Experimental status of CPV in Bs mixing

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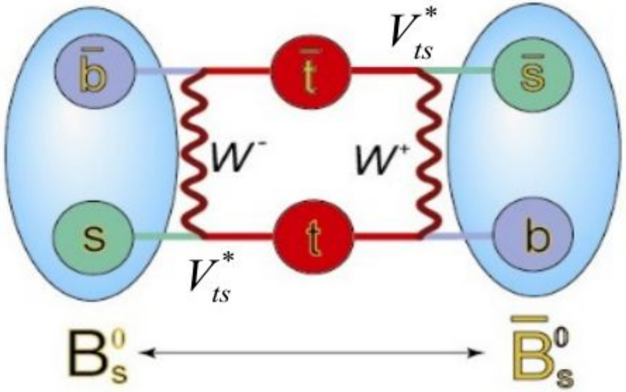
Introduction

- $\boldsymbol{\varphi_s}$ is a CPV phase arising from the interference between $\mathbf{B_s}$ decays proceeding directly and through $\mathbf{B_s}$-$\mathbf{\overline{B}_s}$ mixing to a CP final state.
- $\mathbf{B_s \to J/\psi\phi}$ **golden channel** used to measure CP-violation phase $\boldsymbol{\varphi_s}$ potentially sensitive to New Physics.
  - No direct CPV.
  - Only one weak phase.
  - Easy to reconstruct with high S/B.



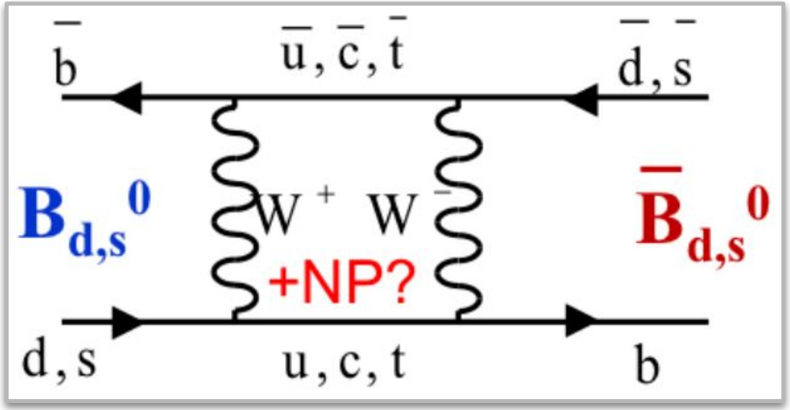
- In SM $\boldsymbol{\varphi_s}$ is related to the CKM elements and predicted with high precision
  - $\beta_s = -36.96^{+0.72}_{-0.84}$ mrad [CKMFitter group]

$$\varphi_s \simeq -2\beta_s, \text{ where } \beta_s = \arg\left(-\frac{V_{ts}V^*_{tb}}{V_{cs}V^*_{cb}}\right)$$

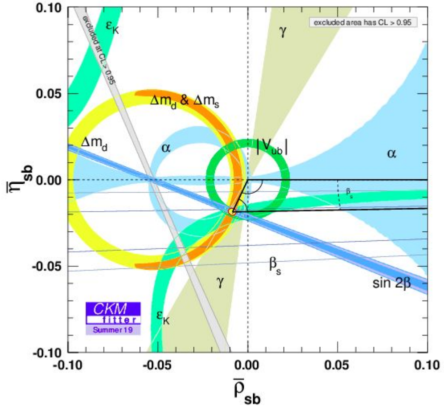
- Other quantities related to $\mathbf{B_s}$ mixing extracted along with $\boldsymbol{\varphi_s}$ with the same analysis : Γ_s, $\Delta\Gamma_s$, $|\lambda|$, Δm_s.

$$\lambda = \frac{q}{p}\frac{\bar{A}_{f.s.}}{A_{f.s.}}, \quad |B_{L,H}\rangle = p|B^0_s\rangle \pm q|\overline{B}^0_s\rangle$$

