Challenges in quarkonium and exotic-state production in small systems

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Small systems

Old paradigm:

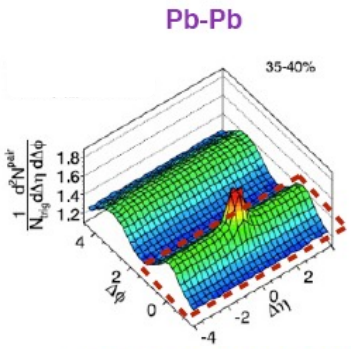
- we study hot & dense matter properties in heavy ion AA collisions
- cold nuclear matter modifications in pA
- and we use pp primarily as QCD baseline appears no longer sensible

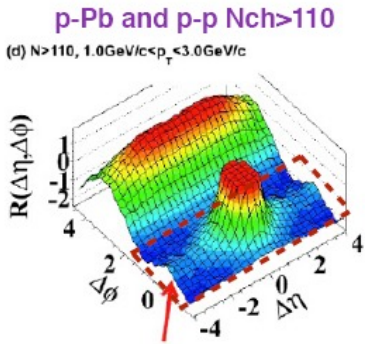
Discovery of correlations –ridge, flow- in small systems pA & pp at high multip

- Smooth continuation of heavy ion phenomena to small systems
- Small systems as pA and pp show QGP-like features

Two different explanations remain today:

- initial state: quantum correlations as calculated by CGC
- final state: with (hydrodynamics) or without equilibration





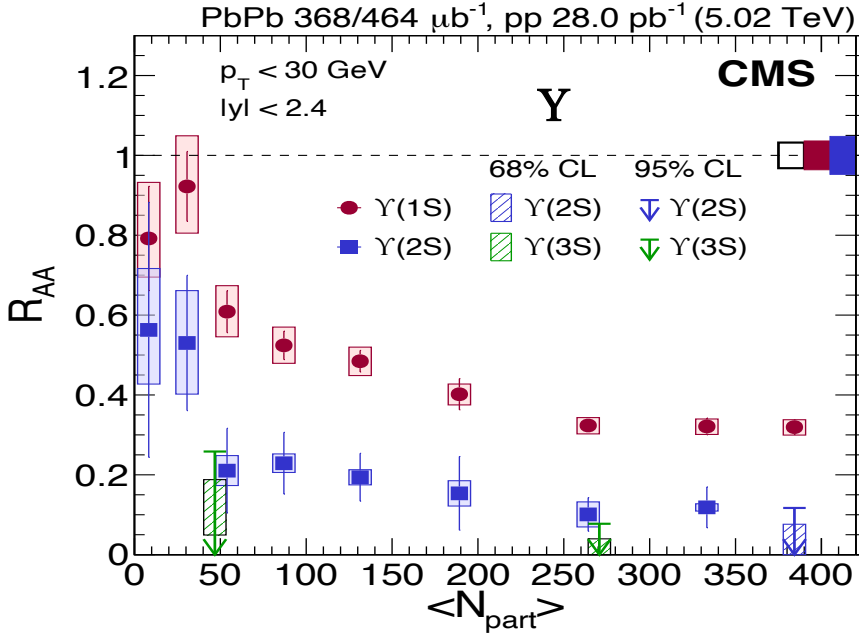
We should examine a new paradigm, where the physics underlying collective signals can be the same in all high energy reactions, from pp to central AA, depending on energy density/mult

Measuring quarkonium nuclear effects: the nuclear modification factor AA

Nuclear modification factor R_{AA}

$$R_{AA} = \frac{d^2N^{pA}/dp_T d\eta}{N_{coll}\, d^2N^{pp}/dp_T d\eta}$$

- R_{AA}<1: suppression
- R_{AA}=1: no nuclear effects
- R_{AA}>1: enhancement



Original motivation to measure quarkonium in nuclear collisions (AA): Signal of QGP

Observable: R_{AA} vs energy density

- The 3 upsilon states are suppressed with increasing centrality/energy density

$R_{AA}[\Upsilon(1S)] > R_{AA}[\Upsilon(2S)] > RAA[\Upsilon(3S)]$

=> Sequential melting

...but the situation is by far much more complex

pp & pA

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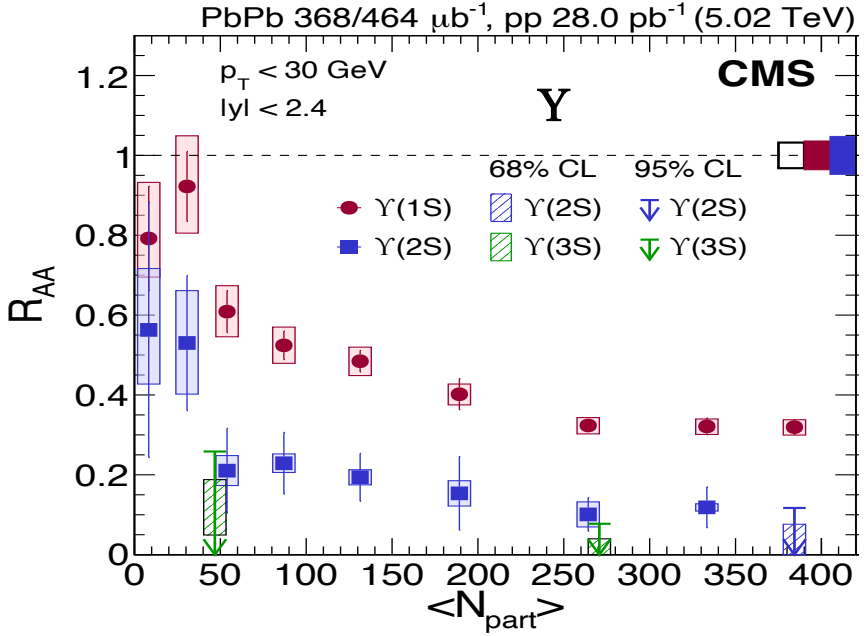

