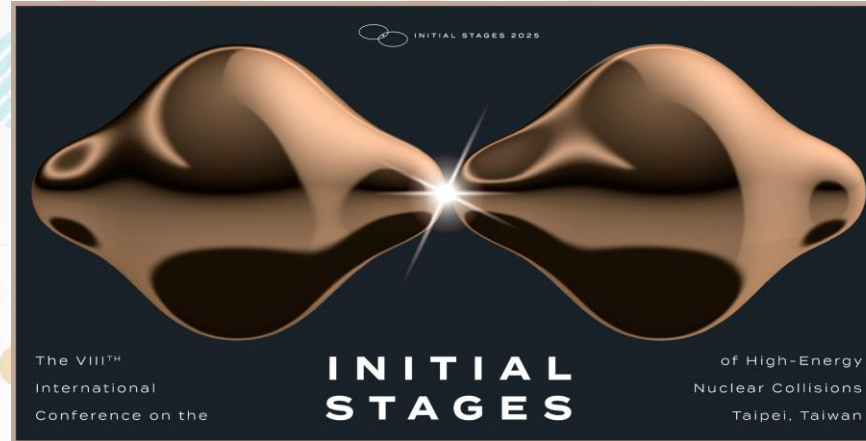


# Upsilon production and polarization measurements in pp collisions with ALICE



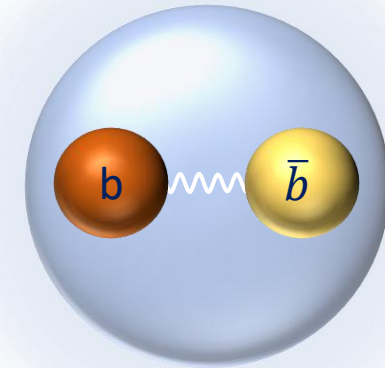
9<sup>th</sup> September 2025

**Kshitish Kumar Pradhan** on behalf of **ALICE Collaboration**

(Indian Institute of Technology Indore, India)

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- **Quarkonia** : bound states of heavy quarks produces in the **hard scatterings** in the initial stages : **Probe to study the QCD dynamics**
- Upsilon ( $\Upsilon$ ) – bound state of bottom quark and anti-quark  $\rightarrow b\bar{b}$
- Production involves two stages:
  - **Perturbative** (hard process) – production of a heavy quark–antiquark pair
  - **Non-perturbative** (soft process) – formation of the bound state
- Multiplicity dependent studies – to investigate the **production mechanisms and interaction with the final state**
- Polarization measurements – provides additional information about production mechanism



## Production in pp collisions

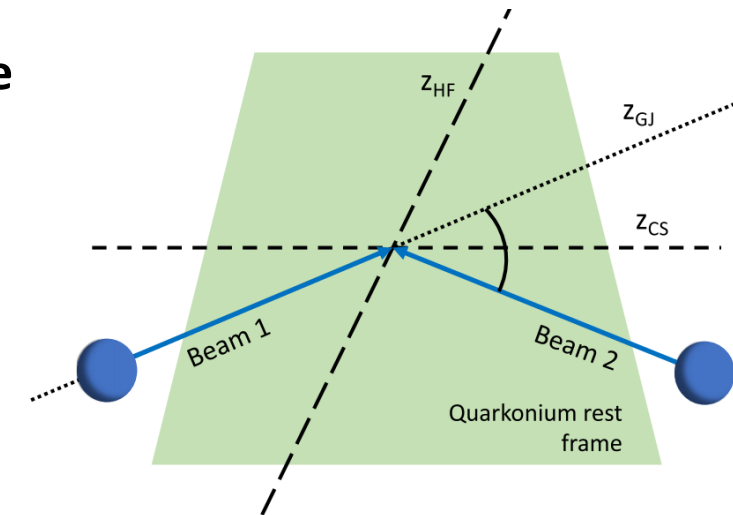
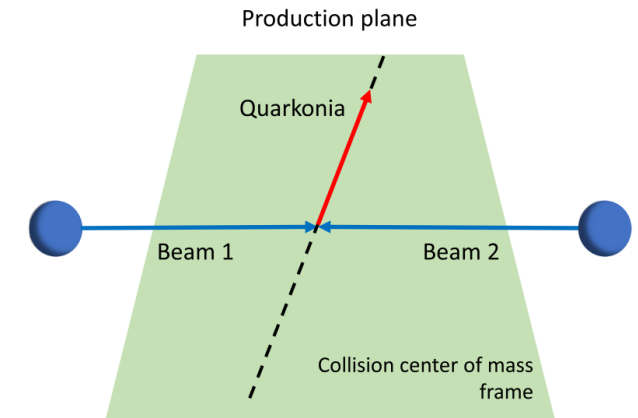
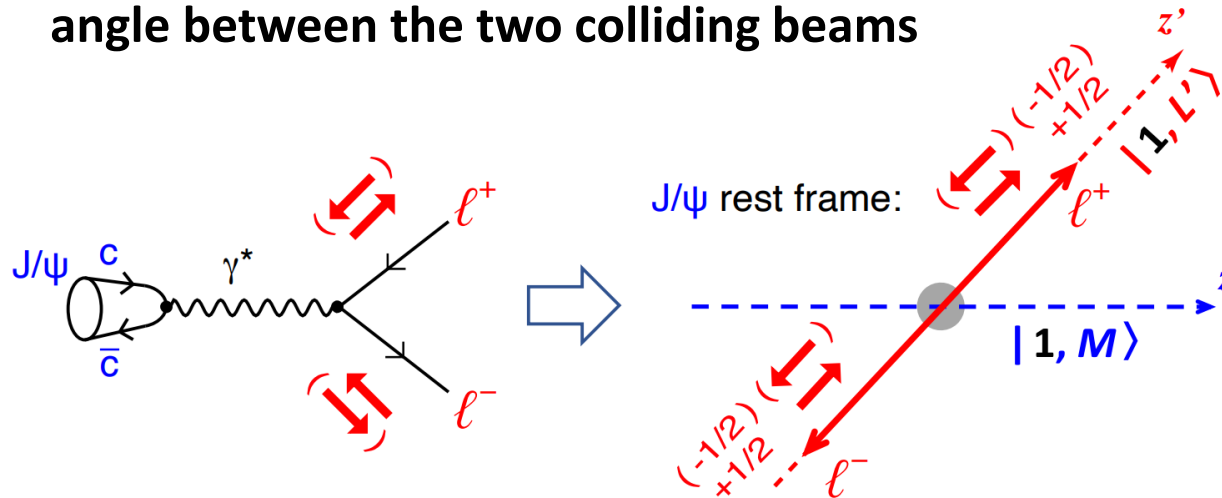
### QCD Aspects

Test perturbative and non-perturbative aspects of QCD.

### Reference

Serve as the reference for both AA and pA collisions.

- **Polarization** is defined as the **alignment of particle spin** to a given quantization axis
- It can be measured by analyzing the **angular distribution of the decay products**
- Frames of reference:
  1. **Helicity frame** : Quantization axis is taken along the **direction of produced Quarkonia momentum**
  2. **Collins-Soper frame** : Along the direction of the **bisector of the angle between the two colliding beams**



[P. Faccioli and C. Louren, DOI:[10.1007/978-3-031-08876-6](https://doi.org/10.1007/978-3-031-08876-6)]

[B. Sahoo, D. Sahu, S. Deb, C. R. Singh and R. Sahoo, Phys. Rev. C. 109, 034910 (2024)]

- The angular distribution can be parametrized as:

$$\frac{d^2N}{d\cos\theta d\varphi} = \frac{3}{4\pi(3 + \lambda_\theta)} (1 + \lambda_\theta \cos^2 \theta + \lambda_\varphi \sin^2 \theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos \varphi)$$

