Measurements of CP violation in B mixing through $B \to J/\psi X$ decays

On behalf of

Science & Technology Facilities Council

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EPS-HEP, Vienna

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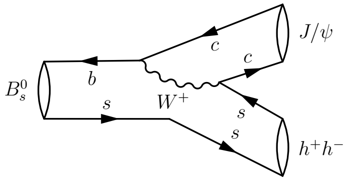
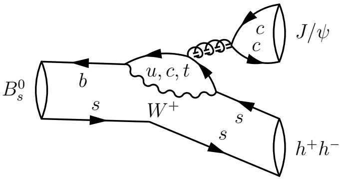
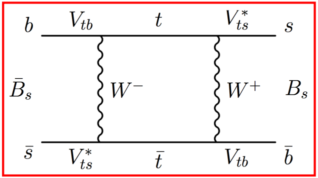
1. **Reminder of CP violation and B mixing**
2. **Measuring CP violation phases: $\sin 2\beta$ and ϕ_s**
   - $B^0 \to J/\psi\, K^0_{\mathrm{S}}$
   - $B^0_s \to J/\psi\, K^+K^- + B^0_s \to J/\psi\, \pi^+\pi^-$
3. **Controlling "penguin pollution"**
   - $B^0_s \to J/\psi\, \overline{K^{*0}}(892)$ NEW!
   - $B^0 \to J/\psi\, \pi^+\pi^-$
   - $B^0_s \to J/\psi\, K^0_{\mathrm{S}}$
   - $B^0_s \to \psi(2S) K^-\pi^+$

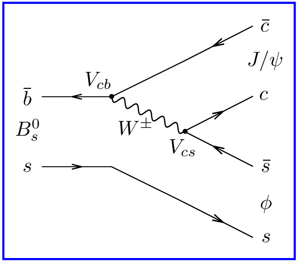




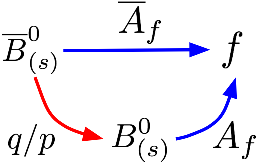
CP violation in $b \to c\bar{c}s(d)$ decays + mixing



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



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



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

- CP violation in interference between mixing and decay:

  $$\phi_s \equiv -\arg(\lambda_f) \equiv -\arg\left(\frac{q}{p}\frac{A_f}{\overline{A}_f}\right) \neq 0$$

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

$$\phi_s \overset{\text{SM}}{=} -0.0365 \pm 0.0012\,\text{rad}$$ [CKMFitter]

(†) Assuming we ignore sub-leading penguin contributions - more later

$$A_{CP}(t) \equiv \frac{\Gamma_{B^0\to f} - \Gamma_{\overline{B}^0\to f}}{\Gamma_{B^0\to f} + \Gamma_{\overline{B}^0\to f}} = \frac{S_f\sin(\Delta m\,t) - C_f\cos(\Delta m\,t)}{\cosh(\Delta\Gamma\,t/2) + A_{\Delta\Gamma}\sinh(\Delta\Gamma\,t/2)}$$

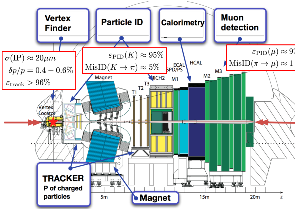
$$C_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$$

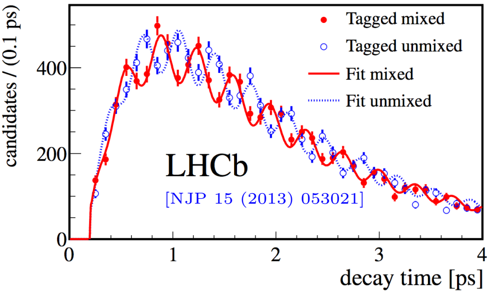
$$S_f \equiv \frac{2\sin\phi_{d,s}}{1+|\lambda_f|^2}$$

$$A_{\Delta\Gamma} \equiv -\frac{2\cos\phi_{d,s}}{1+|\lambda_f|^2}$$

Typical analysis ingredients

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

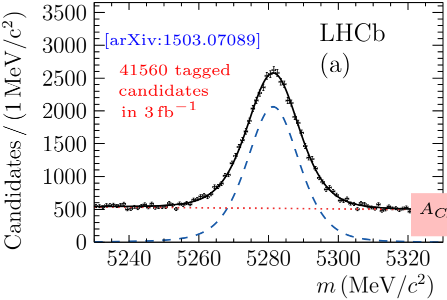


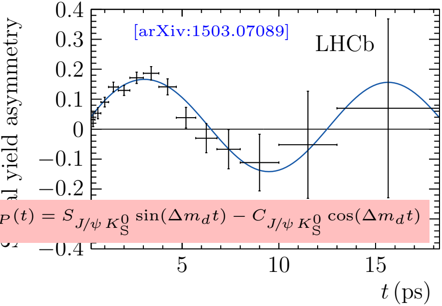


$\Delta m_s = 17.768 \pm 0.023 \pm 0.006\,\mathrm{ps}^{-1}$
$\Rightarrow$ oscillation period of 350 fs

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

CP violation in $B^0 \to J/\psi\, K^0_S$





$$A_{CP}(t) = S_{J/\psi\, K^0_S} \sin(\Delta m_d t) - C_{J/\psi\, K^0_S} \cos(\Delta m_d t)$$

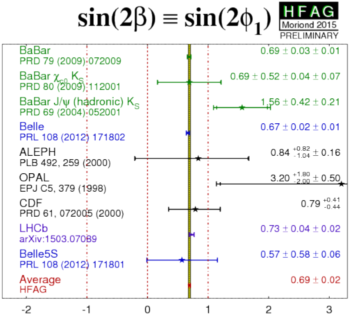
$$S_{J/\psi\, K^0_S} \approx \sin 2\beta$$

$$S_{J/\psi\, K^0_S} = +0.731 \pm 0.035 \pm 0.020$$

$$C_{J/\psi\, K^0_S} = -0.038 \pm 0.032 \pm 0.005$$

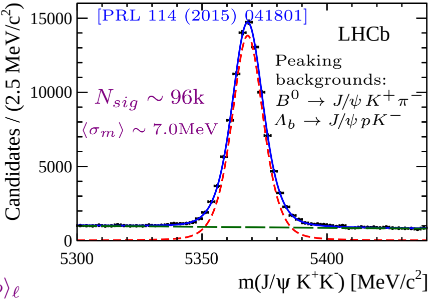
$$\rho(S, C) = 0.483$$

- $\sin 2\beta^{\mathrm{SM}} = 0.771^{+0.017}_{-0.041}$ [CKMFitter arXiv:1501.05013].
- Dominant systematic from background tagging asymmetry.
- Consistent with world average and similar precision to B-factories.

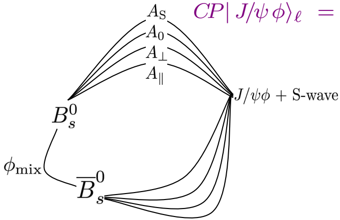


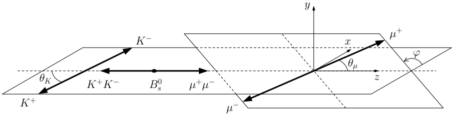
ϕ_s FROM $B_s^0 \to J/\psi\,\phi$

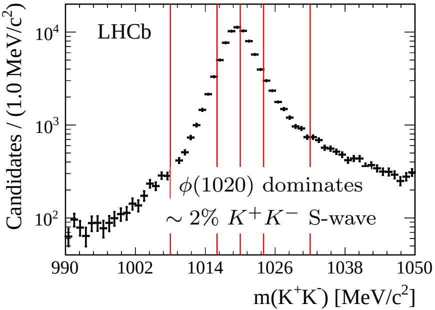
- $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$
- Time-dependent tagged analyses.
- $B_s^0 \to J/\psi\,\phi$ is $P \to VV$ decays so use angular information to disentangle CP-odd and CP-even components.
- Measure $\phi_s, \Delta m_s, \Gamma_s, \Delta\Gamma_s, |\lambda_f| \ldots$
  [this makes $B_s^0 \to J/\psi\,\phi$ special]



$$CP|\,J/\psi\,\phi\rangle_\ell \;=\; (-1)^\ell|\,J/\psi\,\phi\rangle_\ell$$







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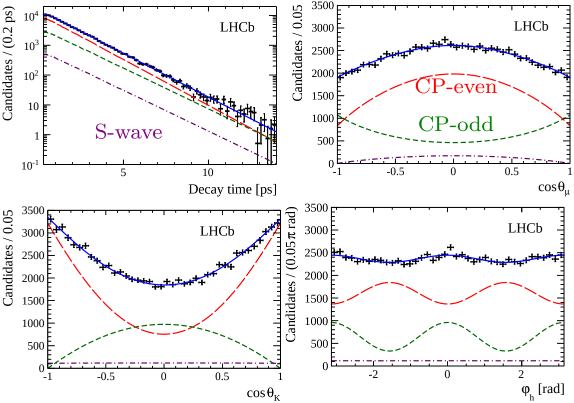
  [this makes $B_s^0 \to J/\psi\,\phi$ special]

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}

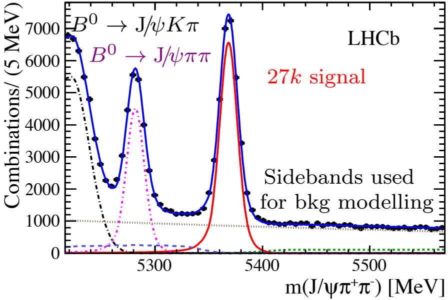


- Consistent with SM. No sign of $|\lambda_f| \neq 1$
- Most precise determine of lifetime parameters
- Dominant systematics from decay-time efficiency, angular efficiency and background subtraction.

