Measurements of ϕ_s & $\Delta\Gamma_s$ in B_s decays at ATLAS and CMS

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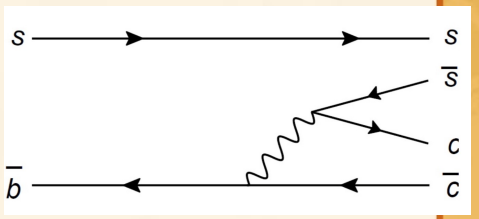
On behalf of the ATLAS and CMS collaborations

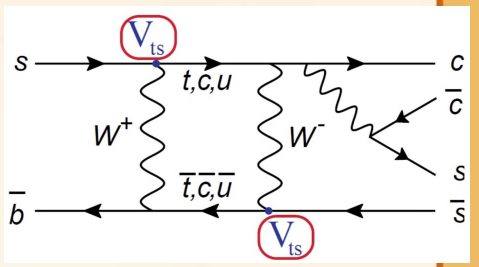
Introduction

- Motivation
- Experimental status (~before these results)
- CMS: Phys Lett B 816 (2021) 136188
  96.4 fb^{-1} (@ 13 TeV) + 19.7 fb^{-1} (@8 TeV)
- ATLAS: EPJC 81(2021) 342
  80.5 fb^{-1} (@ 13 TeV) + 19.2 fb^{-1} (@7 & 8 TeV)

Motivation

- CPV arising from interference between direct and mixing-mediated $B_s \rightarrow J/\psi\phi$
  - ϕ_s: relevant phase in interference (i.e. relative phase of B_s mixing and direct $b \rightarrow ccs$)

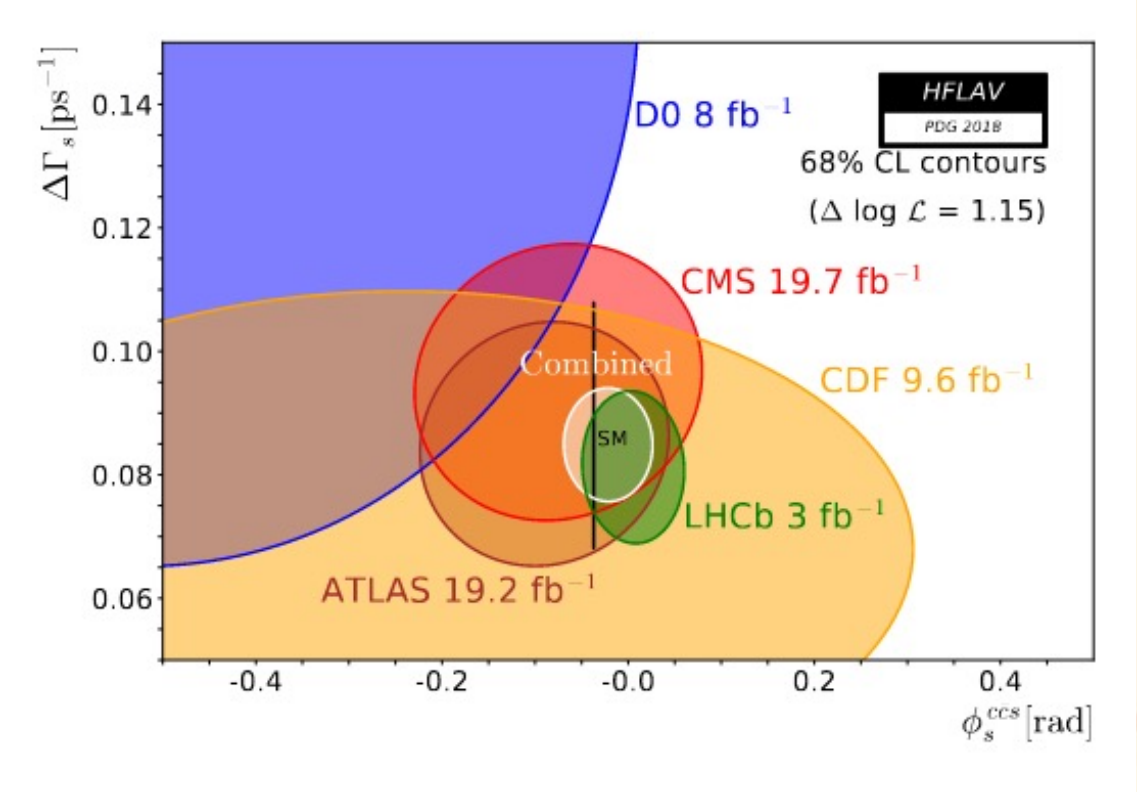




SM: $\phi_s \simeq -2\beta_s = -2arg\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*} = \begin{matrix} -0.03700 \pm 0.00104\ rad \\ -0.03696^{+0.00072}_{-0.00082}\ rad \end{matrix}$ UTfit / CKMFitter

  - $\Delta\Gamma_s$: decay width difference between eigenstates → good test of theory

