Heavy-Flavor Production and $B-$Hadron Lifetime Measurements in ATLAS

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On Behalf of the ATLAS Collaboration

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https://indico.fnal.gov/event/62069/

Introduction

- **Flavor Physics at ATLAS in This Talk!**
  - Measurements of Production Cross-Sections & Spectroscopy
  - Measurements of Weak Decays

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    - **(Sep. 2023)** Differential Production Cross-Section of J/ψ and $\psi(2S)$
    - **(Apr. 2023)** Search for Di-Charmonium Resonances in 4μ Final States
    - **(Apr. 2023)** Search for $\Upsilon(1S) + \mu^+\mu^-$ Resonance in 4μ Final States
  - **Measurements of Weak Decays**
    - **(Aug. 2023)** Effective Lifetime of the $B_s^0 \to \mu^+\mu^-$ Decay

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  - **Measurements of Weak Decays**
    - **(Aug. 2023)** Effective Lifetime of the $B_s^0 \to \mu^+\mu^-$ Decay
- **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

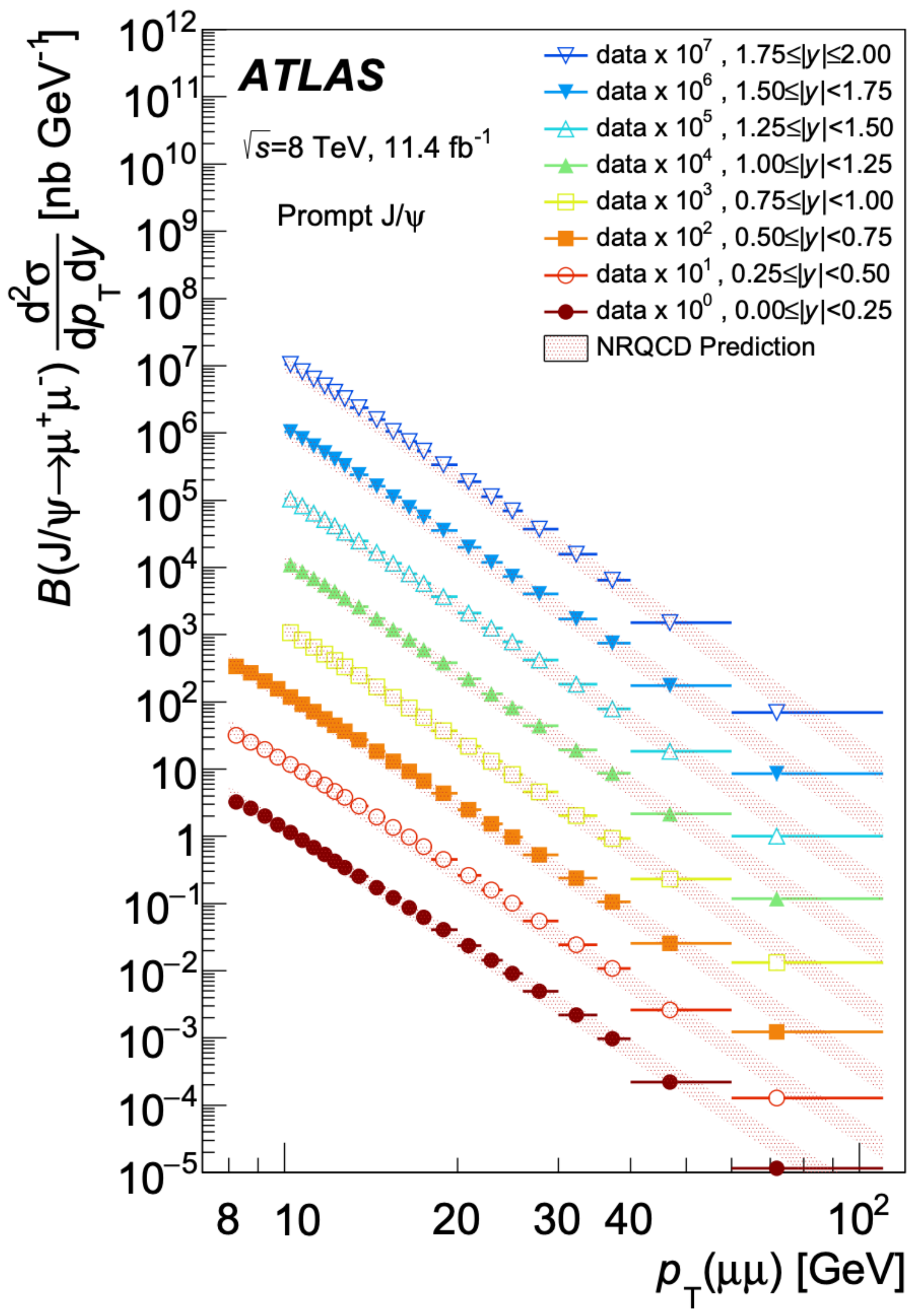
Motivation

- **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: $p_T < 100$ GeV $\rightarrow p_T < 360$ GeV
  - $\psi(2S)$: $p_T < 100$ GeV $\rightarrow p_T < 140$ GeV
- **Possible due to updated trigger-strategy!**
  - **Angular resolution of dimuon triggers not sufficient to resolve highly boosted muons coming from charmonia with $p_T > 100$ 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.**



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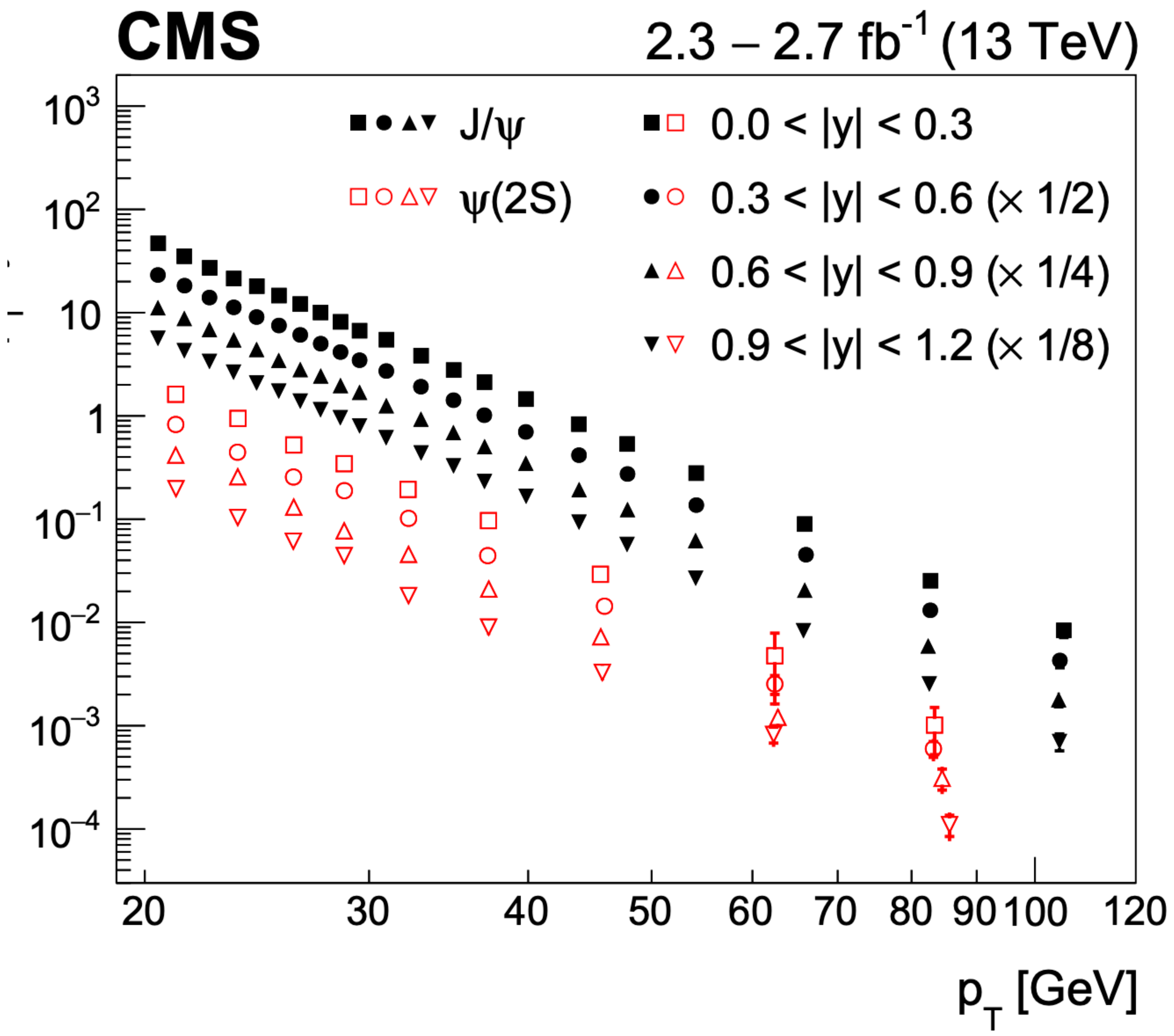


1710.11002

Analysis Strategy

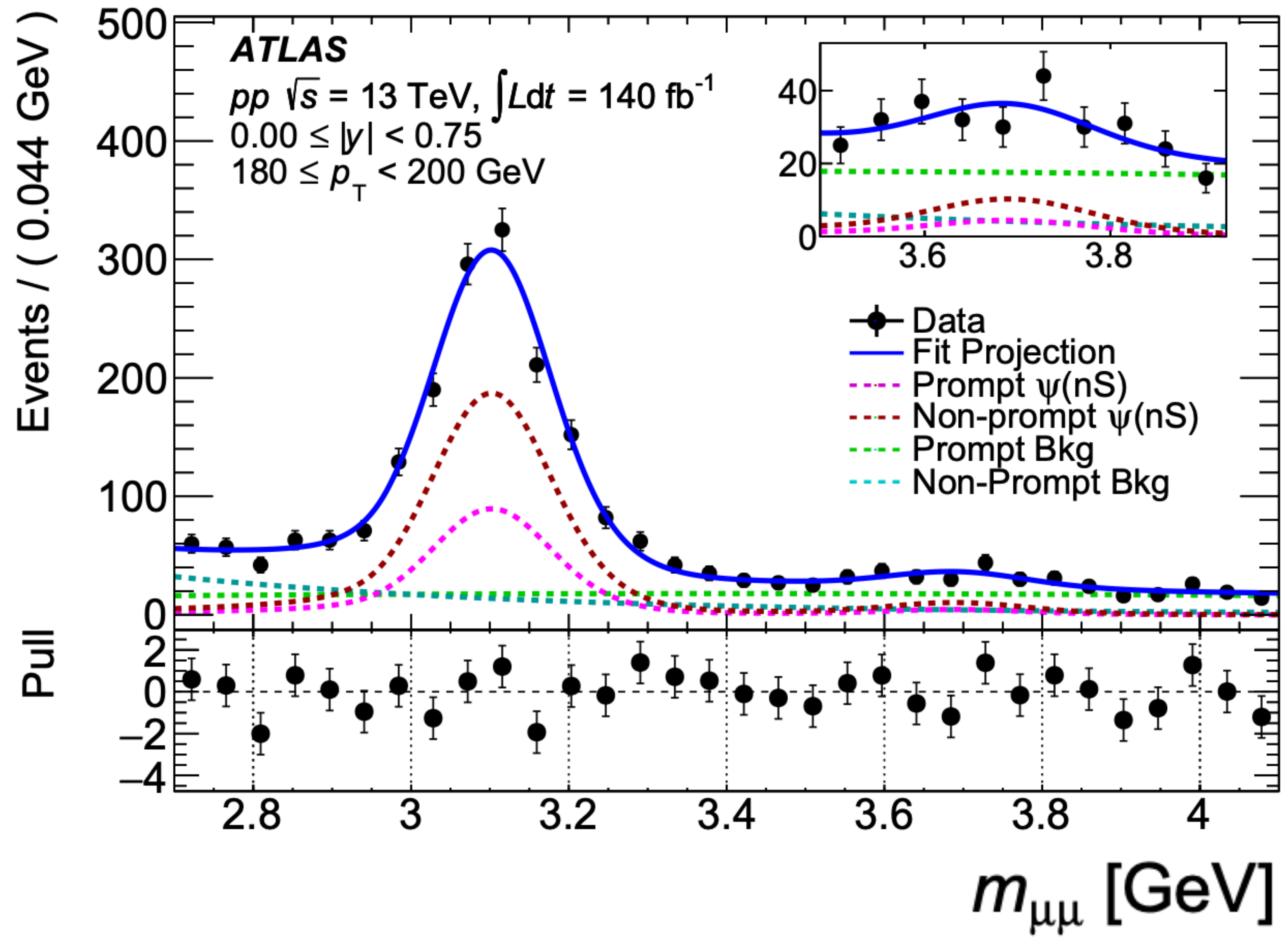
- **Prompt and non-prompt contributions separated using the reconstructed pseudo proper lifetime**
$$\tau = \frac{m_{\mu\mu}}{p_{\mathrm{T}}}\frac{L_{xy}}{c}.$$

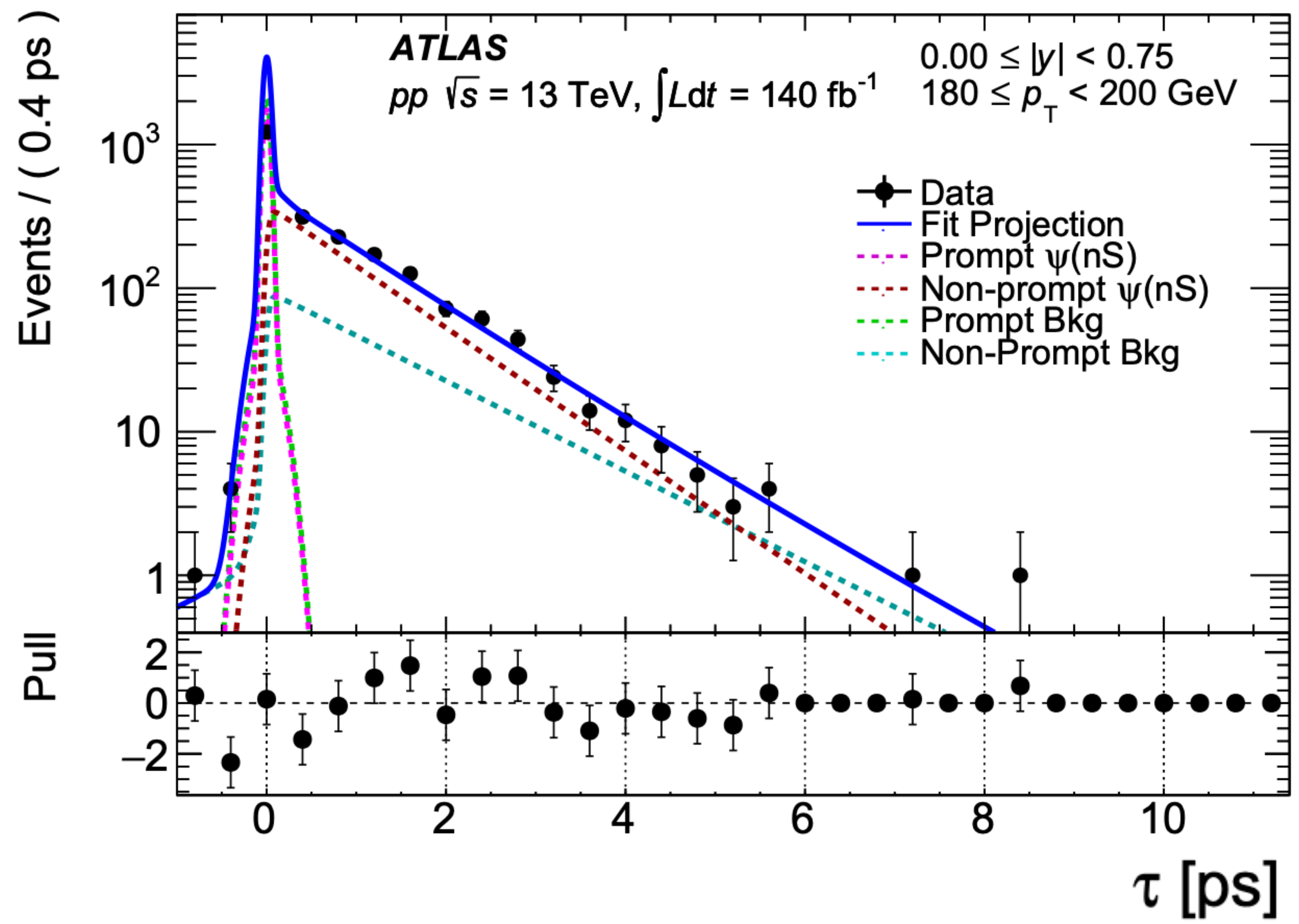
- Measured signal yield extracted from **simultaneous fits to reconstructed mass and pseudo proper lifetime** — in bins of p_{T} and y.

