Measurement of the weak mixing phase ϕ_s through time-dependent CP-violation in $B_s^0 \to J/\psi\phi$ decays in the ATLAS detector

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4-12 September 2020

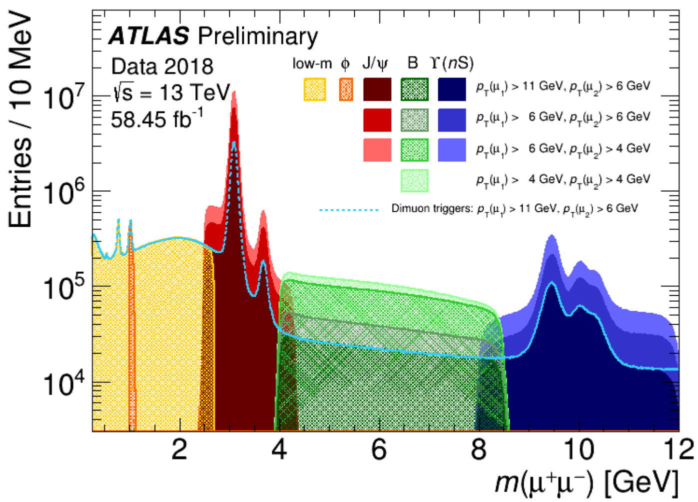
9-th International Conference on New Frontiers in Physics (ICNFP 2020)

Outlook

- Introduction
- Measurement of CP-violation parameters $\Delta\Gamma_s$ and ϕ_s in $B_s \rightarrow J/\psi\phi$ decay, from Flavour-tagged time-dependent Partial Wave analysis
- Analysis of 2015-2017 data (*pp collisions* at 13 TeV)
- Combination with results from data at 7 and 8 TeV and theoretical predictions.
- Comparison with other experiments
- Summary

Introduction

- The data were collected in 2015-2017 years (Run 2), in data taking periods with different instantaneous luminosity, therefore several triggers were used in the analysis. All of them were based on the identification of a $J/\psi \to \mu^+ \mu^-$ decay, with transverse momentum pT thresholds either 4 GeV or 6 GeV for the muons.
- Trigger prescaling factors changed during the physics run in dependence on the instantaneous luminosity.



Modifications in Run2 in comparison with Run 1:

- new IBL detector close to new beam tube (better precision of lifetime measurement)
- new three-muon trigger, it improves the opposite-side muon tagging.
- control of trigger quality with express reconstruction of charged B^{+-} candidates

B_s time evolution parameters

- Like the K^0 meson, B_s meson can be produced in CP-even or CP-odd state with different lifetimes. **$\Delta\Gamma_s$** is a difference between inverse lifetimes. CP-odd state has a longer lifetime than the CP-even one, the relative difference is ~13-17%.
- Observed $(\boldsymbol{b}\ \overline{\boldsymbol{s}}) \leftrightarrow (\overline{\boldsymbol{b}}\ \boldsymbol{s})$ **oscillations via box diagrams with intermediate u, c, t $q\overline{q}$ pairs in t-channel and possibly New Physics.** The mass difference between heavy (B^H) and light (B^L) CP-eigenstates leads to measured oscillation frequency with Δm_s - $17.77\ ps^{-1}$.
- CP-violating phase **ϕ_s** manifests itself in interference terms between mixing and decay amplitudes (non-diagonal elements in Time-dependent Partial Wave Analysis).

B_s time evolution and $B_s \to J/\psi\phi$ decay

- In SM, CP-violating phase $\phi_s \approx -2\beta_s$, where β_s is angle in Kobayashi-Maskawa triangle,
- $$\beta_s = \arg\frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}$$ (NOT β angle ! It is other unitary triangle, with d instead of s quark, see PDG!)
- SM predictions: $\Delta\Gamma = 0.087\pm0.021$ ps

  $\phi_s = -0.0363^{+16}_{-15}$ rad Phys. Rev. D, 84 (2011), p. 033005 ,

. also CKMfitter group, J.Charles et al., Phys.Rev. D91 (2015) 073007 (Table III)

- Measurements of ϕ_s and ΔΓ test theoretical predictions.
- The analysis of data at 13 TeV is similar for published analysis of 7 and 8 TeV data (Phys.Rev. D90 (2014) 052007) . The number of signal events at 13 TeV is greater by a factor of 4 in comparison with Run 1. Due to high statistics, more detailed study of acceptance, signal shape and background was performed. Opposite-side tagging with muons, electrons and jets were applied. Finally, results at 13 TeV were statistically combined with Run 1 measurements.

