# Charmonium production in pp and p–Pb collisions with ALICE

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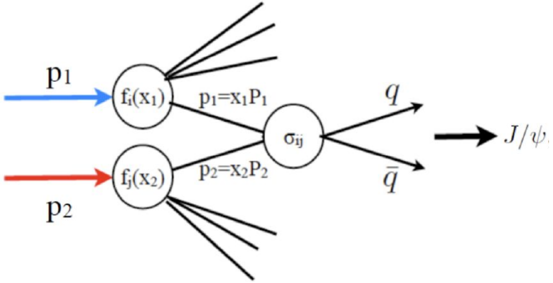
# Charmonium production in nuclear collisions

**pp collisions**:

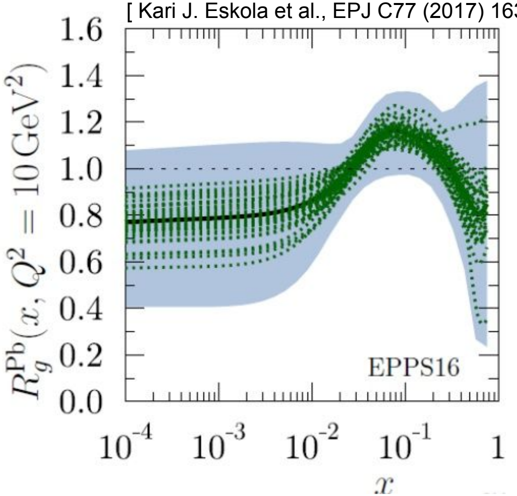
- Understand the charmonium production mechanisms at partonic level → benchmark for perturbative and non-perturbative quantum chromodynamics (QCD) models
  - high multiplicity regime: sensitive to multiple parton interactions
- Reference for p–A, A–A studies at the same $\sqrt{s}$

**p–Pb collisions**:

- Understand effects due to the presence of cold nuclear matter (CNM)
  - (anti-)shadowing modifications for nuclear PDFs
  - gluon saturation, Colour Glass Condensate (CGC)
  - parton energy loss
  - final state dissociation (absorption, comovers)
- High multiplicity regime: collective effects on heavy quarks?



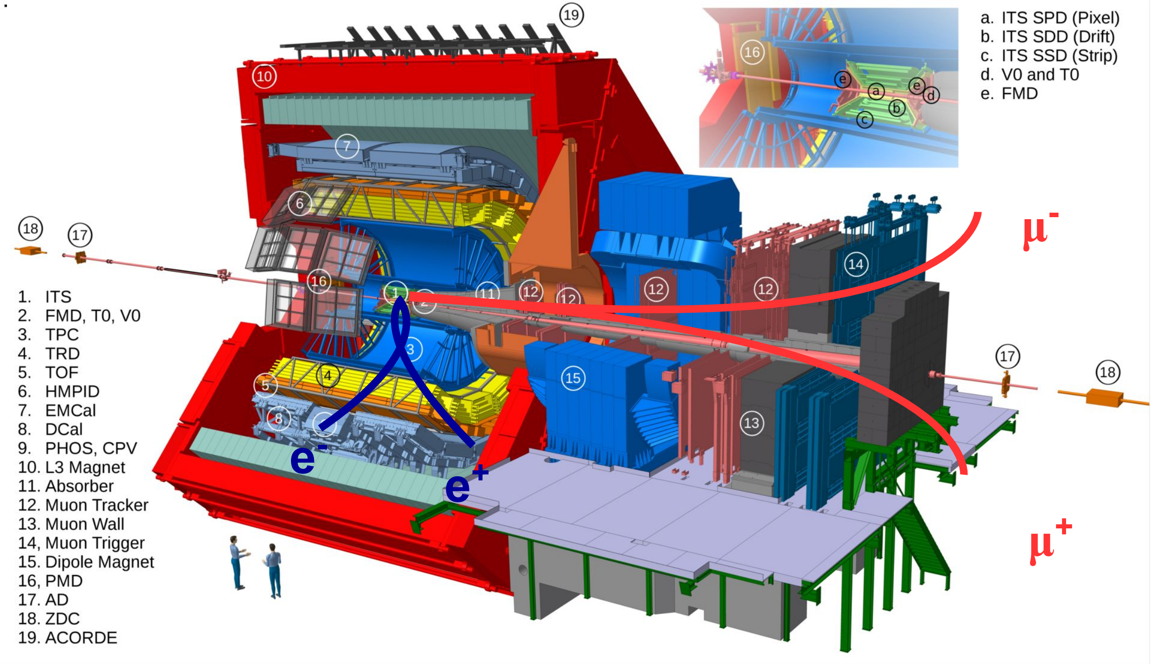

[ Kari J. Eskola et al., EPJ C77 (2017) 163]



# Charmonium measurements in ALICE

- Charmonium detection at midrapidity $|y| < 0.9$ J/ψ → **e+e-** down to zero $p_T$
  - Inner Tracking System(ITS)+Time Projection Chamber (TPC): tracking and PID
  - Silicon Pixel Detectors (SPD): primary and secondary vertices Separation of prompt and non-prompt J/ψ

- Charmonium detection at forward rapidity $2.5 < y < 4$ J/ψ, ψ(2S) → **μ+μ-** down to zero $p_T$
  - 10 tracking planes (Cathode Pad Chambers)
  - 4 trigger planes (Resistive Plate Chambers)

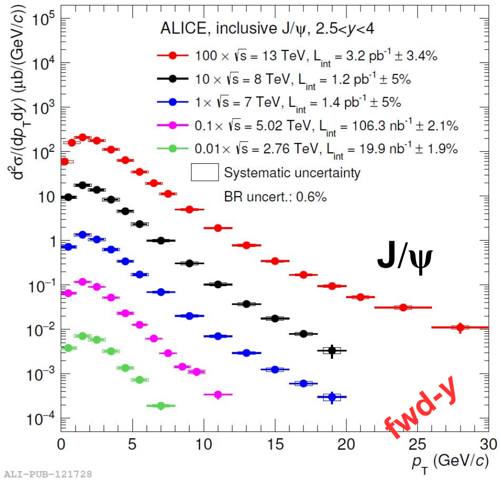


# Selected highlights in pp collisions

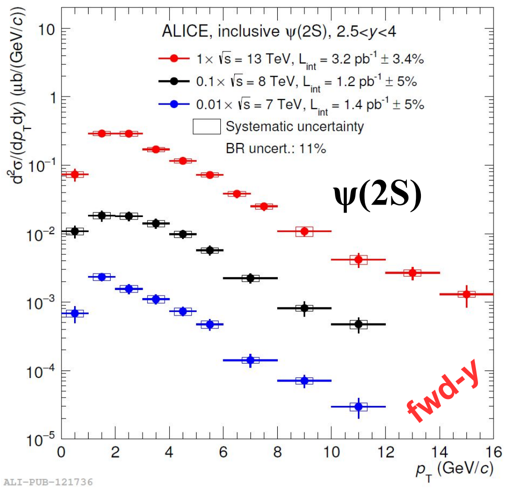
# Charmonium cross sections in pp

- Extensive and precise charmonium production measurements at several centre-of-mass energies, both at mid and forward rapidity
- Hardening of the $p_T$ differential cross sections with increasing energy

