Heavy Flavour results from ATLAS

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McGill

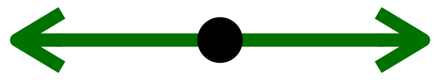
ATLAS EXPERIMENT

Outline

- ATLAS heavy-flavour physics studies span numerous topics:
  - **Production**: heavy open-flavour hadrons and onia cross-sections
  - **Decay**: branching fractions, *CP* studies, lifetimes
  - **Spectroscopy**: exotic and conventional hadrons
  - **Strengths**: muon final states, vertexing, extensive kinematic ranges

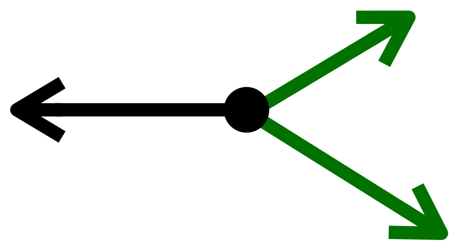
- Latest topics, for Epiphany 2025:

  - **Charmonium**: differential J/ψ and $\psi(2S)$ meson production cross-sections — Eur. Phys. J. C 84 (2024) 189; ATLAS Briefing



  - **Open charm**: differential $D^{\pm}$ and $D_s^{\pm}$ meson production cross-sections — arXiv:2412.15742 (submitted JHEP)

    Today: first public presentation



  - **Open beauty**: precision B^0 meson effective lifetime measurement — arXiv:2411.09962 (submitted EPJC); ATLAS Briefing

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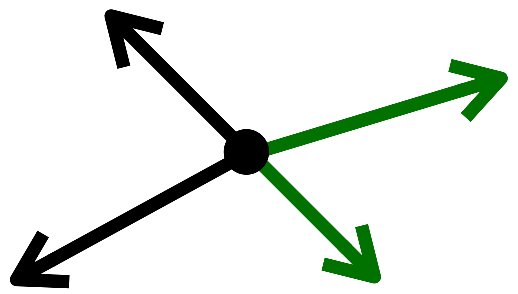
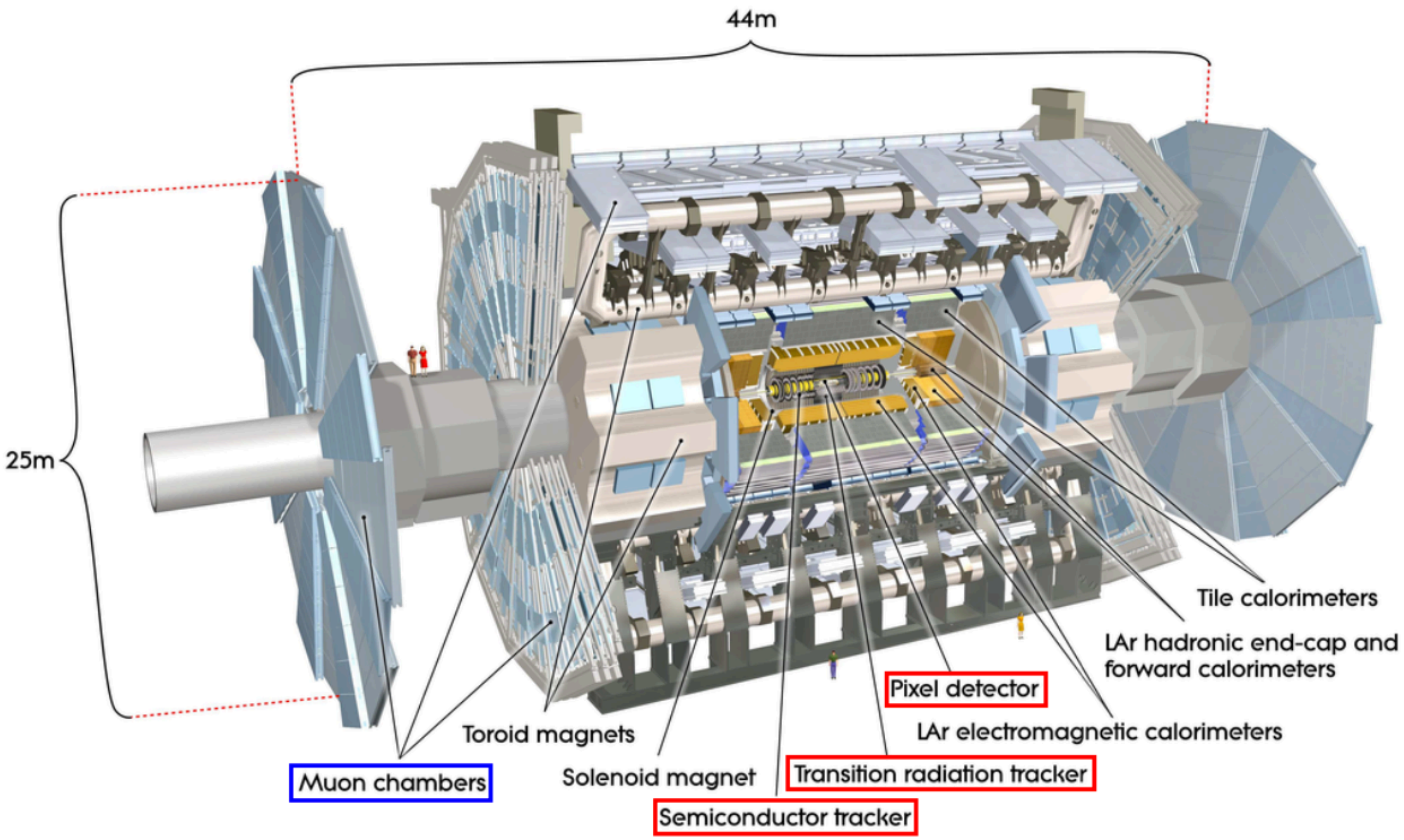
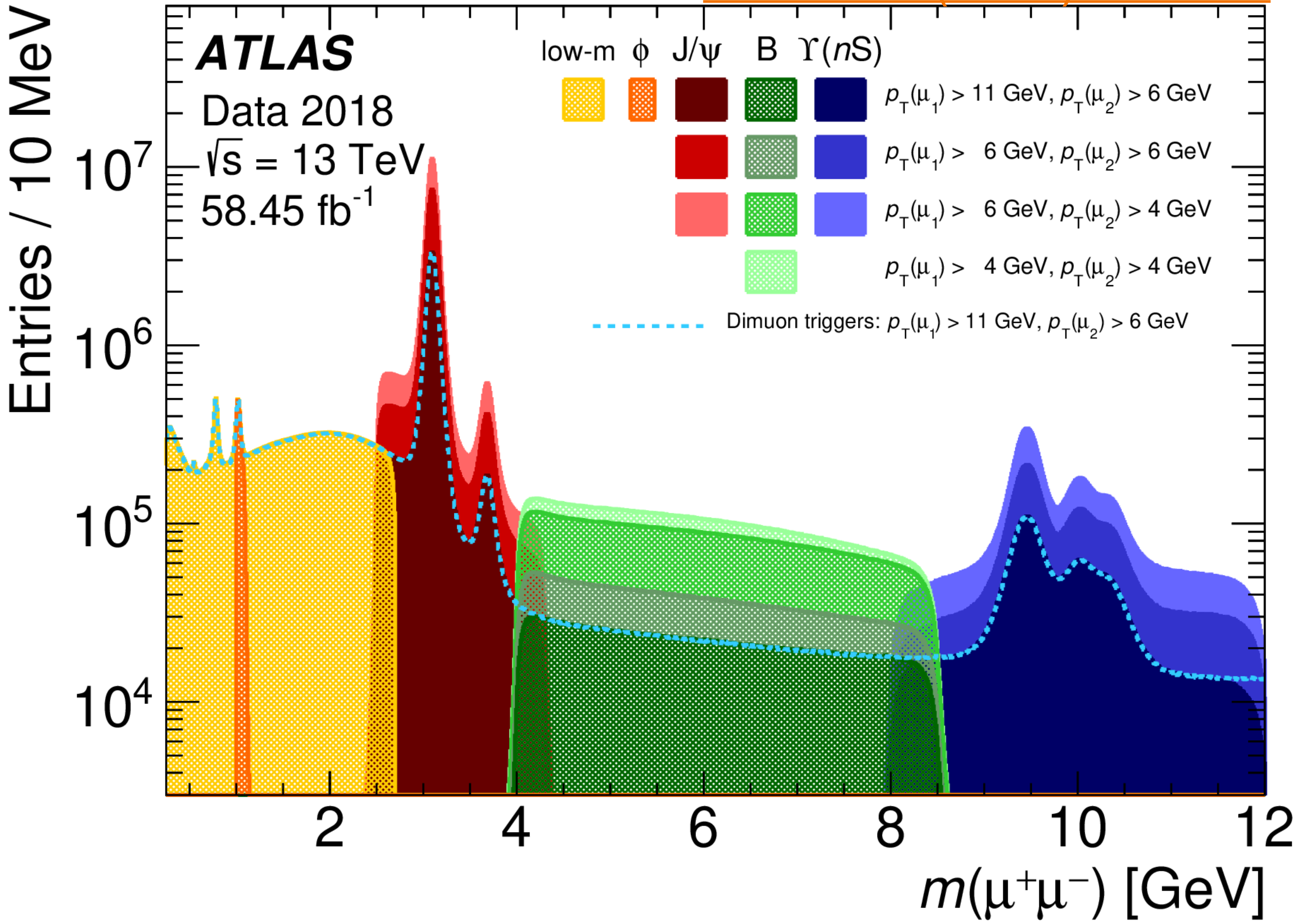


ATLAS detector subsystems and triggers for Heavy Flavour studies



- **Muon Spectrometer**: reconstruction $p_T > 2.5$ GeV
- **Inner Detector tracking systems**: $p_T > 0.5$ GeV, $|\eta| < 2.5$

JINST 15 (2020) P09015



- **Multi-level trigger system**: L1 (hardware) and High-Level Trigger (software)
- **Triggering for heavy flavour**, typically
  - di-muon and single-muon triggers
  - Muon p_T thresholds: 4, 6, 11 GeV
  - More info: *B-physics trigger performance*

Charmonium: differential J/ψ and $\psi(2S)$ production cross-sections

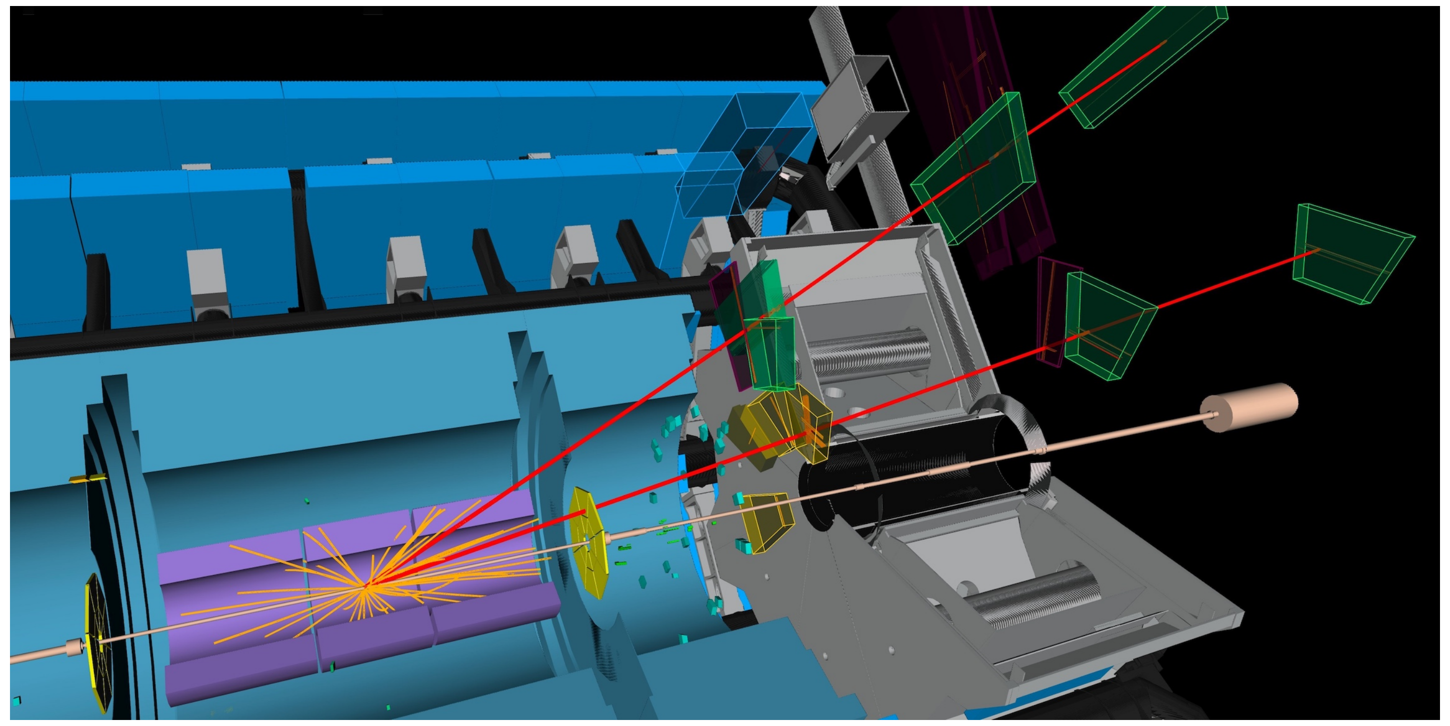
Motivation and Analysis Approach

Eur. Phys. J. C 84 (2024) 189

ATLAS Briefing

- Heavy quarkonia uniquely probe near the boundary between pQCD and non-pQCD

- Quarkonium production occurs via two mechanisms:
  - **Prompt**: short-lived QCD processes, either in *pp* interactions or feed-down from heavier states
  - **Non-prompt**: *b*-hadron decays



- pQCD much better at describing non-prompt than prompt production

- Kinematic range now pushed to significantly higher regimes, previously unexplored:
  - J/ψ : $p_T < 100$ GeV $\rightarrow$ $p_T < 360$ GeV
  - $\psi(2S)$: $p_T < 100$ GeV $\rightarrow$ $p_T < 140$ GeV

- Achieved using an **updated trigger strategy**, to overcome insufficient angular resolution at high p_T:
  - Low $p_T(\psi) < 60$ GeV: use di-muon triggers
  - High $p_T(\psi) > 60$ GeV: use single-muon trigger (50 GeV muon p_T threshold)

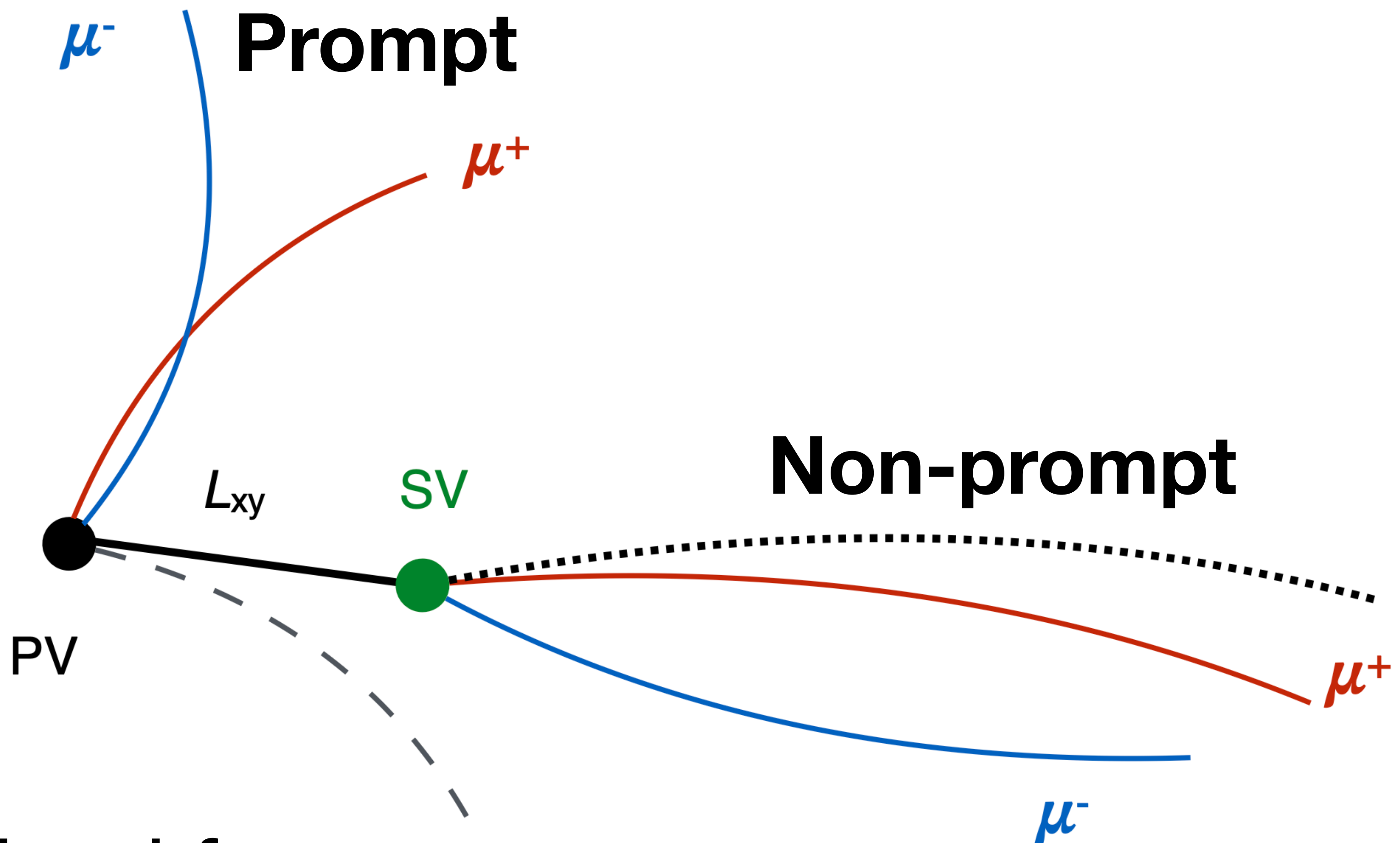
- Distinguish between [J/ψ, $\psi(2S)$] and [Prompt, Non-prompt] by 2D fits of **di-muon mass** and **pseudo-proper lifetime**