Partial waves in J/ψϕ analysis

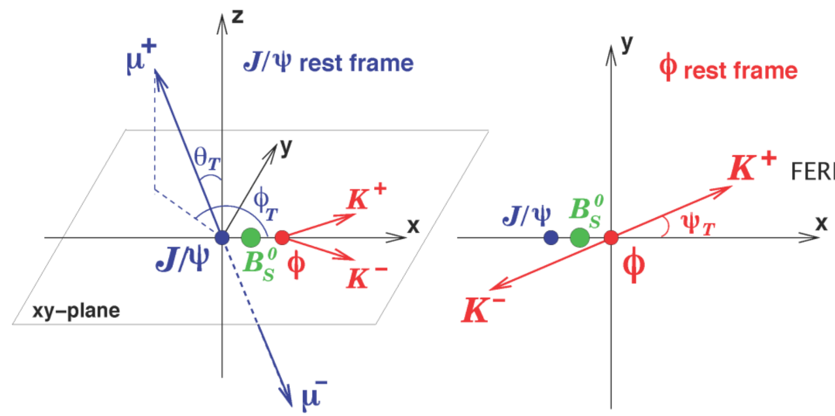
- $B_s \to J/\psi\phi \to (\mu^+\mu^-)(K^+ K^-)$ without Kaon identification
- $B_s \to J/\psi\phi$ - pseudo-scalar to vector-vector decay, waves :
- CP-even (L=0,2) and CP-odd (L=1) final states,
- added 4th wave with (KK) in S-wave, J/ψKK
- Distinguishable through time-dependent angular analysis
- Used 3 angles between final-state particles in Transversity basis
  - Multi-dimensional fit to the data; three amplitudes and strong phases extracted.

A_0 – longitudinal CP-even final state

$A_\parallel$ – transverse CP-even

$A_\perp$ – transverse CP-odd

$$\delta_0 = 0$$
$$\delta_\parallel = \arg[A_\parallel(0)A_0^*(0)]$$
$$\delta_\perp = \arg[A_\perp(0)A_0^*(0)]$$



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- 3 amplitudes and so called strong phases extracted alongside with ϕ_s and $\Delta\Gamma_s$
- 4-th amplitude A_s and phase δ_s for J/ψKK (CP-odd) also determined from the fit.

Event selection in 2015-2017 data analysis

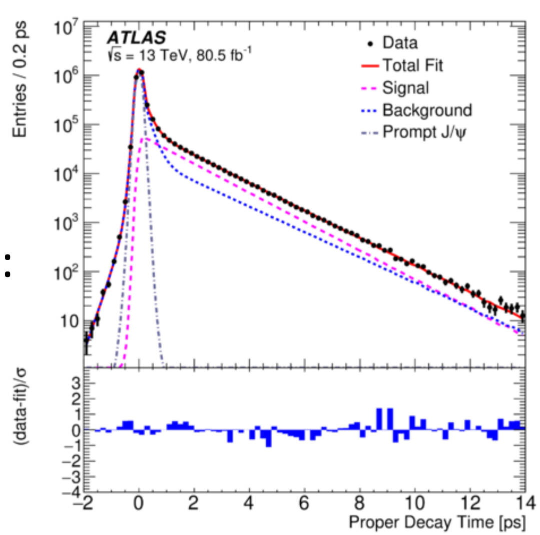
- Events selected from $\mu^+ \mu^-$ pairs using 80.5 fb^{-1} data acquired at $\sqrt{s}$ = 13 TeV
- and 2 other opposite sign tracks with p_t > 1 GeV/c and $|\eta|$<2.5 taken with Kaon mass.
- Retain pairs consistent with ϕ : 1008.5 < $m(K^+ K^-)$< 1030.5 MeV.
- 4-track Vertex Fit, using J/ψ mass constraint, candidates with χ^2 /NDF < 3 accepted.
- Primary vertex selected with smallest 3D-impact parameter.
- Proper decay time:

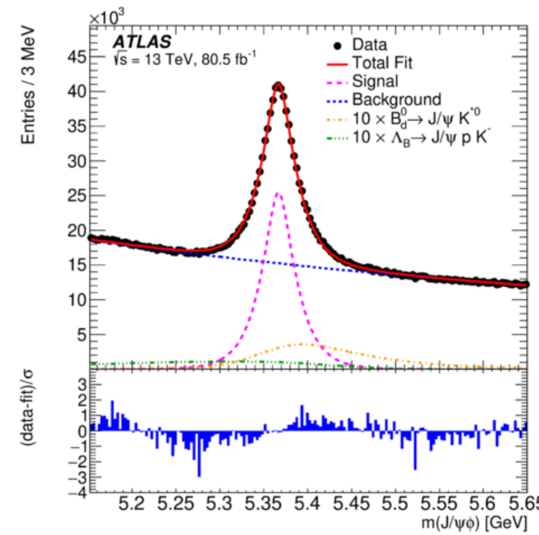
$$t = \frac{L_{xy} M_B}{p_{T_B}}$$

with B_s World Average mass M_B

- 3.210 million B_s candidates in range: 5.150 – 5.650 GeV, from which
- 477240 ± 760 are the fitted B_s