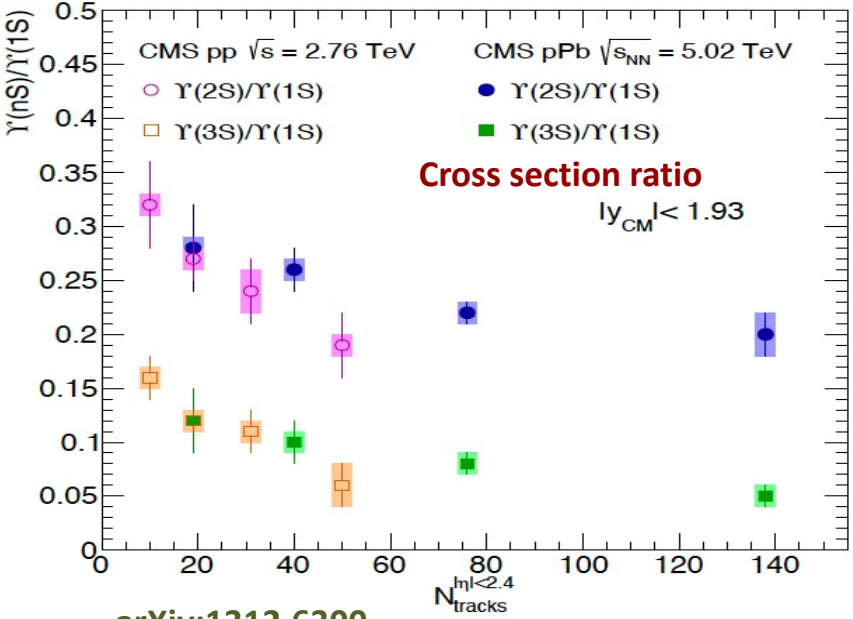

arXiv:1312.6300

...but the situation is by far much more complex

pp & pA

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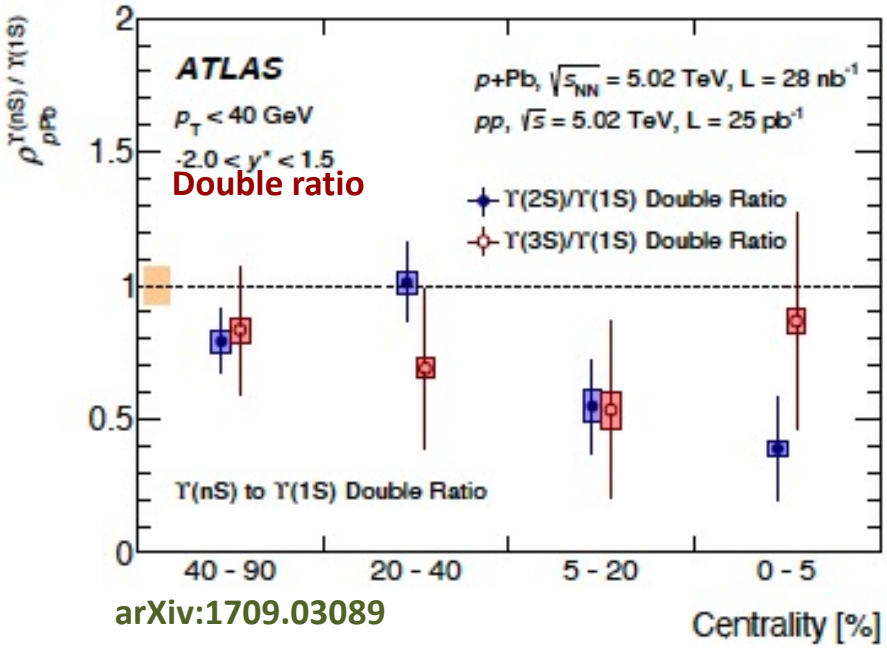
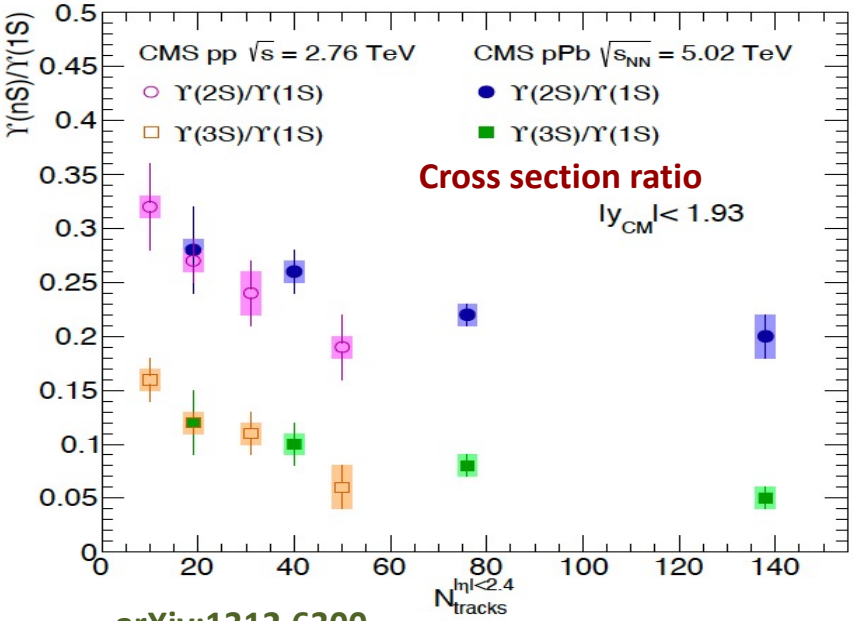


arXiv:1709.03089



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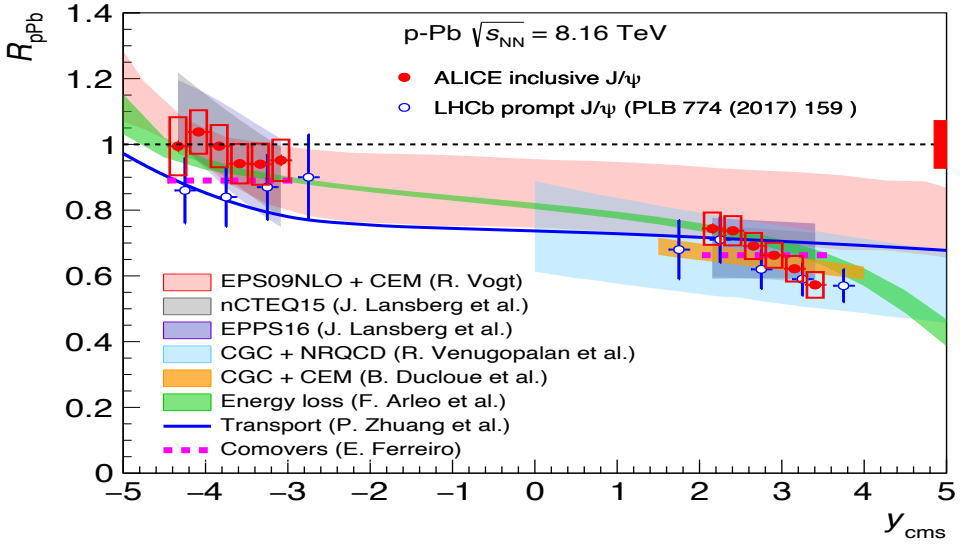
...but the situation is by far much more complex pA

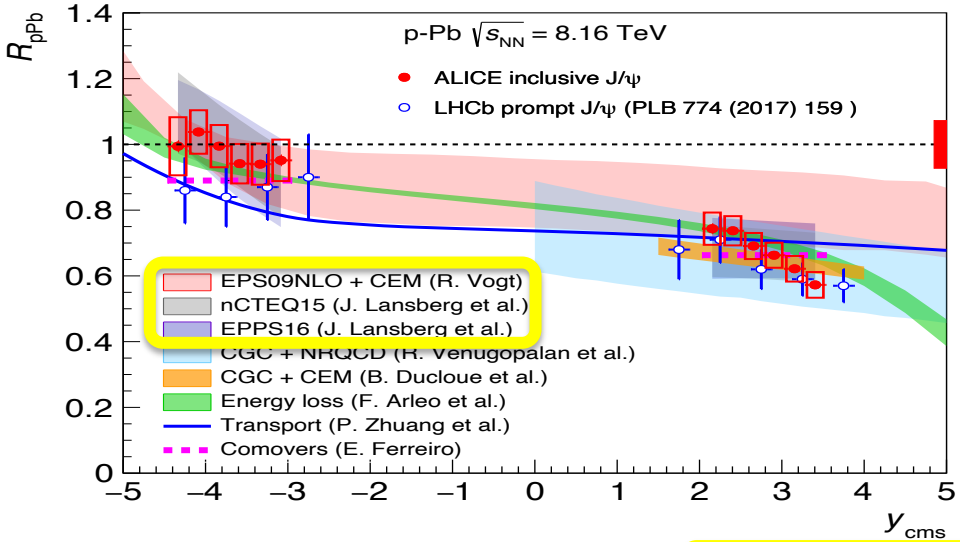


- There are other effects, not related to colour screening, that induce suppression of quarkonium states
- These effects are not all mutually exclusive
- They should be also taken into account in AA collisions

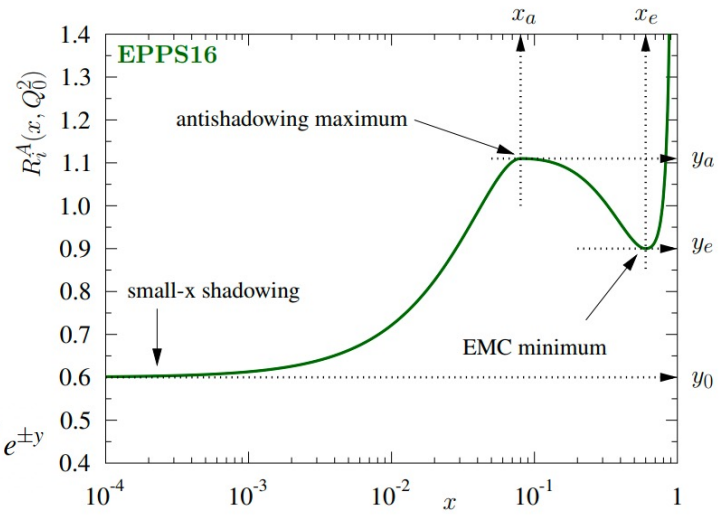
the distinction of these effects is not straightforward, their factorization is not easily established

- Modification of the gluon flux *initial-state effect*
  - Nuclear PDF in nuclei: nPDF shadowing
  - Gluon saturation at low x: CGC
- Parton propagation in medium *initial/final effect*
  - Coherent energy loss
- Quarkonium-medium interaction *final-state effect*
  - Comover interaction/transport models
  - Nuclear break-up
- Other QGP-like effects?