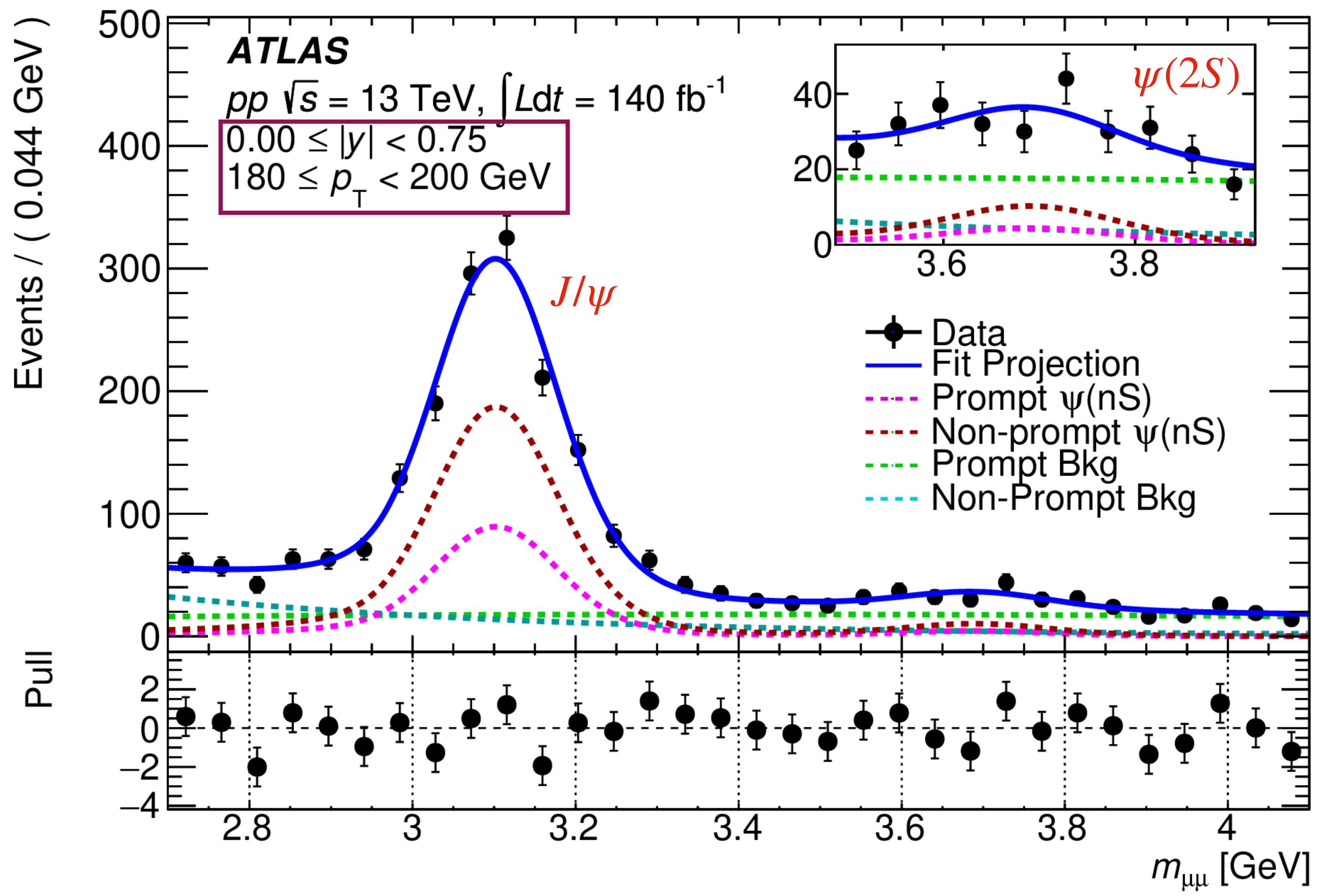
Charmonium: differential J/ψ and $\psi(2S)$ production cross-sections

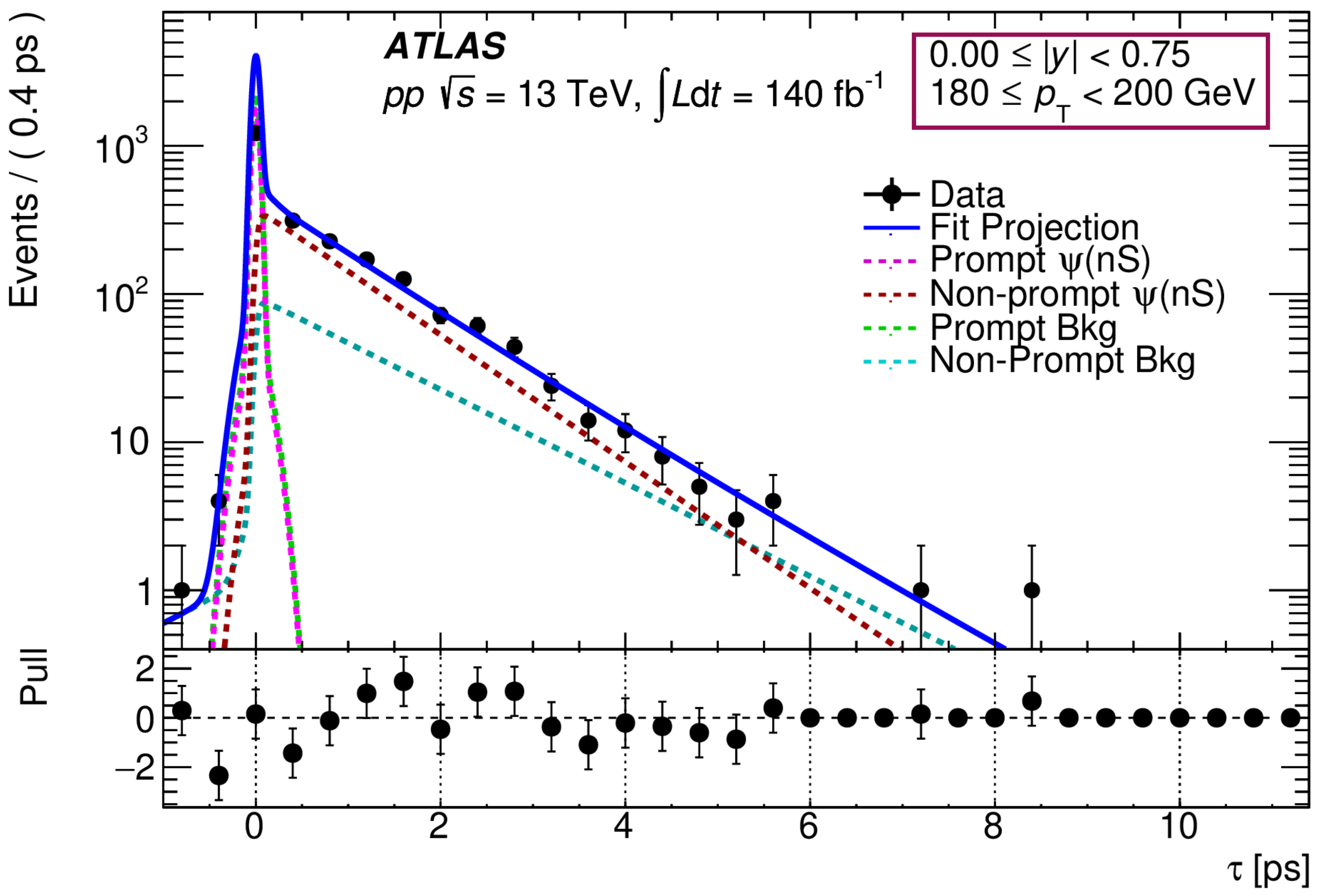
- 2D $m_{\mu\mu}$, τ Fits: 3 rapidity (y) bins × 34 p_T bins (in interval 8-360 GeV) = 102 phase-space bins

- Reconstructed pseudo-proper lifetime:

$$\tau = \frac{m_{\mu\mu} L_{xy}}{p_T}$$







- Differential cross-sections determined from prompt (P) and non-prompt (NP) J/ψ and $\psi(2S)$ yields:

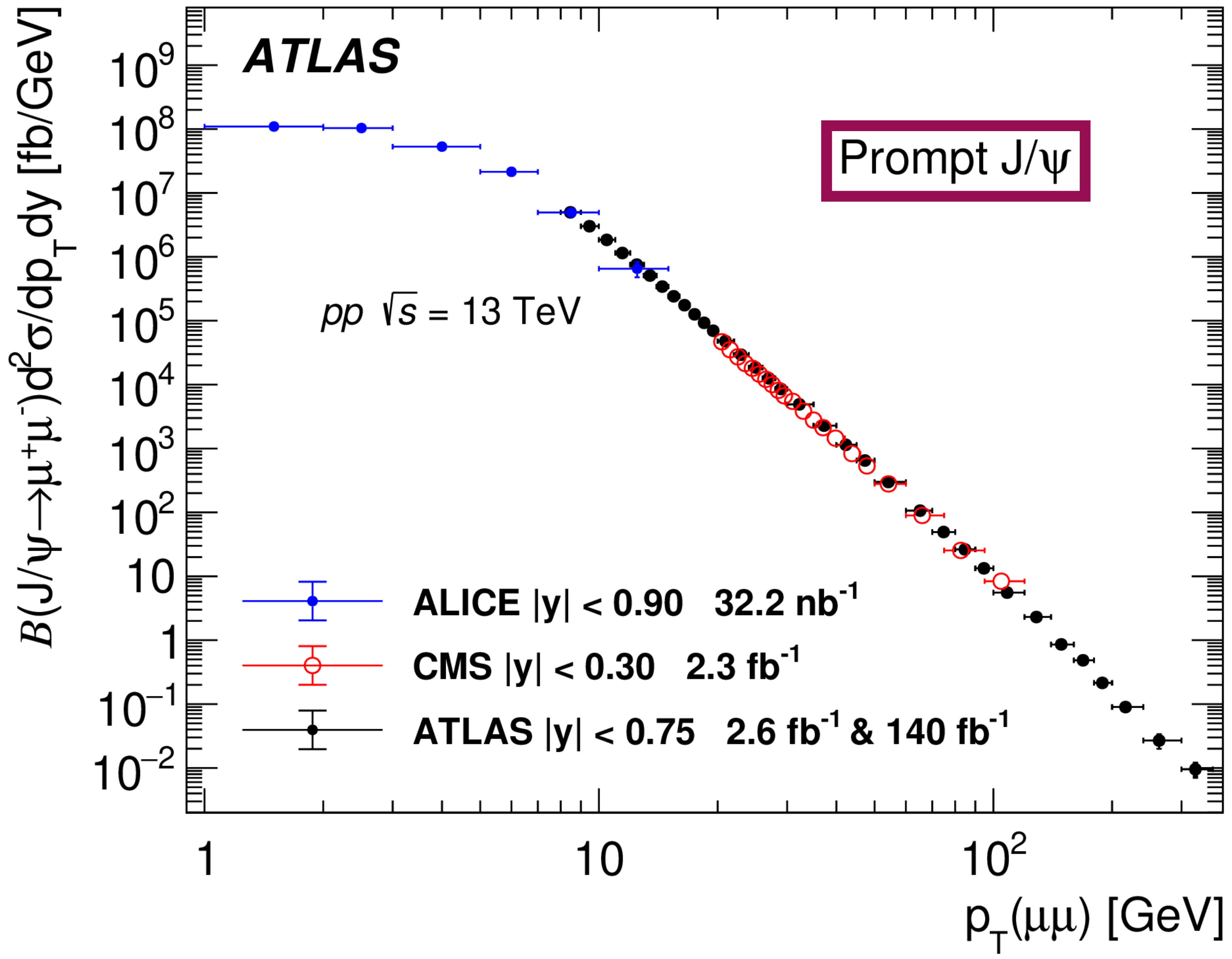
$$\frac{d^2\sigma^{P,NP}(pp \to \psi)}{dp_T dy} \times \mathcal{B}(\psi \to \mu^+\mu^-) = \frac{1}{\mathcal{A}(\psi)\epsilon_{trig}\epsilon_{trigSF}\epsilon_{reco}\epsilon_{recoSF}} \frac{N_\psi^{P,NP}}{\Delta p_T \, \Delta y \, \int \mathcal{L}dt}$$

- Also extracted: fraction of NP production F_ψ^{NP} and $R^{P,NP}$, the $\psi(2S)$ to J/ψ production ratios

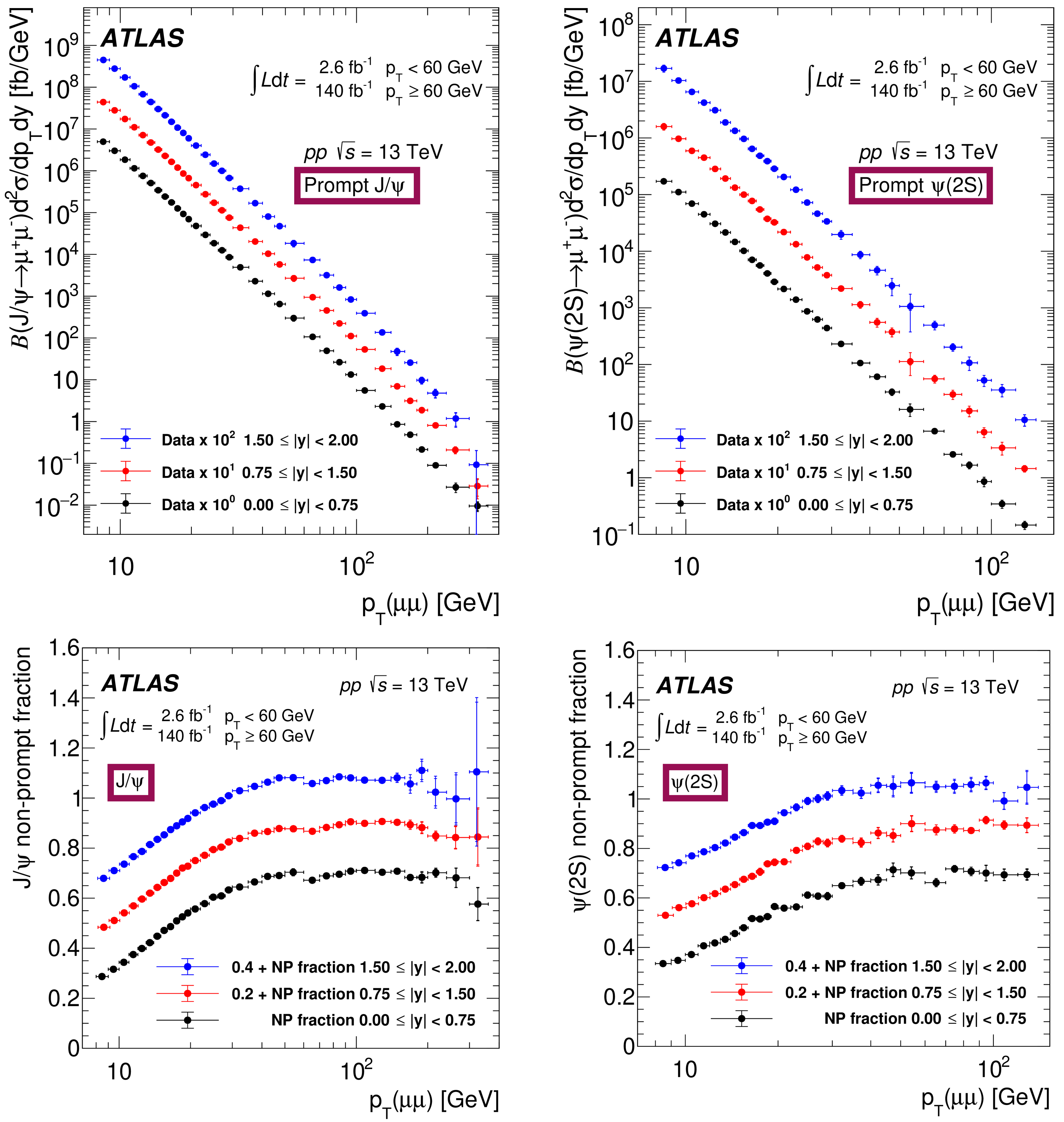
Charmonium: differential J/ψ and $\psi(2S)$ production cross-sections

Results (nominal isotropic spin-alignment scenario assumed)

- 9 [6] orders of magnitude spanned by J/ψ [$\psi(2S)$] cross-sections
- Non-prompt fractions increase at lower p_T, plateau at higher p_T
- Consistency with other LHC experiments; overlapping kinematic ranges:



ALICE: JHEP (2022) 190
CMS: PLB 780 (2018) 251



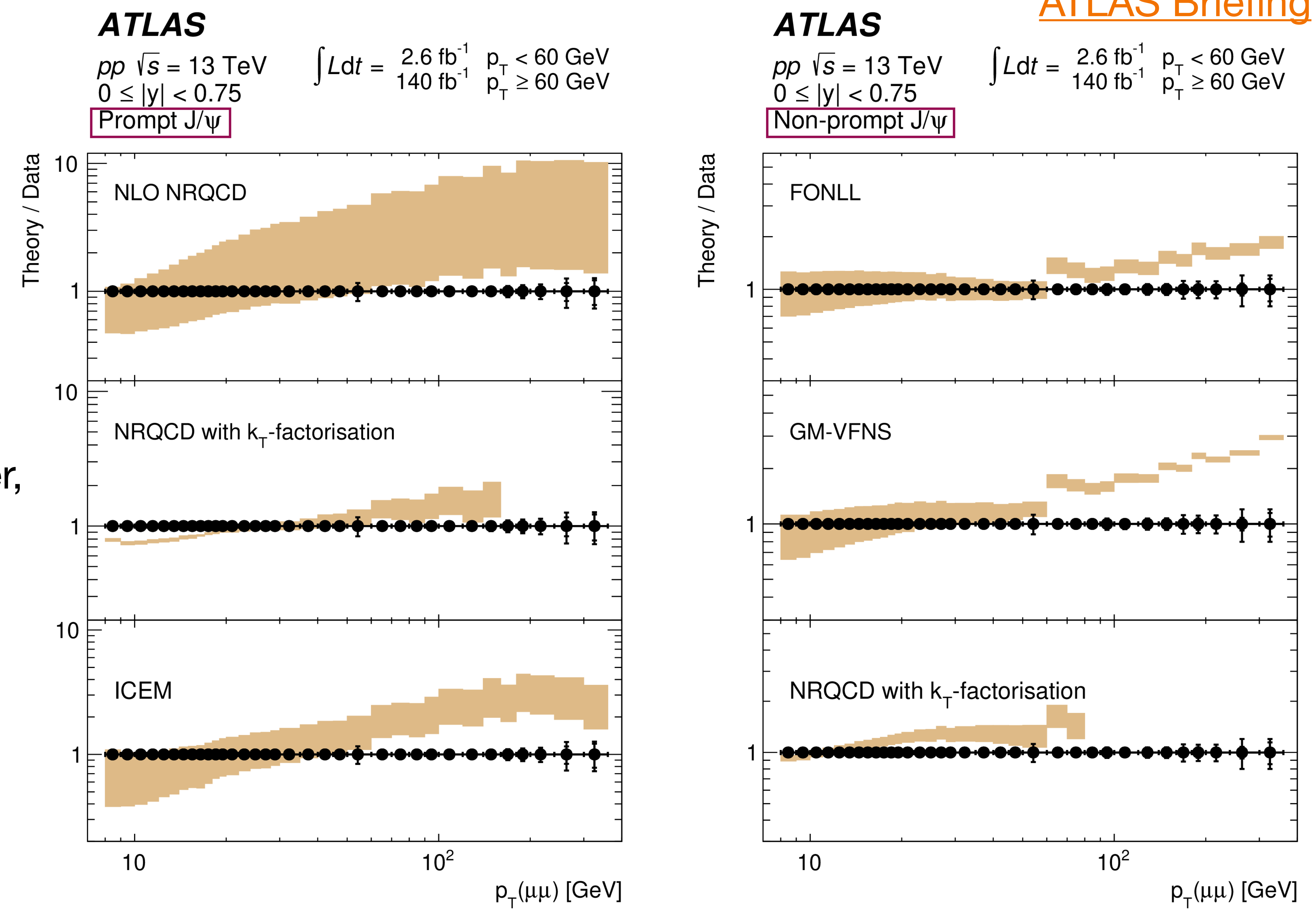
Charmonium: differential J/ψ and $\psi(2S)$ production cross-sections

Eur. Phys. J. C 84 (2024) 189

ATLAS Briefing

Theory-Comparison Implications

- **Prompt** J/ψ production: predicted spectra harder than those measured; room to improve all models
- **Non-prompt** J/ψ production: predictions better, though still over-estimating at higher p_T
- Similar trends for the $\psi(2S)$ analogues

