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

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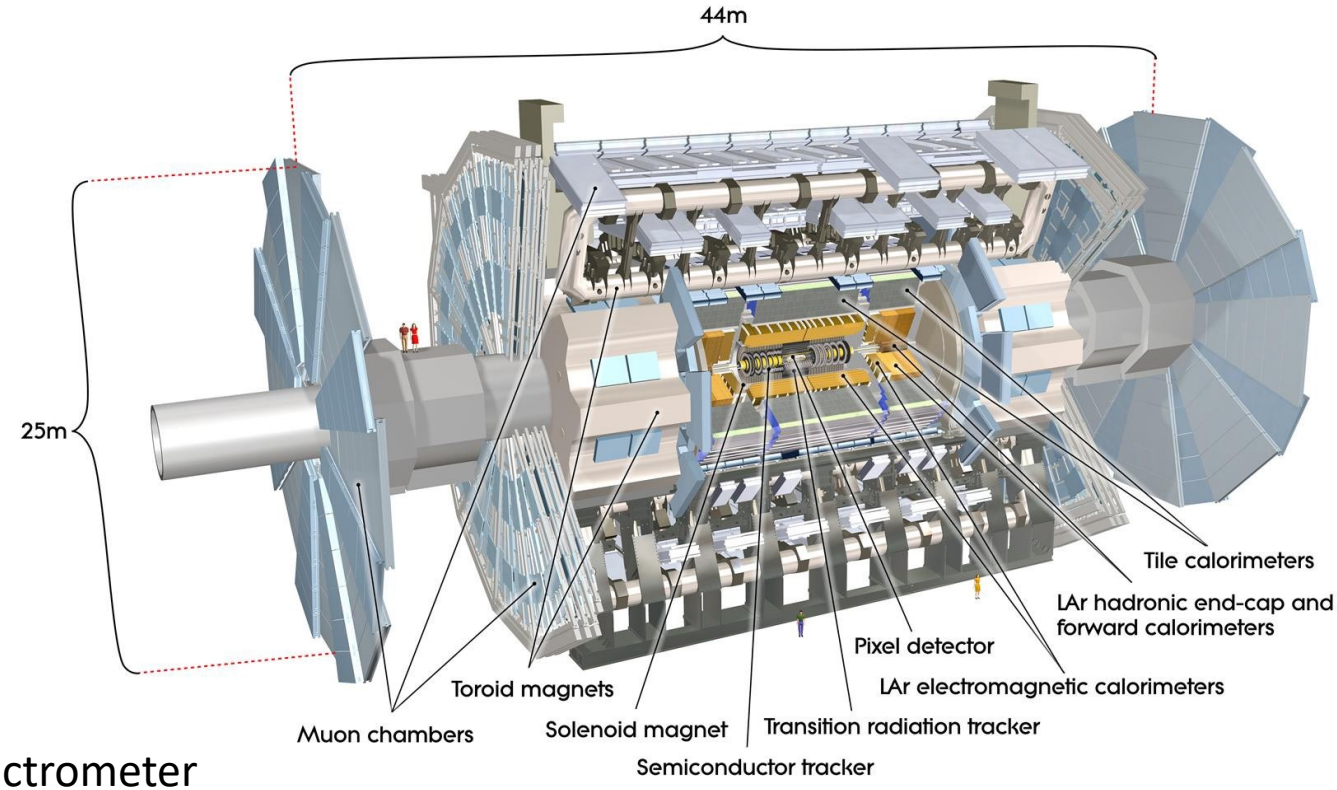
On behalf of the ATLAS Collaboration

ICNFP 2021
Kolymvari, August 2021

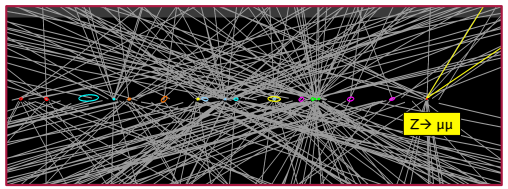
Outline

- ATLAS detector, (multi-) muon triggers
- CPV from J/ψϕ EPJC 81(2021) 342 80.5 fb^{-1} at 13 TeV, + 19.2fb^{-1} at 7 & 8 TeV
- Rare B decays in ATLAS and the LHC: JHEP 04 (2019) 098; ATLAS-CONF-2020-049, 26.3fb^{-1} of 2015-2016 13 TeV data
- Summary and perspectives

