Conventional and Exotic Heavy Quarkonium Production and Spectroscopy in ATLAS

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https://indico.in2p3.fr/event/33627/contributions/155127/

Introduction

- **Flavor Physics at ATLAS**
  - Measurements of Production Cross-Sections & Spectroscopy **in This Talk!**
  - Measurements of Weak Decays
- **Despite being a general purpose detector, competitive at flavor physics...**
  - Large statistics
  - $\sim$Full coverage $\rightarrow$ phase space complements LHCb
  - Good muon performance
  - Often constrained by trigger, however, constantly optimizing :)

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    - More results in the talk by Adam Barton (9th July, 17:40)
  - Measurements of Weak Decays
    - See, the talk by Adam Barton (9th July, 17:40)

In the Flavor Session in Touze

- **Despite being a general purpose detector, competitive at flavor physics...**
  - Large statistics, ~full coverage → phase space complements LHCb, good muon performance, often constrained by trigger, however, constantly optimizing! :)

Differential Production Cross-Section of J/ψ and $\psi(2S)$

arXiv:2309.17177

Eur. Phys. J. C 84 (2024) 169

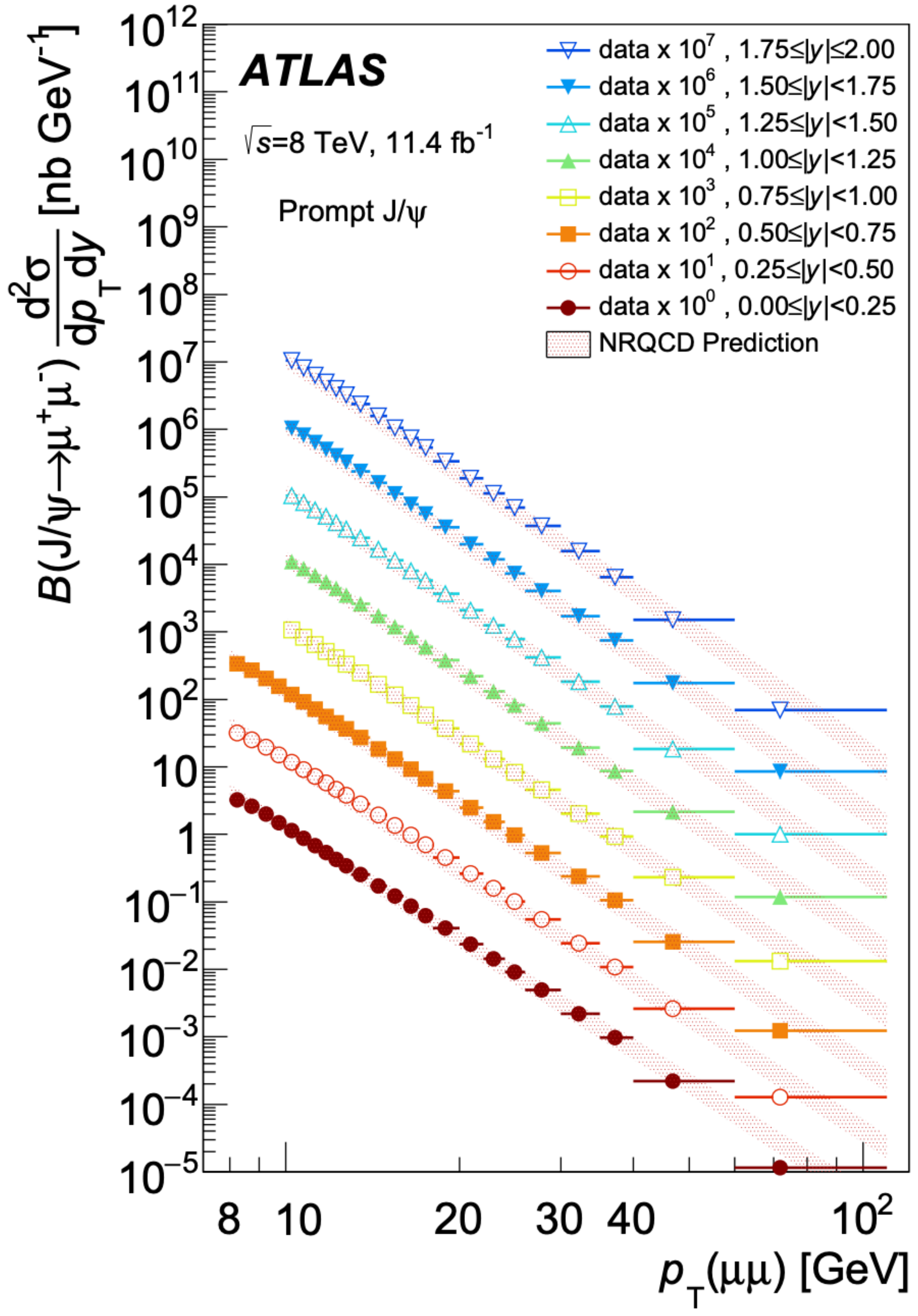
Motivation

- **Two sources of quarkonia production:**
  - **Prompt:** Coming from short-lived QCD processes.
  - **Non-prompt:** Coming from decays of $b-$hadrons.
- **Understanding quarkonium production in hadronic collisions still incomplete:**
  - Perturbative QCD can describe the non-prompt production well but not prompt production.
  - NRQCD approach to build a universal library of LDMEs has achieved mixed success.
  - Color Evaporation Model is simpler in terms of parameters but faces its own problem in describing data.
- **This analysis:**
  - Provides experimental data in **previously unmeasured kinematic range** of quarkonia production!
  - Can help theoretical models with **qualitatively new information**.

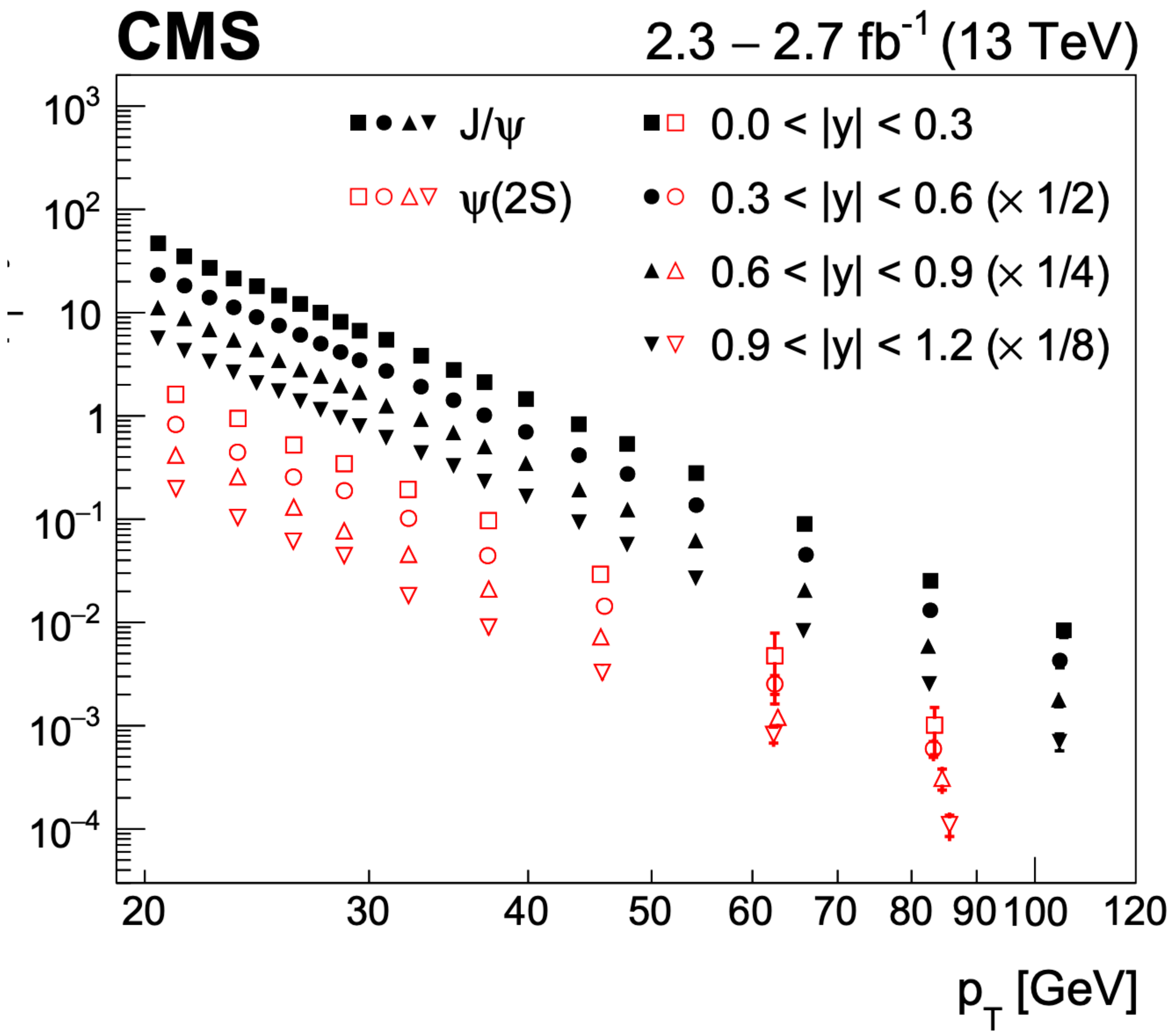
Experimental Strategy

2309.17177

- Kinematic range extension:
  - J/ψ : $p_{\mathrm{T}} < 100$ GeV $\rightarrow$ $p_{\mathrm{T}} < 360$ GeV
  - $\psi(2S)$: $p_{\mathrm{T}} < 100$ GeV $\rightarrow$ $p_{\mathrm{T}} < 140$ GeV
- Possible due to updated trigger-strategy!
  - Angular resolution of dimuon triggers not sufficient to resolve highly boosted muons coming from charmonia with $p_{\mathrm{T}} > 100$ GeV.
  - Instead, trigger on a single muon trigger with high muon p_{T} threshold (~ 50 GeV)!
    - Dimuon triggers still used to cover lower charmonia p_{T} phase space.



1512.03657
(ATLAS Run1)



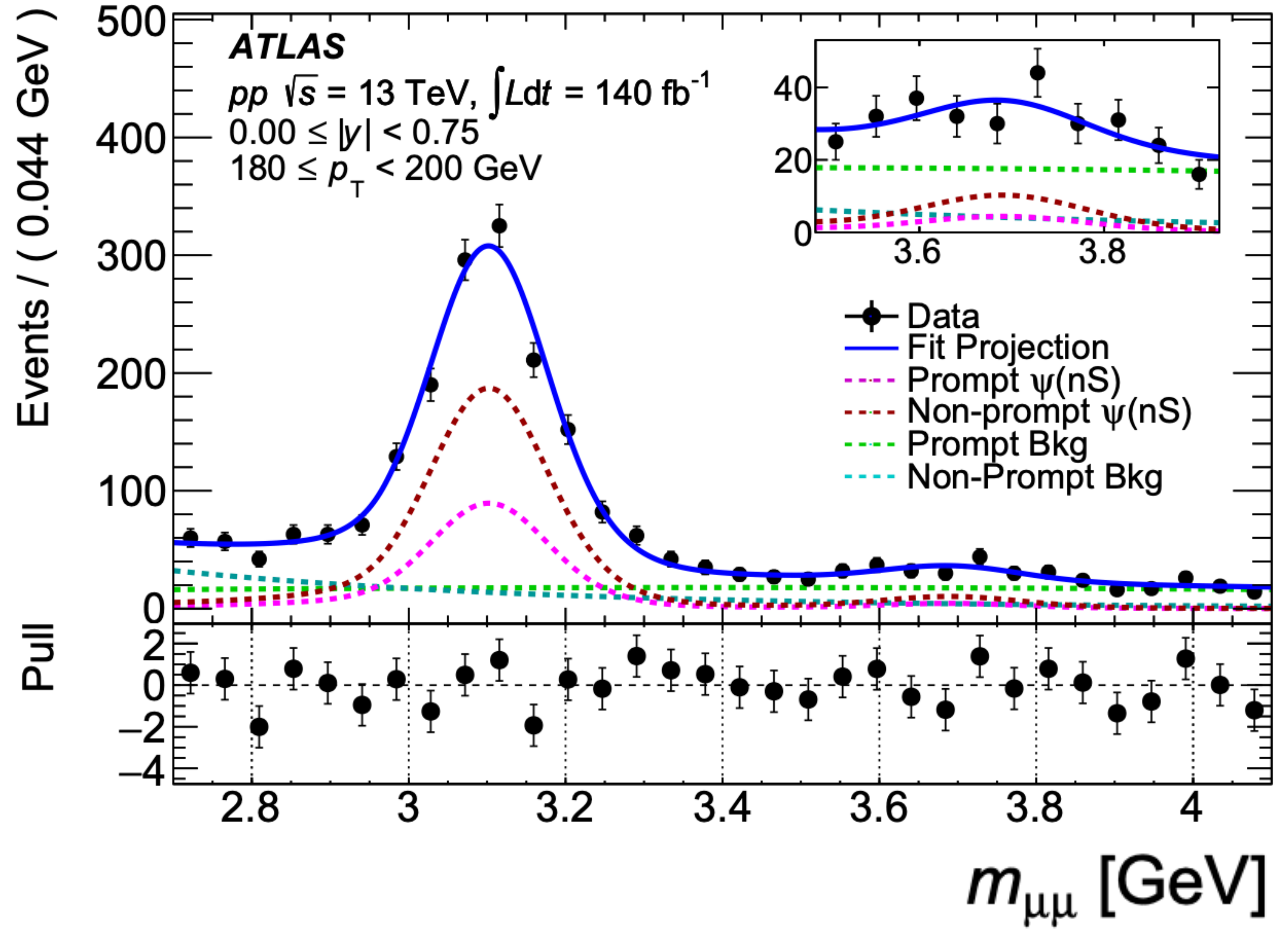
1710.11002
(CMS Run2)

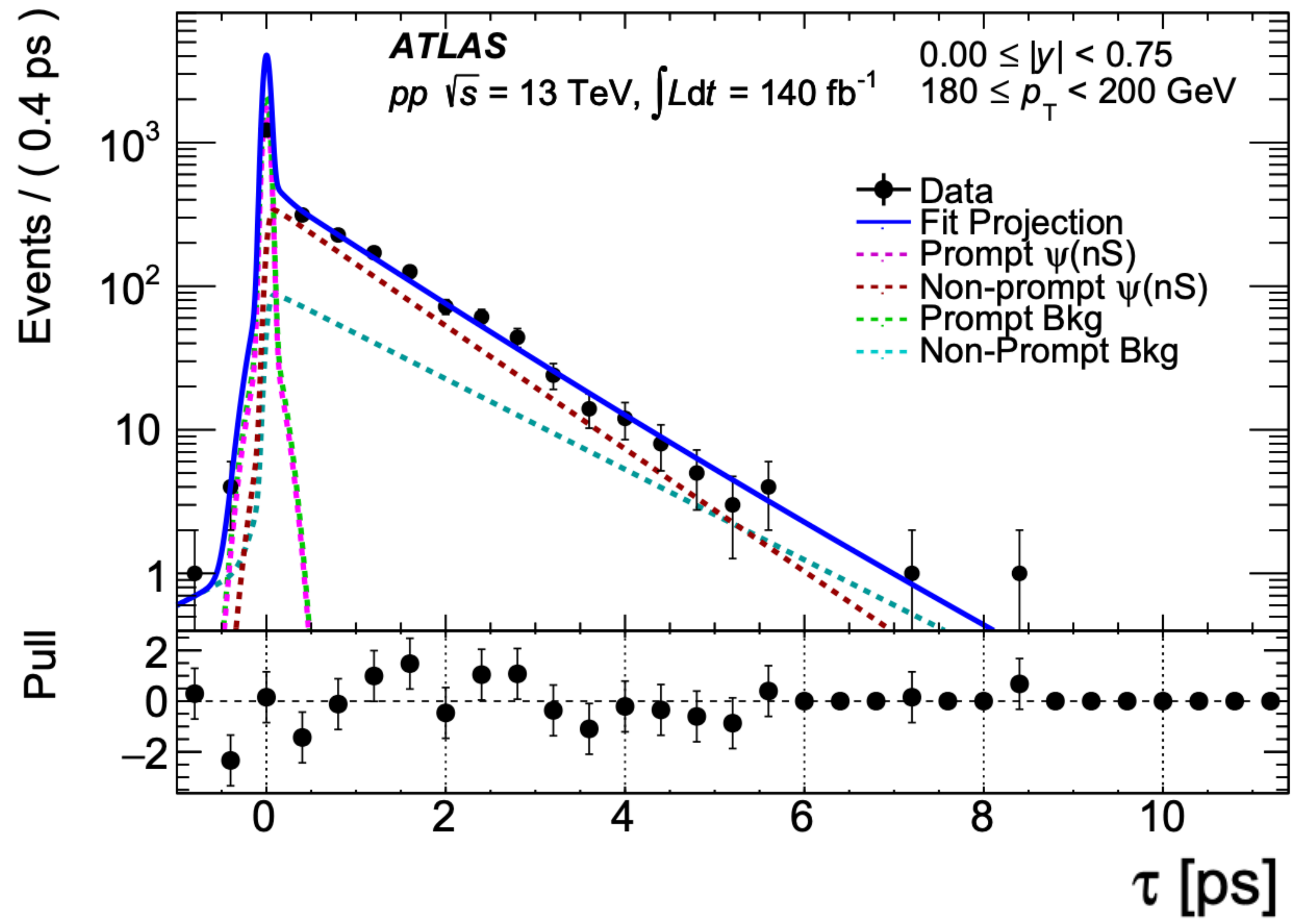
Analysis Strategy

- **Prompt and non-prompt contributions separated using the reconstructed pseudo proper lifetime** $\tau = \frac{m_{\mu\mu}}{p_T}\frac{L_{xy}}{c}$.
- Measured signal yield extracted from **simultaneous fits to reconstructed mass and pseudo proper lifetime** — in bins of p_T and y.
- Differential cross-section measured from the measured yield as:

$$\frac{d^2\sigma^{P,NP}(pp\to\psi)}{dp_T dy} = \frac{1}{\mathscr{B}(\psi\to\mu\mu)\int \mathscr{L}dt}\cdot\frac{1}{\mathscr{A}(\psi)\epsilon_{trig}\epsilon_{reco}SF_{trig}SF_{reco}}\cdot\frac{N_\psi^{P,NP}}{\Delta p_T \Delta y}$$