Modification of the gluon flux: Nuclear modification of PDFs pA



$$x = \frac{M_{J/\psi}}{\sqrt{s}} e^{\pm y}$$

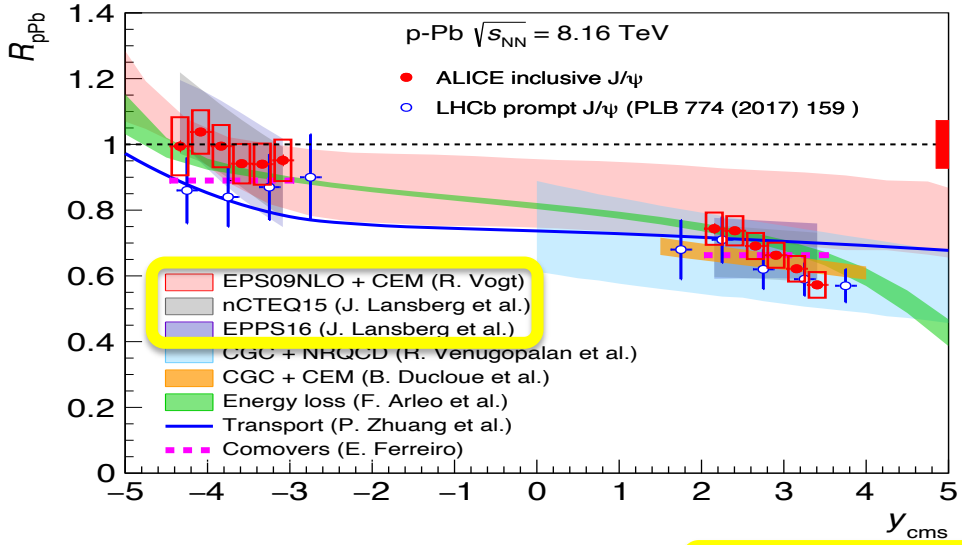


- Modification of the gluon flux *initial-state effect*
- Nuclear PDF in nuclei: nPDF shadowing

Gluon shadowing/antishadowing: Parton distribution functions are modified by the nuclear environment

⇒ J/ψ suppression or enhancement as a function of the parton momentum fraction x in the nucleon

Modification of the gluon flux: Nuclear modification of PDFs pA



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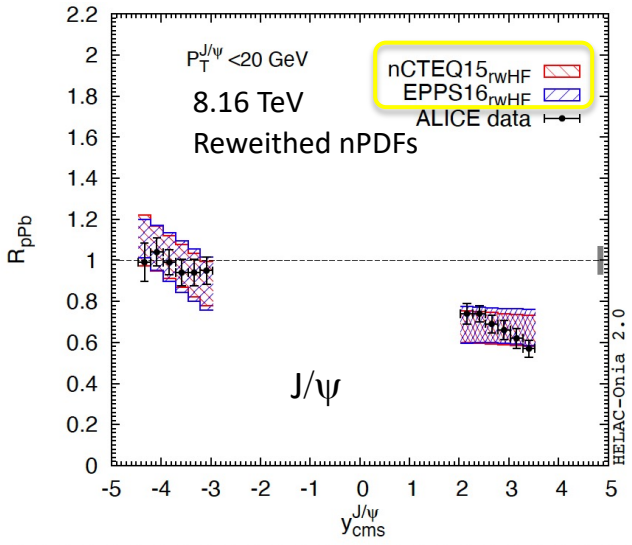

- Modification of the gluon flux *initial-state effect* ◆ Nuclear PDF in nuclei: nPDF shadowing

Gluon shadowing/antishadowing: Parton distribution functions are modified by the nuclear environment

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- It can explain the suppression at forward rapidity, the effect is around 1 at backward rapidity
- Roughly agrees with quarkonium ground-state data
- Issue: results very much widespread, applicability of reweithing? Extra effect in the backward region?

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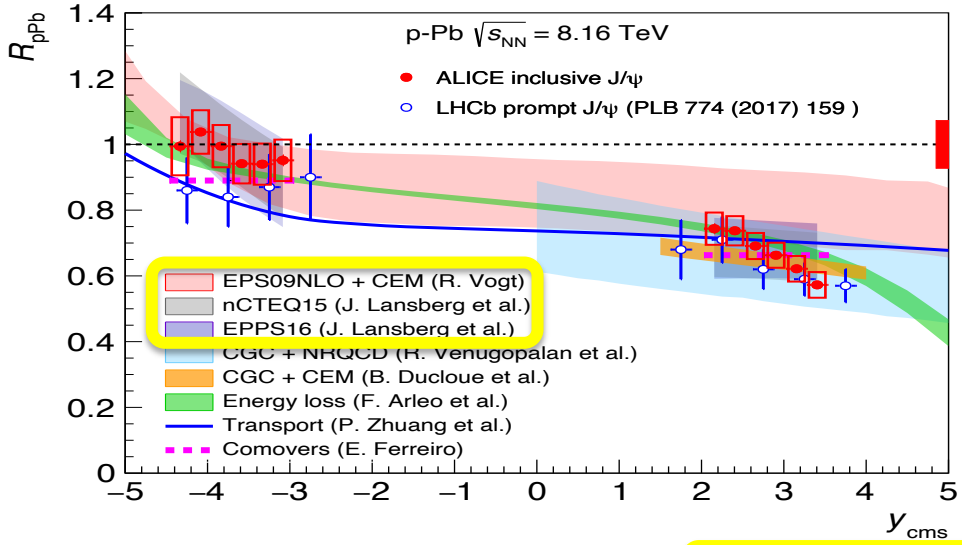

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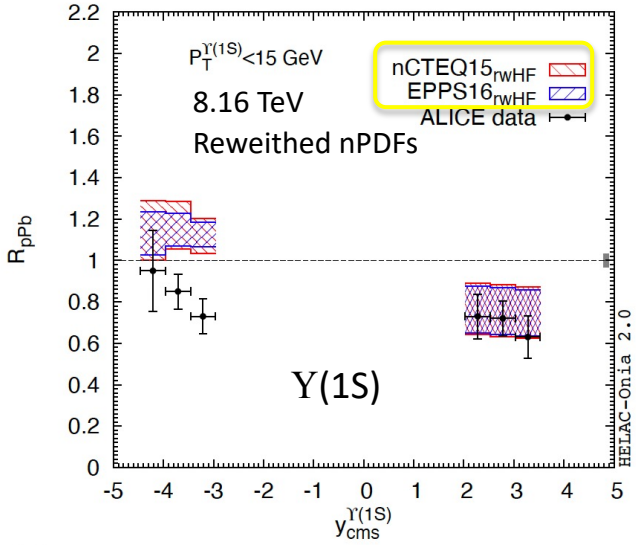


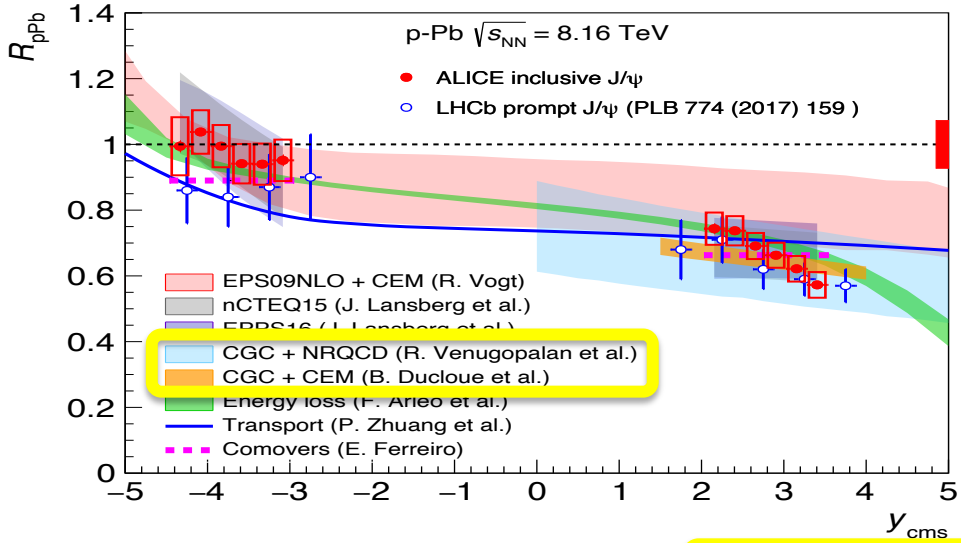
- Modification of the gluon flux *initial-state effect* ◆ Nuclear PDF in nuclei: nPDF shadowing

