5th International Conference on Particle Physics and Astrophysics (ICPPA2020), 5-9 October 2020

Measurement of the CP violation in B_s^0 -> J/ψϕ decays in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

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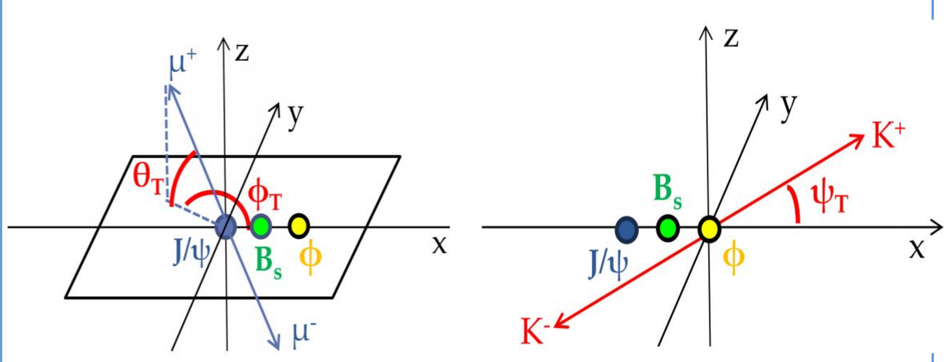
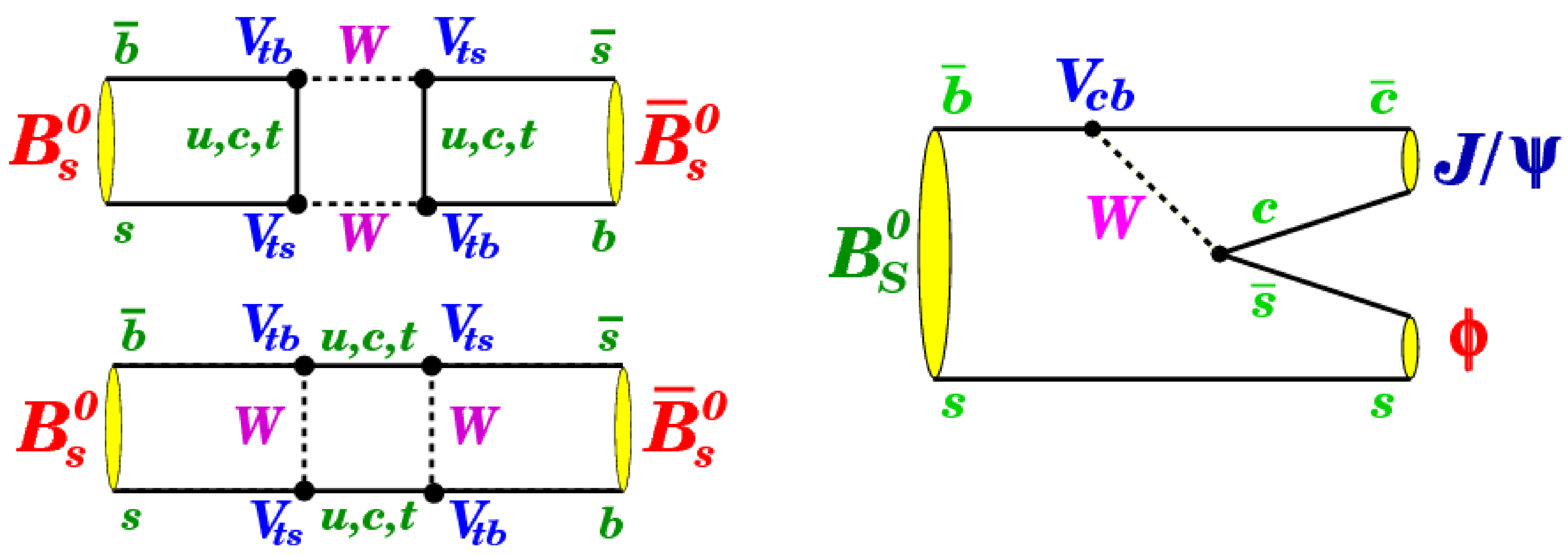
Analysis strategy