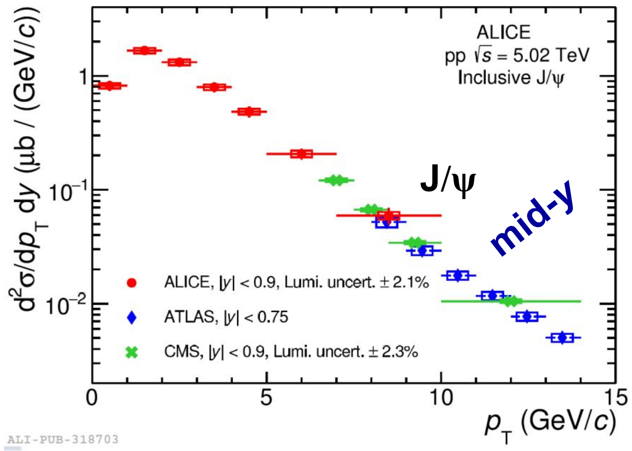
[Eur. Phys. J. C (2017) 77]




[Eur. Phys. J. C (2017) 77]




[JHEP 10 (2019) 084]

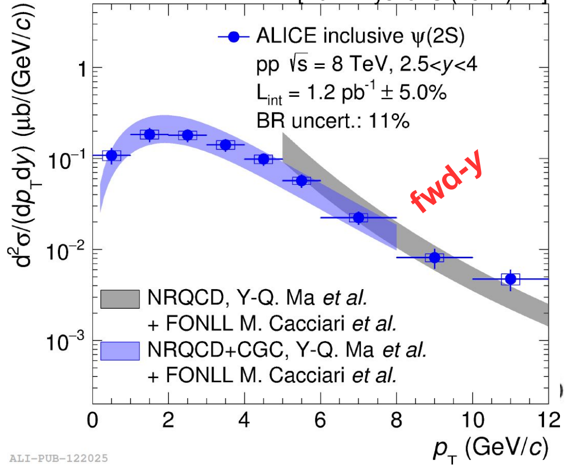



[ATLAS: Eur. Phys. J. C 78 (2018) 171]
[CMS: Eur. Phys. J. C 77 (2017) 269]

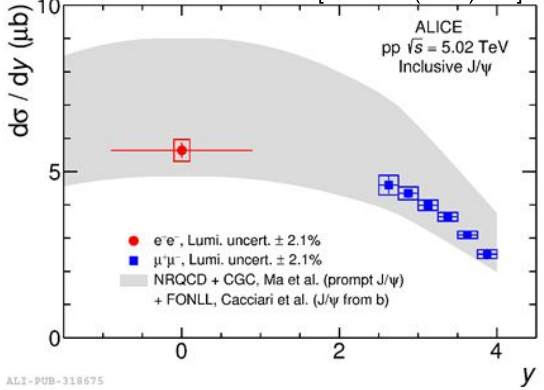
# Charmonium cross sections in pp

- Non-relativistic QCD (NRQCD)+CGC (+ fixed-to-next-to-the-leading order (FONLL)) model provides a good description of the $p_T$-differential cross sections (at both mid and forward rapidity)
- Rapidity dependence well reproduced by NRQCD+CGC(+FONLL)

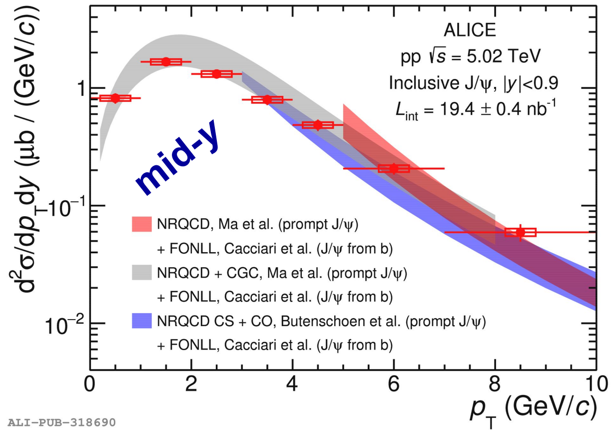
[Eur. Phys. J. C (2017) 77]




[JHEP 10 (2019) 084]



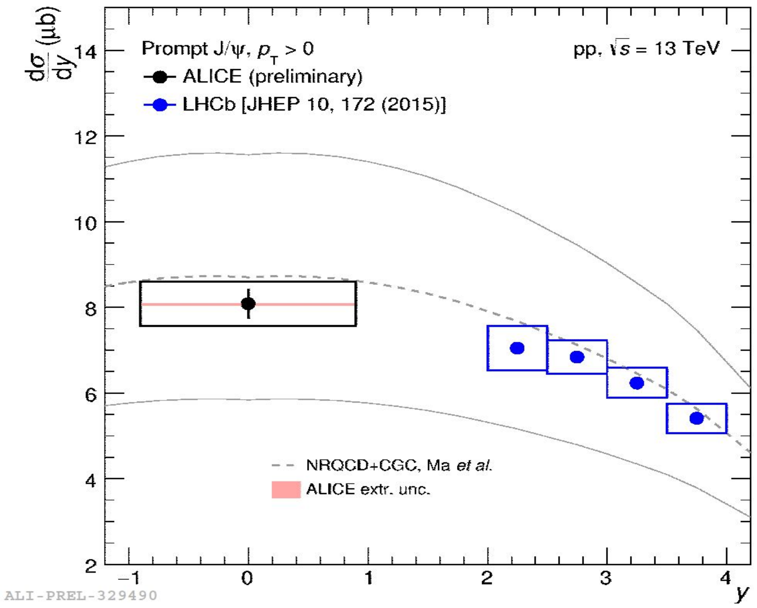

[JHEP 10 (2019) 084]

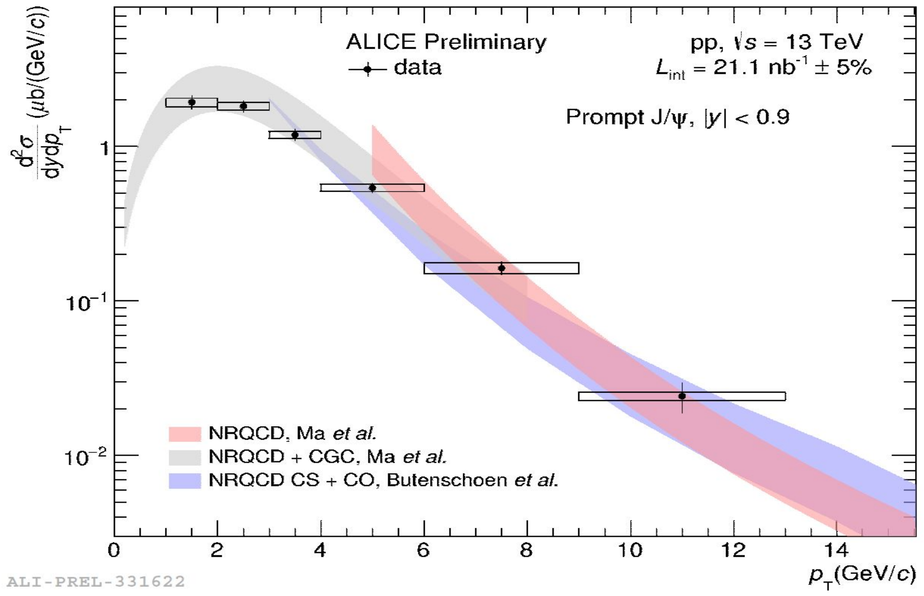



NRQCD+CGC: Y.-Q. Ma and R. Venugopalan, PRL 113 no. 19, (2014)
NRQCD: Y.-Q. Ma, K. Wang, and K.-T. Chao, PRL 106 (2011) 042002
M. Butenschoen and B. A. Knieh, PRL 106 (2011) 022003
FONLL: M. Cacciari et al, JHEP 10 (2012) 137