  - **Fraction of non-prompt production** F_ψ^{NP} **and** $\psi(2S)$**-to-**J/ψ **production ratios** $R^{P,NP}_{\psi(2S)}$ **also extracted** with partial cancellations of uncertainties!





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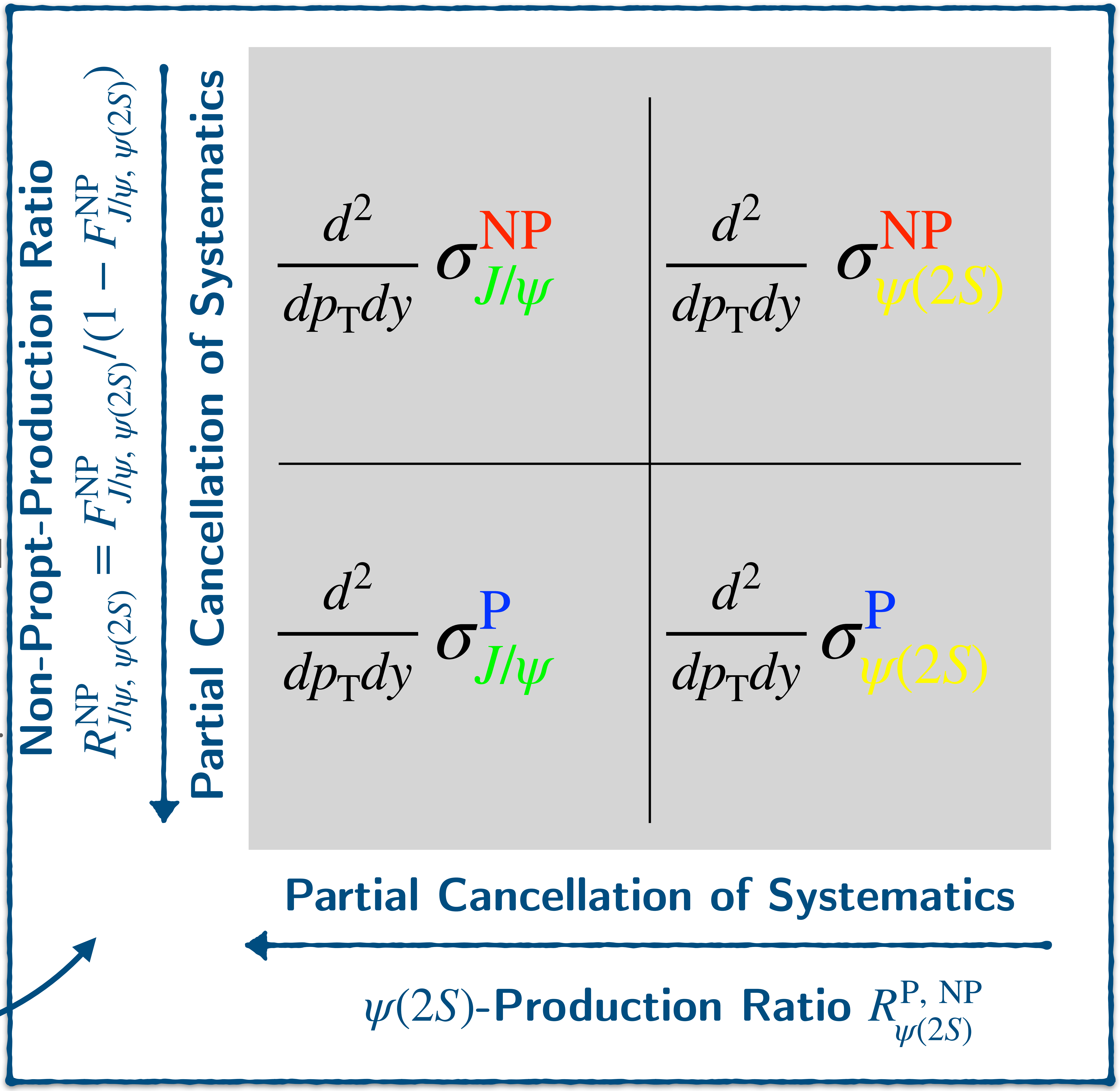
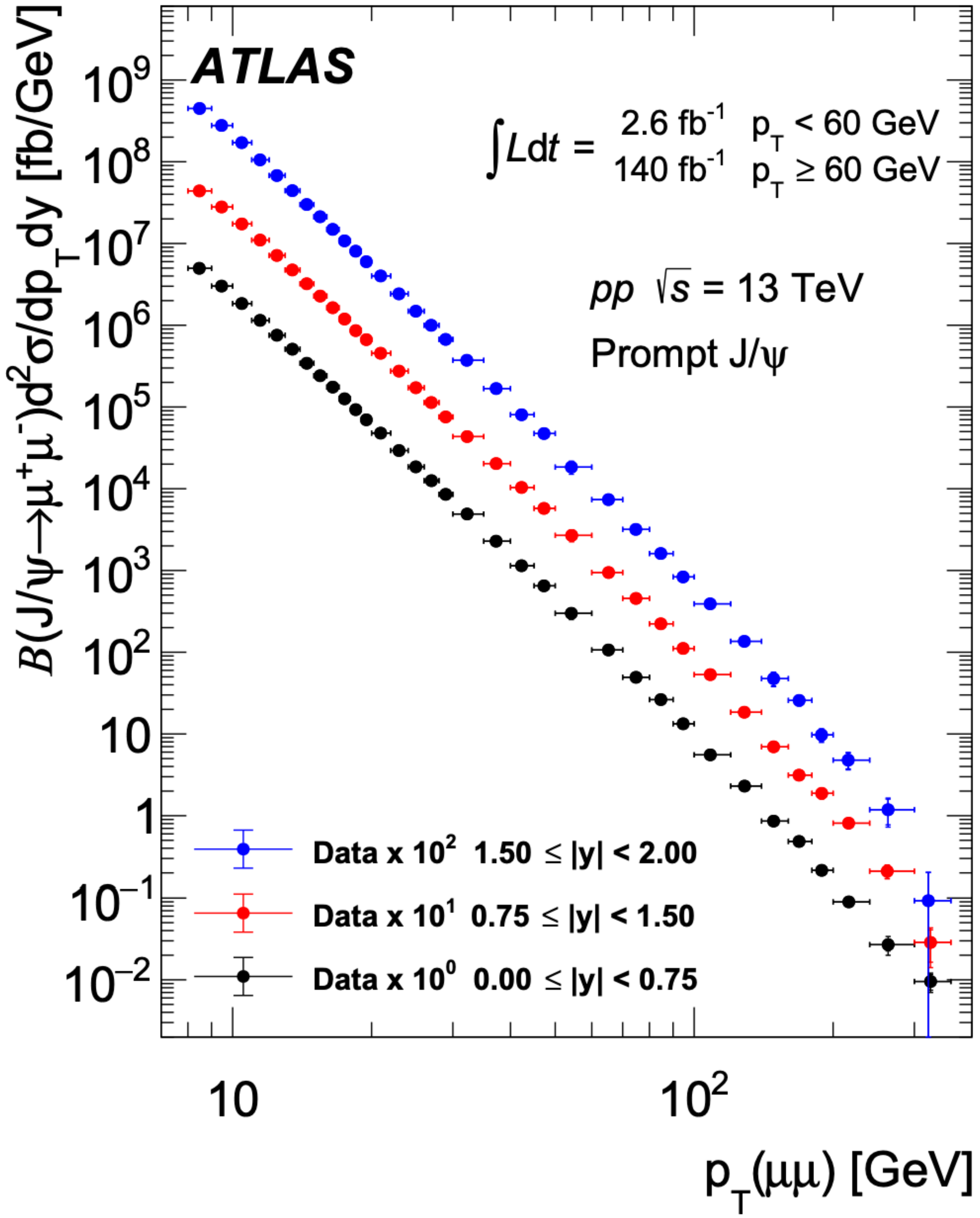
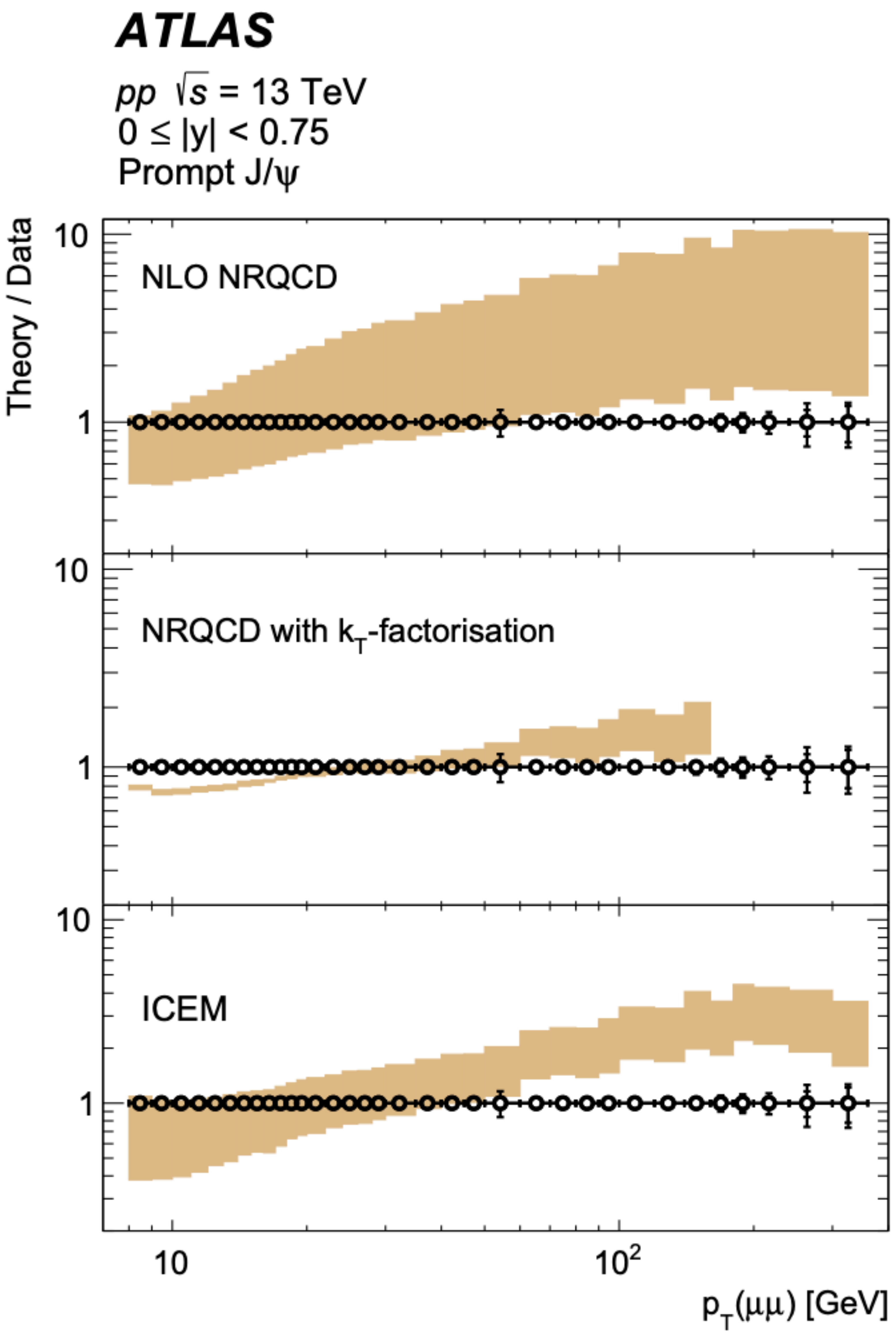
  - **Fraction of non-prompt production** F_{ψ}^{NP} **and** $\psi(2S)$**-to-**J/ψ **production ratios** $R_{\psi(2S)}^{\mathrm{P,NP}}$ **also extracted** with partial cancellations of uncertainties!



Results: Prompt J/ψ Production

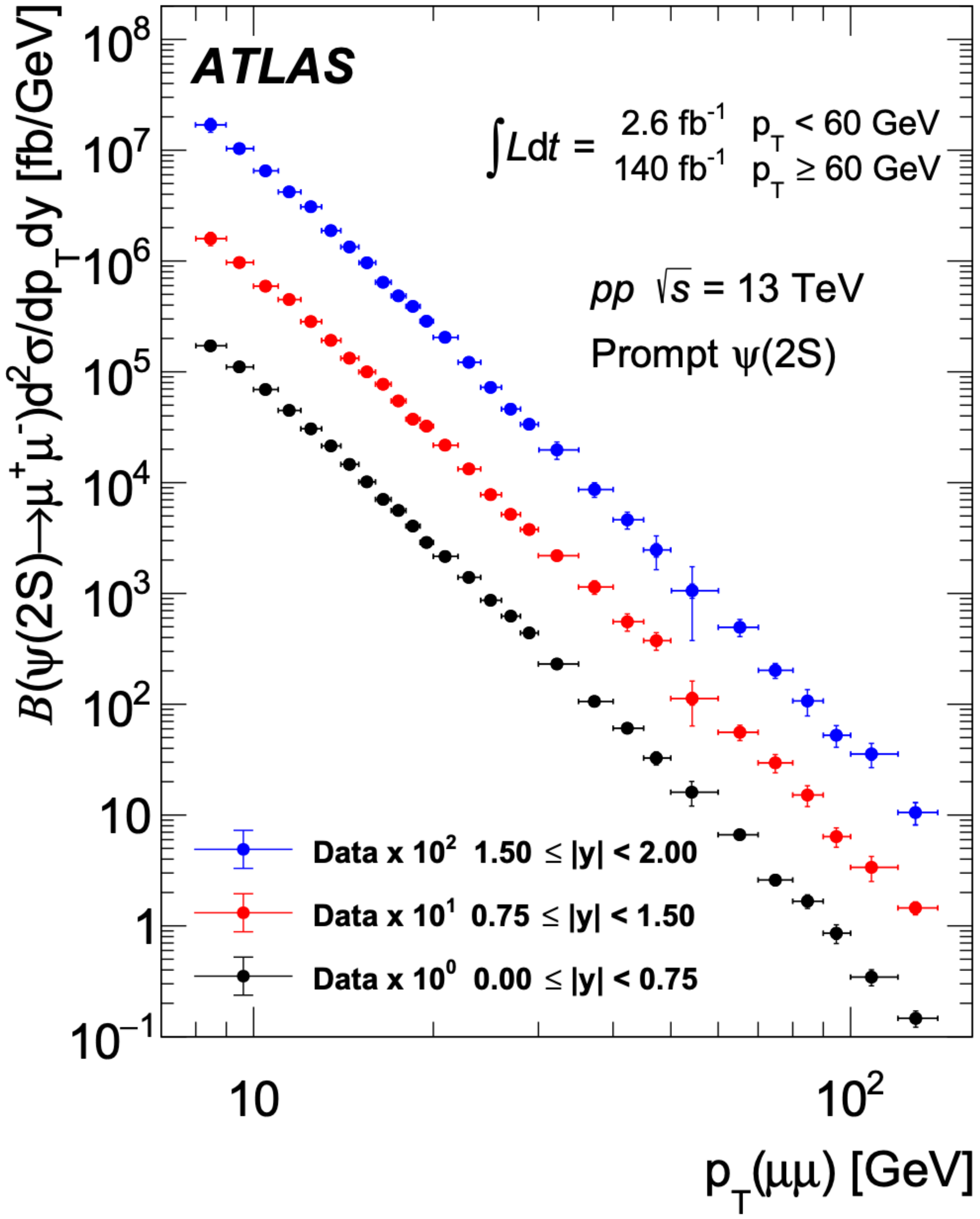
- NLO NRQCD and ICEM seem to overestimate the high-p_{T} production.
- NRQCD with k_{T} -factorization seems to underestimate the low-p_{T} production.