- $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decay = decay of pseudoscalar to vector-vector
- Final state: admixture of CP-odd (L = 1) and CP-even (L = 0, 2) states
- Distinguishable through time-dependent angular analysis
- Non-resonant S-wave decay B_s^0 -> J/ψK⁺K⁻ contributes to the final state and is included in the differential decay rate due to interference with the signal $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decay
- The transversity angles, $\Omega = (\Theta_T, \Psi_T, \phi_T)$ are defined as below



CP-violation in B_s^0 -> J/ψϕ decays

- Interference of direct decay and decay with mixing into the same final state of B_s^0 -> J/ψφ gives rise to time-dependent CP violation (CPV)



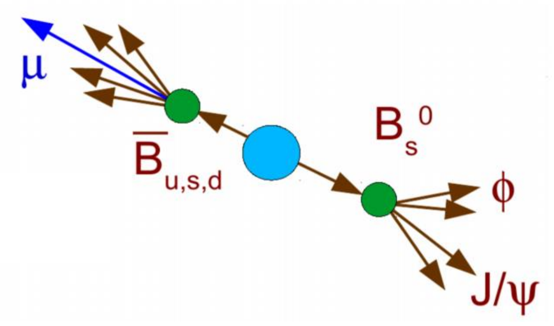
- CPV phase ϕ_s is the weak phase difference between the B_s^0 – $\overline{B_s^0}$ mixing amplitude and the b→c$\bar{c}$s decay amplitude
- In the Standard Model (SM) the ϕ_s is related to the CKM matrix and is small:

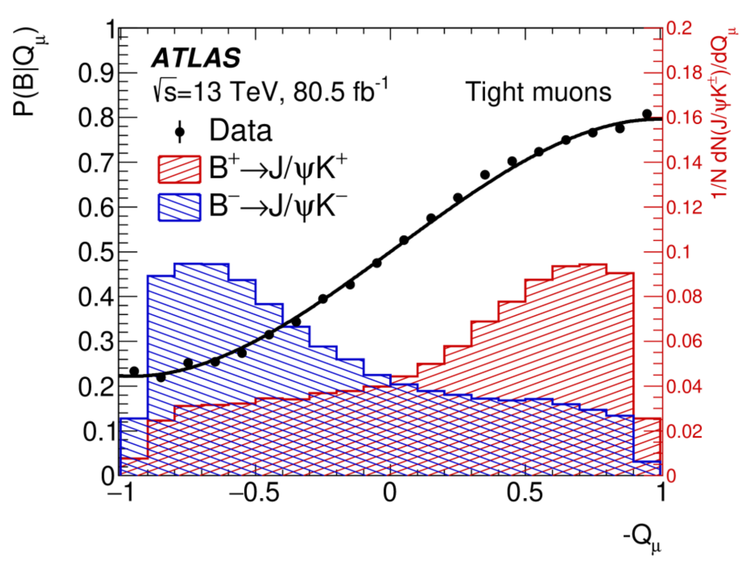
$$\varphi_s \simeq -2\beta^s = -2\arg\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*} = -0.03696^{+0.00072}_{-0.00082}\ \mathrm{rad}$$

- New Physics (NP) processes could contribute to the mixing box diagrams, potentially allowing for large deviations in ϕ_s from the SM prediction
- Other parameters describing Bs mixing and decay are mass difference $\Delta m_s = m_H - m_L$, decay width difference $\Delta\Gamma_s = \Gamma_L - \Gamma_H$, and $\Gamma_s = \frac{\Gamma_L + \Gamma_H}{2}$ — mean of the two decay widths ("L" and "H" stand for light and heavy mass eigenstates respectively).

