First $\psi(2S)$ measurement at midrapidity and $\Upsilon(nS)$ cross section at forward rapidity in pp collisions at $\sqrt{s} = 13$ TeV

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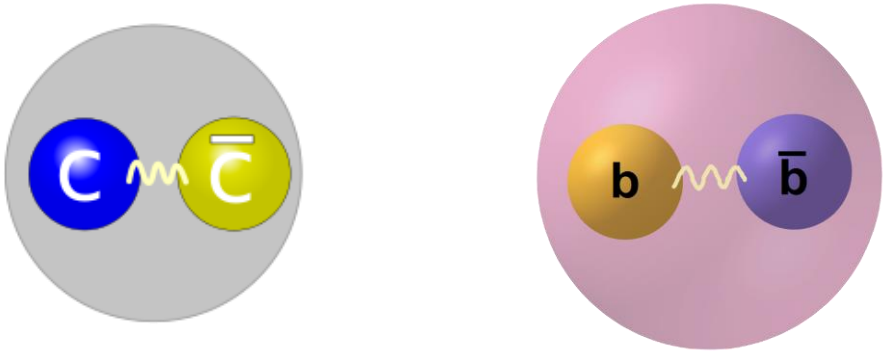
University of Science and Technology of China

16th International Workshop on Heavy Quarkonium (QWG 2024)

Introduction

- **Quarkonia: bound states of heavy quark and heavy anti-quark pairs.**
  - **Charmonia: J/ψ, ψ(2S)…**
  - **Bottomonia: ϒ(nS)**



The simplest system in QCD: “Hydrogen atom in QCD”

Introduction

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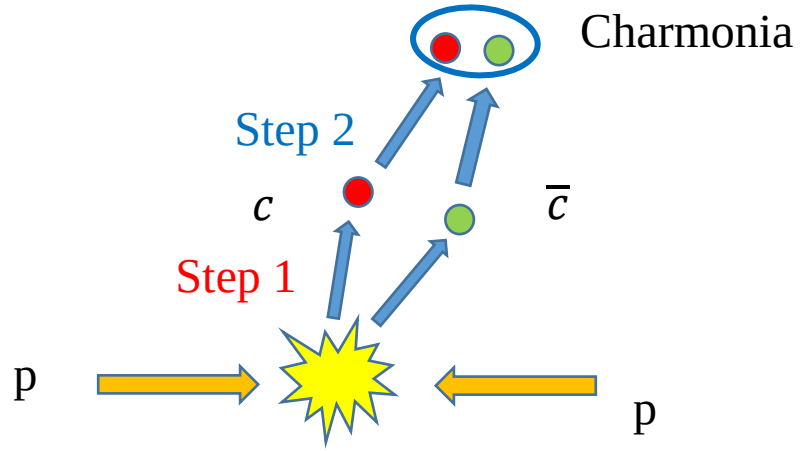
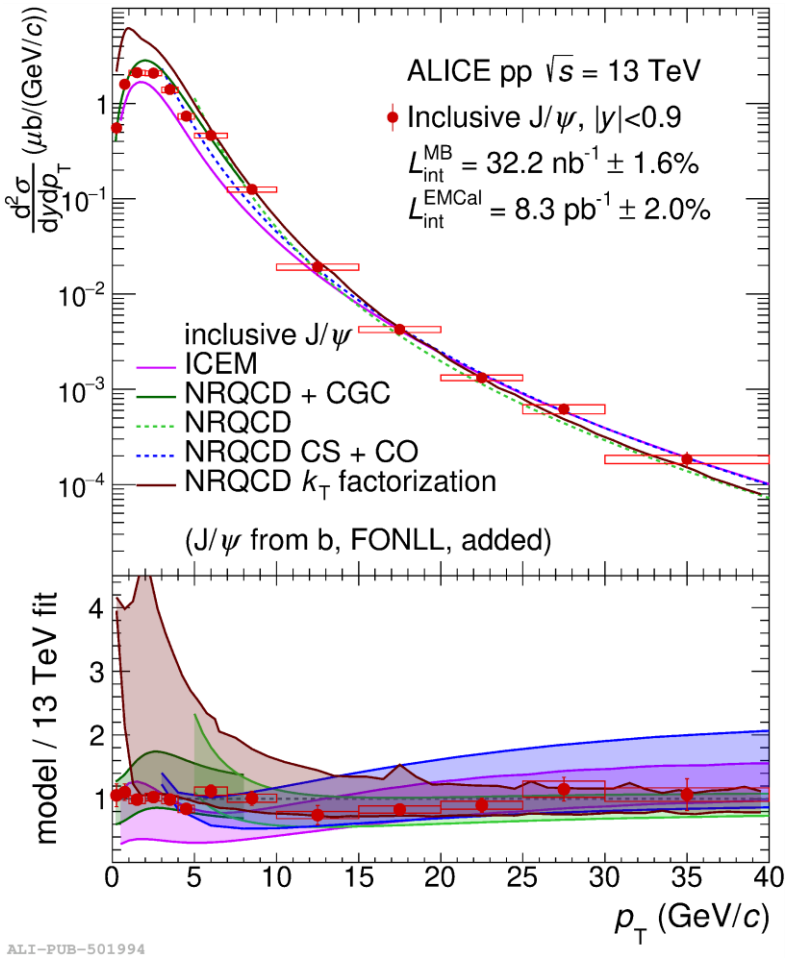
  - **Charmonia: J/ψ, ψ(2S)…**
  - **Bottomonia: ϒ(nS)**
- **The production of quarkonia in pp collisions:**
  - Heavy-quark production (perturbative QCD)
  - Formation of the quarkonium states (non-perturbative QCD)



Eur. Phys. J. C 81 (2021) 1121



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Phys.Rev.D 94 (2016) 11, 114029

Nonrelativistic QCD (NRQCD):

Phys.Rev.D 51 (1995) 1125-1171

- Long-distance effects are described by long distance matrix elements (LDMEs) in an effective field theory (NRQCD).

$$(2\pi)^3 2P_H^0 \frac{d\sigma_H}{d^3P_H} = \sum_n d\hat{\sigma}_n(P_H)\langle \mathcal{O}_n^H \rangle$$

Production of a heavy quark pair
Expansion in: α_s

Hadronization (LDMEs)
Expansion in: v (typical velocity of the heavy quark)

Improved Color Evaporation Model (ICEM):

- A fixed fraction to become ψ if the invariant mass of $c\bar{c}$ pair is below the D-meson threshold.
- Momentum shift due to soft particles emission in hadronizaiton process.