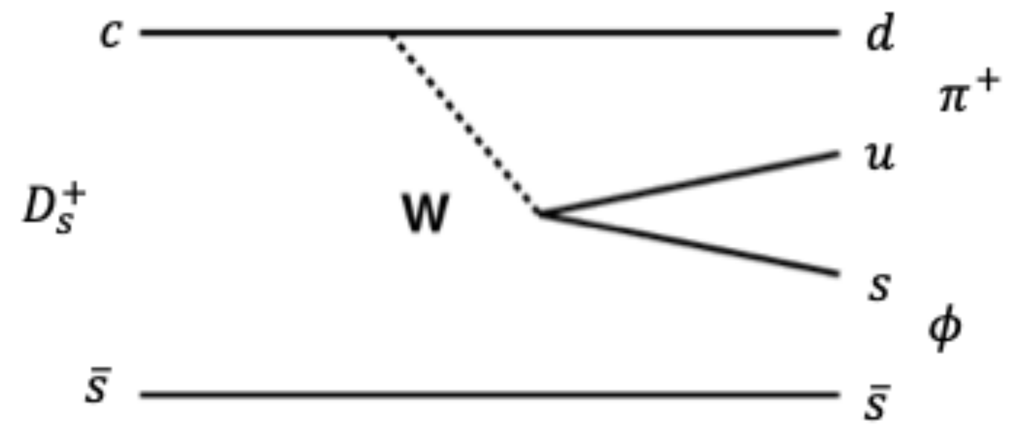


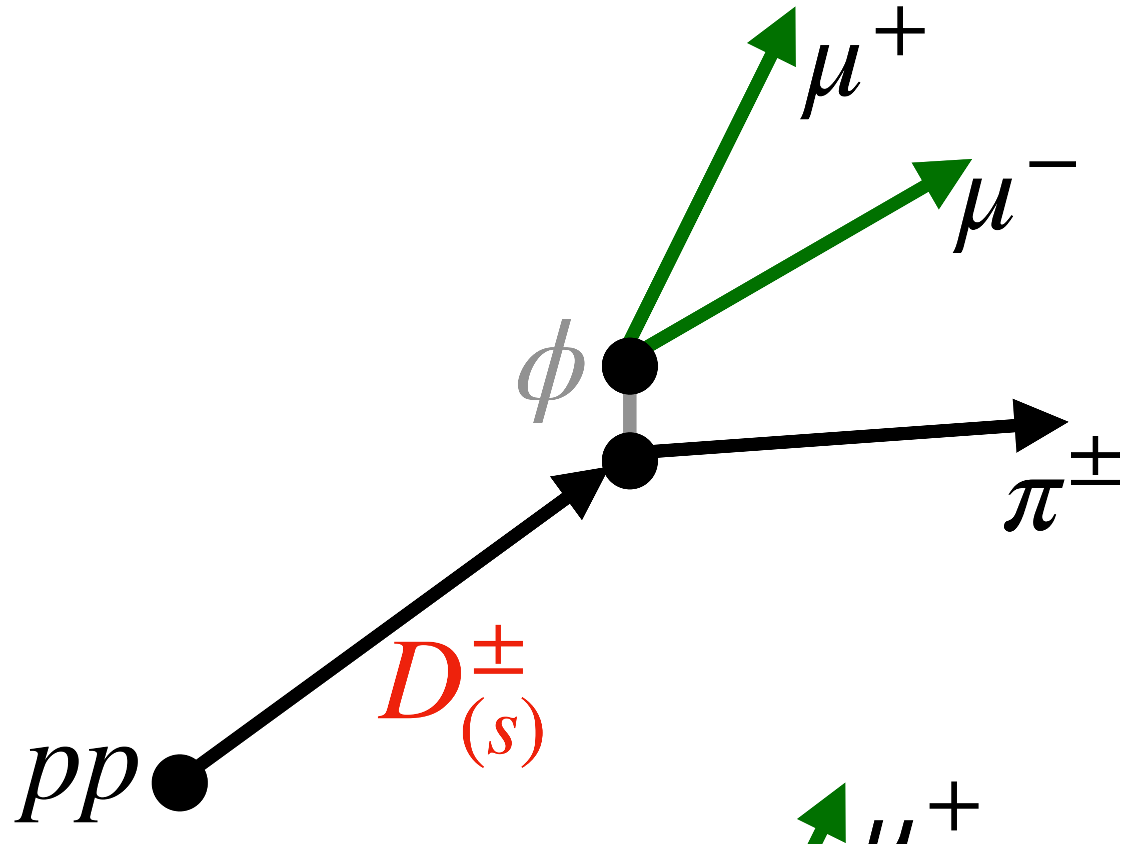
Open Charm: differential $D^{\pm}$ and $D_s^{\pm}$ meson cross-sections

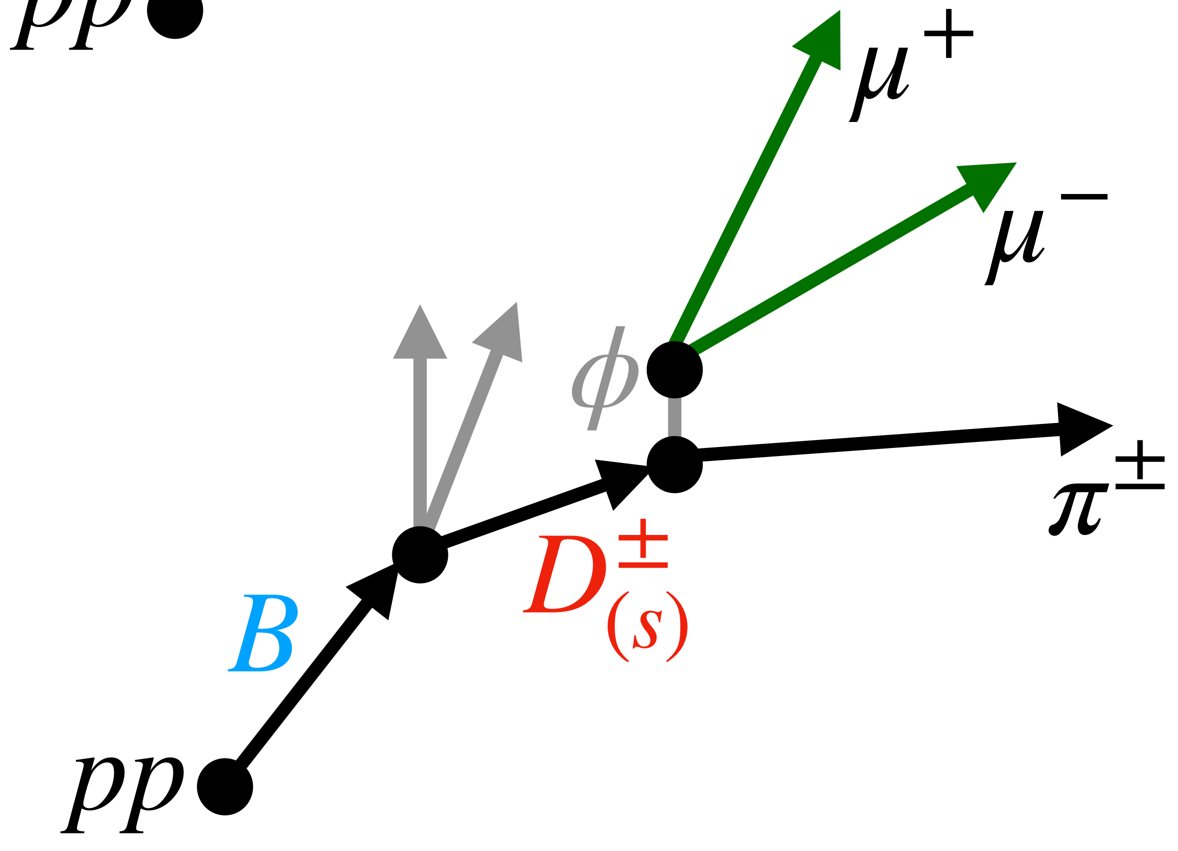
- Heavy hadron production in *pp* collisions is a fundamental process that tests perturbative QCD calculations, which have had persistently large uncertainties:
  - Hard-scatter **energy scales** are comparable to the **heavy quark** masses
  - **Prompt hadronisation** of charm quarks vs. **non-prompt production** via *b*-decays
  - Challenges modelling **non-perturbative effects**, *e.g.*, hadronisation

- **This study**:
  - Measure $D^{\pm}$ and $D_s^{\pm}$ production cross-sections simultaneously and differentially using the channels $D^{\pm}_{(s)} \to \phi\pi^{\pm} \to \mu^{+}\mu^{-}\pi^{\pm}$; less abundant than the analogous $\phi \to K^{+}K^{-}$ process, but can use di-muon triggers and have less background
  - Push measurement of the $D_s^{\pm}$ cross-section up to p_T = 100 GeV (a first)
  - **Selection**:
    - Di-muon system: triggers, opposite charge, invariant-mass criterion
    - Track requirements: total charge, minimum p_T, secondary-vertex criteria
    - Main observable: invariant mass, $m_{\mu\mu\pi}$

arXiv:2412.15742 (submitted JHEP)







Open Charm: differential $D^{\pm}$ and $D_s^{\pm}$ meson cross-sections

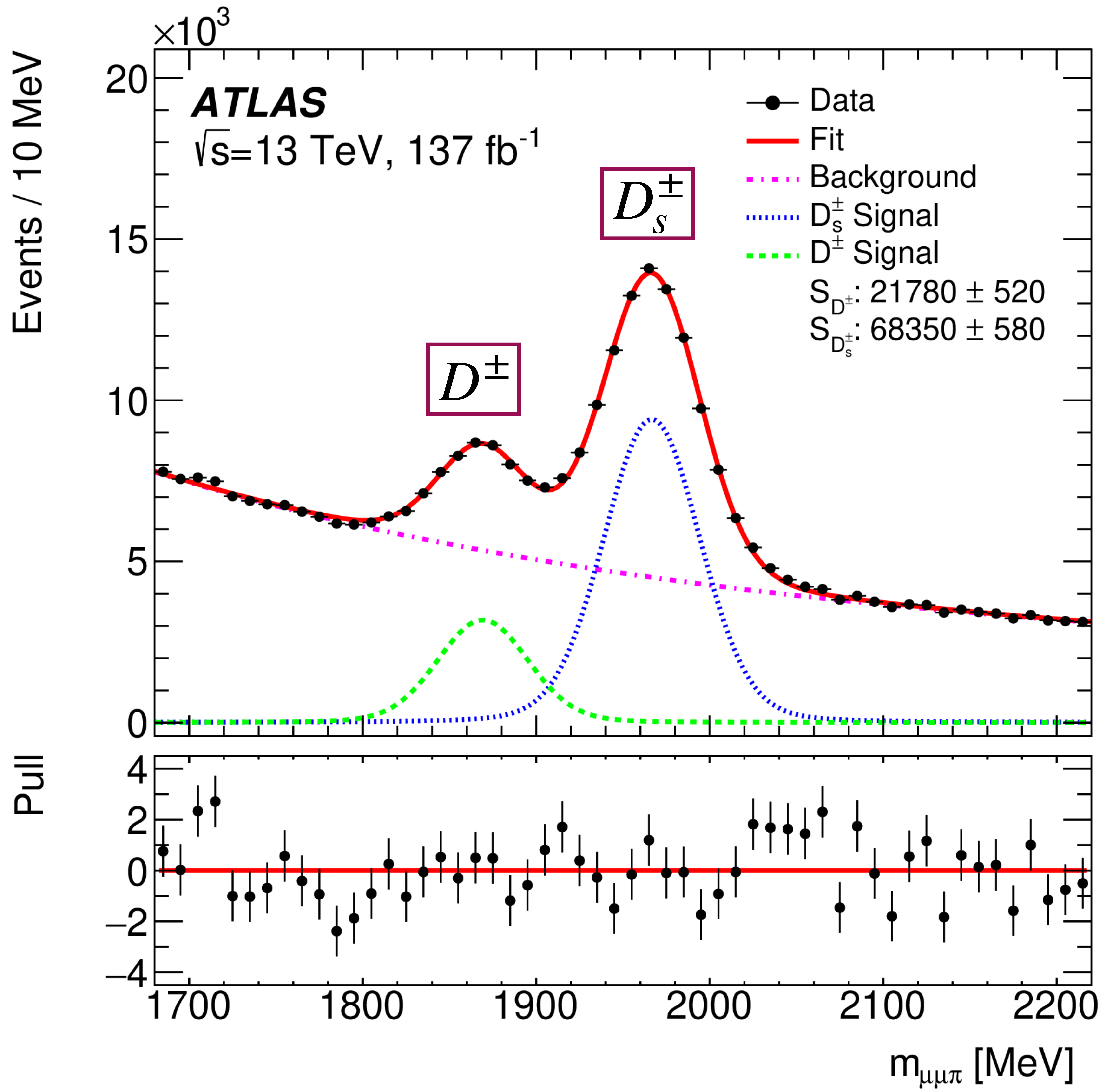
Invariant mass fitting

- Extended unbinned maximum likelihood fit for signal yields in terms of invariant mass $m_{\mu\mu\pi}$:

$$\mathcal{L}(m) = \frac{e^{-(S_{D^\pm}+S_{D_s^\pm}+B)}}{n!} \prod \left[S_{D^\pm} P_{D^\pm}(m) + S_{D_s^\pm} P_{D_s^\pm}(m) + B P_{\mathrm{Bkg}}(m) \right] \times \mathcal{G}(\Delta)$$

$$P_{D^\pm}(m) = \mathrm{Voigt}(m; m_{D^\pm}, \gamma_{D^\pm}, \sigma_{D^\pm})$$
$$P_{D_s^\pm}(m) = \mathrm{Voigt}(m; m_{D_s^\pm}, \gamma_{D_s^\pm}, \sigma_{D_s^\pm})$$
$$P_{\mathrm{Bkg}}(m) = A_{\mathrm{norm}} \cdot e^{(c_1 m + c_2 m^2)}$$
$$\mathcal{G}(\Delta) = \mathrm{Gauss}(\Delta; \mu_\Delta, \sigma_\Delta)$$

- Voigtian distribution: convolution of Breit-Wigner and Gaussian
- $\Delta \equiv m_{D_s^\pm} - m_{D^\pm}$ mass difference, required to be close to the world-average value μ_Δ under a Gaussian constraint
- Fit is designed to be compatible with data in a broad set of kinematic regions while using a small number of parameters

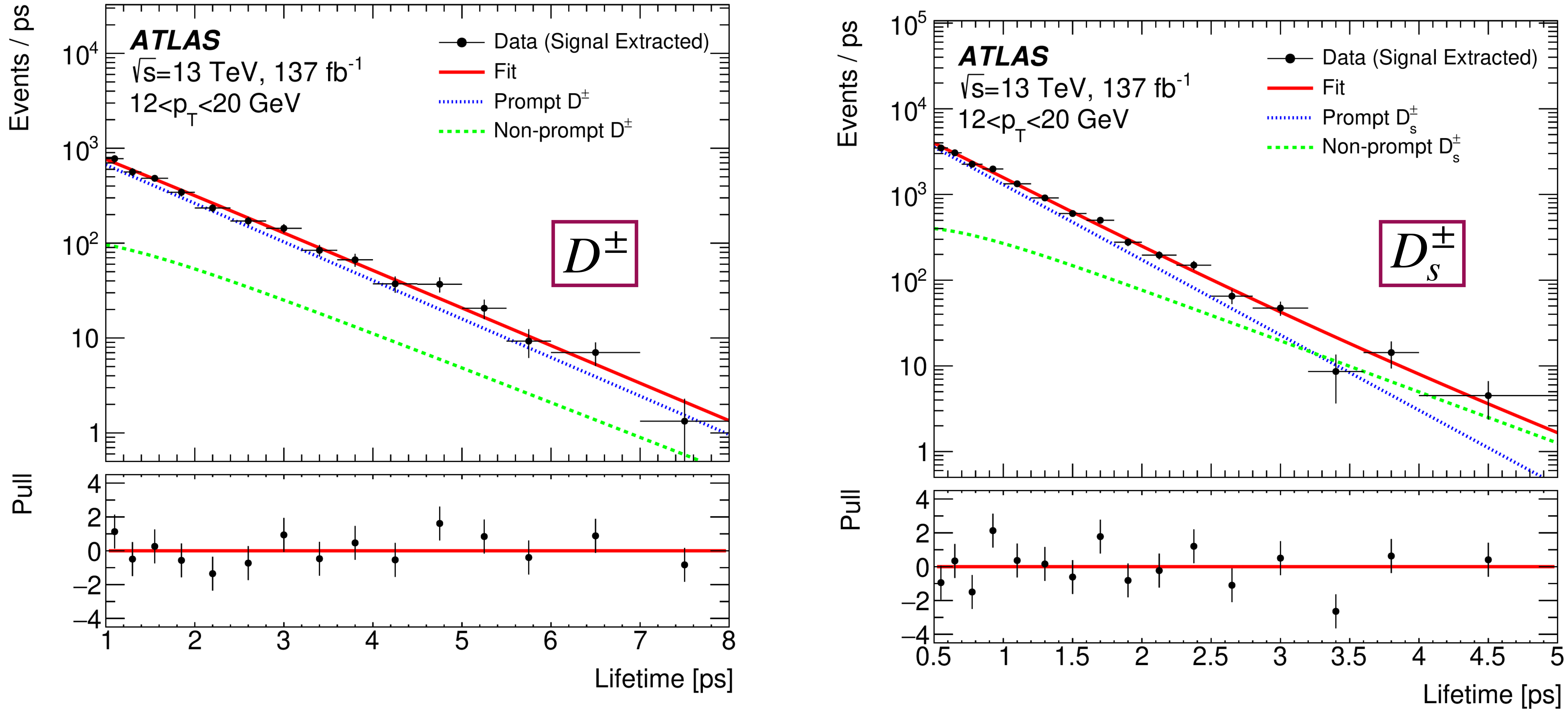


Open Charm: differential $D^{\pm}$ and $D_s^{\pm}$ meson cross-sections

Lifetime fitting

- **Prompt** ($pp \to c\bar{c}X \to D^{\pm}_{(s)}X'$) and **non-prompt** ($pp \to b\bar{b}Y \to cY' \to D^{\pm}_{(s)}Y''$) production processes manifest differently in the ATLAS detector; constrain their relative contributions using the pseudo-proper lifetime observable $m_{\mu\mu\pi}L_{xy}^{\mu\mu\pi}/p_T^{\mu\mu\pi}$

- **Lifetime fits**: convolutions of Gaussian and error functions with 1 [2] exponentials for prompt [non-prompt] PDFs



Open Charm: differential $D^{\pm}$ and $D_s^{\pm}$ meson cross-sections

Cross-section determination

- **Fiducial volume**: $12 < p_T < 100\,\mathrm{GeV}$ (9 bins)
  $|\eta| < 2.5$ (5 bins)

- Extract signal yields from **invariant mass fits** for $D^{\pm}$ and $D_s^{\pm}$ simultaneously

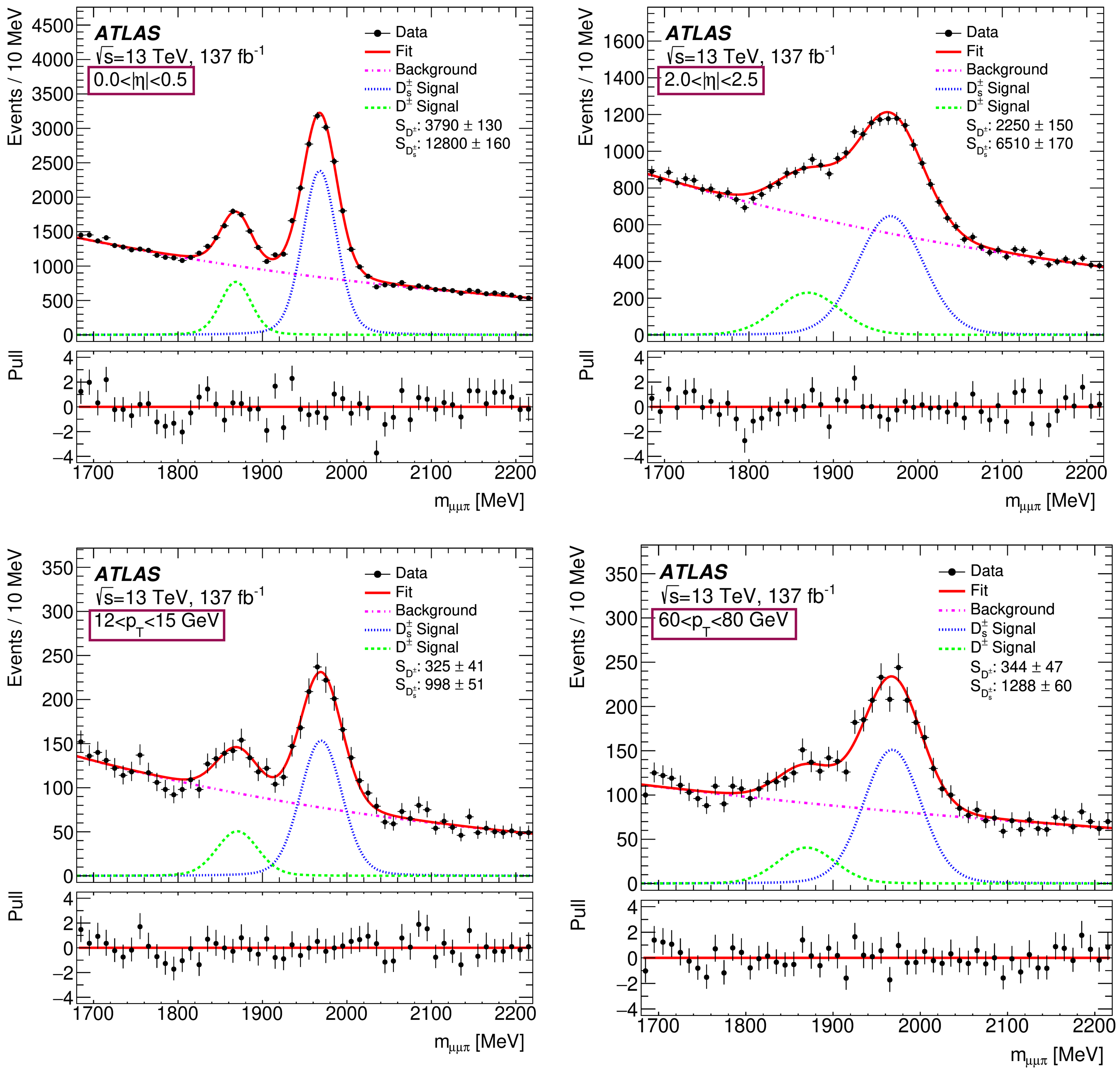
- Correct for **reconstruction efficiencies** in each bin, suitably weighted for prompt and non-prompt production fractions (determined from the lifetime fits)