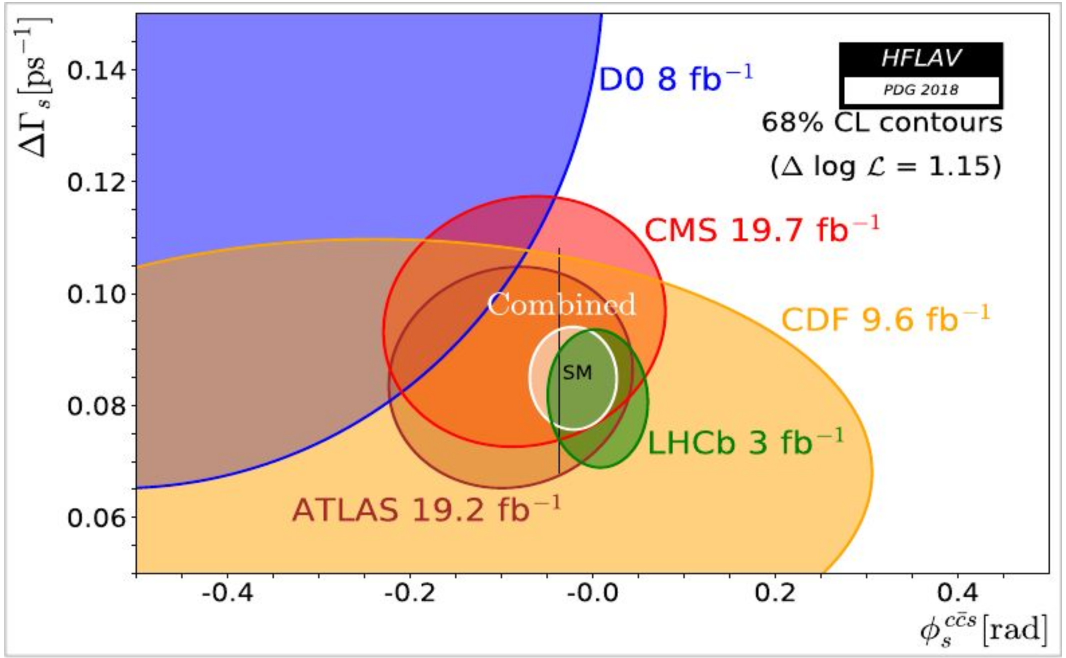
Introduction



CKMFitter group



PDG 2018



Sensitive probe of **New Physics** in $\mathbf{B_s}$ mixing

Precise test of Standard Model

Outline

Physics results

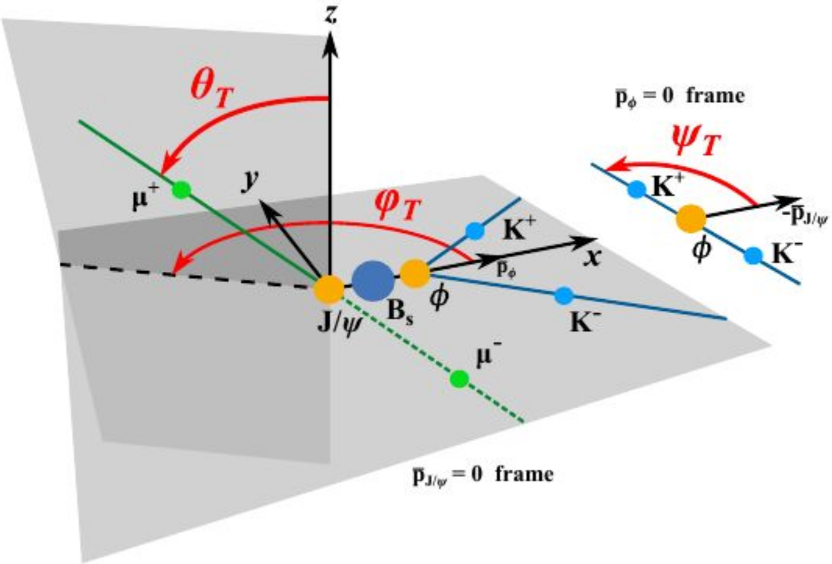
★ Measurement of the CP-violating phase φ_s in $B_s \rightarrow J/\psi\phi$ decays in ATLAS at 13 TeV. CERN-EP-2019-218, Eur. Phys. J. C 81 (2021) 342. — **ATLAS**

★ Updated measurement of time-dependent *CP*-violating observables in $B_s \rightarrow J/\psi K^+K^-$ decay. EUR.PHYS.J.C79(2019)706. — **LHCb**

★ Measurement of the CP violating phase φ_s in the $B_s \rightarrow J/\psi\phi(1020) \rightarrow \mu^+\mu^- K^+K^-$ channel in proton-proton collisions at 13 TeV. CMS-PAS-BPH-20-001, Phys. Lett. B 816 (2021) 136188. — **CMS**

General comment for the three analysis 1

- **Angular analysis** to separate the different CP eigenstate of the final state
  - Helicity angle of **K+** in the **ϕ** rest frame.
  - Polar angle of **μ+** in the **J/ψ** rest frame
  - Azimuthal angle of **μ+** in the **J/ψ** rest frame.



- **The differential decay rate**
  - **O_i** are time-dependent functions, **g_i** are angular functions, and **α** is a set of physics parameters.

$$\frac{d^4\Gamma(B_s^0)}{d\Theta\, d(ct)} = f(\Theta, ct, \alpha) \propto \sum_{i=1}^{10} O_i(ct,\alpha)\, g_i(\Theta)$$

we need flavor tagging to separate **B_s** from **$\bar{B}_s$** decays, since the final state is the same for the two mesons.

$$O_i(ct,\alpha) = N_i e^{-\Gamma_s t}\left[a_i \cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + b_i \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + c_i \cos(\Delta m_s t) + d_i \sin(\Delta m_s t)\right]$$

General comment for the three analysis 2

i	$g_i(\theta_T, \psi_T, \varphi_T)$	N_i	a_i	b_i	c_i	d_i
1	$2\cos^2\psi_T(1-\sin^2\theta_T\cos^2\varphi_T)$	$\lvert A_0(0)\rvert^2$	1	D	C	$-S$
2	$\sin^2\psi_T(1-\sin^2\theta_T\sin^2\varphi_T)$	$\lvert A_\parallel(0)\rvert^2$	1	D	C	$-S$
3	$\sin^2\psi_T\sin^2\theta_T$	$\lvert A_\perp(0)\rvert^2$	1	$-D$	C	S
4	$-\sin^2\psi_T\sin 2\theta_T\sin\varphi_T$	$\lvert A_\parallel(0)\rvert\lvert A_\perp(0)\rvert$	$C\sin(\delta_\perp-\delta_\parallel)$	$S\cos(\delta_\perp-\delta_\parallel)$	$\sin(\delta_\perp-\delta_\parallel)$	$D\cos(\delta_\perp-\delta_\parallel)$
5	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin^2\theta_T\sin 2\varphi_T$	$\lvert A_0(0)\rvert\lvert A_\parallel(0)\rvert$	$\cos(\delta_\parallel-\delta_0)$	$D\cos(\delta_\parallel-\delta_0)$	$C\cos(\delta_\parallel-\delta_0)$	$-S\cos(\delta_\parallel-\delta_0)$
6	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin 2\theta_T\cos\varphi_T$	$\lvert A_0(0)\rvert\lvert A_\perp(0)\rvert$	$C\sin(\delta_\perp-\delta_0)$	$S\cos(\delta_\perp-\delta_0)$	$\sin(\delta_\perp-\delta_0)$	$D\cos(\delta_\perp-\delta_0)$
7	$\frac{2}{3}(1-\sin^2\theta_T\cos^2\varphi_T)$	$\lvert A_S(0)\rvert^2$	1	$-D$	C	S
8	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin^2\theta_T\sin 2\varphi_T$	$\lvert A_S(0)\rvert\lvert A_\parallel(0)\rvert$	$C\cos(\delta_\parallel-\delta_S)$	$S\sin(\delta_\parallel-\delta_S)$	$\cos(\delta_\parallel-\delta_S)$	$D\sin(\delta_\parallel-\delta_S)$
9	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin 2\theta_T\cos\varphi_T$	$\lvert A_S(0)\rvert\lvert A_\perp(0)\rvert$	$\sin(\delta_\perp-\delta_S)$	$-D\sin(\delta_\perp-\delta_S)$	$C\sin(\delta_\perp-\delta_S)$	$S\sin(\delta_\perp-\delta_S)$
10	$\frac{4}{3}\sqrt{3}\cos\psi_T(1-\sin^2\theta_T\cos^2\varphi_T)$	$\lvert A_S(0)\rvert\lvert A_0(0)\rvert$	$C\cos(\delta_0-\delta_S)$	$S\sin(\delta_0-\delta_S)$	$\cos(\delta_0-\delta_S)$	$D\sin(\delta_0-\delta_S)$