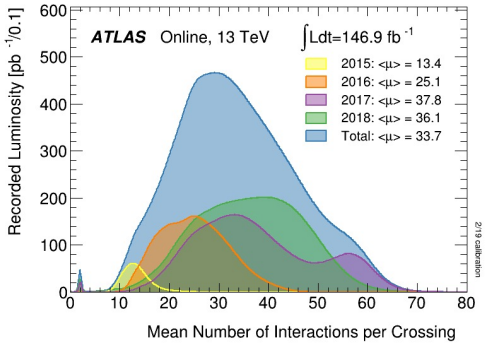
The ATLAS detector at LHC



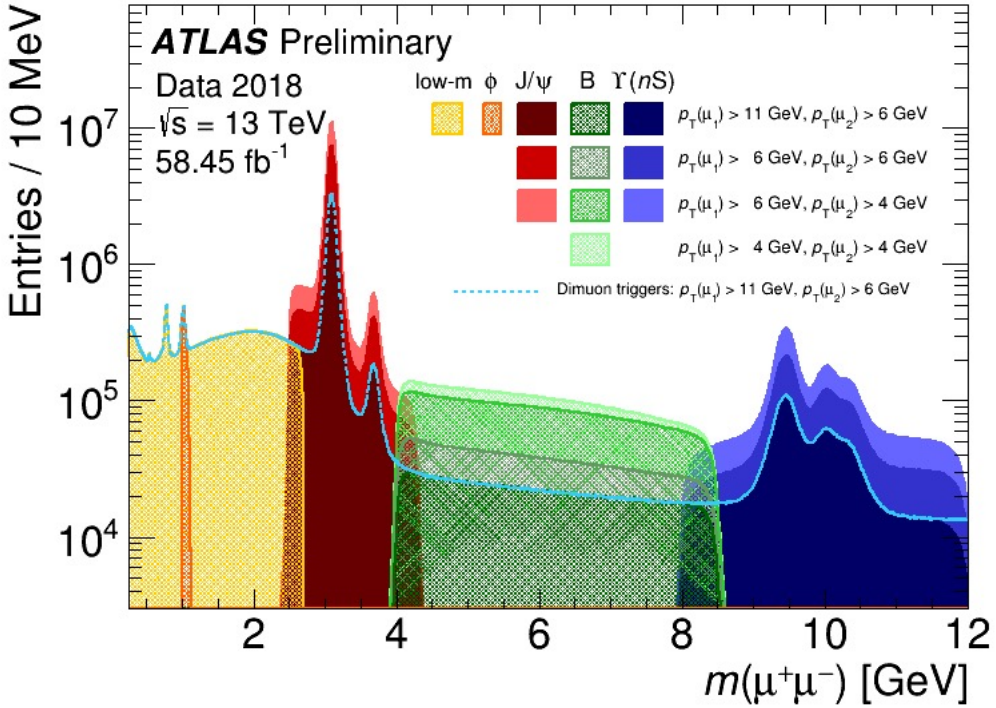
Muon Spectrometer
Triggering $|\eta| < 2.4$
Precise tracking $|\eta| < 2.7$

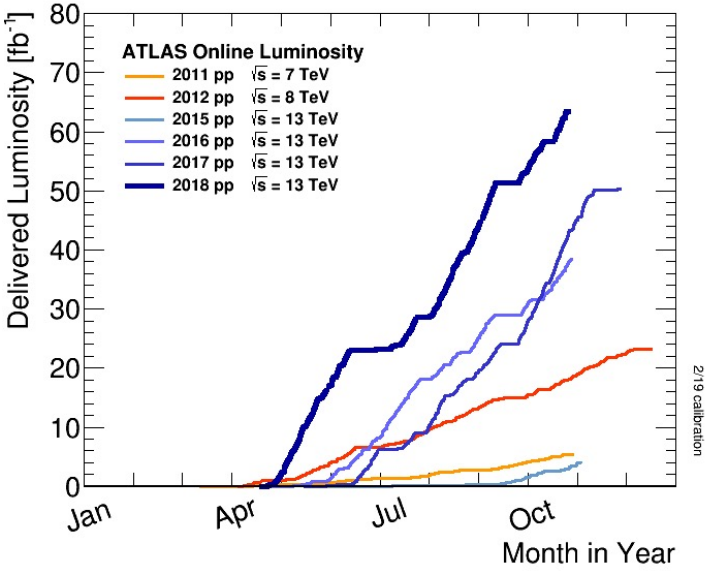


ID: pT > 0.4GeV, $|\eta| < 2.5$
Run 2: IBL gives 25% improvement in time resolution (~0.6ps)
Time and mass resolutions stable despite increasing pile-up



Muon and dimuon triggers for B





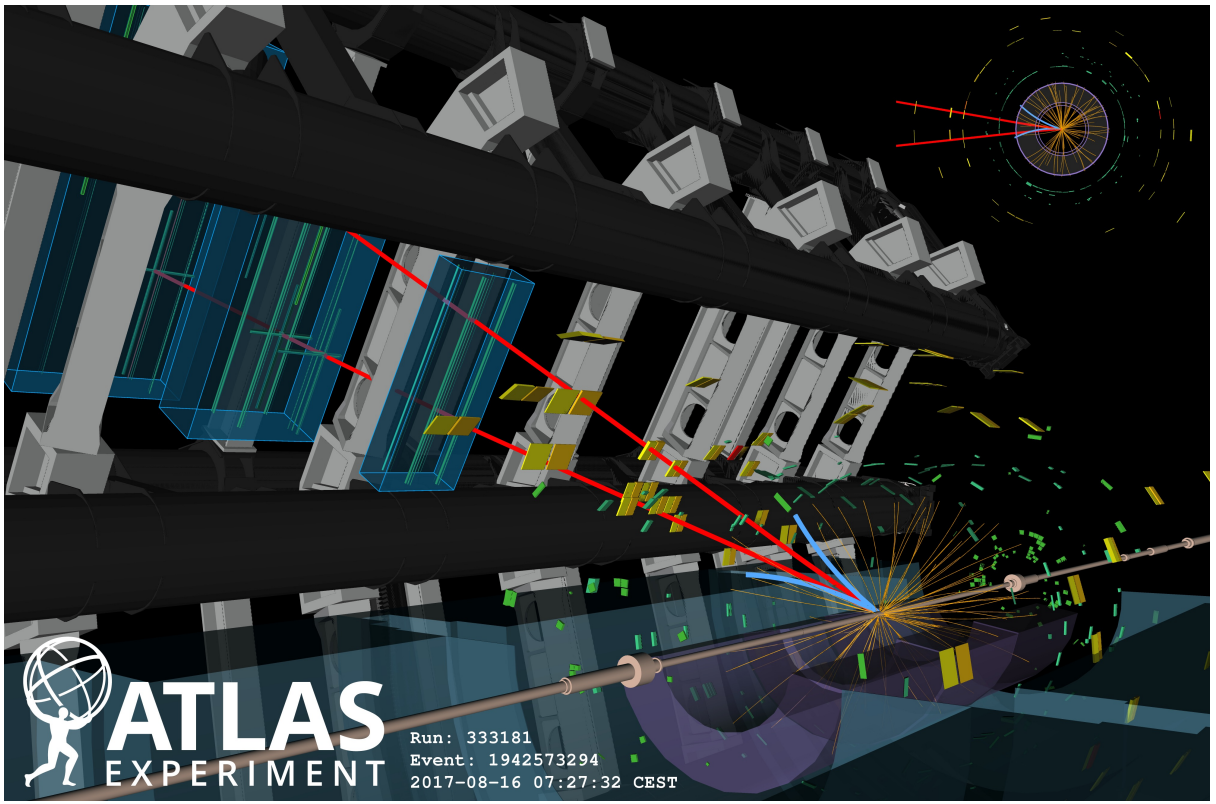
Total of 139 fb^{-1} in run 2 and 25 fb^{-1} in run 1

