Measurement of the B_s^0 mixing phase at LHCb

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On behalf of the LHCb collaboration

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CERN LHC Seminar

Introduction: What is missing in Standard Model

matter and anti-matter asymmetry

why is the universe made of matter?

not enough CP violation

Are there other sources of CPV?

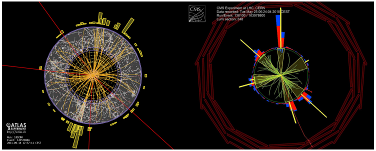
Presence of dark matter in the universe

what is dark matter made of?

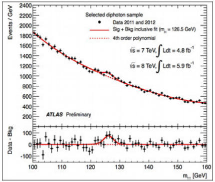
Flavor physics in the LHC era

High energy frontier

ATLAS & CMS



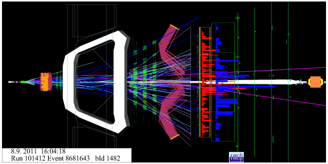
Direct searches → few TeV



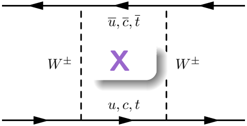
Higgs discovery!

Precision frontier

LHCb



Indirect searches → O(100 TeV)++



Quantum loop corrections

CP violation in SM

- Violation of combined Charge and Parity symmetry
- Discovered in the weak interaction in 1964
- accommodated in CKM mechanism $\Rightarrow$ small

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

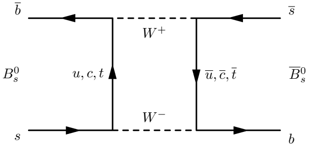
only source of CPV in SM

Probes for new physics in B_s^0 mixing

$$i\frac{d}{dt}\begin{bmatrix} |\mathrm{B}_s^0(t)\rangle \\ |\overline{\mathrm{B}}_s^0(t)\rangle \end{bmatrix} = \left[\begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{11} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{11} \end{pmatrix}\right]\begin{bmatrix} |\mathrm{B}_s^0(t)\rangle \\ |\overline{\mathrm{B}}_s^0(t)\rangle \end{bmatrix}$$

Mass eigenstates mixtures of weak states

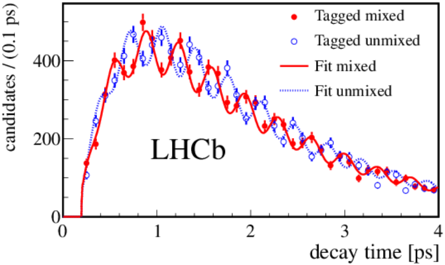
$$\left|B_{sH}^0\right\rangle = p\left|B_s^0\right\rangle - q\left|\bar{B}_s^0\right\rangle \qquad \left|B_{sL}^0\right\rangle = p\left|B_s^0\right\rangle + q\left|\bar{B}_s^0\right\rangle$$



New J. Phys. 15 (2013) 053021

- mass difference: $\Delta m_s = M_H - M_L \approx 2|M_{12}|$
  $\Rightarrow$ rate of mixing diagram
- decay width difference:
  $\Delta\Gamma_s = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos\phi_{12}$
- Mixing phase: $\phi_M = arg(M_{12})$

  $\Rightarrow$ time dependent CP violation

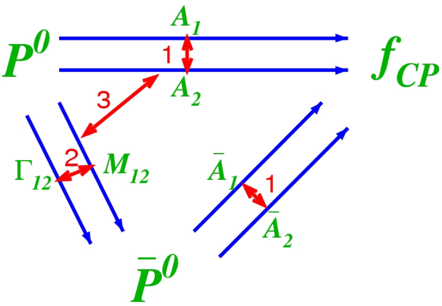


(1) CPV in decay:

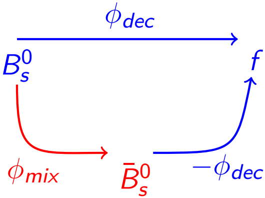
$P(B \to f) \neq P(\bar{B} \to \bar{f})$

(2) CPV in mixing

$P(B \to \bar{B}) \neq P(\bar{B} \to B)$



More on CPV in mixing see:
Cern Seminar by M. Vesterinen
Sept. 30



(3) CPV in the interference of decay and mixing

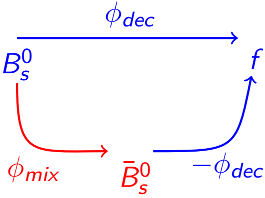
$P(B \to f) \neq P(B \to \bar{B} \to f)$

phase difference: $\phi_s = \phi_M - 2\phi_{dec}$

CPV in the interference of decay and mixing

ϕ_s: relative phase between interfering

$A(B_s^0 \to J/\psi h^+ h^-)$ and $A(B_s^0 \to \bar{B}_s^0 \to J/\psi h^+ h^-)$



ϕ_s is sensitive to new physics in B_s^0 mixing

$\phi_s = \phi_s^{SM} + \Delta\phi_s \Rightarrow \Delta\phi_s = arg(M_{12}/M_{12}^{SM})$