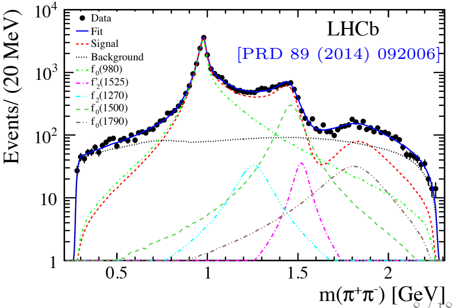
[PRL 114 (2015) 041801]

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

- 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
- $\phi_s^{\pi\pi} = 0.070 \pm 0.068 \pm 0.008\,\text{rad}$
- $|\lambda^{\pi\pi}| = 0.89 \pm 0.05 \pm 0.01$
  [PLB713 378 (2012)]



- Main systematic from knowledge of $\pi^+\pi^-$ resonance model.
- Cross-check by measuring ϕ_s using only decay time - consistent result.



COMBINED $K^+K^-, \pi^+\pi^-$ [PRL 114 (2015) 041801]

$\phi_s = -0.010 \pm 0.039$ rad
$|\lambda| = \quad 0.957 \pm 0.017$
Assuming CPV in decay is same in both channels

PENGUIN POLLUTION IN ϕ_s AND $\sin 2\beta$

Controlling penguins pollution

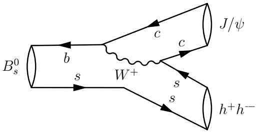
$$\phi_q^{\text{measured}} = \phi_q + \delta_{\text{Penguin}} + \delta_{\text{New Physics}}$$

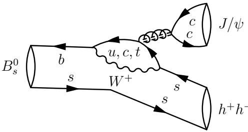
Enhancement could be caused by non-perturbative hadronic effects that are difficult to calculate in QCD.
[Nierste et al. arXiv:1503.00859], [Liu et al. PRD 89, 094010 (2014)]

1. Measure $\phi_s/\sin 2\beta$ for different polarisation states.
2. Measure δ_{Penguin} using decays where penguin/tree ratio is not suppressed.
   - Use SU(3)-flavour relations to link B_s^0 and B^0 (broken at 20-30% level).

$$A(B_s^0 \to (J/\psi\,\phi)_f) = (1-\lambda^2/2)\mathcal{A}'_f\left[1+\epsilon a'_f e^{i\theta'_f} e^{i\gamma}\right]$$

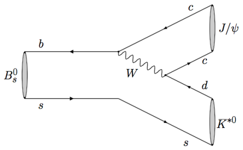
Penguin/tree suppressed by $\epsilon = \frac{|V_{us}|^2}{1-|V_{us}|^2} = 0.05$

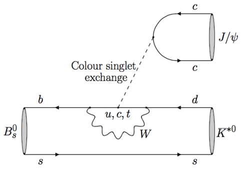




$$A(B_s^0 \to (J/\psi\,\overline{K^{*0}})_f) = -\lambda\mathcal{A}_f\left[1-a_f e^{i\theta_f} e^{i\gamma}\right]$$

Penguin/tree not suppressed (but overall rate suppressed)



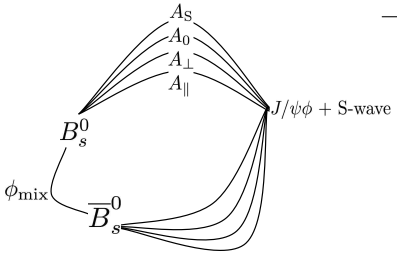


[Faller et al. PRD 79, 014005 (2009)] [De Bruyn, Fleischer, JHEP1503 (2015) 145]

Polarisation-dependent ϕ_s?

PRL 114 (2015) 041801

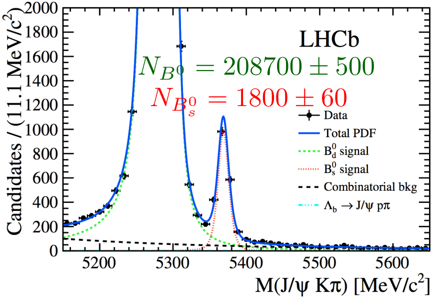
- Penguin pollution and/or *CP* violation could be different for each polarisation state, $i \in (0, \perp, \parallel, \mathrm{S})$ [Bhattacharya et al., IJMP A28 (2013) 1350063].
- Relax assumption that $\lambda^i \equiv \eta_i \frac{q}{p}\frac{\overline{A}_i}{A_i}$ is same for all $(J/\psi\, K^+K^-)_i$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



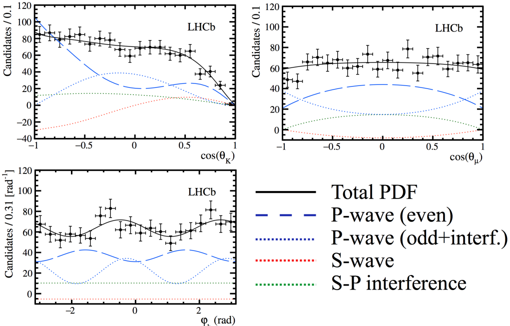
Parameter	Fitted value
$\lvert\lambda^0\rvert$	$1.012 \pm 0.058 \pm 0.013$
$\lvert\lambda^\parallel/\lambda^0\rvert$	$1.02 \pm 0.12 \pm 0.05$
$\lvert\lambda^\perp/\lambda^0\rvert$	$0.97 \pm 0.16 \pm 0.01$
$\lvert\lambda^\mathrm{S}/\lambda^0\rvert$	$0.86 \pm 0.12 \pm 0.04$
ϕ_s^0 [rad]	$-0.045 \pm 0.053 \pm 0.007$
$\phi_s^\parallel - \phi_s^0$ [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.

Angular analysis of $B_s^0 \to J/\psi \overline{K^{*0}}$ NEW!



- Angular analysis performed in 4 bins around $K^*(892)^0 \to K^+\pi^-$ mass, for B_s^0 and $\overline{B}_s^0$.
- Use simulation to get angular efficiency correction (+ correction for lack of S-wave in MC).
- Account for production and detection asymmetries [PRL 114 (2015) 041601],[PLB 739 (2014) 218], [JHEP 07 (2014) 041].



Parameter	Fitted value
f_0	$0.497 \pm 0.025 \pm 0.025$
$f_\parallel$	$0.179 \pm 0.027 \pm 0.013$
A_0^{CP}	$-0.048 \pm 0.057 \pm 0.020$
$A_\parallel^{CP}$	$0.171 \pm 0.152 \pm 0.028$
$A_\perp^{CP}$	$-0.049 \pm 0.096 \pm 0.025$

$\mathcal{B}(B_s^0 \to J/\psi \overline{K^{*0}}) =$
$(4.13 \pm 0.16 \pm 0.25 \pm 0.24(f_s/f_d)) \times 10^{-5}$

[LHCb-PAPER-2015-034]

Controlling penguins with $B_s^0 \to J/\psi \overline{K^{*0}}$ NEW!

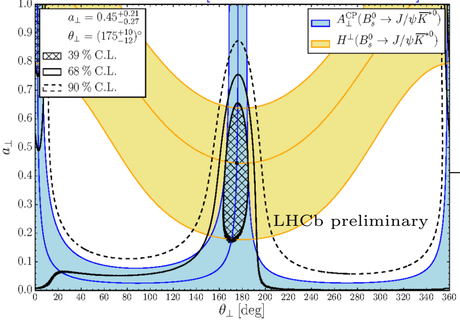
- Use results from **angular analysis** and **branching fraction** of $B_s^0 \to J/\psi \overline{K^{*0}}$ to measure $\Delta\phi_{s,i}^{J/\psi\,\phi}$ for each polarisation $i \in (0, \perp, \parallel, S)$.

$$H_i \propto \frac{1}{\epsilon}\left|\frac{\mathcal{A}_i'}{\mathcal{A}_i}\right|^2 \frac{\mathcal{B}(B_s^0 \to \mathrm{J}/\psi \overline{K^{*0}})}{\mathcal{B}(B_s^0 \to \mathrm{J}/\psi\phi)} \frac{f_i}{f_i'} = \frac{1 - 2a_i \cos\theta_i \cos\gamma + a_i^2}{1 + 2\epsilon a_i' \cos\theta_i' \cos\gamma + \epsilon^2 a_i'^2}$$

$$A_i^{CP} = -\frac{2a_i \sin\theta_i \sin\gamma}{1 - 2a_i' \cos\theta_i' \cos\gamma + a_i'^2}$$

> $SU(3)$: $a_i = a_i'$, $\theta_i = \theta_i'$
>
> $\left|\frac{\mathcal{A}_i'}{\mathcal{A}_i}\right|$ computed with LCSR [Barucha et al, arXiv:1503.05534]
>
> $\gamma = 73 \pm 7°$ [CKM]

[LHCb-PAPER-2015-034]



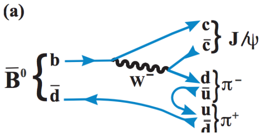
- Extract penguin parameters from χ^2 fit to H_i and A_i^{CP} information for each polarisation $i \in (0, \perp, \parallel, S)$.
- Translate to penguin phase shift:

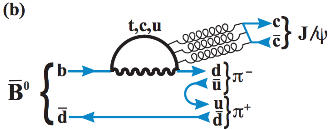
Param.	Value	± (stat)	± (syst)	$\pm(\lvert\mathcal{A}_i'/\mathcal{A}_i\rvert)$
$\Delta\phi_{s,0}^{J/\psi\,\phi}$	0.001	$^{+0.087}_{-0.011}$	$^{+0.013}_{-0.008}$	$^{+0.048}_{-0.030}$
$\Delta\phi_{s,\parallel}^{J/\psi\,\phi}$	0.031	$^{+0.049}_{-0.038}$	$^{+0.013}_{-0.013}$	$^{+0.031}_{-0.033}$
$\Delta\phi_{s,\perp}^{J/\psi\,\phi}$	-0.046	$^{+0.012}_{-0.012}$	$^{+0.007}_{-0.008}$	$^{+0.017}_{-0.024}$

