ATLAS EXPERIMENT

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ATLAS Measurements of CP-Violation and Rare Decays Processes with Beauty Mesons

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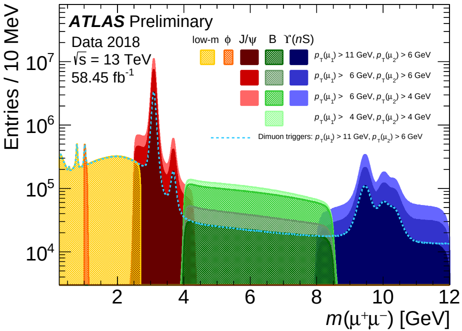
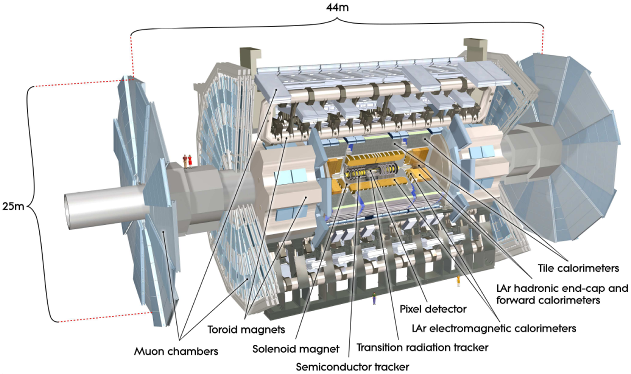
FACULTAS MATHEMATICA PHYSICAQUE

B-Physics at ATLAS

- ATLAS Run 2: $139\,\text{fb}^{-1}$ of pp collisions at $\sqrt{s} = 13\,\text{TeV}$ collected in 2015-2018
- Producing 2.5 M $b\bar{b}$ pairs/second, B_s, B_c, Λ_b, etc. available
- Program focused mostly on muonic final states, fully reconstructable
- Typical trigger: low-p_T di-muons at low invariant mass, using information from tracker and muon detectors
- B-physics trigger rate up to $\sim 200\,\text{Hz}$





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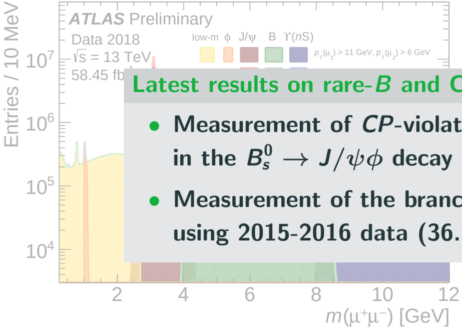
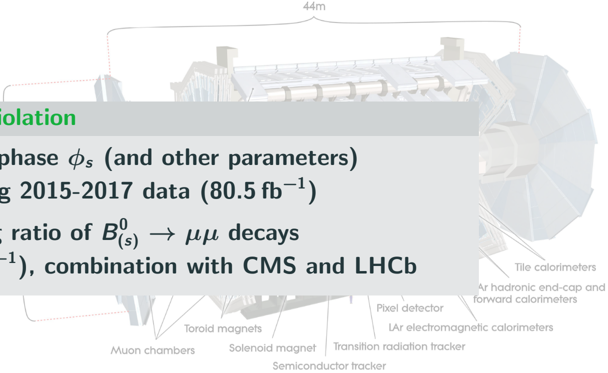




Latest results on rare-B and CP-violation

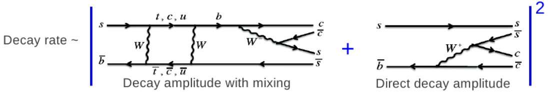
- **Measurement of CP-violating phase ϕ_s (and other parameters) in the $B_s^0 \to J/\psi\phi$ decay using 2015-2017 data ($80.5\,\text{fb}^{-1}$)**
- **Measurement of the branching ratio of $B_{(s)}^0 \to \mu\mu$ decays using 2015-2016 data ($36.2\,\text{fb}^{-1}$), combination with CMS and LHCb**

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

Eur. Phys. J. C 81 (2021) 342

CPV in $B_s^0 \to J/\psi\phi$ and the measurement

- Interference of direct decay and decay with mixing into the same final state of $B_s^0 \to J/\psi\phi$ gives rise to time-dependent CP violation