CP violation in decay given by:

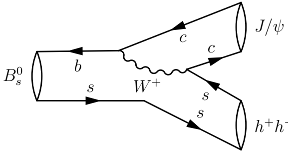
$\lambda = \frac{q}{p}\frac{\bar{A}(\bar{\mathrm{B}}_s^0 \to f_{CP})}{A(\mathrm{B}_s^0 \to f_{CP})}$, with $\phi_s = -arg(\lambda)$

only if one dominant amplitude

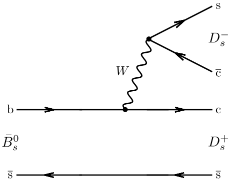
$+\Delta\phi_s^{pen}$ for penguin amplitude

Decay Channels to measure ϕ_s

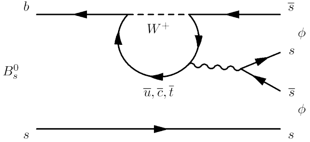
- $\mathrm{B}_s^0 \to J/\psi K^+K^-$: benchmark mode
- $\mathrm{B}_s^0 \to J/\psi \pi^+\pi^-$: dominantly CP-odd



- $\mathrm{B}_s^0 \to \mathrm{D}_s^-\mathrm{D}_s^+$: pure hadronic final state

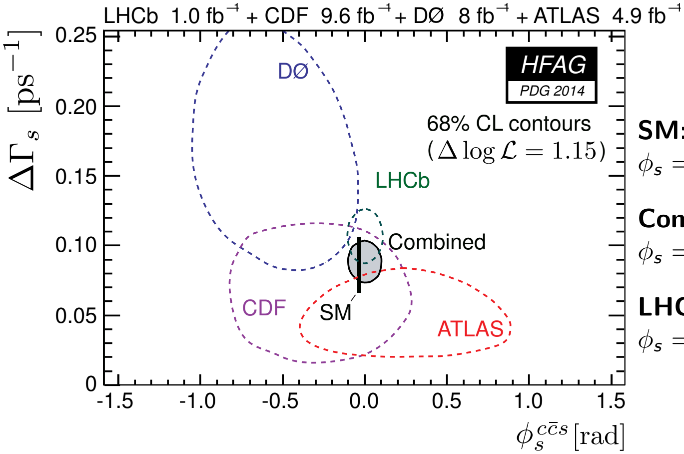


- $\mathrm{B}_s^0 \to \phi\phi$: pure penguin decay



$\star$ to estimate penguin contribution $\mathrm{B}^0 \to J/\psi\rho$: tree + penguin

Status as of early 2014



SM:
$\phi_s = -0.0364 \pm 0.0016$

Combined exp:
$\phi_s = 0.00 \pm 0.07$

LHCb:
$\phi_s = 0.01 \pm 0.07 \pm 0.01$

- Atlas, D0 and CDF: $B_s^0 \to J/\psi K^+K^-$
- LHCb: $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi \pi^+\pi^-$

Key ingredients

- Theoretical time dependent CP asymmetry

  $$A_{CP}(t) = \frac{\Gamma(\bar{B}_s^0 \to f) - \Gamma(B_s^0 \to f)}{\Gamma(\bar{B}_s^0 \to f) + \Gamma(B_s^0 \to f)} = \eta_f \sin\phi_s \sin(\Delta m_s t)$$

- Experimentally

  $$A_{CP} \approx (1 - 2w) e^{-\frac{1}{2}\Delta m_s^2 \sigma_t^2} \eta_f \sin\phi_s \sin(\Delta m_s t)$$

  - w Probability of getting the initial flavor wrong
  - σ_t Decay time resolution
  - η_f CP eigenvalue $\rightarrow$ angular analysis

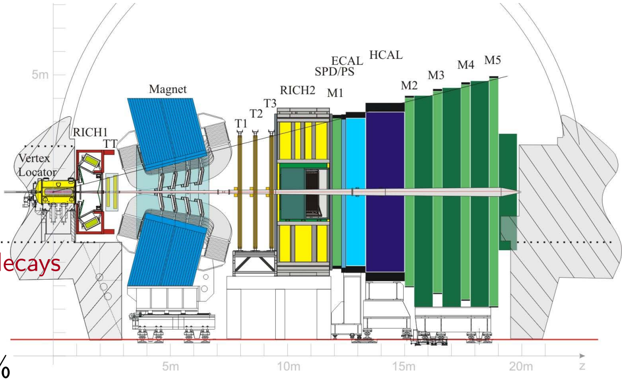
- Minimum requirements:
  - excellent decay time resolution
  - good flavor tagging
  - large statistics

