Precision B-physics measurements by experiment ATLAS in CERN and prospects.

Maria Smizanska
on behalf of the ATLAS collaboration

Lancaster University

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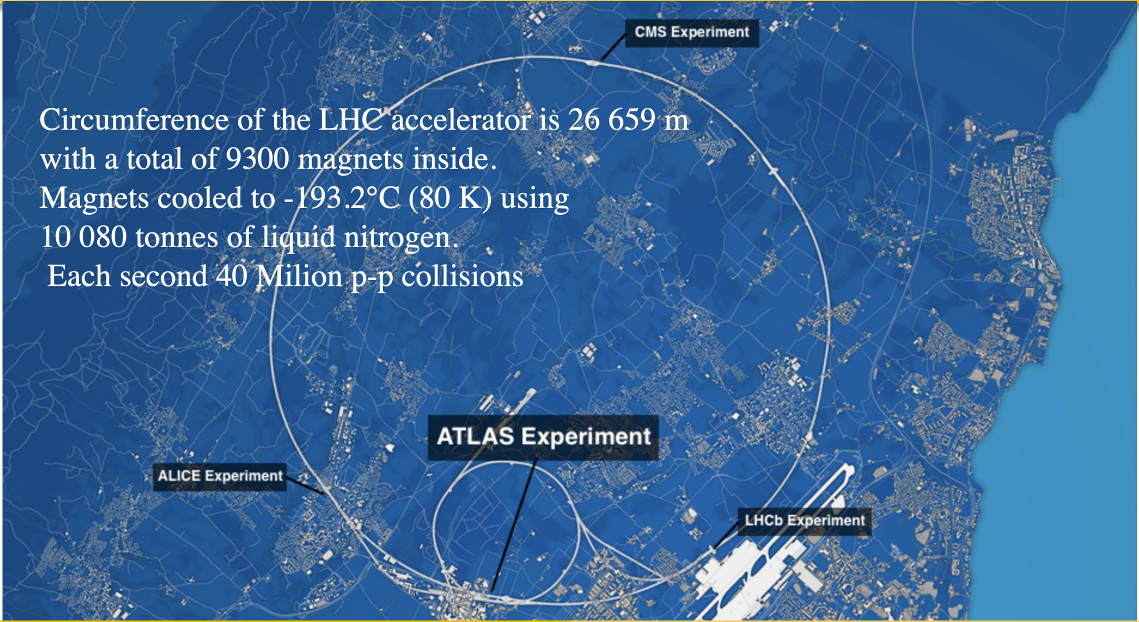
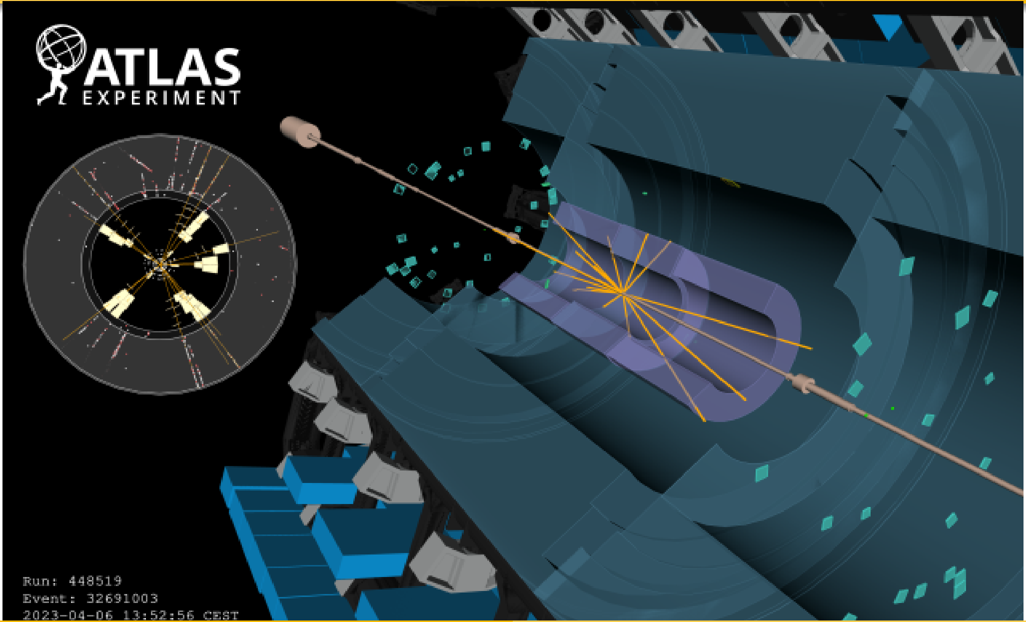
Outline

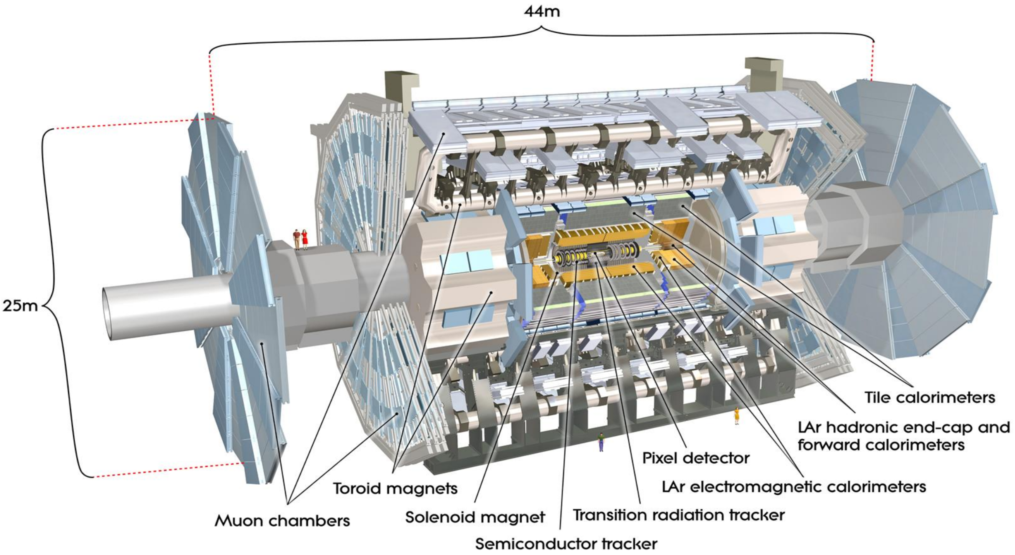
- Several representative high precision measurements in B-physics ATLAS are shown. Many other interesting results:
  ATLAS B-phys public results
- CP violation in $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$
  Eur. Phys. J. C 81 (2021) 342
- Rare decays $B_{(s)}^0 \to \mu^+\mu^-$
  JHEP 04 (2019) 098
- Study of $B_c^+ \to J/\psi D_s^{(*)+}$ decays with $\sqrt{s} = 13$ TeV data
  arXiv:2203.01808, 3 Mar 2022, CERN-EP-2022-025
- HL-LHC and B-physics performance in ATLAS


