Precision measurements of B meson decays at ATLAS

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28th May 2024
FPCP 2024 Bangkok

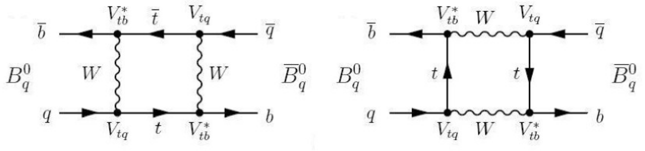
Motivation

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

- Analysis using years 2015, 2016 and 2017 [EPJC 81 (2021) 342]
- The HL-LHC prospects [ATLAS Note]

Theoretical description

- In Standard Model the CP violation occurs due to interference between a direct decay and a decay with B_s^0 - $\bar{B}_s^0$ mixing. Described by the CKM matrix elements. $\phi_s \simeq 2\arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)]$.



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

Motivation

New physics

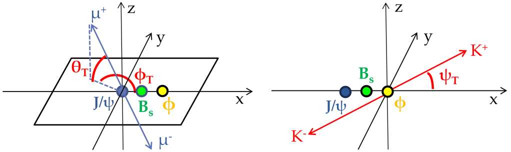
- In the presence of new physics phenomena, additional sources of CPV can arise

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

- CPV is described by the parameters ϕ_s, Γ_s^L, Γ_s^H ($\Gamma_s, \Delta\Gamma_s$)
- ϕ_s can be predicted in the SM with high precision (3%)
  - $\phi_s = -0.03696^{+0.00072}_{-0.00082}$ rad by [CKMFitter], $\phi_s = -0.03700 \pm 0.00104$ rad according to [UTfit]
- Γ_s can be predicted as well (but with higher uncertainties):
  - $\Gamma_s = 0.63^{+0.11}_{-0.07}$ [JHEP 01 (2023) 004]
- Γ_s/Γ_d (theoretical uncertainties cancel in ratio)
  - $\Gamma_s/\Gamma_d = 1.003 \pm 0.006$ [JHEP 01 (2023) 004]
  - ATLAS is working on a precise measurement of $\tau_{B_d^0}$

Decay description - $B_s^0 \to J/\psi\phi$

Accessible through a measurement of the time dependent angular distribution



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

The unbinned maximum likelihood fit

- Observables: B_s^0 mass (m_i), decay time (t_i) and the decay angles $\Omega = (\theta_T, \Psi_T, \phi_T)$
- Conditional observables: σ_{m_i}, σ_{t_i}, p_{Ti} and B-tagging probability: $P(B|Q)$
- Physics parameters:
  - CPV phase ϕ_s, decay width and difference: Γ_s, $\Delta\Gamma_s$
  - decay amplitudes and phases: $|A_0(0)|^2$, $|A_{||}(0)|^2$, $\delta_{||}$, $\delta_\perp$ and S-wave aplitude and phase: $|A_S(0)|^2$, δ_S
  - difference in mass of both states Δm_s fixed to PDG, λ fixed to 1 (no direct CPV assumption)
- Likelihood has 4 components - signal, B_d^0, Λ_b and combinatorial background (see bckup)

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

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

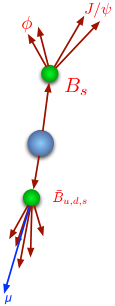
3. step - $B^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-))$

- 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; propagated into the likelihood
- 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: $Q_X = \frac{\Sigma_i^{N_{tracks}} p_{Ti}^{\kappa} q_i}{\Sigma_i^{N_{tracks}} p_{Ti}^{\kappa}}$

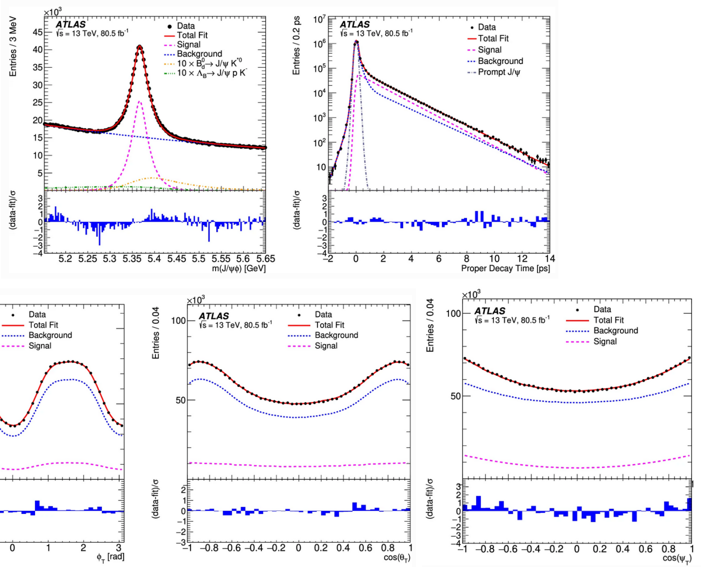


Taggers performance

- Calibration on self-tagged $B^{\pm} \to J/\psi K^{\pm}$ (data)

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

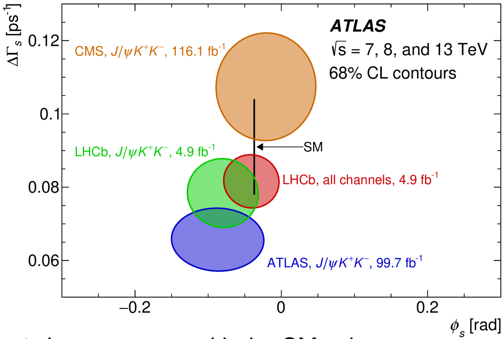
- ϵ_x - efficiency,
- D_x - effective dilution,
- T_x - tagging power