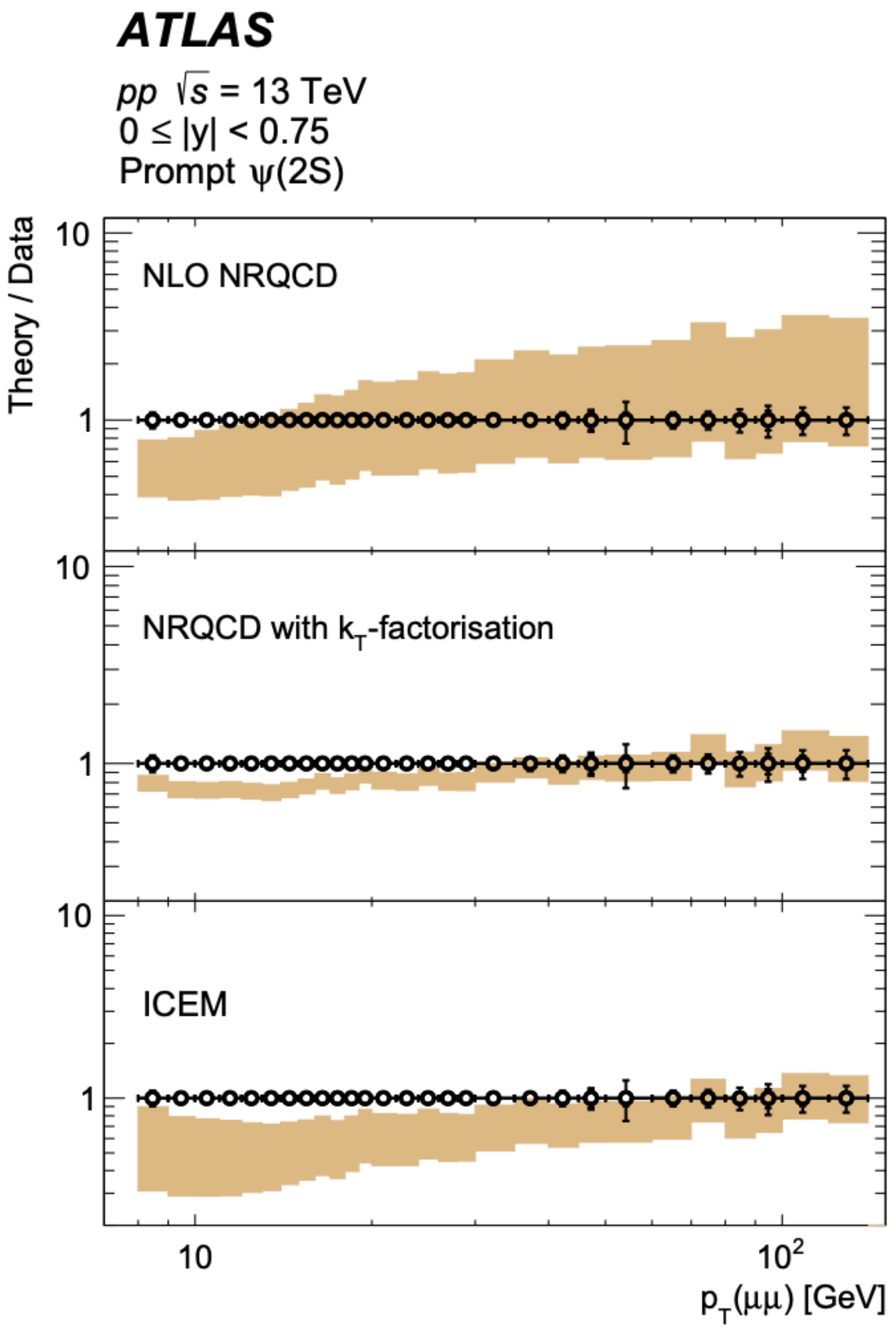




Results: Prompt $\psi(2S)$ Production

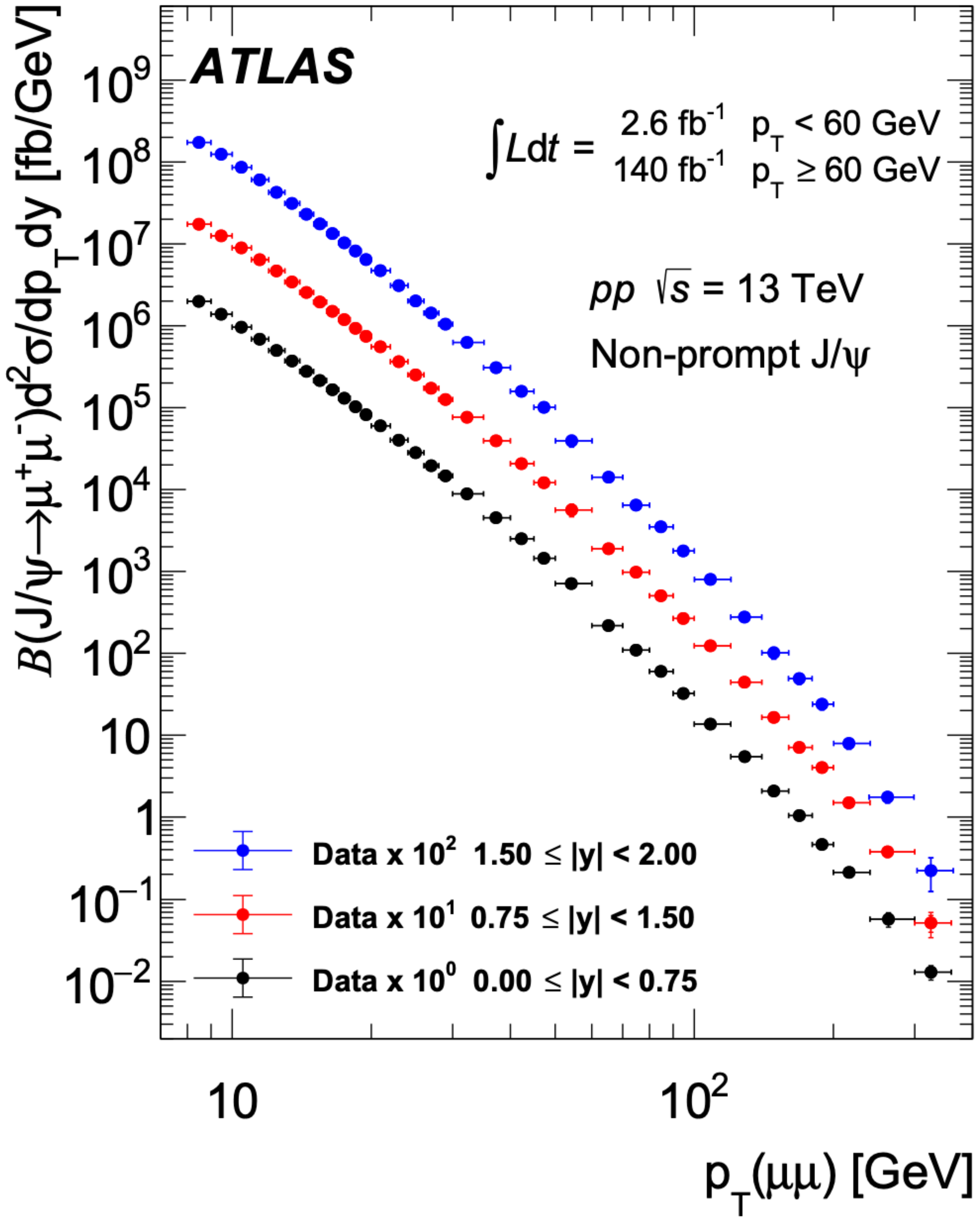
- NLO NRQCD seems to over-estimation of high-p_T production.
- NRQCD with k_T -factorization seems to underestimate the $\psi(2S)$ production.

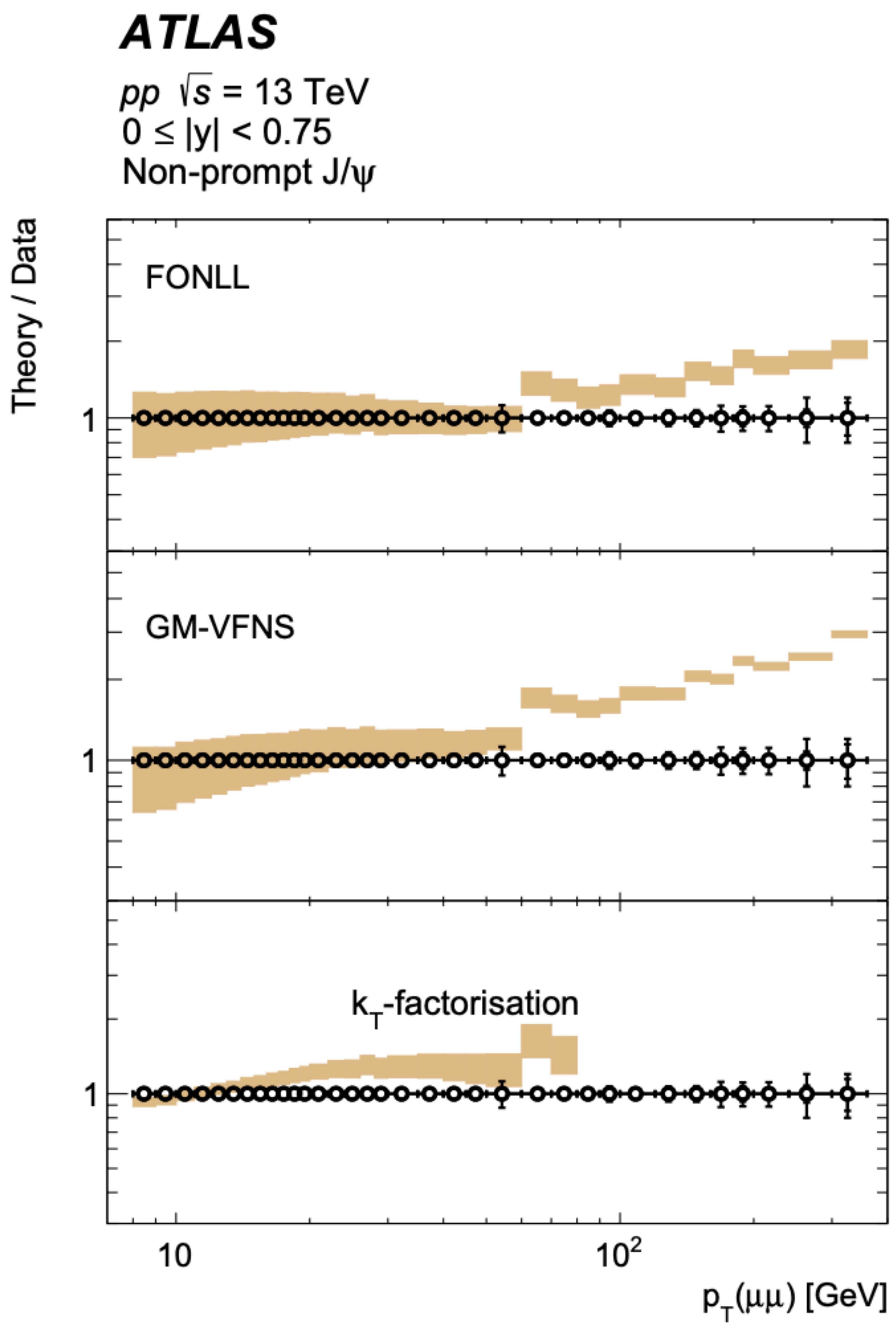




Results: Non-Prompt J/ψ Production

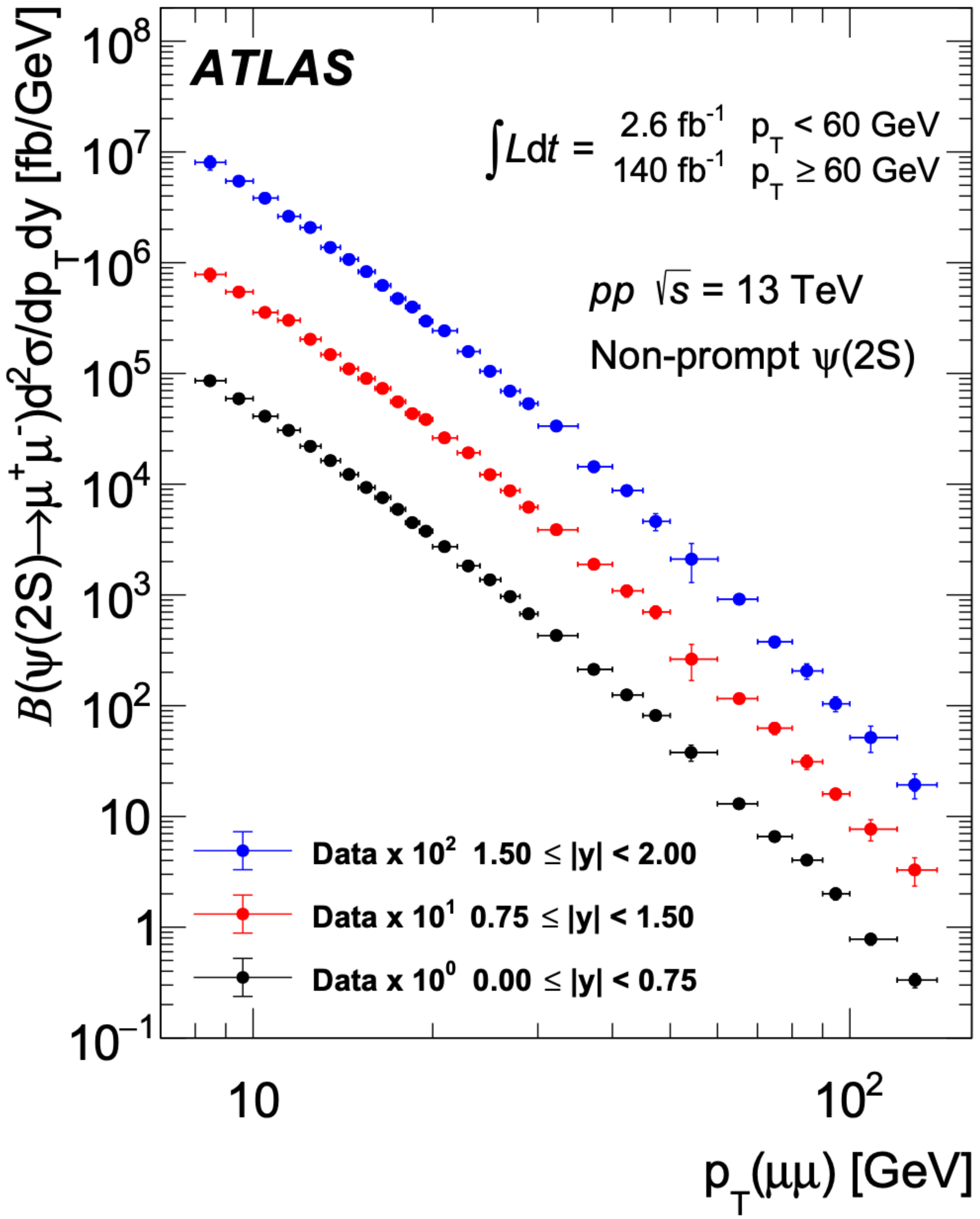
- FONLL and GM-VFNS seem to overestimate the high-p_T production.
- k_T-factorization limited in availability at high-p_T.

