Highlights from LHCb

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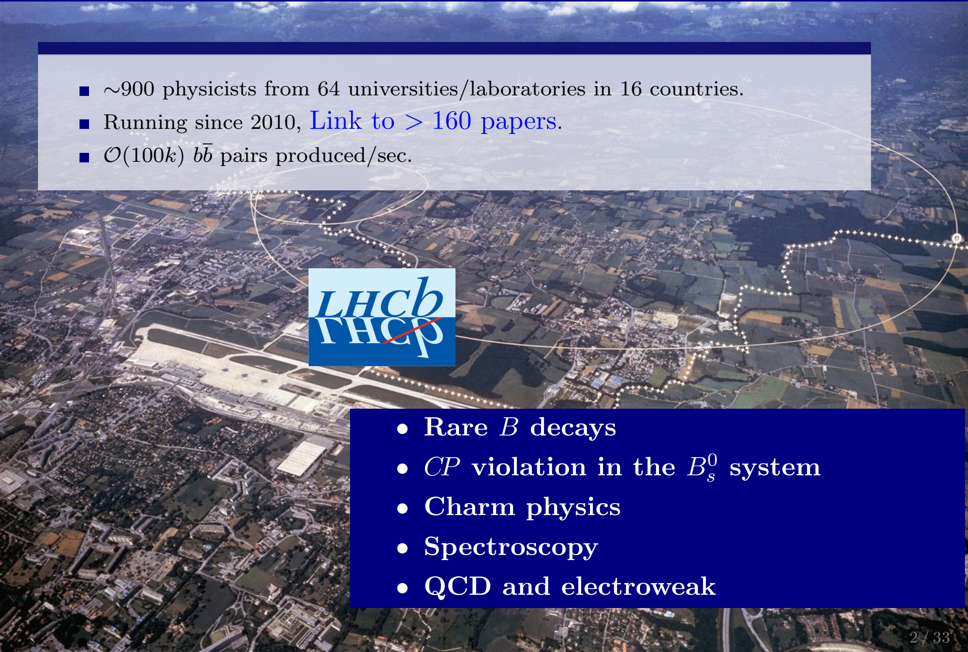
On behalf of the LHCb collab.

Epiphany XX, Jan 8th 2014

THE LHCb COLLABORATION

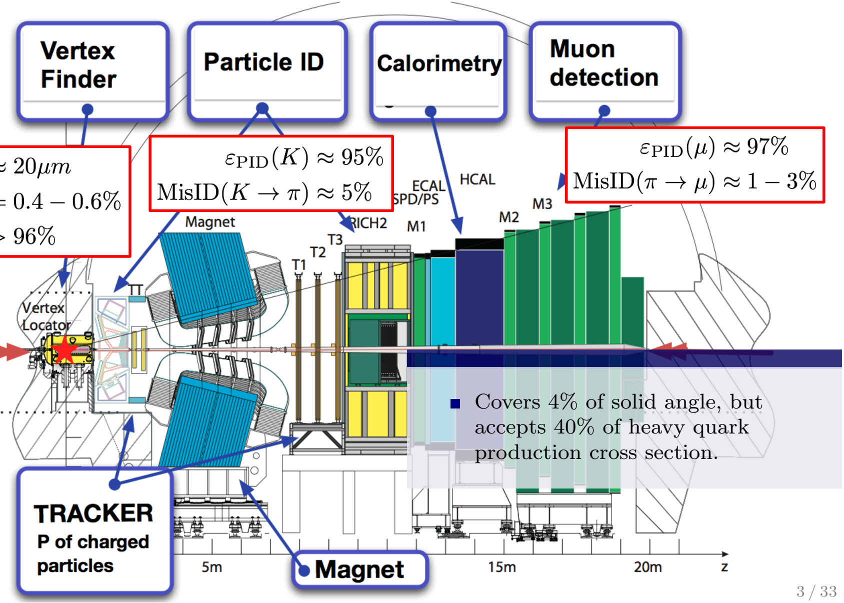
- $\sim$900 physicists from 64 universities/laboratories in 16 countries.
- Running since 2010, Link to $>$ 160 papers.
- $\mathcal{O}(100k)$ $b\bar{b}$ pairs produced/sec.



- **Rare B decays**
- **CP violation in the B_s^0 system**
- **Charm physics**
- **Spectroscopy**
- **QCD and electroweak**

The LHCb detector

2008 JINST 3 S08005



$\sigma(\mathrm{IP}) \approx 20\mu m$

$\delta p/p = 0.4 - 0.6\%$

$\varepsilon_{\mathrm{track}} > 96\%$

$\varepsilon_{\mathrm{PID}}(K) \approx 95\%$

$\mathrm{MisID}(K \to \pi) \approx 5\%$

$\varepsilon_{\mathrm{PID}}(\mu) \approx 97\%$

$\mathrm{MisID}(\pi \to \mu) \approx 1 - 3\%$

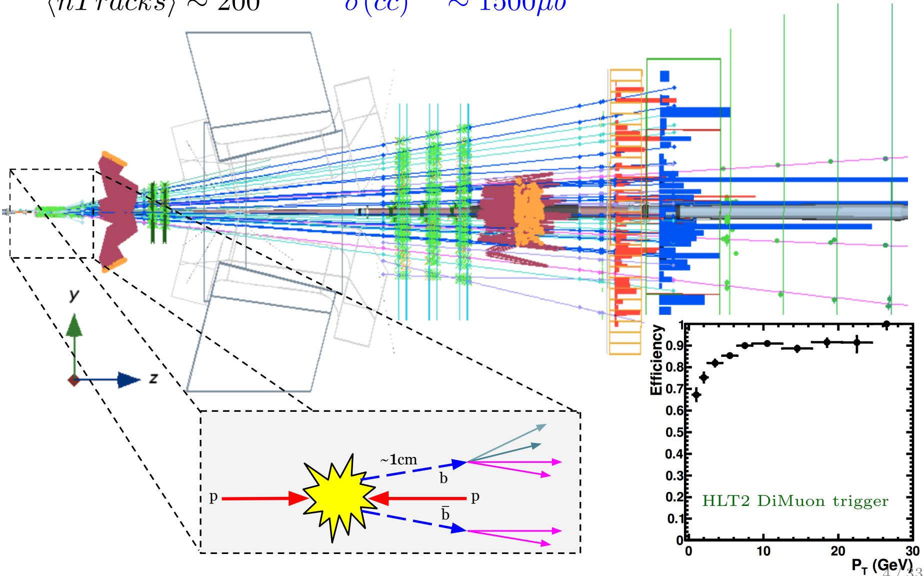
- Covers 4% of solid angle, but accepts 40% of heavy quark production cross section.

A TYPICAL LHCB EVENT

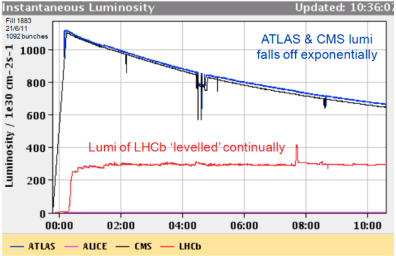
2008 JINST 3 S08005

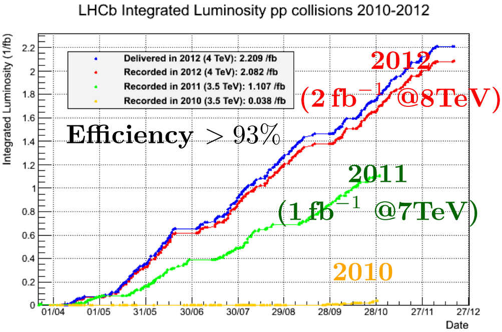
$\langle nPVs \rangle \sim 2.0$
$\langle nTracks \rangle \sim 200$

$\sigma(p\bar{p} \to b\bar{b}X) \sim 80\mu b$
$\sigma(c\bar{c}) \sim 1500\mu b$



Luminosity levelling

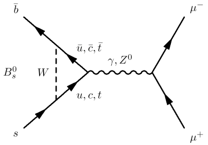




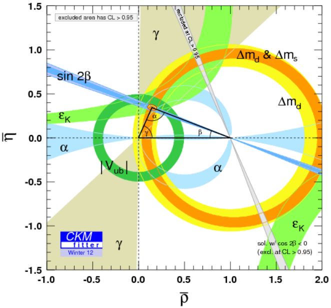
- LHCb designed to run at lower luminosity than ATLAS/CMS.
  - LHCb tracking/PID is sensitive to pile-up.
- LHC pp beams are displaced to reduce instantaneous luminosity - stable running conditions.
- $\langle \mathcal{L} \rangle_{2011} \sim 2.7 \times 10^{32} cm^{-2} s^{-1}$
- $\langle \mathcal{L} \rangle_{2012} \sim 4.0 \times 10^{32} cm^{-2} s^{-1}$

Searching for New Physics

- **INDIRECT**: Higher energy particles can appear virtually in quantum loops
- Flavour physics gives constraints on scale of new physics, $> TeV$.
- $\mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}(\overline{Q}_i Q_j)(\overline{Q}_i Q_j)$

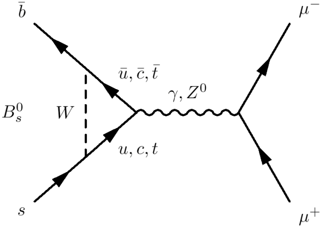


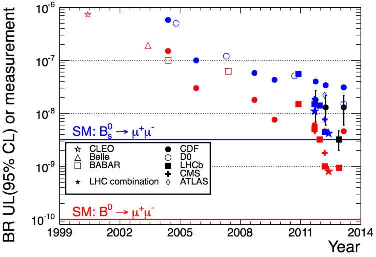
Operator	Bounds on Λ in TeV ($c_{ij}=1$)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}



$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

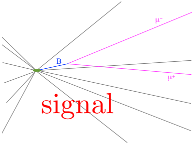
Isidori et al, arXiv:1002.0900

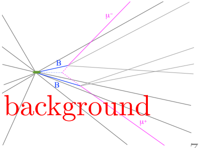




Jose Lazo-Flores, FPCP2013

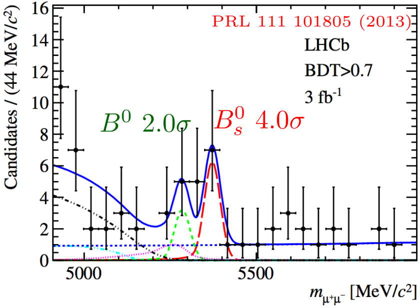
- Requires FCNC transition.
- Helicity suppressed by factor $(m_\mu/m_B)^2$.
  - $\mathcal{B}(B_s^0 \to \mu\mu) = (3.35 \pm 0.28) \times 10^{-9}$
  - $\mathcal{B}(B^0 \to \mu\mu) = (1.07 \pm 0.10) \times 10^{-10}$
- Sensitive to new physics. i.e., MSSM $\mathcal{B} \propto (\tan\beta)^6$.

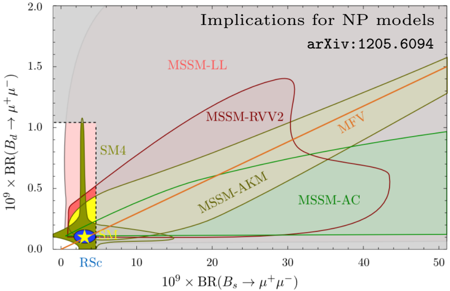




First evidence for $B_s^0 \to \mu^+\mu^-$! More details in talk by A. Oyanguren

	$\mathcal{B}(B_s^0 \to \mu\mu) \times 10^{-9}$	$\mathcal{B}(B^0 \to \mu\mu) \times 10^{-9}$	
LHCb	$2.9^{+1.1+0.3}_{-1.0-0.1}$	$3.7^{+2.4+0.6}_{-2.1-0.4}$	PRL 111 101805 (2013)
CMS	$3.0^{+1.0}_{-0.9}$	$3.5^{+2.1}_{-1.8}$	PRL 111 101804 (2013)
Combined	2.9 ± 0.7	$3.6^{+1.6}_{-1.4}$	LHCb-CONF-2013-012 CMS-PAS-BPH-13-007

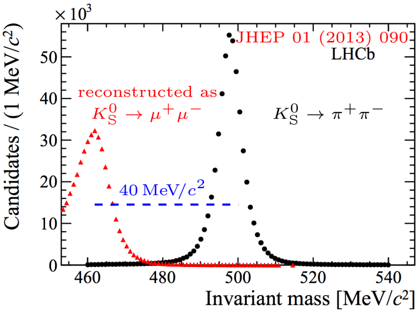




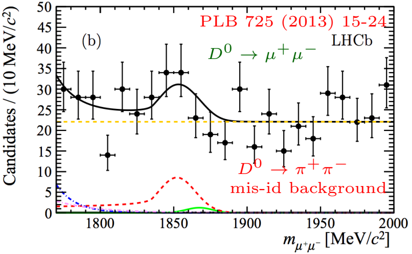
- Normalise to large sample of $\mathcal{B}(B^+ \to J/\psi K^+)$ or $\mathcal{B}(B^0 \to K^+\pi^-)$.
- Systematic comes from modelling of the background in the fit.

