Measurements of ϕ_s at LHCb

@GreigCowan (Edinburgh)

CKM workshop, Mumbai

Nov 29th 2016

On behalf of LHCb

Science & Technology Facilities Council

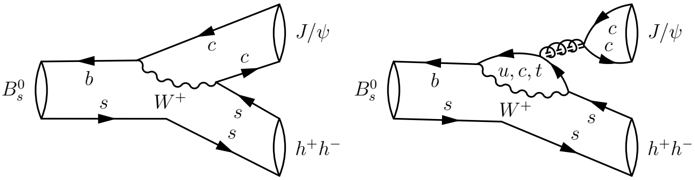
1 **Reminder of CP violation and B mixing**

2 **How we have measured $\phi_s^{c\bar{c}s}$:**

- $B_s^0 \to J/\psi\,\phi$
- $B_s^0 \to J/\psi\,\pi^+\pi^-$
- $B_s^0 \to \psi(2S)\phi$
- $B_s^0 \to \phi\phi$ **(this measures $\phi_s^{s\bar{s}s}$)**

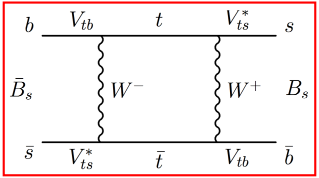
3 **Future potential for measuring ϕ_s:**

- $B_s^0 \to J/\psi\,\eta$
- $B_s^0 \to \eta_c\phi$, $B_s^0 \to J/\psi\,K^+K^-$ **(high K^+K^- mass)**

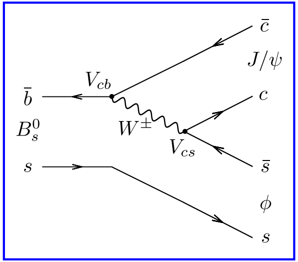


Controlling "penguin pollution"
- see following talk

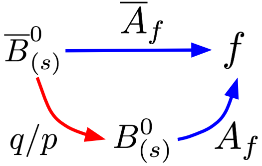
CP violation in $b \to c\bar{c}s$ decays + mixing



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



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



$$|\lambda_f| \equiv \left|\frac{q}{p}\frac{\bar{A}_f}{A_f}\right| \approx 1$$

- CP violation in interference between mixing and decay: $\phi_s \equiv -\arg(\lambda_f) \equiv -\arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \neq 0$

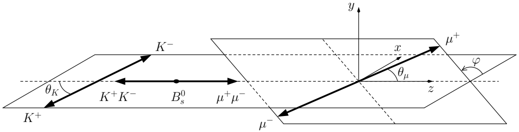
$$\phi_s \overset{\text{SM}}{=} -2\arg\left(-\frac{V_{cb}V_{cs}^*}{V_{tb}V_{ts}^*}\right) \equiv -2\beta_s$$

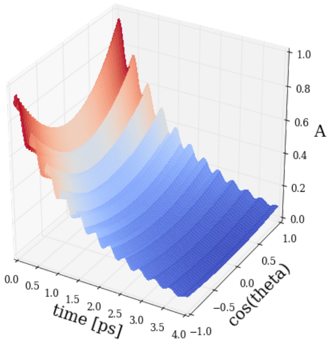
$$\phi_s \overset{\text{SM}}{=} -0.0376 \pm 0.0008\,\text{rad}$$ [CKMFitter]

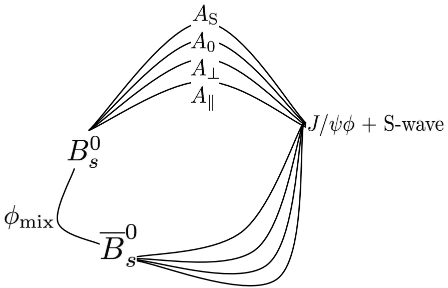
(†) Assuming we ignore sub-leading penguin contributions

ϕ_s FROM $B^0_s \to J/\psi\,\phi$

- $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$
- Time-dependent tagged analyses ($\sigma_t \sim 45\,\mathrm{fs}, \varepsilon\mathcal{D}^2 \sim 4\%$).
- $B^0_s \to J/\psi\,\phi$ is $P \to VV$ decay so use angular information to disentangle CP-odd and CP-even components.
- Measure $\phi_s, \Delta m_s, \Gamma_s, \Delta\Gamma_s, |\lambda_f| \ldots$
  [this makes $B^0_s \to J/\psi\,\phi$ special]