Flavour Tagging

- b-quarks are produced in quark-antiquark pairs
- Initial flavour is correlated with the charge of decay product (e/μ/jet)
- Measuring weighted sum of charges of tracks in a cone around an opposite-side e/μ/jet gives information about B_s^0 meson flavour
- Method calibrated with B± → J/ψK± decays





Tagging power and efficiency

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: Fraction of signals with specific tagger, $\varepsilon = \frac{N_{tagged}}{N_{Bcand}}$
- Dilution: D = (1 – 2w), where w is the miss-tag probability
- Tagging Power: figure of merit of tagger performance
  - Depends on dilution and efficiency:
  - $TP = \varepsilon D^2 = \varepsilon(1-2w)^2$

Unbinned Maximum Likelihood Fit

$$\ln\mathcal{L} = \sum_{i+1}^{N} w_i \cdot \ln[f_s \cdot \mathcal{F}_s(m_i, t_i, \sigma_{m_i}, \sigma_{t_i}, \Omega_i, P_i(B|Q_x), p_{T_i}) + f_s \cdot f_{B^0} \cdot \mathcal{F}_{B^0}(m_i, t_i, \sigma_{m_i}, \sigma_{t_i}, \Omega_i, P_i(B|Q_x), p_{T_i})$$
$$+ f_s \cdot f_{\Lambda_b} \cdot \mathcal{F}_{\Lambda_b}(m_i, t_i, \sigma_{m_i}, \sigma_{t_i}, \Omega_i, P_i(B|Q_x), p_{T_i})$$
$$+ (1 - f_s \cdot (1 + f_{B^0} + f_{\Lambda_b})) \cdot \mathcal{F}_{bkg}(m_i, t_i, \sigma_{m_i}, \sigma_{t_i}, \Omega_i, P_i(B|Q_x), p_{T_i})]$$

Trigger lifetime efficiency weights

Signal PDF

B_d background PDF

Λ_b background PDF

PDF for other background sources

Physics parameters:

- CPV phase ϕ_s
- Decay widths: $\Delta\Gamma_s$, Γ_s
- Decay amplitudes: $|A_0(0)|^2$, $|A_\parallel(0)|^2$, $\delta_\parallel$, $\delta_\perp$
- S-wave: $|A_s(0)|^2$, δ_S
- Δm_s fixed to PDG

Observables

Base observables: m_i, t_i, Ω_i

- Conditional observables per-candidate:
  - resolutions: σ_{m_i}, σ_{t_i} (B-p_{T_i} dependent)
  - tagging probability and method: P(B|Q)

Systematic Uncertainties

Uncertainty in the calibration of the tag probability

Effect of residual misalignment (studied in signal MC)

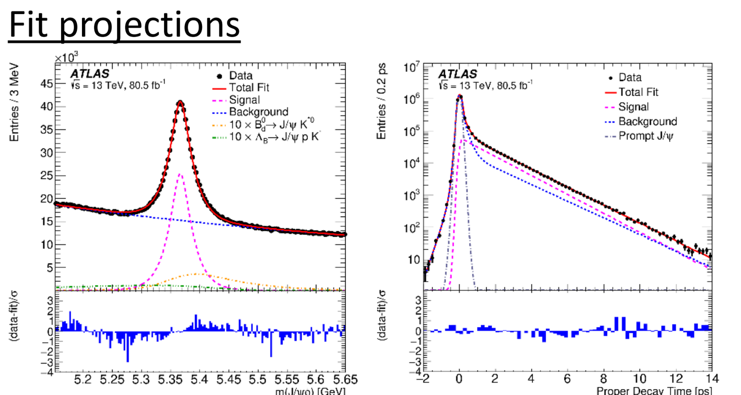
Contributions from peaking backgrounds $B_d \to J/\psi K^*$, $B_d \to J/\psi K\pi$ and $\Lambda_b \to J/\psi Kp$,

