ATLAS Measurements of Charm and B Hadron Production and Properties

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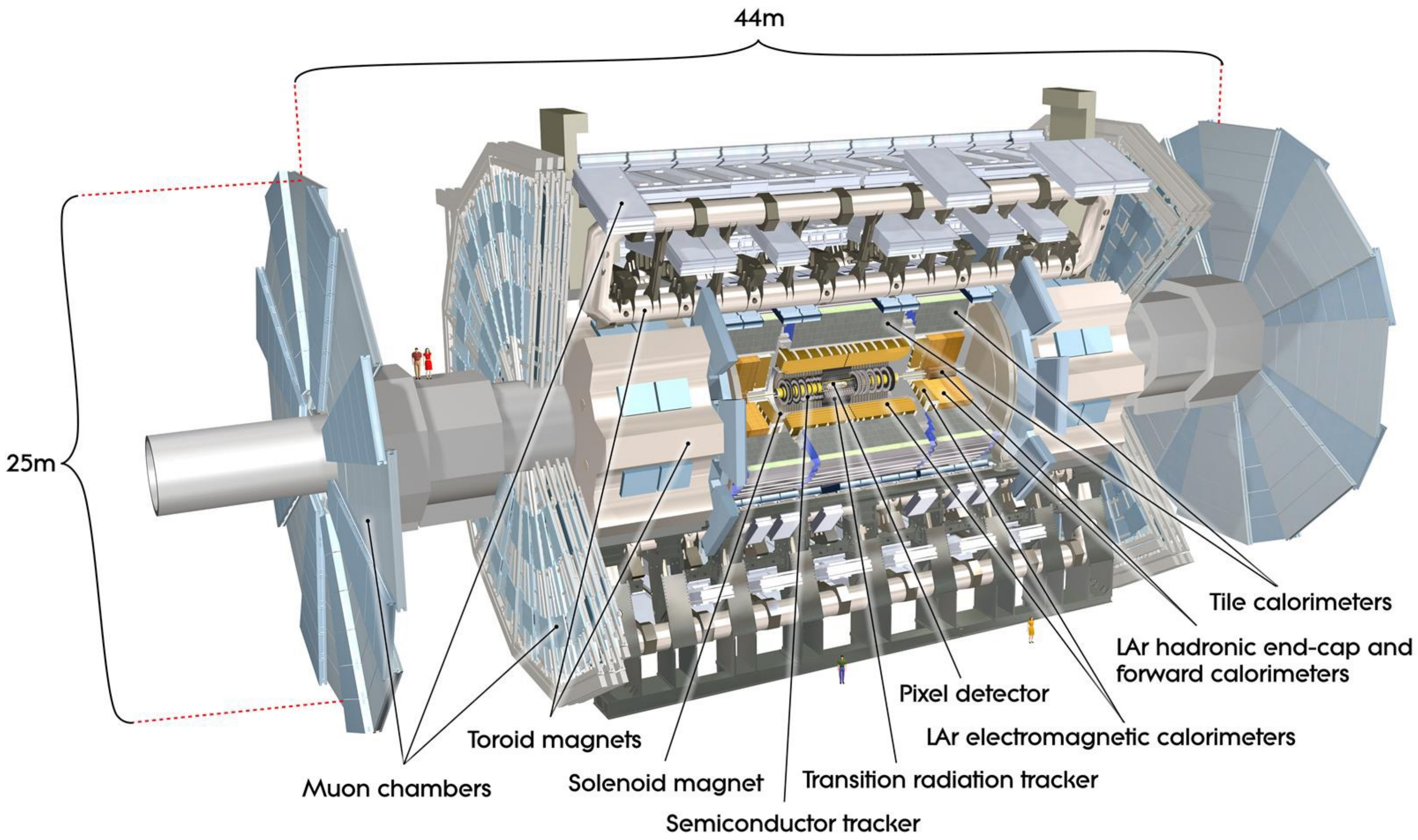
On behalf of the ATLAS Collaboration

I. Introduction
II. Measurement of the effective lifetime of the $B_s^0 \rightarrow \mu^+\mu^-$ decay
III. Measurement of the production cross section of J/ψ and ψ(2S) at High Transverse Momentum
IV. Conclusion

Two recent results on charm and b-hadron production from ATLAS, using LHC pp data.



ATLAS from inside to out:

- Inner detector (pixel, silicon microstrips, straw-tube TRT) $|\eta| < 2.5$, surrounded by a 2T axial B field from the solenoid
- Sampling calorimeters (LAr EM $|\eta| < 3.2$; Scint tile HAD $|\eta| < 3.2$; LAr HAD $1.5 < |\eta| < 4.9$)
- Air core toroids provide B field for Muon drift tubes + cathode strip chambers (muon tracking to $|\eta| < 2.7$) and resistive plate + thin gap chambers (triggering to $|\eta| < 2.4$)

