Measurement of the *CP*-violating phase ϕ_s at LHCb

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on behalf of the LHCb collaboration

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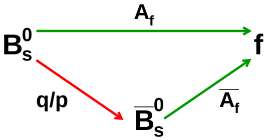
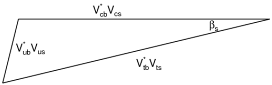
LHCb

- $\phi_s = -\arg(\lambda_f)$ – mixing-induced CPV phase in B_s^0 decays such as $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi \pi^+\pi^-$

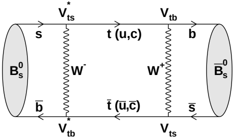


- Assuming only a SM tree contribution

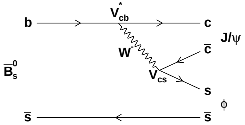
$$\phi_s^{SM} = -\arg(\lambda_f) = \phi_M^{SM} - 2\phi_D = -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$



$$\phi_M^{SM} = 2\arg(V_{ts}V_{tb}^*)$$



$$\phi_D = \arg(V_{cs}V_{cb}^*)$$



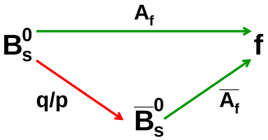
$$\phi_s^{SM} = -36.8\,^{+1.0}_{-0.8}\text{ mrad}$$

no penguins [CKMFitter]

$$\phi_s^{SM} = -37.0 \pm 1.0\,\text{mrad}$$

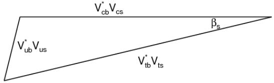
no penguins [UTFit]

- Phase ϕ_s sensitive to physics beyond the SM even at high energy scales that might be unaccessible in direct searches

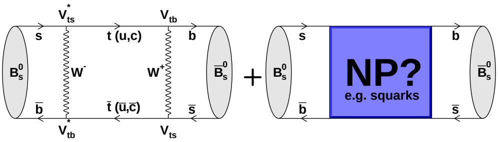


- Physics BSM could enter in the B_s^0-$\overline{B}_s^0$ mixing

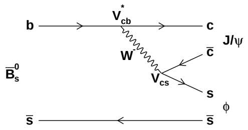
$$\phi_s = -\arg(\lambda_f) = \phi_M - 2\phi_D = -2\beta_s + \Delta\phi_{NP}$$



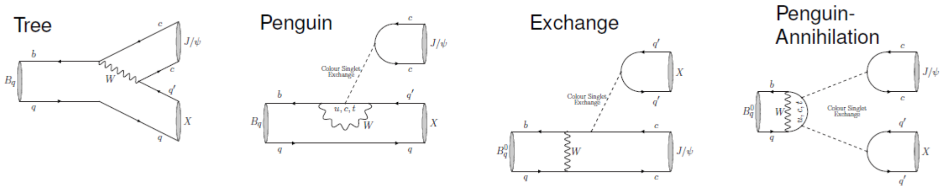
$$\phi_M = \phi_M^{SM} + \Delta\phi_{NP}$$



$$\phi_D = \arg(V_{cs}V_{cb}^*)$$



- Phase $\phi_s \approx -2\beta_s$ measured most precisely in processes dominated by $b \to c\bar{c}s$, where (SM) penguin pollution is small
- Decays admixture of *CP* -even and *CP* -odd final states



Golden mode

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

- Relatively large BF, $\mathcal{O}(10^{-3})$
- Also measurement of $\Gamma_s = \frac{\Gamma_H+\Gamma_L}{2}$, $\Delta\Gamma_s = \Gamma_L - \Gamma_H$, $\Delta m_s = m_H - m_L$

Silver mode

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

- BF $\mathcal{O}(10^{-4})$
- Crosscheck of $B_s^0 \to J/\psi K^+K^-$
- Mainly *CP* -odd, direct access to Γ_H