Other rare decays: $K^0_S \to \mu^+\mu^-$ and $D^0 \to \mu^+\mu^-$

- FCNC, suppressed in SM: $\mathcal{B}^{SM}(K^0_S \to \mu^+\mu^-) = (5.0 \pm 1.5) \times 10^{-12}$
- $\mathcal{B}(K^0_S \to \mu^+\mu^-) < 11 \times 10^{-9}$ @ 90% CL.
- $\times 30$ better than previous limit!
- Mass resolution of $\sim 4\,\mathrm{MeV}/c^2$.

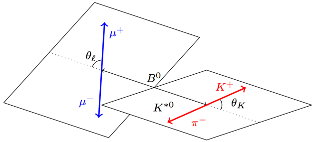


- FCNC, large GIM suppression due to absence of high-mass d-type quark and helicity suppression.
- $\mathcal{B}^{SM}(D^0 \to \mu^+\mu^-) <\sim 6 \times 10^{-11}$
- $\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2 \times 10^{-9}$ @ 90% CL.
- $\times 20$ better than previous limit!



FCNC $b \to s$ transitions: $B^0 \to K^{(*)}\mu^+\mu^-$

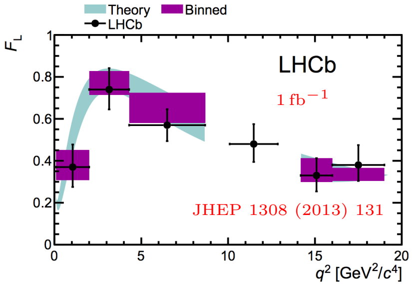
- Rich system of observables (rates, angles, asymmetries) that are sensitive to NP.
- $q^2 \equiv m(\mu^+\mu^-)^2$

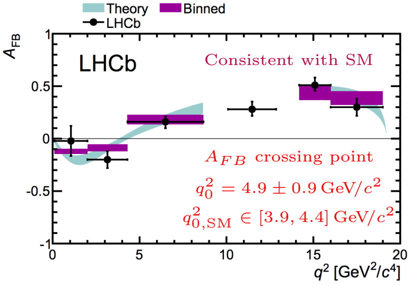


$$\frac{1}{\mathrm{d}\Gamma/dq^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big],$$

$F_L = K^*$ longitudinal polarisation fraction

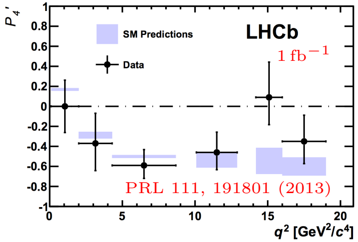
$A_\mathrm{FB} = 4/3\ S_6$



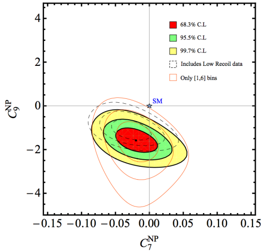


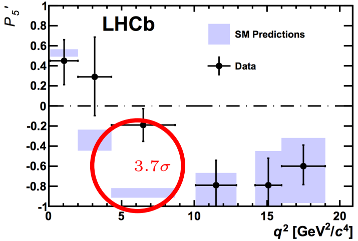
$B^0 \to K^{(*)}\mu^+\mu^-$ Form factor independent variables at large recoil

- New basis of observables, less dependent on hadronic form factors (Descotes-Genon et al arXiv:1303.5794).
- $P'_{i=4,5,6,8} = \frac{S_{j=4,5,6,8}}{\sqrt{F_L(1-F_L)}}$
- Across 24 bins, global discrepancy wrt SM is 2.8σ.



Descotes et al arxiv:1307.5683



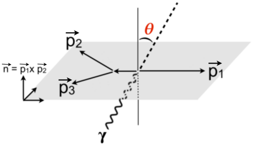


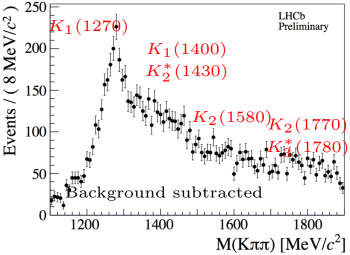
Possible explanation: smaller value of C_9 Wilson coefficient through a Z'?

(Gauld et al arXiv:1308.1959, Buras, Girrbach arXiv:1309.2466)

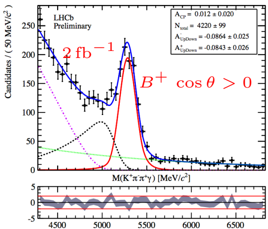
$b \to s\gamma$ FCNC: photon polarisation

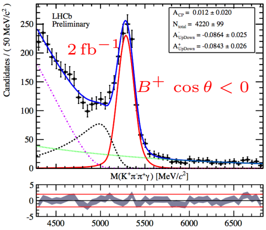
- γ from b decays is **left-handed**, but NP could modify this.
- Measure λ_γ from 3-body decay of K_{res}: $B \to K_{res}\gamma \to P_1 P_2 P_3 \gamma$
- Count number of γ's emitted above/below $\vec{p}_1 \times \vec{p}_2$ plane $\to$ proportional to λ_γ.
- Use $K^+\pi^-\pi^+$: complication of many interfering resonances.





$$A_{ud} = -0.085 \pm 0.019(stat) \pm 0.003(syst) \quad 4.6\sigma \text{ from zero}$$

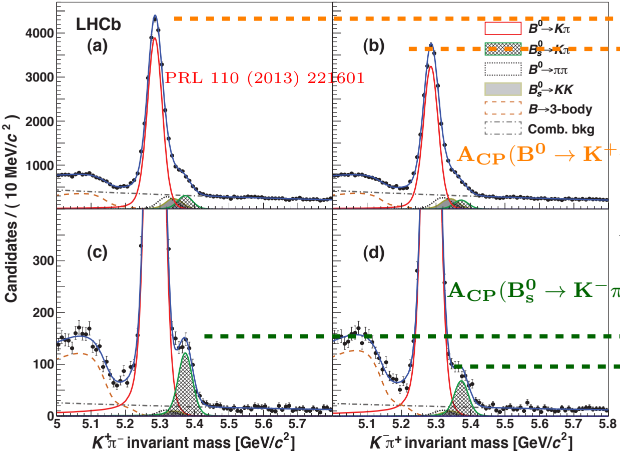




Measurement of *CP* asymmetry is consistent with zero.

- Arises from interfering amplitudes with different weak and strong phases.
- B^0 mode more precise than and compatible with B-factories.
- **B_s^0 mode: first observation!**

$$A_{CP} = \frac{\Gamma(\overline{B}^0_{(s)} \to \bar{f}) - \Gamma(B^0_{(s)} \to f)}{\Gamma(\overline{B}^0_{(s)} \to \bar{f}) + \Gamma(B^0_{(s)} \to f)}$$



PRL 110 (2013) 221601

$$\mathbf{A_{CP}(B^0 \to K^+\pi^-) = -0.080 \pm 0.007 \pm 0.003}$$

After correcting for production and detection asymmetries

$$\mathbf{A_{CP}(B^0_s \to K^-\pi^+) = 0.27 \pm 0.04 \pm 0.01}$$

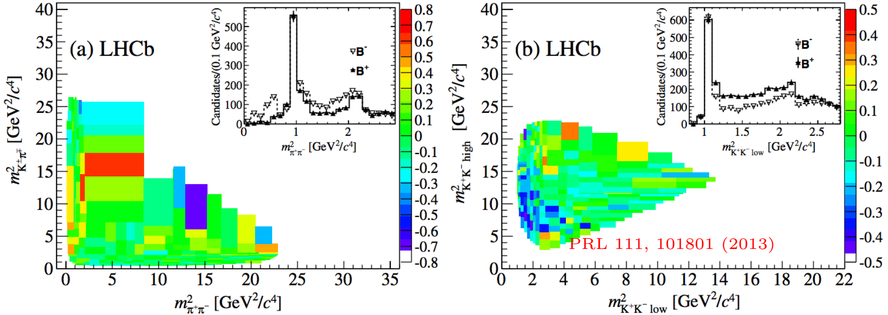
More details in talk by R. Koopman

Large direct CP violation in 3-body B decays

$A_{CP}(B^\pm \to K^\pm\pi^+\pi^-) = +0.032 \pm 0.008(\text{stat}) \pm 0.004(\text{syst}) \pm 0.007(J/\psi K^\pm)$	2.8σ
$A_{CP}(B^\pm \to K^\pm K^+K^-) = -0.043 \pm 0.009(\text{stat}) \pm 0.003(\text{syst}) \pm 0.007(J/\psi K^\pm)$	3.7σ

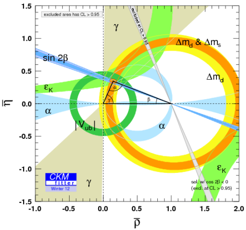
- First evidence of inclusive CP asymmetry in charmless 3-body decays, but. . .
- . . . CP violation > 50% in localised regions of Dalitz space: **not expected!**
- Compound CP violation (Cheng et alPRD 71, 014030 (2005)) or hadron rescattering?

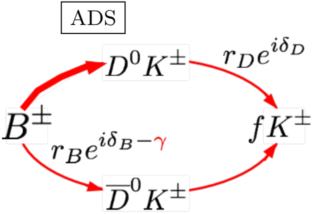
$B^\pm \to K^\pm\pi^+\pi^-$ $\qquad\qquad$ $B^\pm \to K^\pm K^+K^-$



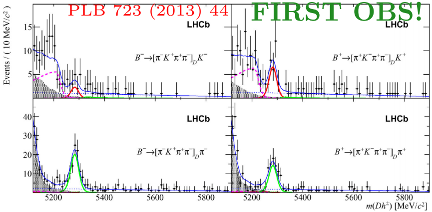
Measurement of γ from $B^\pm \to D^0 K^\pm$

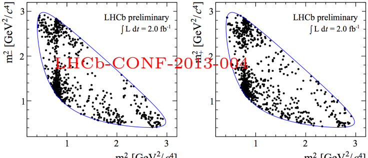
- Use interference between $B^\pm \to D^0 K^\pm$, $D^0 \to f$ decay amplitudes
- Small theoretical uncertainty on the tree level diagrams – no NP contributions





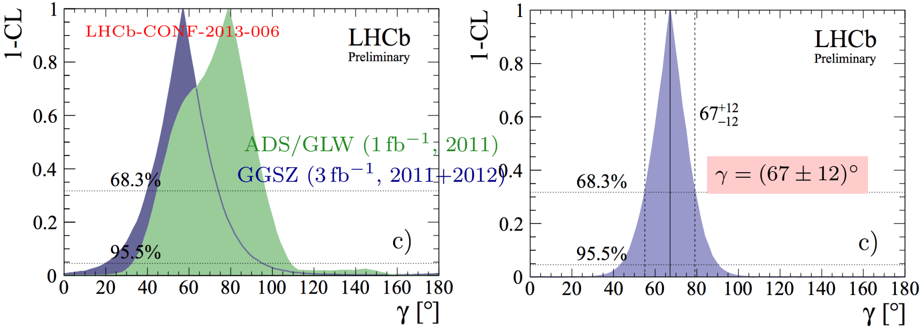
1. **GLW:** f is *CP* eigenstate $(D^0 \to K^+K^-, \pi^+\pi^-)$
   - Large rate, small interference.
   - PLB 712 (2012) 203
2. **ADS:** f is common final state $(D^0 \to K^\pm\pi^\mp, K^\pm\pi^\mp\pi^+\pi^-)$
   - Lower rate, larger interference.
   - PLB 723 (2013) 44, PLB 712 (2012) 203
3. **GGSZ:** f is common final state $(D^0 \to K^0_S K^+K^-, K^0_S\pi^+\pi^-)$
   - Requires Dalitz analysis.
   - PLB 718 (2012) 43





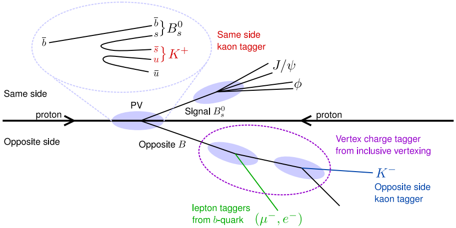
Measurement of γ : LHCb combination

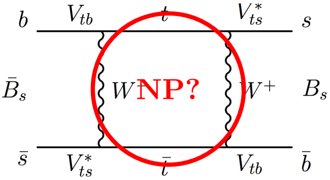
- $B^{\pm} \to D^0 K^{\pm}$ results are combined to single confidence interval.



