MIXING-INDUCED CP VIOLATION IN B_S DECAYS

FPCP 2015

Flavor Physics & CP Violation

University of Nagoya, Japan
25-29 May 2015

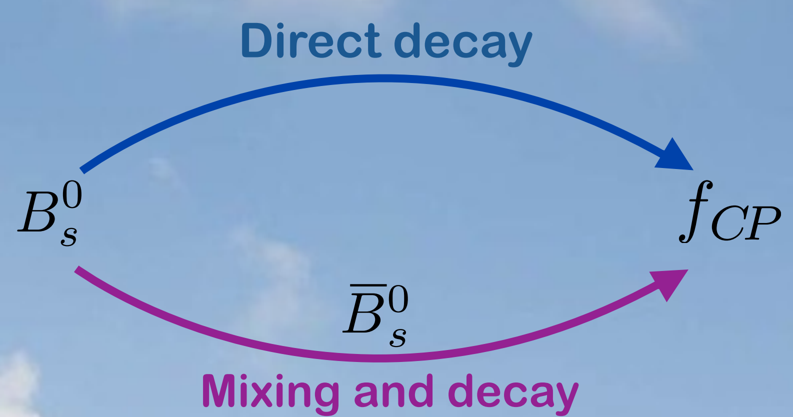
Simon Akar

on behalf of the LHCb collaboration,
including results from other collaborations

CNRS IN2P3 Les deux infinis

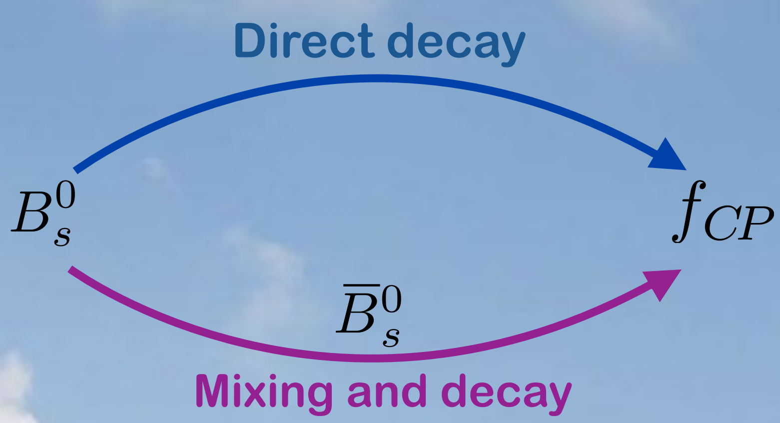
CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM

OUTLINE



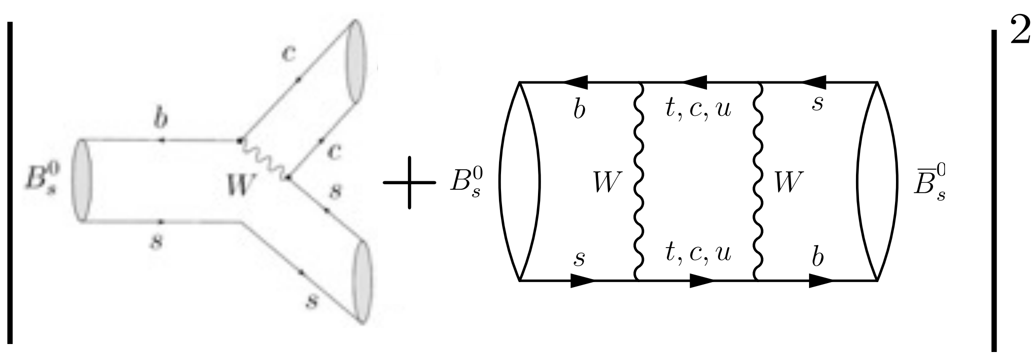
1. **Physics motivation**
2. **Measurement ingredients**
3. **Measurement of ϕ_s**
4. **Constraining penguins in ϕ_s**

Outline

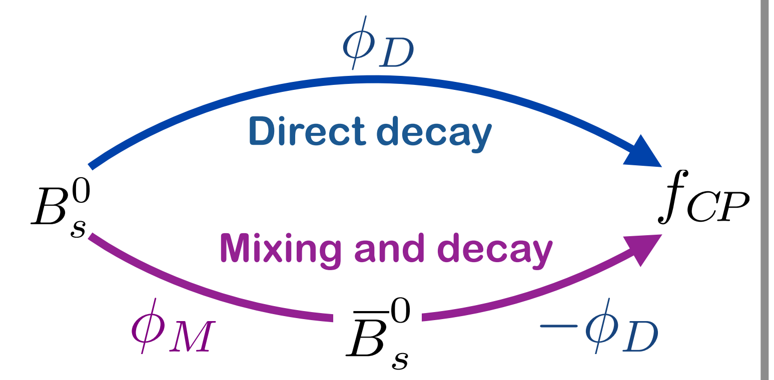


1. Physics motivation
2. Measurement ingredients
3. Measurement of ϕ_s
4. Constraining penguins in ϕ_s

✦ CPV in interference between mixing and decay:



dominant
“tree“contribution

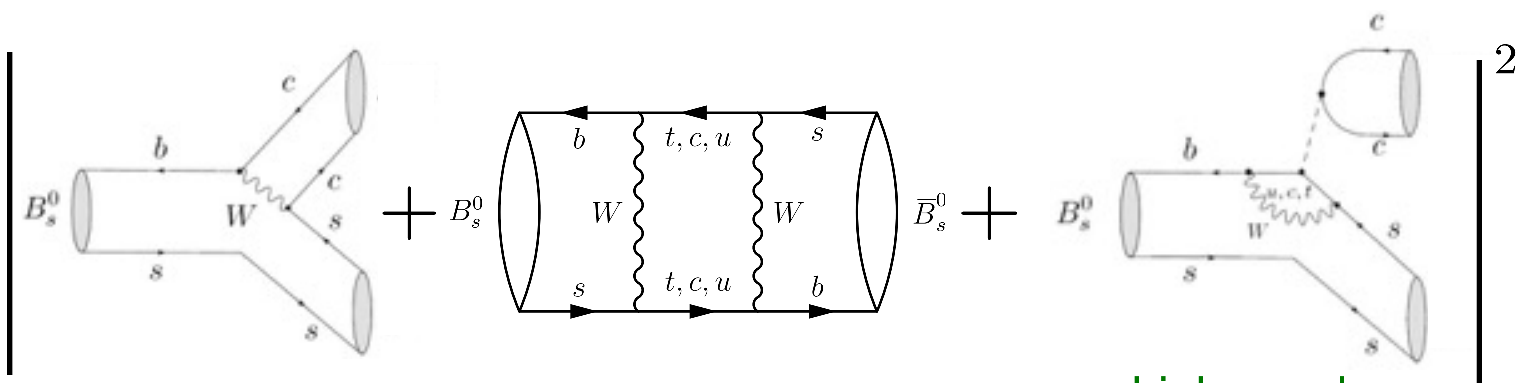


$$\phi_s = \phi_M - 2\phi_D$$
$$= -2\beta_s$$

$$\beta_s = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

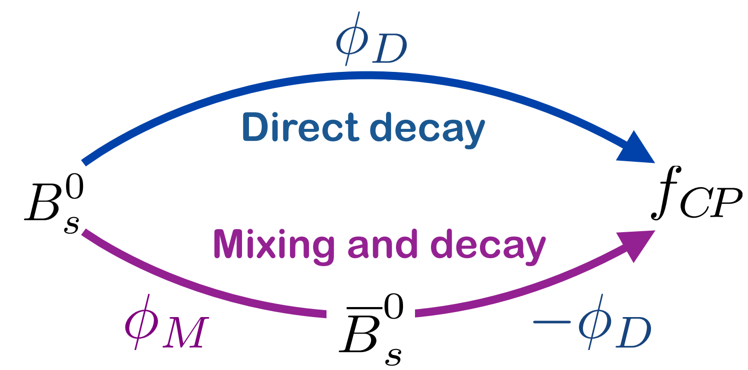
Physics motivation

✦ CPV in interference between mixing and decay:



dominant
"tree"contribution

higher order
"penguin"
contributions

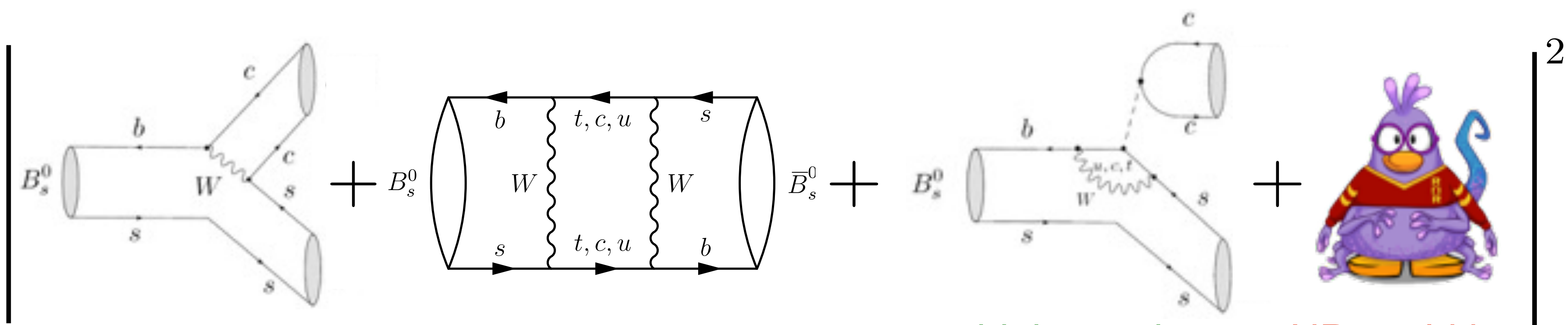


$$\phi_s = \phi_M - 2\phi_D$$
$$= -2\beta_s + \Delta\phi_s^{\text{Peng.}}$$

$$\beta_s = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

PHYSICS MOTIVATION

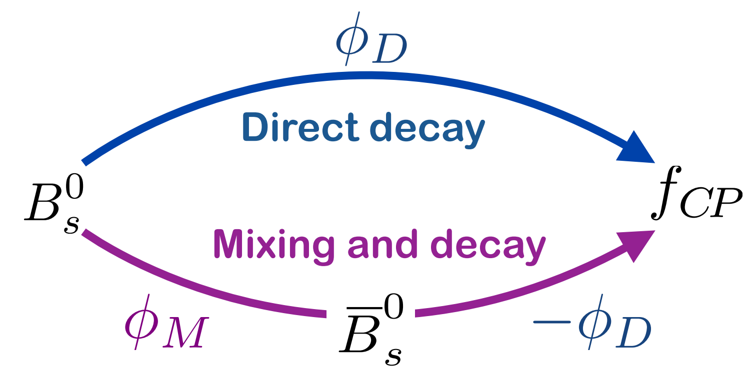
✦ CPV in interference between mixing and decay:



dominant
“tree“contribution

higher order
“penguin“
contributions

NP could be
comparable to
penguins…

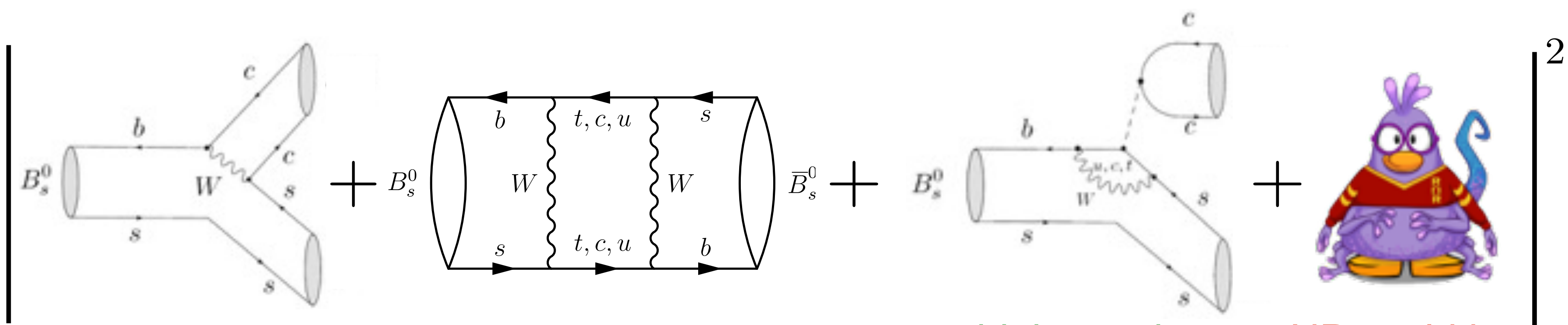


$$\phi_s = \phi_M - 2\phi_D$$
$$= -2\beta_s + \Delta\phi_s^{\mathrm{Peng.}} + \delta^{\mathrm{NP}}$$

$$\beta_s = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

Physics motivation

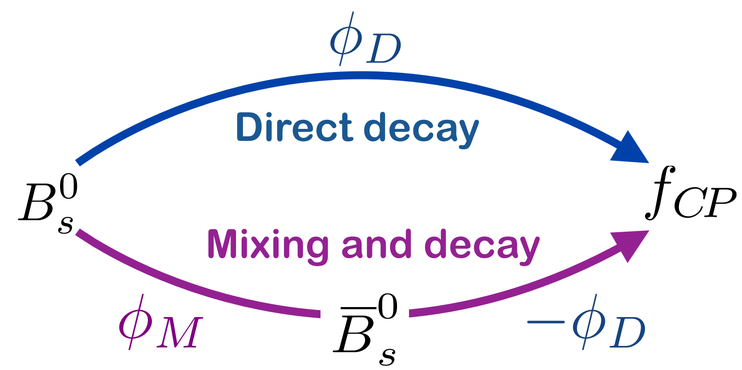
✦ CPV in interference between mixing and decay:



dominant "tree"contribution

higher order "penguin" contributions

NP could be comparable to penguins…



$$\phi_s = \phi_M - 2\phi_D$$
$$= -2\beta_s + \Delta\phi_s^{\text{Peng.}} + \delta^{\text{NP}}$$

$$\beta_s = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

- **ϕ_s determination via global fit to experimental results ignores contributions from penguin diagrams:**

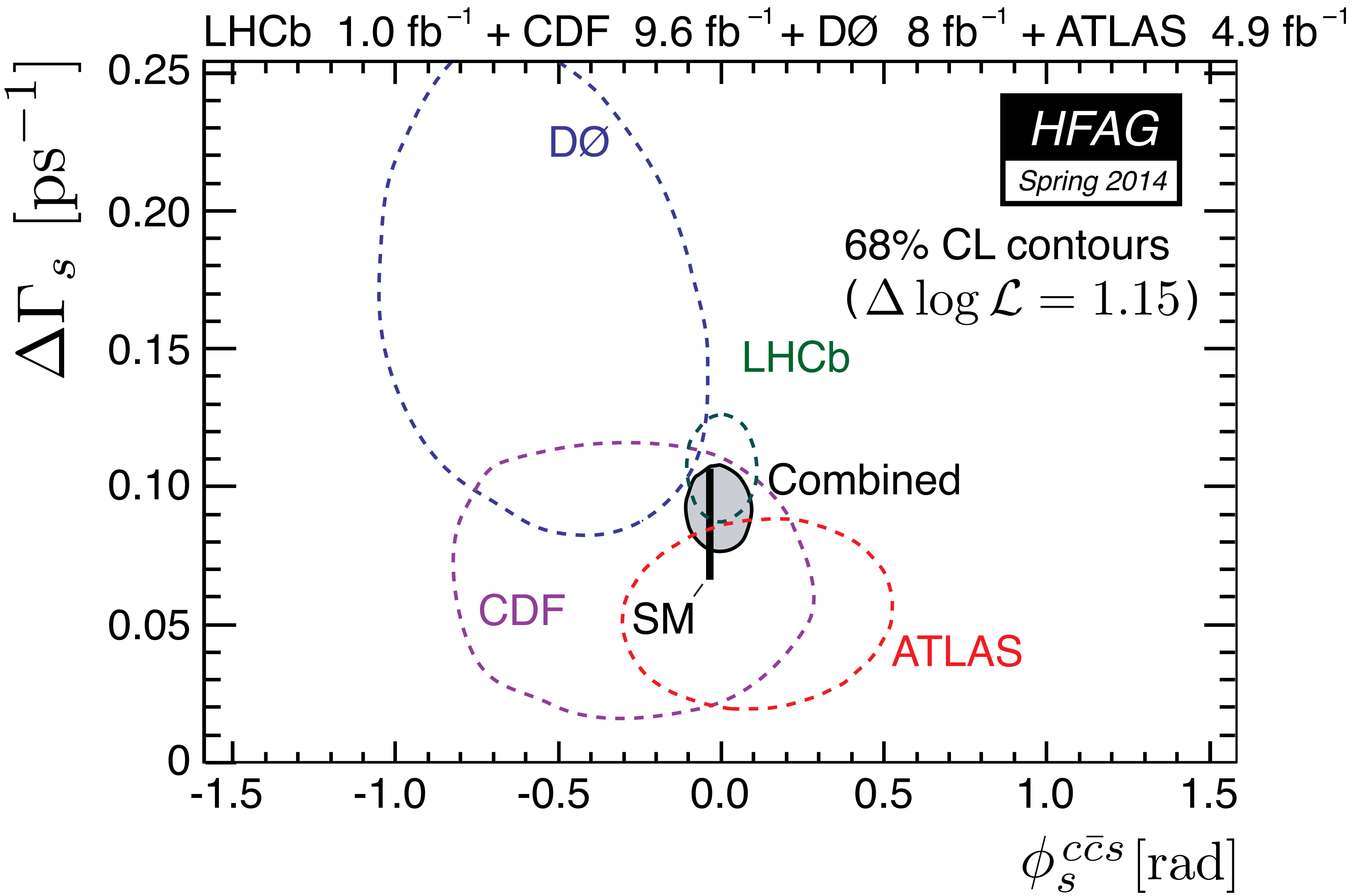
$$\phi_s^{\text{SM no Peng}} = -2\beta_s = -0.0365^{+0.0013}_{-0.0012}$$

[CKMFitter]

Physics motivation

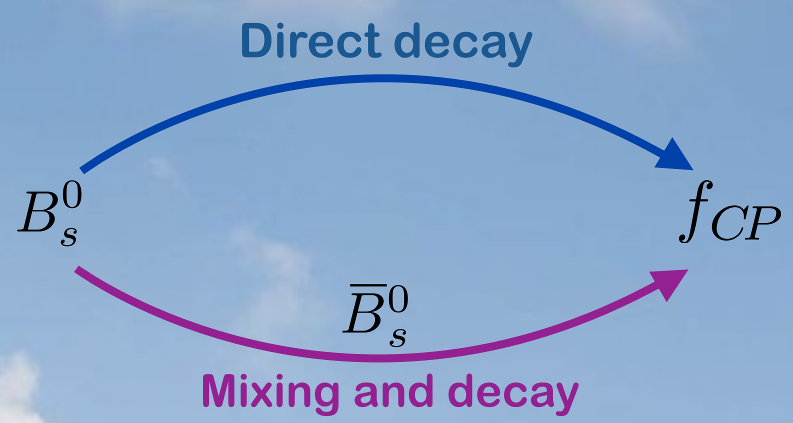
- Toward a precise measurement of ϕ_s:

State of the art at FPCP 2014



- ϕ_s measurement is an excellent probe for the presence of NP…
- …but it is now mandatory to constrain penguin contributions!