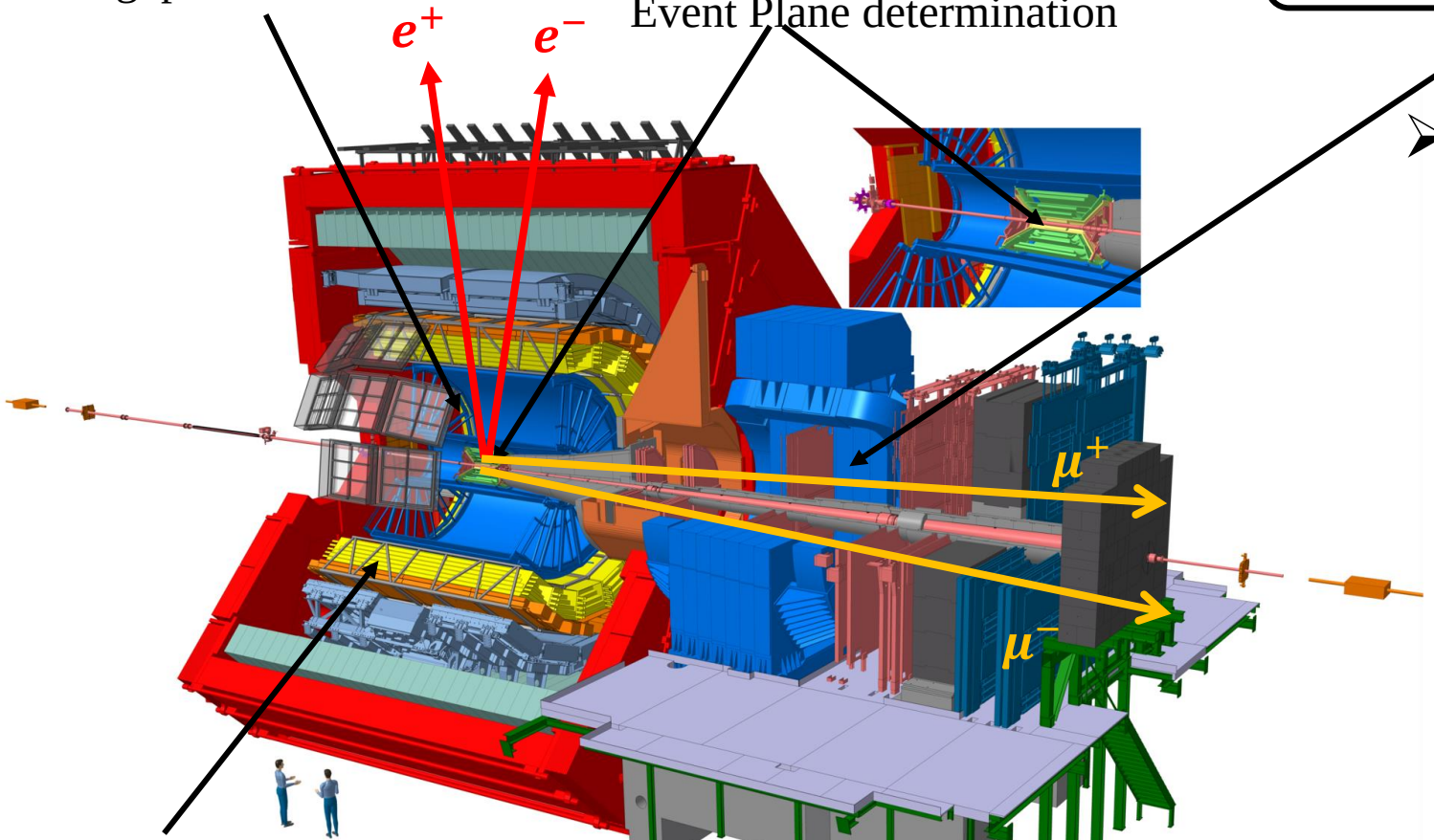
$$\frac{d\sigma_\psi(P)}{d^3P} = F_\psi \int_{M_\psi}^{2M_D} d^3P' dM \frac{d\sigma_{c\bar{c}}(M,P')}{dM d^3P'} \delta^3\left(P - \frac{M_\psi}{M}P'\right)$$

Quarkonium reconstruction with ALICE (Run 2)

Time Projection Chamber
Tracking, particle identification

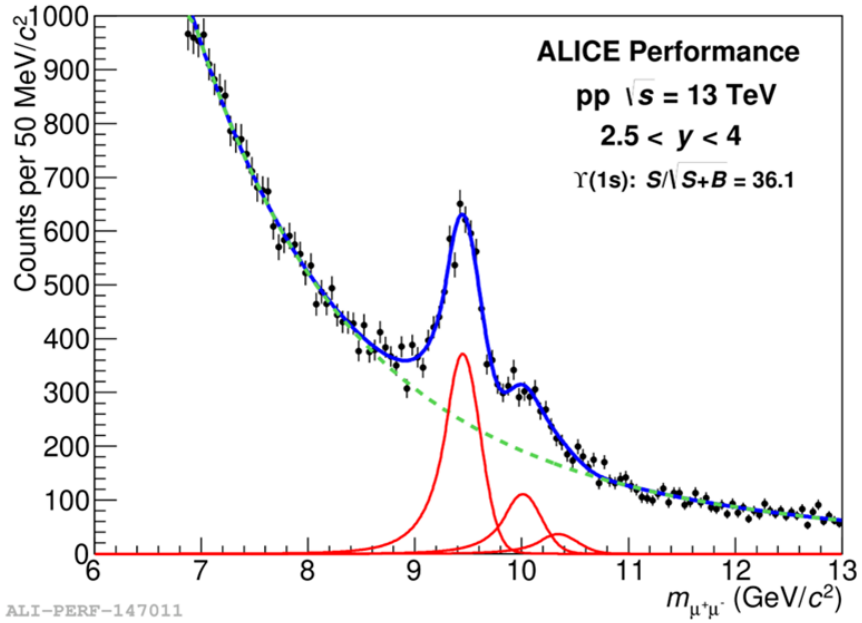
Inner Tracking System
Tracking, vertex reconstruction,
Event Plane determination

Muon Spectrometer
Trigger and tracking for muons



Transition Radiation Detector
Triggering, PID

- Inclusive quarkonium:
  - Muon spectrometer ($\mu^+\mu^-$, 2.5 < y < 4)
    - J/ψ, ψ(2S), ϒ(nS) down to p_T = 0