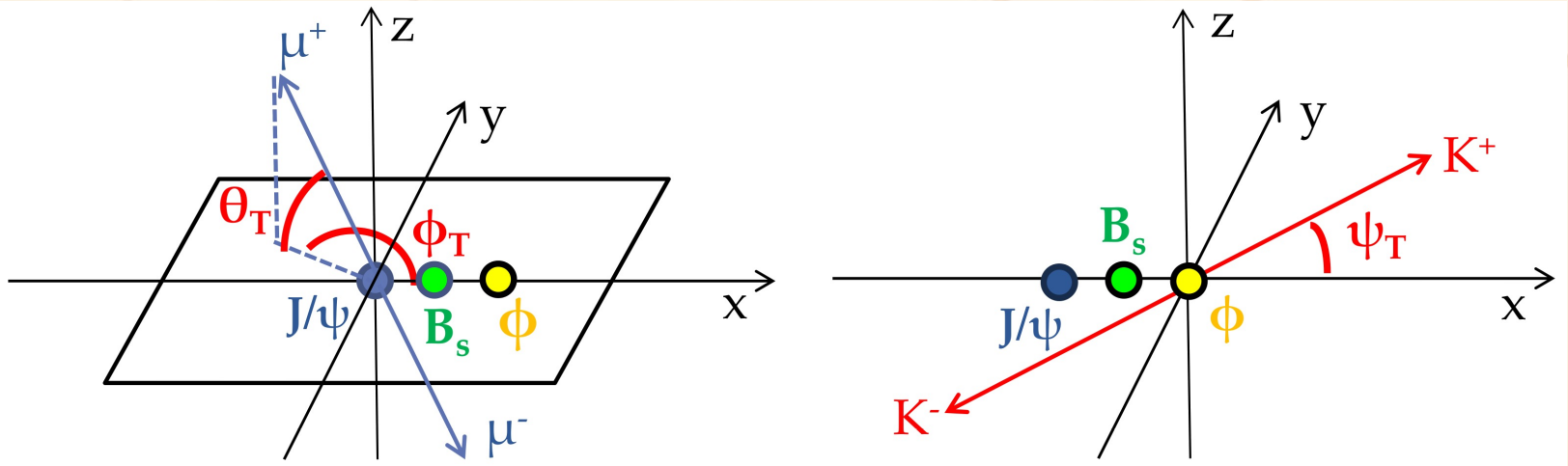
Experimental status as of 2018



- All consistent with SM prediction (…even in 2021 SM prediction is 20x more accurate than LHC combination)
- Increase in precision needed to gain sensitivity around SM prediction

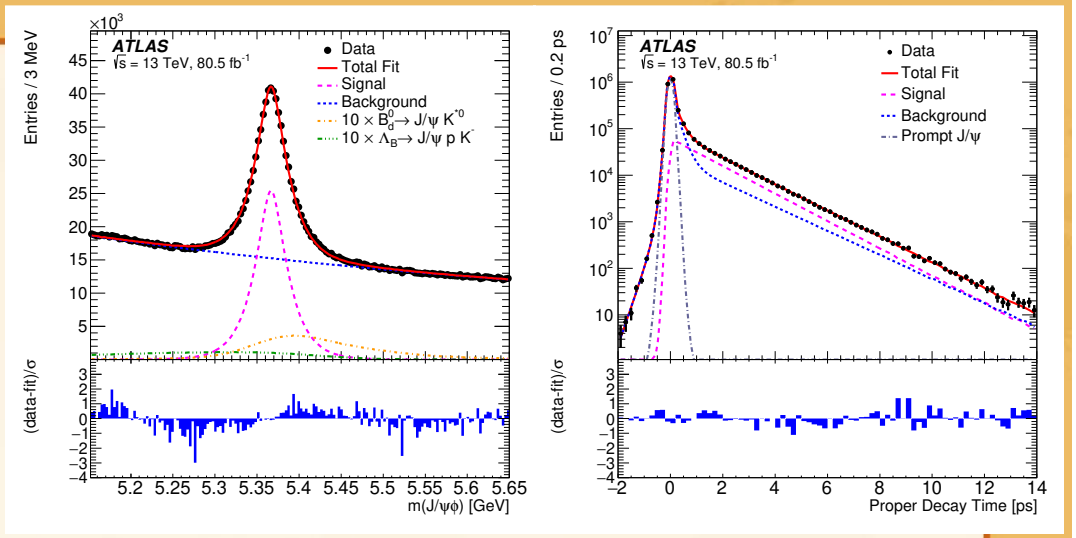
ATLAS Result

- Analysis of Run 2 data
- Continue using di-muon events in line with Run 1 analysis
- VV final state contains CP-odd (L=1) and CP-even (L=0,2)
- Interference from S-wave $B_s \rightarrow J/\psi KK$ (non resonant)
- Time-dependent angular analysis to disentangle
- Angular parameterization in transversity basis:



Parameters Fit

- $U_{nbinned}$ M_{aximum} $L_{ikelihood}$ fit simultaneous in m, t and angles [$\Omega=(\psi_T, \theta_T, \phi_T)$]:



$$\ln \mathcal{L} = \sum_{i=1}^{N} \{ w_i \cdot \ln(f_s \cdot \mathcal{F}_s(m_i, t_i, \sigma_m, \sigma_t, \Omega_i, P(B|Q), p_{T_i})$$
$$+ f_s \cdot f_{B^0_d} \cdot \mathcal{F}_{B^0_d}(m_i, t_i, \sigma_m, \sigma_t, \Omega_i, P(B|Q), p_{T_i})$$
$$+ f_s \cdot f_{\Lambda_b} \cdot \mathcal{F}_{\Lambda_b}(m_i, t_i, \sigma_m, \sigma_t, \Omega_i, P(B|Q), p_{T_i})$$
$$+ (1 - f_s \cdot (1 + f_{B^0_d} + f_{\Lambda_b})) \cdot \mathcal{F}_{bkg}(m_i, t_i, \sigma_m, \sigma_t, \Omega_i, P(B|Q), p_{T_i}))\}$$

