Workshop "Exploring Quark-Gluon Plasma through soft and hard probes"
29-31 May 2023, SANU (Serbian Academy of Science and Arts) - Belgrade, Serbia

Challenges in quarkonium and exotic-state production: from small to large 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

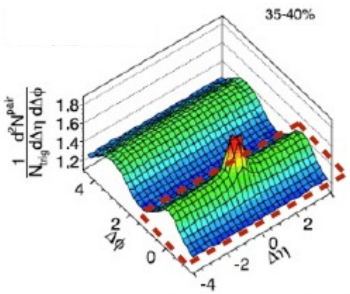
Discovery of correlations –ridge, flow- in small systems pA & pp at high multip

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

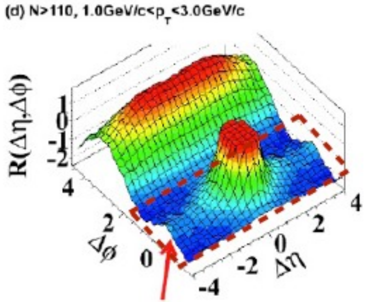
Two different explanations remain today:

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

Pb-Pb



p-Pb and p-p Nch>110

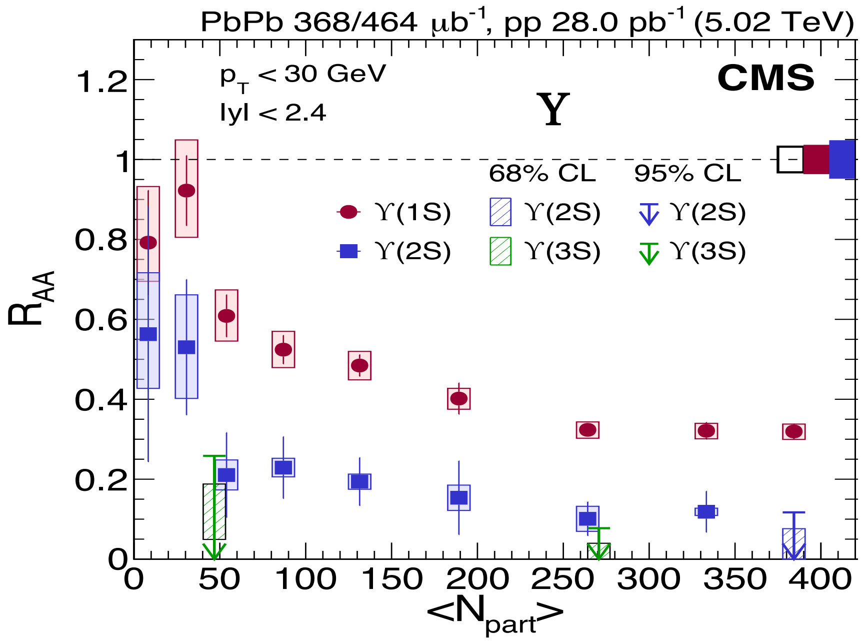


We should examine a new paradigm, where the physics underlying collective signals can be the same in all high energy reactions, from pp to central AA, depending on energy density/multiplicity

Nuclear modification factor R_{AA}

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

- $R_{AA}<1$: 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}[Y(1S)] > R_{AA}[Y(2S)] > RAA[Y(3S)]

=> Sequential melting

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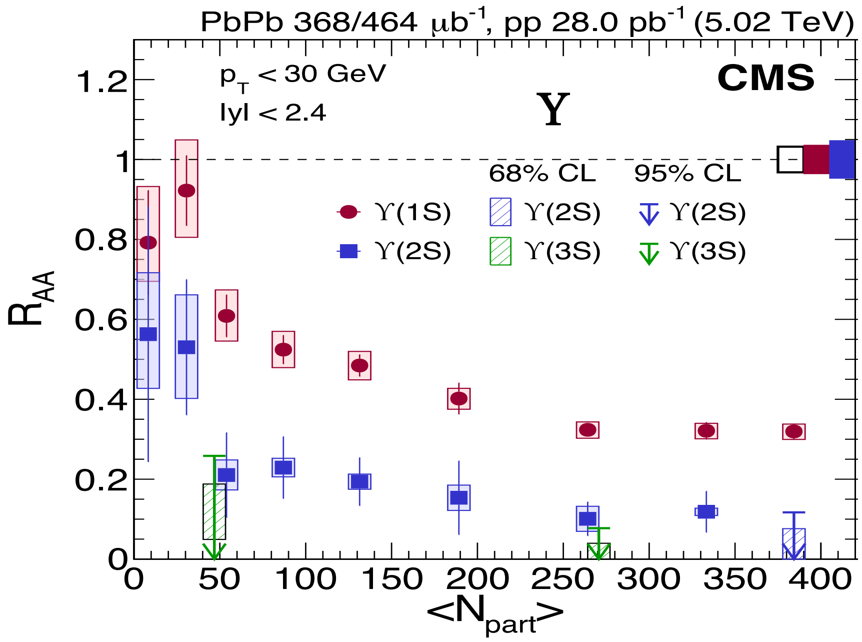