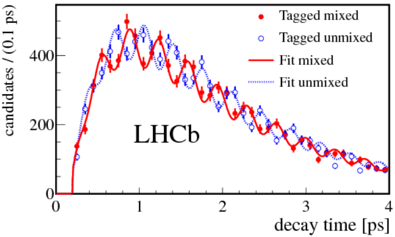
Experimental requirements

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

$$a_{CP}(t) \equiv \frac{\Gamma\left(\overline{B}^0_s \to f\right) - \Gamma\left(B^0_s \to f\right)}{\Gamma\left(\overline{B}^0_s \to f\right) + \Gamma\left(B^0_s \to f\right)}$$

$$\approx \eta_f \sin\phi_s \sin\Delta m_s t$$

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



Time resolution

B^0_s oscillations fast, $T \approx 350$ fs! Need excellent time resolution, $\sigma_t << T$

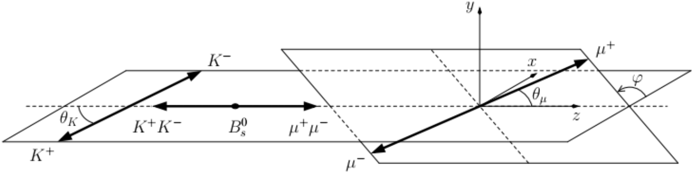
Flavour tagging

Need to know initial B^0_s flavour, experimentally limited by the probability of mistag, ω.

Tagging power $\varepsilon_{\text{tag}} = \varepsilon(1-2\omega)^2$

***CP* eigenvalue**

Using angular distribution of decay products, angles θ_K, θ_μ and φ



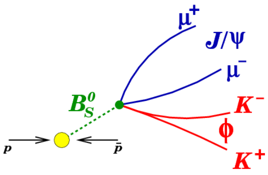
LHCb experiment

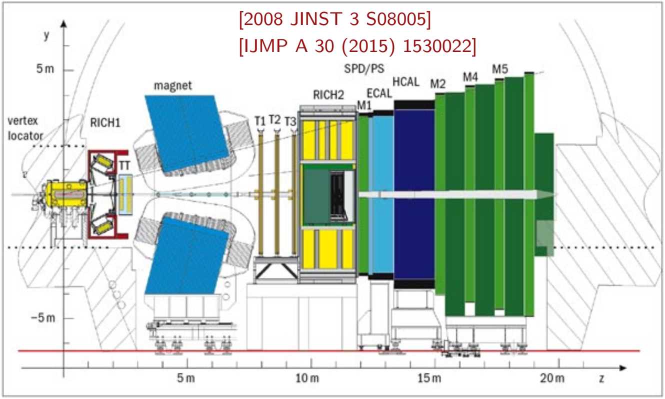
[See talk by Katharina Müller on Tue 9am]

Mixing-induced CPV access through time-dependent decay rates

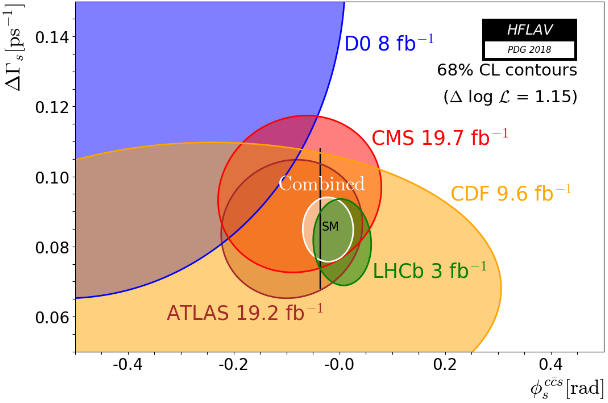
- ✓ Excellent time resolution $\langle \sigma_t \rangle \approx 42 - 45$ fs
- ✓ B_s^0 flavour tagging power $\approx 5\%$
- PID efficiencies $> 95\%$