- Account for **branching fractions**:

$$\mathcal{B}(D^{\pm} \to \phi(\mu\mu)\pi^{\pm}) = \mathcal{B}(D^{\pm} \to \phi\pi^{\pm}) \times \mathcal{B}(\phi \to \mu\mu)$$

$$\mathcal{B}(D_s^{\pm} \to \phi(\mu\mu)\pi^{\pm}) = \frac{\mathcal{B}(D_s^{\pm} \to \phi(K^+K^-)\pi^{\pm})}{\mathcal{B}(\phi \to K^+K^-)} \times \mathcal{B}(\phi \to \mu\mu)$$

Since this quotient of world averages has smaller uncertainty than the $\mathcal{B}(D_s^{\pm} \to \phi\pi^{\pm})$ world average



Open Charm: differential $D^{\pm}$ and $D_s^{\pm}$ meson cross-sections

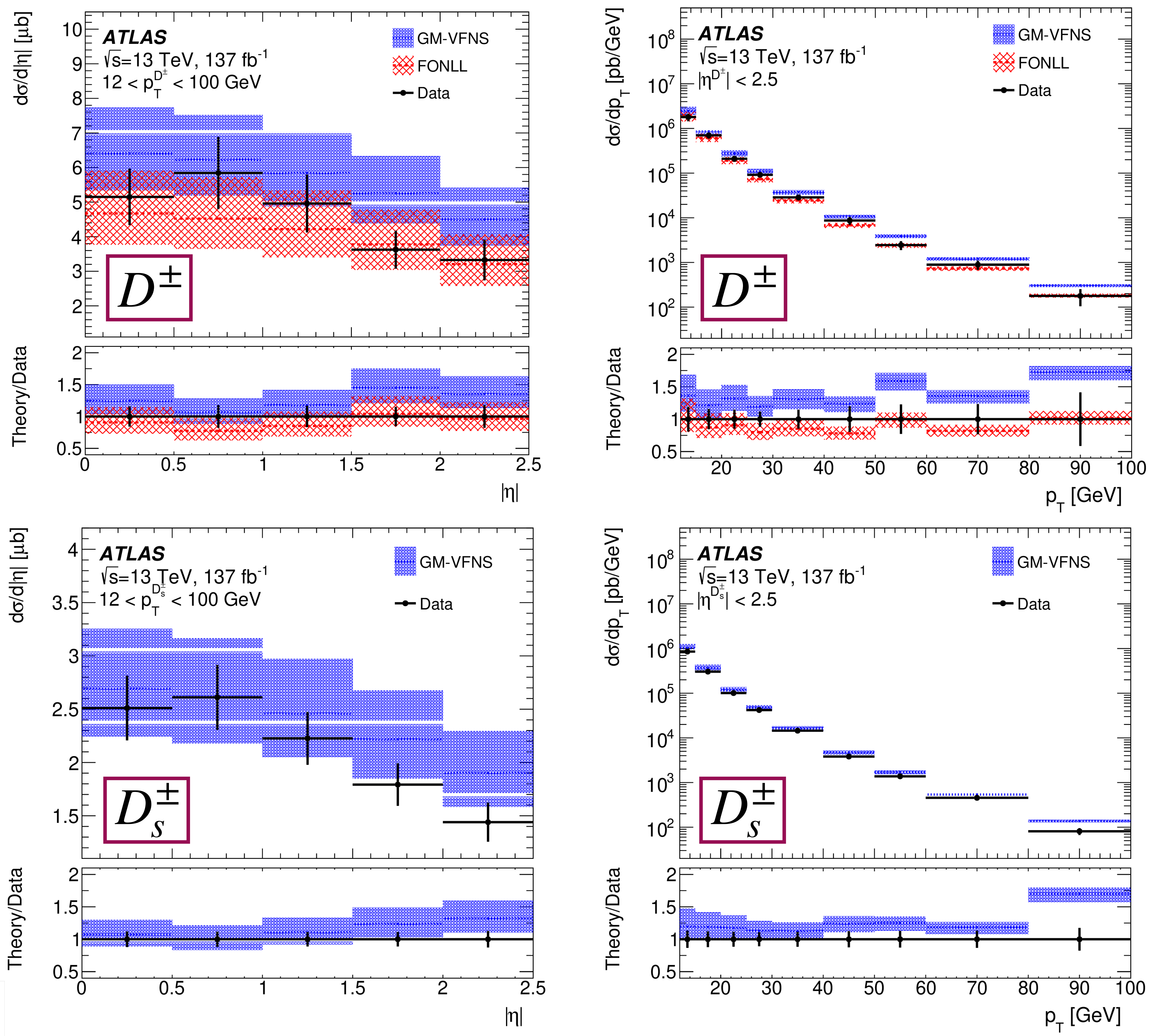
Cross-section results

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}|\eta|}\right|_j = \frac{S^j_{D^\pm/D_s^\pm}}{\int \mathcal{L}\mathrm{d}t \times C^j \times \mathcal{B}(D^\pm/D_s^\pm \to \phi(\mu\mu)\pi^\pm) \times \Delta^j|\eta|}$$

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}p_\mathrm{T}}\right|_i = \frac{S^i_{D^\pm/D_s^\pm}}{\int \mathcal{L}\mathrm{d}t \times C^i \times \mathcal{B}(D^\pm/D_s^\pm \to \phi(\mu\mu)\pi^\pm) \times \Delta^i p_\mathrm{T}}$$

Theory comparisons

- $D^{\pm}$ **production**: at low p_T and in all $|\eta|$ bins, both GM-VFNS and FONLL predictions show good agreement; GM-VFNS shows some overestimation at high p_T
- $D_s^{\pm}$ **production**: only GM-VFNS is available for comparison, showing a similar upward deviation at higher p_T



arXiv:2412.15742 (submitted JHEP)

Open Beauty: precision B^0 meson lifetime measurement

arXiv:2411.09962 (submitted EPJC)

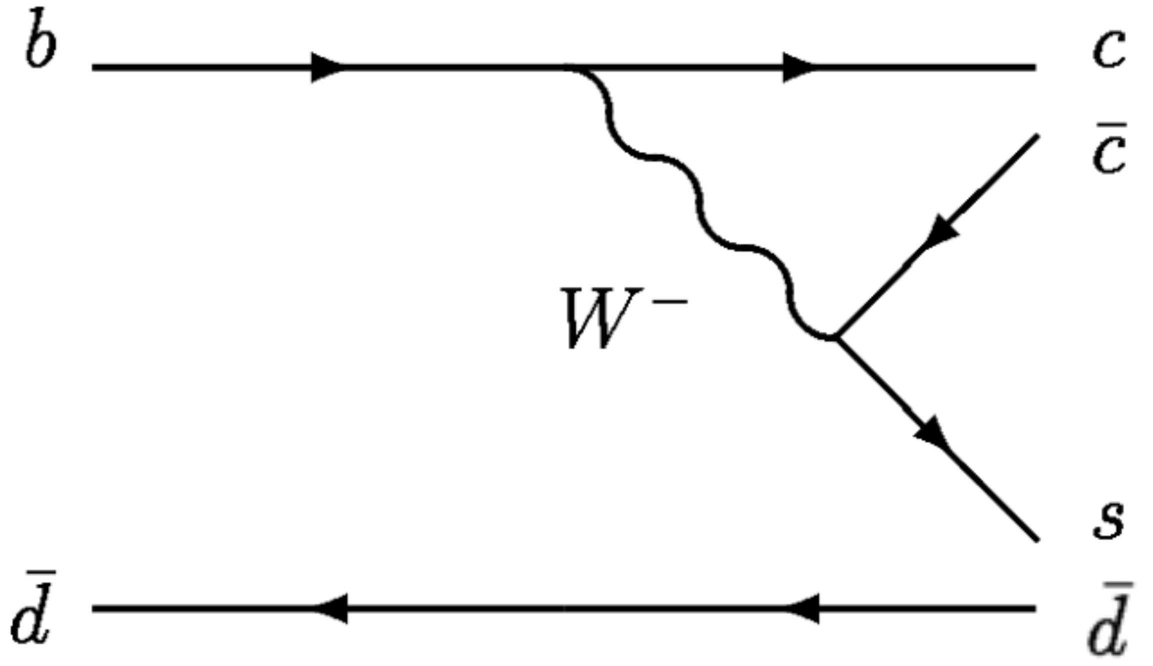
ATLAS Briefing

- Precise B-meson lifetimes and their ratios test weak-interaction roles and have potential BSM sensitivity

- **HQE (heavy quark expansion)** theory describes total decay rate $\Gamma = 1/\tau$ as free b-quark decay at LO plus sub-leading power-suppressed terms invoking perturbative (Wilson coefficients) and non-perturbative matrix elements

- **This study**: Reconstruct weak hadronic spectator-internal colour-suppressed decays

$$B^0 \to J/\psi K^*(892)^0$$



and measure their **Effective Lifetime** τ_{B^0}

- $B^0 - \bar{B}^0$ system has light (L) and heavy (H) mass eigenstates with an **average decay width** $\Gamma_d \equiv (\Gamma_L + \Gamma_H)/2$, a **normalized width difference** $y \equiv \Delta\Gamma_d/(2\Gamma_d) = (\Gamma_L - \Gamma_H)/(2\Gamma_d)$, and a final-state ($f$) dependent **amplitude asymmetry** $A \equiv (R^f_H - R^f_L)/(R^f_H + R^f_L)$ such that:

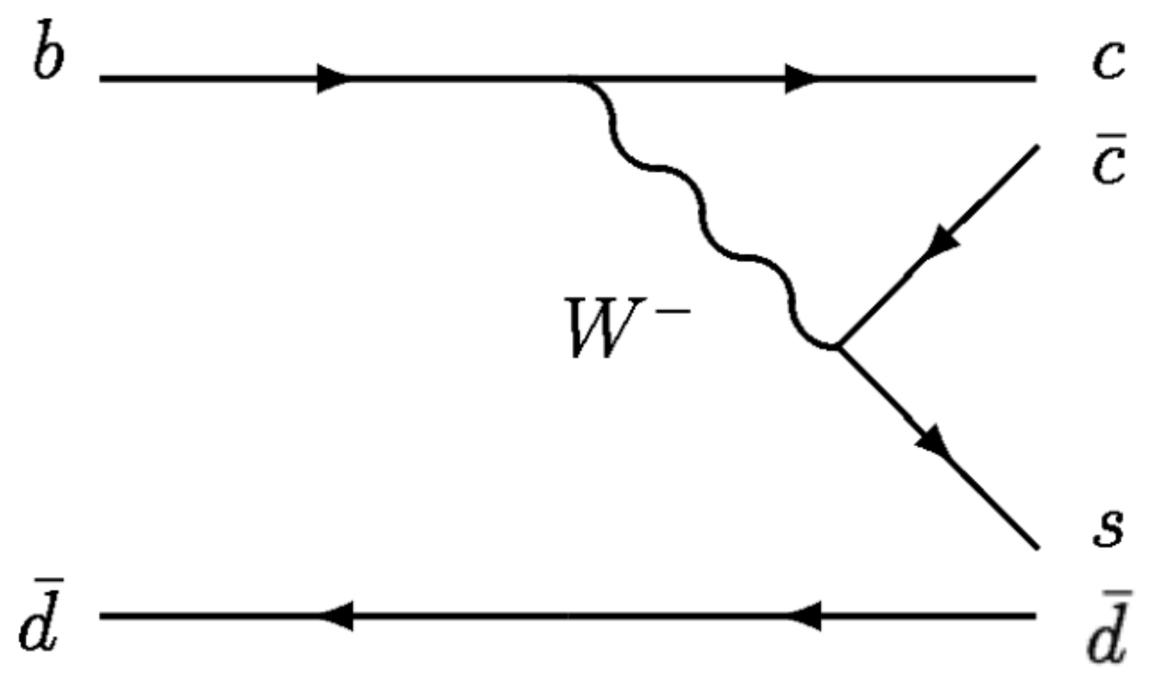
$$\tau_{B^0} = \frac{1}{\Gamma_d} \frac{1}{1 - y^2} \left(\frac{1 + 2Ay + y^2}{1 + Ay} \right)$$

Open Beauty: precision B^0 meson lifetime measurement

Candidate reconstruction and selection criteria

- $B^0 \to J/\psi K^{*0}$ candidates:
  - At least one $J/\psi \to \mu^+\mu^-$ with $\chi^2/\mathrm{ndof} < 10$; within mass window retaining 99.7% J/ψ candidates
  - K^{*0}: Out of the two $K^+\pi^-/K^-\pi^+$ hypotheses, select that closer to $K^*(892)^0$ PDG mass
  - J/ψ and K^{*0}: fit to a common **secondary vertex (SV)**, with di-muon mass constraint to J/ψ PDG mass; $\chi^2/\mathrm{ndof} < 3$
  - 10% events have multiple (avg. 2.1) $J/\psi K^{*0}$ candidates; select that with smaller χ^2/ndof

- **Primary vertex (PV)** selection:
  - Need to choose most likely B_d^0 **production vertex** under pileup conditions (avg. 31)
  - PV positions are recalculated after removing tracks used to reconstruct B_d^0 candidate
  - PV candidate with smallest 3D B_d^0 impact parameter is chosen



- For each B_d^0 candidate, determine pseudo-proper decay time t:

$$t = \frac{m_B L_{xy}^B}{p_T^B}$$

, where L_{xy}^B is the transverse distance between PV and SV, projected on to p_T^B

Open Beauty: precision B^0 meson lifetime measurement

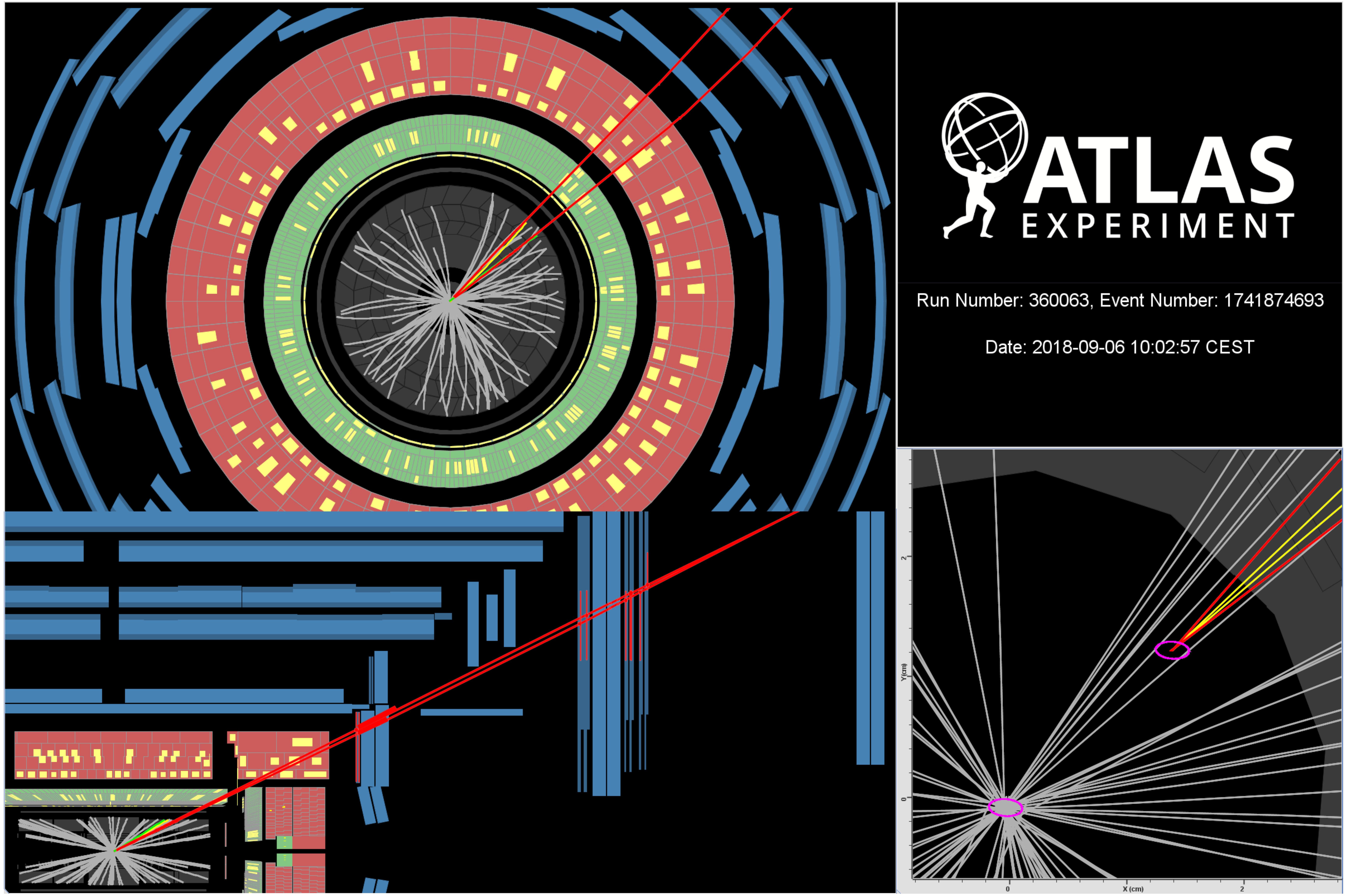
$$B^0 \longrightarrow J/\psi \;\; K^*(892)^0$$

$$K^*(892)^0 \rightarrow K^+ \pi^-$$

$$J/\psi \rightarrow \mu^+ \mu^-$$

Candidate event display

- **Red lines**: muon candidates
- **Yellow lines**: charged hadrons
- **Pink ellipses**: vertices (PV & SV), separated by ~2 cm
- Energy of 4-track system: **83 GeV**, so highly boosted, jet-like!