ϕ_s FROM $B_s^0 \to J/\psi\,\phi$

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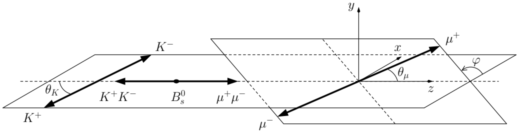
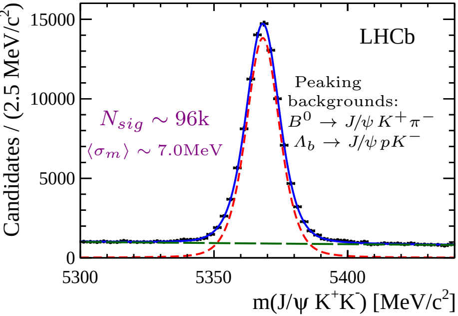
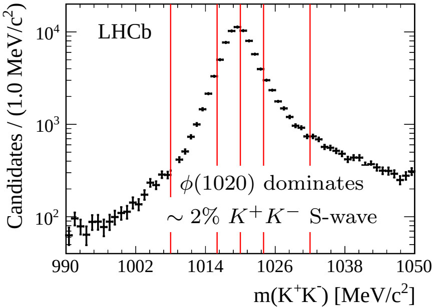


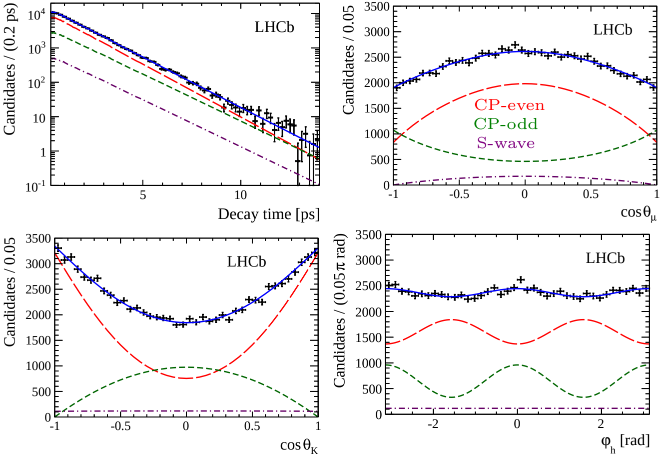




- Simultaneous fit in 6 bins of m_{KK} to account for K^+K^- S-wave
- Background subtracted fit [Xie, arXiv:0905.0724]

ϕ_s FROM $B_s^0 \to J/\psi\,\phi$

[PRL 114 (2015) 041801]



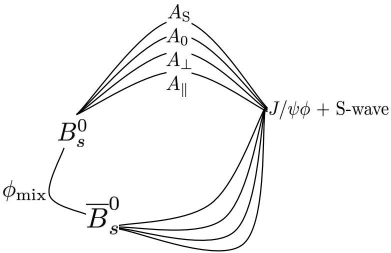
ϕ_s	$-0.058 \pm 0.049 \pm 0.006$ rad
$\lvert\lambda\rvert$	$0.964 \pm 0.019 \pm 0.007$
Γ_s	$0.6603 \pm 0.0027 \pm 0.0015$ ps^{-1}
$\Delta\Gamma_s$	$0.0805 \pm 0.0091 \pm 0.0032$ ps^{-1}
Δm_s	$17.711\ ^{+0.055}_{-0.057} \pm 0.011$ ps^{-1}

- Consistent with SM. No sign of $|\lambda_f| \neq 1$
- Most precise measurement of lifetime parameters
- Dominant systematics from decay-time efficiency, angular efficiency and background subtraction

Polarisation-dependent ϕ_s?

[PRL 114 (2015) 041801]

- Penguin pollution and/or *CP* violation could be different for each polarisation state, $i \in (0, \perp, \parallel, \mathrm{S})$
  [Bhattacharya et al., IJMP A28 (2013) 1350063] [Faller et al., PRD 79 (2009) 014005]
- Relax assumption that $\lambda^i \equiv \eta_i \frac{q}{p} \frac{\bar{A}_i}{A_i}$ is same for all $(J/\psi K^+ K^-)_i$ polarisation states.
  - Measure $\lambda^i = |\lambda^i| e^{-i\phi_s^i}$



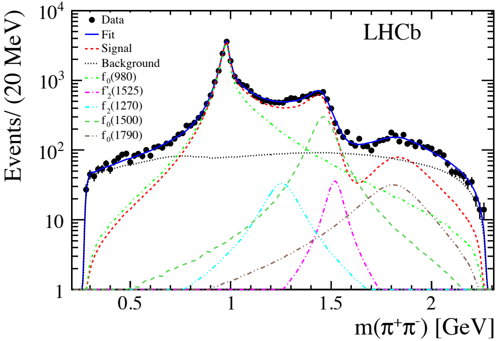
Parameter	Fitted value
$\lvert\lambda^0\rvert$	$1.012 \pm 0.058 \pm 0.013$
$\lvert\lambda^\parallel/\lambda^0\rvert$	$1.02 \pm 0.12 \pm 0.05$
$\lvert\lambda^\perp/\lambda^0\rvert$	$0.97 \pm 0.16 \pm 0.01$
$\lvert\lambda^\mathrm{S}/\lambda^0\rvert$	$0.86 \pm 0.12 \pm 0.04$
ϕ_s^0 [rad]	$-0.045 \pm 0.053 \pm 0.007$
$\phi_s^\parallel - \phi_s^0$ [rad]	$-0.018 \pm 0.043 \pm 0.009$
$\phi_s^\perp - \phi_s^0$ [rad]	$-0.014 \pm 0.035 \pm 0.006$
$\phi_s^\mathrm{S} - \phi_s^0$ [rad]	$0.015 \pm 0.061 \pm 0.021$