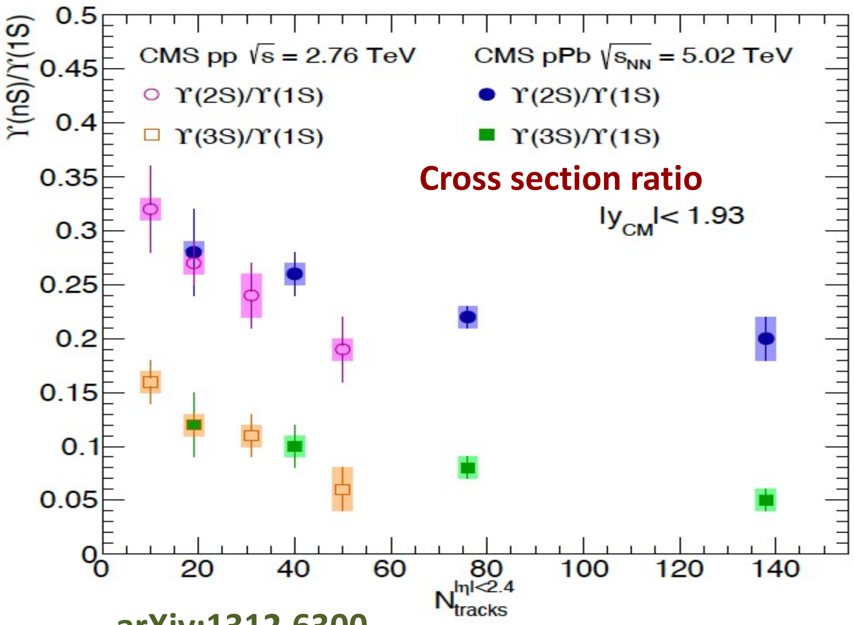

arXiv:1312.6300

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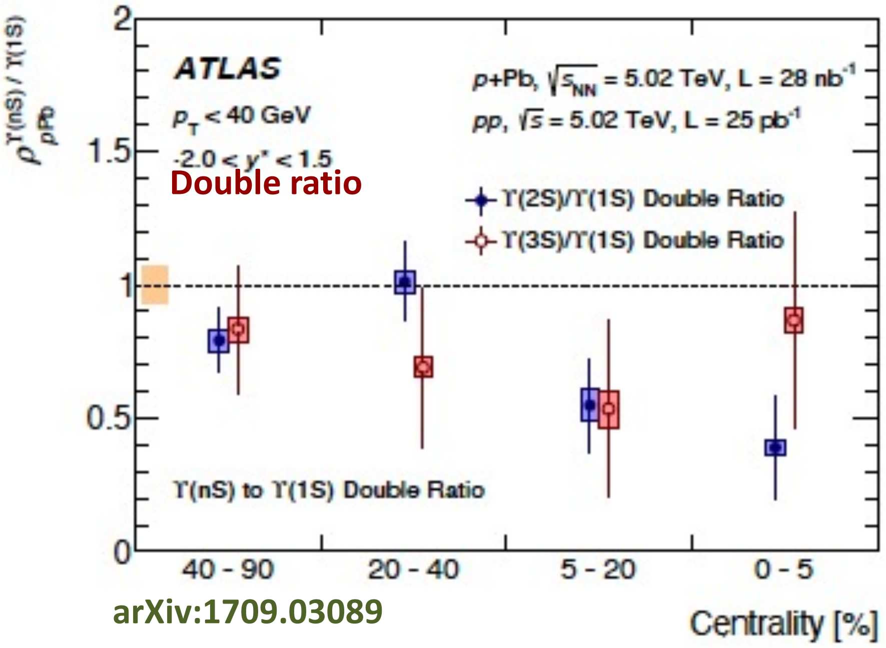
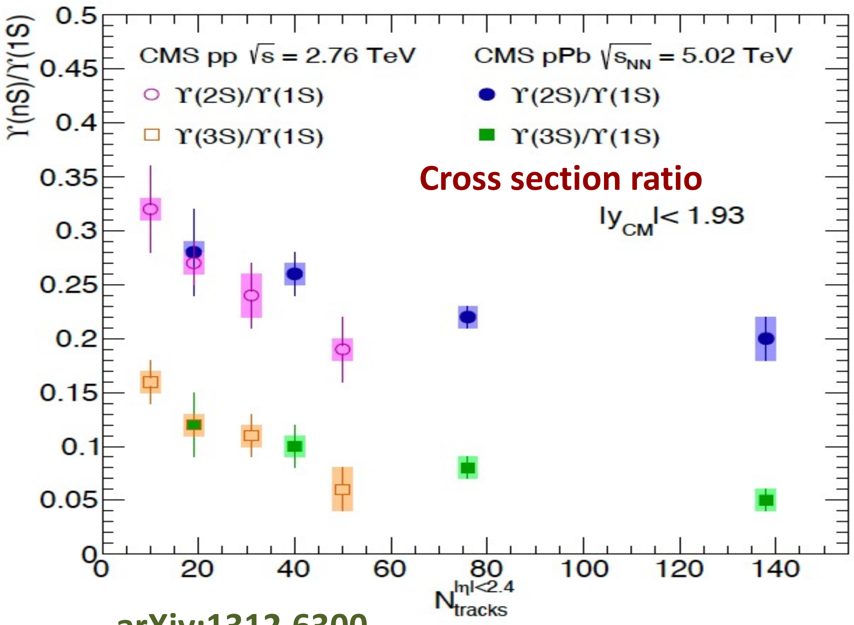


arXiv:1709.03089



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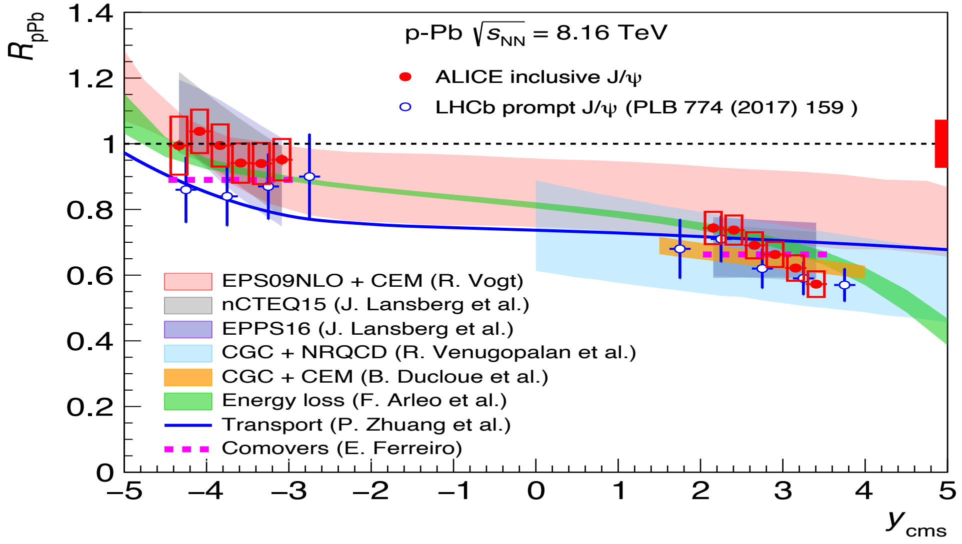
...but the situation is by far much more complex pA

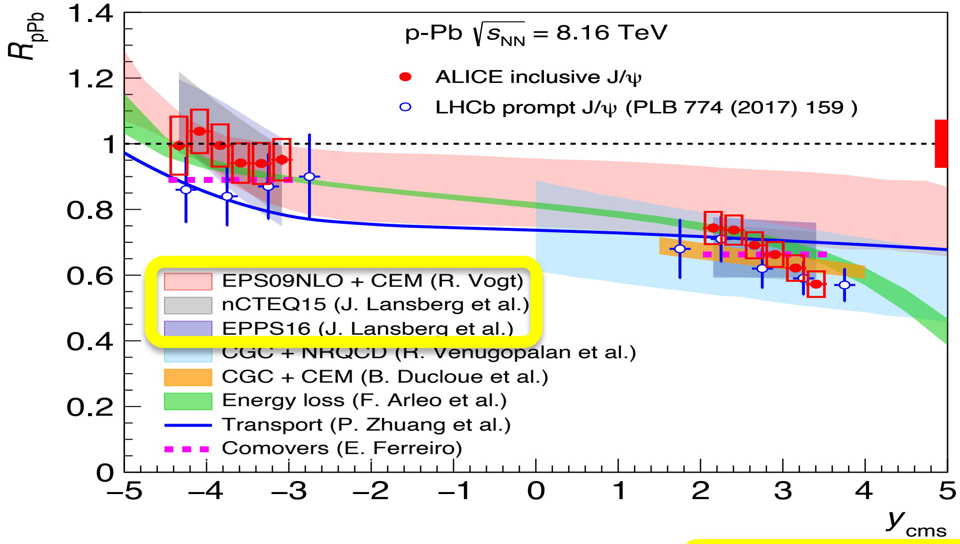


- There are other effects, not related to colour screening, that induce suppression of quarkonium states
- These effects are not all mutually exclusive
- They should be also taken into account in AA collisions

