Quarkonium production in pp and p-Pb collisions

Workshop on Advances, Innovations, and Future Perspectives in High-Energy Nuclear Physics

22nd October 2024

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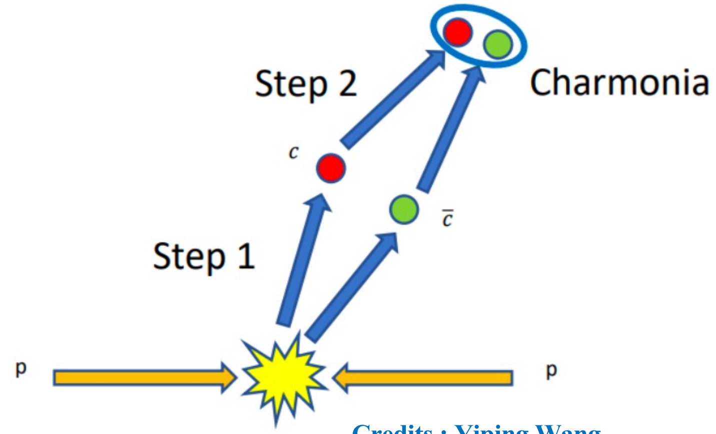
Introduction – Quarkonia in small systems

- Quarkonia are bound states of a heavy quark pair ($c\bar{c}$ or $b\bar{b}$)

- Measurements in pp collisions :
  - Reference for the measurement in p–Pb and Pb–Pb collisions
  - Study of quarkonium production mechanisms: both perturbative (i.e. $q\bar{q}$ formation) and non-perturbative (formation of the quarkonium state) QCD processes involved
    ➔Measurements of quarkonium production in pp allows to refine QCD based models

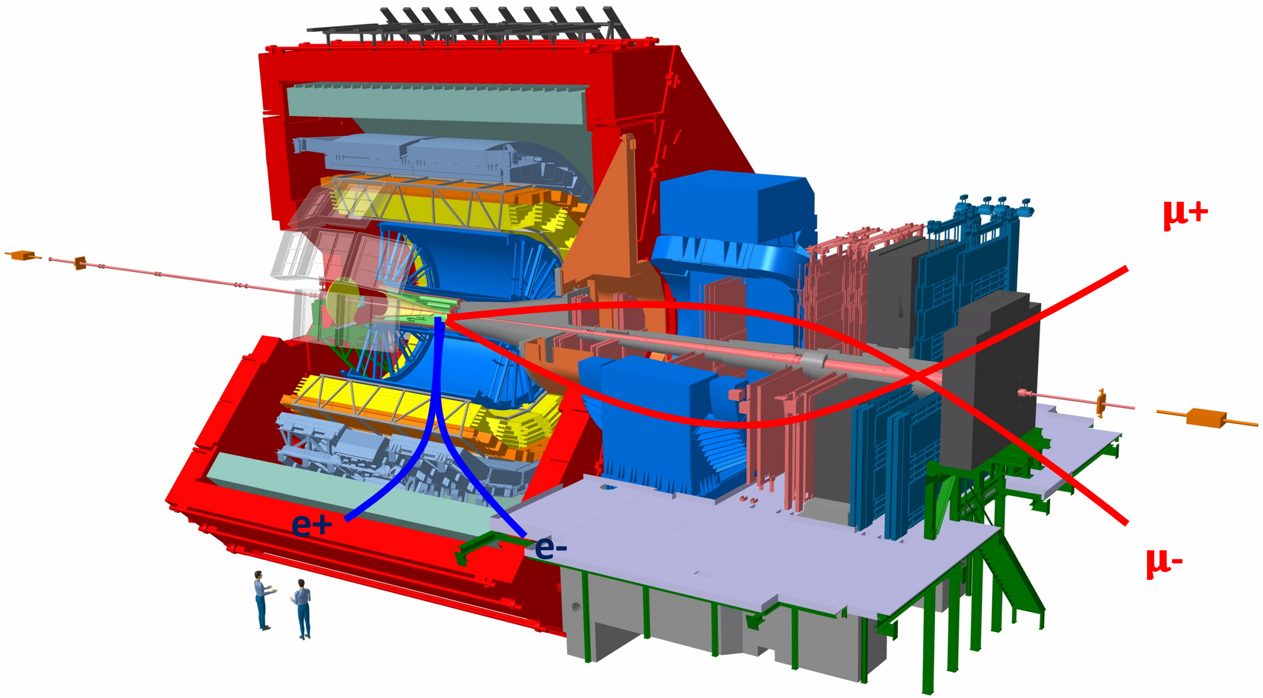


Credits : Yiping Wang

- Measurements in p–Pb collisions:
  - Investigate cold nuclear matter (CNM) effects (shadowing, coherent parton energy loss,…)
    ➔Help the interpretation of the measurements in Pb–Pb collisions

Introduction – The ALICE detector

- ALICE offers the possibility to study quarkonia in two channels



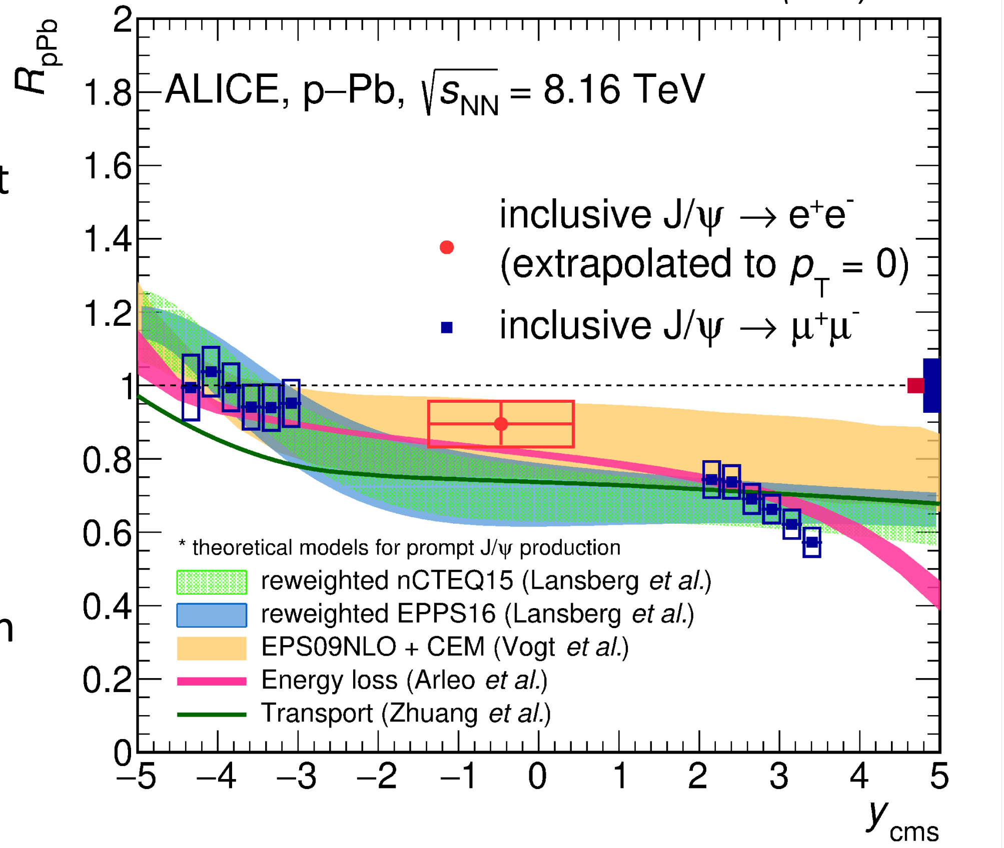
- Muon Arm :
  - J/ψ, ψ(2S), Υ(nS) → $\mu^+\mu^-$
  - Acceptance: $2.5 < y < 4.0$
  - Inclusive quarkonia down to $p_T = 0$
  - **NEW :** with MFT, separation of prompt and non-prompt quarkonia

