Measurement of the CP violating phase ϕ_s originating in $B_s^0 \to J/\psi\phi$ using LHCb Run 2 data

[LHCb-PAPER-2019-013 (in preparation)]

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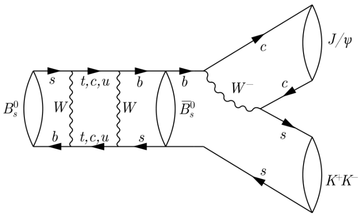
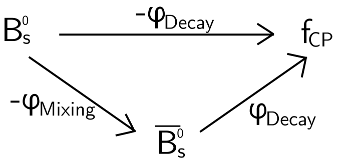
On behalf of the LHCb Collaboration

IoP Joint APP and HEPP Annual Conference
8th - 10th of April 2019

CP Violating Phase ϕ_s



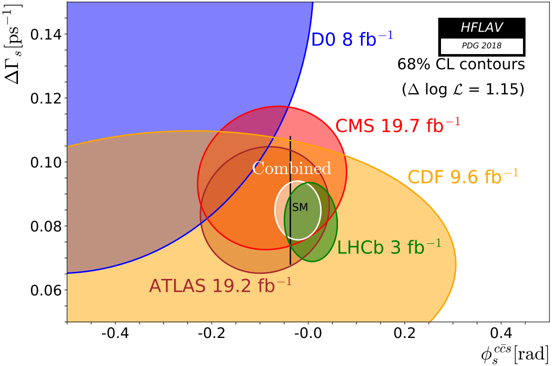


$$\phi_s = \phi_{\text{mixing}} - 2\phi_{\text{decay}} \approx -2\beta_s = -2arg\left(\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

- B_s^0 mesons have the possibility to **oscillate** into their anti-particles before decaying into CP eigenstates f_{CP}
- CP violating phase ϕ_s: phase difference due to **interference** between $b \to c\bar{c}s$ decays directly and via oscillation
- ϕ_s is precisely predicted assuming the SM, so **New Physics** particles could significantly affect the measurement

Current Results

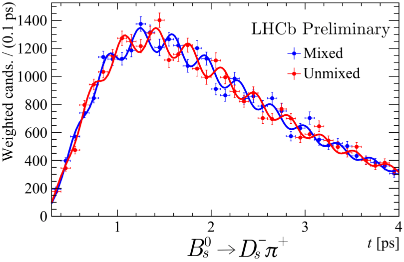
- Standard Model $\phi_s^{\mathbf{SM}} = \mathbf{-36.9^{+1.0}_{-0.7}}$ **mrad** [CKM Fitter] very precise
- Pre-Moriond World Average $\phi_s^{\mathbf{WA}} = \mathbf{-21 \pm 31}$ **mrad** [HFLAV] consistent with SM prediction and dominated by **LHCb**
- At Moriond added Run 2 $B_s^0 \to J/\psi K^+ K^-$ [LHCb-PAPER-2019-013 (in preparation)]



Ingredients

- Fast $B_s^0 - \bar{B}_s^0$ oscillation ($P = 2\pi/\Delta m_s \sim 350$ fs)
- Clearly visible in $B_s^0 \to D_s^- \pi^+$
- What we measure experimentally:

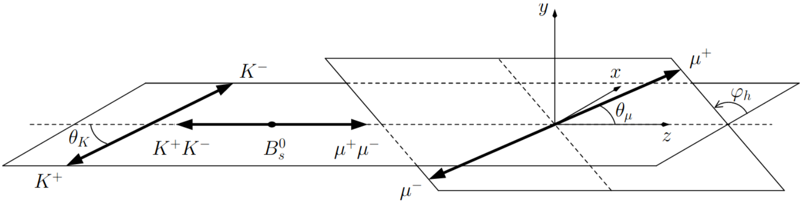
$$\sin(\phi_s)(1 - 2\omega_{\mathrm{tag}})D(\sigma_t)\sin(\Delta m_s t)$$