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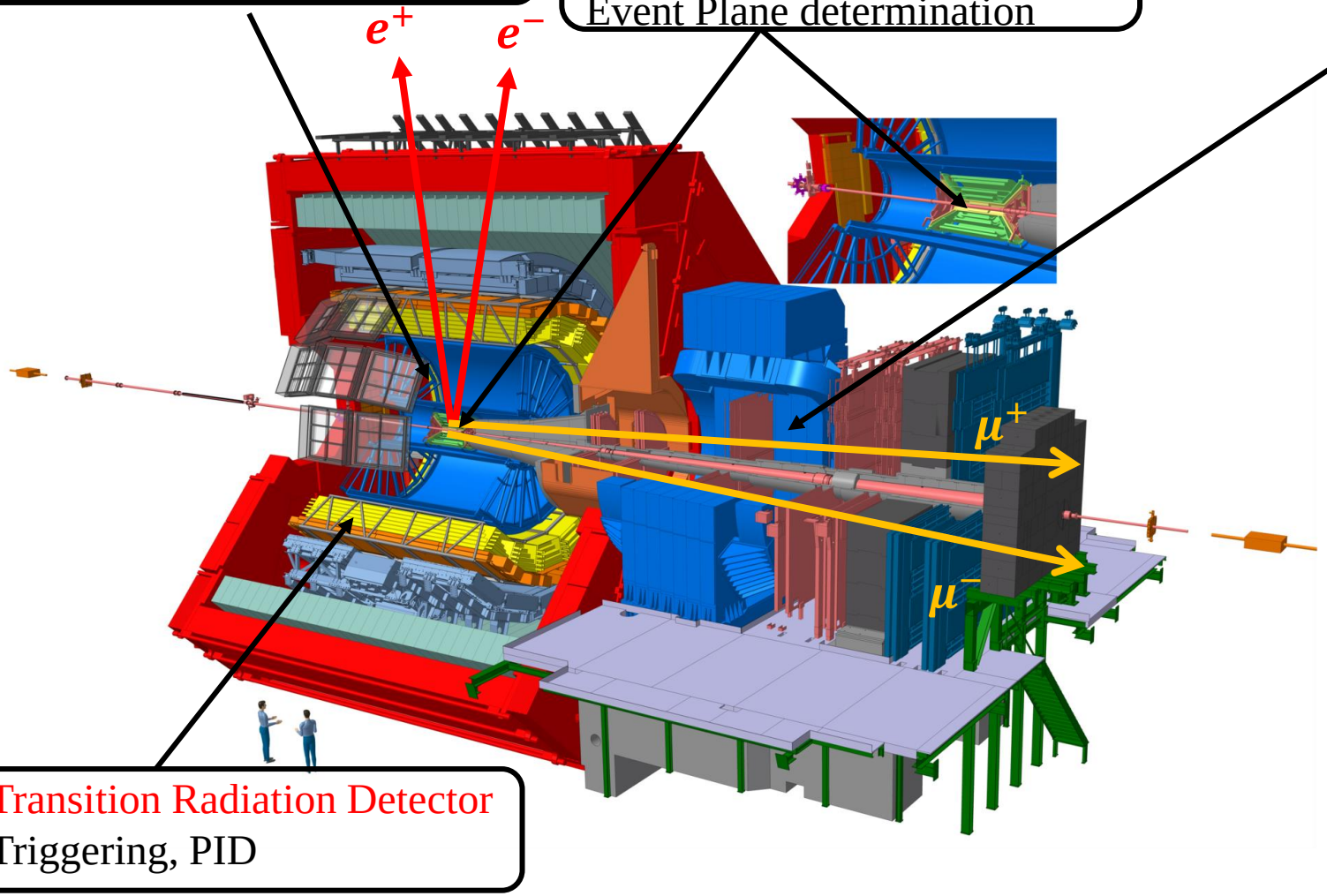
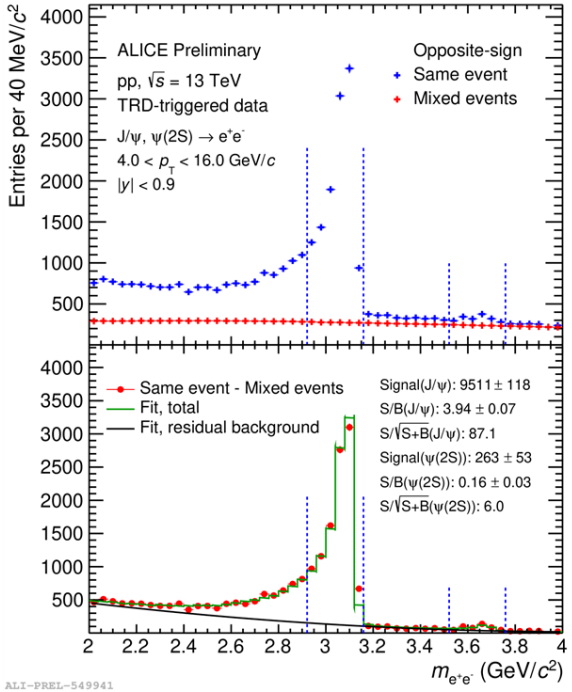
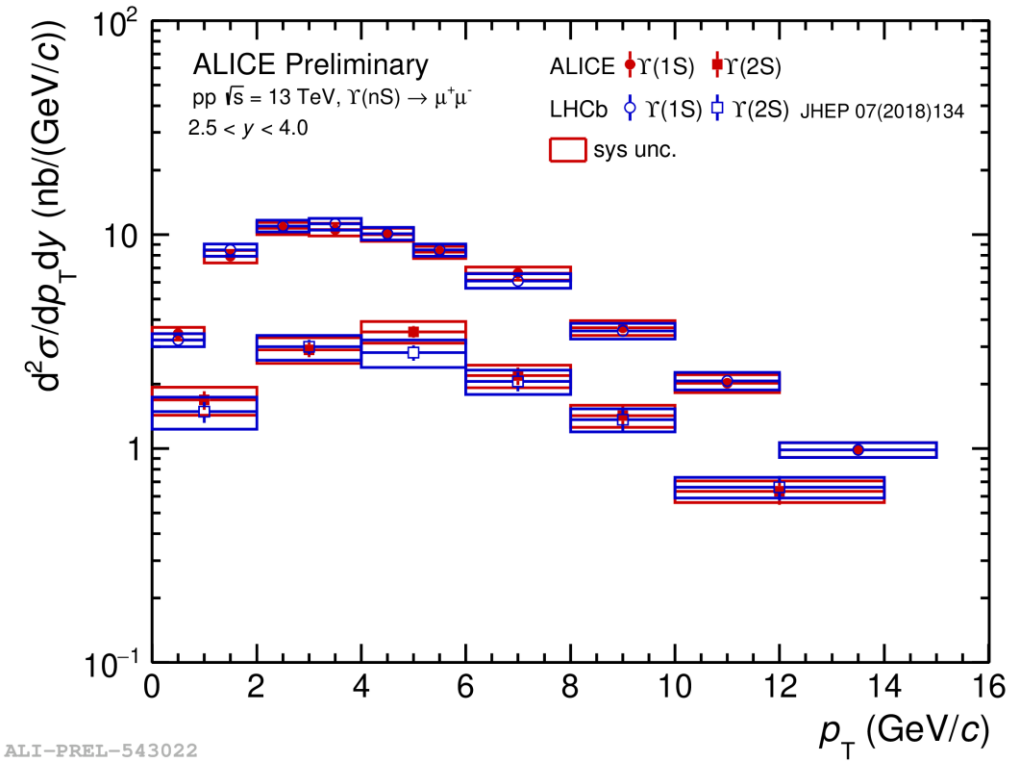


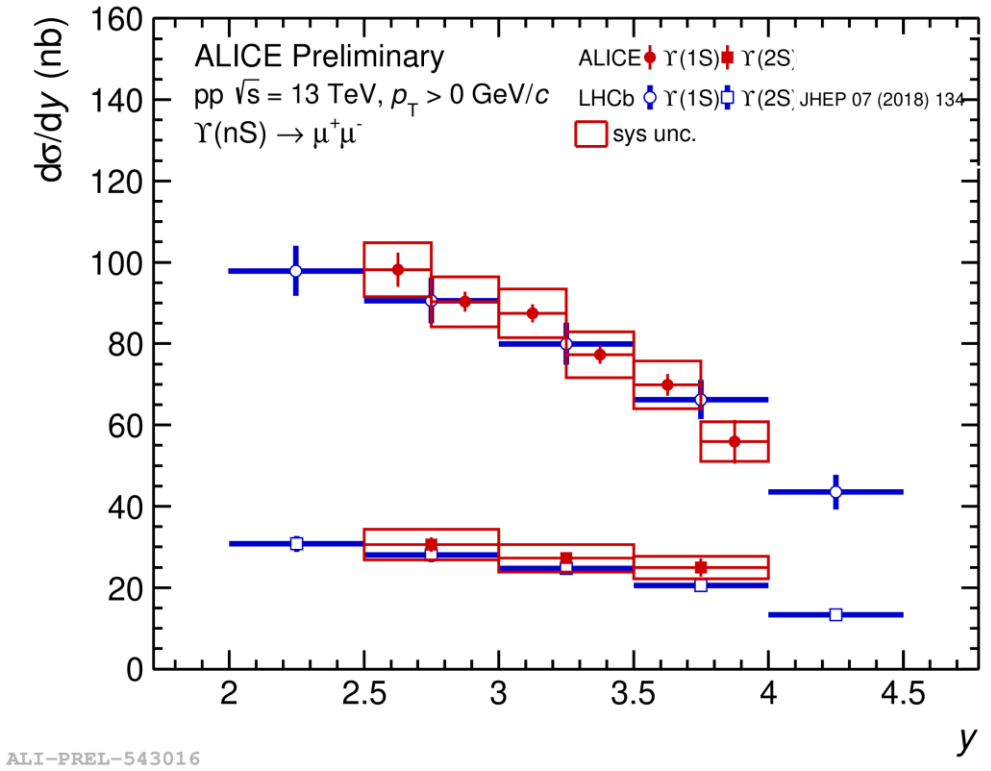
Transition Radiation Detector
Triggering, PID

