ATLAS measurements of CP violation and rare decay processes with beauty mesons

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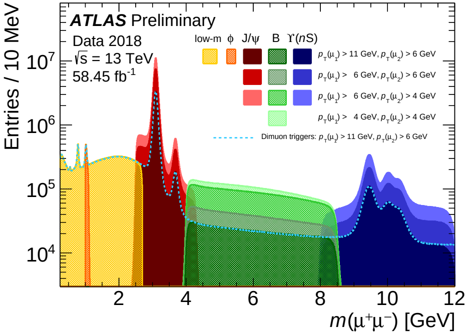
ATLAS EXPERIMENT

B Physics in ATLAS

- ATLAS has collected 25 fb^{-1} of data in Run 1, and 139 fb^{-1} in Run 2
- B physics in ATLAS mostly focus on final states with muons
- CP violation in $B_s^0 \to J/\psi\phi$ analysis (Run2, 2015-2017) and $B_{(s)} \to \mu\mu$ analysis (Run2, 2015-2016)
  - Events collected with a mixture of triggers based on $J/\psi \to \mu^+\mu^-$ identification, with muon p_T thresholds of either 4 GeV or 6 GeV (vary over run periods)



Measurement of the CP-violating phase ϕ_s in $B_s^0 \to J/\psi\phi$ decays in ATLAS at 13 TeV

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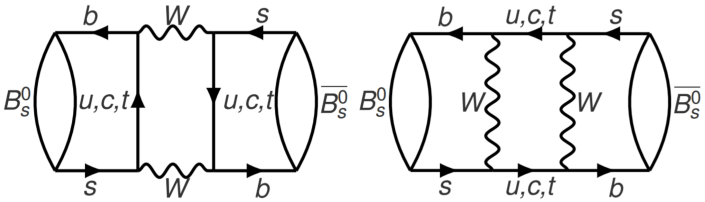
CP violation measurement in $B_s^0 \to J/\psi\phi$

- $B_s^0 \to \mathrm{J}/\psi\phi$ used to measure the CP-violating phase ϕ_s
  - Potentially sensitive to New Physics (NP)
- The CP violation due to interference between a direct decay and a decay with $B_s^0 - \overline{B}_s^0$ mixing
- In the Standard Model (SM), ϕ_s is related to the CKM elements and predicted with high precision: $\phi_s \simeq 2\arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)] = -0.03696^{+0.00072}_{-0.00082}$ rad

Phys. Rev. D 91 (2015), 073007

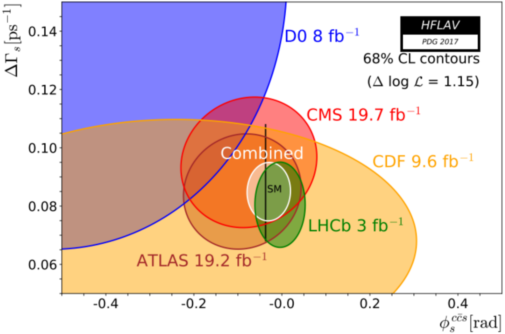


- Any deviations from SM: SUSY particles, Dark Matter, ... in the box diagram?

CP violation measurement in $B_s^0 \to J/\psi\phi$ Eur. Phys. J. C 81 (2021) 342

- The other quantities in B_s^0 mixing are $\Delta m_s = |m_L - m_H|$, $\Delta\Gamma_s = \Gamma_s^L - \Gamma_s^H$ and $\Gamma_s = (\Gamma_s^L + \Gamma_s^H)/2$
- $\Delta\Gamma_s$, Γ_s not as sensitive to New Physics, however the measurement is interesting to test the theory ($\Delta\Gamma_s = (0.091 \pm 0.013)\ \mathrm{ps}^{-1}$)
- Similar measurements were previously performed at the LHC in Run1 and at the Tevatron by the CDF and D0 experiments

- Situation before LHC Run2:



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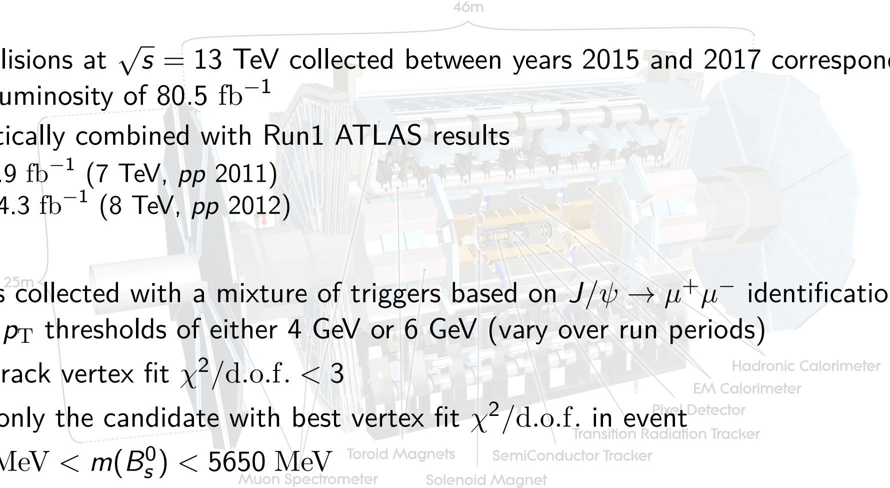
Data:

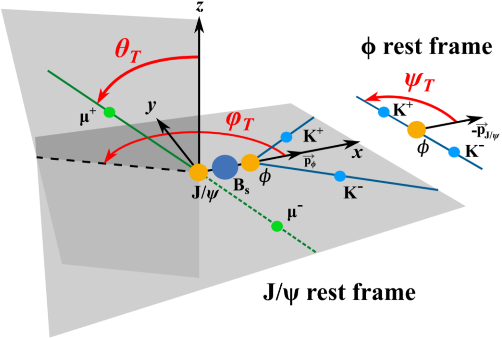
- pp collisions at $\sqrt{s} = 13$ TeV collected between years 2015 and 2017 corresponding to a total luminosity of 80.5 fb^{-1}
- Statistically combined with Run1 ATLAS results
  - 4.9 fb^{-1} (7 TeV, pp 2011)
  - 14.3 fb^{-1} (8 TeV, pp 2012)

Selection:

- Events collected with a mixture of triggers based on $J/\psi \rightarrow \mu^+\mu^-$ identification, with muon p_{T} thresholds of either 4 GeV or 6 GeV (vary over run periods)
- Four-track vertex fit $\chi^2/\mathrm{d.o.f.} < 3$
- Keep only the candidate with best vertex fit $\chi^2/\mathrm{d.o.f.}$ in event
- $5150\ \mathrm{MeV} < m(B_s^0) < 5650\ \mathrm{MeV}$

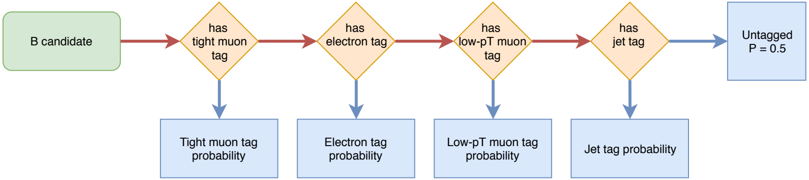


- $B_s^0 \to J/\psi\phi$ is a decay of pseudoscalar into a pair of vectors
- Final state: admixture of CP-odd (L = 1) and CP-even (L = 0, 2) states
- Contribution from non-resonant S-wave $B_s^0 \to J/\psi K^+ K^-$ - CP-odd
- Distinguishable through time-dependent angular analysis
- differential decay rate depends on amplitudes A_0, $A_\perp$, $A_\parallel$, A_S (and interferences) and angles θ_T, ψ_T, ϕ_T

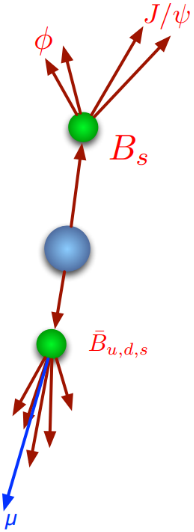


CP Violation and Lifetime Measurement: Opposite Side Tagging

- Opposite side tagging (Tight muons, Electrons, Low-p_{T} muons and Jets),
  - Events tagged by the method with the highest statistical power



- Muon and Electron Tagging
  - $b \to l$ transitions are clean tagging method
  - $b \to c \to l$ and neutral B-meson oscillations dilute the tagging
  - Tracks in cone around lepton also included $\Rightarrow$ weighted sum of charges used
- Jet-Charge
  - information from tracks in b-tagged Jet, when no lepton is found
- Calibration using $B^{\pm} \to J\psi K^{\pm}$



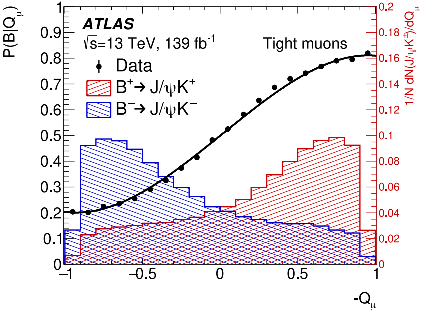
- Cone around OST lepton:

$$Q = \frac{\sum_i^{Ntracks} q^i (p_\mathrm{T}^i)^\kappa}{\sum_i^{Ntracks} (p_\mathrm{T}^i)^\kappa} \rightarrow P(Q|B^\pm)$$