Signal

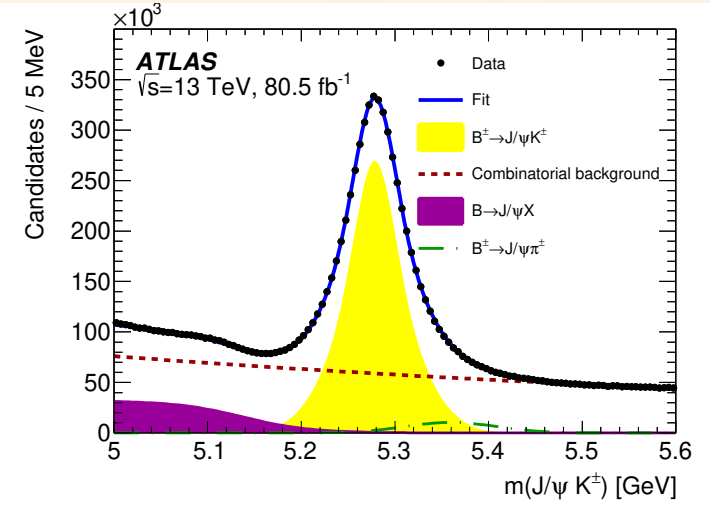
B^0 and Λ_b

Background

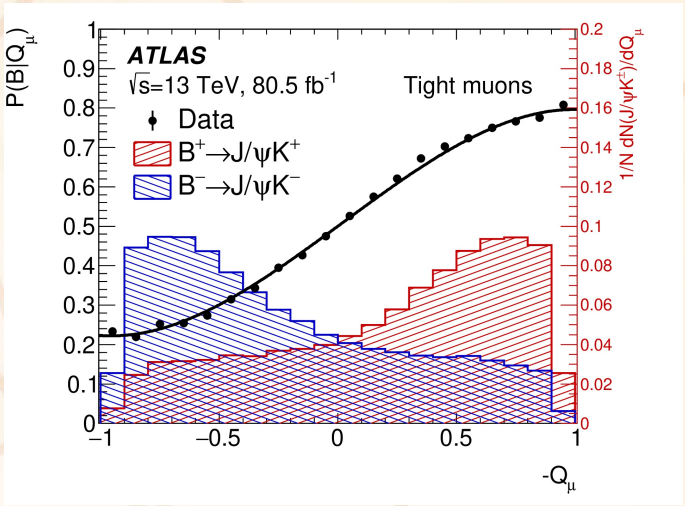
- Observables: m, σ_m, t, σ_t, Ω, tag method & probability P(B|Q)
- Physics parameters: $\boldsymbol{\phi_s}$, $\boldsymbol{\Delta\Gamma_s}$, $\boldsymbol{\Gamma_s}$ ($\boldsymbol{\Delta m_s}$ fixed to SM)
- Amplitudes: $\boldsymbol{|A_0(0)|^2}$, $\boldsymbol{|A_\parallel(0)|^2}$, $\boldsymbol{|A_S(0)|^2}$, $\boldsymbol{\delta_\parallel}$, $\boldsymbol{\delta_\perp}$, $\boldsymbol{\delta_S}$

Flavour Tagging

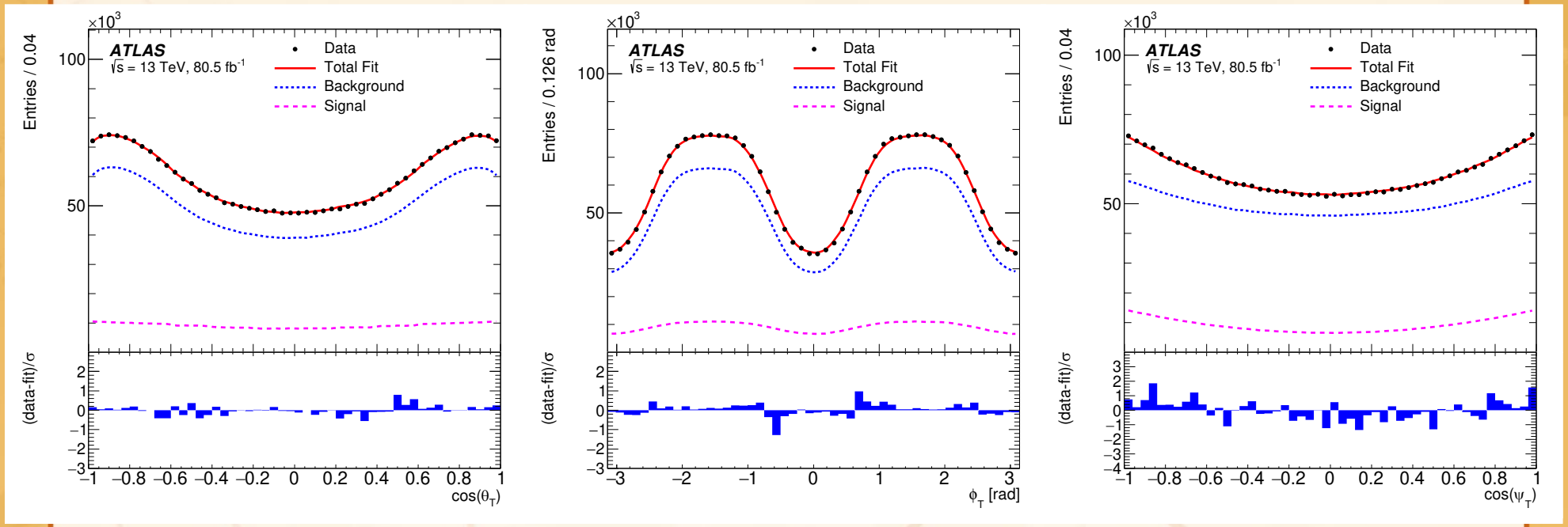
- Opposite Side Taggers
  - μ/e: pure but diluted by oscillations
  - Jet Charge calibrated on $B^{\pm} \rightarrow J/\psi K^{\pm}$

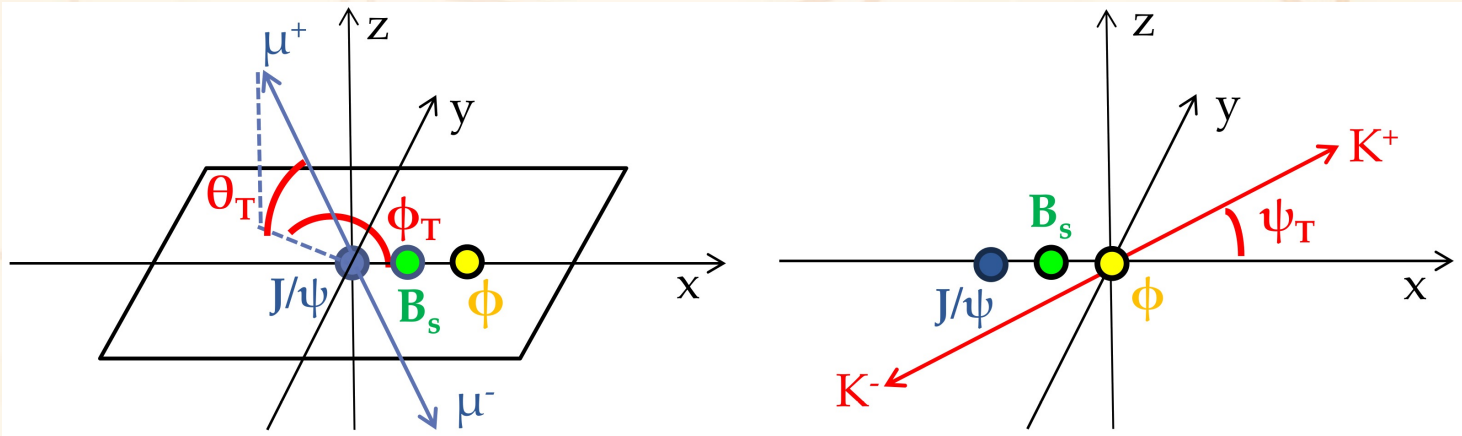


Tag method	ϵ_x [%]	D_x [%]	ϵD^2 [%]
Tight muon	4.50 ± 0.01	43.8 ± 0.2	0.862 ± 0.009
Electron	1.57 ± 0.01	41.8 ± 0.2	0.274 ± 0.004
Low-p_T muon	3.12 ± 0.01	29.9 ± 0.2	0.278 ± 0.006
Jet	12.04 ± 0.02	16.6 ± 0.1	0.334 ± 0.006
Total	21.23 ± 0.03	28.7 ± 0.1	1.75 ± 0.01