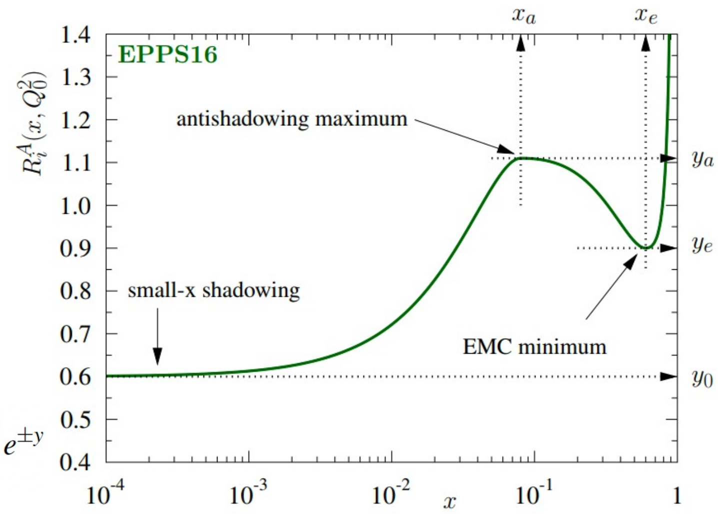
the distinction of these effects is not straightforward, their factorization is not easily established

- 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



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

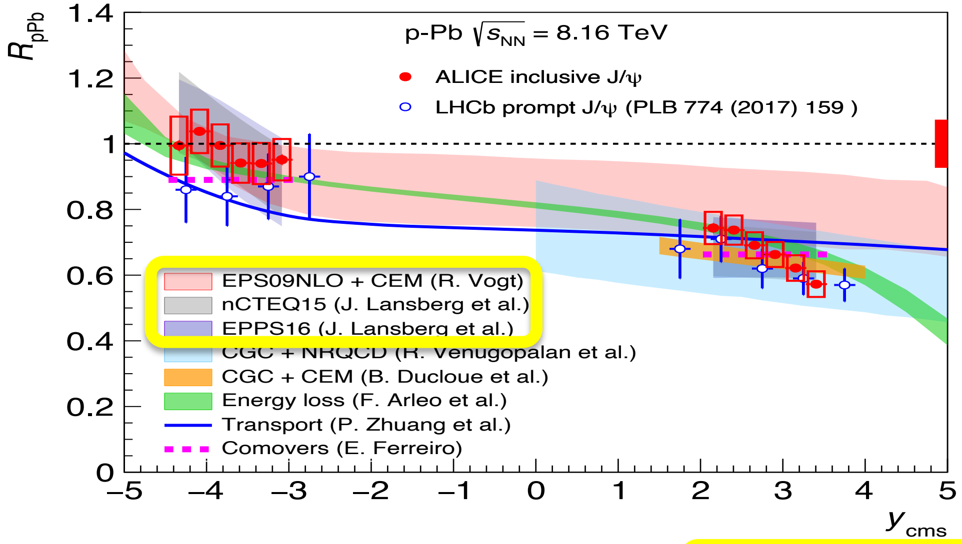


- Modification of the gluon flux *initial-state effect* ◆ Nuclear PDF in nuclei: nPDF shadowing

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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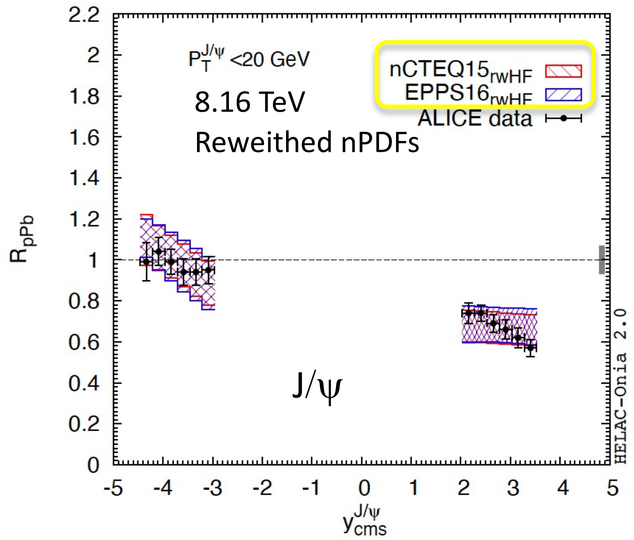


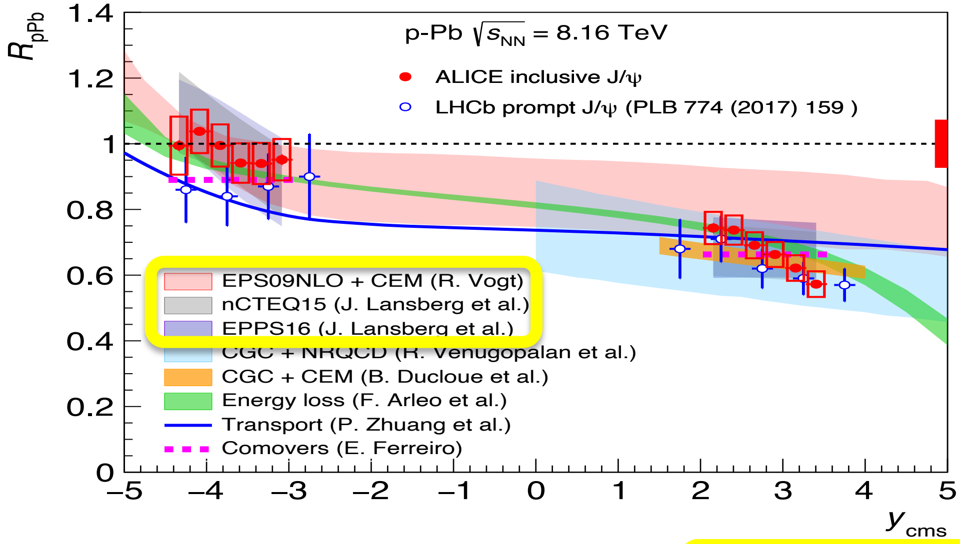
- Modification of the gluon flux *initial-state effect* ◆ Nuclear PDF in nuclei: nPDF shadowing