- Differential cross-section measured from the measured yield as:

$$\frac{d^2\sigma^{\mathrm{P,NP}}(pp \to \psi)}{dp_{\mathrm{T}}dy} = \frac{1}{\mathscr{B}(\psi \to \mu\mu)\int \mathscr{L}dt} \cdot \frac{1}{\mathscr{A}(\psi)\epsilon_{\mathrm{trig}}\epsilon_{\mathrm{reco}}\mathrm{SF}_{\mathrm{trig}}\mathrm{SF}_{\mathrm{reco}}} \cdot \frac{N_{\psi}^{\mathrm{P,NP}}}{\Delta p_{\mathrm{T}}\Delta y}$$

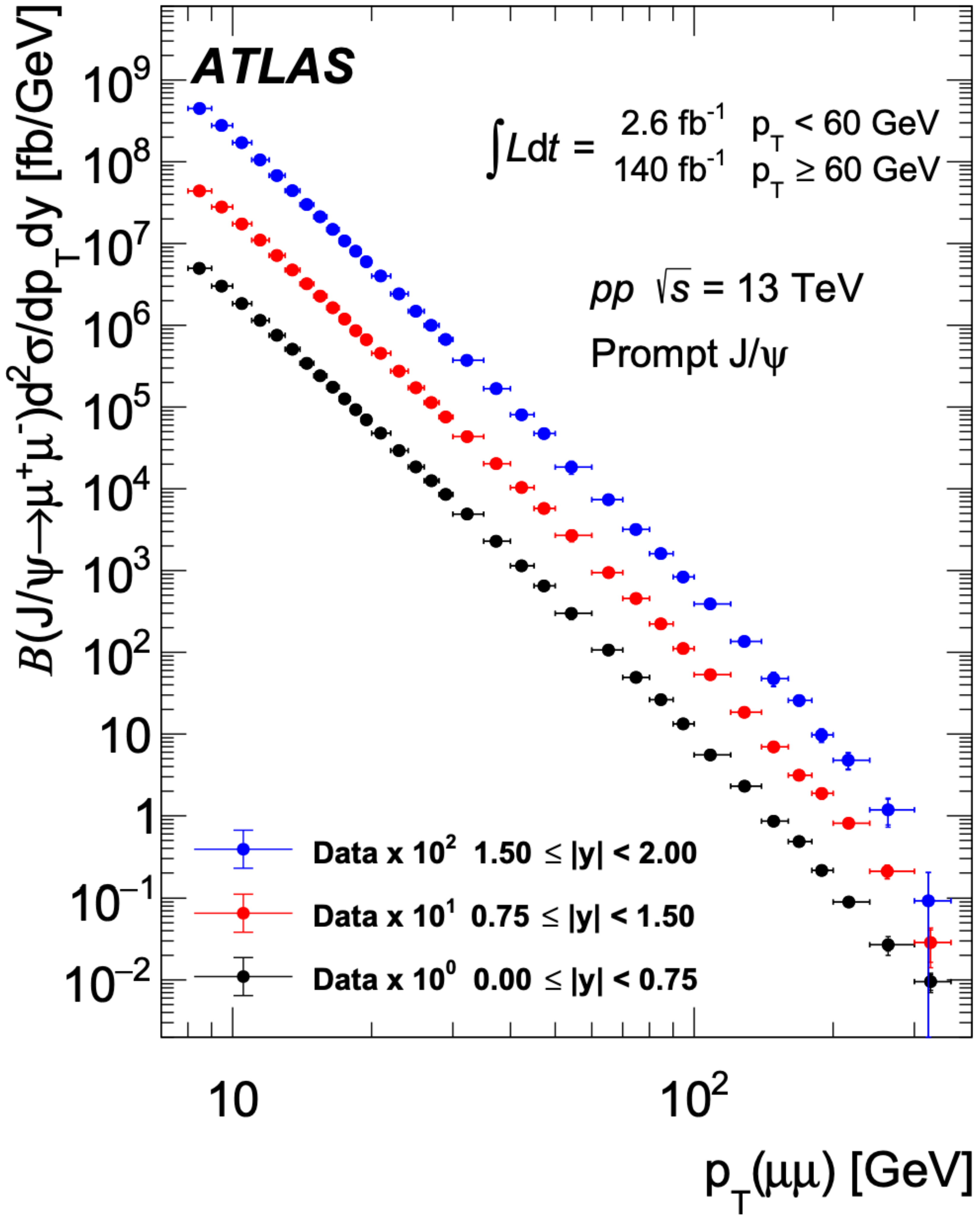
  - **Fraction of non-prompt production F_{ψ}^{NP} and $\psi(2S)$-to-J/ψ production ratios $R^{\mathrm{P,NP}}$ also extracted** with partial cancellations of uncertainties!

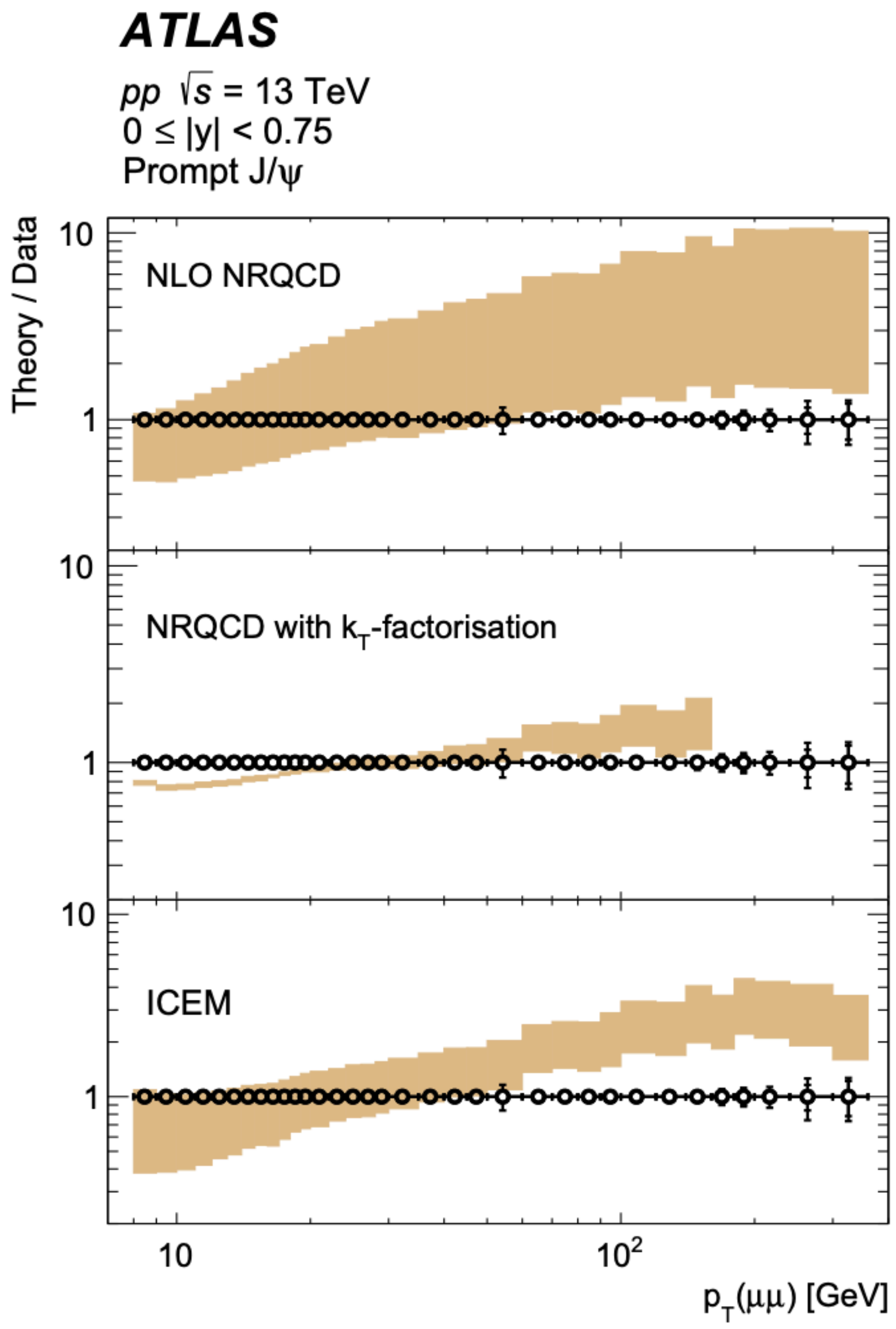




Results: Prompt J/ψ Production

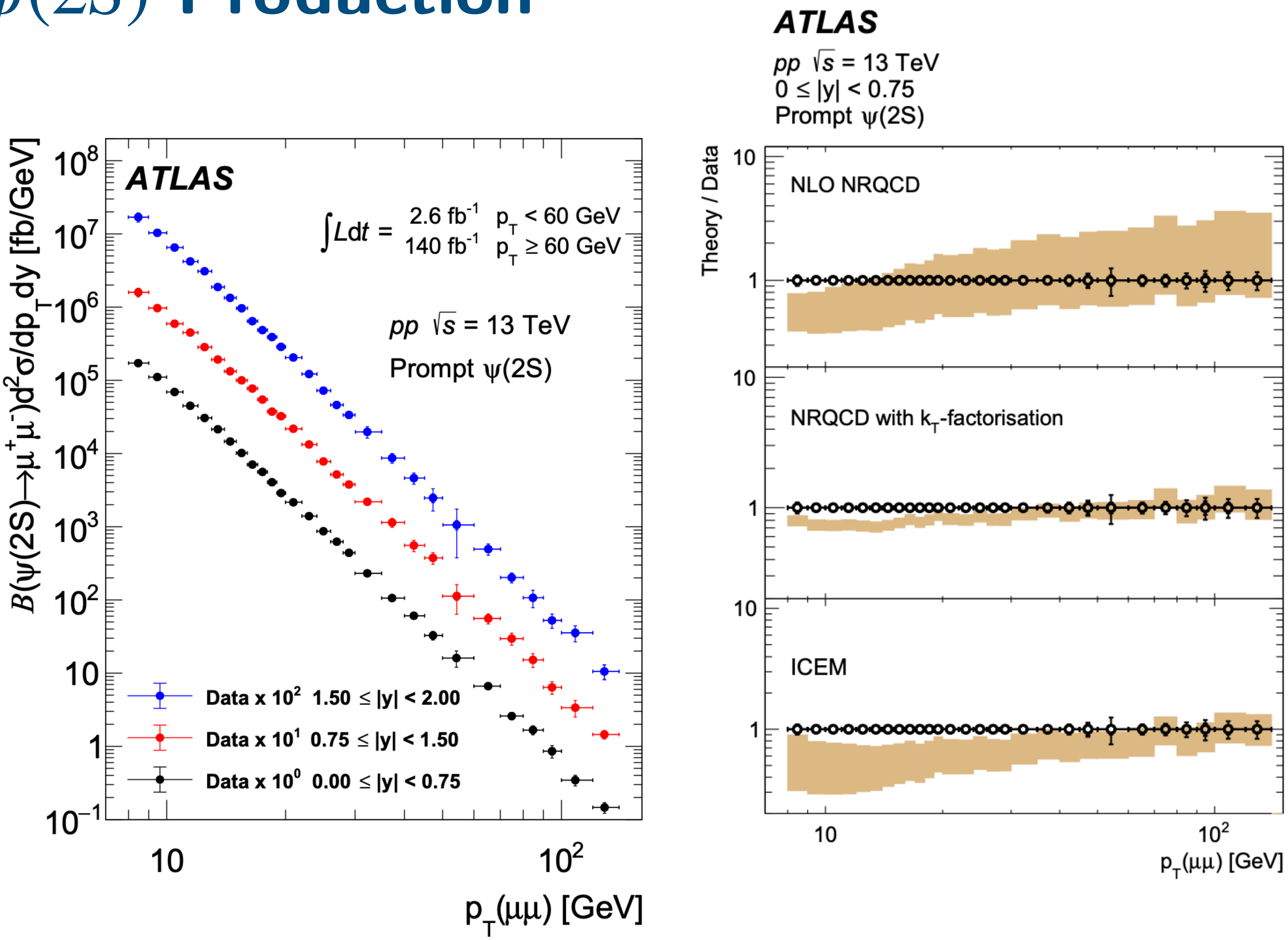
- NLO NRQCD and ICEM seem to overestimate the high-p_T production.
- NRQCD with k_T -factorization seems to underestimate the low-p_T production.





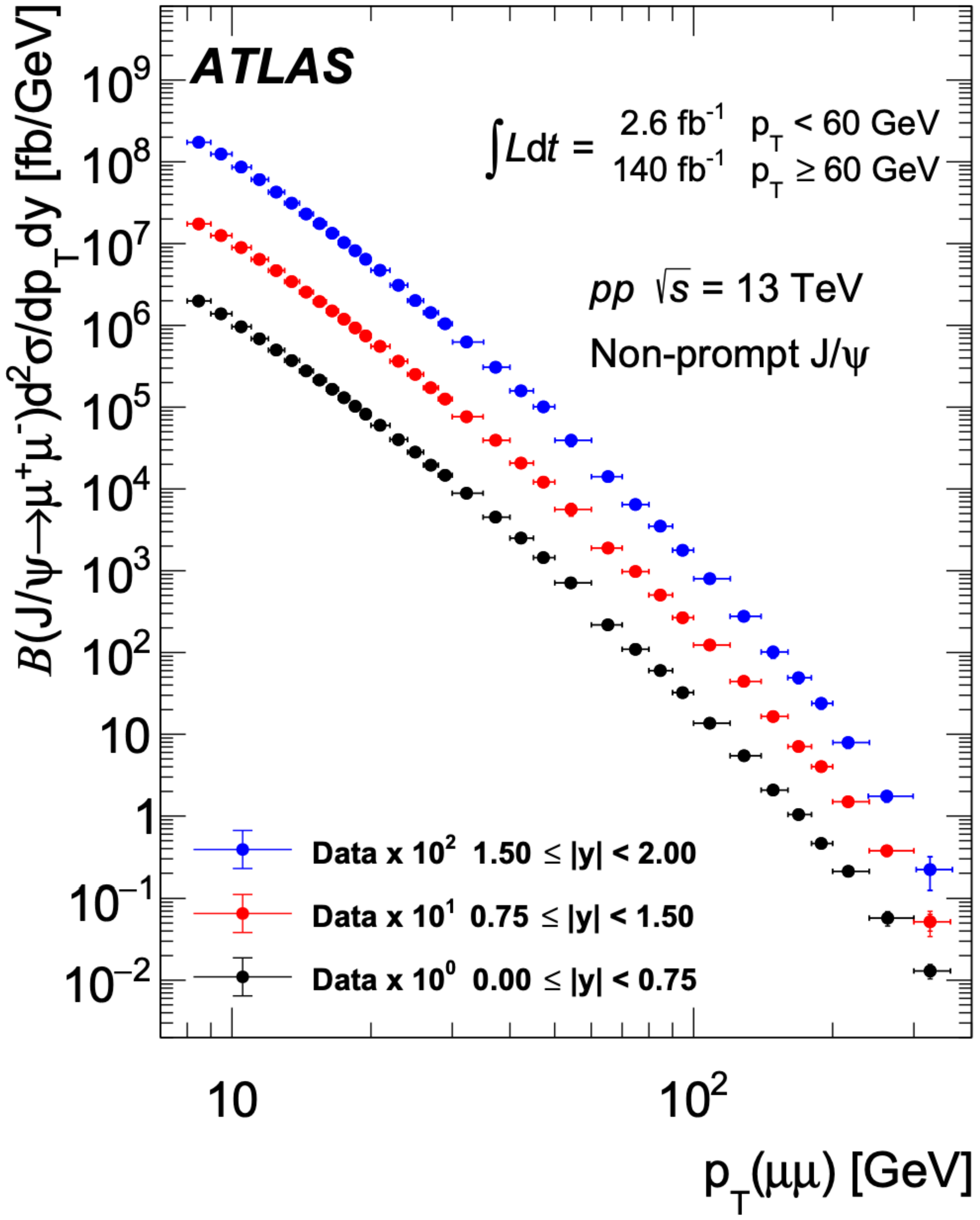
Results: Prompt $\psi(2S)$ Production

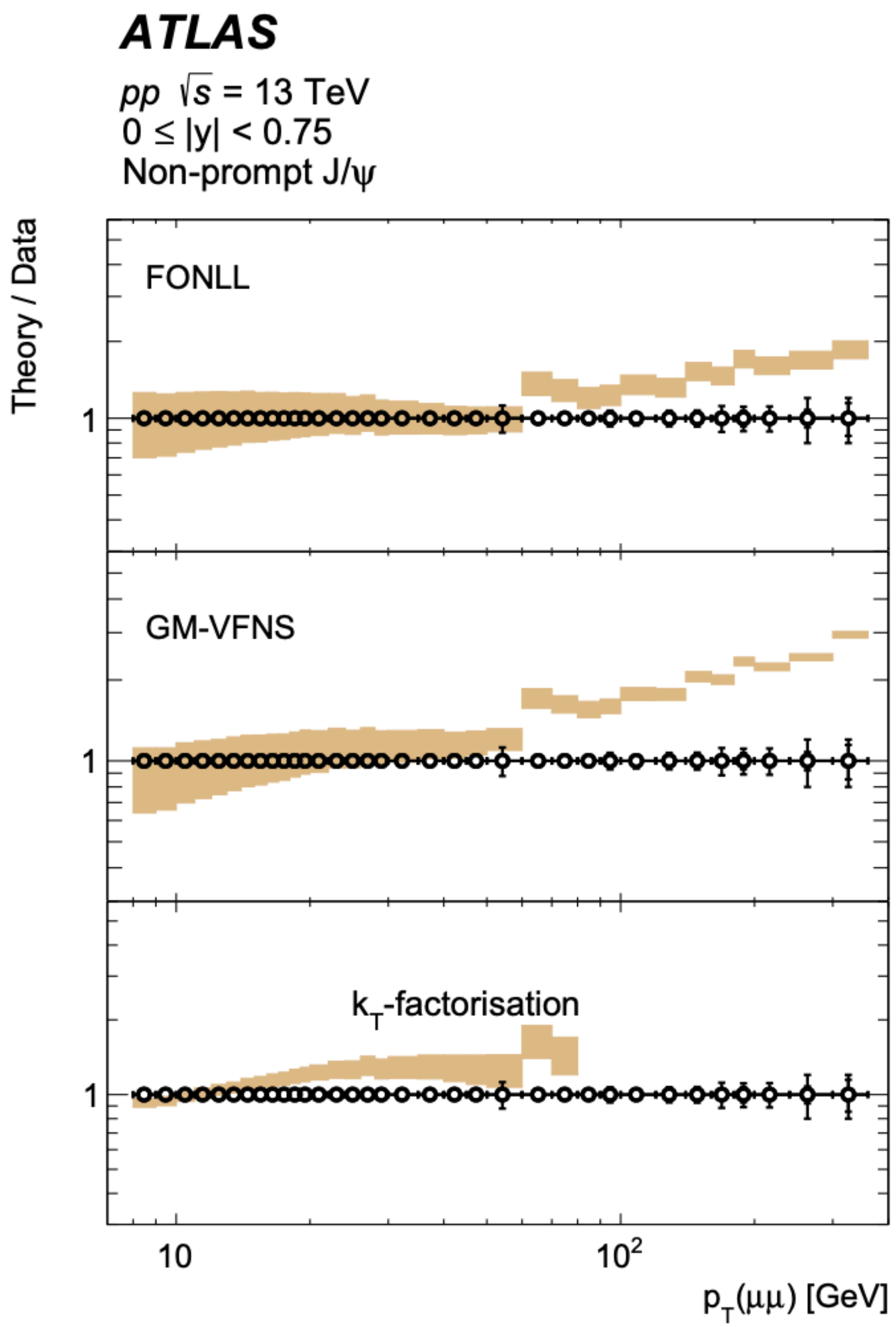
- NLO NRQCD seems to over-estimation of high-p_T production.
- NRQCD with k_T -factorization seems to underestimate the $\psi(2S)$ production.