Fit Projections: transversity angles

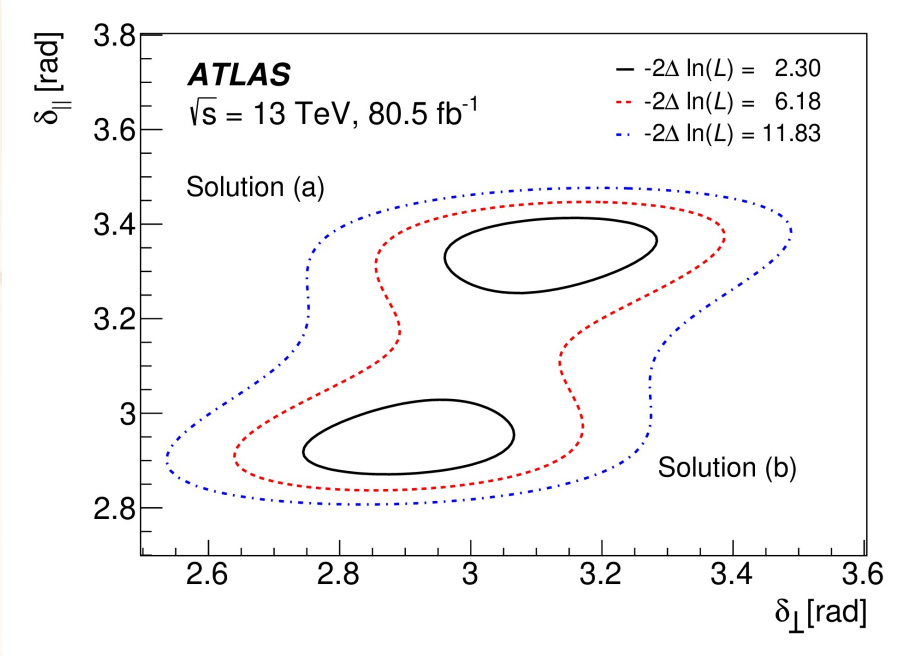




Fit Result

- Run 2 data: single solution for all parameters except $\delta_{\parallel}$, $\delta_{\perp}$
  - Solution (a) slightly favored wrt (b) [-2 Δln(L)=0.03]
- Systematics: lifetime models, background models, tagging parameterisation, calibration etc.

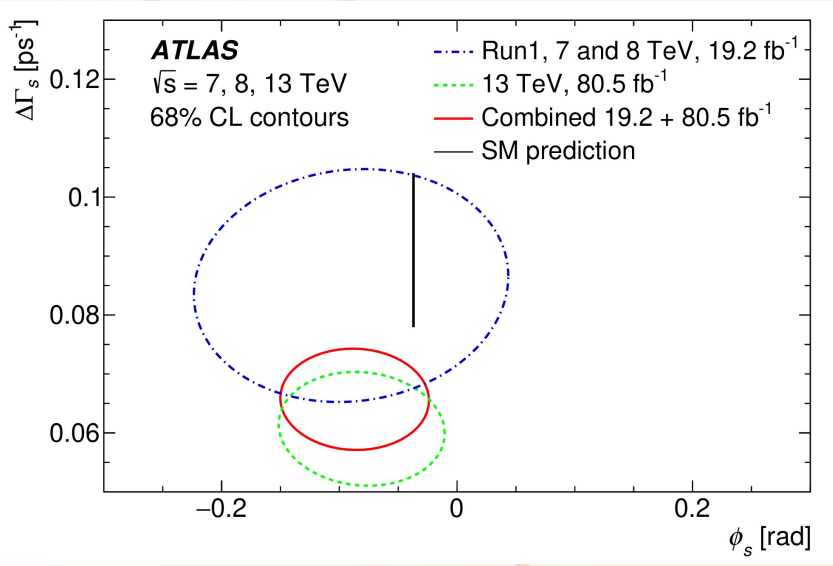
Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	−0.081	0.041	0.022
$\Delta\Gamma_s$ [ps^{-1}]	0.0607	0.0047	0.0043
Γ_s [ps^{-1}]	0.6687	0.0015	0.0022
$\lvert A_{\parallel}(0)\rvert^2$	0.2213	0.0019	0.0023
$\lvert A_0(0)\rvert^2$	0.5131	0.0013	0.0038
$\lvert A_S(0)\rvert^2$	0.0321	0.0033	0.0046
$\delta_{\perp} - \delta_S$ [rad]	−0.25	0.05	0.04
Solution (a)			
$\delta_{\perp}$ [rad]	3.12	0.11	0.06
$\delta_{\parallel}$ [rad]	3.35	0.05	0.09
Solution (b)			
$\delta_{\perp}$ [rad]	2.91	0.11	0.06
$\delta_{\parallel}$ [rad]	2.94	0.05	0.09



Latest updated ATLAS result

Parameter	Solution (a) Value	Statistical uncertainty	Systematic uncertainty	Solution (b) Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	−0.087	0.036	0.021	−0.087	0.036	0.021
$\Delta\Gamma_s$ [ps^{-1}]	0.0657	0.0043	0.0037	0.0657	0.0043	0.0037
Γ_s [ps^{-1}]	0.6703	0.0014	0.0018	0.6704	0.0014	0.0018
$\lvert A_\parallel(0)\rvert^2$	0.2220	0.0017	0.0021	0.2218	0.0017	0.0021
$\lvert A_0(0)\rvert^2$	0.5152	0.0012	0.0034	0.5152	0.0012	0.0034
$\lvert A_S\rvert^2$	0.0343	0.0031	0.0045	0.0348	0.0031	0.0045
$\delta_\perp$ [rad]	3.22	0.10	0.05	3.03	0.10	0.05
$\delta_\parallel$ [rad]	3.36	0.05	0.09	2.95	0.05	0.09
$\delta_\perp - \delta_S$ [rad]	−0.24	0.05	0.04	−0.24	0.05	0.04