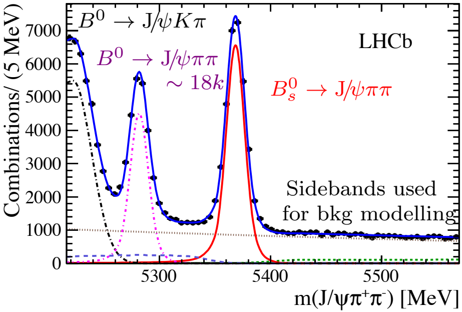
Compare to current experimental precision: $\sigma(\phi_s) = \pm 0.035\,\mathrm{rad}$, $\sigma(\phi_d) = \pm 0.028\,\mathrm{rad}$

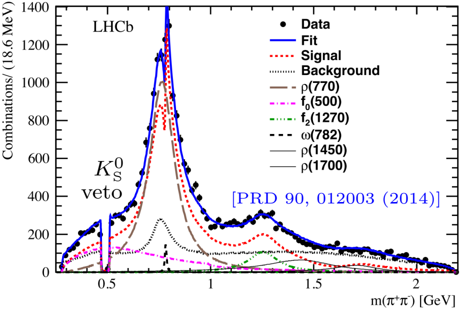
CP violation in $B^0 \to J/\psi\, \rho^0(770)$

PLB 742 (2015) 38-49









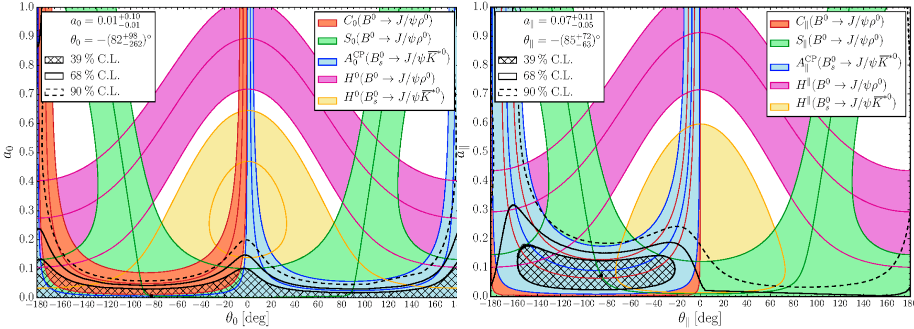
- Use $\rho^0(770)$ component to measure:

$$\phi_d^{\rm eff} = (41.7 \pm 9.6^{+2.8}_{-6.3})^\circ,\ \alpha_{CP} \equiv \frac{1-|\lambda_f|}{1+|\lambda_f|} = (-32 \pm 28^{+9}_{-7}) \times 10^{-3}$$

$$\Rightarrow \Delta\phi_d = (-0.9 \pm 9.7^{+2.8}_{-6.3})^\circ$$

(equivalent to $0.016 \pm 0.169^{+0.049}_{-0.110}$ rad)

Controlling penguins with $B_s^0 \to J/\psi\,\overline{K^{*0}}$ + $B^0 \to J/\psi\,\rho^0$ **NEW!**



[LHCb-PAPER-2015-034]

- Now fit for $|\mathcal{A}_i'/\mathcal{A}_i|$ to limit sensitivity to hadronic uncertainties.
- Assume $|\mathcal{A}_i'/\mathcal{A}_i|(B_s^0 \to J/\psi\,\overline{K^{*0}}) = |\mathcal{A}_i'/\mathcal{A}_i|(B^0 \to J/\psi\,\rho^0)$

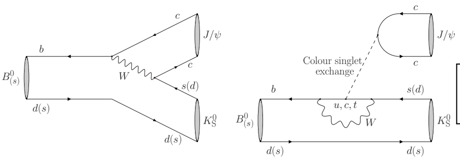
Parameter	Fitted value
$\Delta\phi_{s,0}^{J/\psi\,\phi}$	$0.000^{+0.009}_{-0.011}(\text{stat})^{+0.004}_{-0.009}(\text{syst})$
$\Delta\phi_{s,\parallel}^{J/\psi\,\phi}$	$0.001^{+0.010}_{-0.014}(\text{stat})^{+0.007}_{-0.008}(\text{syst})$
$\Delta\phi_{s,\perp}^{J/\psi\,\phi}$	$0.003^{+0.010}_{-0.014}(\text{stat})^{+0.007}_{-0.008}(\text{syst})$

- Penguin parameters effectively constrained from *CP* asymmetry measurements.
- Combined results dominated by $B^0 \to J/\psi\,\rho^0$ (access to mixing-induced asymmetry not available in flavour-specific $B_s^0 \to J/\psi\,\overline{K^{*0}}$ channel).

Penguins are small!

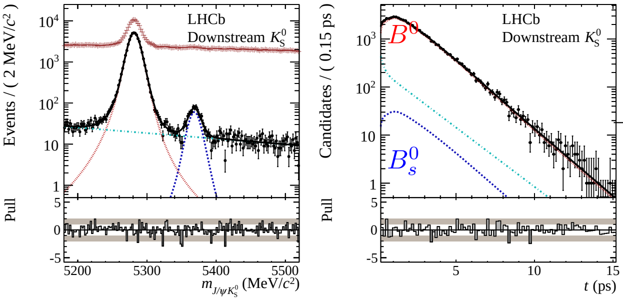
CP asymmetry in $B_s^0 \to J/\psi K_S^0$

JHEP 06 (2015) 131



$$A_{CP}(t) \equiv \frac{S_{\text{mix}} \sin(\Delta m_s\, t) - C_{\text{dir}} \cos(\Delta m_s\, t)}{\cosh(\Delta\Gamma_s\, t/2) + A_{\Delta\Gamma} \sinh(\Delta\Gamma_s\, t/2)}$$

- Use $B_s^0 \to J/\psi K_S^0$ to constrain penguin pollution in $\sin 2\beta$ from $B^0 \to J/\psi K_S^0$.
- Suppressed mode, use neural net to remove $B^0 \to J/\psi\, K^{*0}$ + combinatorial.
  - Trained on data using $B^0 \to J/\psi\, K_S^0$ as proxy.

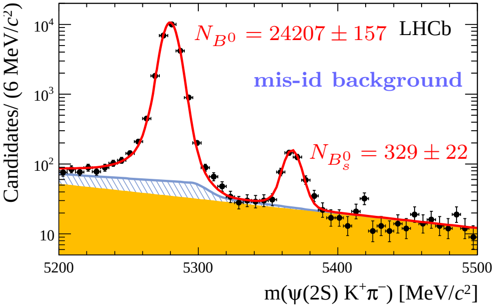


Param	Fitted value
$A_{\Delta\Gamma}$	$0.49^{+0.77}_{-0.65} \pm 0.06$
C_{dir}	$-0.28 \pm 0.41 \pm 0.08$
S_{mix}	$-0.08 \pm 0.40 \pm 0.08$

- Really just proof-of-principle, not able to constrain penguins yet...

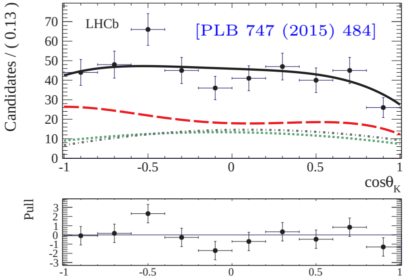
Observation of $\overline{B}^0_s \to \psi(2S)K^+\pi^-$

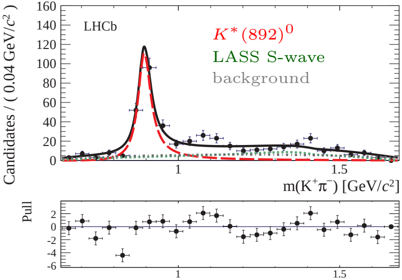
- Use 4D amplitude fit to understand resonant structure.
- Build model from coherent sum of $K^+\pi^-$ resonances and NR components.
- **No sign** of exotic $Z^+ \to \psi(2S)\pi^+$ with current data sample.
- Future: understand penguin pollution in $B^0_s \to \psi(2S)\phi$.



$K^*(892)^0$ parameters:

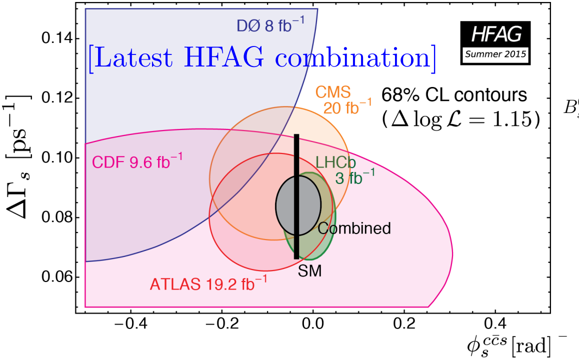
fit fraction	$= 0.605 \pm 0.046 \pm 0.041$
f_0	$= 0.532 \pm 0.057 \pm 0.035$

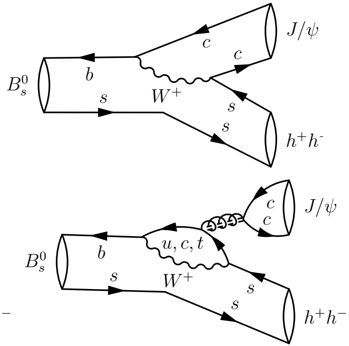




Summary

- Run-1 analysis of $B_s^0 \to J/\psi K^+K^-$ and $B^0 \to J/\psi K_S^0$ for precision measurement of CP violating phases ϕ_s and $\sin 2\beta$.
- **Contribution from "penguin pollution" shown to be small!** Important as precision of CP violation measurements continues to improve (LHCb upgrade).



