# B-physics highlights from Run2/3 and strategies for HL-LHC

Maria Smizanska
**on behalf of the ATLAS collaboration**

Lancaster University

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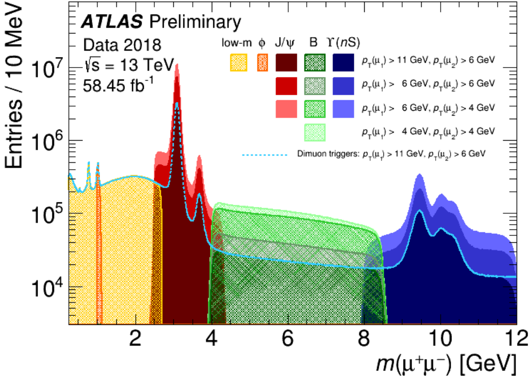
# Outline

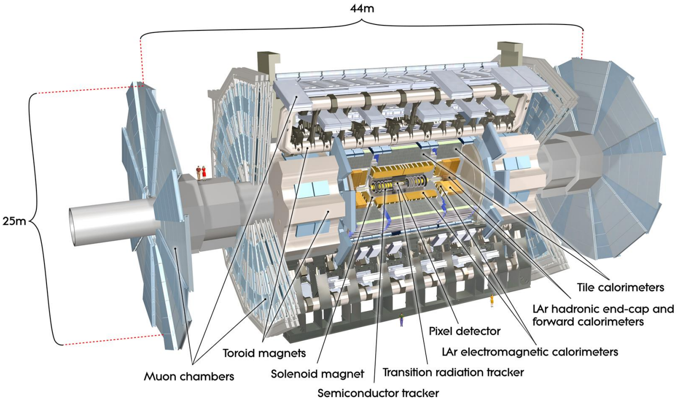
- ATLAS detector and B-physics data in Run2
- Measurement of effective lifetime in $B^0_{(s)} \to \mu^+\mu^-$
  JHEP 09 (2023) 199 W
- Observation of structures in di-charmonium mass spectrum
  PRL 131 (2023) 151902 W
- Study of $\Upsilon + 2\mu$ mass spectrum
  ATLAS-CONF-2023-041
- Run3 data highlights
- HL-LHC and B-physics performance in ATLAS

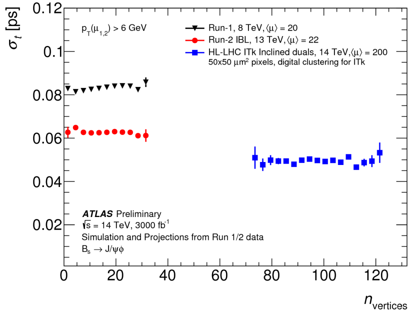
# ATLAS data in B-physics analysis

- ATLAS has collected 139 $\mathrm{fb}^{-1}$ of data in Run 2, and 25 $\mathrm{fb}^{-1}$ in Run 1
- Focus mostly on final states with muons
- Typical triggers di-muons with $p_{\mathrm{T}}$ 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.



# ATLAS detector




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, $p_T > 0.4$ 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
- Muon Spectrometer: triggering ($|\eta| < 2.4$), precision tracking ($|\eta| < 2.7$)

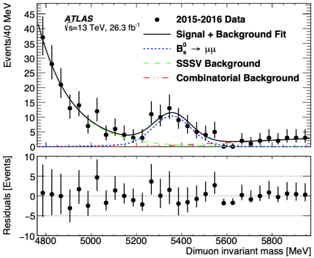
- In Standard Model (SM) only the *CP*-odd heavy-mass eigenstate in the $B_s^0 - \bar{B}_s^0$ pair decays into $\mu^+\mu^-$ M. Beneke JHEP 10 (2019) 232 and errata JHEP 11 (2022) 099.
- Beyond the Standard Model (BSM) such as minimal supersymmetric Standard Model extensions D. M. Straub Il Nuovo Cimento C 35 (2012) 249 can potentially perturb the effective lifetime in $B_{(s)}^0 \to \mu^+\mu^-$ decays. These perturbations can be significant also in absence of measurable BSM effects on the $B_{(s)}^0 \to \mu^+\mu^-$ branching fraction (BR).
- The effective $B_{(s)}^0 \to \mu^+\mu^-$ lifetime is defined as