Open Beauty: precision B^0 meson lifetime measurement

2D unbinned maximum likelihood fit

Mass PDFs

- Signal: Johnson S_U - distribution
- Background: linear + sigmoid functions

Pseudo-proper decay time PDFs

- Signal: exponential convolved with 3-Gaussian resolution function
- Prompt background: 3-Gaussian resolution function
- Combinatorial background: sum of 3 exponentials, each convolved with 3-Gaussian resolution function

Fit projections

- Based on 2,450,500 ± 2400 $B^0 \to J/\psi K^{*0}$ candidate signal events

- Measured effective lifetime: $\tau_{B^0} = 1.5053 \pm 0.0012\ \text{(stat.)} \pm 0.0035\ \text{(syst.)}\ \text{ps}$

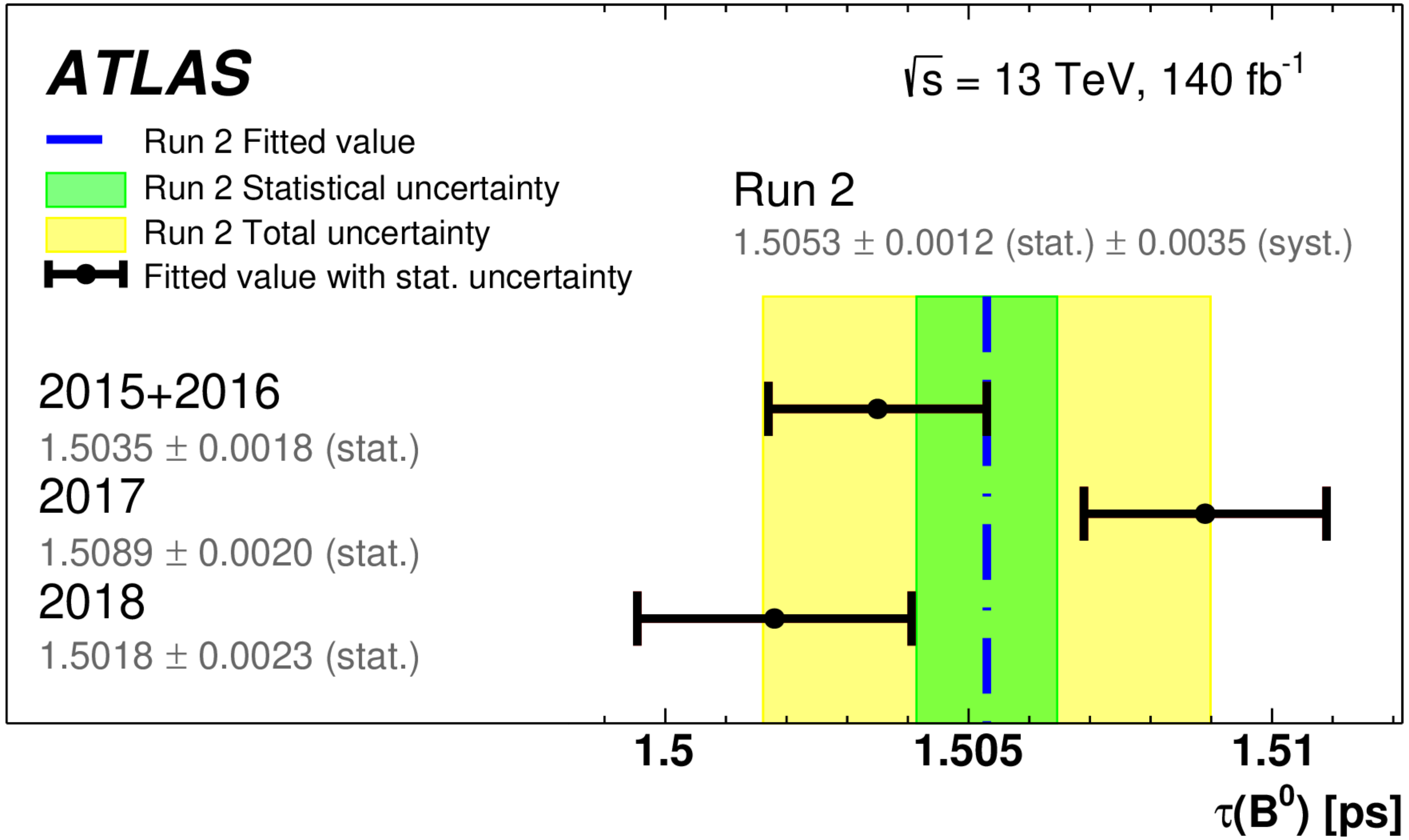
Open Beauty: precision B^0 meson lifetime measurement

arXiv:2411.09962 (submitted EPJC)

ATLAS Briefing

Consistency and stability test

- Separate B^0 lifetime fits for each of 3 data-taking periods
- Black points: subsample lifetimes, stat.-only uncertainties
- *p*-value for consistency, stat.-only: 0.038
- Subsample results are consistent, mutually and with full-sample result



Open Beauty: precision B^0 meson lifetime measurement

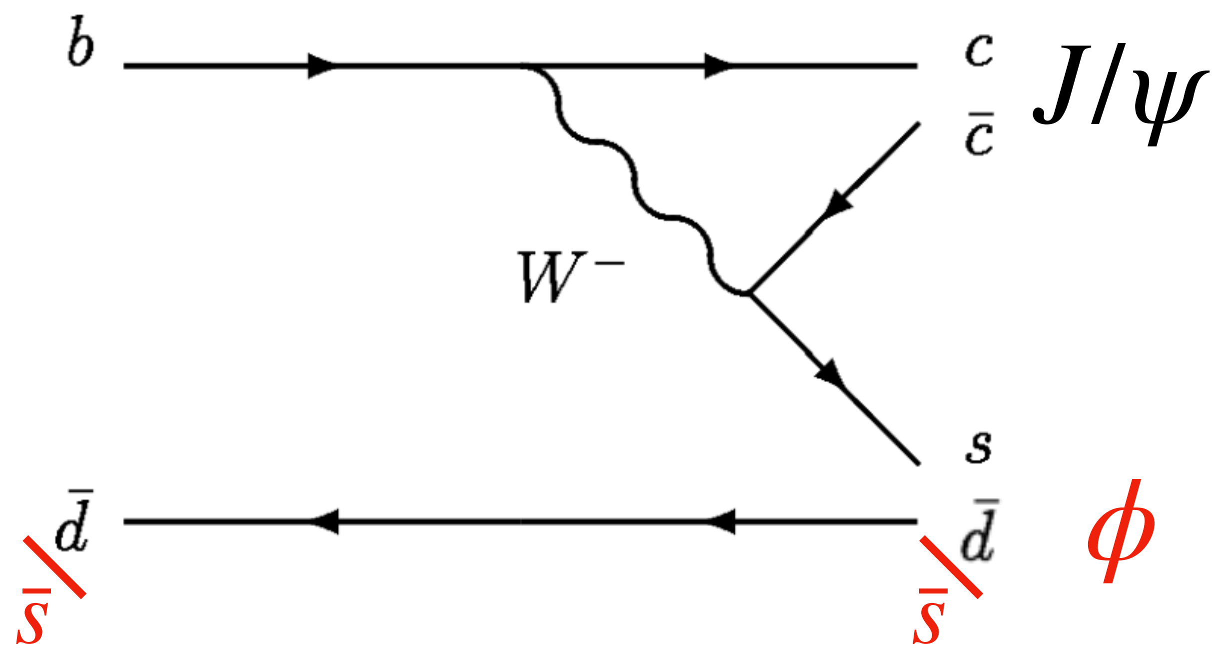
Results: Determination of the B^0 average decay width Γ_d and the ratio Γ_d/Γ_s

Γ_d

- Use HFLAV (2023) input values of $2y = \Delta\Gamma_d/\Gamma_d = 0.001 \pm 0.010$ and asymmetry $A = -0.578 \pm 0.136$ with the ATLAS measured effective lifetime τ_{B^0} to find:

$$\Gamma_d = 0.6639 \pm 0.0005\,(\text{stat.}) \pm 0.0016\,(\text{syst.}) \pm 0.0038\,(\text{ext.})\ \text{ps}^{-1}$$

where the uncertainty (denoted 'ext.') is due to HFLAV inputs and listed separately



- The value of Γ_d agrees with HQE theory (Lenz *et al*., 2023): $0.63^{+0.11}_{-0.07}\ \text{ps}^{-1}$

Γ_d/Γ_s

- Use $\Gamma_s = 0.6703 \pm 0.0014\,(\text{stat.}) \pm 0.0018\,(\text{syst.})\ \text{ps}^{-1}$ measured by ATLAS (Eur. Phys. J. C 81 (2021) 342) to find:

$$\frac{\Gamma_d}{\Gamma_s} = 0.9905 \pm 0.0022\,(\text{stat.}) \pm 0.0036\,(\text{syst.}) \pm 0.0057\,(\text{ext.})$$

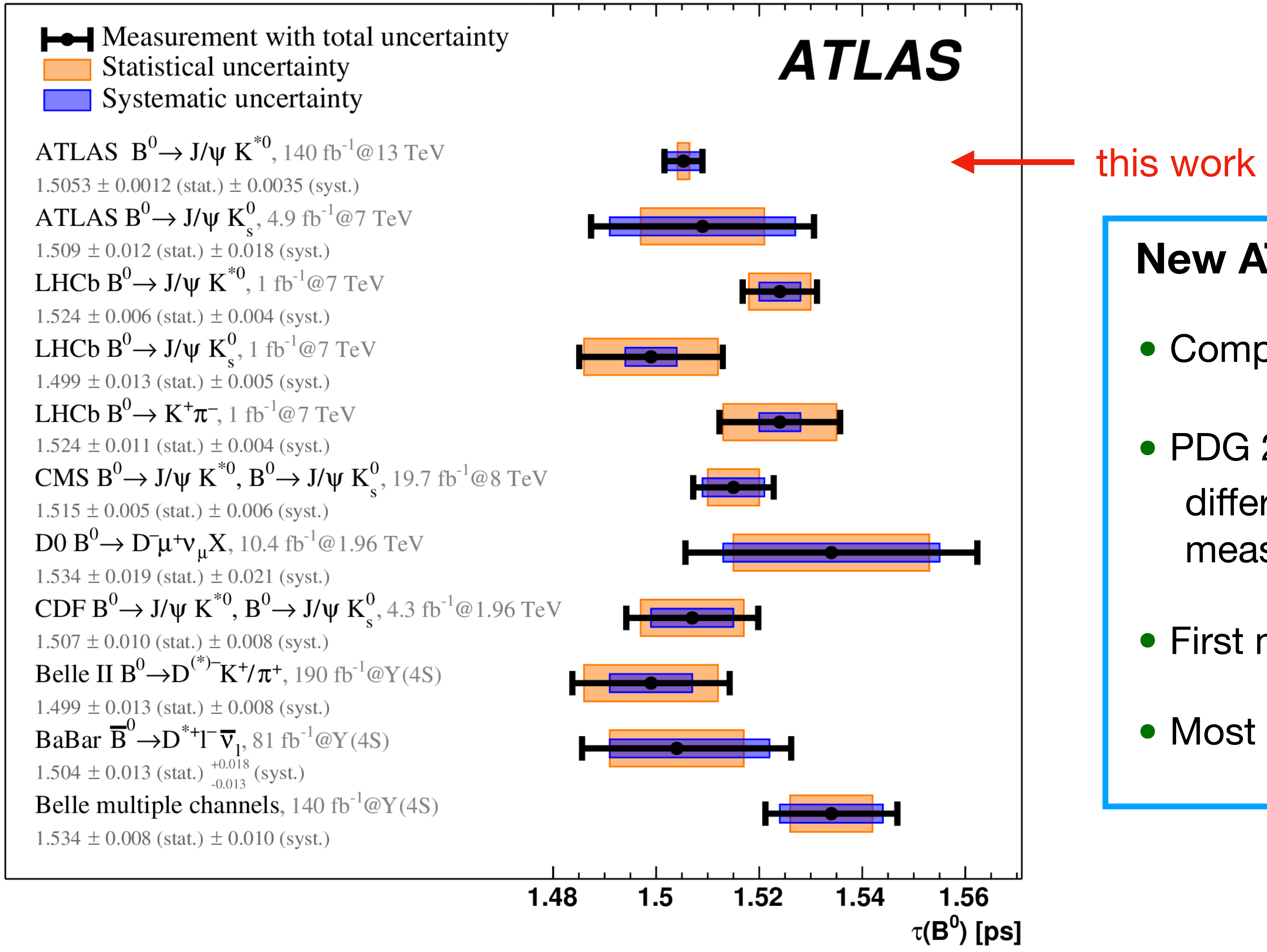
- The value of Γ_d/Γ_s agrees with HQE (1.003 ± 0.006) and lattice QCD (1.00 ± 0.02) theory model predictions

Open Beauty: precision B^0 meson lifetime measurement

Comparison of ATLAS B^0 lifetime with other recent measurements

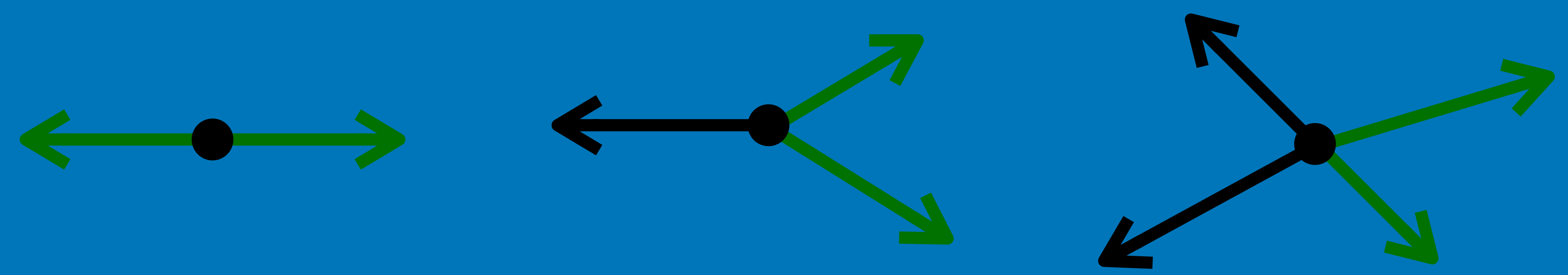
arXiv:2411.09962 (submitted EPJC)

ATLAS Briefing



New ATLAS result:

- Compatible with most other recent measurements
- PDG 2024 world average: 1.517 ± 0.004 ps, differs by 2.1σ (draws on full history of B^0 lifetime measurements)
- First measurement in *pp* collisions at 13 TeV
- Most precise single measurement to date



Closing remarks

- ATLAS heavy-flavour programme is amassing competitive results from LHC Run 2

- **Charmonium**: Differential J/ψ and $\psi(2S)$ production **cross-sections extended** up to p_T = 360 and 140 GeV
  - Most comprehensive measurement of charmonium production to date

- **Open charm**: differential $D^{\pm}$ and $D_s^{\pm}$ meson production **cross-sections extended** up to p_T = 100 GeV
  - First $D_s^{\pm}$ cross-section measurement to reach transverse momenta of 100 GeV

  Today: first public presentation

- None of the consulted **theory predictions** describes charm production well, especially at higher p_T

- **Open beauty**: **precision** B^0 meson **effective lifetime** measurement
  - Most precise single measurement to date

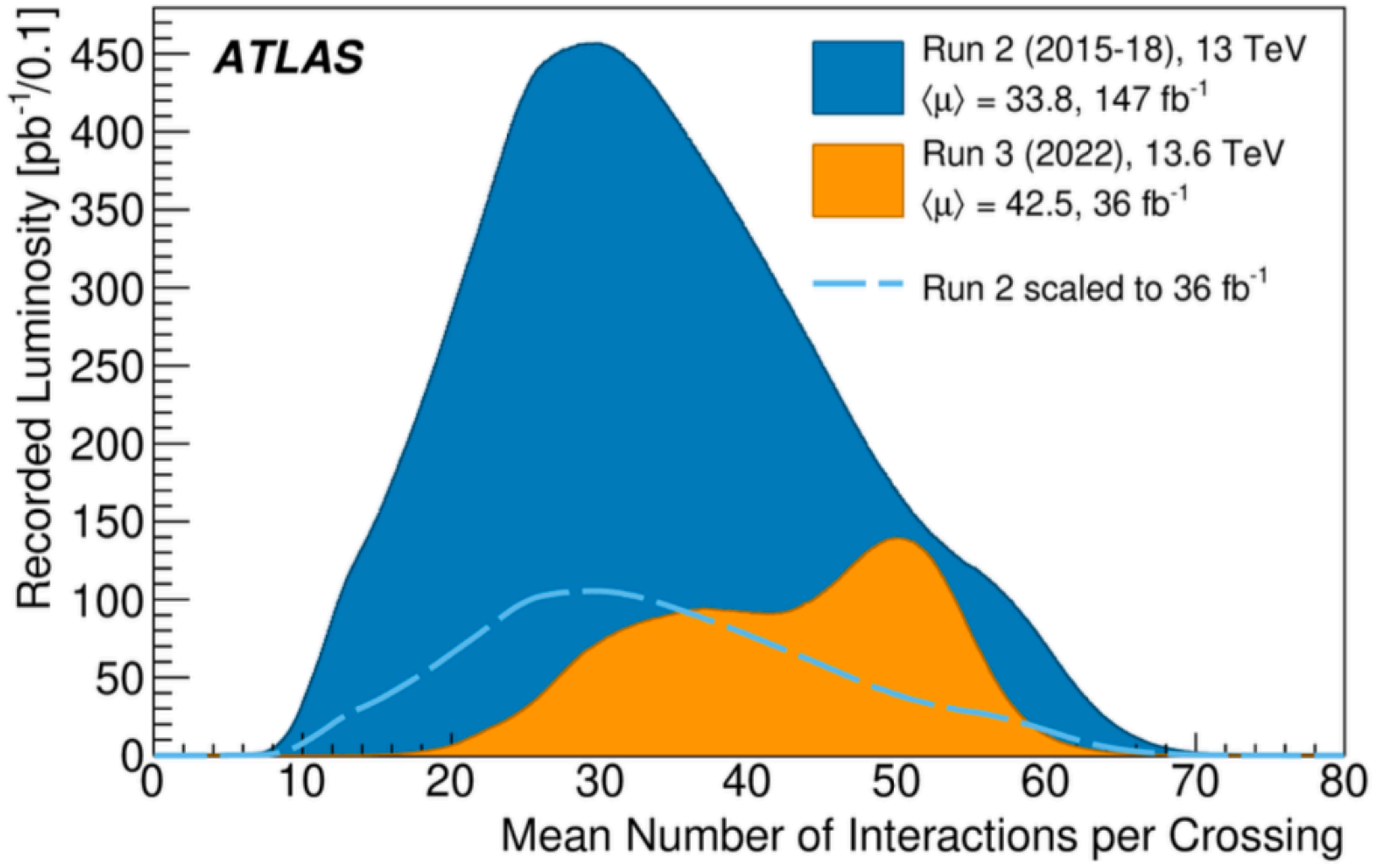
  Today: first international-conference presentation

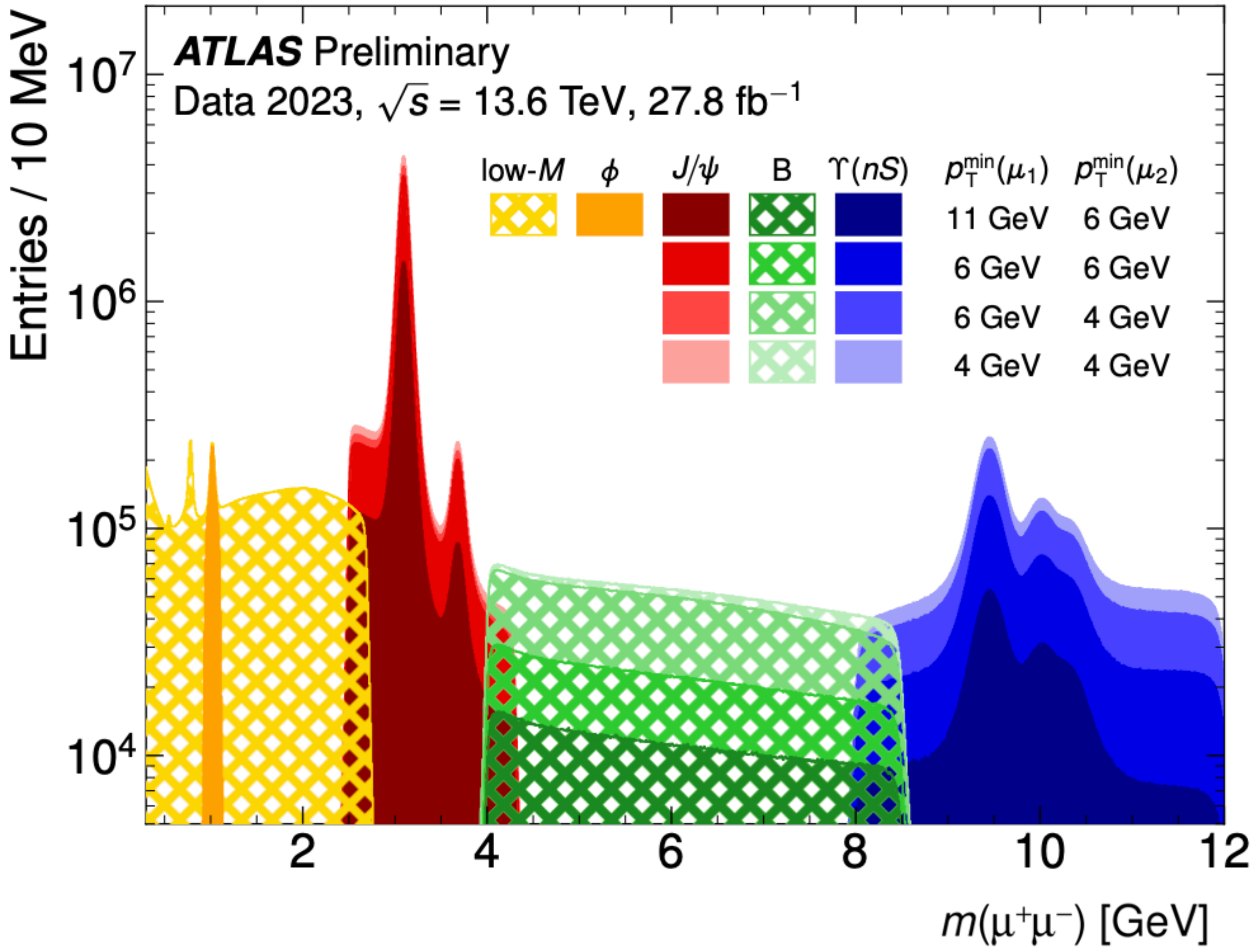
- Further results under preparation, including combinations of Run 2 + Run 3 statistics

