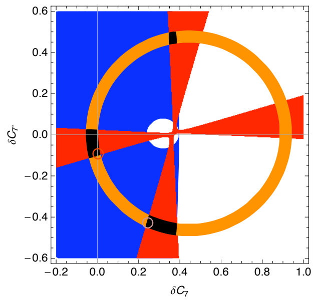
- Take advantage of a symmetry of the system, by folding the distribution in ϕ, to reduce the number of free parameters.
- $\hat{\phi} = \phi + \pi$ if $\phi < 0$ and $\hat{\phi} = \phi$ if $\phi > 0$, leading to:

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

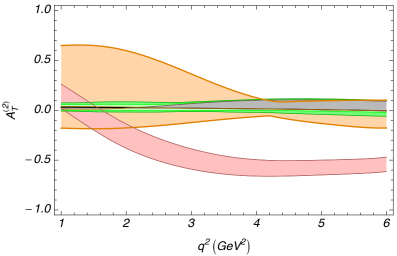
New physics sensitivity to $\mathcal{C}_7^{(\prime)}$

- $\mathcal{C}_7$ 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

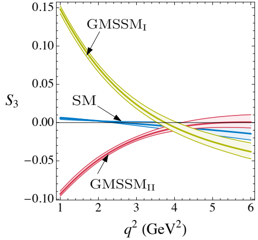
Sensitivity to NP through A_{FB} and S_3

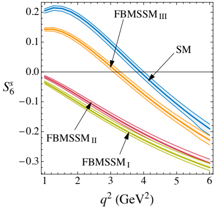
- Can be highly sensitive to NP contributions to $\mathcal{C}_7^{(\prime)}$, $\mathcal{C}_9^{(\prime)}$ and $\mathcal{C}_{10}^{(\prime)}$.

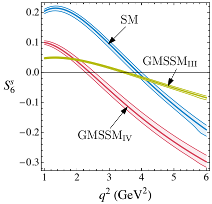
e.g. W. Altmannshofer et. al. [arXiv:0801.1214v5] , where $S_6 = -\frac{4}{3}A_{FB}$.

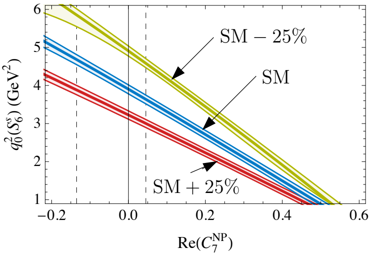
Generic MSSM

Flavour blind MSSM



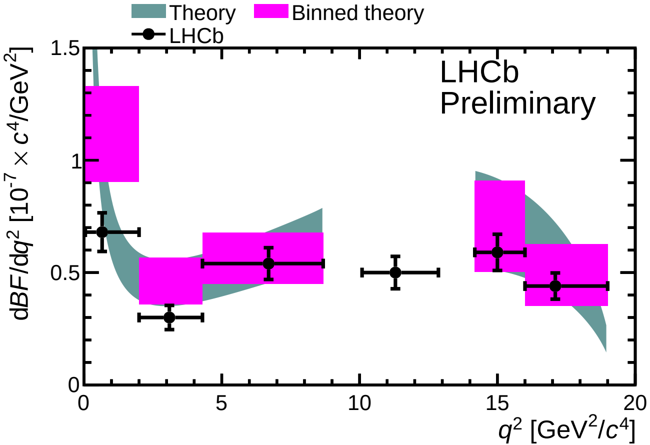






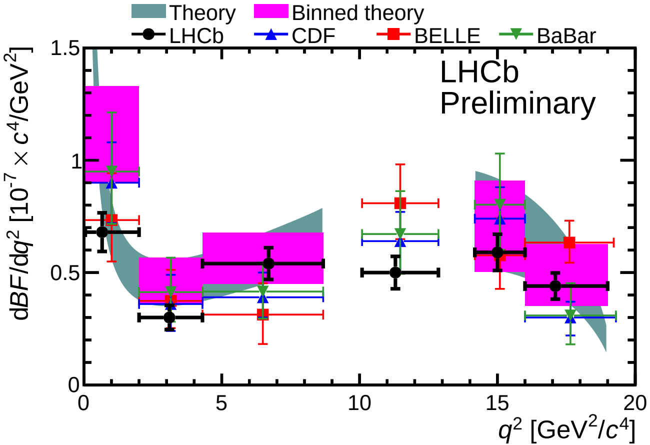
SM ±25% refers to a 25% change in $\mathcal{C}_9$.

$B_d \to K^{*0}\mu^+\mu^-$ differential branching fraction



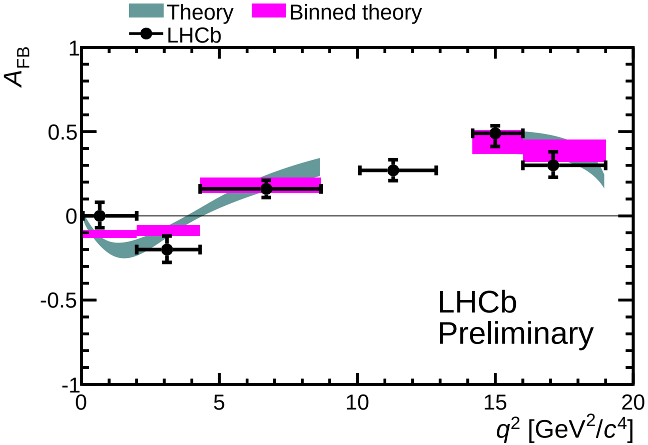
Theory prediction from C. Bobeth et al. [arXiv:1105.0376] (and references therein)

$B_d \to K^{*0}\mu^+\mu^-$ differential branching fraction



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

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



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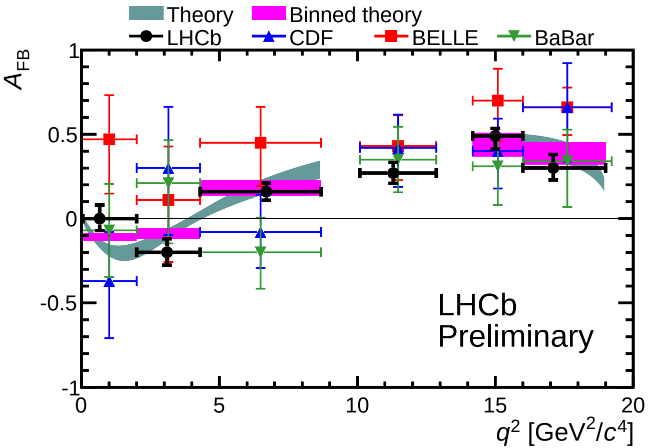
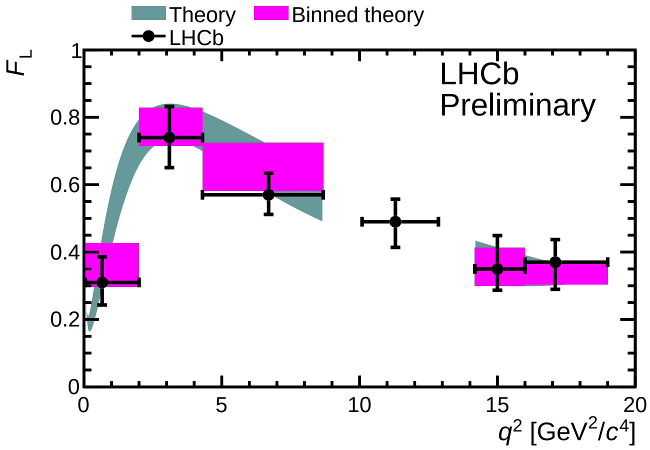