- $\sin(\phi_s)$ proportional to amplitude of the oscillation
- Diluted by wrong tagging probability ω_{tag}
- Good **flavour tagging** crucial to distinguish B_s^0 from $\bar{B}_s^0$
- Diluted by decay time resolution σ_t
- $\Delta m_s = m_H - m_L$ mass difference between heavy and light B_s^0 mass eigenstates

Angular Analysis

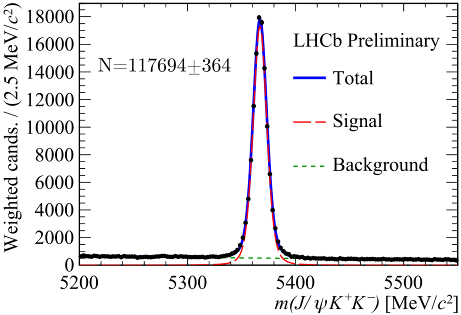
- Final state $B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi(\to K^+K^-)$ is an admixture of **CP-even** and **CP-odd** final states $\to$ need analysis of decay angle distribution
- Three helicity angles, $\Omega = (\cos\theta_K, \cos\theta_\mu, \phi_h)$



- Separating even and odd states gives access to heavy Γ_H and light Γ_L **B_s^0 lifetimes** and the measurement of

$$\Gamma_s = \frac{\Gamma_H + \Gamma_L}{2} \qquad \Delta\Gamma_s = \Gamma_H - \Gamma_L$$

Analysis Strategy



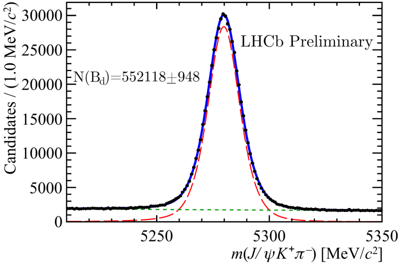
- $B_s^0 \to J/\psi K^+K^-$ has a large branching fraction and a large reconstruction efficiency
- Analyse 2015 ($\sim 0.3\ \mathrm{fb}^{-1}$) and 2016 ($\sim 1.6\ \mathrm{fb}^{-1}$) data to measure main parameters $\boldsymbol{\phi_s}$, $\boldsymbol{\Delta\Gamma_s}$, $\boldsymbol{\Gamma_s - \Gamma_d}$
- Use **BDT** trained avoiding variables that could introduce decay-time bias and model **efficiencies** as a function of time and decay angles

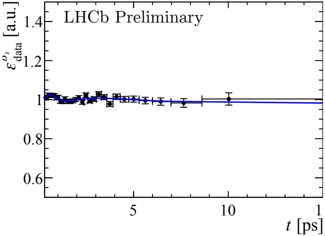
Decay Time Efficiency

- Reconstruction efficiency **not constant** as a function of B_s^0 decay time
- Use control channel $B_d^0 \to J/\psi K^*(\to K^+\pi^-)$
  - **Well-known lifetime**, high yield and similar kinematics
- Determine **decay time efficiency** $\varepsilon_{\mathrm{data}}^{B_d^0}(t)$ using known lifetime $\tau(B_d^0)$
- Correction from simulation for kinematic differences between decays

$$\varepsilon_{\mathrm{data}}^{B_s^0}(t) = \varepsilon_{\mathrm{data}}^{B^0}(t) \times \frac{\varepsilon_{\mathrm{sim}}^{B_s^0}(t)}{\varepsilon_{\mathrm{sim}}^{B^0}(t)}$$

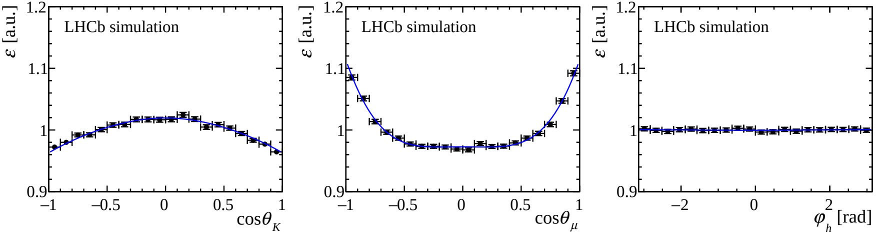
- Final fit parameter $\mathbf{\Gamma_s - \Gamma_d}$, where $\Gamma_d = 1/\tau(B_d^0)$