Use Muon triggers for these analyses:

- **Typically 2 muons, threshold p_T > 4 or 6 GeV, $|\eta| < 2.4$**

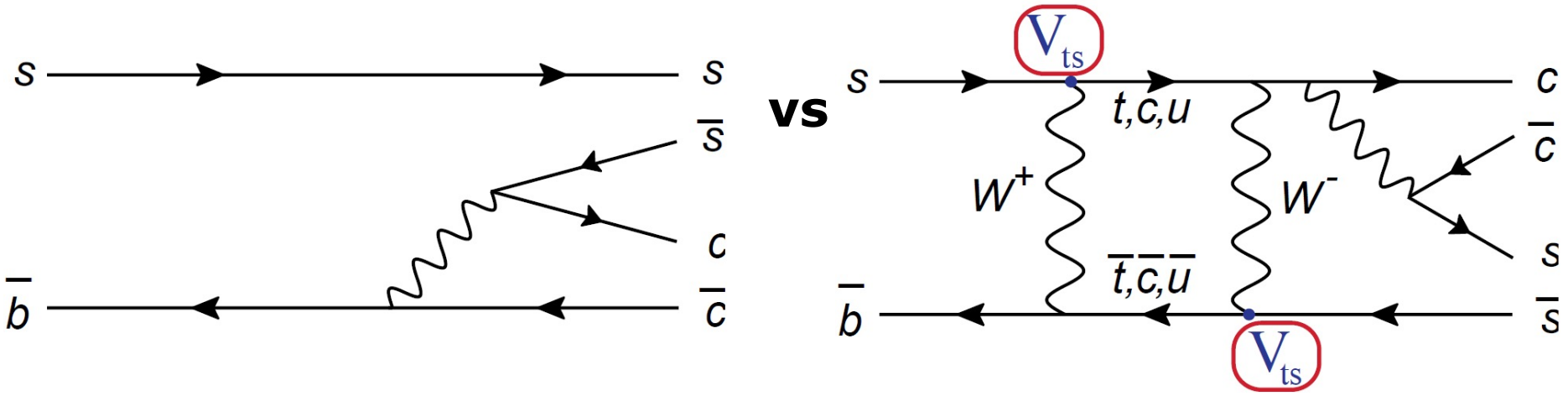
CPV in $B_s \rightarrow J/\psi\varphi$

- Eur. Phys. J. C81 (2021) 342, arXiv:2001.07115



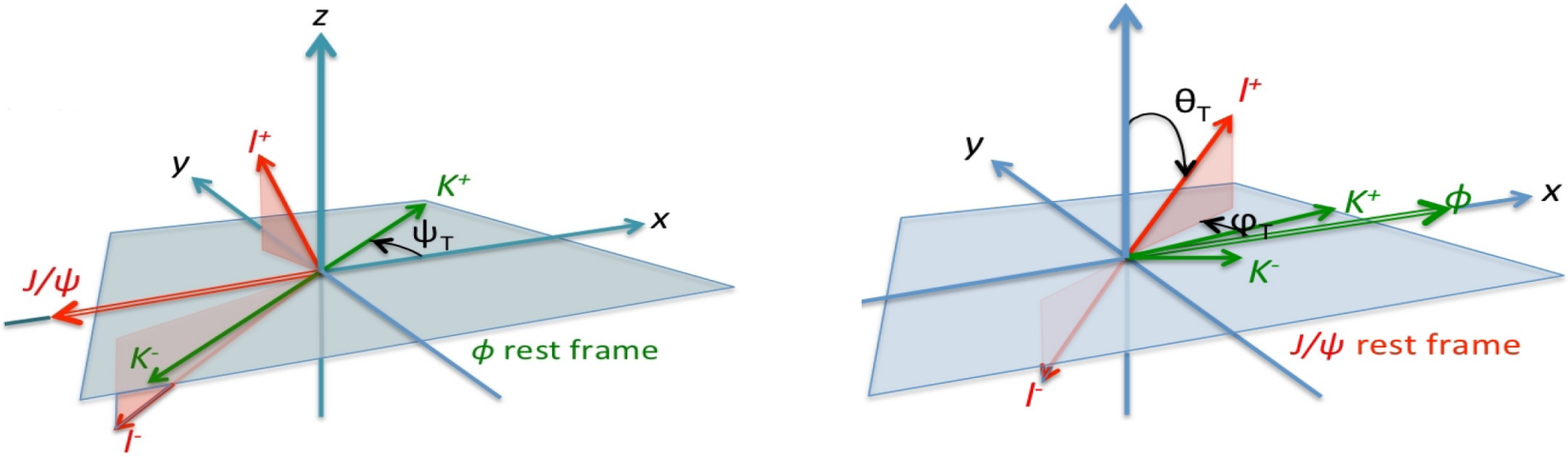
CPV in $B_s \rightarrow J/\psi\phi$

- $B_s \rightarrow J/\psi\phi$ measures CP-violation phase φ_s and sensitive to new physics
- In SM, $\varphi_s \simeq 2\ \arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)$ and well constrained
  - $\Phi_s = -0.03700 \pm 0.00104$ rad UTfit arXiv: hep-ph/0606167 [hep-ph]
  - $\Phi_s = -0.03696\ ^{+\ 0.00072}_{-\ 0.00082}$ rad CKMFitter Phys. Rev. D91.073007
- LHC combined 2021 $\Phi_s = -0.050 \pm 0.019$ rad still not at same level of precision (but more Run 2 data to be added)
- Also probes $\Delta\Gamma_s = \Gamma^H - \Gamma^L$, widths of the two mass eigenstates: good test of theory



CPV in $B_s \rightarrow J/\psi\varphi$

- Interference between mixing and unmixed decays
- (Pseudoscalar) $B_s \rightarrow$ Vector-Vector decay, three spin states
- L=0,2 (A_0, $A_\parallel$) CP-even L=1 ($A_\perp$) CP-odd
- Time dependent angular analysis to disentangle contributions



- Non-resonant $B_s \rightarrow J/\psi K^+K^-$ contributes, interferes with our reconstructed mode $B_s \rightarrow J/\psi(l^+l^-)\varphi(K^+K^-)$