- Inclusive quarkonium:
  - Central barrel (e^+e^-, |y|<0.9)
    - J/ψ down to p_T = 0
    - ψ(2S) (p_T > 4 GeV/c)



Υ(nS) cross section



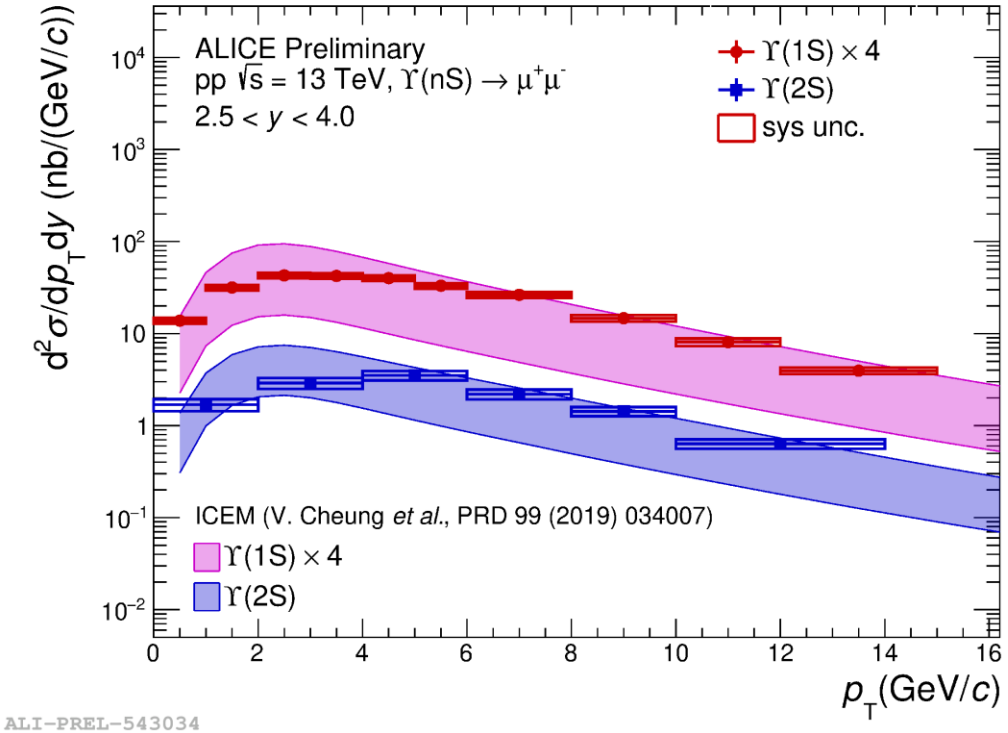


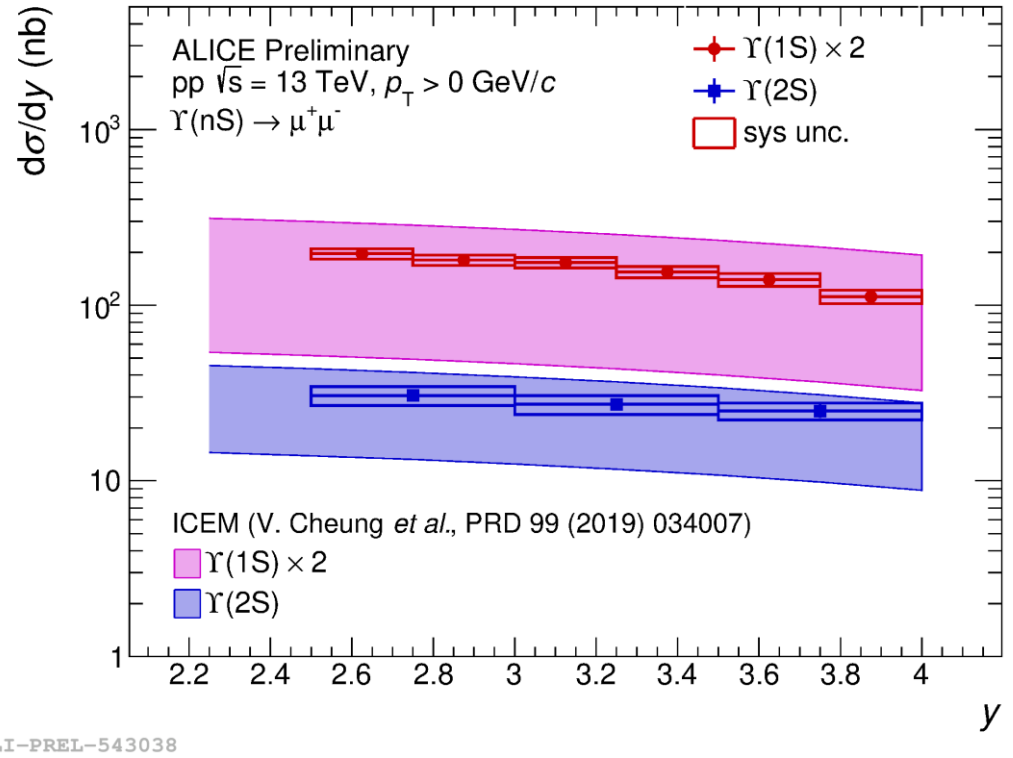
LHCb: *JHEP* 07 (2018) 134

- The cross sections of Υ(1S) and Υ(2S) are measured as functions of p_T and y at forward rapidity using dimuon channel in pp collisions at $\sqrt{s} = 13$ TeV.
  - The ALICE results (Red) are in agreement with results from LHCb (Blue).