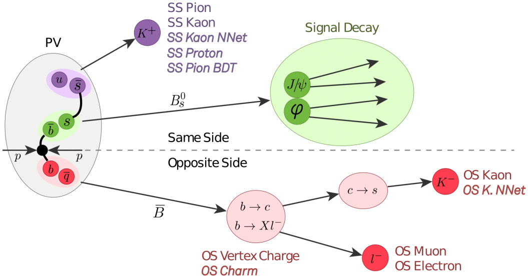


Angular Efficiency

- LHCb geometry and selection **introduce efficiency** as function of decay angles, $\Omega = (\cos\theta_K, \cos\theta_\mu, \phi_h)$
- Effect is modelled with **normalisation weights** for each **individual polarisation final state** determined from fully simulated events
- Simulation **iteratively reweighted** to correct for kinematic differences simulation/data



Flavour Tagging



- Flavour tagging crucial to determine **B_s^0 flavour** at production
- $b\bar{b}$ pair from pp will create **signal B_s^0** and **OS B** decay
- s-partner from B_s^0 $s\bar{s}$ pair will create **SS $K(\bar{s}u)$**

- Taggers **optimised** using Neural Nets
- OS taggers **calibrated** using $B^+ \to J/\psi K^+$
- SSK tagger **calibrated** using $B_s^0 \to D_s^- \pi^+$

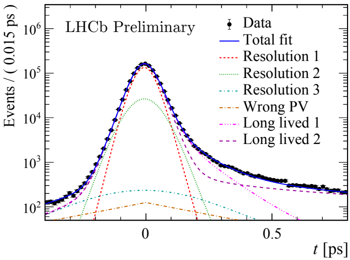
Category	Faction(%)	ε(%)	D^2	εD^2(%)
OS-only	14.595	11.349	0.078	0.88 $\pm$0.04
SSK-only	54.751	42.574	0.032	1.38 $\pm$0.30
OS&SSK	30.654	23.837	0.104	2.47 $\pm$0.15
Total	100	77.760	0.061	4.73 $\pm$0.34

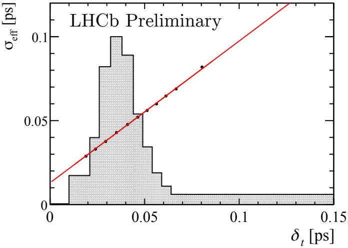
Decay Time Resolution

- Need well determined resolution to resolve fast B_s^0 oscillation (~ 350 fs)
- Extract resolution from **prompt J/ψ data** coming from *pp* interaction
- In 10 bins of uncertainty δ_t fit with **triple Gaussian** plus wrong PV and long lived components
- Dilution D translated into effective single Gaussian width σ_{eff}

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

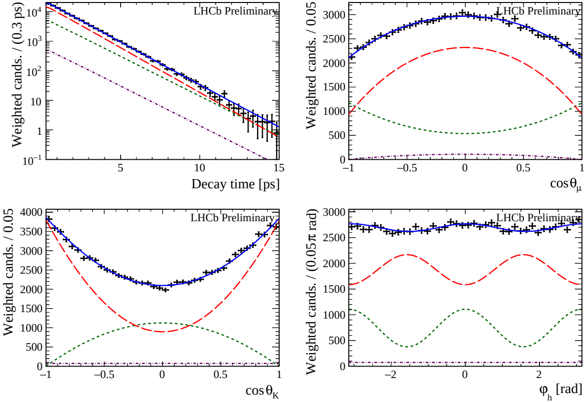
- Final resolution $\boldsymbol{\delta_t = 45.54 \pm 0.04 \pm 0.05}$ **fs**