LHCb pp coll. data	
Run 1 (2011-2012)	
7–8 TeV	$\int \mathcal{L} = 3\,\mathrm{fb}^{-1}$
Run 2 (2015-2018)	
13 TeV	$\int \mathcal{L} = 6\,\mathrm{fb}^{-1}$





Status of ϕ_s before Moriond 2019



- World average dominated by LHCb
- Results consistent with SM-based global fits to data, though plenty of room for new physics

$$\phi_s^{SM} = -36.8^{+1.0}_{-0.8}\ \text{mrad}$$ [CKMFitter]

$$\phi_s^{EXP} = -21 \pm 31\text{mrad}$$ [HFLAV]

LHCb Run 1

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

  $M(KK)$ around $\phi(1020)$
  [PRL 114, 041801 (2015)]

  $M(KK)$ above $\phi(1020)$
  [JHEP 08 (2017) 037]
- $B_s^0 \to J/\psi\pi^+\pi^-$
  [PLB 736 (2014) 186]
- $B_s^0 \to \psi(2S)\phi$
  [PLB 762 (2016) 253]
- $B_s^0 \to D_s^+D_s^-$
  [PRL 113, 211801 (2014)]

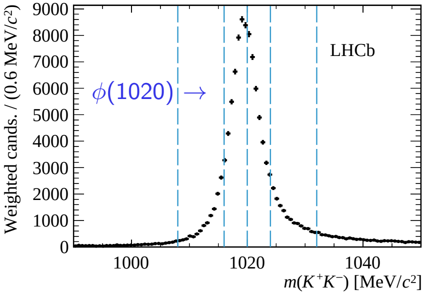
ATLAS and CMS Run 1

- $B_s^0 \to J/\psi K^+K^-$ in $\phi(1020)$ region
  [JHEP 1608 (2016) 147]
  [PLB 757 (2016) 97]

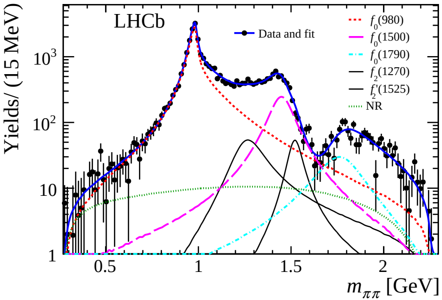
NEW $B_s^0 \to J/\psi K^+K^-$ [arXiv:1906.08356] and $B_s^0 \to J/\psi \pi^+\pi^-$ [arXiv:1903.05530]

- Run 2 LHCb measurements with $1.9\,\text{fb}^{-1}$ from 2015 ($0.3\,\text{fb}^{-1}$) and 2016 ($1.6\,\text{fb}^{-1}$)
- $B_s^0 \to J/\psi K^+K^-$ in region around $\phi(1020)$, small S-wave contribution
- $B_s^0 \to J/\psi \pi^+\pi^-$ predominantly $B_s^0 \to J/\psi f_0(980)$

Fit in six $m(K^+K^-)$ bins



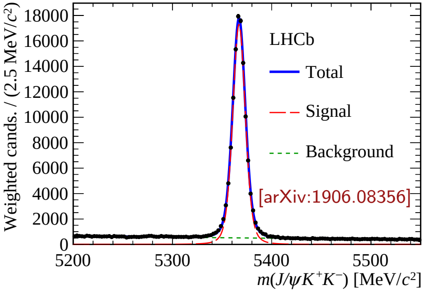
Fit to $m(\pi^+\pi^-)$



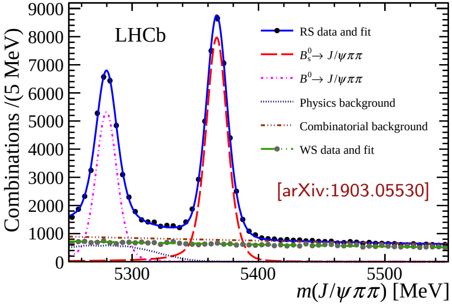
Analysis procedure for both modes similar