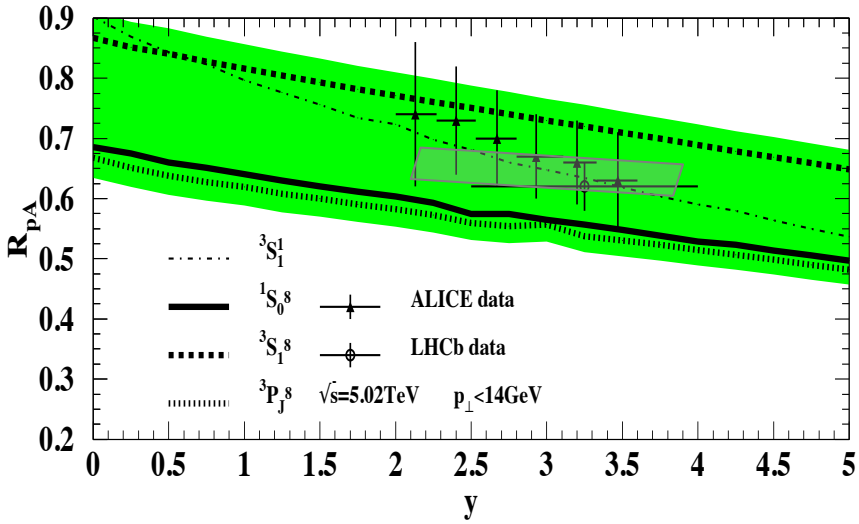
Gluon shadowing/antishadowing: Parton distribution functions are modified by the nuclear environment

⇒ Υ(1S) suppression or enhancement as a function of the parton momentum fraction x in the nucleon

- It can explain the suppression at forward rapidity, the effect is around 1 at backward rapidity
- Roughly agrees with quarkonium ground-state data
- Issue: results very much widespread, applicability of reweithing? Extra effect in the backward region?

Modification of the gluon flux: Gluon saturation pA





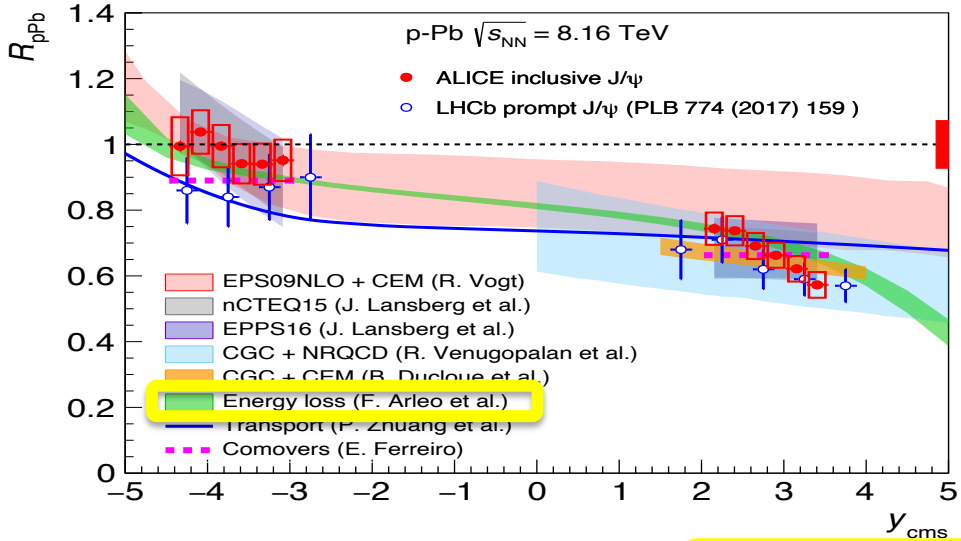
- Modification of the gluon flux *initial-state effect*
- Gluon saturation at low x: CGC

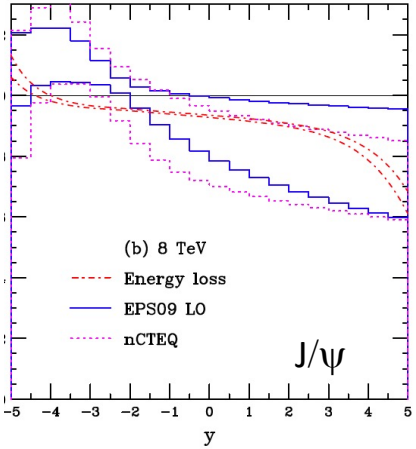
Gluon saturation: Result of gluon recombination at small x at LHC $Q^2_{sA} = A^{\frac{1}{3}} \times 0.2 \times \left(\frac{x_0}{x}\right)^{\lambda}$ $\lambda \sim 0.2 \div 0.3$ $x_0 = 0.01$

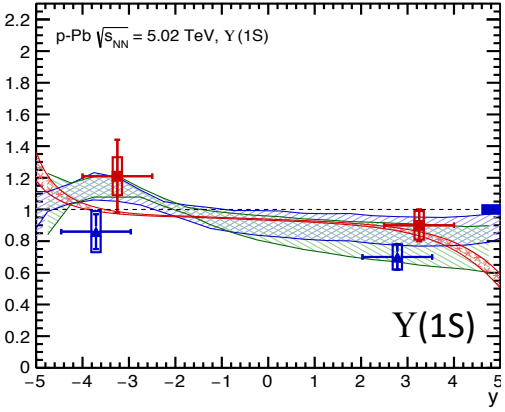
$\Rightarrow$ J/ψ suppression at forward rapidity (this effect does not apply in the backward rapidity region)

- CEM with improved geometry **Ducloue et al**
- NRQCD: results depend on the CO channel mix, contribution of CS channel relatively small **Venugopalan et al**
- Issue: Results can vary depending of the production mechanism Shadowing & CGC are mutually exclusive

Parton propagation in medium: Coherent energy loss pA







- Parton propagation in medium *initial/final effect*
- Nuclear transverse momentum broadening of the heavy quark pair induces coherent gluon radiation => J/ψ & Υ(1S) yield modification

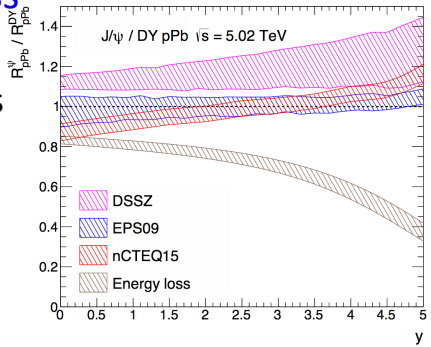
$$\Delta E = \int d\omega\, \omega \left.\frac{dI}{d\omega}\right|_{\text{ind}} = N_c \alpha_s \frac{\sqrt{\Delta q_\perp^2}}{m_T} E$$

- Roughly agrees with quarkonium ground-state data
- Issue: Imposible to discriminate from nPDF modification