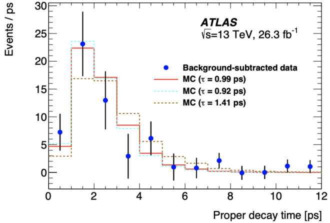
$$\tau_{\mu\mu} = \frac{\int_0^\infty t\Gamma(B_s^0(t)\to\mu\mu)\,dt}{\int_0^\infty \Gamma(B_s^0(t)\to\mu\mu)\,dt}, \text{ where: } \Gamma\left(B_s\left(t\right) \to \mu\mu\right) = \Gamma\left(B_s^0\left(t\right) \to \mu\mu\right) + \Gamma\left(\bar{B}_s^0\left(t\right) \to \mu\mu\right)$$

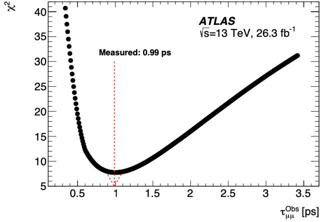
  and $t$ is the proper decay time of the $B_s^0$ and $\bar{B}_s^0$ mesons.
- In the SM hypothesis $\tau_{\mu\mu}$ coincides with the lifetime of the heavy $B_s^0$ eigenstate $\tau_{B_s^H}$.
- The experimental average of the $B_s^0$ - $\bar{B}_s^0$ lifetimes and their difference Phys. Rev. D 107 (2023) 052008 yields the prediction $\tau_{\mu\mu}^{SM} = (1.624 \pm 0.009)$ ps, with new physics effects perturbing it at most by the difference between the heavy and light eigenstate lifetimes (0.193 ps ).

# Measurement of effective lifetime in $B^0_{(s)} \to \mu^+\mu^-$ , cont 1

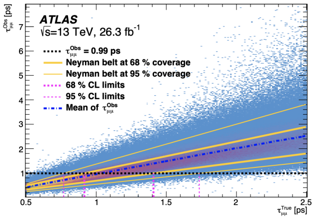
- Data from 2015-2016 are used in this measurement.
- Un-binned maximum likelihood fit to candidates in the [4766 – 5966] MeV mass region (Left Fig) , yielding 58 ± 13 (stat. only) $B^0_{(s)} \to \mu^+\mu^-$ signal events.
- Signal and backgrounds weights calculated from the result of the mass fit are used to construct the proper decay time data histogram - background-subtracted employing per-event weights calculated according to the *sPlot* technique (Middle Fig).
- The lifetime measurement is obtained by minimising the binned $\chi^2$ between the data histogram and lifetime-dependent pure signal MC templates extracted from MC simulated samples, as illustrated in the Middle and Right Fig.

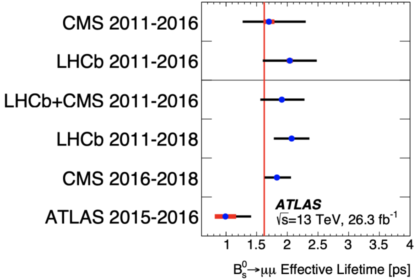


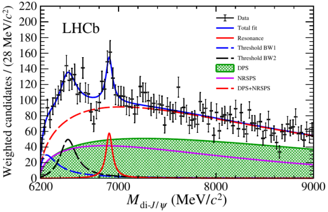



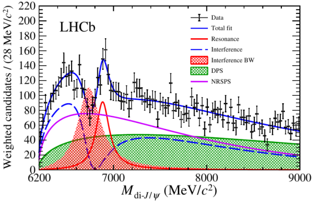
- The statistical uncertainty is derived from the Neyman CL band construction Figure Left. The $\chi^2$ minimum and the Neyman belt construction yield $\tau_{\mu\mu} = 0.99^{+0.42}_{-0.07}$ (stat) ps. The imbalance between positive and negative statistical uncertainties is already suggested by the asymmetry in the $\chi^2$ scan.
- The systematic errors are dominated by data-MC discrepancies, followed by uncertainties in backgrounds lifetime modelling.
- The result using 2015-2016 data is $\tau_{\mu\mu} = 0.99^{+0.42}_{-0.07}$ (stat.) $\pm$ 0.17 (syst.) ps. It is consistent with the SM prediction $\tau^{SM}_{\mu\mu} = (1.624 \pm 0.009)$ ps Phys. Rev. D 107 (2023) 052008 as well as with the other available experimental results.