Measurement of the effective lifetime of the $B_s^0 \to \mu^+\mu^-$ decay

Message: According to the Standard Model, only the CP-odd component of $B_s^0 - \bar{B}_s^0$ mixing can contribute to the B_s^0 decay into 2 muons. BSM contributions[1] could allow decays of the CP-even eigenstate or admixtures of the two, altering the effective lifetime. BSM effects upon the lifetime can be significant even in the absence of measurable BSM effects in the branching ratio for $B_s^0 \to \mu^+\mu^-$ decays.[2,3]

The outcome –

- A fit on the candidates' proper decay time distribution yields

$$\tau_{\mu\mu} = 0.99^{+0.42}_{-0.07}(\text{stat.}) \pm 0.17(\text{syst.})\ \text{ps}$$

- In the Standard Model, $\tau_{\mu\mu}$ coincides with the lifetime of the heavy B_s^0 eigenstate, which allows the existing experimental average to yield a SM prediction. This ATLAS measurement is consistent with that SM prediction and with other experiments.

- This is the first ATLAS measurement of this quantity.

[1] D.M. Straub, New physics searches in flavor physics, Il Nuovo Cimento C 35 (2012) 249.
[2] M. Beneke et al., Power-enhanced leading-logarithmic QED corrections to $B_q^0 \to \mu^+\mu^-$. JHEP 10 (2019) 232.
[3] K.D. Bruyn et al., Probing new physics via the $B_s^0 \to \mu^+\mu^-$ effective lifetime. PRL 109 (2012) 041801.

The method –

- The analysis uses 26.3 fb^{-1} of data collected at $\sqrt{s} = 13$ TeV in 2015-16
- The effective lifetime is defined as:

$$\tau_{\mu\mu} = \frac{\int_0^\infty t\Gamma(B_s(t) \to \mu\mu)dt}{\int_0^\infty \Gamma(B_s(t) \to \mu\mu)dt}$$

where t is the proper decay time of the B_s^0 and $\bar{B}_s^0$ mesons, and $\Gamma(B_s(t) \to \mu\mu) = \Gamma(B_s^0(t) \to \mu\mu)+\Gamma(\bar{B}_s^0(t) \to \mu\mu)$.

- Reconstruct muon trajectories in the Inner Detector and Muon Spectrometer.

- Reconstruct the primary vertex using all other tracks, constrained to the luminous region of the colliding beams.

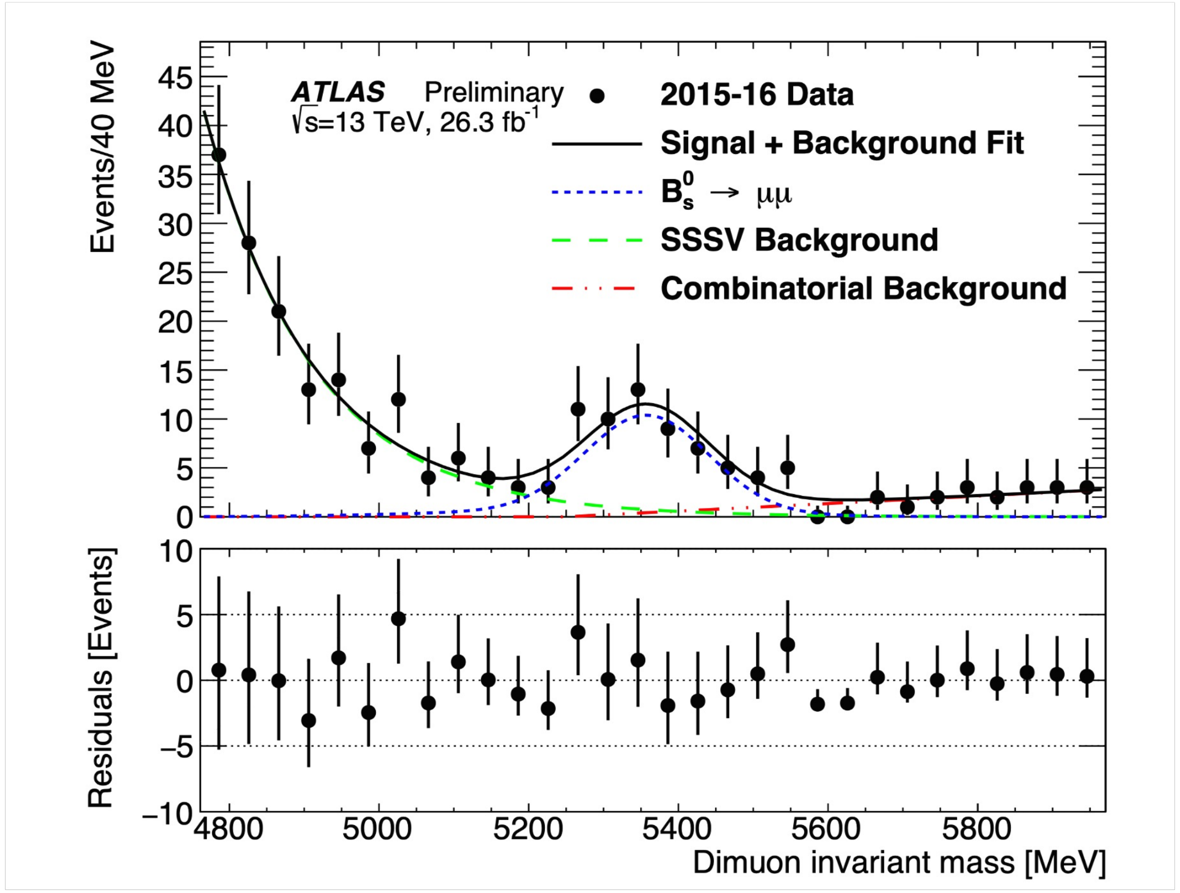
- Extrapolate each B candidate to the point of closest approach to the beam axis and choose the primary vertex with the smallest distance along z (this is > 99% successful)