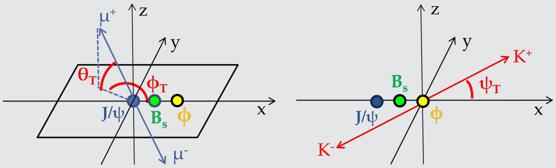


- In the Standard Model (SM) the ϕ_s is small: $\phi_s \simeq -2\beta_s = -0.03696^{+0.00072}_{-0.00082}$ rad
- New Physics (NP) could contributed to the mixing box diagrams, potentially enlarging ϕ_s

- Whole system described by:
  - weak phase ϕ_s and direct-CPV parameter λ
  - CP-state amplitudes (and their phases)
  - the mixing parameters Δm_s, $\Delta\Gamma_s$, Γ_s

Measurement

- Final state: admixture of CP-odd ($L = 1$) and CP-even ($L = 0, 2$) states
- Distinguishable through time-dependent angular analysis: $\frac{d^4\Gamma}{dt\ d\Omega} = \sum_{k=1}^{10} \mathcal{O}^{(k)}(t) g^{(k)}(\theta_T, \psi_T, \phi_T)$
- Analyzing signal final state $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$
- S-wave decay $B_s^0 \to J/\psi K^+K^-$ contribution included in the differential decay rate

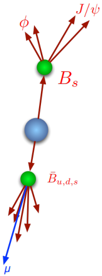


Opposite-side flavour tagging

- Use $b - \bar{b}$ correlation $\Longrightarrow$ initial B_s^0 flavour
  - $b(\bar{b}) \to l^{-(+)}$ transition
  - diluted by oscillations and $b \to c \to l$
- Key variables: charge of p_T-weighted tracks in cone $\Delta R(\phi, \eta)$ around the opposite side lepton

$$Q_x = \frac{\sum_i^{N \text{ tracks}} q_i \cdot (p_{\mathrm{T}i})^\kappa}{\sum_i^{N \text{ tracks}} (p_{\mathrm{T}i})^\kappa}$$

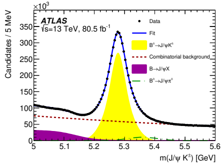
- Building per-candidate tag probability $P(B|Q)$



Four taggers

- **Muon**: tight-ID or low-p_T, $\kappa = 1.1$, $\Delta R = 0.5$
- **Electron**: $p_T(e) > 0.5$ GeV, $\kappa = 1.0$, $\Delta R = 0.5$
- **Jet**: b-tagged jets, $\kappa = 1.1$, $\Delta R = 0.5$
- Search order based on best purity

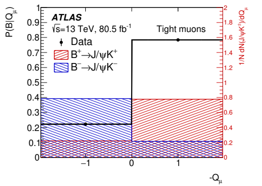
- Calibrated on self-tagged $B^\pm \to J/\psi K^\pm$ data

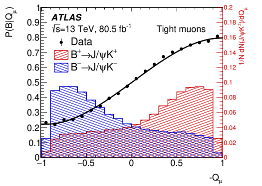


Tagging performance

ϵ_x = tag efficiency, D = 1 - 2× wrong-tag fraction, $T_x = \epsilon_x D^2$ = tagging power

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





Unbinned maximum likelihood fit

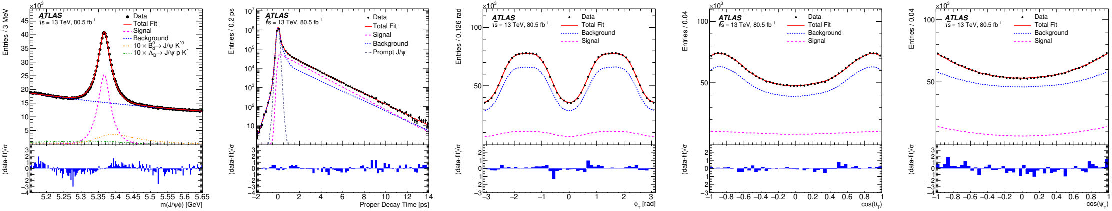
- An unbinned maximum likelihood (UML) fit performed in 10 D space

$$\ln \mathcal{L} = \sum_{i=1}^{N} \{ w_i \cdot \ln(f_\mathrm{s} \mathcal{F}_\mathrm{s} + f_\mathrm{s} f_{B^0} \mathcal{F}_{B^0} + f_\mathrm{s} f_{\Lambda_b} \mathcal{F}_{\Lambda_b} + (1 - f_\mathrm{s}(1 + f_{B^0} + f_{\Lambda_b}))\mathcal{F}_\mathrm{bkg}) \}$$