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

⇒ J/ψ 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: Nuclear modification of PDFs pA



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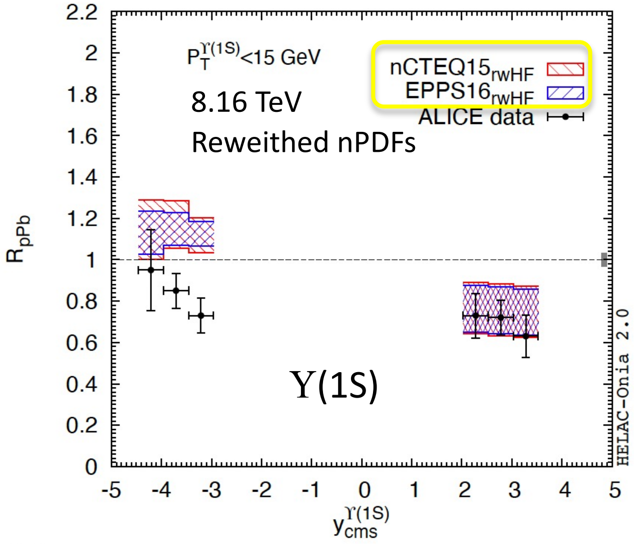


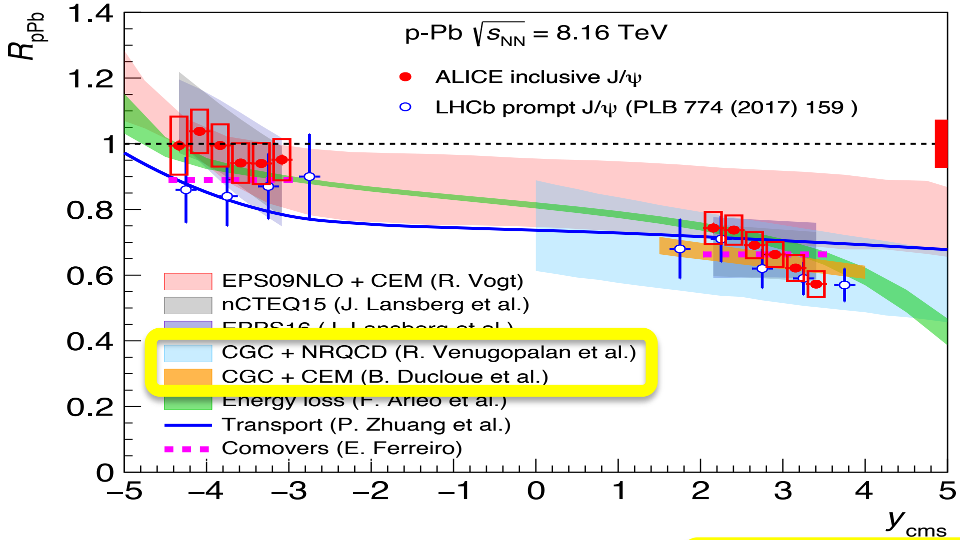
- Modification of the gluon flux *initial-state effect* ◆ Nuclear PDF in nuclei: nPDF shadowing

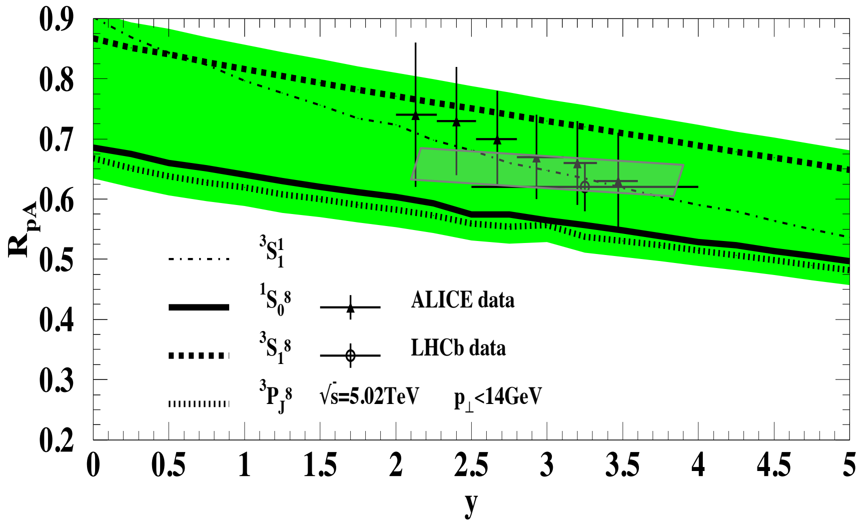
Gluon shadowing/antishadowing: Parton distribution functions are modified by the nuclear environment

⇒ 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





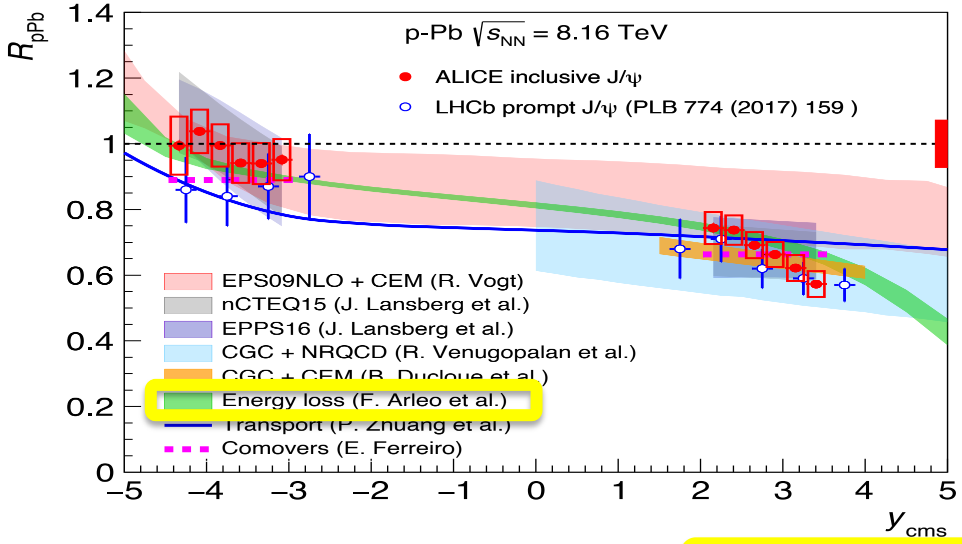
- Modification of the gluon flux *initial-state effect*
- Gluon saturation at low x: CGC