- The probability to tag a B_s^0 meson as containing a $\bar{b}$-quark:

$$P(B|Q) = \frac{P(Q|B^+)}{P(Q|B^+) + P(Q|B^-)}$$

- Tagging performance quality described by:
  - **Efficiency** ε**:** Fraction of tagged events
  - **Dilution:** $D = (1 - 2\omega)$, where ω is the mistag probability
  - **Tagging Power:** $T = \varepsilon D^2$ figure of merit of tagger performance



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

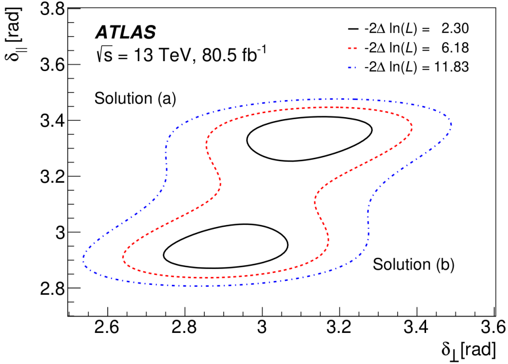
CP Violation and Lifetime Measurement: Fit Model

- Unbinned maximum likelihood (ML) fit:

$$\mathcal{L} = \sum_{i=1}^{N} \{ \underbrace{w_i}_{\text{trigger weight}} \cdot \ln(\underbrace{f_s \mathcal{F}_s}_{\text{signal}} + \underbrace{f_s \cdot f_{B_d^0} \mathcal{F}_{B_d^0} + f_s f_{\Lambda_b} \mathcal{F}_{\Lambda_b}}_{\text{peaking background}} + \underbrace{(1 - f_s)(1 + f_{B_d^0} + f_{\Lambda_b}) \mathcal{F}_{\rm bkg}}_{\text{combinatorial background}})\}$$

- Base observables: mass m, lifetime t, angles $\Omega(\psi_T, \phi_T, \theta_T)$
- Conditional observables per-candidate: mass and lifetime resolution (σ_m, σ_t), candidate $p_{\rm T}$, tagging probability and method
- Likelihood corrected to lifetime weight - trigger efficiencies
- Contributions from $B_d \to J/\psi K^{*0}$, $B_d \to J/\psi K\pi$ and $\Lambda_b \to J/\psi Kp$ misidentified as B_s^0 candidates
  - Efficiencies and acceptance from MC
  - BR from PDG
  - Fragmentation fractions from other measurements

- Results - two solutions observed for strong phases
  - Well separated local maxima in the likelihood
    - Interesting parameters are almost insensitive to strong phase ambiguity



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
Solution (a)			
$\delta_\perp$ [rad]	3.12	0.11	0.06
$\delta_\parallel$ [rad]	3.35	0.05	0.09
Solution (b)			
$\delta_\perp$ [rad]	2.91	0.11	0.06
$\delta_\parallel$ [rad]	2.94	0.05	0.09

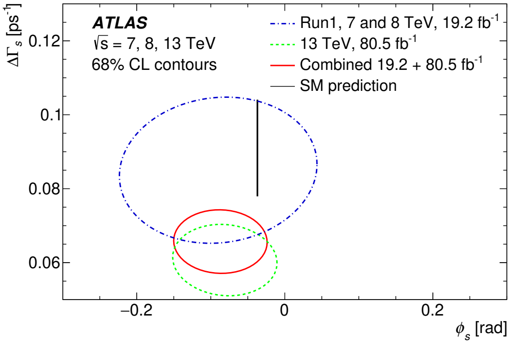
CP Violation Measurement: Results

- Used 80.5 fb^{-1} of 2015-17 data from *pp* collisions collected by the ATLAS detector
- Combined with Run 1 results: 4.9 fb^{-1} (7 TeV, *pp* 2011) and 14.3 fb^{-1} (8 TeV, *pp* 2012)

$$\phi_s = -87 \pm 36(\text{stat.}) \pm 21(\text{syst.})\ \text{mrad}$$

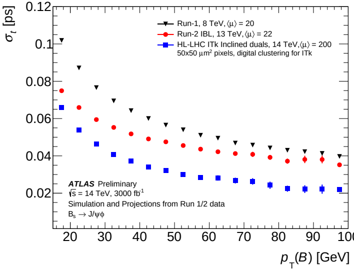
$$\Delta\Gamma_s = 65.7 \pm 4.3(\text{stat.}) \pm 3.7(\text{syst.})\ \text{ns}^{-1}$$