LHCb experiment

Momentum resolution:
σ_p/p: 0.4% – 0.6%

Time resolution:
40-50 fs

Mass resolution:
$8\ MeV/c^2$ for $B \to J/\psi X$ decays



Particle identification:
$\varepsilon(\mu) = 97\%$, mis-id: 0.7%
$\varepsilon(K) > 90\%$, mis-id: 5%

Data set in run I:

2010: 37 pb^{-1} @ 7 TeV
2011: 1 fb^{-1} @ 7 TeV
2012: 2 fb^{-1} @ 8 TeV

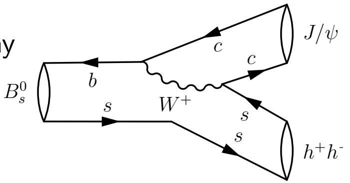
All results shown today are with $3fb^{-1}$

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

- Theoretically clean, tree dominating decay
- Precise SM prediction:

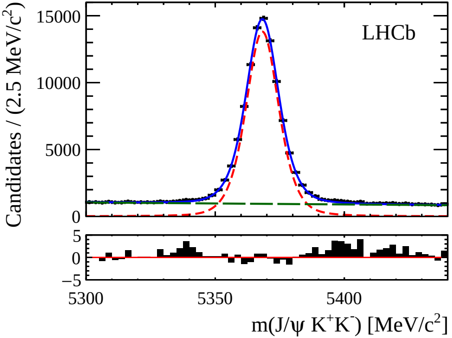
  $\phi_s = (-0.036 \pm 0.002) rad$

- Signal: 95690±350 events



- Background:
  - combinatorial
  - peaking:

    $\Lambda_b^0 \to J/\psi p K^-$: 4800 evt.
    $B_d \to J/\psi K^+ \pi^-$: 1700 evt.



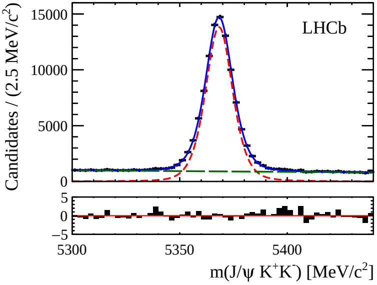
Background subtraction

Background events subtracted statistically

$\Rightarrow$ avoid parametrization in multiple dimensions

- Combinatorial background:
  - discriminating variable: $J/\psi K^+K^-$ mass
  - assign a signal weight to each event
- Peaking backgrounds:
  - MC events re-weighted to match data
  - added to data with negative weights

peaking back. subtracted



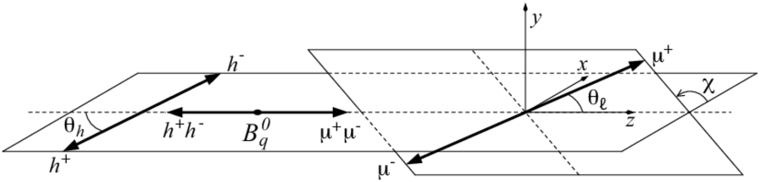
Angular analysis of $\mathrm{B}_s^0 \to J/\psi K^+K^-$

$P \to VV$ final state

K^+K^- in P-wave: 0 (CP even), $\parallel$ (CP even), $\perp$ (CP odd)
K^+K^- in S-wave: CP odd

Mixture of CP-even and -odd
$\Rightarrow$ need angular analysis to disentangle
$\Rightarrow$ have access to both Γ_s and $\Delta\Gamma_s$

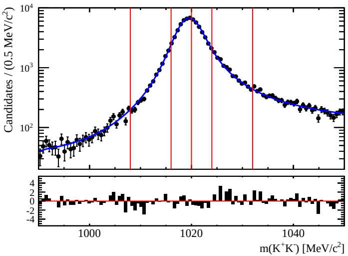
Use of helicity angles: $\Omega(\theta_\mu, \theta_K, \phi_h)$



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

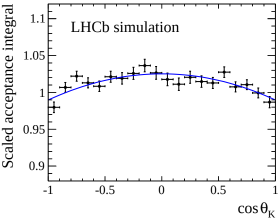
simultaneous fit in:

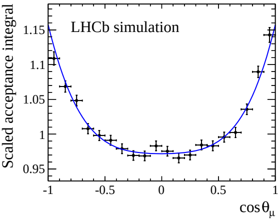
- six bins of m(K^+K^-) to account for S-wave