# Prompt J/ψ cross sections in pp

mid-y




- Possibility to disentangle prompt / non-prompt J/ψ at midrapidity
- NRQCD+CGC describes well prompt J/ψ cross sections vs $p_T$ and rapidity




NRQCD+CGC: Y.-Q. Ma and R. Venugopalan, Phys. Rev. Lett. 113 no. 19, (2014)
NRQCD: Y.-Q. Ma, K. Wang, and K.-T. Chao, Phys. Rev. Lett. 106 (2011) 042002
M. Butenschoen and B. A. Knieh, Phys. Rev. Lett. 106 (2011) 022003

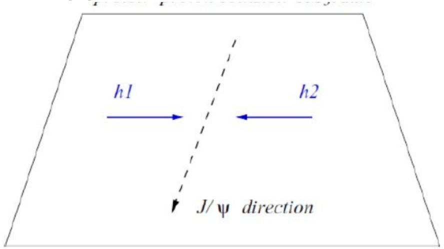

ALICE

# J/ψ polarization

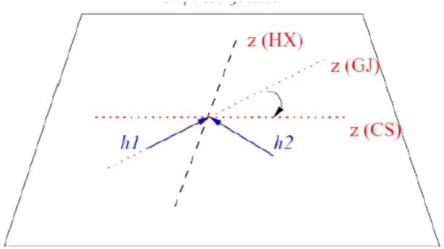
$$W(\cos\theta,\varphi) \propto \frac{1}{3+\lambda_\theta}[1+\lambda_\theta \cos^2\theta + \lambda_\theta sin^2\theta \cos(2\varphi) + \lambda_{\theta\varphi}\sin(2\theta)\cos\varphi]$$

- Polarization parameters studied through the angular distributions of leptons (W(θ,φ)) in the quarkonium rest frame
- Measurements performed in different polarization frames (Collins-Soper and Helicity)