Outline



1. Physics motivation
2. Measurement ingredients
3. Measurement of ϕ_s
4. Constraining penguins in ϕ_s

MEASUREMENT INGREDIENTS

✦ Time-dependent CP asymmetry:

$$\mathcal{A}_{CP}(t) = \frac{(\overline{B}^0_s(t) \to f) - (B^0_s(t) \to f)}{(\overline{B}^0_s(t) \to f) + (B^0_s(t) \to f)} = \frac{\mathcal{S}_f \sin(\Delta m t) - \mathcal{C}_f \cos(\Delta m t)}{\cosh\left(\frac{\Delta\Gamma t}{2}\right) + \mathcal{A}_{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma t}{2}\right)}$$

- **Mixing parameters:**

$$\Delta m = m_{\rm H} - m_{\rm L} \qquad \Delta\Gamma = \Gamma_{\rm L} - \Gamma_{\rm H}$$

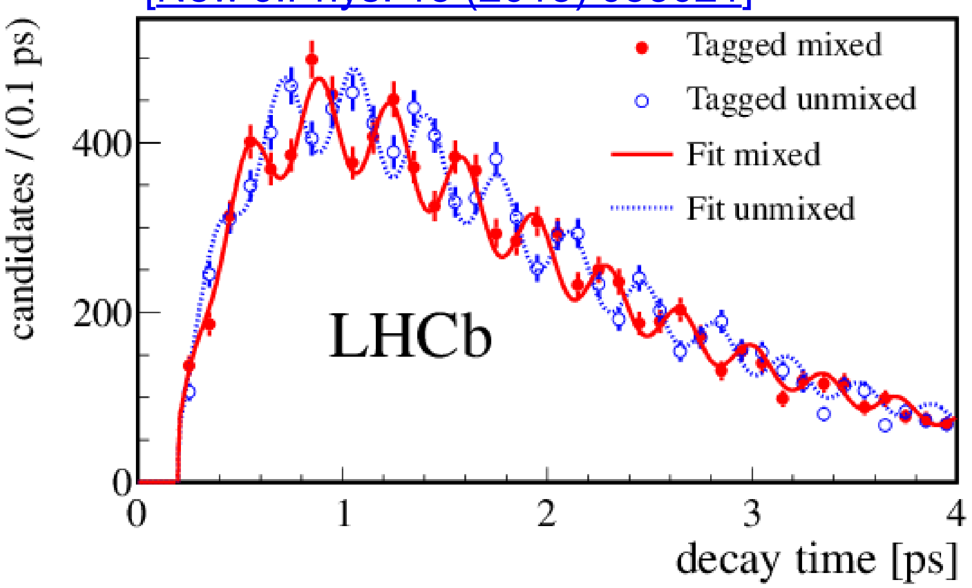
- **CP observables:**

$$\mathcal{S}_f = \frac{2\Im(\lambda_f)}{1+|\lambda_f|^2}\,, \quad \mathcal{C}_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}\,, \quad \mathcal{A}_{\Delta\Gamma} = -\frac{2\Re(\lambda_f)}{1+|\lambda_f|^2}$$

$$\lambda_f = \eta_f \frac{q}{p}\frac{A(\overline{B}^0_s(t) \to f)}{A(B^0_s(t) \to f)} = \eta_f|\lambda_f|e^{i\phi_s}$$

$$\mathcal{S}_f = -\eta_f\frac{2|\lambda_f|\sin(\phi_s)}{1+|\lambda_f|^2}\,, \quad \mathcal{A}_{\Delta\Gamma} = \eta_f\frac{2|\lambda_f|\cos(\phi_s)}{1+|\lambda_f|^2}$$

[New J.Phys. 15 (2013) 053021]



Measurement ingredients

Tagging, resolution and other nuisance effects:

$$\mathcal{A}_{\text{meas}}(t) = \mathcal{A}_{CP}(t) \times D_{\text{res}} \times D_{\text{tag}} \pm \mathcal{A}_{\text{det/prod}}$$

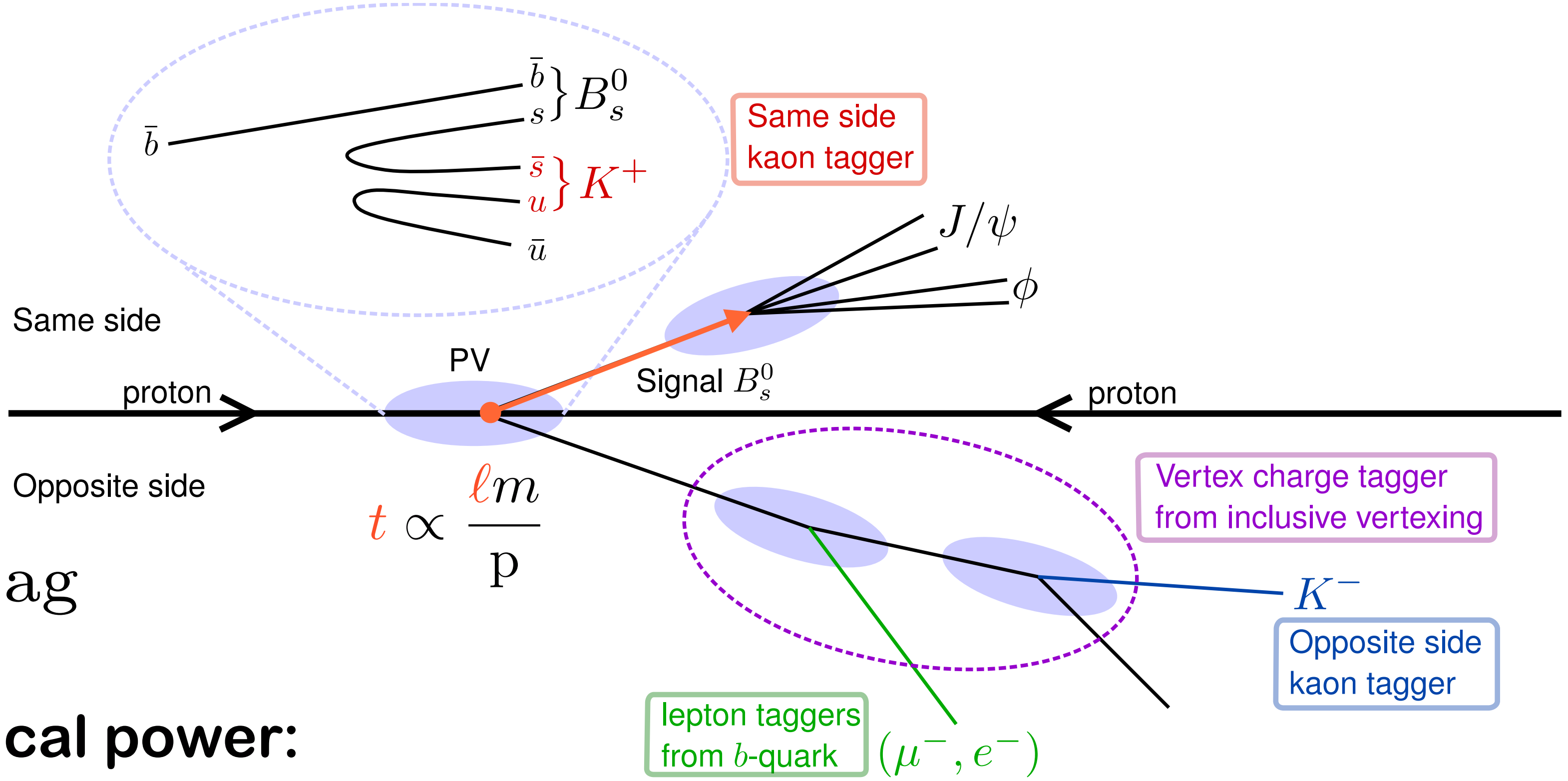
- **Decay time resolution**:

$$D_{\text{res}} = e^{-\frac{\Delta m^2 \sigma_t^2}{2}}$$

- **Tagging dilution**:

$$D_{\text{tag}} = (1 - 2\omega)$$

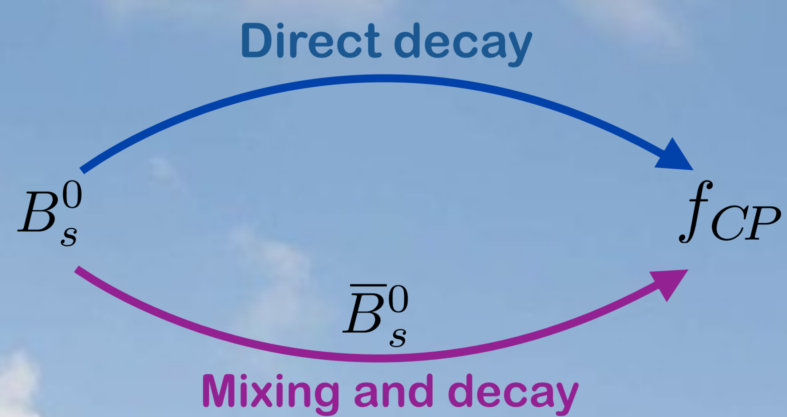
  - **Initial B flavor efficiency:** ϵ_{tag}
  - **Wrong tag rate:** ω
  - **Effective reduction in statistical power:**



$$\epsilon_{\text{eff}} = \epsilon_{\text{tag}}(1 - 2\omega)^2 \sim \mathcal{O}(\%) \qquad \sigma^{\text{stat}}(\phi_s) \propto \frac{1}{\sqrt{\epsilon_{\text{eff}} N}}$$

- **Also need to account for detection/production asymmetries, acceptance effects on time and angular variables, …**

Outline



1 Physics motivation

2 Measurement ingredients

3 Measurement of ϕ_s:

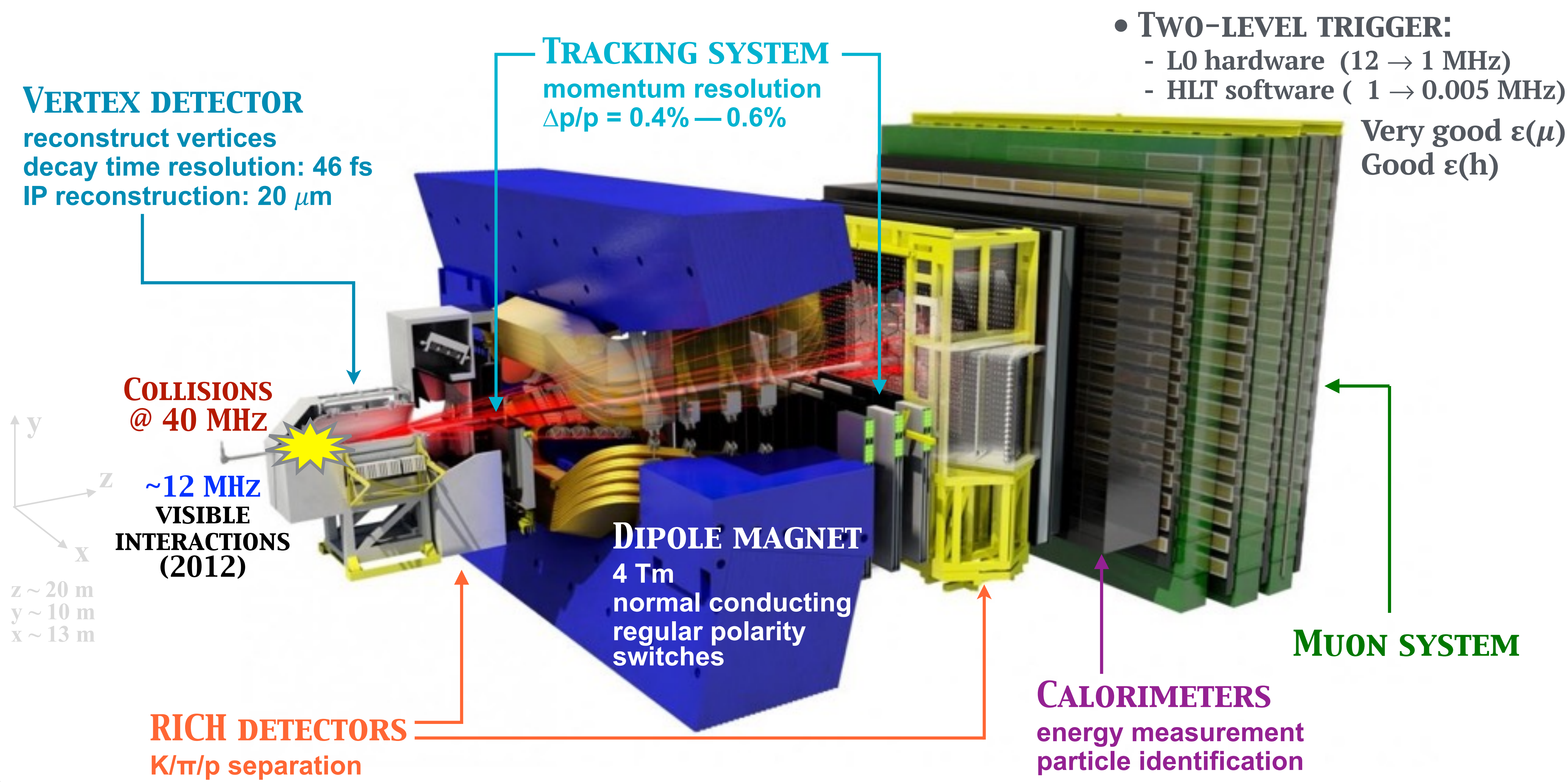
- $B_s \to J/\psi K^+K^-$
- $B_s \to J/\psi \pi^+\pi^-$
- $B_s \to D^+_s D^-_s$
- $B_s \to J/\psi K^0_S$

4 Constraining penguins in ϕ_s:

- $B_d \to J/\psi \pi^+\pi^-$

The LHCb experiment
Detector overview

- Forward General-Purpose Detector at the LHC
- ~30 % of heavy quark production cross-section with just 4% of solid angle

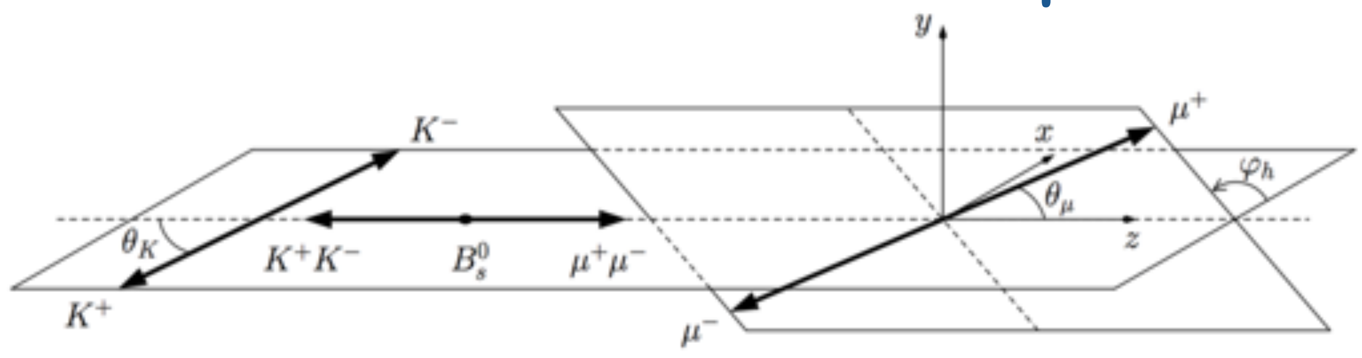


Measurement of ϕ_s in $B_s \to J/\psi K^+K^-$ (3 fb^{-1})

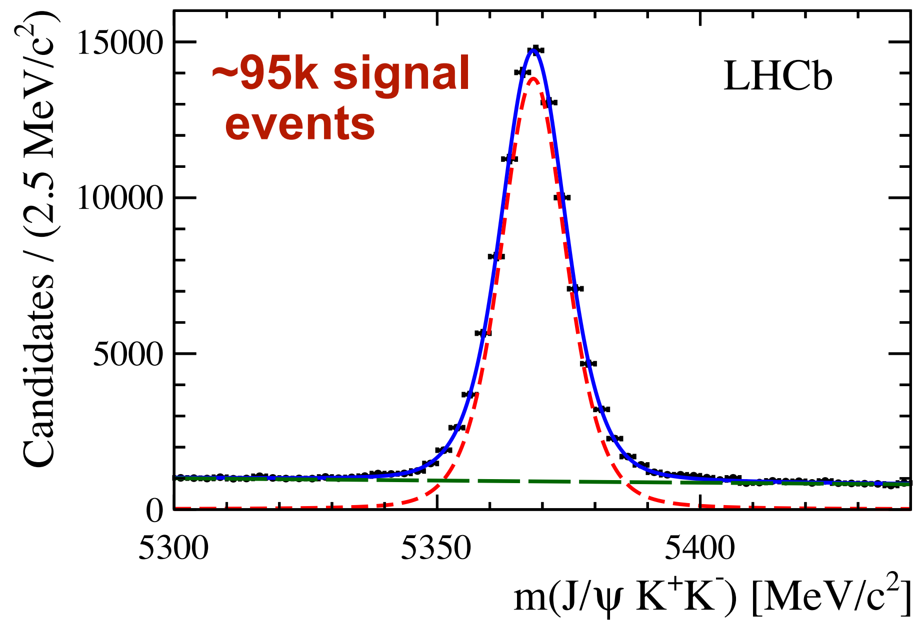
[Phys. Rev. Lett. 114 041801 (2015)]