$B_d \to K^{*0}\mu^+\mu^-$ fraction of longitudinal polarisation of the K^{*0}



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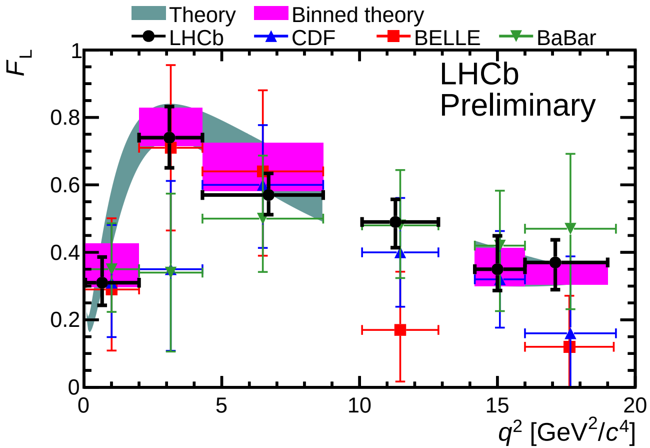
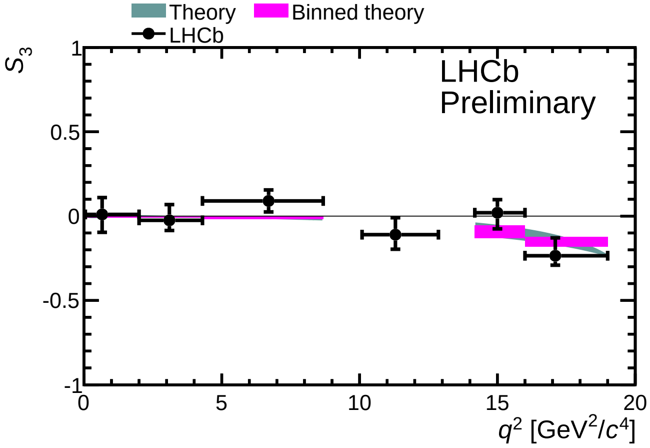
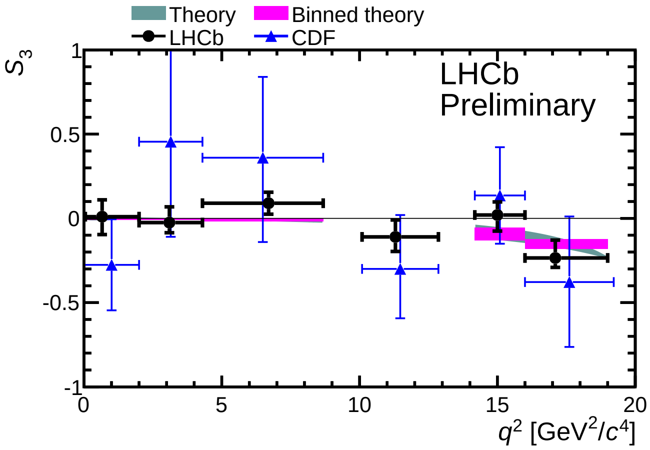


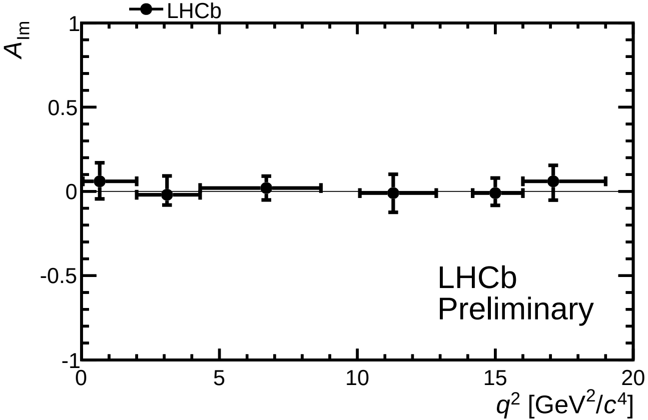
$B_d \to K^{*0}\mu^+\mu^-$ transverse asymmetry



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

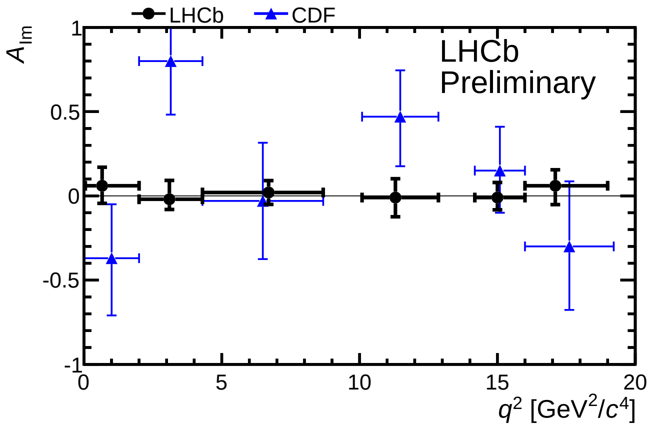


$B_d \to K^{*0}\mu^+\mu^-$ T-odd asymmetry



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

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



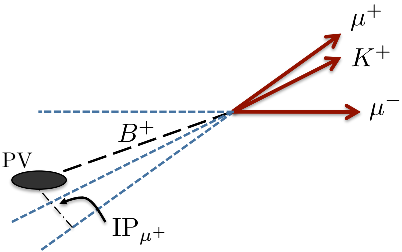
Why don't we go to the kinematic limit of $q^2 = (m_B - m_X)^2$?

- In our $B \to X\mu^+\mu^-$ analyses we typically limit the range of q^2 to be less than the kinematically allowed region (e.g. $B_d \to K^{*0}\mu^+\mu^-$, $0.05 < q^2 < 19.0\,\mathrm{GeV}^2/c^4$). Why?

- Using $B^+ \to K^+\mu^+\mu^-$ as an example, at the end-point of the q^2 spectrum, $q^2 = (m_B - m_{K^+})^2$, the K^+ ends up being soft and collinear with the B_d.

$\rightarrow$ K^+ has little or no impact parameter.

- Experimentally it can be difficult to understand the efficiency at this point.

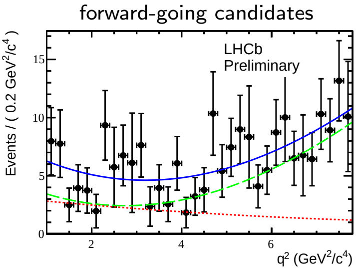


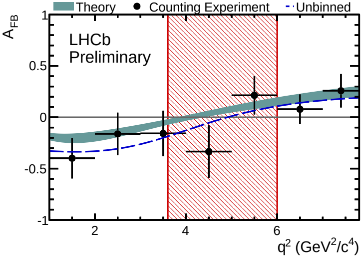
Zero-crossing point of the forward-backward asymmetry

- 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.