- Central Barrel:
  - J/ψ → e^+e^-
  - Acceptance: $|y| < 0.9$
  - Inclusive quarkonia down to $p_T = 0$
  - Separation of prompt and non-prompt J/ψ down to very low p_T

J/ψ R_{pPb} at $\sqrt{s_{NN}} = 8.16$ TeV

- $R_{pPb} = \frac{dN_{pPb}/dy}{\langle N_{coll}\rangle \times dN_{pp}/dy}$
- Significant suppression at forward rapidity, no significant deviation from 1 at mid- and backward rapidity
- The p_T-integrated inclusive yield is strongly dominated by the prompt J/ψ
- Theoretical calculations, including various combinations of cold nuclear matter effects, reproduce the data within uncertainties

JHEP 07 (2023) 137



Transport : *Zhuang et al., Phys. Lett. B 765 (2017) 323–327*
Energy Loss : *Arleo et al, JHEP 10 (2014) 073*
EPS09NL0+CEM *: Vogt et al., Int.J.Mod.Phys.E 22 (2013) 1330007*
EPPS16 & nCTEQ15 reweight : *Lansberg et al, Phys. Rev. Lett. 121 no. 5, (2018) 052004*
EPP16 : *Eskola et al, Eur. Phys. J. C 77 no. 3, (2017) 163*

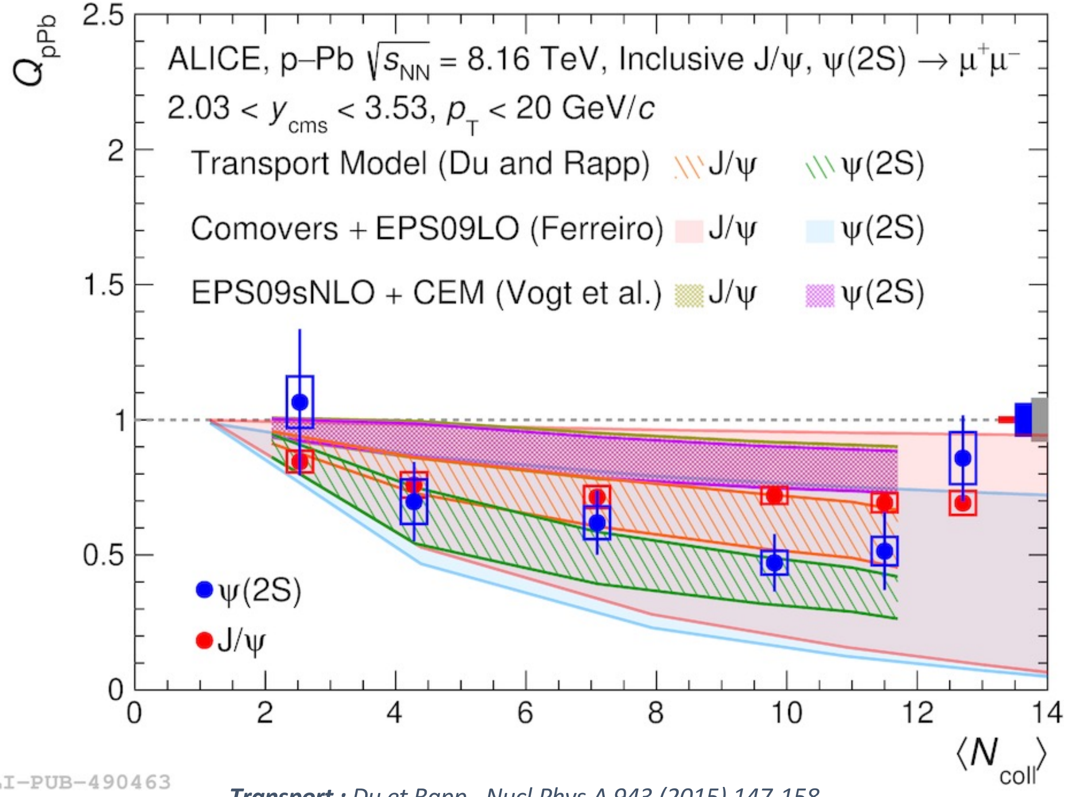
Charmonium Q_{pPb} at $\sqrt{s_{\text{NN}}} = 8.16$ TeV

- $Q_{\text{pPb}} = \frac{\mathrm{d}N_{\text{pPb}}/\mathrm{d}y}{N_{\text{coll}} \times \mathrm{d}N_{\text{pp}}/\mathrm{d}y}$

- At forward rapidity, the Q_{pPb} is similar for the ψ(2S) and the J/ψ.

- EPS09s NLO + CEM calculations fail to describe ψ(2S) behavior
- Transport Model describes both J/ψ and ψ(2S) at forward
- Comovers + EPS09LO model describes well the data within uncertainties

JHEP 02 (2021) 002



Transport : *Du et Rapp., Nucl.Phys.A 943 (2015) 147-158*
Comover+EPS09LO : *Ferreiro et al., Phys.Lett.B 749 (2015) 98-103*
EPS09sNLO + CEM : *Vogt et al., Phys.Rev.C 87 (2013) 5 054910*