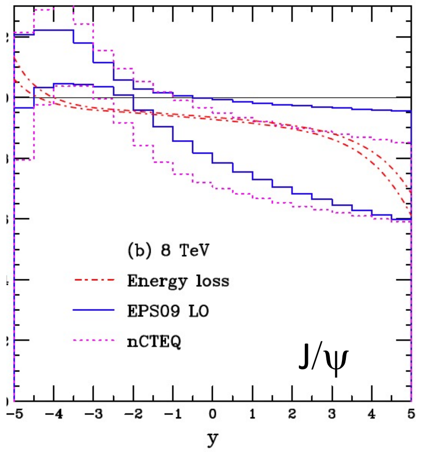
Gluon saturation: Result of gluon recombination at small x at LHC $Q^2_{sA} = A^{\frac{1}{3}} \times 0.2 \times \left(\frac{x_0}{x}\right)^{\lambda}$ $\lambda \sim 0.2 \div 0.3$ $x_0 = 0.01$

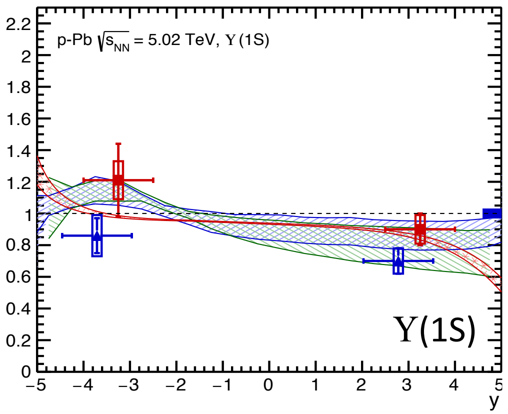
⇒ J/ψ suppression at forward rapidity (this effect does not apply in the backward rapidity region)

- 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*
- ◆ Coherent energy loss

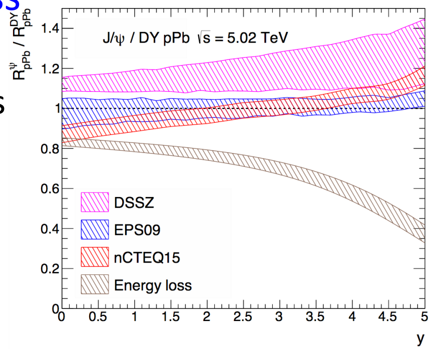
- Nuclear transverse momentum broadening of the heavy quark pair induces coherent gluon radiation => J/ψ & Υ(1S) yield modification

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

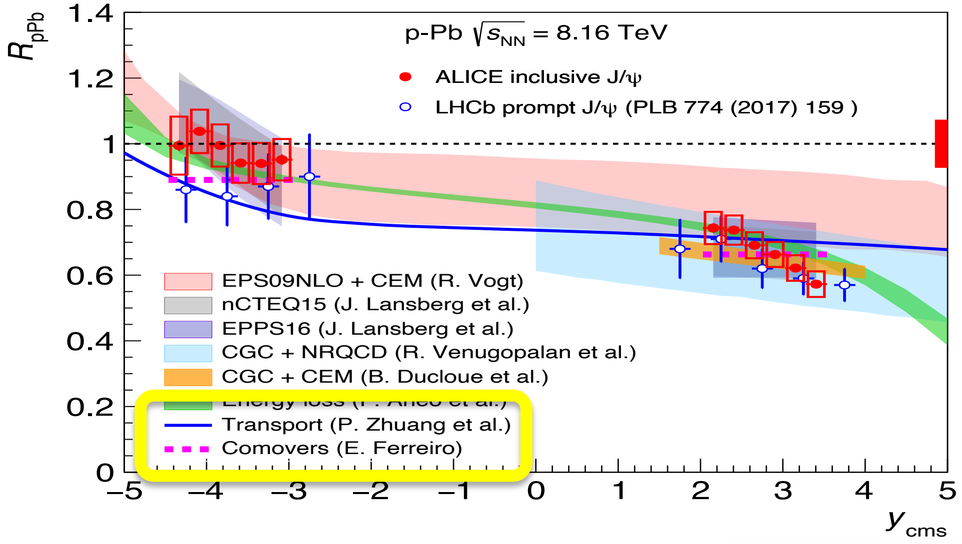
- Roughly agrees with quarkonium ground-state data
- Issue: Imposible to discriminate from nPDF modification

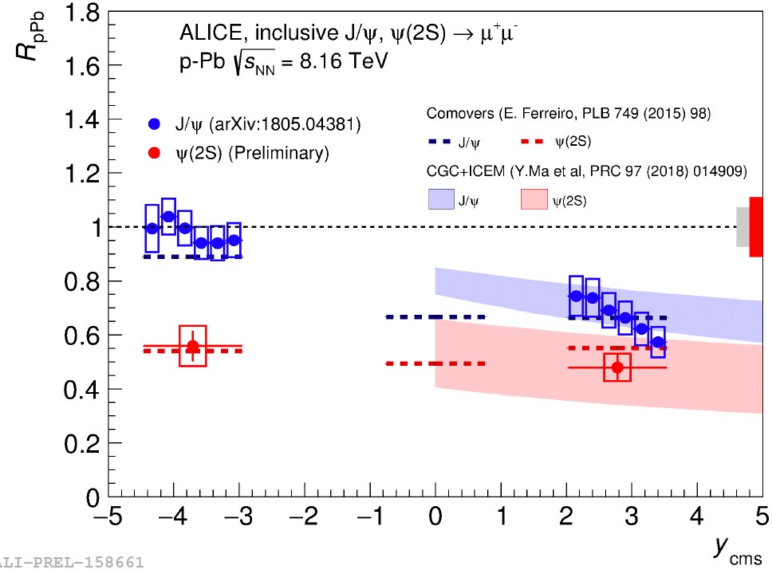
DY measurements could help

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

Distinguishing initial from 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:

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

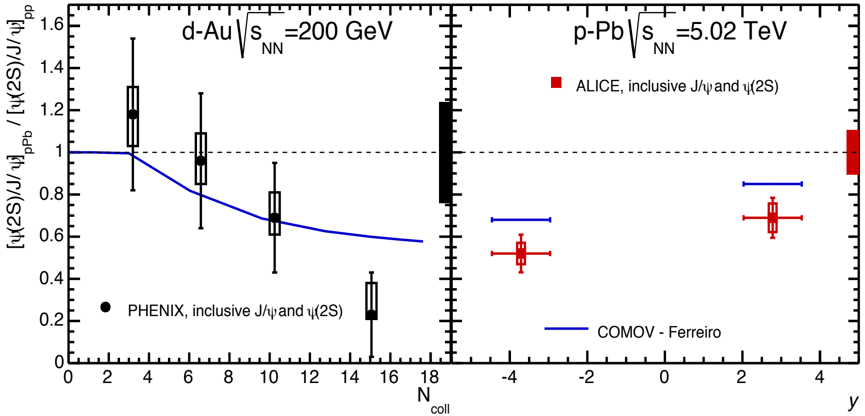
$\sigma^{\mathcal{Q}}_{\mathrm{geo}} \simeq \pi r^2_{\mathcal{Q}}$