- ATLAS *B*-physics public results page: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults

Backup Slides

ATLAS heavy flavour in Run 3





- Increasing instantaneous luminosity, higher $<\mu>$: ~34 (Run 2) $\rightarrow$ ~42 in 2022, ~50 in 2023
- Similar dimuon triggers used, but, early in fills, more aggressive pre-scaling of those with lower di-muon p_T
- For high-precision measurements (*e.g.*, lifetimes, *CP* violation), errors on pseudo-proper lifetimes get reduced with the shift to higher p_T (even with the associated loss of lower-p_T statistics)

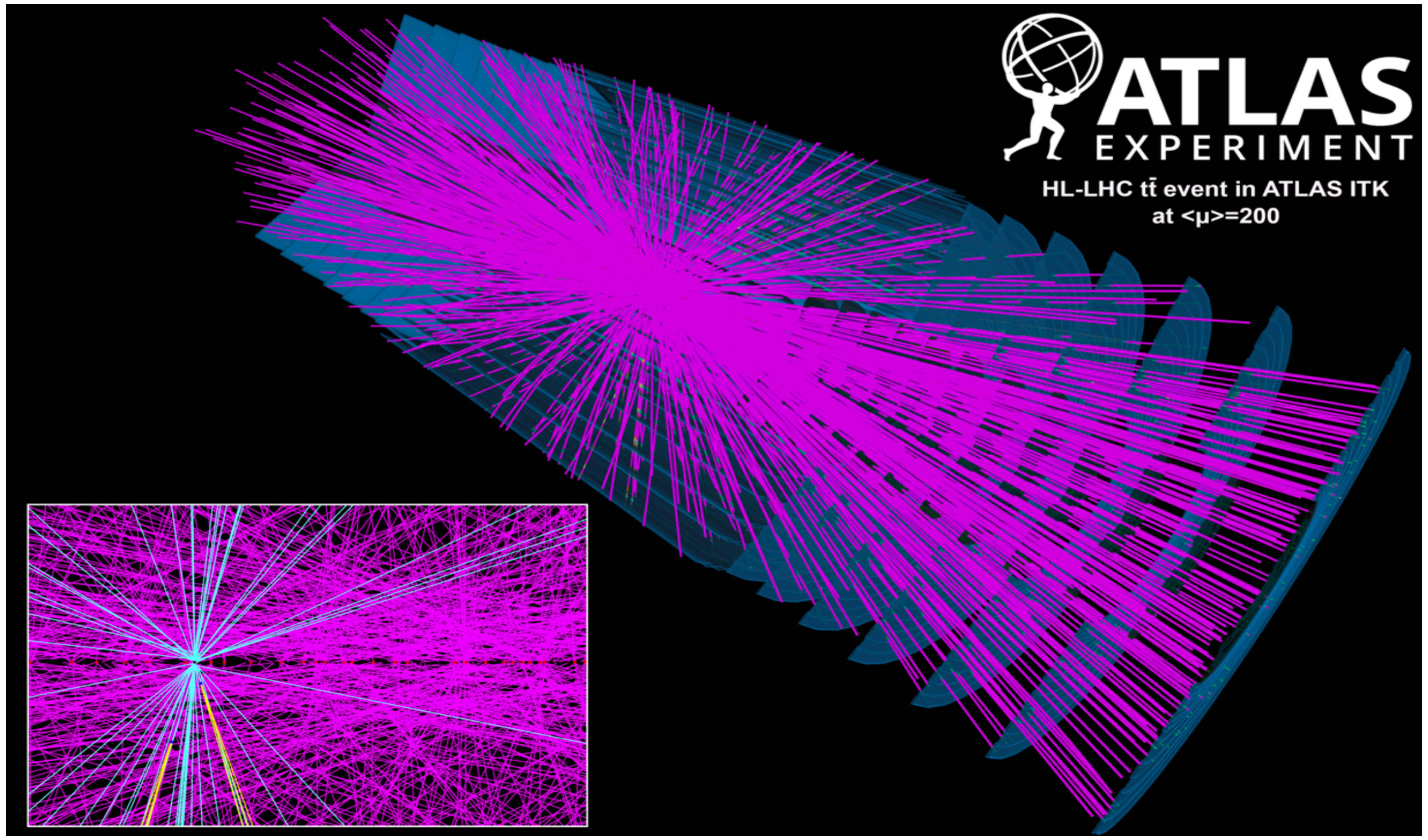
ATLAS heavy flavour in Run 4, HL-LHC

- Replacement of entire inner tracking system (ITk upgrade):
  - Refer to talk by Savanna Shaw, Upgrades session
  - Copes with higher instantaneous luminosities, pileup
  - Greater angular acceptance
  - Expect ~21% improvements in pseudo-proper-decay time resolutions

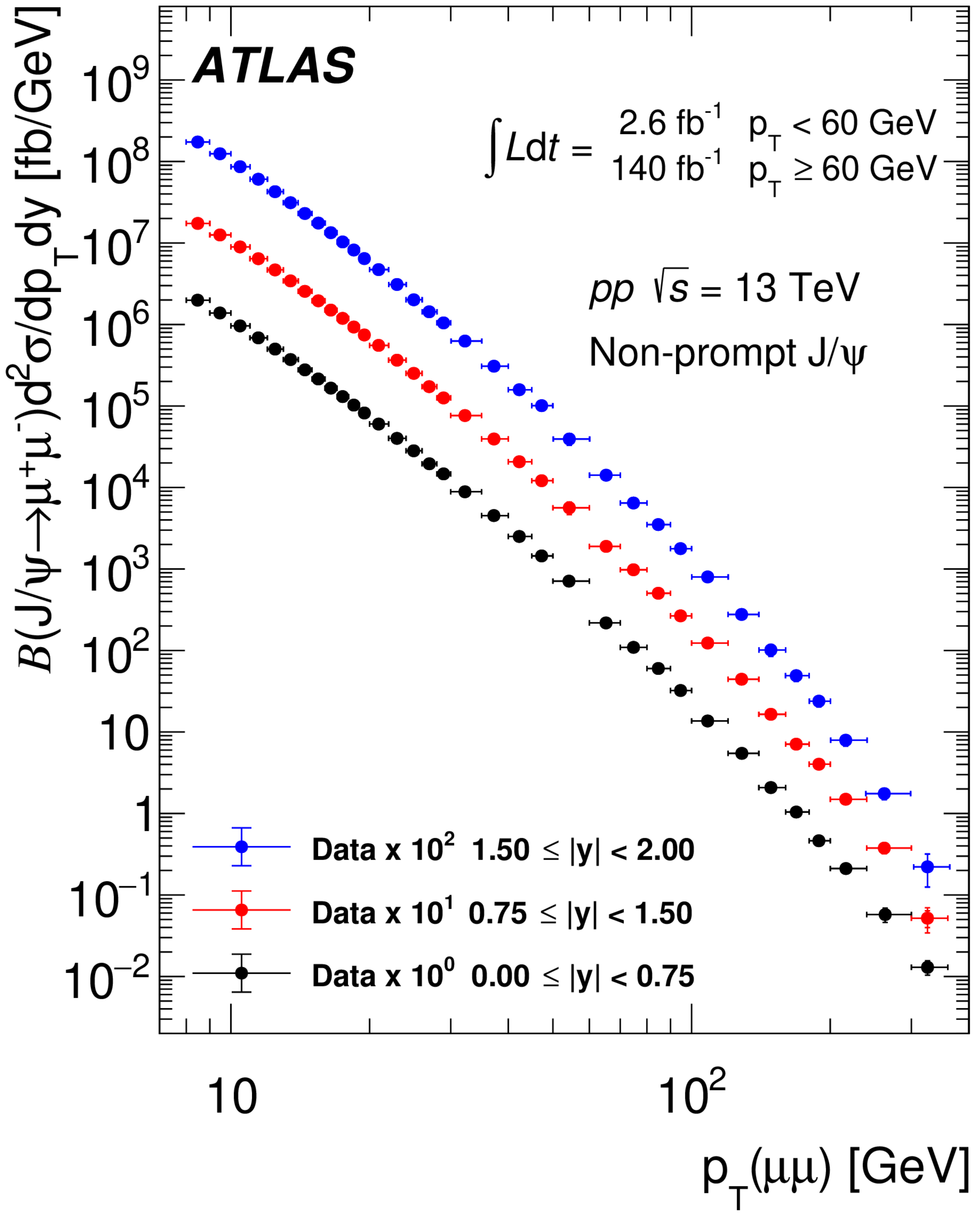
- Reach studies use di-muon triggers with thresholds: $\mu_{10}\mu_{10}$, $\mu_{6}\mu_{10}$, $\mu_{6}\mu_{6}$

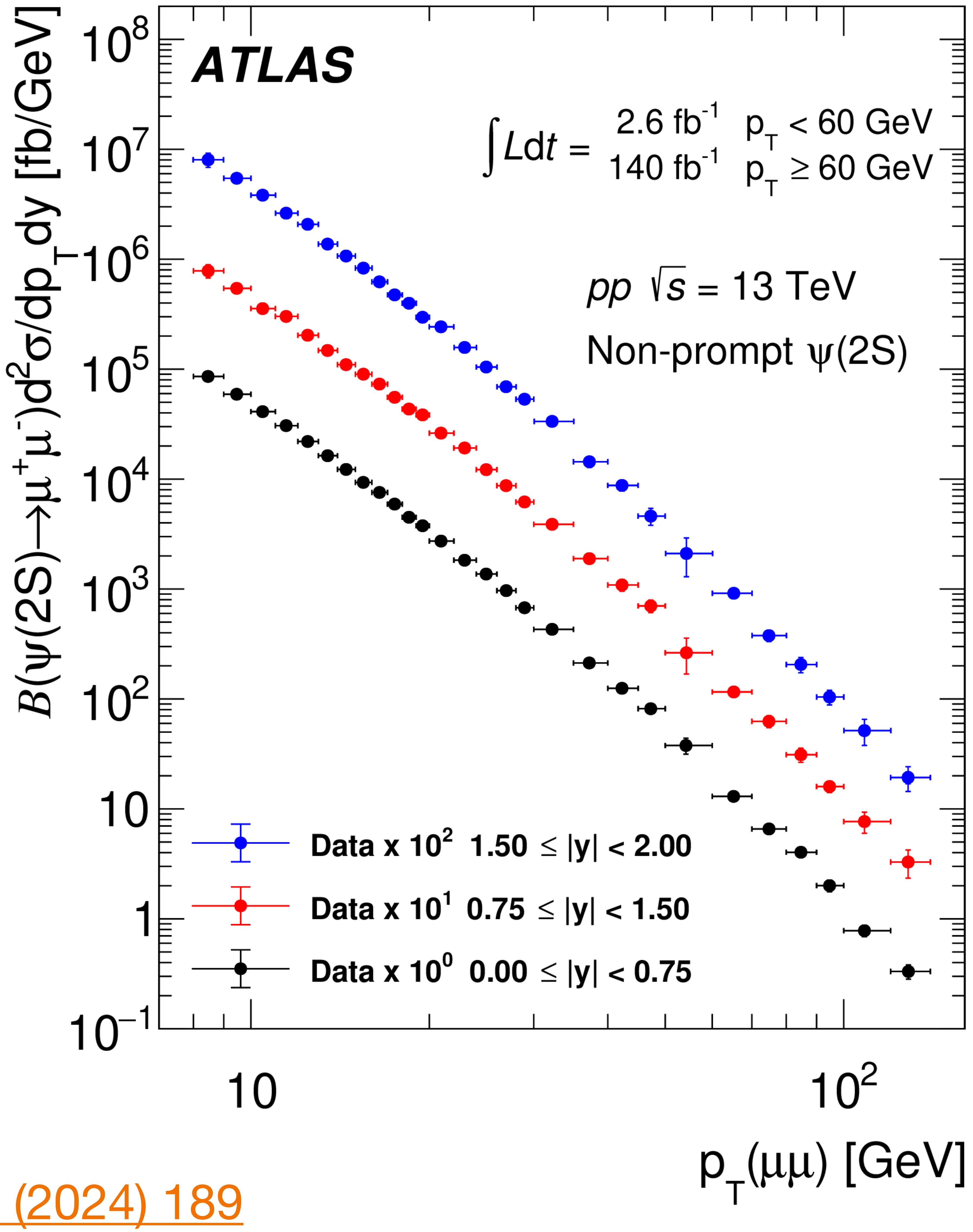
- $B_{(s)} \to \mu^+\mu^-$: ATL-PHYS-PUB-2018-005

- $B_s^0 \to J/\psi\phi$: ATL-PHYS-PUB-2018-041



Charmonium: differential J/ψ and $\psi(2S)$ production cross-sections





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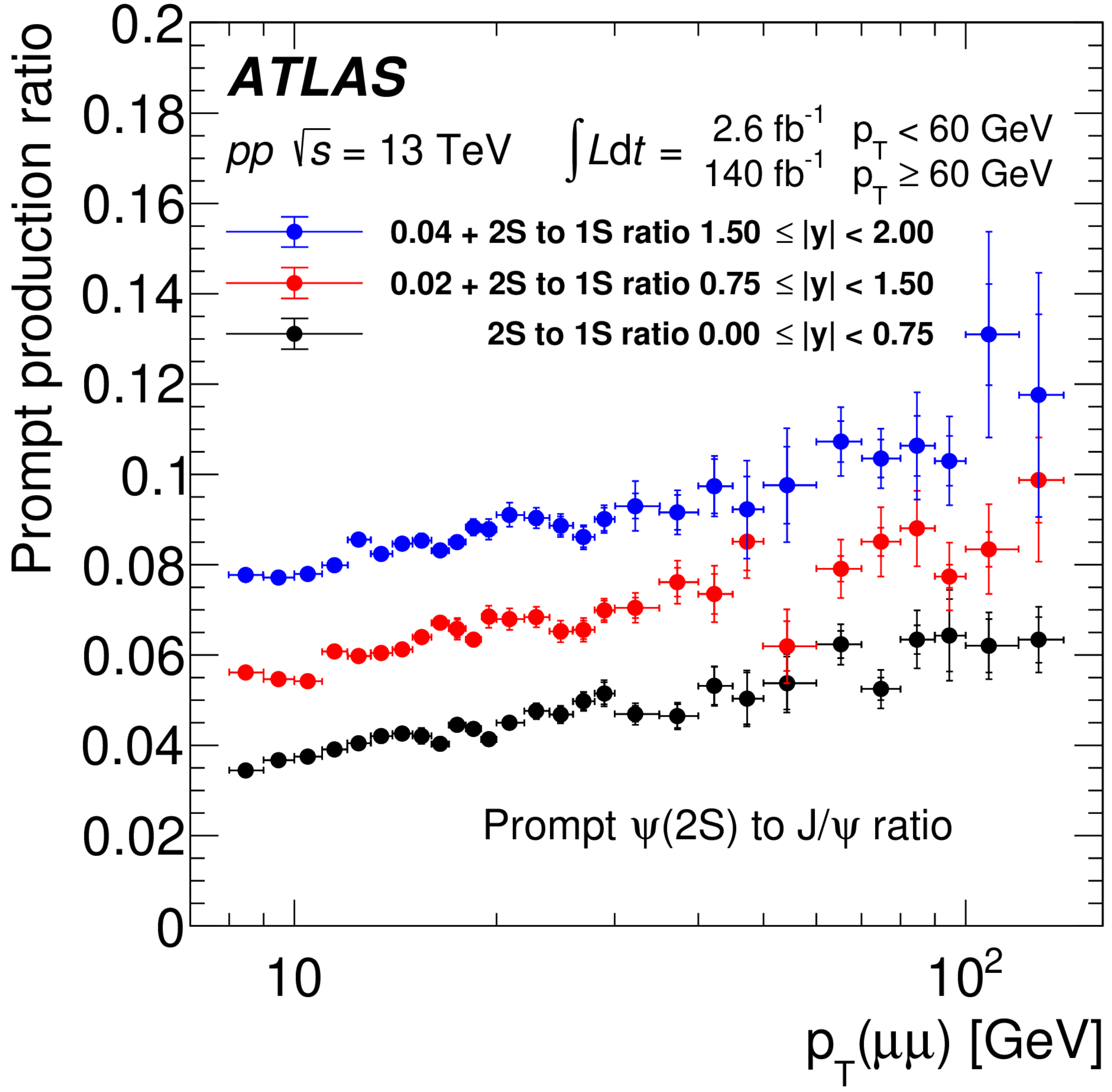
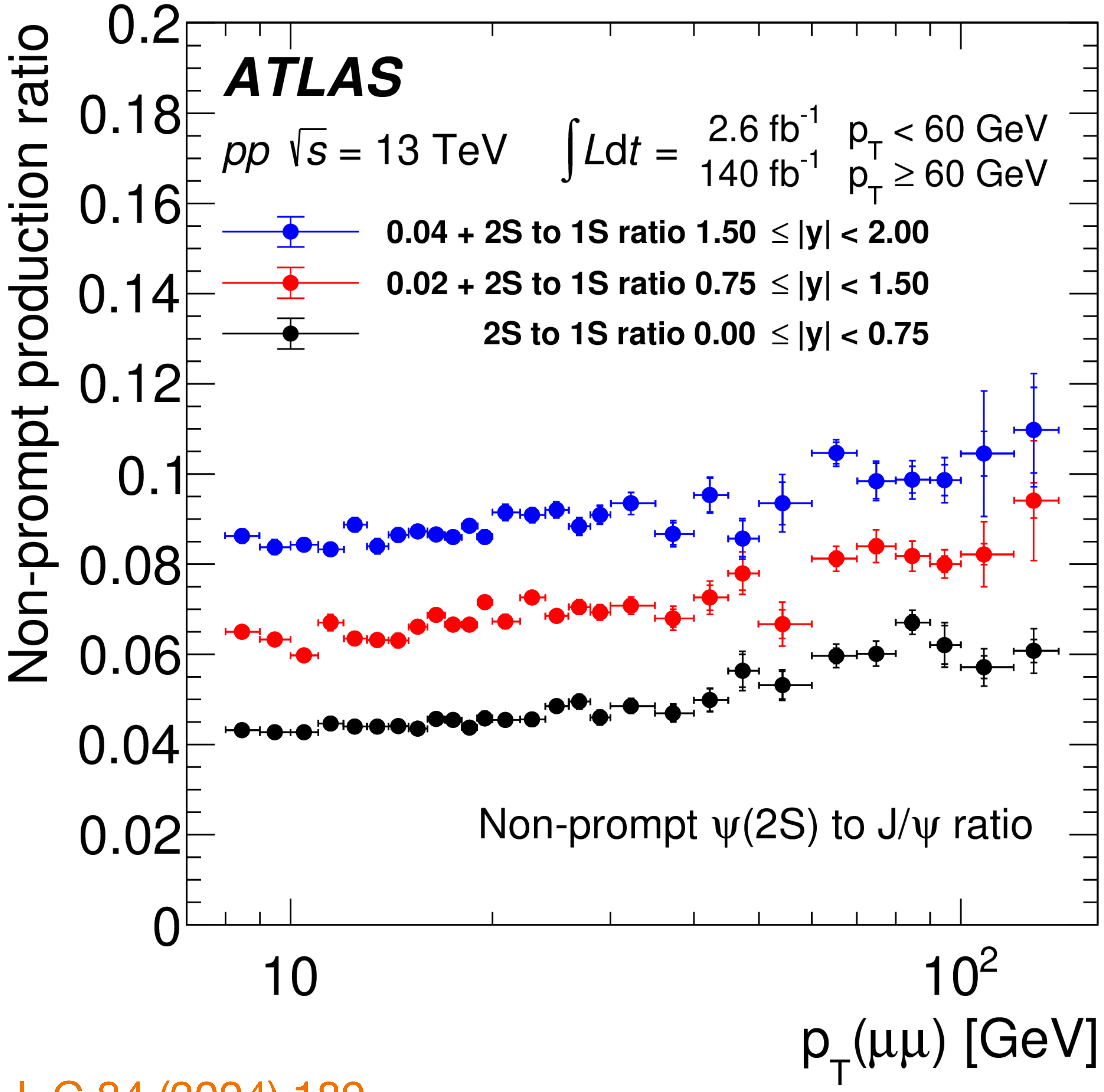
Charmonium: differential J/ψ and $\psi(2S)$ production cross-sections