Other on-going $b \to s\ell^+\ell^-$ analyses

- On-going analyses for:
  - $B^+ \to K^+\mu^+\mu^-$ angular analysis (F_H and A_{FB}) and differential branching fraction (with ~ 1000 candidates).
  - $B_d \to K^0_s\mu^+\mu^-$ differential branching fraction.
  - $B^+ \to K^{*+}\mu^+\mu^-$ differential branching fraction.
  - $\Lambda_b \to \Lambda^{(*)}\mu^+\mu^-$ differential branching fractions.
  - $\mathcal{CP}$ asymmetries.
  - $B_d \to K^{*0}e^-e^-$ at low-q^2.

and many more . . .

$b \to d\ell^+\ell^-$ processes (?)

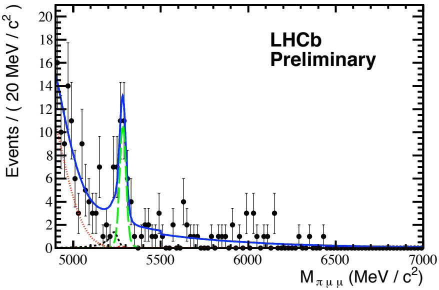
What can we do with $b \to d\mu^+\mu^-$ processes?

- Could also envisage models with FCNC outside the CKM structure: i.e. $b \to d$ versus $b \to s$ not suppressed by $|V_{td}/V_{ts}|^2$.
- With a $\gtrsim 1\,\text{fb}^{-1}$ data set LHCb can have sensitivity to some of the Cabibbo suppressed modes.

- Very rare decay with SM branching fraction of $(2 \pm 0.2) \times 10^{-8}$.

  Hai-Zhen et al. [Commun. Theor. Phys. 50].
- Previous best limit from Belle:

  $\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-) < 6.9 \times 10^{-8}$ [PRD 78 (2008)].



- LHCb observes $25.3\,^{+6.7}_{-6.4}$ candidates in 1 fb^{-1}.

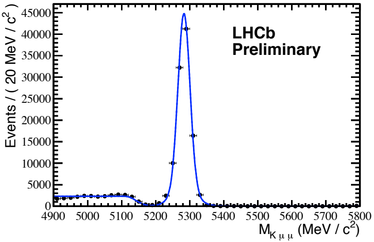
$$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-) = (2.4 \pm 0.6 \pm 0.2) \times 10^{-8}$$ LHCb Preliminary

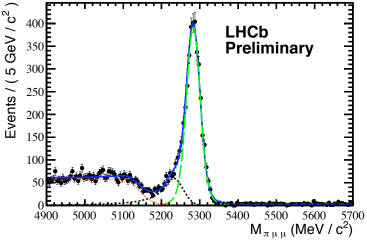
$\to$ Observation of $B^+ \to \pi^+\mu^+\mu^-$ at 5.2σ (rarest observed B decay).

$B^+ \to \pi^+\mu^+\mu^-$ (a few details)

- Branching fraction is normalised with respect to high statistics $B^+ \to J/\psi K^+$ sample.
- Multivariate selection is used to reject combinatorial background.
- Main challenges are to remove combinatorial background and background from $B^+ \to K^+\mu^+\mu^-$ with $K \to \pi$ mis-id and to account for partially reconstructed decays.

NB Can use $B^+ \to J/\psi \pi^+$ to understand the fitting and take shapes where possible from the data.



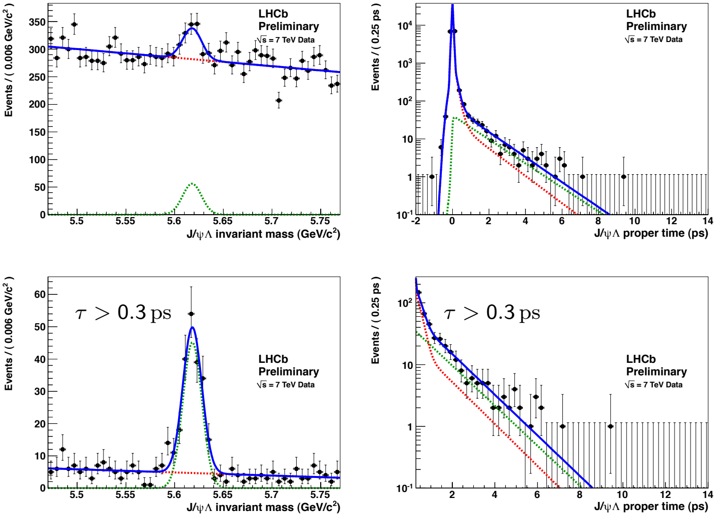


Meson and Baryon lifetimes

- Preliminary measurement have been made with $36\,\mathrm{pb}^{-1}$ of integrated luminosty, using lifetime unbiased selection and trigger.

NB B_s lifetime measured with $B_s \to J/\psi\,\phi$ candidates using a single exponential fit (i.e. ignoring $\Delta\Gamma_s$).

Example: Λ_b lifetime



B meson and baryon lifetimes

[LHCb-CONF-2011-001]

- In 36 pb^{-1} LHCb measures (Preliminary)

$$
\begin{aligned}
\tau(B^+ \to J/\psi K^+) &= 1.689 \pm 0.022 \pm 0.047 \text{ ps}\,, \\
\tau(B^0 \to J/\psi K^{*0}) &= 1.512 \pm 0.032 \pm 0.042 \text{ ps}\,, \\
\tau(B^0 \to J/\psi K^0_{\mathrm{S}}) &= 1.558 \pm 0.056 \pm 0.022 \text{ ps}\,, \\
\tau^{\text{single}}(B^0_s \to J/\psi \phi) &= 1.447 \pm 0.064 \pm 0.056 \text{ ps}\,, \\
\tau(\Lambda_b \to J/\psi \Lambda) &= 1.353 \pm 0.108 \pm 0.035 \text{ ps}\,.
\end{aligned}
$$

  which are compatible with but not quite competitive with world averages, e.g. $\tau_{\Lambda^0_b} = 1.391\,^{+0.038}_{-0.037}$ (PDG).
- Systematic uncertainty is dominated by understanding of the event reconstruction efficiency with proper time. Observe a reduced efficiency for tracking with high-IP tracks.