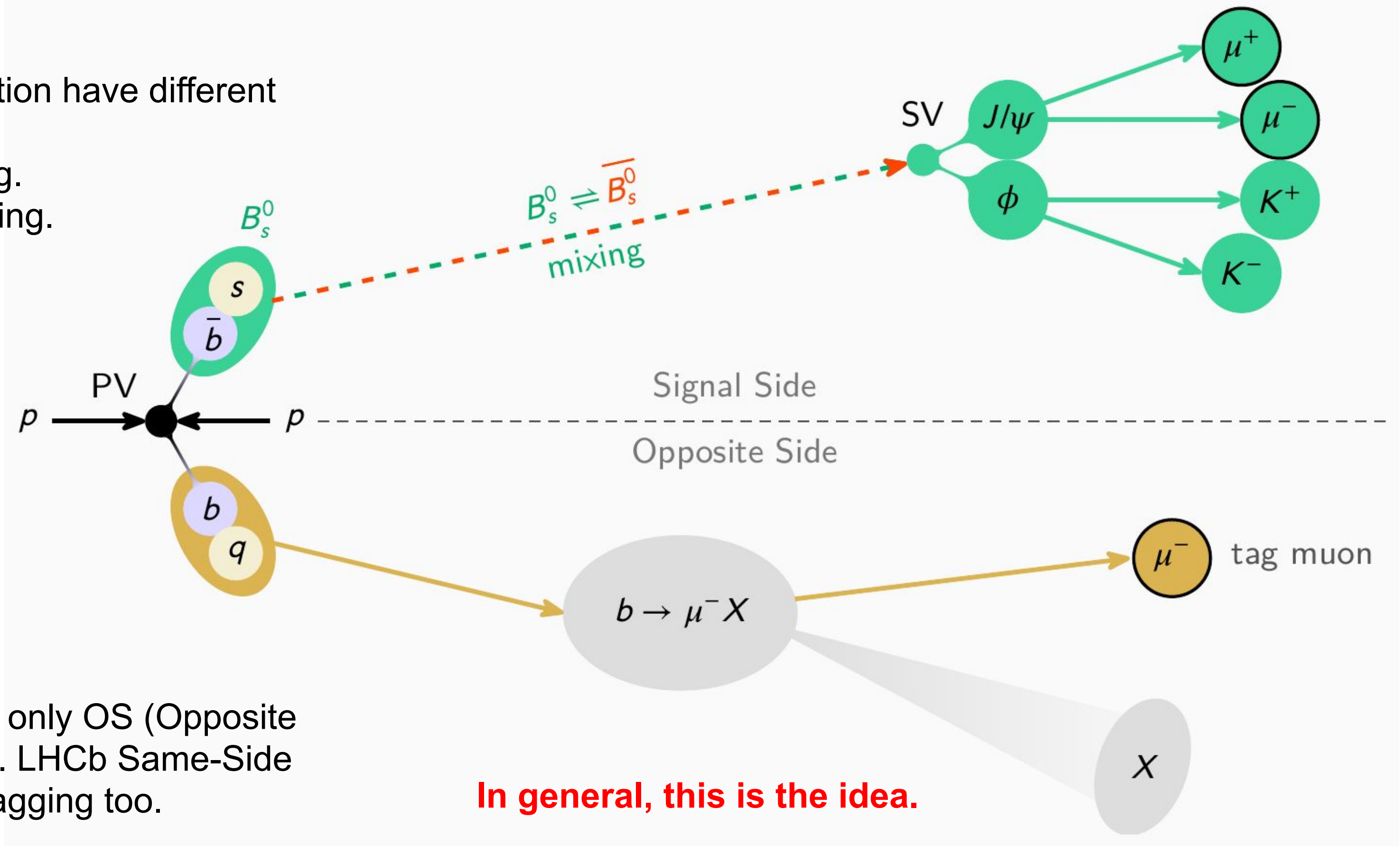
The terms C, S, and D contain the information about CP violation and are defined as:

$$C = \frac{1-|\lambda|^2}{1+|\lambda|^2}, \qquad S = -\frac{2|\lambda|\sin\phi_s}{1+|\lambda|^2}, \qquad D = -\frac{2|\lambda|\cos\phi_s}{1+|\lambda|^2},$$

General comment for the three analysis 3

The three collaboration have different approaches:

- ➔ Muon Tagging.
- ➔ Electron Tagging.
- ➔ Jet-Charge.



- ➔ No necessary only OS (Opposite Side) Tagging. LHCb Same-Side Kaon (SSK) tagging too.

In general, this is the idea.

CERN-EP-2019-218:

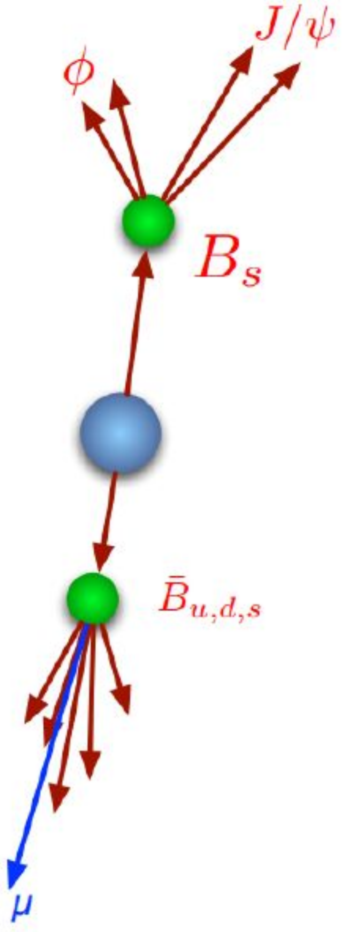
Measurement of the CP-violating phase φ_s in $B_s \rightarrow J/\psi\phi$ decays in ATLAS at 13 TeV.

Datasets and Selection

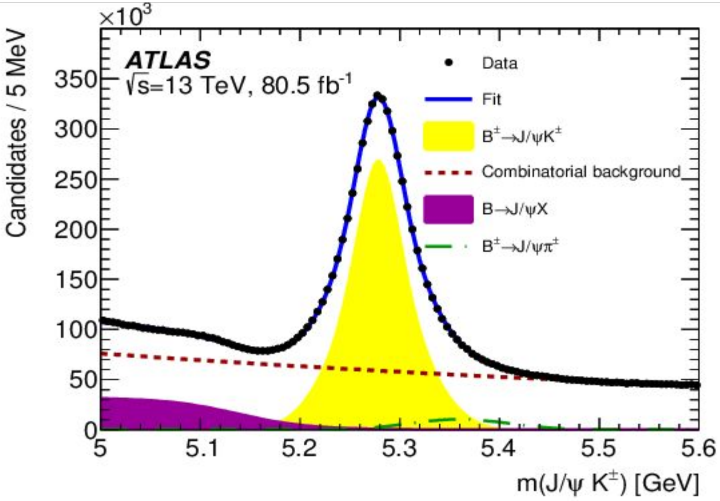
- This analysis follows previous measurement using **19.2 fb^{-1}** of 7 TeV and 8 TeV ("run 1").
- The new analysis uses datasets from 2015 to 2017 with 13 TeV totaling **80.5 fb^{-1}**.
- **MC Samples**
  - Signal **$B_s \to J/\psi\phi$ MC events.**
  - MC samples for peaking backgrounds: **$B_d \to J/\psi K^*$, $B_d \to J/\psi K\pi$, $\Lambda_b \to J/\psi Kp$.**
  - MC samples for tagging calibration channel **$B^+ \to J/\psi K^+$**.
- Full decay reconstruction using inner detector and muon detectors:
  - Events collected with mixture of triggers based on **$J/\psi \to \mu^+\mu^-$** identification, with muon pT thresholds of either 4 GeV or 6 GeV (vary over run periods).
  - **No lifetime or impact parameter cut at HLT level.**
  - ϕ selection – **pT(K±)>1** GeV, Invariant mass window 22 MeV.
  - B candidates – **4-track vertex χ^2/NDF <3**, (5.15 – 5.65) GeV. Vertex fit performed with **J/ψ** mass constraint.