- Unless mentioned here, data quality cuts and reconstruction corrections are the same as in the ATLAS $B \to \mu\mu$ branching ratio paper.[1]

[1] ATLAS Collaboration, 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.

The method, continued –

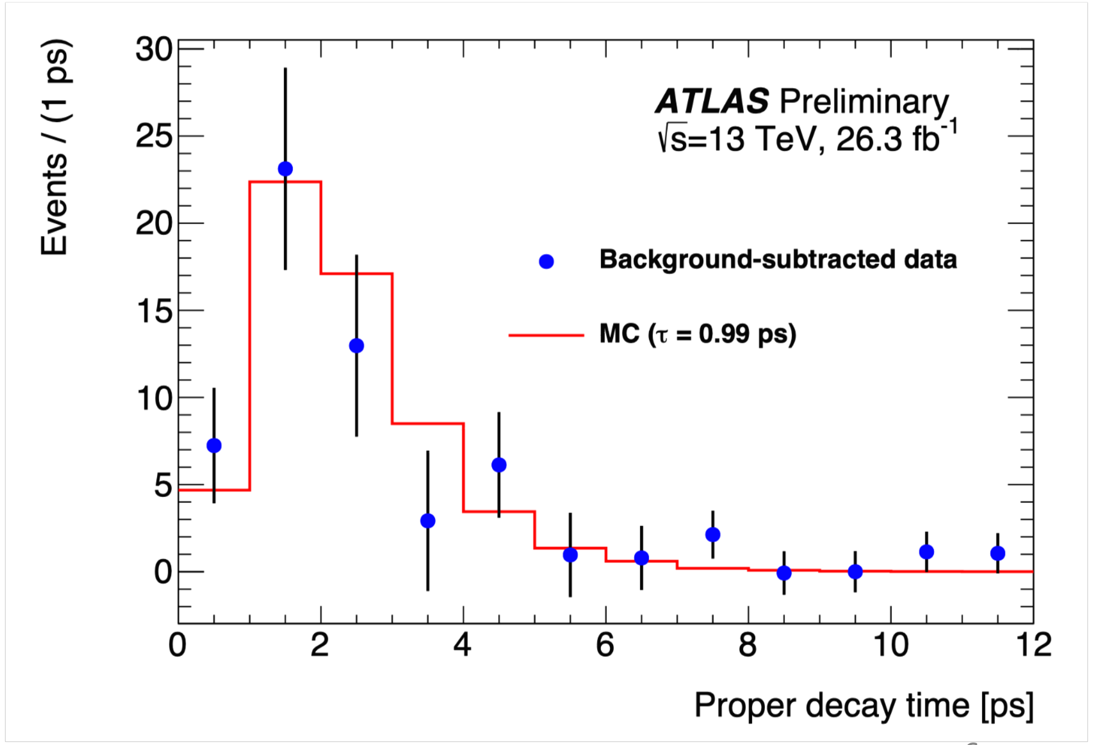
- Reconstruct the B mass from the $\mu\mu$ four-momentum.



- Reconstruct the B proper decay time as

$$\tilde{t}_{\mu^+\mu^-} = \frac{L_{xy} m_{B_s}^{PDG}}{p_T^{B_s}}$$

where L_{xy} is the decay length projected along the reconstructed B_s momentum in the transverse plane.



The method, continued –

- BDT algorithm suppresses combinatorial background, optimizing $\frac{S}{\sqrt{S+B}}$ in the range 5166-5526 MeV. MC are used for Signal (normalized to SM expectation). Bkg taken from a control region with a fixed looser BDT cut.

- **58 ± 13** signal candidates obtained with 5-parameter unbinned extended maximum likelihood fit of the mass distribution to

  - double-gaussian signal
  - exponentially falling bkg (muons corresponding to particles produced from the decay of a single b)
  - linear bkg (combinatorial bkg - dimuons originating from different quarks in the $pp \to b\bar{b}$ process)

- Additional bkg contributions are neglected in the fit and taken in the systematics.

- sPlot technique[1] extracts proper decay time distribution of the candidates using lifetime-dependent histogram templates.

- Extract lifetime: minimize binned χ^2 between the data histogram and pure signal MC templates

- Extract uncertainties: using a Neyman construction.[2]

- Contributions from non-combinatoric sources (e.g. $B_d^0 \to \mu^+\mu^-$) are merged separately.