$B_s \rightarrow J/\psi\phi$ Likelihood

- Unbinned likelihood fit
- Signal
- B^0, Λ_b background
- Background

$$\Omega = (\psi_T, \theta_T, \phi_T)$$

$$\ln \mathcal{L} = \sum_{i=1}^{N} \{ w_i \cdot \ln(f_s \cdot \mathcal{F}_s(m_i, t_i, \sigma_m, \sigma_t, \Omega_i, P(B|Q), p_{T_i}) + f_s \cdot f_{B_d^0} \cdot \mathcal{F}_{B_d^0}(m_i, t_i, \sigma_m, \sigma_t, \Omega_i, P(B|Q), p_{T_i}) + f_s \cdot f_{\Lambda_b} \cdot \mathcal{F}_{\Lambda_b}(m_i, t_i, \sigma_m, \sigma_t, \Omega_i, P(B|Q), p_{T_i}) + (1 - f_s \cdot (1 + f_{B^0} + f_{\Lambda_b})) \cdot \mathcal{F}_{bkg}(m_i, t_i, \sigma_m, \sigma_t, \Omega_i, P(B|Q), p_{T_i})) \}$$

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

Δm_s fixed to PDG

Observables

Basic: m_i, t_i, Ω_i

Per candidate

- Resolutions σ_{mi} σ_{ti}
- Tagging probability/method P(B|Q)

Flavour tagging

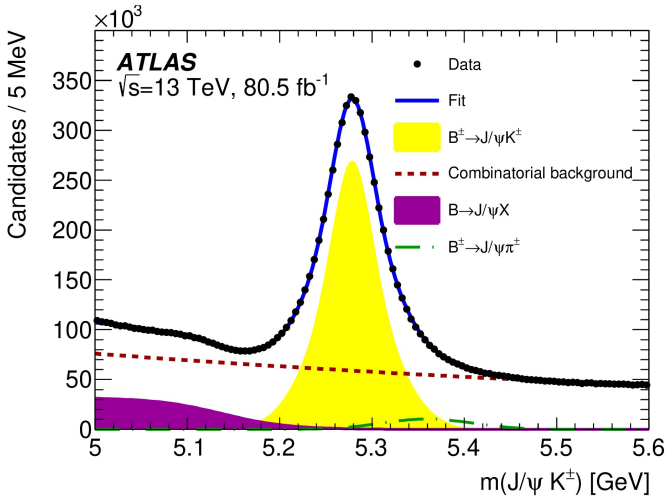
Tag if quark/antiquark on production using the other parton in the $b\bar{b}$ pair

Use muon or electron

- b → l transitions are clean
- b → c → l and B^0 oscillations dilute

Jet Charge

- Use tracks in tagged b-jet when no l
- Calibrate using $B^{\pm} \rightarrow J/\psi K^{+}$

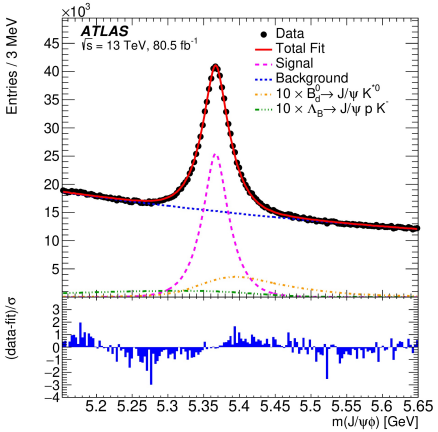


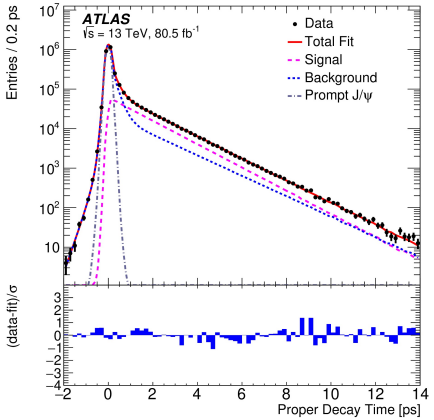
Tag method	Efficiency [%]	Effective Dilution [%]	Tagging Power [%]
Tight muon	4.50 ± 0.01	43.8 ± 0.2	0.862 ± 0.009
Electron	1.57 ± 0.01	41.8 ± 0.2	0.274 ± 0.004
Low-p_T muon	3.12 ± 0.01	29.9 ± 0.2	0.278 ± 0.006
Jet	5.54 ± 0.01	20.4 ± 0.1	0.231 ± 0.005
Total	14.74 ± 0.02	33.4 ± 0.1	1.65 ± 0.01

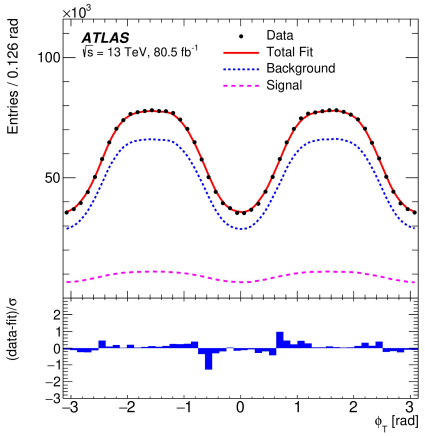
Efficiency, $\epsilon = \frac{N_{tagged}}{N_{B\ cand}}$ Dilution, $D = (1 - 2w)$, w is mistag probability