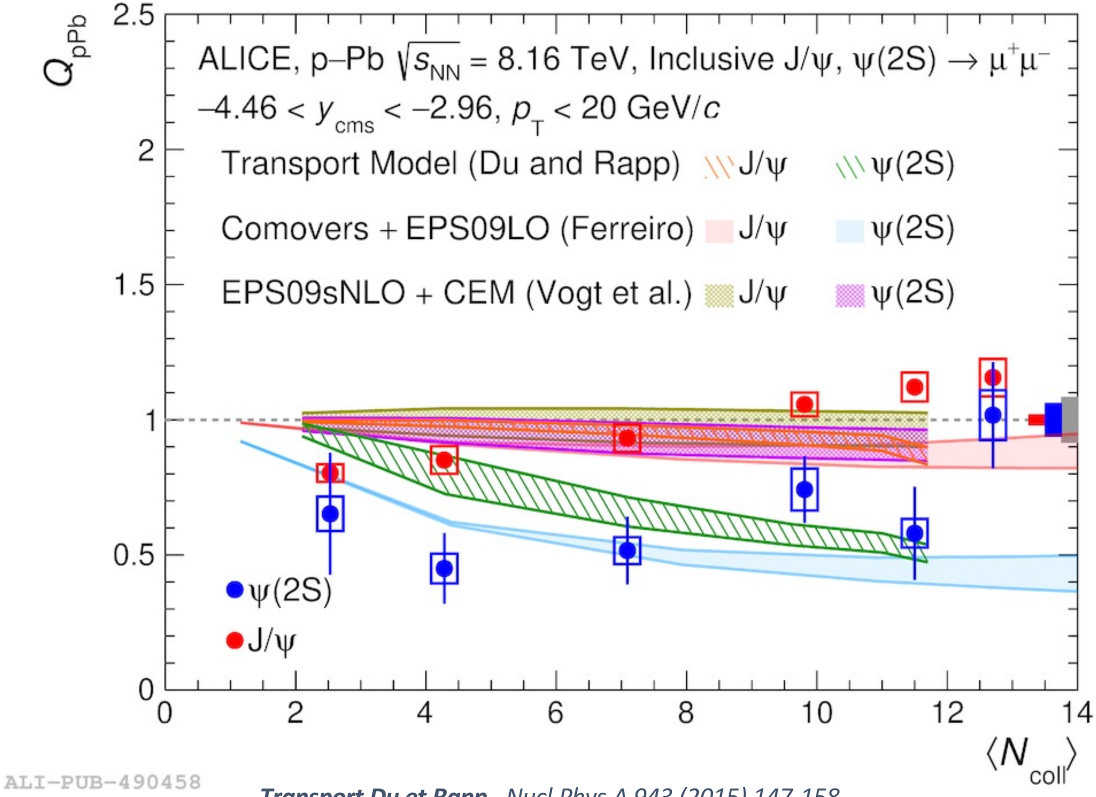
Charmonium Q_{pPb} at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV

- $Q_{\mathrm{pPb}} = \frac{\mathrm{d}N_{\mathrm{pPb}}/\mathrm{d}y}{N_{\mathrm{coll}} \times \mathrm{d}N_{\mathrm{pp}}/\mathrm{d}y}$

- At backward rapidity, a systematically stronger suppression of the ψ(2S) relative to the J/ψ is observed

- EPS09s NLO + CEM calculations fail to describe ψ(2S) behavior
- Transport Model describes J/ψ but overestimate ψ(2S) suppression in peripheral collisions at backward rapidity
- Comovers + EPS09LO model describes well the stronger suppression of the ψ(2S) suppression at backward rapidity

JHEP 02 (2021) 002



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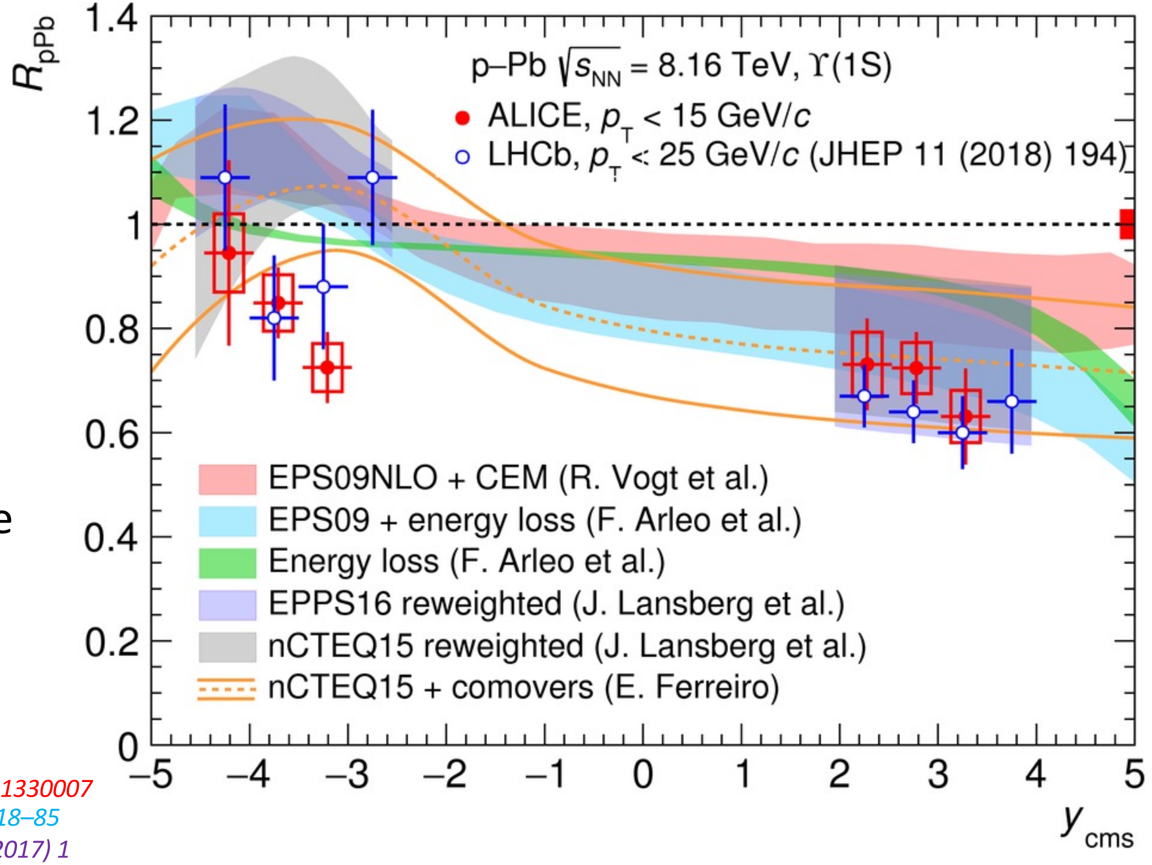
Upsilon R_{pPb} at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV

- $R_{\mathrm{pPb}} = \frac{\mathrm{d}N_{\mathrm{pPb}}/\mathrm{d}y}{\langle N_{\mathrm{coll}}\rangle \times \mathrm{d}N_{\mathrm{pp}}/\mathrm{d}y}$
- Significant Υ(1S) suppression at forward and backward rapidity
- Good agreement between ALICE and LHCb
- Models with nuclear shadowing models describe the data well at forward but overestimate it at backward rapidity