CMS Experiment
Circumference of the LHC accelerator is 26 659 m
with a total of 9300 magnets inside.
Magnets cooled to -193.2°C (80 K) using
10 080 tonnes of liquid nitrogen.
Each second 40 Milion p-p collisions
ATLAS Experiment
ALICE Experiment
LHCb Experiment

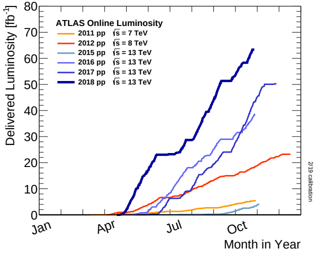
LHC collision in ATLAS 2023 first stable beams 900 MeV

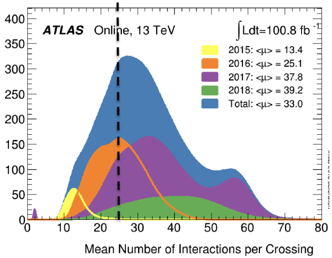


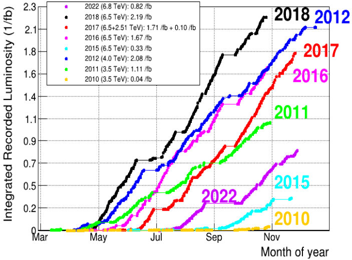
ATLAS detector



- At LHC B-physics is measured by: LHCb dedicated experiment, and General purpose experiments: ATLAS/CMS.



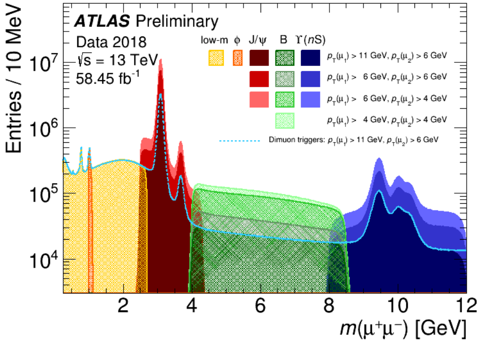


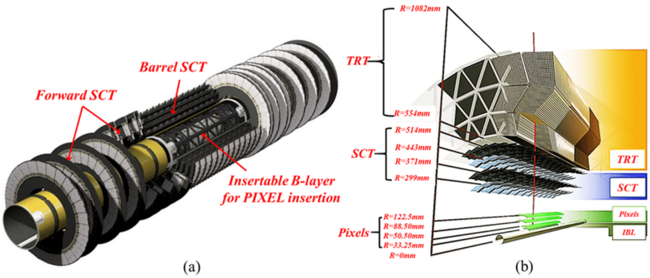


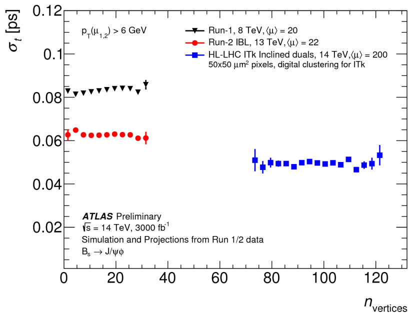
- LHCb strategy: cover forward (close to beam direction) bb production. Pro: high B-cross section. Contra: very narrow b-jets - can accept just 1 pp interaction per BX. Dilute beams. Took just 6fb-1.
- ATLAS/CMS B-phys strategy: cover central bb production (transverse to beam). Pro: b-jet tracks well separated, can work at full LHC luminosity. Took 160 fb-1. Contra: to benefit from high lumi must be very selective in B-triggers: collecting di-muon B-events with pT-thresholds.
- Finally ATLAS collects similar statistics of di-muon B-events as LHCb. While B-hadronic decays remain a domain of LHCb. LHCb also constructed expensive vertex detector, 2x better precision.

ATLAS data triggered and collected for B-physics analysis

- ATLAS has collected 139 fb^{-1} of data in Run 2, and 25 fb^{-1} in Run 1
- B-physics in ATLAS focus mostly on final states with muons, since it is an efficient way how to trigger/store B-events while staying within budget
- Typical triggers di-muons with p_{T} thresholds of either 4 GeV or 6 GeV (vary over run periods)
- Additional trigger selections are applied, e.g. on di-muon masses, targeting different analyses, as shown in Fig.







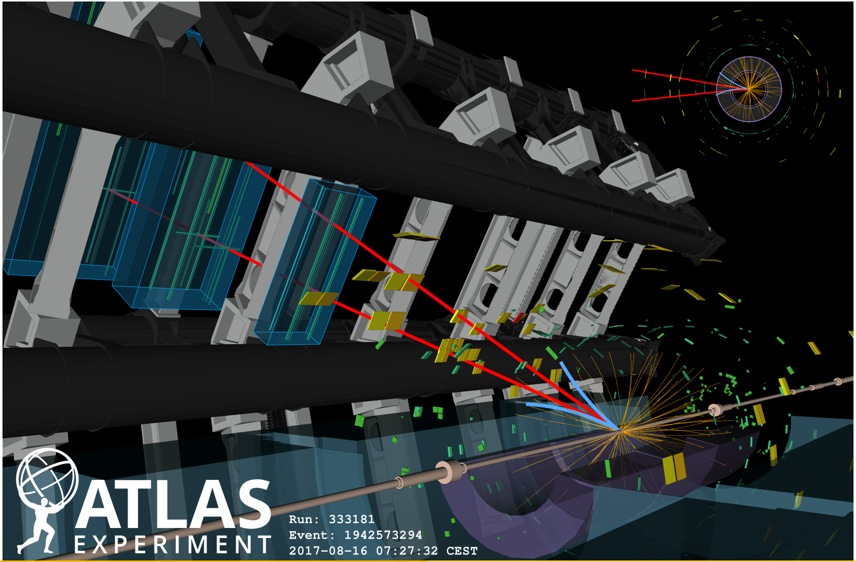
Time resolution of $B_s^0 \to J/\psi\phi$ for different numbers of reconstructed PV in the same bunch crossing.