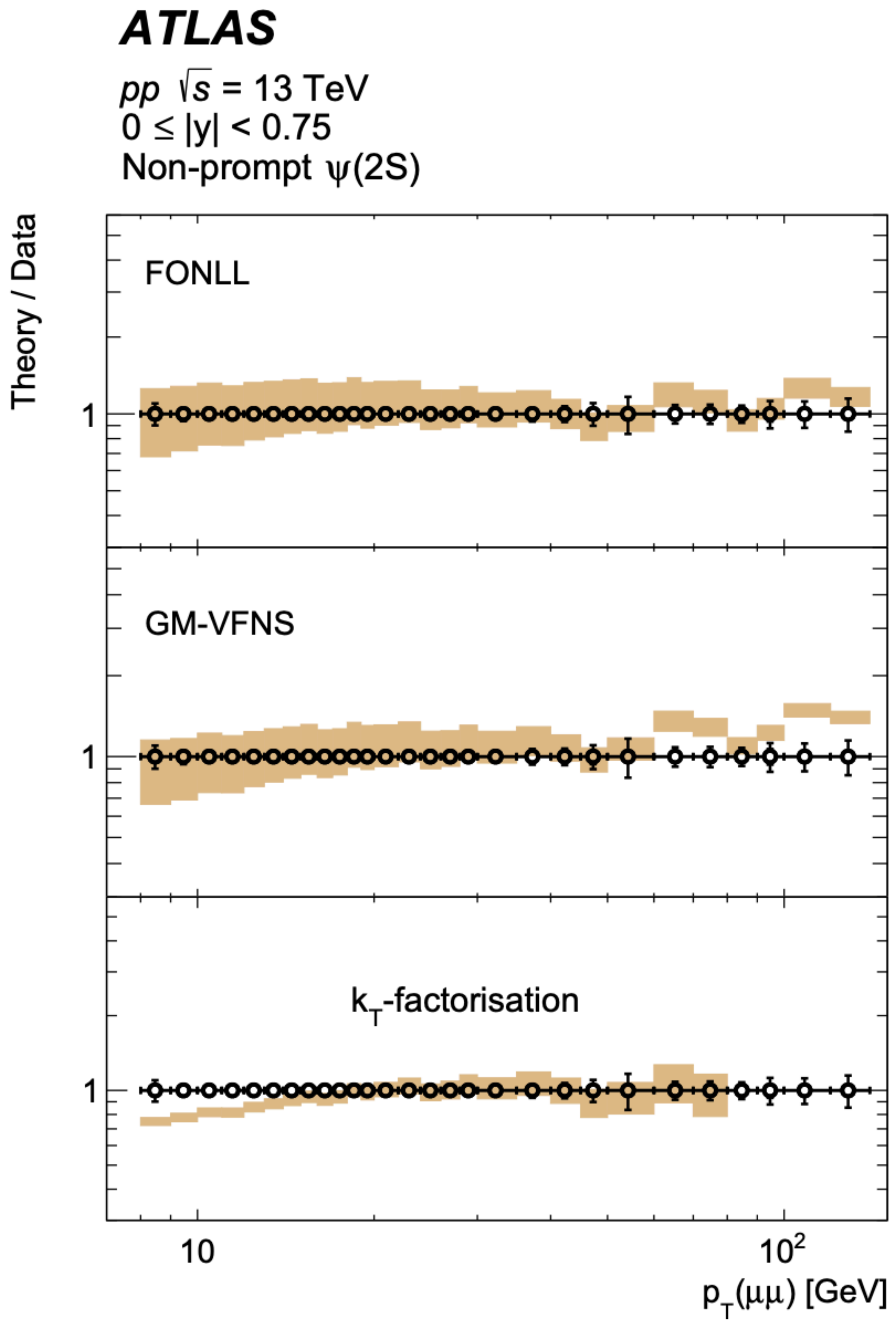




Results: Non-Prompt $\psi(2S)$ Production

- k_{T}-factorization seems to underestimate the production at low-p_{T}.





Results: $\psi(2S)$-to-J/ψ Production Ratios

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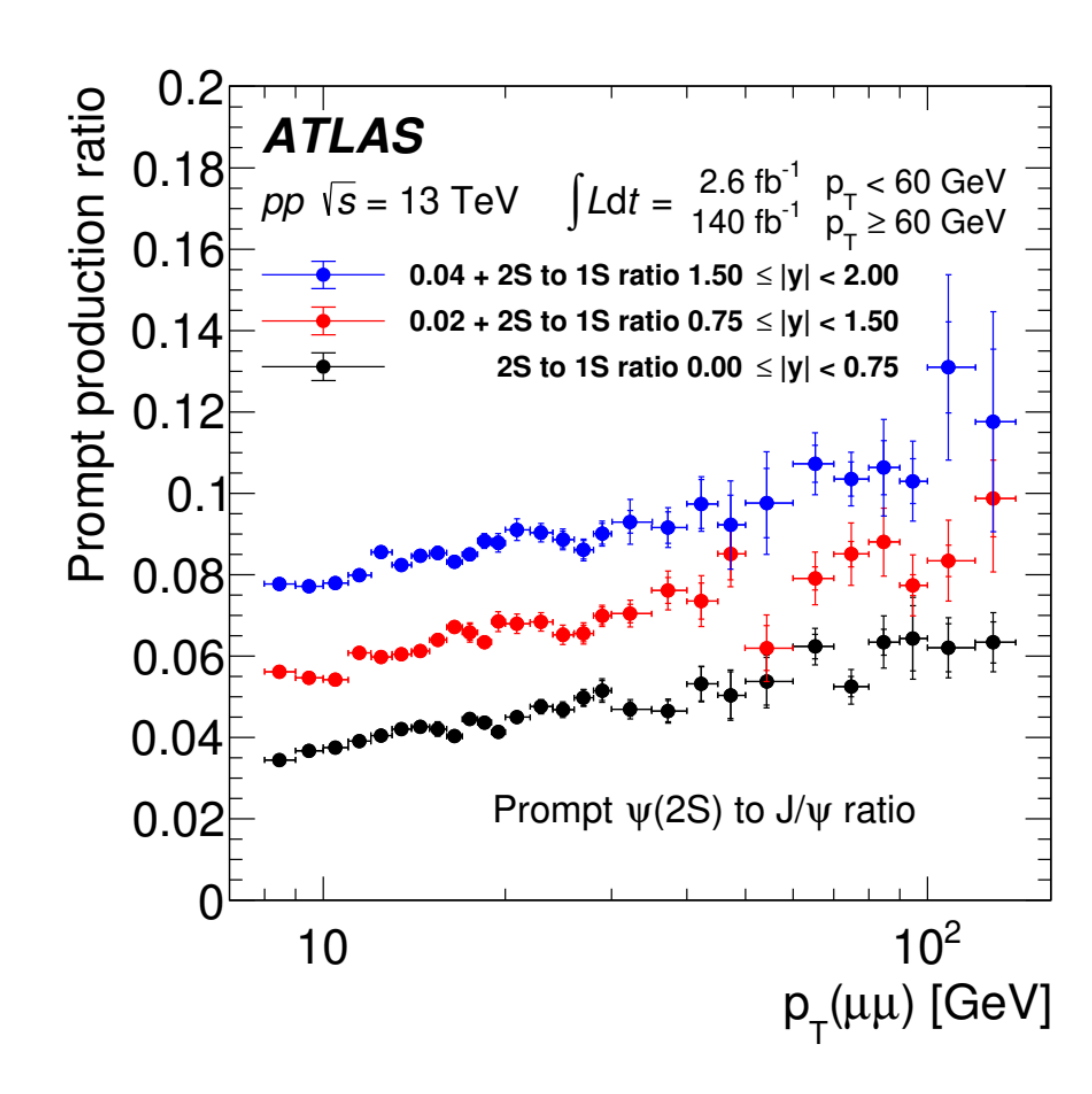