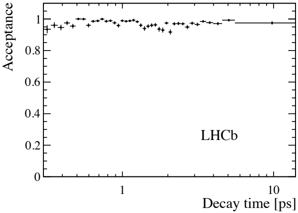


Acceptance

- Angular acceptance
  - detector acceptance and event selection
  - based on data corrected simulation
- Time acceptance:
  - selection, reconstruction
  - obtained from data

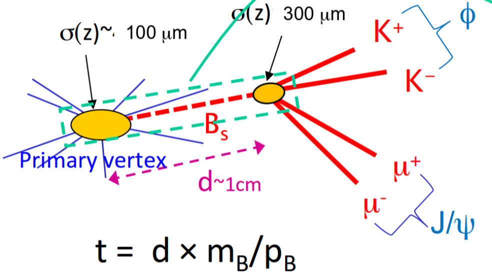


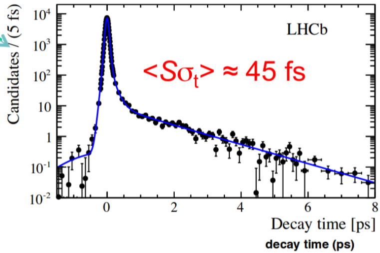




$B_s^0 \to J/\psi K^+K^-$ time resolution

calibration with prompt J/ψ





c.f. oscillation period ~ 350 fs

- σ_t per-event decay time error
- average $\sim$ 45 fs $\Rightarrow$ dilution factor $e^{-\frac{1}{2}\Delta m_s^2\sigma_t^2} = 0.73$

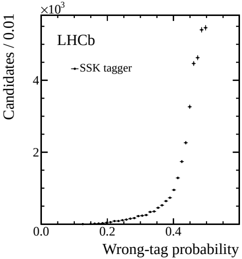
$B_s^0 \to J/\psi K^+ K^-$ Flavor tagging

need to resolve fast oscillations of B_s^0-$\bar{B}_s^0$

b quarks are produced in pairs:

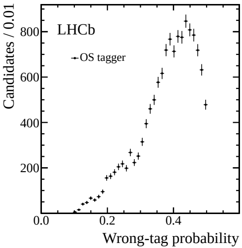
- Same-side tagging:

  Use charge of kaon produced in the fragmentation



- Opposite-side tagging:

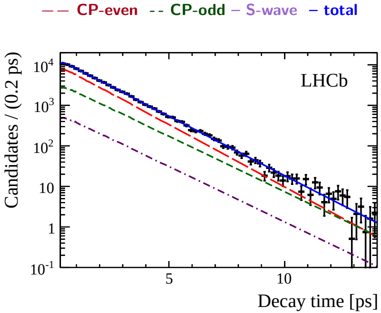
  Use charge of final state particles of other B

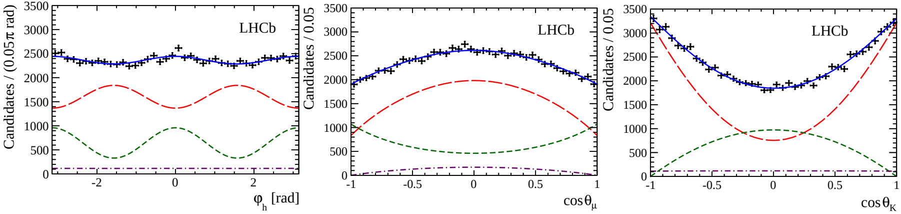


- total tagging power: $\epsilon(1-w)^2 = (3.73 \pm 0.15)\%$
  - ⋆ 20% improvement compare to 1fb^{-1} analysis

$B_s^0 \to J/\psi K^+ K^-$ results arXiv:1411.3104

Parameter	Value
ϕ_s [rad]	$-0.058 \pm 0.049 \pm 0.006$
$\|\lambda\|$	$0.964 \pm 0.019 \pm 0.007$
$\Delta\Gamma_s$ [ps^{-1}]	$0.0805 \pm 0.0091 \pm 0.0033$
Γ_s [ps^{-1}]	$0.6603 \pm 0.0027 \pm 0.0015$
Δm_s [ps^{-1}]	$17.711\ ^{+0.055}_{-0.057} \pm 0.011$



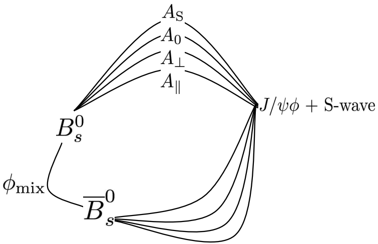


Polarization dependence arXiv:1411.3104

For non-negligible penguin contributions

- size of pollution could be different for 3 P-wave and the S-wave states
- CPV might be polarization dependent
- complicates the search for NP effects

e.g.,Bhattacharya, Datta, Int. J. Mod, Phys. **A28**(2013) 1350063



We measure:

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} = |\lambda_f| e^{-i\phi_s^f}$$

for each $f = 0, \parallel, \perp, S$

assume zero CPV in mixing

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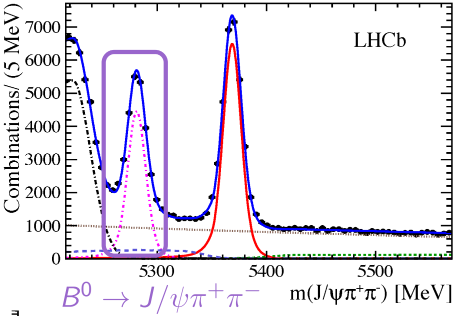
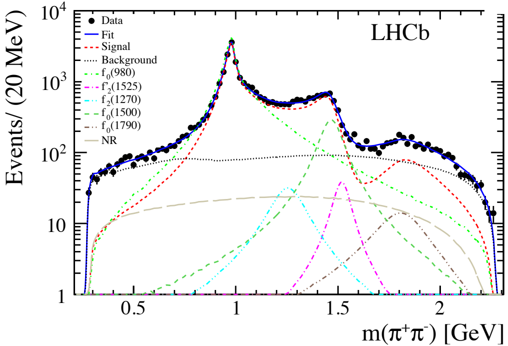
ϕ_s^0 [rad]	$-0.045 \pm 0.053 \pm 0.007$
$\phi_s^\parallel - \phi_s^0$ [rad]	$-0.018 \pm 0.043 \pm 0.009$
$\phi_s^\perp - \phi_s^0$ [rad]	$-0.014 \pm 0.035 \pm 0.006$
$\phi_s^{\rm S} - \phi_s^0$ [rad]	$0.015 \pm 0.061 \pm 0.021$
$\lvert\lambda^0\rvert$	$1.012 \pm 0.058 \pm 0.013$
$\lvert\lambda^\parallel/\lambda^0\rvert$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

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

- 27100 ± 200 signal events
- Effective time resolution: 40.3 fs
- Effective tagging power: $(3.89 \pm 0.25)\%$





- from the amplitude analysis 2.3% CP even @ 95% CL
- largest component $f_0(980)$

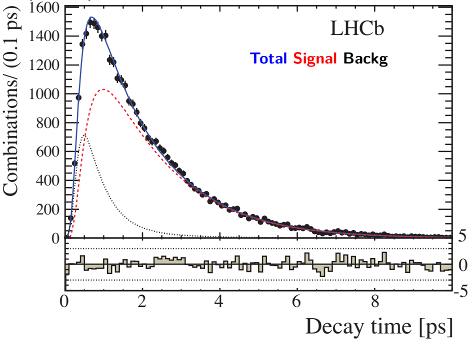
$B_s^0 \to J/\psi\pi^+\pi^-$ Phys. Lett. B 736 (2014) 186

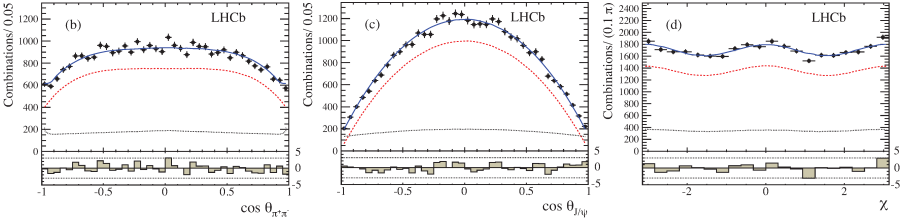
⋆ 6 dimensional fit:
$m_{\pi\pi}$, $m_{J/\psi\pi\pi}$, t and Ω

Results:

$\phi_s = 0.070 \pm 0.068 \pm 0.008$ rad

$|\lambda| = 0.89 \pm 0.05 \pm 0.01$





$\mathrm{B}_s^0 \rightarrow J/\psi K^+K^-$ and $\mathrm{B}_s^0 \rightarrow J/\psi \pi^+\pi^-$ Combination

arXiv:1411.3104

under the assumptions:

- both decays proceed dominantly via $b \rightarrow c\bar{c}s$

  $\Rightarrow$ CPV in decay same

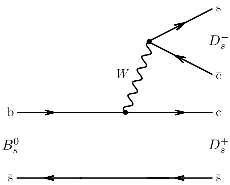
- ratio between penguin and tree diagrams is the same