[1] M. Pivk and F. Le Diberder, NIM A555 (2005) 356; R. Brun and F. Rademakers, NIM A389 (1997) 81.
[2] J. Neyman, Phil. Trans. Royal Soc. of London. Series A, Math. and Phys. Sci. 236 (1937) 333.

The method, continued –

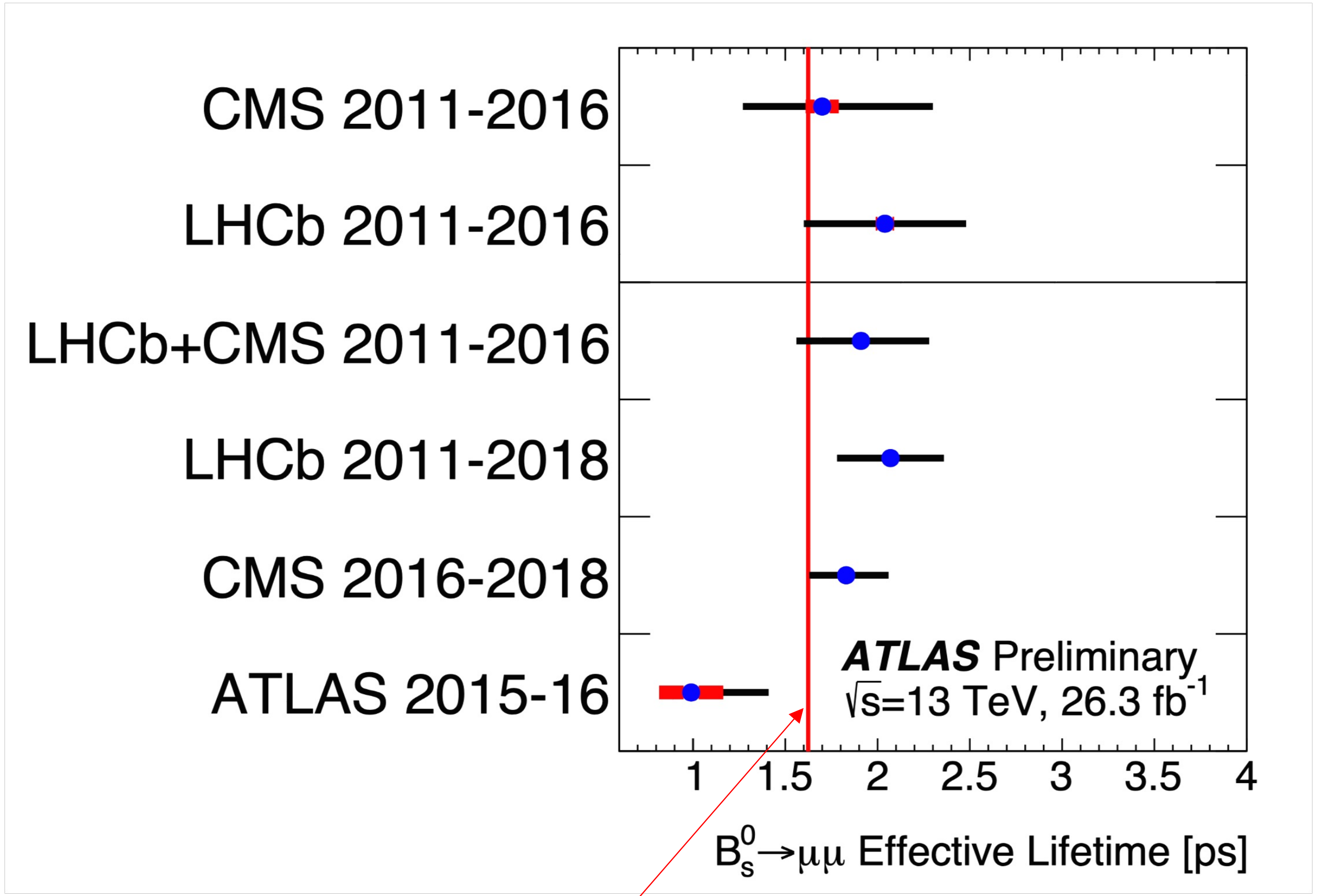
- Systematics:

  - fit procedure (analytical models, normalization assumptions, sideband application), data/MC differences, neglected bkg.). All assessed with simulation.
  - To correct for differences in vertex resolution in MC and data, the identical procedure is applied to the precision reference channel $B^{\pm} \to J/\psi(\to \mu^{+}\mu^{-})K^{\pm}$ and compared to PDG value; difference is taken as a systematic.

The result - statistics-dominated at this time, is:

$$\tau_{\mu\mu} = 0.99^{+0.42}_{-0.07}(\text{stat.}) + 0.17(\text{syst.})\text{ps}$$

which is *consistent with other experiments*[1,2,3] *and the SM prediction*[4] *of (1.624 ± 0.009) ps.* This is the first ATLAS measurement of this quantity.