◆ Coherent energy loss

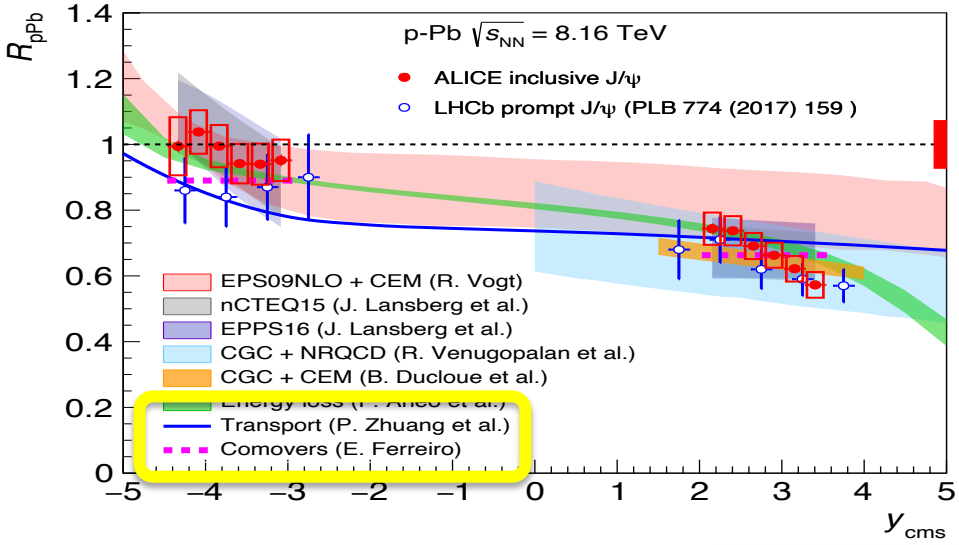
DY measurements could help

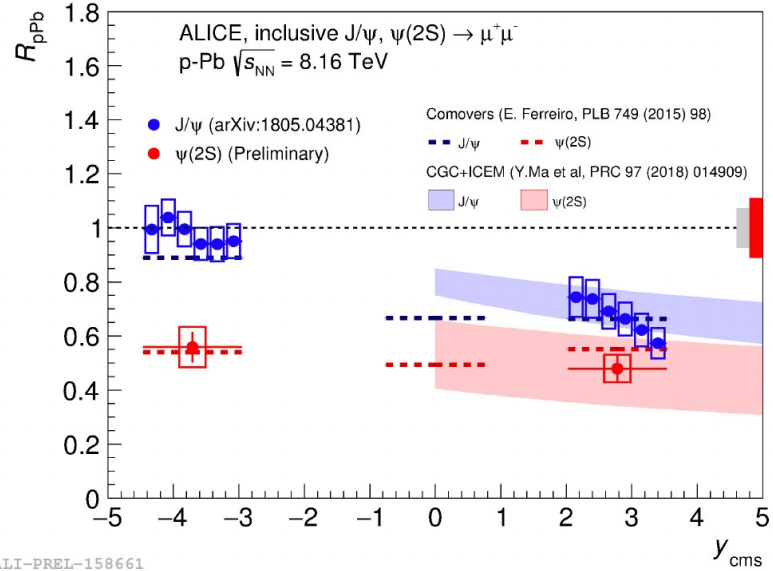
Extra effect in the backward region?



Final state effects

pA





- Quarkonium-medium interaction *final-state effect*
  - Comover interaction & transport models

J/ψ shows stronger suppression at forward rapidity while compatible with 1 at backward rapidity.

- The pattern is consistent with initial- and final-state effect models

ψ(2S) shows similar suppression in both intervals

- Cannot be described by only initial state effects
- Inclusion of final-state effects give a good description for both states

Final state effects: the excited states pA

Data from RHIC & LHC

- Relative $\psi(2S)/J/\psi$ suppression in dAu collisions @ 200 GeV (PHENIX)
- Relative $\psi(2S)/J/\psi$ suppression in pPb collisions @ 5 & 8 TeV (ALICE & LHCB)
- Relative $\psi(2S)/J/\psi$ suppression in pPb collisions @ 5 TeV (CMS & ATLAS)
- Relative $\Upsilon(nS)/\Upsilon(1S)$ suppression in pPb collisions @ 5 TeV & 8TeV (CMS & ATLAS & LHCB)

- Initial-state effects –modification of nPDFs / coherent E loss- identical for the family
- Any difference among the states should be due to final-state effect

- At low E: the relative suppression can be explained by nuclear absorption $\sigma_{breakup} \alpha\, r^2_{meson}$
  At high E: too long formation times $t_f = \gamma\, \tau_f >> R$ => the quantum state does not matter!

A natural explanation would be a final-state effect acting over sufficiently long time
=> **interaction with a comoving medium through a transport equation**

Excited states: Comover interaction pA

- In a comover model: suppression from scatterings of the nascent $\mathcal{Q}$ with comoving medium of partonic/hadronic origin **Gavin, Vogt, Capella, Armesto, EGF, Tywoniuk…**

- Rate equation governing the charmonium density:

$$\tau \frac{d\rho^{\psi}}{d\tau}(b,s,y) = -\sigma^{co-\psi}\,\rho^{co}(b,s,y)\,\rho^{\psi}(b,s,y)$$

$\sigma^{co-\psi}$ originally fitted from SPS data

- Going to a microscopic level:

$$\sigma^{\mathrm{co}-\mathcal{Q}}(E^{\mathrm{co}}) = \sigma^{\mathcal{Q}}_{\mathrm{geo}} \times \left(1 - \frac{E^{\mathcal{Q}}_{\mathrm{thr}}}{E^{\mathrm{co}}}\right)^{n}$$

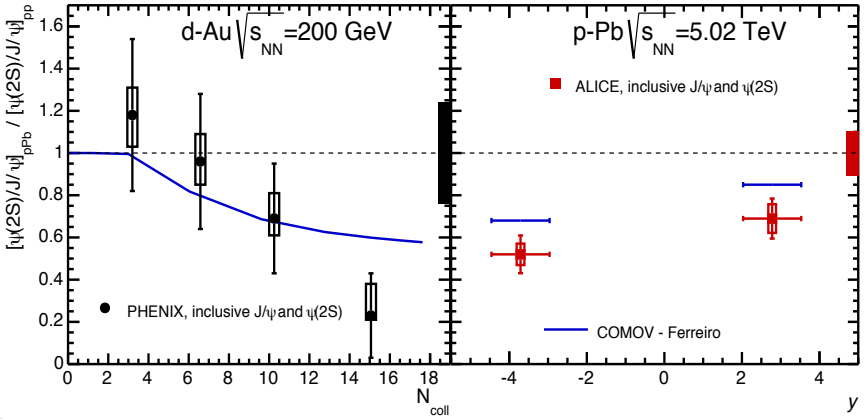
$\sigma^{\mathcal{Q}}_{\mathrm{geo}} \simeq \pi r^2_{\mathcal{Q}}$

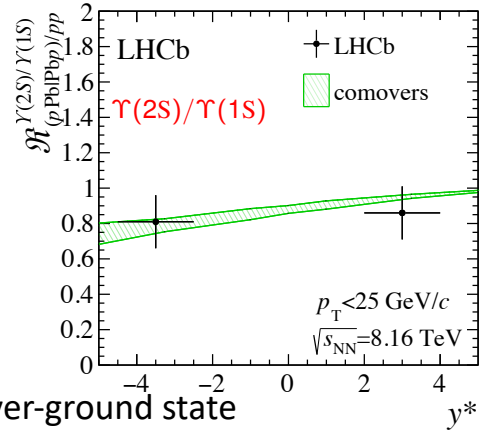
$E^{\mathcal{Q}}_{\mathrm{thr}} = 2M_B - M_{\mathcal{Q}_{b\bar{b}}}$

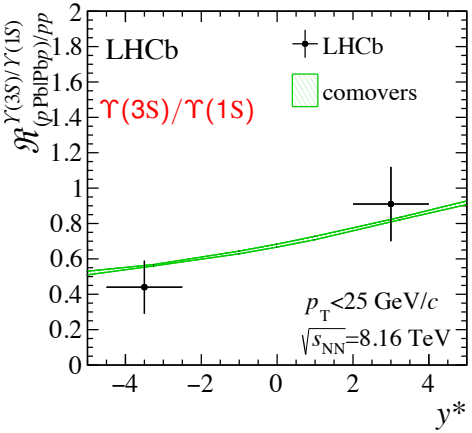
$E^{co} = \sqrt{p^2 + m^2_{co}}$

$\mathcal{P}(E^{\mathrm{co}}; T_{\mathrm{eff}})$ Bose Einstein distr.

$$\langle \sigma^{\mathrm{co}-\mathcal{Q}} \rangle (T_{\mathrm{eff}}, n) = \frac{\int_0^{\infty} dE^{\mathrm{co}}\, \mathcal{P}(E^{\mathrm{co}}; T_{\mathrm{eff}})\, \sigma^{\mathrm{co}-\mathcal{Q}}(E^{\mathrm{co}})}{\int_0^{\infty} dE^{\mathrm{co}}\, \mathcal{P}(E^{\mathrm{co}}; T_{\mathrm{eff}})}$$