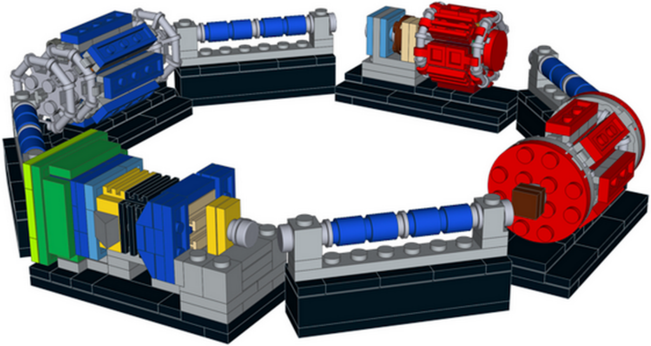


[See next talks for information about ATLAS/CMS results]

Backup

The LHCb detector

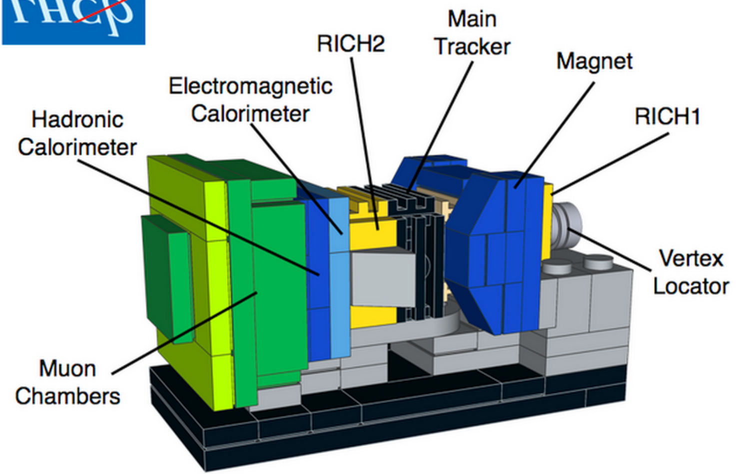
2008 JINST 3 S08005



https://ideas.lego.com/projects/94885

The LHCb detector

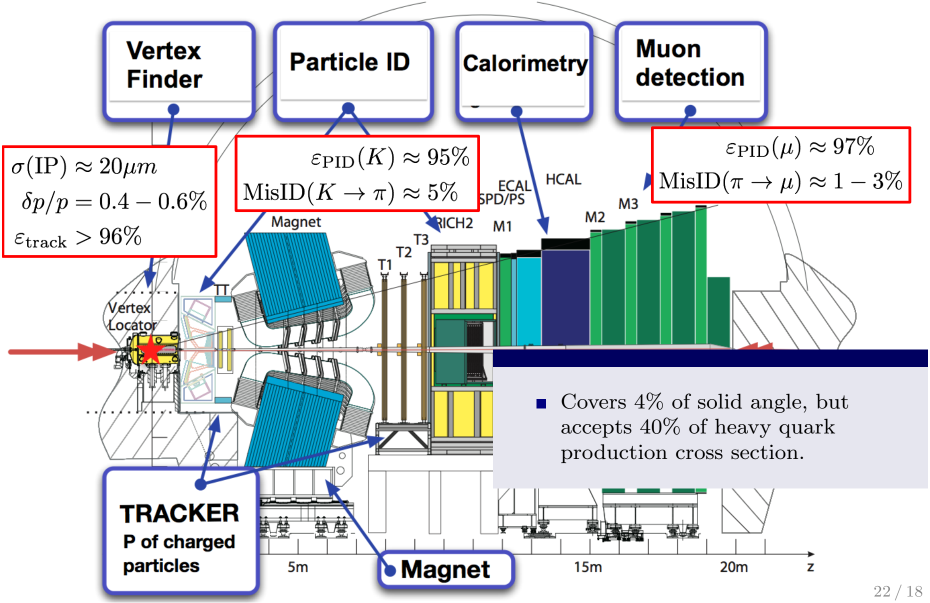
2008 JINST 3 S08005



https://ideas.lego.com/projects/94885

THE LHCB DETECTOR

2008 JINST 3 S08005



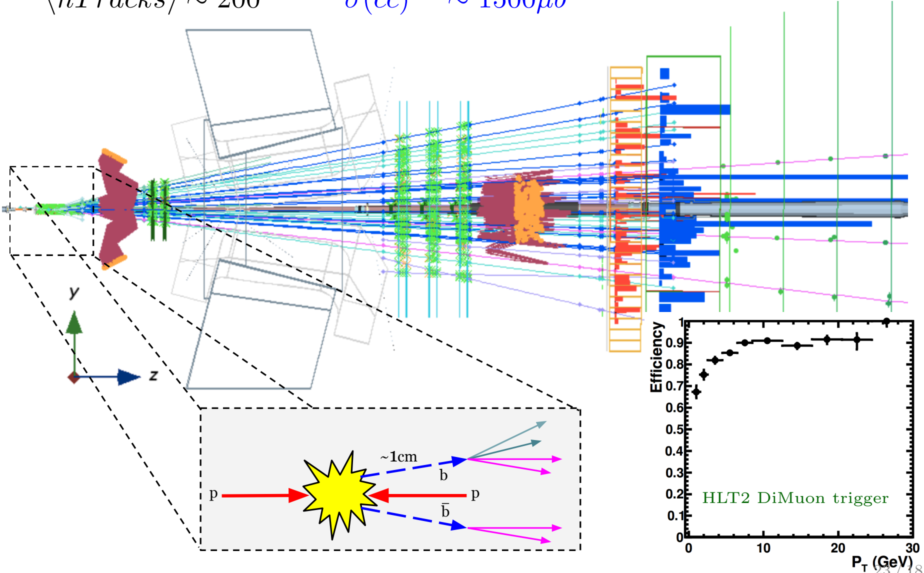
- Covers 4% of solid angle, but accepts 40% of heavy quark production cross section.

A typical LHCb event

2008 JINST 3 S08005

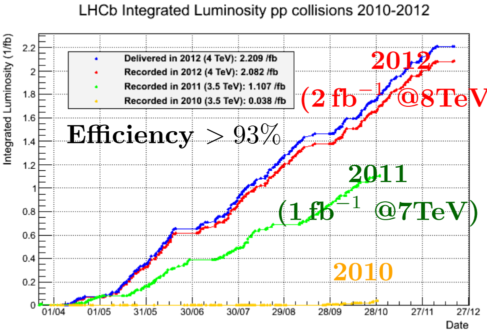
$\langle nPVs \rangle \sim 2.0$
$\langle nTracks \rangle \sim 200$

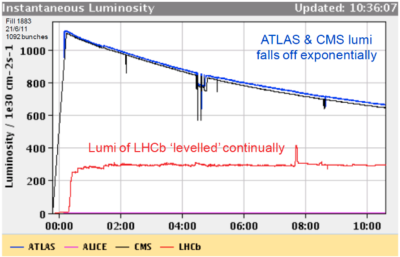
$\sigma(p\bar{p} \to b\bar{b}X) \sim 80\mu b$
$\sigma(c\bar{c}) \sim 1500\mu b$



Run-1 data sample

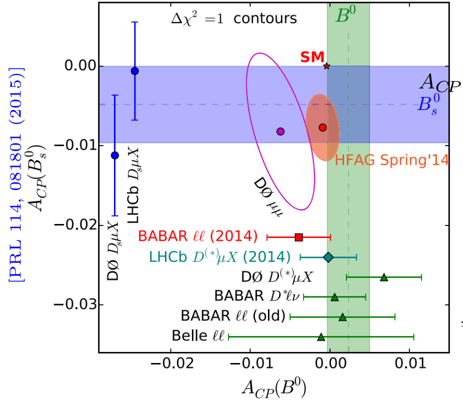
- $\sim$900 physicists from 64 universities/laboratories in 16 countries.
- Running since 2010, Link to $>$ 240 papers.
- $\mathcal{O}(100k)$ $b\bar{b}$ pairs produced/sec.





- 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.
- $\langle\mathcal{L}\rangle_{2011} \sim 2.7 \times 10^{32} cm^{-2} s^{-1}$
- $\langle\mathcal{L}\rangle_{2012} \sim 4.0 \times 10^{32} cm^{-2} s^{-1}$

CP violation in $B^0_{(s)}$ mixing $(|B^0_{\mathrm{L,H}}\rangle = p|B^0\rangle \pm q|\overline{B}^0\rangle)$



$$A_{CP} = a_{\rm sl} = \frac{\Gamma(\overline{B}\to B\to f) - \Gamma(B\to\overline{B}\to\overline{f})}{\Gamma(\overline{B}\to B\to f) + \Gamma(B\to\overline{B}\to\overline{f})} = \frac{1-|q/p|^4}{1+|q/p|^4}$$

[Lenz arXiv:1205.1444] - tiny in SM

$a^d_{\rm sl} = (-4.1 \pm 0.6) \times 10^{-4}$

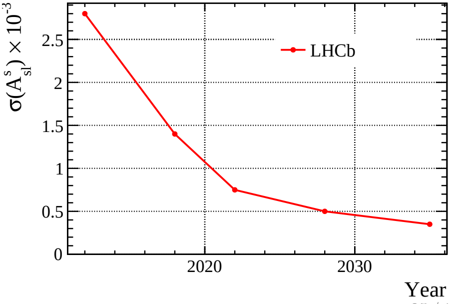
$a^s_{\rm sl} = (+1.9 \pm 0.3) \times 10^{-5}$

$a^s_{\rm sl} = [-0.06 \pm 0.50 \pm 0.36]\%$ (LHCb, $1\,{\rm fb}^{-1}$)

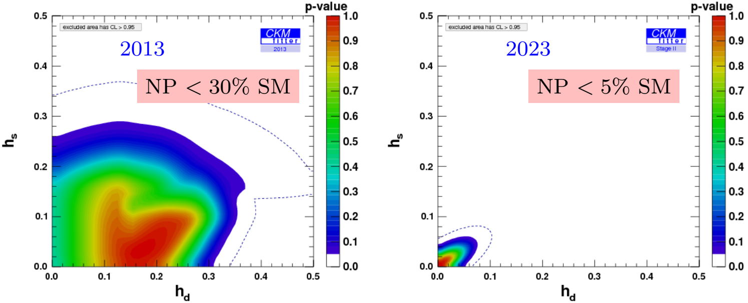
$a^d_{\rm sl} = [-0.02 \pm 0.19 \pm 0.30]\%$ (LHCb, $3\,{\rm fb}^{-1}$)