98000 B_a in 2011-2012 data

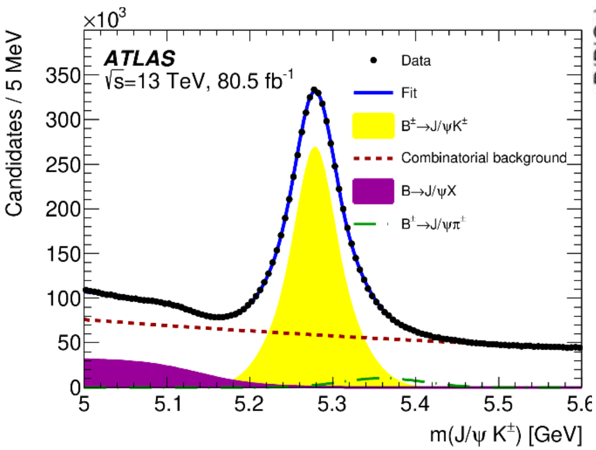


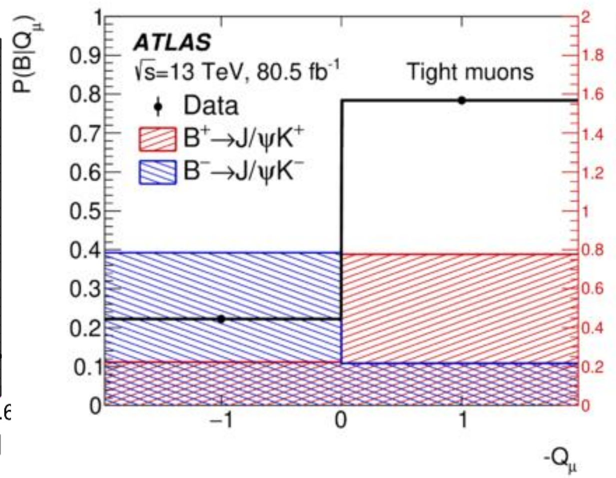


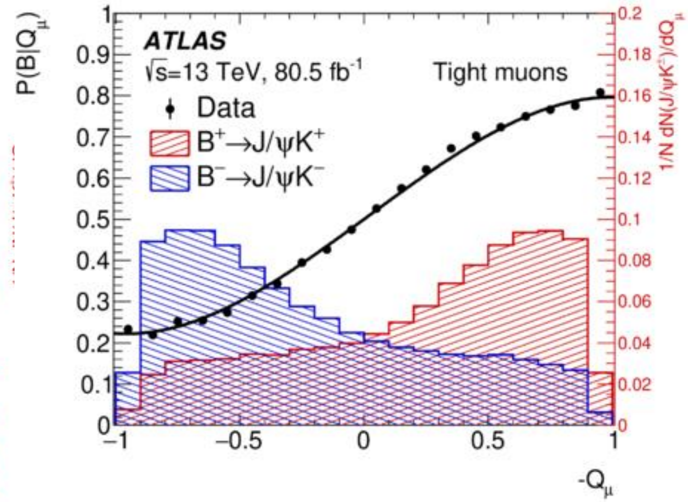
No decay time cut applied in analysis

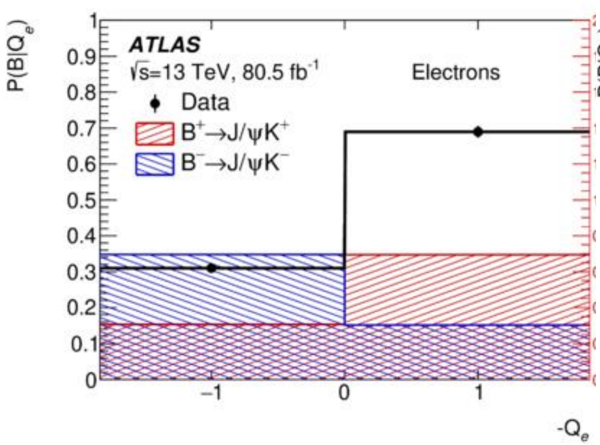
b-quark charge tagging, calibration curves

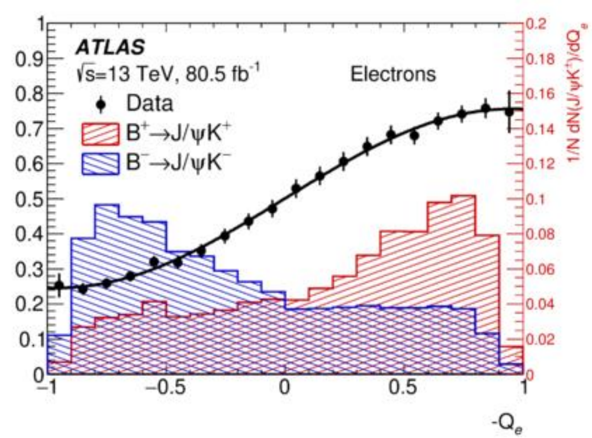
- Identification of b or anti-b quark in B_s at the production time improves precision of ϕ_s measurement and helps with sign ambiguities
- Information from opposite side tagging used, i.e. leptons and/or jet charge from decay of 2nd B-hadron in the event
- Methods were calibrated on B^{+-} candidates in data











Tagger	Tagging power [%]
Tight muon	0.862 ± 0.009
Electron	0.274 ± 0.004
Low-pT muon	0.278 ± 0.006
Jet charge	0.334 ± 0.006
Total	1.75 ± 0.01

Fit model – signal component

- Unbinned likelihood fit: 9 physics parameters

$$\ln \mathscr{L} = \sum_{i=1}^{N} \{w_i \ln(f_s \cdot \mathscr{F}_s(m_i, t_i, \sigma_{t_i}, \Omega_i, P(B|Q)) + f_s \cdot f_{B^0} \cdot \mathscr{F}_{B^0}(m_i, t_i, \sigma_{t_i}, \Omega_i, P(B|Q)) + (1 - f_s \cdot (1 + f_{B^0}))\mathscr{F}_{\mathrm{bkg}}(m_i, t_i, , \sigma_{t_i}, \Omega_i, P(B|Q))\}$$

- Observables:
  - $m(J/\psi KK)$, τ, $\sigma(\tau)$
  - $\Omega = (\theta_T, \psi_T, \phi_T)$
  - Tagging probability

Signal components: Mass – Single Gaussian (per-candidate errors)
Lifetime – 2 Exp ·Gaussian (per-candidate errors)
Angular functions; Tagging probability distribution (PDF)
Scaling factor was applied to per-event timing errors from the Vertex fit.
It was estimated from negative tail in distribution, due to absence of lifetime selection in Trigger.