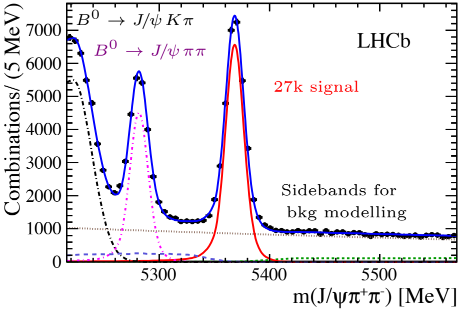
- Everything compatible with no polarisation dependence.

Resonant structure of $B_s^0 \to J/\psi\,\pi^+\pi^-$

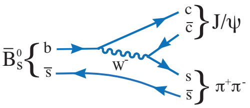
[PRD 89 (2014) 092006]

- $B_s^0 \to J/\psi\,\pi^+\pi^-$ is another $b \to c\bar{c}s$ transition.
- 4D amplitude analysis to understand structure in $\pi^+\pi^-$ spectrum.
- $\pi^+\pi^-$ is $> 97.7\%$ *CP*-odd @ 95% CL
  - Measure ϕ_s using the decay time [PLB 713 378 (2012)].

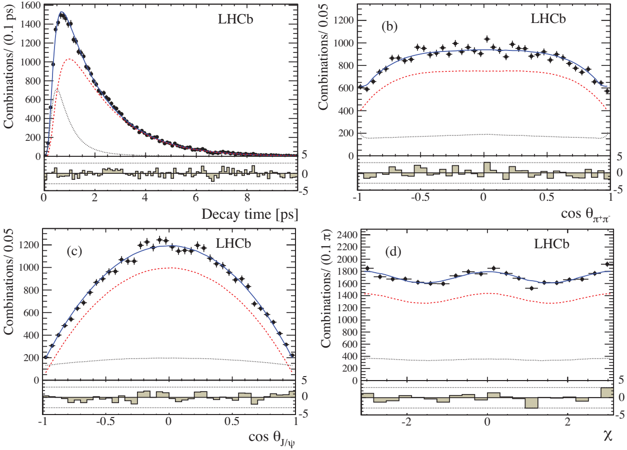




Component	Fit fraction
$f_0(980)$	$70.3 \pm 1.5^{+0.4}_{-5.1}$
$f_0(1500)$	$10.1 \pm 0.8^{+1.1}_{-0.3}$
$f_0(1790)$	$2.4 \pm 0.4^{+5.0}_{-0.2}$
$f_2(1270)_0$	$0.36 \pm 0.07 \pm 0.03$
$f_2(1270)_\parallel$	$0.52 \pm 0.15^{+0.05}_{-0.02}$
$f_2(1270)_\perp$	$0.63 \pm 0.34^{+0.16}_{-0.08}$
$f_2'(1525)_0$	$0.51 \pm 0.09^{+0.05}_{-0.04}$
$f_2'(1525)_\parallel$	$0.06^{+0.13}_{-0.04} \pm 0.01$
$f_2'(1525)_\perp$	$0.26 \pm 0.18^{+0.06}_{-0.04}$



ϕ_s FROM $B_s^0 \to J/\psi\,\pi^+\pi^-$ [PLB 736 (2014) 186]



$\phi_s^{\pi\pi}$	$0.070 \pm 0.068 \pm 0.008$ rad
$\lvert\lambda^{\pi\pi}\rvert$	$0.89 \pm 0.05 \pm 0.01$

$\phi_s^{\text{SM}} = -0.0376 \pm 0.0008$ rad

- Main systematic from knowledge of $\pi^+\pi^-$ resonance model.
- Consistent result when measuring ϕ_s using only decay time.

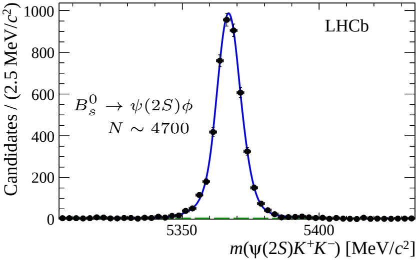
Combined K^+K^- and $\pi^+\pi^-$ [PRL 114 (2015) 041801]