Observables

$\mathcal{F}_x(m_i, t_i, \sigma_{m_i}, \sigma_{t_i}(p_{\mathrm{T}_i}), \theta_T, \psi_T, \phi_T, P(B|Q_i))$

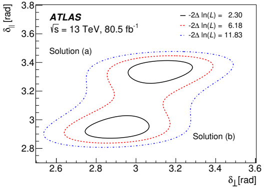
- Base B_s^0 decay observables: mass, time, angles
  - Conditional observables: per-candidate tagging Q_x and mass/time resolutions ($p_\mathrm{T}(B)$ dependent)
- Full time-angular PDF including S-wave
- Fixed parameters: Δm_s = PDG, direct CP $\lambda = 1$
- Trigger causing decay time inefficiency, modeled in MC



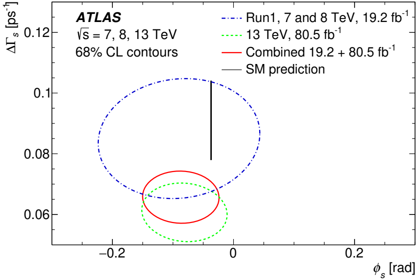
Results

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

- Two solutions in $\delta_\parallel - \delta_\perp$ plane, with negligible impact on other parameters



- Statistical (BLUE) combination with Run 1 result



- Almost 500 k signal candidates
- Weak phase ϕ_s as well as decay width difference $\Delta\Gamma_s$ compatible with Standard Model
- Dominant systematics on ϕ_s measurement from tagging
  - Accounting for pile-up dependence, calibration curves model and MC precision, "Punzi" PDFs variations, difference between $B^\pm$ and B_s^0 kinematics

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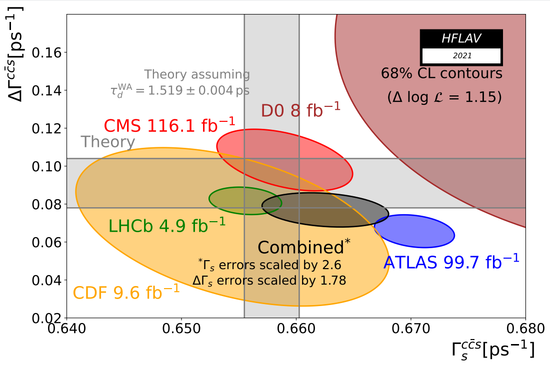
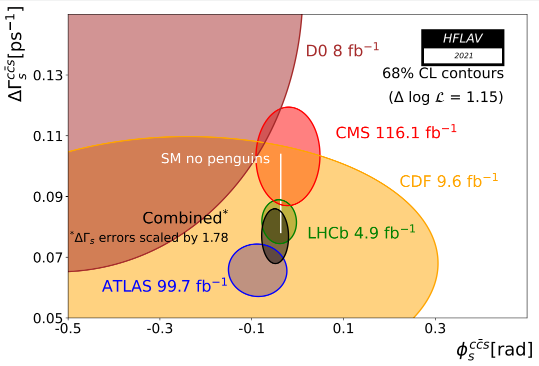
- Statistical (BLUE) combination

Comparison with other experiments





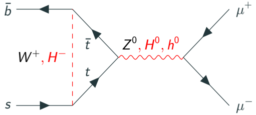
- Accounting for pile-up dependence, calibration curves model and MC precision, "Punzi" PDFs variations, difference between $B^{\pm}$ and B_s^0 kinematics

Study of the rare decays of B_s^0 and B^0 mesons into muon pairs using data collected during 2015 and 2016 with the ATLAS detector

JHEP 04 (2019) 098

Analysis of rare $B^0_{(s)} \to \mu\mu$ decays

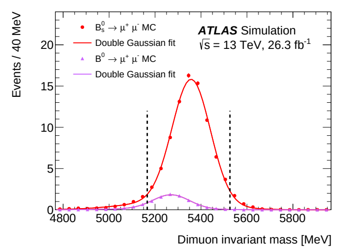
- FCNC in the SM proceeding via loop and box diagrams, and helicity suppressed $\implies \mathcal{B} \sim 10^{-9}$
- BSM can significantly contribute, modifying the branching ratio