With 4 decay channels -> 4 diagonal + 6 non-diagonal Angular & Lifetime functions, an example:

AMPL	$O^{(k)}$ f(t)	$g^{(k)}(\theta_T, \psi_T, \phi_T)$
$(1/2)\lvert A_0(0)\rvert^2$	$(1+\cos(\phi_s))\exp(-\Gamma_L^{(s)} t) + (1-\cos(\phi_s))\exp(-\Gamma_H^{(s)} t) \pm$	$2\cos^2\psi_T (1-\sin^2\theta_T \cos^2\phi_T)$
	$\pm 2\exp(-\Gamma_s t)\sin(\Delta m_s t)\sin(\phi_s)$	

oscillating term with $\sin(\phi_s)$ arises due to Tagging , other terms with $\cos(\phi_s)$
Angle ϕ_s is small -> terms with $\sin(\phi_s)$ significantly improves precision of ϕ_s measurement.
Event-by event efficiency was estimated from MC, as a function of three angles and pT.

Time and angular functions for $B_s \to J/\psi\phi$

k	$\mathcal{O}^{(k)}(t)$	$g^{(k)}(\theta_T, \psi_T, \phi_T)$
1	$\frac{1}{2}\lvert A_0(0)\rvert^2 \left[(1+\cos\phi_s)\, e^{-\Gamma_{\rm L}^{(s)}t} + (1-\cos\phi_s)\, e^{-\Gamma_{\rm H}^{(s)}t} \pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$2\cos^2\psi_T(1-\sin^2\theta_T\cos^2\phi_T)$
2	$\frac{1}{2}\lvert A_\parallel(0)\rvert^2 \left[(1+\cos\phi_s)\, e^{-\Gamma_{\rm L}^{(s)}t} + (1-\cos\phi_s)\, e^{-\Gamma_{\rm H}^{(s)}t} \pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\sin^2\psi_T(1-\sin^2\theta_T\sin^2\phi_T)$
3	$\frac{1}{2}\lvert A_\perp(0)\rvert^2 \left[(1-\cos\phi_s)\, e^{-\Gamma_{\rm L}^{(s)}t} + (1+\cos\phi_s)\, e^{-\Gamma_{\rm H}^{(s)}t} \mp 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\sin^2\psi_T\sin^2\theta_T$
4	$\frac{1}{2}\lvert A_0(0)\rvert\lvert A_\parallel(0)\rvert\cos\delta_{\parallel}$ $\left[(1+\cos\phi_s)\, e^{-\Gamma_{\rm L}^{(s)}t} + (1-\cos\phi_s)\, e^{-\Gamma_{\rm H}^{(s)}t} \pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin^2\theta_T\sin 2\phi_T$
5	$\lvert A_\parallel(0)\rvert\lvert A_\perp(0)\rvert[\frac{1}{2}(e^{-\Gamma_{\rm L}^{(s)}t} - e^{-\Gamma_{\rm H}^{(s)}t})\cos(\delta_\perp-\delta_{\parallel})\sin\phi_s$ $\pm e^{-\Gamma_s t}(\sin(\delta_\perp-\delta_{\parallel})\cos(\Delta m_s t) - \cos(\delta_\perp-\delta_\parallel)\cos\phi_s\sin(\Delta m_s t))]$	- $\sin^2\psi_T\sin 2\theta_T\sin\phi_T$
6	$\lvert A_0(0)\rvert\lvert A_\perp(0)\rvert[\frac{1}{2}(e^{-\Gamma_{\rm L}^{(s)}t} - e^{-\Gamma_{\rm H}^{(s)}t})\cos\delta_\perp\sin\phi_s$ $\pm e^{-\Gamma_s t}(\sin\delta_\perp\cos(\Delta m_s t) - \cos\delta_\perp\cos\phi_s\sin(\Delta m_s t))]$	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin 2\theta_T\cos\phi_T$
7	$\frac{1}{2}\lvert A_S(0)\rvert^2 \left[(1-\cos\phi_s)\, e^{-\Gamma_{\rm L}^{(s)}t} + (1+\cos\phi_s)\, e^{-\Gamma_{\rm H}^{(s)}t} \mp 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\frac{2}{3}\left(1-\sin^2\theta_T\cos^2\phi_T\right)$
8	$\lvert A_S(0)\rvert\lvert A_\parallel(0)\rvert[\frac{1}{2}(e^{-\Gamma_{\rm L}^{(s)}t} - e^{-\Gamma_{\rm H}^{(s)}t})\sin(\delta_\parallel-\delta_S)\sin\phi_s$ $\pm e^{-\Gamma_s t}(\cos(\delta_\parallel-\delta_S)\cos(\Delta m_s t) - \sin(\delta_\parallel-\delta_S)\cos\phi_s\sin(\Delta m_s t))]$	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin^2\theta_T\sin 2\phi_T$
9	$\frac{1}{2}\lvert A_S(0)\rvert\lvert A_\perp(0)\rvert\sin(\delta_\perp-\delta_S)$ $\left[(1-\cos\phi_s)\, e^{-\Gamma_{\rm L}^{(s)}t} + (1+\cos\phi_s)\, e^{-\Gamma_{\rm H}^{(s)}t} \mp 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin 2\theta_T\cos\phi_T$
10	$\lvert A_0(0)\rvert\lvert A_S(0)\rvert[\frac{1}{2}(e^{-\Gamma_{\rm H}^{(s)}t} - e^{-\Gamma_{\rm L}^{(s)}t})\sin\delta_S\sin\phi_s$ $\pm e^{-\Gamma_s t}(\cos\delta_S\cos(\Delta m_s t) + \sin\delta_S\cos\phi_s\sin(\Delta m_s t))]$	$\frac{4}{3}\sqrt{3}\cos\psi_T\left(1-\sin^2\theta_T\cos^2\phi_T\right)$