- As an alternative to a multi-parameter fit to the above relation, **the one-dimensional angular distributions** are used:

$$W(\cos\theta) \propto \frac{1}{3+\lambda_\theta} (1 + \lambda_\theta \cos^2 \theta)$$

$$W(\varphi) \propto 1 + \frac{2\lambda_\varphi}{3+\lambda_\theta} \cos 2\varphi$$

$$W(\tilde{\varphi}) \propto 1 + \frac{\sqrt{2}\lambda_{\theta\varphi}}{3+\lambda_\theta} \cos \tilde{\varphi}, \quad \text{where } \tilde{\varphi} = \varphi - \frac{3}{4}\pi \text{ for } \cos\theta < 0$$

$$\tilde{\varphi} = \varphi - \frac{\pi}{4} \text{ for } \cos\theta > 0$$

With the polarization parameters,

$$(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (1, 0, 0) \quad \text{Transverse polarization}$$

$$(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (-1, 0, 0) \quad \text{Longitudinal polarization}$$

$$(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (0, 0, 0) \quad \text{Unpolarized state}$$

Frame Invariant variable:

$$\tilde{\lambda} = \frac{\lambda_\theta + 3\lambda_\varphi}{1 - \lambda_\varphi}$$

[P. Faccioli, C. Lauroenco, J. Seixas and H. K. Wohri, Eur. Phys. J. C. 69, 657 (2010)]

- Theoretical models like **colour-singlet model (CSM)** and **non-relativistic QCD (NRQCD)** are developed to explain quarkonia production
- None of the models explain both production cross-section and polarization simultaneously
- **Improved Color Evaporation Model (ICEM)** – Quarkonium momentum depends to that of parent  $q\bar{q}$  pair - Improves description of spectra and polarization

## Why study bottomonium resonances?

### Robust calculations

Being **massive**, satisfy **non-relativistic approach** better than charmonium states



### Cleaner QGP Probe

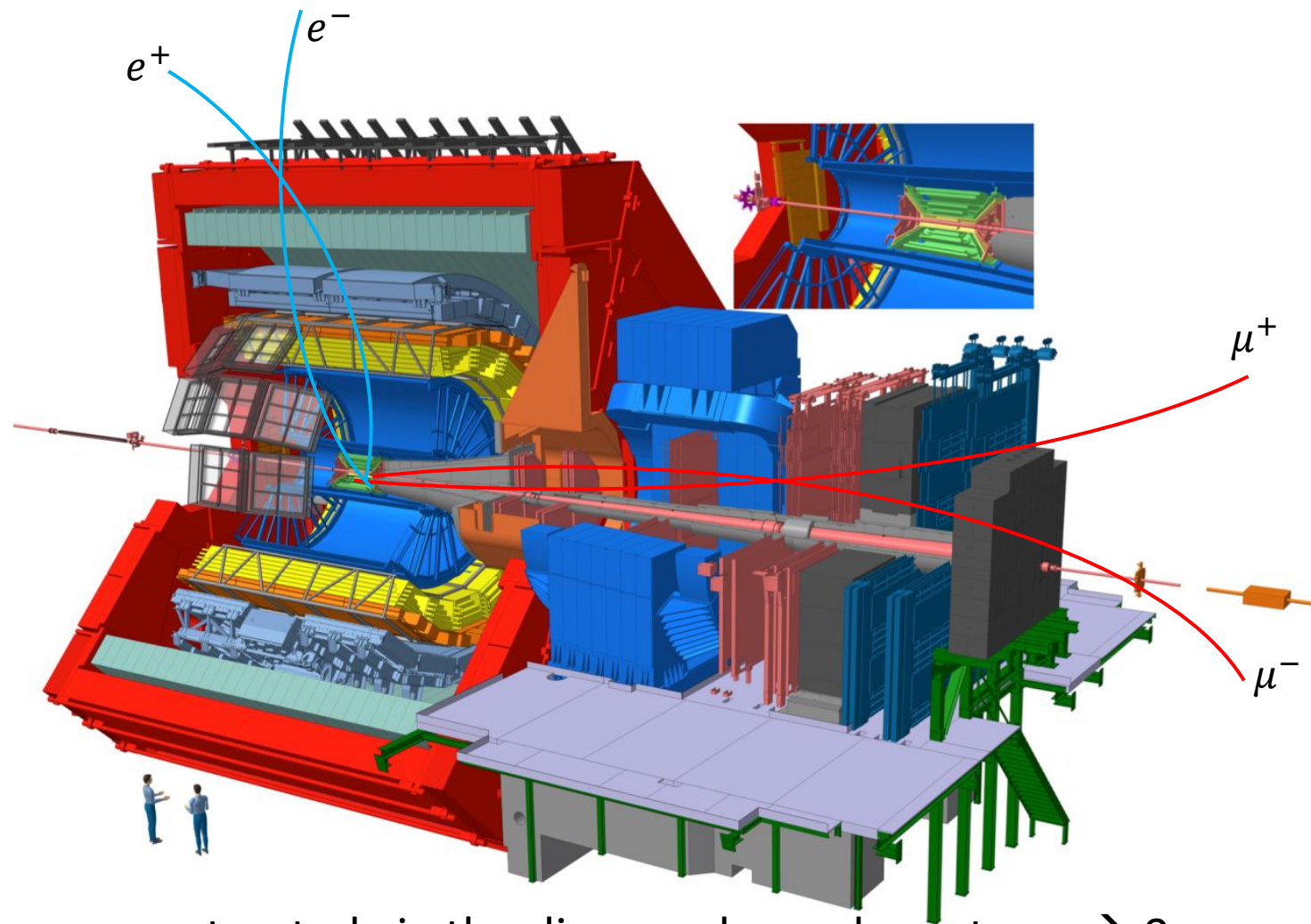
Regeneration contribution in nuclear collisions **is very small** – **Better probe** to study suppression in pA and AA collisions

Experimental results will help better in constraining model parameters

# A Large Ion Collider Experiment (Run 2 configuration)

Central Barrel  $\rightarrow e^+e^-$   
Midrapidity :  $|\eta| < 0.9$   
Inner Tracking System (ITS)  
➤ Tracking and vertexing  
Time Projection Chamber (TPC)  
➤ Tracking and PID

Muon Spectrometer  $\rightarrow \mu^+\mu^-$   
Forward rapidity :  $2.5 < \eta < 4$   
Muon Chamber (MCH)  
➤ Muon tracking  
Muon Trigger / Muon Identifier (MID)  
➤ Identifying high momentum muons

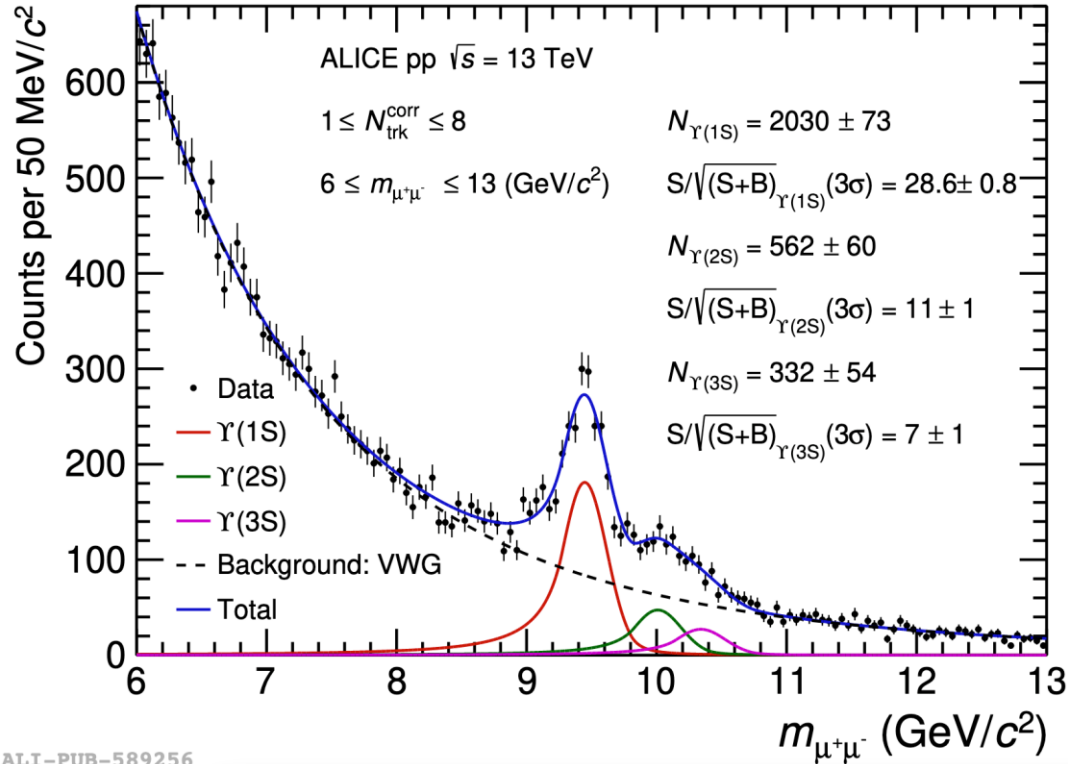


❖ At forward rapidity, quarkonium states are reconstructed via the dimuon decay down to  $p_T \rightarrow 0$  using the Muon Spectrometer