ϕ_s, $\Delta\Gamma_s$ and Δm_s

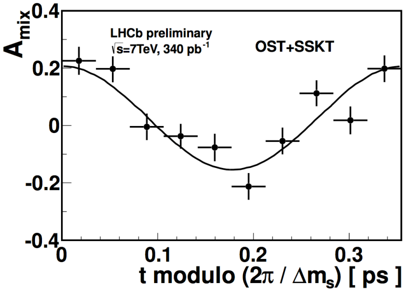
- Measure Δm_s in flavour-tagged time-dependent analysis of $B_s \to D_s\pi$ events, where $D_s \to \phi\pi$ and $D_s \to K^+K^-\pi$.

$$\mathcal{P}_t(t, q|\sigma_t, \eta) \propto \left\{\Gamma_s e^{-\Gamma_s t}\frac{1}{2}\left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + q\,[1-2\omega(\eta)]\cos(\Delta m_s t)\right]\theta(t)\right\} \otimes G(t, S_{\sigma_t}\,\sigma_t)\,\epsilon(t)\,\epsilon_{\rm s}.$$

- Effective tagging efficiency, $\varepsilon_{\text{eff},SS} = 1.3 \pm 0.4\%$ and $\varepsilon_{\text{eff},OS} = 2.1 \pm 0.2\%$.
- In $0.34\,\text{fb}^{-1}$:

$$\Delta m_s = 17.725 \pm 0.041 \pm 0.026\,\text{ps}^{-1}$$

(LHCb Preliminary)

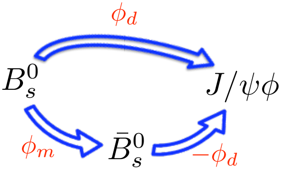


- Dominant systematic is from $z-$scale of the detector.

- Interference between mixing and decay gives rise to a $\not{CP}$ phase: $\phi_s = \phi_m - 2\phi_d$.

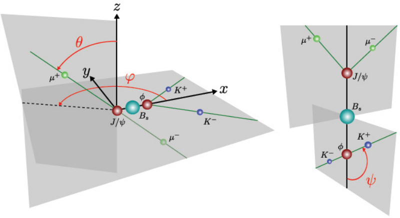
$$\phi_s^{\mathrm{SM}} = -2arg\left(\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = 0.036 \pm 0.002\,\mathrm{rad}$$

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.



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

acceptance   flavour tagging   time resolution

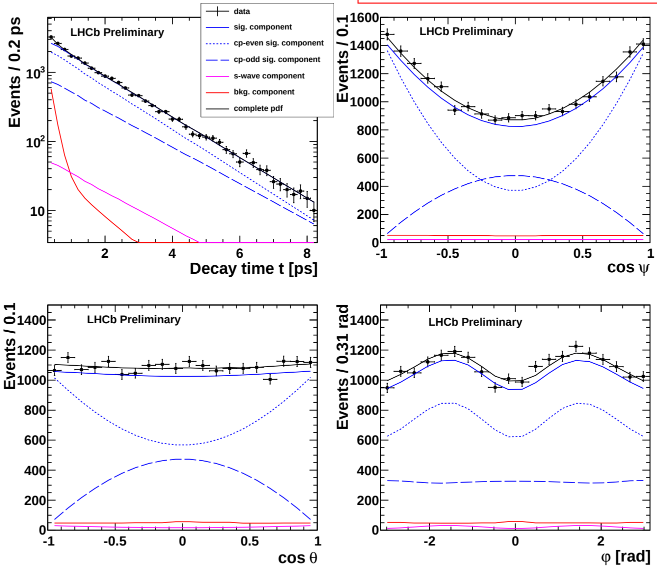
$$\vec{\lambda} = (\Gamma_s, \Delta\Gamma_s, \Delta m_s, \phi_s, |A_0|^2, |A_\perp|^2, \delta_\parallel, \delta_\perp, |A_S|^2, \delta_S)$$

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

- 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 $B_s \to J/\psi\,\phi$ [LHCb-CONF-2012-002]

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



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

  $\phi_s = 0.00 \pm 0.10 \pm 0.03\,\mathrm{rad}$

  $\Delta\Gamma_s = 0.12 \pm 0.02 \pm 0.01\ \ \mathrm{ps}^{-1}$

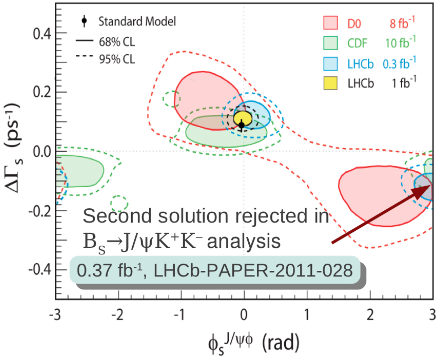
  (Preliminary)

  [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]

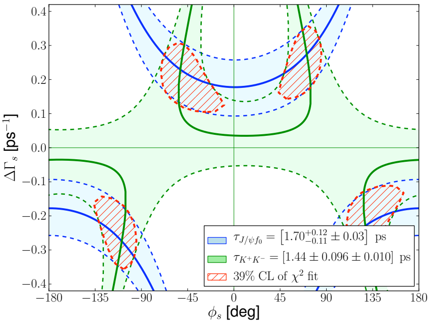
- Can also constrain $\Delta\Gamma_s$ and ϕ_s using effective lifetime measurements of:
  - $B_s \to J/\psi f_0$ (CP-odd)
  - $B_s \to K^+K^-$ (CP-even)

  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 for $B_s \to K^+K^-$ with $1\,\mathrm{fb}^{-1}$, using a lifetime unbiassed trigger and offline selection:

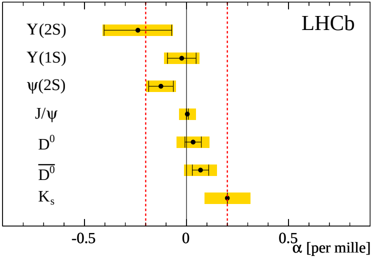
$1.468 \pm 0.046(\mathrm{stat})\,\mathrm{ps}$

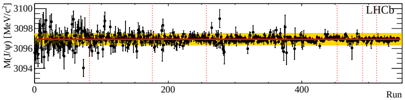
LHCb Preliminary
[LHCb-CONF-2012-001]

Meson and Baryon masses

- LHCb profits from large tracking volume + large integral field.
- With a dedicated alignment programme can reach 2×10^{-4} on momentum scale (calibrated using $J/\psi \to \mu^+\mu^-$ decays).

NB Momentum scale becomes dominant systematic for many high mass states (can also look at decays with small q-value).





- With $35\,\mathrm{fb}^{-1}$ measure:

Quantity	LHCb measurement	Best previous measurement	PDG fit
$M(B^+)$	5279.38 ± 0.35	5279.10 ± 0.55 [4]	5279.17 ± 0.29
$M(B^0)$	5279.58 ± 0.32	5279.63 ± 0.62 [4]	5279.50 ± 0.30
$M(B_s^0)$	5366.90 ± 0.36	5366.01 ± 0.80 [4]	5366.3 ± 0.6
$M(\Lambda_b^0)$	5619.19 ± 0.76	5619.7 ± 1.7 [4]	–
$M(B^0) - M(B^+)$	0.20 ± 0.20	0.33 ± 0.06 [15]	0.33 ± 0.06
$M(B_s^0) - M(B^+)$	87.52 ± 0.32	–	–
$M(\Lambda_b^0) - M(B^+)$	339.81 ± 0.72	–	–

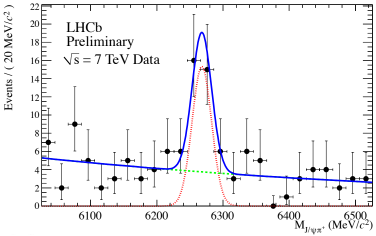
[4] CDF, [PRL 96 (2006)] , [15] BaBar, [PRD 78 (2008)]

- World best measurement of B^+, B_d, B_s and Λ_b^0 masses.