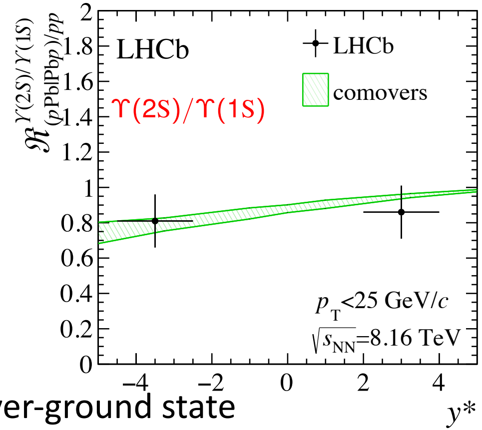
$E^{\mathcal{Q}}_{\mathrm{thr}} = 2M_B - M_{\mathcal{Q}_{b\bar{b}}}$

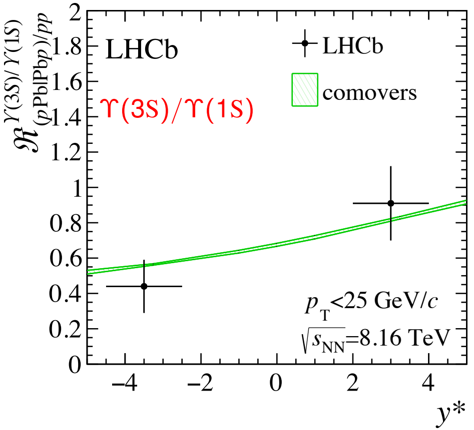
$E^{co} = \sqrt{p^2 + m^2_{co}}$

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

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





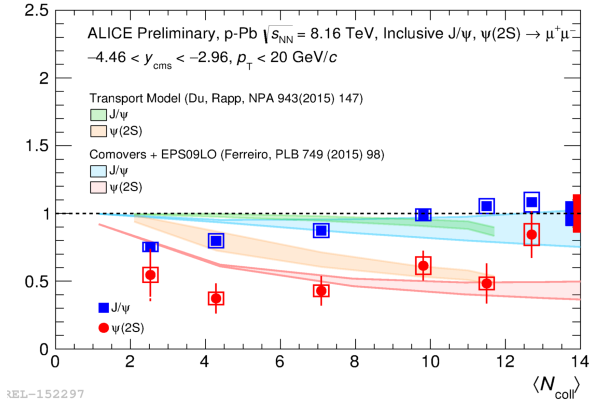


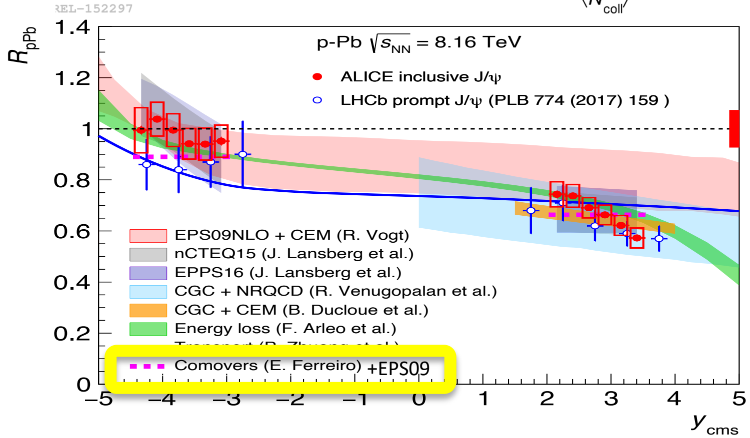
- To get rid of initial-state effects: double ratio excited-over-ground state

Excited states: Comover interaction pA

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

"similar in spirit to comover suppression"

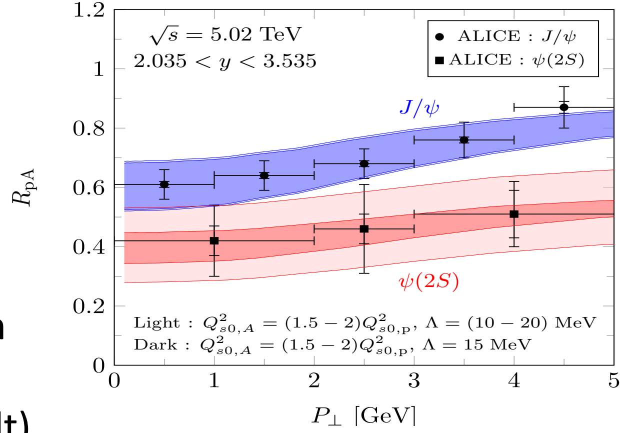




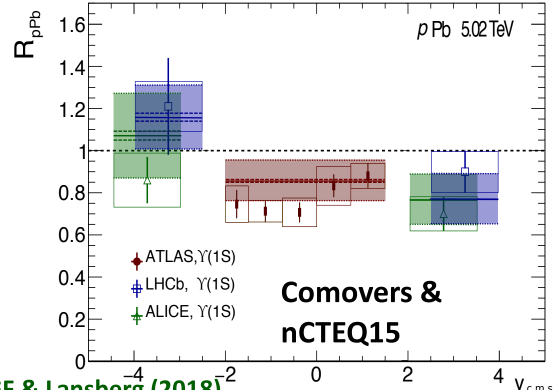
→New results on ψ(2S) confirm stronger suppression w.r.t. to J/ψ in the Pb-going direction.