- Single best measurement, agrees with B-factories.
- Improvements when using 3 fb^{-1} for ADS/GLW modes.
- Combination using $B^{\pm} \to D^0 \pi^{\pm}$ events is available, only using 2011 data (PLB 726 (2013) 151-163).

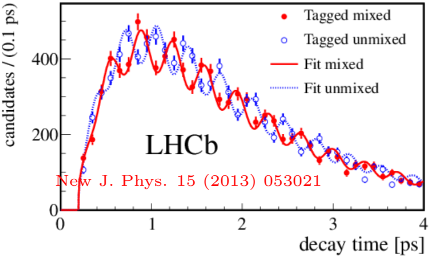
$B^0_{(s)}$ MESON MIXING



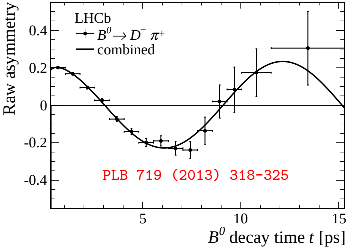


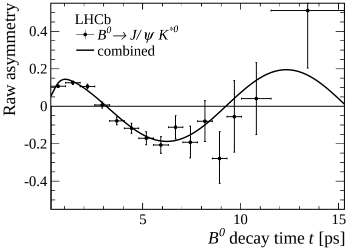
$$\mathcal{P}(\mathrm{t}|\sigma_\mathrm{t}) \propto \left[\Gamma \mathrm{e}^{-\Gamma \mathrm{t}} \tfrac{1}{2} \left[\cosh(\Delta\Gamma\, \mathrm{t}/2) + \mathcal{D} \cos(\Delta \mathrm{m}\, \mathrm{t})\right]\right] \otimes \mathrm{G}(\mathrm{t}; \mathrm{S}_{\sigma_\mathrm{t}}, \sigma_\mathrm{t}) \varepsilon(\mathrm{t})$$

- Time dependent *CP* violation measurements are core LHCb physics programme.
- Excellent decay time resolution: $\sigma \sim 45$ fs.
- Best measurement of Δm_s using $B^0_s \to D_s \pi$

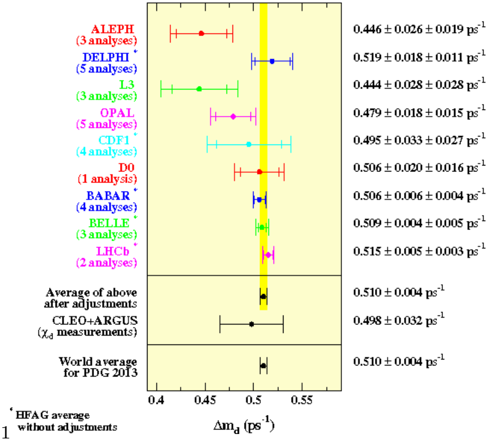


Δm_d USING $B^0 \to D\pi$, $B^0 \to J/\psi K^{*0}$





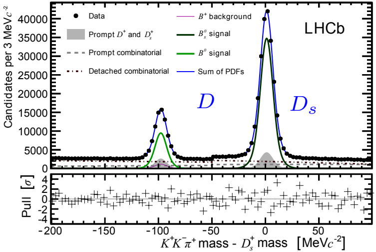
$$A_{mix}(t) = \frac{N(\text{unmixed}) - N(\text{mixed})}{N(\text{unmixed}) + N(\text{mixed})} \propto \frac{\cos(\Delta m_d t)}{\cosh(\Delta\Gamma_d t/2)}$$

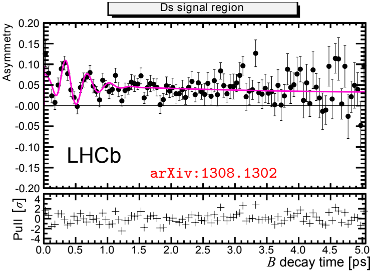


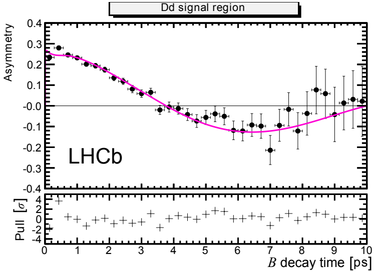
$$\Delta m_d^{SM} = 0.555 \pm 0.073\,\text{ps}^{-1}$$
$$\Delta m_d = 0.515 \pm 0.005 \pm 0.003\,\text{ps}^{-1}$$

Semileptonic $\Delta m_s, \Delta m_d$

- 1.8×10^6 $B^0_{(s)} \to D^-_{(s)} \mu^+ \overline{\nu}_\mu$ (+ anything) events.
- Time resolution is $\sim 1\,\mathrm{ps}$, dominated by correction to momentum from missing ν_μ.
- First observation of B^0_s mixing with only semileptonic decays.







$\Delta m_s = 17.93 \pm 0.22 \pm 0.15\,\mathrm{ps}^{-1}$

$\Delta m_d = 0.503 \pm 0.011 \pm 0.013\,\mathrm{ps}^{-1}$

CP VIOLATION IN $B^0_{(s)}$ MIXING

arxiv:1308.1048, PLB

- CP violation in mixing is very small in the SM.
- $a_{sl} \equiv 1 - \left|\frac{q}{p}\right|^2$

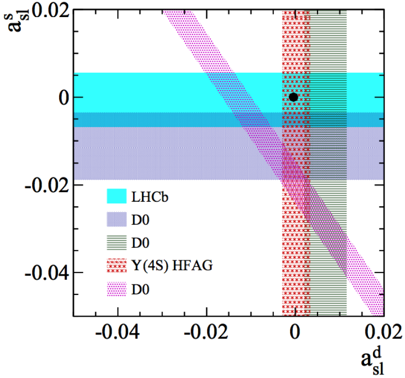
Lenz + Nierste, 2011
$a^d_{sl}(B^0) = (-4.1 \pm 0.6) \times 10^{-4}$
$a^s_{sl}(B^0_s) = (+1.9 \pm 0.3) \times 10^{-5}$

- Experimentally, measure time-integrated asymmetry in semileptonic B^0_s decays (between $D_s^+ X \mu^- \bar{\nu}_\mu$ and $D_s^- X \mu^+ \nu_\mu$)

$$A_{CP}^{measured} = \frac{\Gamma[D_s^- \mu^+] - \Gamma[D_s^+ \mu^-]}{\Gamma[D_s^- \mu^+] + \Gamma[D_s^+ \mu^-]} = \frac{a^s_{sl}}{2} + \left[a_p - \frac{a^s_{sl}}{2}\right] \frac{\int e^{-\Gamma_s t} \cos(\Delta m_s t)\varepsilon(t)dt}{\int e^{-\Gamma_s t} \cosh(\Delta\Gamma_s/2 t)\varepsilon(t)dt}$$

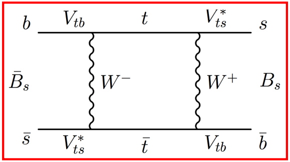
$a^s_{sl} = [-0.06 \pm 0.50(\text{stat}) \pm 0.36(\text{syst})]\%$

- Fast B^0_s mixing dilutes second term below precision of this measurement.
- Dominant systematic is from limited statistics in control sample.
- **3σ tension with SM in the D0 result, not confirmed or excluded by LHCb.**

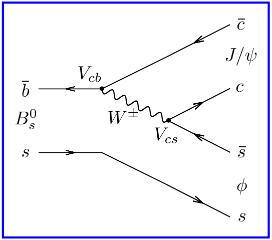


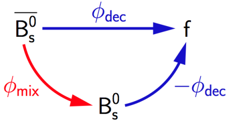
CP violation in $B^0_{(s)}$ meson mixing/decay

$\phi_{\text{mix}} = 2\,\arg(\mathrm{V_{ts}V^*_{tb}})$



$\phi_{\text{dec}} = \arg(\mathrm{V_{cs}V^*_{cb}})$





$$\mathrm{A_{CP}(t)} = \frac{\Gamma(\overline{B}{}^0 \to f) - \Gamma(B^0 \to f)}{\Gamma(\overline{B}{}^0 \to f) + \Gamma(B^0 \to f)} = \mathcal{D}\eta_f \sin\phi_f \sin(\Delta m t)$$

- Decay to CP-eigenstate f
  $\mathrm{A_f} \equiv \langle \mathrm{f}|\mathcal{H}|\mathrm{B}^0\rangle$, $\overline{\mathrm{A}}_\mathrm{f} \equiv \langle \mathrm{f}|\mathcal{H}|\overline{\mathrm{B}}{}^0\rangle$
- **Use interference between mixing and decay to measure CP-violating phase**
  $\phi_f = \phi_{\text{mix}} - 2\phi_{\text{dec}}$
- Possible pollution from penguin decays.

Golden modes

$B^0 \to J/\psi\, K^0_\mathrm{S} : \phi^{\mathrm{SM}}_{J/\psi\, K^0_\mathrm{S}} = 2\beta = 0.84 \pm 0.05\ \mathrm{rad}$

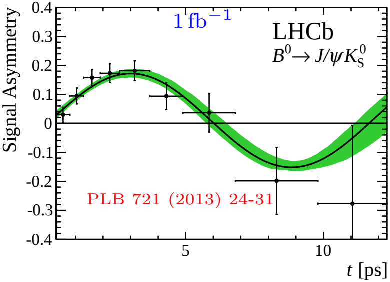
$B^0_s \to J/\psi\,\phi \quad : \phi^{\mathrm{SM}}_{J/\psi\,\phi} = -2\beta_s = -0.036 \pm 0.002$

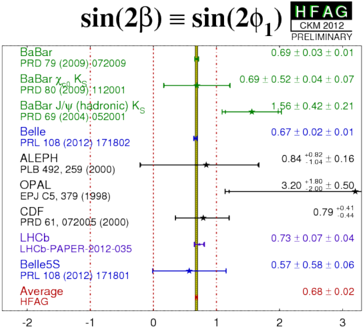
CKMfitter, PRD 83, 036004 (2011)

$\sin 2\beta$ USING $B^0 \to J/\psi K^0_S$

- Can LHCb reproduce B-factory results?
- ~ 8200 $B^0 \to J/\psi K^0_S$ candidates in $1\,\mathrm{fb}^{-1}$
- Tagging power: $\varepsilon_{\mathrm{tag}}\mathcal{D}^2 = (2.38 \pm 0.27)\%$

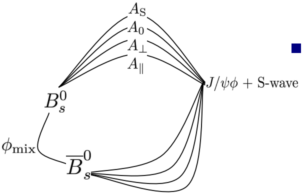
$$S_{J/\psi K^0_S} = 0.73 \pm 0.07 \pm 0.04$$
$$C_{J/\psi K^0_S} = 0.03 \pm 0.09 \pm 0.01$$



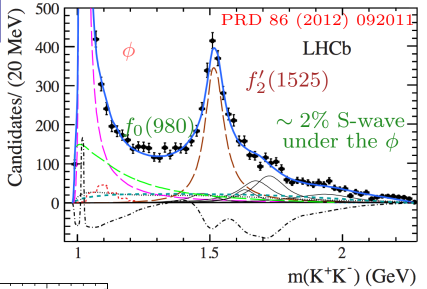


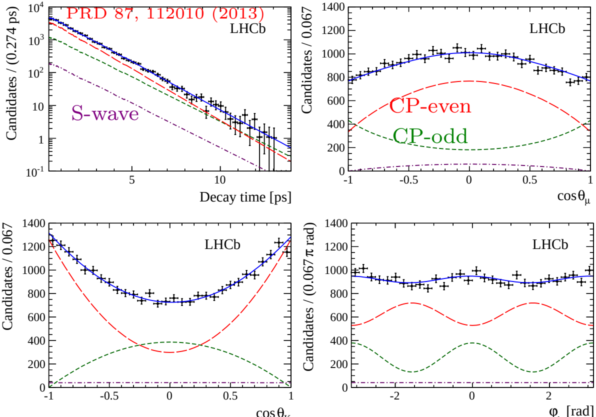
$$A_{CP}(t) \equiv \frac{\Gamma_{B^0\to f} - \Gamma_{\overline{B}^0\to f}}{\Gamma_{B^0\to f} + \Gamma_{\overline{B}^0\to f}} = S_{J/\psi K^0_S}\sin(\Delta m\, t) + C_{J/\psi K^0_S}\cos(\Delta m\, t)$$

ϕ_s FROM $B_s^0 \to J/\psi\phi$

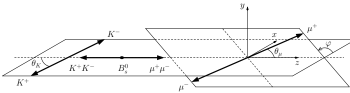


- Final state is ad-mixture of CP-odd and CP-even, $\eta_f^{CP} = (-1)^L$





- 4D, background subtracted fit using sWeights.
- Angular efficiency extracted from simulation.