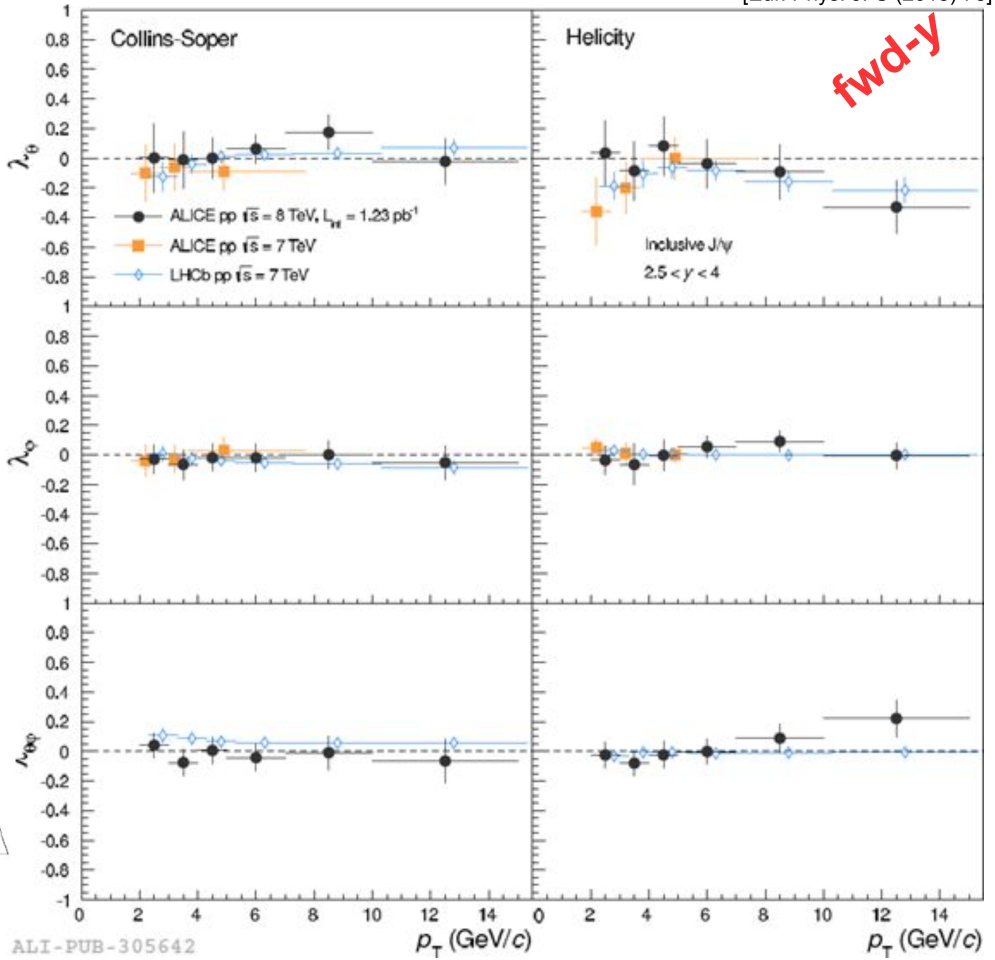
pp collision CM frame




J/ψ rest frame



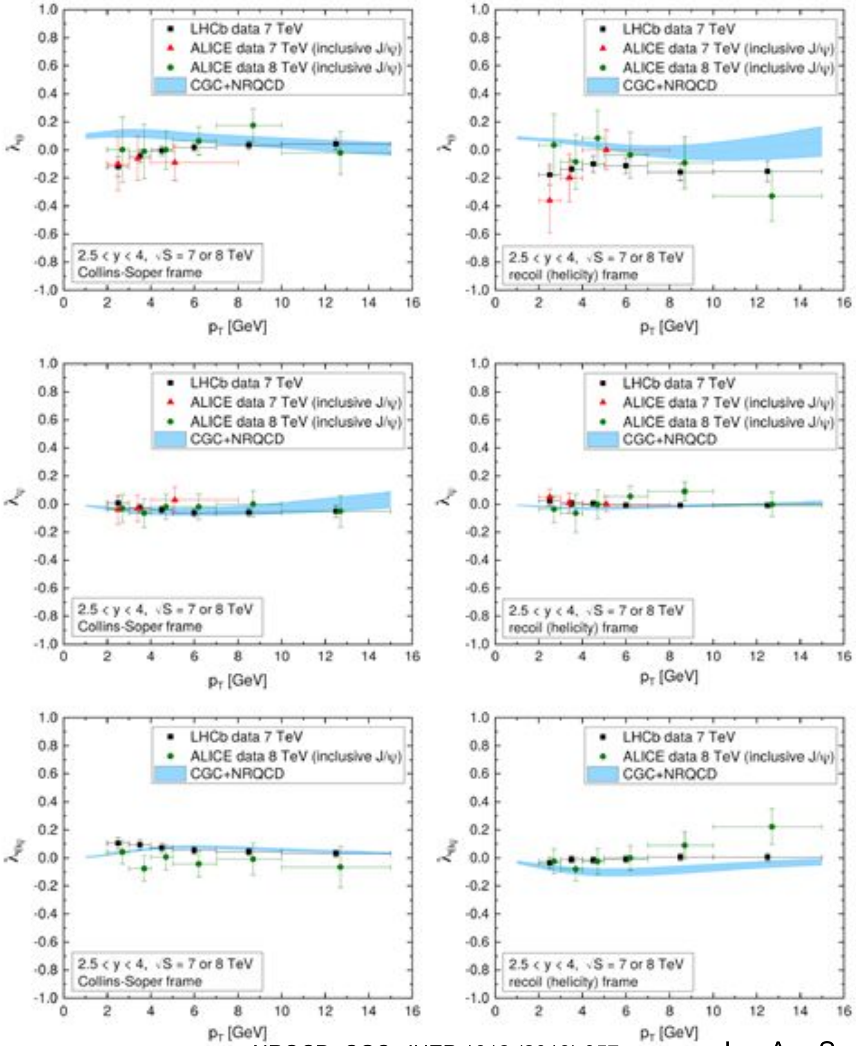

[Eur. Phys. J. C (2018) 78]



# J/ψ polarization

$$W(\cos\theta,\varphi) \propto \frac{1}{3+\lambda_\theta}[1 + \lambda_\theta \cos^2\theta + \lambda_\theta sin^2\theta \cos(2\varphi) + \lambda_{\theta\varphi} \sin(2\theta)\cos\varphi]$$

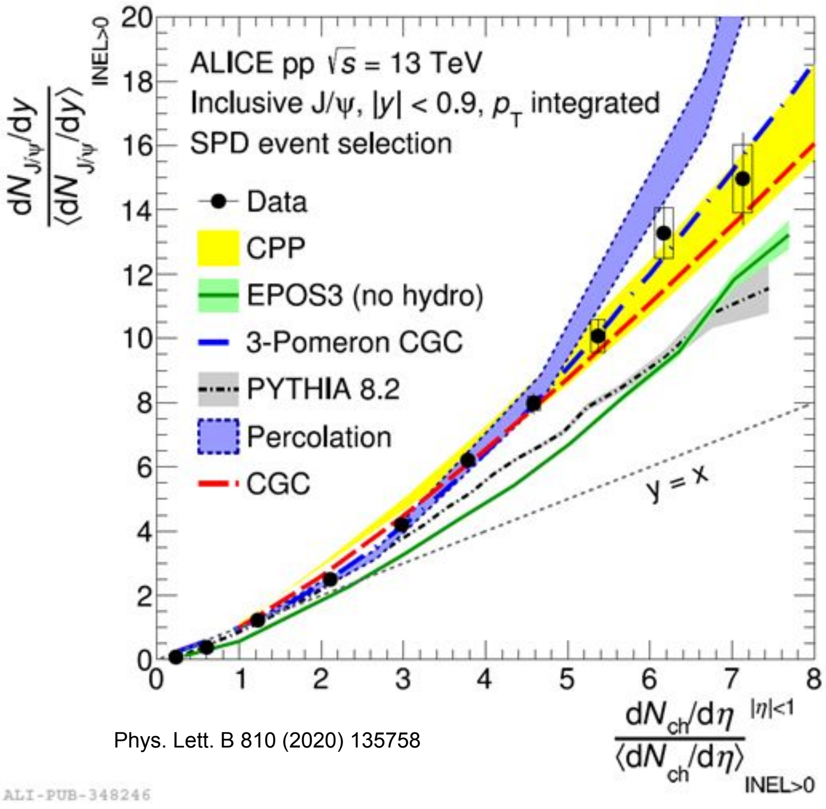
- No significant J/ψ polarization observed
  - compatible with similar measurement in Pb–Pb collisions by ALICE (first at the LHC!)
- Good agreement between ALICE and LHCb measurements at $\sqrt{s}$ = 7 TeV
- Describe simultaneously different observables → challenge for theoretical models!
  - most of the models are not able to describe cross section and polarization simultaneously
  - good agreement within uncertainties observed when comparing with NRQCD+CGC → but small tensions still visible!




NRQCD+CGC: JHEP 1812 (2018) 057

# Inclusive quarkonium production in pp vs multiplicity

mid-y

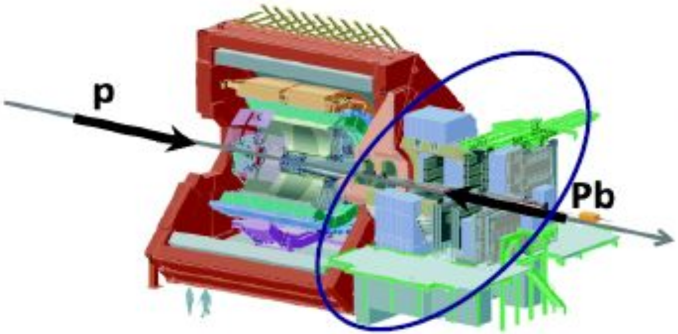



Phys. Lett. B 810 (2020) 135758

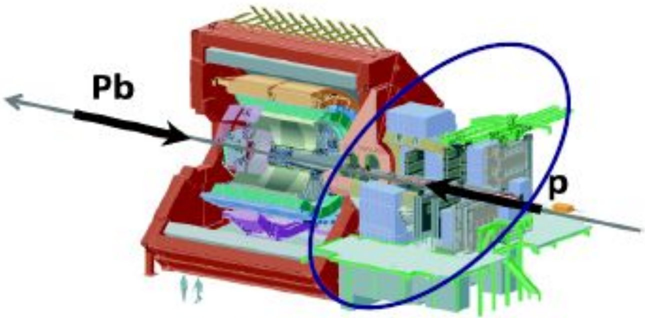
- All models predict a faster than linear increase
- Effect of a reduction of charged particle multiplicity (x-axis) realized through different mechanisms, depending on the model
- Pythia8 and EPOS underpredict data, while percolation model overestimates them at high-multiplicity
- Good agreement observed for coherent particle production (CPP), CGC and 3-Pomeron CGC

CPP: Kopeliovich et al., PRD88 (2013) 116002
EPOS3: Werner et al., Phys.Rept.350 (2001) 93
3-Pomeron CGC: arXiv:1910.13579
PYTHIA8. Sjostrand et al., Comput.Phys.Comm.178(2008)
Percolation: Ferreiro, Pajares, PRC86 (2012) 034903
CGC: Phys. Rev. D98 no. 7, (2018) 074025