- In 2020 LHCb claimed arXiv:2006.16957 an observation of a new X(6900) structure in pp $\to J/\psi$-$J/\psi \to 4\mu$ mass spectrum
  - consistent with predictions for T $cc\overline{cc}$ tetraquarks model (EPJC 80 (2020) 1004 W, PLB 811 (2020) 135952 W
  - non-tetraquark interpretations also possible e.g. in Pomeron exchanges in near-threshold $J/\psi$-$J/\psi$ scattering (PLB 824 (2022) 136794 W).
  - broad lower-mass structure can be e.g. a mixture of multiple tetraquark states or feed-down from their decays via heavier charmonia
- The observation then confirmed by ATLAS PRL 131 (2023) 151902 W and CMS (PRL 132 (2024)



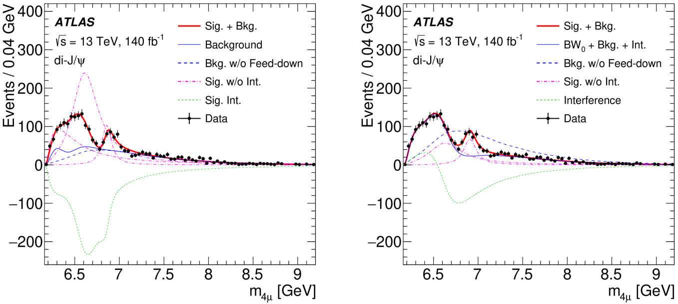

Assuming no interference:

$$m[X(6900)] = 6905 \pm 11 \pm 7\,\text{MeV}/c^2$$
$$\Gamma[X(6900)] = 80 \pm 19 \pm 33\,\text{MeV},$$

With NRSPS interference:

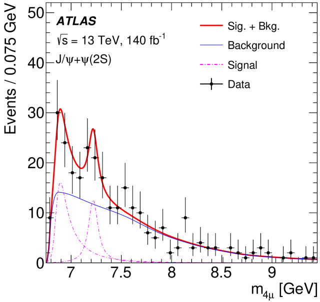
$$m[X(6900)] = 6886 \pm 11 \pm 11\,\text{MeV}/c^2$$
$$\Gamma[X(6900)] = 168 \pm 33 \pm 69\,\text{MeV}.$$

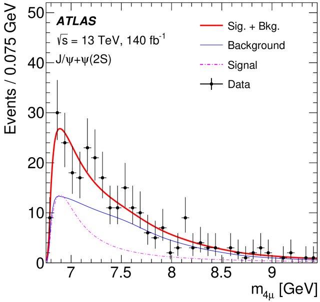
- For di-$J/\psi$ the resonance X(6900) is reliably confirmed with consistent parameters to LHCb
- The excess of $>> 5\ \sigma$ at 6.9 GeV and the broad structure at lower mass, confirmed in both models:
- Model A (Fig left): three interfering S-wave BW resonances;
- Model B (Fig right): two resonances, first interfering with background