Results

- **Decay-time** and **decay angle** distributions for background subtracted $B_s^0 \to J/\psi KK$ decays
- All CP eigenvalues are entangled for the fit: **CP-even**, **CP-odd** and **S-wave** (small fraction $\sim 2\%$)



Results

- Results using 2015 ($0.3\ \mathrm{fb}^{-1}$) and 2016 ($1.6\ \mathrm{fb}^{-1}$) data [LHCb-PAPER-2019-013 (in preparation)] :

$$\phi_s = -0.080 \pm 0.041 \pm 0.006\ \mathrm{rad}$$
$$\Gamma_s - \Gamma_d = -0.0041 \pm 0.0024 \pm 0.0015\ \mathrm{ps}^{-1}$$
$$\Delta\Gamma_s = 0.0772 \pm 0.0077 \pm 0.0026\ \mathrm{ps}^{-1}$$

- Most precise single measurement of ϕ_s
- To be compared to Run 1 ($3\ \mathrm{fb}^{-1}$) statistical uncertainties:
  - $\sigma_{\mathrm{stat}}(\phi_s) = 0.049$ rad
  - $\sigma_{\mathrm{stat}}(\Gamma_s) = 0.0027\ \mathrm{ps}^{-1}$
  - $\sigma_{\mathrm{stat}}(\Delta\Gamma_s) = 0.0091\ \mathrm{ps}^{-1}$

Summary

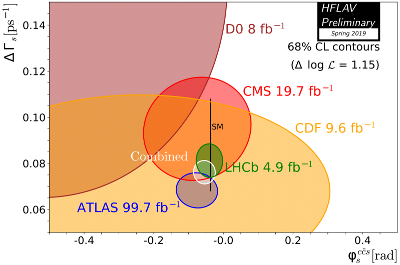
- Run 2 $B_s^0 \to J/\psi K^+K^-$ most precise single measurement of ϕ_s

$$\phi_s = -0.080 \pm 0.041 \pm 0.006 \text{ rad}$$

$$\Gamma_s - \Gamma_d = -0.0041 \pm 0.0024 \pm 0.0015 \text{ ps}^{-1}$$

$$\Delta\Gamma_s = 0.0772 \pm 0.0077 \pm 0.0026 \text{ ps}^{-1}$$

- Post-Moriond result (HFLAV, Preliminary) consistent with SM



Stay tuned for coming results!

2017 and **2018** data yet to be analysed!

Thank you!

Combination of all LHCb ϕ_s Analyses

- Want to combine all available **Run 1** ($3\ \text{fb}^{-1}$) and **Run 2** ($1.9\ \text{fb}^{-1}$) **LHCb results**, e.g. $B_s^0 \to J/\psi\pi^+\pi^-$, $B_s^0 \to \psi(2S)\phi$
- Analyses sometimes overlap with **methods** and **datasets** used
  - Prompt J/ψ sample for decay-time resolution
  - $B_d^0 \to J/\psi K^*(892)$ for decay-time efficiency
- Potential **systematic correlations** taken into account
- **Combination** of all LHCb results yields:

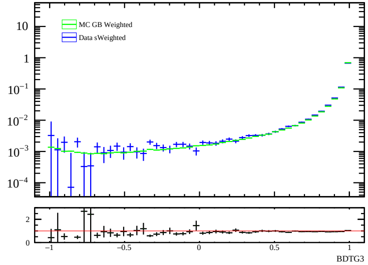
$$\phi_s = -0.040 \pm 0.025\ \text{rad}$$
$$\Gamma_s = 0.6563 \pm 0.0021\ \text{ps}^{-1}$$
$$\Delta\Gamma_s = 0.0812 \pm 0.0048\ \text{ps}^{-1}$$

- ϕ_s^{LHCb} 0.1σ away from SM prediction $\phi_s^{SM} = -0.0369^{+0.0010}_{-0.0007}$ rad
- ϕ_s^{LHCb} 1.6σ away from zero $\to$ consistent with no CPV in interference between direct decay and after mixing