Results: Non-Prompt J/ψ Production

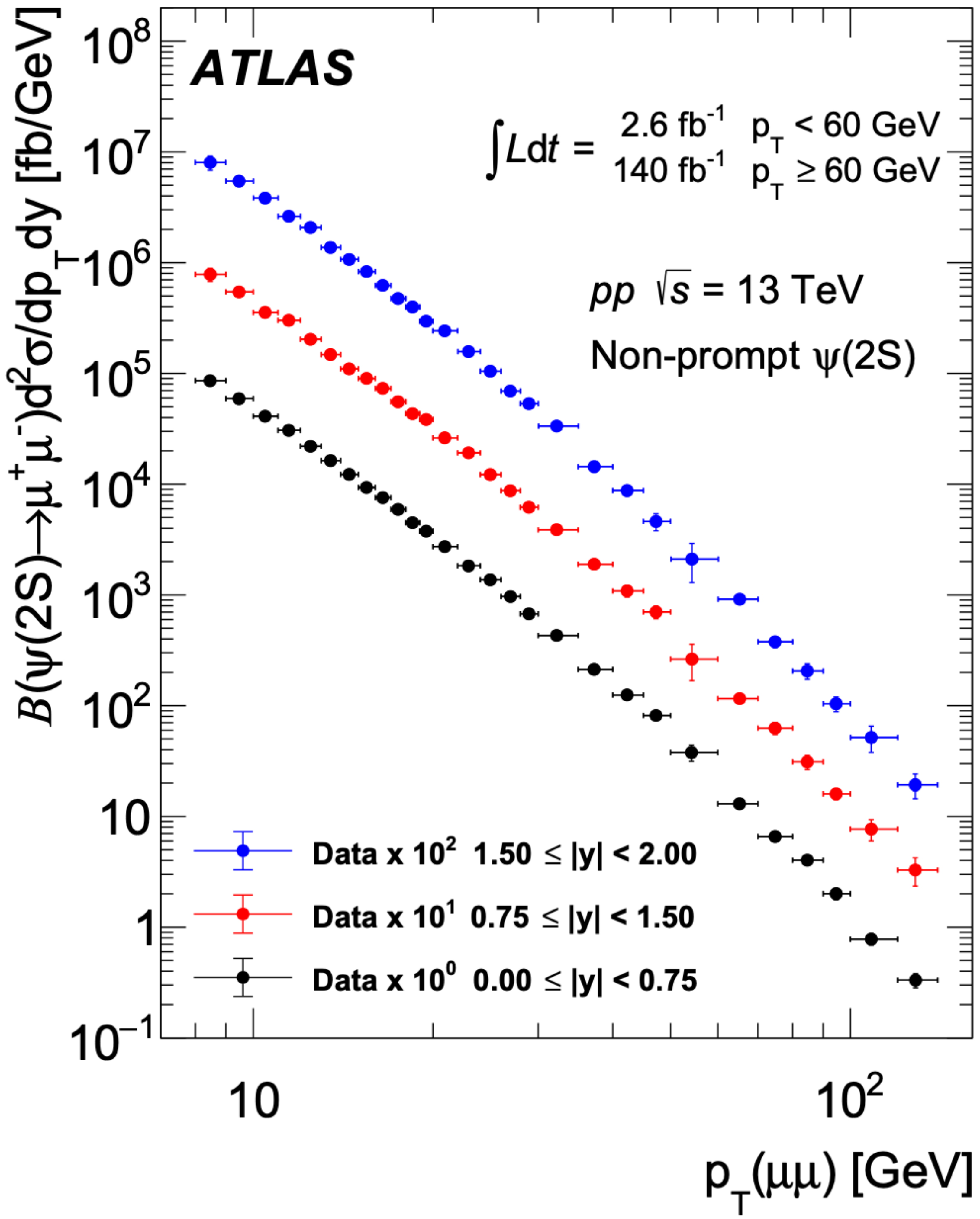
- FONLL and GM-VFNS seem to overestimate the high-p_T production.
- k_T-factorization limited in availability at high-p_T.

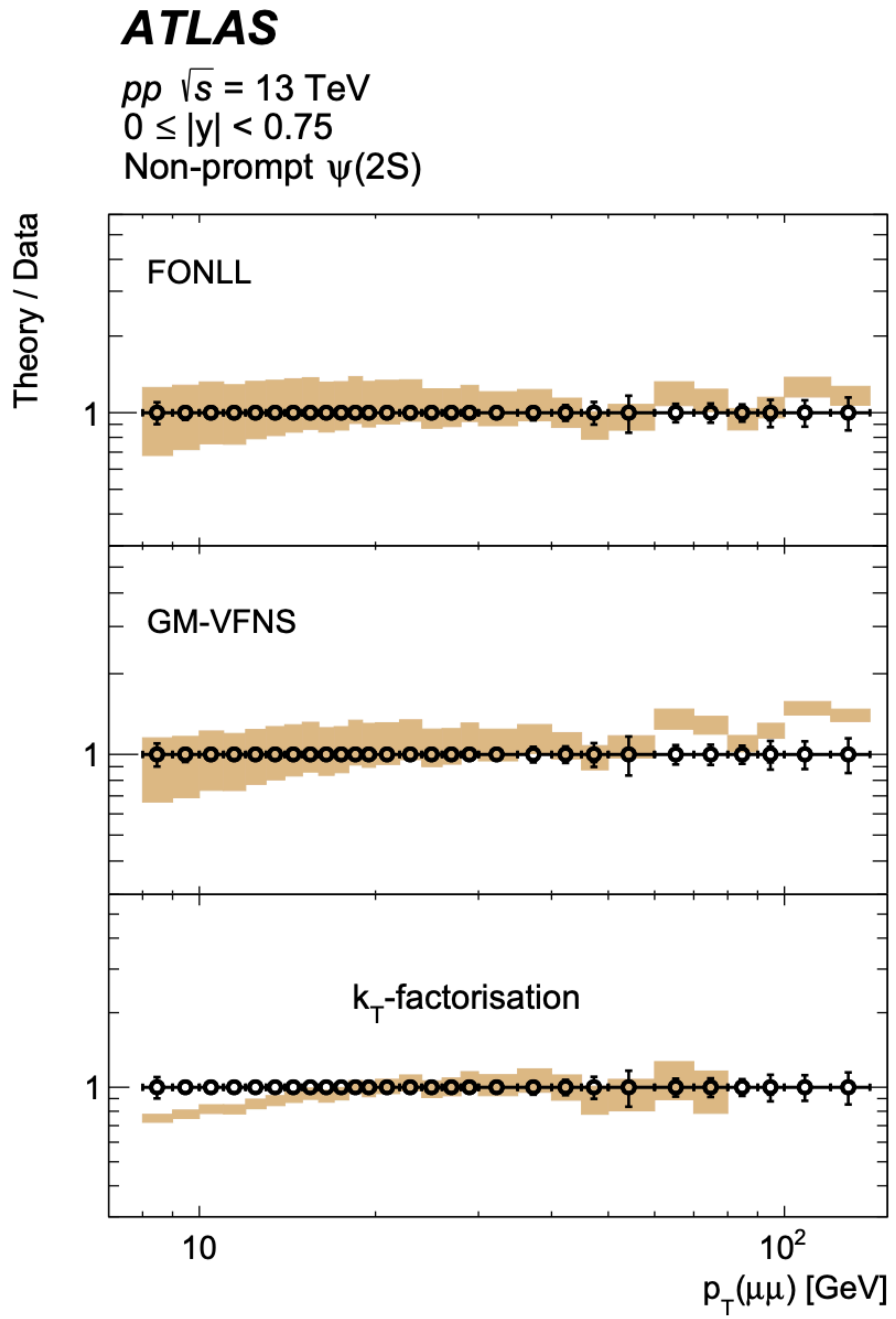




Results: Non-Prompt $\psi(2S)$ Production

- k_T-factorization seems to underestimate the production at low-p_T.





Search for Di-Charmonium Resonances in 4μ Final States

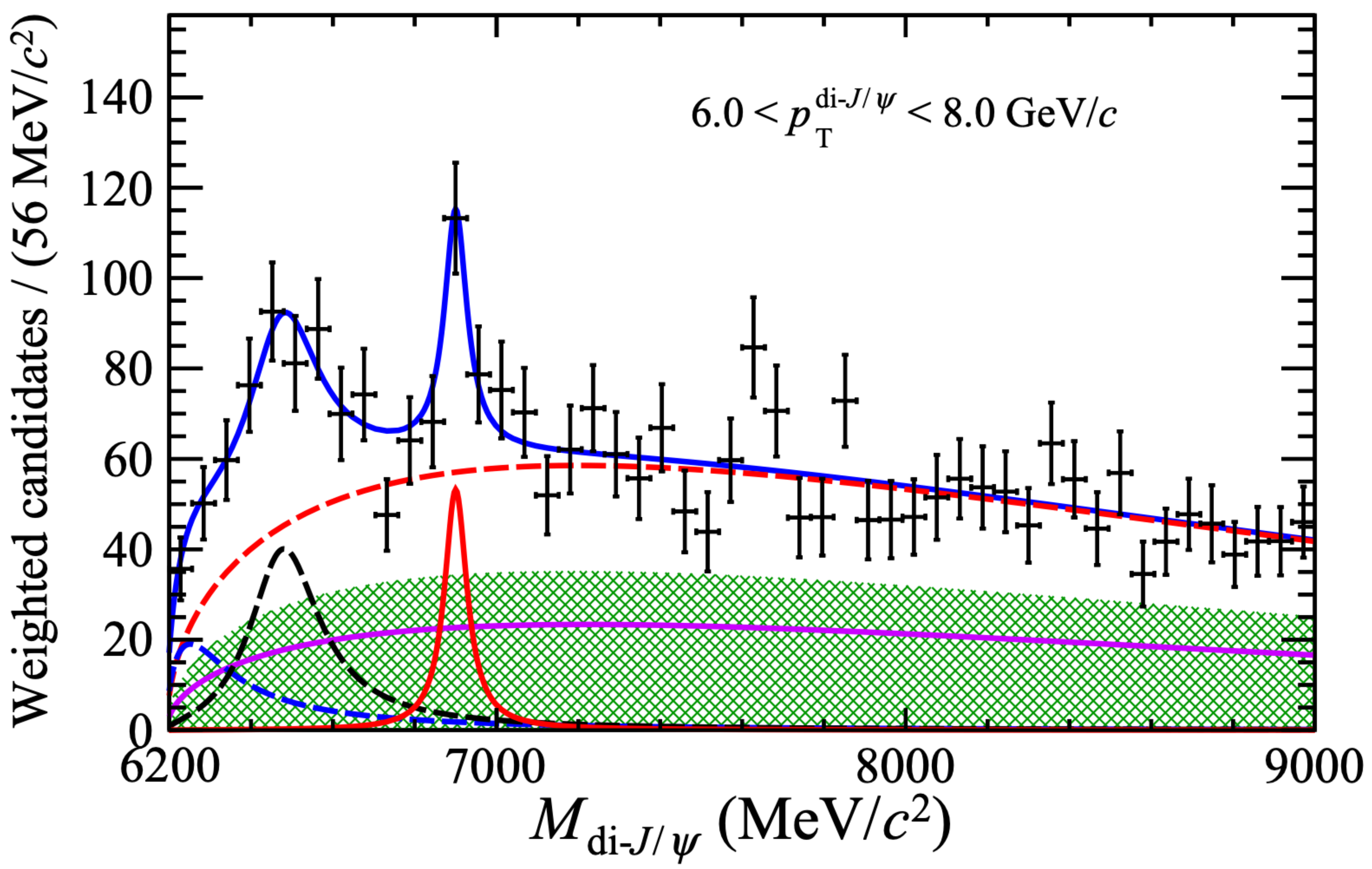
arXiv:2304.08962

Phys. Rev. Lett. 131 (2023) 151902

Motivation

- **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

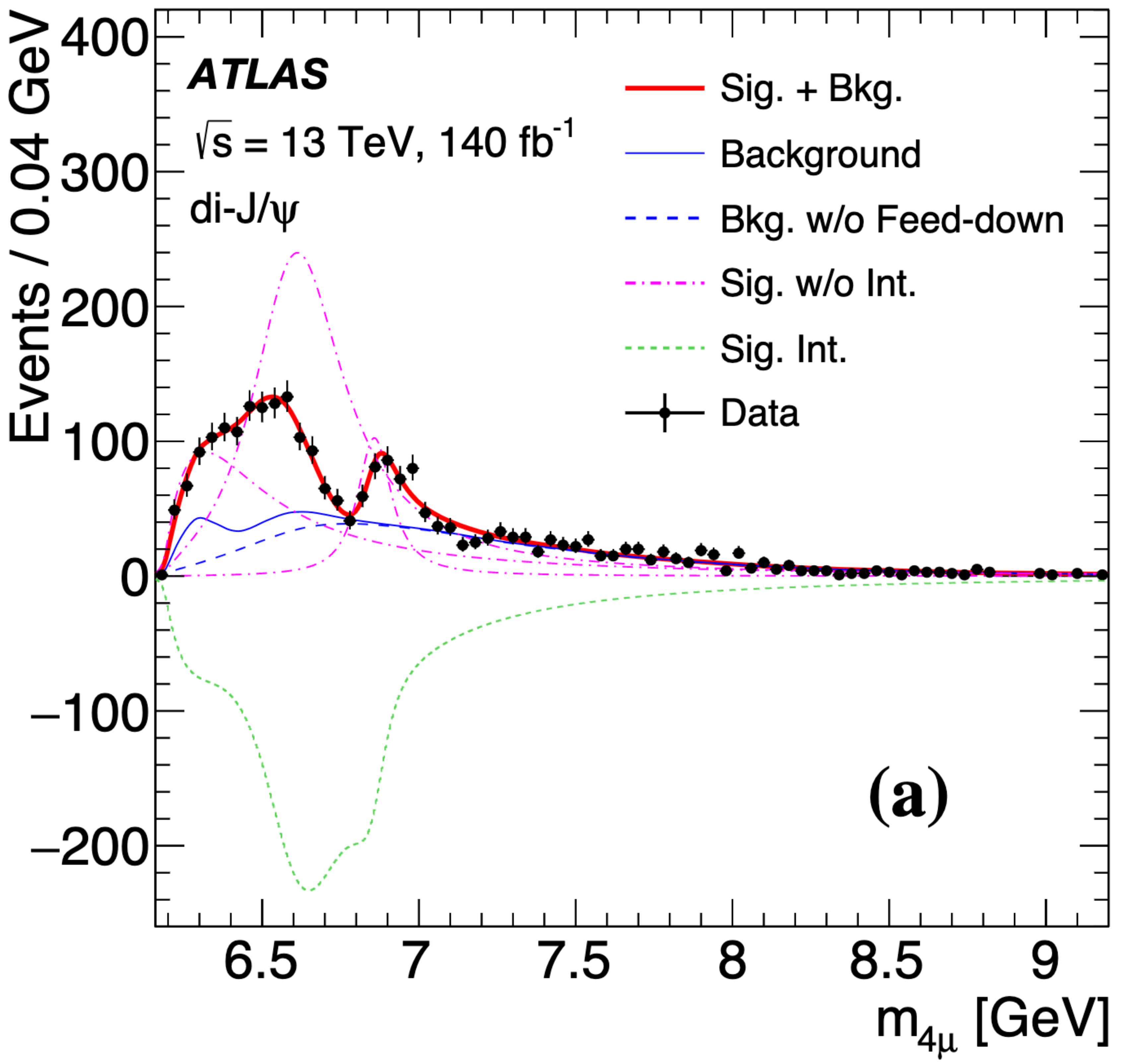


Analysis Strategy

- **Search for 4μ final state produced via**
  - $J/\psi + J/\psi$ Channel
  - $J/\psi + \psi(2S)$ Channel
- **Data**
  - Full Run2 dataset with $L = 140\ \mathrm{fb}^{-1}$ of pp collision data at $\sqrt{s} = 13$ TeV
  - Trigger on low-p_{T} dimuon or trimuon triggers requiring an oppositely charged muon pair.
- **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.**
- **Background Modeling**
  - **Prompt Di-Charmonia**: SPS and DPS events. Modeled with MC corrected with data in mass sidebands.
  - **Non-Prompt Di-Charmonia:** $b-$Hadron Decays. 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.

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

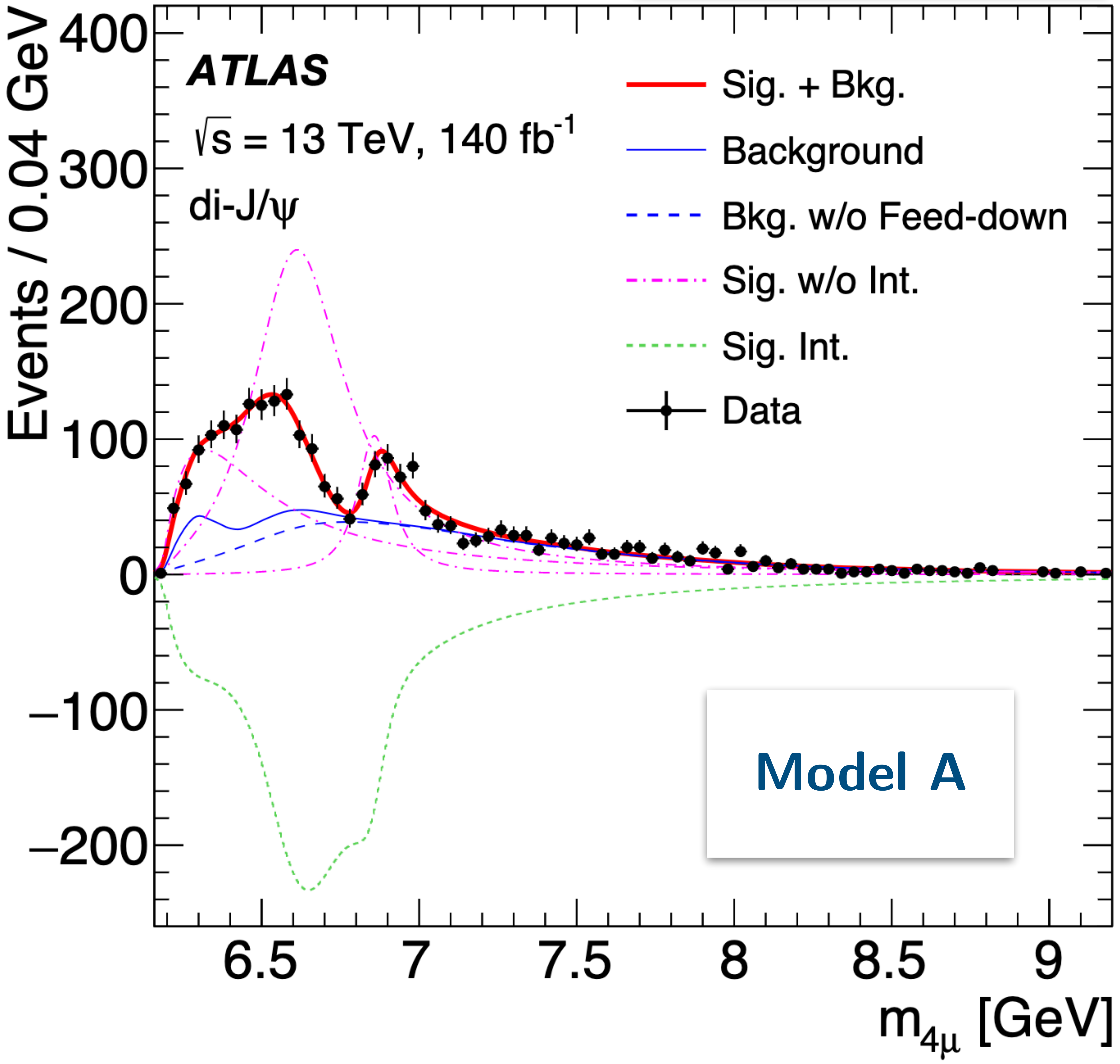
- **Significance for both models far exceeds 5σ**
  - The mass of the m_2 resonance consistent with the LHCb mass as well as with the CMS search now: 2306.07164
- **The broad structure at lower mass can still be from other effects such as feeddown from higher dicharmonium resonances.**
  - $T_{cc\bar{c}\bar{c}}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