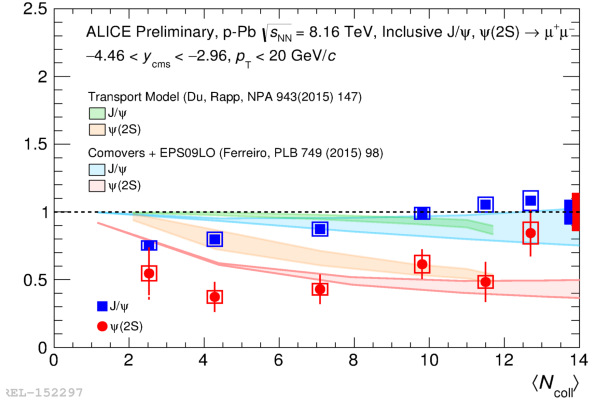


- To get rid of initial-state effects: double ratio excited-over-ground state

Excited states: Comover interaction pA

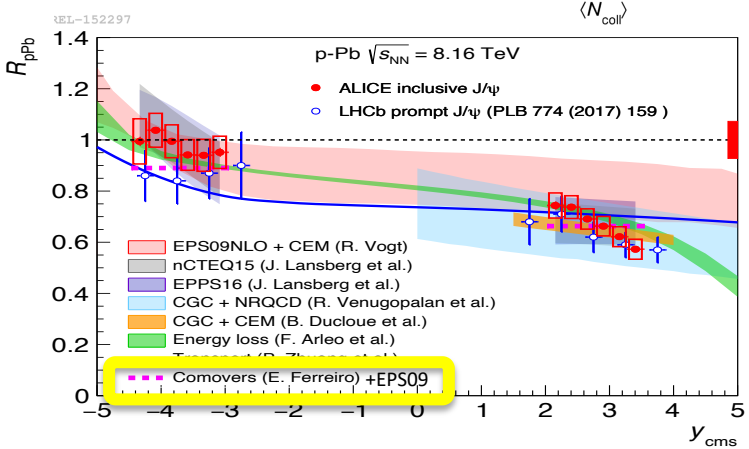
Transport model with final interactions **Du & Rapp (2015)**

"similar in spirit to comover suppression"

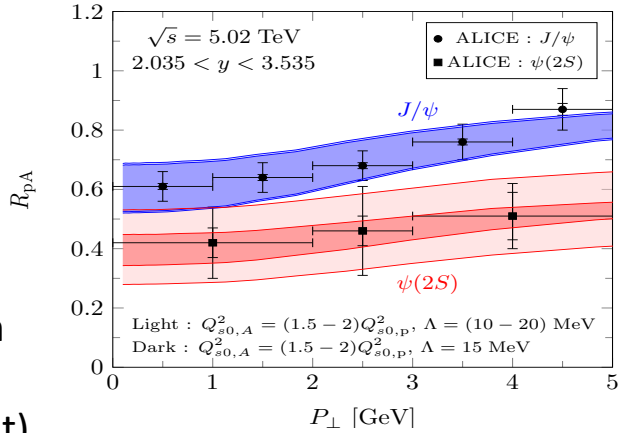


→New results on ψ(2S) confirm stronger suppression w.r.t. to J/ψ in the Pb-going direction.

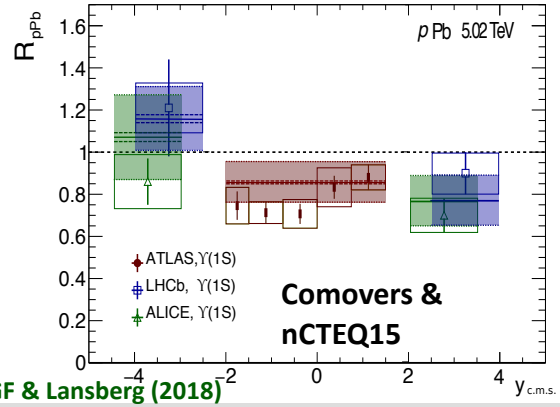
→Final state effects are needed to reproduce the ψ(2S) suppression.



Soft color exchanges between $c\bar{c}$ & comovers at later stage **Ma, Venugopalan, Zhang, Watanabe (2018)**



Stronger suppression in the nucleus-going direction (higher mult) => CI improves agreement for the ground state in the backward region (initial nPDFs modification also included)



EGF & Lansberg (2018)

Measuring *nuclear-like* effects in pp: the observables

pp

Relative multiplicity:

$$\frac{N_{\mathrm{ch}}}{\langle N_{\mathrm{ch}} \rangle}$$

Charged particle multiplicity, number of tracks, transverse energy, . . .

- Numerator characterises each event.
- Denominator is averaged over the full datasample.

Relative yields:

$$\frac{N^{i}_{\mathrm{J}/\psi}}{\langle N_{\mathrm{J}/\psi} \rangle}$$

i defines the multiplicity interval

- Numerator quantifies the number of quarkonia in bin i.
- Denominator gives the average number of quarkonia in the datasample.

Jana Crkovska's slide

Measuring *nuclear-like* effects in pp: the observables

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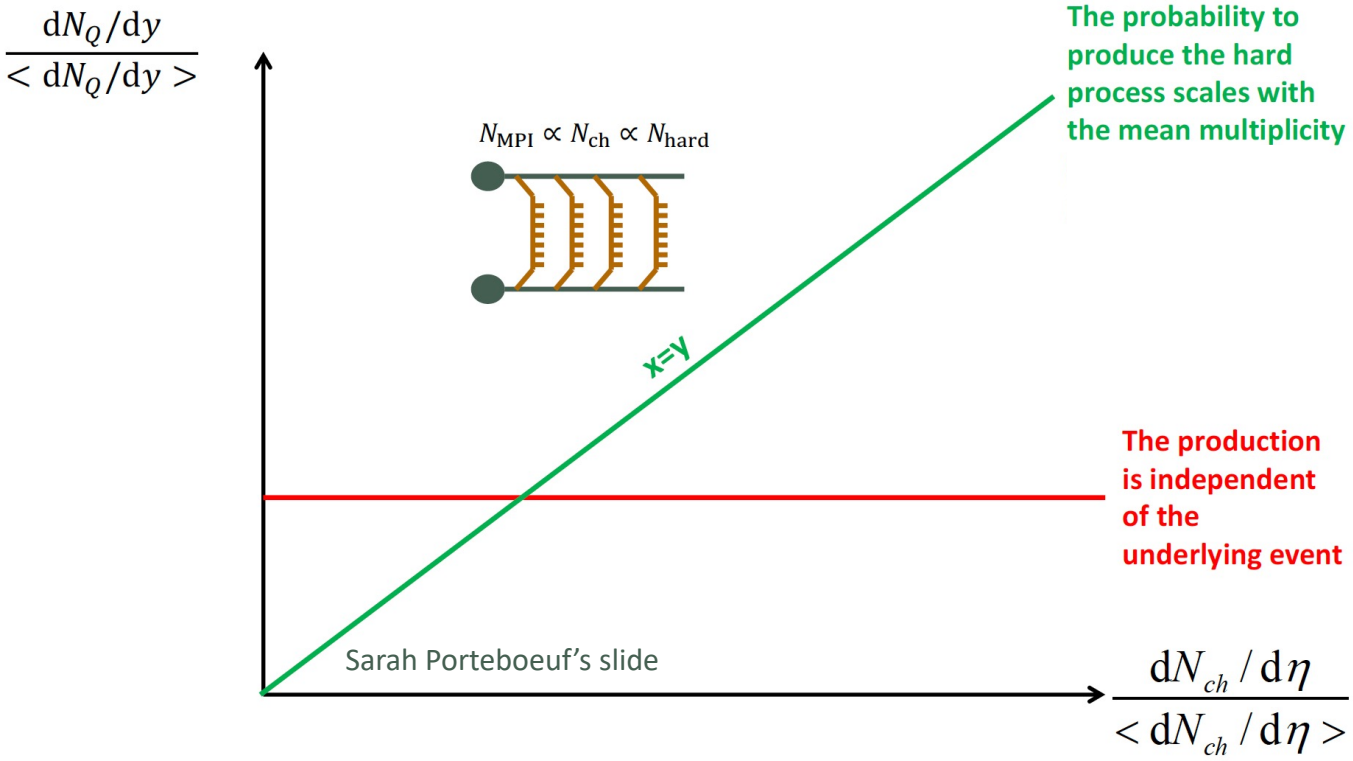
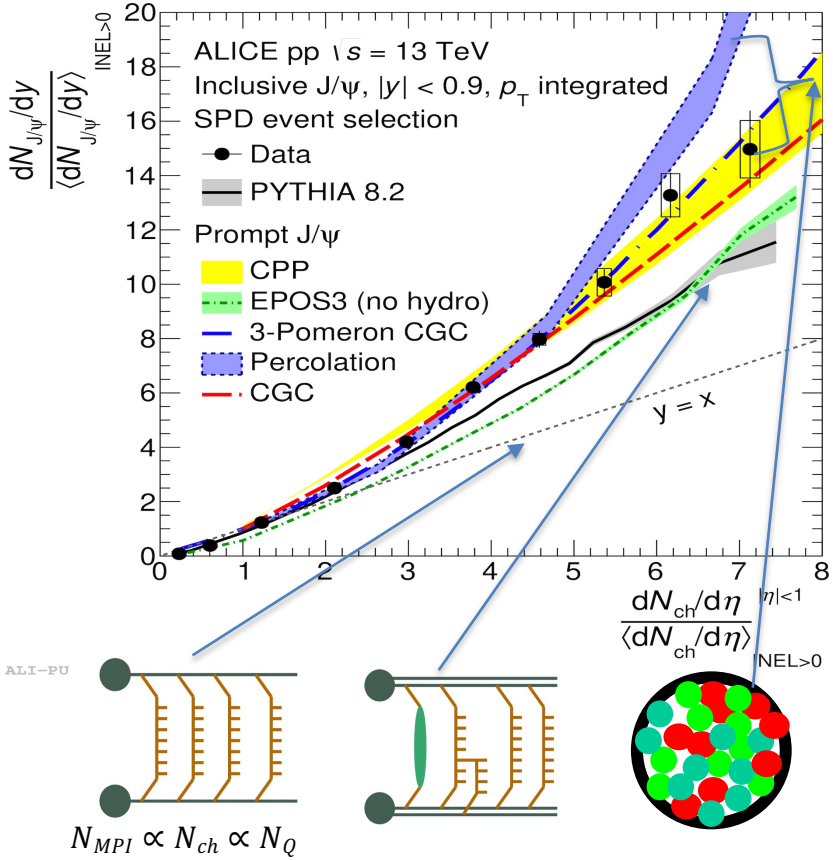