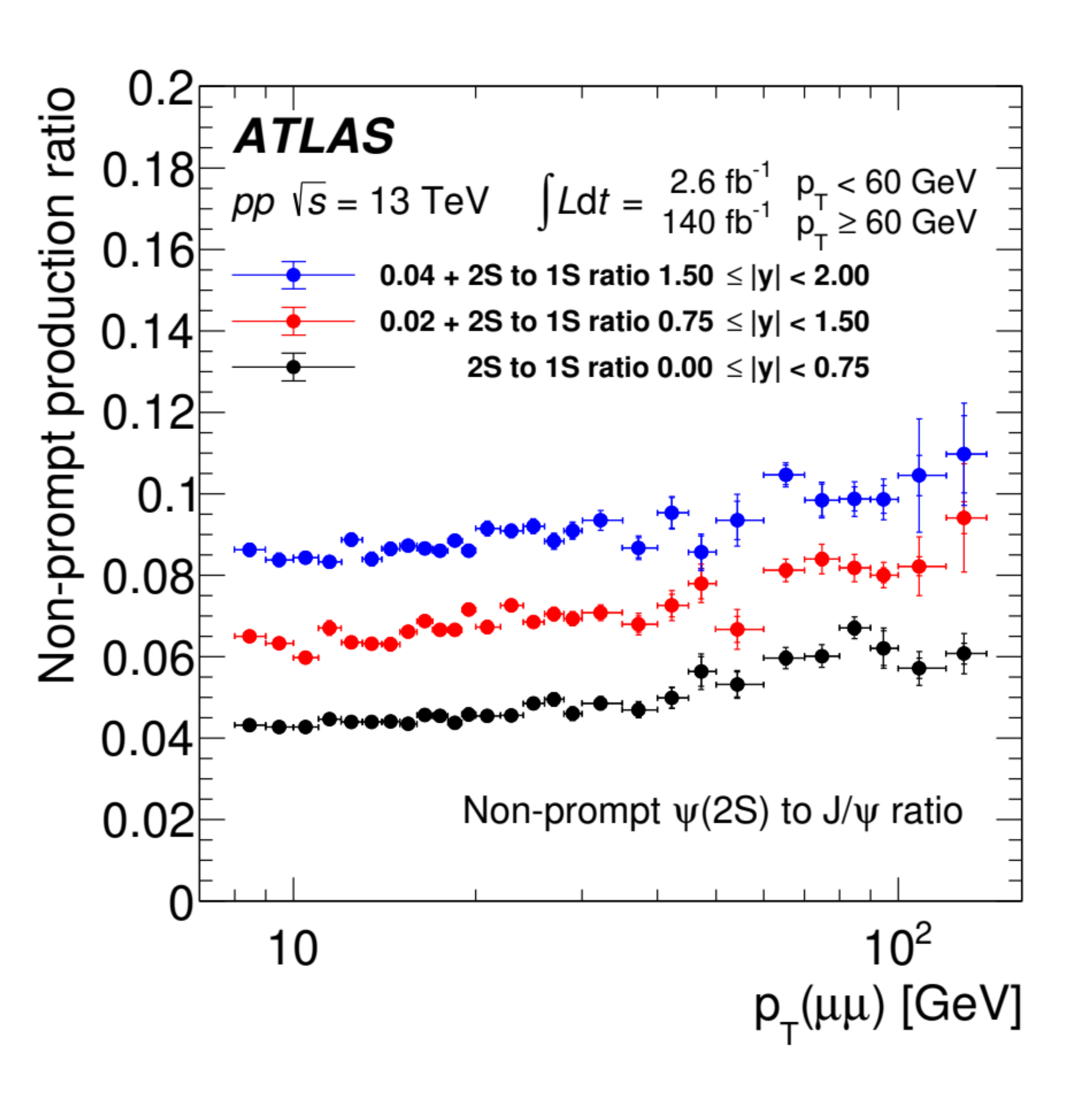

Results: Non-Prompt Production Fractions

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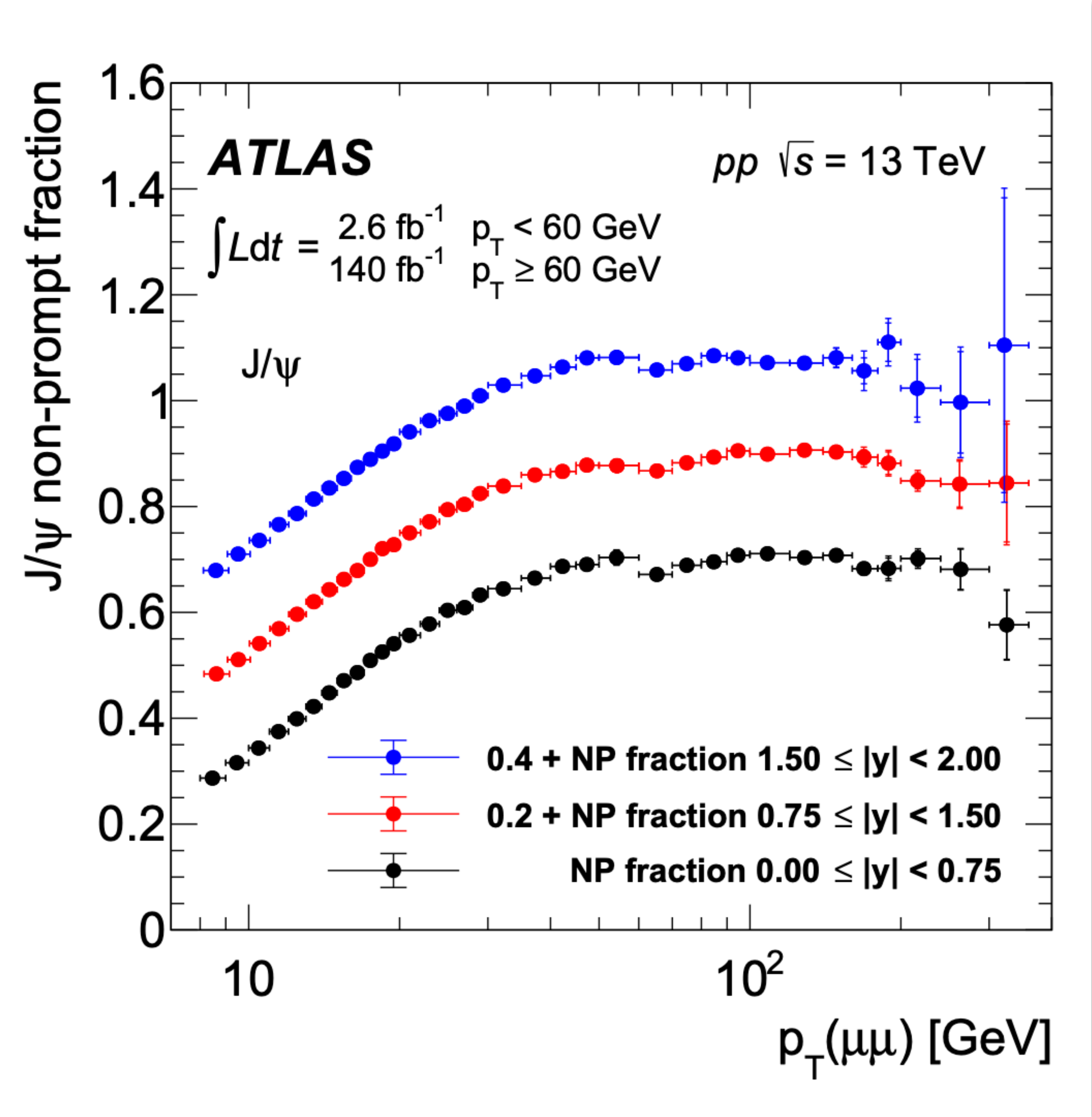
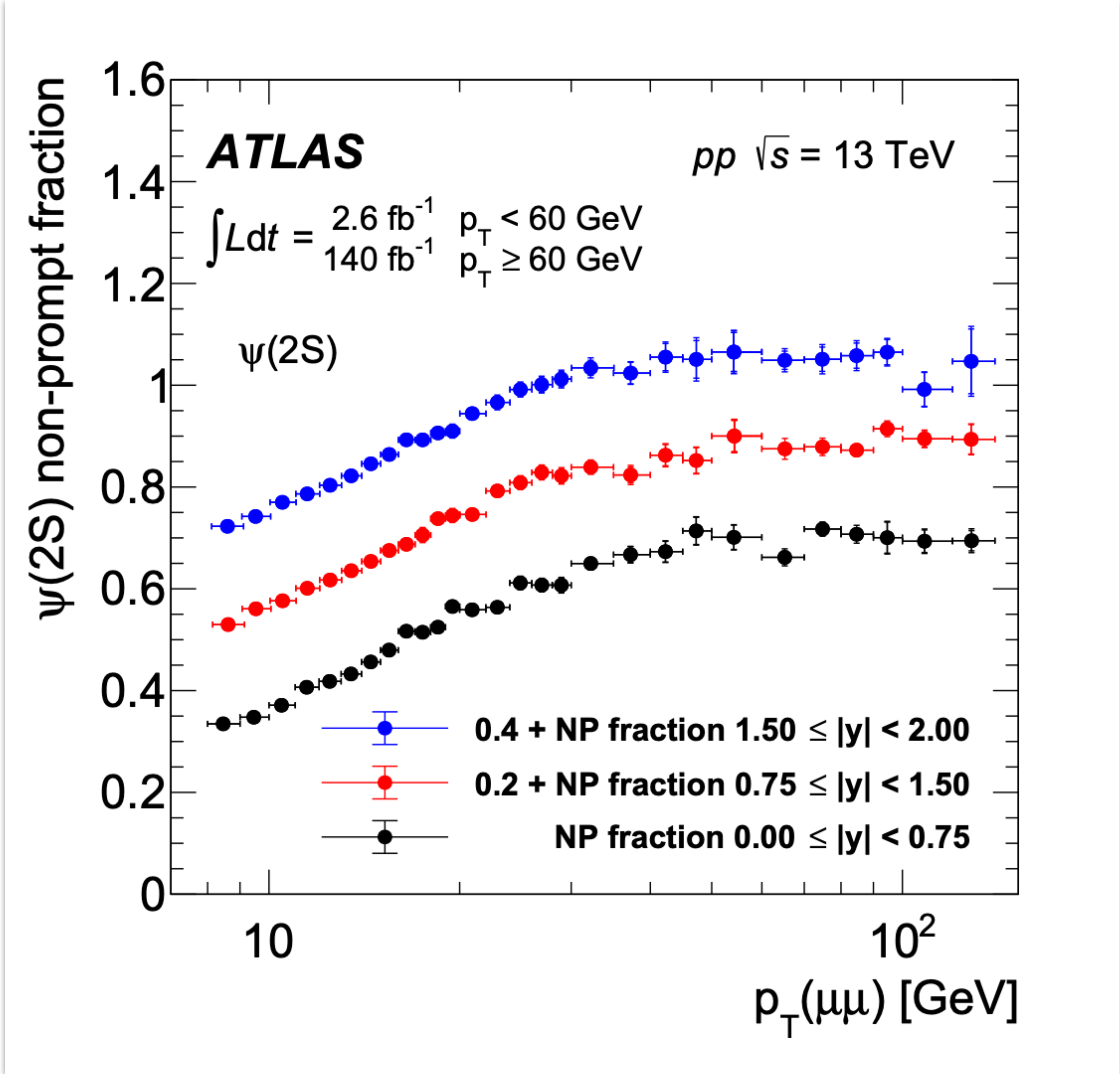




Search for Di-Charmonium Resonances in 4μ Final States

arXiv:2304.08962

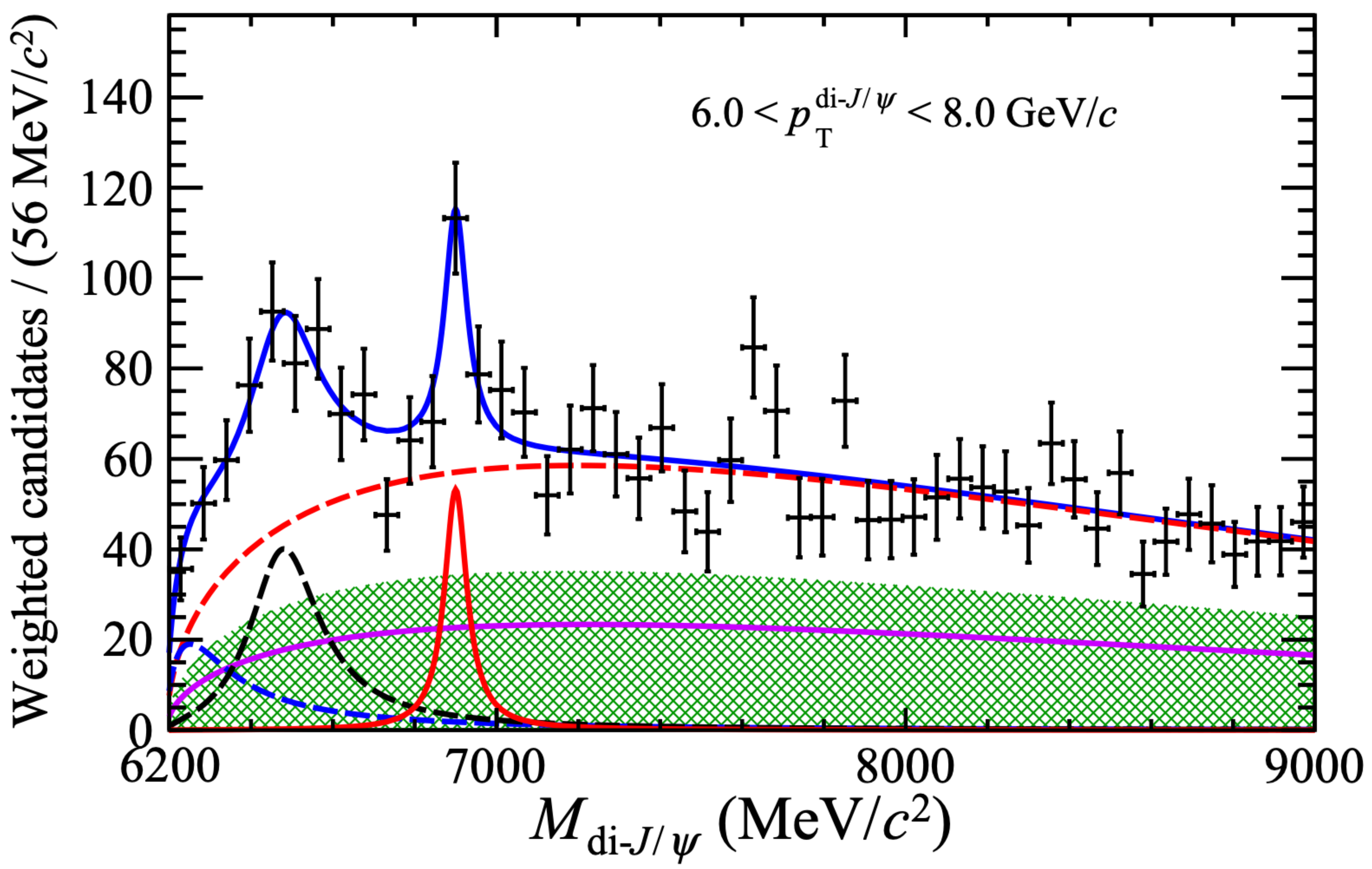
Phys. Rev. Lett. 131 (2023) 151902

Motivation

2304.08962

- **More broadly:**
  - Color-confinement allows for exotic bound states of quarks other than baryons and meson: $qq\bar{q}\bar{q}$, $qqqq\bar{q}$.
  - BSM also predicts resonances in di-quarkonia spectrum.
- **LHCb observed a narrow $X(6900)$ structure in $m(J/\psi J/\psi)$ in 2020!** 2006.16957
  - Consistent with a charming tetraquark $T_{cc\bar{c}\bar{c}}$.
- **This analysis:**
  - Corroborate the LHCb discovery in **a quite different phase space**.
  - Make sense of the **additional enhancement near di-J/ψ mass threshold** that LHCb observed.
  - Search for di-charmonium excesses in $J/\psi + \psi(2S)$ **channel**!

LHCb 2006.16957



Analysis Strategy

2304.08962

- Data
  - Full Run2 dataset with $L = 140\ \text{fb}^{-1}$ of pp collision data at $\sqrt{s} = 13$ TeV
  - Trigger on low-p_{T} dimuon or trimuon triggers requiring an oppositely charged muon pair.
- **Signal: Search for 4μ final state produced via**
  - $J/\psi + J/\psi$ Channel
  - $J/\psi + \psi(2S)$ Channel
- Background:
  - **Prompt Di-Charmonia: SPS and DPS events.**
    Modeled with MC corrected with data in mass sidebands.
  - **Non-Prompt Di-Charmonia: $b-$Hadron Decays: $b\bar{b} \to J/\psi(\to \mu^+\mu^-)J/\psi(\to \mu^+\mu^-)X$**
    Modeled with MC corrected with data in sidebands of vertexing quality and/or displacement of $\mu^+\mu^-$ vertices.
  - **One Charmonium + Non-Resonant $\mu^+\mu^-$: Mostly due to fake muons.**
    Purely data-driven fake estimation.
- Event Selection
  - **4μ vertexing followed by two $\mu^+\mu^-$ vertexings with J/ψ or $\psi(2S)$ mass-constraints in events with two pairs of $\mu^+\mu^-$.**
  - **Background rejection via stringent cuts on the quality of the 4μ vertex fit and on the angle b/w the charmonia candidates.**

Signal

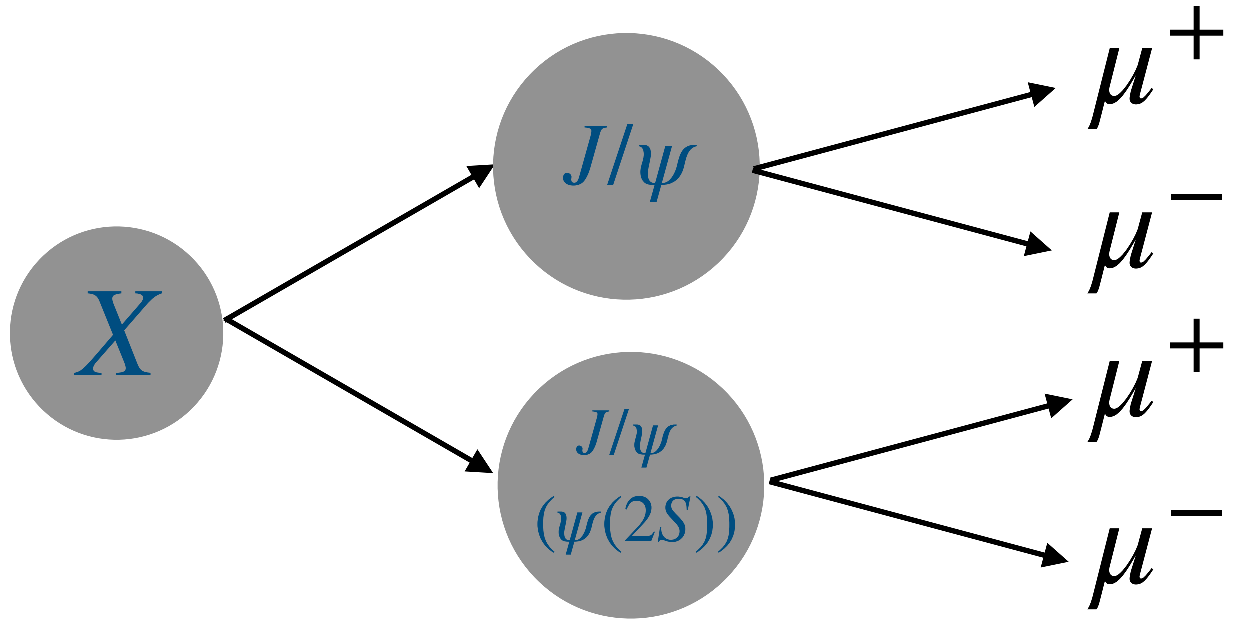
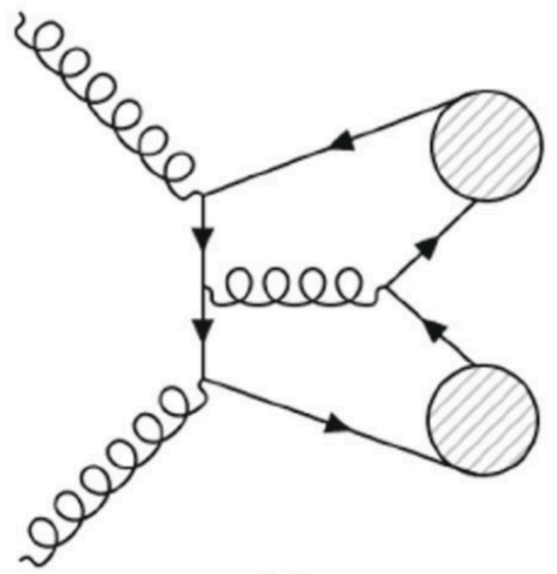
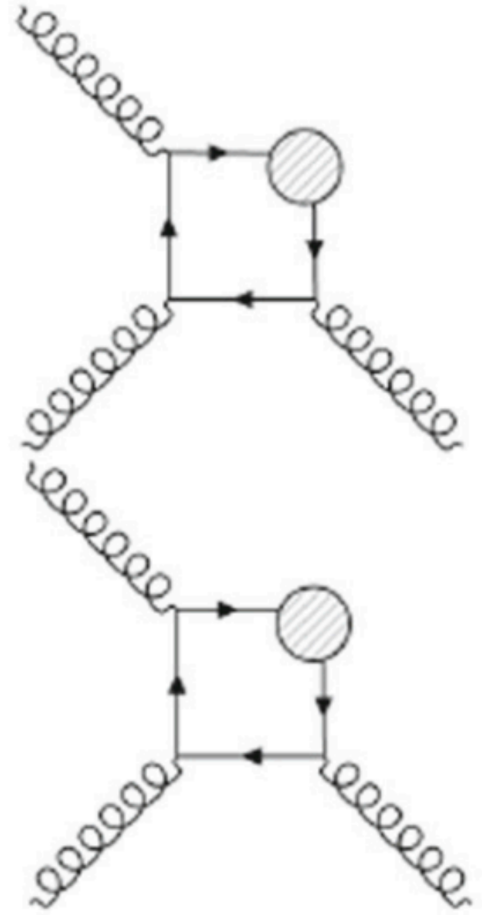


Illustration Credit: Yue Xu (LHCP2025)