- B_c^+ mass measured using $B_c^+ \to J/\psi\,\pi^+$ decays in $35\,\mathrm{pb}^{-1}$ of integrated luminosity.
- Preliminary result:

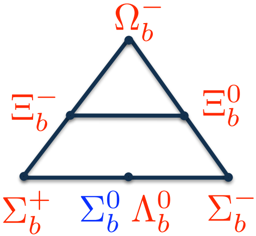
  $M(B_c^+) = 6268.0 \pm 4.0 \pm 0.6\,\mathrm{MeV}/c^2$

c.f. PDG (2010) average of $6277 \pm 6\,\mathrm{MeV}/c^2$



Beautiful baryons

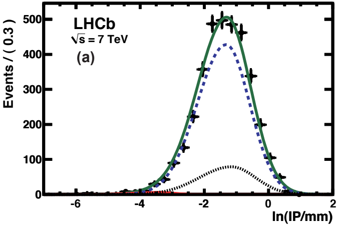
- Seven ground state b-baryons:
  - Σ_b^0 unobserved.
  - Ξ_b^0 recently observed at CDF.

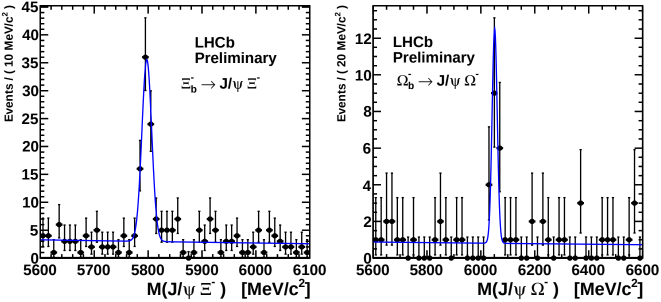


- Large b-Baryon production at the LHC: $\sigma(pp \to b\bar{b}X) = 75.3 \pm 5.4 \pm 13.0 \mu\mathrm{b}$ in $2 < \eta < 6$ [LHCb-PAPER-2010-002].

- Estimate $f_\Lambda/(f_u + f_d)$ using semileptonic decays ($\Lambda_c^+\mu^-$ vs $D^0\mu^-$ and $D^+\mu^-$) to be ~ 0.4 at ($p_T = 0$) and ~ 0.25 ($p_T = 10\,\mathrm{GeV}/c$).
  [LHCb-PAPER-2011-018]

Λ_c^+ in $\Lambda_c^+\mu^-$ combinations





- Using $0.62\,\mathrm{fb}^{-1}$ measure (LHCb Preliminary):

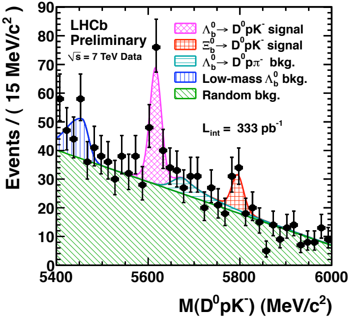
$$M_{\Xi_b^-} = 5796.5 \pm 1.2 \pm 1.2\,\mathrm{MeV}/c^2$$

$$M_{\Omega_b^-} = 6050.3 \pm 4.5 \pm 2.2\,\mathrm{MeV}/c^2$$

$$M_{\Omega_b^-} - M_{\Xi_b^-} = 253.9 \pm 4.8 \pm 1.2\,\mathrm{MeV}/c^2$$

Systematic uncertainty is dominated by the momentum scale.

- First observation by CDF, [PRL 107 (2011)].
- Search in the channel $\Xi_b^0 \to D^0 p K^-$, with $0.33\,\text{fb}^{-1}$.
- Observe hint of a signal with 2.6σ significance.



$$\Delta M_{\Xi_b^0} = M_{\Xi_b^0} - M_{\Lambda_b^0} = 181.8 \pm 5.5 \pm 0.5\,\mathrm{MeV}/c^2$$

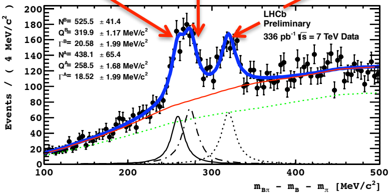
$$M_{\Xi_b^0} = 5802.0 \pm 5.5 \pm 1.7\,\mathrm{MeV}/c^2$$

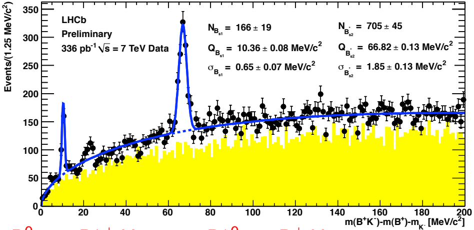
$$M_{\Xi_b^0} = 5787.8 \pm 5.0 \pm 1.3\,\mathrm{MeV}/c^2$$

(LHCb Preliminary)

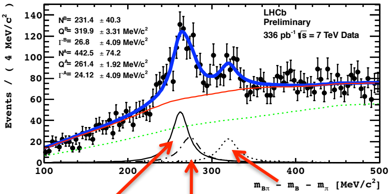
- Perform search for $B^{**}_{(s)}$ states in $B^{\pm}K^{\mp}$, $B^{\pm}\pi^{\mp}$ and $B^{0}\pi^{\pm}$ channels with $0.33\,\mathrm{fb}^{-1}$.
- Photons from B^{*} are not reconstructed $\rightarrow$ shifted Q-values.

$B_1^0 \rightarrow B^{*+}\pi^-$ $B_2^0 \rightarrow B^{*+}\pi^-$ $B_2^0 \rightarrow B^{+}\pi^-$





$B_{s1}^0 \rightarrow B^{*+}K^-$ $B_{s2}^{*0} \rightarrow B^{+}K^-$



$B_1^+ \rightarrow B^{*0}\pi^+$ $B_2^+ \rightarrow B^{*0}\pi^+$ $B_2^+ \rightarrow B^{0}\pi^+$