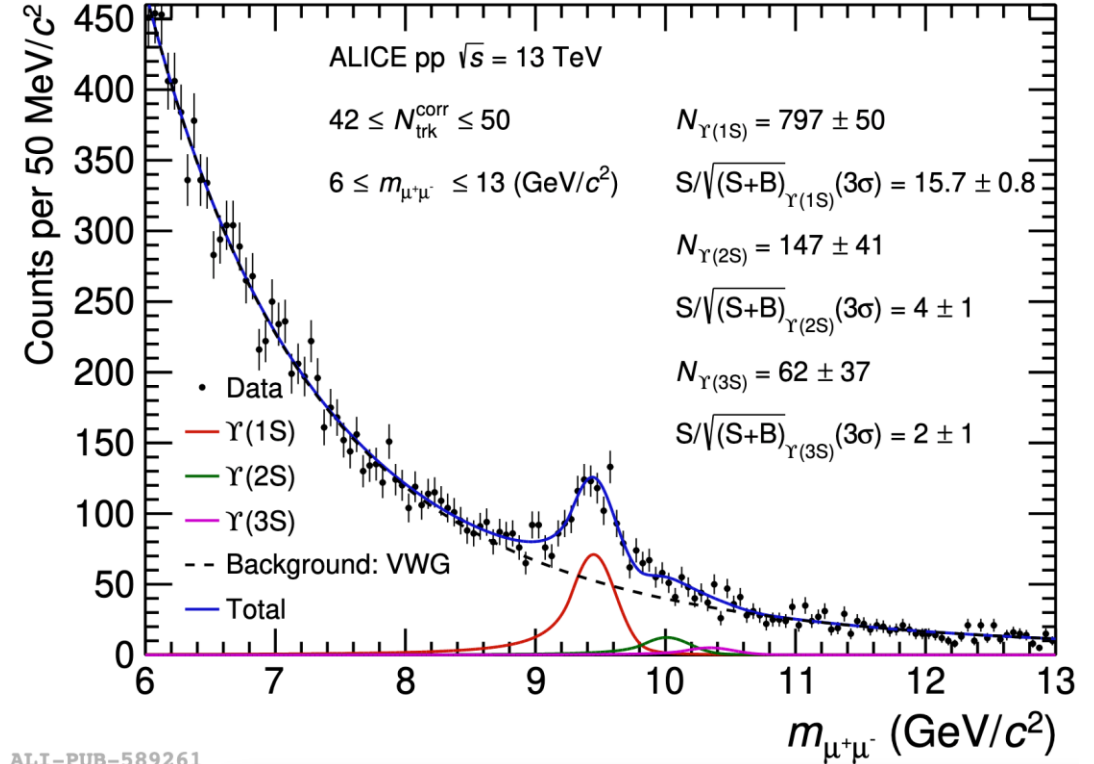
# Upsilon production measurements in pp collisions

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# Upsilon signal in pp collisions at $\sqrt{s} = 13$ TeV



ALI-PUB-589256



ALI-PUB-589261

[ALICE Collaboration, Nucl. Phys. B. 1011, 116786 (2025)]

- Fits to the dimuon invariant mass distributions for low and high multiplicity collisions
- Fitting functions:

Signal  $\rightarrow$  pseudo-gaussian functions

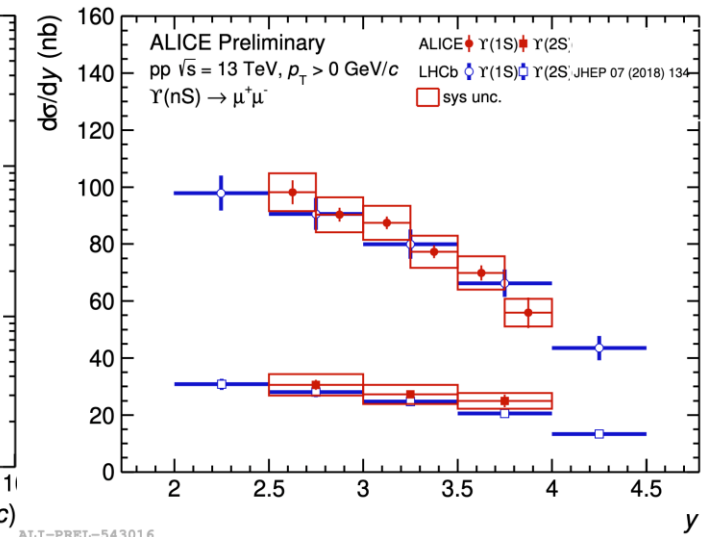
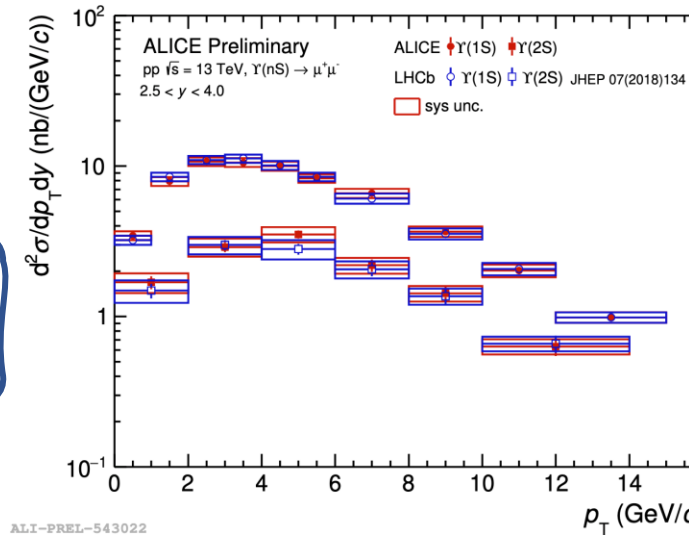
Background  $\rightarrow$  phenomenological functions

# Upsilon production in pp collisions at $\sqrt{s} = 13$ TeV

- Inclusive differential production cross section as a function of  $p_T$  and  $y$

$$\frac{d^2\sigma}{dp_T dy} = \frac{N(\Delta y, \Delta p_T)}{L_{int} \times BR \times (A \times \varepsilon)(\Delta y, \Delta p_T) \times \Delta p_T \times \Delta y}$$

- Reasonable agreement with LHCb for  $\Upsilon(1S)$  and  $\Upsilon(2S)$  at  $\sqrt{s} = 13$  TeV



[ALICE Collaboration, Eur. Phys. J. C 83, 61 (2023)]

[ALICE Collaboration, Eur. Phys. J. C 76, 184 (2016)]

[LHCb Collaboration, JHEP 07, 134 (2018)]

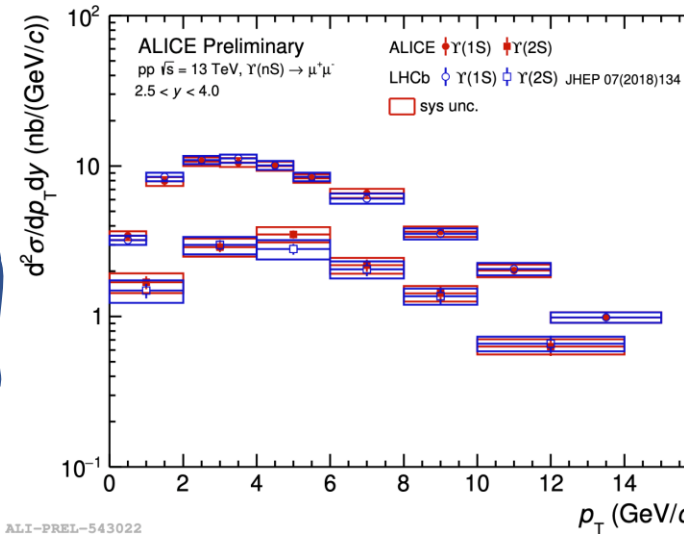
# Upsilon production in pp collisions at $\sqrt{s} = 13$ TeV