# Selected highlights in p–Pb collisions



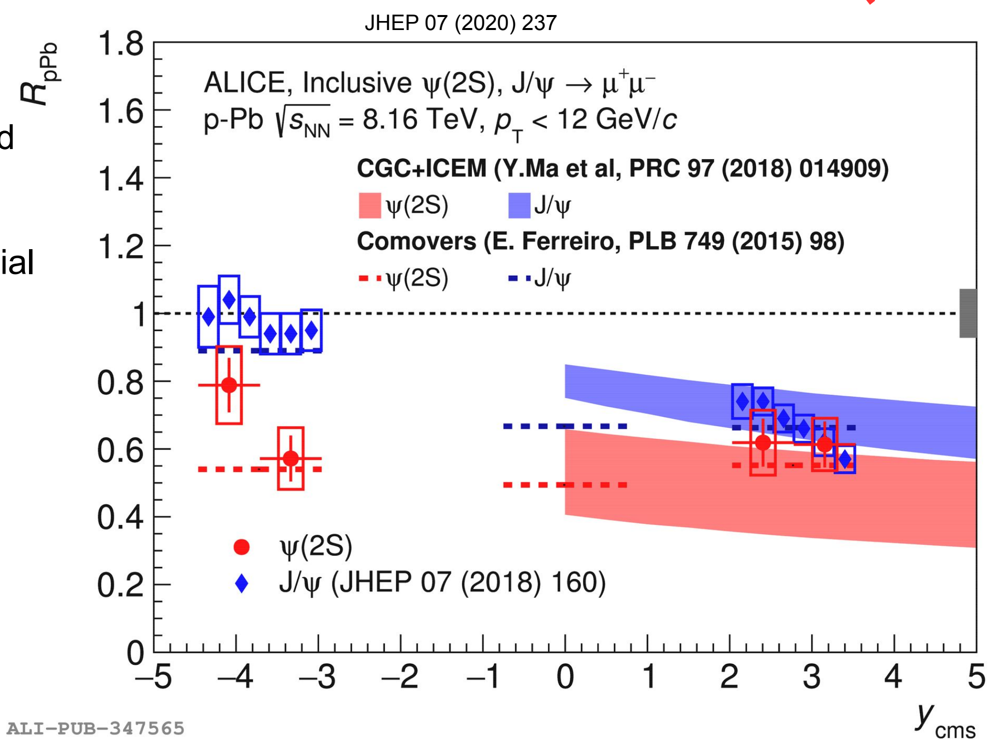
Forward rapidity



Backward rapidity

# Charmonium production in p–Pb collisions

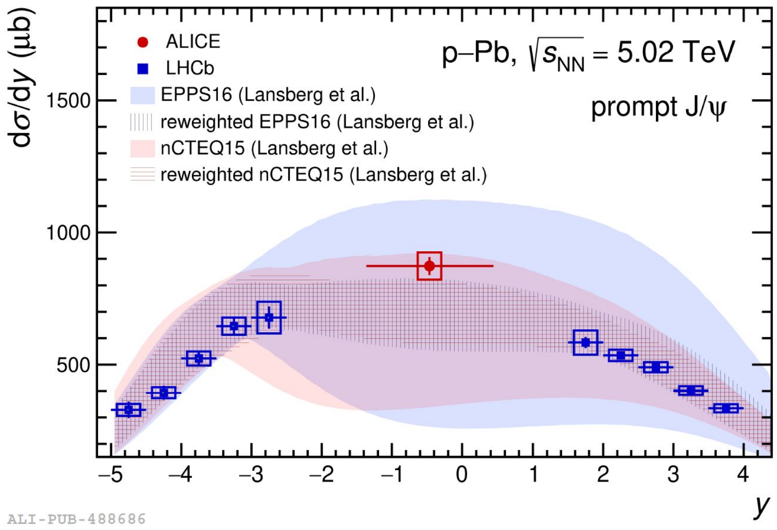
- Stronger suppression of the ψ(2S) w.r.t J/ψ at backward rapidity. Similar suppression at forward rapidity
    - Theoretical calculations based only on initial state effects or coherent energy loss describe the J/ψ results but fail at describing the backward ψ(2S) suppression.
- Need to account for additional final state interactions (soft color exchanges, comovers)



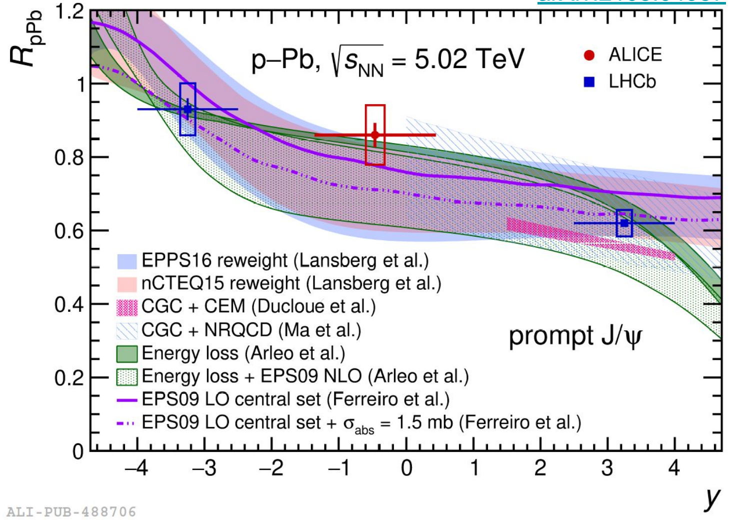
# (Prompt) Charmonium production in p–Pb collisions

mid-y

arXiv:2105.04957




arXiv:2105.04957




- ALICE results at midrapidity complementary to those from LHCb
- Prompt J/ψ cross section and $R_{pPb}$ in agreement within uncertainties with models by Lansberg et al, including nuclear shadowing (based on EPPS16 or nCTEQ15 nuclear PDFs)
  - "Reweighted" version uses LHCb measurements as a constrain for the computations → significant improvement observed for uncertainties

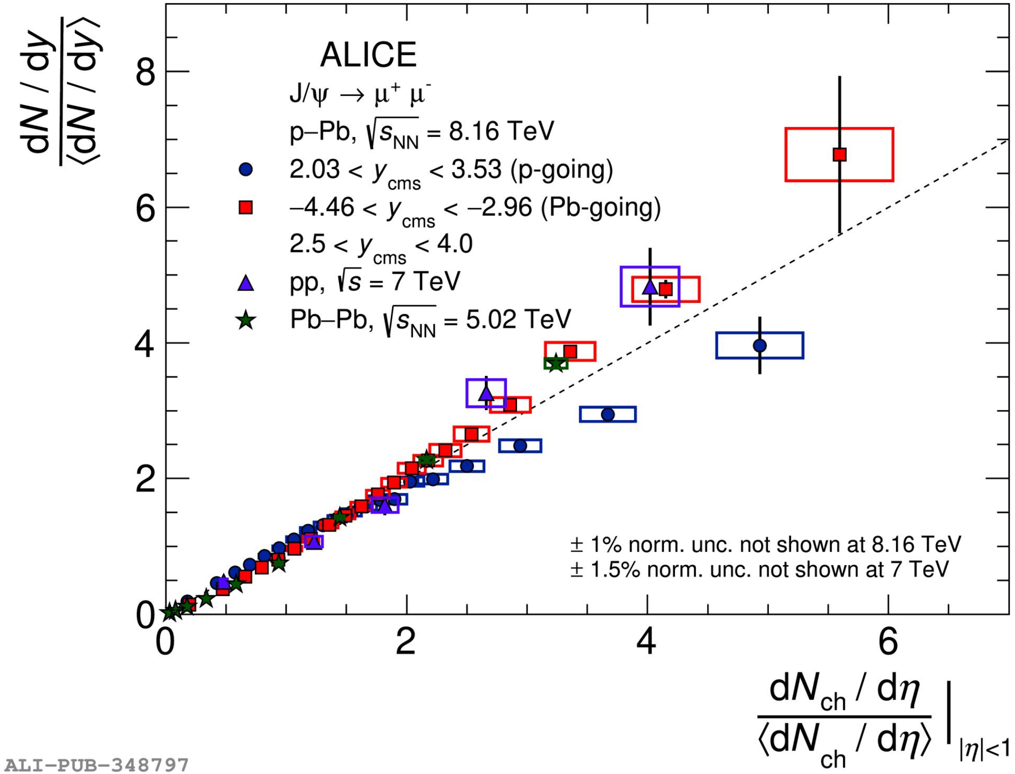
Various model predictions implementing different CNM effects:
F. Arleo et al. J. High Energ. Phys. 05 (2013) 155
A. Kusina et al. Phys. Rev. Lett. 121 no. 5, (2018) 052004
E. G. Ferreiro et al. Phys. Rev. C 88 no. 4, (2013) 047901
B. Ducloué et al. Phys. Rev. D 91 no. 11, (2015) 114005
Y.-Q. Ma et al. Phys. Rev. D 92 (2015) 071901
EPPS16: K. J. Eskola et al. Eur. Phys. J. C 77 no. 3, (2017) 163
nCTEQ15: K. Kovarik et al. Phys. Rev. D 93 no. 8, (2016) 085037