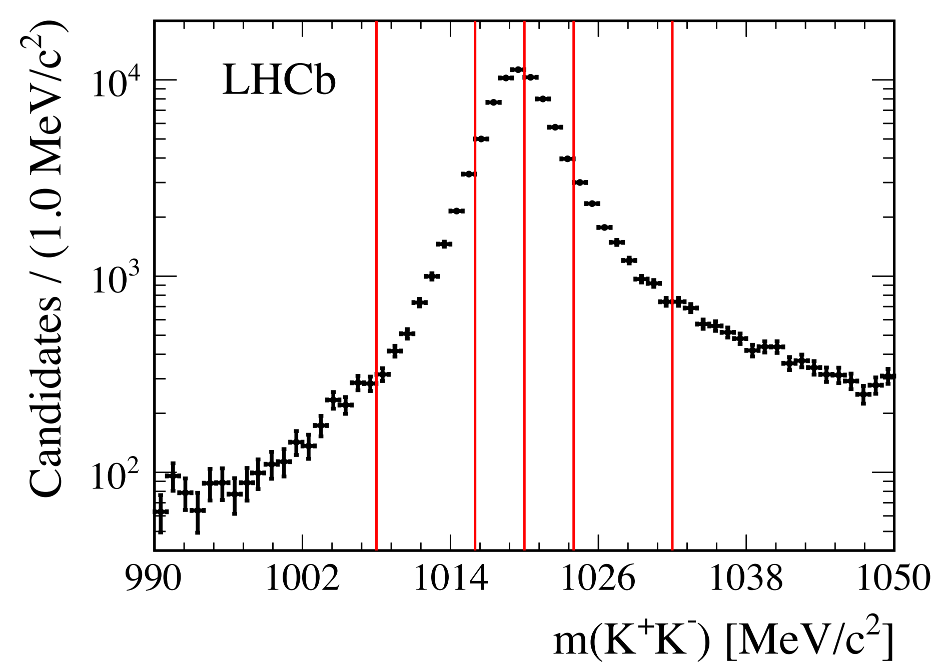
✦ Analysis overview:

- Measures ϕ_s, Γ_s, $\Delta\Gamma_s$ and $|\lambda|$
  - Time-dependent tagged angular analysis (using sWeights)
    - 3 P-wave + 1 S-wave components



    - tagging power ~3.7%
  - Fit simultaneously:
    - 6 bins of m_{KK}
  - Two fit models:
    - polarisation independent (baseline)
    - polarisation dependent (necessary, if CPV does not affect all polarisation states equally)



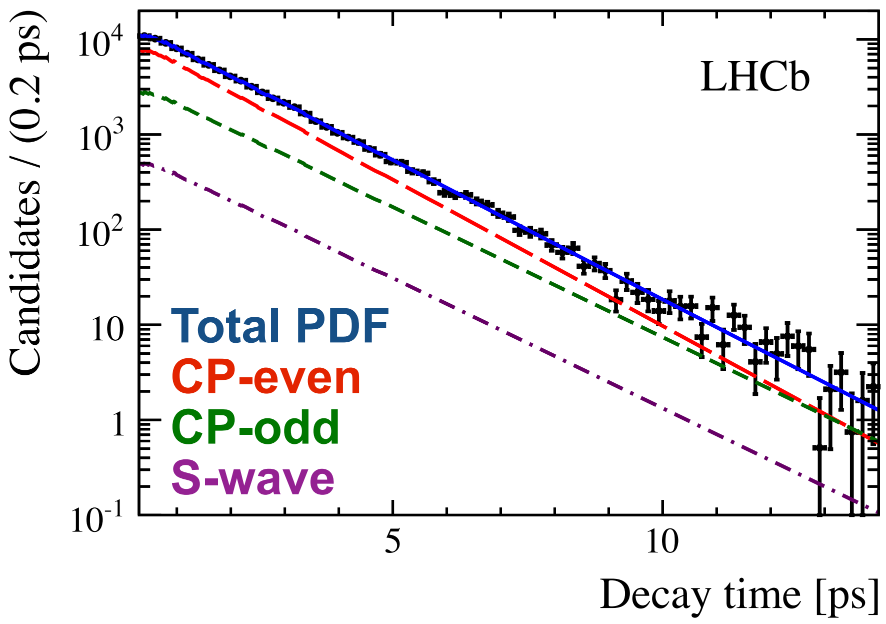


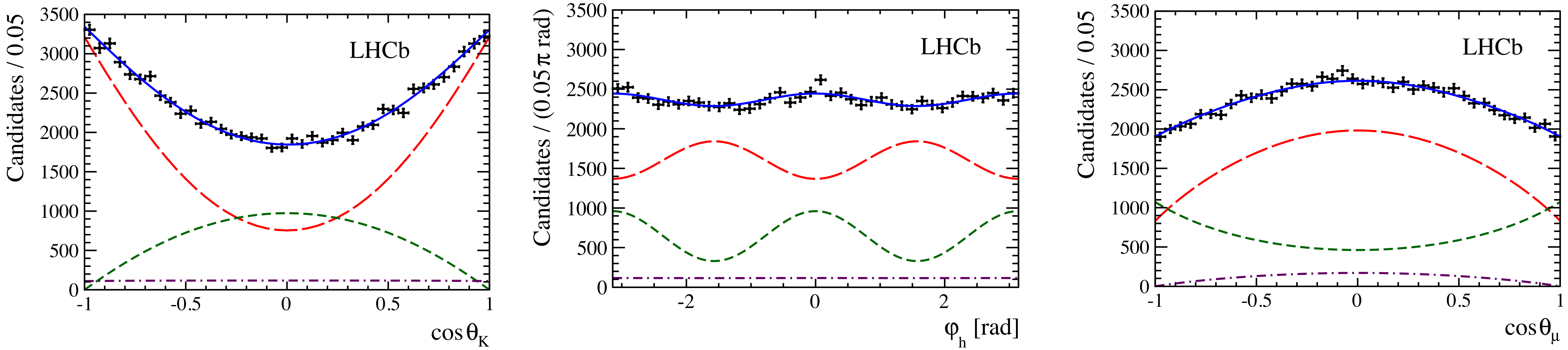
Measurement of ϕ_s in $B_s \to J/\psi K^+K^-$ (3 fb^{-1})

[Phys. Rev. Lett. 114 041801 (2015)]

✦ Results: (polarisation independent)

Parameter	Value
Γ_s [ps^{-1}]	$0.6603 \pm 0.0027 \pm 0.0015$
$\Delta\Gamma_s$ [ps^{-1}]	$0.0805 \pm 0.0091 \pm 0.0032$
ϕ_s [rad]	$-0.058 \pm 0.049 \pm 0.006$
$\lvert\lambda\rvert$	$0.964 \pm 0.019 \pm 0.007$

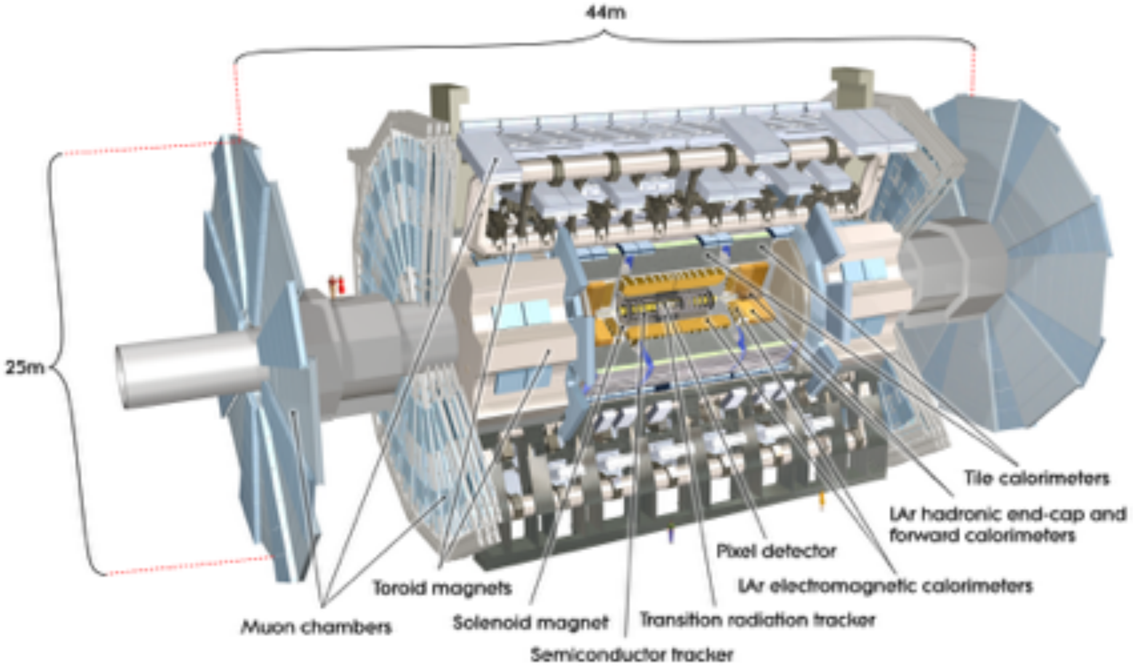




- World most precise single measurement
- Consistant with SM prediction

Measurement of ϕ_s in $B_s \to J/\psi K^+K^-$ (4.9 fb^{-1})

[Phys. Rev. D. 90, 052007 (2014)]



✦ Analysis overview:

- Performed on 2011 data
- Measures ϕ_s, Γ_s and $\Delta\Gamma_s$
  - Time-dependent tagged angular analysis (classic fit)
    - including background contribution
    - S-wave compatible with 0
    - tagging power ~1.5%
    - $|\lambda|$ fixed to unity

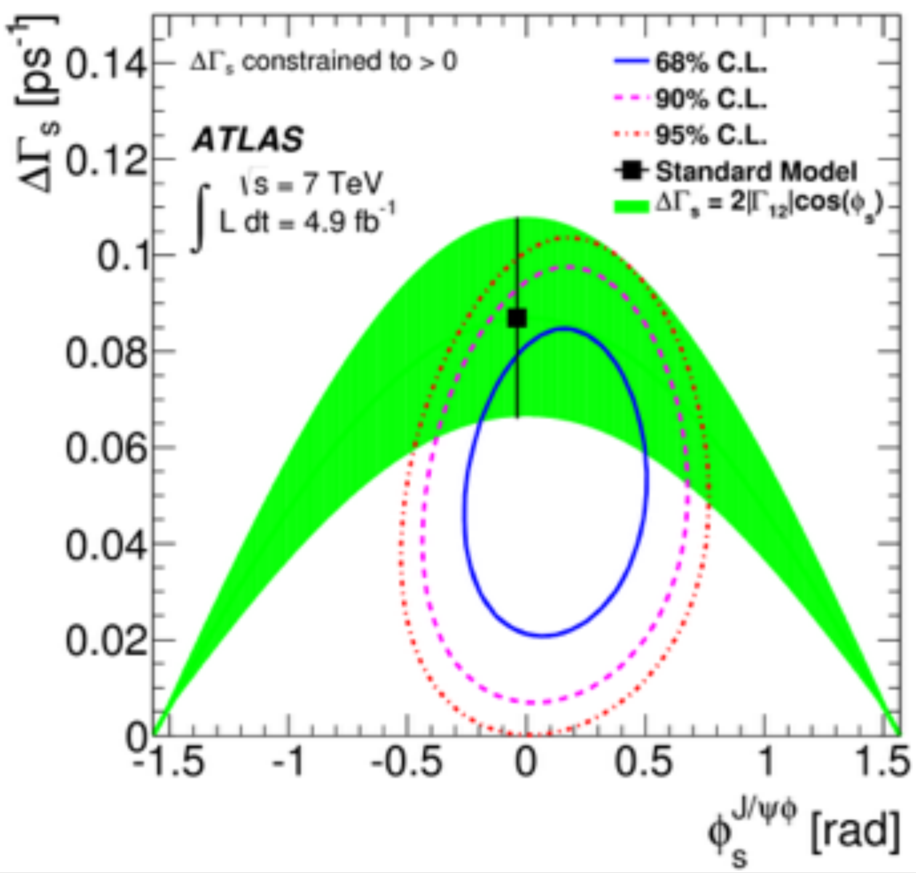
✦ Results:

$$\phi_s = 0.12 \pm 0.25\ (\text{stat.}) \pm 0.05\ (\text{syst.})\ \text{rad}$$

$$\Delta\Gamma_s = 0.053 \pm 0.021\ (\text{stat.}) \pm 0.010\ (\text{syst.})\ \text{ps}^{-1}$$

$$\Gamma_s = 0.677 \pm 0.007\ (\text{stat.}) \pm 0.004\ (\text{syst.})\ \text{ps}^{-1}$$

- Consistant with SM & world average
- Expect an update with 2012 data soon…

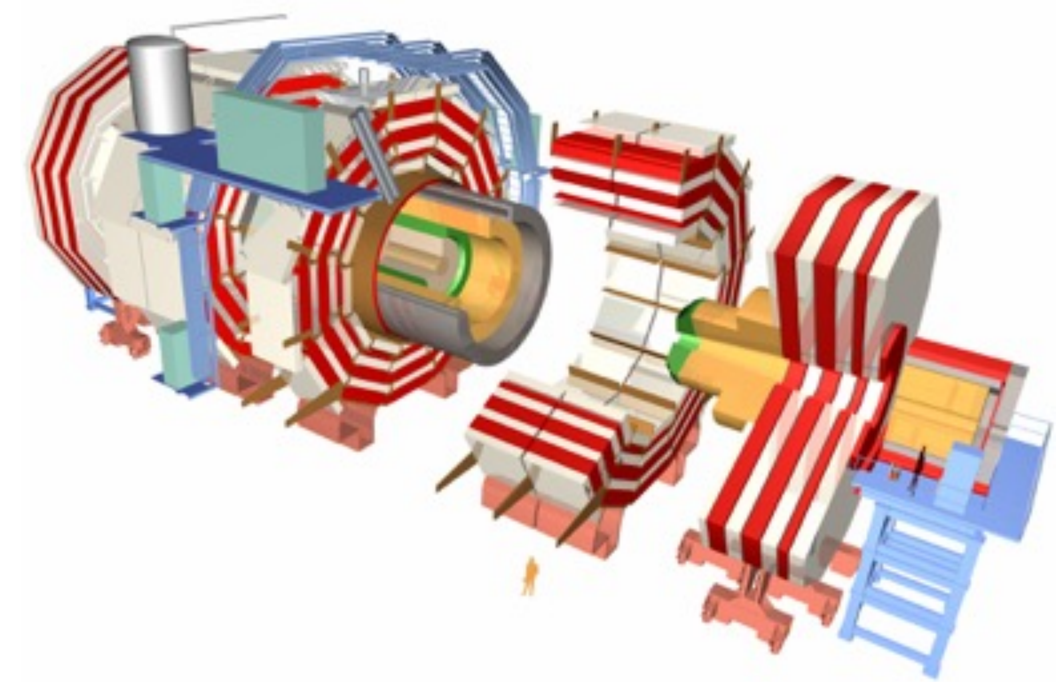


Measurement of ϕ_s in $B_s \rightarrow J/\psi K^+K^-$ (20 fb^{-1})

[CMS-PAS-BPH-13-012]

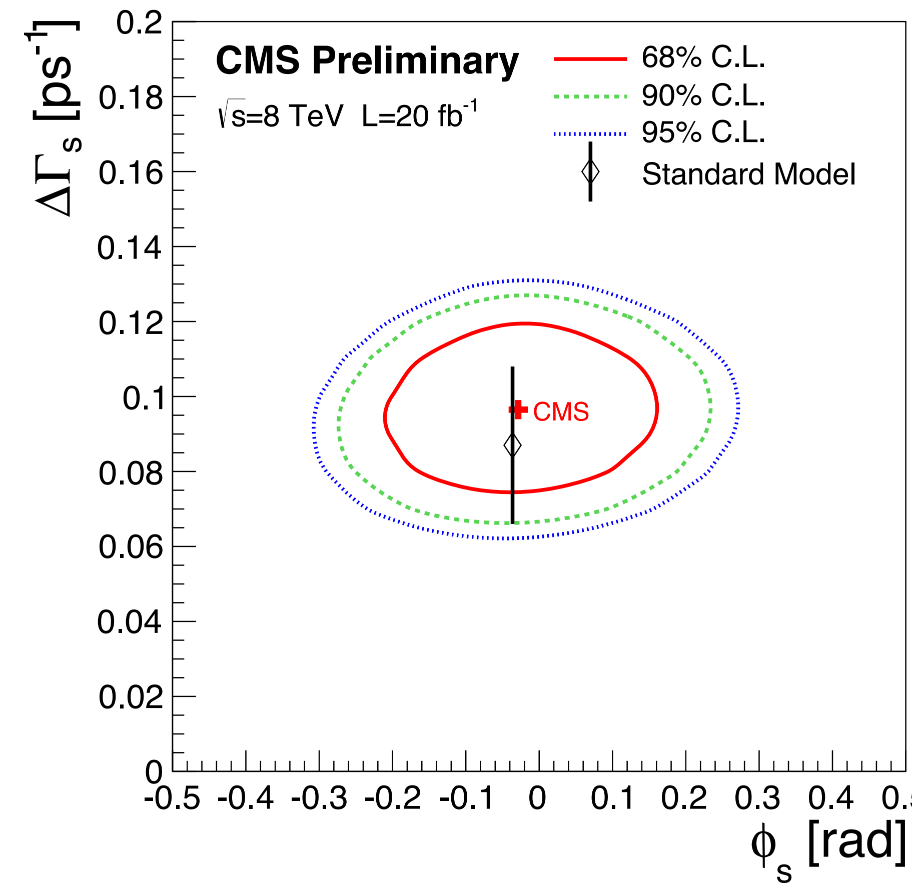
✦ Analysis overview:

- Performed on 2012 data
- Measures ϕ_s and $\Delta\Gamma_s$
  - Time-dependent tagged angular analysis (classic fit)
    - including background contribution
    - S-wave compatible with 0
    - tagging power ~1.0%
    - $|\lambda|$ fixed to unity (let free for syst.)