ϕ_s	-0.010 ± 0.039 rad
$\lvert\lambda\rvert$	0.957 ± 0.017

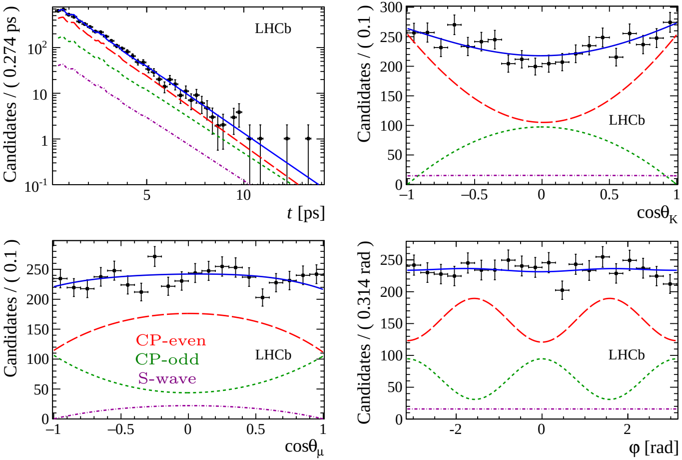
Assuming CPV in decay is same in both channels and hadronic effects can be neglected

ϕ_s FROM $B_s^0 \to \psi(2S)\phi$

[PLB 762 (2016) 253-262]

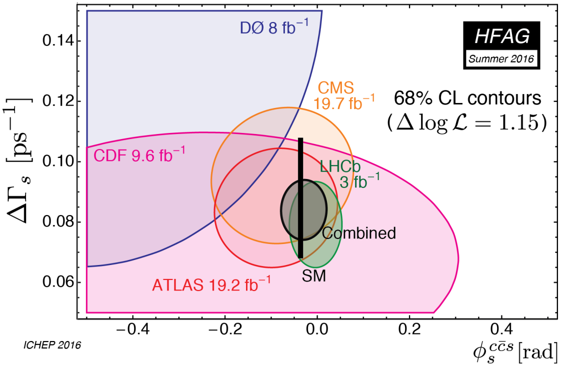


Γ_s [ps^{-1}]	$0.668 \pm 0.011 \pm 0.006$
$\Delta\Gamma_s$ [ps^{-1}]	$0.066^{+0.041}_{-0.044} \pm 0.007$
ϕ_s [rad]	$0.23^{+0.29}_{-0.28} \pm 0.02$
$\lvert\lambda\rvert$	$1.045^{+0.069}_{-0.050} \pm 0.007$



- Replace $J/\psi \to \psi(2S)$ (factor ~ 20 reduction in yield).
- Use $B^0 \to \psi(2S)K^*$ to determine decay-time efficiency.
- Resolution from sample of prompt $J/\psi\, K^+K^-$ events (~ 45 fs).
- Flavour-tagging $\varepsilon(1-2\omega)^2 = (3.88 \pm 0.18)\%$.

$\phi_s - \Delta\Gamma_s$ global combination



$\Delta\Gamma_s = 0.085 \pm 0.006\,\text{ps}^{-1}$

$\phi_s = -0.030 \pm 0.033$ rad

$\Delta\Gamma_s^{\text{SM}} = 0.088 \pm 0.020\,\text{ps}^{-1}$

assumes no NP in B_s^0 mixing

[Artuso et al. arXiv:1511.09466]

- Still room for NP at $\sim 20\%$ [see Zoltan's talk].
- As precision improves, need to control penguin pollution (see next talk).

Mode	$\phi_s^{c\bar{c}s}$ [rad]	$\Delta\Gamma_s$ [ps^{-1}]	Ref.	Exp
$B_s^0 \to J/\psi\,\phi$	$[-0.60, +0.12]$, 68%CL	$+0.068 \pm 0.026 \pm 0.009$	PRL 109 (2012) 171802	CDF (9.6 fb^{-1})
$B_s^0 \to J/\psi\,\phi$	-0.55 ± 0.37	$+0.163 \pm 0.065$	PRD 85 (2012) 032006	D0 (8.0 fb^{-1})
$B_s^0 \to J/\psi\,\phi$	$-0.090 \pm 0.078 \pm 0.041$	$+0.085 \pm 0.011 \pm 0.007$	JHEP 1608 (2016) 147	ATLAS (19.2 fb^{-1})
$B_s^0 \to J/\psi\,\phi$	$-0.075 \pm 0.097 \pm 0.031$	$+0.095 \pm 0.013 \pm 0.007$	PLB 757 (2016) 97	CMS (19.7 fb^{-1})
$B_s^0 \to J/\psi\,\phi$	$-0.058 \pm 0.049 \pm 0.006$	$+0.0805 \pm 0.0091 \pm 0.0033$	PRL 114 (2015) 041801	LHCb (3.0 fb^{-1})
$B_s^0 \to J/\psi\,\pi^+\pi^-$	$+0.070 \pm 0.068 \pm 0.008$	–	PLB 736 (2014)	LHCb (3.0 fb^{-1})
$B_s^0 \to \psi(2S)\phi$	$+0.23 \pm 0.29 \pm 0.02$	$+0.066 \pm 0.042 \pm 0.007$	PLB 762 (2016) 253-262	LHCb (3.0 fb^{-1})
$B_s^0 \to D_s^+ D_s^-$	$+0.02 \pm 0.17 \pm 0.02$	–	PRL 113 (2014) 211801	LHCb (3.0 fb^{-1})