Υ(nS) cross section

Phys.Rev.D 99 (2019) 3, 034007

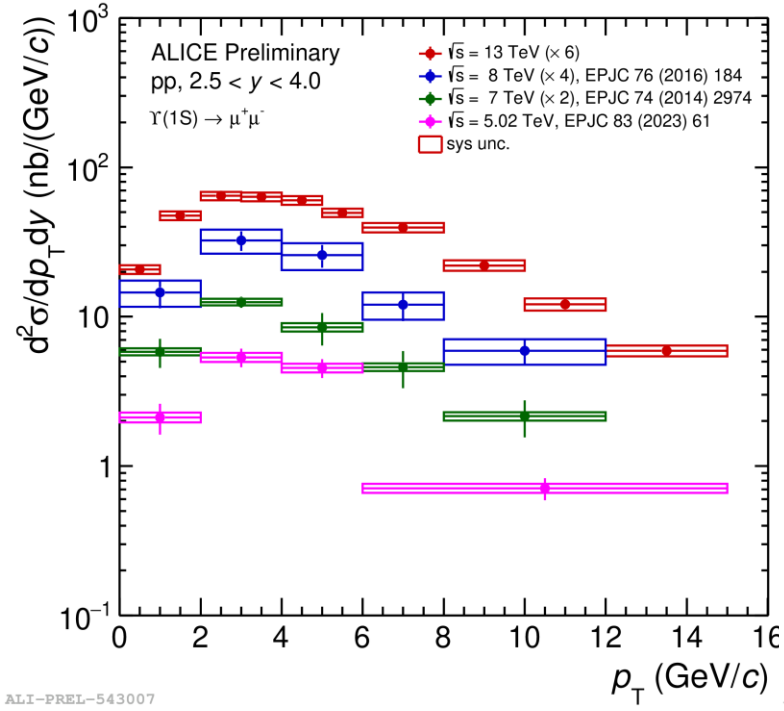


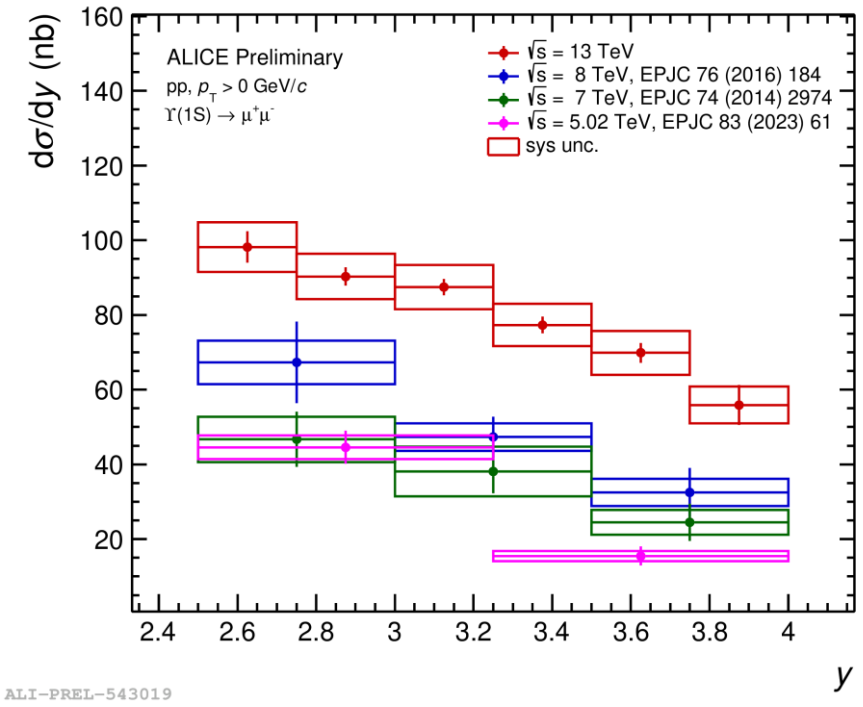


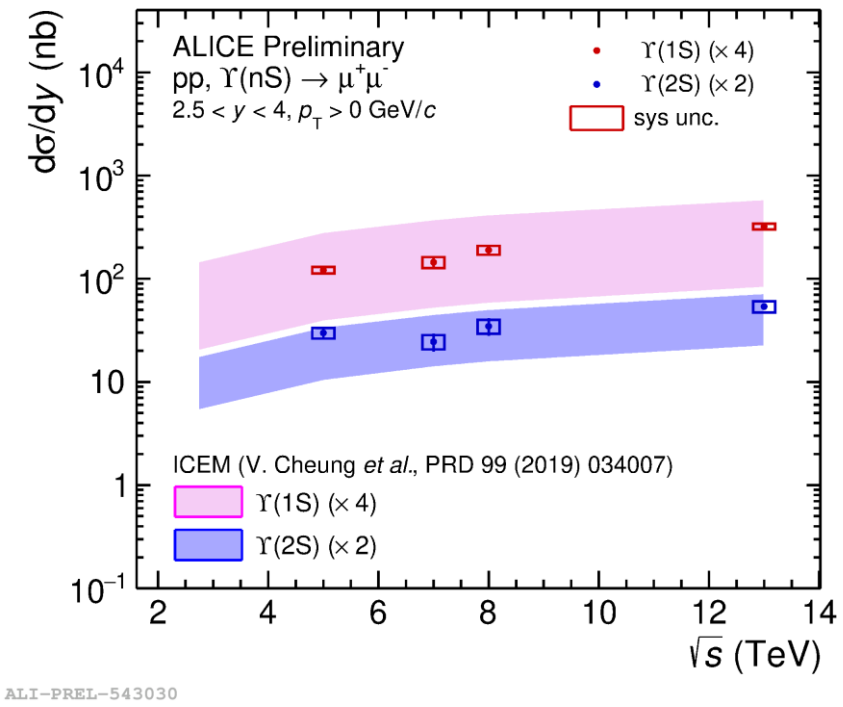
- The cross sections of Υ(1S) and Υ(2S) as functions of p_T and y are compared with ICEM calculation.
  - ICEM model can describe the p_T and y spectra at forward rapidity, but there is a large uncertainty.