✦ Preliminary results:

$$\phi_s = -0.03 \pm 0.11\,(\text{stat.}) \pm 0.03\,(\text{syst.})\ \text{rad}\,,$$
$$\Delta\Gamma_s = 0.096 \pm 0.014\,(\text{stat.}) \pm 0.007\,(\text{syst.})\ \text{ps}^{-1}$$



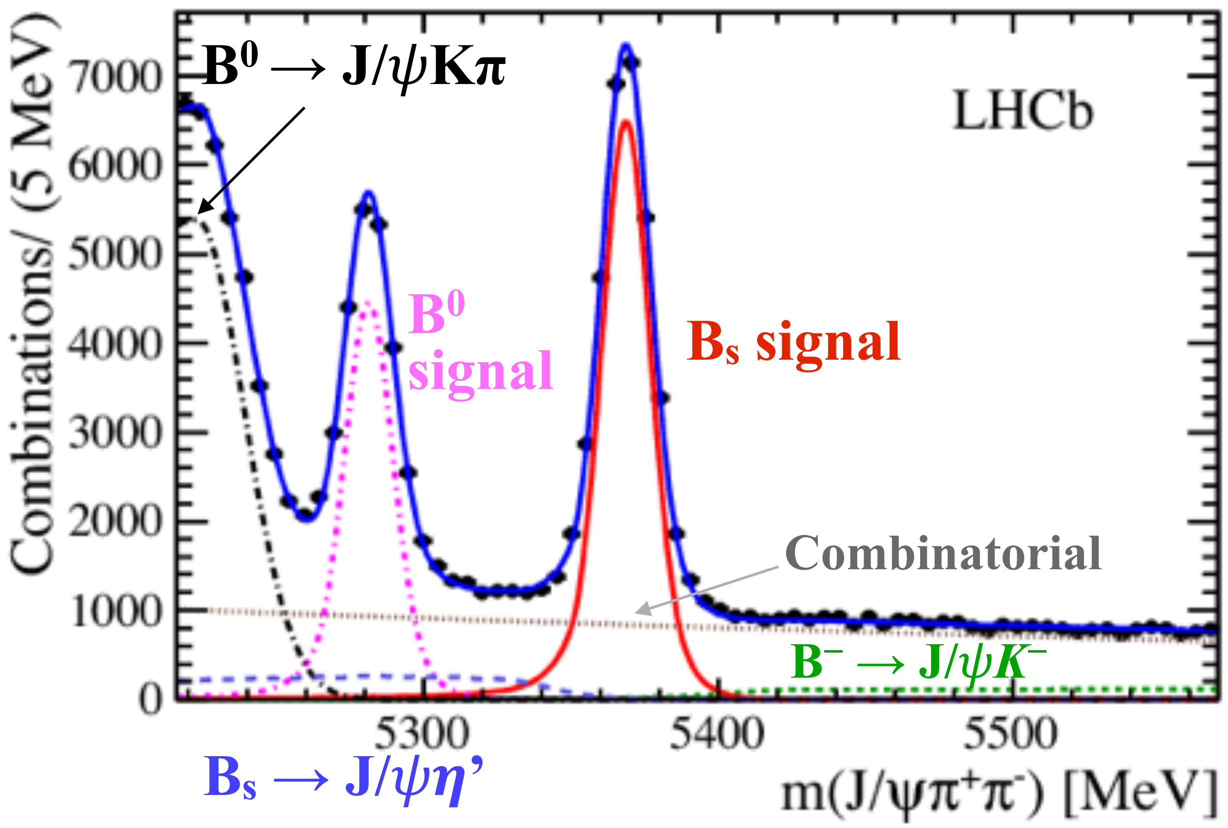
- Consistant with SM & world average

Measurement of ϕ_s in $B_s \to J/\psi \pi^+\pi^-$ ($3\ fb^{-1}$)

[Phys. Lett. B 736 (2014) 186]

✦ Analysis overview:

- Measures ϕ_s, and $|\lambda|$
  - Time-dependent flavor-tagged amplitude analysis
    - ~27k signal events
    - classic fit (signal + background)
    - study $\pi\pi$ invariant-mass up to $m_{\pi\pi}$ ~2.3 GeV
    - tagging power ~3.9%
    - amplitude fit performed only on events within ± 20 MeV from the Bs mass peak
    - includes 5 resonant + 1 non-resonant amplitudes



Measurement of ϕ_s in $B_s \rightarrow J/\psi\, \pi^+\pi^-$ (3 fb^{-1})

[Phys. Lett. B 736 (2014) 186]

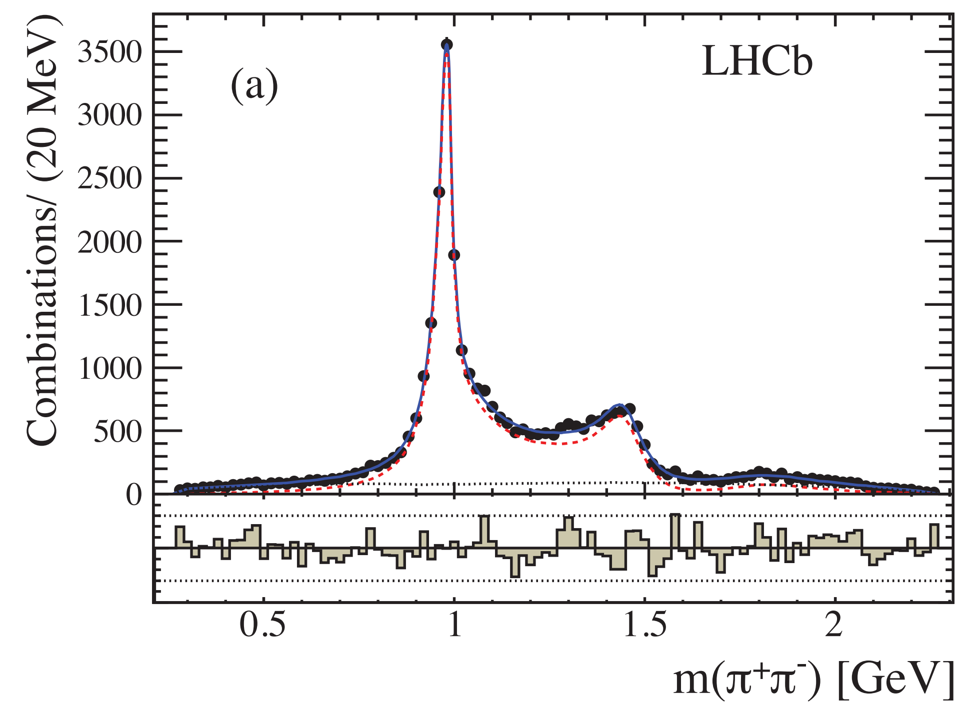
✦ Results:

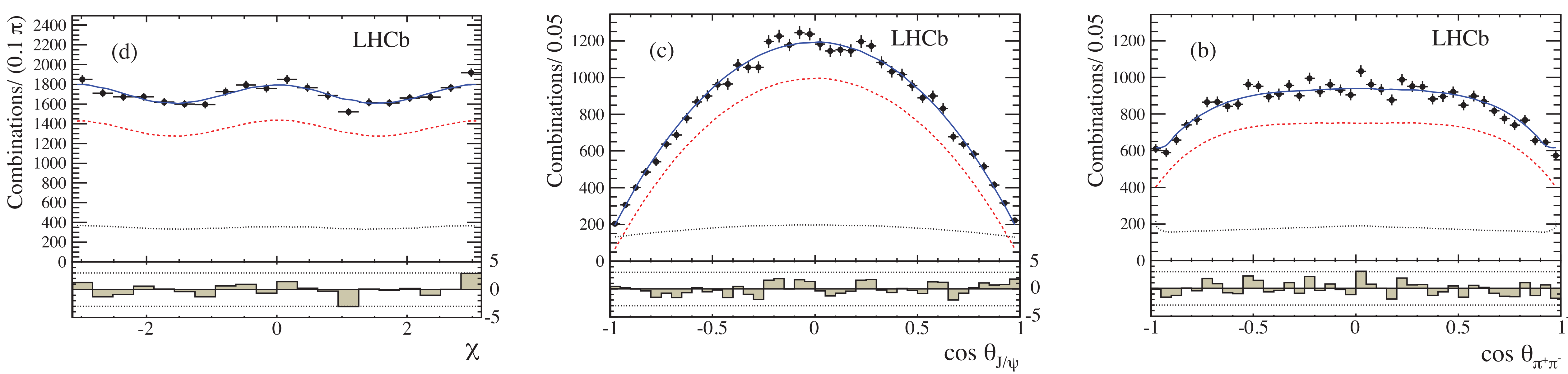
$$\phi_s = 0.070 \pm 0.068 \pm 0.008 \text{ rad}$$

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

$$\phi_s = 0.075 \pm 0.067 \pm 0.008 \text{ rad}$$

for λ fixed to one (no direct CPV)





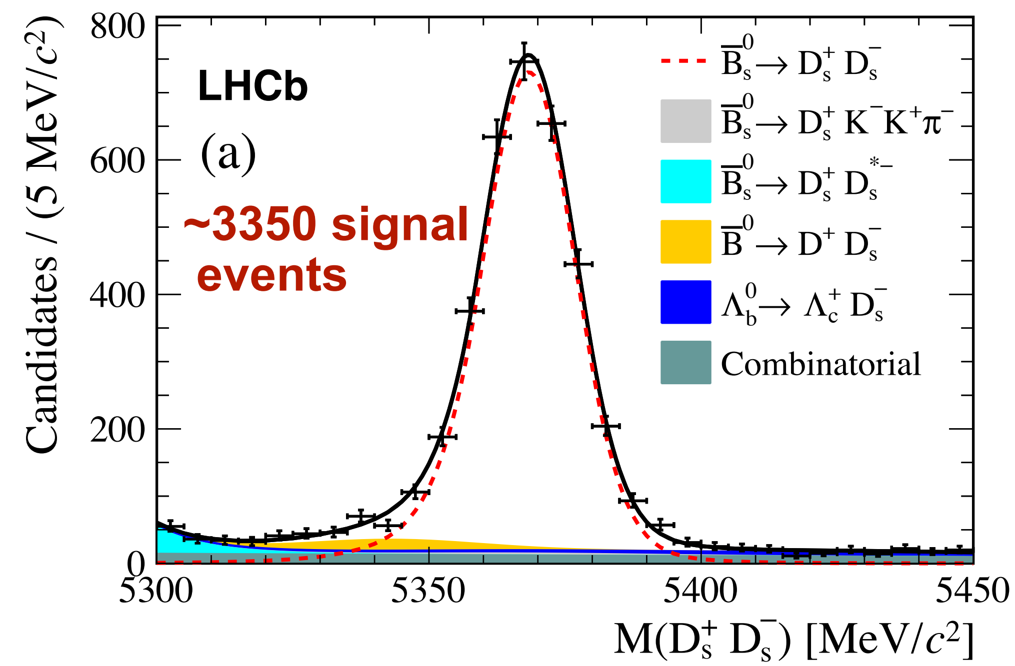
- World second most precise single measurement
- Consistant with SM prediction & world average

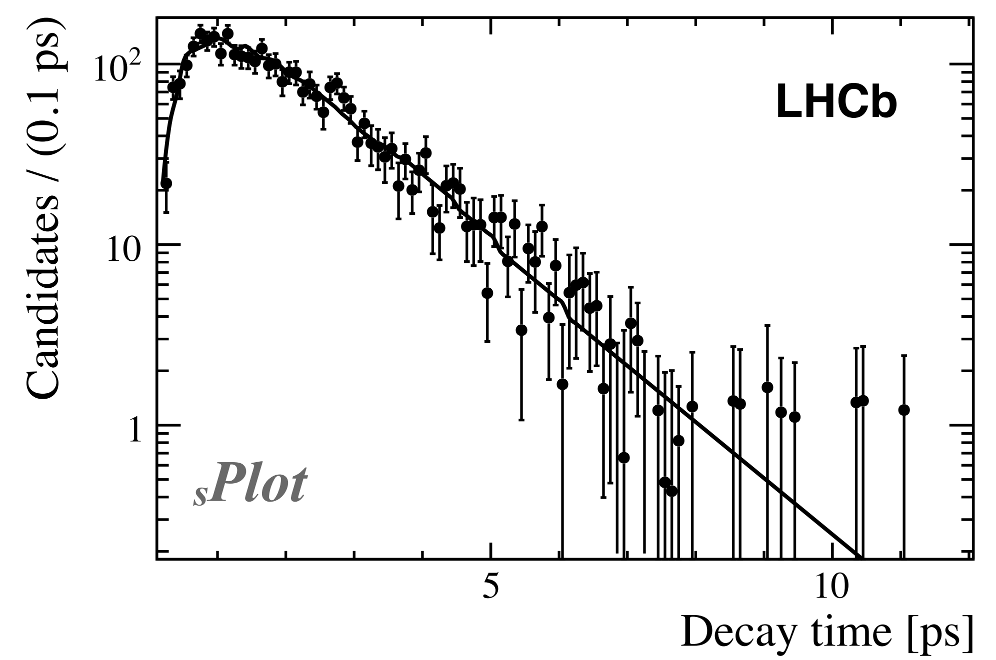
Measurement of ϕ_s in $B_s \to D^+_s D^-_s$ (3 fb^{-1})

[Phys. Rev. Lett. 113 (2014) 211801]

✦ Analysis overview:

- Measures ϕ_s and $|\lambda|$
  - Time-dependent flavor-tagged analysis (classic fit)
    - purely CP-even mode (no angular fit needed)
    - D_s reconstructed as $KK\pi$, $K\pi\pi$ or $\pi\pi\pi$
    - Using $B^0 \to D^- D^+_s$ as control channel
    - tagging power ~5.3%





✦ Results:

$$\phi_s = 0.02 \pm 0.17\,(\text{stat}) \pm 0.02\,(\text{syst})\ \text{rad}$$

$$|\lambda| = 0.91\ ^{+0.18}_{-0.15}\,(\text{stat}) \pm 0.02\,(\text{syst})$$

- Consistant with SM & world average

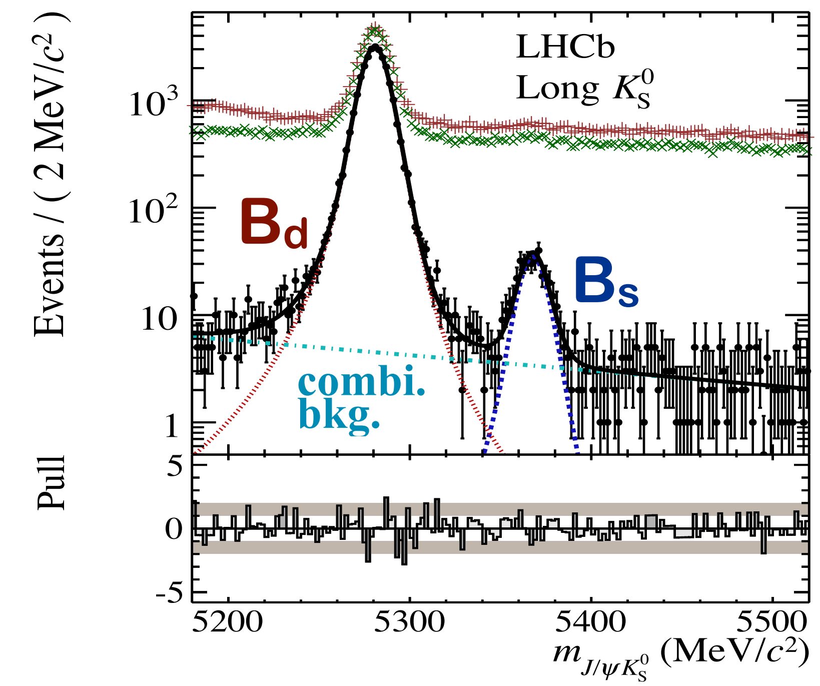
Measurement of TDCP asymmetries in $B_s \to J/\psi K^0_S$ (3 fb^{-1})

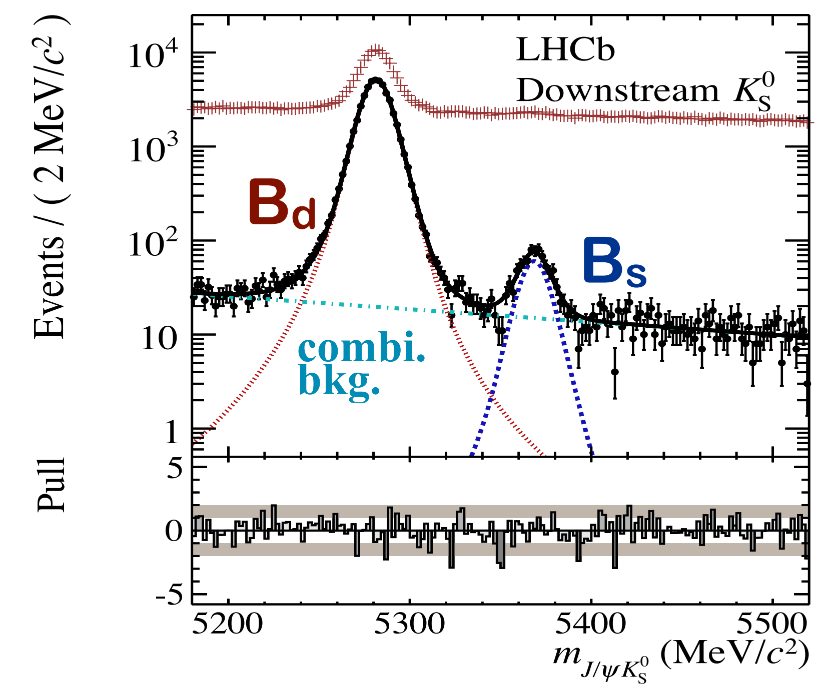
Article submitted to JHEP [arXiv:1503.07055]

✦ Analysis overview:

- First **time-dependent CPV** measurements in this channel
- Flavor-tagged time-dependent analysis:
  - simultaneous fit to a mixed sample of many B_d and few B_s events (100/1)
  - use of multivariate selection trained on B_d proxy
  - split sample in two categories:
    - Downstream K_S (no velo hits)
    - Long K_S (velo hits → better resolution)
  - tagging power:
    - B_s ~ 3.8% / B_d ~ 2.6%
  - also fits for sin2β (as cross-check)
    - see previous talk

Yield	Long K^0_S	Downstream K^0_S
$B^0 \to J/\psi K^0_S$	27 801 ± 168	51 351 ± 231
$B^0_s \to J/\psi K^0_S$	307 ± 20	601 ± 30
Combinatorial background	658 ± 37	2 852 ± 74





Measurement of TDCP asymmetries in $B_s \to J/\psi K^0_S$ (3 fb^{-1})

Article submitted to JHEP [arXiv:1503.07055]