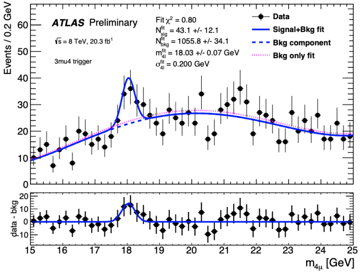


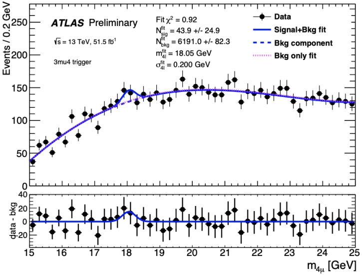

| di-$J/\psi$ | model A | model B |
|---|---|---|
| $m_0$ | $6.41 \pm 0.08^{+0.08}_{-0.03}$ | $6.65 \pm 0.02^{+0.03}_{-0.02}$ |
| $\Gamma_0$ | $0.59 \pm 0.35^{+0.12}_{-0.20}$ | $0.44 \pm 0.05^{+0.06}_{-0.05}$ |
| $m_1$ | $6.63 \pm 0.05^{+0.08}_{-0.01}$ | — |
| $\Gamma_1$ | $0.35 \pm 0.11^{+0.11}_{-0.04}$ | |
| $m_2$ | $6.86 \pm 0.03^{+0.01}_{-0.02}$ | $6.91 \pm 0.01 \pm 0.01$ |
| $\Gamma_2$ | $0.11 \pm 0.05^{+0.02}_{-0.01}$ | $0.15 \pm 0.03 \pm 0.01$ |

- For $J/\psi$-$\psi(2S)$ the resonance at X(6900) is also confirmed, with the significance above $4\sigma$ in both models $\alpha$, $\beta$:
- Model $\alpha$ (Fig left): two interfering S-wave BW resonances
- Model $\beta$ (Fig right): one resonance only.
- Evidence for another resonance, also hinted in LHCb results near 7.2 - 7.3 GeV in $J/\psi$-$\psi(2S)$, at level of (3-4$\sigma$ local significance).





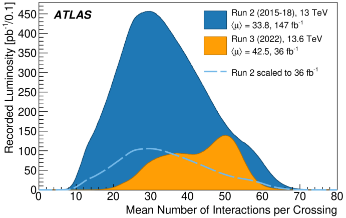



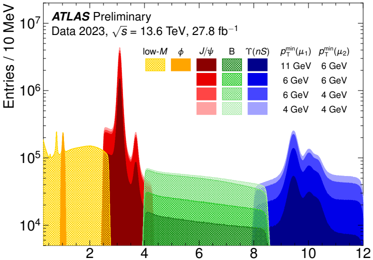

- 8 TeV data analysis: an excess at m($4\mu$) = 18 GeV
- global significance 1.9–5.4 $\sigma$ depending on selection choice, survives extensive validation

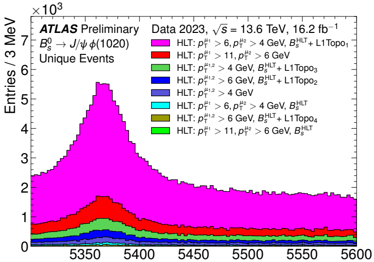
- 13 TeV data: much less significant structure in 2015–17 data and no signal in 2018 (with tighter trigger)
- MC and data-driven studies confirm reduction of sensitivity in Run-2 data
- 13 TeV result is in tension with 8 TeV at 2.7 $\sigma$ level
- To be further studied with Run-3

# Run3 features B-physics triggers and data

- Run3 increasing instantaneous luminosity lead to the increased BX collisions (42 in 2022 and 50 in 2023) relative to 34 in Run2. Integrated luminosities: 2022 (31 $fb^{-1}$) and 2023 ( 27 $fb^{-1}$).
- To scope with trigger output rate limits the ATLAS physics groups have adopted the trigger strategies. The B-physics is using trigger pre-scales: to rely mainly on higher di-muon pT (11-6 GeV and 6-6 GeV) at the start of the fill, while towards the middle and the end of fill the lower pT (6, 4 GeV) triggers are prefered.
- For the high precision measurements, like CP-violation and lifetimes, the shift towards higher pT of B-hadrons is beneficial, as the proper-decay time errors get smaller, even if there is some loss of statistics due to eliminated lower pT events.
- For low mass resonance searches preserving the low pT muon triggers is necessary, they would combine 3-muons in L1.