PLB 806 (2020) 135486



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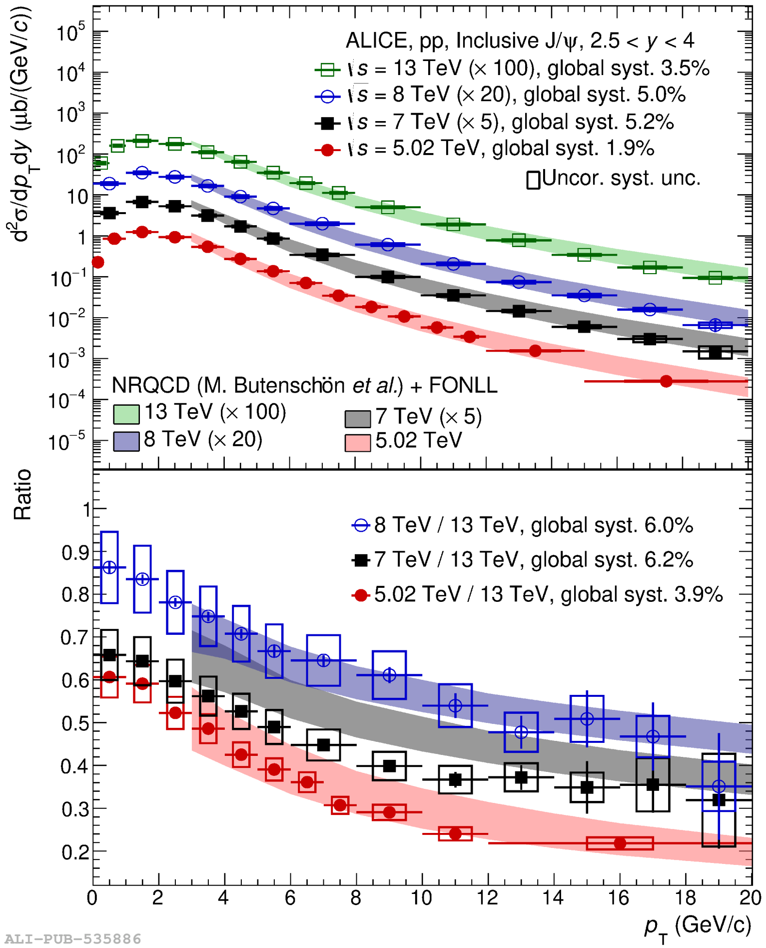
EPS09 + energy loss : *Arleo et al., Nucl. Phys. A972 (2018) 18–85*
EPPS16 reweight : *Lansberg et al, Eur. Phys. J. C77 no. 1, (2017) 1*
nCTEQ15 reweight : *Lansberg et al, Phys. Rev. Lett. 121 no. 5, (2018) 052004*
nCTEQ15+comovers : *Ferreiro, JHEP 10 (2018) 094*

J/ψ production as a function of energy

Eur. Phys. J. C 83 (2023) 61



- Precise measurements accross energy range
- The J/ψ p_T-differential cross section values increase with increasing collision energy
- A stronger hardening of the p_T spectra is observed in 13 TeV data with respect to the 5.02, 7, and 8 TeV data
  ➔derive from the increase of the prompt J/ψ mean p_T with energy, and the increasing contribution from non-prompt J/ψ at high p_T
- NRQCD model describes the data in the available range for all energies, with a slight overestimation at high p_T
- The ratio is also well described except for 7 /13 TeV

NRQCD : *Butenshön et al., Phys. Rev. Lett. 106 (2011) 022003*
ICEM : *Cheung et al., Phys. Rev. D 98 (2018) 114029*
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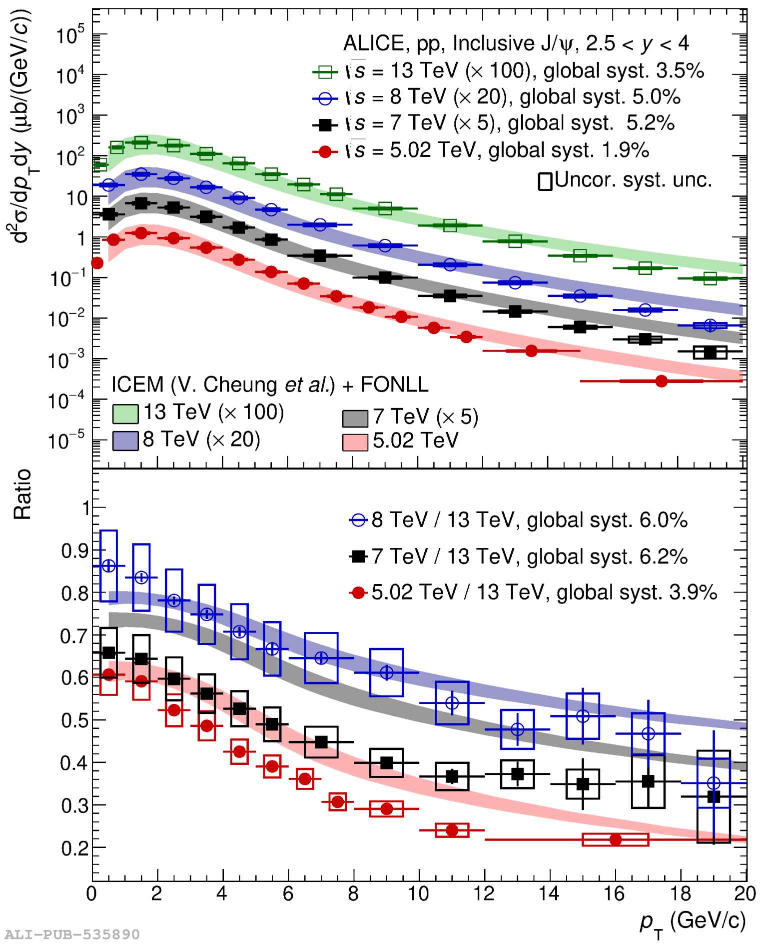

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- ICEM model also agrees with the data for all energies in the whole p_T range, with a slight overestimation at high p_T
- ICEM model tends to overestimate the ratio between energies excdpt 8/13 TeV

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ψ(2S) production as a function of energy