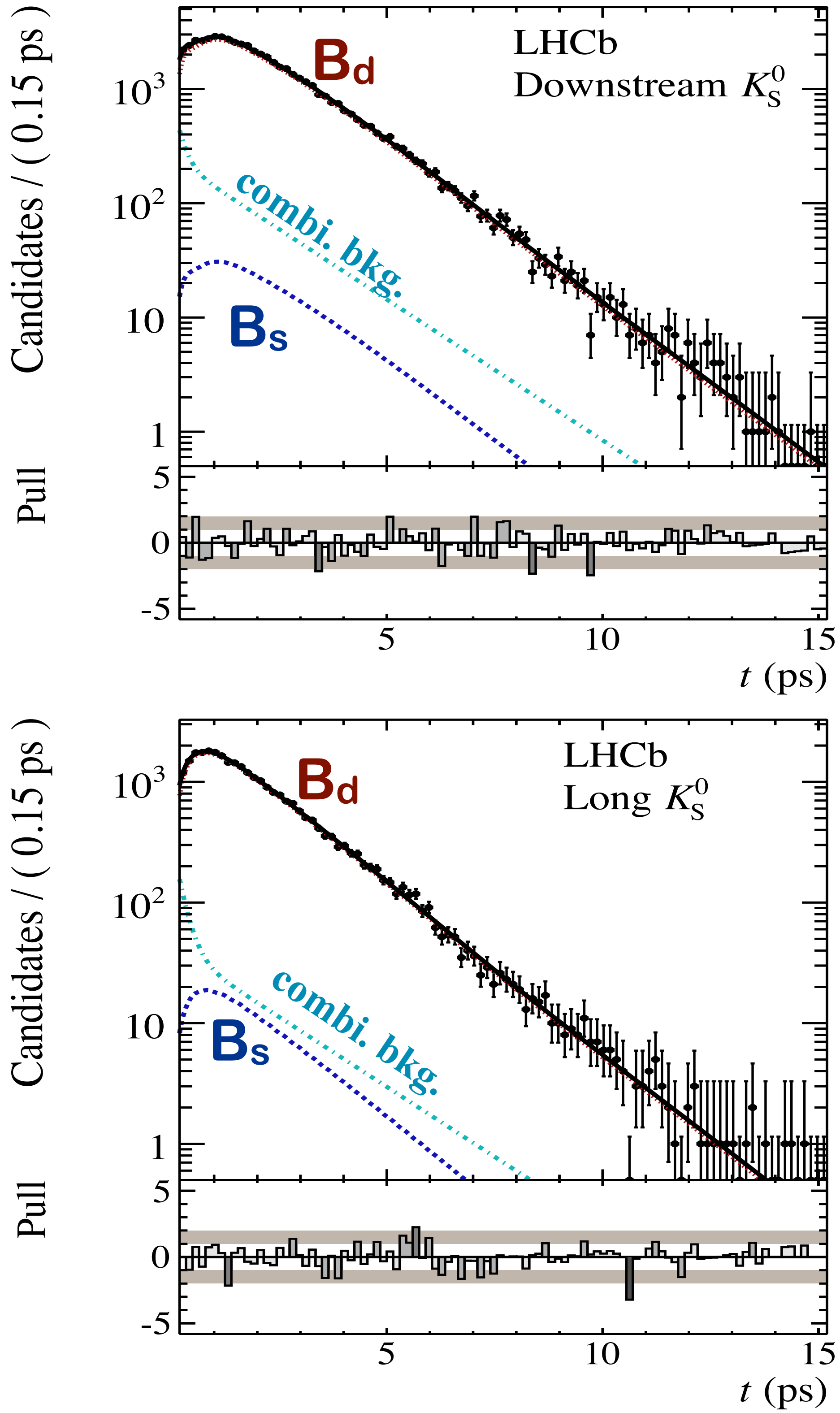
✦ Preliminary results:

$$\mathcal{A}_{\Delta\Gamma}(B^0_s \to J/\psi K^0_S) = 0.49 \pm {}^{0.77}_{0.65}\,(\text{stat}) \pm 0.06\,(\text{syst})$$
$$C_{\text{dir}}(B^0_s \to J/\psi K^0_S) = -0.28 \pm 0.41\,(\text{stat}) \pm 0.08\,(\text{syst})$$
$$S_{\text{mix}}(B^0_s \to J/\psi K^0_S) = -0.08 \pm 0.40\,(\text{stat}) \pm 0.08\,(\text{syst})$$

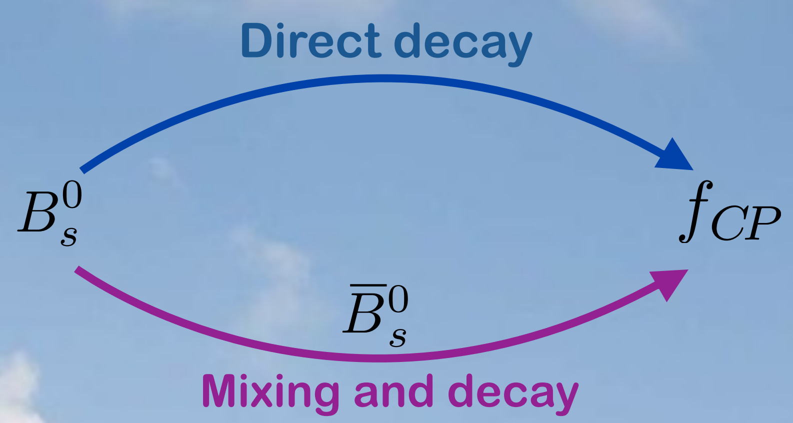
Recent prediction: [arXiv:1412.6834]

$$\mathcal{A}_{\Delta\Gamma}(B^0_s \to J/\psi K^0_S) = 0.957 \pm 0.061$$
$$C_{\text{dir}}(B^0_s \to J/\psi K^0_S) = 0.003 \pm 0.021$$
$$S_{\text{mix}}(B^0_s \to J/\psi K^0_S) = 0.29 \pm 0.20$$

- Successful proof of concept waiting for more statistics
- Can be used to estimate the penguin effects in $\sin 2\beta$ as well as in ϕ_s



Outline



1 Physics motivation

2 Measurement ingredients

3 Measurement of ϕ_s:

- $B_s \to J/\psi K^+K^-$ (LHCb, CMS, ATLAS)
- $B_s \to J/\psi \pi^+\pi^-$
- $B_s \to D^+_s D^-_s$ (LHCb)
- $B_s \to J/\psi K^0_S$

4 Constraining penguins in ϕ_s:

- $B_d \to J/\psi \pi^+\pi^-$ (LHCb)

Measurement of β in $B_d \to J/\psi\, \pi^+\pi^-$ (3 fb^{-1})

[Phys. Lett. B742 (2015) 38]

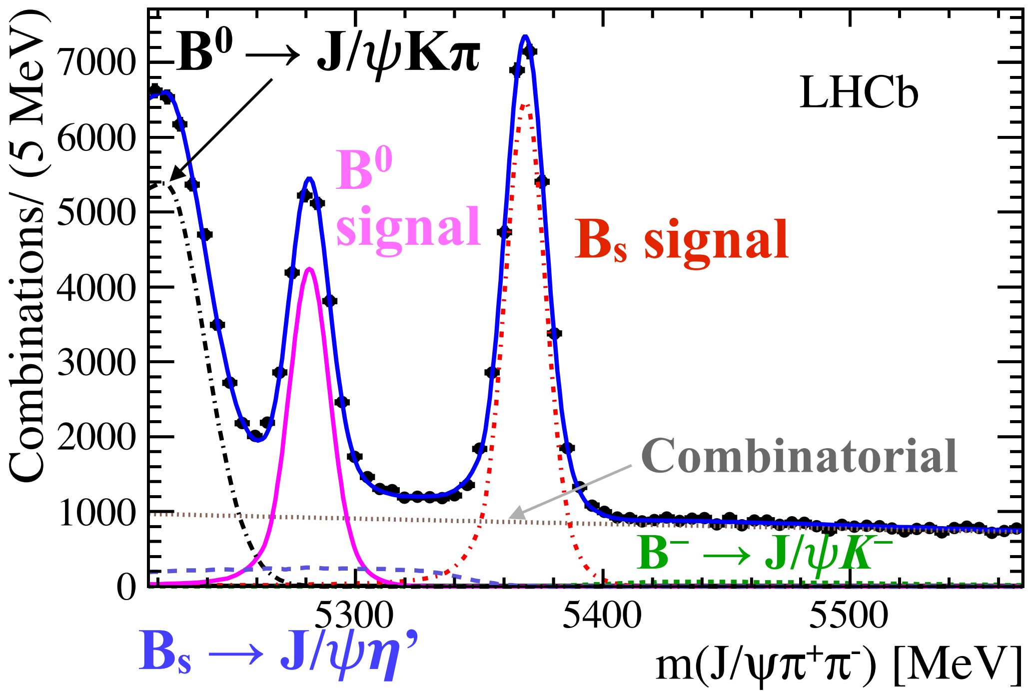
Limits on penguin effects in ϕ_s

✦ Analysis overview:

- **Measures $2\beta^{eff}$ and α_{CP}**

$$\alpha_{CP} = \frac{1-|\lambda_f|}{1+|\lambda_f|}$$

- **Similar to $B_s \to J/\psi\, \pi^+\pi^-$**
  - **Time-dependent flavor-tagged angular analysis** (classic fit)
    - ~ 18k signal events



✦ Results:

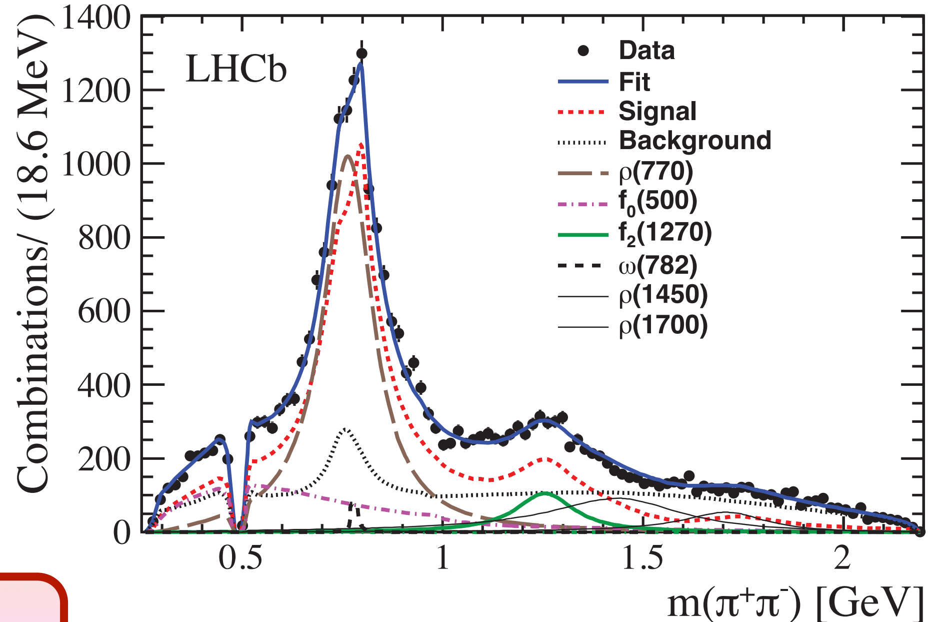
$$2\beta^{\rm eff}(B^0 \to J/\psi\rho^0) = (41.7 \pm 9.6({\rm stat})^{+2.8}_{-6.3}({\rm syst}))^\circ$$

$$\alpha_{CP}(B^0 \to J/\psi\rho^0) = -(32 \pm 28({\rm stat})^{+7}_{-9}({\rm syst})) \times 10^{-3}$$

Used in penguin contribution estimation (next slide)

$$\mathcal{S}_{J/\psi\rho^0} = -0.66^{+0.13}_{-0.12}({\rm stat})^{+0.09}_{-0.03}({\rm syst})$$

$$\mathcal{C}_{J/\psi\rho^0} = -0.063 \pm 0.056({\rm stat})^{+0.019}_{-0.014}({\rm syst})$$



Most precise CP asymmetry measurement in this mode

Measurement of β in $B_d \to J/\psi\, \pi^+\pi^-$ (3 fb^{-1})

[Phys. Lett. B742 (2015) 38]

Limits on penguin effects in ϕ_s

✦ Limits on penguin effects:

$$A(B^0 \to J/\psi\rho^0) = \tilde{A}\left[1 - ae^{i\theta}e^{i\gamma}\right]$$

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

$$\epsilon \equiv \lambda_c^2/(1-\lambda_c^2) = 0.0534$$

$$|\lambda_f| = \left|\frac{1 - ae^{i\theta}e^{-i\gamma}}{1 - ae^{i\theta}e^{i\gamma}}\right| \qquad \alpha_{CP} = \frac{1-|\lambda_f|}{1+|\lambda_f|}$$

$$\Delta 2\beta = \left(2\beta^{\rm eff} - 2\beta\right) = -\arg\left(\frac{1 - ae^{i\theta}e^{-i\gamma}}{1 - ae^{i\theta}e^{i\gamma}}\right)$$

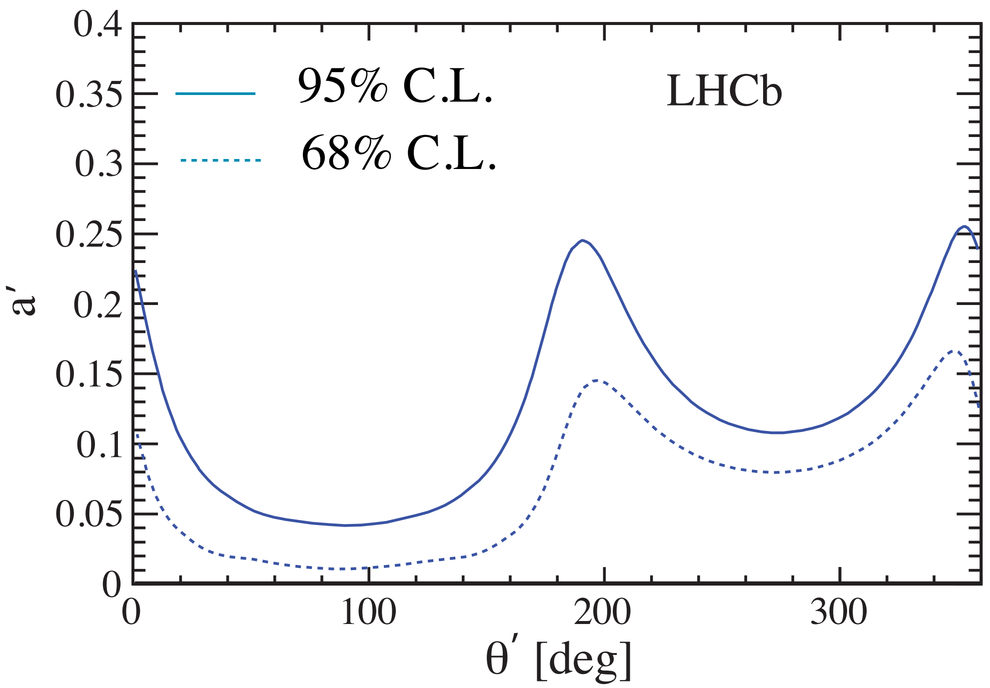
$$\Delta\phi_s = -\arg\left(\frac{(\lambda'_f e^{2i\gamma} - 1) + \epsilon(\lambda'_f - 1)}{(\lambda'_f e^{2i\gamma} - 1) + \epsilon(\lambda'_f - 1)e^{2i\gamma}}\right) \qquad \lambda'_f \equiv |\lambda_f| e^{-i\Delta 2\beta}$$

- **Assuming perfect SU(3) flavor symmetry:** $a = a' \quad \theta = \theta'$

$$\Delta 2\beta = \left(2\beta^{J/\psi\rho} - 2\beta^{J/\psi K_S^0}\right) = \left(-0.9 \pm 9.7({\rm stat})^{+2.8}_{-6.3}({\rm syst})\right)^\circ$$