- Combination with Run 1 result
  - Consistent results across Run 1 and 2
- Competitive measurement of $\Delta\Gamma_s$, Γ_s and helicity parameters
- 60 fb^{-1} remaining to be included from 2018 dataset



CMS Measurement

- Events selected at trigger level to contain tagging muon → enhanced tagging efficiency at analysis level
- Unbinned extended Maximum Likelihood:

$$P_{sig} = \underbrace{\varepsilon(ct)\,\varepsilon(\Theta)}_{\text{efficiency functions}}\left[\tilde{\mathcal{F}}(\Theta, ct, \alpha) \otimes G(ct, \sigma_{ct})\right] P_{\text{sig}}\left(m_{B_s^0}\right) P_{sig}(\sigma_{ct})\, P_{sig}(\zeta)$$

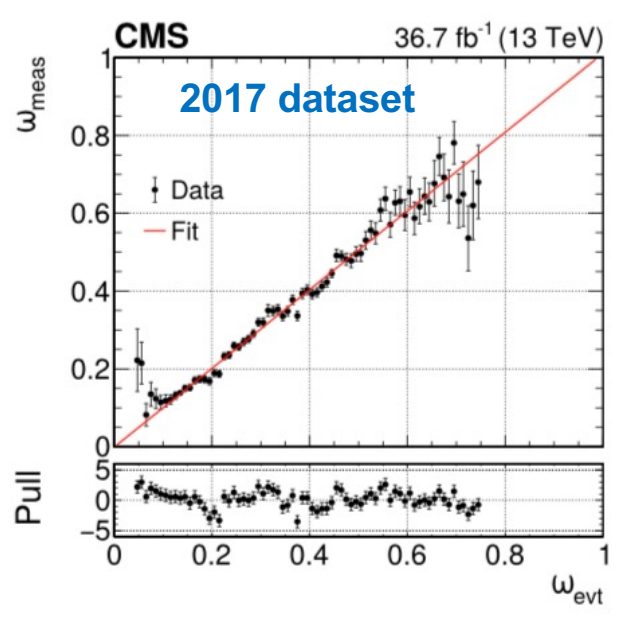
- $\tilde{\mathcal{F}}(\Theta, ct, \alpha)$: differential decay rate
- $G(ct, \sigma_{ct})$: Gaussian resolution model
- $P_{\text{sig}}\left(m_{B_s^0}\right)$: signal mass pdf
- $P_{sig}(\sigma_{ct})$: signal σ_{ct} pdf
- $P_{sig}(\zeta)$: tag distribution

$$P_{\text{bkg}} = \underbrace{P_{\text{bkg}}(cos\vartheta_T, \phi_T)\, P_{\text{bkg}}(cos\psi_T)\, P_{bkg}(ct)}_{\text{bkg angular and lifetime pdfs}}\, P_{bkg}\left(m_{B_s^0}\right) P_{\text{bkg}}(\sigma_{ct})\, P_{\text{bkg}}(\zeta)$$

- Negligible contribution from $\Lambda_b \rightarrow J/\psi Kp$
- Flavour tagging based on opposite muon
- Fit includes λ and Δm_s parameters

CMS Flavour tagging

- MC-trained $D_{eep}N_{eural}N_{etwork}$-based muon tagger:
  - DNN_1 to reject spurious muons (hadrons & light flavour)
  - DNN_2 to identify right tag and predict mis-tag probability ω_{meas}
- Mis-tag probability calibrated on $B^{\pm} \rightarrow J/\psi K^{\pm}$:



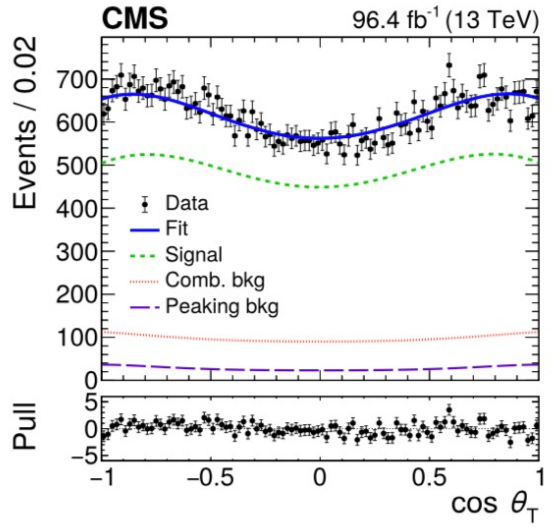
$\omega_{meas}=a+b\times\omega_{evt}$

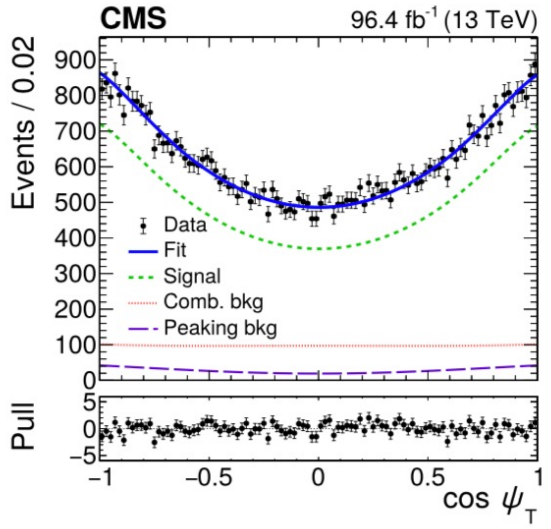
Dataset	a	b
2017	-0.0010±0.0040	1.012±0.013
2018	0.0031±0.0031	1.011±0.010

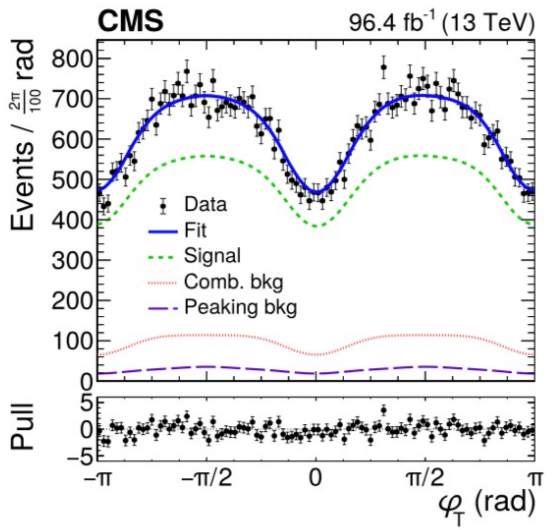
Calibrated opposite-side muon tagger performance evaluated using $B^{\pm} \rightarrow J/\psi K^{\pm}$ events in the 2017 and 2018 data samples. The uncertainties shown are statistical only.