- Inclusive differential production cross section as a function of  $p_T$  and  $y$

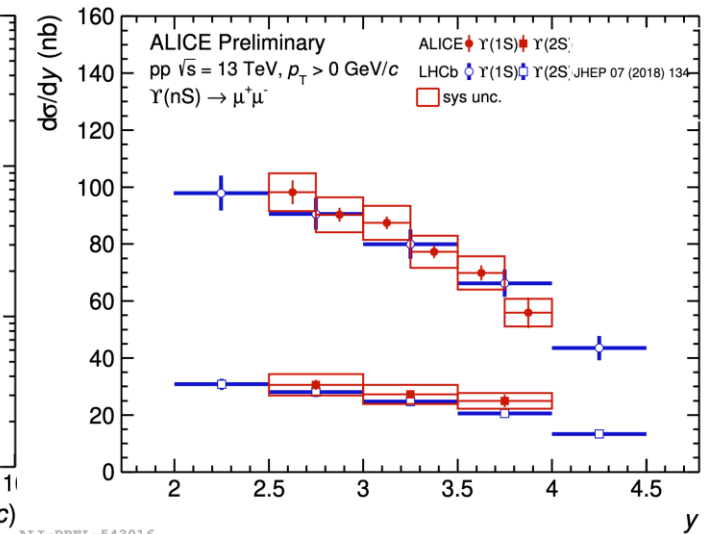
$$\frac{d^2\sigma}{dp_T dy} = \frac{N(\Delta y, \Delta p_T)}{L_{int} \times BR \times (A \times \varepsilon)(\Delta y, \Delta p_T) \times \Delta p_T \times \Delta y}$$

- Reasonable agreement with LHCb for  $\Upsilon(1S)$  and  $\Upsilon(2S)$  at  $\sqrt{s} = 13$  TeV
- $\Upsilon(1S)$  cross sections at  $\sqrt{s} = 5.02, 7, 8,$  and  $13$  TeV are compared
- Clear increase of cross section with collision energy, as a function of both  $p_T$  and  $y$

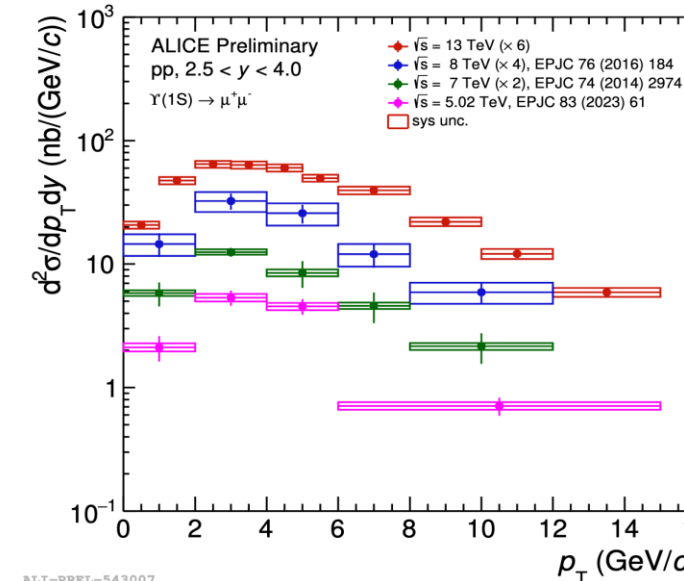
[ALICE Collaboration, Eur. Phys. J. C 83, 61 (2023)]  
 [ALICE Collaboration, Eur. Phys. J. C 76, 184 (2016)]  
 [LHCb Collaboration, JHEP 07, 134 (2018)]



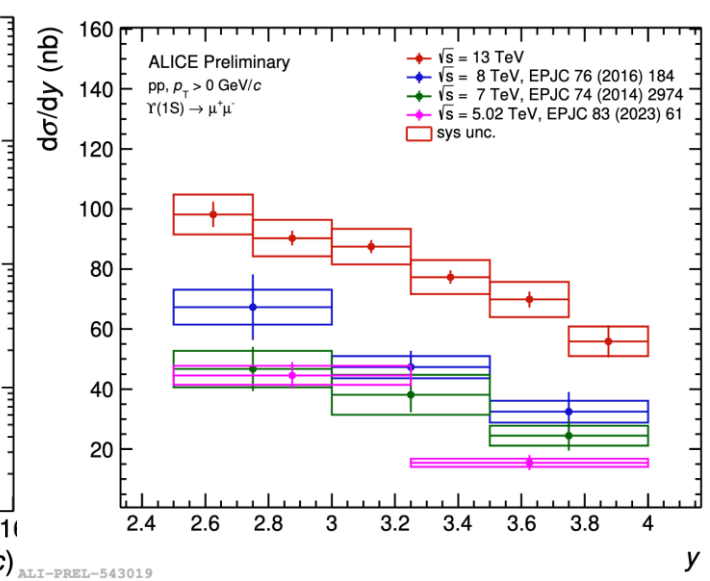
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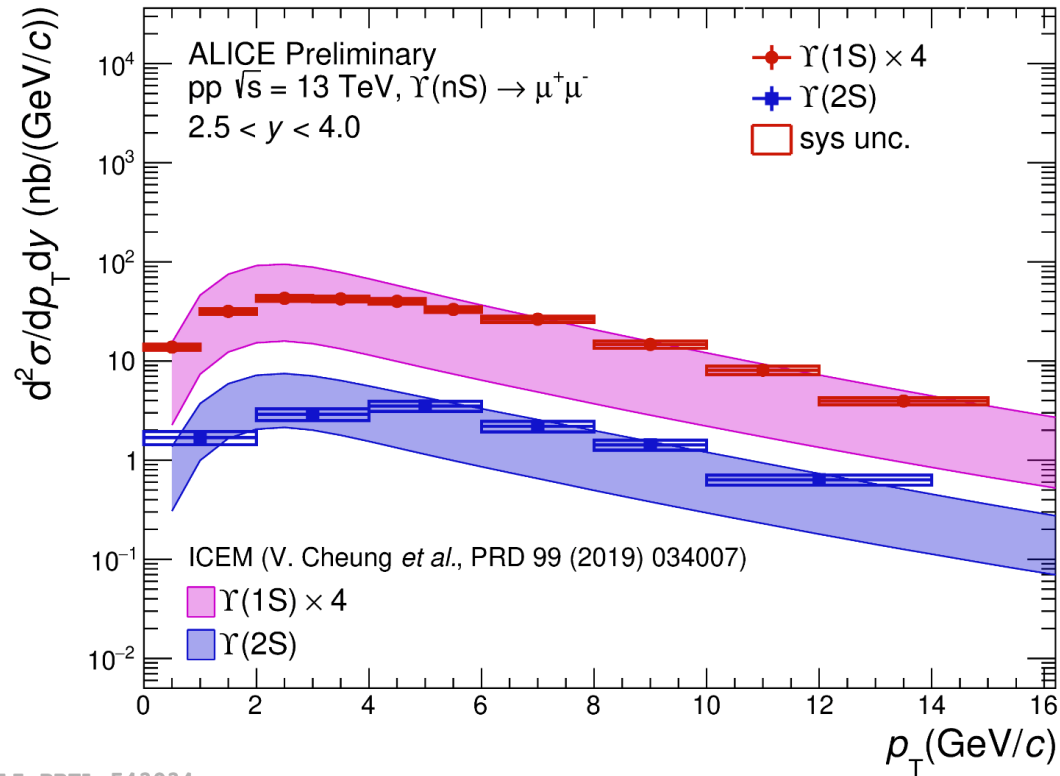
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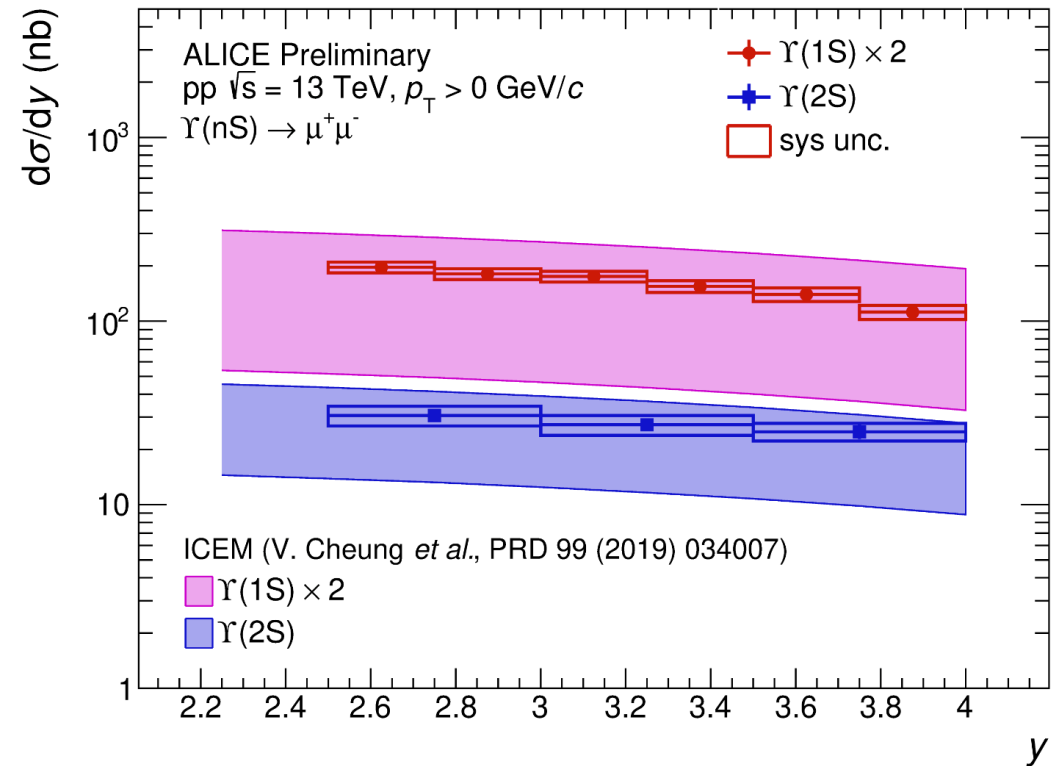
ALI-PREL-543007