Inner Detector: PIX, SCT and TRT, $p_{\mathrm{T}} > 0.4\,\mathrm{GeV}$, $|\eta| < 2.5$

- Run2: new IBL 25% improvement of time resolution with respect to Run1.
- Time, mass resolutions remain stable within increasing pileup in Run 2.

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

- Eur. Phys. J. C 81 (2021) 342, arXiv:2001.07115



Motivation

- $B_s^0 \to J/\psi\phi$ is used to measure CP-violation phase ϕ_s potentially sensitive to New Physics (NP)
- In Standard Model (SM) the CP violation was predicted already 55 years ago. Curently ϕ_s is predicted with high precision
  - $\phi_s = -0.03696^{+0.00072}_{-0.00082}$ rad by CKMFitter group PhysRevD.91.073007
  - $\phi_s = -0.03700 \pm 0.00104$ rad according to UTfit Collaboration arXiv: hep-ph/0606167 [hep-ph].
- LHC combined 2021: $\phi_s = -0.050 \pm 0.019$ rad, consistent with SM, however SM precision still 20 times better - room for New physics.
- Other quantity related to B_s^0 mixing is $\Delta\Gamma_s = \Gamma_s^L - \Gamma_s^H$, Γ_s^L and Γ_s^H are the decay widths of the mass eigenstates. $\Delta\Gamma_s$ was calculated in SM arXiv:1912.07621v2 [hep-ph], 2020 and new experimental results are important to tighten uncertainties and eventually get sensitivity to NP

$B_s^0 \to J/\psi\phi$ fit to data in 5-dimensional space: mass-lifetime-3-angles

Using 2015-2017 data we performed unbinned maximum likelihood fit simultaneously for B_s^0 mass, decay time and the decay angles:

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

Physics parameters

- CPV phase ϕ_s
- Decay widths: $\Delta\Gamma_s$, Γ_s
- Decay amplitudes: $|A_0(0)|^2$, $|A_\parallel(0)|^2$, $\delta_\parallel$, $\delta_\perp$
- S-wave: $|A_S(0)|^2$, δ_S
- Δm_s fixed to PDG

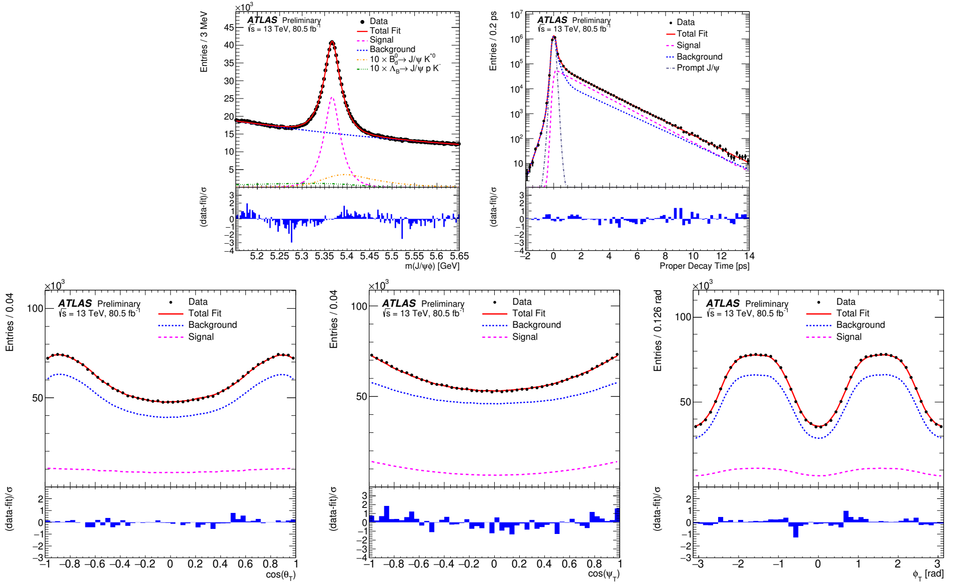
Observables

- Basic observables : m_i, t_i, Ω_i
- Conditional observables per-candidate:
  - resolutions: σ_{m_i}, σ_{t_i}
  - Bs flavour tagging probability and method: $P(B|Q)$

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

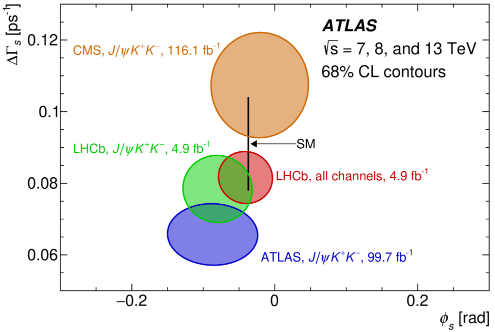
k	$O^{(k)}(t)$	$g^{(k)}(\theta_T, \psi_T, \phi_T)$
1	$\frac{1}{2}\lvert A_0(0)\rvert^2 \left[(1+\cos\phi_s)\, e^{-\Gamma_{\mathrm{L}}^{(s)}t} + (1-\cos\phi_s)\, e^{-\Gamma_{\mathrm{H}}^{(s)}t} \pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$2\cos^2\psi_T(1-\sin^2\theta_T\cos^2\phi_T)$
2	$\frac{1}{2}\lvert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

Table 4: Table showing the ten time-dependent functions, $O^{(k)}(t)$ and the functions of the transversity angles $g^{(k)}(\theta_T, \psi_T, \phi_T)$. The amplitudes $|A_0(0)|^2$ and $|A_\parallel(0)|^2$ are for the CP-even components of the $B_s^0 \to J/\psi\phi$ decay, $|A_\perp(0)|^2$ is the CP-odd amplitude; they have corresponding strong phases δ_0, $\delta_\parallel$ and $\delta_\perp$. By convention δ_0 is set to be zero. The S-wave amplitude $|A_S(0)|^2$ gives the fraction of $B_s^0 \to J/\psi K^+K^-(f_0)$ and has a related strong phase δ_S. The $\pm$ and $\mp$ terms denote two cases: the upper sign describes the decay of a meson that was initially a B_s^0 meson, while the lower sign describes the decays of a meson that was initially $\bar{B}_s^0$.