ϒ(nS) cross section

Phys.Rev.D 99 (2019) 3, 034007

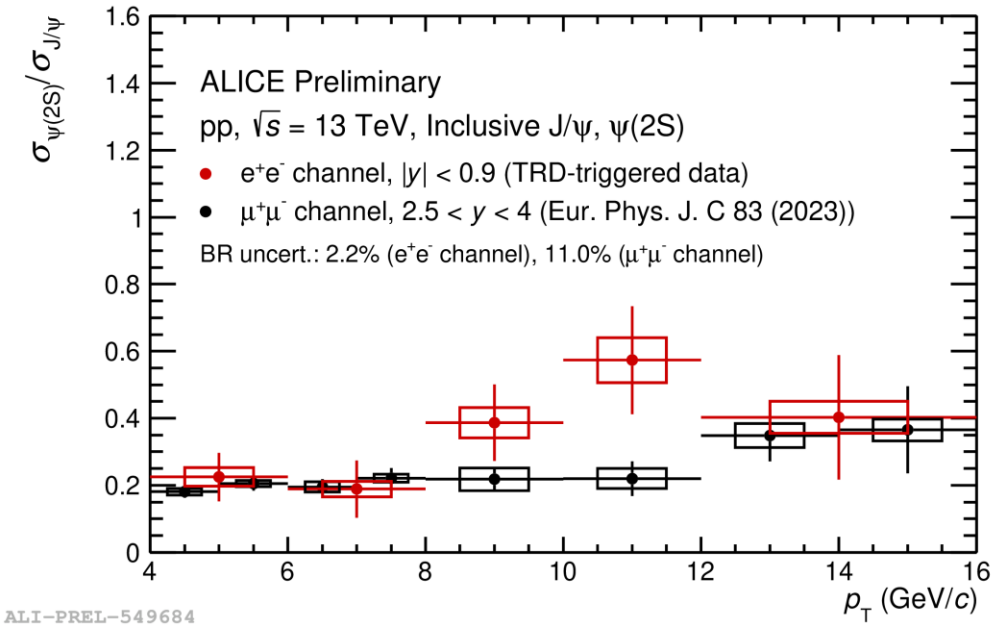


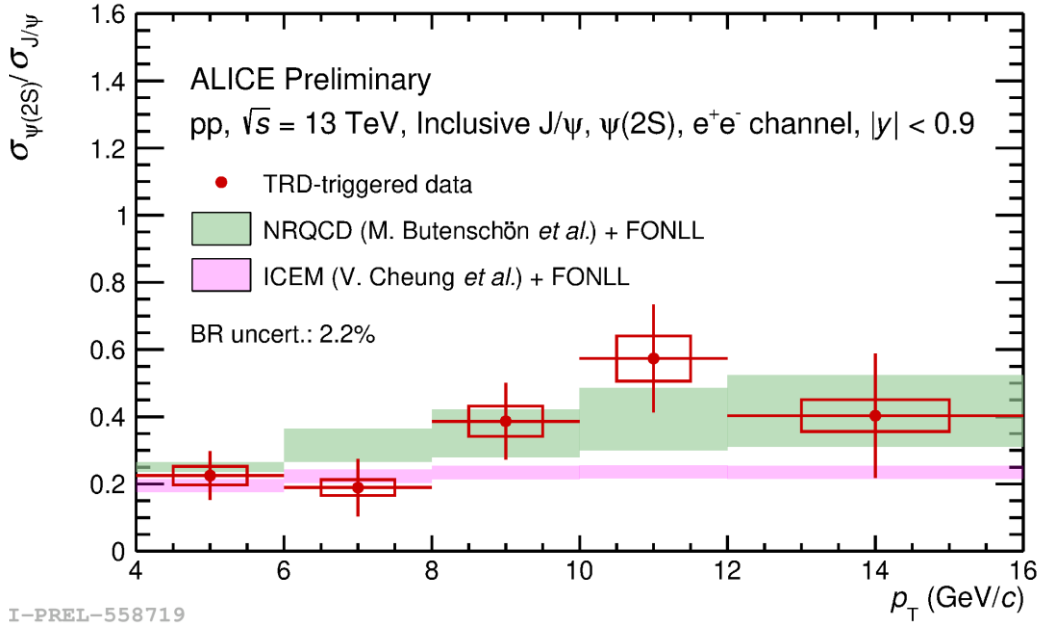




- The cross sections of ϒ(1S) at different collision energies are shown as functions of p_T and y.
- ICEM model can describe the energy dependence of the production of ϒ(nS).

ψ(2S)-to-J/ψ ratio



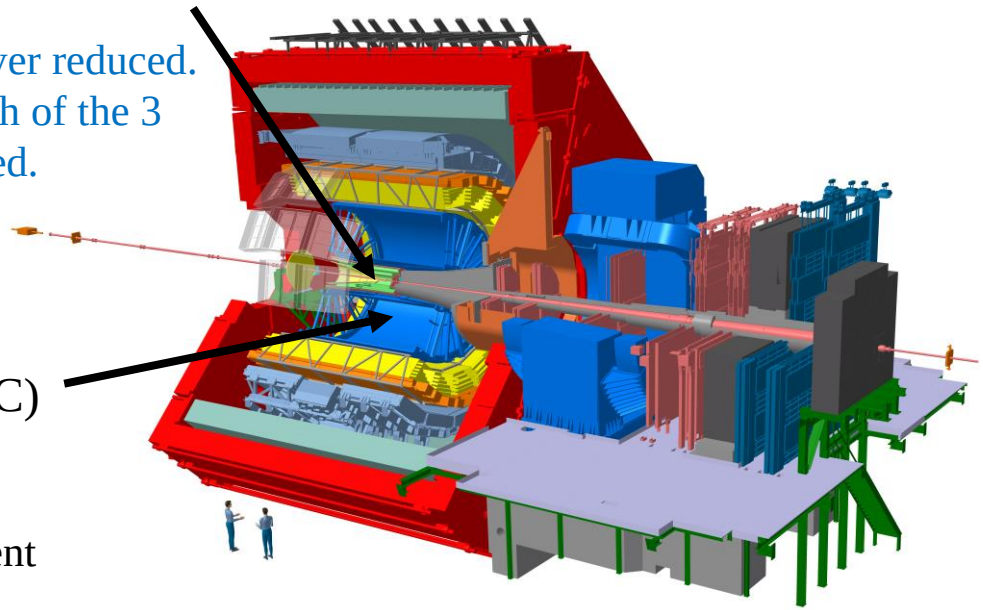


Eur. Phys. J. C 83 (2023) 61
Phys.Rev.Lett. 106 (2011) 022003.
Phys.Rev.D 94 (2016) 11, 114029.
JHEP 10 (2012) 137.

- Results at mid- and forward-rapidity are in agreement within uncertainties.
- The ratios at midrapidity are compared with models.
  - FONLL is used to estimate the non-prompt contribution
  - The results can be reproduced within uncertainties by NRQCD and ICEM.

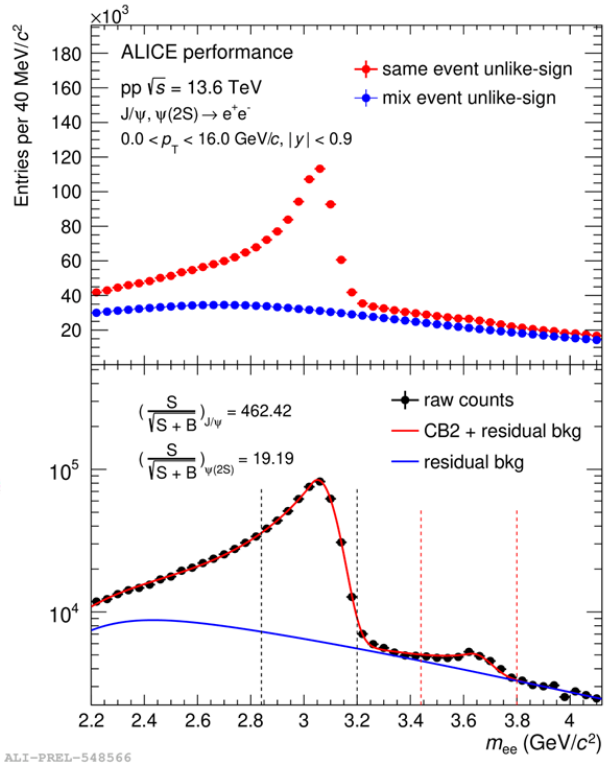
ALICE detector Run 3 upgrade (Barrel)

- Inner Tracking System (ITS)
  - Tracking
  - Vertex reconstruction
- ITS upgrade:
  - 6 layers ⟹ 7 layers equipped with Monolithic Active Pixel Sensors (MAPS).
  - Radius of innermost layer reduced.
  - Material budget for each of the 3 innermost layers reduced.
- Time Projection Chamber (TPC)
  - Tracking
  - Particle identification
  - Momentum measurement
- TPC upgrade:
  - Readout chambers replaced with Gas Electron Multiplier (GEM) chambers.



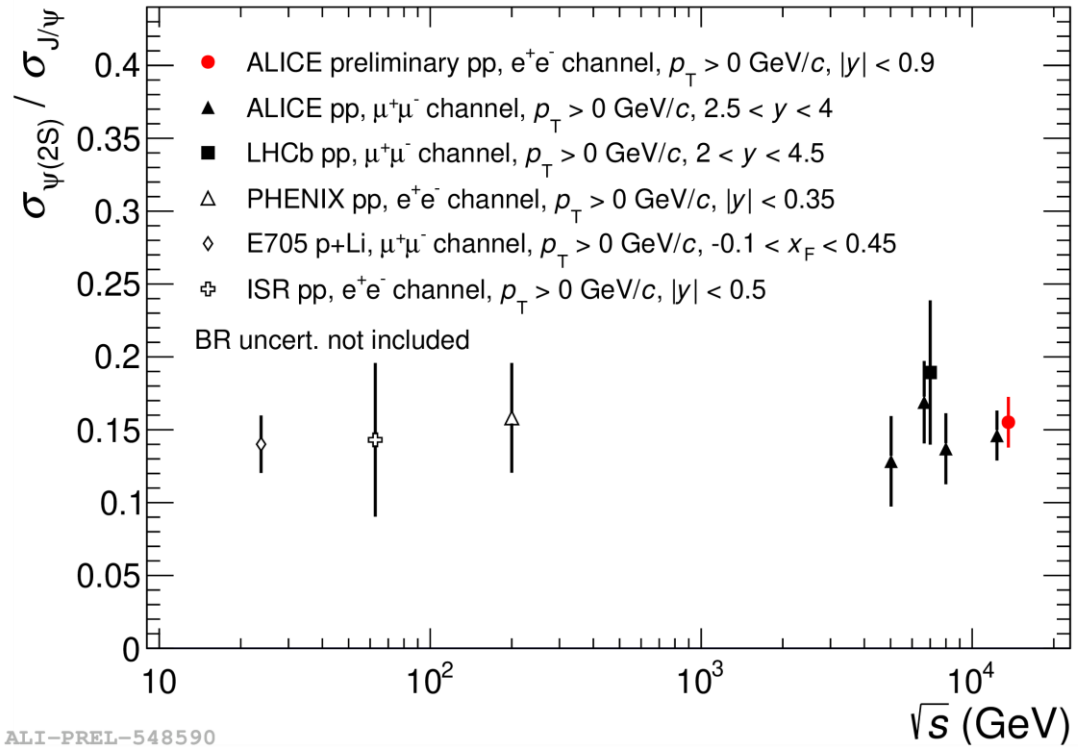
Enable continuous readout of Pb–Pb events at an interaction rate up to 50 kHz (~10^2 w.r.t. run 2).