ALI-PREL-543019



ALI-PREL-543034



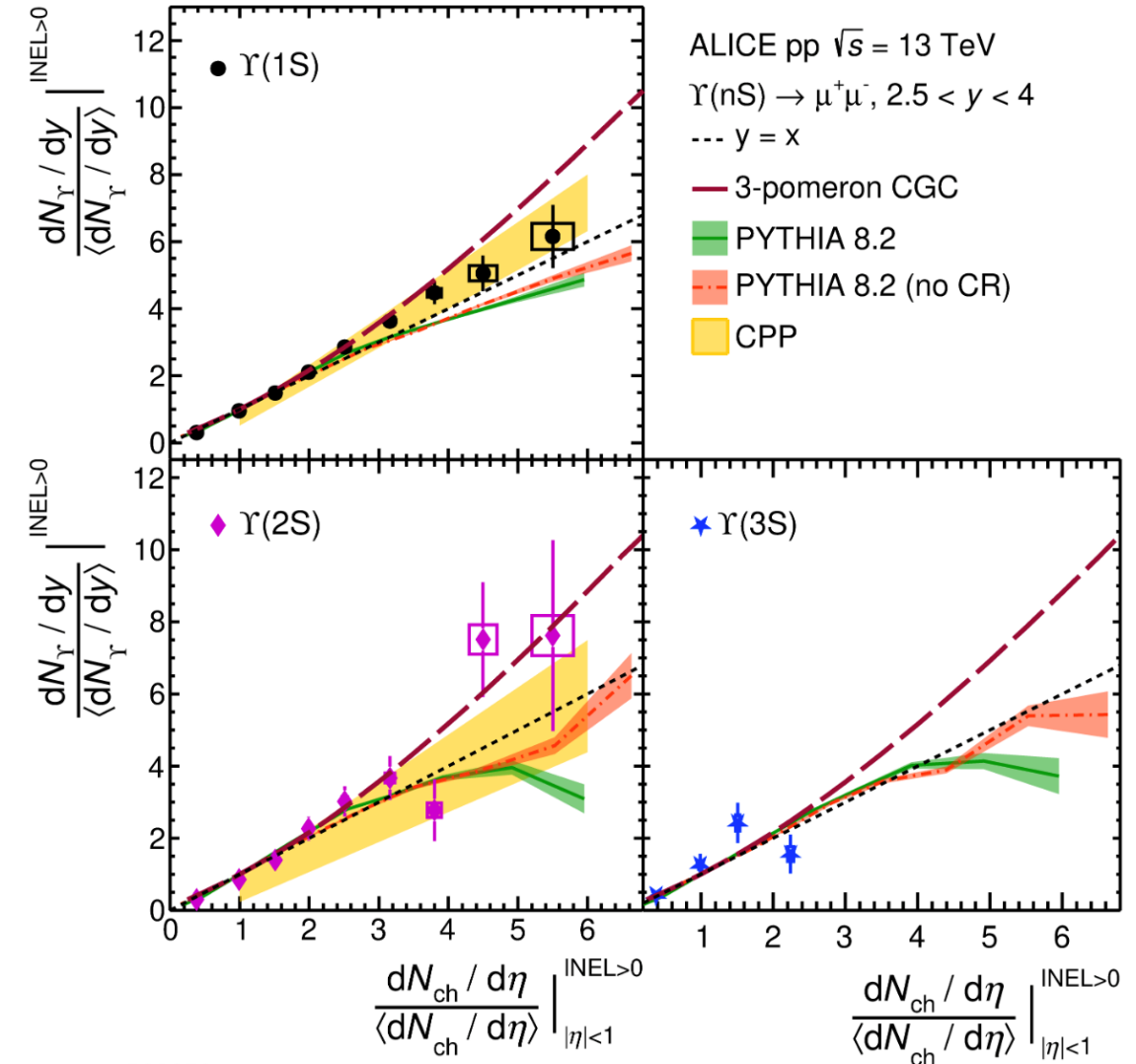
ALI-PREL-543038

- The ICEM model gives a good description of the data as a function of  $p_T$  and  $y$
- $p_T$ -differential cross section has a slight tendency to lie above the central model values
- **Polarization measurements** can help to further discriminate between production mechanisms

[V. Cheung *et al.*, Phys. Rev. D 99 (2019) 034007 (ICEM)]

# Yield vs. multiplicity in pp collisions

- The self-normalized yield of  $\Upsilon(nS)$  states are **compatible with a linear trend**
- PYTHIA 8 with and w/o CR can describe up to  $\sim 4$  times the mean multiplicity
- CR impacts both multiplicity and hard probe – **weakening of correlation at large multiplicity**
- Coherent particle production – qualitatively describe the observation within large uncertainties