Uncertainties of fit model derived in pseudo-experiment studies

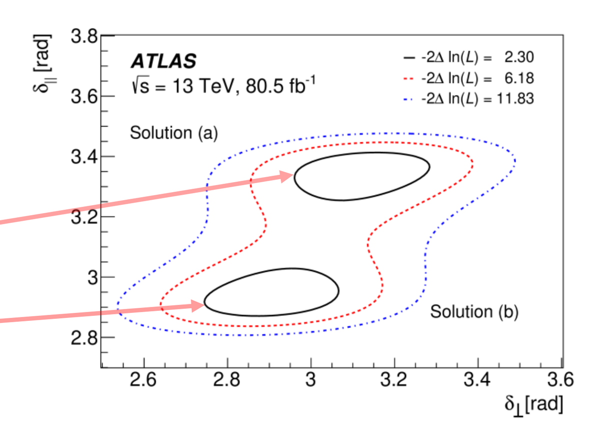
	ϕ_s [10^{-3} rad]	$\Delta\Gamma_s$ [10^{-3} ps^{-1}]	Γ_s [10^{-3} ps^{-1}]	$\lvert A_\parallel(0)\rvert^2$ [10^{-3}]	$\lvert A_0(0)\rvert^2$ [10^{-3}]	$\lvert A_S(0)\rvert^2$ [10^{-3}]	$\delta_\perp$ [10^{-3} rad]	$\delta_\parallel$ [10^{-3} rad]	$\delta_\perp - \delta_S$ [10^{-3} rad]
Tagging	19	0.4	0.3	0.2	0.2	1.1	17	19	2.3
Acceptance	0.5	< 0.1	< 0.1	1.0	0.8	2.6	33	56	7.0
ID alignment	0.8	0.2	0.5	< 0.1	< 0.1	< 0.1	11	7.2	< 0.1
Best candidate selection	0.5	0.4	0.7	0.5	0.2	0.2	12	17	7.5
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 interval	0.4	0.1	0.1	0.3	0.3	1.3	4.4	7.4	2.3
Dedicated backgrounds:									
B_d^0	2.3	1.1	< 0.1	0.2	3.0	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	15	37
Fit bias	5.7	1.3	1.2	1.3	0.4	1.1	3.3	19	0.3
Total	20	2.2	1.8	2.2	3.4	4.4	51	84	38

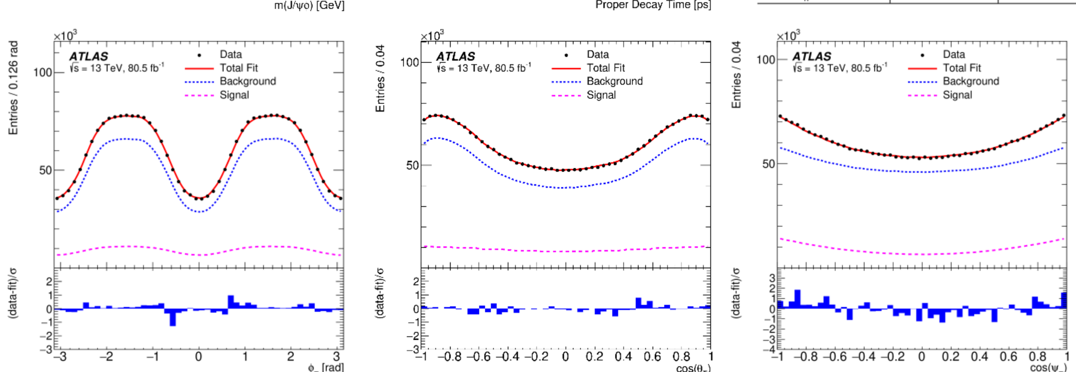
Fit Results(13 TeV Data, 80.5 fb^{-1})