[PLB 728 (2014) 607, PRL 114 (2014) 041601]

- **$\sim 3\sigma$ tension with SM from D0 not confirmed or excluded by LHCb.**



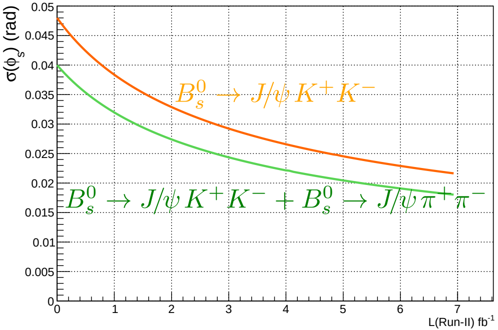
- Assume that NP only enters B^0 and B_s^0 mixing: $M_{12}^{d,s} = (M_{12}^{d,s})_{\rm SM}(1 + h_{d,s} e^{2i\sigma_{d,s}})$.



$$h \approx \frac{|C_{ij}|^2}{|V_{ti}^* V_{tj}|^2} \left(\frac{4.5\,\text{TeV}}{\Lambda}\right)^2$$

Couplings	NP loop order	Scales (in TeV) probed by B_d mixing	Scales (in TeV) probed by B_s mixing
$\lvert C_{ij}\rvert = \lvert V_{ti}V_{tj}^*\rvert$ (CKM-like)	tree level	17	19
	one loop	1.4	1.5
$\lvert C_{ij}\rvert = 1$ (no hierarchy)	tree level	2×10^3	5×10^2
	one loop	2×10^2	40

ϕ_s PROSPECTS

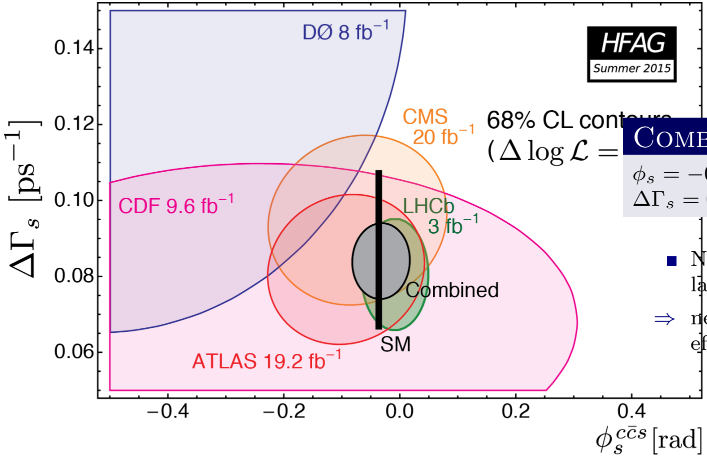


- In future, use other channels:
  - $B_s^0 \to \psi(2S)\phi$
  - $B_s^0 \to J/\psi\,\eta$
  - $B_s^0 \to J/\psi\,(ee)\phi$
  - $B_s^0 \to J/\psi\, K^+K^-$ (high K^+K^- mass)
- Control of penguins essential!
  - $B_s^0 \to J/\psi\, K_S^0$, $B_s^0 \to J/\psi\, K^*$, $B^0 \to J/\psi\, \rho^0$
    [NPB 873 (2013) 275-292, PRD 86 (2012) 071102]

ϕ_s error (rad)	Run 1 (2010–12) 3 fb^{-1}	Run 2 (2015–18) 8 fb^{-1}	Upgrade (2019–??) 50 fb^{-1}	Theory
$B_s^0 \to J/\psi\, K^+K^-$	0.049	0.025	0.009	~ 0.003
$B_s^0 \to J/\psi\, \pi^+\pi^-$	0.068	0.035	0.012	~ 0.01
$B_s^0 \to \phi\phi$	0.15	0.10	0.018	< 0.02

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

$\Delta\Gamma_s - \phi_s$ GLOBAL COMBINATION



Combination

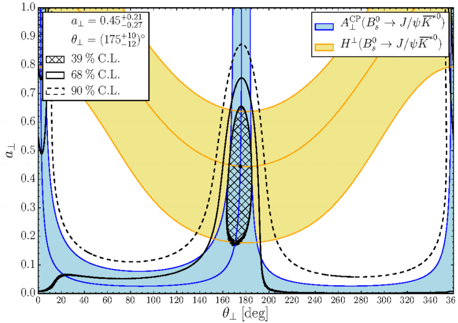
$\phi_s = -0.015 \pm 0.035$rad
$\Delta\Gamma_s = 0.081 \pm 0.006\,\text{ps}^{-1}$

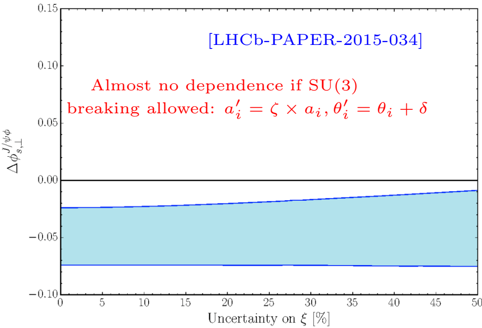
- New physics not a large effect

$\Rightarrow$ need to control SM effects (penguins).

Mode	$\sigma(\phi_s)$[rad]	Ref.	Exp
$B_s^0 \to J/\psi\,\phi$	$-0.058 \pm 0.049 \pm 0.006$	PRL 114 (2015) 041801	LHCb (3 fb^{-1})
$B_s^0 \to J/\psi\,\phi$	$-0.030 \pm 0.110 \pm 0.030$	CMS-PAC-BPH-13-012	CMS (20 fb^{-1})
$B_s^0 \to J/\psi\,\phi$	$+0.120 \pm 0.250 \pm 0.050$	PRD 90 (2014) 052007	ATLAS (4.9 fb^{-1})
$B_s^0 \to J/\psi\,\pi^+\pi^-$	$+0.070 \pm 0.068 \pm 0.008$	PLB 736 (2014)	LHCb (3 fb^{-1})
$B_s^0 \to D_s^+ D_s^-$	$+0.020 \pm 0.170 \pm 0.020$	PRL 113, (2014) 211801	LHCb (3 fb^{-1})

Controlling penguins with $B_s^0 \to J/\psi \overline{K}^{*0}$ NEW!





- Nominal result assumes perfect SU(3) symmetry $a_i = a_i'$, $\theta_i = \theta_i'$.
- Extract penguin parameters from χ^2 fit to H_i and A_i^{CP} information for each polarisation $i \in (0, \perp, \parallel, \mathrm{S})$.
- Translate to penguin phase shift:

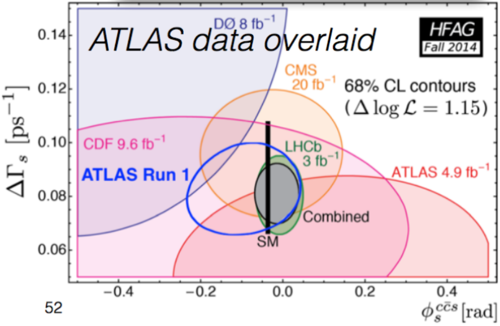
Param.	Fitted value
$\Delta\phi_{s,0}^{J/\psi\,\phi}$	$0.001^{+0.087}_{-0.011}(\text{stat})^{+0.013}_{-0.008}(\text{syst})^{+0.048}_{-0.030}(\lvert\mathcal{A}_i'/\mathcal{A}_i\rvert)$
$\Delta\phi_{s,\parallel}^{J/\psi\,\phi}$	$0.031^{+0.049}_{-0.038}(\text{stat})^{+0.013}_{-0.013}(\text{syst})^{+0.031}_{-0.033}(\lvert\mathcal{A}_i'/\mathcal{A}_i\rvert)$
$\Delta\phi_{s,\perp}^{J/\psi\,\phi}$	$-0.046^{+0.012}_{-0.012}(\text{stat})^{+0.007}_{-0.008}(\text{syst})^{+0.017}_{-0.024}(\lvert\mathcal{A}_i'/\mathcal{A}_i\rvert)$

Compare to current expt. precision:
$\sigma(\phi_s) = \pm 0.035\,\text{rad}$
$\sigma(\phi_d) = \pm 0.028\,\text{rad}$

New ATLAS $B_s^0 \to J/\psi\phi$ result (as of 7th July 2015)

- Preliminary measurement of the time-dependent flavour-tagged CP asymmetry parameters in decays of $B_s \to J/\psi\phi$
- 14.3 fb^{-1} from 8 TeV
  - statistically combined with previous result, 7 TeV 4.9 fb^{-1} Phys.Rev. D90 (2014) 052007
- CP-violating phase, ϕ_s, consistent with other experiments and SM predictions
- $\varphi_s^{(SM)} = -0.0363^{+16}_{-15}$ rad.
- $\Delta\Gamma_s^{(SM)} = 0.087 \pm 0.021$ ps^{-1}

Parameter	Value	Stat.	Syst.	
Φ_s	-0.094	0.083	0.033	rad
$\Delta\Gamma_s$	0.082	0.011	0.007	ps^{-1}
Γ_s	0.677	0.003	0.003	ps^{-1}
$\lvert A_{\parallel}(0)\rvert^2$	0.227	0.004	0.006	
$\lvert A_0(0)\rvert^2$	0.515	0.004	0.002	
$\lvert A_S(0)\rvert^2$	0.086	0.007	0.012	
$\delta_\perp$	4.13	0.34	0.15	rad
$\delta_\parallel$	3.16	0.13	0.05	rad
$\delta_\perp - \delta_S$	-0.08	0.03	0.01	rad