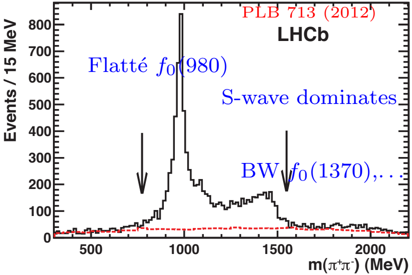


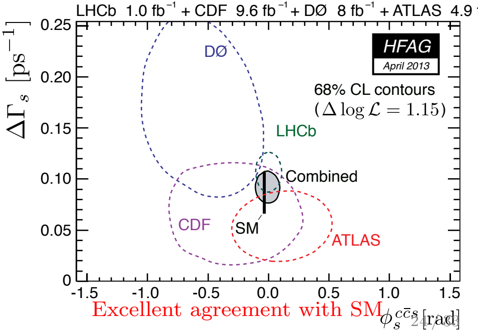
Combined measurement of ϕ_s

- Combine $B_s^0 \to J/\psi\,\phi$ and $B_s^0 \to J/\psi\,\pi^+\pi^-$ (1/3 of $J/\psi\,\phi$ stats).
- $\Delta\Gamma_s$ is in impressive agreement with HQE calculations. $\Delta\Gamma_s \neq 0 \Rightarrow$
  - $\Rightarrow$ the heavy B_s^0 eigenstate lives longer than the light one! (**two lifetimes**)
  - $\Rightarrow$ $\mathcal{B}^{\rm exp}(B_s^0 \to f) \neq \mathcal{B}^{\rm theo}(B_s^0 \to f)$ (PRD 86, 014027 (2012))
- NP contribution to B_s^0 mixing is limited to $< 30\%$ at 3σ (Lenz arXiv:1203.0238v2).

$$\begin{aligned}
\phi_s &= 0.01 \pm 0.07\ (\text{stat}) \pm 0.01\ (\text{syst})\ \text{rad},\\
\Gamma_s \equiv (\Gamma_L + \Gamma_H)/2 &= 0.661 \pm 0.004\ (\text{stat}) \pm 0.006\ (\text{syst})\ \text{ps}^{-1},\\
\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H &= 0.106 \pm 0.011\ (\text{stat}) \pm 0.007\ (\text{syst})\ \text{ps}^{-1},
\end{aligned}$$

$J/\psi\,\pi^+\pi^-$ is $> 97.7\%$ *CP*-odd @ 95% CL.





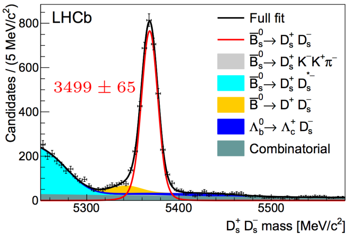
Excellent agreement with SM

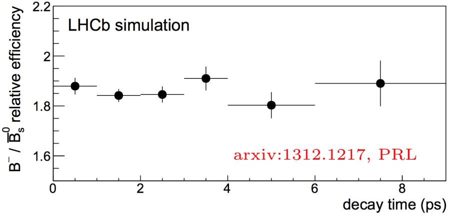
$B_s^0 \to D_s^+ D_s^-$ effective lifetime

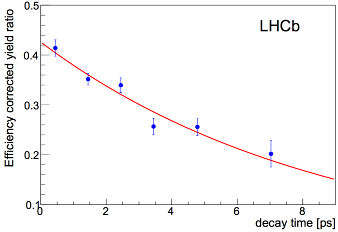
- Final state is CP-even, ϕ_s is small

$\Rightarrow$ $\tau_{\text{eff}} \approx 1/\Gamma_L$

- Determine efficiency using $B^+ \to D^0 D_s^+$ control channel.
- Main systematic is acceptance.



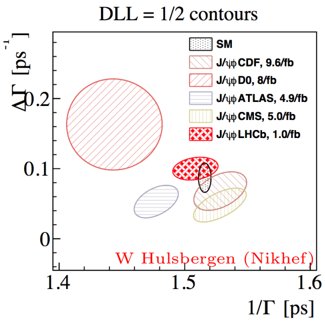


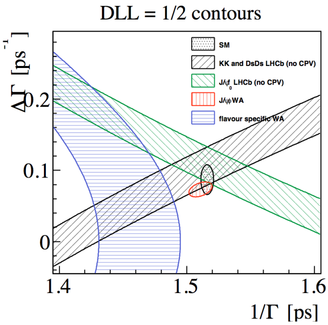


$$\tau^{\text{eff}}_{B_s^0 \to D_s D_s} = 1.379 \pm 0.026 \pm 0.017\,\text{ps} \qquad \Gamma_L = 0.725 \pm 0.014 \pm 0.009\,\text{ps}^{-1}$$

Other B_s^0 effective lifetimes

Channel	CP	τ^{eff} [ps]	Ref.
$B_s^0 \to D_s^+ D_s^-$	even	$1.379 \pm 0.026 \pm 0.017$	arxiv:1312.1217, PRL
$B_s^0 \to K^+ K^-$	even	$1.455 \pm 0.046 \pm 0.006$	PLB 716 (2012) 393-400
$B_s^0 \to J/\psi\, f_0(980)$	odd	$1.700 \pm 0.040 \pm 0.026$	PRL 109 (2012) 152002
$B_s^0 \to J/\psi\, K_S^0$	odd	$1.75 \pm 0.12 \pm 0.07$	Nucl. Phys. B 873 (2013) 275-292

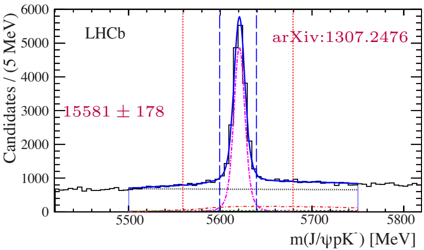


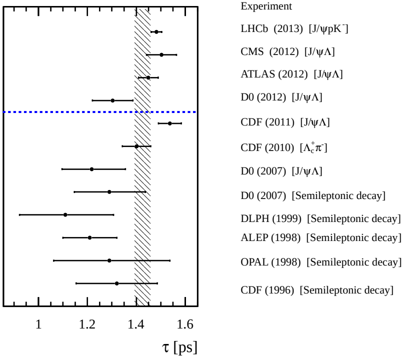


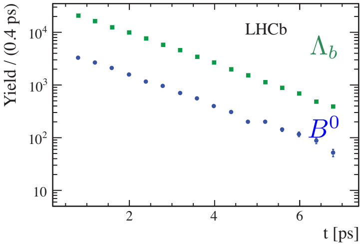
- Perform naive combination of these lifetimes and results on $\Delta\Gamma_s$ and Γ_s from $B_s^0 \to J/\psi\,\phi$ and $B_s^0 \to J/\psi\,\pi\pi$.
- Everything in agreement with SM+HQE predictions.

Λ_b LIFETIME

- HQE: $\frac{\tau_{\Lambda_b}}{\tau_{B^0}} = 0.98 + \mathcal{O}(1/m_b^3)$
- Make use of a previously unobserved decay mode: $\Lambda_b \to J/\psi\, pK$.
- Can use method of normalisation to topologically similar $B^0 \to J/\psi\, K^*$.





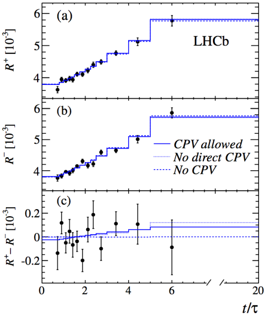


$$\frac{\tau_{\Lambda_b}}{\tau_{B^0}} = 0.976 \pm 0.012 \pm 0.006$$

D^0 MIXING AND CP VIOLATION

More details in talks by T. Lesiak, L. Sun

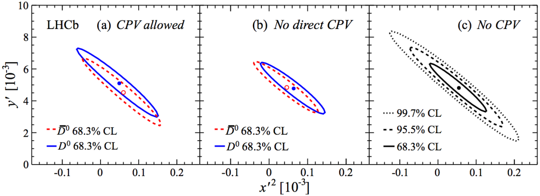
PRL 111, 251801



- Mixing in charm sector dominated by long distance effects ⇒ very small CPV expected.
- First $> 5\sigma$ observation of charm mixing made by LHCb (PRL 110, 101802 (2013)).
- right-sign: $D^{*+} \to D^0\pi^+ \to (K^-\pi^+)\pi^+$ (Cabibbo favoured - 54M events)
- wrong-sign: $D^{*+} \to D^0\pi^+ \to (K^+\pi^-)\pi^+$ (DCS, mixing+CF - 0.23M events)

$$R(t) \equiv \frac{N_{\text{ws}}(t)}{N_{\text{rs}}(t)} \approx R_D + \sqrt{R_D}\,y' t + \frac{1}{4}(x'^2 + y'^2)t^2$$

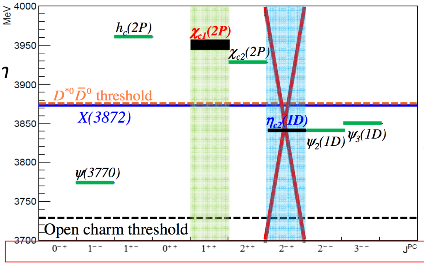
- **No evidence for CP violation when studying D^0 and $\overline{D}^0$ separately.**



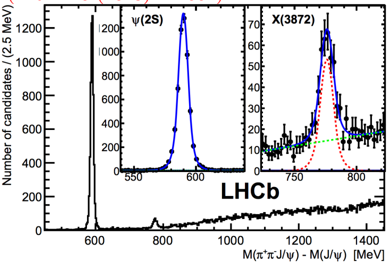
$$x'^2 = (5.5 \pm 4.9) \times 10^{-5}$$
$$y' = (4.8 \pm 1.0) \times 10^{-3}$$
$$A_D \equiv \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-} = (-0.7 \pm 1.9)\%$$
$$|q/p| = 1.00 \pm 0.25$$

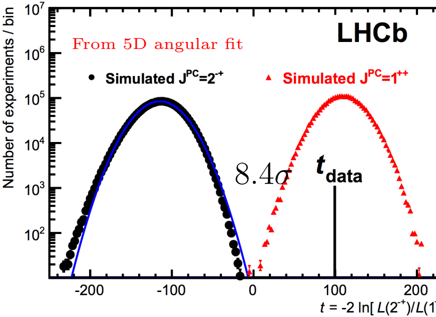
Exotic spectroscopy: quantum numbers of X(3872)

- What is nature of this state (tetra-quark, or DD^* molecule, or ...?)
- Must be $C = +$ since $X(3872) \to J/\psi\,\gamma$ has been observed (Belle).
- CDF previously ruled out all J^{PC} except 1^{++} and 2^{-+}.
- $B^+ \to X(3872)K^+$, $X(3872) \to J/\psi\,\pi^+\pi^-$. 313 events



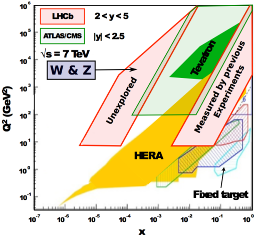
(PRL 110 (2013) 222001)

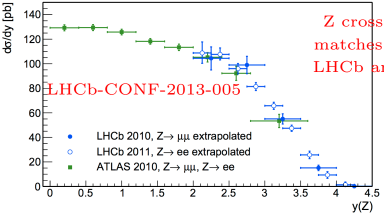




- $J_{PC} = 1^{++}$ established - favours exotic interpretation.

- LHCb allows exploration of EW sector in forward region.

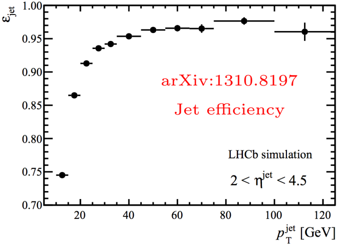




LHCb-CONF-2013-005

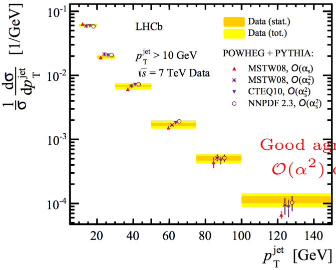
Z cross section matches between LHCb and GPDs

- Measurements of Z+jets are sensitive to the gluon content of the proton.
- Jets are reconstructed using the anti-kT algorithm with $R = 0.5$



arXiv:1310.8197

Jet efficiency



Good agreement with $\mathcal{O}(\alpha^2)$ calculations

So much more...