Selection

BDT variables

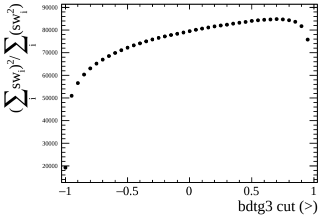
$\max(\chi^2_{TR}(K))$	$p_T(\phi)$
$\max(\chi^2_{TR}(\mu))$	$p_T(B_s^0)$
$\min(\ln(\texttt{ProbNNk}(K)))$	$\chi^2_{VX}(B_s^0)$
$\min(\ln(\texttt{ProbNNmu}(\mu)))$	$\ln(\chi^2_{IP}(B_s^0))$
$\ln(\chi^2_{VX}(J/\psi))$	$\ln(\chi^2_{DTF}(B_s^0))$



Avoid variables with impact on angular or decay time acceptances

Optimised BDT cut at >0.58:

$$\mathrm{FOM} = \frac{(\sum_i w_i)^2}{\sum_i w_i^2}$$



Selection

- **HLT1 selection**: `Jpsi_Hlt1DiMuonHighMassDecision_TOS` || `B_Hlt1TrackMuonDecision_TOS` || `B_Hlt1TwoTrackMVADecision_TOS`
- **HLT2 selection**: `Jpsi_Hlt2DiMuonDetachedJPsiDecision_TOS`
- Trigger efficiency ∼98% on signal MC
- **Stripping**: S28r1 (S24r1) `StrippingBetaSBs2JpsiPhiDetachedLine` for 2016 (2015)
- **PIDCalib** to match PID variables of MC with data
- **Gradient Boosting Reweight** MC in $p_T(B_s^0)$, $\eta(B_s^0)$ $\chi^2_{TR}(\mu^{\pm})$, $\chi^2_{TR}(K^{\pm})$, `nLongTracks`
- **BDT** trained with 2016 MC (signal) and data sideband [5450,5550] MeV$/c^2$ (background)

Systematics

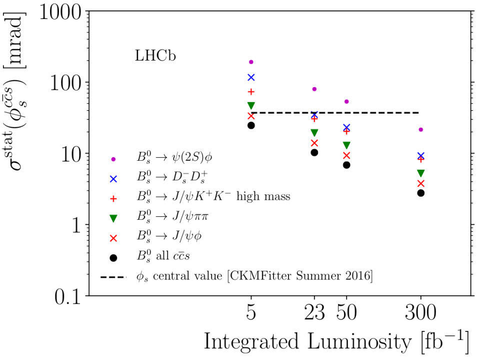
Source	$\|A_0\|^2$	$\|A_\perp\|^2$	ϕ_s [rad]	$\|\lambda\|$	$\delta_\perp - \delta_0$ [rad]	$\delta_\parallel - \delta_0$ [rad]	$\Gamma_s - \Gamma_d$ [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	Δm_s [ps^{-1}]
Central value	0.5186	0.2457	−0.080	1.006	2.64	3.061	−0.0041	0.0772	17.705
Stat. error	$^{+0.0029}_{-0.0029}$	$^{+0.0040}_{-0.0040}$	$^{+0.041}_{-0.041}$	$^{+0.016}_{-0.015}$	$^{+0.13}_{-0.13}$	$^{+0.082}_{-0.074}$	$^{+0.0024}_{-0.0023}$	$^{+0.0076}_{-0.0077}$	$^{+0.057}_{-0.060}$
Multiple candidates	0.00060	0.00012	0.0011	0.0011	0.0073	0.0021	0.00033	0.00011	0.0014
Mass factorisation	0.0002	0.0004	0.004	0.0037	0.0099	0.004	0.0007	0.0022	0.0156
Mass shape	0.0006	0.0005	-	-	0.0465	0.009	-	0.0002	0.001
Fit bias	0.0001	0.0006	0.001	-	0.022	0.033	-	0.0003	0.001
C_{SP} factors	-	0.0001	0.001	0.001	0.013	0.005	-	0.0001	0.002
Time res.: prompt	-	-	-	-	0.001	0.001	-	-	0.001
Time res.: statistical	-	-	-	-	-	-	-	-	-
Time res.: $\mu(\delta t)$	-	-	0.0032	0.001	0.080	0.001	0.0002	0.0003	0.005
Time res.: Wrong PV	-	-	-	-	0.001	0.001	-	-	0.001
Quadratic OS tagging	-	-	-	-	-	-	-	-	-
Ang. acc.: statistical	0.00030	0.00036	0.0011	0.0018	0.0025	0.0044	0.00003	-	0.0011
Ang. acc.: correction	0.00200	0.00112	0.0022	0.0043	0.0057	0.0077	0.00006	0.00021	0.0012
Ang. acc.: t & σ_t dependence	0.00084	0.00120	0.0012	0.0007	0.029	0.0055	0.00021	0.00095	0.0028
Dec. time acc.: knot pos.	-	-	-	-	-	-	0.00019	-	-
Dec. time acc.: p.d.f. reweighting	-	-	-	-	-	-	0.00007	0.00009	-
Dec. time acc.: kinematic reweighting	-	-	-	-	-	-	0.00021	-	-
Dec. time acc.: statistical	0.00020	0.00030	-	-	-	-	0.00120	0.00083	-
Dec. time acc.: Other MC sample	0.00012	0.00018	-	-	-	-	0.00031	0.00050	-
Length scale	-	-	-	-	-	-	-	-	0.004
BKGCAT==60	0.00019	0.00013	0.0005	0.0014	-	0.0017	0.00020	0.00012	-
Quadratic sum of syst.	0.0024	0.0019	0.0061	0.0064	0.1007	0.0365	0.0015	0.0026	0.0175

