Measurement of the CP-violating phase ϕ_s in the $B_s^0 \to J/\psi\phi$ decay

using ATLAS 2015-2017 data, 13 TeV

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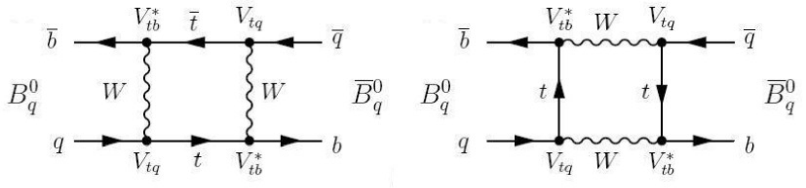
Motivation - Measurement of the CP-violating phase ϕ_s in the $B_s^0 \to J/\psi\phi$ decay

CP violation - history

- In Standard Model the CP violation now well understood
  - Firstly observed in the system of neutral kaons [ref.]
  - CPV occurs due to interference between a direct decay and a decay with B_s^0 - $\bar{B}_s^0$ mixing



  - Transitions between quarks can be described by the CKM matrix:

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97370 \pm 0.00014 & 0.2245 \pm 0.0008 & 0.00382 \pm 0.00024 \\ 0.221 \pm 0.004 & 0.987 \pm 0.011 & 0.0410 \pm 0.0014 \\ 0.0080 \pm 0.0003 & 0.0388 \pm 0.0011 & 1.013 \pm 0.030 \end{bmatrix}$$

Motivation

New physics

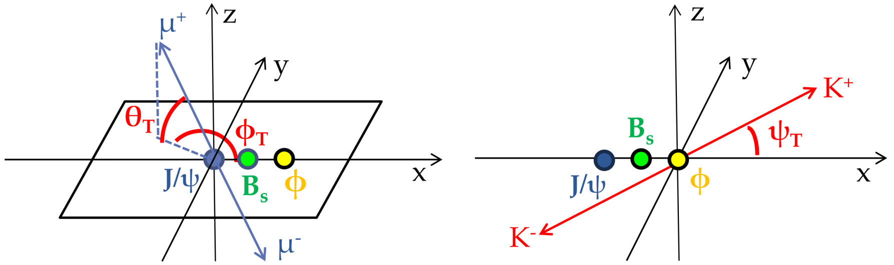
- In the presence of new physics phenomena, sources of CP violation can arise in addition to those predicted by the Standard Model

$B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$

- CPV in $B_s^0 \to J/\psi\phi$ is described by the parameters ϕ_s, Γ_s^L, Γ_s^H $(\Gamma_s, \Delta\Gamma_s)$ [ref.]
- ϕ_s is related to the CKM matrix elements: $\phi_s \simeq 2\arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)]$
    - $(|V_{tb}| \approx |V_{cs}| \approx 1; |V_{ts}| \approx |V_{cb}| \approx 0.04)$
- ϕ_s can be predicted in the SM with high precision (3%)
    - $\phi_s = -0.03696^{+0.00072}_{-0.00082}$ rad by CKMFitter group
    - $\phi_s = -0.03700 \pm 0.00104$ rad according to UTfit Collaboration
- Very precise measurment needed

Motivation

Accessible through a measurement of the time dependent angular distribution



Theoretical description

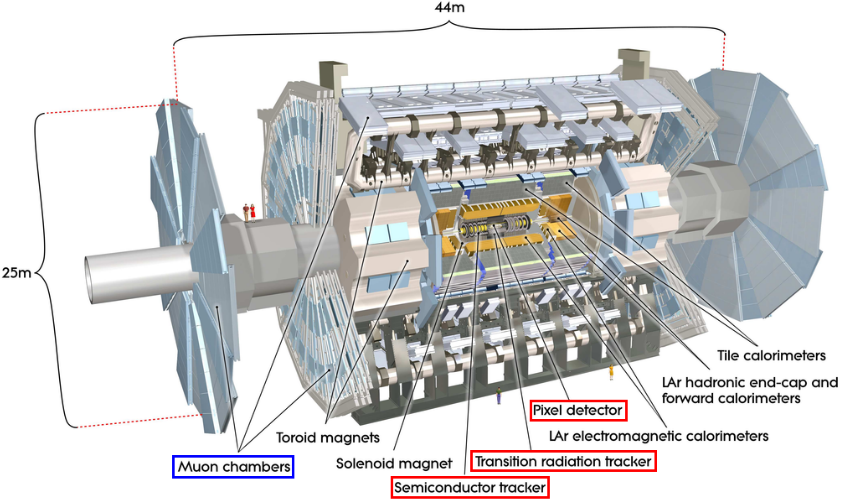
$$\frac{d^4\Gamma}{dt d\Omega} = \sum_{k=1}^{10} O^k(t) g^k(\theta_T, \Psi_T, \phi_T)$$