Standard Model prediction

error bars:
thin bars – stat
thick bars – syst
combination shows total

[1] CMS: JHEP 04 (2020) 118, arXiv:1910.12127, and cds.cern.ch/record/2815334.
[2] LHCb: PRL 118 (2017) 191801, and PRL 128 (2022) 041801.
[3] CMS-LHCb combination: cds.cern.ch/record/2727216.
[4] Y. Amhis et al., Phys. Rev. D 107 (2023) 052008, arXiv:2206.07501.

Measurement of the Production Cross Section of J/ψ and ψ(2S) Mesons at High Transverse Momentum[1]

Message – This analysis broadens the scope of comparison between experiment and theory by adding a high p_T selection on the quarkonium – this is expected to improve discrimination among competing models[2] of vector charmonium production.

***The outcome* -** ATLAS has measured:

- double differential production cross sections of J/ψ and ψ(2S) through their decays to $\mu^+\mu^-$.
- Prompt and non-prompt cross sections separately for both states.
- For each state, the ratio of non-prompt to total (i.e. fraction of non-prompt).
- For both prompt and non-prompt, the production ratios of ψ(2S) relative to J/ψ.

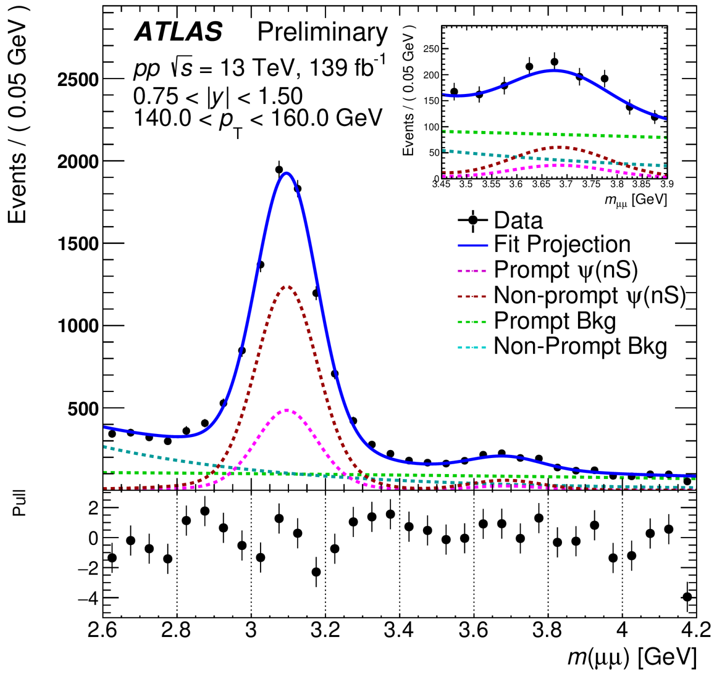
The characteristics of the measured cross sections are compared to predictions based on the FONLL model.[3]

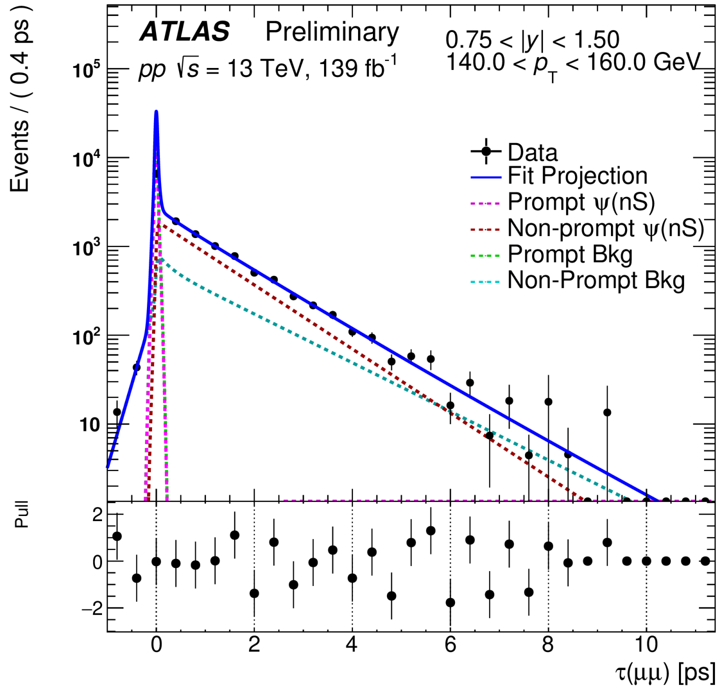
[1]ATLAS-CONF-2019-047.
[2]G. Li et al., PRD 83 (2011) 014001; J.P. Lansberg and C. Lorce, Phys. Lett. B 726 (2013) 218; B. Gong et al., JHEP 03 (2013) 115; M. Song et al., JHEP 02 (2011) 071; M. Butenschoen and B.A. Kniehl, Nucl. Phys. Proc. Suppl. 222-224 (2012) 151.
[3]M. Cacciari et al., JHEP 0103 (2001) 006; M. Cacciari et al., JHEP 1210 (2012) 137.