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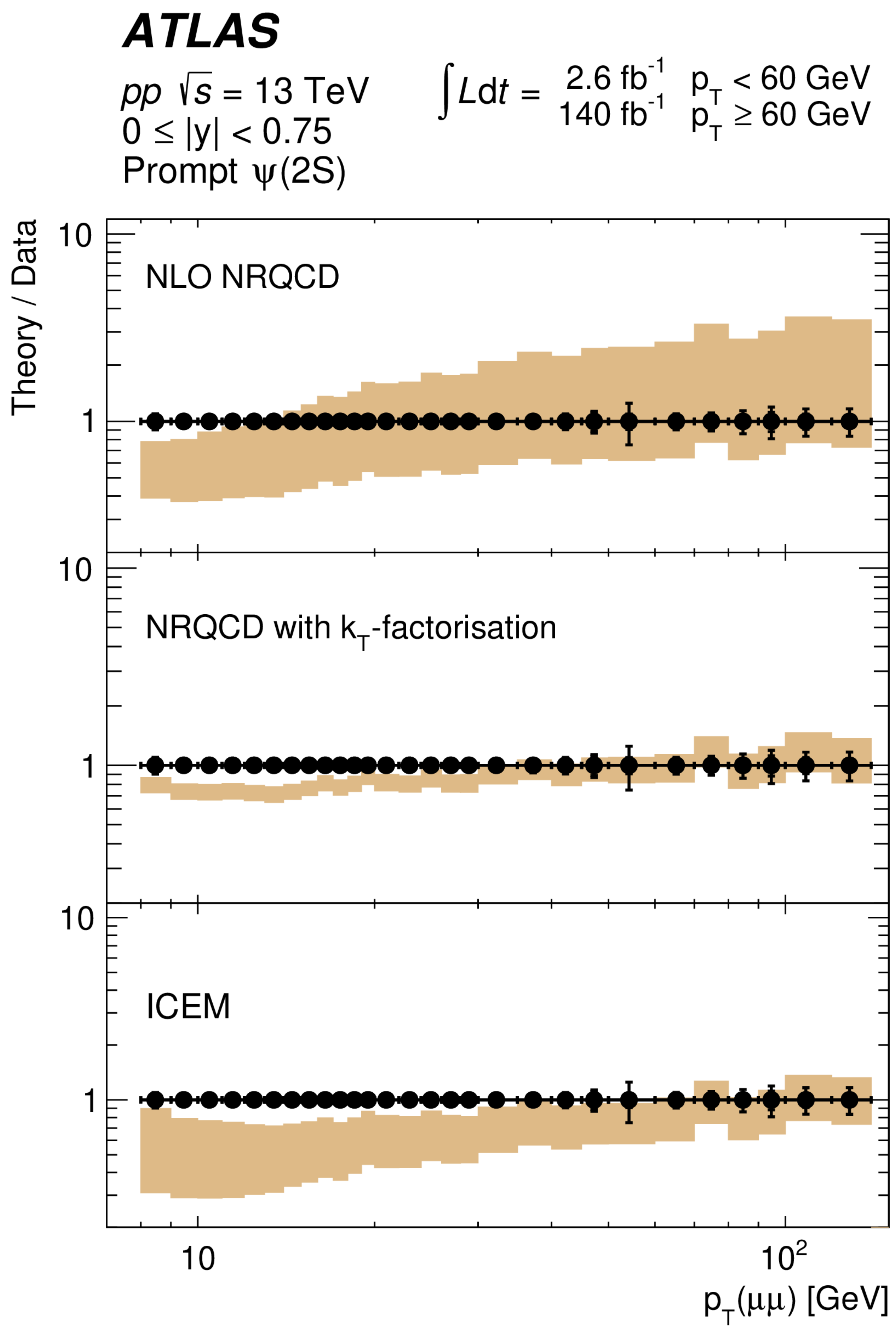
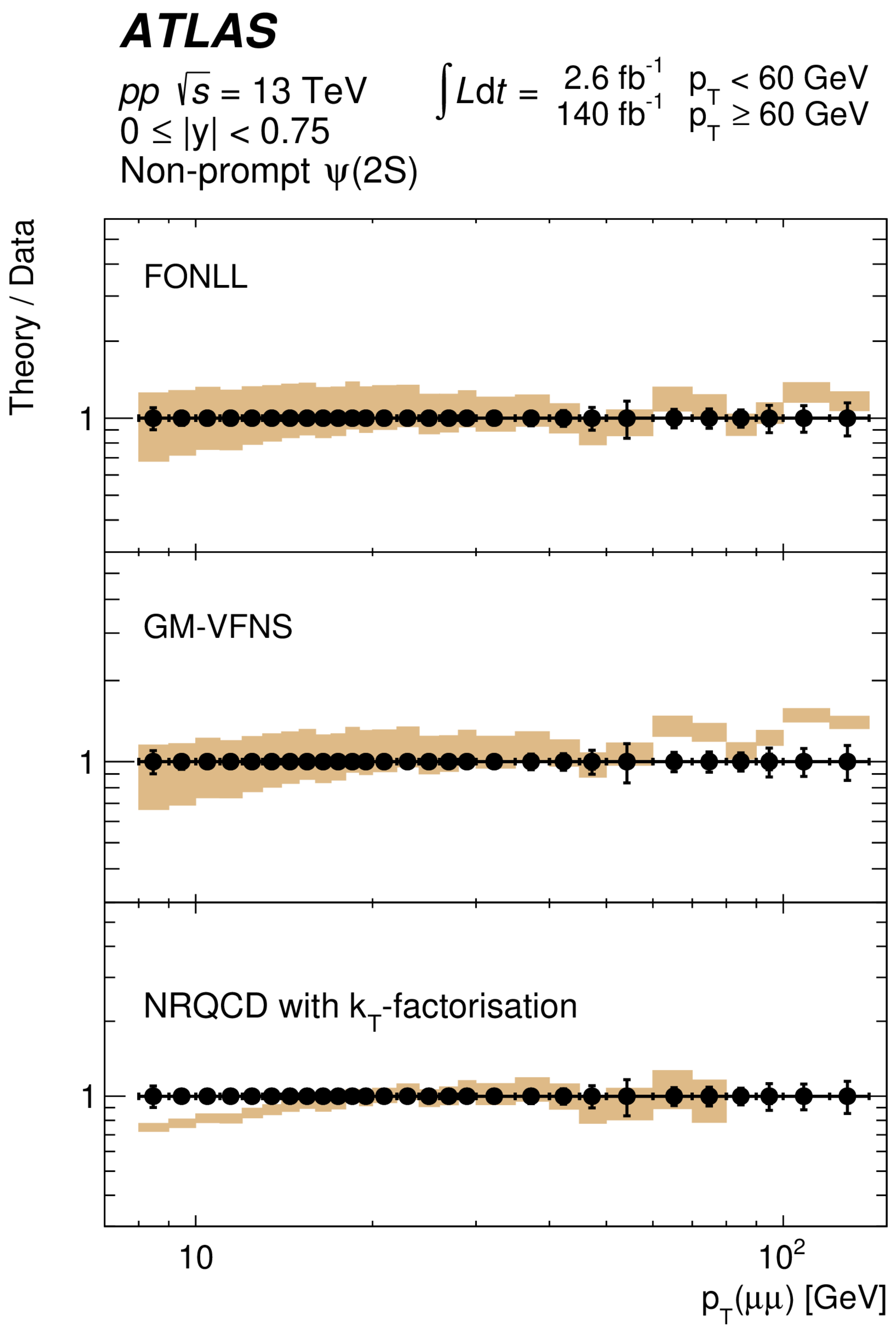
Charmonium: differential J/ψ and $\psi(2S)$ production cross-sections





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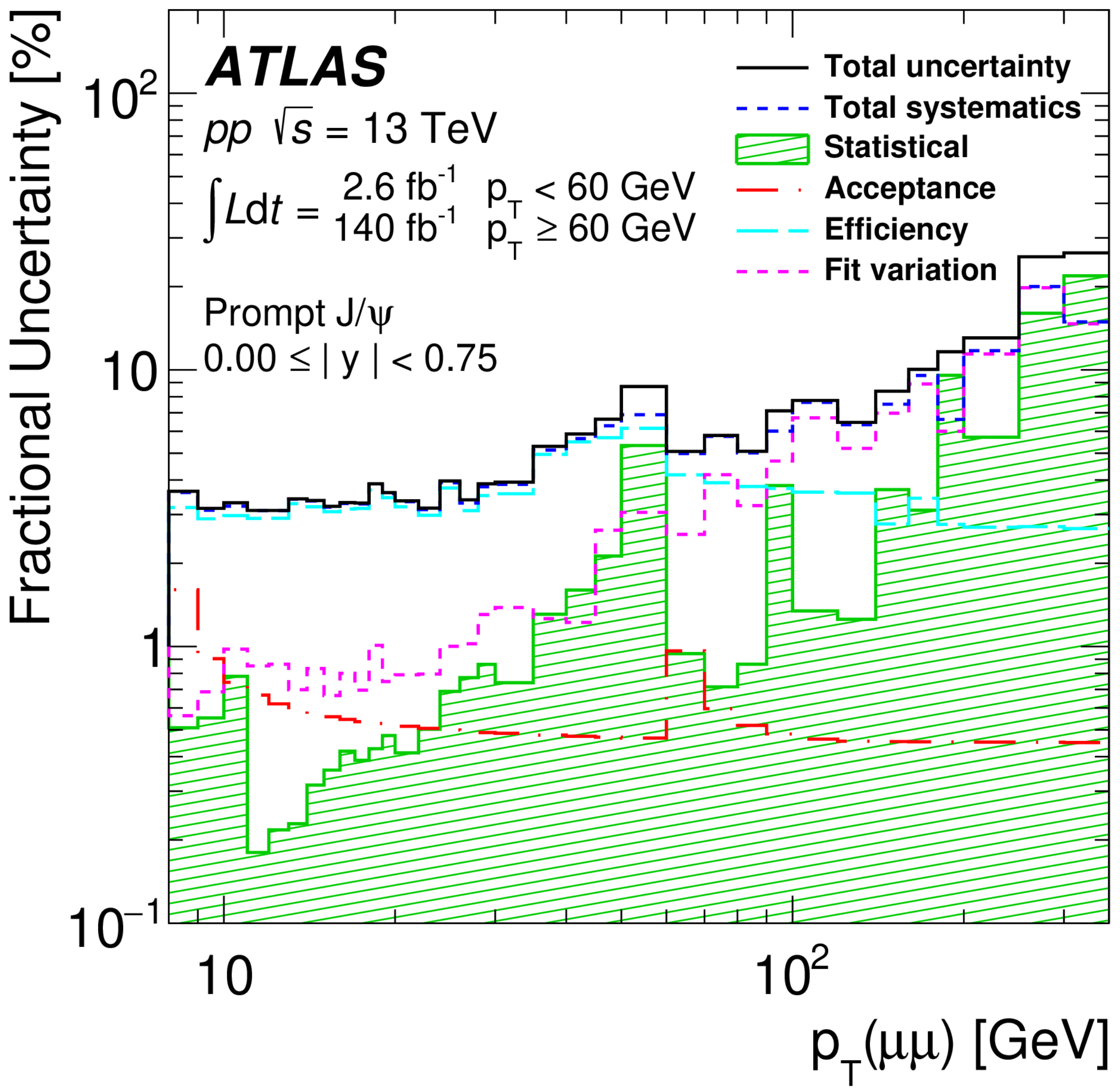
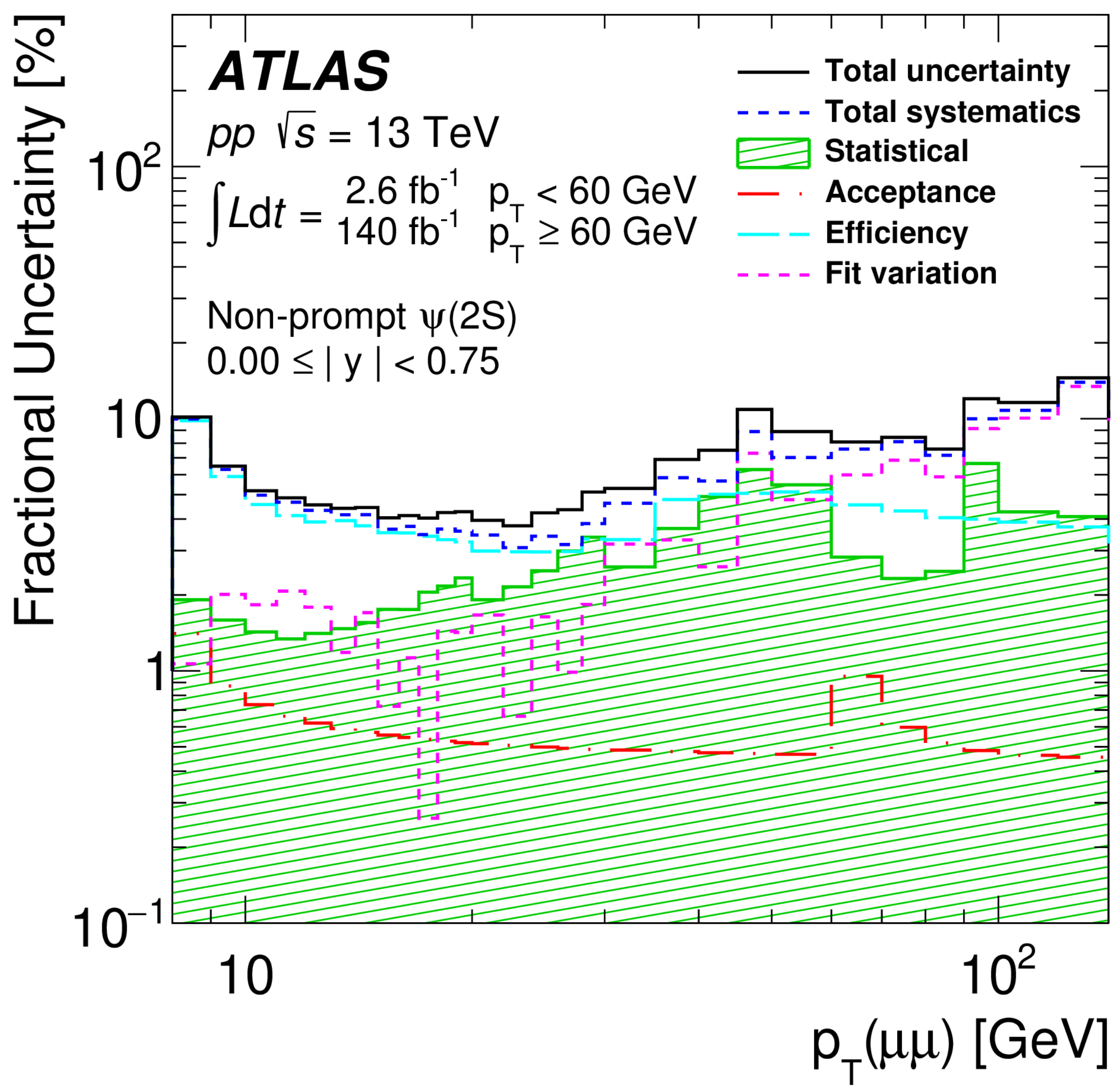
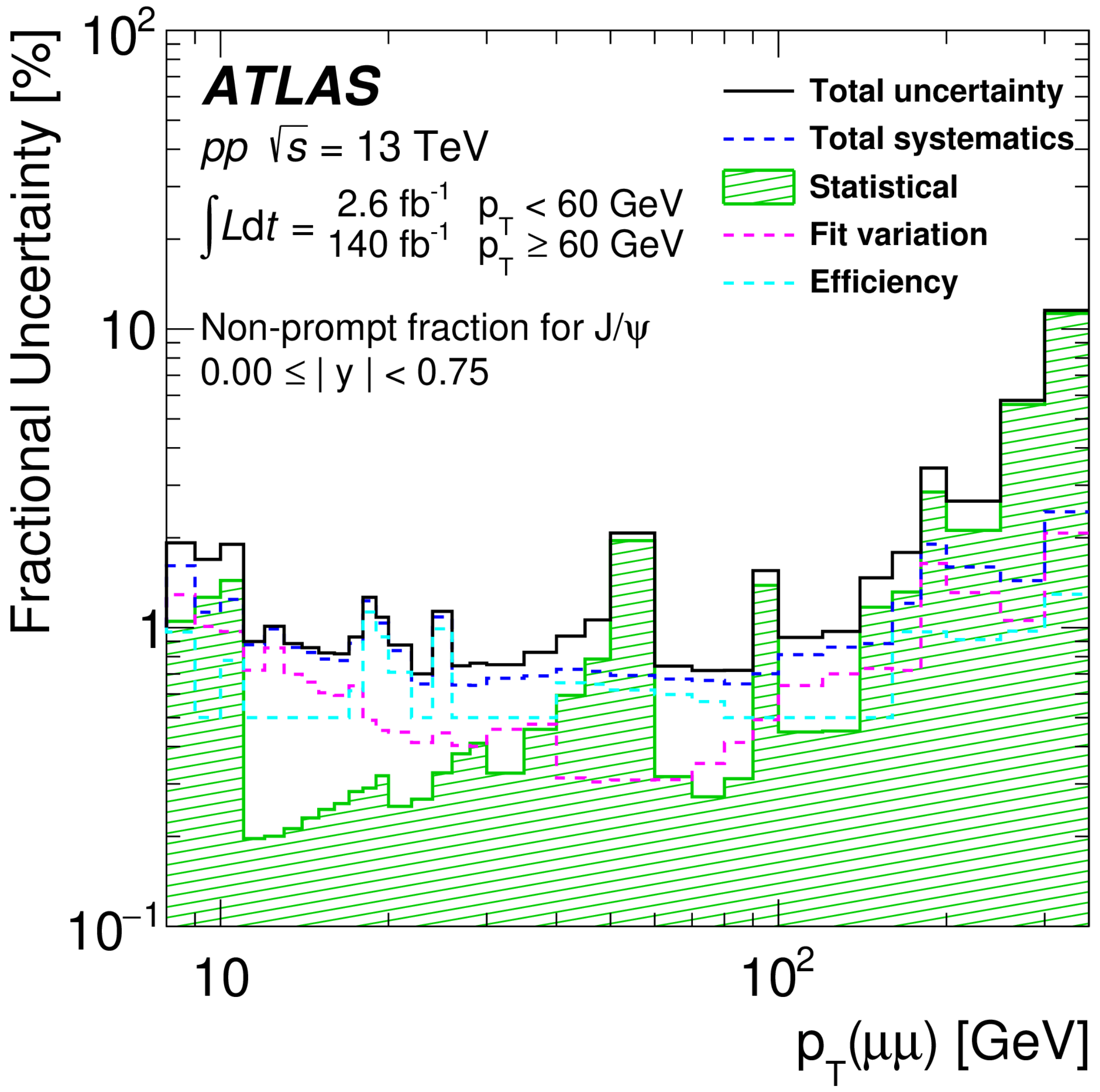
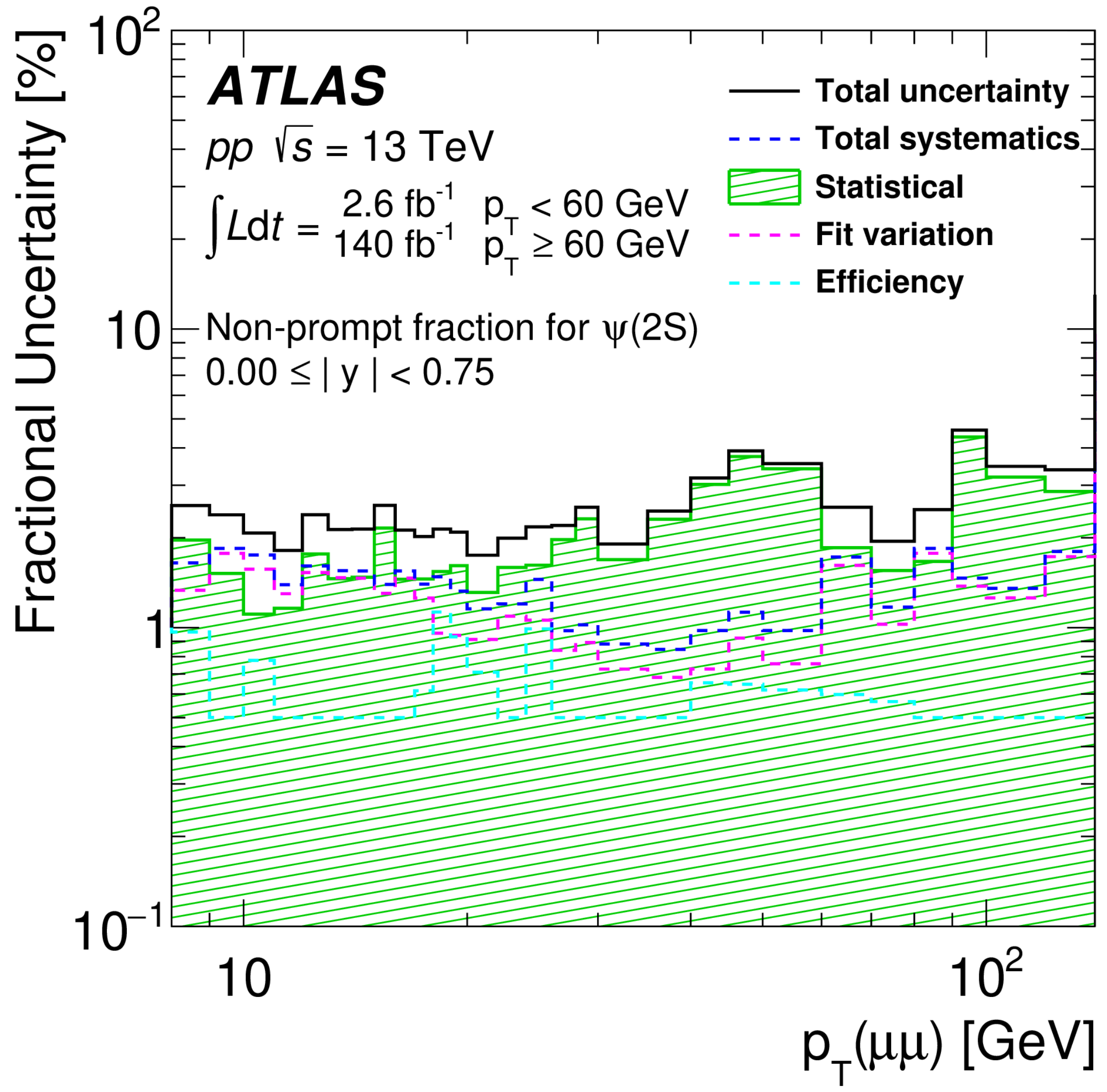
Charmonium: differential J/ψ and $\psi(2S)$ production cross-sections