CP violation and rare decays

- B mixing
- Measurement of γ
- CP violation in penguin decays
- Charmless B decays
- Many rare decay modes ($p\overline{p}$)

Electroweak physics

- W and Z production
- Higgs forward production

Lepton flavour/number violation

More details in talk by B. Rachwal

Charm physics

- D^0 mixing
- CP violation in charm

pA collisions

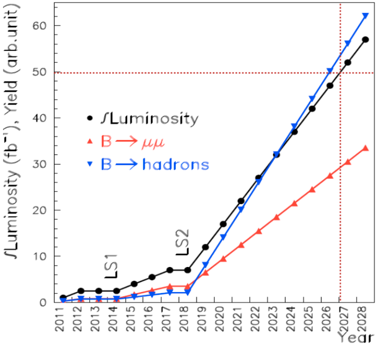
Production and spectroscopy

- Fragmentation fractions
- B_c decays and lifetimes
- Excited states
- Quarkonia polarisation
- XYZ states
- (Double) heavy baryons

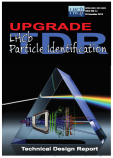
Public results: http://lhcbproject.web.cern.ch/lhcbproject/CDS/cgi-bin/index.php

LOOKING FORWARD: LHCB UPGRADE

- LHC will be upgraded to run at higher luminosity from $\sim$ 2018.
- LHCb will run at $\mathcal{L} \geq 10^{33} cm^{-2} s^{-1}$.



- Upgraded detector will be read out at 40MHz.
  - Factor-10 increase signal yields.
  - Existing design will saturate at higher luminosities.



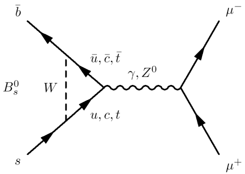
Sensitivity of key measurements (LHCb-PUB-2013-015)

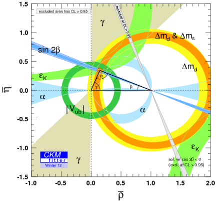
	LHC era			HL-LHC era	
	Run 1	Run 2	Run 3	Run 4	Run 5+
$\phi_s(B_s^0 \to J/\psi\phi)$	0.05	0.025	0.013	0.009	0.006
$\phi_s(B_s^0 \to \phi\phi)$	0.18	0.12	0.04	0.026	0.017
$\frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)}$	220%	110%	60%	40%	28%
$q_0^2\ A_{\mathrm{FB}}(K^{*0}\mu^+\mu^-)$	10%	5%	2.8%	1.9%	1.3%
γ	7°	4°	1.7°	1.1°	0.7°

Summary

- Flavour physics provides access to **high energy scales** where new physics may exist.

- LHCb provides a unique laboratory for the precision study of heavy flavour
  - CP violation in B decays.
  - Rare decays of B mesons.
  - Exotic spectroscopy.
  - And more...





- Most LHCb measurements are **statistics limited**.
- LHCb upgrade will move forward the precision frontier.

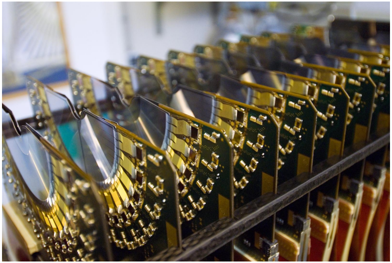
2015–2017	double existing dataset
2017–2019	LS2, upgrade detector
2019–. . .	collect 50 fb^{-1}, with more efficient trigger

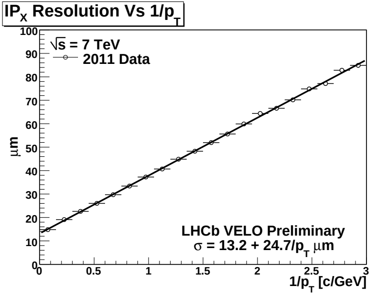
Backup

-

The vertex locator

2008 JINST 3 S08005

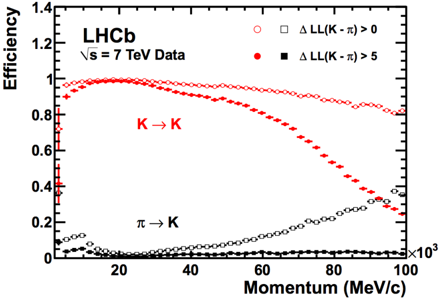




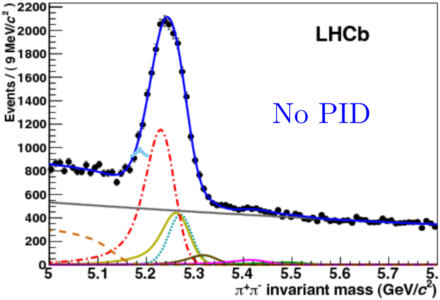
- 21 silicon strip detectors, 8mm from beam line.
- Operates in vacuum, separated from LHC vacuum by $300\mu m$ Al foil.
- Primary vertex resolution $\sim 13, 13, 69\mu$m in x, y, z.
- IP resolution of tracks with $p_T > 2\,\text{GeV/c}^2$ is $\sim 20\mu$m.
- Decay time resolution $\sim 45\,$fs for many B decay channels.

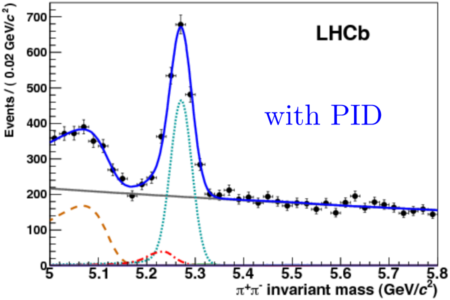
Particle ID

arXiv:1211.6759



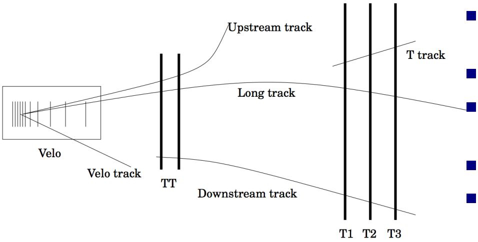
- Gas radiators (C_4F_{10}, CF_4) + aerogel.
- Photomultiplier tubes to detect Cerenkov light.
- Excellent for suppressing backgrounds.
- Muon-ID: $\varepsilon(\mu \to \mu) \sim 97\%, \varepsilon(\pi \to \mu) \sim 1-3\%$



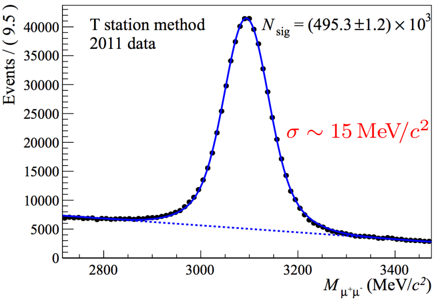


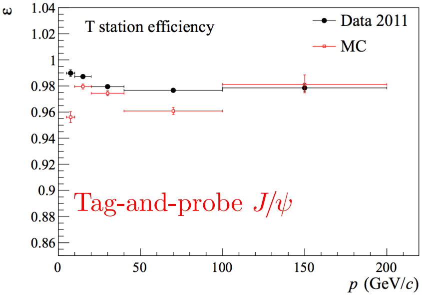
TRACKING

2008 JINST 3 S08005



- Silicon microstrip detectors closest to beam pipe.
- Straw tubes cover larger area.
- Aligned to $\sim 14\mu m$ using large samples of $J/\psi \to \mu\mu$, $D^0 \to K\pi$.
- $\Delta p/p \sim 0.5\%$.
- Mass resolution $\sim 8\,\text{MeV}/c^2$ for $b \to J/\psi\, X$ decays.

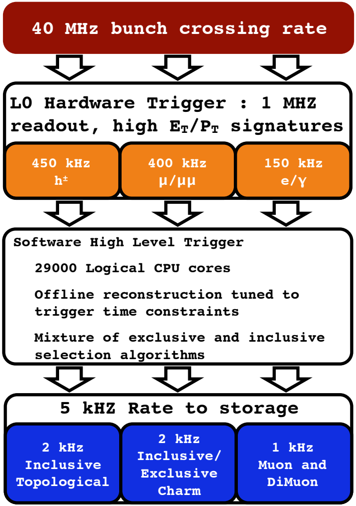


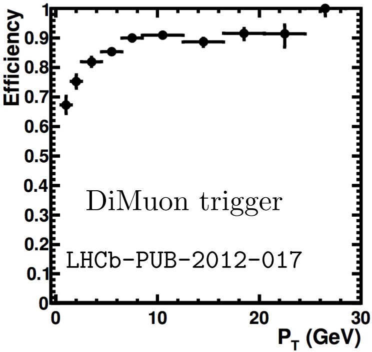


The trigger

arXiv:1211.3055

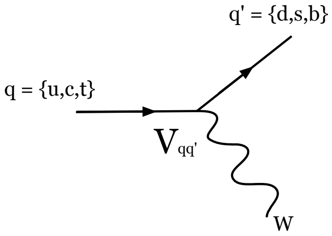
- Approach: try to maintain high efficiency for manageable data rates.





Lower efficiency for multi-body final states

- Coupling of charged current interaction to up, down-type quarks given by CKM matrix:



$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\bar\rho - i\bar\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\bar\rho-i\bar\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

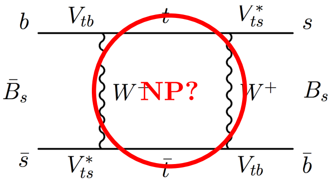
- 3 generations + **1 phase** $\rightarrow \bar\eta \neq 0$ is only source of CP violation in SM.
  - $A = 0.80 \pm 0.02$, $\lambda = 0.225 \pm 0.001$
  - $\bar\rho = 0.140 \pm 0.027$, $\bar\eta = 0.343 \pm 0.015$

Brief introduction to $B^0_{s,d}$ meson mixing

$$i\frac{\partial}{\partial t}\begin{pmatrix} B^0_{s,d}(t) \\ \overline{B}^0_{s,d}(t) \end{pmatrix} = \left(\begin{bmatrix} M_{11} & M_{12} \\ M^*_{12} & M_{11} \end{bmatrix} - \frac{i}{2}\begin{bmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma^*_{12} & \Gamma_{11} \end{bmatrix}\right)\begin{pmatrix} B^0_{s,d}(0) \\ \overline{B}^0_{s,d}(0) \end{pmatrix}$$

$$\varphi_{12} = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$$

$$|B^0_L\rangle = p|B^0\rangle + q|\overline{B}^0\rangle$$
$$|B^0_H\rangle = p|B^0\rangle - q|\overline{B}^0\rangle$$



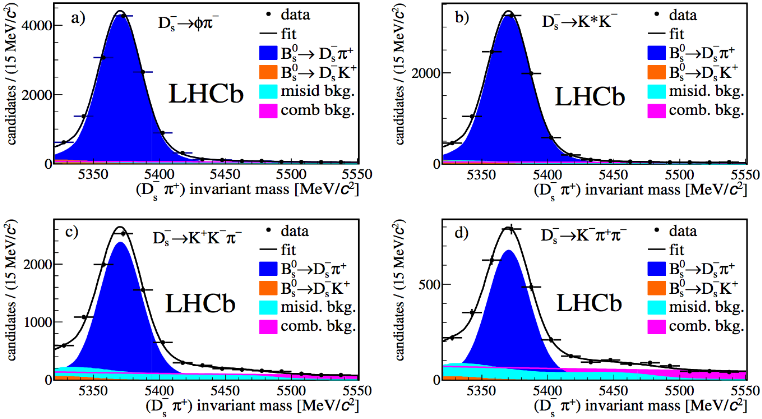
1. Large mass of b quark allows for reliable calculations.
2. Mixing is FCNC process → sensitive to new physics contributions.
3. Need **precision** measurements.

Δm_s USING $B_s^0 \to D_s^- \pi^+$

New J. Phys. 15 (2013) 053021

$$A_{mix}(t) = \frac{N(unmixed) - N(mixed)}{N(unmixed) + N(mixed)} \propto \frac{\cos(\Delta m t)}{\cosh(\Delta\Gamma t/2)}$$

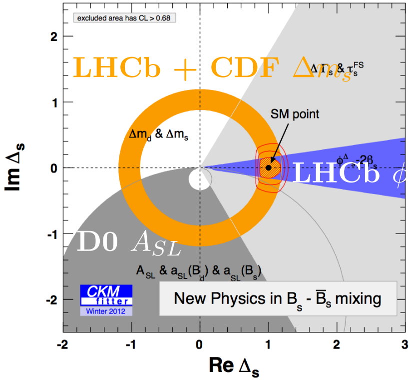
- 5 different D_s decay modes: $D_s \to (K^+K^-)\pi^-, D_s \to (K^-\pi^+)\pi^-, D_s \to \pi^+\pi^-\pi^-$
- 2, 3, 4 track displaced vertex trigger. $\to$ **34k events**
- 1 large IP track, $p_T > 1.7\,\mathrm{GeV}/c$.



Impact on New Physics

Lenz et al. arXiv:1203.0238v2 [hep-ph]

- $M_{12}^{NP,s} = M_{12}^{SM,s} \Delta_s$
- $\Delta_s = |\Delta_s| e^{i\phi_s^\Delta}$
- $\Delta_s^{SM} = 1$
- NP contribution to B_s^0 mixing is limited to $< 30\%$ at 3σ.