→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)**

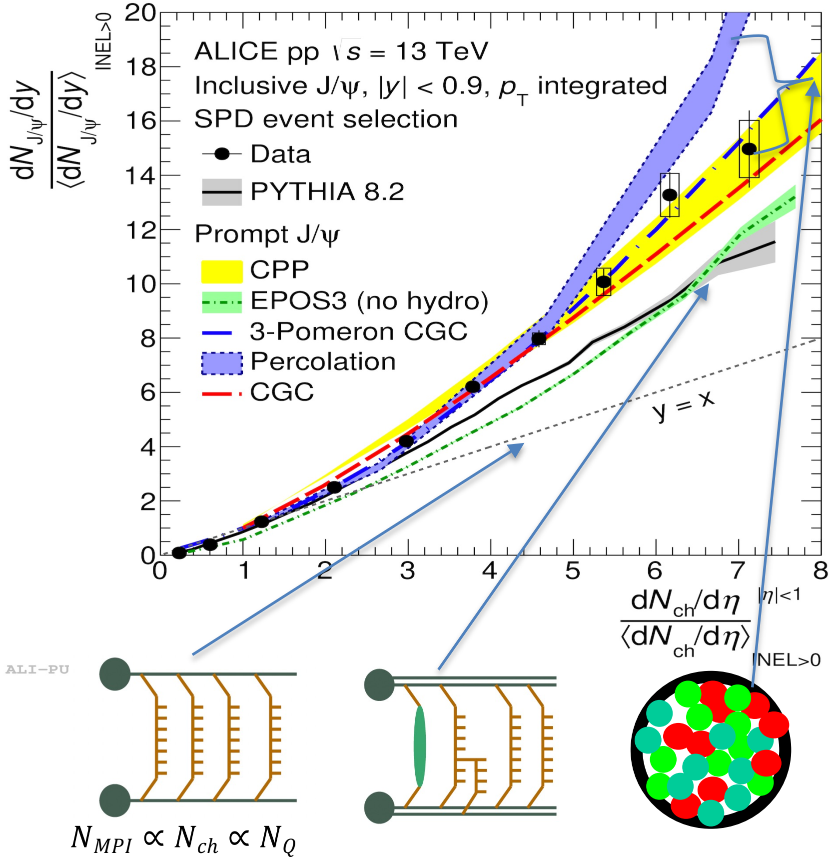


Stronger suppression in the nucleus-going direction (higher mult) => CI improves agreement for the ground state in the backward region (initial nPDFs modification also included)



EGF & Lansberg (2018)

Measuring *nuclear-like* effects in pp: Quarkonium vs multiplicity pp



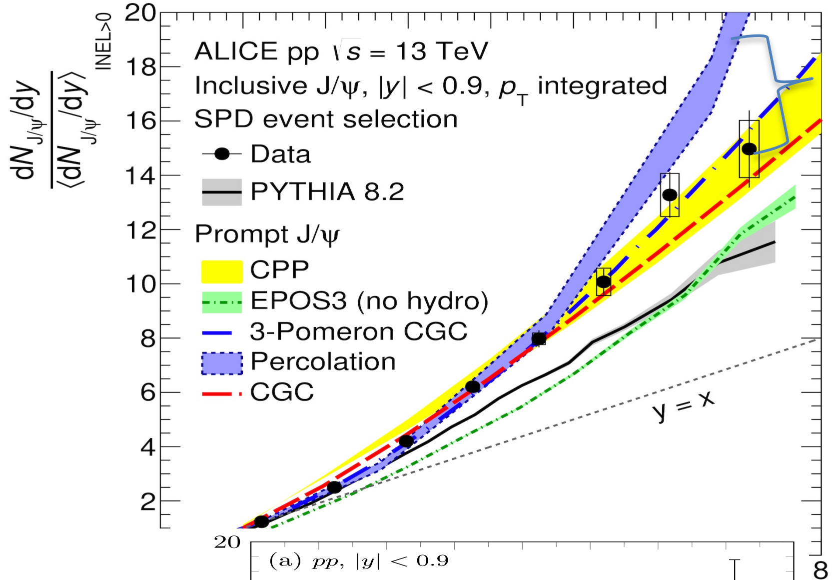
- **EPOS:** MPI via Pomeron exchange (initial) + hydrodynamic expansión (final) hydro on/off has small effect, hadronic cascade on/off has no effect
- **PYTHIA:** MPI, hard scatterings (initial) + color reconnection, string shoving (final)
- **CGC:** Gluon saturation (initial) => Impact on particle producción,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

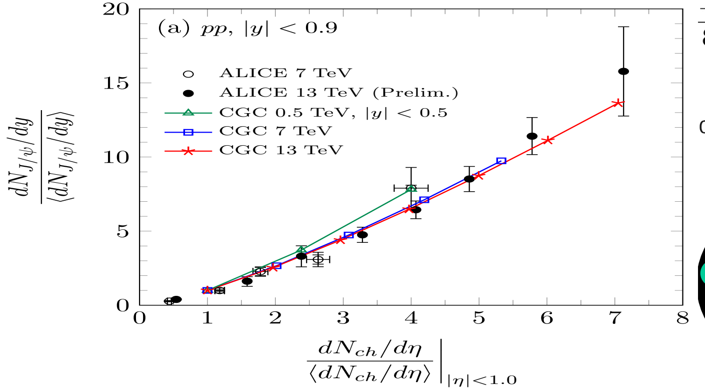
Initial state effects play a fundamental role:

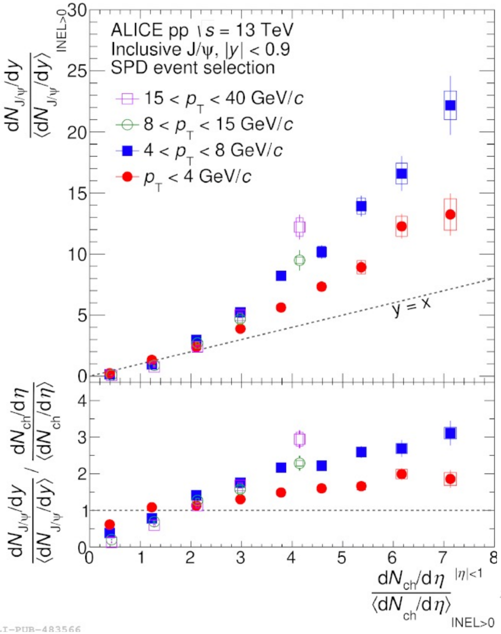
- MPI can introduce collectivity => Increase of hardeness
- Saturation => Decrease on total multiplicities => Indirect increase of the hard probe (not affected by saturation)
  - Events at different energies with the same $\rho_{strings}$ or Q_s are identical
  - The harder the probe, the stronger the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

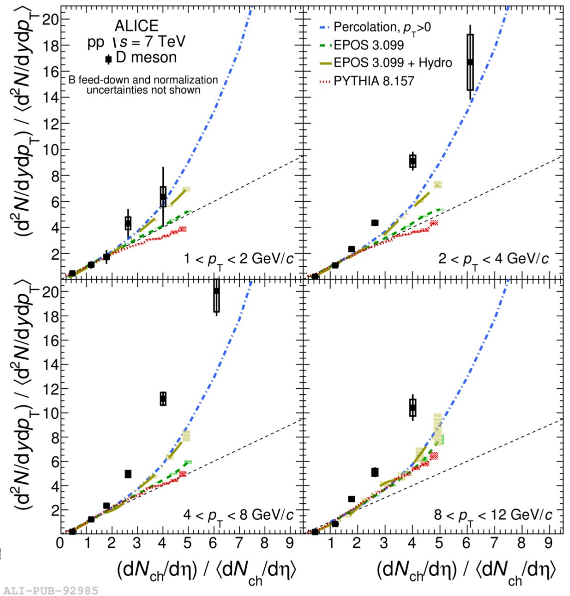
Multiplicity and probe measured in the same rapidity interval (both mid rapidities)