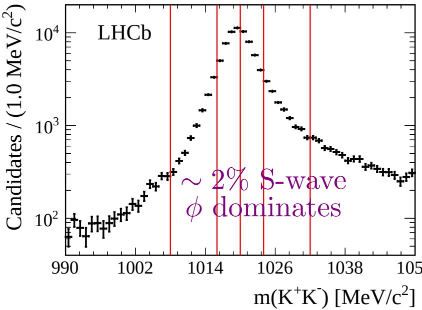


Maximum likelihood fit

PRL 114 (2015) 041801

- Simultaneous fit in 6 bins of m_{KK} to account for K^+K^- S-wave.
- Background subtracted fit (sFit, sPlot [Xie, arXiv:0905.0724]).
- Measure $\phi_s, \Delta m_s, \Gamma_s, \Delta\Gamma_s, |\lambda_f| \ldots$

  [this makes $B_s^0 \to J/\psi\,\phi$ special]
- $C \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$, $S \equiv \frac{2\mathcal{I}m(\lambda_f)}{1+|\lambda_f|^2}$, $D \equiv -\frac{2\mathcal{R}e(\lambda_f)}{1+|\lambda_f|^2}$



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

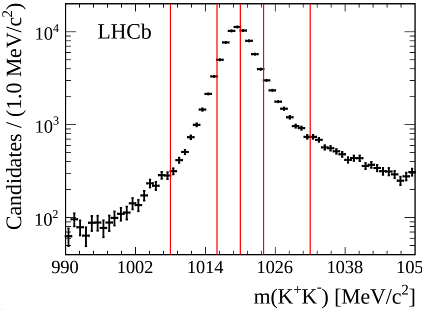
k	$f_k(\theta_\mu, \theta_K, \varphi_h)$	N_k	a_k	b_k	c_k	d_k
1	$2\cos^2\theta_K \sin^2\theta_\mu$	$\lvert A_0\rvert^2$	1	D	C	$-S$
2	$\sin^2\theta_K\left(1-\sin^2\theta_\mu\cos^2\varphi_h\right)$	$\lvert A_\parallel\rvert^2$	1	D	C	$-S$
3	$\sin^2\theta_K\left(1-\sin^2\theta_\mu\sin^2\varphi_h\right)$	$\lvert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

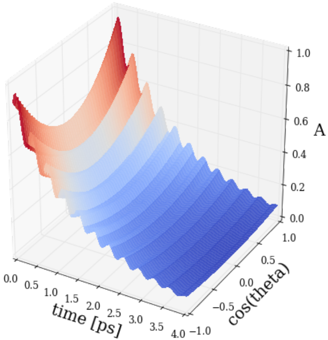
Maximum likelihood fit

PRL 114 (2015) 041801

- Simultaneous fit in 6 bins of m_{KK} to account for K^+K^- S-wave.
- Background subtracted fit (sFit, sPlot [Xie, arXiv:0905.0724]).
- Measure $\phi_s, \Delta m_s, \Gamma_s, \Delta\Gamma_s, |\lambda_f| \ldots$

  [this makes $B_s^0 \to J/\psi\,\phi$ special]
- $C \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$, $S \equiv \frac{2\mathcal{I}m(\lambda_f)}{1+|\lambda_f|^2}$, $D \equiv -\frac{2\mathcal{R}e(\lambda_f)}{1+|\lambda_f|^2}$

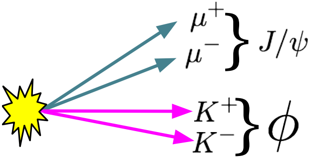


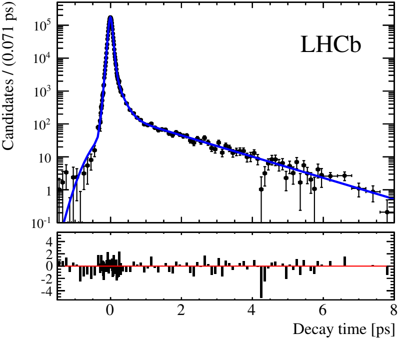


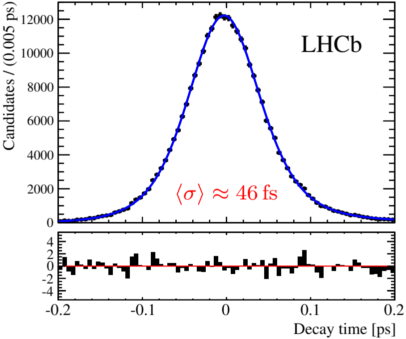
Decay time resolution

PRL 114 (2015) 041801

- Use prescaled sample of prompt-J/ψ events to determine resolution model.
- Double-Gaussian, with width scaled by per-event error.
- Simulation: $\langle \sigma^{\text{signal}} \rangle \approx \langle \sigma^{\text{prompt}} \rangle$



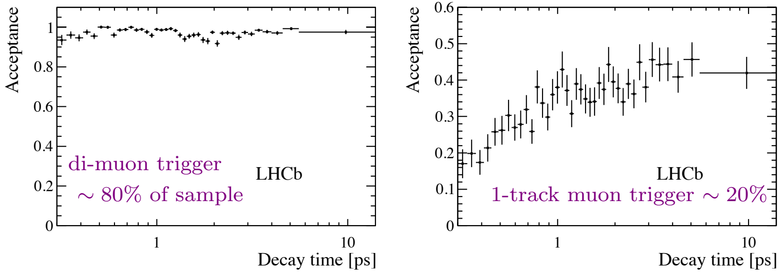




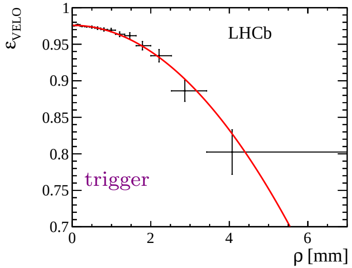
- If $\langle \sigma \rangle \approx 45$ fs $\Rightarrow \mathcal{D} \sim 0.73$; If $\langle \sigma \rangle \approx 90$ fs $\Rightarrow \mathcal{D} \sim 0.28$

PRL 114 (2015) 041801 & JHEP 04 (2014) 114

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

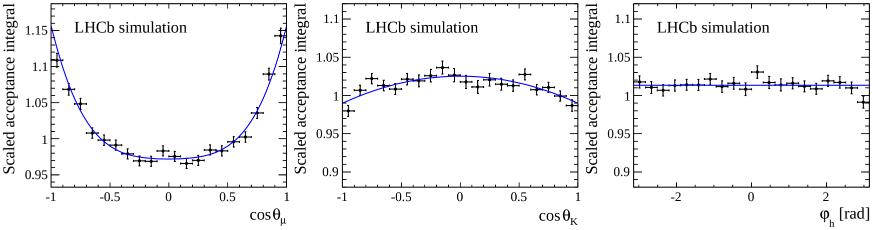


- VELO track reconstruction efficiency depends on distance of track from beam line (ρ).
- Understand this using control sample of $B^+ \to J/\psi\, K^+$.
- Correct in final fit by **weighting** each B^0_s candidate.



Angular efficiency

arXiv:1304.2600



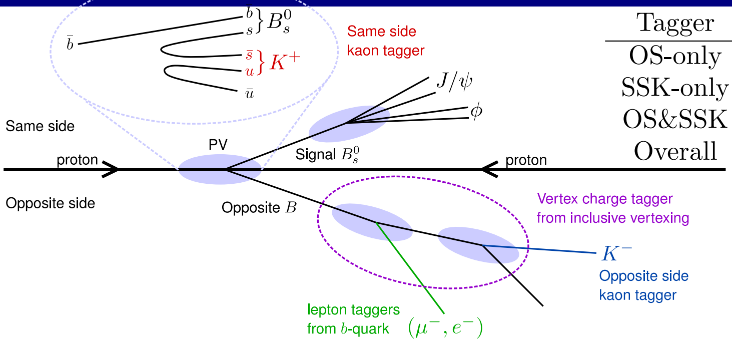
- Detector geometry and implicit momentum cuts introduce efficiency in angles.
- Knowledge of acceptance is dominant source of systematic error for ϕ_s and amplitudes.
- Describe non-factorised 3D efficiency using spherical harmonics [from simulation corrected to look like data].

$$\epsilon(\cos\theta_K, \cos\theta_\mu, \varphi_h) = \sum_{a,b,c} c^{abc} P_a(\cos\theta_K) Y_{bc}(\cos\theta_\mu, \varphi_h).$$

$$c^{abc} = \frac{1}{N_{\mathrm{MC}}} \sum_{i}^{N_{\mathrm{MC}}} \frac{2a+1}{2} P_a(\cos\theta_{K\,i}) Y_{bc}(\cos\theta_{\mu\,i}, \varphi_{h\,i}) \frac{1}{g_i},$$

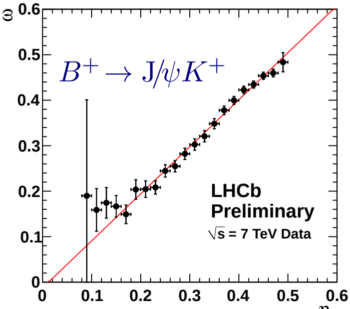
Flavour tagging

PRL 114 (2015) 041801



Tagger	$\varepsilon(1-2\omega)^2$
OS-only	$1.19 \pm 0.06\%$
SSK-only	$0.84 \pm 0.11\%$
OS&SSK	$1.70 \pm 0.08\%$
Overall	$3.73 \pm 0.15\%$

- Tagging decision made on statistical basis, with $\varepsilon \approx 60\%$; $\omega \approx 30\%$.
- Effective size of dataset: $N_{\text{eff}} = N_{\text{all}} \times \varepsilon(1-2\omega)^2$
- Calibrate tagging response using control samples: $B^+ \to J/\psi K^+$, $B^0 \to D_s \mu\nu$, $B_s^0 \to D_s \pi$.
- $\omega = p_0 + p_1(\eta - \langle\eta\rangle)$.