Fit model – background components

- Unbinned likelihood fit: 9 physics parameters

$$\ln \mathscr{L} = \sum_{i=1}^{N}\{w_i \cdot \ln(f_s \cdot \mathscr{F}_s(m_i,t_i,\sigma_{t_i},\Omega_i,P(B|Q)) + f_s \cdot f_{B^0} \mathscr{F}_{B^0}(m_i,t_i,\sigma_{t_i},\Omega_i,P(B|Q)) + (1-f_s \cdot (1+f_{B^0}))\mathscr{F}_{bkg}(m_i,t_i,,\sigma_{t_i},\Omega_i,P(B|Q))\}$$

- Observables:
  - m(J/ψKK), τ, $\sigma(\tau)$
  - $\Omega = (\theta_T, \psi_T, \phi_T)$
  - Tagging probability

B_d and Λ_b components :

Mis-reconstructed *$B_d \rightarrow J/\psi K^{*0}$ (4.3±0.5)% and $\Lambda_b \rightarrow J/\psi\, p\, K^-$ (2.1±0.6)% with respect to number of B_s candidates*

Mass: Landau shape from MC

Lifetime: Exp · Gaussian
(per candidate errors)
(slope fixed to PDG lifetime)

Angular distributions: taken from 3D-fits to MC

Combinatorial BG component

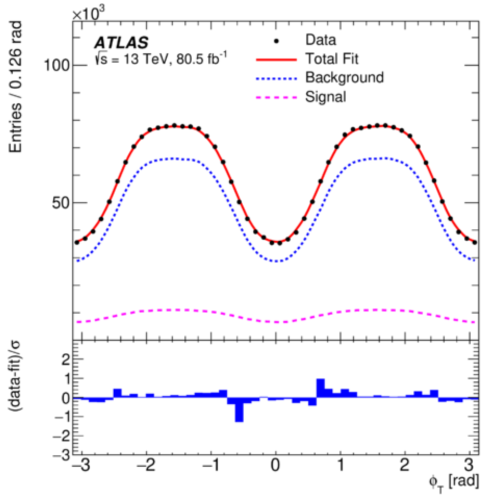
Mass: Exp function

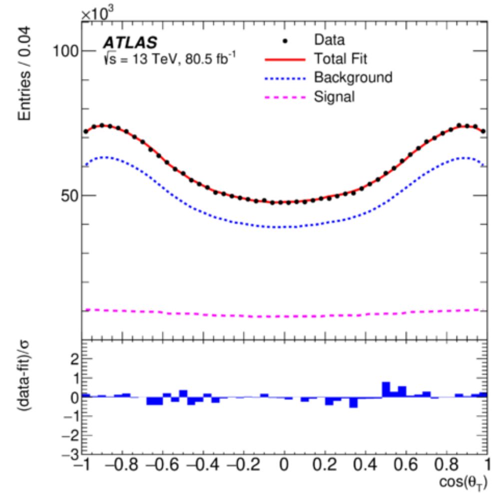
Lifetime: Prompt Exp(±t), and 2 Exp(t>0)

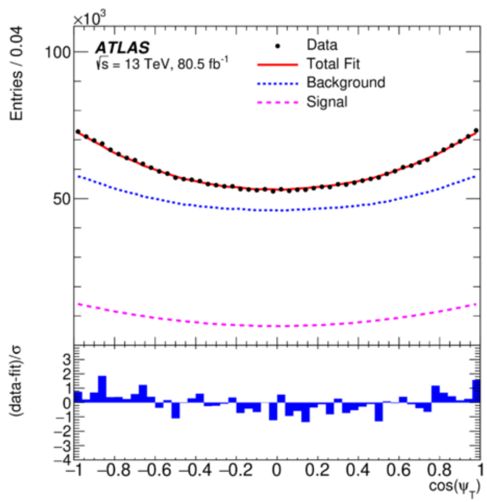
Angular distributions: Spherical harmonics from side-bands regions

"Punzi" terms – accounting for differences between Data and MC in Tagging Efficiency and lifetime uncertainties, Determined from the data

Angular fit projections (signal, background and sum)







- Θ_T is the angle between $p(\mu^+)$ and x-y plane in the J/psi meson rest frame