$$\Delta\phi_s \sim -\epsilon\Delta 2\beta$$

$$\Delta\phi_s \in [-1.05^\circ, 1.18^\circ] \text{ at } 95\% \text{ C.L.}$$

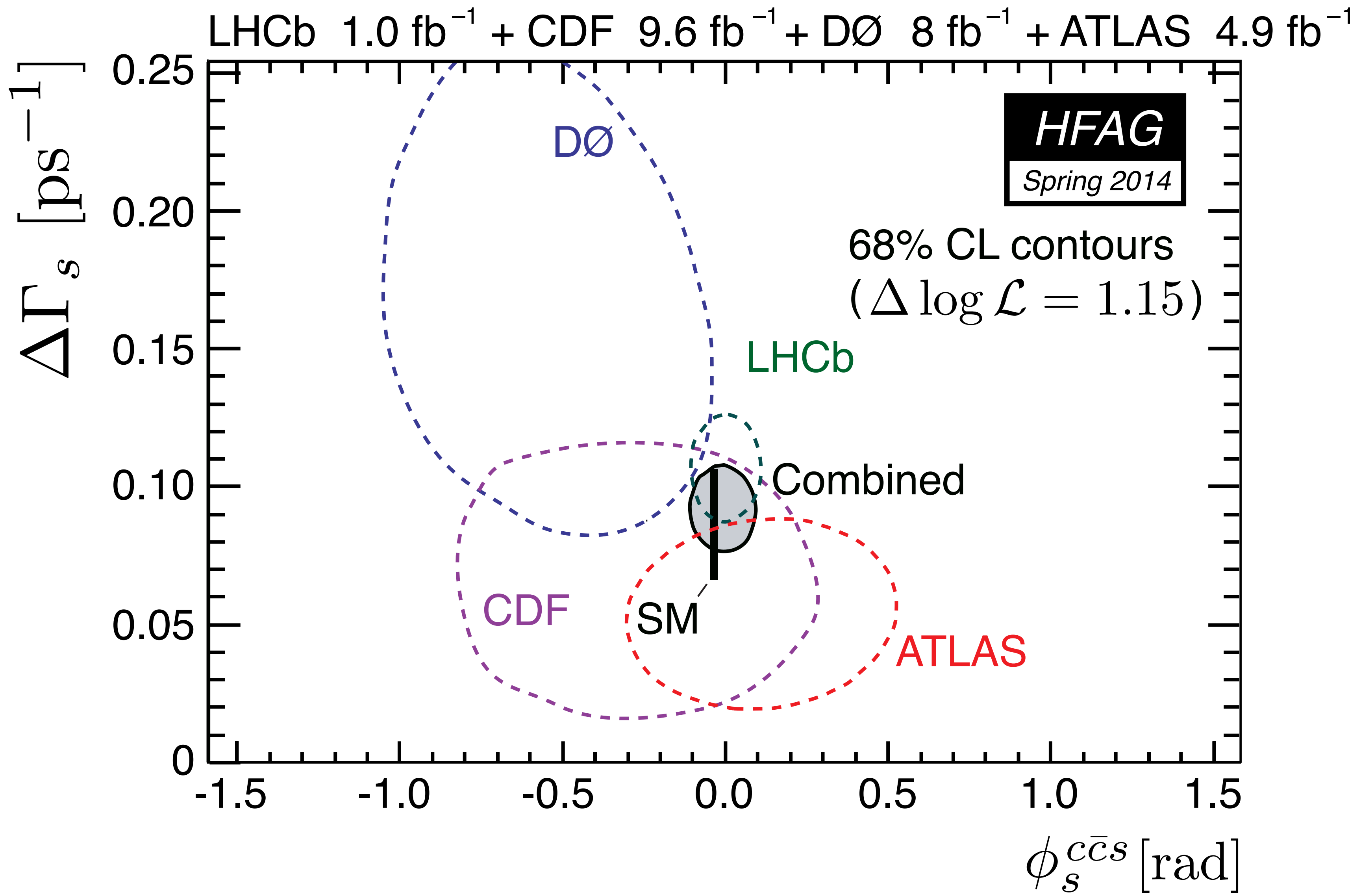


First experimental constraint on penguin contribution on ϕs

IN SUMMARY

✦ **Toward a precise measurement of ϕ_s:**

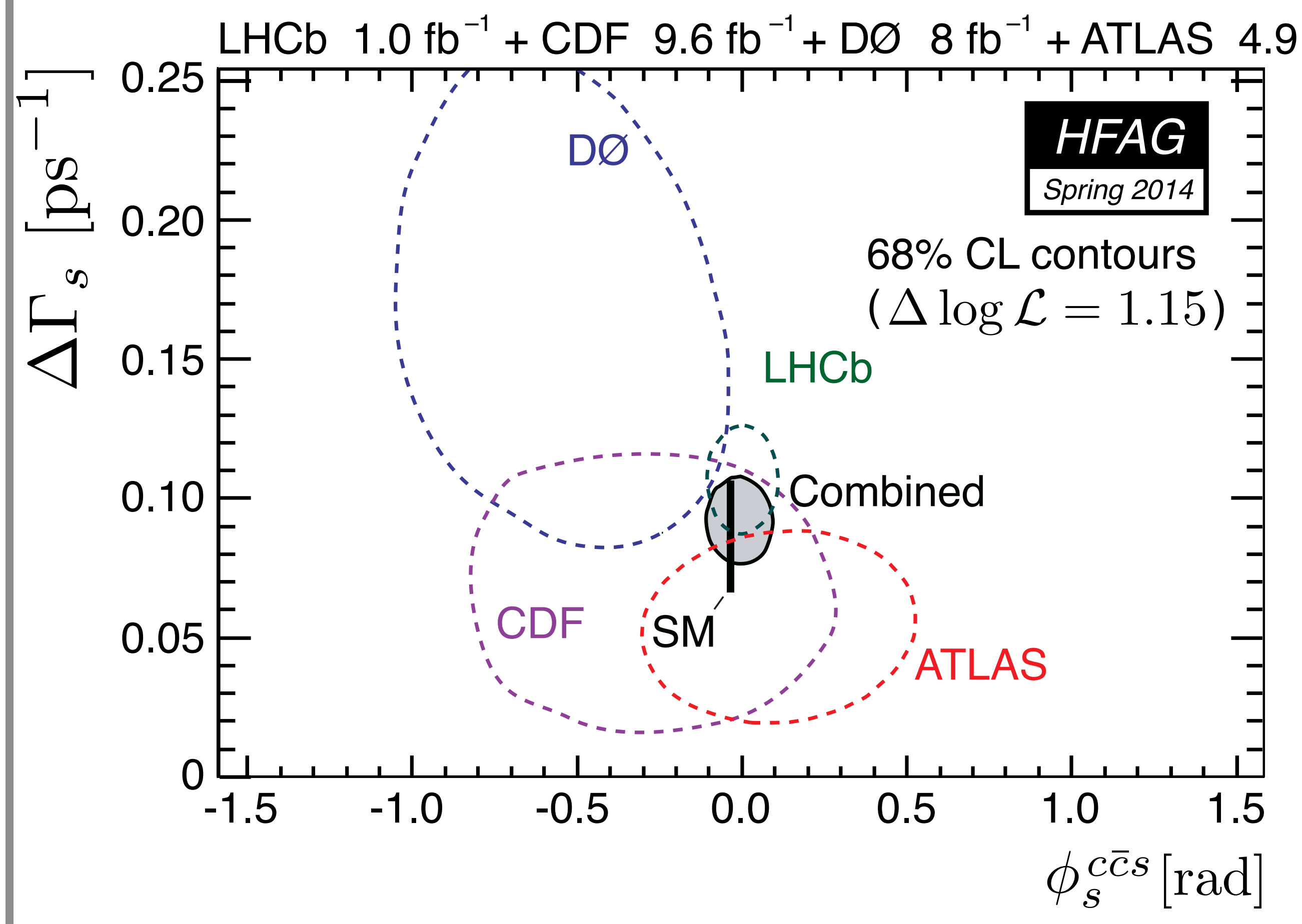
State of the art at FPCP 2014

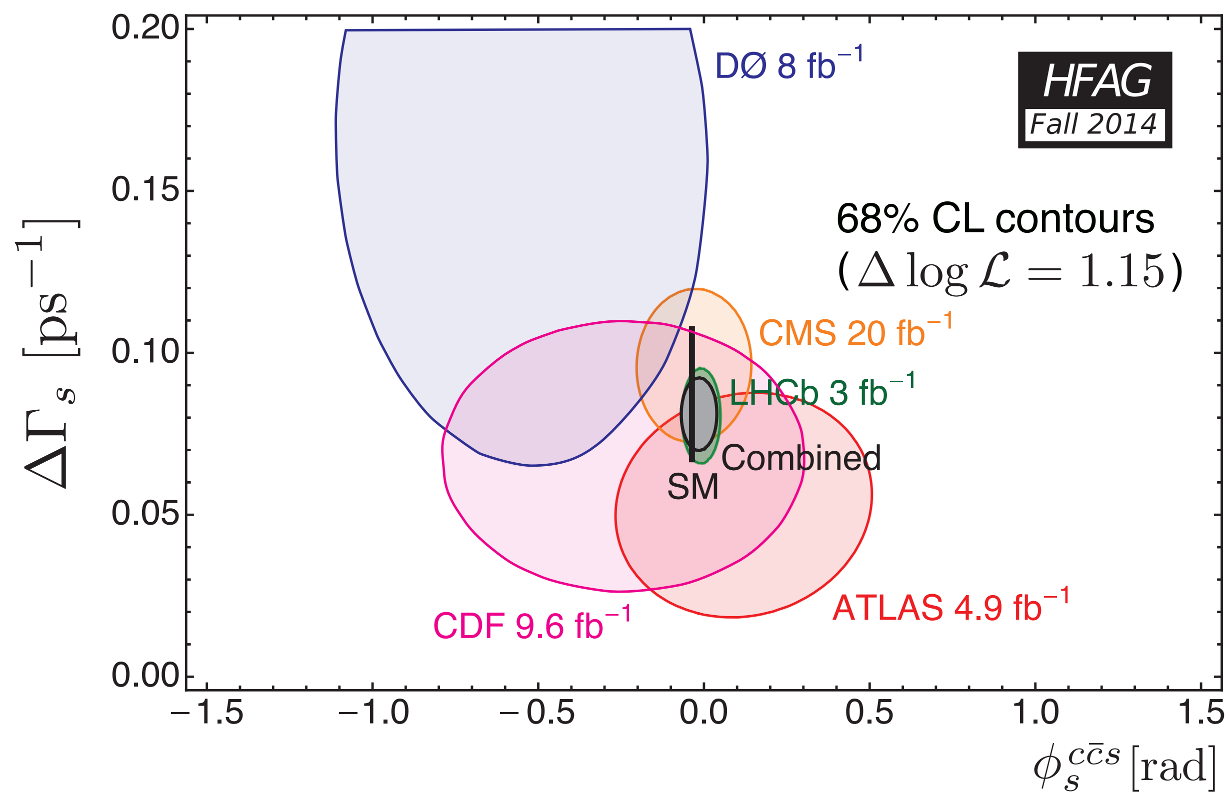


IN SUMMARY

✦ **Toward a precise measurement of ϕ_s:**

State of the art at FPCP 2015





In summary

✦ **Toward a precise measurement of ϕ_s:**

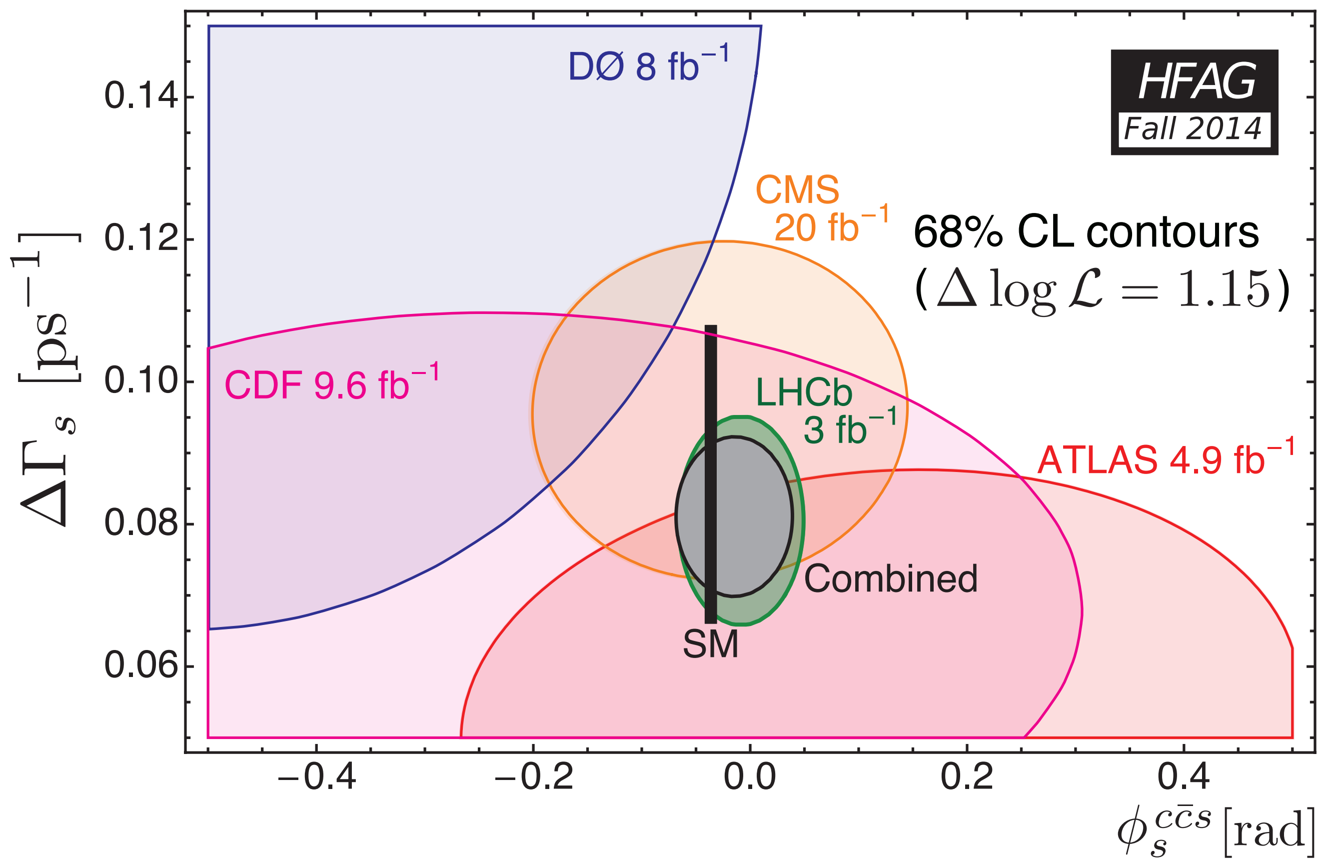
State of the art at FPCP 2015

$$\phi_s^{c\bar{c}s} = -2\beta_s + \Delta\phi_s^{\text{Peng.}} + \delta^{\text{NP}}$$
$$= -0.015 \pm 0.035$$ [HFAG]

$$-2\beta_s = -0.0365^{+0.0013}_{-0.0012}$$ [CKMFitter]

$$\Delta\phi_s^{\text{Peng.}} = 0.001 \pm 0.010$$

$$\delta^{\text{NP}} = ??$$



- **Entered era of precise CPV measurement in the B_s system**
- **First step in controlling penguin contributions**
- **Precision will further increase with LHC RunII & Upgrades adding statistics and new measurements!**

SPARE SLIDES

★ **Mixing-induced CP violation in penguin dominated transitions:** $\phi_s^{s\bar{s}s}$

- $\mathbf{B_s \rightarrow \phi\phi}$ [Phys. Rev. D90, 052011 (2014)]

★ **Complementary material on** $\phi_s^{c\bar{c}s}$ **measurements**

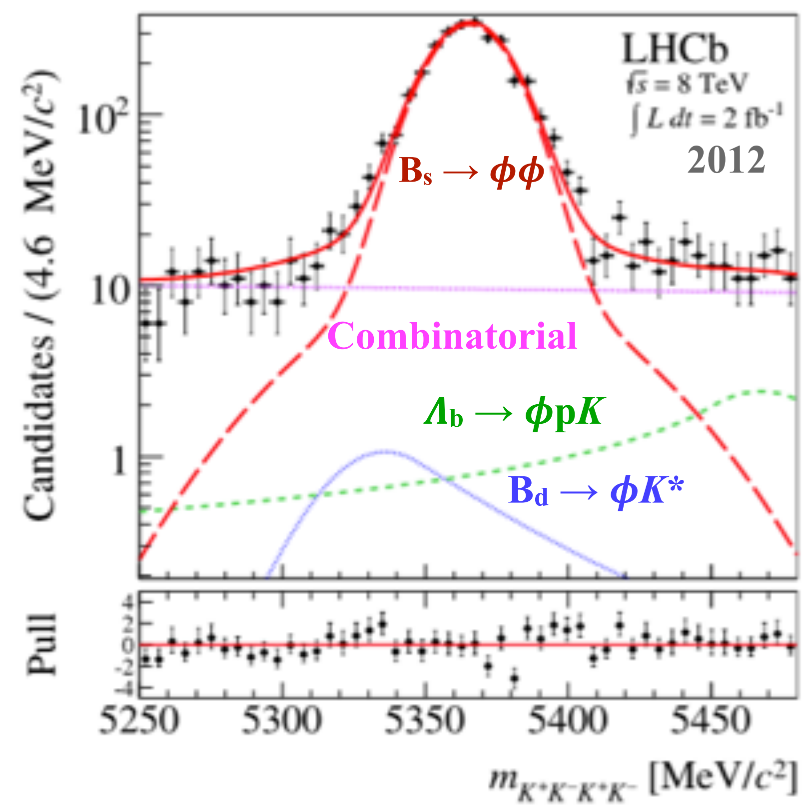
- $\mathbf{B_{d(s)} \rightarrow \pi^+\pi^-(K^+K^-)}$ [Phys. Lett. B 741 (2015) 1]
  Analysis not presented here.
  Making use of CKM angle γ as input in the determination of $-2\beta_s$

Measurement of CP violation in $B_s \to \phi\phi$ (3 fb^{-1})

[Phys. Rev. D90, 052011 (2014)]

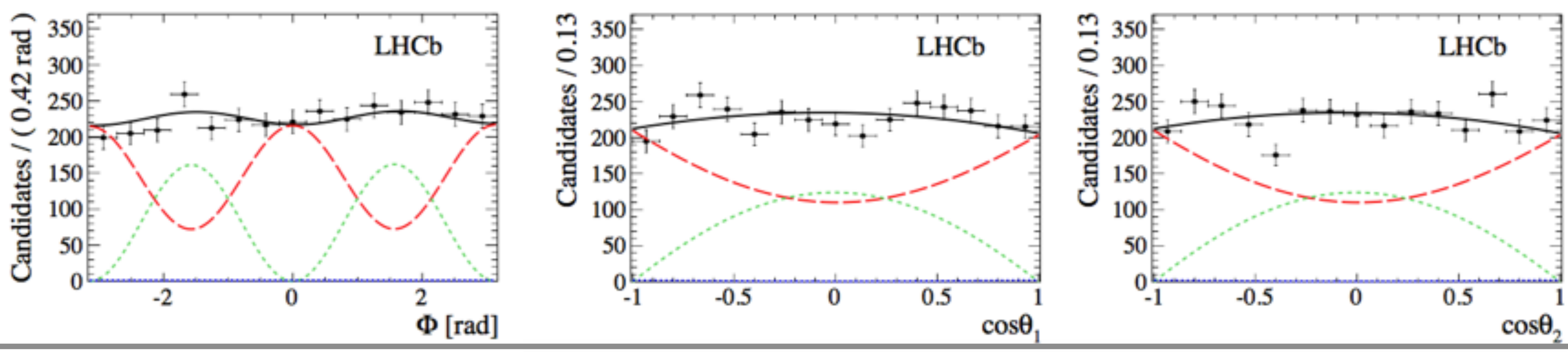
✦ Analysis overview:

- ϕ_s in $b \to s\bar{s}s$ transitions:
  - Dominated by gluonic penguin loops
  - Good sensitivity to NP
  - SM prediction $\phi_s(b \to s\bar{s}s) \sim 0$
- Time-dependent flavor-tagged angular analysis (using $_s$Weights):
  - ~ 4000 signal events



✦ Results:

$$\phi_s = -0.17 \pm 0.15\,(\text{stat}) \pm 0.03\,(\text{syst})\ \text{rad},$$
$$|\lambda| = 1.04 \pm 0.07\,(\text{stat}) \pm 0.03\,(\text{syst}).$$



Measurement of ϕ_s
Motivations for the Upgrades

[CERN-LHCC-2012-007] LHCb Upgrade TDR

Statistical uncertainties

Type		Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\text{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing		$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [9]	0.025	0.008	~ 0.003
	$\phi_s^{c\bar{c}s}$	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [10]	0.045	0.014	~ 0.01
		$A_{\text{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic		$2\beta_s^{\text{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
penguin	$\phi_s^{s\bar{s}s}$	$2\beta_s^{\text{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
		$2\beta^{\text{eff}}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02

[ATL-PHYS-PUB-2013-010]