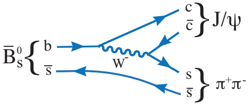
$\sin 2\beta$ SYSTEMATICS **NEW!!**

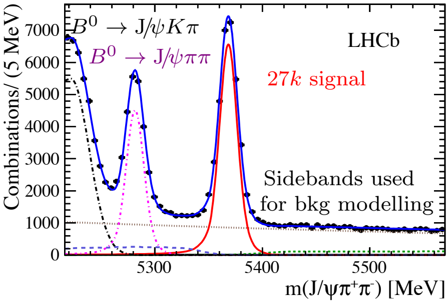
LHCb-PAPER-2015-004

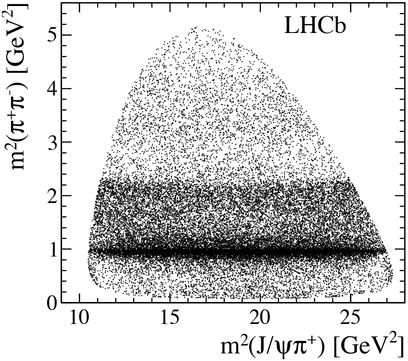
Origin	S	C
Background Tagging Asymmetry	0.0179 (2.5 %)	0.0015 (4.5 %)
Tagging calibration	0.0062 (0.9 %)	0.0024 (7.2 %)
$\Delta\Gamma_d$	0.0047 (0.6 %)	—
Δm_d	—	0.0034 (10.3 %)
Fraction of wrong PV component	0.0021 (0.3 %)	0.0011 (3.3 %)
z-scale	0.0012 (0.2 %)	0.0023 (7.0 %)
Upper decay time acceptance	—	0.0012 (3.6 %)
Low decay time acceptance	—	—
Decay time resolution calibration	—	—
Decay time resolution offset	—	—
Correlation between mass and decay time	—	—
Production asymmetry	—	—
Sum	0.020 (2.7 %)	0.005 (15.2 %)

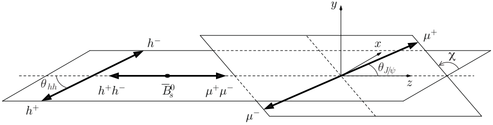
Resonant structure of $B_s^0 \to J/\psi\pi^+\pi^-$ PRD 89 (2014) 092006

- $B_s^0 \to J/\psi\pi^+\pi^-$ 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% Conf. Level
  - Measure ϕ_s using the decay time [PLB713 378 (2012)].









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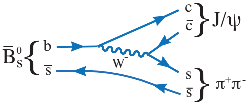
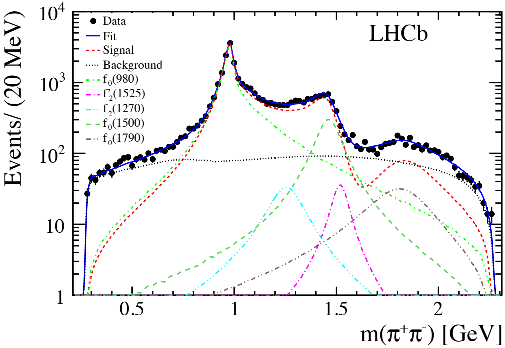


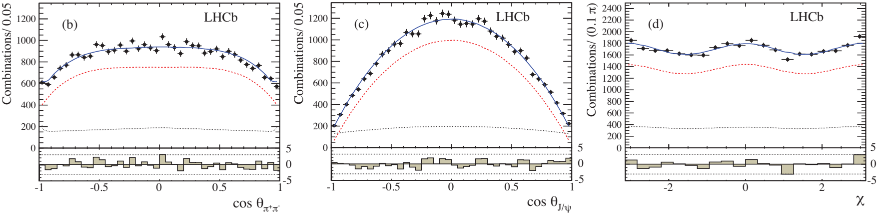


Component	Solution I
$f_0(980)$	$70.3 \pm 1.5^{+0.4}_{-5.1}$
$f_0(1500)$	$10.1 \pm 0.8^{+1.1}_{-0.3}$
$f_0(1790)$	$2.4 \pm 0.4^{+5.0}_{-0.2}$
$f_2(1270)_0$	$0.36 \pm 0.07 \pm 0.03$
$f_2(1270)_\parallel$	$0.52 \pm 0.15^{+0.05}_{-0.02}$
$f_2(1270)_\perp$	$0.63 \pm 0.34^{+0.16}_{-0.08}$
$f_2'(1525)_0$	$0.51 \pm 0.09^{+0.05}_{-0.04}$
$f_2'(1525)_\parallel$	$0.06^{+0.13}_{-0.04} \pm 0.01$
$f_2'(1525)_\perp$	$0.26 \pm 0.18^{+0.06}_{-0.04}$
NR	-
Sum	85.2

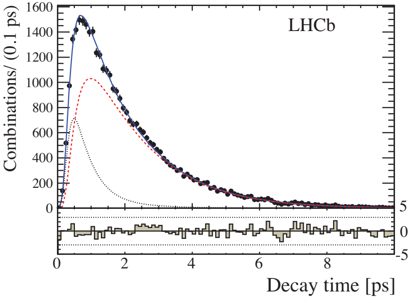
- Sum over $\pi^+\pi^-$ resonances: $\mathcal{A}(m_{\pi\pi},\Omega) = \sum_R \sum_{\lambda=0,\parallel,\perp} A_\lambda^R(m_{\pi\pi},\Omega)$
- $A_\lambda^R(m_{\pi\pi},\Omega)$ is Breit-Wigner or Flatte ($f_0(980)$) amplitude $\times$ barrier factors.

ϕ_s FROM $B_s^0 \to J/\psi\pi^+\pi^-$

PLB 736 (2014) 186



- Main systematic from knowledge of $\pi^+\pi^-$ resonance model.
- Cross-check by measuring ϕ_s using only decay time - consistent result.
- $\phi_s^{\pi\pi} = 0.070 \pm 0.068 \pm 0.008\,\text{rad}$
- $|\lambda^{\pi\pi}| = 0.89 \pm 0.05 \pm 0.01$



Combined $K^+K^- + \pi^+\pi^-$

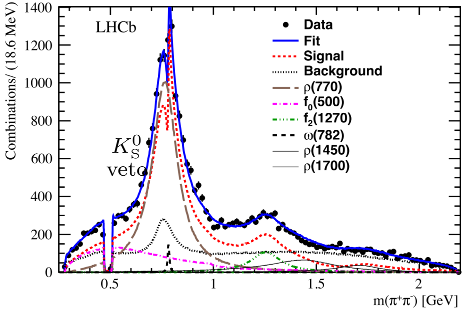
$$\phi_s = -0.010 \pm 0.039 \text{ rad}$$
$$|\lambda| = 0.957 \pm 0.017$$

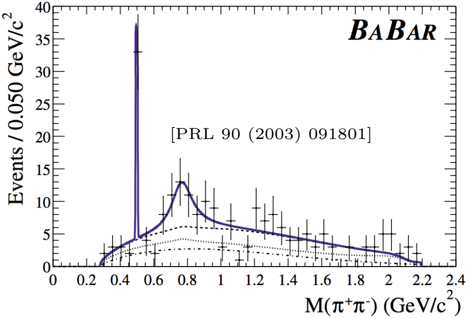
(†) Assuming CPV in decay is same in both channels

$$\phi_s^{\text{SM}} = -0.0365 \pm 0.0012\text{rad}$$

$B^0 \to J/\psi\,\pi^+\pi^-$

PLB 742 (2015) 38-49





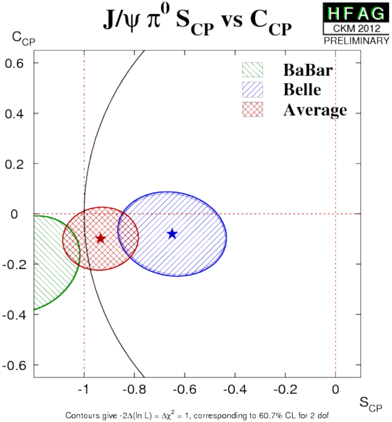
Compare with B-factories

PLB 742 (2015) 38-49

- Convert $2\beta^{\text{eff}}$, α_{CP} to S_f and C_f.
- $B^0 \to J/\psi\,\pi^0$ and $B^0 \to J/\psi\,\rho^0(770)$ have same diagrams, so same CPV.

$$S_f \equiv \frac{2Im(\lambda_f)}{1+|\lambda_f|^2} = \frac{-2\eta_f \sin 2\beta_f^{\text{eff}}}{1+|\lambda_f|^2}$$

$$C_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$$



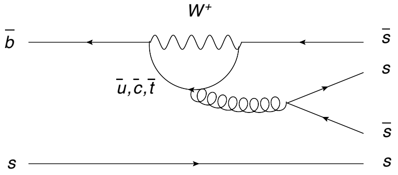
f	Experiment	S_f	C_f	Correlation
$\overset{(-)}{B}{}^0 \to J/\psi\,\rho^0$	LHCb	$-0.62^{+0.13+0.09}_{-0.12-0.03}$	$-0.063 \pm 0.056^{+0.019}_{-0.014}$	-0.30 (stat)
$\overset{(-)}{B}{}^0 \to J/\psi\,\pi^0$	Belle [33]	$-0.65 \pm 0.21 \pm 0.05$	$-0.08 \pm 0.16 \pm 0.05$	-0.10 (stat)
$\overset{(-)}{B}{}^0 \to J/\psi\,\pi^0$	BaBar [34]	$-1.23 \pm 0.21 \pm 0.04$	$-0.20 \pm 0.19 \pm 0.03$	0.20 (stat)

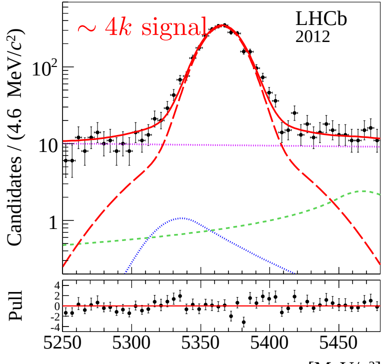
CP VIOLATION IN CHARMLESS B_s^0 DECAYS

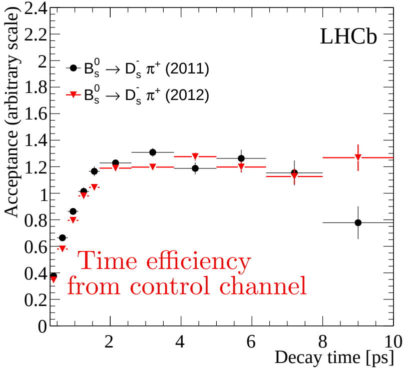
PRD 90 (2014) 052011

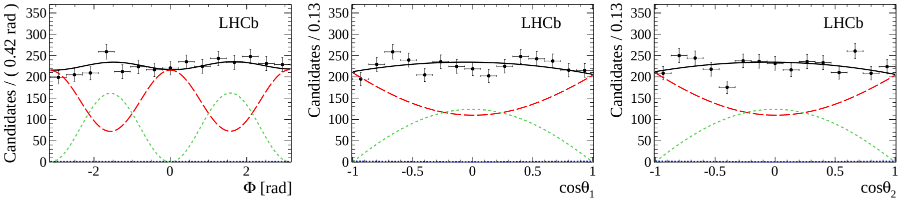
- $B_s^0 \to \phi\phi$: $b \to s$ penguin decays sensitive to NP in the loops.
- $\phi \to KK$: 5 different polarisation amplitudes $\Rightarrow$ angular analysis.
- Decay time resolution: 43fs.
- Tagging power: $\varepsilon(1-2\omega)^2 = 3.04 \pm 0.24\%$
- Angular efficiency from MC.