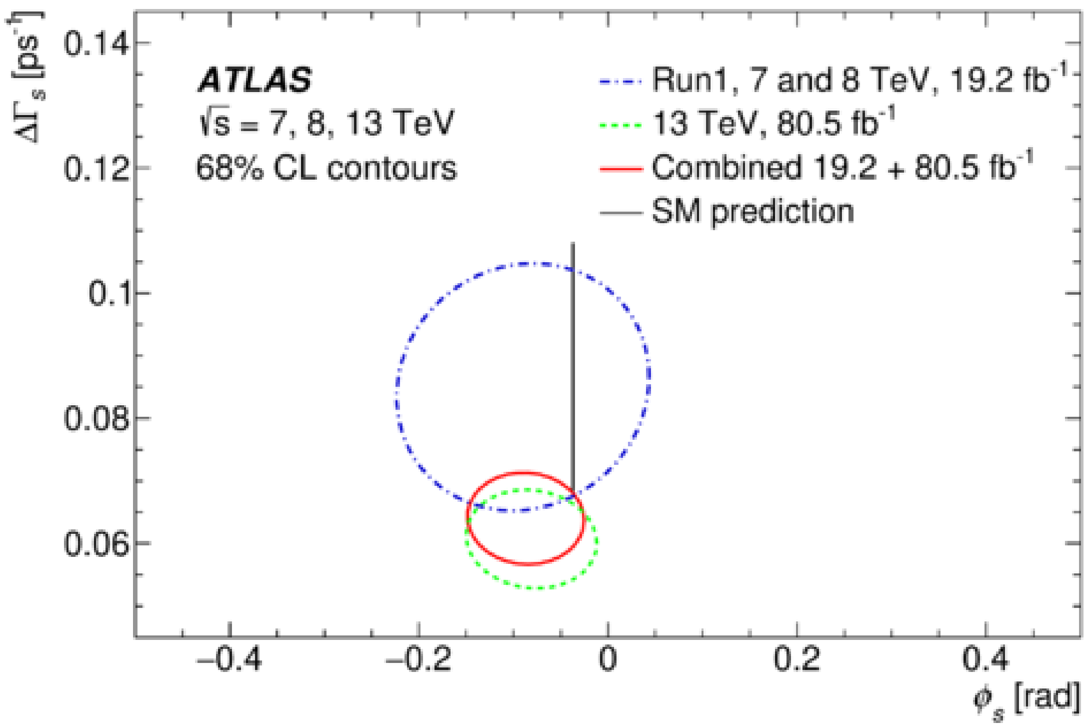
- ϕ_T is the angle between the x-axis and the projection of $p_{xy}(\mu^+)$, the projection of the μ^+ momentum in the x-y plane, in the J/ψ rest frame

- ψ_T is the angle between $p(K^+)$ and $-p(J/\psi)$ in the ϕ meson rest frame.

Systematic uncertainties are evaluated for the following effects:

- Flavour tagging
- Angular acceptance and kinematic cuts
- ID alignment
- Trigger efficiency
- Best candidate selection
- Background angles model
- B_d contribution
- Λ_b contribution
- The systematics due to fixing the parameter Δm_s
- Fit model mass and lifetime
- lS-wave phase
- Possible Fit bias

Likelihood 68% confidence level showing combination of ATLAS Run 1 result with new measurement at 13 TeV



Combination of results performed with BLUE package (Best Linear Likelihood Estimate)

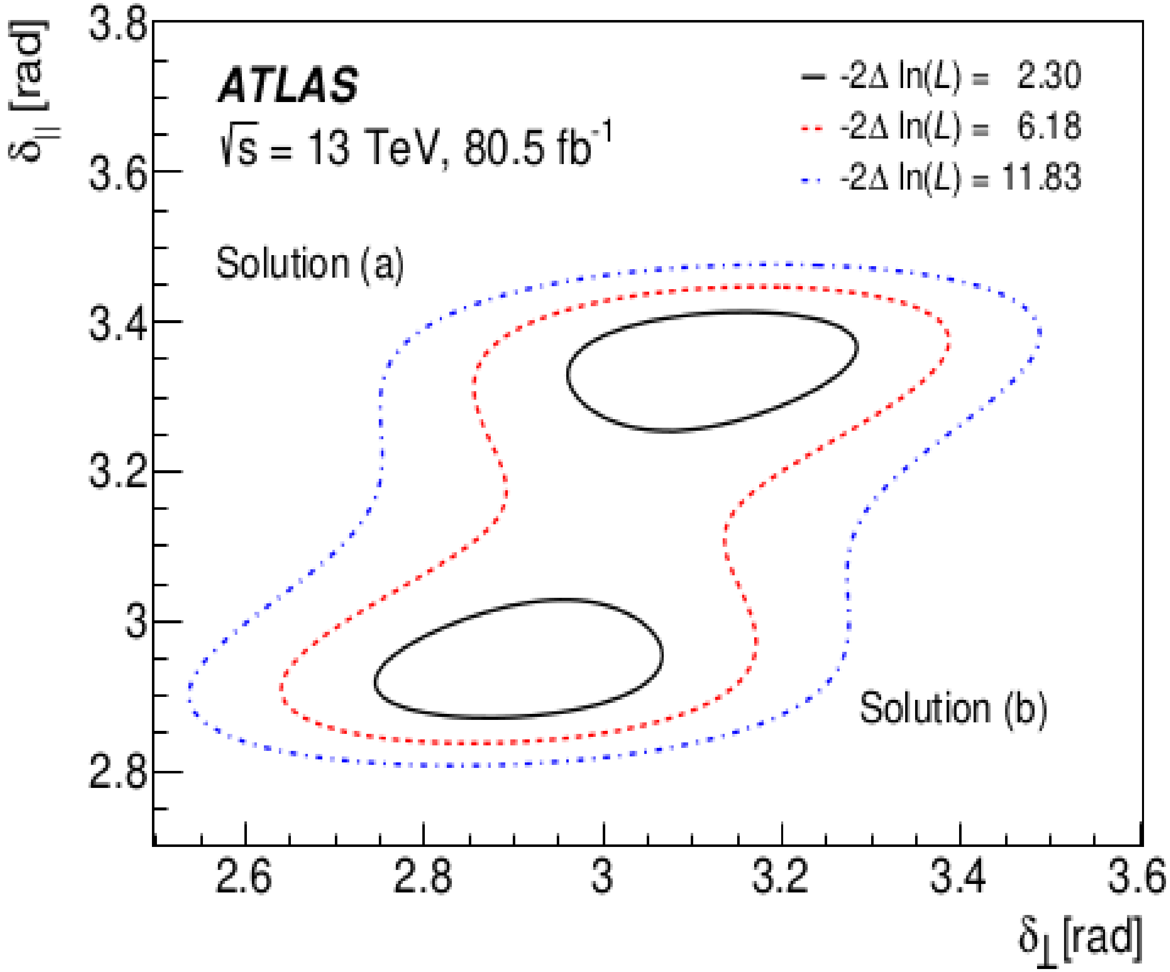
Second minimum was detected during the systematic study