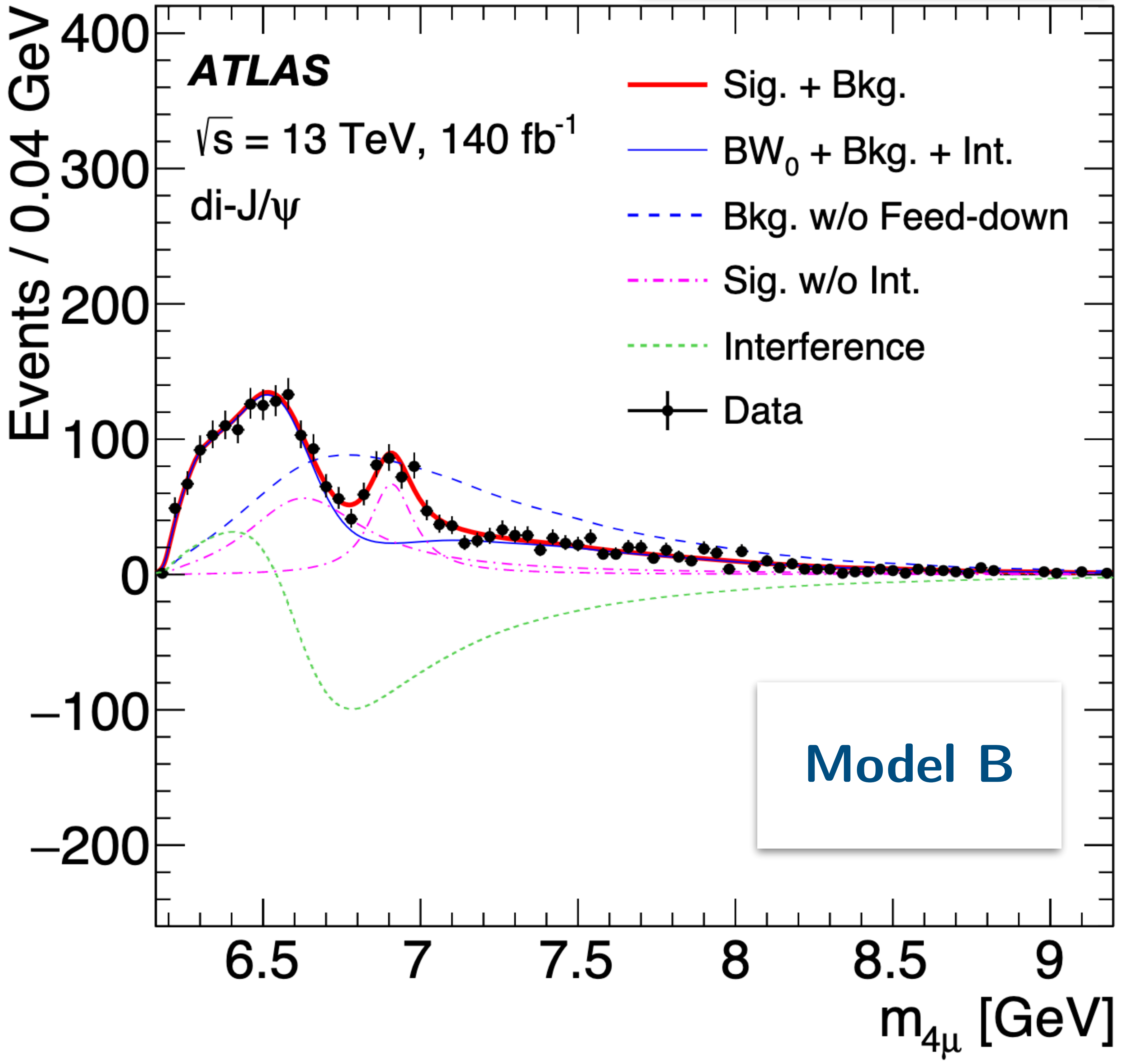
All mutually interfering

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	$0.15 \pm 0.03 \pm 0.01$
$\Delta s/s$	—

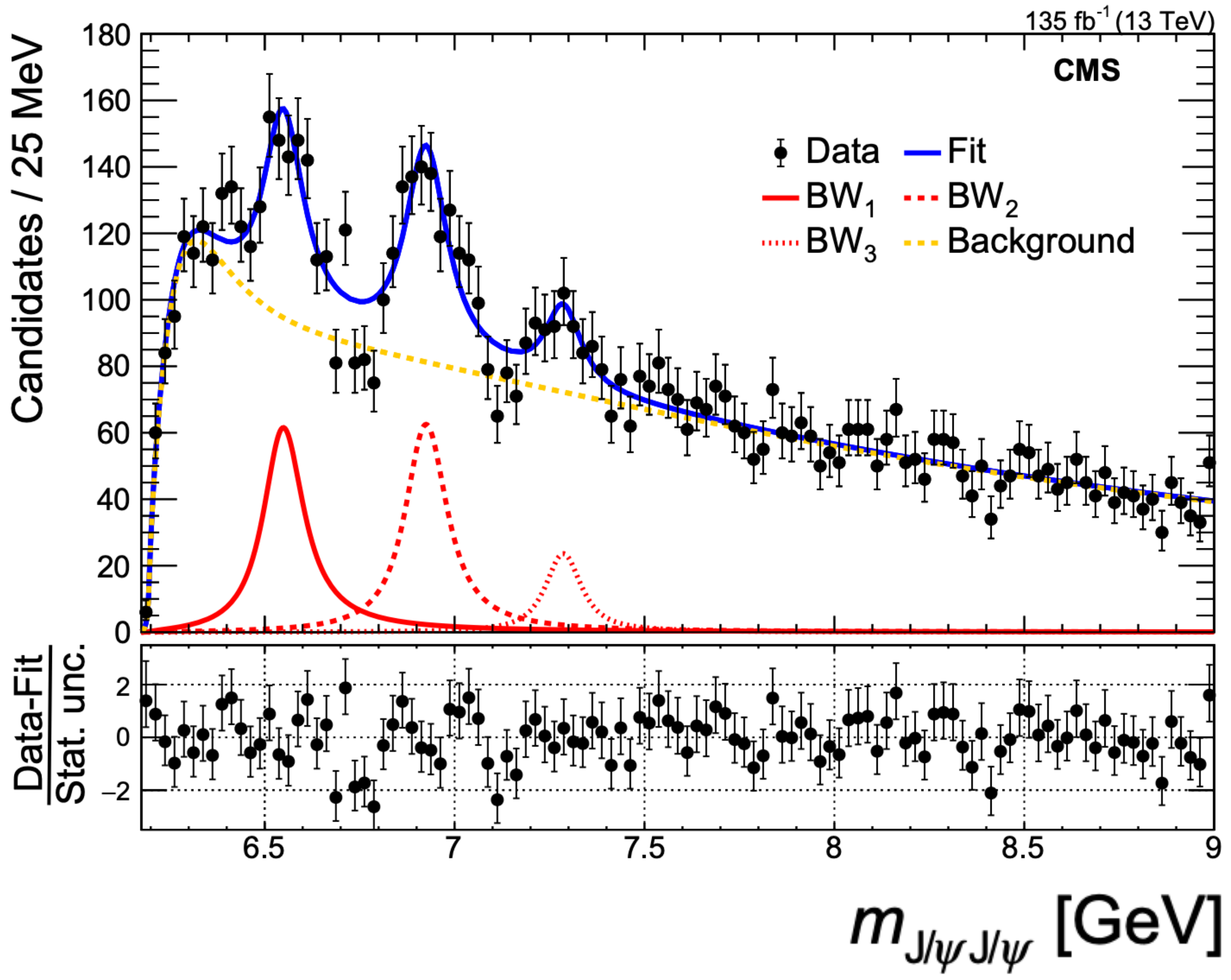




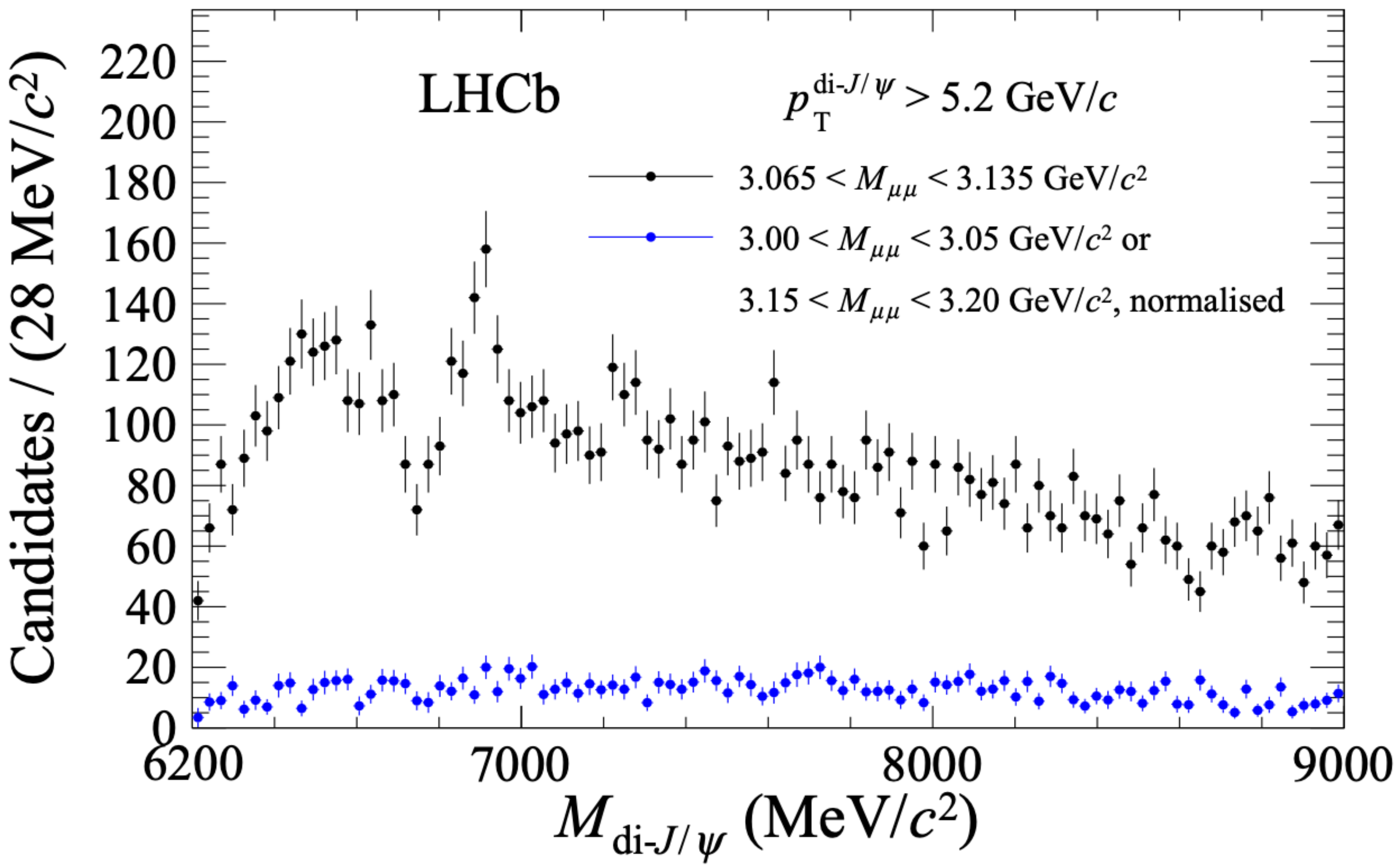
Brief Recap of Context for $J/\psi + \psi(2S)$ Channel

- $X(6900)$ 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

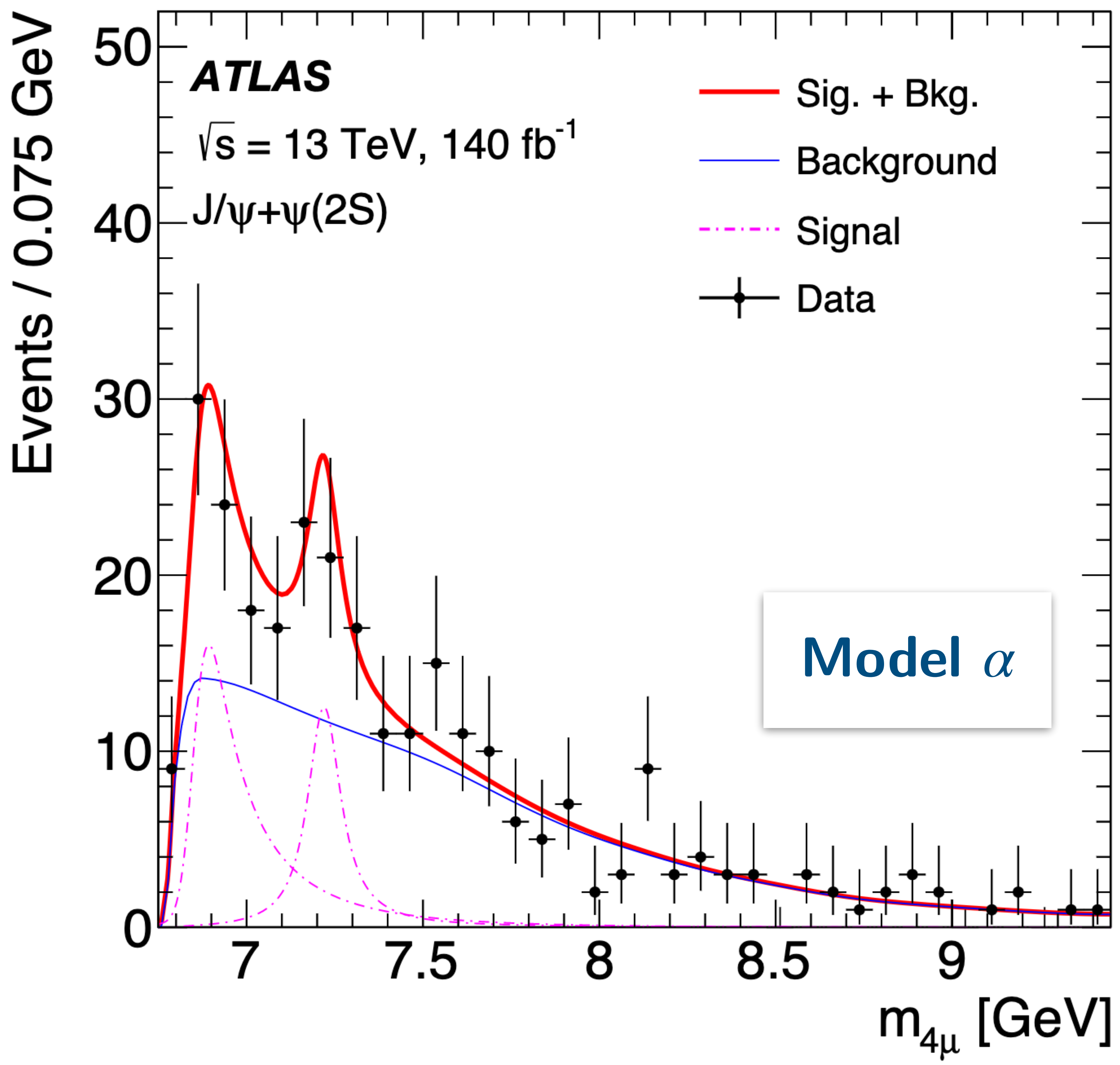
- **Model α:** 4.7σ
  - **Significance for the second resonance alone at 3σ.**
- **Model β:** 4.3σ

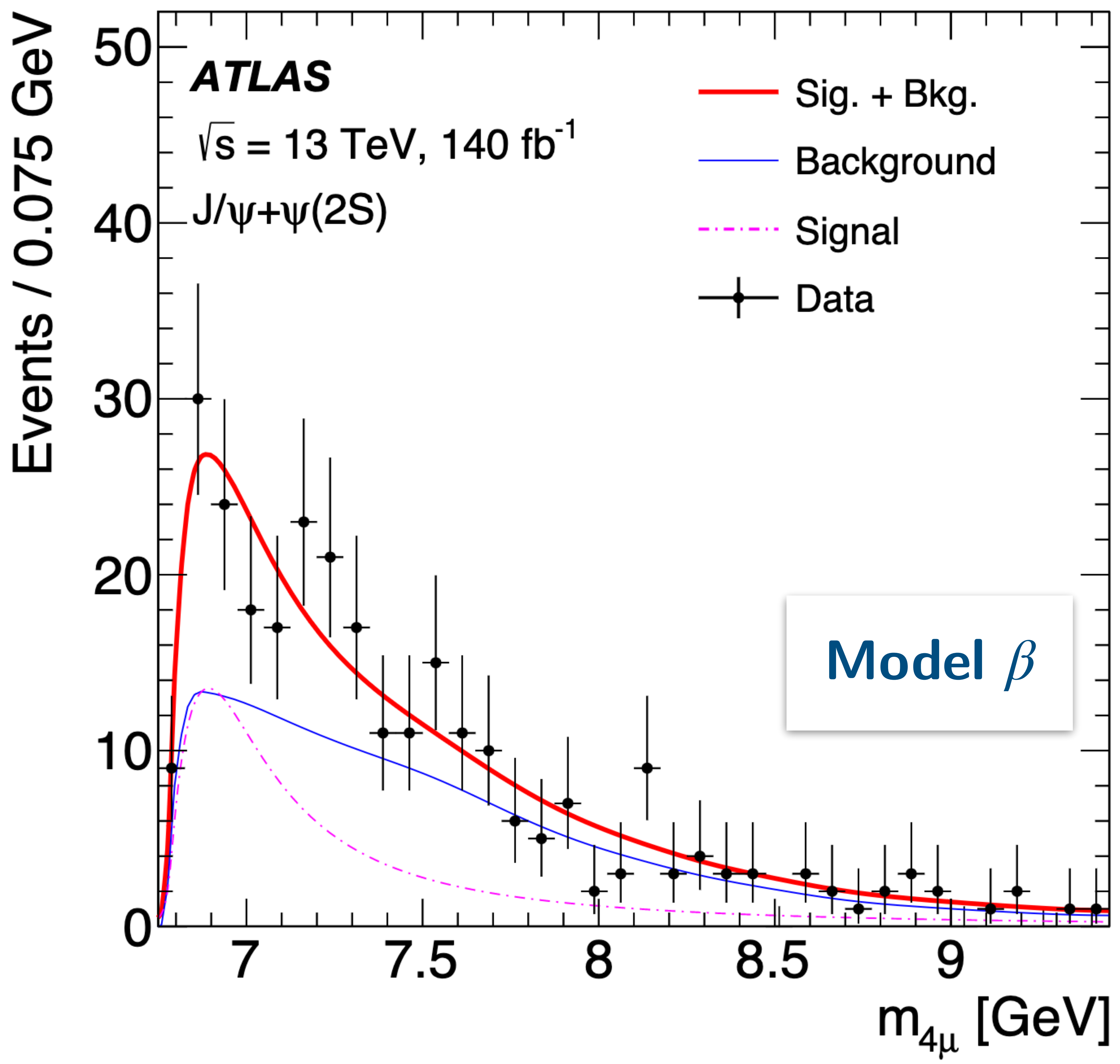
J/ψ+ψ(2S)	model α
m_3	$7.22 \pm 0.03^{+0.01}_{-0.04}$
Γ_3	$0.09 \pm 0.06^{+0.06}_{-0.05}$
$\Delta s/s$	$\pm 21\%^{+25\%}_{-15\%}$

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	$6.86 \pm 0.03^{+0.01}_{-0.02}$
Γ_2	$0.11 \pm 0.05^{+0.02}_{-0.01}$
$\Delta s/s$	$\pm 5.1\%^{+8.1\%}_{-8.9\%}$





Search for $\Upsilon(1S) + \mu^+\mu^-$ Resonance in 4μ Final States

ATLAS-CONF-2023-041

Motivation

- Theories of tetraquarks predict new resonances decaying to four lepton final states.
- BSM models also predict such new resonances.
- **Where to search?**
  - In the context of **search for BSM resonances**, the search for 4μ resonances usually performed in **high** $m_{4\mu}$ **phase-space**.
  - Searches by **LHCb and CMS have set relatively strong limits** on $\Upsilon(1S) + \mu^+\mu^-$ production at **low** $m_{4\mu}$, i.e., $m_{4\mu} < 27$ GeV.
  - **This analysis:** $m_{4\mu} \in [10 \text{ GeV}, 50 \text{ GeV}]$

Analysis Strategy

- Data

Year	$\sqrt{s}$	Dimuon Triggers	Trimuon Triggers	Luminosity Collected
2012	$8\ \text{TeV}$	2μ with $p > 4\ \text{GeV}$, $m(\mu^+\mu^-) \in [2.5\ \text{GeV}, 12\ \text{GeV}]$, Unnprescaled	3μ with $p > 4\ \text{GeV}$, Unprescaled	$20.3\ \text{fb}^{-1}$
2015-2017	$13\ \text{TeV}$		3μ with $p > 4\ \text{GeV}$, Prescaled	$51.5\ \text{fb}^{-1}$
2018	$13\ \text{TeV}$		3μ with $p > 4\ \text{GeV}$, $m(\mu^+\mu^-) \in [8\ \text{GeV}, 12\ \text{GeV}]$, Prescaled	$58.5\ \text{fb}^{-1}$

  - Different trigger strategies in different data-taking periods makes this analysis quite complicated.