ATLAS Preliminary
√s = 13 TeV, 80.5 fb⁻¹
Data
Total Fit
Signal
Background
10 × B⁰d → J/ψ K*0
10 × ΛB → J/ψ p K⁻
Prompt J/ψ
Entries / 3 MeV
Entries / 0.2 ps
Entries / 0.04
Entries / 0.126 rad
(data-fit)/σ
m(J/ψφ) [GeV]
Proper Decay Time [ps]
cos(θT)
cos(ψT)
φT [rad]

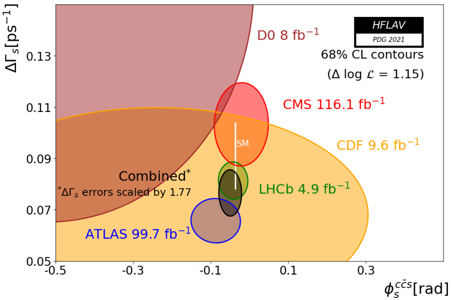
ATLAS $B_s^0 \to J/\psi\phi$ Combination Run2 + 1

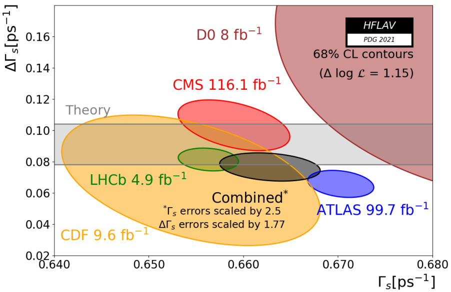
Parameter	Solution (a)		
	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	−0.087	0.036	0.021
$\Delta\Gamma_s$ [ps^{-1}]	0.0657	0.0043	0.0037
Γ_s [ps^{-1}]	0.6703	0.0014	0.0018
$\lvert A_\parallel(0)\rvert^2$	0.2220	0.0017	0.0021
$\lvert A_0(0)\rvert^2$	0.5152	0.0012	0.0034
$\lvert A_S\rvert^2$	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 result consistent with results from CMS, LHCb and SM
- Competitive single measurement of $\Delta\Gamma_s$, Γ_s and helicity parameters
- Still to add 60 fb^{-1} from 2018

High precision test of SM in $B_s^0 \to J/\psi\phi$: experiments w.r.t SM





CP violation phase ϕ_s potentially sensitive to New Physics

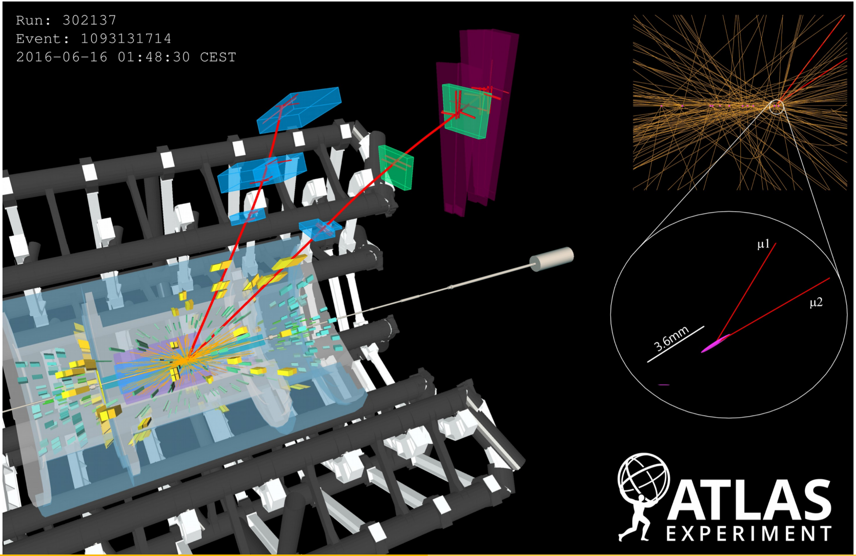
- SM prediction $\phi_s = -0.03696^{+0.00072}_{-0.00082}$ rad CKM Fitter cca 20 more precise than LHC combined.
- There is a room for New physics. An answer is on experimental side: Run3 LHC and HL-LHC

Case of $\Delta\Gamma_s$ and Γ_s

- A potential New Physics enhancement of ϕ_s would also decrease $\Delta\Gamma_s$, Lenz1 et al.
- LenzOct2021 : "Precise experimental knowledge on B-lifetimes and their Ratios, will provide bounds on New Physics
- Currently tensions at level 2σ in $\Delta\Gamma_s$ between ATLAS - CMS and 5σ in Γ_s between ATLAS - LHCb. More data to be used to improve lifetime measurement precision and control of systematic effects.
- All experiments still to add some of Run2. Now Run3 starting. HL-LHC in preparations.

Rare decays $B^0_{(s)} \to \mu^+\mu^-$ in ATLAS

- JHEP 04 (2019) 098, arXiv:1812.03017

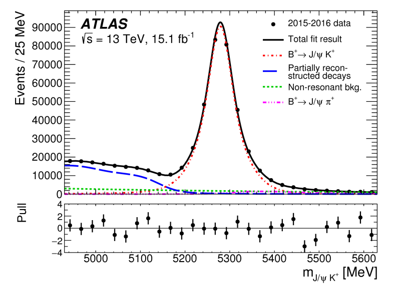


ATLAS analysis rare decays $B^0_{(s)} \to \mu^+\mu^-$ using 2015-16 data

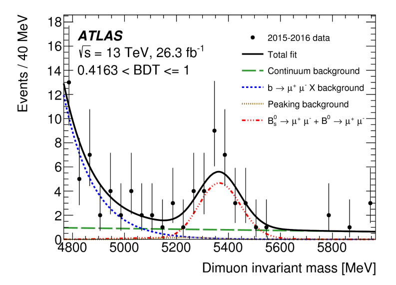
Physics Motivation

- Aim: determination of decay probability of two very rare decays: $B^0_s \to \mu^+\mu^-$ and $B^0_d \to \mu^+\mu^-$
- Multiple suppressions: FCNC current, CKM and Helicity
- New physics models predict higher, also lower rate.
- SM prediction very precise 6-8% uncertainties