- Combinatorial background suppressed with a BDT using kinematic variables
- Background subtracted using *sPlot* with B_s^0 candidate mass
- Careful study of angular and decay-time efficiencies, time resolution, flavour tagging
- *sFit* to 3 helicity angles and B_s^0 cand. decay time ($+\ m(\pi^+\pi^-)$) for $B_s^0 \to J/\psi \pi^+\pi^-$)

$B_s^0 \to J/\psi K^+K^-$, $N_{\rm sig} \sim 117\,000$



$B_s^0 \to J/\psi \pi^+\pi^-$, $N_{\rm sig} \sim 33\,500$

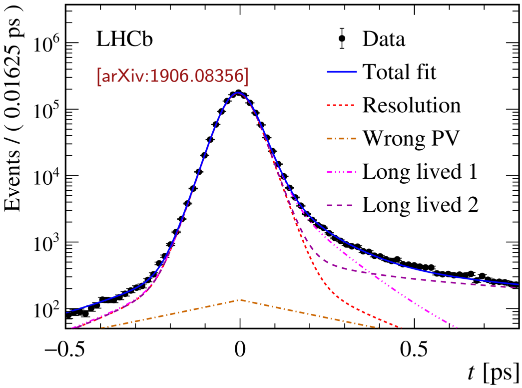


- Subtract $\Lambda_b^0 \to J/\psi p K^-$ with negative MC weights, $B^0 \to J/\psi K^+\pi^-$ negligible
- Background in fit: combinatorial (exp.) + $B^0 \to J/\psi K^+K^-$ (Gauss.)

- Use wrong-sign $B_s^0 \to J/\psi \pi^\pm\pi^\pm$ data for combinatorial
- Physics backgrounds: $\Lambda_b^0 \to J/\psi p K^-$ and $B_s^0 \to J/\psi \eta'(\to \rho\gamma)$

- Decay time $t = L \cdot m_{B_s^0}/p$, $L = L(\mathrm{SV})$ - $L(\mathrm{PV})$

  PV: primary vertex, SV: secondary vertex
- Resolution σ_{eff} obtained from fit to *prompt* sample formed from J/ψ and two kaons from PV ($\tau_{\mathrm{prompt}} = 0$)
- Fit in bins of per-event decay-time error δ_t from vertex fit



$$\sigma_{\mathrm{eff}} = \sqrt{(-2/\Delta m_s^2)\ln(D)}$$
$$D = \sum_{i=1}^{3} f_i e^{-\sigma_i^2 \Delta m_s^2}$$

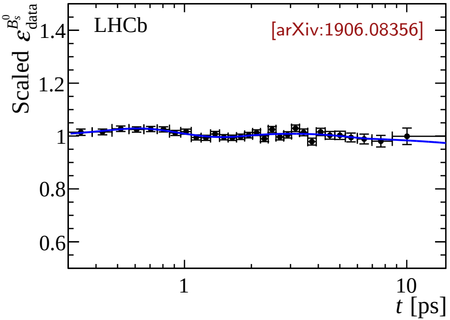
$\sigma_{\mathrm{eff}}(B_s^0 \to J/\psi K^+K^-) \approx 45.5$ fs
$\sigma_{\mathrm{eff}}(B_s^0 \to J/\psi \pi^+\pi^-) \approx 41.5$ fs

Decay-time efficiency

- Using $B^0 \to J/\psi K^{*0}(\to K^+\pi^-)$ as control channel
- Decay-time efficiency product of individual splines for data and simulation to correct residual differences between signal and control samples