ALI-PUB-589271

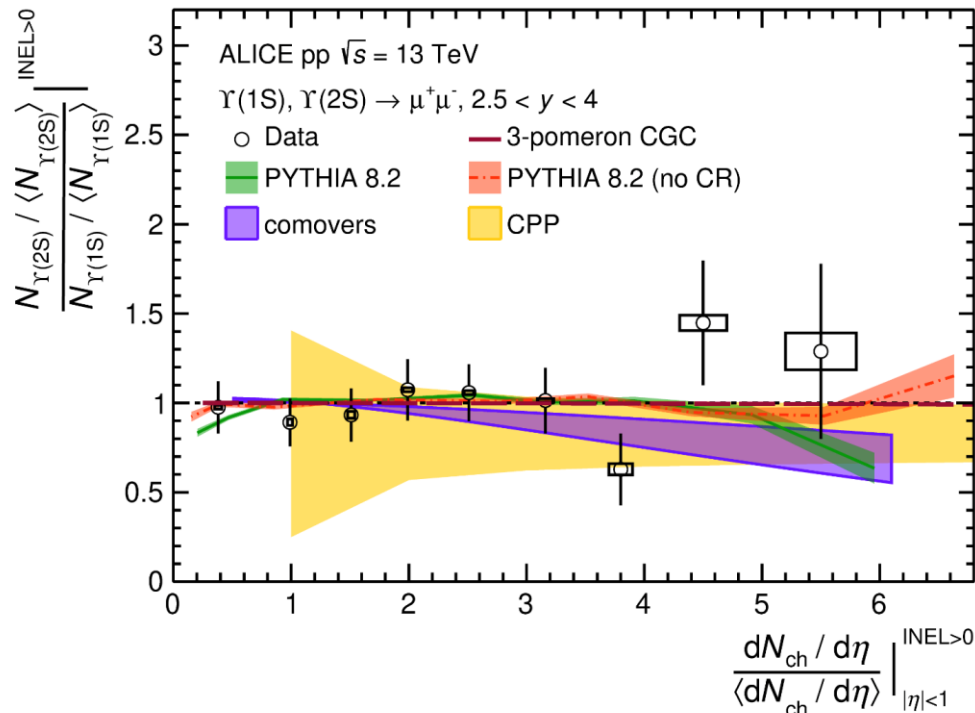
[ALICE Collaboration, Nucl. Phys. B. 1011, 116786 (2025)]

[CPP - B.Z. Kopeliovich et al, Phys. Rev. D 101 (2020) 054023]

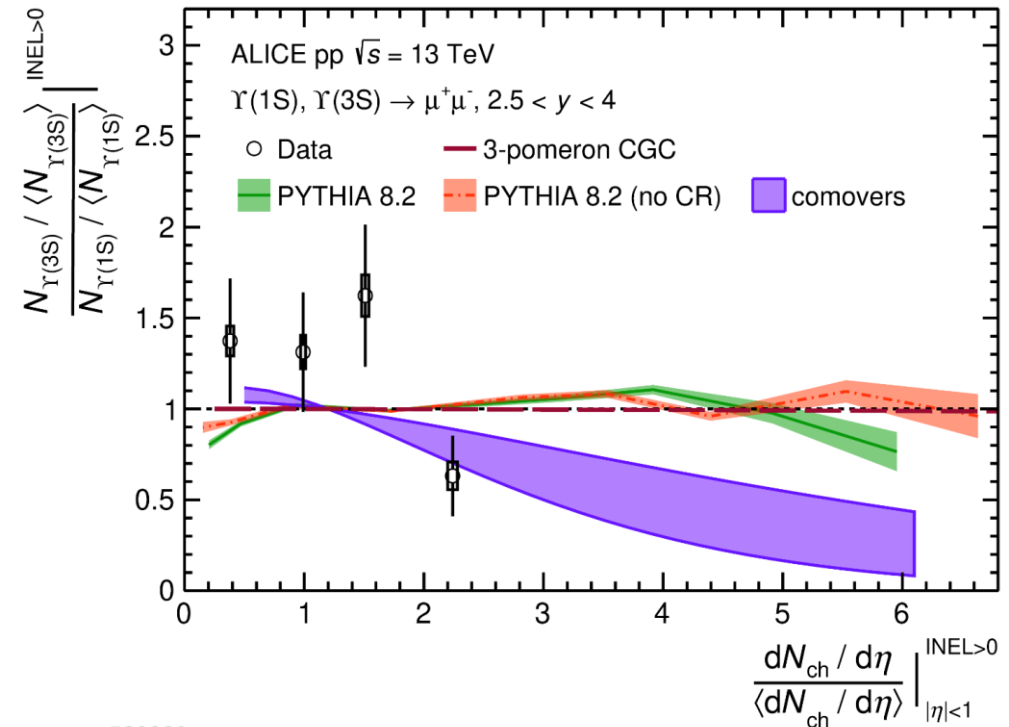
[3 Pomeron CGC - E. Levin et al, Eur. Phys. J. C 80 (2020) 560]

[PYTHIA 8.2 - T. Sjostrand et al, Comput. Phys. Commun. 191 (2015) 159]

# Excited to ground state Upsilon ratios



ALI-PUB-589276



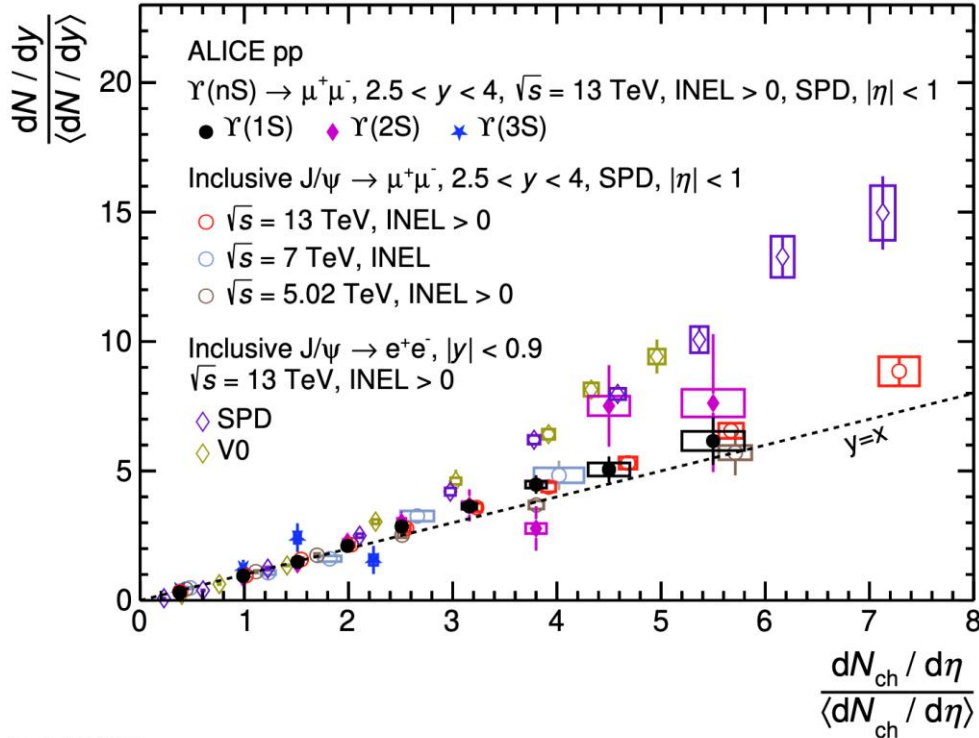
ALI-PUB-589281

[ALICE Collaboration, Nucl. Phys. B. 1011, 116786 (2025)]

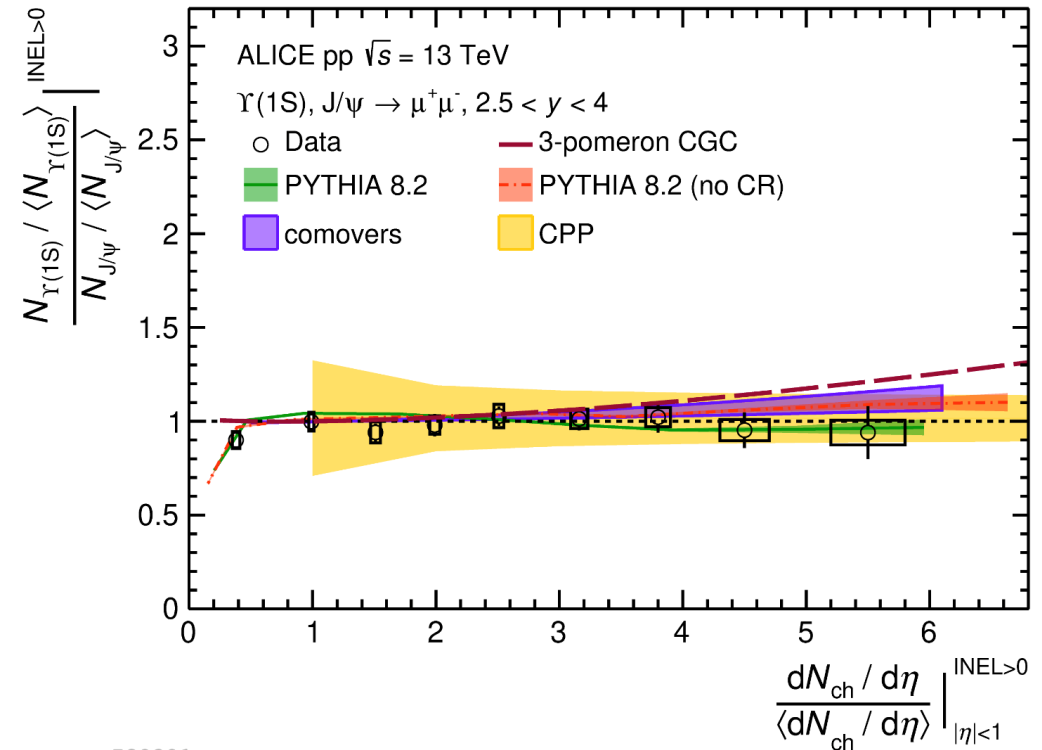
- Self-normalized excited-to-ground state ratios vs. multiplicity are **consistent with unity**
- **Comover model – dissociation of quarkonia** on interaction with final state comoving particles
- **Comover** predicts **suppression for  $\Upsilon(2S)$ ,  $\Upsilon(3S)$  states** – **requires better statistical precision to discriminate between models**