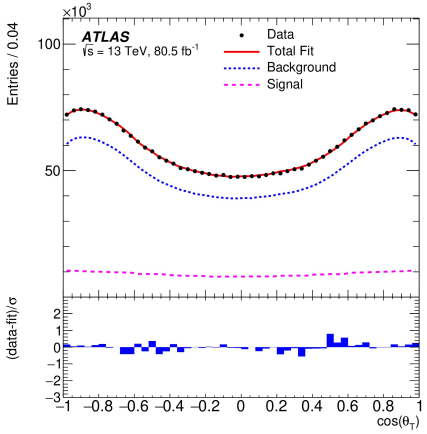
Tag power = ϵD^2

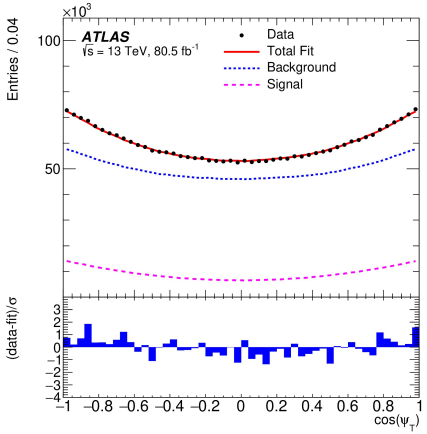
Projections of 2015-2017 results







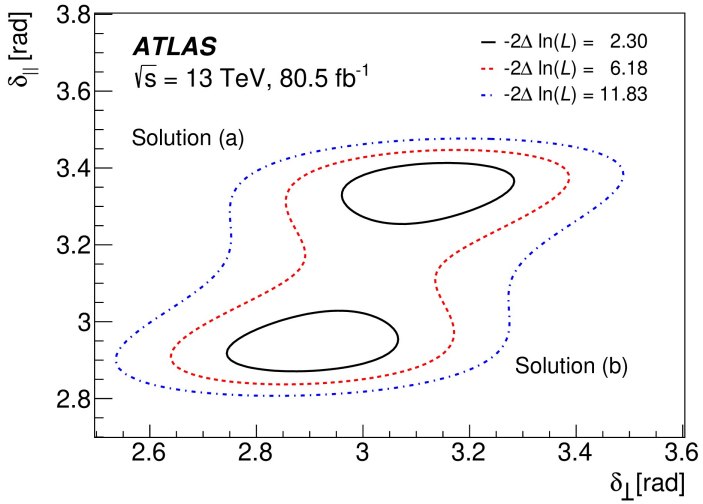




Results 2015-2018 data

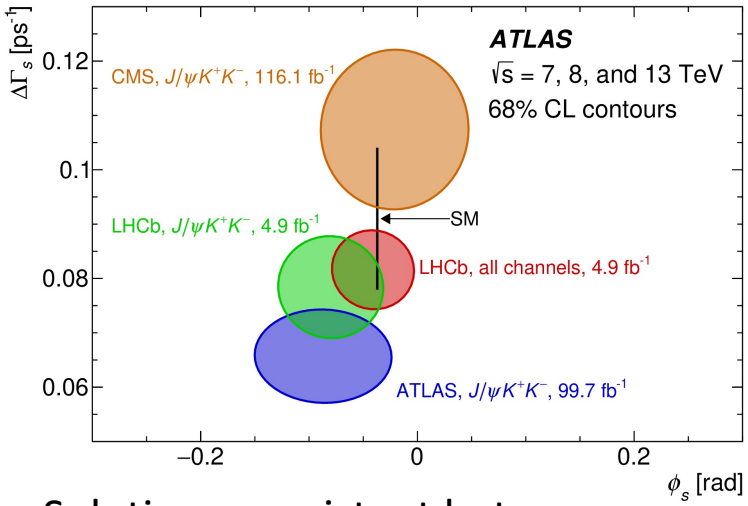
Single favored solution
except for strong phases $\delta_\perp, \delta_\parallel$ with two local minima

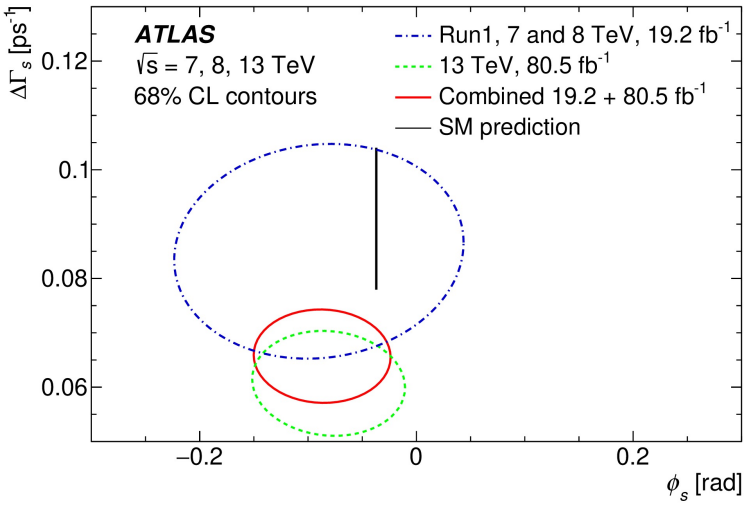
$-2\Delta \ln\{L\} = 0.03$ favouring solution (a)



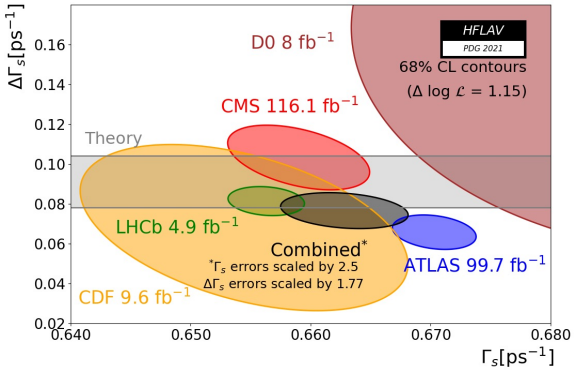
Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	−0.081	0.041	0.022
$\Delta\Gamma_s$ [ps^{-1}]	0.0607	0.0047	0.0043
Γ_s [ps^{-1}]	0.6687	0.0015	0.0022
$\lvert A_\parallel(0)\rvert^2$	0.2213	0.0019	0.0023
$\lvert A_0(0)\rvert^2$	0.5131	0.0013	0.0038
$\lvert A_S(0)\rvert^2$	0.0321	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

Combination with Run 1 result





Solutions consistent between runs
Also with CMS, LHCb and the SM
Competitive single measurements of $\Gamma_s, \Delta\Gamma_s$ and helicity parameters