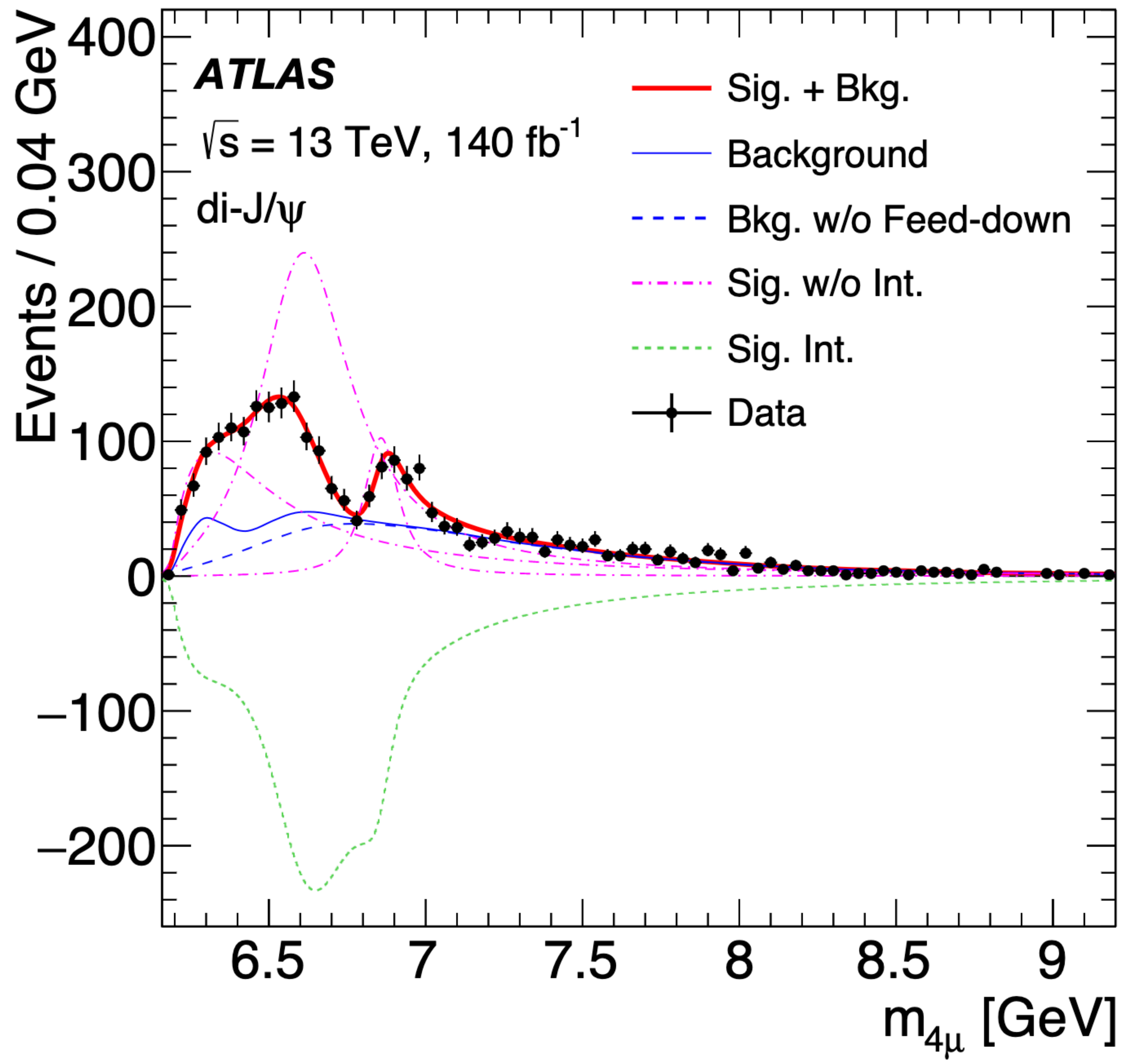
SPS Background



DPS Background

Signal Modeling for the Fits

- Signal Modeling for Fits
  - $J/\psi + J/\psi$ **Channel**
    - Feeddown from $J/\psi + \psi(2S)$ channel signal fit taken as background
    - **Model A:** 3 interfering BW resonances
    - **Model B:** 2 BW where the lower resonance interferes with the SPS background
  - $J/\psi + \psi(2S)$ **Channel**
    - **Model** α: 3 interfering BW resonances of Model A + standalone 4th BW resonance
    - **Model** β**:** Only 1 BW resonance



- **Other models considered but excluded in favor of these with the most promising of the excluded ones used to calculate systematics associated with the models.**

Results: $J/\psi + J/\psi$ Channel

2304.08962

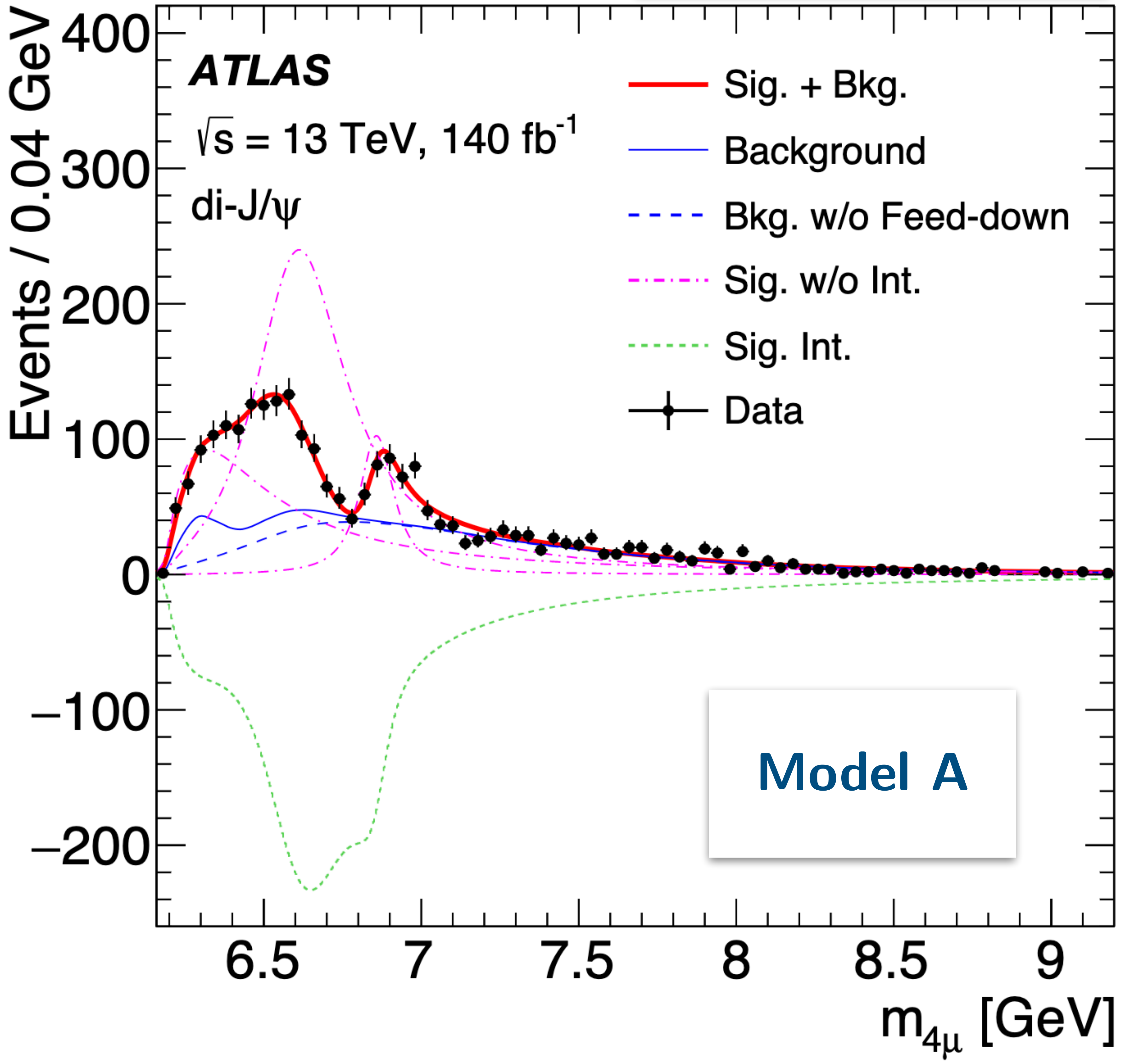
- **Significance for both models far exceeds 5σ**
  - The mass of the m_2 resonance consistent with the LHCb mass as well as with the CMS search now: 2306.07164
- **The broad structure at lower mass can still be from other effects such as feeddown from higher dicharmonium resonances.**
  - $T_{cc\bar{c}\bar{c}} \to \chi_{cJ'}\chi_{cJ'} \to J/\psi J/\psi\gamma\gamma$

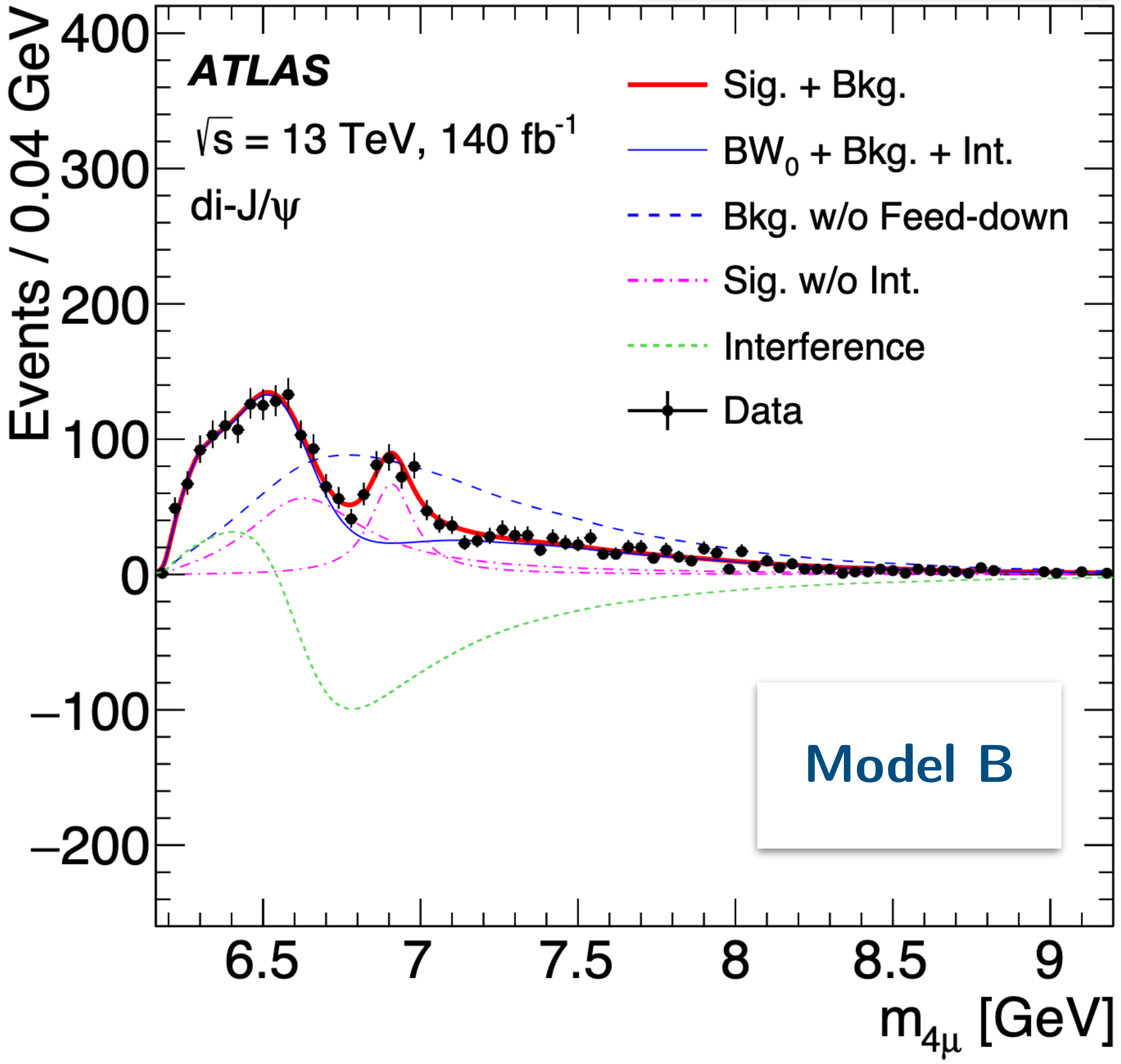
All mutually interfering

di-J/ψ	model A
m_0	$6.41 \pm 0.08^{+0.08}_{-0.03}$
Γ_0	$0.59 \pm 0.35^{+0.12}_{-0.20}$
m_1	$6.63 \pm 0.05^{+0.08}_{-0.01}$
Γ_1	$0.35 \pm 0.11^{+0.11}_{-0.04}$
m_2	$6.86 \pm 0.03^{+0.01}_{-0.02}$
Γ_2	$0.11 \pm 0.05^{+0.02}_{-0.01}$
$\Delta s/s$	$\pm 5.1\%^{+8.1\%}_{-8.9\%}$

Interfering with SPS background

di-J/ψ	model B
m_0	$6.65 \pm 0.02^{+0.03}_{-0.02}$
Γ_0	$0.44 \pm 0.05^{+0.06}_{-0.05}$
m_1	—
Γ_1	
m_2	$6.91 \pm 0.01 \pm 0.01$
Γ_2	$0.15 \pm 0.03 \pm 0.01$
$\Delta s/s$	—





2304.08962

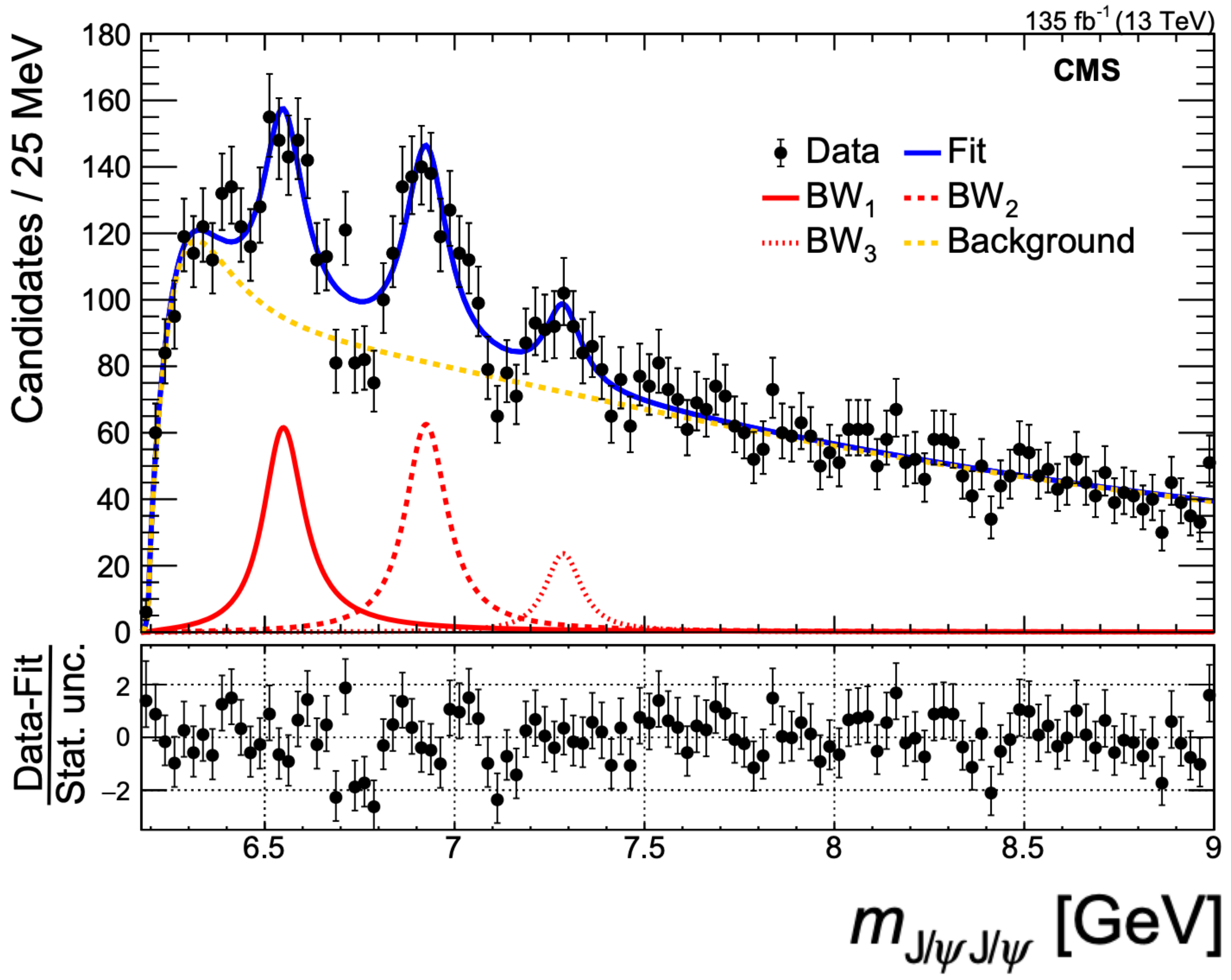
Brief Recap of Context for $J/\psi + \psi(2S)$ Channel

- $X(6900)$ is just above $J/\psi + \psi(2S)$ mass threshold!
  - So, we might expect an excess at the lower-end of $J/\psi + \psi(2S)$ spectrum.