[Comover - E. G. Ferreira et al, Phys. Lett. B 749 (2015) 98-103]

# Ratios – comparison with $J/\psi$



ALI-PUB-589286



ALI-PUB-589291

- The  $\Upsilon(1S)$  self-normalized production yield presents **similar scaling to that of  $J/\psi$**
- Also observed from the double ratio of  $\Upsilon(1S)$ -to- $J/\psi$  self-normalized yield
- **Double ratio is close to unity - no modification of the correlation with respect to mass or quark content**

[ALICE Collaboration, Nucl. Phys. B. 1011, 116786 (2025)]

[ALICE Collaboration, JHEP 06, 015 (2022)]

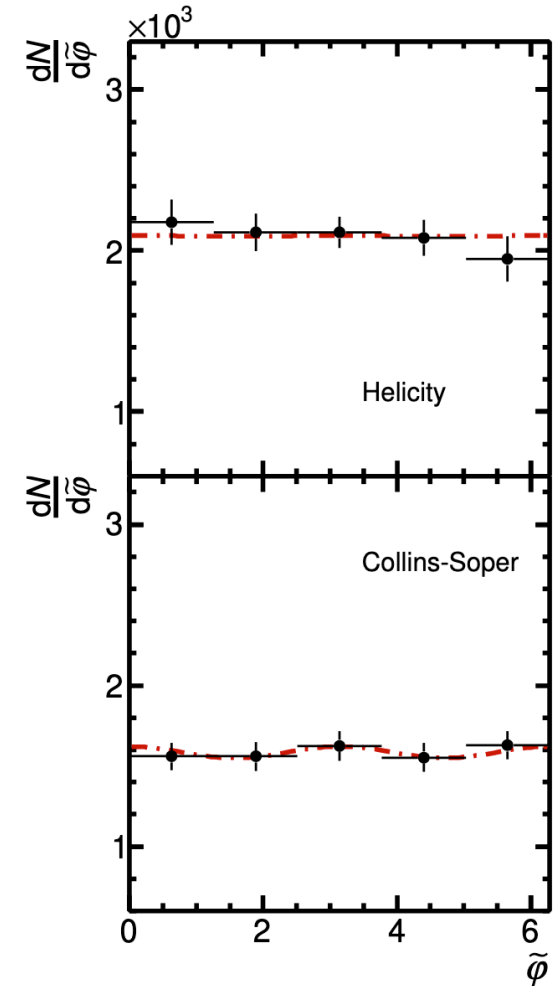
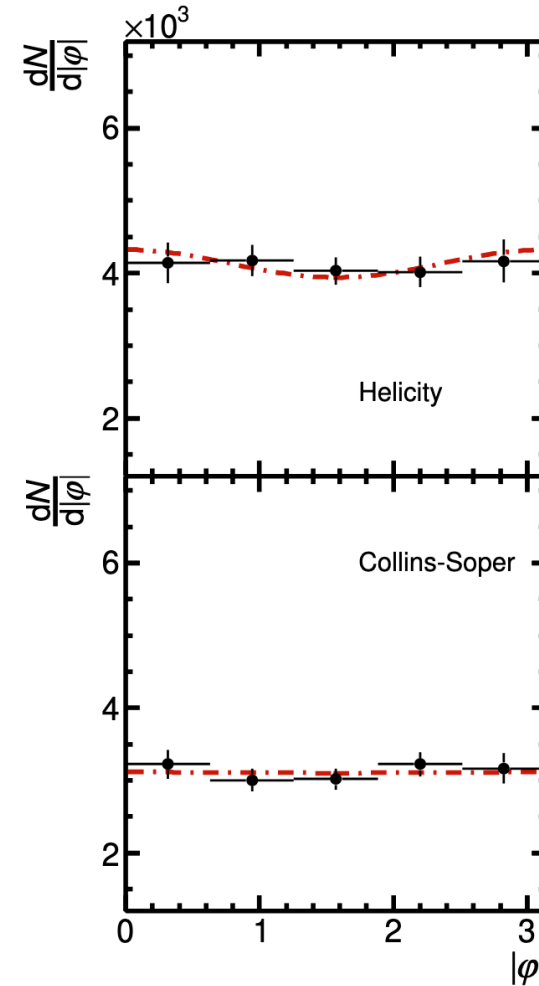
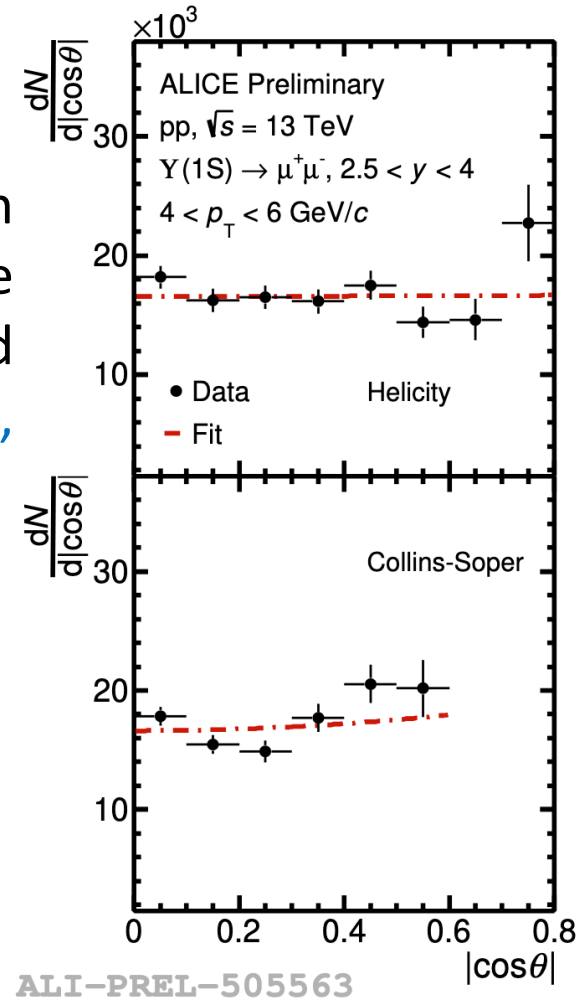
# Upsilon polarization measurements in pp collisions at $\sqrt{s} = 13$ TeV

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Determination of polarization parameters by fitting the functions to the corrected angular distributions for  $\cos\theta$ ,  $\varphi$  and  $\tilde{\varphi}$  in