Normalisation done relative to $B^\pm \to J/\psi K^\pm$



Signal after BDT selection $B^0_{(s)} \to \mu^+\mu^-$



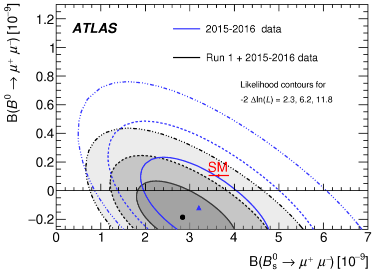
$B^0_{(s)} \to \mu^+\mu^-$ ATLAS results

- 2015-16 yields: Ns =80 $\pm$ 22 and Nd =-12$\pm$ 20 (expected from SM Ns =91 and Nd =10)
- Run2 (2015-16) + Run1 branching fractions:

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

- Compatible with SM within 2.4 σ

Likelihood contours for the simultaneous fit to B($B_s \to \mu^+\mu^-$) and B($B_d \to \mu^+\mu^-$), for $-2\Delta\ \ln(L)$= 2.3, 6.2, 11.8

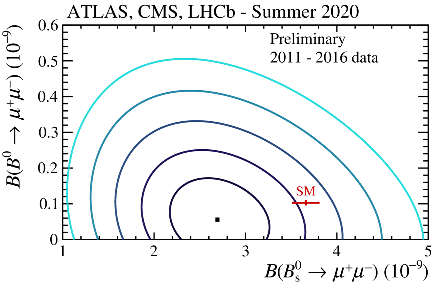


$B^0_{(s)} \to \mu^+\mu^-$ LHC combination 2020 ATLAS-CONF-2020-049

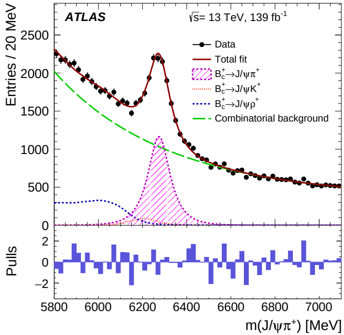
- Compatible with SM within 2.1 σ (latest LHCb result not included)

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \left(2.69\,^{+\,0.37}_{-\,0.35}\right) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) \;<\; 1.9 \times 10^{-10} \text{ at } 95\% \text{ CL}$$

Likelihood contours correspond to $-2\Delta\ \ln(L)$= 2.3, 6.2, 11.8, 19.3, 30.2



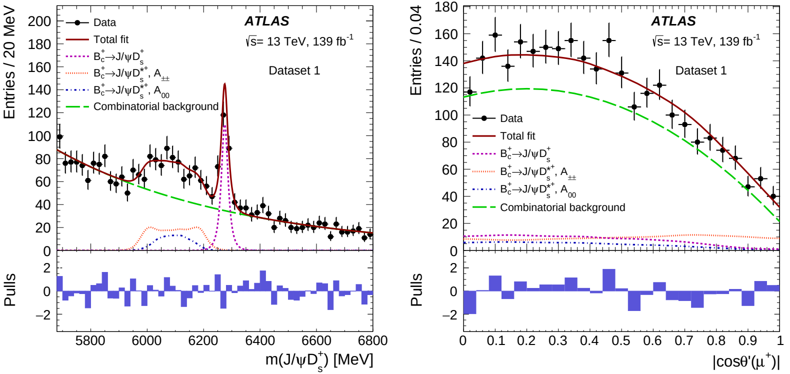
- High precision measurement of branching fractions $\mathcal{B}_r$ and the final state polarization in decays of double HF meson B_c^+
  - Testing predictions of various theory models, e.g. pQCD calculation, relativistic potential models, sum rules calculations.
- Observed earlier by LHCb (PRD 87 (2013) 112012) and ATLAS (EPJC 76 (2016) 4) in Run 1. Now highest precision using total Run2 data.
- D_s^+ and D_s^{*+} are reconstructed from their decays: $D_s^+ \to \phi(K^+K^-)\pi^+$ and $D_s^{*+} \to D_s^+\pi^0/\gamma$ with partial reconstruction.
- Use $B_c^+ \to J/\psi\pi^+$ reference channel for $\mathcal{B}_r$ measurement
- Fiducial range: $p_T(B_c^+) > 15\,\mathrm{GeV}$, $|\eta(B_c^+)| < 2.0$



Reference channel with signal statistics

$N_{B_c^+ \to J/\psi\pi^+} = 8440^{+550}_{-470}$

- 2D fit to extract the signal parameters
  - $m(J/\psi D_s^+)$ and the J/ψ helicity angle
- Both sensitive to polarization of the final state particles J/ψ and D_s^+ in $B_c^+ \to J/\psi D_s^{*+}$ decay.



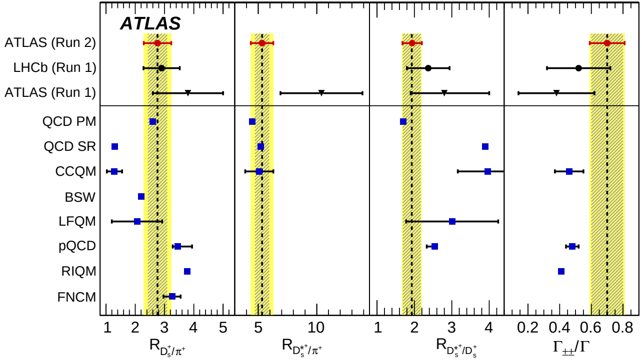
Left: fit to inv. mass $m(J/\psi D_s^+)$. Right: fit to $|\cos\theta'(\mu^+)|$, where $\theta'(\mu^+)$ is the helicity angle between μ^+ and D_s^+ momenta, in J/ψ rest frame.