Parameter	Value Solution (a)	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	-0.087	0.036	0.019
$\Delta\Gamma_s$ [ps^{-1}]	0.0641	0.0043	0.0024
Γ_s [ps^{-1}]	0.6997	0.0014	0.0015
$\|A_{\|\|}(0)\|^2$	0.2221	0.0017	0.0022
$\|A_0(0)\|^2$	0.5149	0.0012	0.0031
$\|A_s(0)\|^2$	0.0343	0.0031	0.0044
$\delta_\perp$ [rad]	3.23	0.10	0.05
$\delta_{\|\|}$ [rad]	3.36	0.05	0.08
$\delta_\perp - \delta_s$[rad]	-0.24	0.04	0.04

Fitted parameters for 2-nd minimum

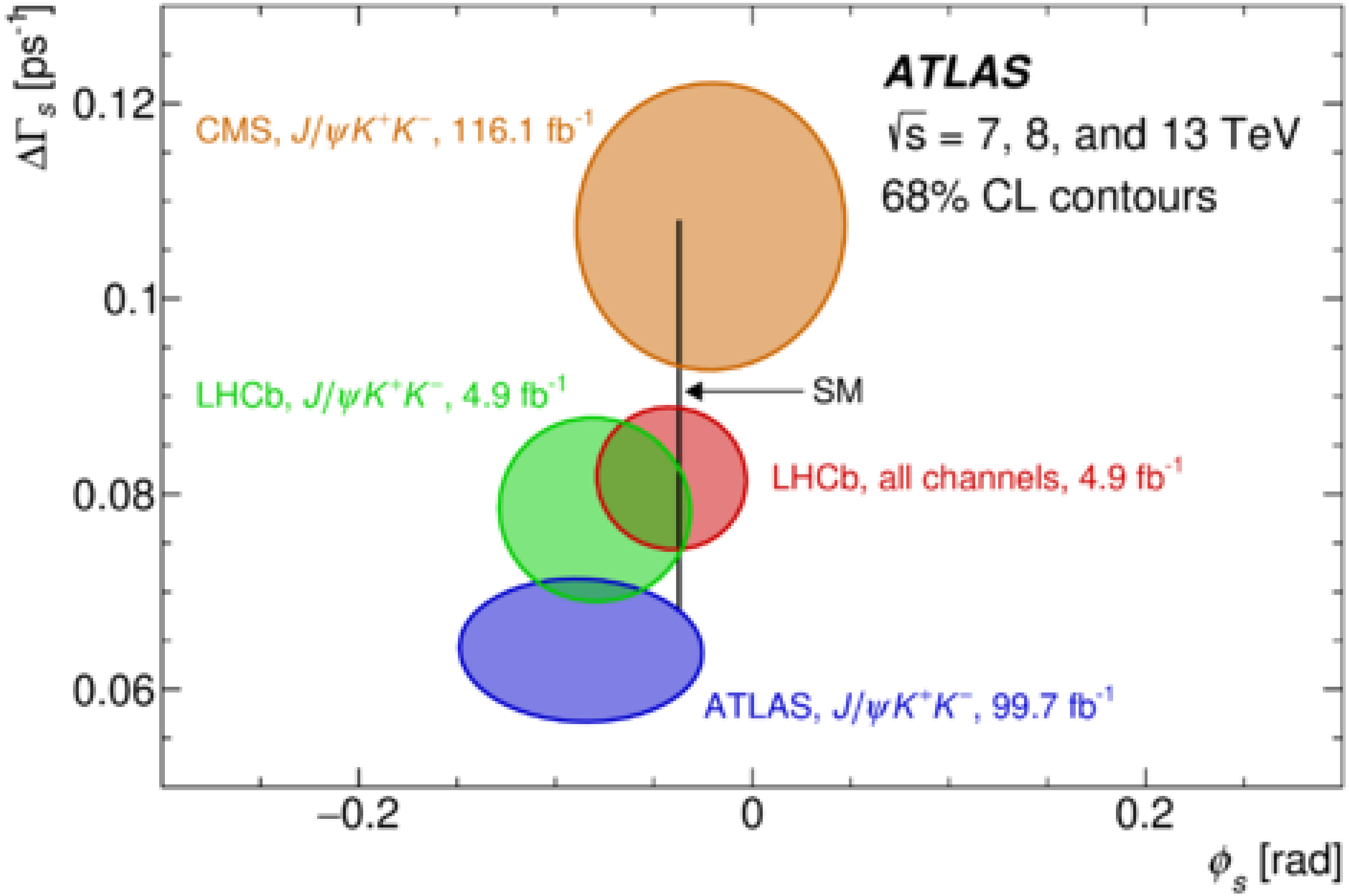
Parameter	Value Solution (b)	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	-0.088	0.036	0.019
$\Delta\Gamma_s$ [ps^{-1}]	0.0640	0.0043	0.0024
Γ_s [ps^{-1}]	0.6698	0.0014	0.0015
$\lvert A_{\parallel}(0)\rvert^2$	0.2218	0.0017	0.0022
$\lvert A_0(0)\rvert^2$	0.5149	0.0012	0.0031
$\lvert A_s(0)\rvert^2$	0.0348	0.0031	0.0044
$\delta_{\perp}$ [rad]	3.03	0.10	0.05
$\delta_{\parallel}$ [rad]	2.85	0.05	0.08
$\delta_{\perp} - \delta_s$ [rad]	-0.24	0.04	0.04