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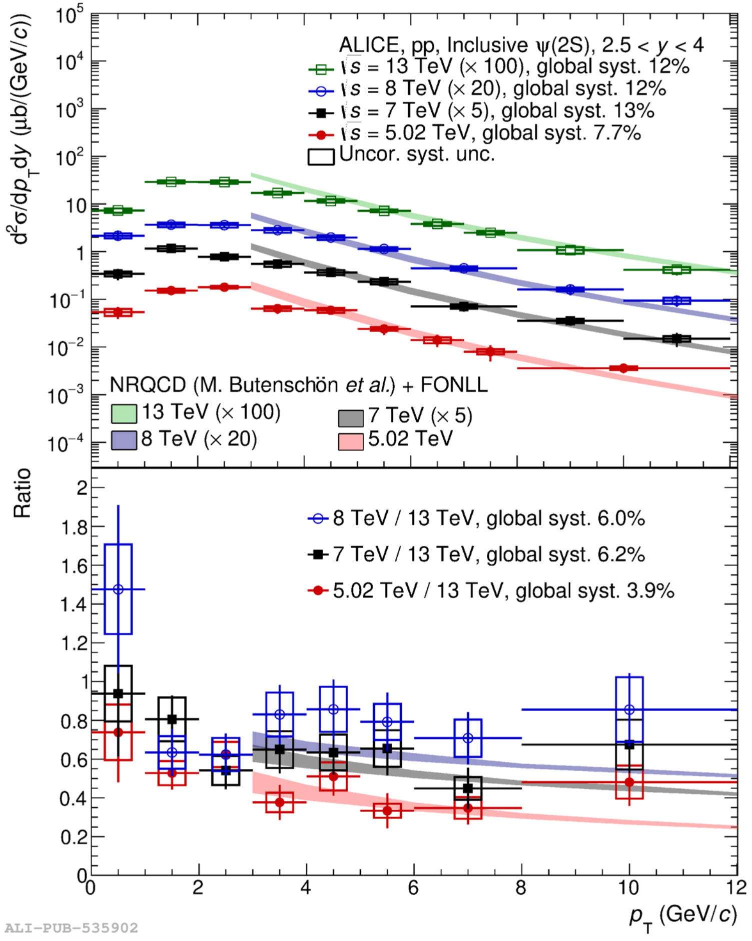

- The ψ(2S) p_T-differential cross section values increase with increasing collision energy
- The ratio between energies exhibits a flat dependence as a function of p_T for p_T > 3 GeV/c
- NRQCD model describes the data in the available range for all energies, with a slight overestimation at high p_T
- The ratio is also well described except for 8/13 TeV which is underestimated

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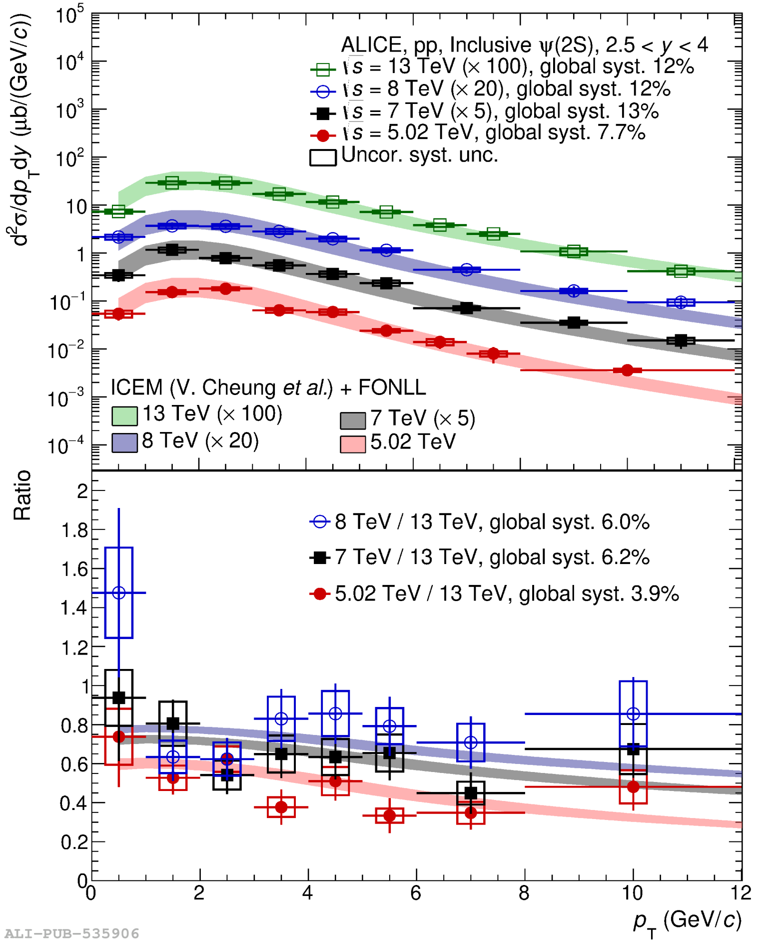

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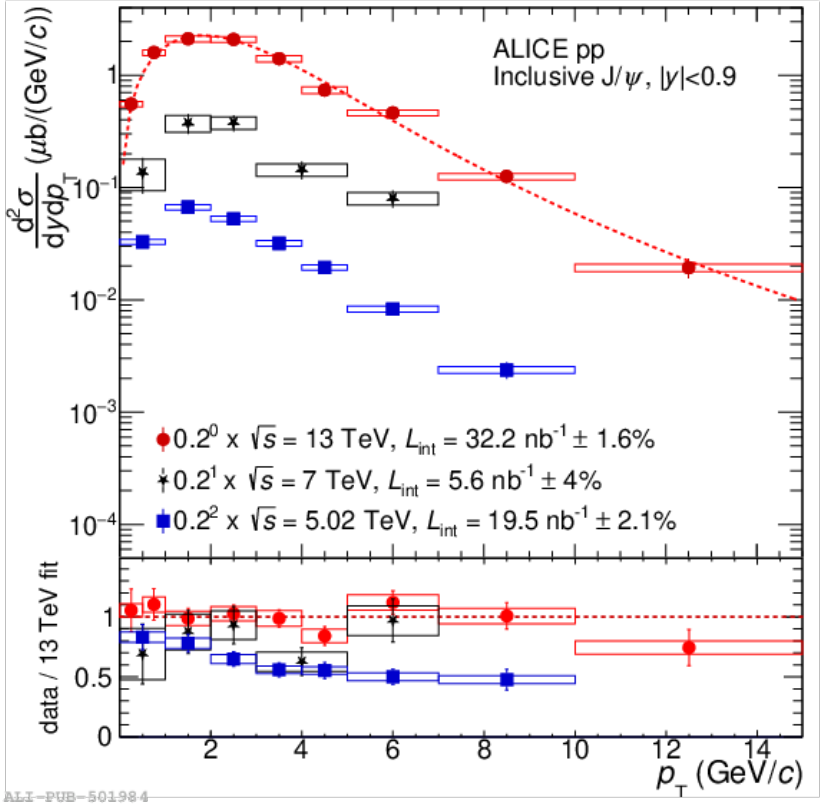
J/ψ production as a function of energy