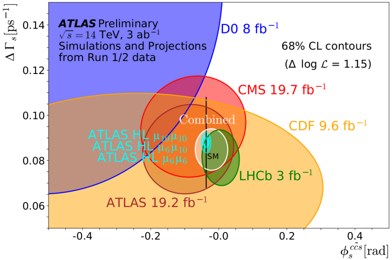
$$\Gamma_s = 670.3 \pm 1.4(\text{stat.}) \pm 1.8(\text{syst.})\ \text{ns}^{-1}$$



ATL-PHYS-PUB-2018-041

- Updated tracking (ITk): proper decay time resolution improved by 21% w.r.t. Run 2
- Three trigger scenarios:
  - 2MU10: $18 \times N_{\text{Run1}}$
  - MU6_MU10: $60 \times N_{\text{Run1}}$
  - 2MU6: $100 \times N_{\text{Run1}}$
- N_{sig} and σ_t scale with statistics, tag power not scaled
- Expected improvements w.r.t. Run 1:
  - ϕ_s stat. uncertainty: better by $\sim 9\times$ to $20\times$
  - $\Delta\Gamma$ stat. uncertainty: better by $\sim 4\times$ to $10\times$
- LHC Run2 results not included in this study





Search for $B^0_{(s)} \rightarrow \mu\mu$

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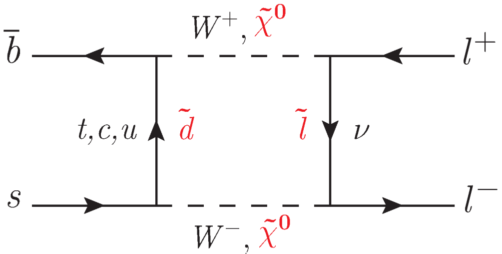
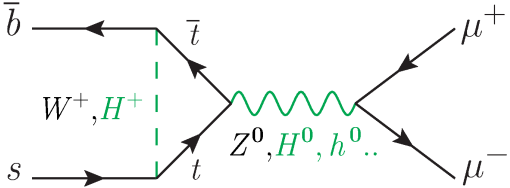
$B^0_{(s)} \to \mu\mu$: Motivation

- Flavour-changing-neutral-current (FCNC) processes **highly supressed in SM**, significant deviations predicted by theories beyond SM
- $B^0_s \to \mu\mu$ and $B^0 \to \mu\mu$ highly sensitive to New Physics
- SM predictions: $\mathcal{B}\left(B^0_s \to \mu\mu\right) = (3.66 \pm 0.14) \cdot 10^{-9}$ and $\mathcal{B}\left(B^0 \to \mu\mu\right) = (1.03 \pm 0.05) \cdot 10^{-10}$





- Any deviation of results from SM: hint for SUSY, dark matter,...?

$B^0_{(s)} \to \mu\mu$: Motivation

- Branching fractions are measured relative to the reference decay mode $B^\pm \to \mathrm{J}/\psi K^\pm$:

$$\mathcal{B}\left(B^0_{(s)} \to \mu\mu\right) = N_{d(s)} \frac{\mathcal{B}\left(B^\pm \to \mathrm{J}/\psi K^\pm\right) \times \mathcal{B}\left(\mathrm{J}/\psi \to \mu\mu\right)}{N_{\mathrm{J}/\psi K^\pm} \frac{\varepsilon_{\mu\mu}}{\varepsilon_{\mathrm{J}/\psi K^\pm}}} \frac{f_u}{f_{d(s)}}$$

  - Branching ratios known from PDG, $f_u/f_{d(s)}$ from HFLAV
  - Relative reconstruction efficiencies estimated from MC (corrected for data-MC differences): $\varepsilon_{\mu\mu}/\varepsilon_{\mathrm{J}/\psi K^\pm} = 0.1176 \pm 0.0009(\mathrm{stat.}) \pm 0.0047(\mathrm{syst.})$
  - Yields $N_{d(s)}$ and $N_{\mathrm{J}/\psi K^\pm}$ exctracted from unbinned ML fit
- $B^0_s \to \mathrm{J}/\psi\phi$ used as control channel

$B^0_{(s)} \to \mu\mu$: Data and Selection

- pp collisions at $\sqrt{s} = 13\ \mathrm{TeV}$ collected between years 2015 and 2016 corresponding to $36.2\ \mathrm{fb}^{-1}$
  - Due to the trigger prescales, $26.3\ \mathrm{fb}^{-1}$
- Data were collected with triggers based on the identification of a $\mathrm{J}/\psi \to \mu^+\mu^-$ ($p_\mathrm{T} > 4$ or 6 GeV)
- Signal sample :
  - Distance between primary vertex and the dimuon vertex in the transverse plane: $L_{xy} > 0$
  - Di-muon candidate in 4.0–8.5 GeV
- Reference and control channel
  - two, three or four track vertex fit: $\chi/\mathrm{n.d.f.} < 6$
  - J/ψ vertex: $\chi^2/\mathrm{n.d.f.} < 10$
  - Mass ranges: 5050–5650 MeV (B^0_s) and 4930–5630 $B^\pm$
- $B^0_{(s)} \to \mu\mu$ mass range: 4766–5966 MeV