ATLAS
√s = 13 TeV, 80.5 fb⁻¹
Data
Total Fit
Signal
Background
Prompt J/ψ
Background
Entries / 3 MeV
(data-fit)/σ
m(J/ψφ) [GeV]
Entries / 0.2 ps
Proper Decay Time [ps]
Entries / 0.126 rad
ϕ_T [rad]
Entries / 0.04
cos(θ_T)
cos(ψ_T)

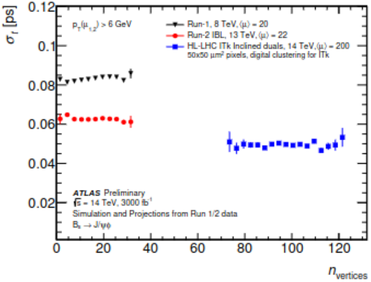
Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	−0.081	0.041	0.020
$\Delta\Gamma_s$ [ps^{-1}]	0.0607	0.0047	0.0025
Γ_s [ps^{-1}]	0.6687	0.0015	0.0016
$\|A_{\parallel}(0)\|^2$	0.2213	0.0019	0.0023
$\|A_0(0)\|^2$	0.5131	0.0013	0.0034
$\|A_S(0)\|^2$	0.0321	0.0033	0.0045
$\delta_{\perp} - \delta_S$ [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

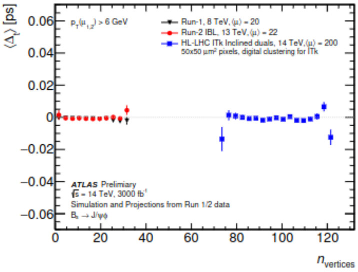
Combined result with Run1 [EPJC 81 (2021) 342]:

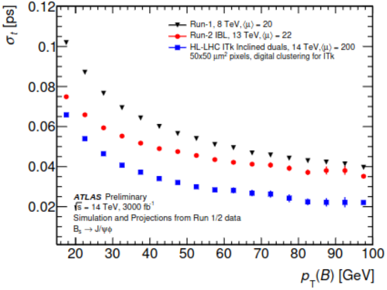
$$\phi_s = -0.087 \pm 0.036\ (\textit{stat.}) \pm 0.021\ (\textit{syst.})$$



- ϕ_s in agreement with the SM value
- Statistical uncertainty is still dominating
- ATLAS is consistent with CMS and LHCb in ϕ_s



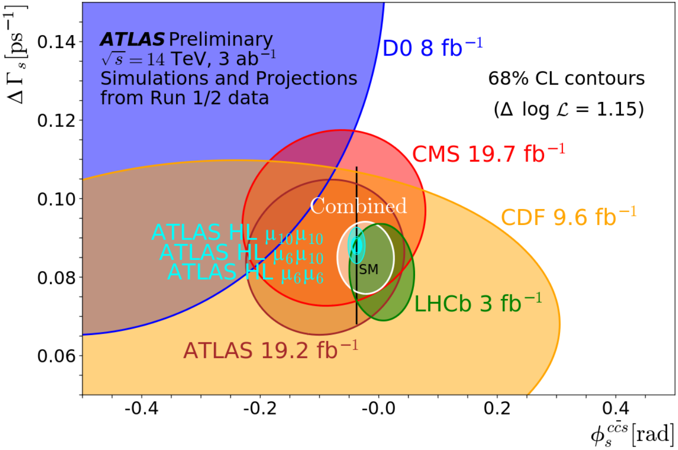




Lifetime measurement precision

- Run 2: The IBL was added to the ID
- HL-LHC: The ID replacement by ITk
- Even for higher number $n_{vertices}$, the lifetime resolution will be improved

Prospects for $B_s \to J/\psi\phi$ in HL-LHC



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)

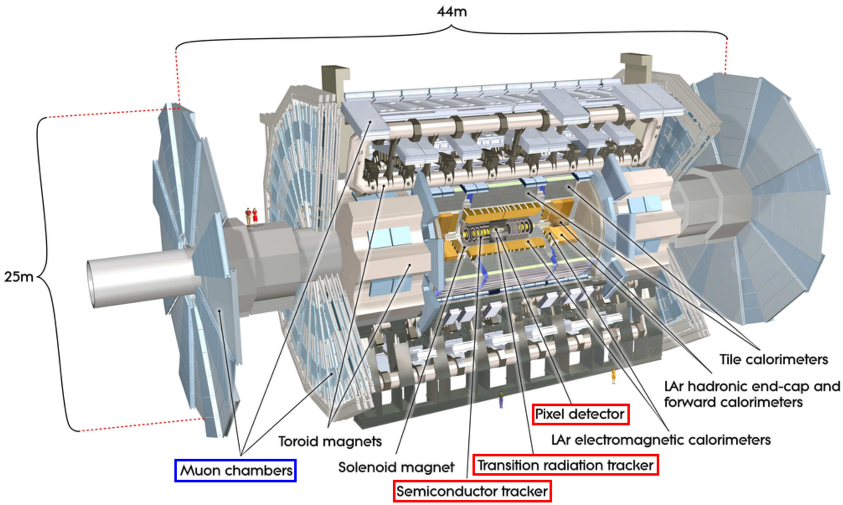
Expected improvement of the lifetime measurement precision for HL-LHC was reported

Stay tuned for more results

- High precision B_d lifetime measurement with $B_d^0 \to J/\psi K^*$ (with Γ_s/Γ_d ratio)
- Measurement of the CP violation in $B_s \to J/\psi\phi$ with full Run 2 statistics (to add 60 fb^{-1} from 2018)
- and more ...

Thank you for your attention!

The ATLAS detector



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

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

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)

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