$$R_{D_s^+/\pi^+} \equiv \mathcal{B}_r(B_c^+ \to J/\psi D_s^+)/\mathcal{B}_r(B_c^+ \to J/\psi \pi^+) = 2.76 \pm 0.33(\text{stat.}) \pm 0.30(\text{syst.}) \pm 0.16(\text{BF})$$

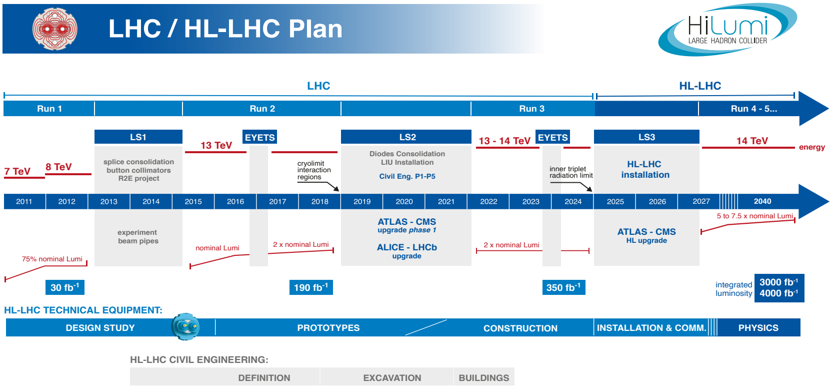
$$R_{D_s^{*+}/\pi^+} \equiv \mathcal{B}_r(B_c^+ \to J/\psi D_s^{*+})/\mathcal{B}_r(B_c^+ \to J/\psi \pi^+) = 5.33 \pm 0.61(\text{stat.}) \pm 0.67(\text{syst.}) \pm 0.32(\text{BF})$$

$$R_{D_s^{*+}/D_s^+} \equiv \mathcal{B}_r(B_c^+ \to J/\psi D_s^+)/\mathcal{B}_r(B_c^+ \to J/\psi D_s^{*+}) = 1.93 \pm 0.24(\text{stat.}) \pm 0.10(\text{syst.})$$

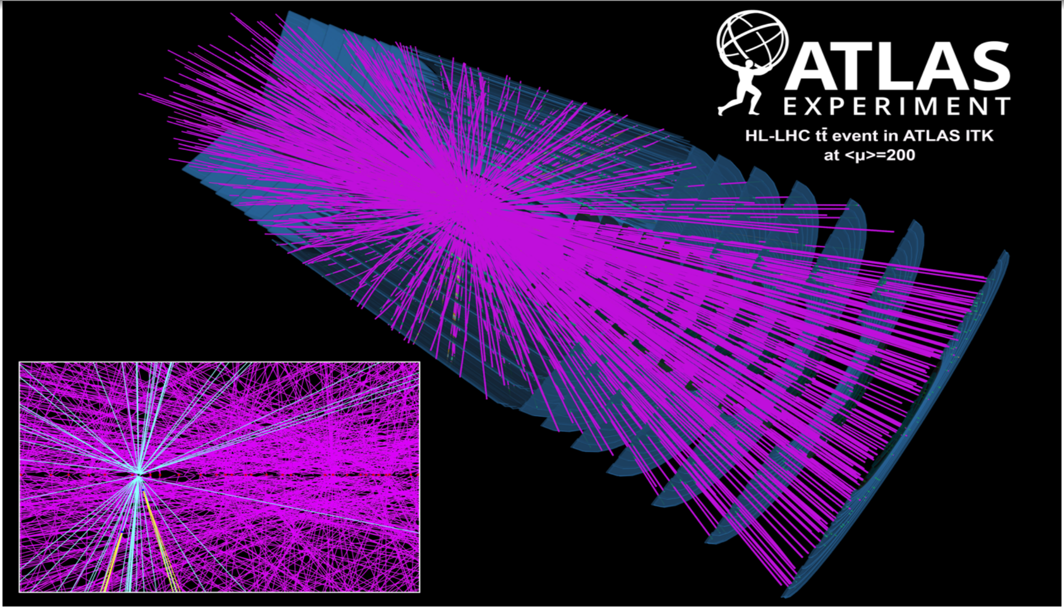
$$B_c^+ \to J/\psi D_s^{*+} \textit{ transvers polarisation fraction } \Gamma_{\pm\pm}/\Gamma = 0.70 \pm 0.10(\text{stat.}) \pm 0.04(\text{syst.})$$



- New results consistent with earlier measurements
- $R_{D_s^{*+}/\pi^+}$ described well by the predictions
- $R_{D_s^+/\pi^+}$ and $R_{D_s^{*+}/D_s^+}$ predictions consistently deviate from data
  - except QCD PM (PRD 61 (2000) 034012) perfectly agreeing
- $\Gamma_{\pm\pm}/\Gamma$ agrees with a naive spin-counting estimate of 2/3 and larger than the dedicated predictions
- Hatched areas - statistical uncertainties of this measurement and yellow bands total uncertainties.

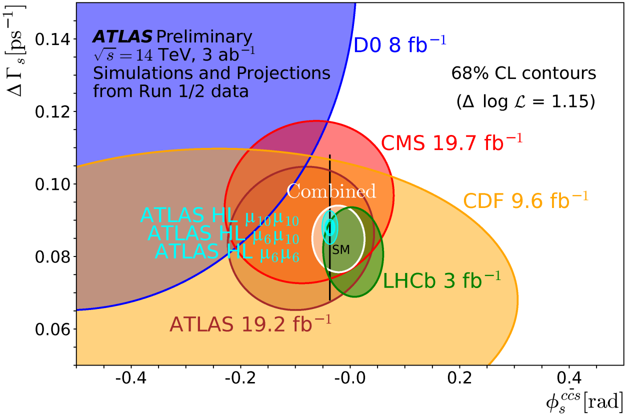


- Increase > 10 x $\int$ Ldt of LHC $\rightarrow$ 3000-4000 fb^{-1}
- Peak luminosity 5 - 7.5 x 10^{34} cm^{-2} s^{-1}
- Average amount of pp interactions 140-200 per BX with a time space 25 ns
- These conditions require Detector Upgrades.