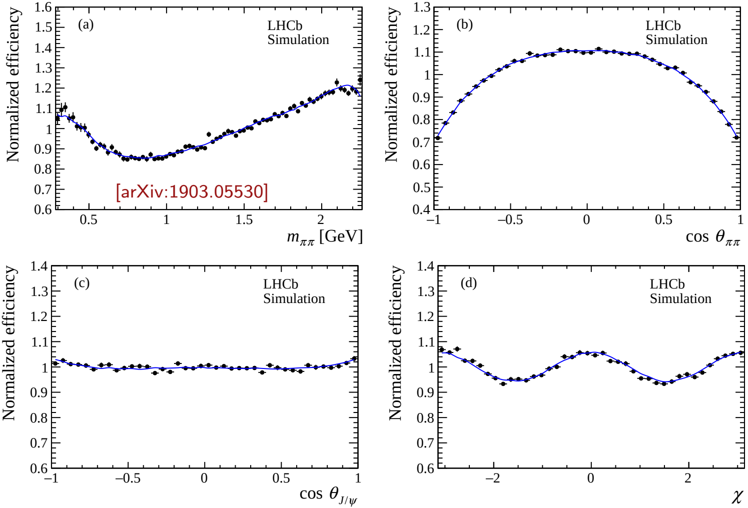
$$\varepsilon^{B^0_s}_{\rm data}(t) = \varepsilon^{B^0}_{\rm data}(t) \times \frac{\varepsilon^{B^0_s}_{\rm MC}(t)}{\varepsilon^{B^0}_{\rm MC}(t)}$$

- NB $\varepsilon^{B^0_s}_{\rm data}(t)$ function of Γ_d
  $\to$ access to $\Gamma_s - \Gamma_d$ $(\Gamma_H - \Gamma_d)$ in decay-time fit to $B^0_s \to J/\psi K^+K^-$ $(B^0_s \to J/\psi\pi^+\pi^-)$

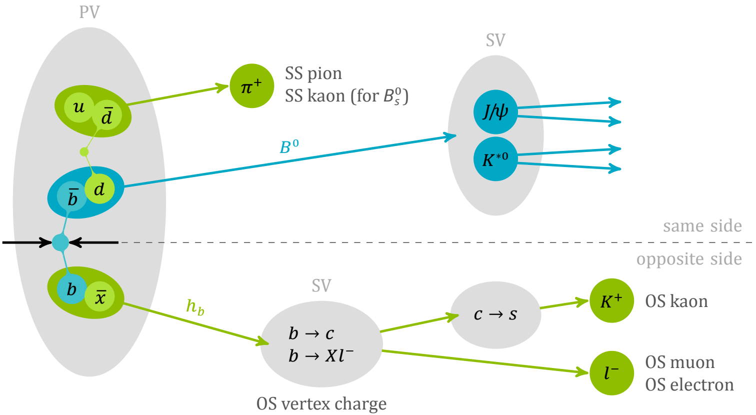


Angular efficiency

- Selection and detector acceptance introduce efficiency effects in angular and $m(\pi^+\pi^-)$ distributions
- Efficiencies obtained from simulation and corrected to match the data
  $\rightarrow$ Method in $B_s^0 \rightarrow J/\psi K^+K^-$ validated on $B^+ \rightarrow J/\psi K^+$ and $B^0 \rightarrow J/\psi K^*$ data, good agreement



- Tagging in Run 2 improved $\Rightarrow$ 30% higher tagging power than Run 1
  $\varepsilon_{\rm tag}(B_s^0 \to J/\psi K^+K^-) = 4.73 \pm 0.34\%$ (vs $\approx 3.73\%$ in Run 1)
  $\varepsilon_{\rm tag}(B_s^0 \to J/\psi \pi^+\pi^-) = 5.06 \pm 0.38\%$ (vs $\approx 3.89\%$ in Run 1)



- Main syst. uncertainty on ϕ_s is flavour tagging ~ 0.015 rad, incorporated in statistical