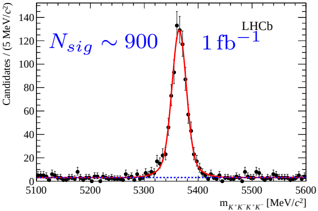
Next step

- Use full 2011+2012 LHCb dataset (factor 3 more data).
- Precision measurement.
  - Control of systematic uncertainties is **essential**.
  - Extend physics reach by including rarer modes: $B_s^0 \to \psi(2S)\phi, B_s^0 \to J/\psi\eta^{(\prime)} \ldots$

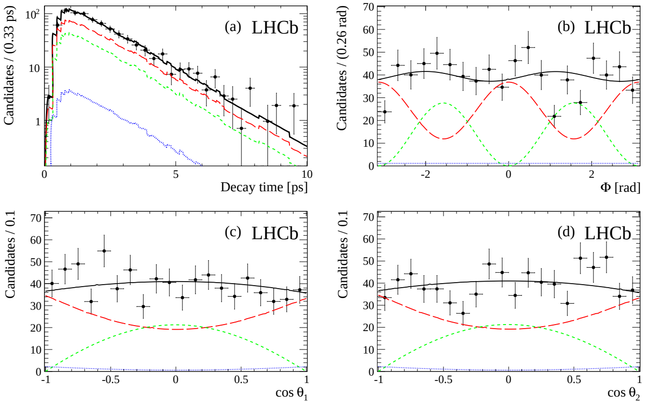
ϕ_s FROM $B_s^0 \to \phi\phi$

PRL 110, 241802 (2013)

- First measurement using $b \to s\bar{s}s$ transition.
- Expect cancellation between (small) phase in the mixing and decay.
  - Measuring $\phi_s \neq 0$ would be null test of SM.



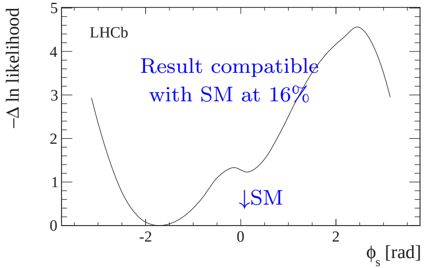
$\phi_s \in [-2.46, -0.76]$ rad at 68% CL



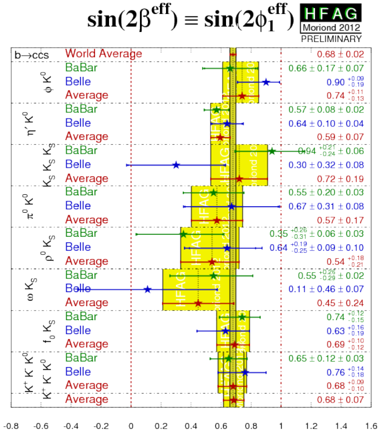
ϕ_s FROM $B_s^0 \to \phi\phi$

Phys. Rev. Lett. 110, 241802 (2013)

$\phi_s \in [-2.46, -0.76]$ rad at 68% CL

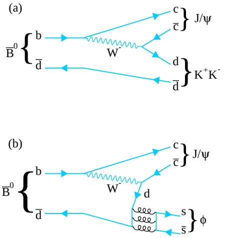


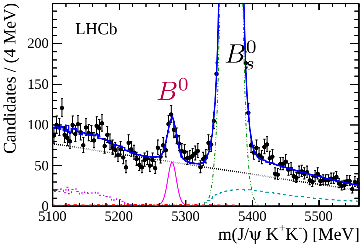
Hopefully help to resolve the $\sin 2\beta^{eff}$ situation.

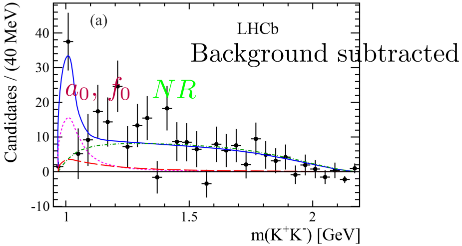


Amplitude analysis of $B^0 \to J/\psi K^+ K^-$ arXiv:1308.5916

- First observation of $B^0 \to J/\psi K^+ K^-$.
- Amplitude analysis $\to 3.9\sigma$ evidence for $B^0 \to J/\psi a_0(980), a_0(980) \to K^+ K^-$.
- No evidence of $B^0 \to J/\psi \phi$.
- NR contribution dominates.







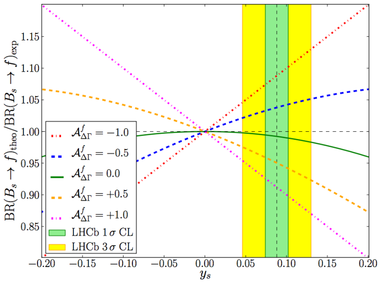
$$\mathcal{B}(B^0 \to J/\psi a_0(980), a_0(980) \to K^+ K^-) = (4.70 \pm 3.31 \pm 0.72) \times 10^{-7}$$

Consequence of $\Delta\Gamma_s \neq 0$

PRD 86, 014027 (2012)

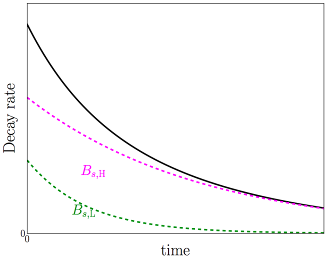
- Leads to different value for BR compared to theoretical ones.
- Biases of $\sim 10\%$, depending on decay mode.

$$\mathrm{BR}^{\mathrm{exp}}(\mathrm{B}_s^0 \to \mathrm{f}) = \mathrm{BR}^{\mathrm{theo}}(\mathrm{B}_s^0 \to \mathrm{f}) \left[\frac{1 + \mathrm{y_s A_f}}{1 - \mathrm{y_s^2}}\right]$$



- B_s^0 has two lifetimes, can define "effective lifetime".

$$\tau_{\mathrm{eff}} = \frac{1}{\Gamma_s}\left[\frac{1 + 2\mathrm{y_s A_f} + \mathrm{y_s^2}}{(1 - \mathrm{y_s^2})(1 + \mathrm{y_s A_f})}\right]$$

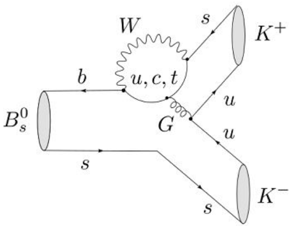


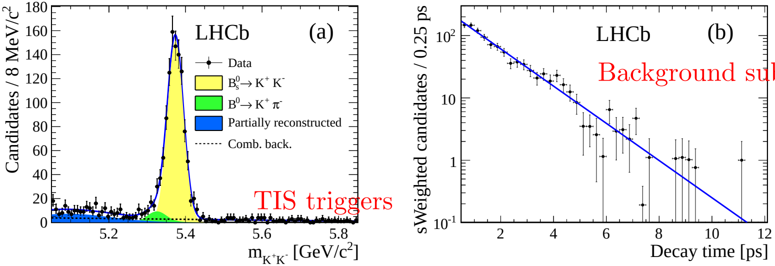
$$\mathrm{A_f} = \mathrm{D_f} \qquad \mathrm{y_s} = \frac{\Delta\Gamma_s}{2\Gamma_s}$$

$B_s^0 \to K^+K^-$ EFFECTIVE LIFETIME

PLB 716 (2012) 393-400

- Penguin dominated decay $\Rightarrow$ sensitive to NP at loop level.
- K^+K^- final state is CP-even eigenstate $\Rightarrow$ decay is produced by light B_s^0 mass eigenstate.
  - Assuming no CP-violation: $\tau_{B_s^0 \to KK} = 1/\Gamma_L$.

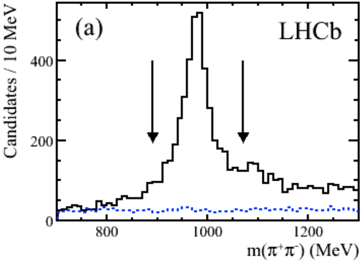


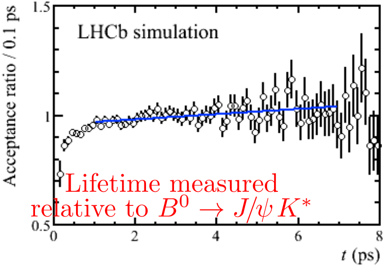


$\tau^{SM}_{Bs\to KK} = 1.40 \pm 0.02\,\text{ps}$[1] $\qquad \tau_{KK} = 1.455 \pm 0.046 \pm 0.006\,\text{ps}$

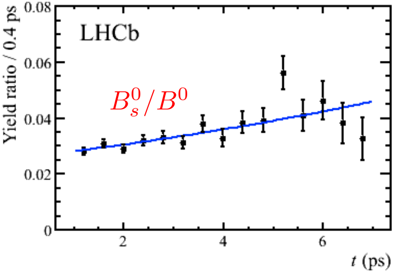
[1] (EPJC71, 1532)

- $J/\psi\, f_0(980)$ final state is CP-odd eigenstate $\Rightarrow$ decay is produced by heavy B_s^0 mass eigenstate.
  - Assuming no CP-violation: $\tau_{Bs \to KK} = \tau_H$.
- Main systematic related to acceptance from MC.



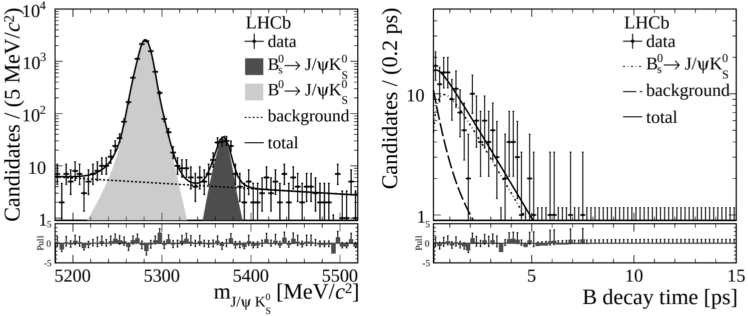


Lifetime measured relative to $B^0 \to J/\psi\, K^*$



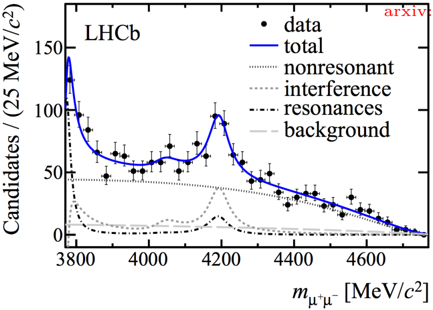
$\tau_{J/\psi\, f_0} = 1.700 \pm 0.040 \pm 0.026\,\text{ps}$ $\Gamma_H = (0.588 \pm 0.014 \pm 0.009\,\text{ps}^{-1})^2$

- $J/\psi\, K_S^0$ final state is another CP-odd eigenstate.
- Split sample of events depending on K_S^0 reconstruction (LL, DD).
- Determine decay time acceptance using large sample of $B^0 \to J/\psi\, K_S^0$.
- Main systematic comes from background parameterisation.
- Future: use to control penguin pollution in $\sin 2\beta$ from $B^0 \to J/\psi\, K_S^0$.



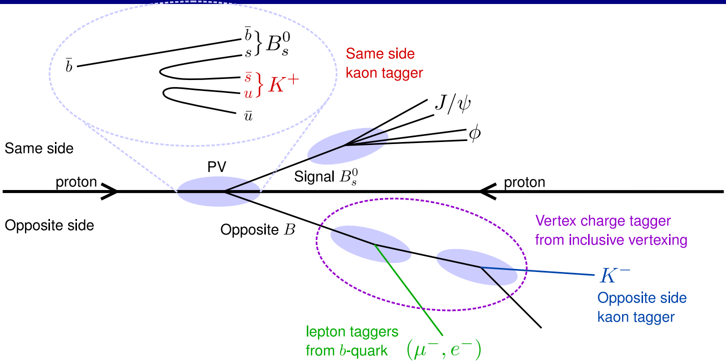
$$\tau^{SM}_{J/\psi\, K_S^0} = 1.639 \pm 0.022\,\text{ps} \qquad \tau_{J/\psi\, K_S^0} = 1.75 \pm 0.12 \pm 0.07\,\text{ps}$$

- $> 6\sigma$, resonant+interference accounts for 20% - bigger than predicted.
- Compatible with the properties of the $\psi(4160)$ observed by BES.
- Important for controlling charmonium effects in future inclusive and exclusive $b \to s\mu^+\mu^-$ measurements.



arxiv:1307.7595

Flavour tagging

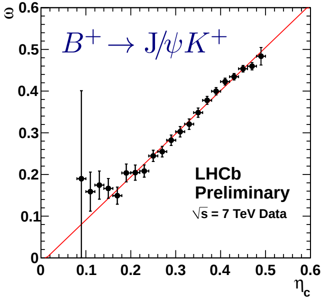


Specialised tagging algorithms to analyse event to determine initial flavour b or $\overline{\text{b}}$.