Systematics under control (most are $<$ 10% of stat. uncertainty)

ϕ_s mostly affected by mass factorisation and time resolution, $\Gamma_s - \Gamma_d$ by decay time efficiency, $\Delta\Gamma_s$ by mass factorisation

Expected Precision $\phi_s^{c\bar{c}s}$ at LHCb

- Run 1 + 2015 and 2016 a total of 4.9 fb^{-1}. After Run 3 anticipate 23 fb^{-1} and after Run 5 (after Upgrade II) 500 fb^{-1}

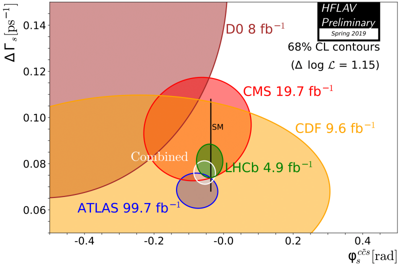


arXiv:1808.08865v3

- Expected precision after Upgrade II from $B_s^0 \to J/\psi\phi(\to K^+K^-)$ only $\sigma_{stat} = 4$ mrad and from all modes combined $\sigma_{stat} = 3$ mrad

HFLAV plot

$$\phi_s^{SM} = -36.9^{+1.0}_{-0.7} \text{ mrad [CKM Fitter]}$$
$$\phi_s^{WA} = -49 \pm 23 \text{ mrad [HFLAV, preliminary]}$$



LHCb

- $J/\psi\phi$ [PRL114, 041801 (2015)] and [LHCb-PAPER-2019-013 (in preparation)]
- $J/\psi\pi^+\pi^-$ [JHEP 08, 037 (2017)] and [arXiv:1903.05530]
- $J/\psi K^+K^-$ [Phys. Lett. B736, 186 (2014)]
- $\Psi(2S)\phi$ [Phys. Lett. B762, 253-262 (2016)]
- $D_s^+D_s^-$ [PRL113, 211801 (2014)]

CMS

- $J/\psi\phi$ [Phys. Lett. B757, 97 (2016)]

ATLAS

- $J/\psi\phi$ [JHEP 08, 147 (2016)] and [ATLAS-CONF-2019-009]