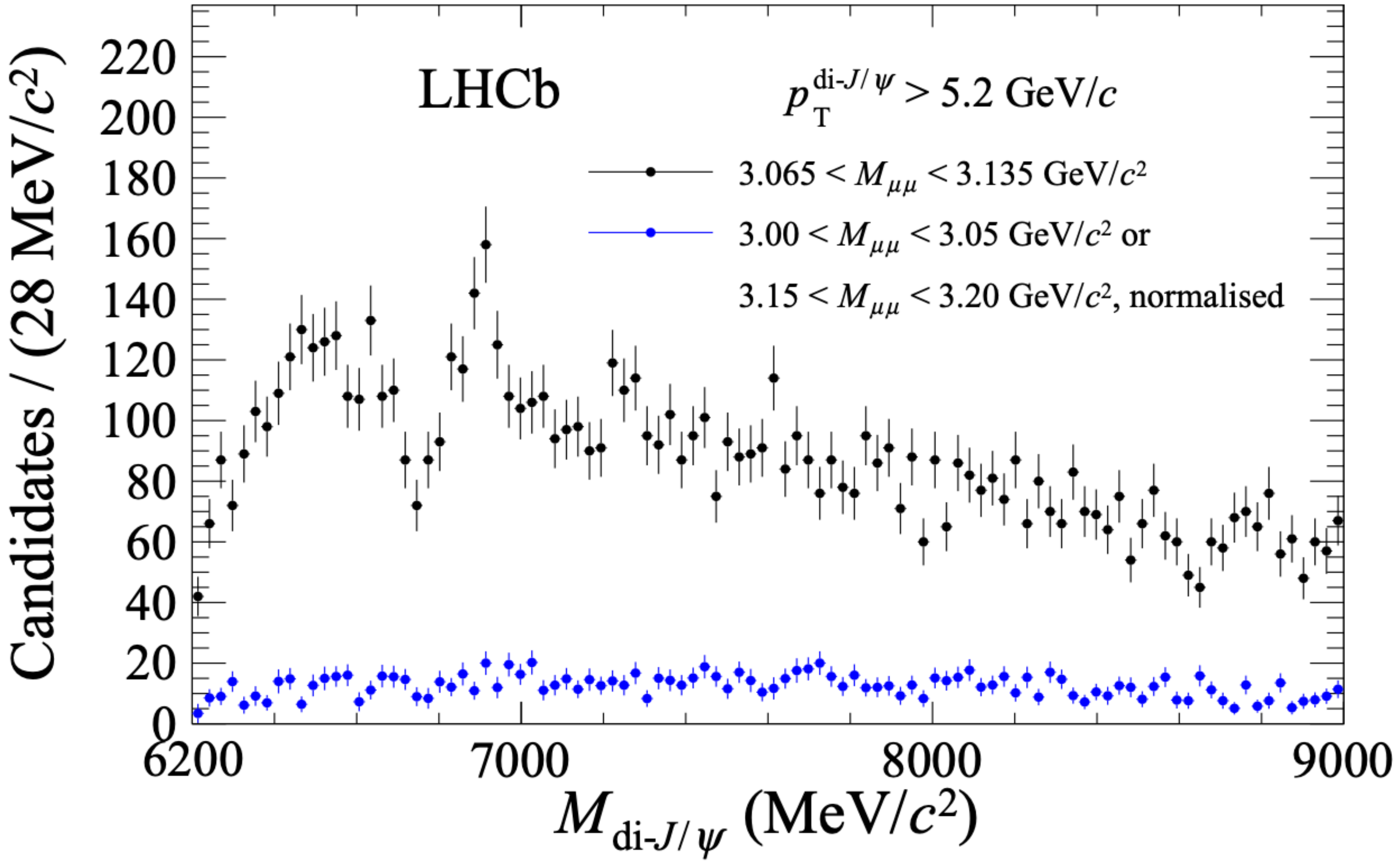
- Is there something going on also at ~ 7.2 GeV in the dicharmonia spectrum?

- Technical: To fit the feed-down background for $J/\psi + J/\psi$ channel.

CMS 2306.07164



LHCb 2006.16957



Results: $J/\psi + \psi(2S)$ Channel

- **Model α:** 4.7σ
  - **Significance for the second resonance alone at 3σ.**
- **Model β:** 4.3σ

J/ψ+ψ(2S)	model α
m_3	$7.22 \pm 0.03^{+0.01}_{-0.04}$
Γ_3	$0.09 \pm 0.06^{+0.06}_{-0.05}$
$\Delta s/s$	$\pm 21\%^{+25\%}_{-15\%}$

J/ψ+ψ(2S)	model β
m_3	$6.96 \pm 0.05 \pm 0.03$
Γ_3	$0.51 \pm 0.17^{+0.11}_{-0.10}$
$\Delta s/s$	$\pm 20\% \pm 12\%$

All mutually interfering

di-J/ψ	model A
m_0	$6.41 \pm 0.08^{+0.08}_{-0.03}$
Γ_0	$0.59 \pm 0.35^{+0.12}_{-0.20}$
m_1	$6.63 \pm 0.05^{+0.08}_{-0.01}$
Γ_1	$0.35 \pm 0.11^{+0.11}_{-0.04}$
m_2	$6.86 \pm 0.03^{+0.01}_{-0.02}$
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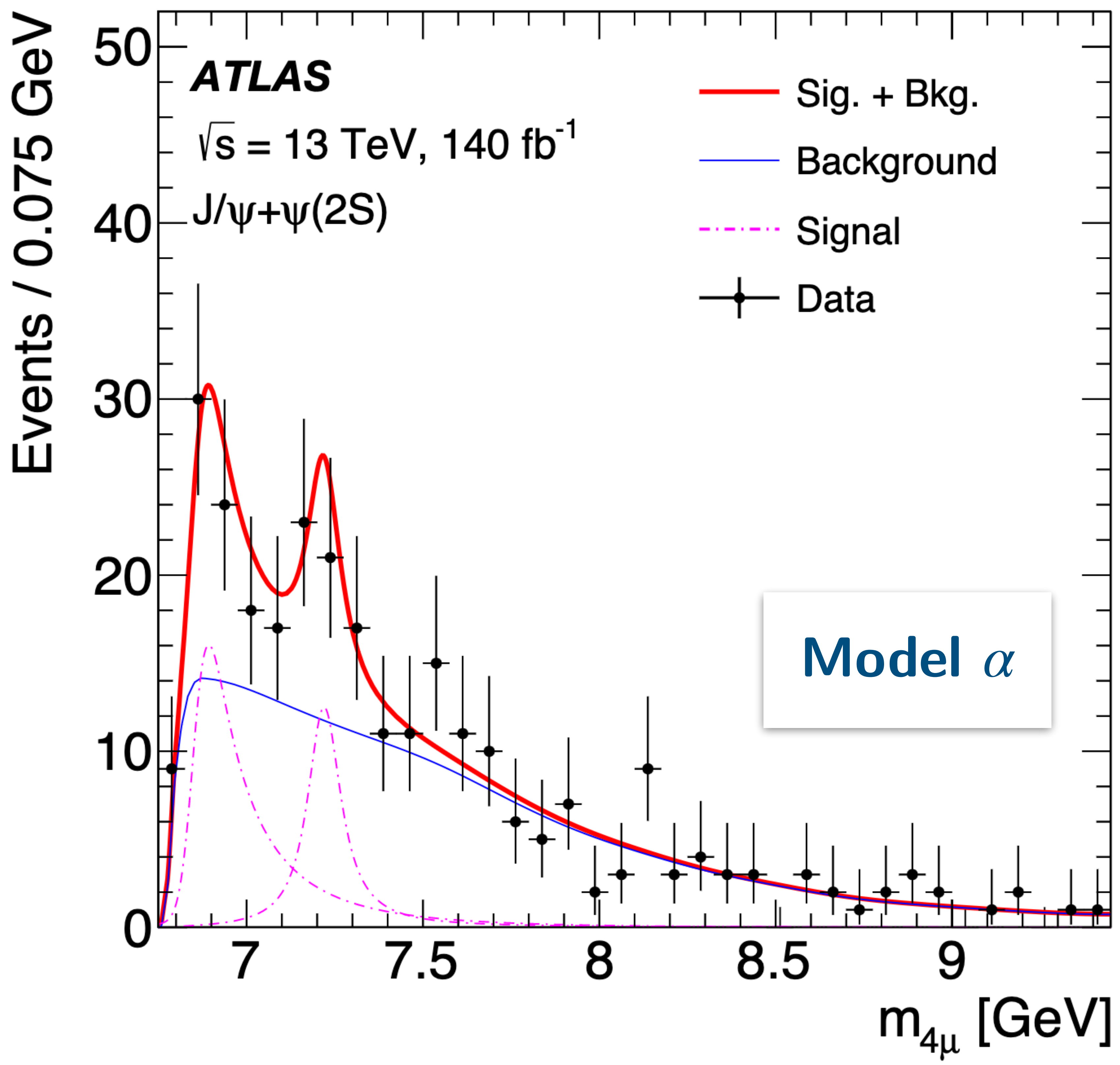
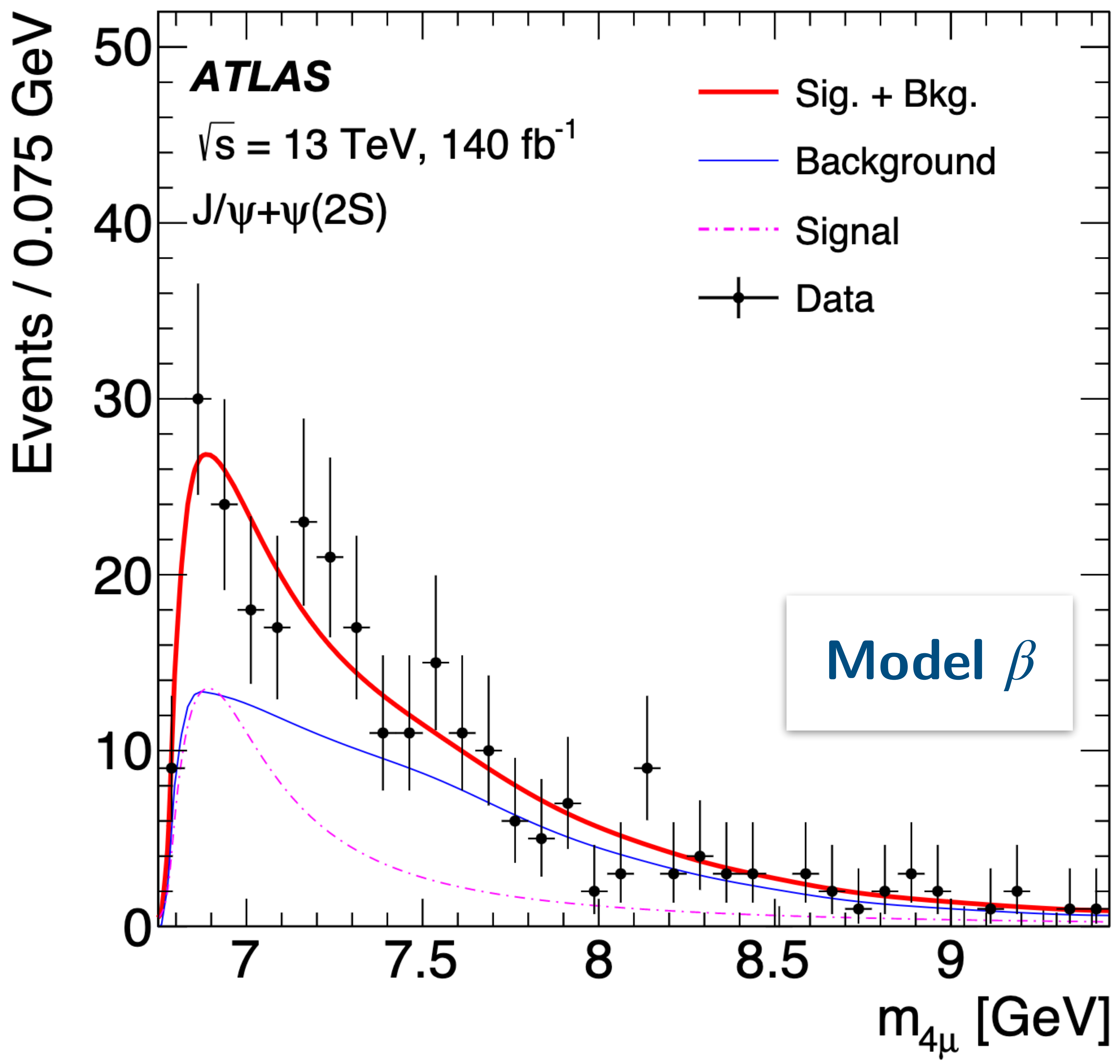
$\Delta s/s$	$\pm 5.1\%^{+8.1\%}_{-8.9\%}$





Outlook: Heavy Quarkonium Production and Spectroscopy ATLAS in This Talk and Beyond!

- Differential Production Cross-Section of J/ψ and $\psi(2S)$
  - Extended up to $p_{\mathrm{T}}^{J/\psi} = 360$ GeV. A lot to work with for theoretical models!
- Search for Di-Charmonium Resonances in 4μ Final States
  - Corroborated the LHCb discovery of $X(6900)$ in di-J/ψ.
  - Look out for more work on the evidence of excess in $J/\psi + \psi(2S)$.
  - More work also needed to understand the low-mass broad structure observed, also by LHCb.

ATLAS Public Results

Thank You!