Flavour tagging

- The analysis uses opposite-side tagging (OST)
  - Use **b−$\bar{b}$** pair correlation to infer initial signal flavour from the other B_s meson.
  - Provide the probability of the signal candidate to be B_s-$\bar{B}_s$ at production.
- It uses 4 tagging methods: “Tight” muons, electrons, Low-pT muons, Jet.
  - **b→l** transitions are clean tagging method.
  - **b→c→l** and neutral B-meson oscillations dilute the tagging.
  - Jet-charge. information from tracks in b-tagged jet, when no lepton is found.
- Charge of pT -weighted tracks in a cone around the opposite primary object, used to build per-candidate B_s tag probability.
- Calibrated with $B^+ \to J/\psi K^+$ sample



Tag calibration and performance



- Self tagging non oscillating channel
- Opposite side lepton or jet, with tracks in cone $\Delta R < 0.5$

$$Q_x = \frac{\sum_i^{N \text{ tracks}} q_i \cdot (p_{\text{T}i})^\kappa}{\sum_i^{N \text{ tracks}} (p_{\text{T}i})^\kappa}$$

Tag method	ϵ_x [%]	D_x [%]	T_x [%]
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

- ➢ **Efficiency: ε.** Fraction of signals with a specific tagger.
- ➢ **Dilution: D = (1 − 2w)**, where **w** is the miss-tag probability.
- ➢ **Tagging Power:** figure of merit of tagger performance.

$$\mathbf{TP = \varepsilon D^2 = \varepsilon(1\text{-}2w)^2}$$

Mass-lifetime-angular Maximum Likelihood Fit

wi is a weighting factor to account for the trigger efficiency

$B_d \to J/\psi K^*$, $\Lambda_b \to J/\psi Kp$ peaking backgrounds derived from MC, PDG and the LHCb $\Lambda_b \to J/\psi Kp$ measurement; fixed shape and relative contribution in the fit.

Combinatorial background description, derived from data sidebands; angular distribution described by spherical harmonics and fixed in the fit

Measured variables:

B_s mass m_i

B_s proper decay time t_i

and its uncertainty σ_{ti}

3 angles $\Omega_i(\theta_T, \psi_T, \varphi_T)$

B_s momentum p_T

B_s tag probability $p_{B|Qi}$

tagging method M_i

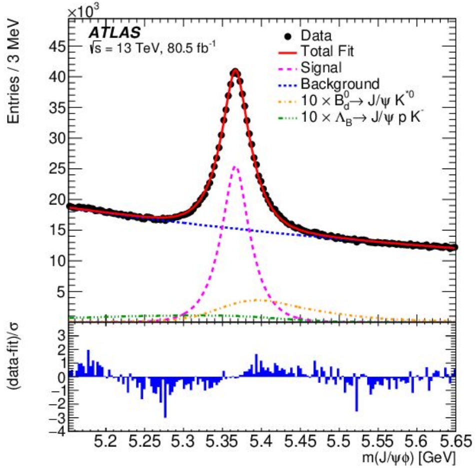
$$\ln \mathcal{L} = \sum_{i=1}^{N} w_i \cdot \ln[f_s \cdot \mathcal{F}_s(m_i, t_i, \sigma_{m_i}, \sigma_{t_i}, \Omega_i, P_i(B|Q_x), p_{T_i})$$

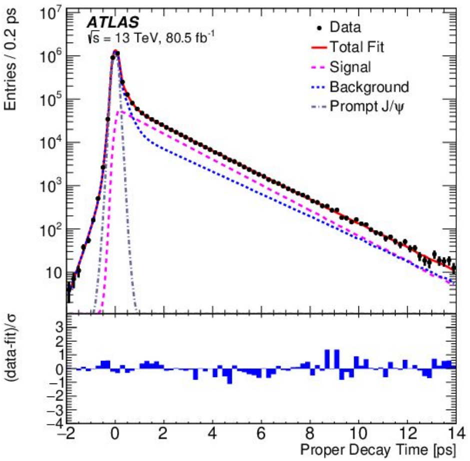
$$+ f_s \cdot f_{B^0} \cdot \mathcal{F}_{B^0}(m_i, t_i, \sigma_{m_i}, \sigma_{t_i}, \Omega_i, P_i(B|Q_x), p_{T_i})$$

$$+ f_s \cdot f_{\Lambda_b} \cdot \mathcal{F}_{\Lambda_b}(m_i, t_i, \sigma_{m_i}, \sigma_{t_i}, \Omega_i, P_i(B|Q_x), p_{T_i})$$

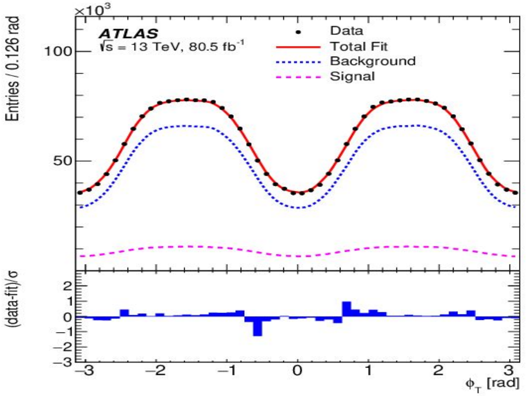
$$+ (1 - f_s \cdot (1 + f_{B^0} + f_{\Lambda_b}))\mathcal{F}_{\mathrm{bkg}}(m_i, t_i, \sigma_{m_i}, \sigma_{t_i}, \Omega_i, P_i(B|Q_x), p_{T_i})]$$