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



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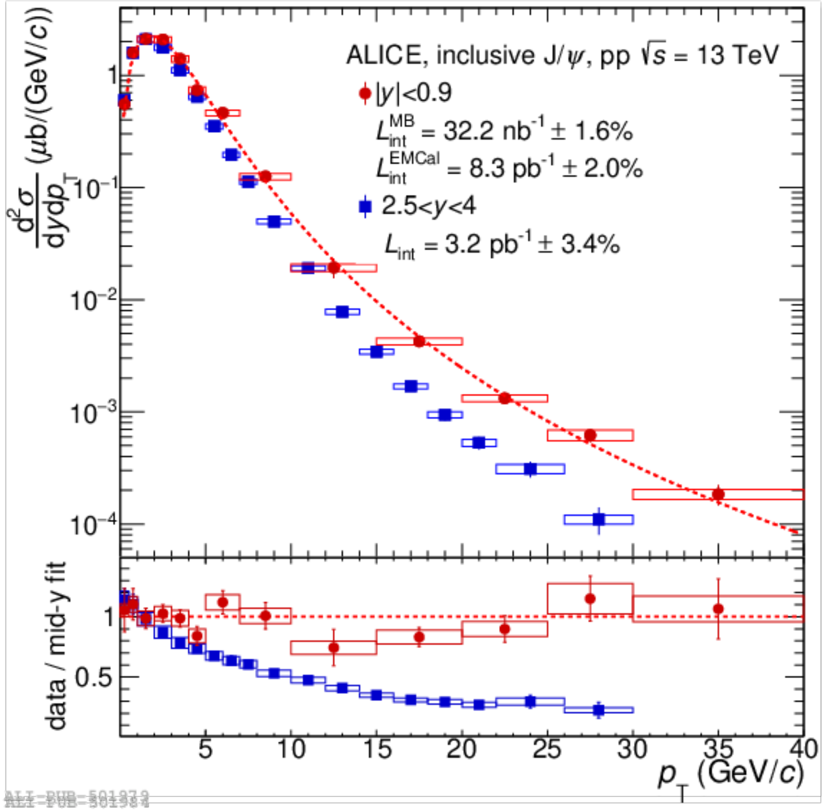
Eur. Phys. J. C 81 (2021) 1121



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- Harder distribution at midrapidity w.r.t forward rapidity

J/ψ production as a function of energy

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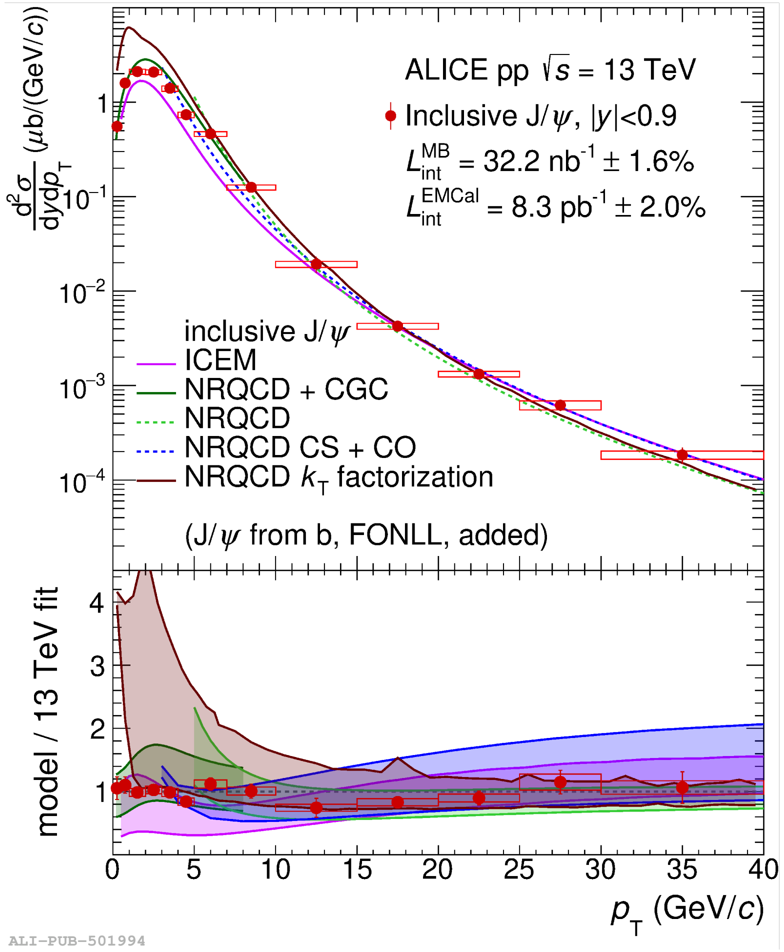

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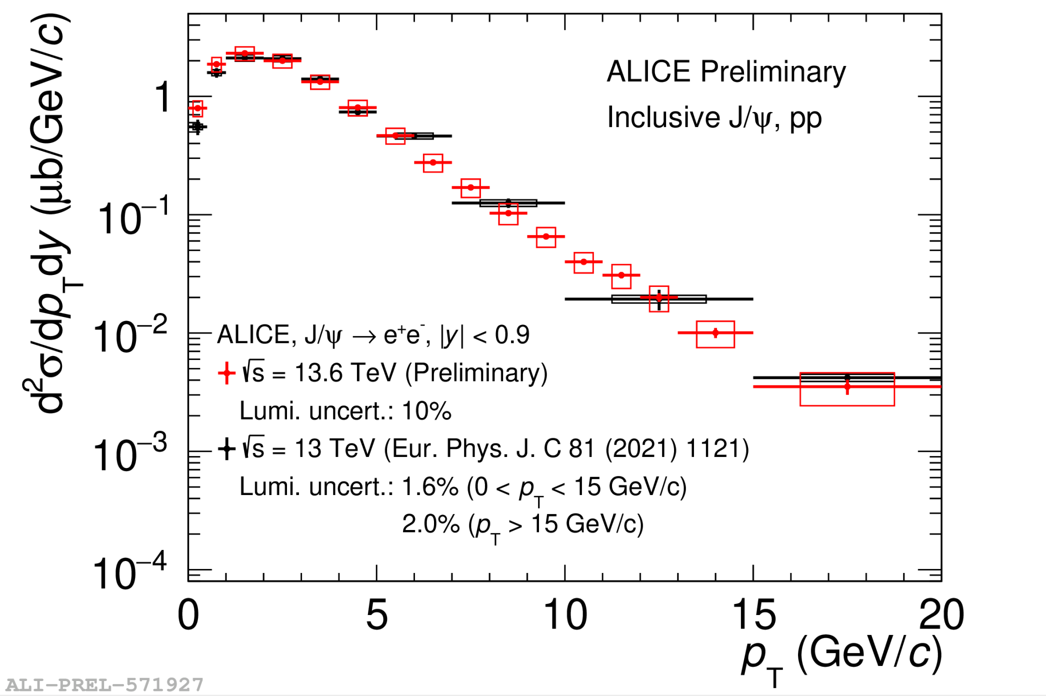
- Harder distribution at midrapidity w.r.t forward rapidity