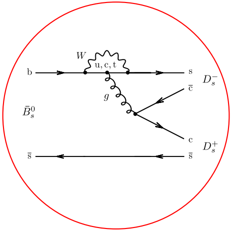
	$B_s^0 \rightarrow J/\psi K^+K^-$	$B_s^0 \rightarrow J/\psi \pi^+\pi^-$	Combined
ϕ_s[rad]	$-0.058 \pm 0.049 \pm 0.006$	$0.070 \pm 0.068 \pm 0.008$	-0.010 ± 0.039
$\|\lambda\|$	$0.964 \pm 0.019 \pm 0.007$	$0.89 \pm 0.05 \pm 0.01$	0.957 ± 0.017

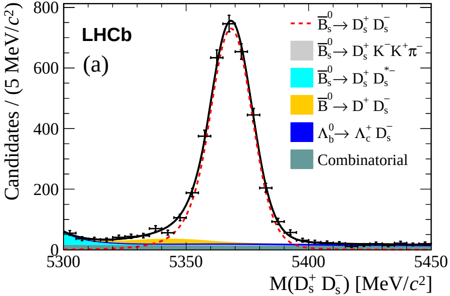
$\star$ correlations between common parameters are accounted for

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

- another decay with $b \to c\bar{c}s$ transition
  $\Rightarrow$ measurement of $\phi_s$in a hadronic final state
- just CP-even
  $\Rightarrow$ no angular analysis
- what about the penguin?







- 3345 ± 62 events in 3 fb^{-1}
- Control channel: $B^0 \to D^- D_s^+$
  21320 ± 148 events

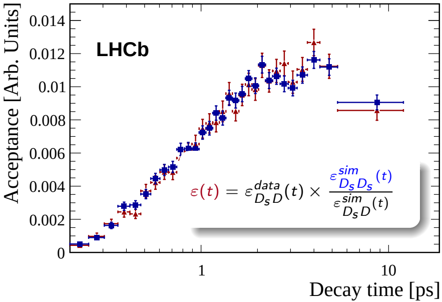
$B_s^0 \to D_s^- D_s^+$ arXiv:1409.4619

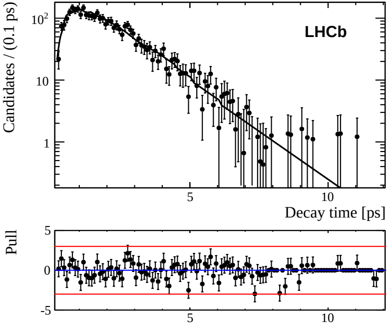
- background subtracted decay time fit
- per-event decay time resolution

effective resolution: 54 fs

- flavor tagging

effective tag. pow.: $(5.33 \pm 18 \pm 17)$ %





Results:

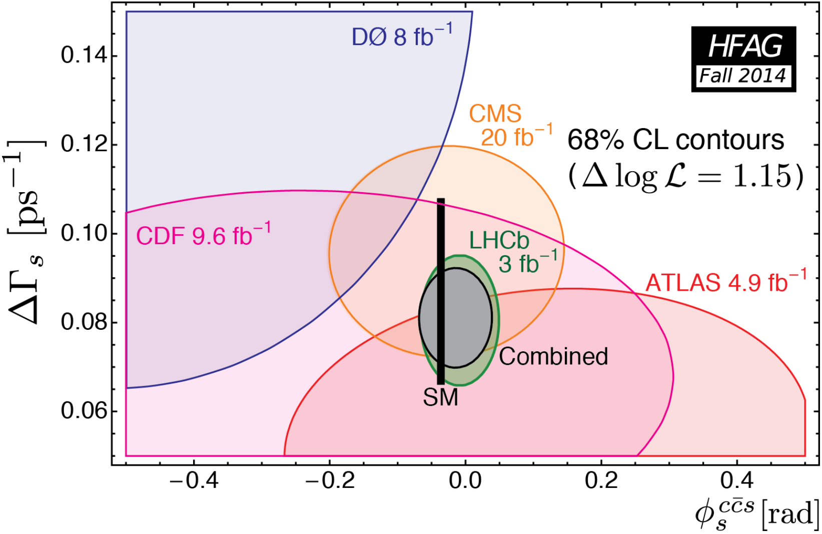
$\phi_s = 0.02 \pm 0.17(stat) \pm 0.02(syst)$ rad

$|\lambda| = 0.91^{+0.18}_{-0.17}(stat) \pm 0.02(syst)$

$\Rightarrow$ consistent with other measurements

$\Rightarrow$ consistent with no CPV in decay

ϕ_s-$\Delta\Gamma_s$ world average



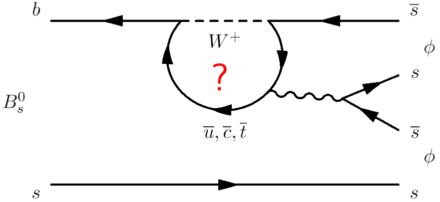
Side note: ϕ_s in $B_s^0 \to \phi\phi$ Phys. Rev. D 90 (2014) 052011