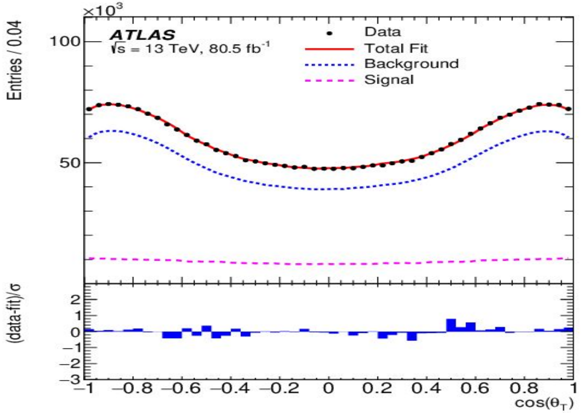
Projection and results of the fit

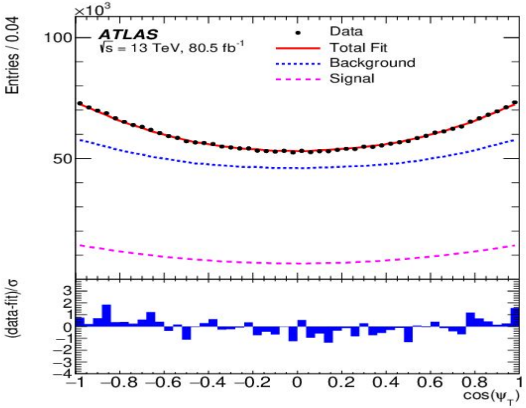




Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	-0.081	0.041	0.022
$\Delta\Gamma_s$ [ps^{-1}]	0.0607	0.0047	0.0043
Γ_s [ps^{-1}]	0.6687	0.0015	0.0022
$\lvert A_{\parallel}(0)\rvert^2$	0.2213	0.0019	0.0023
$\lvert A_0(0)\rvert^2$	0.5131	0.0013	0.0038
$\lvert A_S(0)\rvert^2$	0.0321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

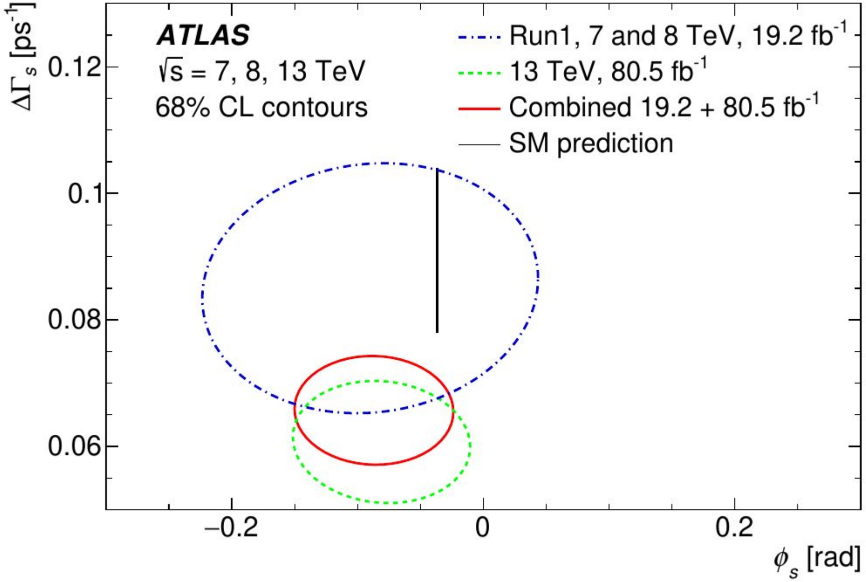






Combination results with 7 TeV and 8 TeV

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

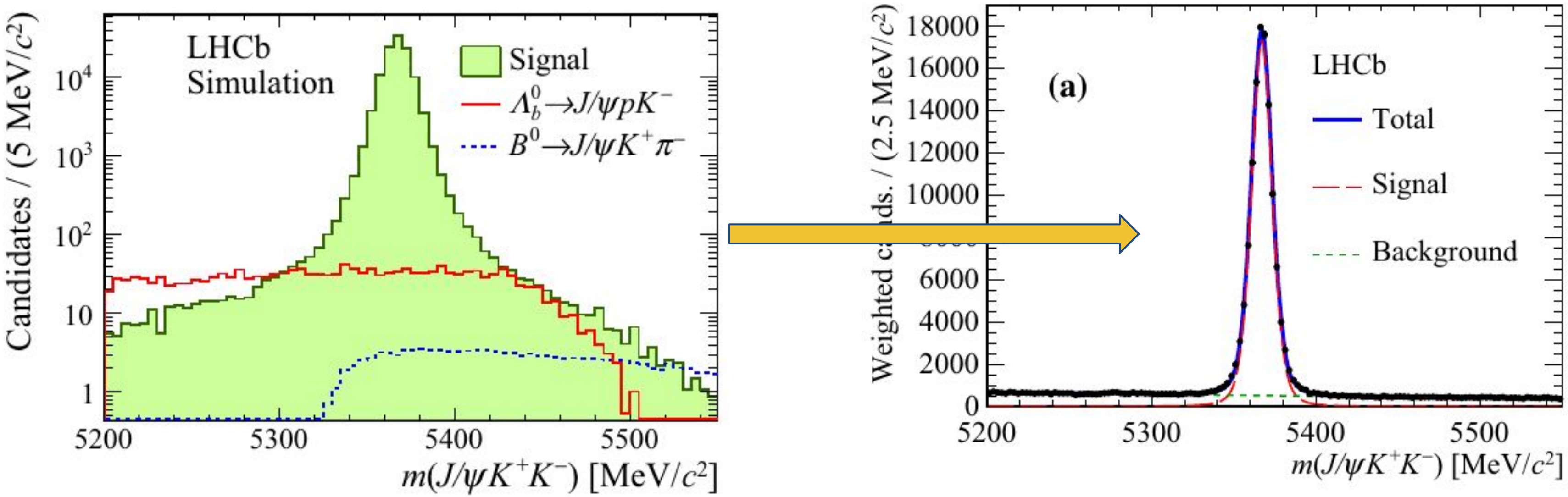


- A Best Linear Unbiased Estimate (BLUE) combination is performed to combine the current result with the Run 1 measurement.
- The BLUE combination uses the measured values and uncertainties of the parameters as well as the correlations between them.

<u>EUR.PHYS.J.C79(2019)706</u>:

Updated measurement of time-dependent *CP*-violating observables in $B_s \to J/\psi K^+K^-$ decay.