Measurement

$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) = N_{d(s)} \cdot \frac{\mathcal{B}(B^\pm \to J/\psi K^\pm) \cdot \mathcal{B}(J/\psi \to \mu^+\mu^-)}{N_{J/\psi K^\pm} \cdot \frac{\epsilon_{\mu^+\mu^-}}{\epsilon_{J/\psi K^\pm}}} \cdot \frac{f_u}{f_{d(s)}}$$

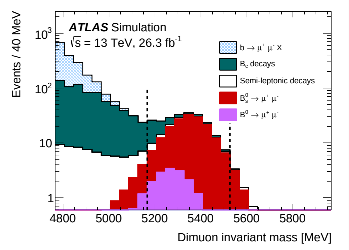
- $\mathcal{B}(B^0_{(s)} \to \mu\mu)$ measurement relative to $\mathcal{B}(B^\pm \to J/\psi K^\pm)$, $B^0_s \to J/\psi\phi$ as control channel
- Blinded signal di-muon invariant mass region
- BDT based background suppresion, trained on sidebands data
- Yields $N_{d(s)}$ and $N_{J/\psi K^\pm}$ obtained from UML fits to the mass spectra
- Relative reconstruction efficiencies estimated from MC (corrected for data-MC differences)
- Known branching ratios from PDG, $f_u/f_{d(s)}$ from HFLAV



Backgrounds

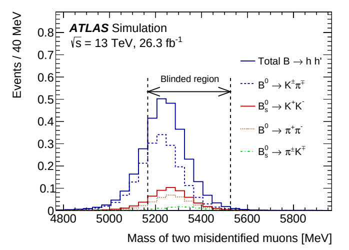
Partially reconstructed *b*-hadron decays

- Mostly in the low di-muon mass region
- Shape free in the mass fit



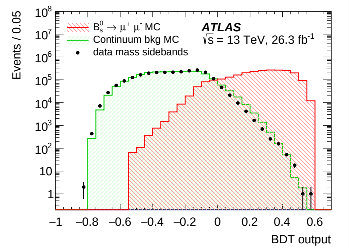
Peaking backgrounds

- Hadronic B_s^0 decays where hadrons are misidentified as muons
- Simulated and fixed in the mass fit

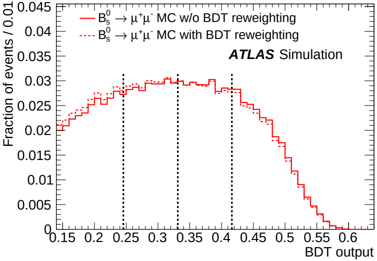


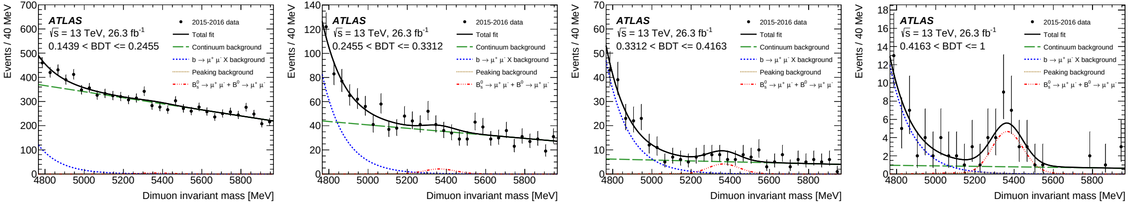
Continuum background

- Combinatorics of μ and uncorrelated hadron decays
- Reduced by BDT
- Linear shape constrained in the mass fit across BDT bins
- Systematics due to $B_c^\pm \to J/\psi\mu\nu$ and $B^0_{(s)}/\Lambda_b^0 \to h\mu\nu$ decays



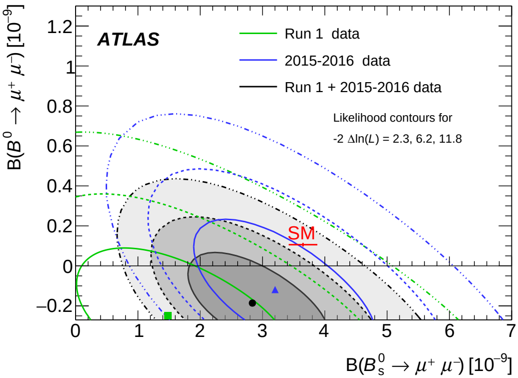
- BDT formed from 15 variables
  - kinematics, isolation, B-vertex separation from PV
- BDT output validated on reference $B^{\pm} \to J/\psi K^{\pm}$ and control $B_s^0 \to J/\psi\phi$ channels, observed difference applied as a correction to signal channel
- Signal region divided into four BDT bins with constant signal efficiency
- Simultaneous extraction of $B_s^0 \to \mu\mu$ and $B^0 \to \mu\mu$ yields from unbinned maximum likelihood fit to di-muon mass distributions in the four BDT bins