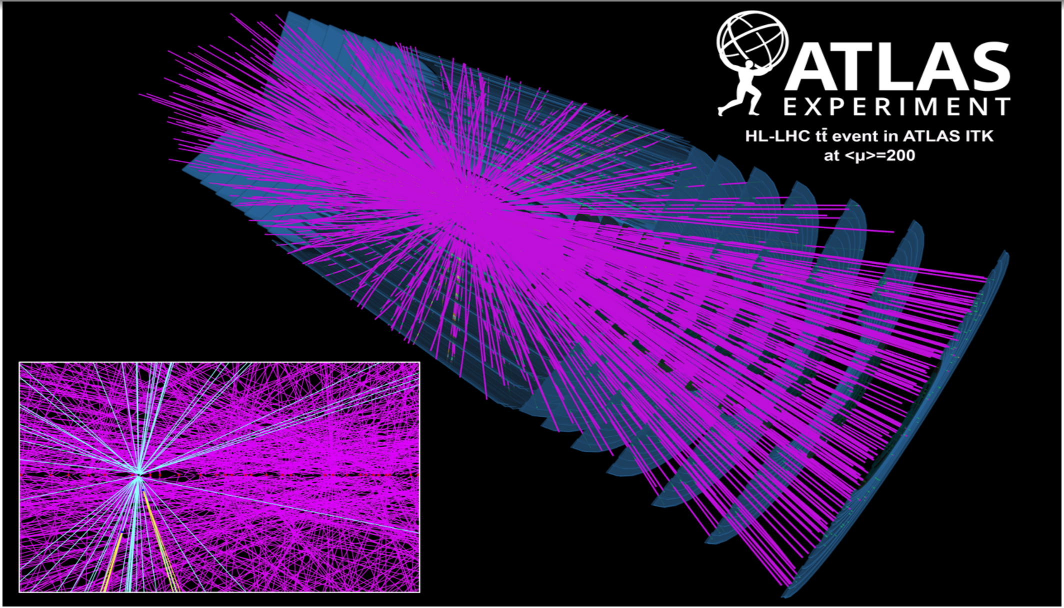


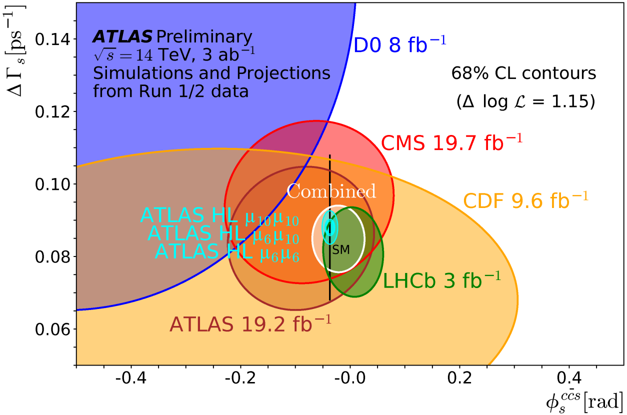

- Increase $>$ 10 x $\int$ Ldt of LHC $\rightarrow$ 3000-4000 fb$^{-1}$
- Peak luminosity 5 - 7.5 x $10^{34}$ cm$^{-2}$ s$^{-1}$
- Average amount of pp interactions 140-200 per BX with a time space 25 ns
- These conditions require Detector Upgrades.

# High Luminosity-LHC - ATLAS track density in Inner detector



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

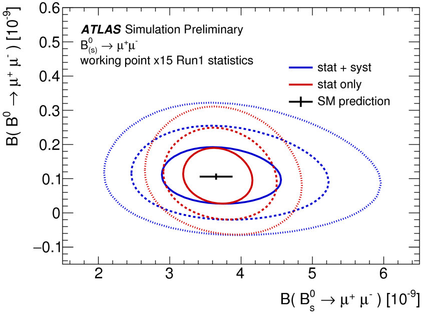
- ATL-PHYS-PUB-2018-041
- Inner Detector upgrade: proper decay time resolution improved by 21% w.r.t. Run 2
- Three trigger scenarios for muon momenta thresholds
- $\phi_s$ precision improves (9 - 20) times w.r.t.Run1, or (4 - 9) times w.r.t. current result combining Run1 and Run2 99.7 fb$^{-1}$



## $B^0_{(s)} \rightarrow \mu^+\mu^-$ 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

- Recent ATLAS B-physics measurement published in 2023-2024, based on Run2 data have been presented.
- Many other analysis of Run2 data are on the way.
- In Run3 the integrated luminosities taken since far - have not allowed to improve Run2 high precision measurements, however searches for low mass resonance requiring the low pT muons can already benefit.
- HL-LHC B-physics strategy carefully prepared by using full simulation and reconstruction. This is being updated for important updates in reconstruction software.