CP violation in charmless B_s^0 decays [PRD 90 (2014) 052011]

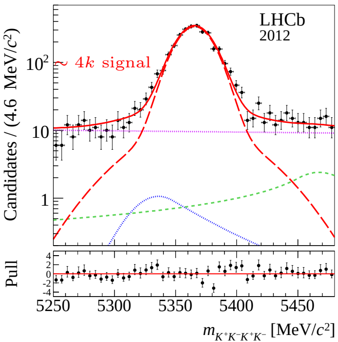
- $B_s^0 \to \phi\phi$: $b \to s$ penguin decays sensitive to NP in the loops.
- $\phi \to KK$: 5 different polarisation amplitudes $\Rightarrow$ angular analysis.
- Decay time resolution: ~ 43 fs.
- Tagging power: $\varepsilon(1-2\omega)^2 = 3.04 \pm 0.24\%$
- Angular efficiency from MC.

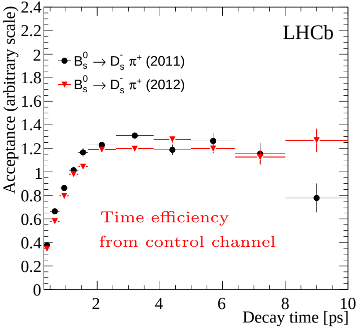
$$|\phi_s^{s\bar{s}s}|^{\mathrm{SM}} < 0.02\,\mathrm{rad}$$

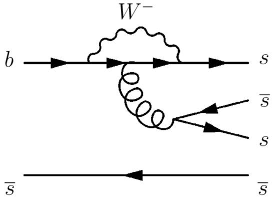
[Bartsch et al. arXiv:0810.0249]

[Beneke et al. NPB 774 (2007) 64-101]

[Cheng et al. PRD 80 (2009) 114026]







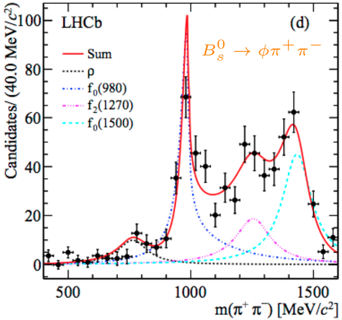
$\phi_s^{s\bar{s}s}$ [rad]	$-0.17 \pm 0.15 \pm 0.03$
$\lvert\lambda\rvert$	$1.04 \pm 0.07 \pm 0.03$

[See dedicated talk from J. Garcia Pardinas on $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$]

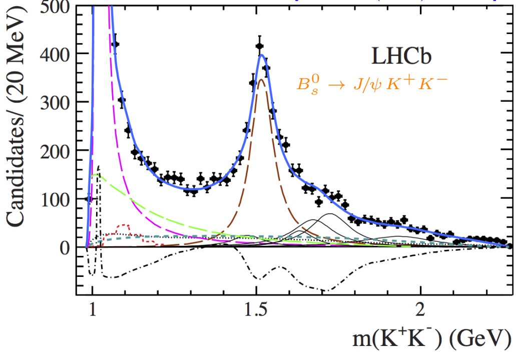
Future potential for measuring ϕ_s

$B_s^0 \to \phi\pi^+\pi^-$ AND $B_s^0 \to \phi K^+K^-$ (HIGH MASS)

[arXiv:1610.05187]



[PRD 87 (2013) 072004]



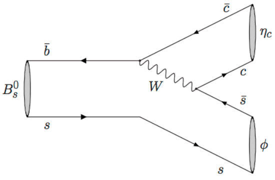
- In Run-1, observed $B_s^0 \to \phi\pi^+\pi^-$ ($N_{\text{signal}} \sim 700$).
- Gluonic penguin dominated decay, can measure $\phi_s^{s\bar{s}s}$ with tagged, time-dependent measurement.
- Need more data from Run-2.

$$\mathcal{B}(B_s^0 \to \phi f_0(980)) = (1.12 \pm 0.16^{+0.09}_{-0.08} \pm 0.11) \times 10^{-6}$$
$$\mathcal{B}(B_s^0 \to \phi\rho) = (2.7 \pm 0.7 \pm 0.2 \pm 0.2) \times 10^{-7}$$