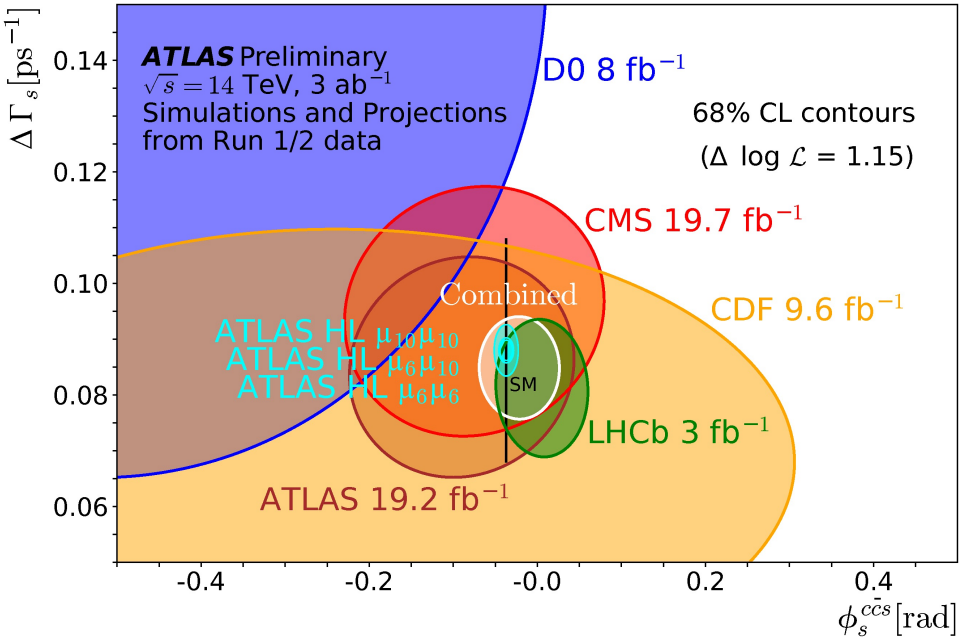
Parameter	Solution (a) Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	−0.087	0.036	0.021
$\Delta\Gamma_s$ [ps^{-1}]	0.0657	0.0043	0.0037
Γ_s [ps^{-1}]	0.6703	0.0014	0.0018
$\lvert A_\parallel(0)\rvert^2$	0.2220	0.0017	0.0021
$\lvert A_0(0)\rvert^2$	0.5152	0.0012	0.0034
$\lvert A_S\rvert^2$	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

$B_s \rightarrow J/\psi\phi$ prospects

Still 60fb^{-1} of 2018 data to be added

And beyond….