- No direct detrmination of quantum numbers. Matching to expected states from HQET.
- LHCb Preliminary result:

$$
\begin{aligned}
M_{B_{s1}^0} &= (5828.99 \pm 0.08_{\rm stat} \pm 0.13_{\rm syst} \pm 0.45^{B\,{\rm mass}}_{\rm syst})\ {\rm MeV}/c^2\,, & Q_{B_{s1}^0} &= (10.36 \pm 0.08_{\rm stat} \pm 0.13_{\rm syst})\ {\rm MeV}/c^2\,,\\
M_{B_{s2}^{*0}} &= (5839.67 \pm 0.13_{\rm stat} \pm 0.17_{\rm syst} \pm 0.29^{B\,{\rm mass}}_{\rm syst})\ {\rm MeV}/c^2\,, & Q_{B_{s2}^{*0}} &= (66.82 \pm 0.13_{\rm stat} \pm 0.17_{\rm syst})\ {\rm MeV}/c^2\,,\\
M_{B_1^0} &= (5724.1 \pm 1.7_{\rm stat} \pm 2.0_{\rm syst} \pm 0.5^{B\,{\rm mass}}_{\rm syst})\ {\rm MeV}/c^2\,, & Q_{B_1^0} &= (259.6 \pm 1.7_{\rm stat} \pm 2.0_{\rm syst})\ {\rm MeV}/c^2\,,\\
M_{B_1^+} &= (5726.3 \pm 1.9_{\rm stat} \pm 3.0_{\rm syst} \pm 0.5^{B\,{\rm mass}}_{\rm syst})\ {\rm MeV}/c^2\,, & Q_{B_1^+} &= (261.4 \pm 1.9_{\rm stat} \pm 3.0_{\rm syst})\ {\rm MeV}/c^2\,,\\
M_{B_2^{*0}} &= (5738.6 \pm 1.2_{\rm stat} \pm 1.2_{\rm syst} \pm 0.3^{B\,{\rm mass}}_{\rm syst})\ {\rm MeV}/c^2\,, & Q_{B_2^{*0}} &= (319.9 \pm 1.2_{\rm stat} \pm 1.3_{\rm syst})\ {\rm MeV}/c^2\,,\\
M_{B_2^{*+}} &= (5739.0 \pm 3.3_{\rm stat} \pm 1.6_{\rm syst} \pm 0.3^{B\,{\rm mass}}_{\rm syst})\ {\rm MeV}/c^2\,, & Q_{B_2^{*+}} &= (319.9 \pm 3.3_{\rm stat} \pm 1.6_{\rm syst})\ {\rm MeV}/c^2\,,
\end{aligned}
$$

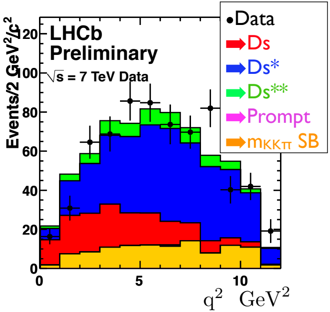
- The masses of B_1^+ and B_2^{*+} are measured for the first time.

NB Masses of Isospin partners are compatible.

Semileptonic b-decays

- Semileptonic B_d, B^+, B_s and Λ_b decays have been extensively used to understand $b\bar{b}$ production and $B_d/B^+/B_s/\Lambda_b$ hadronisation fractions in LHCb.
- Ongoing programme to measure:
  1. Exclusive Cabibbo favoured and suppressed decays (including B_s and Λ_b), probing form-factors and CKM parameters:
     - e.g. V_{ub} from $B_s \to K\mu\nu$.
  2. Semileptonic asymmetry, A_{sl}.

- Can perform neurtino 'reconstruction' (with two-fold using ambiguity) using B pointing constraints to separate different semileptonic contributions.



LHC~~b~~ $^{\text{c(harm)}}$

- LHCb is not just a place to study B decays / production.
- Also have prolific charm production:

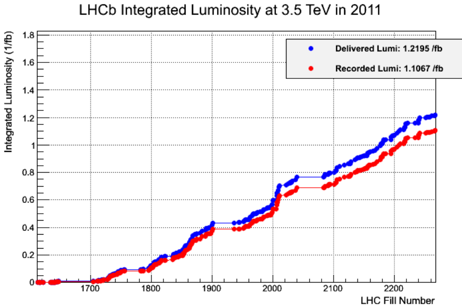
  $\sigma_{c\bar{c}} \sim 20 \times \sigma_{b\bar{b}}$.

→ Charm mixing and CP violation ($y_{\mathcal{CP}}$, A_{Γ}, $A_{\mathcal{CP}}$), charm rare decays, charm semileptonic decays, charm masses and $D_{(s)}^{**}$ spectroscopy.

Outlook and Summary

Outlook

- Current analyses are based on 2010 dataset ($36\,\text{pb}^{-1}$), Summer 2011 dataset ($0.33\,\text{fb}^{-1}$) or full 2011 dataset ($1\,\text{fb}^{-1}$).
- Updates of many analyses to the full 2011 dataset are ongoing.
- In 2012 expect to record an integrated luminosity of $\sim 1.5\,\text{fb}^{-1}$ at $\sqrt{s} = 8\,\text{TeV}$.



Summary

Excellent performance from LHC and LHCb in 2011.

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

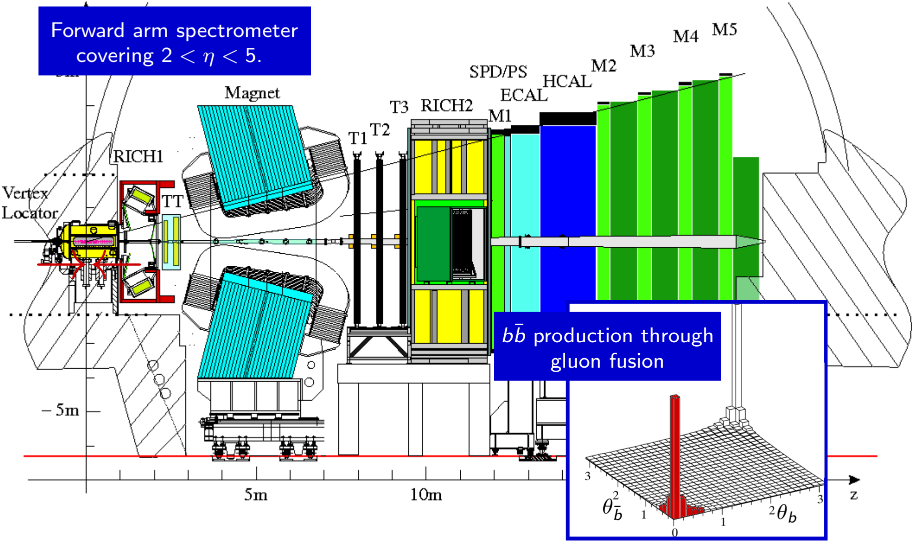
Feedback from the theory community is very welcome!

BACKUP

The LHCb detector

Forward arm spectrometer covering $2 < \eta < 5$.