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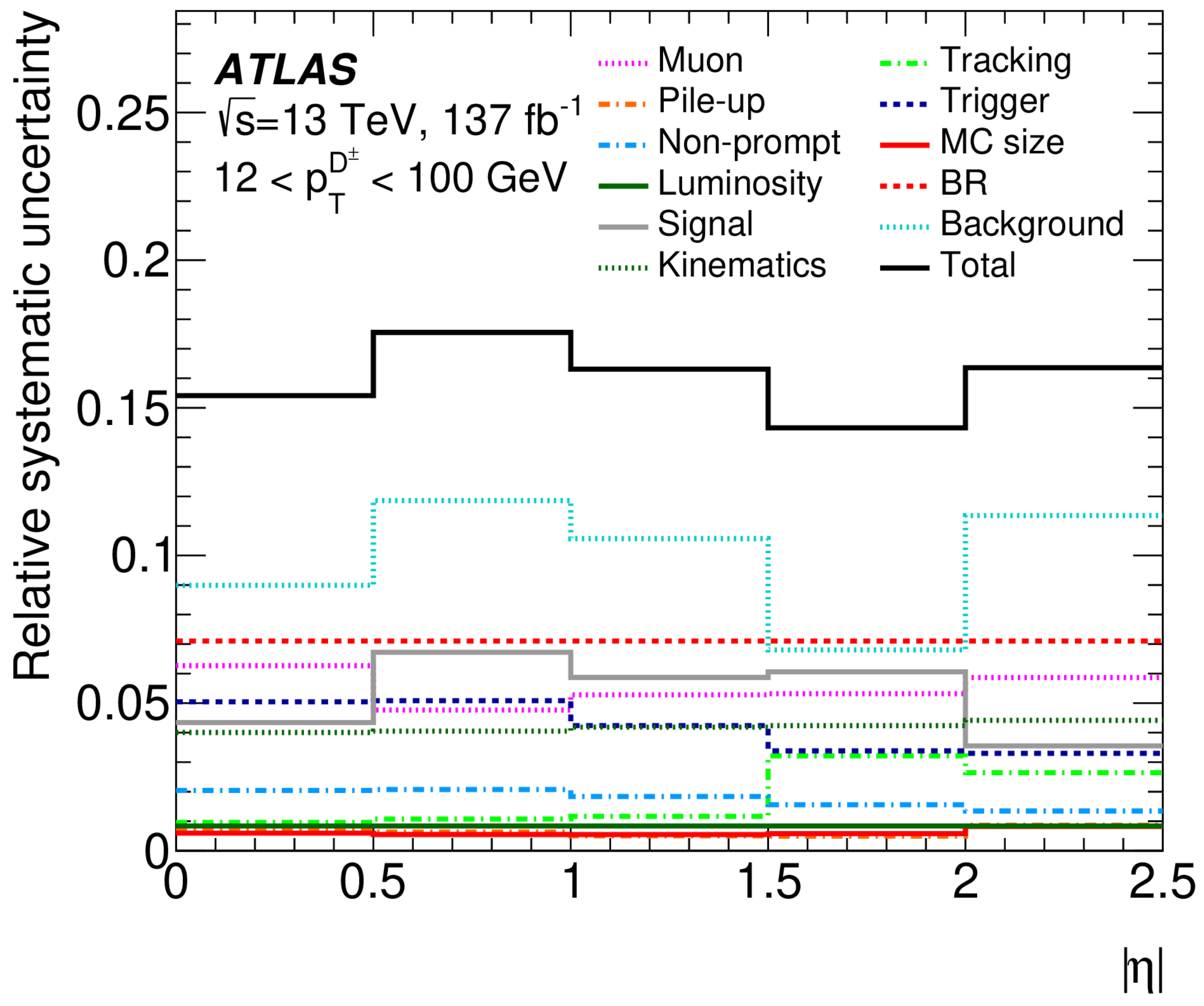
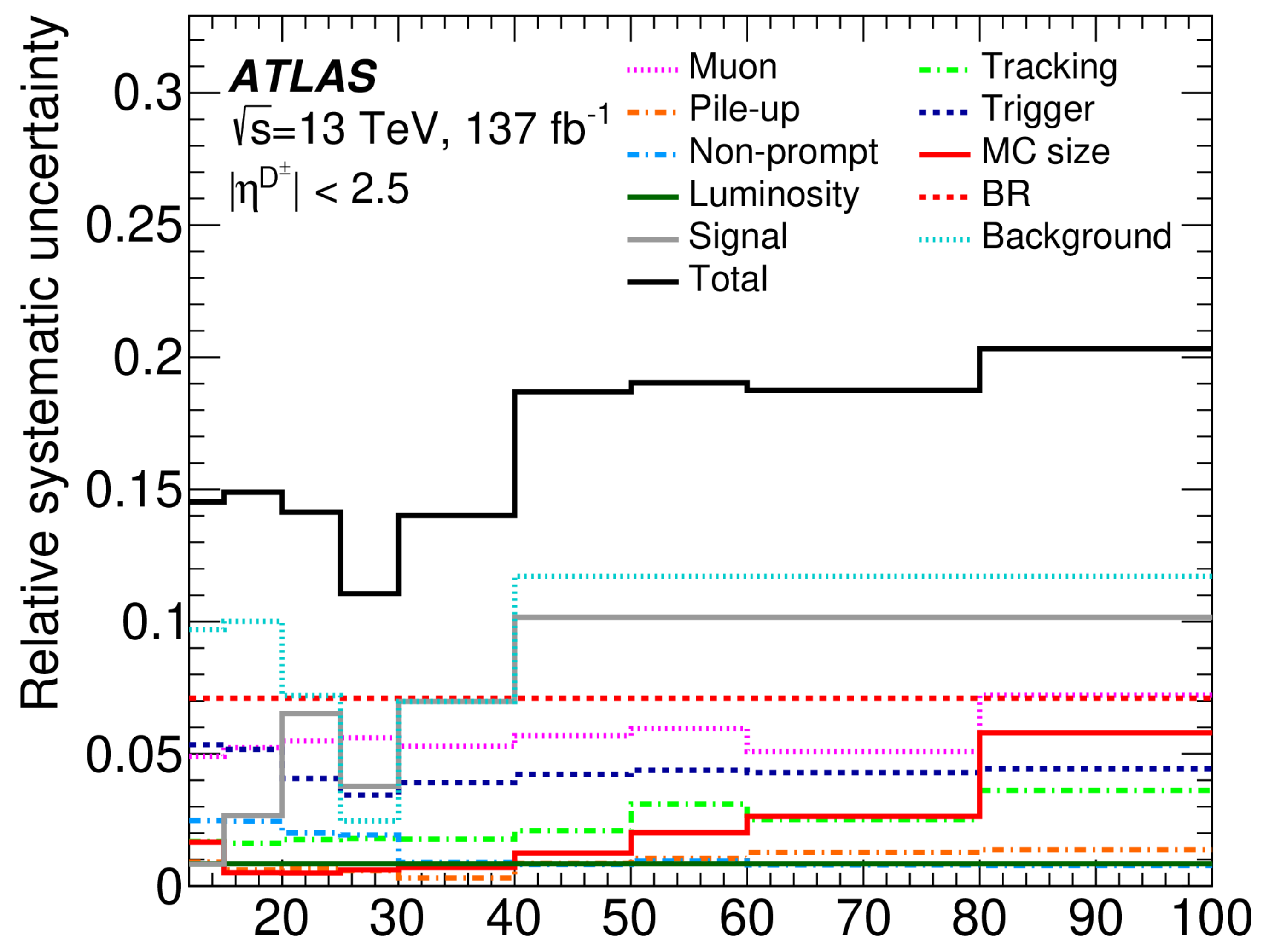
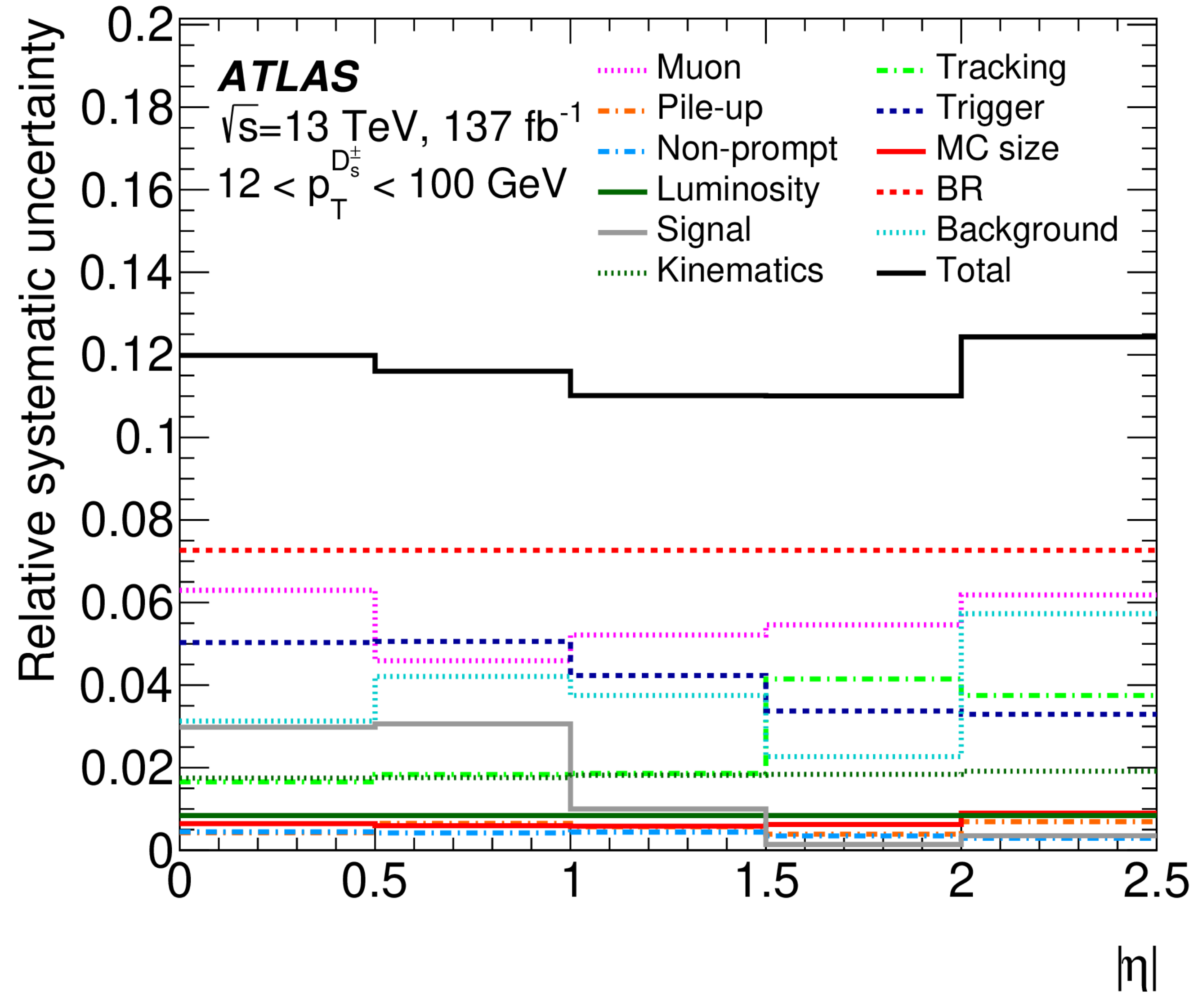
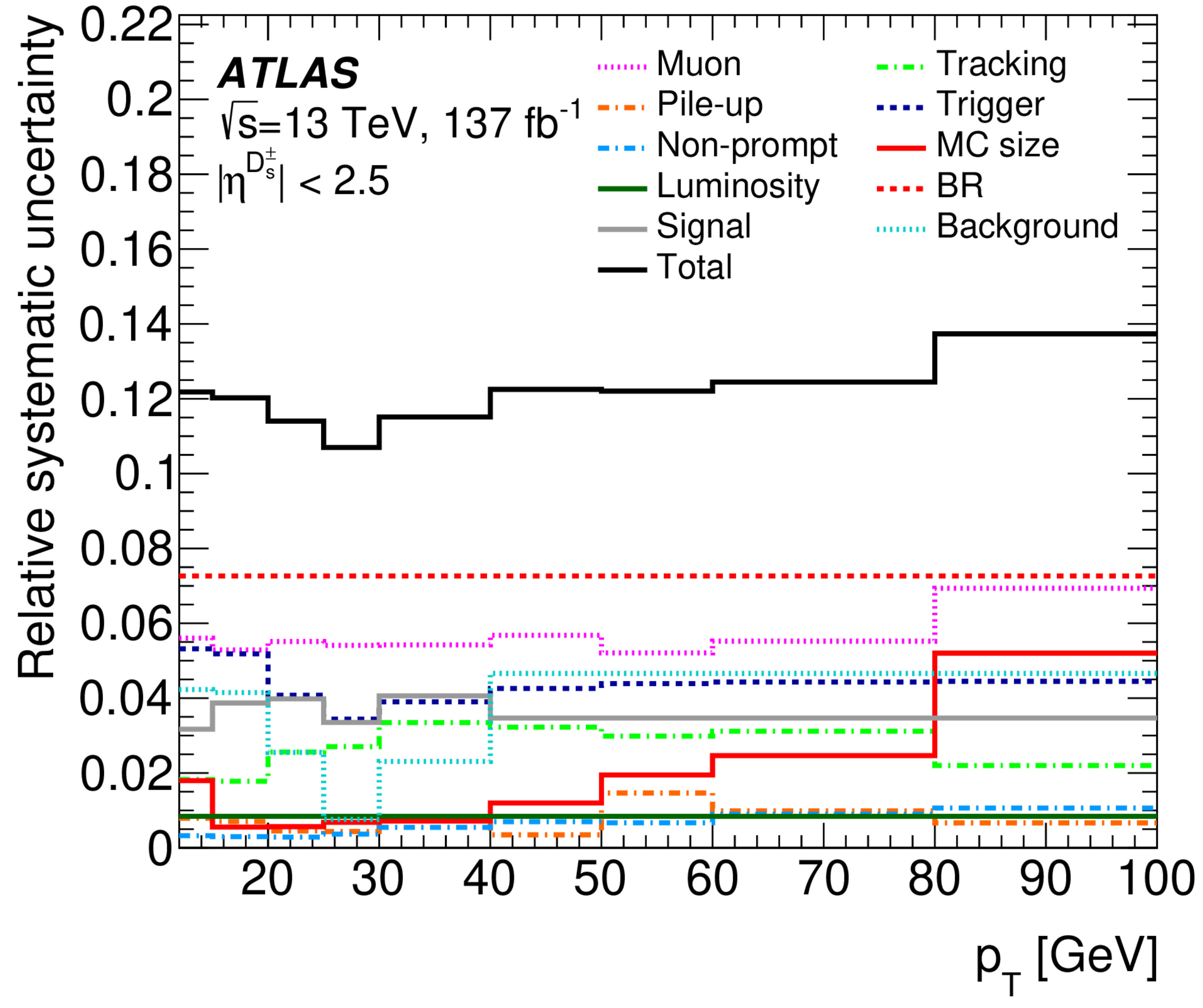
Open Charm: differential $D^{\pm}$ and $D_s^{\pm}$ meson cross-sections





arXiv:2412.15742 (submitted JHEP)





Open beauty: precision B^0 meson lifetime measurement

arXiv:2411.09962 (submitted EPJC)

Source of uncertainty	Systematic uncertainty [ps]
ID alignment	0.00108
Choice of mass window	0.00104
Time efficiency	0.00130
Best-candidate selection	0.00041
Mass fit model	0.00152
Mass-time correlation	0.00229
Proper decay time fit model	0.00010
Conditional probability model	0.00070
Fit model test with pseudo-experiments	0.00002
Total	0.0035