Analysis strategy and selection

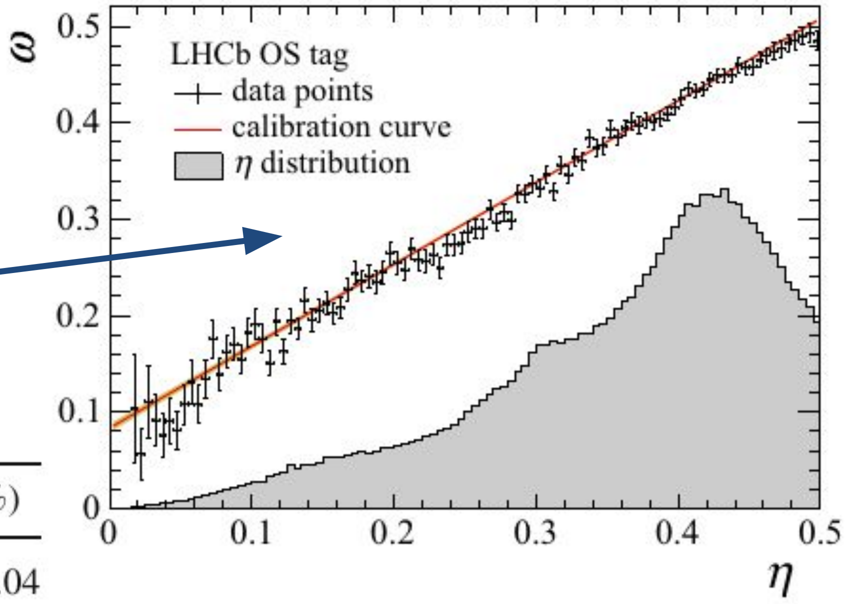


- ❑ Boosted decision tree is trained to select signal candidates.
- ❑ The $\mathbf{\Lambda_b}$ background is statistically subtracted by inserting simulated $\mathbf{\Lambda_b}$ decays into the data sample with negative weights.
- ❑ $\mathbf{B_d \to J/\psi K\pi}$ background is neglected (systematic uncertainty assigned due to).
- ❑ Vertex fit performed with **J/ψ** mass constraint.

Tagging the B_s meson flavour at production

Two tagging algorithms are used: **opposite side and same side.** For each algorithm true mistag probability is calibrated assuming linear dependency with estimated one

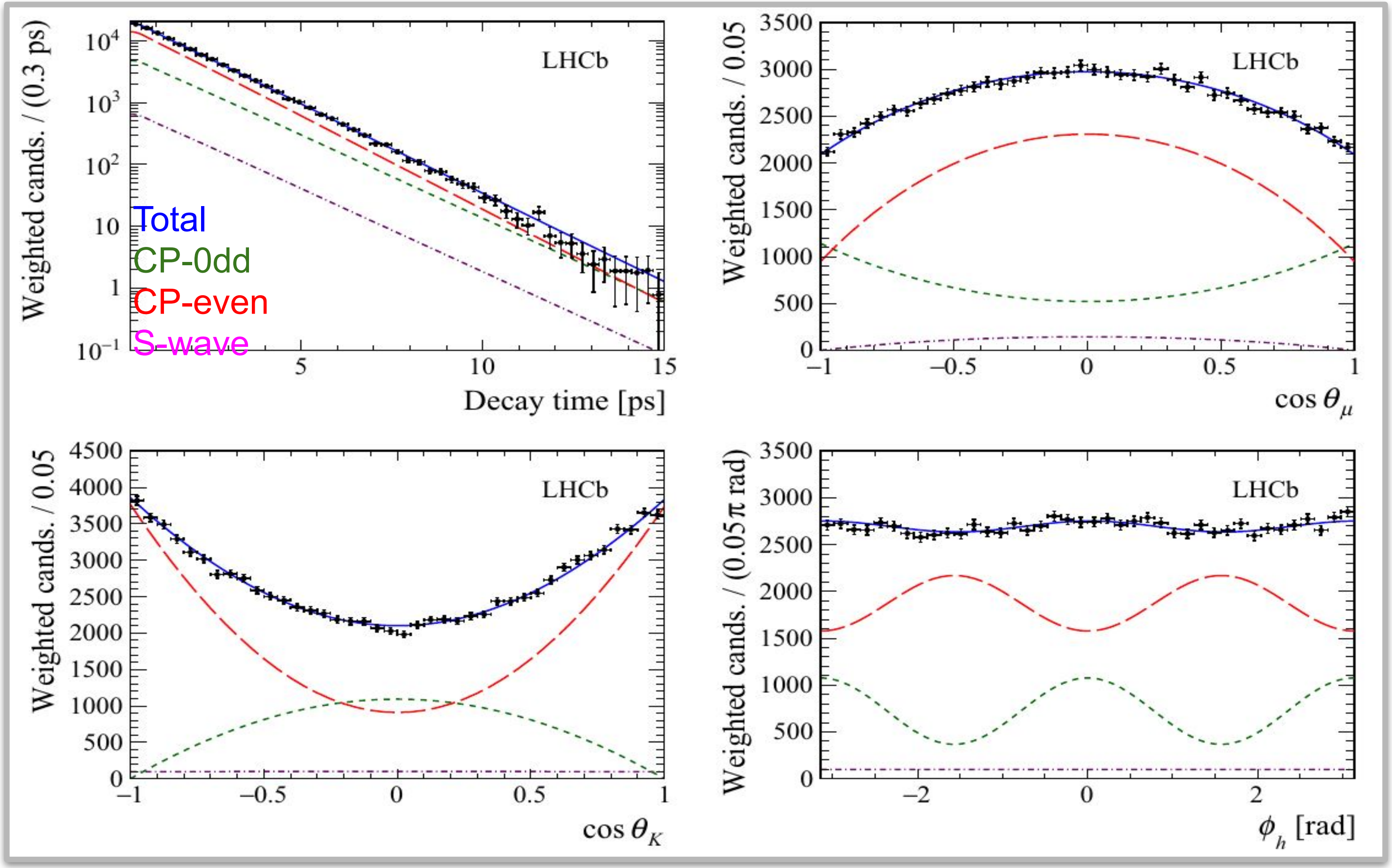
w = p0 + p1*η



Category	$\epsilon_{tag}(\%)$	D^2	$\epsilon_{tag} D^2(\%)$
OS only	11.4	0.078	0.88 ± 0.04
SSK only	42.6	0.032	1.38 ± 0.30
OS & SSK	23.8	0.104	2.47 ± 0.15
Total	77.8	0.061	4.73 ± 0.34

$$TP = \varepsilon D^2 = \varepsilon(1-2w)^2$$

Fit projections



Results of the fit

1.9 fb^{-1} data 13 TeV

$$\phi_s = -0.083 \pm 0.041 \pm 0.006\,\text{rad}$$
$$|\lambda| = 1.012 \pm 0.016 \pm 0.006$$
$$\Gamma_s - \Gamma_d = -0.0041 \pm 0.0024 \pm 0.0015\,\text{ps}^{-1}$$
$$\Delta\Gamma_s = 0.077 \pm 0.008 \pm 0.003\,\text{ps}^{-1}$$
$$\Delta m_s = 17.703 \pm 0.059 \pm 0.018\,\text{ps}^{-1}$$
$$|A_\perp|^2 = 0.2456 \pm 0.0040 \pm 0.0019$$
$$|A_0|^2 = 0.5186 \pm 0.0029 \pm 0.0024$$
$$\delta_\perp - \delta_0 = 2.64 \pm 0.13 \pm 0.10\,\text{rad}$$
$$\delta_\parallel - \delta_0 = 3.06^{+0.08}_{-0.07} \pm 0.04\,\text{rad.}$$