Data sample	ε_{tag} (%)	ω_{tag} (%)	P_{tag} (%)
2017	45.7 ± 0.1	27.1 ± 0.1	9.6 ± 0.1
2018	50.9 ± 0.1	27.3 ± 0.1	10.5 ± 0.1

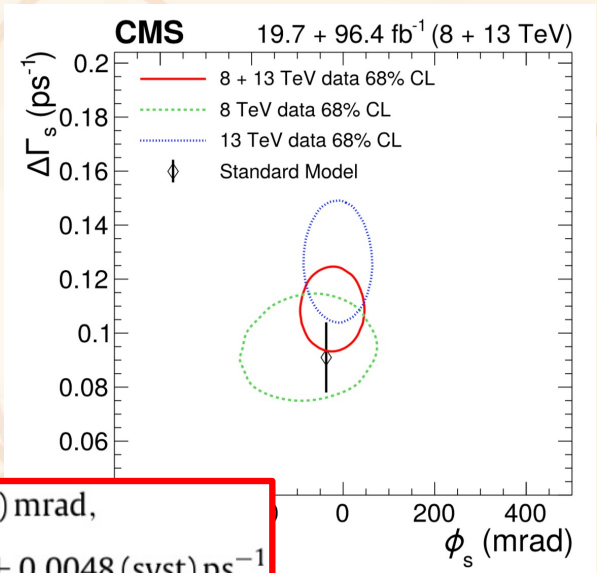
CMS Fit Result







Parameter	Fit value	Stat. uncer.	Syst. uncer.
ϕ_s [mrad]	-11	± 50	± 10
$\Delta\Gamma_s$ [ps^{-1}]	0.114	± 0.014	± 0.007
Δm_s [$\hbar$ ps^{-1}]	17.51	$^{+0.10}_{-0.09}$	± 0.03
$\lvert\lambda\rvert$	0.972	± 0.026	± 0.008
Γ_s [ps^{-1}]	0.6531	± 0.0042	± 0.0026
$\lvert A_0\rvert^2$	0.5350	± 0.0047	± 0.0049
$\lvert A_\perp\rvert^2$	0.2337	± 0.0063	± 0.0045
$\lvert A_S\rvert^2$	0.022	$^{+0.008}_{-0.007}$	± 0.016
$\delta_\parallel$ [rad]	3.18	± 0.12	± 0.03
$\delta_\perp$ [rad]	2.77	± 0.16	± 0.05
$\delta_{S\perp}$ [rad]	0.221	$^{+0.083}_{-0.070}$	± 0.048



Combined with 8 TeV result:

$$\phi_s = -21 \pm 44\,(\text{stat}) \pm 10\,(\text{syst})\,\text{mrad},$$

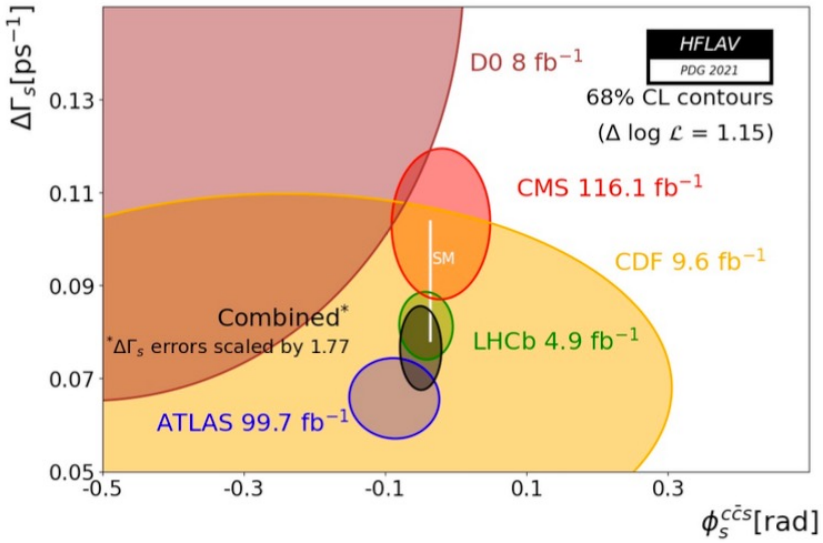
$$\Delta\Gamma_s = 0.1032 \pm 0.0095\,(\text{stat}) \pm 0.0048\,(\text{syst})\,\text{ps}^{-1}$$

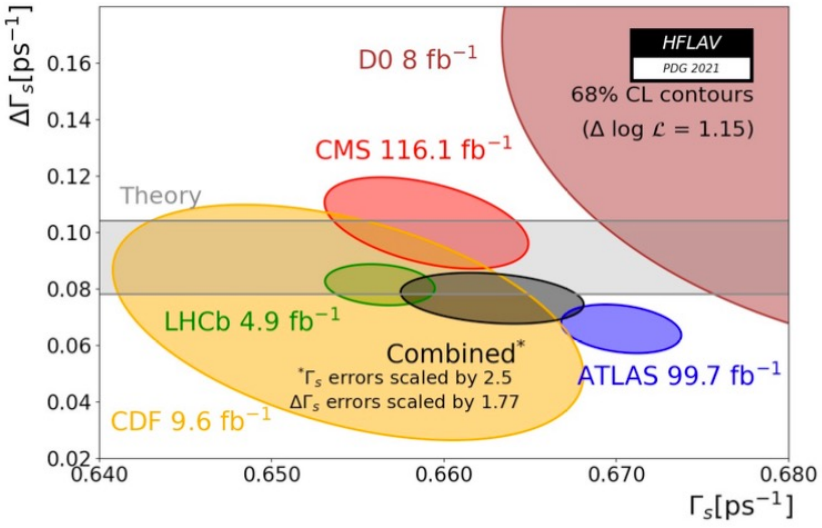
Experimental Averages

HFLAV average for PDG21:

$\phi_s = -0.050 \pm 0.019$ rad

Because of tensions, errors on Γ_s and $\Delta\Gamma_s$ scaled by 2.5 and 1.77





$$SM\colon \phi_s = \begin{cases} -0.03700 \pm 0.00104\ rad & \text{UTfit} \\ -0.03696^{+0.00072}_{-0.00082}\ rad & \text{CKMFitter} \end{cases}$$

Still plenty of room for NP perturbations on top of the SM phase!

Outlook

- Both experiments aiming at new round of analyses in Run 3
- HL-LHC:
  - **CMS** expects ~9E6 candidates
    → $\sigma_{\phi s}$~ 5-6 mrad
    (assuming 1.2-2.4% ϵD^2)
  - **ATLAS** expects 1÷10E6 candidates
    → $\sigma_{\phi s}$~4-9 mrad

  (bigger range as considering several trigger scenarios)

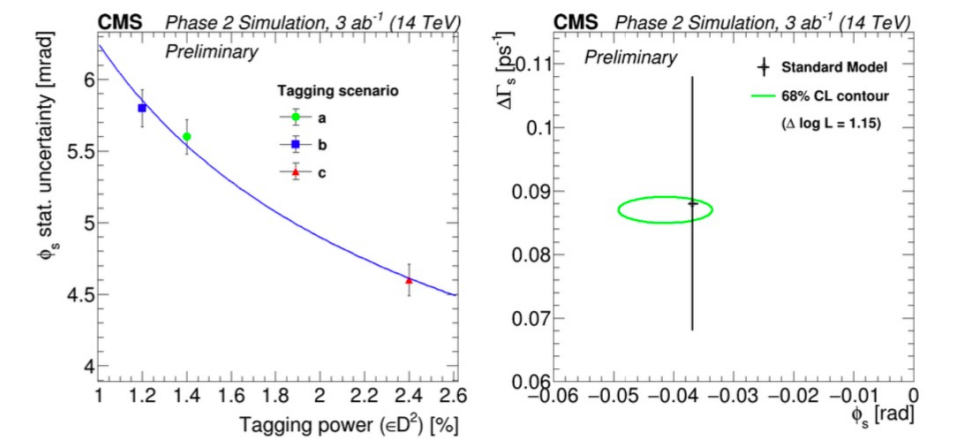
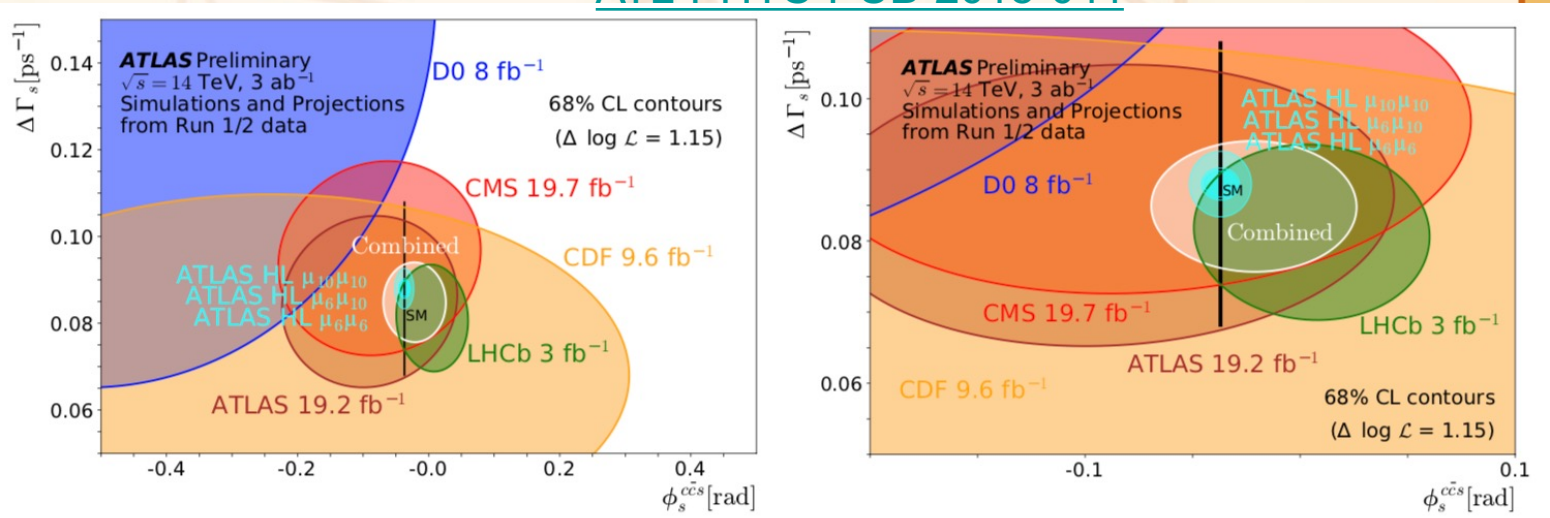


Figure 2: Left: variation of the ϕ_s statistical uncertainty as function of the tagging power (ϵD^2) see equation 1, measured in different flavour tagging scenarios. A function proportional to $1/\sqrt{\epsilon D^2}$ is shown to describe the behaviour of the ϕ_s uncertainty in the selected range. Right: 68% confidence level (CL) contour from the fit of a toy MC pseudo-experiment generated in the tagging scenario *c*. The contour combines statistical and systematic uncertainties. The black cross represents the SM expectations [2][1].