Partially reconstructed b-hadrons

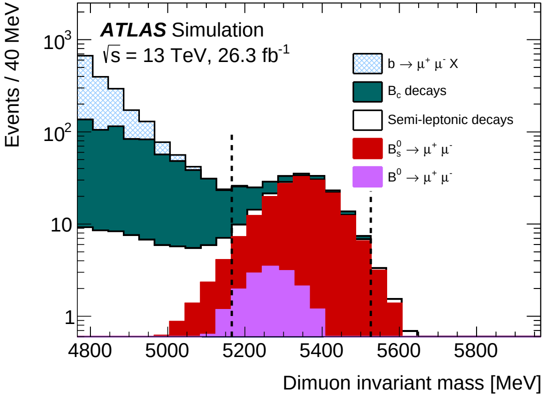
- one or more of the final-state particles (X) in a b-hadron decay is not reconstructed
- Mostly in the low di-muon mass region

Peaking backgrounds

- $B^0_{(s)} \to hh'$ decays, both hadrons misreconstructed as muons
- Simulated and fixed in the mass fit
- Very small contribution by comparison to signal yield

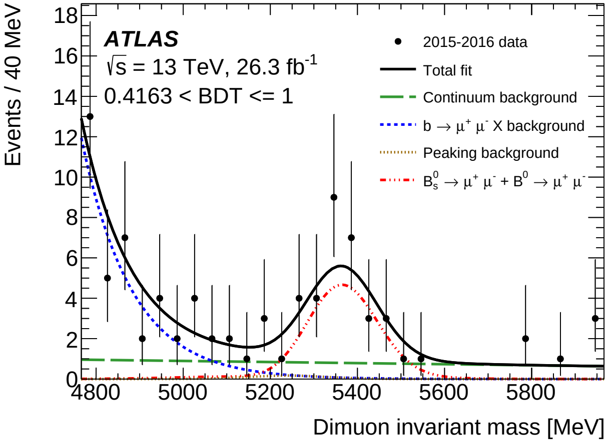
Continuum background

- Muons originating from uncorrelated hadron decays
- Reduced by BDT (15 variables)



$B^0_{(s)} \to \mu\mu$: Signal extraction

- BDT with 15 variables used (kinematics, isolation)
- BDT output validated on reference and control channels
- Signal region divided into four BDT bins
- B^0_s and B^0 yields extracted from simultaneous unbinned ML fit



$B^0_{(s)} \to \mu\mu$: Results

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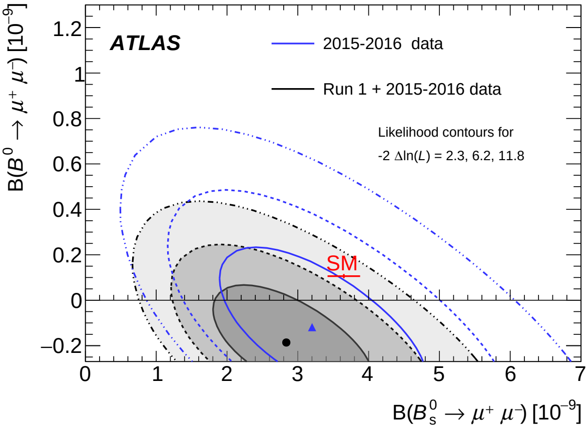
- Results combined with ATLAS Run1:

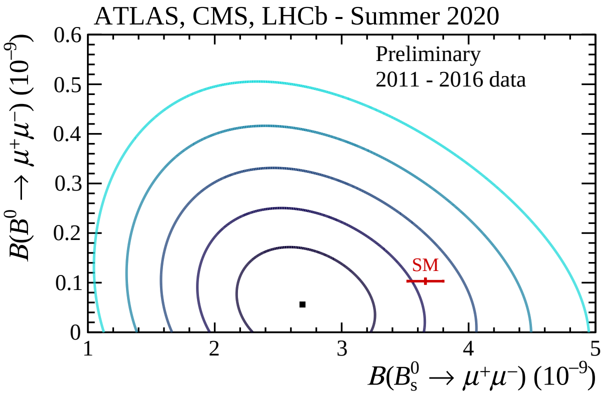
$$\mathcal{B}\left(B^0_s \to \mu\mu\right) = \left(2.8^{+0.8}_{-0.7}\right) \cdot 10^{-9}$$

$$\mathcal{B}\left(B^0 \to \mu\mu\right) < 2.1 \cdot 10^{-10} \text{at } 95\% \text{ CL}$$

- Combined measurement compatible with SM at 2.4σ
- Statistic uncertainties dominate