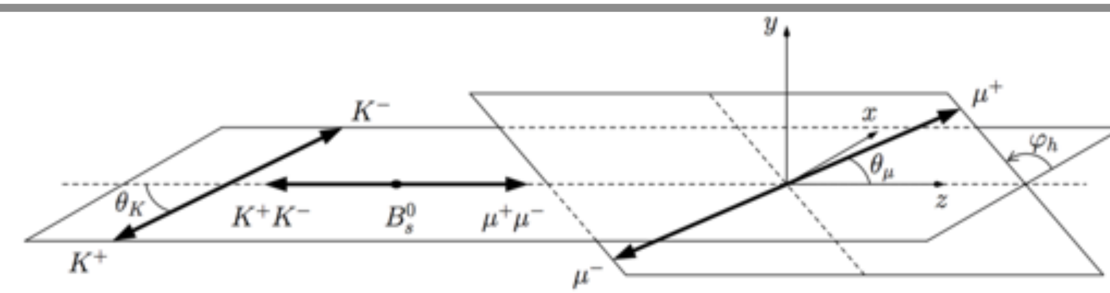
	2011	2012	2015-17		2019-21	2023-30+
Detector	current	current	IBL		IBL	ITK
Average interactions per BX $<\mu>$	6-12	21	60		60	200
Luminosity, fb^{-1}	4.9	20	100		250	3 000
Di-μ trigger p_T thresholds, GeV	4 - 4(6)	4 - 6	6 - 6	11 - 11	11 - 11	11 - 11
Signal events per fb^{-1}	4 400	4 320	3 280	460	460	330
Signal events	22 000	86 400	327 900	45 500	114 000	810 000
Total events in analysis	130 000	550 000	1 874 000	284 000	758 000	6 461 000
MC $\sigma(\phi_s)$ (stat.), rad	0.25	0.12	0.054	0.10	0.064	0.022

- **Will be on the verge of reaching theoretical uncertainties!**

Measurement of ϕ_s in $B_s \to J/\psi\, K^+K^-$ (3 fb^{-1})

[Phys. Rev. Lett. 114 041801 (2015)]

$$\frac{d^4\Gamma(t)}{dm^2_{KK}\,d\cos\theta_K\,d\cos\theta_l\,d\phi} = \sum_{k=1}^{10} N_k h_k(t) f_k(\theta_K, \theta_l, \phi),$$



$$h_k(t) = \frac{3}{4\pi} e^{-\Gamma t}\left\{a_k \cosh\frac{\Delta\Gamma t}{2} + b_k \sinh\frac{\Delta\Gamma t}{2} + c_k\cos(\Delta m t) + d_k \sin(\Delta m t)\right\}.$$

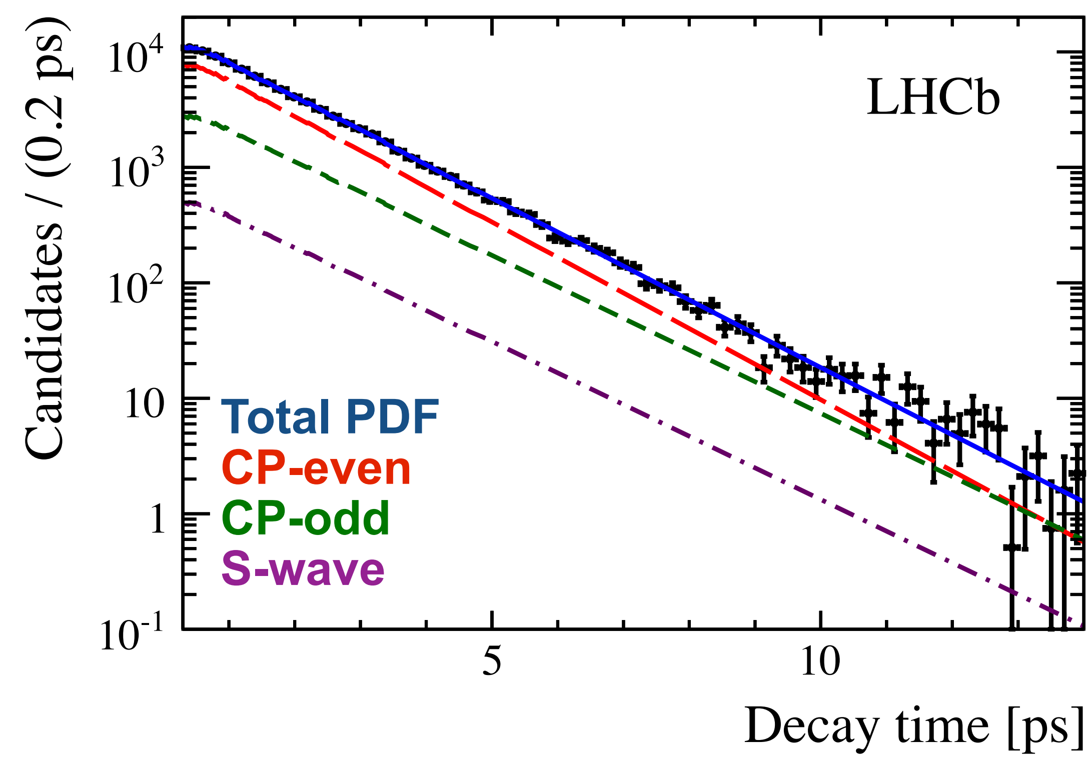
f_k	N_k	a_k	b_k	c_k	d_k
$c_K^2 s_l^2$	$\lvert A_0\rvert^2$	$\frac{1}{2}(1+\lvert\lambda_0\rvert^2)$	$-\lvert\lambda_0\rvert\cos(\phi_0)$	$\frac{1}{2}(1-\lvert\lambda_0\rvert^2)$	$\lvert\lambda_0\rvert\sin(\phi_0)$
$\frac{1}{2}s_K^2(1-c_\phi^2 s_l^2)$	$\lvert A_\parallel\rvert^2$	$\frac{1}{2}(1+\lvert\lambda_\parallel\rvert^2)$	$-\lvert\lambda_\parallel\rvert\cos(\phi_\parallel)$	$\frac{1}{2}(1-\lvert\lambda_\parallel\rvert^2)$	$\lvert\lambda_\parallel\rvert\sin(\phi_\parallel)$
$\frac{1}{2}s_K^2(1-s_\phi^2 s_l^2)$	$\lvert A_\perp\rvert^2$	$\frac{1}{2}(1+\lvert\lambda_\perp\rvert^2)$	$\lvert\lambda_\perp\rvert\cos(\phi_\perp)$	$\frac{1}{2}(1-\lvert\lambda_\perp\rvert^2)$	$-\lvert\lambda_\perp\rvert\sin(\phi_\perp)$
$s_K^2 s_l^2 s_\phi c_\phi$	$\lvert A_\perp A_\parallel\rvert$	$\frac{1}{2}\big[\sin(\delta_\perp-\delta_\parallel)-\lvert\lambda_\perp\lambda_\parallel\rvert \sin(\delta_\perp-\delta_\parallel-\phi_\perp+\phi_\parallel)\big]$	$\frac{1}{2}\big[\lvert\lambda_\perp\rvert\sin(\delta_\perp-\delta_\parallel-\phi_\perp) +\lvert\lambda_\parallel\rvert\sin(\delta_\parallel-\delta_\perp-\phi_\parallel)\big]$	$\frac{1}{2}\big[\sin(\delta_\perp-\delta_\parallel)+\lvert\lambda_\perp\lambda_\parallel\rvert \sin(\delta_\perp-\delta_\parallel-\phi_\perp+\phi_\parallel)\big]$	$-\frac{1}{2}\big[\lvert\lambda_\perp\rvert\cos(\delta_\perp-\delta_\parallel-\phi_\perp) +\lvert\lambda_\parallel\rvert\cos(\delta_\parallel-\delta_\perp-\phi_\parallel)\big]$
$\sqrt{2}s_K c_K s_l c_l c_\phi$	$\lvert A_0 A_\parallel\rvert$	$\frac{1}{2}\big[\cos(\delta_0-\delta_\parallel)+\lvert\lambda_0\lambda_\parallel\rvert \cos(\delta_0-\delta_\parallel-\phi_0+\phi_\parallel)\big]$	$-\frac{1}{2}\big[\lvert\lambda_0\rvert\cos(\delta_0-\delta_\parallel-\phi_0) +\lvert\lambda_\parallel\rvert\cos(\delta_\parallel-\delta_0-\phi_\parallel)\big]$	$\frac{1}{2}\big[\cos(\delta_0-\delta_\parallel)-\lvert\lambda_0\lambda_\parallel\rvert \cos(\delta_0-\delta_\parallel-\phi_0+\phi_\parallel)\big]$	$-\frac{1}{2}\big[\lvert\lambda_0\rvert\sin(\delta_0-\delta_\parallel-\phi_0) +\lvert\lambda_\parallel\rvert\sin(\delta_\parallel-\delta_0-\phi_\parallel)\big]$
$-\sqrt{2}s_K c_K s_l c_l s_\phi$	$\lvert A_0 A_\perp\rvert$	$-\frac{1}{2}\big[\sin(\delta_0-\delta_\perp)-\lvert\lambda_0\lambda_\perp\rvert \sin(\delta_0-\delta_\perp-\phi_0+\phi_\perp)\big]$	$\frac{1}{2}\big[\lvert\lambda_0\rvert\sin(\delta_0-\delta_\perp-\phi_0) +\lvert\lambda_\perp\rvert\sin(\delta_\perp-\delta_0-\phi_\perp)\big]$	$-\frac{1}{2}\big[\sin(\delta_0-\delta_\perp)+\lvert\lambda_0\lambda_\perp\rvert \sin(\delta_0-\delta_\perp-\phi_0+\phi_\perp)\big]$	$-\frac{1}{2}\big[\lvert\lambda_0\rvert\cos(\delta_0-\delta_\perp-\phi_0) +\lvert\lambda_\perp\rvert\cos(\delta_\perp-\delta_0-\phi_\perp)\big]$
$\frac{1}{3}s_l^2$	$\lvert A_S\rvert^2$	$\frac{1}{2}(1+\lvert\lambda_S\rvert^2)$	$\lvert\lambda_S\rvert\cos(\phi_S)$	$\frac{1}{2}(1-\lvert\lambda_S\rvert^2)$	$-\lvert\lambda_S\rvert\sin(\phi_S)$
$\frac{2}{\sqrt{6}}s_K s_l c_l c_\phi$	$\lvert A_S A_\parallel\rvert$	$\frac{1}{2}\big[\cos(\delta_S-\delta_\parallel)-\lvert\lambda_S\lambda_\parallel\rvert \cos(\delta_S-\delta_\parallel-\phi_S+\phi_\parallel)\big]$	$\frac{1}{2}\big[\lvert\lambda_S\rvert\cos(\delta_S-\delta_\parallel-\phi_S) -\lvert\lambda_\parallel\rvert\cos(\delta_\parallel-\delta_S-\phi_\parallel)\big]$	$\frac{1}{2}\big[\cos(\delta_S-\delta_\parallel)+\lvert\lambda_S\lambda_\parallel\rvert \cos(\delta_S-\delta_\parallel-\phi_S+\phi_\parallel)\big]$	$\frac{1}{2}\big[\lvert\lambda_S\rvert\sin(\delta_S-\delta_\parallel-\phi_S) -\lvert\lambda_\parallel\rvert\sin(\delta_\parallel-\delta_S-\phi_\parallel)\big]$
$-\frac{2}{\sqrt{6}}s_K s_l c_l s_\phi$	$\lvert A_S A_\perp\rvert$	$-\frac{1}{2}\big[\sin(\delta_S-\delta_\perp)+\lvert\lambda_S\lambda_\perp\rvert \sin(\delta_S-\delta_\perp-\phi_S+\phi_\perp)\big]$	$-\frac{1}{2}\big[\lvert\lambda_S\rvert\sin(\delta_S-\delta_\perp-\phi_S) -\lvert\lambda_\perp\rvert\sin(\delta_\perp-\delta_S-\phi_\perp)\big]$	$-\frac{1}{2}\big[\sin(\delta_S-\delta_\perp)-\lvert\lambda_S\lambda_\perp\rvert \sin(\delta_S-\delta_\perp-\phi_S+\phi_\perp)\big]$	$-\frac{1}{2}\big[-\lvert\lambda_S\rvert\cos(\delta_S-\delta_\perp-\phi_S) +\lvert\lambda_\perp\rvert\cos(\delta_\perp-\delta_S-\phi_\perp)\big]$
$\frac{2}{\sqrt{3}}c_K s_l^2$	$\lvert A_S A_0\rvert$	$\frac{1}{2}\big[\cos(\delta_S-\delta_0)-\lvert\lambda_S\lambda_0\rvert \cos(\delta_S-\delta_0-\phi_S+\phi_0)\big]$	$\frac{1}{2}\big[\lvert\lambda_S\rvert\cos(\delta_S-\delta_0-\phi_S) -\lvert\lambda_0\rvert\cos(\delta_0-\delta_S-\phi_0)\big]$	$\frac{1}{2}\big[\cos(\delta_S-\delta_0)+\lvert\lambda_S\lambda_0\rvert \cos(\delta_S-\delta_0-\phi_S+\phi_0)\big]$	$\frac{1}{2}\big[\lvert\lambda_S\rvert\sin(\delta_S-\delta_0-\phi_S) -\lvert\lambda_0\rvert\sin(\delta_0-\delta_S-\phi_0)\big]$

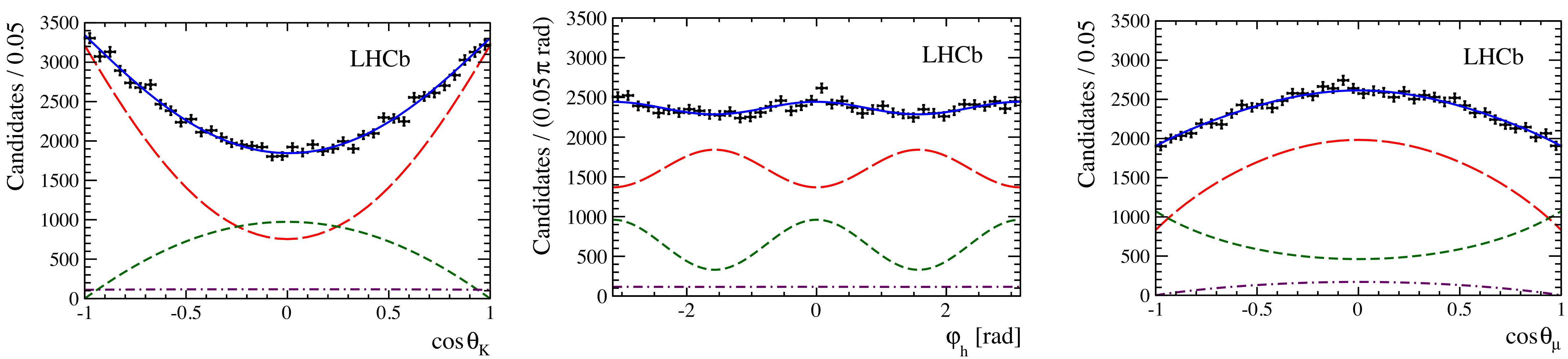
Measurement of ϕ_s in $B_s \to J/\psi K^+K^-$ (3 fb^{-1})

[Phys. Rev. Lett. 114 041801 (2015)]

✦ Results: (polarisation independent)

Parameter	Value
Γ_s [ps^{-1}]	$0.6603 \pm 0.0027 \pm 0.0015$
$\Delta\Gamma_s$ [ps^{-1}]	$0.0805 \pm 0.0091 \pm 0.0032$
$\lvert A_\perp \rvert^2$	$0.2504 \pm 0.0049 \pm 0.0036$
$\lvert A_0 \rvert^2$	$0.5241 \pm 0.0034 \pm 0.0067$
$\delta_\parallel$ [rad]	$3.26\ ^{+0.10}_{-0.17}\ ^{+0.06}_{-0.07}$
$\delta_\perp$ [rad]	$3.08\ ^{+0.14}_{-0.15} \pm 0.06$
ϕ_s [rad]	$-0.058 \pm 0.049 \pm 0.006$
$\lvert \lambda \rvert$	$0.964 \pm 0.019 \pm 0.007$
Δm_s [ps^{-1}]	$17.711\ ^{+0.055}_{-0.057} \pm 0.011$





Measurement of ϕ_s in $B_s \to J/\psi K^+K^-$ (3 fb^{-1})

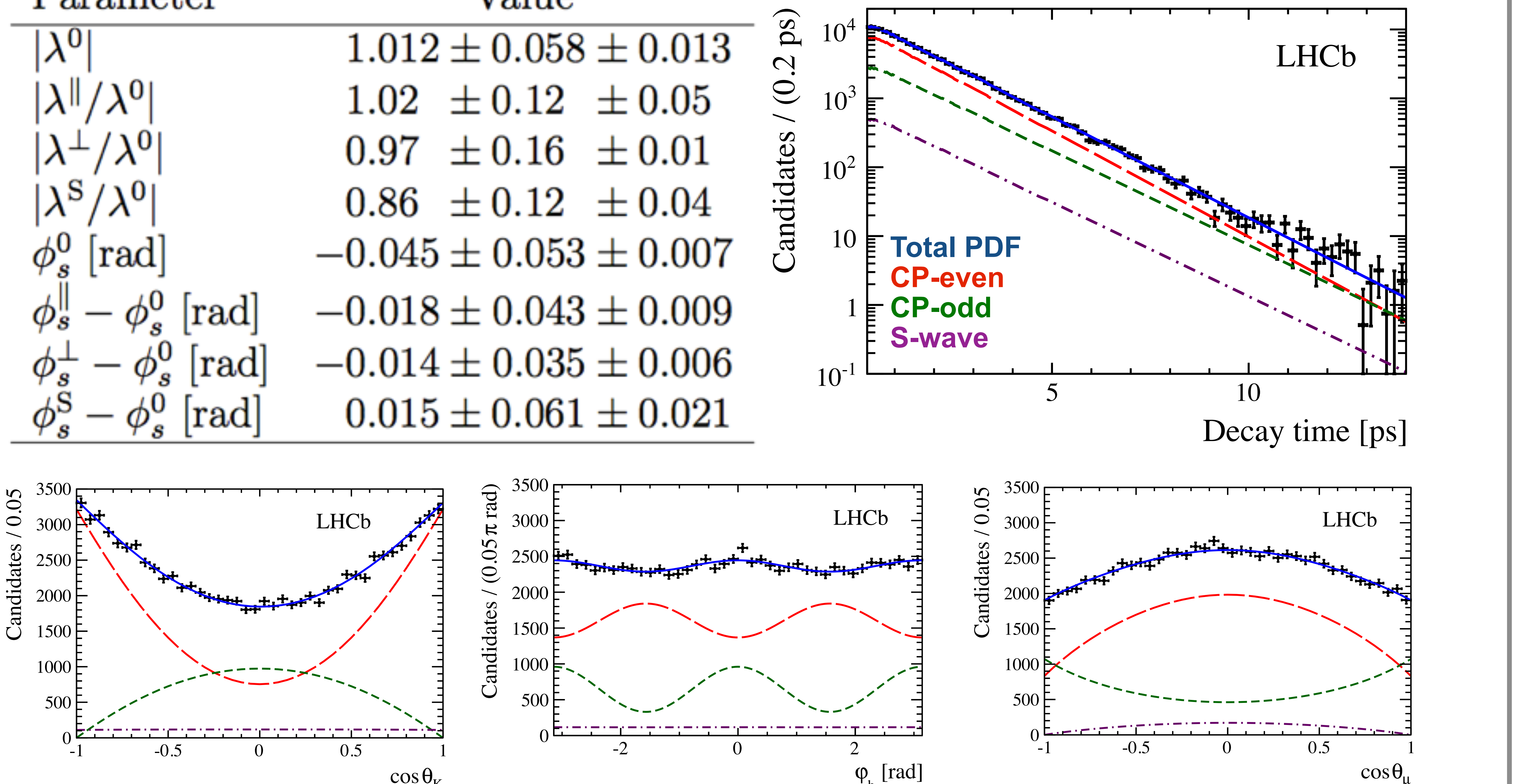
[Phys. Rev. Lett. 114 041801 (2015)]