ATLAS
EXPERIMENT
HL-LHC $t\bar{t}$ event in ATLAS ITK
at <μ>=200

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

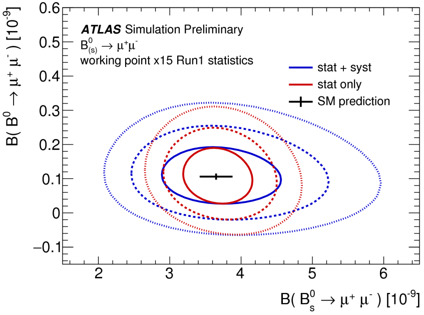
- ATL-PHYS-PUB-2018-041
- Inner Detector upgrade: proper decay time resolution improved by 21% w.r.t. Run 2
- Three trigger scenarios for muon momenta thresholds
- ϕ_s precision improves (9 - 20) times w.r.t.Run1, or (4 - 9) times w.r.t. current result combining Run1 and Run2 99.7 fb^{-1}



$B^0_{(s)} \to \mu^+\mu^-$ HL-LHC Prospects in ATLAS, ATL-PHYS-PUB-2018-005

- 3 trigger scenarios for thresholds $p_{\mathrm{T}}(\mu_1)$, $p_{\mathrm{T}}(\mu_2)$
- Conservative (10-10) GeV (x15 Run1); Intermediate (6-10) GeV (x60 Run1); High-yield (6-6) GeV (x75 Run1).

Likelihood contours for 68.3%, 95.5%, and 99.7% confidence levels



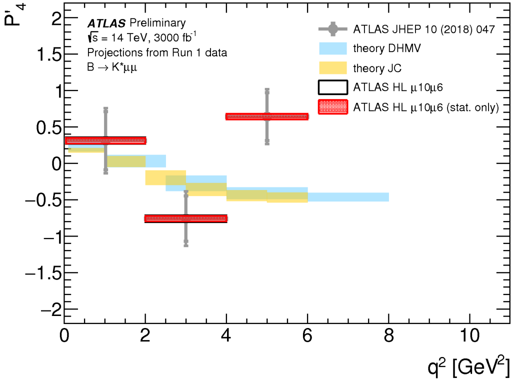
Summary

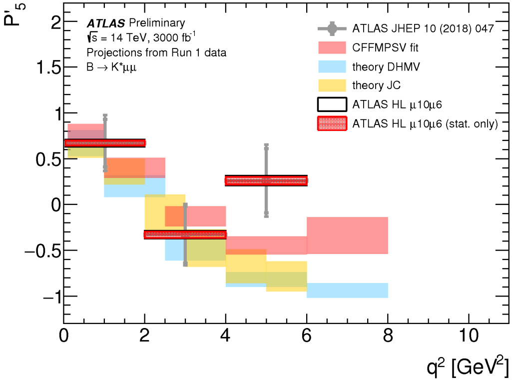
- Using Run2 and Run1 data ATLAS B-physics performed high precision measurements, addressing limitations of Standard Model in flavour sector. As in other LHC experiments the results still compatible with SM - more precision needed (Run3 and HL-LHC).
- ATLAS confirms the CP violation phase ϕ_s in $B_s^0 \to J/\psi\phi$ consistent with SM. 2018 data to be included.
- In rare decays $B_{(s)}^0 \to \mu^+\mu^-$ combining 2015-16 and Run1, ATLAS result compatible with SM within 2.4 σ.
- $B_c^+ \to J/\psi D_s^{(*)+}$ results consistent with LHCb, while majority of theory models deviate from data.
- ATLAS B-physics team work hard to run the most optimal triggers in data taking Run3 data ! Specialised shifters and quality monitoring of main B-physics signatures.
- HL-LHC B-physics strategy carefully preparing.

Backup Slides

ATLAS HL-LHC prospects for semi-rare decay $B_d^0 \to \mu^+\mu^- K^{0*}$

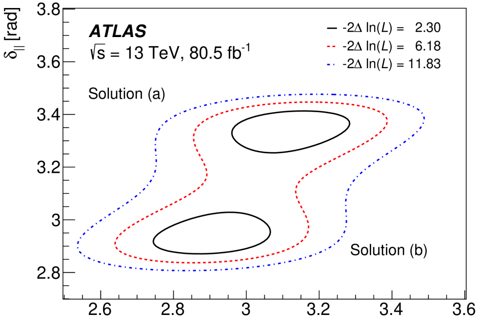
- ATL-PHYS-PUB-2019-003
- ATLAS HL-LHC measurement precision in the P_4 and P_5 parameters is estimated using Toy-MC simulations and consequent fit to the decay angular distributions.
- 3 trigger scenarios for thresholds $p_{\mathrm{T}}(\mu_1)$, $p_{\mathrm{T}}(\mu_2)$
- Expected improvements are: Conservative (10-10) GeV (x5 Run1); Intermediate (6-10) GeV (x8 Run1); High-yield (6-6) GeV (x9 Run1).





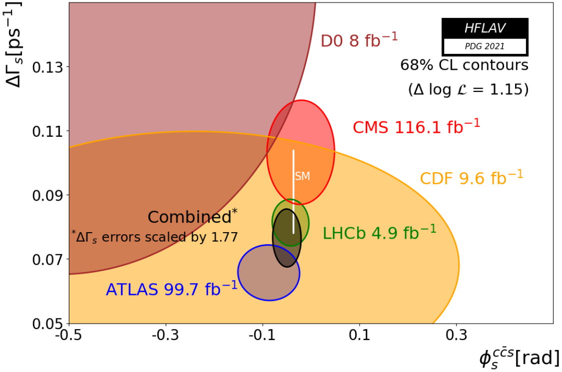
$B_s^0 \to J/\psi\phi$ ATLAS results 2015-2017 data

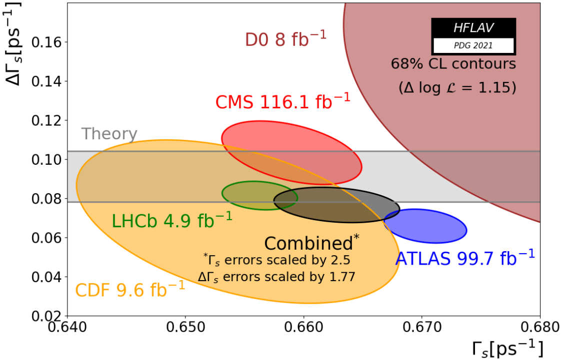
- While for most of the physics parameters, including ϕ_s , $\Delta\Gamma_s$, Γ_s, the fit determines a single solution, for the strong-phases $\delta_{||}$ and $\delta_{\perp}$ two well separated local maxima of the likelihood are found, and shown as solution (a) and (b) in table of results
- The difference in likelihoods, $-2\Delta\ln(L)$, between the two solutions is equal to 0.03, favouring (a) but without ruling out (b).