# Charmonium production as a function of charged particle multiplicity in p–Pb collisions

fwd-y

- Yield at backward rapidity (Pb-going) increases faster than at forward rapidity (p-going)
- Slower than linear increase at forward rapidity.
  → Stronger CNM effects at forward rapidity (shadowing/saturation)
- Similar evolution of the J/ψ self-normalized yield with multiplicity for pp, p–Pb (backward) and Pb–Pb systems

JHEP 2009 (2020) 162



# Summary

**pp:**

Charmonium production cross sections and polarization:

→ Well reproduced by NRQCD+CGC in a wide range of $p_T$ and rapidity, for both J/ψ and ψ(2S); however tensions between data and models still visible

→ ALICE results compatible with similar measurements from other LHC experiments

→ Multiplicity dependence of quarkonia: faster than linear increase observed for J/ψ; some of the models ( CPP, CGC and 3-Pomeron CGC) are able to reproduce the trend

**p–Pb:**

→ Inclusive J/ψ at forward y and prompt low-$p_T$ J/ψ at mid y strongly suppressed in Cold Nuclear Matter

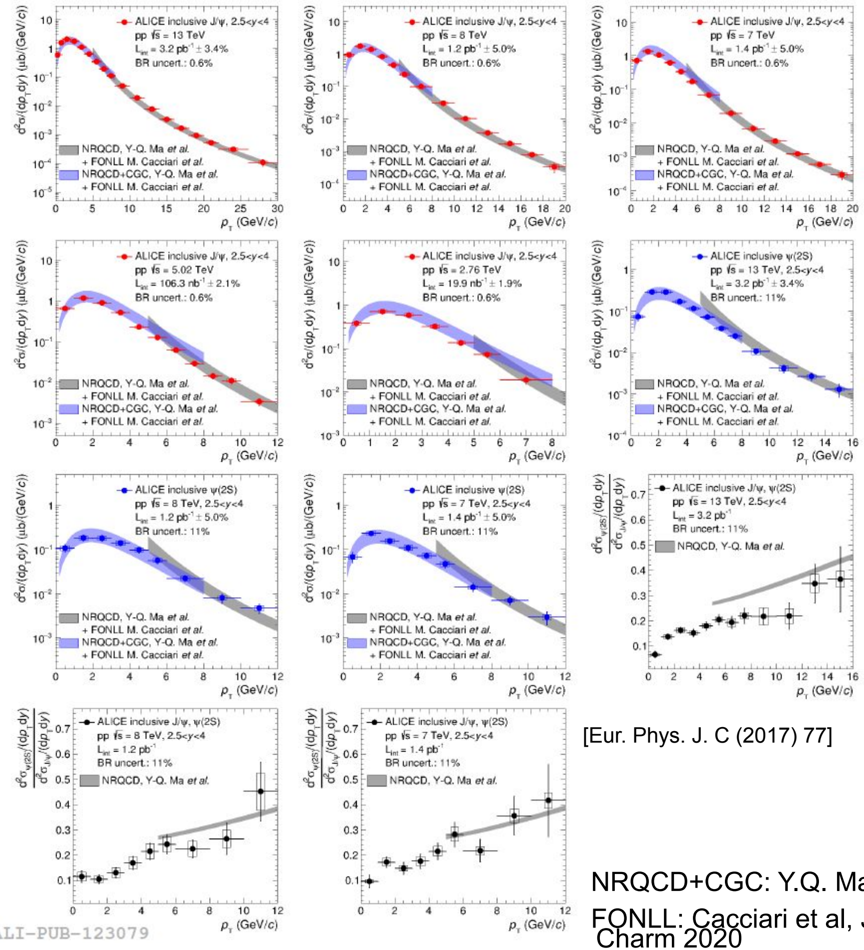
→ Stronger suppression of the ψ(2S) w.r.t J/ψ at backward y in p–Pb described by final state interactions

→ Multiplicity dependence at backward rapidity: similar evolution as in pp; slower than linear at forward rapidity

# Backup

# Charmonium cross sections in pp

fwd-y



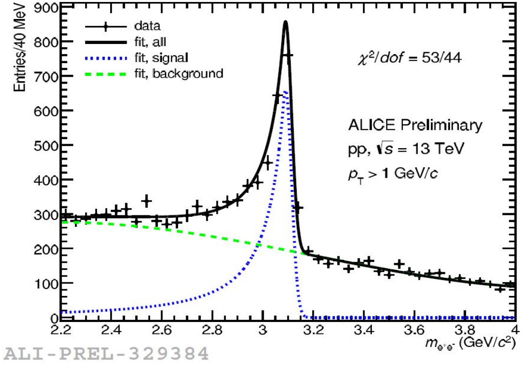

[Eur. Phys. J. C (2017) 77]

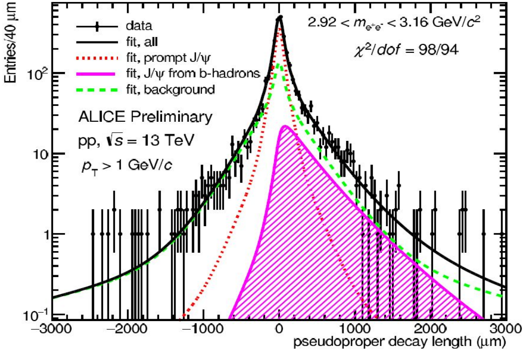
- NRQCD combined with FONLL is able to describe $p_T$ spectra at forward rapidity
- NRQCD+CGC provides a good description down to $p_T = 0$
- Tensions between models and data still visible in the ratio ψ (2S) / J/ψ

NRQCD+CGC: Y.Q. Ma et al, Phys. Rev. Lett. 113 no. 19, (2014)
FONLL: Cacciari et al, JHEP 10 (2012) 137