Source	ϕ_s [rad]	$\|\lambda\|$	$\Gamma_s - \Gamma_d$ [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	Δm_s [ps^{-1}]	$\|A_\perp\|^2$	$\|A_0\|^2$	$\delta_\perp - \delta_0$ [rad]	$\delta_\parallel - \delta_0$ [rad]
Mass: width parametrisation	-	-	-	0.0002	0.001	0.0005	0.0006	0.05	0.009
Mass: decay-time & angles dependence	0.004	0.0037	0.0007	0.0022	0.016	0.0004	0.0002	0.01	0.004
Multiple candidates	0.0011	0.0011	0.0003	0.0001	0.001	0.0001	0.0006	0.01	0.002
Fit bias	0.0010	-	-	0.0003	0.001	0.0006	0.0001	0.02	0.033
C_{SP} factors	0.0010	0.0010	-	0.0001	0.002	0.0001	-	0.01	0.005
Time resolution: model applicability	-	-	-	-	0.001	-	-	-	0.001
Time resolution: t bias	0.0032	0.0010	0.0002	0.0003	0.005	-	-	0.08	0.001
Time resolution: wrong PV	-	-	-	-	0.001	-	-	-	0.001
Angular efficiency: simulated sample size	0.0011	0.0018	-	-	0.001	0.0004	0.0003	-	0.004
Angular efficiency: weighting	0.0022	0.0043	0.0001	0.0002	0.001	0.0011	0.0020	0.01	0.008
Angular efficiency: clone candidates	0.0005	0.0014	0.0002	0.0001	-	0.0001	0.0002	-	0.002
Angular efficiency: t & σ_t dependence	0.0012	0.0007	0.0002	0.0010	0.003	0.0012	0.0008	0.03	0.006
Decay-time efficiency: statistical	-	-	0.0012	0.0008	-	0.0003	0.0002	-	-
Decay-time efficiency: kinematic weighting	-	-	0.0002	-	-	-	-	-	-
Decay-time efficiency: PDF weighting	-	-	0.0001	0.0001	-	-	-	-	-
Decay-time efficiency: $\Delta\Gamma_s = 0$ simulation	-	-	0.0003	0.0005	-	0.0002	0.0001	-	-
Length scale	-	-	-	-	0.004	-	-	-	-
Quadratic sum of syst.	0.0061	0.0064	0.0015	0.0026	0.018	0.0019	0.0024	0.10	0.037

Systematic uncertainties $B_s^0 \to J/\psi\pi^+\pi^-$ [arXiv:1903.05530]

Source	$\Gamma_H - \Gamma_{B^0}$ [fs^{-1}]	$\lvert\lambda\rvert$ [$\times10^{-3}$]	ϕ_s [mrad]
Decay-time acceptance	2.0	0.0	0.3
τ_{B^0}	0.2	0.5	0.0
Efficiency ($m_{\pi\pi}$, Ω)	0.2	0.1	0.0
Decay-time resolution width	0.0	4.3	4.0
Decay-time resolution mean	0.3	1.2	0.3
Background	3.0	2.7	0.6
Flavour tagging	0.0	2.2	2.3
Δm_s	0.3	4.6	2.5
Γ_L	0.3	0.4	0.4
B_c^+	0.5	-	-
Resonance parameters	0.6	1.9	0.8
Resonance modelling	0.5	28.9	9.0
Production asymmetry	0.3	0.6	3.4
Total	3.8	29.9	11.0

$B_s^0 \to J/\psi K^+K^-$ [arXiv:1906.08356]

$$\phi_s = -83 \pm 41 \pm 6\,\text{mrad}$$
$$|\lambda| = 1.012 \pm 0.016 \pm 0.006$$
$$\Gamma_s - \Gamma_d = -0.0041 \pm 0.0024 \pm 0.0015\,\text{ps}^{-1}$$
$$\Delta\Gamma_s = 0.077 \pm 0.008 \pm 0.003\,\text{ps}^{-1}$$