$B^0_{(s)} \to \mu\mu$: LHC Combination



- Combination from LHC experiments results calculated
- 2.1σ compatibility of LHC combination and SM

$$\mathcal{B}\left(B_s^0 \to \mu\mu\right) = \left(2.69^{+0.37}_{-0.35}\right) \cdot 10^{-9}$$

$$\mathcal{B}\left(B^0 \to \mu\mu\right) < 1.9 \cdot 10^{-10} \text{at } 95\% \text{ CL}$$

ATLAS-CONF-2020-049

Summary

- CP violation in $B_s^0 \to J/\psi\phi$ and $B_{(s)} \to \mu\mu$ analysis on the latest LHC Run2 data performed

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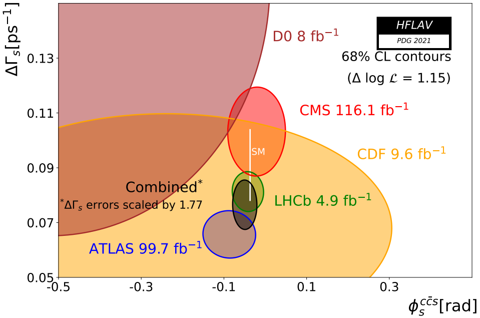
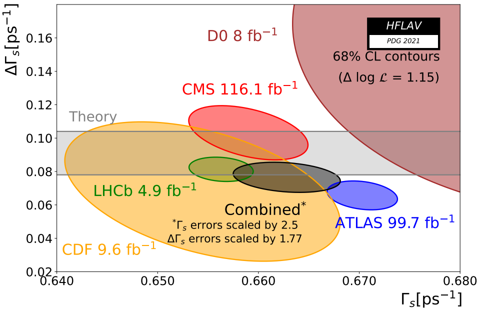
- The results are consistent with the Run1 results and with SM predictions





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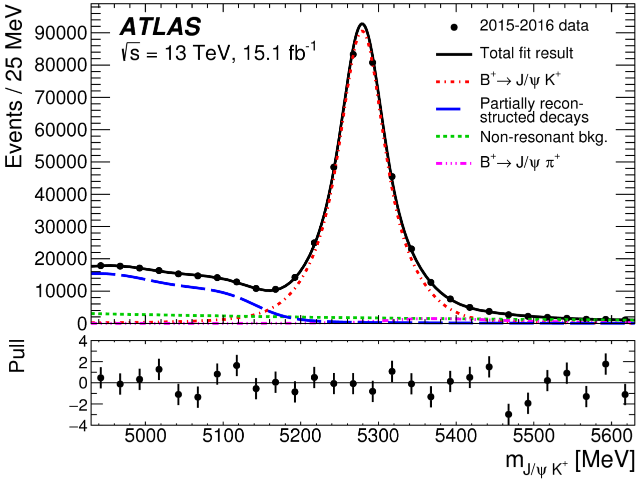
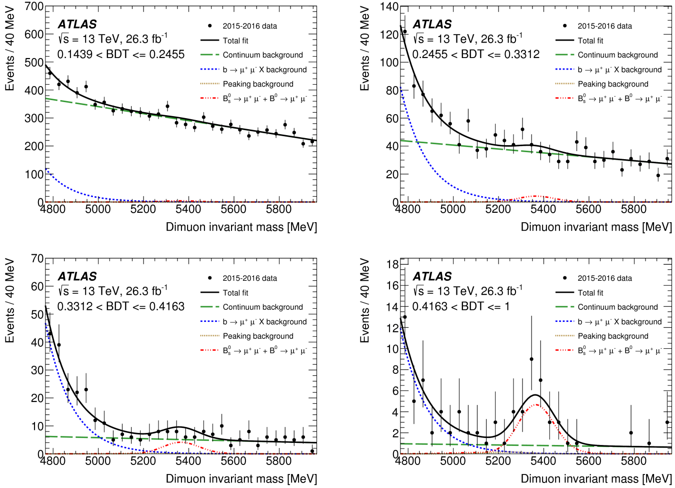
Back-up Slides

- $B^{\pm}$ mass distribution:



- Simultaneous ML binned fit in four BDT bins:



CP Violation and Lifetime Measurement: Parameters of Interest

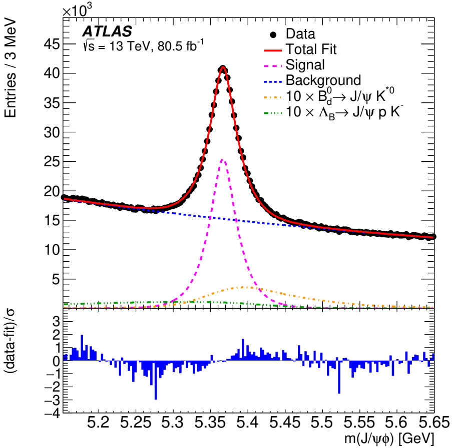
- Unbinned maximum likelihood fit performed on the combined data samples extracting parameters of interest
  - textitCP-violating phase ϕ_s
  - The average decay width Γ_s and the decay width difference $\Delta\Gamma_s$
  - The *CP*-state amplitudes at $t = 0$: $|A_0(0)|^2$, $|A_\perp(0)|^2$, $|A_{||}(0)|^2$, $|A_S(0)|^2$