- Event Selection

Candidate object	Requirements
Muons	$p_T(\mu) > 3$ GeV and $\lvert\eta\rvert < 2.5$, $\lvert z_0 \sin\theta\rvert < 1$ mm and $\lvert d_0/\sigma_{d_0}\rvert < 6$
Muon quadruplet	≥ 3 muons passing LowPt selection criteria, $\sum q_\mu = 0$, four-muon vertex fit $\chi^2/N_{\text{d.o.f}} \leq 10$, $10\ \text{GeV} \leq m_{4\mu} \leq 50$ GeV
Muon doublet	di-muon vertex fit $\chi^2 < 3$
$\Upsilon(1S)$ candidate	OS muon doublet with $p_T(\mu_{1,2}) > 4$ GeV, $9.2\ \text{GeV} \leq m_{\mu^+\mu^-} \leq 9.7$ GeV
$\Upsilon(1S) + \mu^+\mu^-$ candidate events	$\Upsilon(1S)$ candidate plus OS muon doublet with $m_{\mu^+\mu^-} > 1$ GeV, both muon doublets point to a common PV

If multiple such candidates, one with lowest χ^2 chosen.

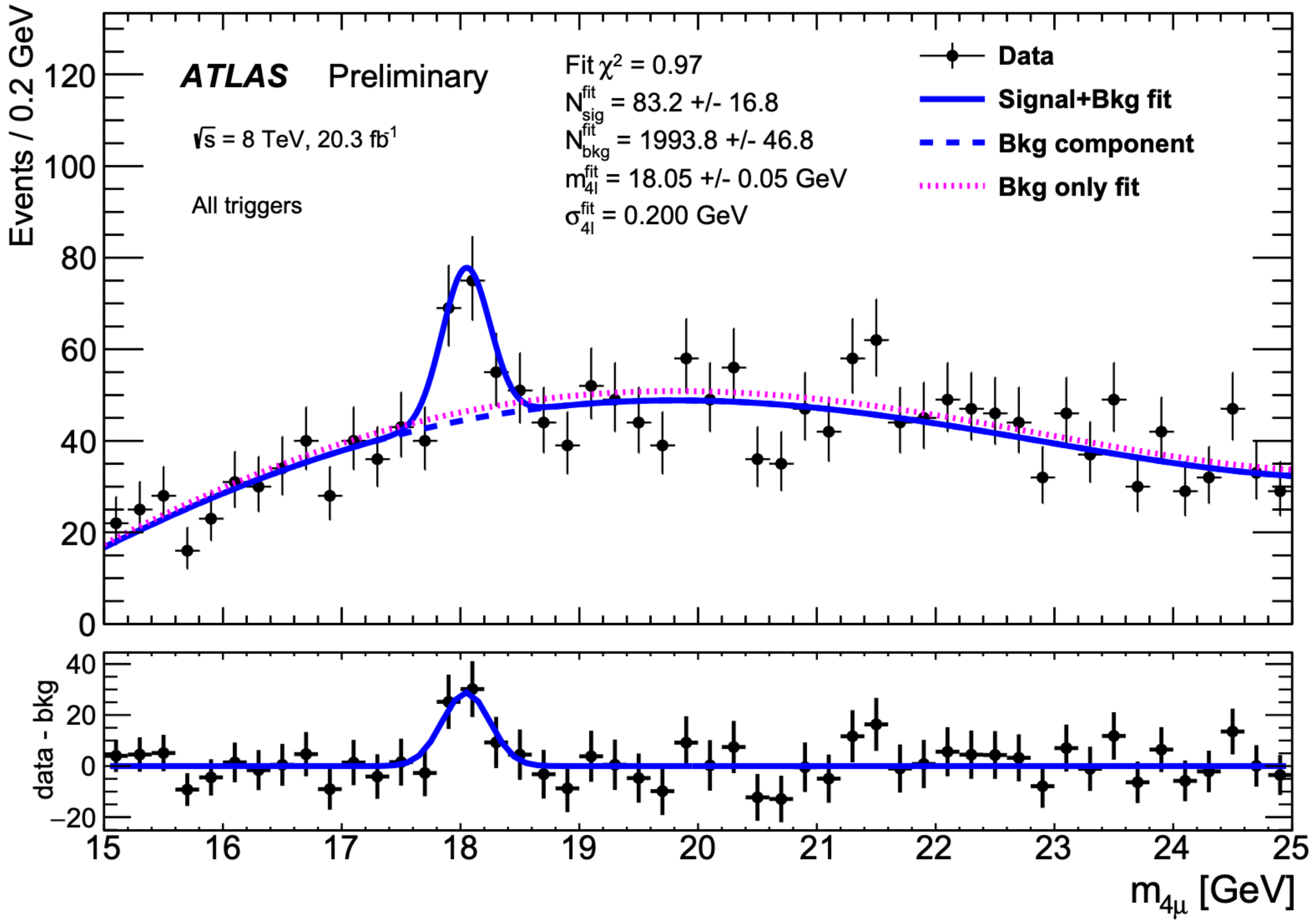
Rejects muon background from $B-$decays

This coincides with the PV selected by maximizing $\sum p_T^2$ in $99\,\%$ of events

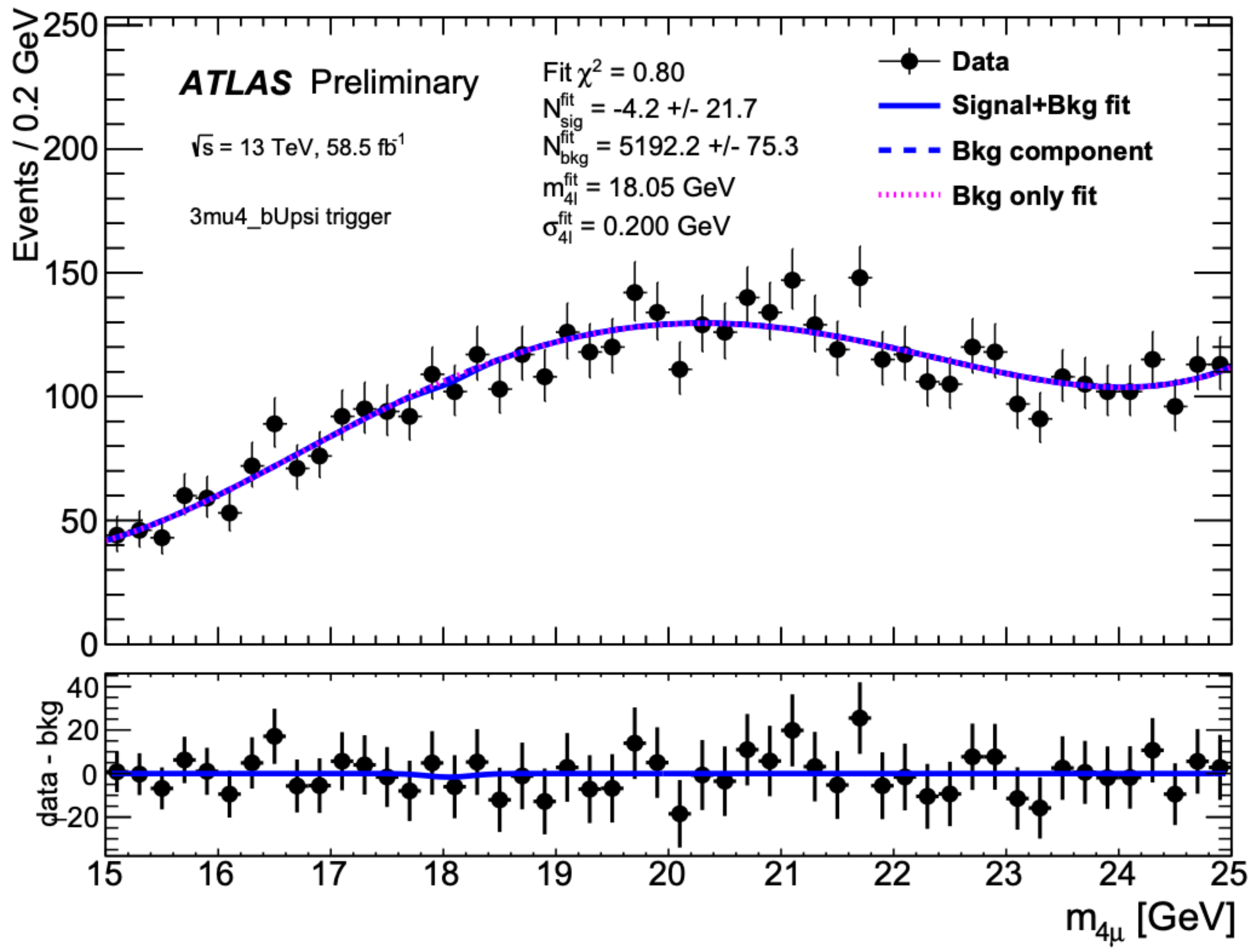
Results

- **Run1: 2012**
  - **Excess at 18 GeV** with global (local) significance of $1.9\sigma - 5.4\sigma$ $(3.6\sigma - 6.3\sigma)$.
  - Variation in the significance arising from the variation in fit-range and selection cuts.
- **Run2: 2015-2017**
  - **Excess at the same 18 GeV** with a significance of 1.9σ.
- **Run2: 2018**
  - **No excess** found!

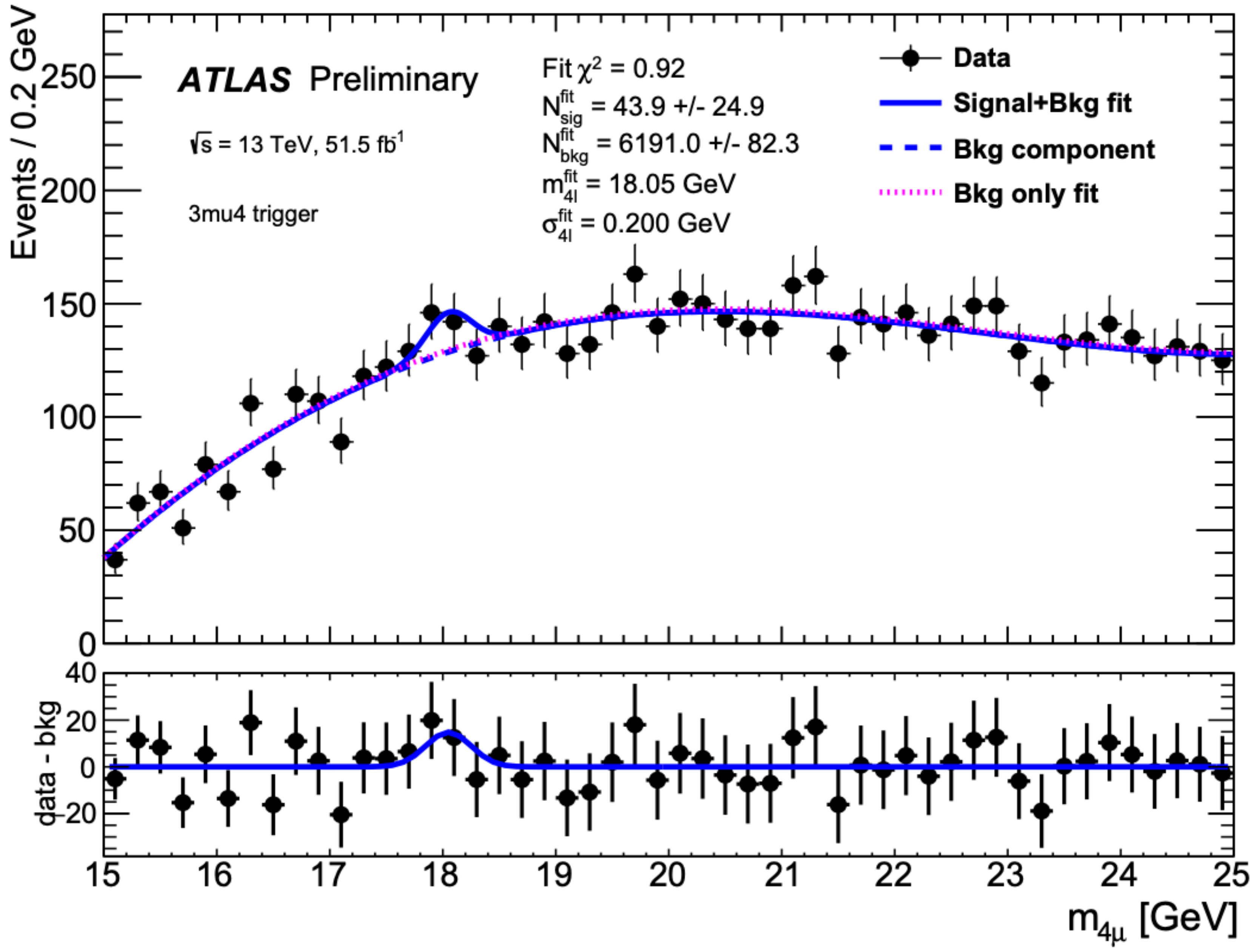
2012
2μ Trigger + **Less restrictive** 3μ Trigger