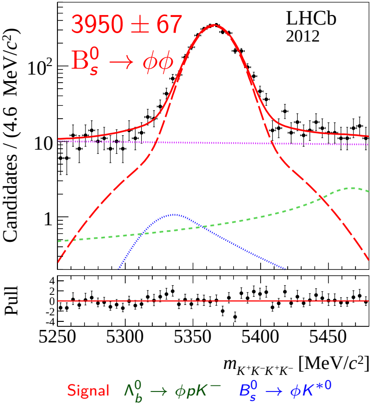
- forbidden at tree level in SM

  sensitivity to NP in decay

- gluonic $b \to s\bar{s}s$ transition

  $\phi_s^{s\bar{s}s} < 0.02$ rad





$\phi_s = -0.17 \pm 0.15(stat) \pm 0.03(syst)$ rad

$|\lambda| = 1.04 \pm 0.07 \pm 0.03(syst)$

⇒ agreement with prediction

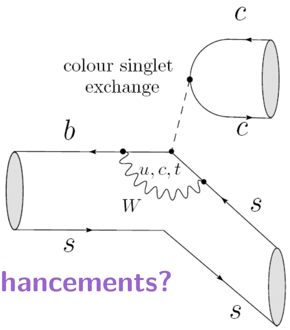
⇒ no evidence of CPV in decay or mixing

Penguin Pollution in ϕ_s

What we really measure:

$\phi_s = \phi_{SM} + \Delta\phi_{NP} + \Delta\phi_{pen}$

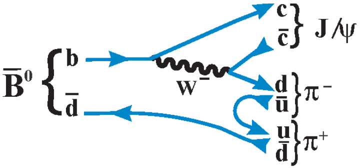
- **doubly Cabibbo suppressed**
- **non-perturbative hadronic enhancements?**

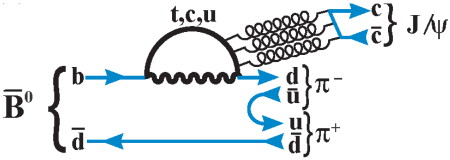


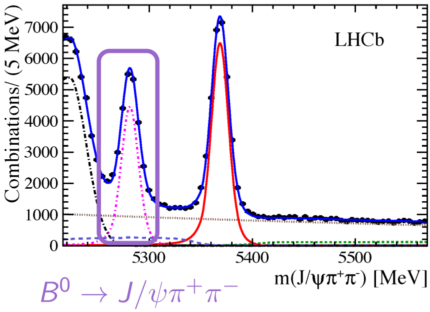
Control penguins via flavor symmetry:

- use U-spin-related modes
  $\Rightarrow$ with increased relative penguin influence
- can extract $\Delta\phi_{pen}$
  $\Rightarrow$ with problem of dependence on SU(3) breaking
- Useful modes: $B_s^0 \to J/\psi K^\star$ and $B^0 \to J/\psi \rho$

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







- 17650 ± 200 signal events
- from amplitude analysis

65% of signal from $\mathrm{B}^0 \to J/\psi\rho$

$B^0 \to J/\psi\pi^+\pi^-$ arXiv:1411.1634

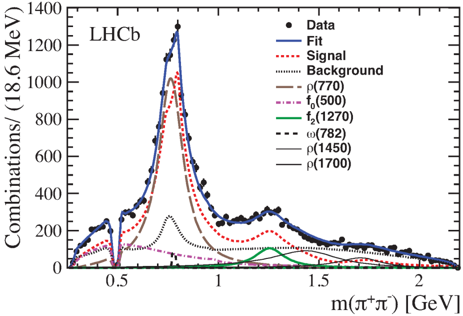
- using $\mathrm{B}^0 \to J/\psi\rho$ events:

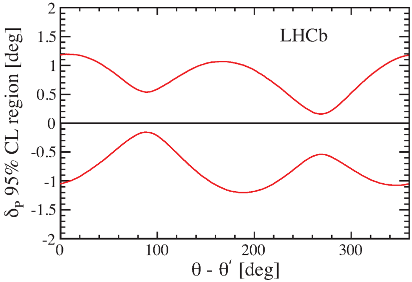
  $2\beta^{J/\psi\rho} = (41.7 \pm 9.6^{+2.8}_{-6.3})^\circ$

- and 2β from $B^0 \to J/\psi K_S$

- Penguin contribution:

  $\Delta 2\beta = 2\beta^{J/\psi\rho} - 2\beta^{J/\psi K^0_S}$





- from SU(3) symmetry $\epsilon = \frac{|V_{us}|^2}{1-|V_{us}|^2}$

  the penguin shift in ϕ_s: $\delta_P \approx -\epsilon\Delta 2\beta$

  $\Rightarrow [-1.05^\circ, 1.18^\circ]$ @ 95% CL

Prospects

- Additional decay modes can reduce ϕ_s uncertainty

  $\mathrm{B}_s^0 \to J/\psi(e^+e^-)K^+K^-$

  $\mathrm{B}_s^0 \to \psi(2S)K^+K^-$

  $\mathrm{B}_s^0 \to J/\psi K^+K^-$ (above ϕ mass)

- More studies on penguin contributions

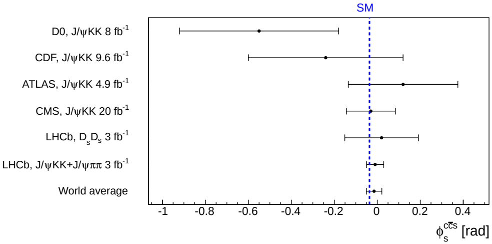
  Decays related by flavor symmetry: $\mathrm{B}_s^0 \to J/\psi K^\star$, $\mathrm{B}_s^0 \to J/\psi K_S^0$, $B^0 \to J/\psi\omega$

- Projected sensitivity

	Run 1 (2010-12)	Run 2 (2015-17)	Upgrade (2019-)	Theory
	$3\mathrm{fb}^{-1}$	$8\mathrm{fb}^{-1}$	$50\mathrm{fb}^{-1}$	
$\mathrm{B}_s^0 \to J/\psi K^+K^-$	0.05	0.025	0.009	~ 0.003
$\mathrm{B}_s^0 \to J/\psi\pi^+\pi^-$	0.09	0.05	0.016	~ 0.001
$\mathrm{B}_s^0 \to \phi\phi$	0.18	0.12	0.026	0.02

Summary

- LHC run I data proven to be fruitful for ϕ_s
  - experimental $\sigma(\phi_s) < 0.038$



  - first polarization dependent measurements
  - first measurement in a purely penguin mode $B_s^0 \to \phi\phi$

- good agreement with SM overall
- expected sensitivity ~ 0.02 by the end of Run 2
- theory input needed for penguin pollution estimates

BACKUP

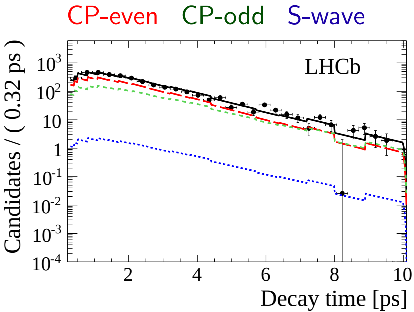
Side note: ϕ_s in $B_s^0 \to \phi\phi$

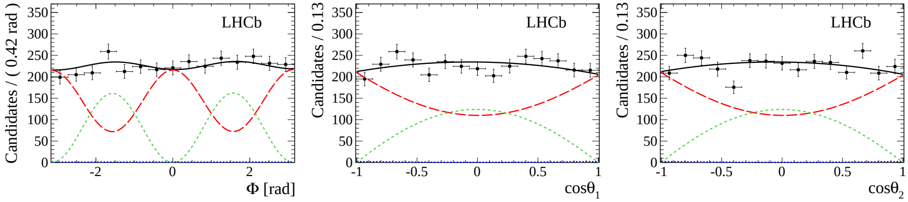
$\phi_s = -0.17 \pm 0.15(stat) \pm 0.03(syst)$ rad

$|\lambda| = 1.04 \pm 0.07 \pm 0.03(syst)$

⇒ agreement with prediction

⇒ no evidence of CPV in decay or mixing





penguin amplitude not suppressed

measure an effective $2\beta^{eff}$

$$\eta_f \lambda_f = |\lambda_f| e^{-i2\beta_f^{eff}} = \frac{1 - a'_f e^{i\theta'_f} e^{-i\gamma}}{1 - a'_f e^{i\theta'_f} e^{i\gamma}} e^{-i2\beta}$$

eff. penguin amplitude relative to tree amplitude: a'_f and θ'_f

$\Delta 2\beta_f = 2\beta_f^{eff} - 2\beta$

from SU(3) symmetry $\epsilon = \frac{|V_{us}|^2}{1-|V_{us}|^2}$

the penguin shift in 2β: $\delta_P \approx \epsilon \Delta 2\beta_f$