# Separation of prompt and non-prompt J/ψ procedure

mid-y

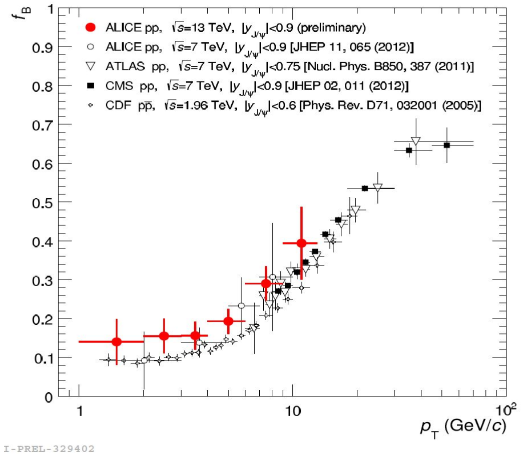



$$x = \frac{c \cdot L_{xy} \cdot m_{J/\psi}}{p_t^{J/\psi}}$$

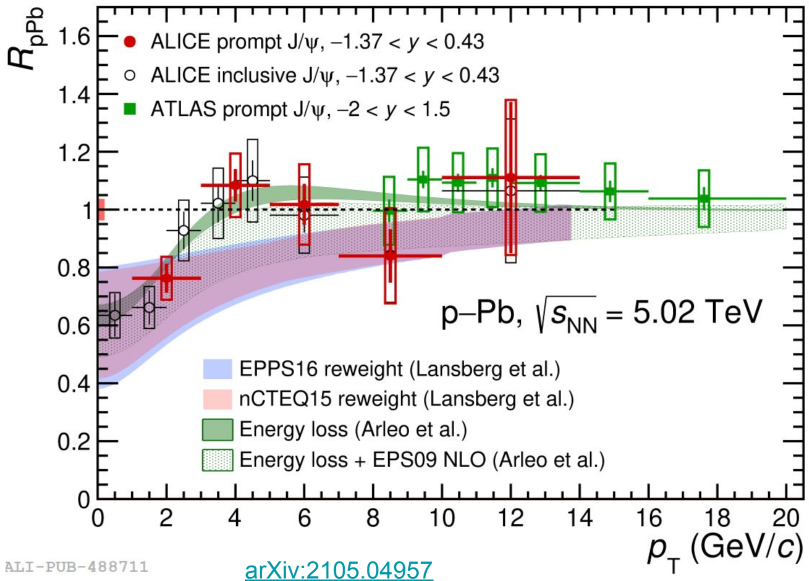
$$L_{xy} = \vec{L} \cdot \vec{p}_t^{\,J/\psi} / p_t^{J/\psi}$$

- Un-binned 2D likelihood fit to measure the fraction of the J/ψ yield originating from beauty hadron decays
- Composed of different probability density function terms

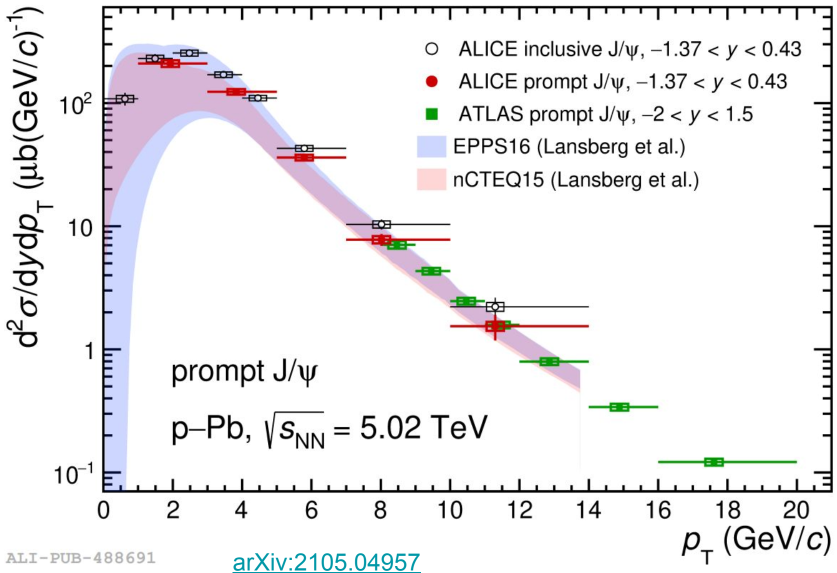


# Charmonium production in p–Pb collisions

mid-y



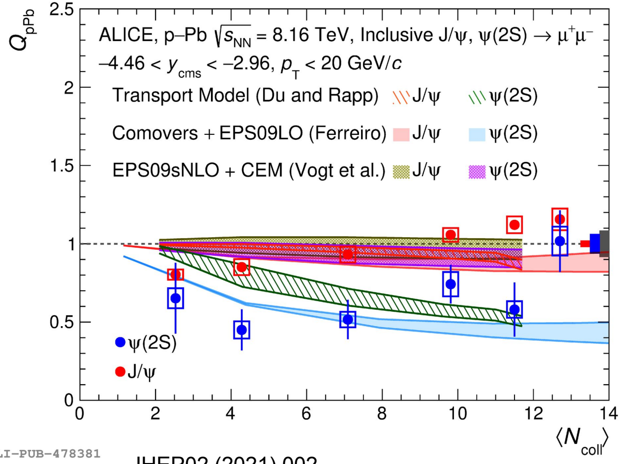

[arXiv:2105.04957](arXiv:2105.04957)



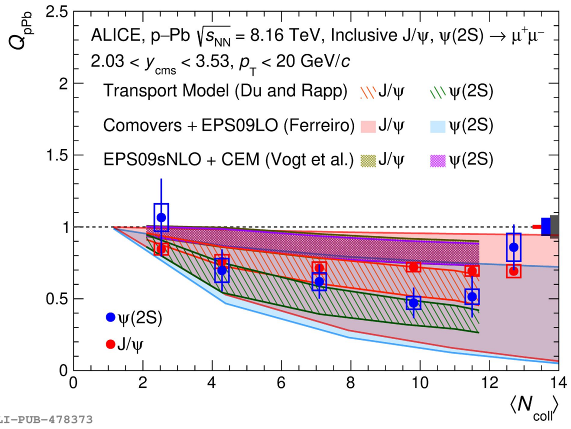

[arXiv:2105.04957](arXiv:2105.04957)

- ALICE results complementary to ATLAS and consistent with them at high pT
- Prompt J/ψ cross section in agreement with models by Lansberg et al, including nuclear shadowing (based on EPPS16 or nCTEQ15 nuclear PDFs)
- Prompt J/ψ suppression at mid-rapidity for pT < 3 GeV/c, reproduced by CNM models considering only initial state effects or coherent energy loss