2018
More restrictive 3μ Trigger

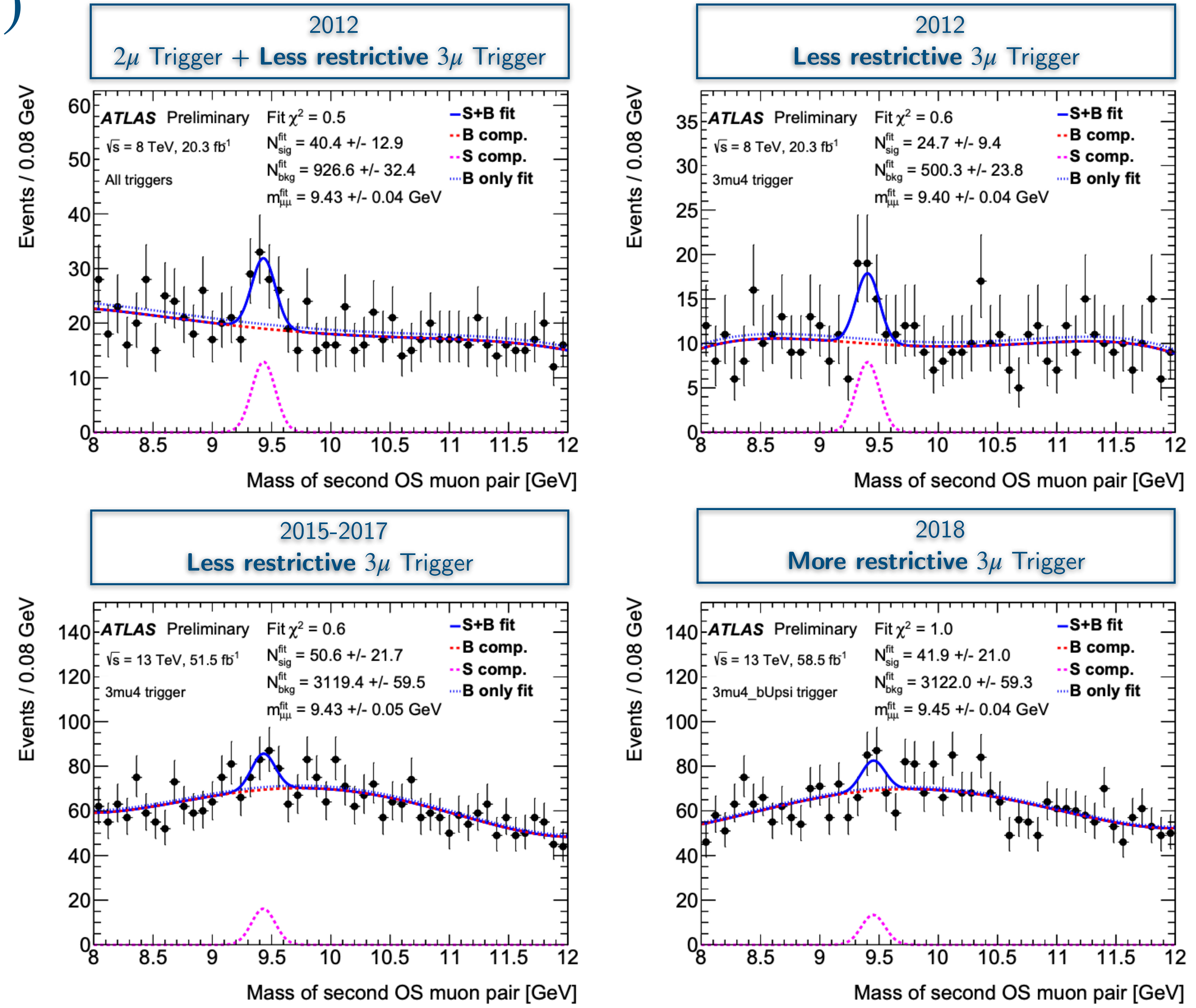


2015-2017
Less restrictive 3μ Trigger

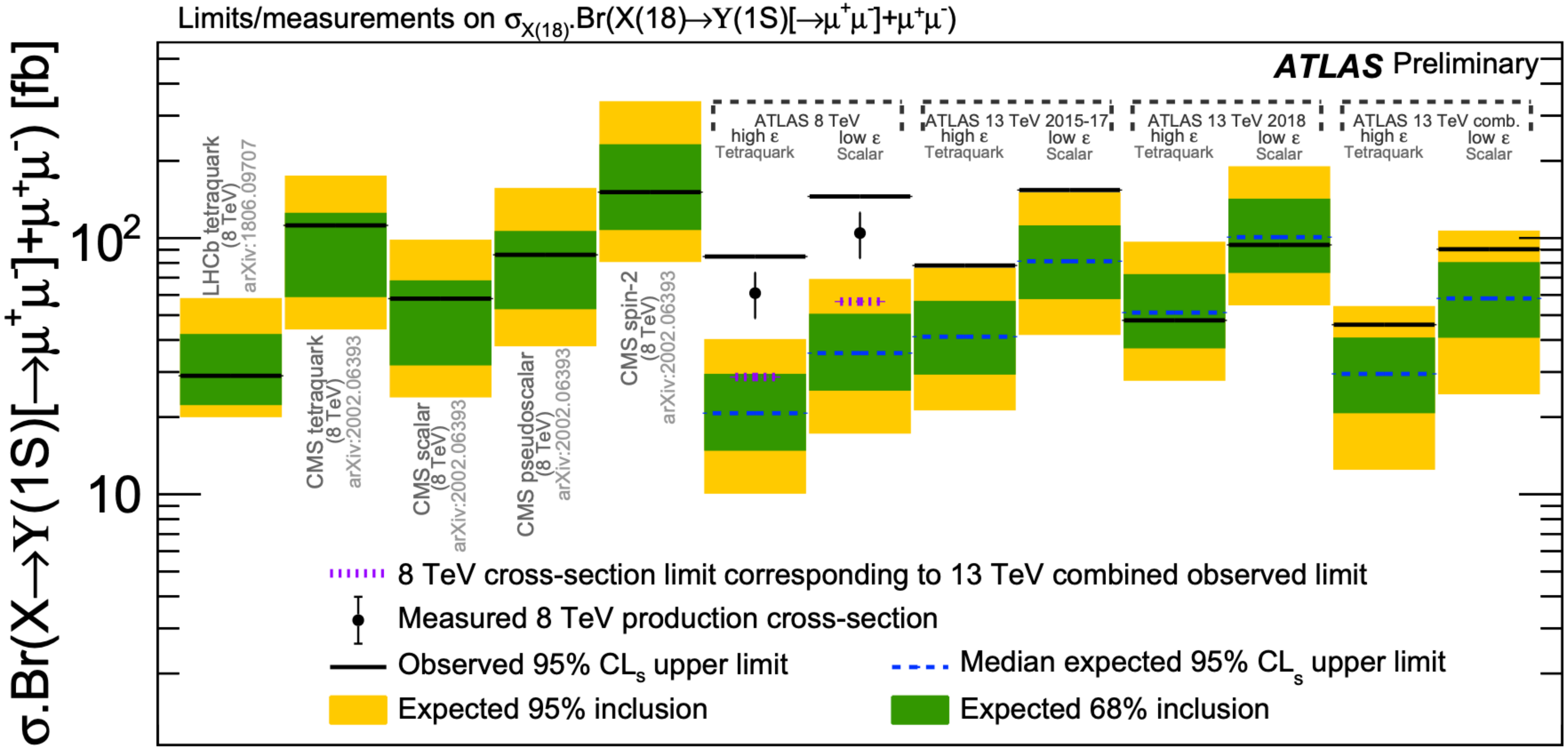


Cross-Checks with di-$\Upsilon(1S)$

- **Use associated production of di-$\Upsilon(1S)$ as a validation channel.**
  - Apply selections identical to the main analysis.
  - Look at the mass-spectrum of the second OS muon pair.
- **Reduction in the signal yield of di-$\Upsilon(1S)$ from 2012 to 2018 consistent with MC expectations.**
- **Even after taking into account such reductions in signal sensitivity, 2.7σ tension b/w Run1 and Run2 results for the $\Upsilon(1S)+\mu^{+}\mu^{-}$ search.**
- **Also check if the di-$\Upsilon(1S)$ events cause the $m_{4\mu}$ peaks.**
  - Found to be flat!



Limit-Setting Interpretation



- **Note: LHCb and CMS did not find any excess at 18 GeV in their spectrum of $\Upsilon(1S) + \mu^+\mu^-$.**
  - CMS: 2002.06393, LHCb: 1806.09707

Effective Lifetime of the $B_s^0 \to \mu^+\mu^-$ Decay

arXiv:2308.01171

JHEP09(2023) 199

Motivation

- Effective lifetime: $\tau_{\mu\mu} = \frac{\int dt \; t \cdot \langle \Gamma(B_s(t) \to \mu\mu) \rangle}{\int dt \; \langle \Gamma(B_s(t) \to \mu\mu) \rangle}$
- Related to the mass-eigenstate asymmetry:

$$A^{\mu\mu}_{\Delta\Gamma} = \frac{\Gamma(B^0_{sH} \to \mu\mu) - \Gamma(B^0_{sL} \to \mu\mu)}{\Gamma(B^0_{sH} \to \mu\mu) + \Gamma(B^0_{sL} \to \mu\mu)} = \frac{1}{y_s}\left[\frac{(1-y_s^2)\tau_{\mu\mu} - (1+y_s^2)\tau_{B_s}}{2\tau_{B_s} - (1-y_s^2)\tau_{\mu\mu}}\right]$$

1 in SM

$$y_s = \frac{\Delta\Gamma_s}{2\Gamma_s} \qquad \tau_{B_s} = \frac{1}{\Gamma_s}$$

SM Prediction: 1.624 ± 0.009 ps

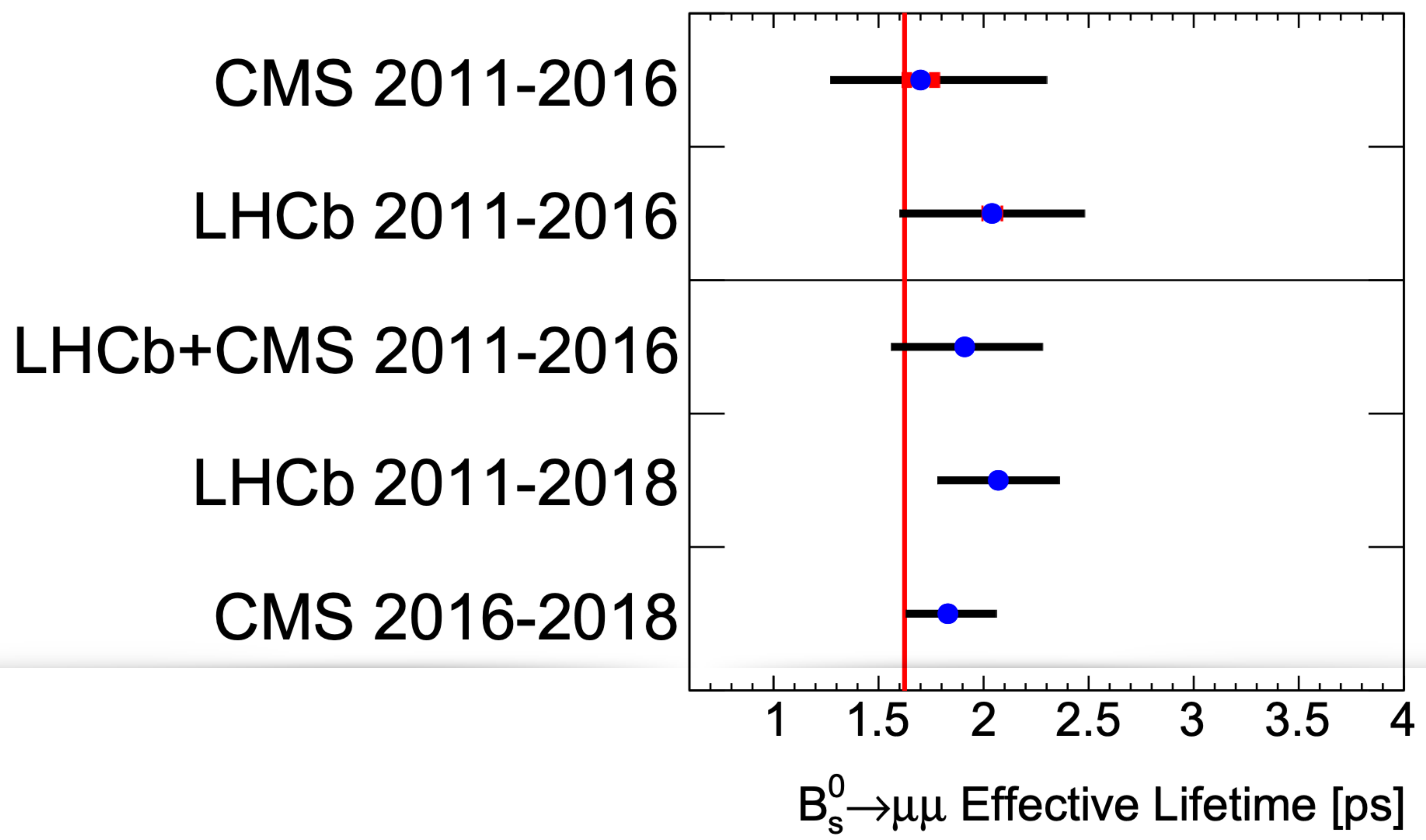
- **Uniquely sensitive to BSM contributions that might mediate $B^0_{sL} \to \mu\mu$!**
  - These can be completely hidden in $\mathscr{B}(B^0_s \to \mu\mu)$ despite the rarity of the decay.

Motivation

- Effectiv...

$\int dt\, t \cdot \langle \Gamma(B_s(t) \to \mu\mu) \rangle$

Before this analysis...



- Relatec...

$A^{\mu\mu}_{\Delta\Gamma} = \frac{\Gamma}{\Gamma} \ldots \left[\frac{\ldots_{\mu\mu} - (1+y_s^2)\tau_{B_s}}{\ldots(1-y_s^2)\tau_{\mu\mu}} \right]$

1 in SM

$\frac{\ldots}{2\Gamma_s}$ $\frac{1}{\Gamma_s}$

SM Prediction: 1.624 ± 0.009 ps

- **Uniquely sensitive to BSM contributions that might mediate $B^0_{sL} \to \mu\mu$!**
  - These can be completely hidden in $\mathscr{B}(B^0_s \to \mu\mu)$ despite the rarity of the decay.

Analysis Strategy

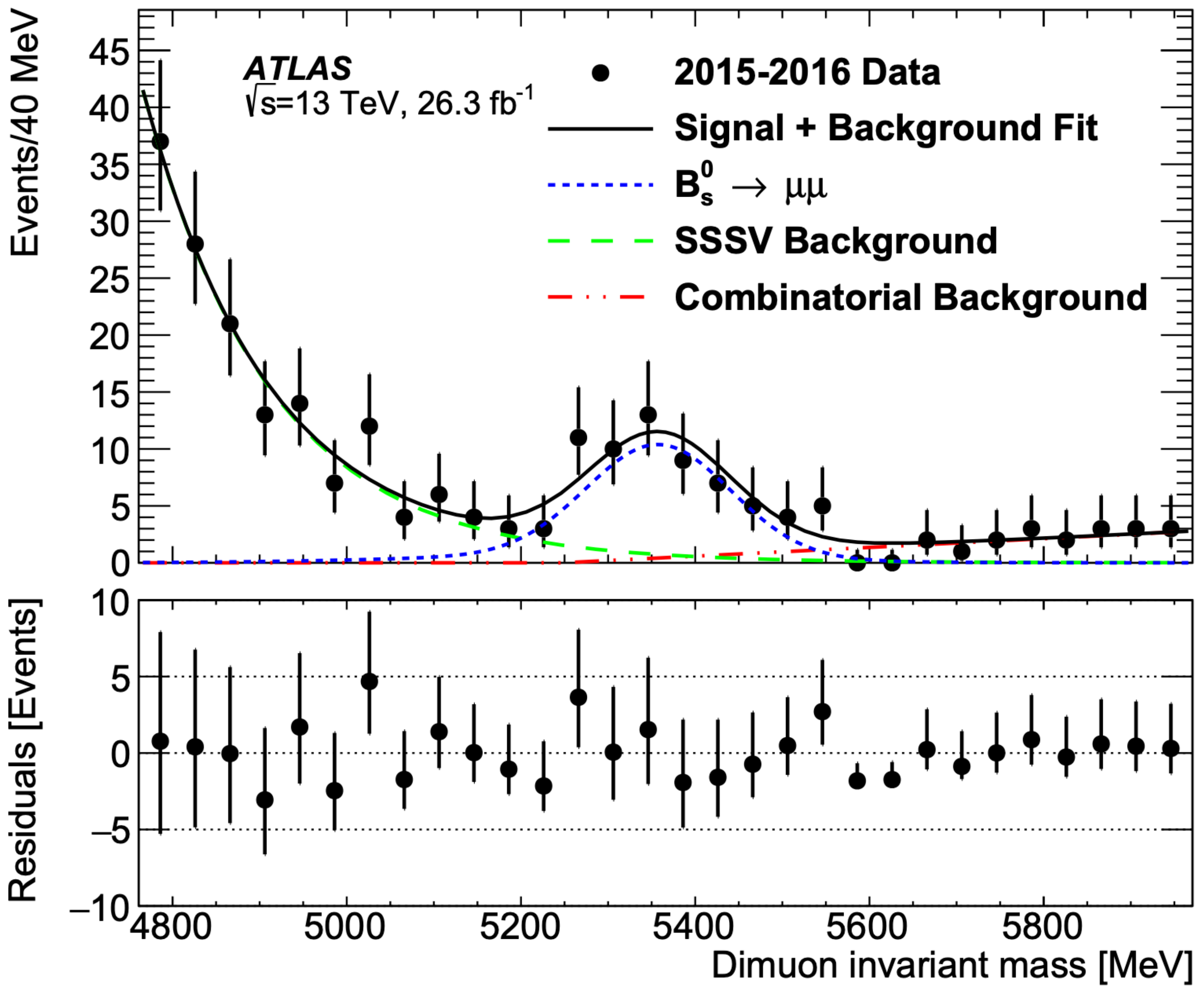
- **Data**
  - Early Run2 data (2015, 2016) with effective $L = 26.3\ \text{fb}^{-1}$.
- **Event Selection**
  - $B_s^0 \to \mu^+\mu^-$ decay vertex using two muon tracks.
  - Primary Vertex selected to minimize Δz w.r.t. the decay vertex ($\sim 99\,\%$ accurate).

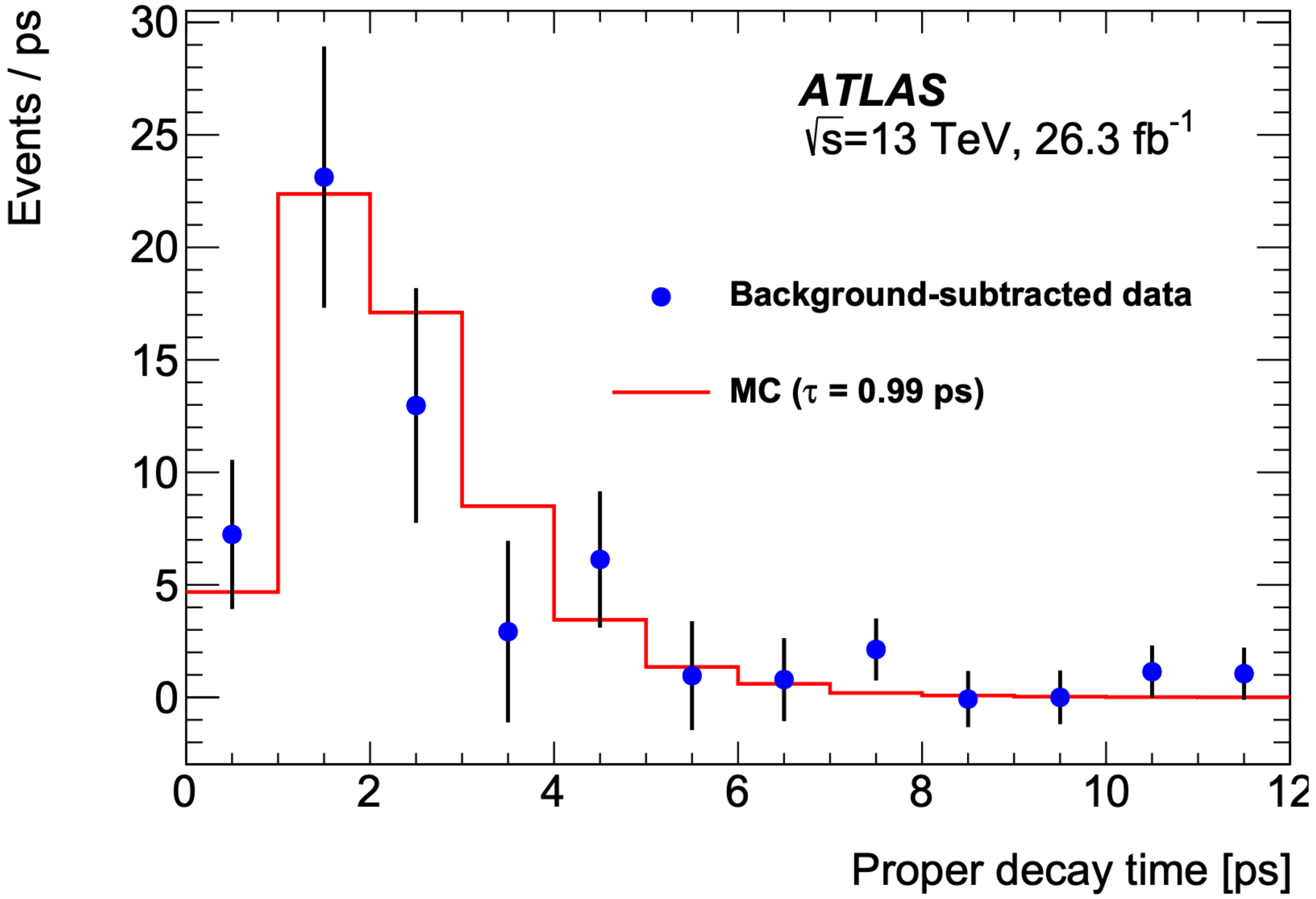
➡ $t_{\mu\mu}^i = \dfrac{1}{c} \dfrac{L_{xy}^i}{p_{\mathrm{T}}^i(B_s^0)} m_{B_s^0}^{\mathrm{PDG}}$ and $m_{\mu\mu}^i$ extracted per candidate using "combined" muons.