ATL-PHYS-PUB-2018-41

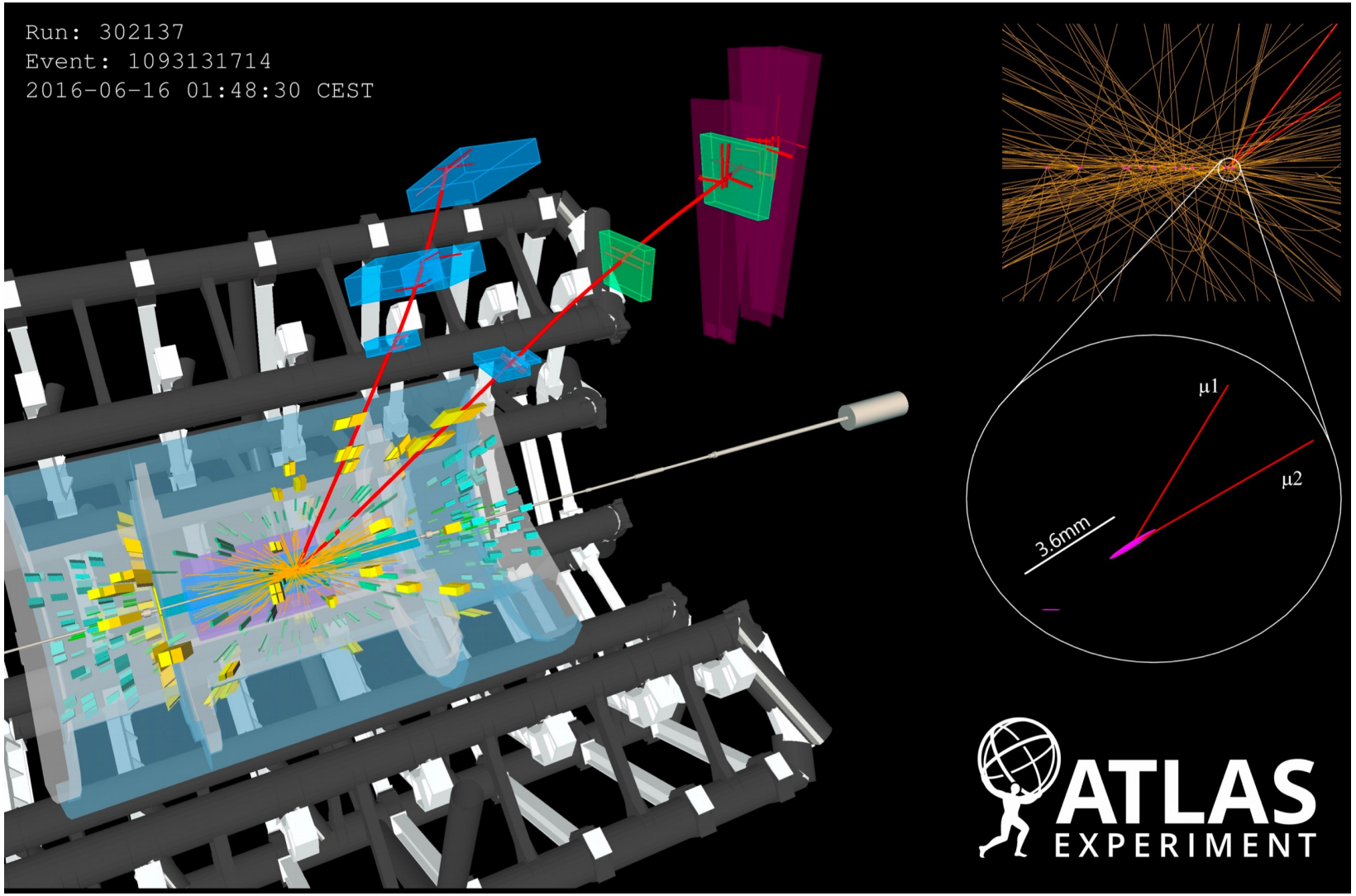


Run 3 data, then upgraded ID - ~20% improvement in time resolution

Three scenarios considered for triggers

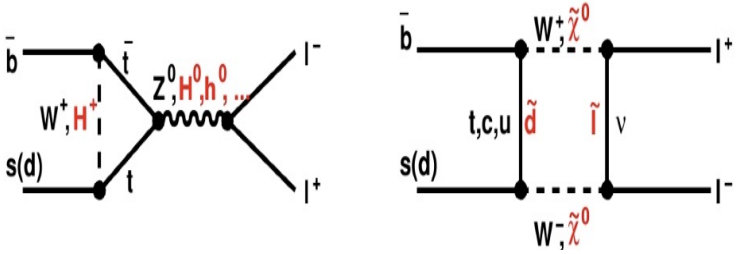
ϕ_s improved by factor of 4-9 on current result

Rare Decays - $B_s \rightarrow \mu\mu$



Rare Decays: $B_{(s)} \to \mu\mu$

- Rare decays sensitive to new physics through loops
  - **In SM $Br(B_s \to \mu\mu) \sim (3.2 \pm 0.2) \times 10^{-9}$**
  - **NP enhancement or suppression**



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \underbrace{\mathcal{B}(B^\pm \to J/\psi K^\pm \to \mu^+\mu^- K^\pm) \times \frac{f_u}{f_s}}_{\text{Relative production rate}} \times \frac{N_{\mu^+\mu^-}}{N_{J/\psi K^\pm}} \times \underbrace{\frac{A_{J/\psi K^\pm}}{A_{\mu^+\mu^-}} \times \frac{\varepsilon_{J/\psi K^\pm}}{\varepsilon_{\mu^+\mu^-}}}_{\text{Relative efficiency \& acceptance}}$$

$$= N_{\mu^+\mu^-} \times \boxed{\text{SES}}$$

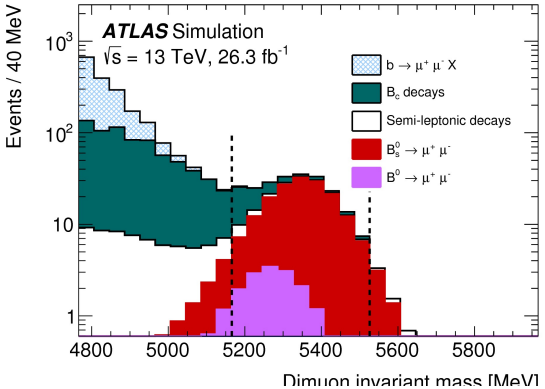
and similar for B^0

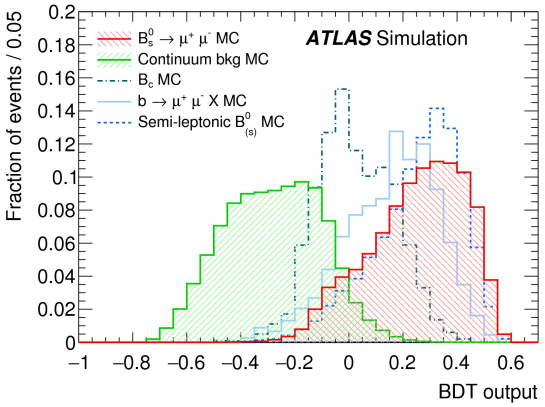
- Signal yield normalized to reference decay $B^\pm \to J/\psi K^\pm$
- SES: Single Event Sensitivity

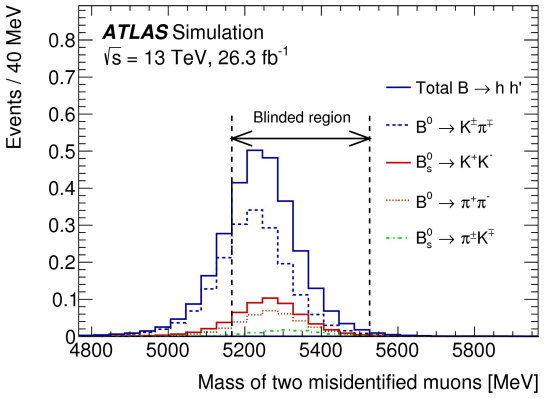
- Unbinned maximum likelihood fit to invariant mass of $J/\psi K^\pm$
- Used $26.3 fb^{-1}$ of 2015-2016 data
- Dimuon triggers with $p_T > 4$ or 6 GeV, L_{xy} cuts applied online

Background: $B_{(s)} \rightarrow \mu\mu$

- Continuum Background:
  - μ's produced independently from fragmentation/decay-chains of $b, \bar{b}$ quarks.
  - Reduced by boosted decision tree (BDT) with 15 variables
- Partially reconstructed decays
  - same side – cascades $b \rightarrow c\ \mu X \rightarrow s(d)\mu X'$
  - Same side vertex e.g. $B_s^0 \rightarrow K^* \mu^+\ \mu^-$, $B \rightarrow J/\psi \mu X, B_c \rightarrow J\ /\psi(\mu\mu)\mu\nu$
  - Semileptonic decay with misidentified hadron
- Peaking background
  - $B \rightarrow h^+h^-$, both misidentified as μ
    - Use tight μ criteria (calorimeter energy profile, matching to tracker)