- Inclusive ψ(2S) can be reconstructed in e^+e^- channel at midrapidity ($|y| < 0.9$) down to $p_T = 0$.



Only Run 3 data collected in 2022 is used in this analysis.

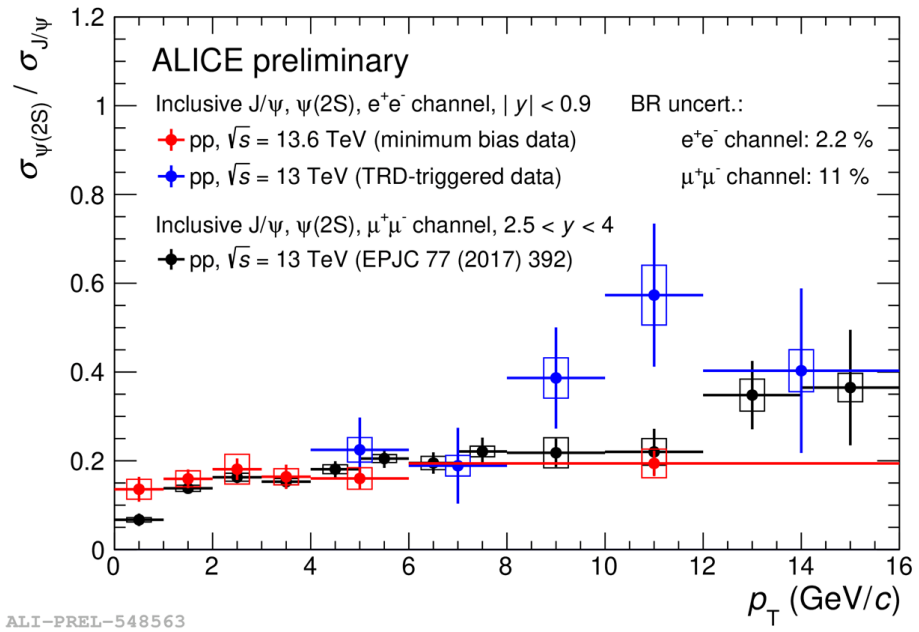
ψ(2S)-to-J/ψ ratio

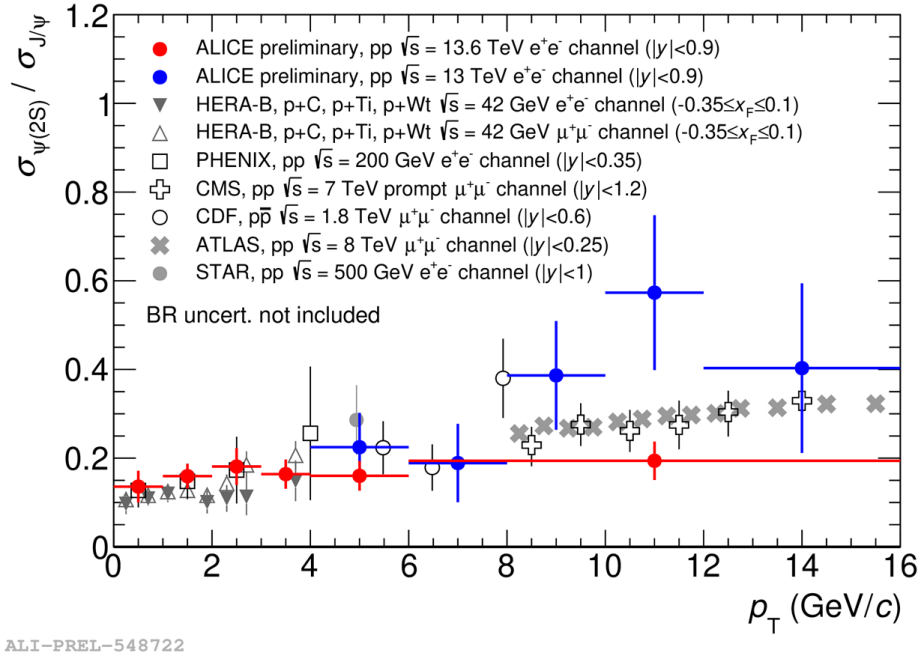


Eur. Phys. J. C 83 (2023) 61.
J. Phys. G 40 (2013) 045001.
Phys. Rev. D 85 (2012) 092004.
Phys.Rev.Lett. 70 (1993) 383-386.
Nucl. Phys. B 142 (1978) 29.

- The result (red point) is shown together with existing results from ALICE at forward rapidity and from other experiments.
  - The uncertainty is reduced because of the improvement of statistics.
  - No significant energy and rapidity dependence observed.