The method –

- Apply single-muon trigger with threshold $p_T > 50$ GeV.
- Find the J/ψ's and ψ(2S) through their decays to $\mu^+\mu^-$. At least one muon must have $p_T > 52.5$ GeV.
- Compute dilepton mass m(μμ) and pseudo-proper decay time τ for each event.
- Sort data into (12 intervals in p_T^{dimuon}) × (3 intervals in $|y|^{dimuon}$). Correct each bin for efficiencies, apply 2-dimensional [in m(μμ), τ] unbinned max likelihood fit to each bin.

Example bins with fit projections:





The method, continued –

- Extract yields N^{prompt} and $N^{non\text{-}prompt}$ from fits for "ψ" = J/ψ, ψ(2S)
- Compute double-differential cross section (*A* is acceptance, *C* is correction):

$$\frac{d^2\sigma^{P,NP}(pp\to\psi)}{dp_T dy}\times B(\psi\to\mu^+\mu^-)=\frac{1}{A(\psi)}C_{bin-migration}C_{\substack{pileup\ and\\ angular\\ correlations}}\frac{N_\psi^{P,NP}}{\Delta p_T\Delta y\int L\,dt}$$

- Compute non-prompt fractions:

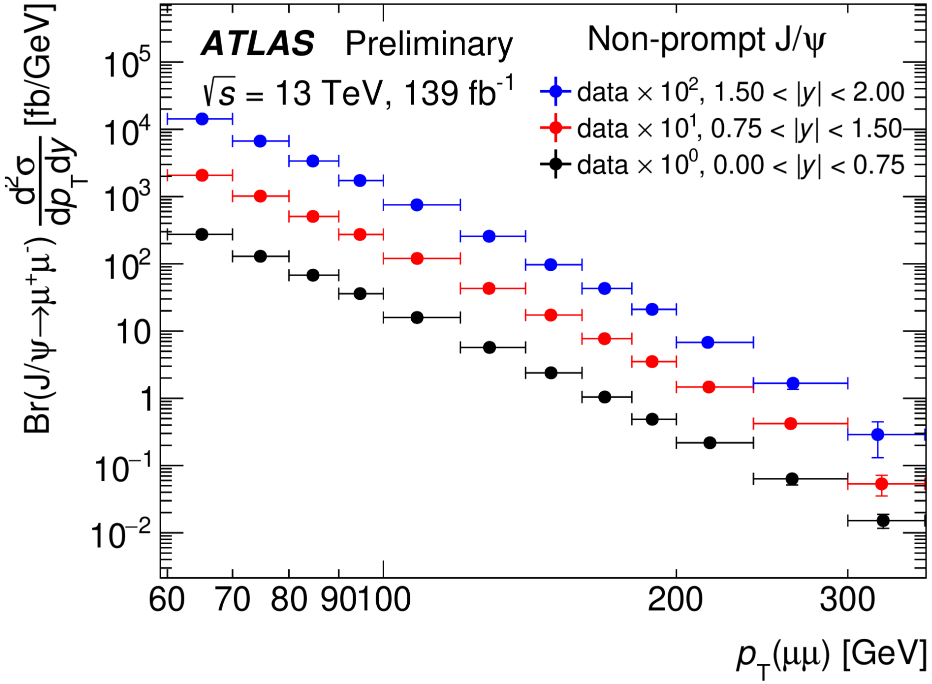
$$F^{NP}(p_T,y)=\frac{N_\psi^{NP}}{N_\psi^{P}+N_\psi^{NP}}$$

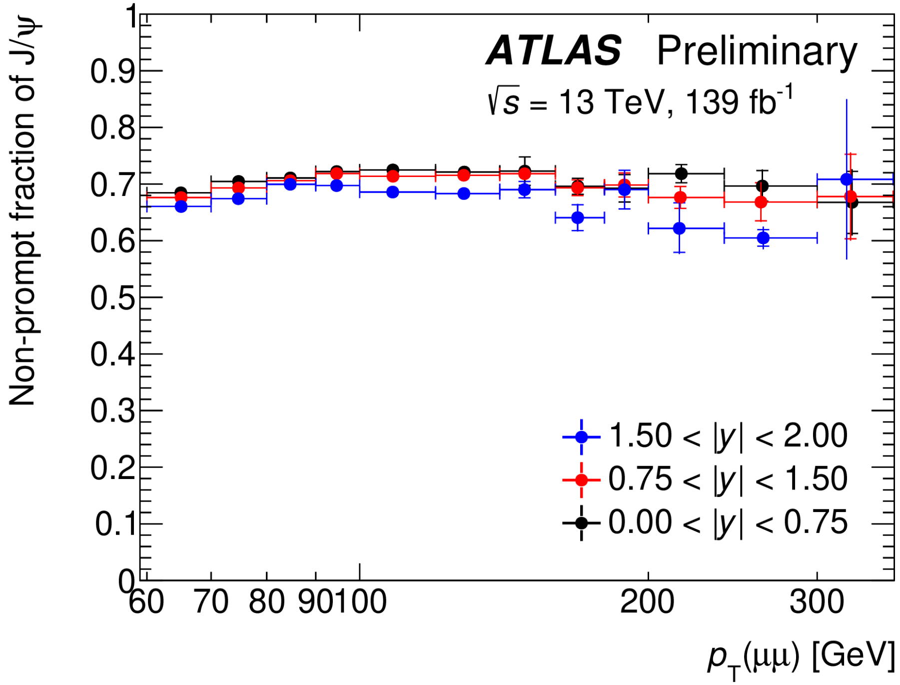
- Compute production ratios of ψ(2S) relative to J/ψ:

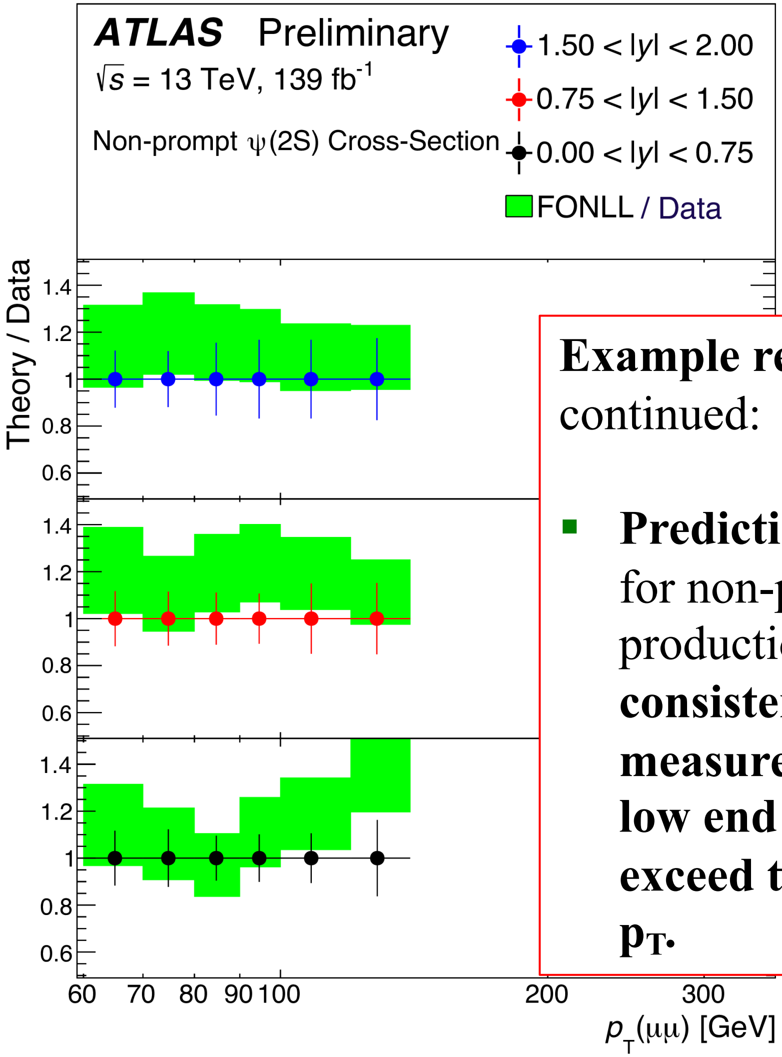
$$R^{P,NP}(p_T,y)=\left(\frac{A(\psi(2S))}{A(J/\psi)}\right)^{-1}\frac{N_{\psi(2S)}^{P,NP}}{N_{J/\psi}^{P,NP}}$$

Example results:

- **Similar p_T dependence for prompt and non-prompt cross sections**
- **Non-prompt fraction close to constant** in this p_T range