✦ Systematics: (polarisation independent)

Source	Γ_s [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	$\|A_\perp\|^2$	$\|A_0\|^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	ϕ_s [rad]	$\|\lambda\|$	Δm_s [ps^{-1}]
Total stat. uncertainty	0.0027	0.0091	0.0049	0.0034	$^{+0.10}_{-0.17}$	$^{+0.14}_{-0.15}$	0.049	0.019	$^{+0.055}_{-0.057}$
Mass factorisation	–	0.0007	0.0031	0.0064	0.05	0.05	0.002	0.001	0.004
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	0.001
B_c^+ feed-down	0.0005	–	–	–	–	–	–	–	–
Angular resolution bias	–	–	0.0006	0.0001	$^{+0.02}_{-0.03}$	0.01	–	–	–
Ang. efficiency (reweighting)	0.0001	–	0.0011	0.0020	0.01	–	0.001	0.005	0.002
Ang. efficiency (stat.)	0.0001	0.0002	0.0011	0.0004	0.02	0.01	0.004	0.002	0.001
Decay-time resolution	–	–	–	–	–	0.01	0.002	0.001	0.005
Trigger efficiency (stat.)	0.0011	0.0009	–	–	–	–	–	–	–
Track reconstruction (simul.)	0.0007	0.0029	0.0005	0.0006	$^{+0.01}_{-0.02}$	0.002	0.001	0.001	0.006
Track reconstruction (stat.)	0.0005	0.0002	–	–	–	–	–	–	0.001
Length and momentum scales	0.0002	–	–	–	–	–	–	–	0.005
S-P coupling factors	–	–	–	–	0.01	0.01	–	0.001	0.002
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	0.011

✦ Results: (polarisation dependent)

Parameter	Value
$\lvert\lambda^0\rvert$	$1.012 \pm 0.058 \pm 0.013$
$\lvert\lambda^{\parallel}/\lambda^0\rvert$	$1.02 \pm 0.12 \pm 0.05$
$\lvert\lambda^{\perp}/\lambda^0\rvert$	$0.97 \pm 0.16 \pm 0.01$
$\lvert\lambda^{S}/\lambda^0\rvert$	$0.86 \pm 0.12 \pm 0.04$
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]	$-0.014 \pm 0.035 \pm 0.006$
$\phi_s^{S} - \phi_s^0$ [rad]	$0.015 \pm 0.061 \pm 0.021$



Measurement of ϕ_s in $B_s \to J/\psi K^+K^-$ (3 fb^{-1})

[Phys. Rev. Lett. 114 041801 (2015)]

✦ Systematics: (polarisation dependent)

Source	$\|\lambda^0\|$	$\|\lambda^{\|\|}/\lambda^0\|$	$\|\lambda^{\perp}/\lambda^0\|$	$\|\lambda^{S}/\lambda^0\|$	ϕ_s^0 [rad]	$\phi_s^{\|\|} - \phi_s^0$ [rad]	$\phi_s^{\perp} - \phi_s^0$ [rad]	$\phi_s^{S} - \phi_s^0$ [rad]
Total stat. uncertainty	0.058	0.12	0.16	0.12	0.053	0.043	0.035	0.061
Mass factorisation	0.010	0.04	0.01	0.03	0.003	0.005	0.003	0.016
b-hadron background	0.002	0.01	–	0.01	0.003	0.001	0.001	0.009
Ang. efficiency (reweighting)	–	–	–	0.02	0.001	0.002	0.001	0.007
Ang. efficiency (stat.)	0.004	0.02	0.01	0.01	0.004	0.007	0.005	0.004
Decay-time resolution	0.006	0.01	–	0.01	0.003	0.002	0.001	0.002
S-P coupling factors	–	–	–	–	–	–	–	0.006
Quadratic sum of syst.	0.013	0.05	0.01	0.04	0.007	0.009	0.006	0.021

Measurement of ϕ_s in $B_s \to J/\psi K^+K^-$ (3 fb^{-1})

✦ Results:

[Phys. Rev. D. 90, 052007 (2014)]

$$\phi_s = 0.12 \pm 0.25 \text{ (stat.)} \pm 0.05 \text{ (syst.) rad}$$
$$\Delta\Gamma_s = 0.053 \pm 0.021 \text{ (stat.)} \pm 0.010 \text{ (syst.) ps}^{-1}$$
$$\Gamma_s = 0.677 \pm 0.007 \text{ (stat.)} \pm 0.004 \text{ (syst.) ps}^{-1}$$
$$|A_{\parallel}(0)|^2 = 0.220 \pm 0.008 \text{ (stat.)} \pm 0.009 \text{ (syst.)}$$
$$|A_0(0)|^2 = 0.529 \pm 0.006 \text{ (stat.)} \pm 0.012 \text{ (syst.)}$$
$$\delta_{\perp} = 3.89 \pm 0.47 \text{ (stat.)} \pm 0.11 \text{ (syst.) rad}$$

[CMS-PAS-BPH-13-012]

Parameter	Fit result
$\lvert A_0\rvert^2$	0.511 ± 0.006
$\lvert A_S\rvert^2$	0.015 ± 0.016
$\lvert A_{\perp}\rvert^2$	0.242 ± 0.008
$\delta_{\parallel}$ [rad]	3.48 ± 0.09
$\delta_{S\perp}$ [rad]	0.34 ± 0.24
$\delta_{\perp}$ [rad]	2.73 ± 0.36
$c\tau$ [μm]	447.3 ± 3.0
$\Delta\Gamma_s$ [ps^{-1}]	0.096 ± 0.014
ϕ_s [rad]	-0.03 ± 0.11

Measurement of ϕ_s in $B_s \to J/\psi K^+K^-$ (3 fb^{-1})

✦ Systematics:

[Phys. Rev. D. 90, 052007 (2014)]

	ϕ_s [rad]	$\Delta\Gamma_s$ [ps^{-1}]	Γ_s [ps^{-1}]	$\lvert A_\parallel(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\lvert A_S(0)\rvert^2$	$\delta_\perp$ [rad]	$\delta_\parallel$ [rad]	$\delta_\perp - \delta_S$ [rad]
ID alignment	$<10^{-2}$	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	-	$<10^{-2}$	$<10^{-2}$	-
Trigger efficiency	$<10^{-2}$	$<10^{-3}$	0.002	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	$<10^{-2}$	$<10^{-2}$	$<10^{-2}$
B^0 contribution	0.03	0.001	$<10^{-3}$	$<10^{-3}$	0.005	0.001	0.02	$<10^{-2}$	$<10^{-2}$
Tagging	0.03	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	0.04	$<10^{-2}$	$<10^{-2}$
Acceptance	0.02	0.004	0.002	0.002	0.004	-	-	$<10^{-2}$	-
Models:									
Default fit	$<10^{-2}$	0.003	$<10^{-3}$	0.001	0.001	0.006	0.07	0.01	0.01
Signal mass	$<10^{-2}$	0.001	$<10^{-3}$	$<10^{-3}$	0.001	$<10^{-3}$	0.03	0.04	0.01
Background mass	$<10^{-2}$	0.001	0.001	$<10^{-3}$	$<10^{-3}$	0.002	0.06	0.02	0.02
Resolution	0.02	$<10^{-3}$	0.001	0.001	$<10^{-3}$	0.002	0.04	0.02	0.01
Background time	0.01	0.001	$<10^{-3}$	0.001	$<10^{-3}$	0.002	0.01	0.02	0.02
Background angles	0.02	0.008	0.002	0.008	0.009	0.027	0.06	0.07	0.03
Total	0.05	0.010	0.004	0.009	0.012	0.028	0.11	0.09	0.04

[CMS-PAS-BPH-13-012]

Source of uncertainty	$\lvert A_0\rvert^2$	$\lvert A_S\rvert^2$	$\lvert A_\perp\rvert^2$	$\Delta\Gamma_s$ [ps^{-1}]	$\delta_\parallel$ [rad]	$\delta_{S\perp}$ [rad]	$\delta_\perp$ [rad]	ϕ_s [rad]	$c\tau$ [μm]
Statistical uncertainty	0.0058	0.016	0.0077	0.0138	0.092	0.24	0.36	0.109	3.0
Angular efficiency	0.0060	0.008	0.0104	0.0021	0.674	0.14	0.66	0.016	0.8
$\lvert\lambda\rvert$ as a free parameter	0.0001	0.005	0.0001	0.0003	0.002	0.01	0.03	0.015	-
Model bias	0.0008	-	-	0.0012	0.025	0.03	-	0.015	0.4
Kaon p_T re-weighting	0.0094	0.020	0.0041	0.0015	0.085	0.11	0.02	0.014	1.1
Proper decay length resolution	0.0009	-	0.0008	0.0021	0.004	-	0.02	0.006	2.9
PDF modelling assumptions	0.0016	0.002	0.0021	0.0021	0.010	0.03	0.04	0.006	0.2
Flavour tagging	-	-	-	-	-	-	0.02	0.005	-
Background mistag modelling	0.0021	-	0.0013	0.0018	0.074	1.10	0.02	0.002	0.7
Proper decay length efficiency	0.0015	-	0.0023	0.0057	-	-	-	0.002	1.0
Total systematics	0.0116	0.022	0.0117	0.0073	0.684	1.12	0.66	0.032	3.5

Measurement of ϕ_s in $B_s \to J/\psi K^+K^-$ (3 fb^{-1})

✦ Tagging:

[Phys. Rev. D. 90, 052007 (2014)]

Tagger	Efficiency [%]	Dilution [%]	Tagging Power [%]
Combined μ	3.37 ± 0.04	50.6 ± 0.5	0.86 ± 0.04
Segment Tagged μ	1.08 ± 0.02	36.7 ± 0.7	0.15 ± 0.02
Jet charge	27.7 ± 0.1	12.68 ± 0.06	0.45 ± 0.03
Total	32.1 ± 0.1	21.3 ± 0.08	1.45 ± 0.05

[CMS-PAS-BPH-13-012]

	Muons	Electrons
Mistag fraction ω [%]	$30.7 \pm 0.4 \pm 0.7$	$34.8 \pm 0.3 \pm 1.0$
Tagging efficiency ϵ_{tag} [%]	$4.55 \pm 0.03 \pm 0.08$	$3.26 \pm 0.02 \pm 0.01$
Tagging power P_{tag} [%]	$0.68 \pm 0.03 \pm 0.05$	$0.30 \pm 0.02 \pm 0.04$

Measurement of ϕ_s in $B_s \to D^+_S D^-_S$ (3 fb^{-1})

[Phys. Rev. Lett. 113 (2014) 211801]

✦ Systematics:

Systematic uncertainty	ϕ_s ($\lvert\lambda\rvert = 1$)	ϕ_s	$\lvert\lambda\rvert$
Resolution	$\pm 0.098\ \sigma$	$\pm 0.094\ \sigma$	$\pm 0.100\ \sigma$
Mass	$\pm 0.044\ \sigma$	$\pm 0.043\ \sigma$	$\pm 0.010\ \sigma$
Acceptance (model)	$\pm 0.022\ \sigma$	$\pm 0.027\ \sigma$	$\pm 0.027\ \sigma$
Acceptance (stat.)	$\pm 0.013\ \sigma$	$\pm 0.013\ \sigma$	$\pm 0.014\ \sigma$
Background subtraction	$\pm 0.009\ \sigma$	$\pm 0.008\ \sigma$	$\pm 0.046\ \sigma$
Total	$\pm 0.11\ \sigma$	$\pm 0.11\ \sigma$	$\pm 0.11\ \sigma$

Measurement of TDCP asymmetries in $B_s \rightarrow J/\psi K^0_S$ (3 fb^{-1})

Article submitted to JHEP [arXiv:1503.07055]

✦ Systematics:

Source	$\mathcal{A}_{\Delta\Gamma}$	C_{dir}	S_{mix}	Long $R \times 10^5$	Downstream $R \times 10^5$
Mass modelling	0.045	0.009	0.009	15.5	17.2
Decay-time resolution	0.038	0.066	0.070	0.6	0.3
Decay-time acceptance	0.022	0.004	0.004	0.6	0.5
Tagging calibration	0.002	0.021	0.023	0.1	0.2
Mass resolution	0.010	0.005	0.006	12.6	8.0
Mass–time correlation	0.003	0.037	0.036	0.2	0.1
Total	0.064	0.079	0.083	20.0	19.0

Measurement of β in $B_d \to J/\psi \pi^+\pi^-$ (3 fb^{-1})

[Phys. Lett. B742 (2015) 38]

Limits on penguin effects in ϕ_s

- **Systematics:**

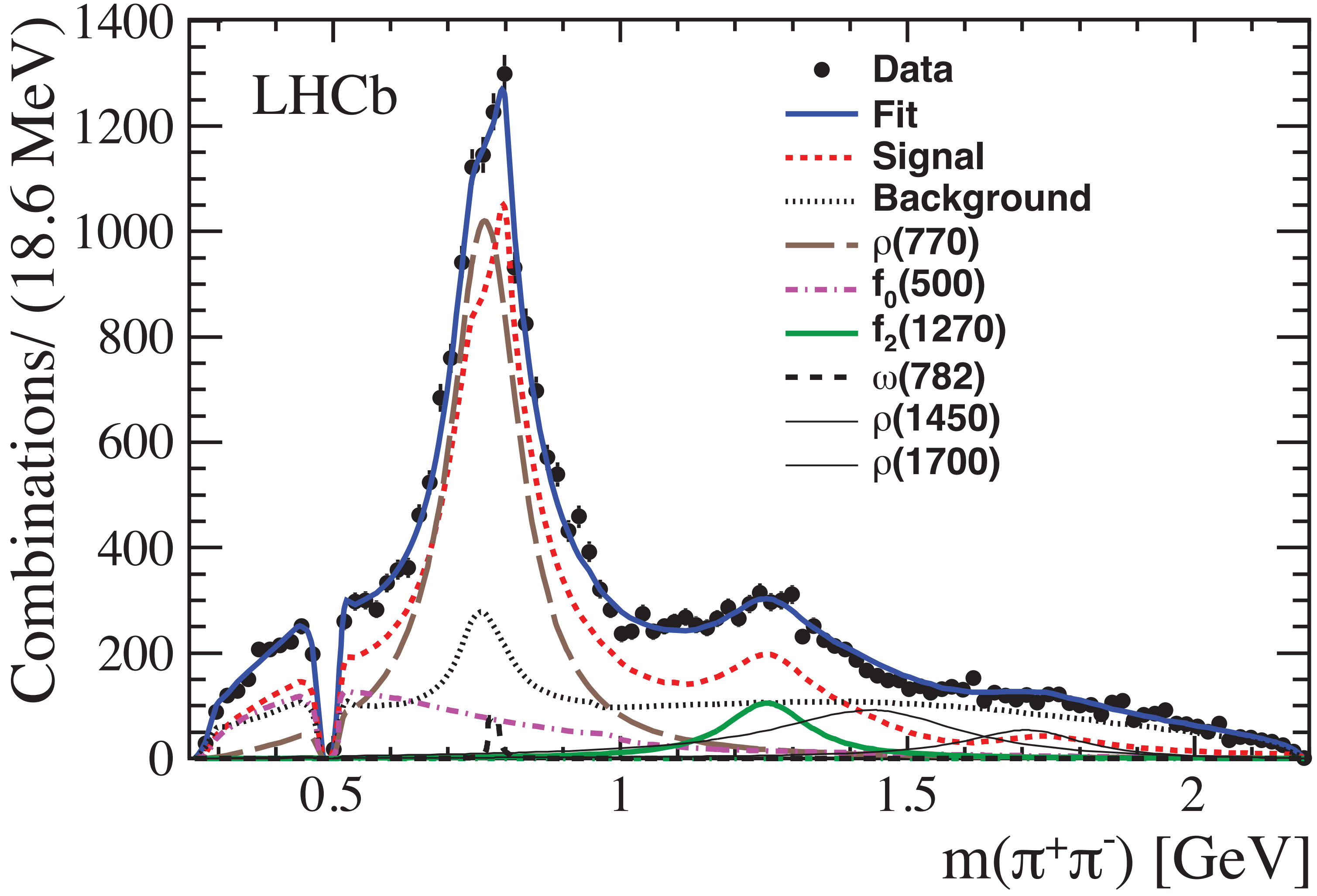
Sources	ϕ_s(mrad)	λ
Decay time acceptance	± 0.6	± 0.0008
Mass acceptance	± 0.3	± 0.0003
Background time PDF	± 0.2	± 0.0011
Background mass distribution PDF	± 0.6	± 0.0016
Resonance model	± 6.0	± 0.0100
Resonance parameters	± 0.7	± 0.0007
Other fixed parameters	± 0.4	± 0.0009
Production asymmetry	± 5.8	± 0.0017
Total	± 8.4	± 0.010

Measurement of β in $B_d \to J/\psi\, \pi^+\pi^-$ (3 fb^{-1})

[Phys. Lett. B742 (2015) 38]

Limits on penguin effects in ϕ_s

- $\pi\pi$ spectrum resonant composition:



Component	Fit fraction (%)
$\rho(770)$	65.6 ± 1.9
$f_0(500)$	20.1 ± 0.7
$f_2(1270)$	7.8 ± 0.6
$\omega(782)$	$0.64^{+0.19}_{-0.13}$
$\rho(1450)$	9.0 ± 1.8
$\rho(1700)$	3.1 ± 0.7