Back-Up

Differential Production Cross-Section of J/ψ and $\psi(2S)$

arXiv:2309.17177

Eur. Phys. J. C 84 (2024) 169

The Spin-Alignment Correction Factors

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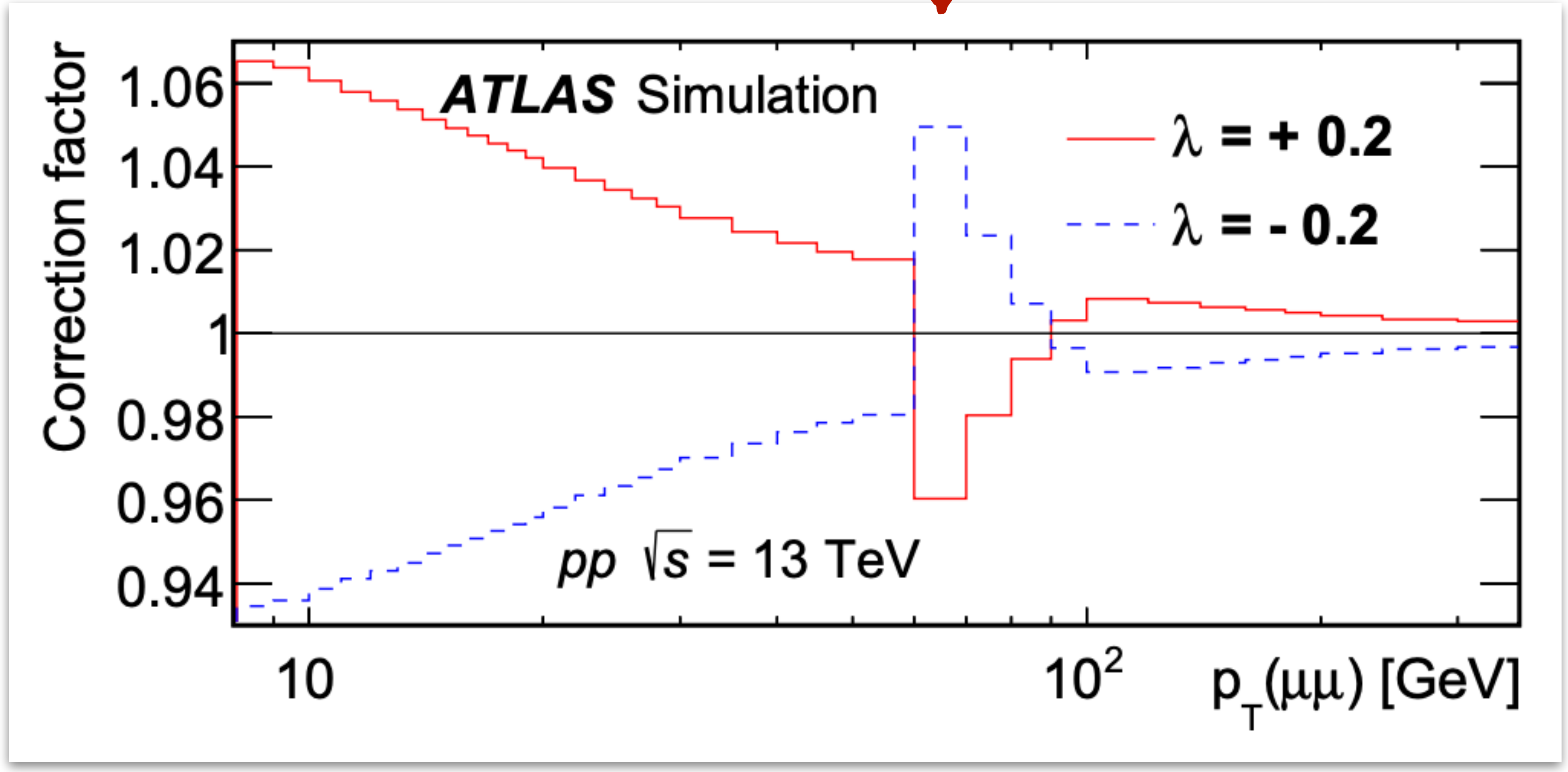
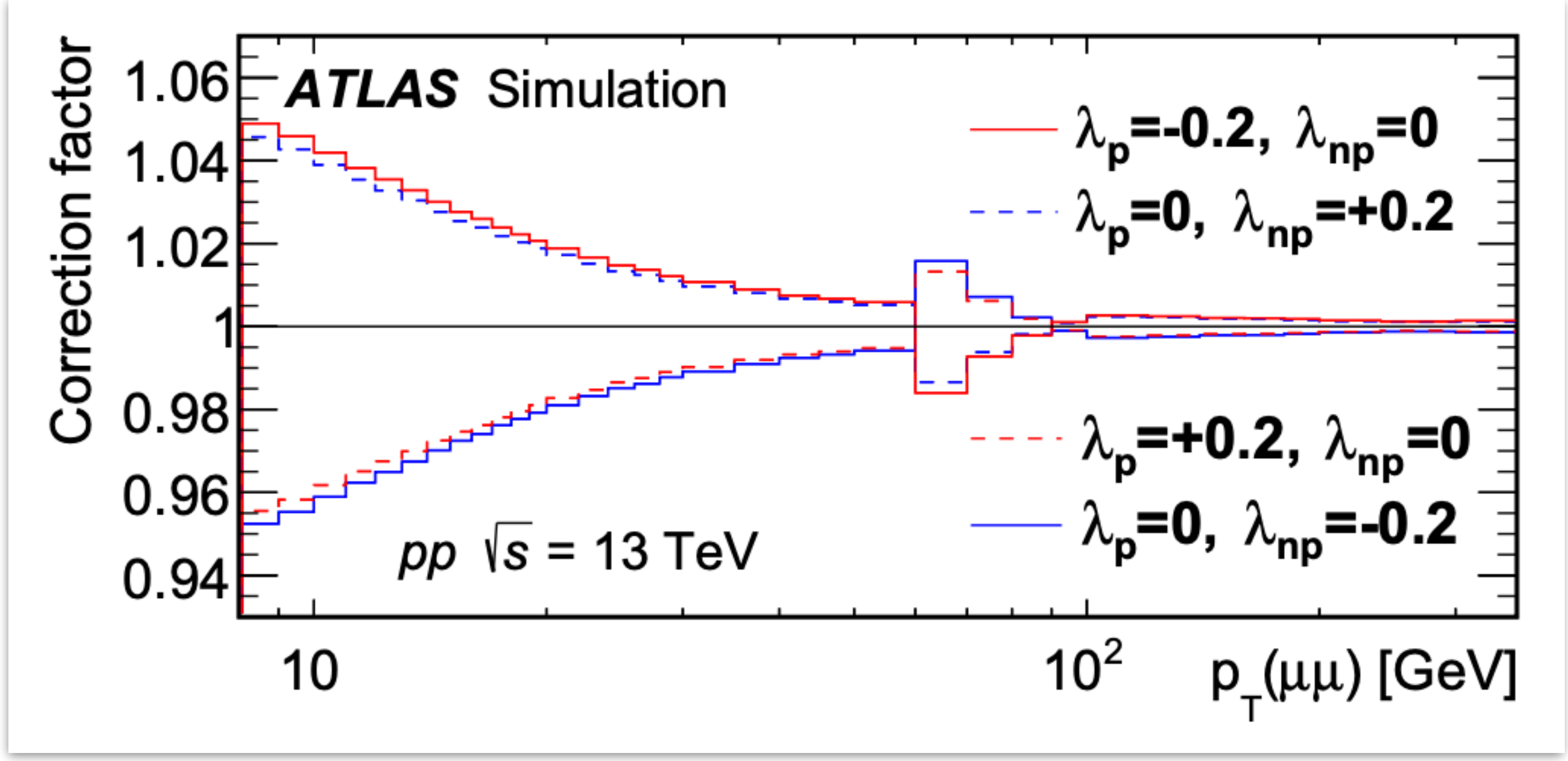
The switch in trigger strategy kicks in...
at 60 GeV

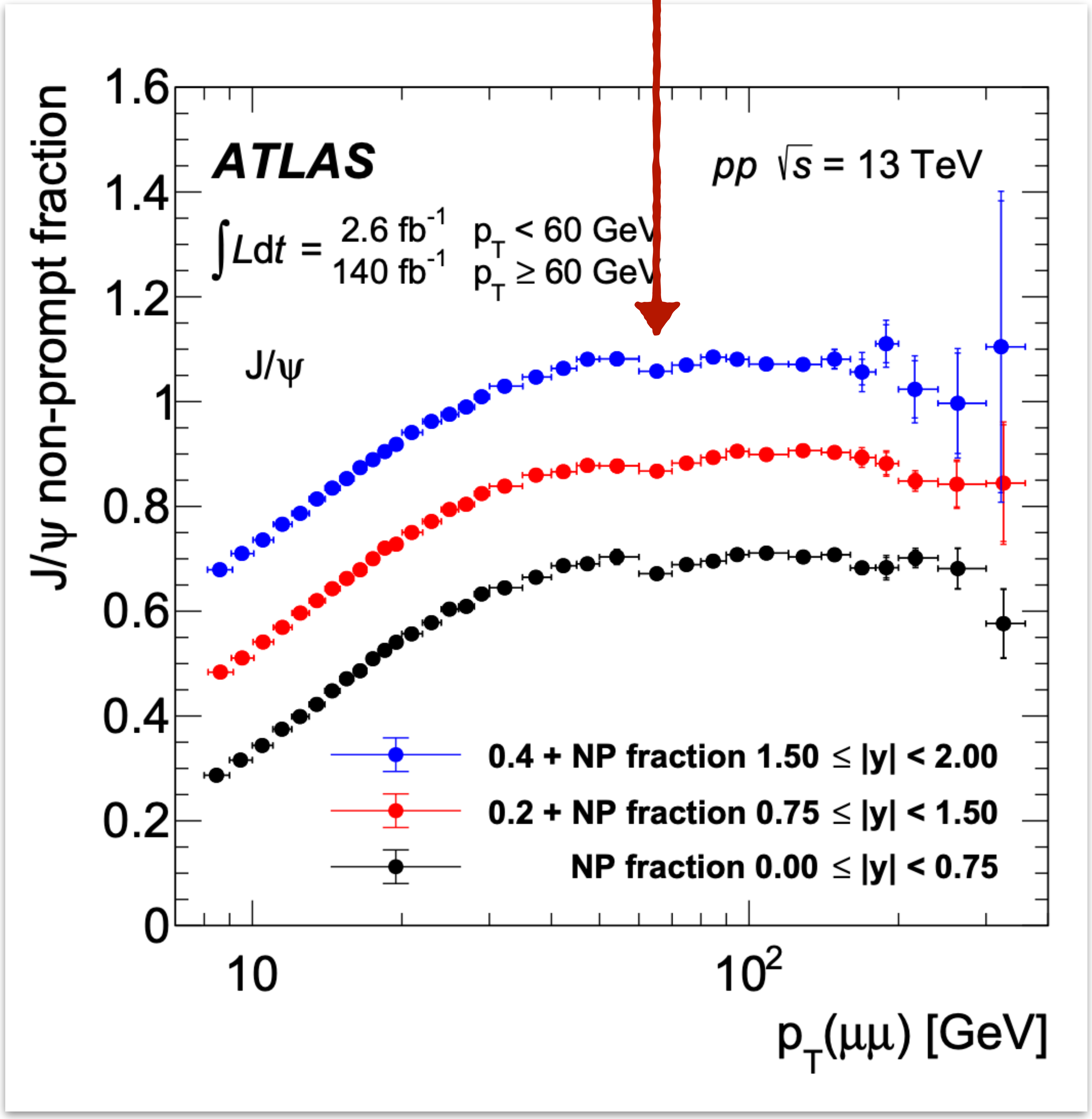


Prompt J/ψ



Non-Prompt J/ψ

Most dominant corrections to acceptance under the isotropic assumption, based on the best available data and theory, are taken as systematics.



Systematics

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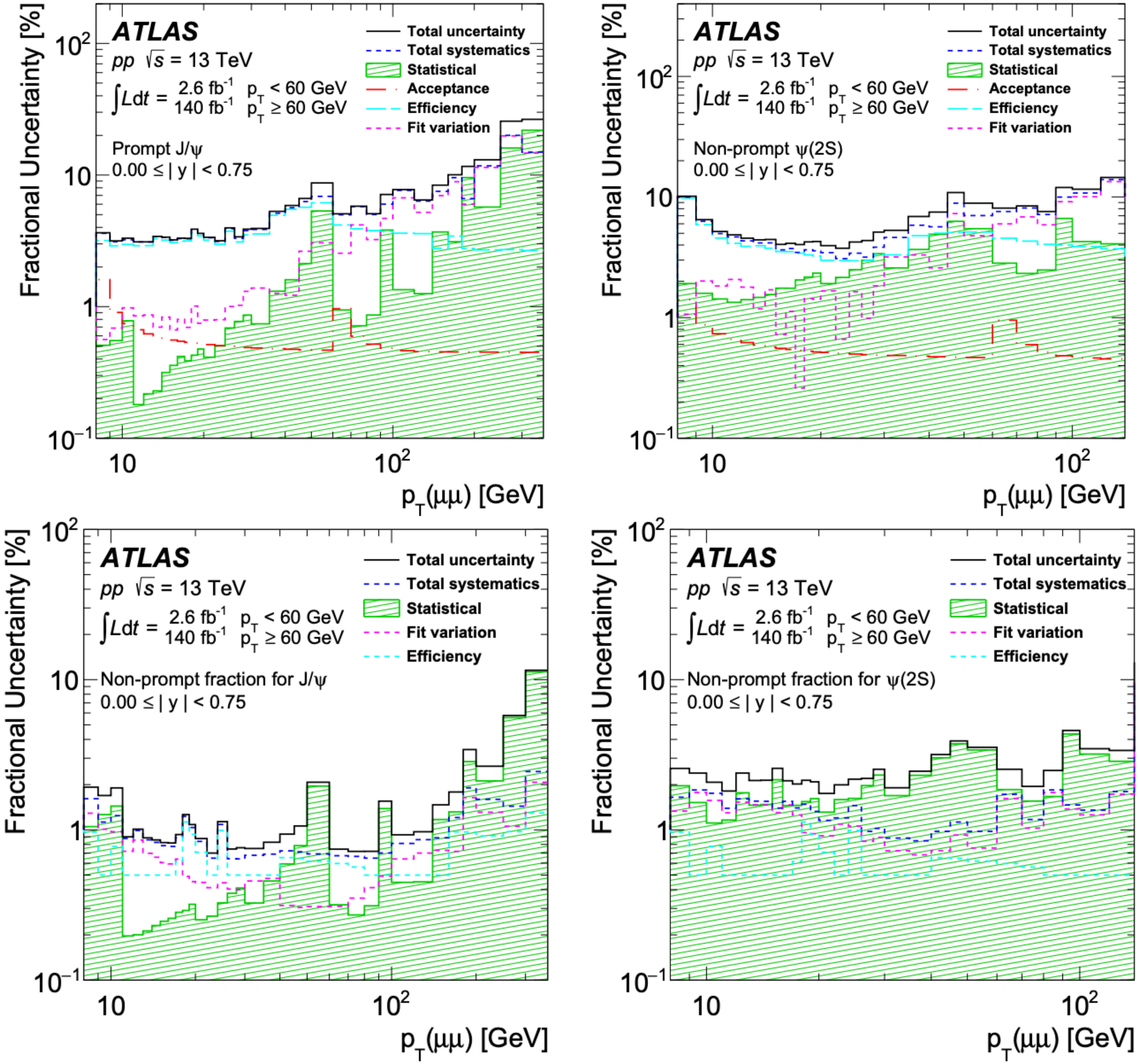

Fit Model

Each Signal/Background Component

$$P_i(m_{\mu\mu},\tau) = f_i(m_{\mu\mu}) \cdot [h_i(\tau) \otimes R(\tau)]$$

$$F(m_{\mu\mu},\tau) = \sum_{i=1}^{7} \kappa_i P_i(m_{\mu\mu},\tau)$$

Total PDF

$$R(\tau) = \omega_A G_A(\tau) + \omega_B G_B(\tau) + (1-\omega_A-\omega_B) G_C(\tau)$$

Lifetime Resolution

† Some correlation between mass and lifetime resolution is modeled (next slide.)

i	Type	P/NP	$f_i(m)$	$h_i(\tau)$
1†	J/ψ	P	$\omega_0 G_1(m) + (1-\omega_0)[\omega_1 CB(m) + (1-\omega_1)G_2(m)]$	$\delta(\tau)$
2	J/ψ	NP	$\omega_0 G_1(m) + (1-\omega_0)[\omega_1 CB(m) + (1-\omega_1)G_2(m)]$	$\omega_2 E_1(\tau) + (1-\omega_2)E_1(b\tau)$
3	$\psi(2S)$	P	$\omega_0 G_1(\beta m) + (1-\omega_0)[\omega_1 CB(\beta m) + (1-\omega_1)G_2(\beta m)]$	$\delta(\tau)$
4	$\psi(2S)$	NP	$\omega_0 G_1(\beta m) + (1-\omega_0)[\omega_1 CB(\beta m) + (1-\omega_1)G_2(\beta m)]$	$E_2(\tau)$
5	Bkg	P	P	$\delta(\tau)$
6	Bkg	NP	$E_3(m)$	$E_4(\tau)$
7	Bkg	NP	$E_5(m)$	$E_6(\lvert\tau\rvert)$

Fit Model

2309.17177

Each Signal/Background Component

$$P_i(m_{\mu\mu}, \tau) = f_i(m_{\mu\mu}) \cdot [h_i(\tau) \otimes R(\tau)]$$

$$F(m_{\mu\mu}, \tau) = \sum_{i=1}^{7} \kappa_i P_i(m_{\mu\mu}, \tau)$$

Total PDF

$$R(\tau) = \omega_A G_A(\tau) + \omega_B G_B(\tau) + (1 - \omega_A - \omega_B) G_C(\tau)$$

Lifetime Resolution

i	Type	P/NP	$f_i(m)$	$h_i(\tau)$
1†	J/ψ	P	$\omega_0 G_1(m) + (1-\omega_0)[\omega_1 CB(m) + (1-\omega_1) G_2(m)]$	$\delta(\tau)$

† In the $i = 1$ term, describing the prompt J/ψ peak, the product of the narrowest Gaussian term in $f_1(m_{\mu\mu})$ and the narrowest Gaussian term in $R(\tau)$ was replaced by a bivariate Gaussian function in $m_{\mu\mu}$ and τ with a correlation coefficient $\rho = 0.3$,

$$\omega_0 G_1(m_{\mu\mu}; \sigma_1) \cdot f_A G_A(\tau; \sigma_A) \mapsto \omega_0 f_A G_{BV}(m_{\mu\mu}, \tau; \sigma_1, \sigma_A, \rho), \quad (4)$$

to take into account the observed correlation between the measured values of these quantities. The effect of this correlation was found to be negligible for other terms.