SM: $|\phi_s| < 0.02\,\text{rad}$

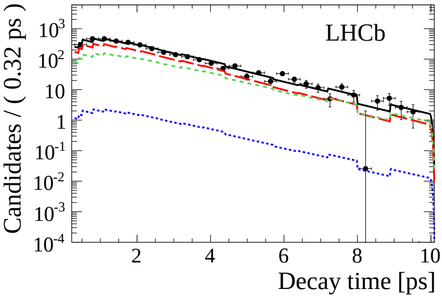






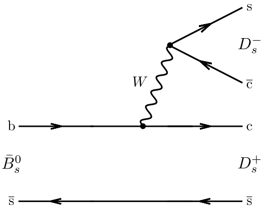


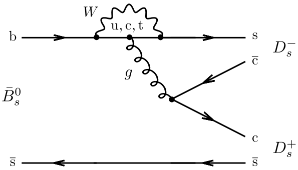
- $\phi_s = -0.17 \pm 0.15 \pm 0.03$ rad.
- $|\lambda| = 1.04 \pm 0.07 \pm 0.03$.
- Background subtracted fit using sWeights.
- Dominant systematic from understanding of angular and decay-time efficiencies.
- K^+K^- S-wave under the $\phi(1020)$ consistent with 0%.

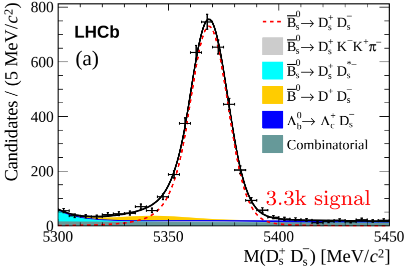


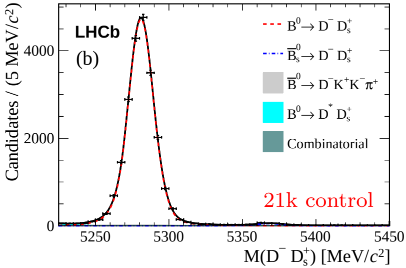
ϕ_s FROM $B_s^0 \to D_s^+ D_s^-$

arXiv:1409.4619 , accepted by PRL





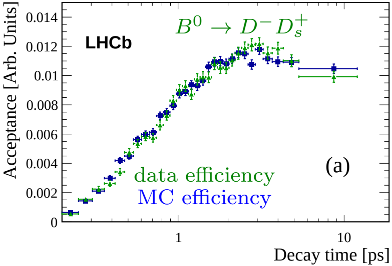


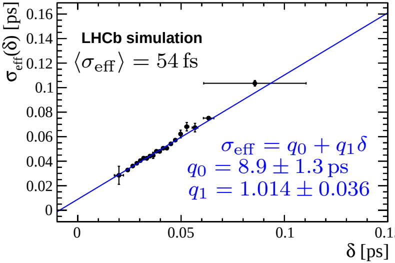


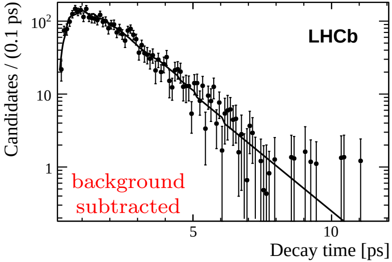
- Important to measure ϕ_s in $b \to c\bar{c}s$ decays with different penguin amps.
- $B_s^0 \to D_s^+ D_s^-$ is CP-even, no angular analysis needed.
- 4 final states: combination of $D_s \to KK\pi, K\pi\pi, \pi\pi\pi$.

ϕ_s FROM $B_s^0 \to D_s^+ D_s^-$

arXiv:1409.4619 , accepted by PRL





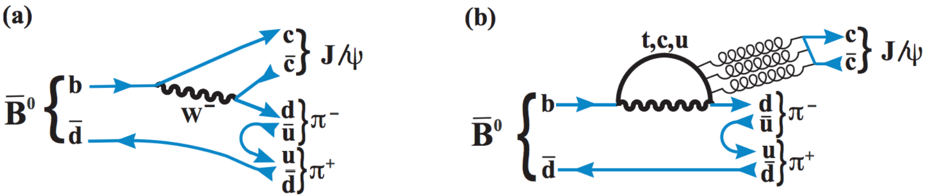


- Use $B^0 \to D^- D_s^+$ to determine decay time efficiency (τ_{B^0} from PDG).
- Simulation to calibrate the decay time uncertainty (δ) for resolution.
- Tagging: $\varepsilon(1-2\omega)^2 = (5.33 \pm 0.25)\%$
- Constrain $\Gamma_s, \Delta\Gamma_s$ from $B_s^0 \to J/\psi K^+ K^-$.

- $\phi_s = 0.02 \pm 0.17 \pm 0.02$ rad, $|\lambda| = 0.91^{+0.18}_{-0.15} \pm 0.02$

$B_s^0 \to J/\psi K^+K^-$ SYSTEMATICS

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]	$\lvert\lambda\rvert$	Δ [ps
Total stat. uncertainty	0.0027	0.0091	0.0049	0.0034	$^{+0.10}_{-0.17}$	$^{+0.14}_{-0.15}$	0.049	0.019	+0 −0
Mass factorisation	–	0.0007	0.0031	0.0064	0.05	0.05	0.002	0.001	0.
Signal weights (stat.)	0.0001	0.0001	–	0.0001	–	–	–	–	
b-hadron background	0.0001	0.0004	0.0004	0.0002	0.02	0.02	0.002	0.003	0.
B_c^+ feed-down	0.0005	–	–	–	–	–	–	–	
Angular resolution bias	–	–	0.0006	0.0001	$^{+0.02}_{-0.03}$	0.01	–	–	
Ang. efficiency	0.0001	–	0.0011	0.0020	0.01	–	0.001	0.005	0.
Ang. efficiency (stat.)	0.0001	0.0002	0.0011	0.0004	0.02	0.01	0.004	0.002	0.
Decay-time resolution	–	–	–	–	–	0.01	0.002	0.001	0.
Trigger efficiency (stat.)	0.0011	0.0009	–	–	–	–	–	–	
Track reco. (simul.)	0.0007	0.0029	0.0005	0.0006	$^{+0.01}_{-0.02}$	0.002	0.001	0.001	0.
Track reco. (stat.)	0.0005	0.0002	–	–	–	–	–	–	0.
Length and mom. scales	0.0002	–	–	–	–	–	–	–	0.
S-P coupling factors	–	–	–	–	0.01	0.01	–	0.001	0.
Fit bias	–	–	0.0005	–	–	0.01	–	0.001	
Quadratic sum of syst.	0.0015	0.0032	0.0036	0.0067	$^{+0.06}_{-0.07}$	0.06	0.006	0.007	0.



- Decay amplitude is sum of tree + 3 penguins. a', θ' are magnitude and phase of penguin relative to tree.

$$-\sqrt{2}A(B^0 \to (J/\psi\,\rho)_f) = \lambda\mathcal{A}'\left[1 - a'_f e^{i\theta'_f} e^{i\gamma}\right], \quad f \in (0, \perp, \|)$$

- In $B^0 \to J/\psi\ K^0_S$, penguins are suppressed by $\epsilon = \frac{\lambda^2}{1-\lambda^2} = 0.05$ $(\lambda = |V_{us}|)$.

$$A(B^0 \to J/\psi\,K^0_S) = \left(1 - \frac{\lambda^2}{2}\right)\mathcal{A}\left[1 + \frac{\lambda^2}{1-\lambda^2} a e^{i\theta} e^{i\gamma}\right]$$

- **Aim: measure $2\beta^{\rm eff}$ in $B^0 \to J/\psi\,\rho$ and compare to 2β from $B^0 \to J/\psi\,K_S$ (B-factories).**

$$\Delta 2\beta_f \equiv 2\beta_f^{\rm eff} - 2\beta = -\arg\left(\frac{1 - a'_f e^{i\theta'_f} e^{-i\gamma}}{1 - a'_f e^{i\theta'_f} e^{i\gamma}}\right)$$

Resolving the ambiguity

arXiv:1304.2600

- Expressions are invariant under the transformation, giving rise to a two-fold ambiguity.

$$(\phi_s, \Delta\Gamma_s, \delta_0, \delta_\parallel, \delta_\perp, \delta_S) \longmapsto (\pi - \phi_s, -\Delta\Gamma_s, -\delta_0, -\delta_\parallel, \pi - \delta_\perp, -\delta_S)$$

- Physical solution: $\Delta\Gamma_s > 0$
  $\Rightarrow$ the heavy B_s^0 eigenstate lives longer than the light one!