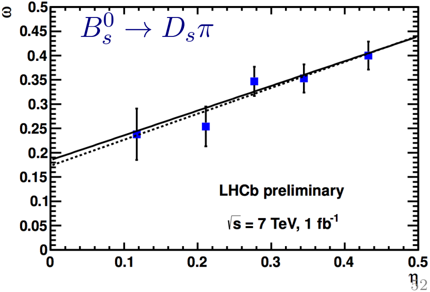
Opposite-side Use charge of leptons/hadrons from other B meson decay

Same-side Use charge of kaon produced from fragmentation of signal B

- Opposite-side
- $\omega = p_0 + p_1(\eta - \langle\eta\rangle)$
- Effective tagging efficiency $2.6 \pm 0.4\%$



- Same-side kaon
- Effective tagging efficiency $1.2 \pm 0.3\%$



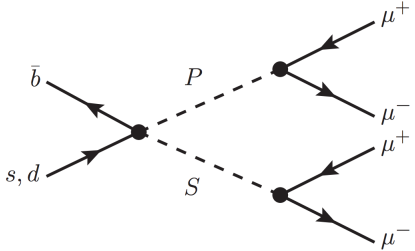
$B_s^0 \to J/\psi\,\phi$

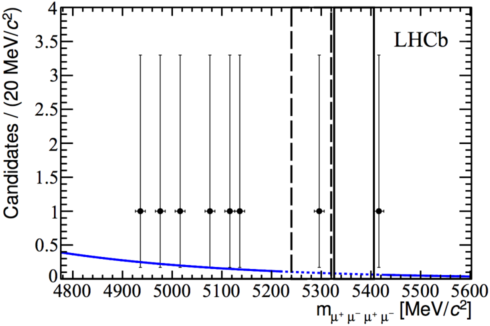
$$h_k(t) = N_k e^{-\Gamma_s t}\left[a_k \cosh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + b_k \sinh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + c_k \cos(\Delta m_s t) + d_k \sin(\Delta m_s t)\right]$$

k	$f_k(\theta_\mu, \theta_K, \varphi_h)$	N_k	a_k	b_k	c_k	d_k
1	$2\cos^2\theta_K \sin^2\theta_\mu$	$\lvert A_0\rvert^2$	1	D	C	$-S$
2	$\sin^2\theta_K\left(1-\sin^2\theta_\mu\cos^2\varphi_h\right)$	$\lvert A_\parallel\rvert^2$	1	D	C	$-S$
3	$\sin^2\theta_K\left(1-\sin^2\theta_\mu\sin^2\varphi_h\right)$	$\lvert A_\perp\rvert^2$	1	$-D$	C	S
4	$\sin^2\theta_K\sin^2\theta_\mu\sin 2\varphi_h$	$\lvert A_\parallel A_\perp\rvert$	$C\sin(\delta_\perp-\delta_\parallel)$	$S\cos(\delta_\perp-\delta_\parallel)$	$\sin(\delta_\perp-\delta_\parallel)$	$D\cos(\delta_\perp-\delta_\parallel)$
5	$\frac{1}{2}\sqrt{2}\sin 2\theta_K\sin 2\theta_\mu\cos\varphi_h$	$\lvert A_0 A_\parallel\rvert$	$\cos(\delta_\parallel-\delta_0)$	$D\cos(\delta_\parallel-\delta_0)$	$C\cos(\delta_\parallel-\delta_0)$	$-S\cos(\delta_\parallel-\delta_0)$
6	$-\frac{1}{2}\sqrt{2}\sin 2\theta_K\sin 2\theta_\mu\sin\varphi_h$	$\lvert A_0 A_\perp\rvert$	$C\sin(\delta_\perp-\delta_0)$	$S\cos(\delta_\perp-\delta_0)$	$\sin(\delta_\perp-\delta_0)$	$D\cos(\delta_\perp-\delta_0)$
7	$\frac{2}{3}\sin^2\theta_\mu$	$\lvert A_S\rvert^2$	1	$-D$	C	S
8	$\frac{1}{3}\sqrt{6}\sin\theta_K\sin 2\theta_\mu\cos\varphi_h$	$\lvert A_S A_\parallel\rvert$	$C\cos(\delta_\parallel-\delta_S)$	$S\sin(\delta_\parallel-\delta_S)$	$\cos(\delta_\parallel-\delta_S)$	$D\sin(\delta_\parallel-\delta_S)$
9	$-\frac{1}{3}\sqrt{6}\sin\theta_K\sin 2\theta_\mu\sin\varphi_h$	$\lvert A_S A_\perp\rvert$	$\sin(\delta_\perp-\delta_S)$	$-D\sin(\delta_\perp-\delta_S)$	$C\sin(\delta_\perp-\delta_S)$	$S\sin(\delta_\perp-\delta_S)$
10	$\frac{4}{3}\sqrt{3}\cos\theta_K\sin^2\theta_\mu$	$\lvert A_S A_0\rvert$	$C\cos(\delta_0-\delta_S)$	$S\sin(\delta_0-\delta_S)$	$\cos(\delta_0-\delta_S)$	$D\sin(\delta_0-\delta_S)$

$B_s^0 \to \mu^+\mu^-\mu^+\mu^-$

LHCb-PAPER-2012-049

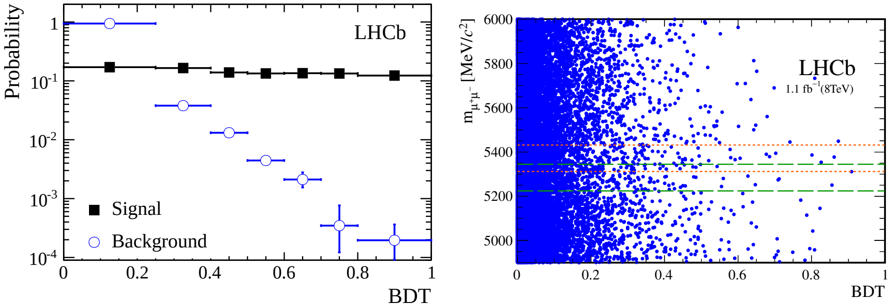




- In SM, non-resonant $BR(B^0_{(s)} \to \mu^+\mu^-\gamma(\to \mu^+\mu^-)) < 10^{-10}$ [PRD70 (2004) 114028]
- Resonant $BR(B_s^0 \to J/\psi\,\phi) = 2.3 \times 10^{-9}$
- Normalise to $BR(B_d^0 \to J/\psi\, K^*(892))$, main systematic uncertainty.
- $BR(B_s^0 \to 4\mu) < 1.6 \times 10^{-8}$ @ 95% CL
- $BR(B^0 \to 4\mu) < 6.6 \times 10^{-9}$ @ 95% CL

Signal selection

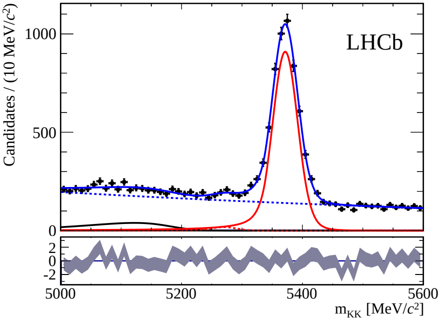
PRL 110 (2013) 021801

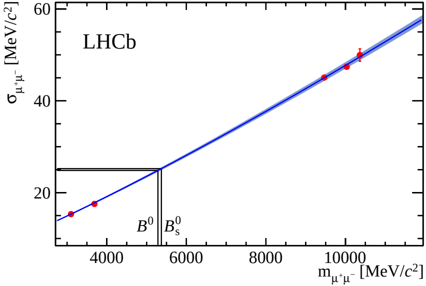


- Single and di-muon trigger.
- Classify signal using 2D discriminant:
  1. $m(\mu\mu)$
  2. BDT containing: B_s^0 impact parameter, p_T; μ p_T, $\chi^2_{IP}\dots$
- Train using MC ($B_s^0 \to \mu\mu$ and $b\bar{b} \to \mu\mu X$).
- Calibrate BDT on data:
  - Background: $m(\mu\mu)$ sidebands
  - Signal: $B \to hh'$ which has same topology

Calibrating the signal models

PRL 110 (2013) 021801

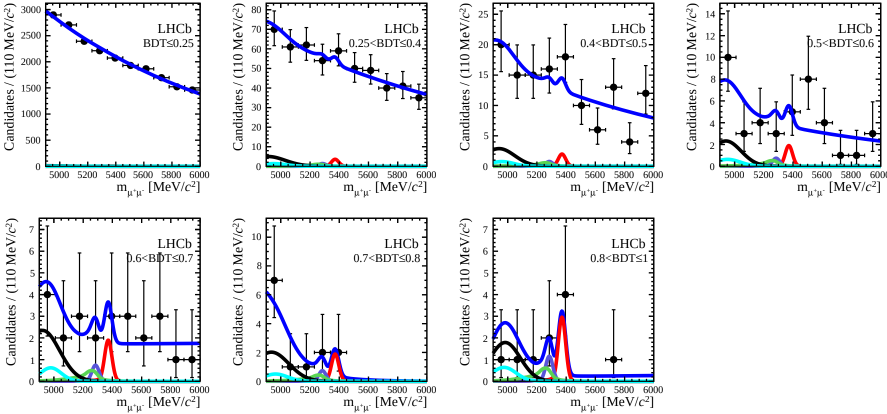




- Signal shape is Crystal Ball:
  - Mean determined from $B \to hh'$.
  - Resolution from interpolation between charmonium/bottomium resonances ($\sigma_m = 25.0 \pm 0.4\,\text{MeV}/c^2$).
  - Radiative tail transition point from $B_s^0 \to \mu\mu$ MC.

Simultaneous fit to all bins

PRL 110 (2013) 021801

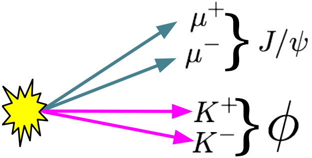


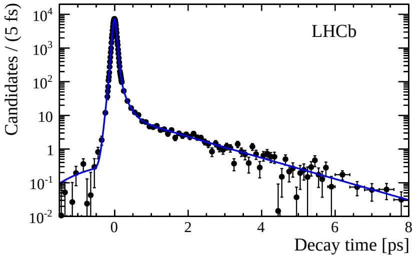
- Combine 2011 ($1.0\,\text{fb}^{-1}$) + 2012 ($1.1\,\text{fb}^{-1}$) data.
- Float yield of background, B^0, B_s^0 in fit.
- Observe excess of events over bkg-only hypothesis (p-value $= 5 \times 10^{-4}$).

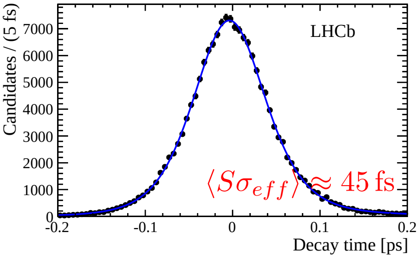
Decay time resolution

arXiv:1304.2600

- Use prescaled sample of prompt-J/ψ events to extract resolution scale factor.



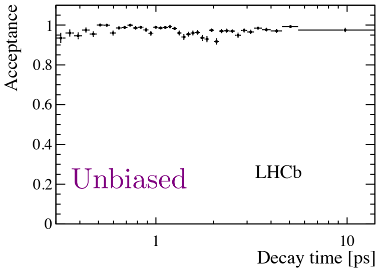




- Use σ_t, per-event decay time error, scaled by $S = 1.45 \pm 0.06$.
- If $\langle S\sigma_{eff}\rangle \approx 45\,\text{fs} \Rightarrow \mathcal{D} \sim 0.73$
- If $\langle S\sigma_{eff}\rangle \approx 90\,\text{fs} \Rightarrow \mathcal{D} \sim 0.28$

Decay time efficiency

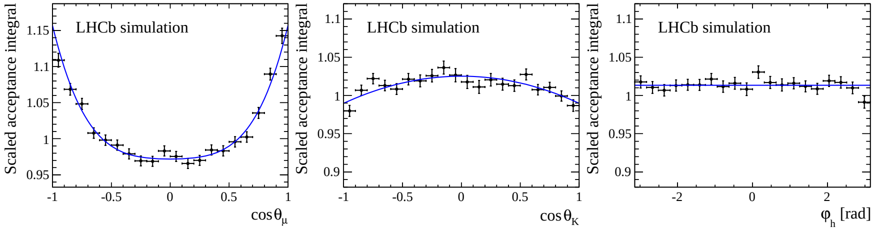
arXiv:1304.2600



- Use sample of unbiased events to understand trigger efficiency.
- Additional efficiency effect at large decay times: $\varepsilon(t) \propto 1 + \beta t$, $\beta \sim 10^{-2}\,\mathrm{ps}^{-1}$.
- Understand this using data: $B^+ \to J/\psi\, K^+$.