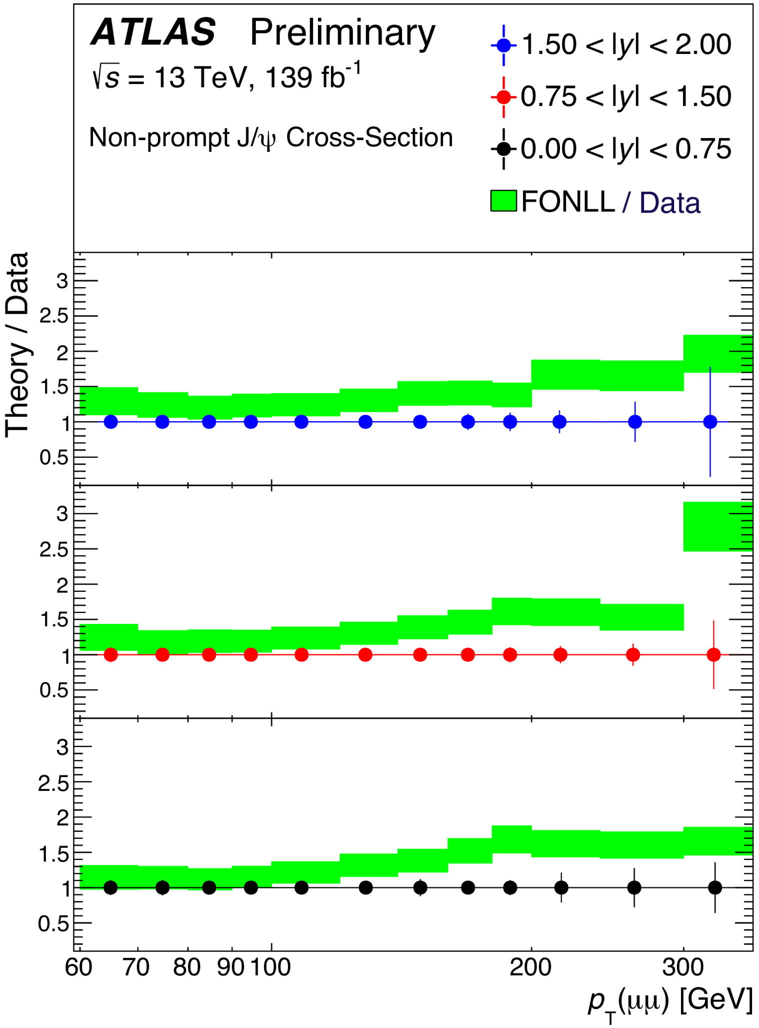


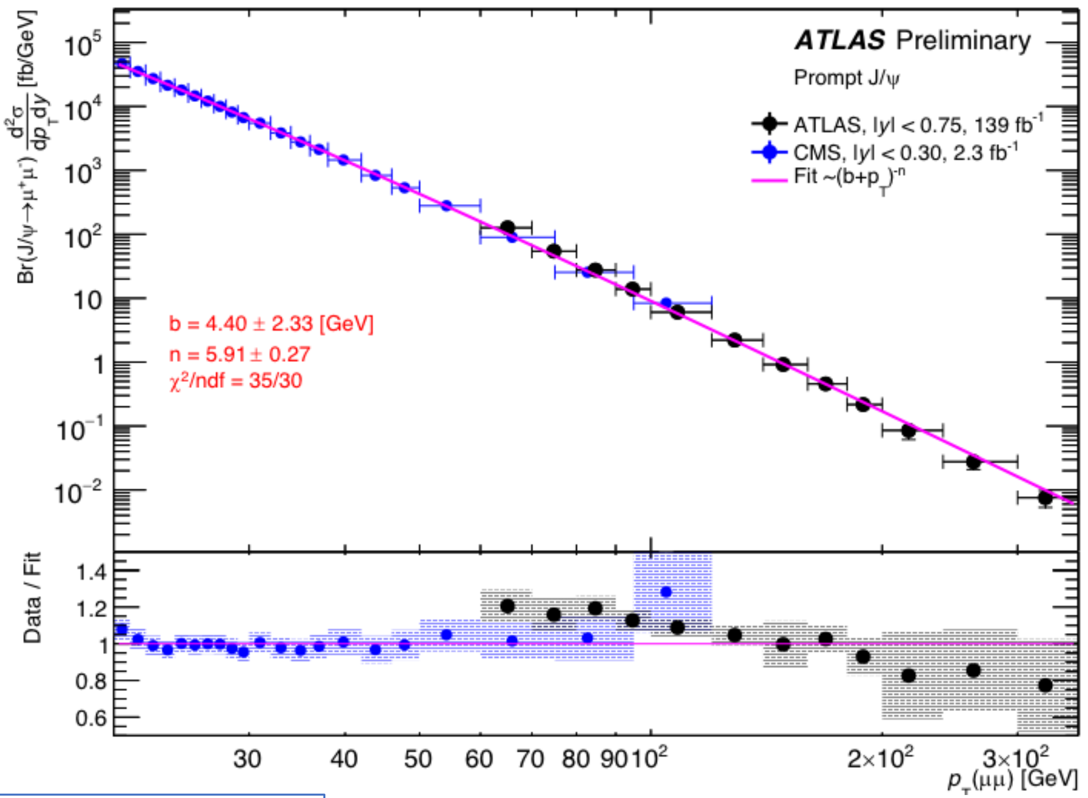




Example results, continued:

- **Predictions** at FONLL for non-prompt production **are consistent with measurement at the low end of p_T but exceed the data at high p_T.**





Excellent agreement between this ATLAS result for prompt J/ψ in the central rapidity range, and the CMS measurement in the closest-matching rapidity range. Both sets of data are fitted to $\sim(b+p_T)^{-n}$ for $b = 4.40 \pm 2.33$ and $n = 5.91 \pm 0.27$.

Summary

ATLAS presents recent results on:

- Measurement of the effective lifetime of the $B_s^0 \to \mu^+\mu^-$ decay – *This first ATLAS measurement of this quantity is consistent with the Standard Model prediction and with measurements by CMS and LHCb.*

- Measurement of the production cross section of J/ψ and ψ(2S) mesons at high p_T – *The p_T range extends beyond previous studies and may help discriminate among models; but the non-prompt production diverges from the prediction increasingly with growing p_T.*