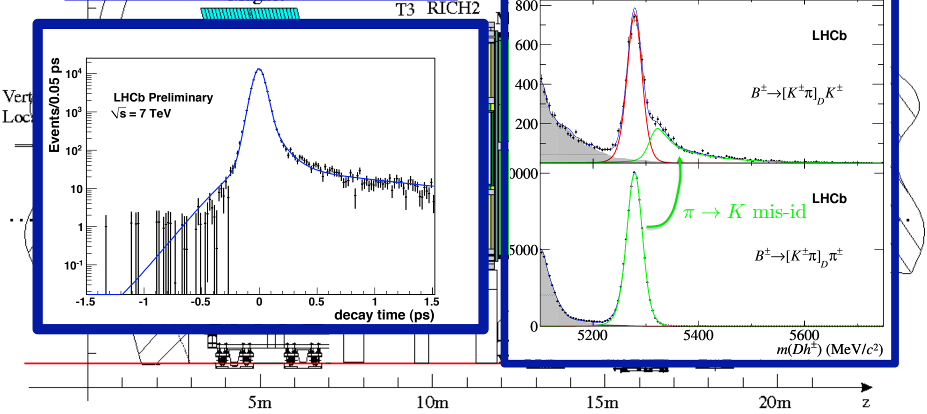
$b\bar{b}$ production through gluon fusion



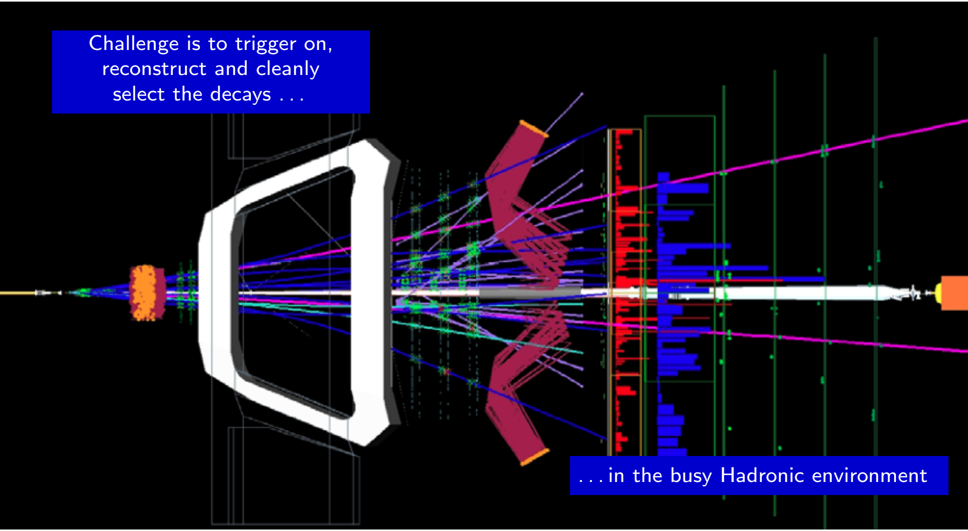
The LHCb detector

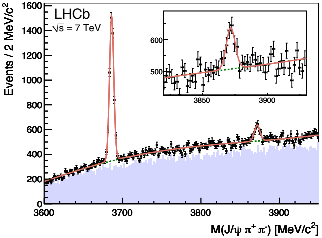
$r - \phi$ vertex detector that approaches within $8\,\mathrm{mm}$ of the beam line + large boost $\rightarrow \sigma_{\tau} \sim 45\,\mathrm{fs}$

RICH detectors $\rightarrow K/\pi/p$ separation from $2 < p < 100\,\mathrm{GeV}/c$



Needle in a haystack?





X3872 [LHCb-PAPER-2011-034]:

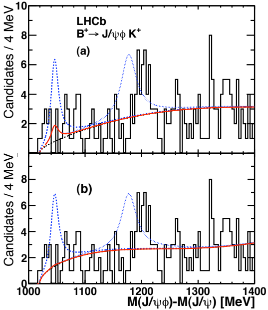
- Measure mass of prompt X(3872):

$$M_{X(3872)} = 3871.95 \pm 0.48 \pm 0.12\,\mathrm{MeV}/c^2$$

- Not yet at the level of Belle [PRD 84 (2011)].

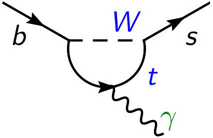
X4140 [LHCb-PAPER-2011-033]:

- Search for X(4140) in $B^+ \to J/\psi\,\phi K^+$ decays in $0.37\,\mathrm{fb}^{-1}$.
- Do not confirm excesses seen by CDF [arXiv:1101.6058].



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

$A_{\mathcal{CP}}(B_d \to K^{*0}\gamma)$ [LHCb-CONF-2012-004]



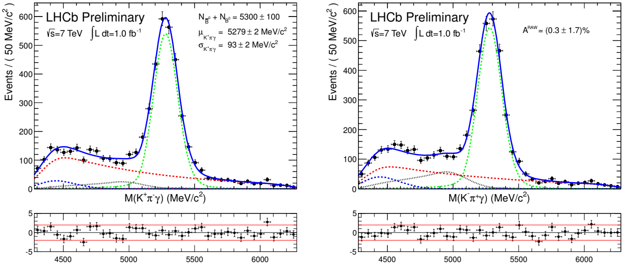
- SM prediction for CP asymmetry:

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

- Previous best measurement from *BABAR*:

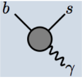
$$A_{\mathcal{CP}} = -0.016 \pm 0.022 \pm 0.007$$ [PRL 103 (2009)]

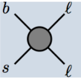
$$\begin{aligned} A_{\mathcal{CP}}(B_d \to K^{*0}\gamma) &= A^{\rm RAW}_{\mathcal{CP}}(B_d \to K^{*0}\gamma) - A_{\rm prod.}(B_d) - A_{\rm det.}(K\pi) \\ &= 0.008 \pm 0.017({\rm stat}) \pm 0.009({\rm syst}) \quad [\text{Preliminary}] \end{aligned}$$



- 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].

Sensitivity to NP through rare decays



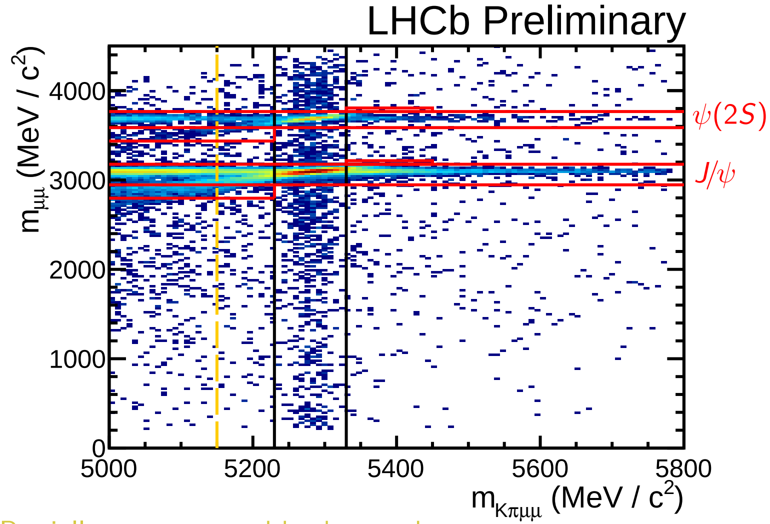


Operator $\mathcal{O}_i$	$B \to K^{*0}\gamma$	$B \to K^{*0}\mu^+\mu^-$	$B \to \mu^+\mu^-$
$\mathcal{O}_7 \sim m_b(\bar{s}_L\sigma_{\mu\nu}b_R)F_{\mu\nu}$	✓	✓	
$\mathcal{O}_9 \sim (\bar{s}b)_{V-A}(\bar{\ell}\ell)_V$		✓	
$\mathcal{O}_{10} \sim (\bar{s}b)_{V-A}(\bar{\ell}\ell)_A$		✓	✓
$\mathcal{O}_{S,P}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

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.