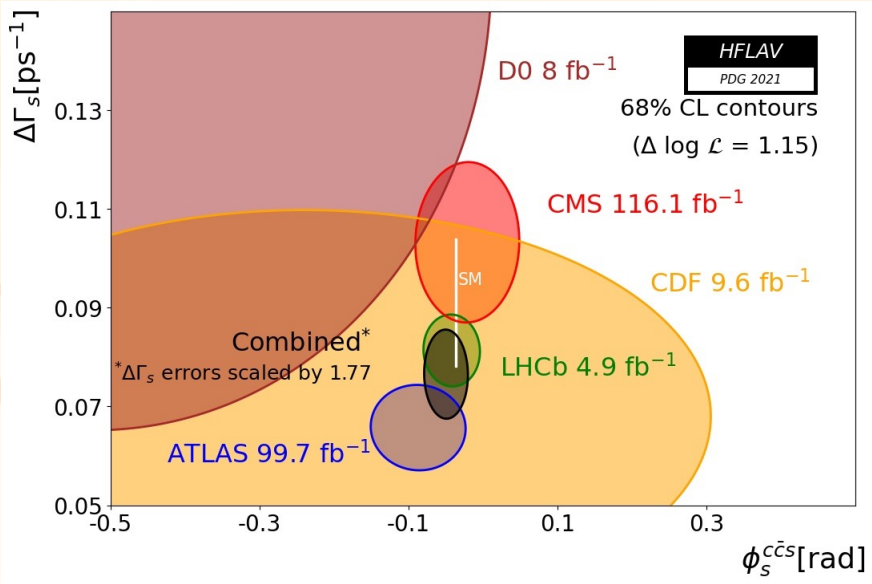
CMS-FTR-18-041

ATL-PHYS-PUB-2018-041



Conclusions

- Both ATLAS and CMS produced results based on most of their Run 2 datasets
  - Update of ATLAS result to include last 60 fb^{-1} under way (including λ and Δm_s)
- Strategic contributions to one of the key closure tests of the b sector
- Stay tuned for more in the coming years!



Backup Material

ATLAS Systematics

	ϕ_s [10^{-3} rad]	$\Delta\Gamma_s$ [10^{-3} ps^{-1}]	Γ_s [10^{-3} ps^{-1}]	$\lvert A_\parallel(0)\rvert^2$ [10^{-3}]	$\lvert A_0(0)\rvert^2$ [10^{-3}]	$\lvert A_S(0)\rvert^2$ [10^{-3}]	$\delta_\perp$ [10^{-3} rad]	$\delta_\parallel$ [10^{-3} rad]	$\delta_\perp - \delta_S$ [10^{-3} rad]
Tagging	19	0.4	0.3	0.2	0.2	1.1	17	19	2.3
ID alignment	0.8	0.2	0.5	< 0.1	< 0.1	< 0.1	11	7.2	< 0.1
Acceptance	0.5	0.3	< 0.1	1.0	0.9	2.9	37	64	8.6
Time efficiency	0.2	0.2	0.5	< 0.1	< 0.1	0.1	3.0	5.7	0.5
Best candidate selection	0.4	1.6	1.3	0.1	1.0	0.5	2.3	7.0	7.4
Background angles model:									
Choice of fit function	2.5	< 0.1	0.3	1.1	< 0.1	0.6	12	0.9	1.1
Choice of p_{T} bins	1.3	0.5	< 0.1	0.4	0.5	1.2	1.5	7.2	1.0
Choice of mass window	9.3	3.3	0.2	0.4	0.8	0.9	17	8.6	6.0
Choice of sidebands intervals	0.4	0.1	0.1	0.3	0.3	1.3	4.4	7.4	2.3
Dedicated backgrounds:									
B_d^0	2.6	1.1	< 0.1	0.2	3.1	1.5	10	23	2.1
Λ_b	1.6	0.3	0.2	0.5	1.2	1.8	14	30	0.8
Alternate Δm_s	1.0	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	15	4.0	< 0.1
Fit model:									
Time res. sig frac	1.4	1.1	0.5	0.5	0.6	0.8	12	30	0.4
Time res. p_{T} bins	0.7	0.5	0.8	0.1	0.1	0.1	2.2	14	0.7
S-wave phase	0.3	< 0.1	< 0.1	< 0.1	< 0.1	0.2	8.0	15	37
Fit bias	5.7	1.3	1.2	1.3	0.4	1.1	3.3	19	0.3
Total	22	4.3	2.2	2.3	3.8	4.6	55	88	39

CMS Systematics

	ϕ_s [mrad]	$\Delta\Gamma_s$ [ps^{-1}]	Δm_s [$\hbar$ ps^{-1}]	$\lvert\lambda\rvert$	Γ_s [ps^{-1}]	$\lvert A_0\rvert^2$	$\lvert A_\perp\rvert^2$	$\lvert A_S\rvert^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	$\delta_{S\perp}$ [rad]
Statistical uncertainty	50	0.014	0.10	0.026	0.0042	0.0047	0.0063	0.0077	0.12	0.16	0.083
Model bias	7.9	0.0019	—	0.0035	0.0005	0.0002	0.0012	0.001	0.020	0.016	0.006
Angular efficiency	3.8	0.0006	0.007	0.0057	0.0002	0.0008	0.0010	0.002	0.006	0.015	0.015
Proper decay length efficiency	0.3	0.0062	0.001	0.0002	0.0022	0.0014	0.0023	0.001	0.001	0.002	0.002
Proper decay length resolution	2.5	0.0008	0.015	0.0009	0.0005	0.0007	0.0009	0.007	0.006	0.025	0.022
Data/simulation difference	0.6	0.0008	0.004	0.0003	0.0003	0.0044	0.0029	0.007	0.007	0.007	0.028
Flavor tagging	0.1	$<10^{-4}$	0.001	0.0002	$<10^{-4}$	0.0003	$<10^{-4}$	$<10^{-3}$	0.001	0.003	0.001
Sig./bkg. ω_{evt} difference	3.0	—	—	—	0.0005	—	0.0008	—	—	—	0.006
Model assumptions	—	0.0008	—	0.0046	0.0003	—	0.0013	0.001	0.017	0.019	0.011
Peaking background	0.3	0.0008	0.011	$<10^{-4}$	0.0002	0.0005	0.0002	0.003	0.005	0.007	0.011
S-P wave interference	—	0.0010	0.019	—	0.0005	0.0005	—	0.013	—	0.019	0.019
Total systematic uncertainty	9.6	0.0067	0.028	0.0082	0.0024	0.0048	0.0044	0.016	0.028	0.045	0.047