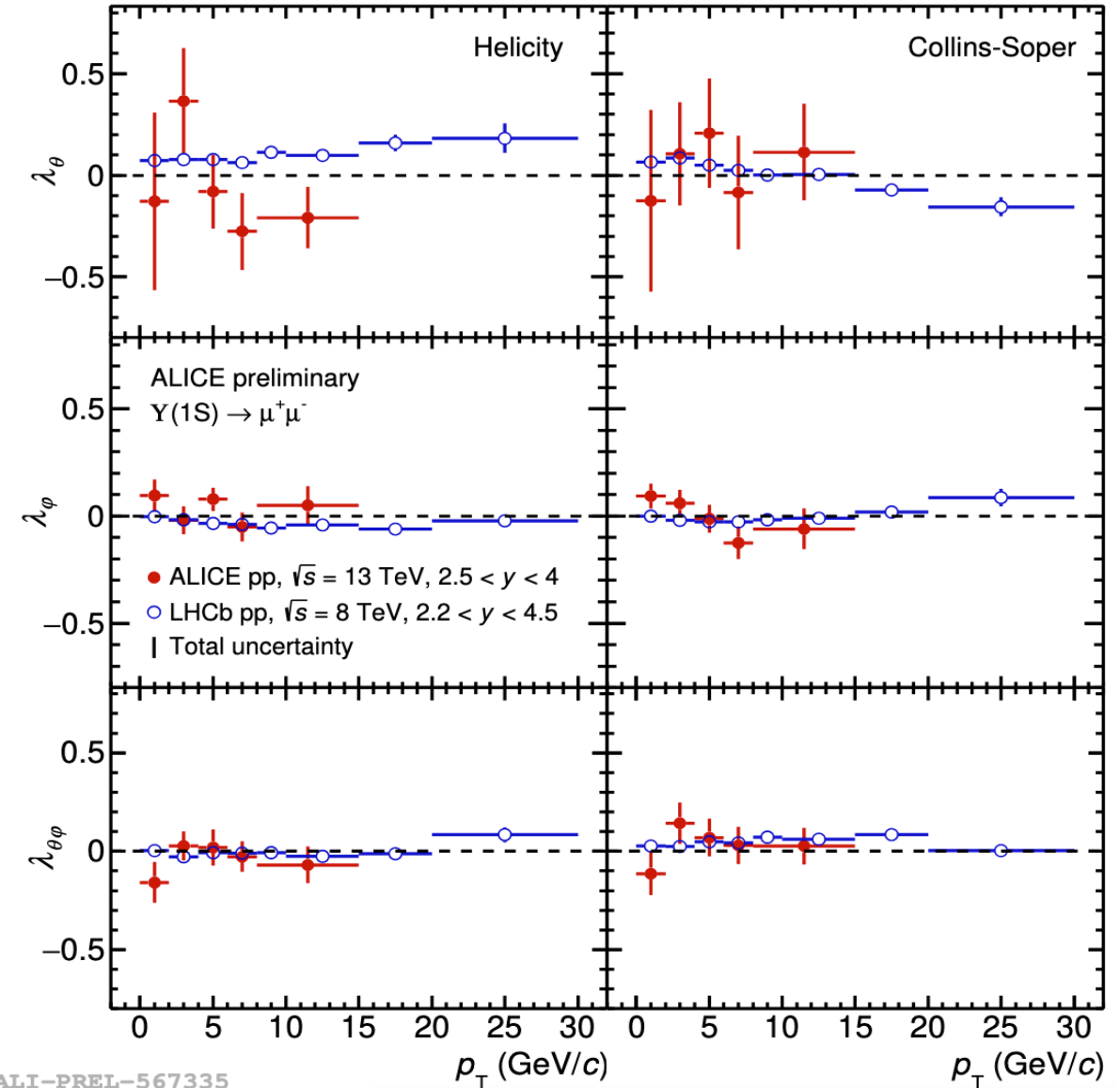
- **Helicity**
- **Collins-Soper frame**

(For  $4 < p_T < 6$  GeV/c)



# Polarization measurements in pp collisions at $\sqrt{s} = 13$ TeV

- The **polarization parameters** are obtained as a function of  $p_T$  for  $\Upsilon(1S)$  at  $\sqrt{s} = 13$  TeV in both Helicity and Collins-Soper frame
- All the polarization parameters ( $\lambda_\theta$ ,  $\lambda_\phi$ ,  $\lambda_{\theta\phi}$ ) are **compatible with zero within uncertainties**
- **Consistent with the LHCb results** at  $\sqrt{s} = 8$  TeV within large uncertainty
- Investigation with large data sample is required to produce the precise results



ALI-PREL-567335

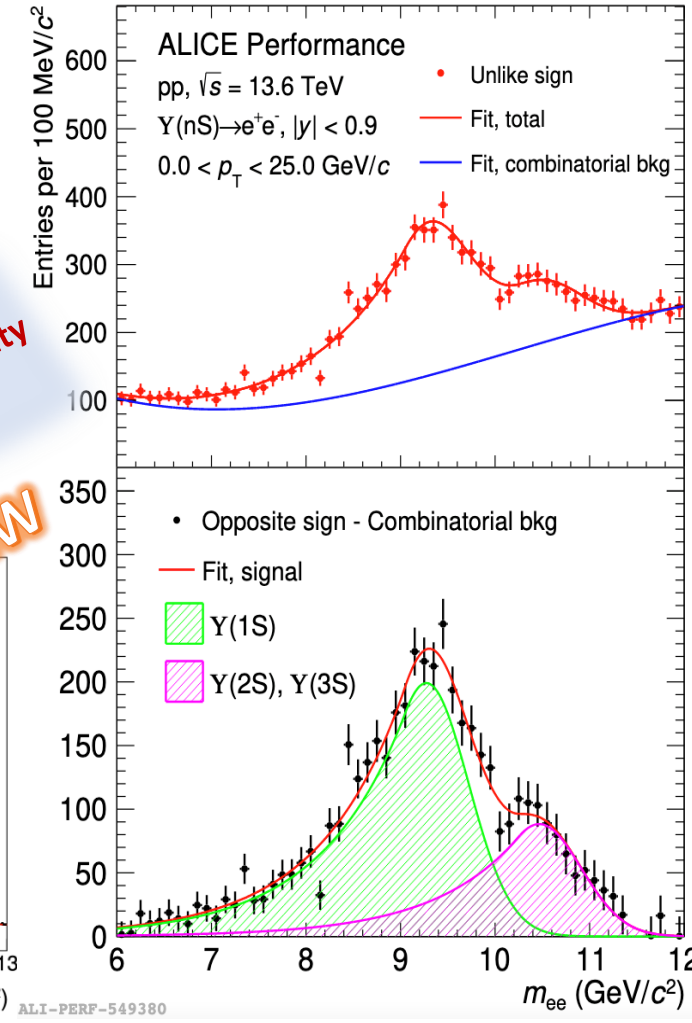
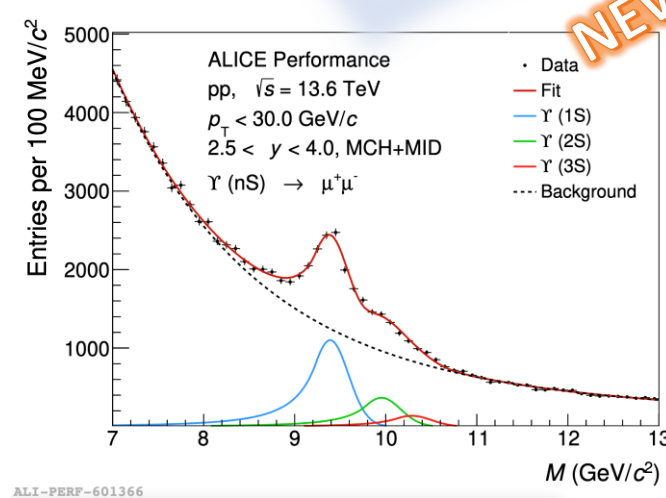
# Summary & Outlook

- ALICE performed  $\Upsilon(nS)$  production cross sections and  $\Upsilon(1S)$  polarization in pp collisions at  $\sqrt{s} = 13$  TeV
- The  $p_T$  and  $y$ -differential production cross sections are in **good agreement** with the measurements by LHCb as well as with theoretical model in the forward rapidity
- **Self-normalized yield** of  $\Upsilon(nS)$  states are observed to be compatible with a **linear trend**
- The  **$\Upsilon(1S)$  polarization** at  $\sqrt{s} = 13$  TeV is **compatible with zero** within uncertainties
- ALICE is currently performing **bottomonium production/polarization measurements** at both mid- and forward rapidity using **Run 3 data**

First look to  $\Upsilon(nS)$  at mid and forward rapidity from Run 3 data

NEW

More results to come



THANK YOU

09-09-2025

Kshitish Kumar Pradhan | Initial Stages 2025

19