# Charmonium production as a function of centrality in p–Pb collisions



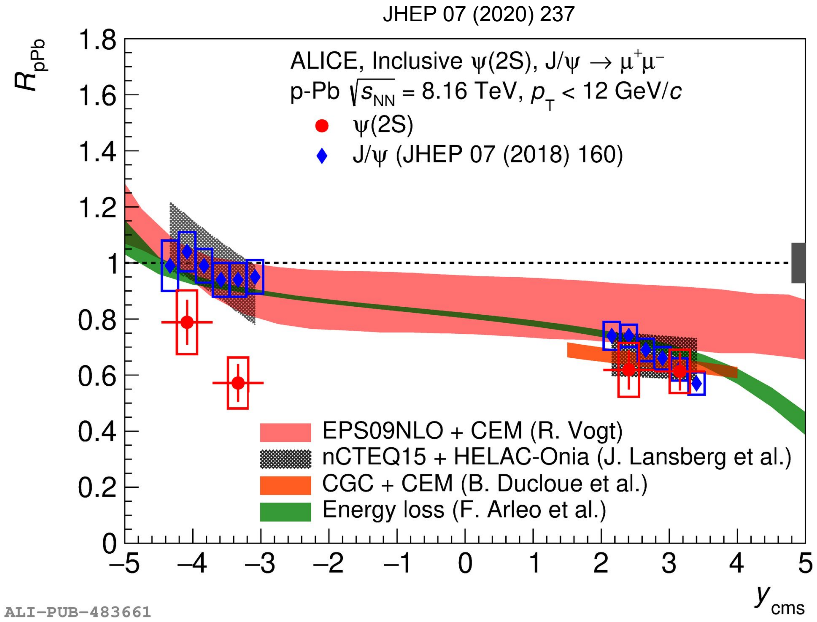

JHEP02 (2021) 002

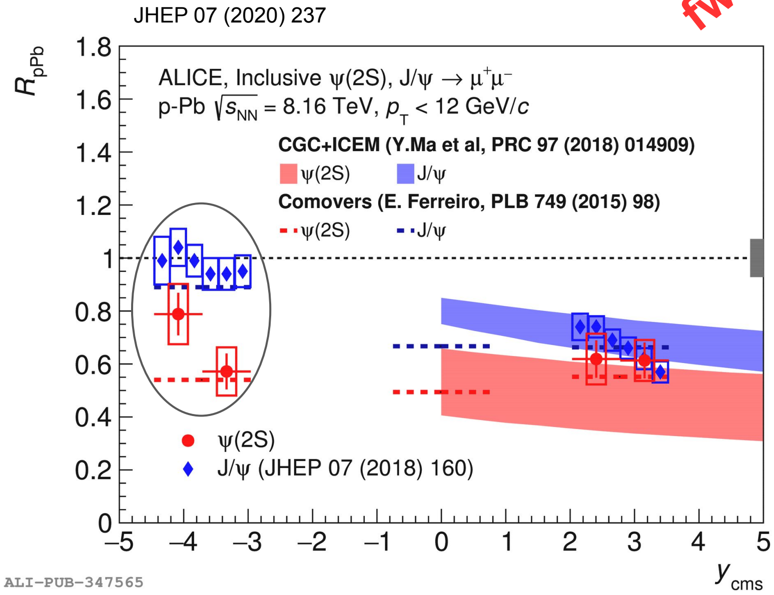



- Similar suppression for the J/ψ and the ψ(2S) as a function of centrality at forward rapidity
- Systematically stronger suppression for the ψ(2S) w.r.t J/ψ as a function of centrality at backward rapidity
- EPS09 + CEM describes the J/ψ QpPb at both rapidities within uncertainties but fails at describing the ψ(2S) QpPb
- Fair description by the Transport Model (TM) for both resonances at forward y. TM overestimates data at backward y in peripheral events
  - Stronger suppression of ψ(2S) in TM due to short QGP + hadron resonance gas
- Comovers + EPS09 : fair description of the ψ(2S) suppression at backward y, no firm conclusion at forward y
  - Larger density of comovers in the Pb-going direction

# Charmonium production in p–Pb collisions

fwd-y



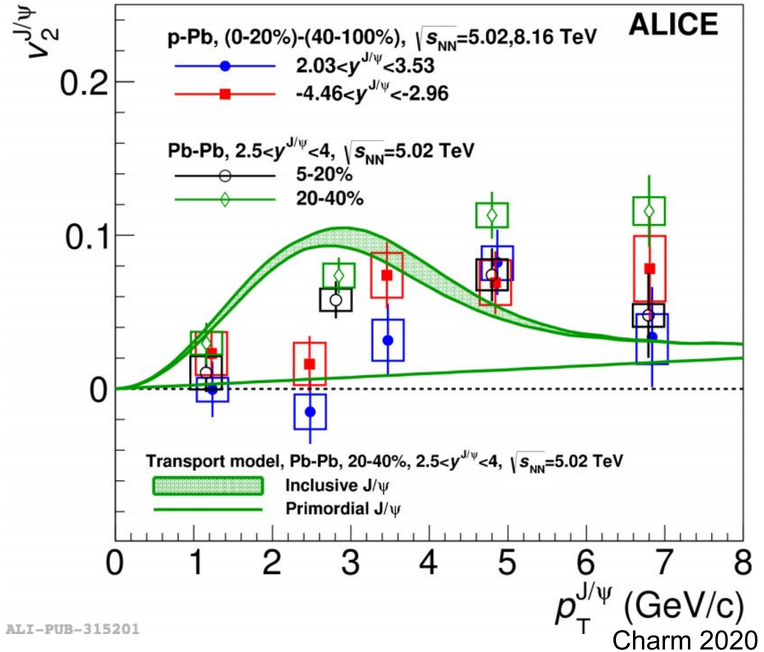




- Stronger suppression of the ψ(2S) w.r.t J/ψ at backward rapidity. Similar suppression at forward rapidity
- Theoretical calculations based only on initial state effects or coherent energy loss describe the J/ψ results but fail at describing the backward ψ(2S) suppression.
- Need to account for additional final state interactions (soft color exchanges, comovers)

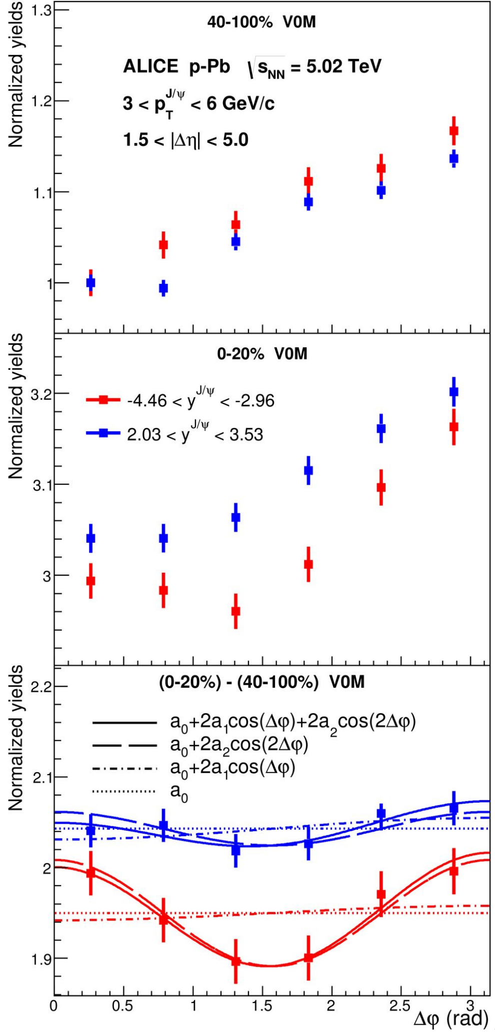
# Charmonium elliptic flow ($v_2$) in p–Pb

- $v_2$ in p-Pb collisions studied through long-range azimuthal correlations technique:
  - associated yields per-trigger particle at low multiplicity (40-100%) subtracted from those at high (0-20%) multiplicity → remaining symmetric structures visible at $\Delta\varphi \sim 0$ and $\Delta\varphi \sim \pi$ → $v_2$ extracted from fitting the subtracted distributions

Phys. Lett. B 780 (2018) 7-20




Non-zero $v_2$ observed for pT > 3 GeV/c (~5 significance)
Similar $v_2$ compared to Pb-Pb measurements→ very intriguing result: common underlying mechanism ?




Phys. Lett. B 780 (2018) 7-20