Results

- Contours obtained using Neyman construction



Standard Model

$\mathcal{B}(B_s^0 \to \mu\mu) = (3.66 \pm 0.14) \times 10^{-9}$

$\mathcal{B}(B^0 \to \mu\mu) = (1.03 \pm 0.05) \times 10^{-10}$

ATLAS 2015 + 2016 data

$\mathcal{B}(B_s^0 \to \mu\mu) = (3.2^{+1.1}_{-1.0}) \times 10^{-9}$

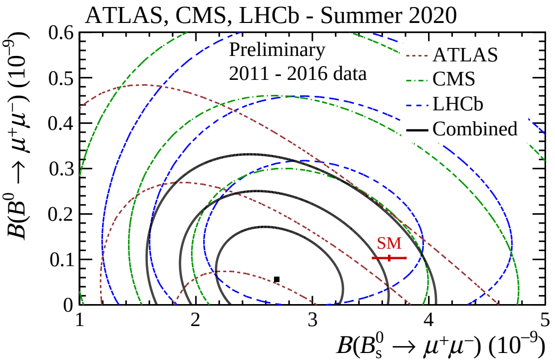
$\mathcal{B}(B^0 \to \mu\mu) < 4.3 \times 10^{-10}$ at 95% CL

ATLAS Run 1 + 2015 + 2016 data

$\mathcal{B}(B_s^0 \to \mu\mu) = (2.8^{+0.8}_{-0.7}) \times 10^{-9}$

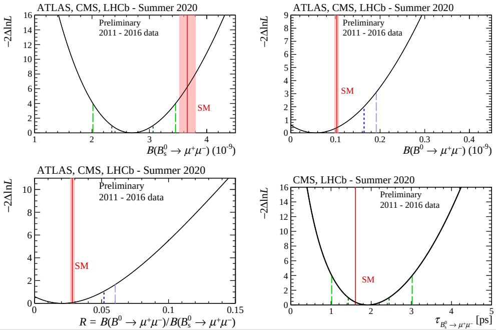
$\mathcal{B}(B^0 \to \mu\mu) < 2.1 \times 10^{-10}$ at 95% CL

- Combined measurement compatible with SM at 2.4 σ
- Statistic uncertainties dominate
- Largest systematics contribution from di-muon mass fit procedure



- Combining binned 2D profile likelihoods, f_s/f_d the only source of correlation between experiments

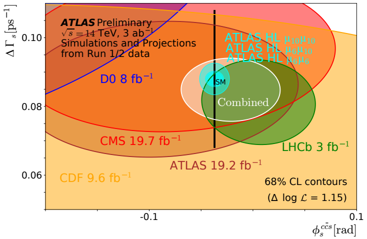
	LHC	SM
$\mathcal{B}(B_s^0 \to \mu\mu) \times 10^{-9}$	$2.69^{+0.37}_{-0.35}$	3.66 ± 0.14
$\mathcal{B}(B^0 \to \mu\mu) \times 10^{-10}$	< 1.9 at 95% CL	1.03 ± 0.05
Ratio of above	< 0.052 at 95% CL	0.0281 ± 0.0016
$\tau_{B_s^0 \to \mu\mu}$ [ps] (LHCb+CMS)	$1.91^{+0.37}_{-0.35}$	1.609 ± 0.010



Summary

- Latest ATLAS measurements of *CP*-violation in $B_s^0 \to J/\psi\phi$ decay and branching ratio measurement of rare $B_{(s)}^0 \to \mu\mu$ decays compatible with Standard Model predictions
- Full Run 2 data analyses in progress
  - CPV measurement releasing Δm_s and direct-*CP* λ, improvements in tagging and fit model
  - Rare decays including $B_s^0 \to \mu\mu$ lifetime analysis
- Program continuation in Run 3 and HL-LHC
  - HL-LHC projections CERN Yellow Report Monograph 7 (2019) pp. 1–1418

$B_s^0 \to J/\psi\phi$ HL-LHC projections



$B_s^0 \to \mu\mu$ full Run 2 and HL-LHC projections