Probability density function for $B_s^0 \to J/\psi\phi$

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

Data collection

Results presented here [Eur. Phys. J. C 81 (2021) 342] use 80.5 fb^{-1} of 2015-2017 Run 2 data, statistically combined with 19.2 fb^{-1} Run 1



Data selection - $B^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$

1. step) J/ψ reconstruction

- μ triggers ($p_T(\mu) > 4$ GeV or 6 GeV)
- $\mu^+\mu^-$ refitted to a common vertex (χ^2/ndof < 10)
- 3 pseudorapidity bins with different $m(\mu\mu)$ window

2. step) ϕ reconstruction

- $p_T(K^\pm) > 1$ GeV
- $m(KK) \in (1008.5, 1030.5)$ MeV

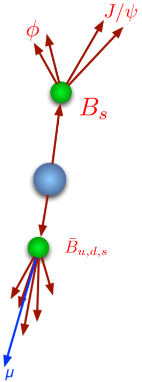
3. step) $B^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$

- 4 tracks - ID momentum measurement only
- B^0 candidates refitted from J/ψ and ϕ
  - $m(J/\psi)$ fixed to the PDG value
  - $m(B^0) \in (5150, 5650)$ MeV
  - χ^2/ndof(SV) < 3
  - B candidate with the smallest χ^2/ndof is selected
- In 2015-2017, 2 977 526 B_s^0 candidates were collected.

Flavour tagging

Opposite-site tagging

- Knowledge of $B_s/\bar{B}_s$ flavour at production significantly increases signal PDF sensitivity to ϕ_s
- Four taggers: Tight muon, electron, Low-p$_T$ muon, *b*-jet
- Key variable: Q_X - charge of p_T-weighted tracks in a cone (ΔR) around the opposite side primary object (μ, *e*, *b*-jet), used to build per-candidates B_s tag probability
    - $Q_X = \frac{\Sigma_i^{N_{tracks}} p_{Ti}^{\kappa} q_i}{\Sigma_i^{N_{tracks}} p_{Ti}^{\kappa}}$
- Calibration on self-tagged $B^\pm \to J/\psi K^\pm$
- Tagging probability is propagated into the likelihood



Maximal Likelihood Fit: mass + lifetime + 3 angles + conditional observables

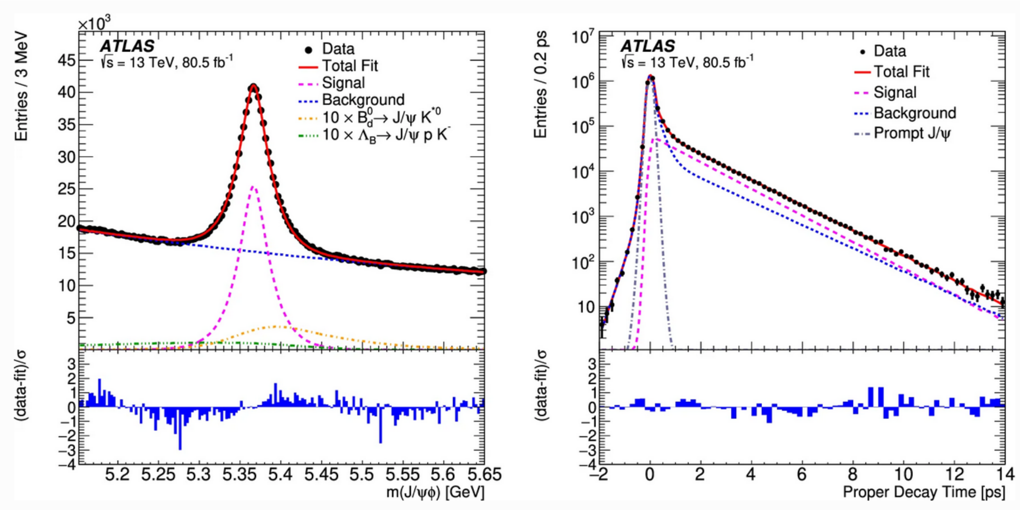
The unbinned maximum likelihood fit was performed for:

- Observables: B_s^0 mass (m_i), decay time (t_i) and the decay angles $\Omega = (\theta_T, \Psi_T, \phi_T)$
- Conditional obsevables: σ_{m_i}, σ_{t_i}, p_{Ti} and B-tagging probability: $P(B|Q)$
- Physics parameters:
  - CPV phase ϕ_s
  - Decay widths: $\Delta\Gamma_s$, Γ_s
  - Decay amplitudes: $|A_0(0)|^2$, $|A_{||}(0)|^2$, $\delta_{||}$, $\delta_\perp$
  - S-wave: $|A_S(0)|^2$, δ_S
  - and Δm_s fixed to PDG, λ=1 (no direct CPV)

$$
\begin{aligned}
\ln\ \mathcal{L} = \sum_{i=1}^{N_{events}} \{ & w_i \cdot \ln(f_\mathrm{s} \cdot \mathcal{F}_\mathrm{s}(m_i, t_i, \sigma_m, \sigma_t, \Omega_i, P(B|Q), p_{\mathrm{T}_i}) \\
& + f_\mathrm{s} \cdot f_{B_d^0} \cdot \mathcal{F}_{B_d^0}(m_i, t_i, \sigma_m, \sigma_t, \Omega_i, P(B|Q), p_{\mathrm{T}_i}) \\
& + f_\mathrm{s} \cdot f_{\Lambda_b} \cdot \mathcal{F}_{\Lambda_b}(m_i, t_i, \sigma_m, \sigma_t, \Omega_i, P(B|Q), p_{\mathrm{T}_i}) \\
& + (1 - f_\mathrm{s} \cdot (1 + f_{B_d^0} + f_{\Lambda_b})) \cdot \mathcal{F}_\mathrm{bkg}(m_i, t_i, \sigma_m, \sigma_t, \Omega_i, P(B|Q), p_{\mathrm{T}_i}))\}
\end{aligned}
$$

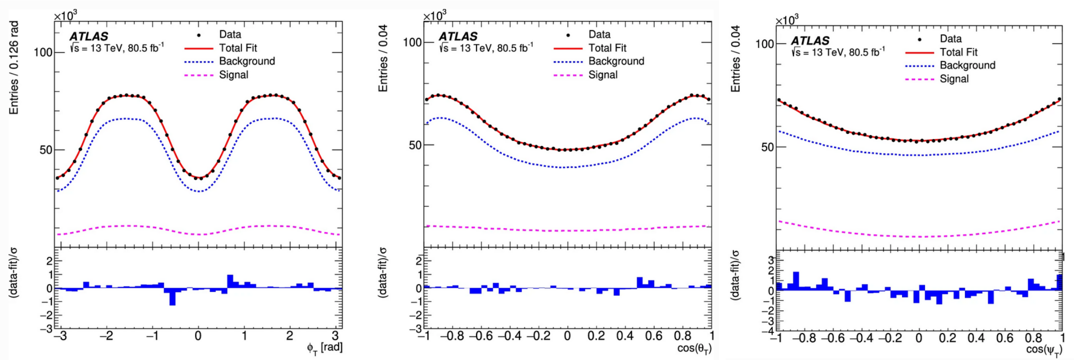
Mass and Proper decay time projections

Fit with a good agreement with data



Decay angles projections

Fit with a good agreement with data

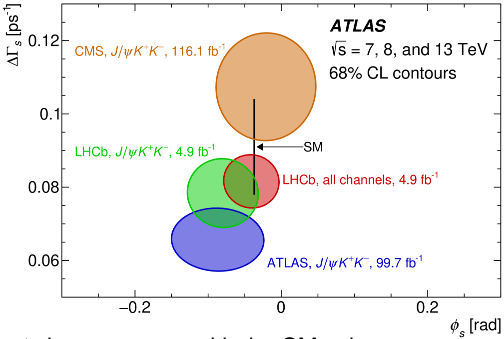


Results

$$\phi_s = -0.087 \pm 0.036\ (\mathit{stat.}) \pm 0.021\ (\mathit{syst.})$$

- Statistical uncertainty still dominant

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



- ϕ_s in agreement with the SM value
- ATLAS is consistent with CMS and LHCb

Summary

Conclusion

Results from ATLAS 2015-2017 combined with Run 1 were presented

- Measurement is consistent with the SM prediction and LHCb and CMS measurements
  - $\phi_s^{ATLAS} = -0.087 \pm 0.036\ (stat.)\ \pm 0.021\ (syst.)$
  - $\phi_s^{SM} = -0.03696^{+0.00072}_{-0.00082}$ rad (CKMFitter)
  - $\phi_s^{SM} = -0.03700 \pm 0.00104$ rad (UTfit)
- Next step towards a more precise measurement
  - to add 60 fb^{-1} from 2018

Stay tuned for more results

- B_d lifetime measurement with $B_d^0 \to J/\psi K^*$ (Γ_s/Γ_d)
- B_s lifetime measurement with $B_s \to \mu\mu$
- Measurement of the CP violation in $B_s \to J/\psi\phi$ with full Run 2 statistics

Thank you for your attention!