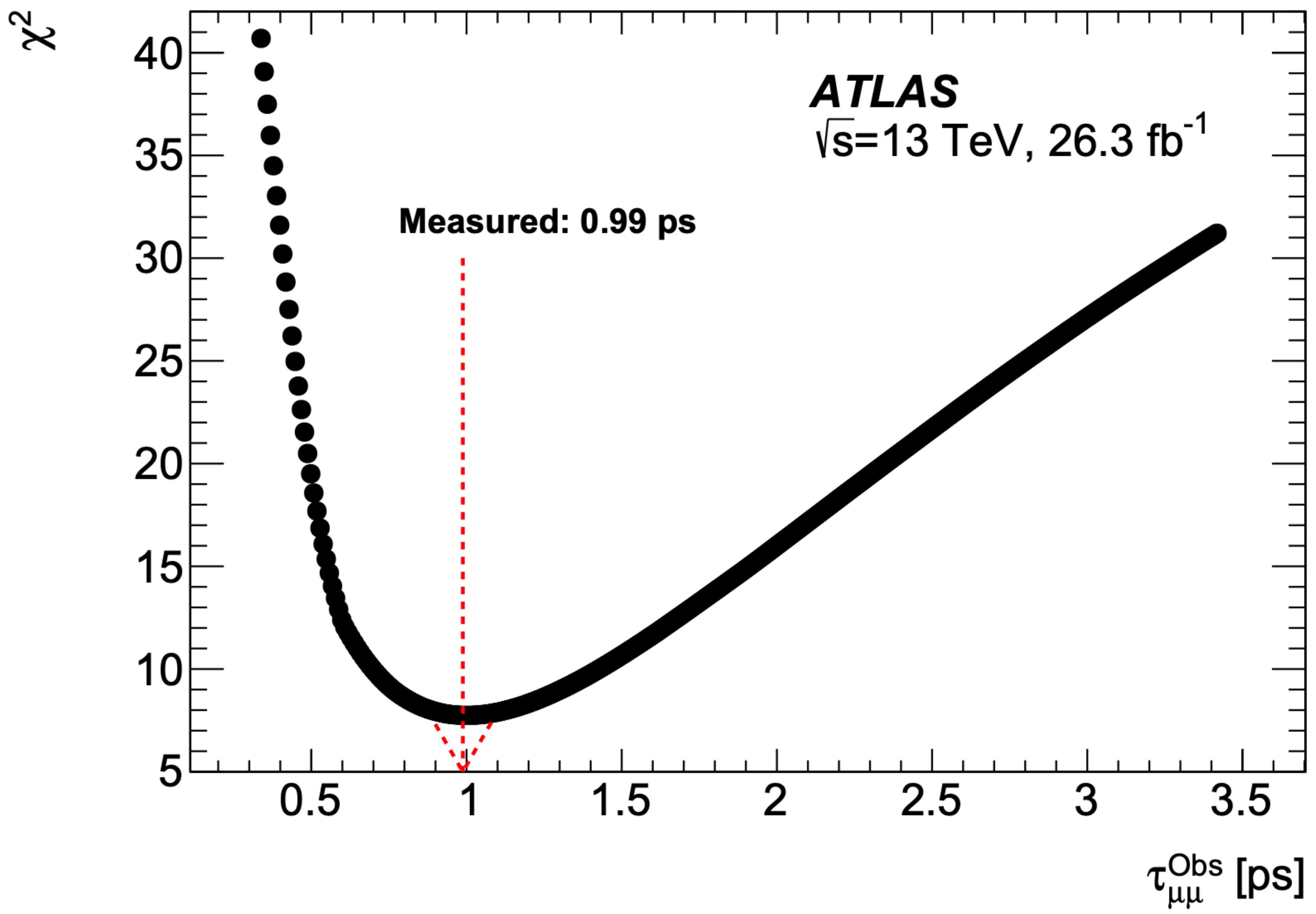
  - BDT selections applied to reduce the large combinatorial background.
- **$\tau_{\mu\mu}$ Measurement**
  - **Signal $t_{\mu\mu}$ distributions in data** extracted with ${}_s\mathcal{P}lot$ **technique** where unbinned extended maximum likelihood fits to $m_{\mu\mu}$ distribution are used to discriminate the signal against background.
  - $\tau_{\mu\mu}$ is measured by **minimizing the binned χ^2** between the **extracted signal $t_{\mu\mu}$ distribution in data and MC templates with varying $\tau_{\mu\mu}$**.

$\tau_{\mu\mu}$ Measurement

- **Mass Fits**
  - **Signal:** Modeled as a double Gaussian. Shape fixed to MC $B_s^0 \to \mu\mu$ within detector resolution.
  - **Background:**
    - **"SSSV":** Muon pairs from $B-$hadron decays → modeled as an exponential contribution.
    - **Combinatorial:** Random pairings of muons from $b\bar{b}$ decays → modeled as a linear contribution.
- **Fitted signal yield:** 58 ± 13
- $\tau_{\mu\mu}$ **Extraction**
  - **MC distributions for** $\tau_{\mu\mu}$: an exponential corrected for acceptance and cuts, convolved with resolution.
- **Nominal value:** $\tau_{\mu\mu} = 0.99$ ps







Systematics

- **Reference channel** $B^{\pm} \to J/\psi(\to \mu^+\mu^-)K^{\pm}$ used to correct for **data/MC discrepancies**.
  - However, due to the **topological and kinematic differences b/w the reference and the signal channels**, data/MC discrepancies remain the largest systematics.
- In addition to the mass shape mismodeling in mass fits, **correlations b/w lifetime and mass that can bias the** $_s\mathcal{P}lot$ results are accounted for in systematics.
- **Potential background sources not modeled in the fit** are also taken as sources of systematics.

Uncertainty source	$\Delta\tau_{\mu\mu}^{\mathbf{Obs}}$ [fs]
Data - MC discrepancies	134
SSSV lifetime model	60
Combinatorial lifetime model	56
B kinematic reweighting	55
B isolation reweighting	32
SSSV mass model	22
B_d background	16
Fit bias lifetime dependency and B_s^0 eigenstates admixture	15
Combinatorial mass model	14
Pileup reweighting	13
B_c background	10
Muon Δ_η correction	6
$B \to hh'$ background	3
Muon reconstruction SF reweighting	2
Semileptonic background	2
Trigger reweighting	1
Total	174

Result

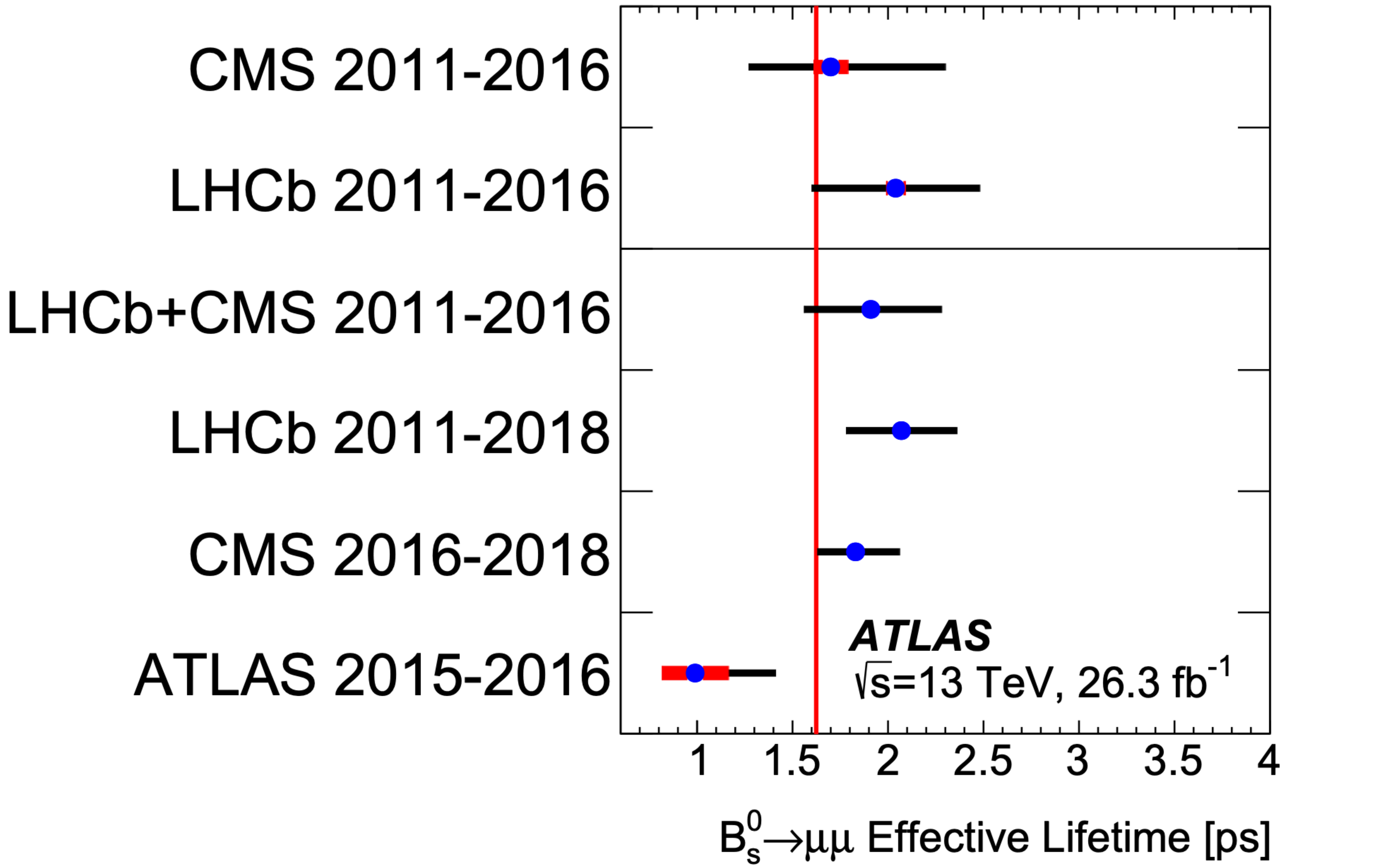
- **Measurement:**

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

  - Recall: fitted signal yield was 58 ± 13.

- **Compatible with both the SM and previous measurements.**

- **Statistically dominated → Full Run2 measurement will certainly help!**



Outlook: Flavor Physics at ATLAS in This Talk and Beyond!

Production Cross-Sections & Spectroscopy

- 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.
- Search for $\Upsilon(1S) + \mu^+\mu^-$ Resonance in 4μ Final States
  - The excess at 18 GeV in 2012 data appears to go away in 2018 data.
  - More work needed to resolve the tension b/w Run1 and Run2.

Measurements of Weak Decays

- Effective Lifetime of the $B_s^0 \to \mu^+\mu^-$ Decay
  - First measurement of effective $B_s^0 \to \mu^+\mu^-$ lifetime by ATLAS with early Run2 data.
  - Stay tuned for full Run2 analysis!

ATLAS Public Results

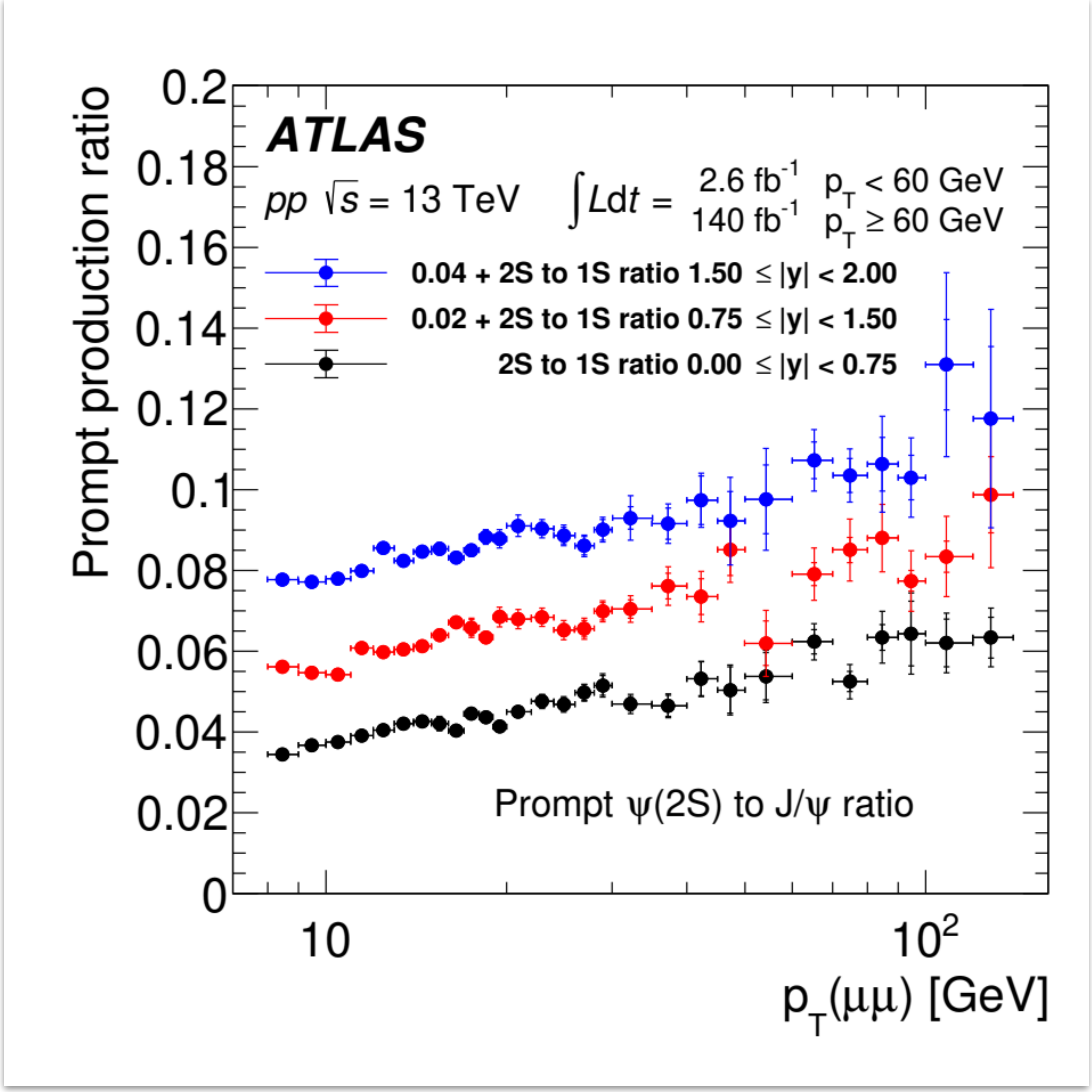
Thank You!