- All models provide a reasonable description of the inclusive J/ψ production cross section within theoretical uncertainties over the entire p_T range
- NRQCD with k_T-factorization provides a good description of the data for p_T > 2 GeV/c, but overestimates data at lower p_T

ICEM : Cheung et al., Phys. Rev. D 98 (2018) 114029
NRQCD +CGC : Phys. Rev. Lett. 113 no. 19, (2014) 192301
NRQCD : Butenschön et al., Phys. Rev. Lett. 106 (2011) 022003
NRQCD CS+CO: Butenschön et al., Phys. Rev. Lett. 106 (2011) 042002
NRQCD kT factorization : Butenschön et al., Eur. Phys. J. C 80 no. 4, (2020) 330
FONLL : Cacciari et al. JHEP 10 (2012) 137

J/ψ production at $\sqrt{s} = 13.6$ TeV



- **New measurement at $\sqrt{s} = 13.6$ TeV!**
- Significant improvement in statistics and precision with respect to Run 2 data
- Measurements agree within uncertainties

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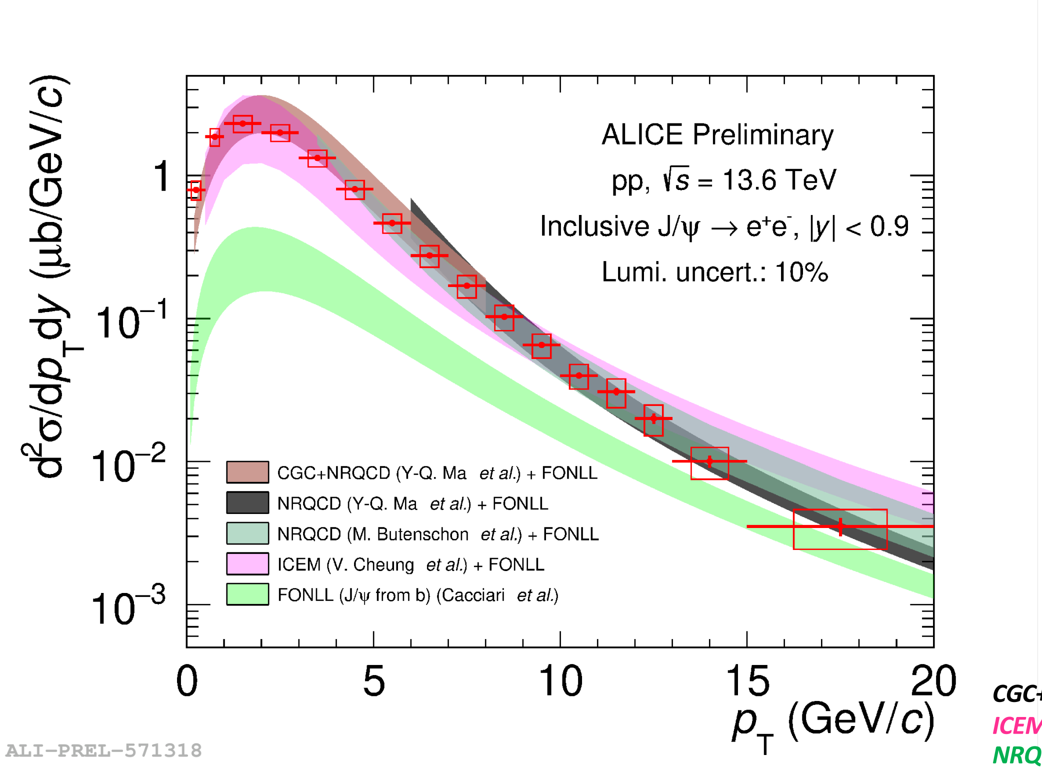

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CGC+NRQCD : *Ma et al., Phys.Rev.Lett. 113 (2014) 192301*
ICEM : *Cheung et al., Phys. Rev. D 98 (2018) 114029*
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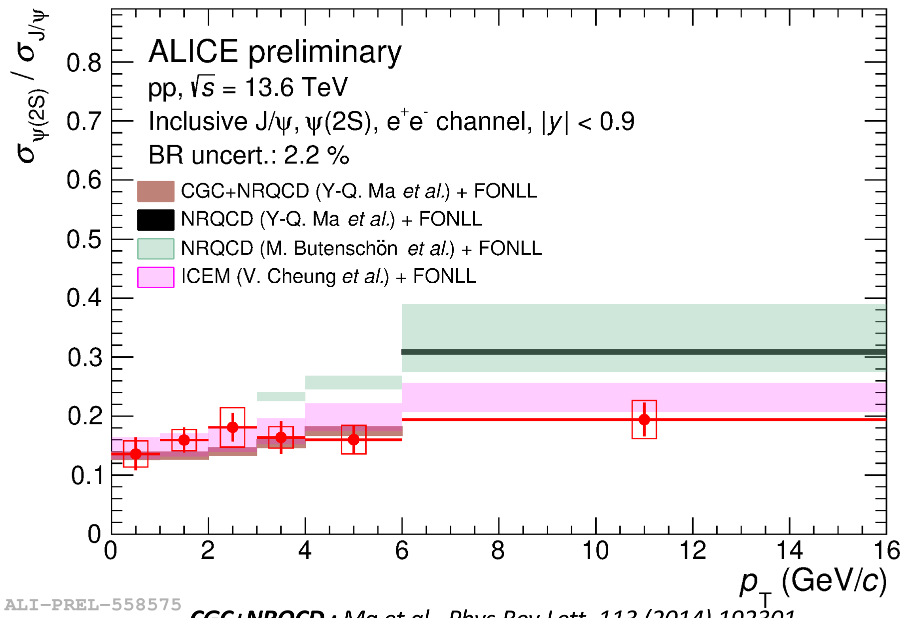
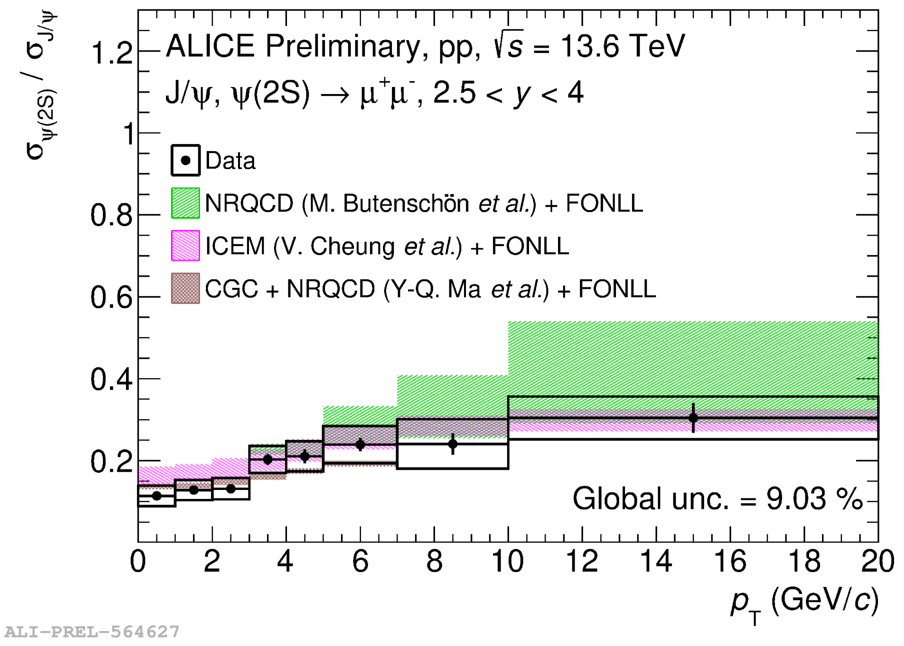
Quarkonium production at $\sqrt{s} = 13.6$ TeV