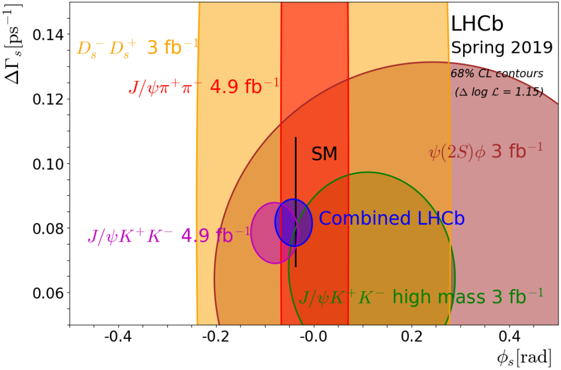
$B_s^0 \to J/\psi \pi^+\pi^-$ [arXiv:1903.05530]

$$\phi_s = -57 \pm 60 \pm 11\,\text{mrad}$$
$$|\lambda| = 1.01\,^{+0.08}_{-0.06} \pm 0.03$$
$$\Gamma_H - \Gamma_d = -0.050 \pm 0.004 \pm 0.004\,\text{ps}^{-1}$$

Results in agreement with previous measurements and SM predictions

All LHCb [arXiv:1906.08356]

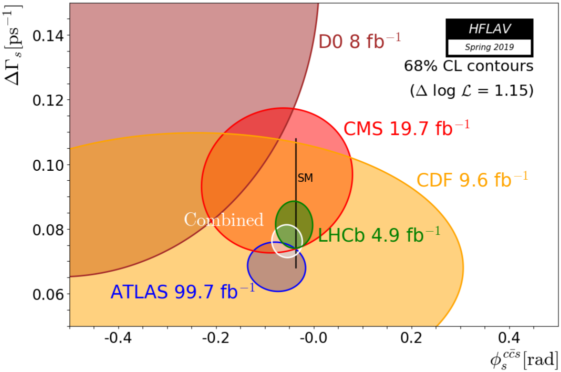
$$\phi_s = -41 \pm 25\,\text{mrad}$$
$$|\lambda| = 0.993 \pm 0.010$$
$$\Gamma_s = 0.6562 \pm 0.0021\,\text{ps}^{-1}$$
$$\Delta\Gamma_s = 0.0816 \pm 0.0048\,\text{ps}^{-1}$$

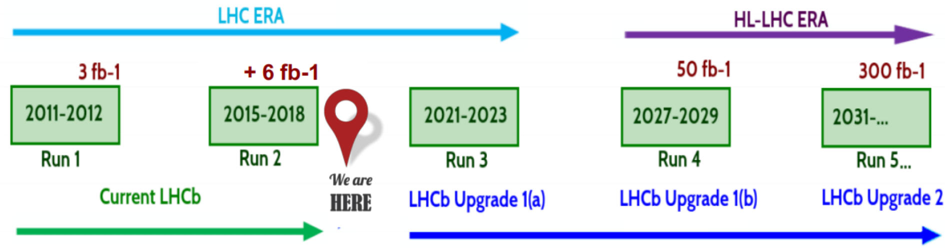


- Combination with preliminary ATLAS Run 2 result [ATLAS-CONF-2019-009] (next talk)
- In agreement with SM, experimental uncertainty on ϕ_s improved by 30%!
- Previous HFLAV: $\phi_s = -21 \pm 31\,\text{mrad}$

HFLAV

$$\phi_s = -55 \pm 21\,\text{mrad}$$
$$\Delta\Gamma_s = 0.0764 \pm 0.0024\,\text{ps}^{-1}$$





LHCb 300 fb^{-1}

$B_s^0 \to J/\psi K^+K^-$ $\quad \sigma^{\text{stat}}(\phi_s) \approx 4\,\text{mrad}$

Total $\quad \sigma^{\text{stat}}(\phi_s) \approx 3\,\text{mrad}$

- Precision will be statistically dominated
- Improvements in trigger to benefit $B_s^0 \to D_s^+D_s^-$
- Include other modes, e.g. $B_s^0 \to J/\psi(\to e^+e^-)K^+K^-$, $B_s^0 \to J/\psi\eta'$