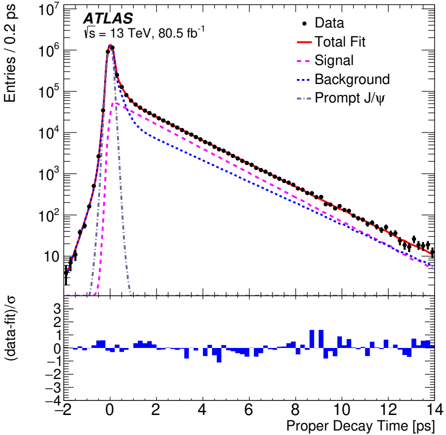
$$|A_0(0)|^2 + |A_\perp(0)|^2 + |A_{||}(0)|^2 = 1$$

  - The strong phases $\delta_\perp$, $\delta_{||}$, $\delta_0 = 0$, δ_S
  - ATLAS sensitive to $\delta_\perp$, $\delta_{||}$ and $\delta_S - \delta_\perp$
- No direct *CP* violation assumed
- $\Delta m_s = |m_L - m_H|$ value fixed to PDG: $\Delta m_s = 17.77\ \mathrm{ps}^{-1}$
- Opposite side tagging (OST) used to identify initial flavour of B_s^0

CP Violation and Lifetime Measurement: Results

- Projections of mass $m(J/\psi\phi)$, lifetime t and three transversity angles $\Omega(\psi_T, \phi_T, \theta_T)$
- Combinatorial background for angular distribution use Legendre polynomials from sidebands





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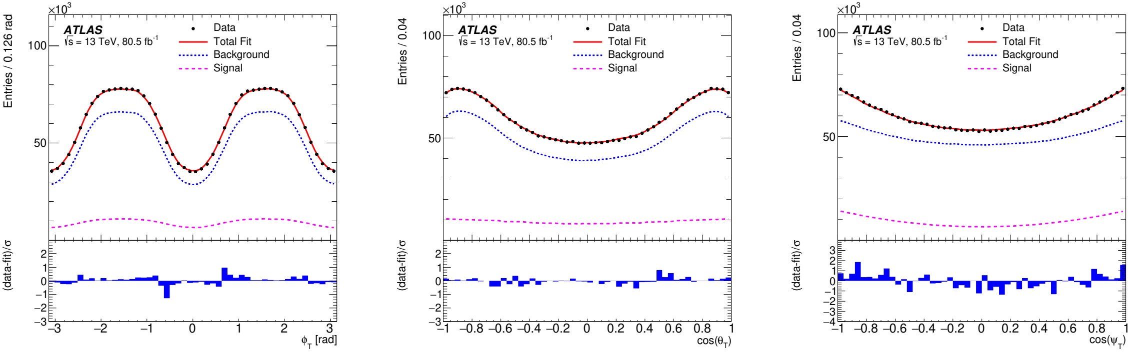

- Extensive systematic study was performed
- Here is the list of the major contributions to the total systematics:
    - **Flavour tagging:** calibration, $B_s^0 - B^{\pm}$ MC difference and dependencies on the pile-up distribution
    - **Fit bias:** fit stability is validated by the pseudo-experiments with default fit results
    - **Background angles model:** varying the bin boundaries, invariant mass window and sideband definition
    - **Best candidate selection:** statistically equivalent sample is created where all candidates in the event are retained
    - **Angular acceptance method:** different acceptance functions are calculated using different numbers of p_{T} bins as well as different widths and central values of the bins

	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
ID alignment	0.8	0.2	0.5	< 0.1	< 0.1	< 0.1	11	7.2	< 0.1
Acceptance	0.5	0.3	< 0.1	1.0	0.9	2.9	37	64	8.6
Time efficiency	0.2	0.2	0.5	< 0.1	< 0.1	0.1	3.0	5.7	0.5
Best candidate selection	0.4	1.6	1.3	0.1	1.0	0.5	2.3	7.0	7.4
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 window	9.3	3.3	< 0.1	0.4	0.8	0.4	17	8.6	1.8
Choice of sidebands intervals	0.4	0.1	0.1	0.3	0.3	1.3	4.4	7.4	2.3
Dedicated backgrounds:									
B_d^0	2.6	1.1	< 0.1	0.2	3.1	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	8.0	15	37
Fit bias	5.7	1.3	1.2	1.3	0.4	1.1	3.3	19	0.3
Total	22	4.3	2.2	2.3	3.8	4.6	55	88	39