Sarah Porteboeuf's slide

Quarkonium vs multiplicity pp



- **EPOS:** MPI via Pomeron exchange (initial) + hydrodynamic expansión (final) hydro on/off has small effect, hadronic cascade on/off has no effect
- **PYTHIA:** MPI, hard scatterings (initial) + color reconnection, string shoving (final)
- **CGC:** Gluon saturation (initial) => Impact on particle producción, reduction
- **Percolation:** String saturation (initial) => Reduction on the number of charged particle

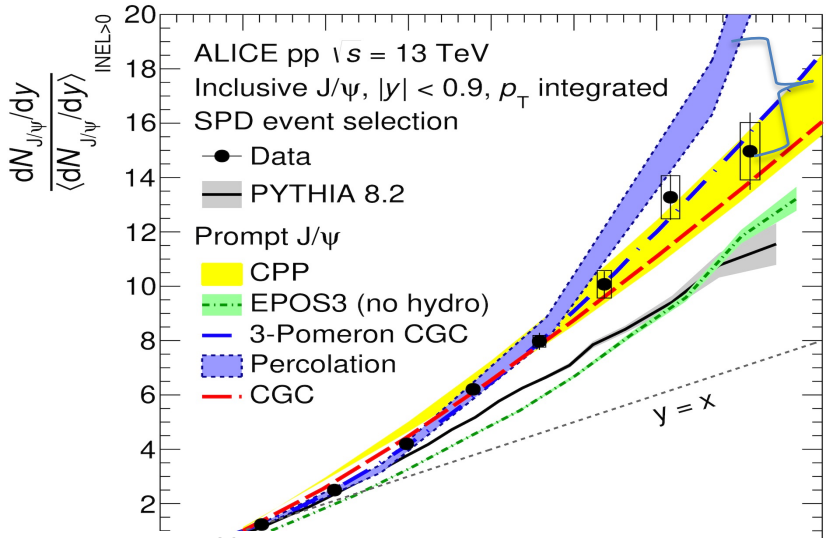
Initial state effects play a fundamental role:

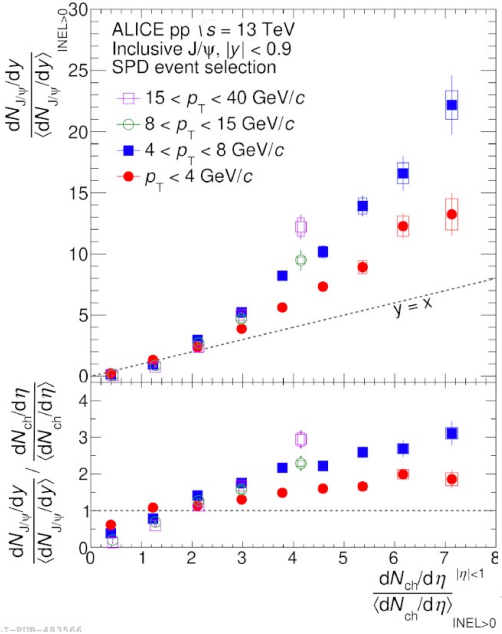
- MPI can introduce collectivity => Increase of hardeness
- Saturation => Decrease on total multiplicities => Indirect increase of the hard probe (not affected by saturation)
  - Events at different energies with the same $\rho_{strings}$ or Q_s are identical
  - The harder the probe, the stronger the difference

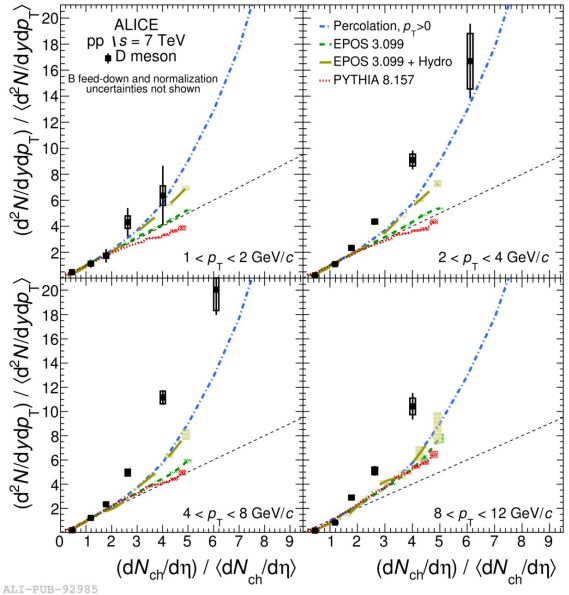
Multiplicity and probe measured in the same rapidity interval (both mid rapidities)