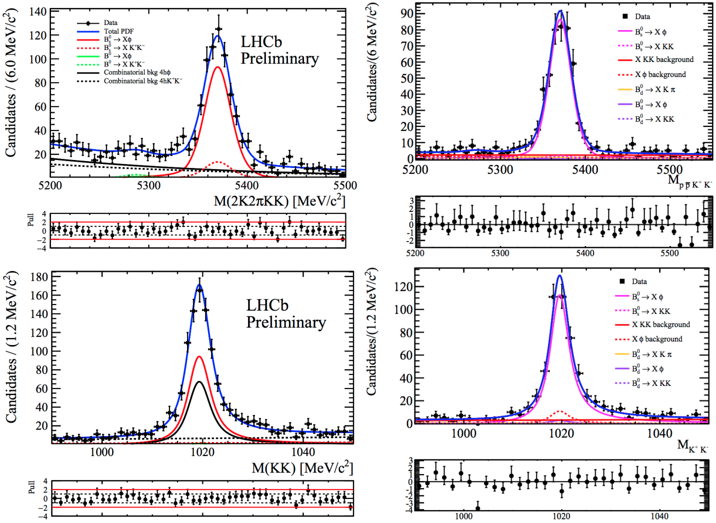
- Significant contribution from $f_2'(1525)$ above the $\phi(1020)$ region.
- Need similar analysis to $B_s^0 \to J/\psi\pi^+\pi^-$ [PLB 736 (2014) 186].
- Expect update with full Run-1 sample.

Observation of $B_s^0 \to \eta_c \phi$

[LHCb-PAPER-2016-056, preliminary]



- $b \to c\bar{c}s$ transition like $B_s^0 \to J/\psi\,\phi$.
- CP-even final state, so no angular analysis required to measure ϕ_s.
- $J/\psi\,, \eta_c \to$ $K^+K^-\pi^+\pi^-, \pi^+\pi^-\pi^+\pi^-,$ $K^+K^-K^+K^-, p\bar{p}$ final states.
- Normalise to J/ψ mode to same final state.
- Isolate signal using 2D fit to B_s^0 and ϕ masses.

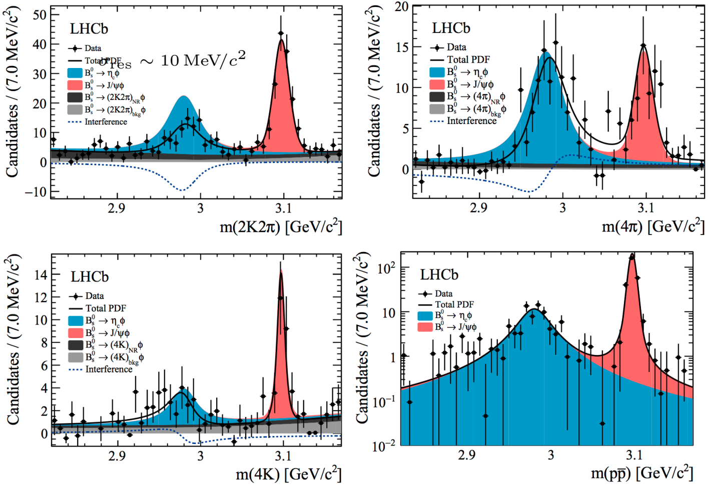


Observation of $B_s^0 \to \eta_c \phi$

[LHCb-PAPER-2016-056, preliminary]

$$|A(m_i; c_k^i, \vec{x})|^2 = \sum_J |\sum_k c_k^i R_k^J(m_i; \vec{x})|^2$$

$\sigma_{res} \sim 10$ MeV$/c^2$



- Simultaneous fit to all modes.
- Account for interference between η_c and non-resonant components.
- Also first evidence for $B_s^0 \to \eta_c \pi^+ \pi^-$.
- **Future:** measure ϕ_s with more data.

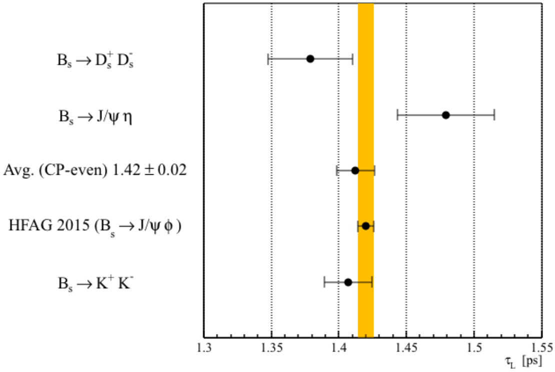
$$\mathcal{B}(B_s^0 \to \eta_c \phi) = (5.01 \pm 0.53(\text{stat}) \pm 0.27(\text{syst}) \pm 0.64(\mathcal{B})) \times 10^{-4}$$

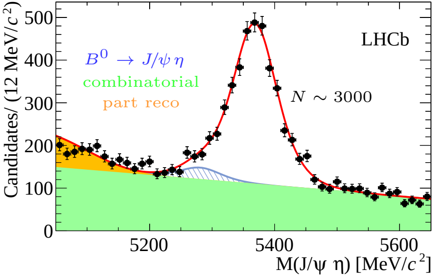
$$\mathcal{B}(B_s^0 \to \eta_c \pi^+ \pi^-) = (1.76 \pm 0.59(\text{stat}) \pm 0.12(\text{syst}) \pm 0.29(\mathcal{B})) \times 10^{-4}$$