Systematic uncertainties

Solution a:

	$\Delta\Gamma$	Γ_s	$\lvert A_{\parallel}(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\lvert A_S(0)\rvert^2$	$\delta_{\parallel}$	$\delta_{\perp}$	$\delta_{\perp} - \delta_S$
ϕ_s	−0.080	0.017	−0.003	−0.004	−0.007	0.007	0.004	−0.007
$\Delta\Gamma$	1	−0.586	0.090	0.095	0.051	0.032	0.005	0.020
Γ_s		1	−0.125	−0.045	0.080	−0.086	−0.023	0.015
$\lvert A_{\parallel}(0)\rvert^2$			1	−0.341	−0.172	0.522	0.133	−0.052
$\lvert A_0(0)\rvert^2$				1	0.276	−0.103	−0.034	0.070
$\lvert A_S(0)\rvert^2$					1	−0.362	−0.118	0.244
$\delta_{\parallel}$						1	0.254	−0.085
$\delta_{\perp}$							1	0.001

Solution b:

	$\Delta\Gamma$	Γ_s	$\lvert A_{\parallel}(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\lvert A_S(0)\rvert^2$	$\delta_{\parallel}$	$\delta_{\perp}$	$\delta_{\perp} - \delta_S$
ϕ_s	−0.084	0.019	−0.011	−0.003	−0.006	0.007	0.005	−0.006
$\Delta\Gamma$	1	−0.586	0.090	0.096	0.057	−0.029	−0.010	0.021
Γ_s		1	−0.116	−0.048	0.071	0.070	0.017	0.015
$\lvert A_{\parallel}(0)\rvert^2$			1	−0.338	−0.110	−0.444	−0.106	−0.052
$\lvert A_0(0)\rvert^2$				1	0.269	0.080	0.017	0.070
$\lvert A_S(0)\rvert^2$					1	0.291	0.060	0.251
$\delta_{\parallel}$						1	0.235	0.097
$\delta_{\perp}$							1	0.056

CP Violation Measurement: Angular analysis

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

CP Violation Measurement: Using Tag Information in B_s^0 Fit

- Opposite side lepton or jet, with tracks in cone $\Delta R < 0.5$

$$Q = \frac{\sum_i^{Ntracks} q^i (p_\mathrm{T}^i)^\kappa}{\sum_i^{Ntracks} (p_\mathrm{T}^i)^\kappa}$$

- Events separated - discrete contribution (cone charge +1 or -1) and continuous contribution
- By using calibration curves: we get the B_s^0 tag probability
- Fractions of events f_{+1} and f_{-1} with charges +1 and -1, respectively, are determined separately for signal and background
- Remaining fraction of events, $1 - f_{+1} - f_{-1}$, constitute the continuous part

Tag Method	Signal		Background	
	f_{+1}	f_{-1}	f_{+1}	f_{-1}
Tight μ	0.073 ± 0.005	0.081 ± 0.006	0.051 ± 0.001	0.053 ± 0.001
Medium e	0.18 ± 0.01	0.16 ± 0.01	0.159 ± 0.003	0.161 ± 0.003
Low-pt μ	0.120 ± 0.008	0.125 ± 0.008	0.074 ± 0.001	0.080 ± 0.001
Jets	0.038 ± 0.002	0.039 ± 0.002	0.0324 ± 0.0004	0.0323 ± 0.0004

CP Violation Measurement: Using Tag Information in B_s^0 Fit

- Opposite side lepton or jet, with tracks in cone $\Delta R < 0.5$

$$Q = \frac{\sum_i^{Ntracks} q^i (p_{\mathrm{T}}^i)^\kappa}{\sum_i^{Ntracks} (p_{\mathrm{T}}^i)^\kappa}$$

- Events separated - discrete contribution (cone charge $+1$ or -1) and continuous contribution
- By using calibration curves: we get the B_s^0 tag probability
- Fractions of events f_{+1} and f_{-1} with charges $+1$ and -1, respectively, are determined separately for signal and background
- Remaining fraction of events, $1 - f_{+1} - f_{-1}$, constitute the continuous part

Tag method	Signal	Background
Tight μ	0.0400 ± 0.0006	0.0316 ± 0.0001
Electron	0.0187 ± 0.0004	0.01480 ± 0.0001
Low-pT μ	0.0291 ± 0.0005	0.0264 ± 0.0001
Jets	0.144 ± 0.001	0.1196 ± 0.0002
Untagged	0.767 ± 0.003	0.8077 ± 0.0005

CP Violation Measurement: Tagging