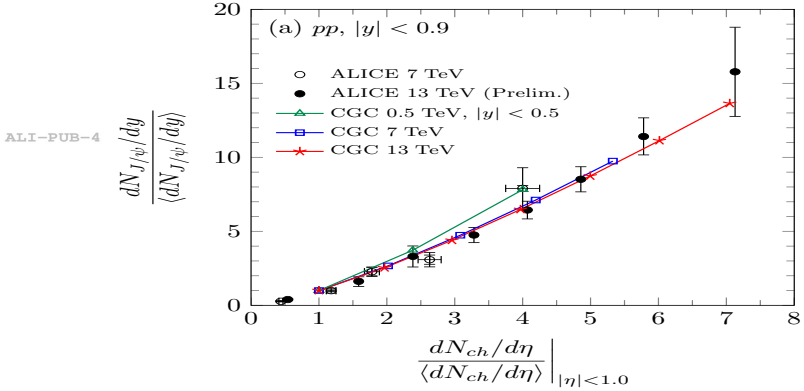
Quarkonium vs multiplicity

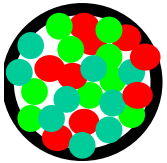
pp











- Saturation => Decrease on total multiplicities => Indirect increase of the hard probe (not affected by saturation)
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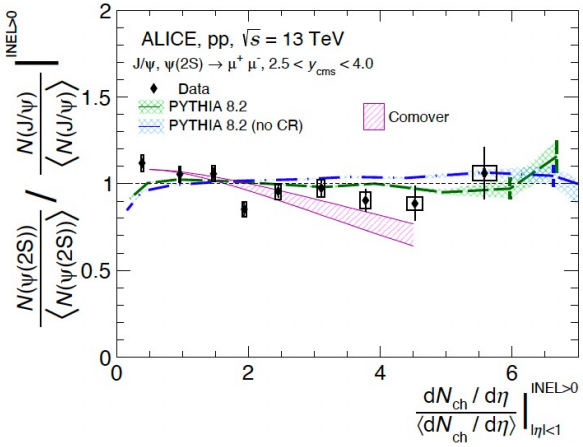
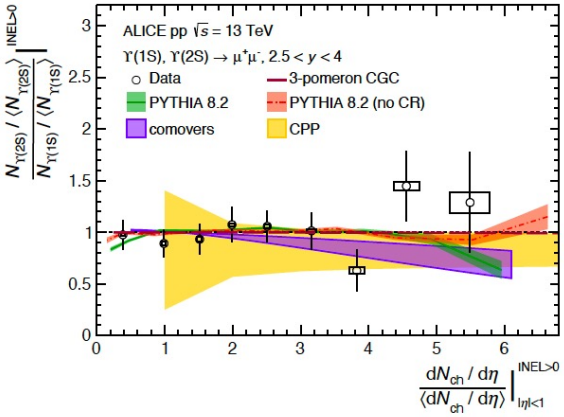
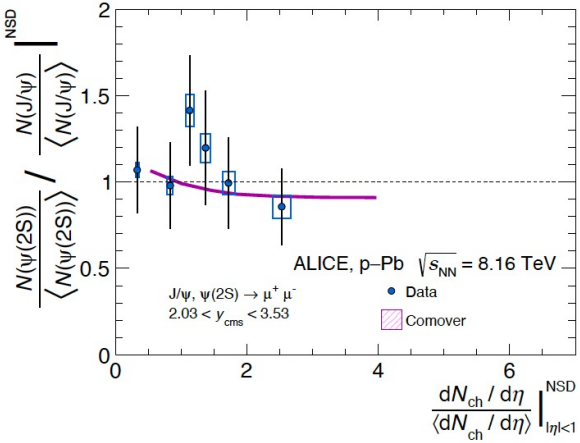
Multiplicity and probe measured in the same rapidity interval (both mid rapidities)

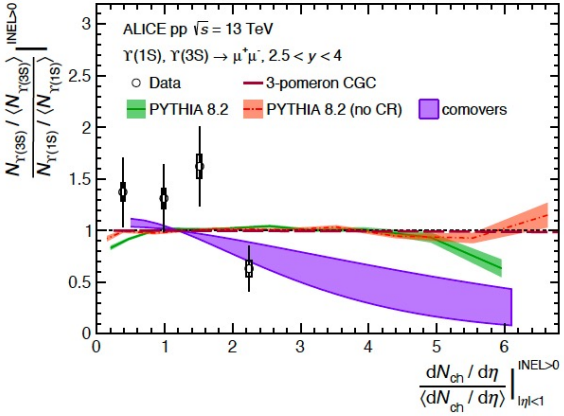
To get rid of initial-state effects: double ratio excited-over-ground state

- Initial-state effects cancel
- Final-state effects at play?



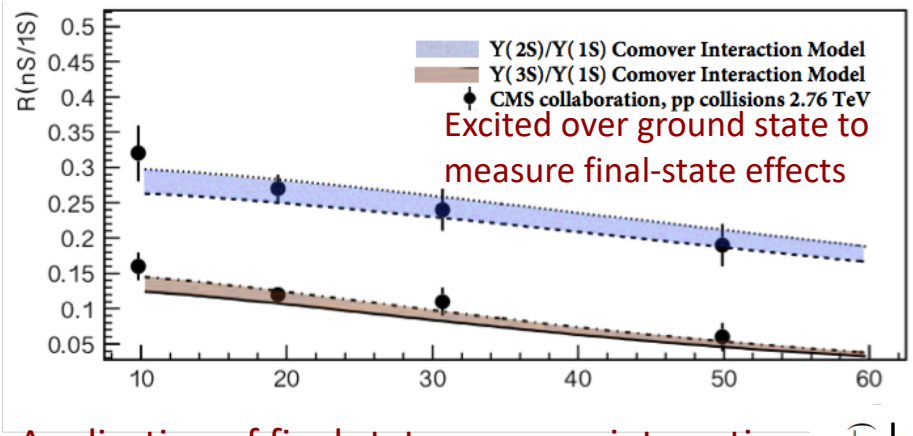




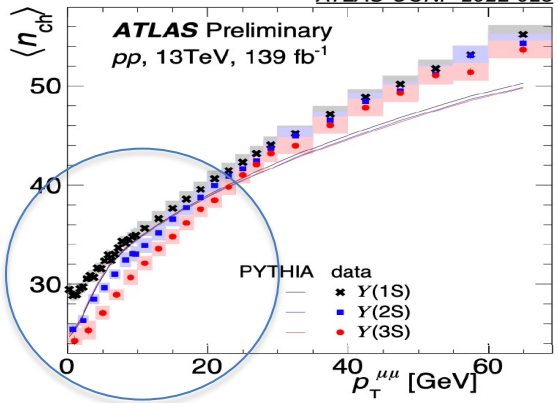


Quarkonium & HF vs multiplicity: excited states pp

- **Studies of ground vs excited states** can improve our understanding of the final-state effects

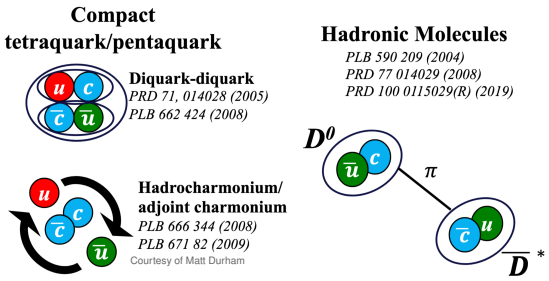


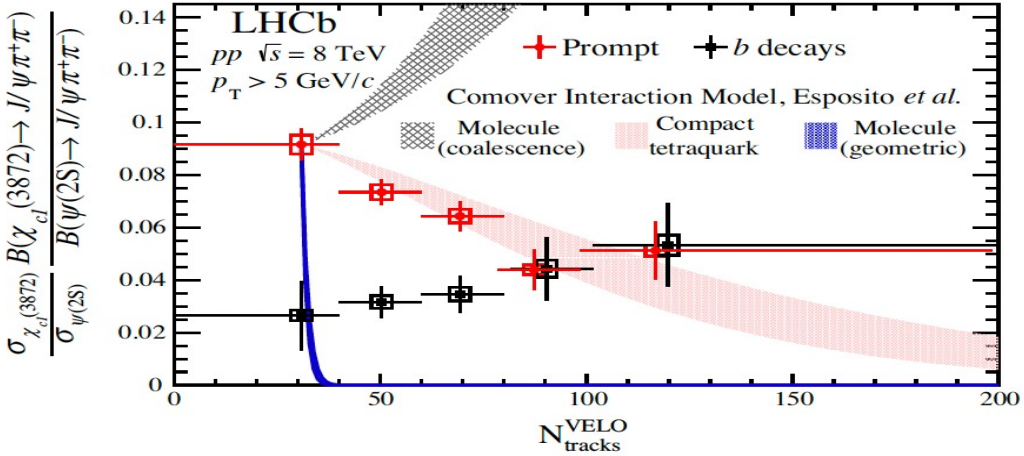
ATLAS-CONF-2022-023



consistent with a suppression of the excited Υ states at high charged-particle multiplicity.

Application of final state comover interaction to spectroscopy in pp collisions





Final remarks

- **Quarkonium ground states and open heavy mesons R_{pA}** can be reasonably well described by ***initial state effects***: nPDF modifications *or* CGC *and/or* coherent energy loss
- In order to describe **excited states R_{pA}** , ***final state effects*** become mandatory: Botzmann eq to describe the interaction with the medium, not necessarily in thermal equilibrium
- Clearly the extrapolated pA effects are significant and need to be understood for a proper interpretation of the AA results: **The effects that are at play in pA should be also taken into account in AA collisions**
- **Collectivity effects are also present in high-multiplicity pp collisions: *initial* or *final* effects?** The similarity between the D and J/ψ suggests that this behaviour is most likely related to the production processes. Moreover, no significant energy dependence is observed, which agrees with saturation approach
- **Final effects** are required to explain excited over ground state data also in pp high-multiplicity collisions
- In more general terms, if equilibrium is no longer a requirement, this naturally explain why pp data on azimuthal correlations appears to be so similar to data obtained in AA collisions (hydro vs. non-hydro initial-state explanation) How far can we go in this direction?