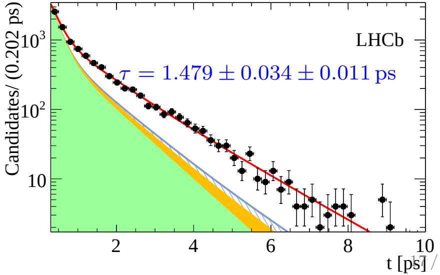
$B_s^0 \to J/\psi\,\eta(\to \gamma\gamma)$ EFFECTIVE LIFETIME

[PLB 762 (2016) 484-492]

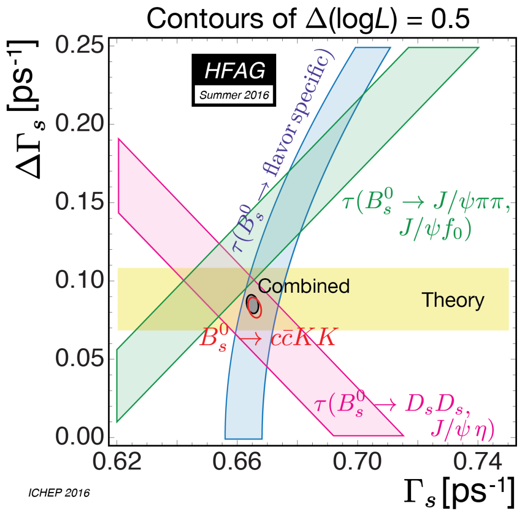
- CP-even eigenstate $\to$ no angular analysis necessary to measure ϕ_s.
- **First step:** measure Γ_L from decay time distribution.
- Mass resolution $\sim 48\,\text{MeV}/c^2 \to$ overlapping $B^0 \to J/\psi\,\eta$ component.







B_s^0 LIFETIME GLOBAL COMBINATION



$\Gamma_s = 0.6648 \pm 0.0020\,\text{ps}^{-1}$ $\Delta\Gamma_s = 0.085 \pm 0.006\,\text{ps}^{-1}$

$\Delta\Gamma_s^{\text{SM}} = 0.088 \pm 0.020\,\text{ps}^{-1}$ assumes no NP in B_s^0 mixing

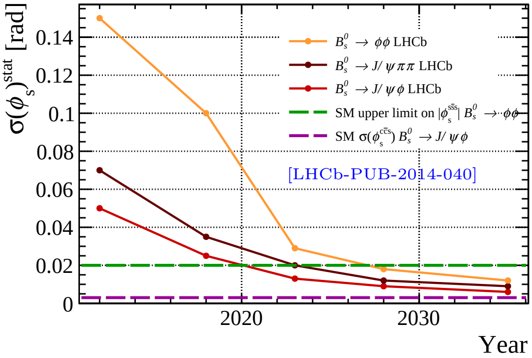
[Artuso et al. arXiv:1511.09466]

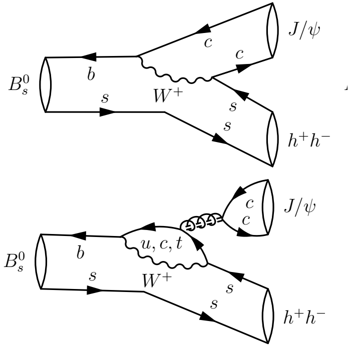
- CP-even + CP-odd: $B_s^0 \to J/\psi\,\phi$
- CP-even: $B_s^0 \to D_s^+ D_s^-$, $B_s^0 \to J/\psi\,\eta$ (Γ_L)
- CP-odd: $B_s^0 \to J/\psi\, f_0(980), B_s^0 \to J/\psi\,\pi^+\pi^-$ (Γ_H)
- Flavour-specific:
  $B_s^0 \to D_s^-\pi^+, B_s^0 \to D_s^- l^+\nu_l, B_s^0 \to D_s^- D^+$

- Absolute lifetime predictions suffer from uncertainties $\propto m_b^5$ [Lenz arXiv:1405.3601]
- Lifetime ratios under better control [Jubb et al, arXiv:1603.07770]

Summary

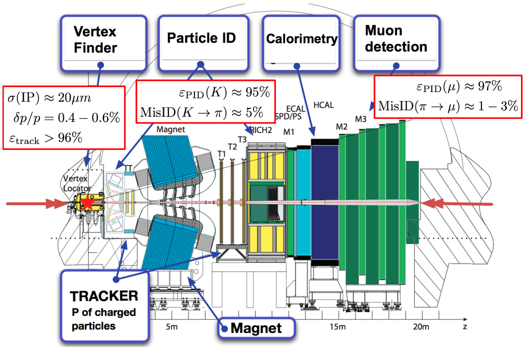
- LHCb has made leading measurements of ϕ_s and lifetimes in the B_s^0 system using Run-1 data.
- Now exploring **other modes** beyond the "golden" $B_s^0 \to J/\psi\,\phi$.
- Precision expected to reach ~ 0.01 rad at end of Run-3 (LHCb upgrade era) [see talk from V. Chobanova].
- **Next steps:** essential to control contribution from "penguin pollution" [see talk from S. Akar].