Fit projections



Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	−0.081	0.041	0.020
$\Delta\Gamma_s$ [ps^{-1}]	0.0607	0.0047	0.0022
Γ_s [ps^{-1}]	0.6687	0.0015	0.0018
$\lvert A_\parallel(0)\rvert^2$	0.2213	0.0019	0.0022
$\lvert A_0(0)\rvert^2$	0.5131	0.0013	0.0034
$\lvert A_S(0)\rvert^2$	0.0321	0.0033	0.0044
$\delta_\perp - \delta_S$ [rad]	−0.25	0.05	0.04
Solution (a)			
$\delta_\perp$ [rad]	3.12	0.11	0.05
$\delta_\parallel$ [rad]	3.35	0.05	0.08
Solution (b)			
$\delta_\perp$ [rad]	2.91	0.11	0.05
$\delta_\parallel$ [rad]	2.94	0.05	0.08

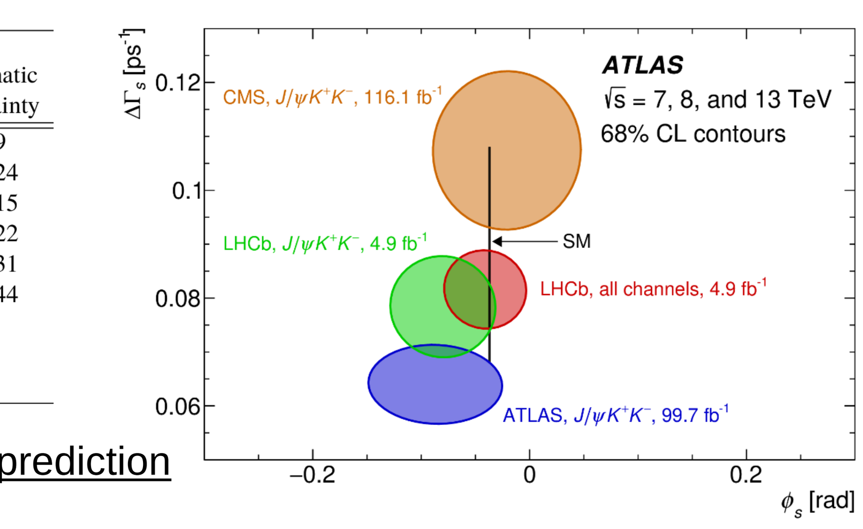




While for most of the physics parameters, including ϕ, ΔΓ, Γ, the fit determines a single solution, for the strong-phases $\delta_\perp$ and $\delta_{||}$ two well separated local maxima of the likelihood are found, and shown as solution (a) and (b) in the table of results.

Combination with the previous from Run 1

Parameter	Solution (a) Value	Solution (a) Statistical uncertainty	Solution (a) Systematic uncertainty	Solution (b) Value	Solution (b) Statistical uncertainty	Solution (b) Systematic uncertainty
ϕ_s [rad]	−0.087	0.036	0.019	−0.088	0.036	0.019
$\Delta\Gamma_s$ [ps^{-1}]	0.0641	0.0043	0.0024	0.0640	0.0043	0.0024
Γ_s [ps^{-1}]	0.6697	0.0014	0.0015	0.6698	0.0014	0.0015
$\lvert A_\parallel(0)\rvert^2$	0.2221	0.0017	0.0022	0.2218	0.0017	0.0022
$\lvert A_0(0)\rvert^2$	0.5149	0.0012	0.0031	0.5149	0.0012	0.0031
$\lvert A_S\rvert^2$	0.0343	0.0031	0.0044	0.0348	0.0031	0.0044
$\delta_\perp$ [rad]	3.22	0.10	0.05	3.03	0.10	0.05
$\delta_\parallel$ [rad]	3.36	0.05	0.08	2.95	0.05	0.08
$\delta_\perp - \delta_S$ [rad]	−0.24	0.05	0.04	−0.24	0.05	0.04



Compatible results with LHCb and CMS and the SM prediction

These results are published in: arXiv:2001.07115 (Submitted to EPJC)