ψ(2S)-to-J/ψ ratio

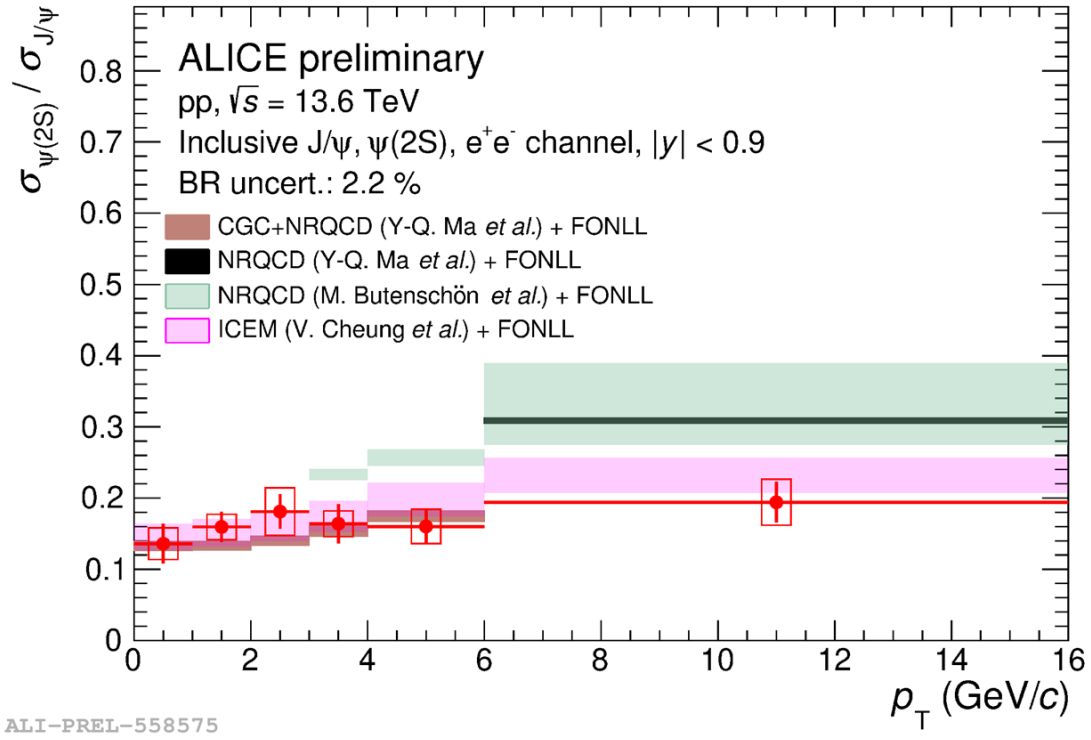


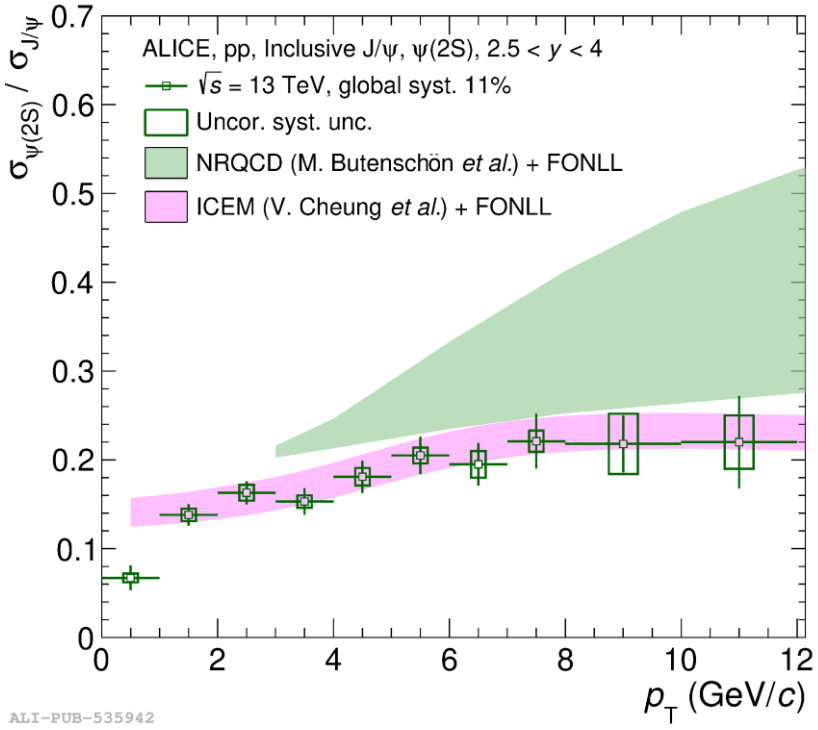


Eur.Phys.J.C 77 (2017) 392.
Eur.Phys.J.C 49 (2007) 545-558.
Phys. Rev. D 85 (2012) 092004.
JHEP 02 (2012) 011.
Phys.Rev.Lett. 79 (1997) 572-577.
Eur.Phys.J.C 76 (2016) 5, 283.
Phys. Rev. D 100 (2019) 052009.

- The results (red points) are shown together with existing results from ALICE (left) and from other experiments (right).
  - In agreement with other results.
  - No significant energy and rapidity dependence.
  - Slight p_T dependence (also expected from models).

ψ(2S)-to-J/ψ ratio



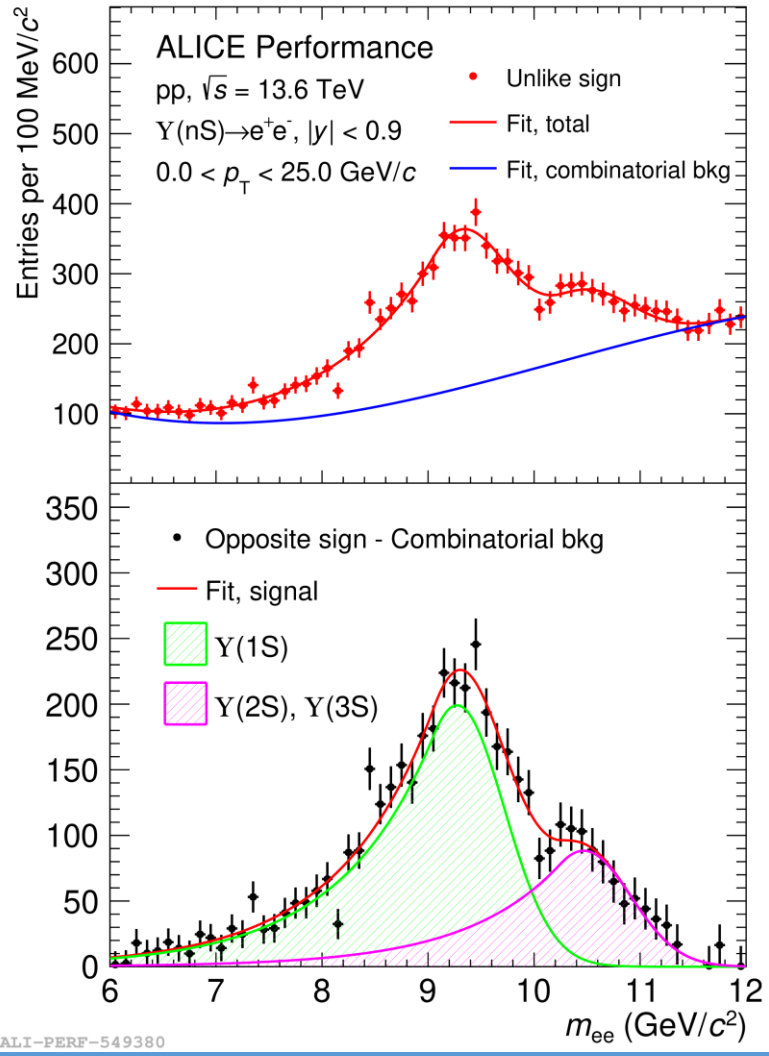


Phys.Rev.Lett. 106 (2011) 042002.
Phys.Rev.Lett. 106 (2011) 022003.
Phys.Rev.D 94 (2016) 11, 114029.
JHEP 10 (2012) 137.
Eur. Phys. J. C 83 (2023) 61

- The higher precision of the ratio allows us to distinguish between different models:
  - NRQCD overestimates the ratio.
  - CGC + NRQCD describes the ratio at low p_T up to 6 GeV/c.
  - ICEM can reproduce the data.

First ϒ(nS) results at midrapidity in Run 3

- The cross section of ϒ(nS) can be measured at midrapidity using dielectron channel in Run 3.



Conclusion

- ϒ(nS) production:
  - The p_T, y and energy dependence were measured and can be described by ICEM model.

- ψ(2S)-to-J/ψ ratio:
  - It was measured at midrapidity using TRD-triggered Run 2 data, and results with higher precision were obtained by using Run 3 data.
  - Both the CGC + NRQCD (+ FONLL) and ICEM (+ FONLL) can describe the p_T dependence of the ratio at low p_T up to 6 GeV/c. At high p_T the results can be described by ICEM (+ FONLL) within uncertainties.
  - The uncertainty of the results can be further reduced with more statistics of Run 3 data.

Thank you