Combination with Run 1 $B_s \to J/\psi KK$

$$\phi_s = -0.080 \pm 0.032\,\text{rad}\,,$$
$$|\lambda| = 0.993 \pm 0.013\,,$$
$$\Gamma_s = 0.6570 \pm 0.0023\,\text{ps}^{-1}$$
$$\Delta\Gamma_s = 0.0784 \pm 0.0062\,\text{ps}^{-1}$$

Combination with other LHCb results

$$\phi_s = -0.041 \pm 0.025\,\text{rad}\,,$$
$$|\lambda| = 0.993 \pm 0.010\,,$$
$$\Gamma_s = 0.6562 \pm 0.0021\,\text{ps}^{-1}$$
$$\Delta\Gamma_s = 0.0816 \pm 0.0048\,\text{ps}^{-1}$$

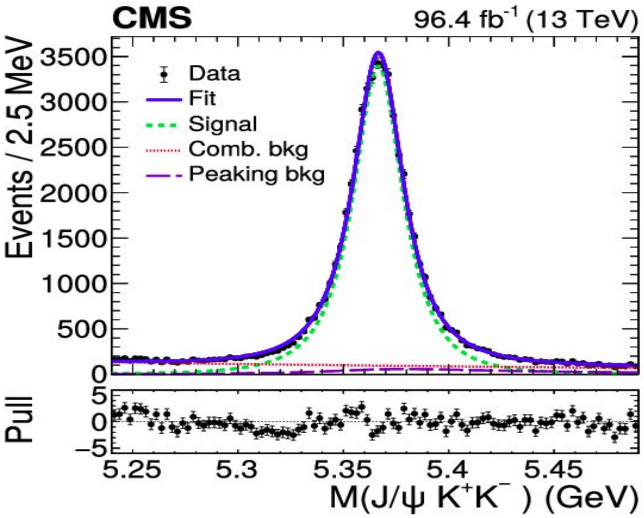
<u>CMS-PAS-BPH-20-001</u>:

Measurement of the CP violating phase φ_s in the Bs$\to$J/$\psi\phi$(1020)$\to\mu+\mu-$K+K− channel in proton-proton collisions at 13 TeV.

Trigger strategy and selection

Trigger: **J/ψ→μ+μ−** candidate plus an additional muon

- **The additional muon is used to tag the flavour of the B_s, via b→μX decays of the other b hadrons.**
- **Improves the tagging efficiency at the cost of the reduced number of signal events.**
- **No displacement cut at HLT level.**



Offline selection

$p_T(\mu)$	≥ 3.5 GeV
$\lvert\eta(\mu)\rvert$	≤ 2.4
$p_T(K)$	≥ 1.2 GeV
$\lvert\eta(K)\rvert$	≤ 2.5
$\left\lvert m(\mu^+\mu^-) - m_{J/\psi}^{PDG}\right\rvert$	< 150 MeV
$\left\lvert m(K^+K^-) - m_{\phi(1020)}^{PDG}\right\rvert$	< 10 MeV
$p_T(B_s^0)$	≥ 11 GeV
$\mathbf{ct(B_s^0)}$	$\mathbf{\geq 70\ \mu m}$
$B_s^0 \to J/\psi\,\phi$ Vtx prob	$\geq 0.1\%$
$m(\mu^+\mu^-K^+K^-)$	[5.24, 5.49] GeV

This analysis uses **96.4 fb^{-1}** data collected in 2017 and 2018.

Vertex fit performed with **J/ψ** mass constraint.

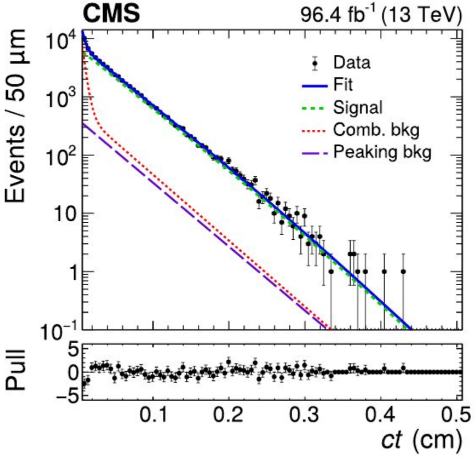
Tagger performance

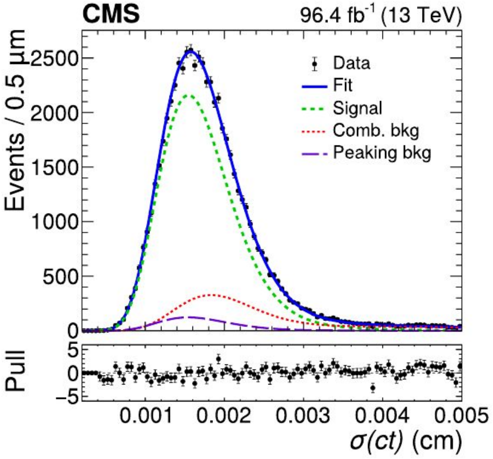
Tagger performance evaluated using **$B^+ \to J/\psi K^+$** events

Data set	ϵ_{tag}	ω_{tag}	P_{tag}
2017	$(45.7 \pm 0.1)\,\%$	$(27.1 \pm 0.1)\,\%$	$(\mathbf{9.6} \pm 0.1)\,\%$
2018	$(50.9 \pm 0.1)\,\%$	$(27.3 \pm 0.1)\,\%$	$(\mathbf{10.5} \pm 0.1)\,\%$
Run-1	$(8.31 \pm 0.03)\,\%$	$(30.2 \pm 0.3)\,\%$	$(1.31 \pm 0.03)\,\%$

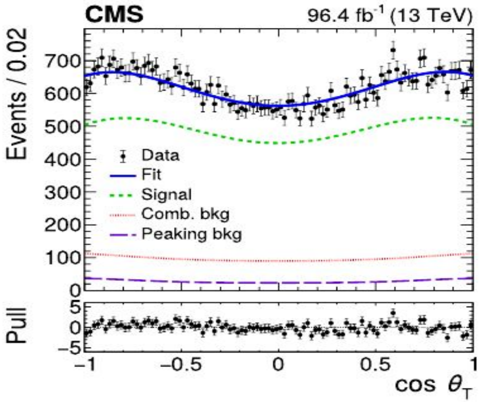
- ➢ The **Efficiency is higher** due to the requirement of an additional OS muon at the HLT.
- ➢ Final performance, normalized by the event rate, **~ 50% higher w.r.t. Run-1**.