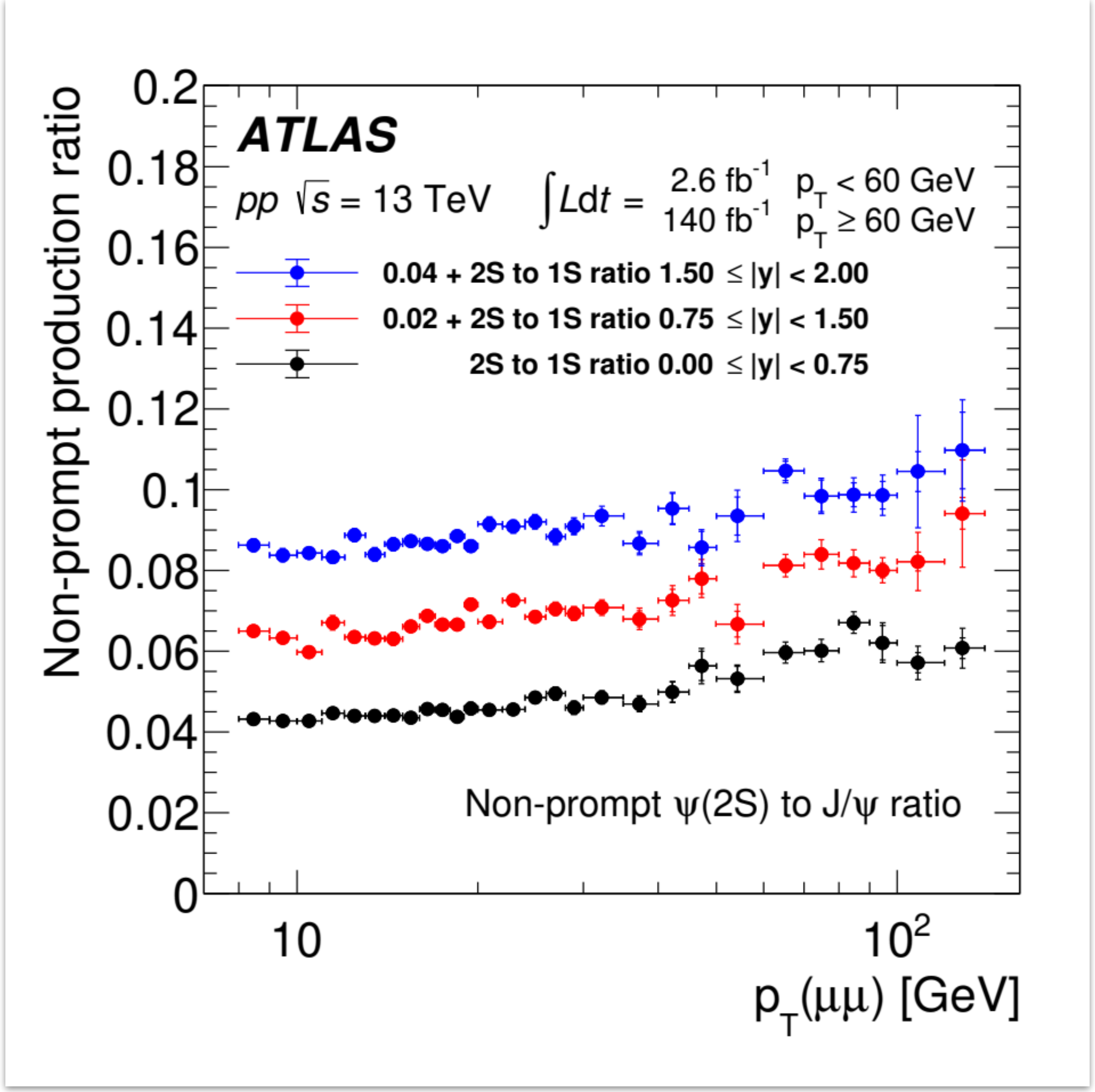
Back-Up

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

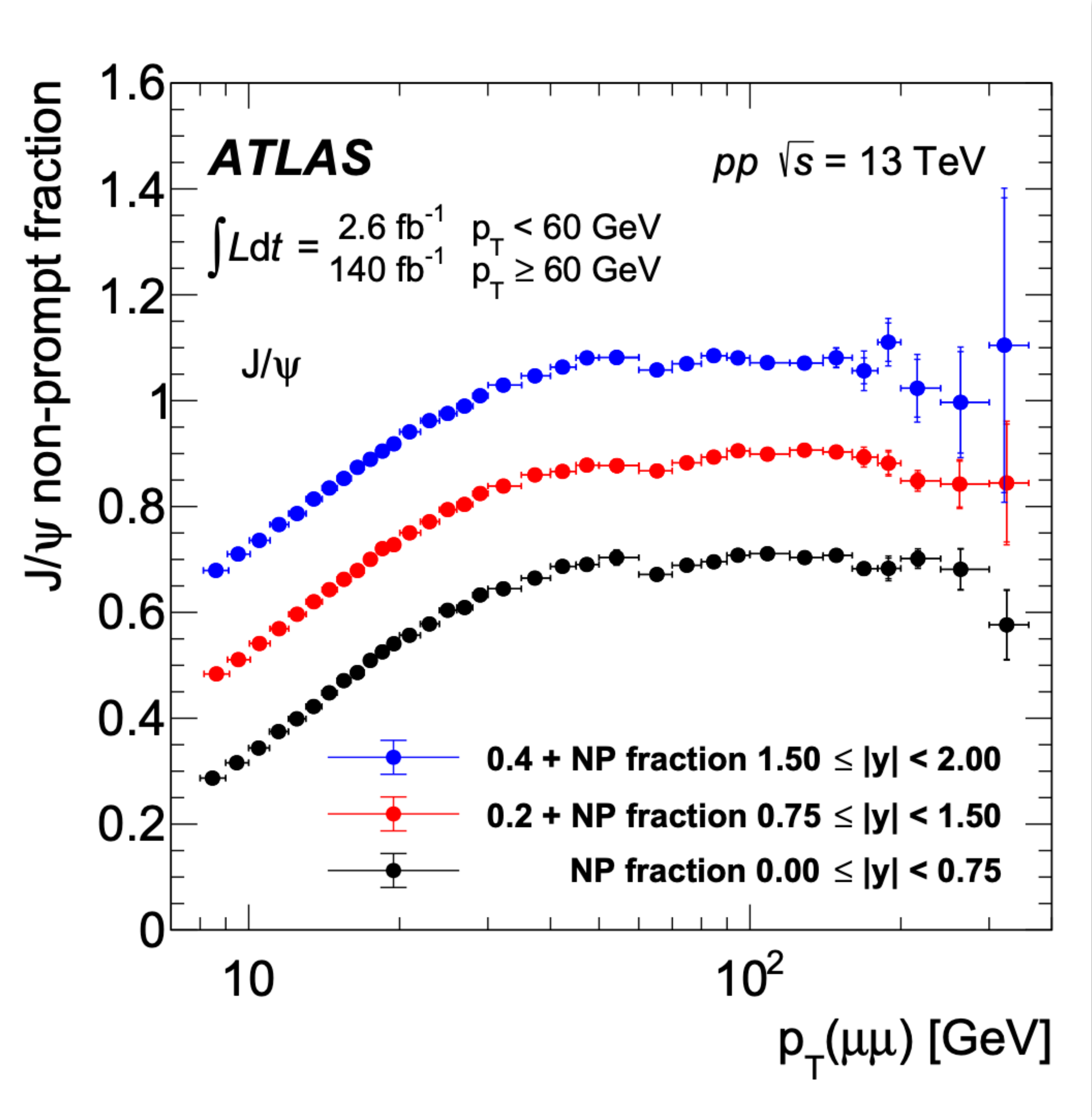
arXiv:2309.17177
Eur. Phys. J. C 84 (2024) 169

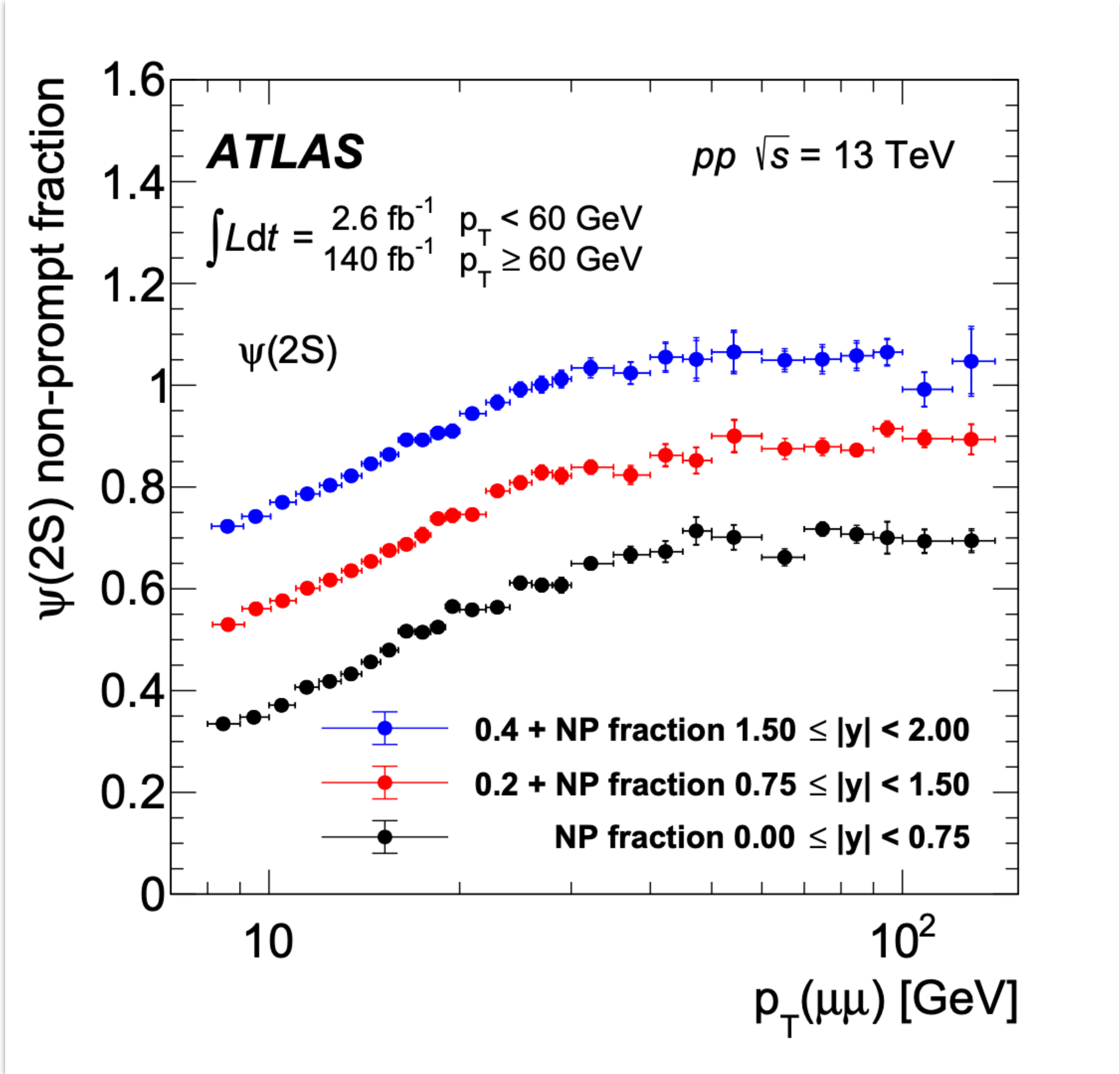
Results: $\psi(2S)$-to-J/ψ Production Ratios





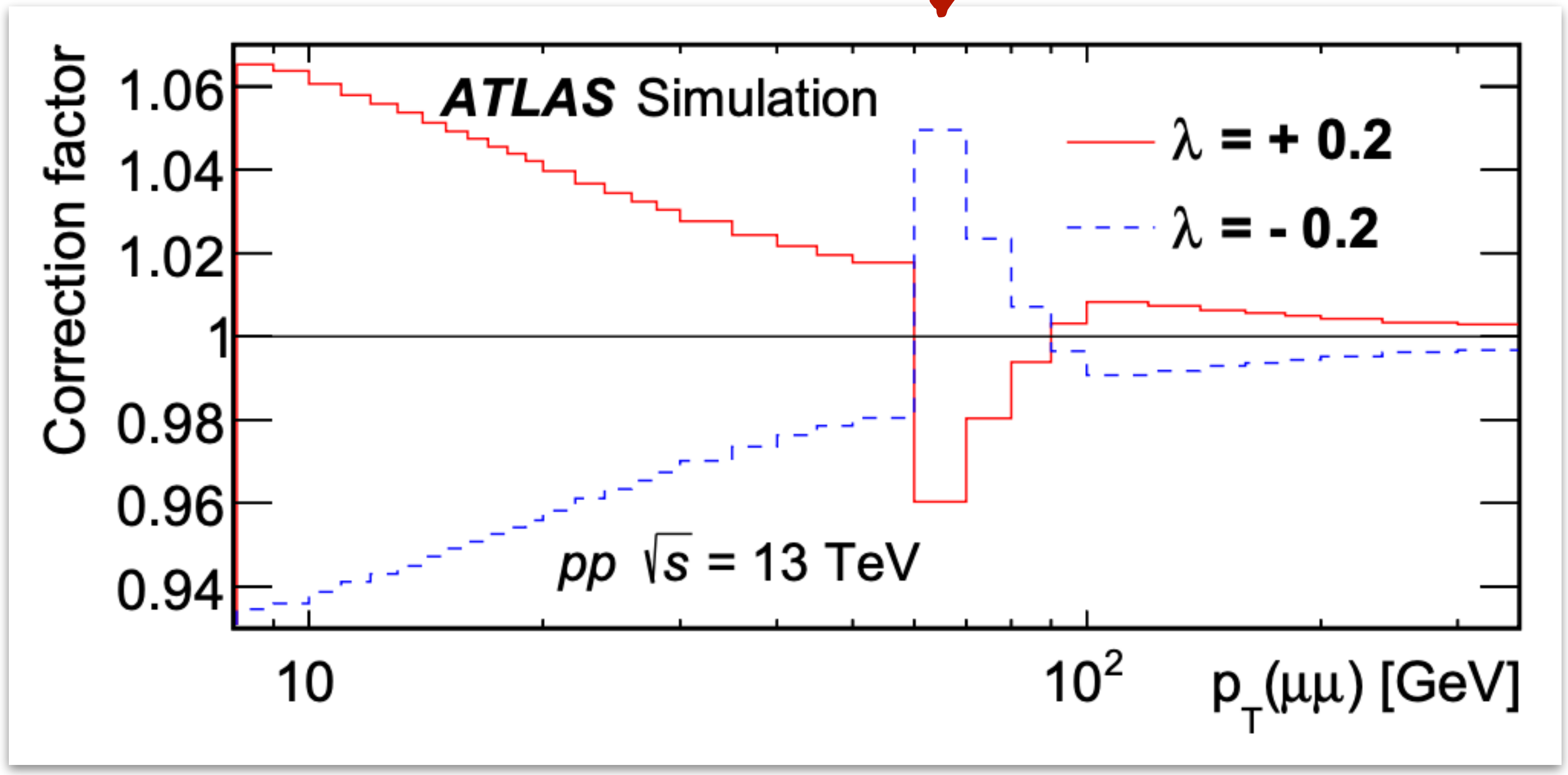
Results: Non-Prompt Production Fractions



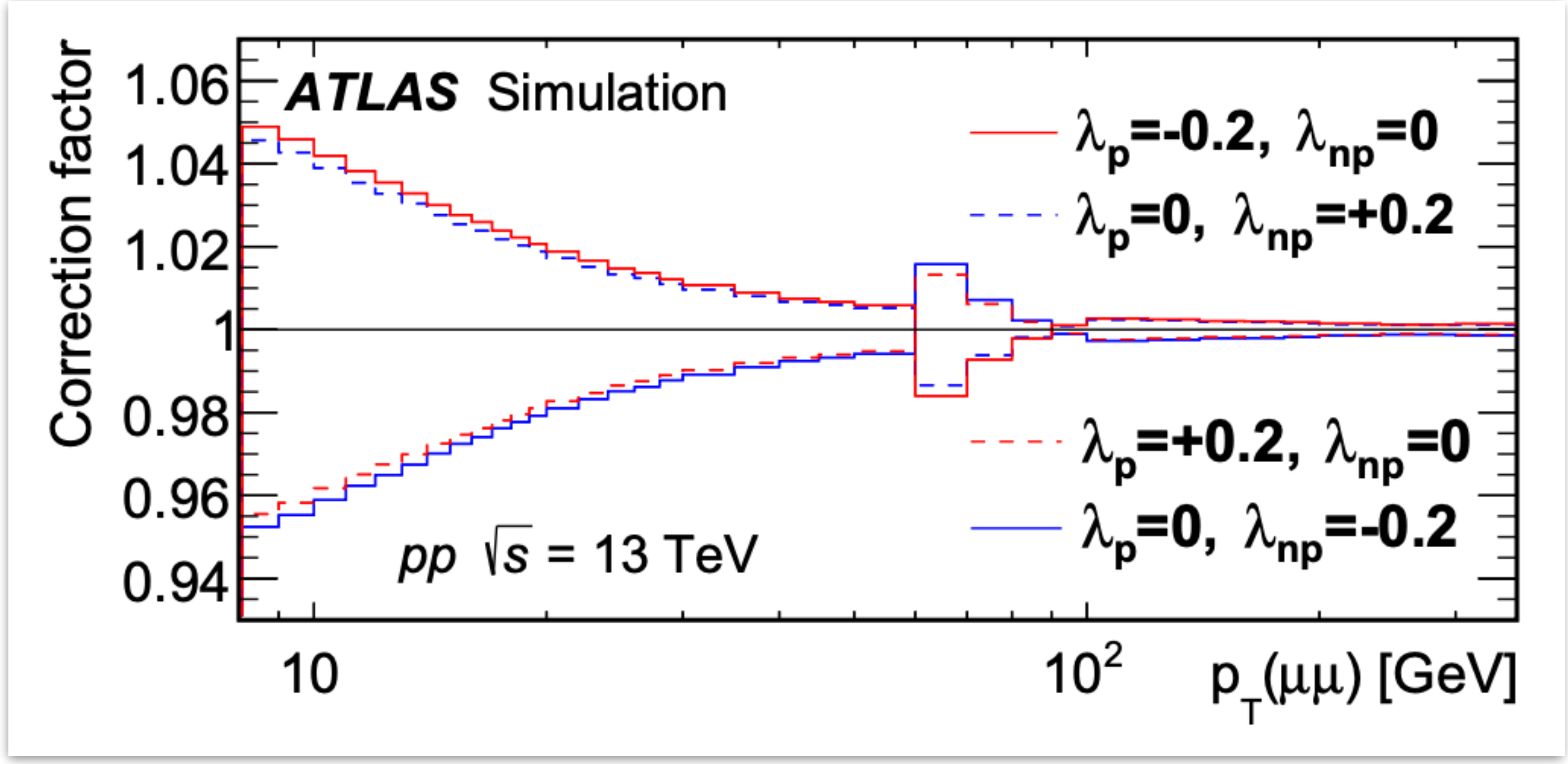


The Spin-Alignment Correction Factors

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

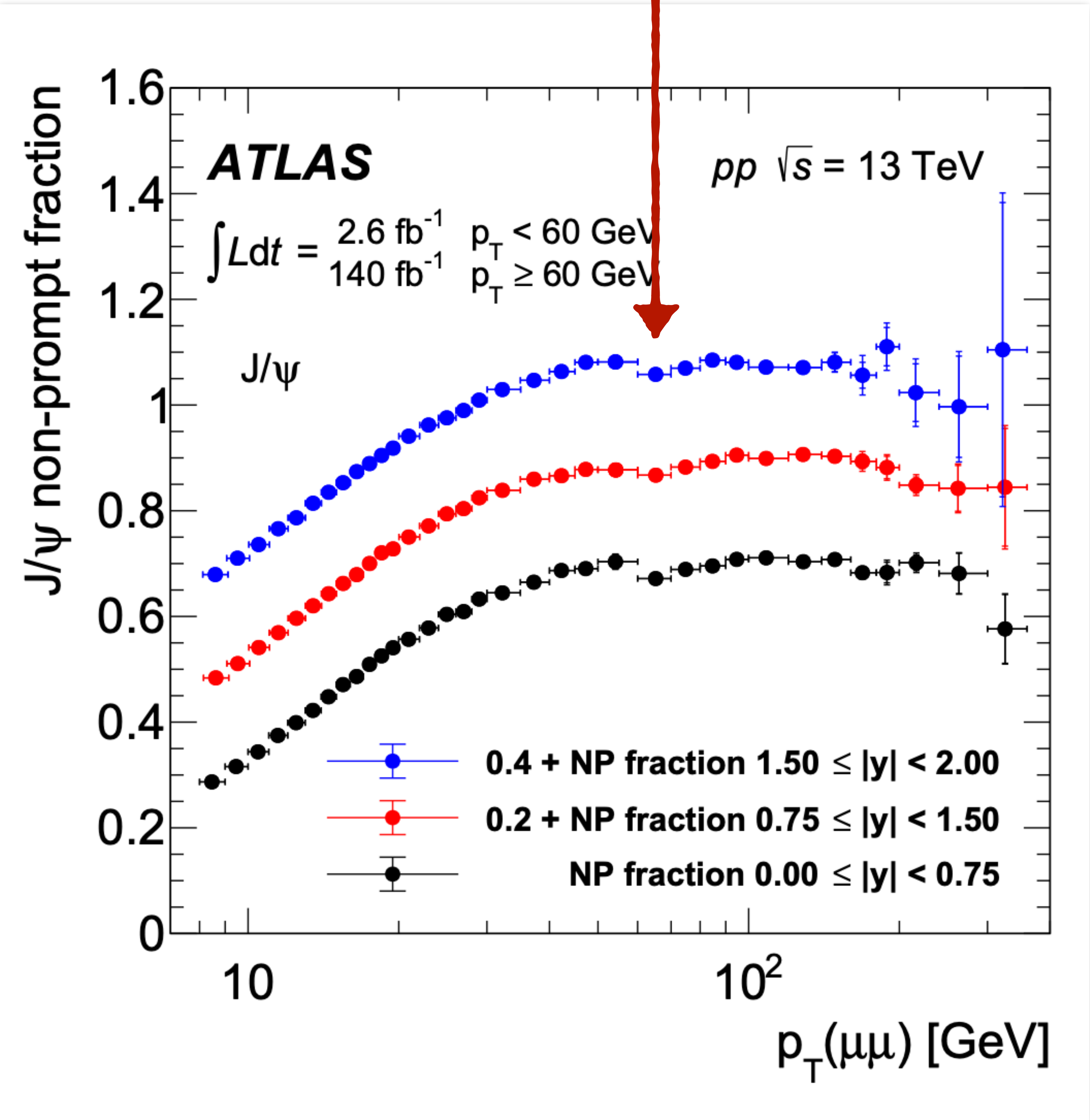


Prompt J/ψ



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

2309.17177

Partial Cancellation of Systematics