- First measurement of the ψ(2S) down to $p_T = 0$ at midrapidity !
- Hint of an increase of the ratio at forward rapidity, no evevidence of p_T dependence at midrapidity
- ICEM model describes both regions well, NRQCD model overestimates the data at high p_T at midrapidity





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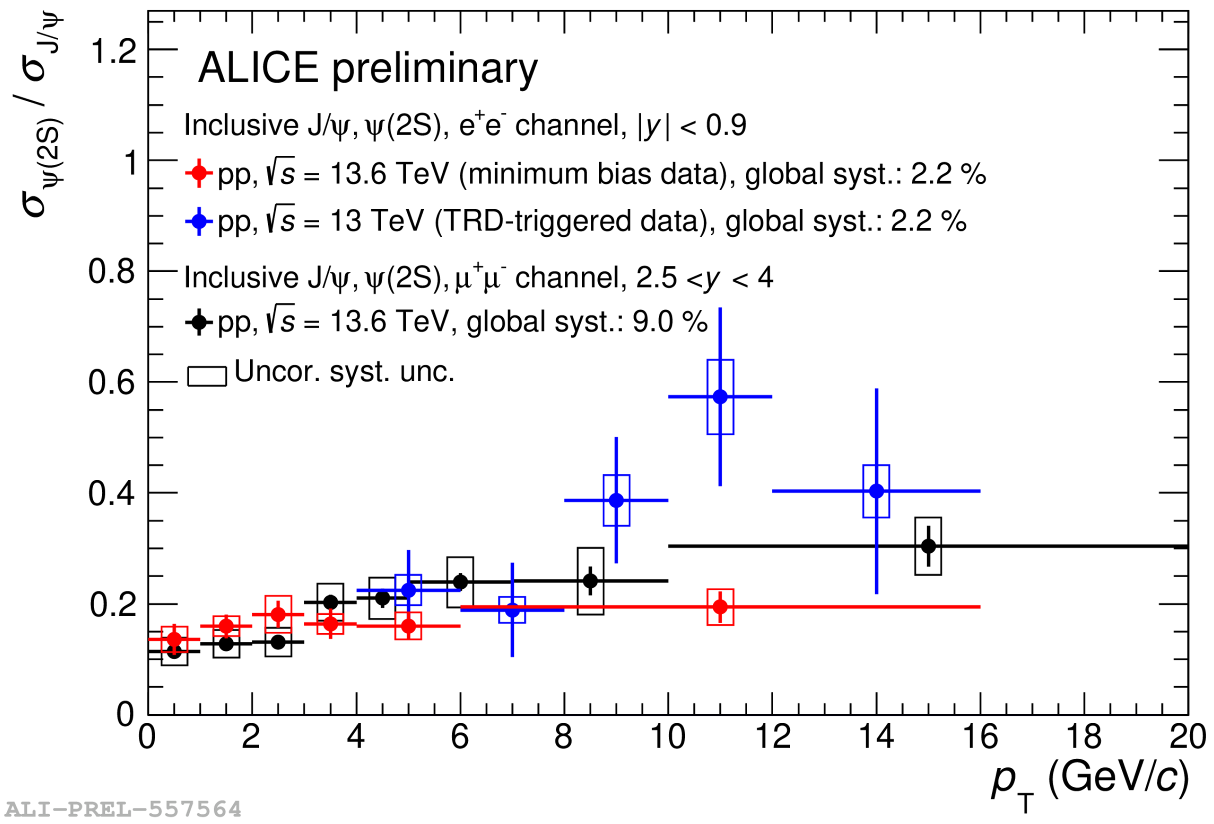
Quarkonium production at $\sqrt{s} = 13.6$ TeV

- The results from different rapidity intervals are consistent within uncertainties



Conclusion and Outlook

- In p-Pb collisions, J/ψ show a suppression at forward rapidity, but no significant suppression at mid and backward rapidity
- ψ(2S) and Υ(1S) also show suppression at backward rapidity
- Models with shadowing tend to describe the data rather well, but uncertainties prevent from discriminating between models

- In pp collisions, a large panel of measurement is available
- Models describe the prompt and non-prompt contribution well over a large p_T range
- New Run 3 measurements (ψ(2S) and Υ(1S) at mid-rapidity, X(3872), prompt and non-prompt separation at forward rapidity…) allow to complete the picture of pQCD

THANK YOU FOR YOUR ATTENTION!

BACK-UP

Description of models

- **NRQCD model** : non-Relativistic QCD approach, long-distance matrix elements (LDME) fitted to experimental data
- **NRQCD+CGC : ** Color Glass Condensate effective theory coupled to leading order NRQCD calculations
- **ICEM : ** using the k_T-factorization approach to improve Color Evaporation Model (CEM).

Description of models

- **Lansberg et al.** : based on the framework of NRQCD factorisation with nCTEQ15 and EPPS16 nPDF sets reweighted to include results from the RHIC and LHC colliders. The uncertainty bands represent the convolution of the uncertainties on the nPDFs sets and on the factorisation scale

- **Vogt et al.** : based on a pure shadowing scenario employing the next-to-leading order (NLO) Color Evaporation Model (CEM) with the EPS09 shadowing parametrisation EPS09 parametrisation The uncertainty bands are dominated by the uncertainties of the EPS09 parametrisation

- **Arleo et al.** : includes effects of momentum broadening and coherent parton energy loss

- **Ferrerio et al.** : includes a shadowing contribution (nCTEQ15) on top of the suppression of the due to interactions with comoving particles