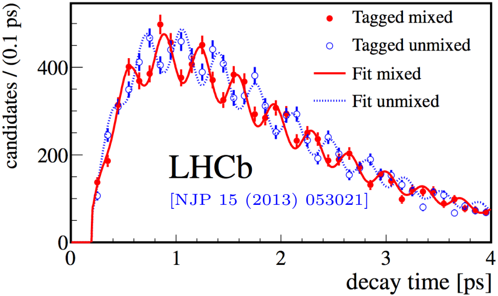




[See previous talks for information about ATLAS/CMS results]

Typical analysis ingredients





1. Decay time resolution (~ 45 fs)
2. Tagging the B meson flavour ($\varepsilon\mathcal{D}^2 \sim 4\%$)
3. Decay time efficiencies
4. Angular efficiencies (for $P \to VV$ decays)
5. Control backgrounds using B sidebands

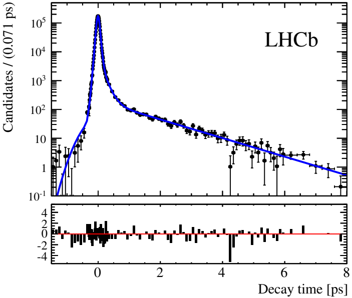
$\Delta m_s = 17.768 \pm 0.023 \pm 0.006\,\text{ps}^{-1}$
$\Rightarrow$ oscillation period of 350 fs

$$\mathcal{P}(t|\sigma_t) \propto \left[\Gamma e^{-\Gamma t'}\,\tfrac{1}{2}\left[\cosh(\Delta\Gamma t'/2) + \mathcal{D}\cos(\Delta m t')\right]\right] \otimes G(t - t'|\sigma_t)\varepsilon(t)$$

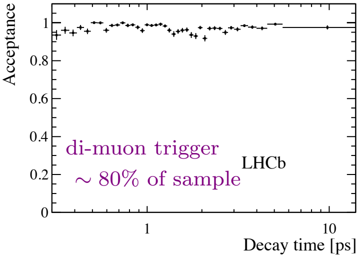
Decay time resolution and efficiency

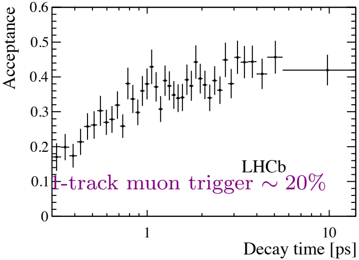
[PRL 114 (2015) 041801]

- Use prescaled sample of prompt-J/$\psi K^+ K^-$ events to determine resolution model.
- Double-Gaussian, with width scaled by per-event error.
- Simulation: $\langle\sigma^{\text{signal}}\rangle \approx \langle\sigma^{\text{prompt}}\rangle \sim 45$ ps
- If $\langle\sigma\rangle \approx 45\,\text{fs} \Rightarrow \mathcal{D} \sim 0.73$; If $\langle\sigma\rangle \approx 90\,\text{fs} \Rightarrow \mathcal{D} \sim 0.28$

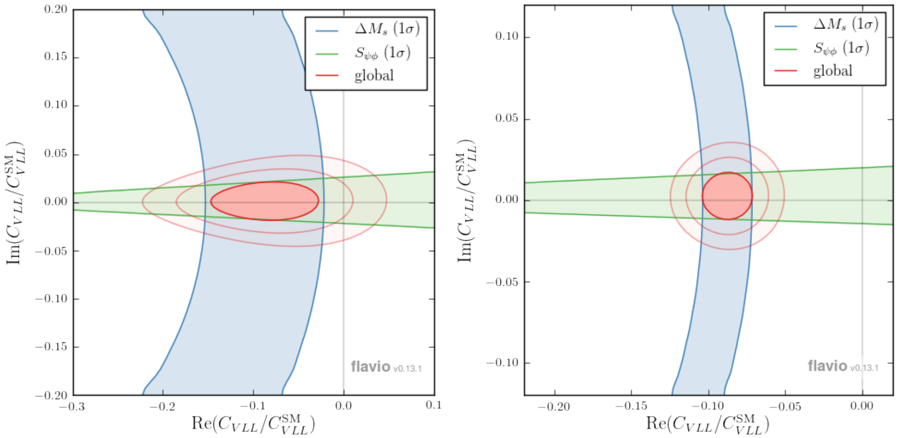


- Use $B_s^0 \to J/\psi\, K^+ K^-$ events with no lifetime cut to understand trigger efficiency.





Room for new physics?



- Still room for NP contributions at the 20% level [see Zoltan's talk yesterday].
- More data required!