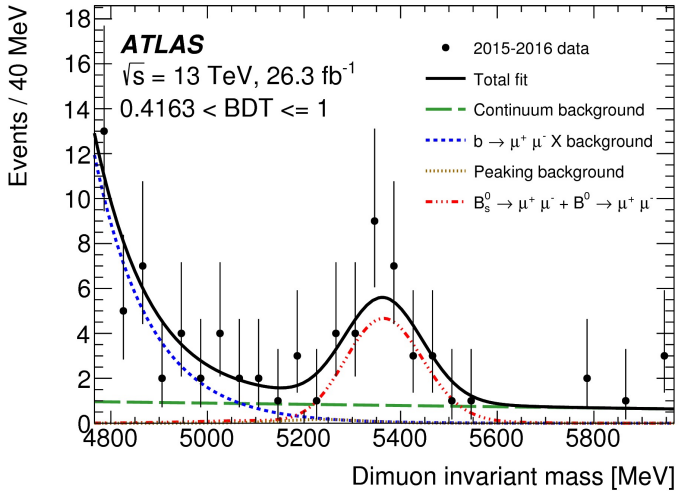




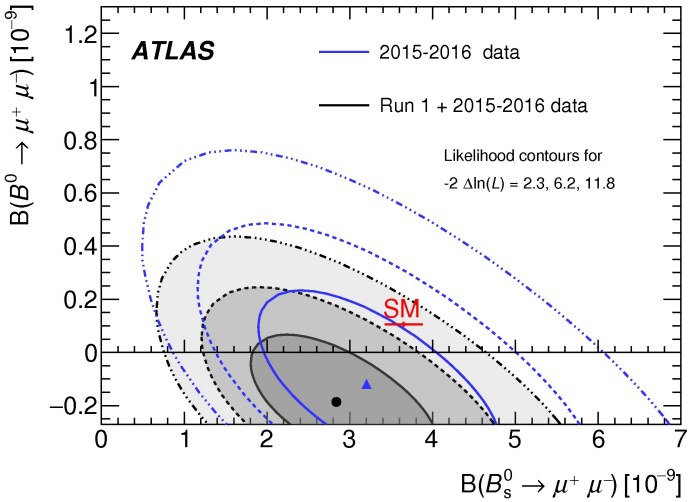


Signal extraction $B_{(s)} \to \mu\mu$

- Simultanious likelihood for to μμ mass in 4 equal signal efficiency BDT bins
- Signal model from MC, two double Gauss, centred on B_d and B_s masses
- Non-peaking backgrounds, single exponential from low mass sideband; peaking background from MC



- 2015-16: $N_s = 80 \pm 22$ and $N_d = -12 \pm 20$
- SM: $N_s = 91$ and $N_d = 10$



- Run 1 and Run 2 combined branching fractions compatible with SM at 2.4σ

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.8^{+0.8}_{-0.7}\right) \times 10^{-9} \text{ and } \mathcal{B}(B^0 \to \mu^+\mu^-) < 2.1 \times 10^{-10}$$

$B_{(s)} \rightarrow \mu\mu$ combination and prospects

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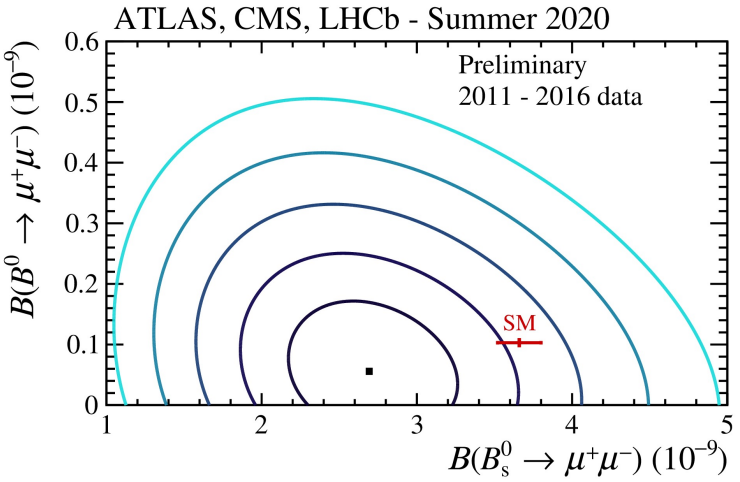
ATLAS, CMS and LHCb 2020

- Combination from binned 2D profile likelihood
  - Only f_d/f_s correlated
- Compatible with SM at 2.1σ
  - (Latest LHCb result not included)

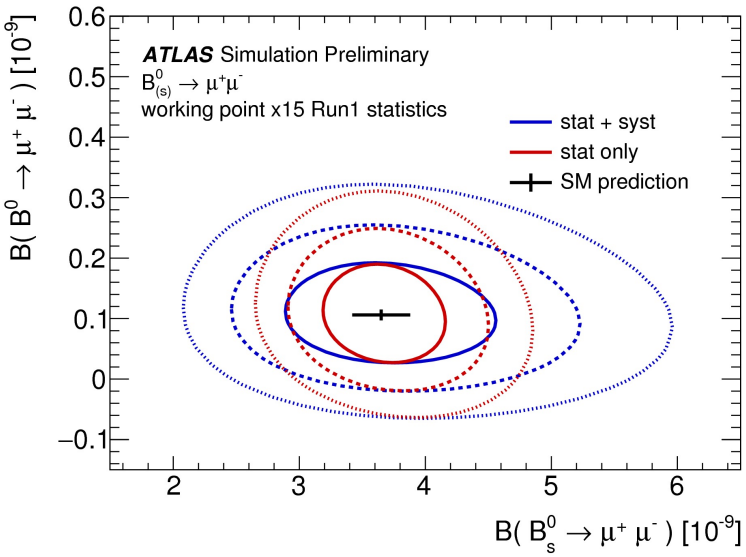


$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = \left(2.69\,^{+0.37}_{-0.35}\right) \times 10^{-9}$$

$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) \;<\; 1.9 \times 10^{-10} \text{ at } 95\%\ \text{CL}$$

HL-LHC at ATLAS

- *ATL-PHYS-PUB-2018-005*
- 3 trigger scenarios for p_T thresholds (conservative, medium, high yield)



Summary

- ATLAS Bs→J/ψϕ with 99.7fb-1 shows weak phase ϕ_s compatible with the SM; 2018 data still to be added
- Significant improvement (towards a factor of 10) from run 3 and HL-LHC and tracker upgrade

- Rare $B_{(s)} \rightarrow \mu\,\mu$ from Run 1 and 2015/16 data compatible with SM at 2.4σ
- LHC combination compatible with SM at 2.1 σ
- ATLAS adding 2017-18 data and preparing for run 3
- HL-LHC will improve precision by 3-5 times

- Overall well advanced studies in ATLAS for B physics in HL-LHC and good prospects with improved tracker despite increased pile-up

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THANK YOU!