Angular efficiency

arXiv:1304.2600



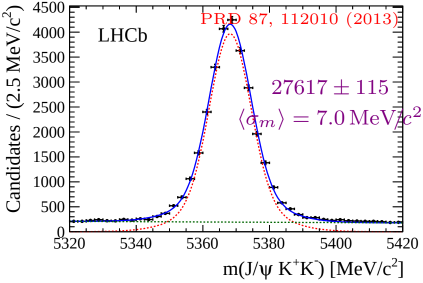
- Detector geometry and implicit momentum cuts cause majority of effect.
- Knowledge of acceptance is dominant source of systematic error.

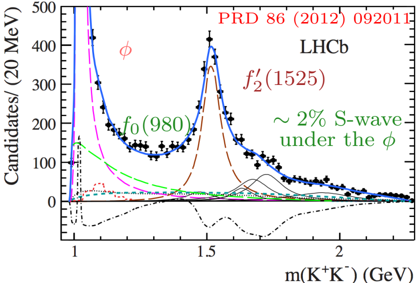
Tagging the B_s^0 flavour

Tagger	ε_{eff}
OS	$2.29 \pm 0.06\%$
SSK	$0.89 \pm 0.17\%$
Overall	$3.13 \pm 0.20\%$

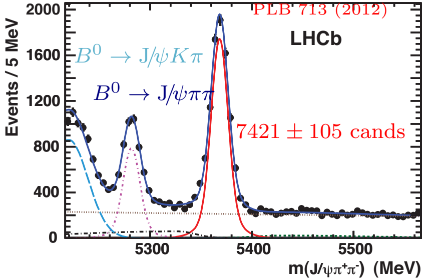
ϕ_s FROM $B_s^0 \to J/\psi\phi$ AND $B_s^0 \to J/\psi\pi^+\pi^-$

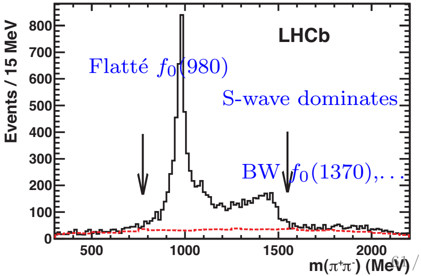
$B_s^0 \to J/\psi\phi$





$B_s^0 \to J/\psi\pi^+\pi^-$

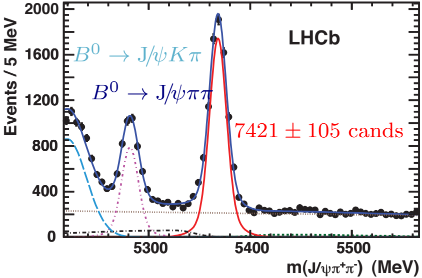


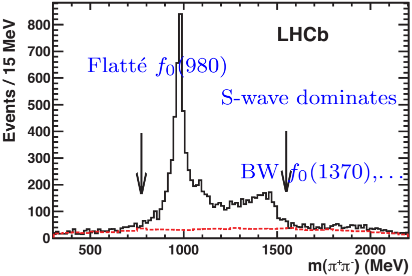


ϕ_s FROM $B_s^0 \to J/\psi\pi^+\pi^-$

PLB 713 (2012) 378-386, PRD 87,112010 (2013)

- $B_s^0 \to J/\psi\pi^+\pi^-$ is another $\bar{b} \to \bar{c}c\bar{s}$ transition; $\sim 1/3$ of $B_s^0 \to J/\psi\phi$ yield.
- $\pi^+\pi^-$ is $> 97.7\%$ CP-odd @ 95% Conf. Level.





k	$f_k(\theta_\mu, \theta_K, \varphi_h)$	N_k	a_k	b_k	c_k	d_k
7	$\frac{2}{3}\sin^2\theta_\mu$	$\|A_S\|^2$	1	$-D$	C	S

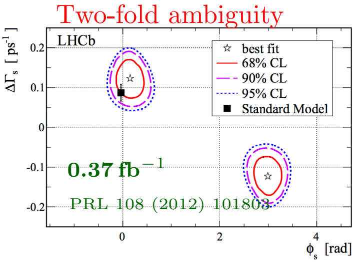
$$\phi_s = -0.014^{+0.17}_{-0.16} \pm 0.01\,\text{rad}$$

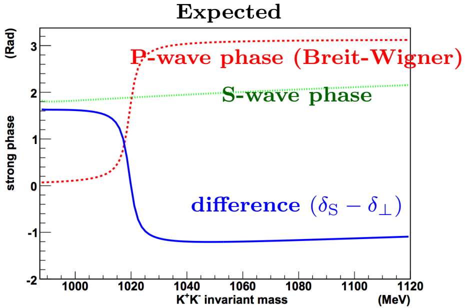
RESOLVING THE AMBIGUITY

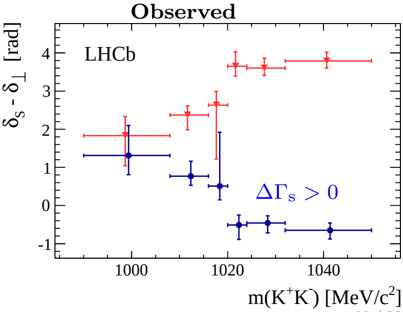
PRD 87, 112010 (2013)

- Expressions are invariant under the transformation $(\phi_s, \Delta\Gamma_s, \delta_0, \delta_\parallel, \delta_\perp, \delta_S) \mapsto (\pi - \phi_s, -\Delta\Gamma_s, -\delta_0, -\delta_\parallel, \pi - \delta_\perp, -\delta_S)$
- Physical solution: $\Delta\Gamma_s > 0$
- $\Delta\Gamma_s \neq 0$ implies
  - $\Rightarrow$ the heavy B_s^0 eigenstate lives longer than the light one! (**two lifetimes**)
  - $\Rightarrow$ $\mathcal{B}^{\text{exp}}(B_s^0 \to f) \neq \mathcal{B}^{\text{theo}}(B_s^0 \to f)$

    PRD 86, 014027 (2012)



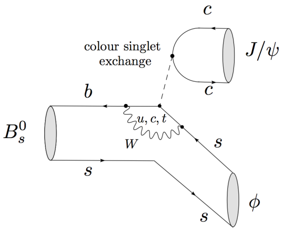


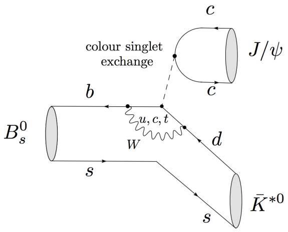


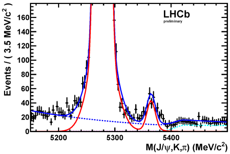
Penguin pollutions

Phys. Rev. D 86 (2012) 071102

- Penguin contributions to ϕ_s are expected to be small. How can we control them?
- Possible to use $B_s^0 \to J/\psi \bar{K}^{*0}(892)$ $(\bar{b} \to \bar{c}c\bar{d})$ via U-spin symmetry.
  - Angular and time dependent analysis.
  - Direct CP asymmetries.







$0.37\ \text{fb}^{-1}$

Result and systematics

$$\phi_s = 0.07 \pm 0.09\ (\text{stat}) \pm 0.01\ (\text{syst})\ \text{rad}$$
$$\Gamma_s \equiv (\Gamma_\text{L} + \Gamma_\text{H})/2 = 0.663 \pm 0.005\ (\text{stat}) \pm 0.006\ (\text{syst})\ \text{ps}^{-1}$$
$$\Delta\Gamma_s \equiv \Gamma_\text{L} - \Gamma_\text{H} = 0.100 \pm 0.016\ (\text{stat}) \pm 0.003\ (\text{syst})\ \text{ps}^{-1}$$

Source	Γ_s [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	$\lvert A_\perp\rvert^2$	$\lvert A_0\rvert^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	ϕ_s [rad]	$\lvert\lambda\rvert$
Stat. uncertainty	0.0048	0.016	0.0086	0.0061	$^{+0.13}_{-0.21}$	0.22	0.091	0.031
Background subtraction	0.0041	0.002	–	0.0031	0.03	0.02	0.003	0.003
$B^0 \to J/\psi K^{*0}$ background	–	0.001	0.0030	0.0001	0.01	0.02	0.004	0.005
Ang. acc. reweighting	0.0007	–	0.0052	0.0091	0.07	0.05	0.003	0.020
Ang. acc. statistical	0.0002	–	0.0020	0.0010	0.03	0.04	0.007	0.006
Lower decay time acc. model	0.0023	0.002	–	–	–	–	–	–
Upper decay time acc. model	0.0040	–	–	–	–	–	–	–
Length and mom. scales	0.0002	–	–	–	–	–	–	–
Fit bias	–	–	0.0010	–	–	–	–	–
Decay time resolution offset	–	–	–	–	–	0.04	0.006	–
Quadratic sum of syst.	0.0063	0.003	0.0064	0.0097	0.08	0.08	0.011	0.022
Total uncertainties	0.0079	0.016	0.0107	0.0114	$^{+0.15}_{-0.23}$	0.23	0.092	0.038

- Dominant systematics come from angular acceptance, decay time efficiency and background.

$B^0_{s,d}$ MIXING OBSERVABLES

$$\mathrm{M_{B^0}} \equiv \frac{1}{2}(\mathrm{M_H} + \mathrm{M_L}) = \mathrm{M}_{11}, \qquad \Gamma \equiv \frac{1}{2}(\Gamma_\mathrm{L} + \Gamma_\mathrm{H}) = \Gamma_{11}$$

$$\Delta \mathrm{m} \equiv \mathrm{M_H} - \mathrm{M_L} \approx 2|\mathrm{M}_{12}|, \qquad \Delta\Gamma \equiv \Gamma_\mathrm{L} - \Gamma_\mathrm{H} \approx 2|\Gamma_{12}| \cos\varphi_{12}$$

	SM predictions (Lenz et al, 1102.4274, 1008.1593)	
	B^0	B^0_s
φ_{12} [rad]	-0.075 ± 0.024	0.004 ± 0.001
$\Delta\Gamma$ [ps^{-1}]	$(2.7 \pm 0.5) \cdot 10^{-3}$	0.087 ± 0.021
Δm [ps^{-1}]	0.555 ± 0.073	17.3 ± 2.6
$\mathrm{a_{fs}}$	$-(4.1 \pm 0.6) \cdot 10^{-4}$	$(1.9 \pm 0.3) \cdot 10^{-5}$
$\phi^{c\bar{c}s}$ [rad]	0.84 ± 0.05	-0.036 ± 0.002

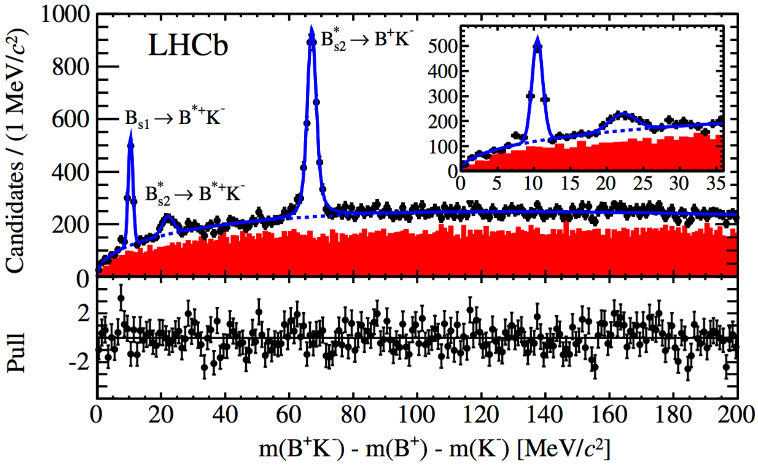
- Flavour specific final states, assuming no CP violation in decay:

$$\mathrm{a_{fs}} \equiv \frac{\Gamma_{\mathrm{B^0}\to\bar{\mathrm{f}}} - \Gamma_{\overline{\mathrm{B}}^0\to\mathrm{f}}}{\Gamma_{\mathrm{B^0}\to\bar{\mathrm{f}}} + \Gamma_{\overline{\mathrm{B}}^0\to\mathrm{f}}} \approx 1 - |\mathrm{q/p}|^2 \approx \frac{\Delta\Gamma}{\Delta\mathrm{m}} \tan\varphi_{12}$$

(Guennadi's talk)

Studies of excited B_s^0 mesons

PRL 110, 151803 (2013)



- First observation of $B_{s2}(5840)^0 \to B^{*+}K^-$
- Help understand heavy quark effective theory, used for calculating B meson properties.

Semileptonic asymmetries

LHCb-CONF-2012-022

- 190k B_s^0 signal candidates in magnetic up and down.
- Background asymmetries from $K, \pi \to \mu$ mis-id. Small systematic.