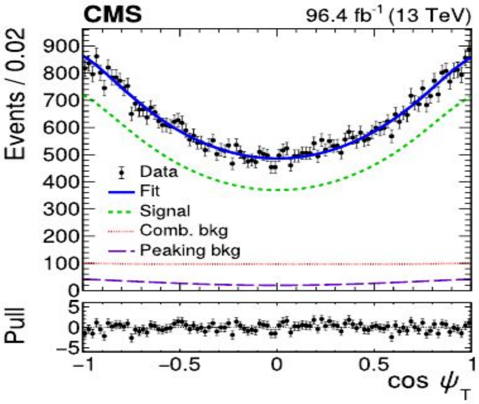
Projection and results of the fit

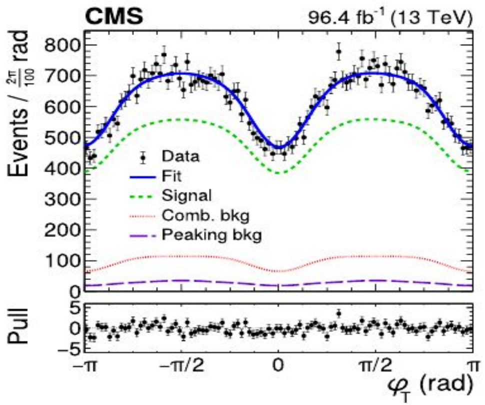




Parameter	Fit value	Stat. uncer.	Syst. uncer.
ϕ_s [mrad]	-11	± 50	± 10
$\Delta\Gamma_s$ [ps^{-1}]	0.114	± 0.014	± 0.007
Δm_s [$\hbar$ ps^{-1}]	17.51	$^{+0.10}_{-0.09}$	± 0.03
$\lvert\lambda\rvert$	0.972	± 0.026	± 0.008
Γ_s [ps^{-1}]	0.6531	± 0.0042	± 0.0026
$\lvert A_0\rvert^2$	0.5350	± 0.0047	± 0.0049
$\lvert A_\perp\rvert^2$	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



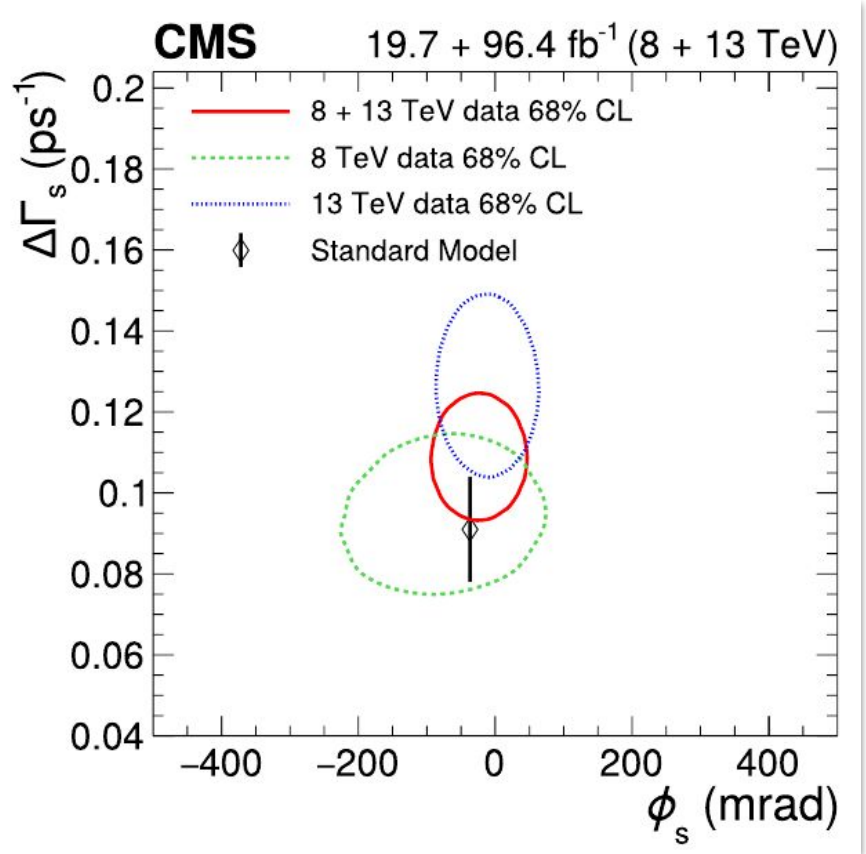




Combination with 8 TeV results

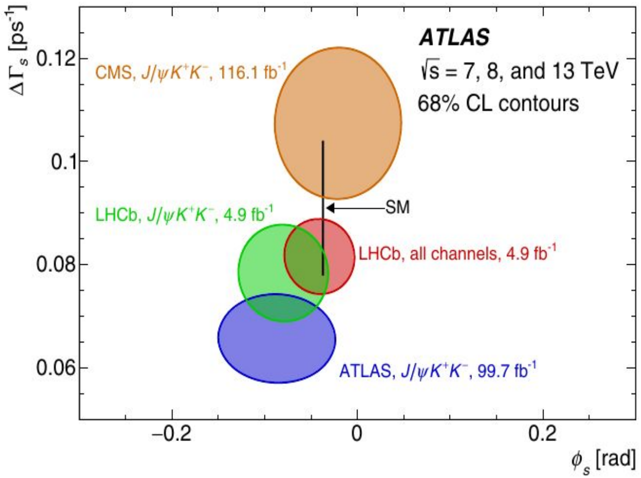
$$\phi_s = -21 \pm 44\,(\text{stat}) \pm 10\,(\text{syst})\,\text{mrad},$$
$$\Delta\Gamma_s = 0.1032 \pm 0.0095\,(\text{stat}) \pm 0.0048\,(\text{syst})\,\text{ps}^{-1}$$

- The results presented are further combined with the earlier CMS result [**Phys.Lett.B757(2016)97**].
- The systematic uncertainties in the two measurements are treated as uncorrelated.
- The statistical and systematic uncertainties are summed in quadrature and correlations between the parameters obtained in each measurement are taken into account



Summary

	φ_s [Mrad]	$\Delta\Gamma_s$	Reference
ATLAS	-87 ± 42	0.0657 ± 0.0057	**CERN-EP-2019-218**
LHCb	-80 ± 32	0.0784 ± 0.0062	**EUR.PHYS.J.C79(2019)706**
CMS	-21 ± 45	0.1032 ± 0.0106	**CMS-PAS-BPH-20-001**
SM	$-36.96^{+0.84}_{-0.72}$	0.087 ± 0.021	**CKMFitter group**



- ➢ The CPV phase $\boldsymbol{\varphi_s}$ and the decay width difference $\Delta\Gamma_s$ are measured using (partial) run 2 data.
- ➢ Results combined with Run1 results.
- ➢ Results are compatible between experiments and they are **consistent with the Standard Model predictions.**
- ➢ $\Delta\Gamma_s$ shows **tensions** between experiments (**Full Run-2 measurements will clarify the situation**).

Thanks!