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

$B_s^0 \to J/\psi\phi$ world combination 2021



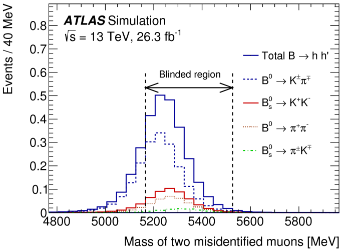


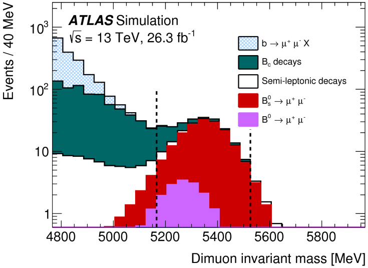
World combined 2021: $\phi_s = -0.050 \pm 0.019$ rad, consistent with SM.

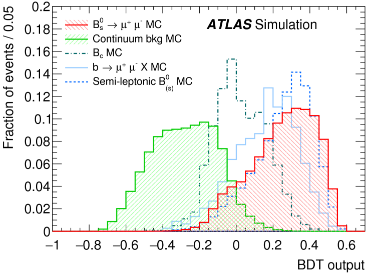
Because of tensions between the measurements, the errors on Γ_s and $\Delta\Gamma_s$ have been scaled by 2.5 and 1.77, respectively (the ellipses representing the results of each experiment are shown before scaling, while the combined ellipses include the scale factors).

$B^0_{(s)} \to \mu^+\mu^-$: Background composition

- Continuum Bg: μ's produced independently from fragmentation/decay-chains of b, $\overline{b}$ quarks.
  - Reduced by boosted decision tree (BDT) with 15 variables.
- Partially reconstructed decays:
  - same side - cascades $b \to c\mu X \to s(d)\mu X'$;
  - same vertex e.g. $B^0_{(s)} \to K^*\mu^+\mu^-$, $B \to J/\psi\mu X$, $B_c \to J/\psi(\mu^+\mu^-)\mu\nu$
- Peaking background $B \to h^+h^-$ two hadrons misidentified as μ.
  - tight μ criteria:

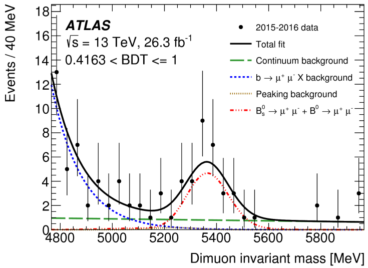




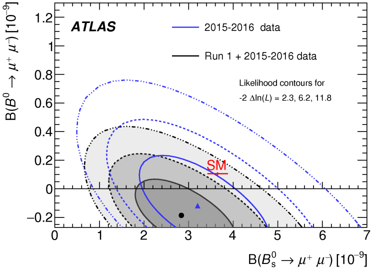


$B^0_{(s)} \to \mu^+\mu^-$ Extraction of the Signal yield

- Simultaneous likelihood fit to di-μ mass in 4 BDT bins, chosen to give equal sig efficiency 18%
- Signal model from MC: two Double-Gauss centred at B_d and B_s mass.
- Non-peaking backgrounds: common exponential - from data in low mass sideband
- Peaking backgrounds $B \to h^+h^-$ - Double-Gauss from MC



Likelihood contours for the simultaneous fit to B($B_s \to \mu^+\mu^-$) and B($B_d \to \mu^+\mu^-$), for $-2\Delta\ \ln(L)$= 2.3, 6.2, 11.8



Results

- 2015-16 yields: Ns =80 $\pm$ 22 and Nd =-12$\pm$ 20 (expected from SM Ns =91 and Nd =10)
- Run2 (2015-16) + Run1 branching fractions:

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

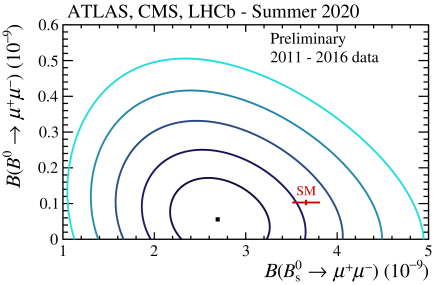
- Compatible with SM within 2.4 σ

$B^0_{(s)} \to \mu^+\mu^-$ LHC combination 2020 ATLAS-CONF-2020-049

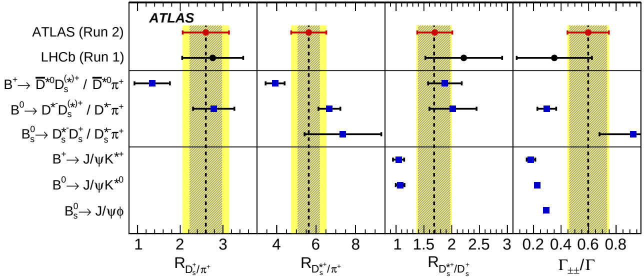
- Combination from binned 2D profile likelihoods
- Independent systematics, except for ratio of fragmentation fractions f_d/f_s, treated individually
- Compatible with SM within 2.1 σ (latest LHCb result not included)

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \left(2.69\,^{+0.37}_{-0.35}\right) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10} \text{ at } 95\% \text{ CL}$$

Likelihood contours correspond to $-2\Delta\ln(L)$= 2.3, 6.2, 11.8, 19.3, 30.2



$B_c^+ \to J/\psi D_s^{(*)+}$ results and comparisons with light B-mesons



- Ratios on light B-mesons extracted from PDG
- Final states with $D^{(*)}$, $D_s^{(*)+}$ occurring via the colour-favoured spectator diagram reasonably agree with $B_c^+ \to J/\psi D_s^{(*)+}$
- Colour suppressed modes $B \to J/\psi X$ deviate from $B_c^+ \to J/\psi D_s^{(*)+}$