$B_d \to K^{*0}\mu^+\mu^-$ $m_{\mu^+\mu^-}$ versus $m_{K^+\pi^-\mu^+\mu^-}$

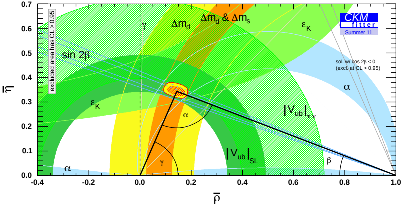


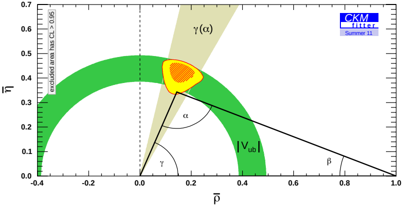
Partially reconstructed backgrounds

Towards a measurement of γ

- CKM picture seems to describe nature remarkably well.

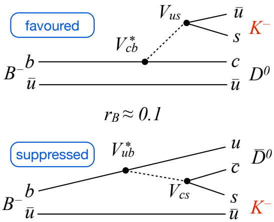
But Have just been discussing the possible effects from NP to loop-order processes. The picture from tree-level is much less complete . . .



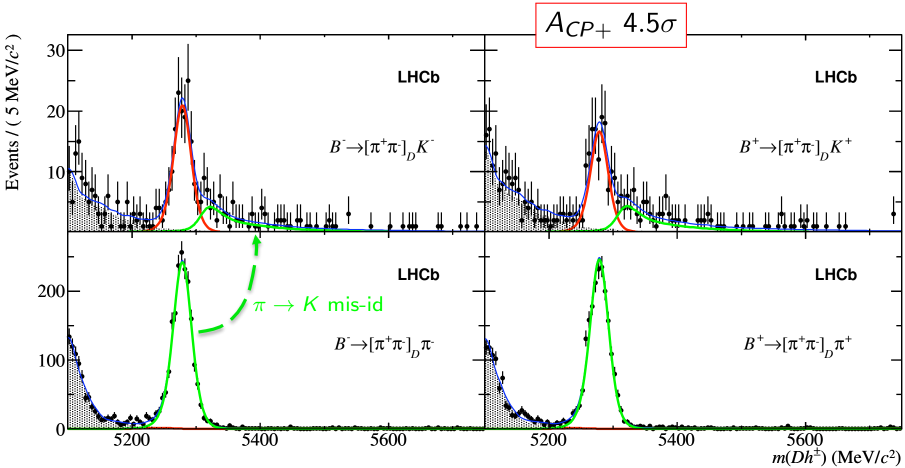


How can we access γ

- 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)]

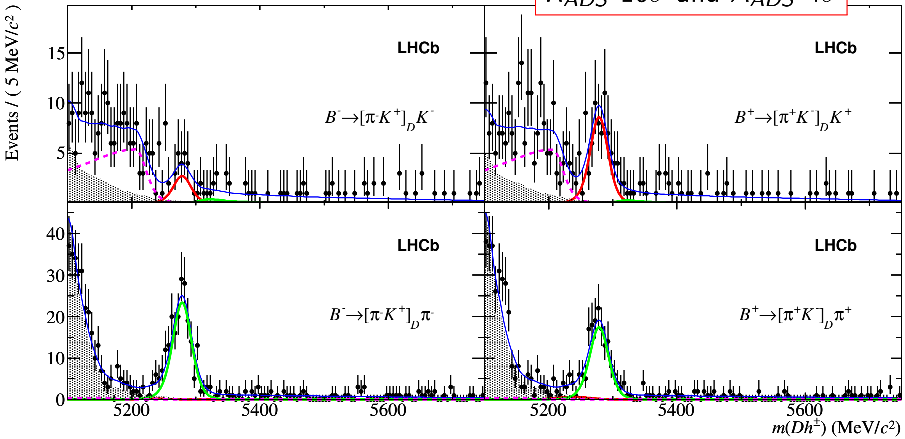


- ADS mode is experimentally challenging:
  - It's a fully hadronic B decay with an effective branching fraction of 2×10^{-7}!



A_{CP+} 4.5σ
Events / (5 MeV/c^2)
LHCb
$B^- \to [\pi^+\pi^-]_D K^-$
$B^+ \to [\pi^+\pi^-]_D K^+$
$B^- \to [\pi^+\pi^-]_D \pi^-$
$B^+ \to [\pi^+\pi^-]_D \pi^+$
$\pi \to K$ mis-id
$m(Dh^\pm)$ (MeV/c^2)

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.

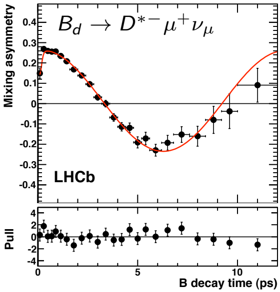
- Anatomy of the decay was explained in detail by Christoph yesterday. Described by 12 angular terms:

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

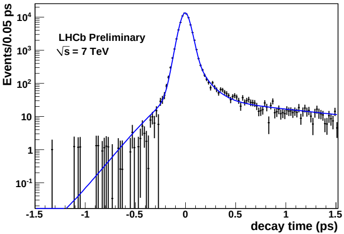
- Some possibility to access S_4, S_5, S_7 and S_8 using other folding techniques. See A. Bharucha & W. Reece [arXiv:1002.4310].

- Opposite side tagging (μ, K, e and vertex charge) calibrated using $B_d \to D^{*-}\mu^+\nu_\mu$, $B^+ \to J/\psi K^+$ and $B_d \to J/\psi K^{*0}$ events.
- Performance is typically $\varepsilon\mathcal{D}^2 \sim 2-3\%$.
- Work ongoing to improve tagging performance and to include same-sign tagging.

[LHCB-PAPER-2011-027]



- Propertime resolution measured in data using prompt events ($\tau = 0$): $\sigma_\tau \sim 45\,\mathrm{fs}$ (c.f. $\sim 350\,\mathrm{fs}$ period of B_s).
- In practice per-event resolutions and mistag probabilities are used in time dependent + tagged analyses.



$$\mathcal{P}_t(t,q|\sigma_t,\eta) \;\propto\; \left\{\Gamma_s e^{-\Gamma_s t}\,\frac{1}{2}\left[\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + q\,[1-2\omega(\eta)]\cos(\Delta m_s t)\right]\;\theta(t)\right\} \otimes G(t,S_{\sigma_t}\sigma_t)\,\epsilon(t)\,\epsilon_{\rm s}.$$

- Measure Δm_s in flavour-tagged time-dependent analysis of $B_s \to D_s^+\pi^+$ and $B_s \to D_s^+\pi^+\pi^-\pi^+$ events, where $D_s^+ \to \phi\pi^-$ and $D_s^+ \to K^+K^-\pi^-$,
- Effective tagging efficiency, $\varepsilon_{\rm eff} = 3.8 \pm 2.1\%$.
- In 36 $\rm pb^{-1}$:

$$\Delta m_s = 17.63 \pm 0.11 \pm 0.02\,\rm ps^{-1}$$

- Dominant systematic is from $z-$scale of the detector.