Comparison of two solutions for strong phases



Two-dimensional constraints on the values of $\delta_{||}$ and $\delta_{\perp}$ for solutions (a) and (b) at the level of $-2\Delta\ln(L)=2.30, 6.18,$ and 11.83 respectively, created using a full 2D scan. The minimum of the solution (b) is $-2\Delta\ln(L)=0.03$ higher than the minimum of the solution (a).

Comparison with the last LHCb and CMS results



Summary

- - ATLAS can provide precise measurements in B_s -decays, which are relevant for searches of effects beyond SM
- - measured CP-violating phase ϕ_s and decay width difference $\Delta\Gamma_s$

  - **Analysed 2015-2017 data (80.5 fb^{-1})**
  - **statistical combination with Run 1 data (19.2 fb^{-1})**

  ϕ_s = -0.087 ± 0.036(stat.) ± 0.019(syst.) rad

  $\Delta\Gamma_s$ = 0.0641 ± 0.0043(stat) ± 0.0024(syst) ps^{-1}

  average decay width Γ_s = 0.6697 ± 0.0014(stat) ± 0.0015(syst) ps^{-1}

  - ϕ_s and $\Delta\Gamma_s$ are consistent with SM predictions and other experiments

  The Γ_s measurement deviates from the PDG world average (0.661 ± 0.004 ps^{-1})

- This measurement can be compared with new LHCb measurement at 4.9 fb^{-1} including 2015 and 2016 data **in the same decay:**
- - **ϕ_s = -0.083 ± 0.041(stat) ± 0.006(syst) rad**
- **$\Delta\Gamma$ = 0.077 ± 0.008(stat) ± 0.003(syst) ps^{-1}**
- Statistical errors dominate in measurements, we expect better precision from analysis of 2018 data due to supplementary statistics and improvements in the analysis.

References

- ATLAS:
- Flavor tagged time-dependent angular analysis of the $B_s \to J/\psi\phi$ decay and extraction of $\Delta\Gamma_s$ and the weak phase ϕ_s in ATLAS, Phys. Rev. D90 (2015) 5, 052007, arXiv:1407.1796
- Measurement of the CP violating phase ϕ_s in $B_s \to J/\psi\phi$ decays in ATLAS at 13 TeV , arXiv:2001.07115v3 [hep-ex], submitted to EPJC.
- CMS
- Measurement of the CP-violating phase ϕ_s in the $B_s \to J/\psi\phi(1020) \to \mu^+\mu^- K^+ K^-$ decay channel in *proton-proton* collisions at √s=13 TeV, arXiv:2007.02434[hep-ex].
- LHCb
- Updated measurement of time-dependent CP}-volating observables in B^0_s -> J/psi K+K- decays, Eur.Phys.J. C79 (2019) no.8, 706, Erratum: Eur.Phys.J. C80 (2020) no.7, 601, e-Print: arXiv:1906.08356
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- CKMfitter group, J.Charles et al., Current status of the standard model CKM fit and constraints on \Delta F = 2 new physics, Phys.Rev. D91 (2015) 073007, arHyv 1501.05013, DOI https://doi.org/10.1103/PhysRevD.91.073007 (see Table III)
- UTfit Collaboration (M. Bona et al.), The Unitarity Triangle Fit in the Standard Model and Hadronic Parameters from Lattice QCD: A Reappraisal after the Measurements of Delta m(s) and BR(B ---> tau nu(tau)), JHEP 0610 (2006) 081, DOI: 10.1088/1126-6708/2006/10/081 (see Table 2).