Measuring *nuclear-like* effects in pp: Quarkonium vs multiplicity pp









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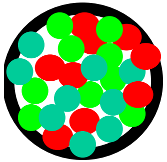

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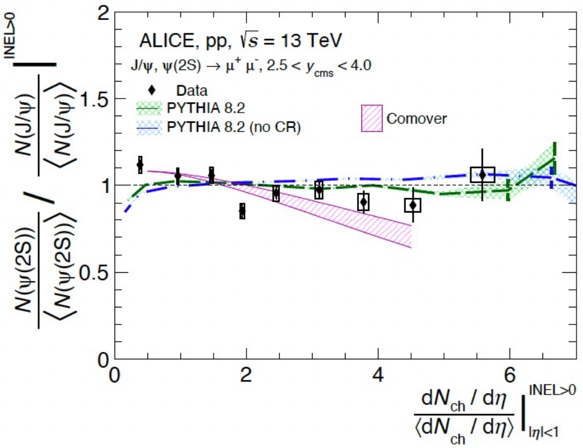
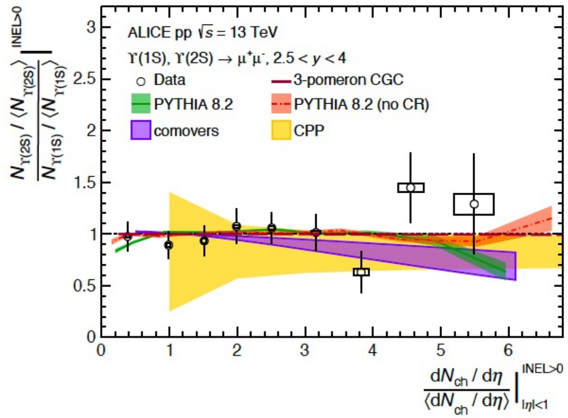
Multiplicity and probe measured in the same rapidity interval (both mid rapidities)

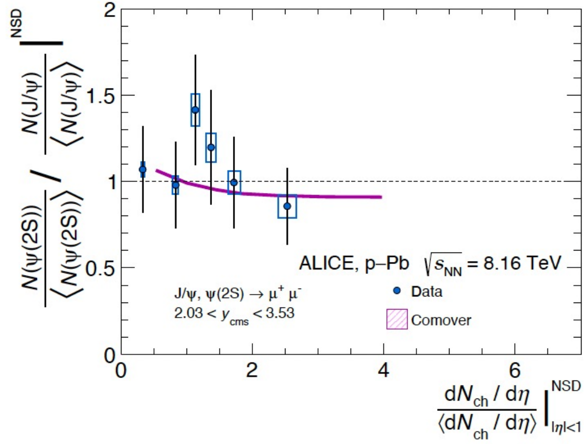
To get rid of initial-state effects: double ratio excited-over-ground state pp

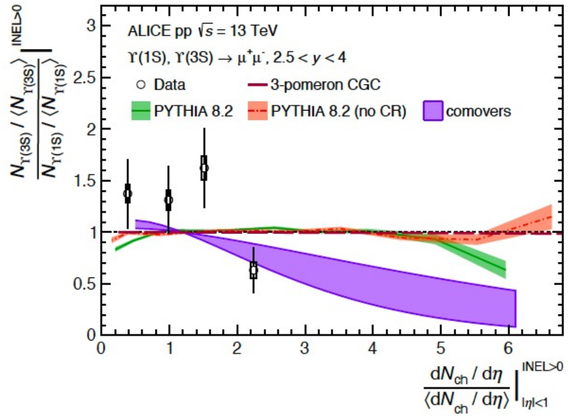
- Initial-state effects cancel

- Final-state effects at play?



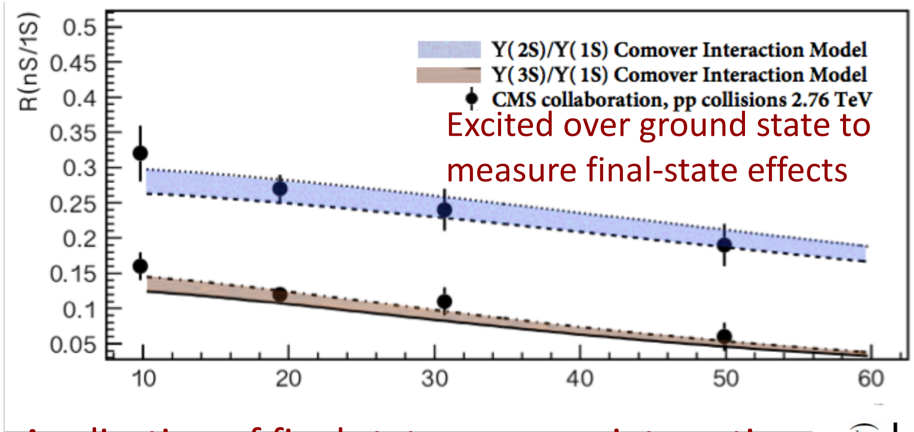


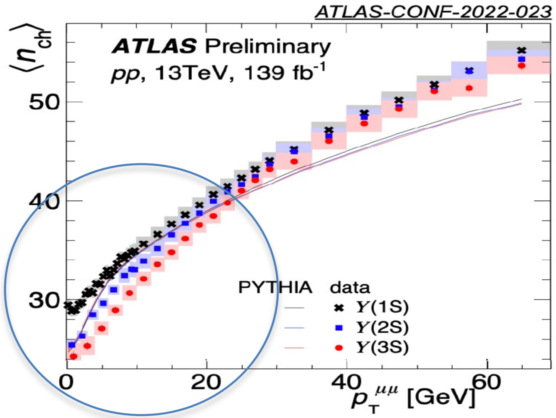




Quarkonium & HF vs multiplicity: excited states pp

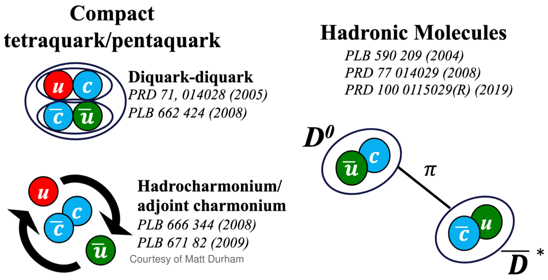
- **Studies of ground vs excited states** can improve our understanding of the final-state effects

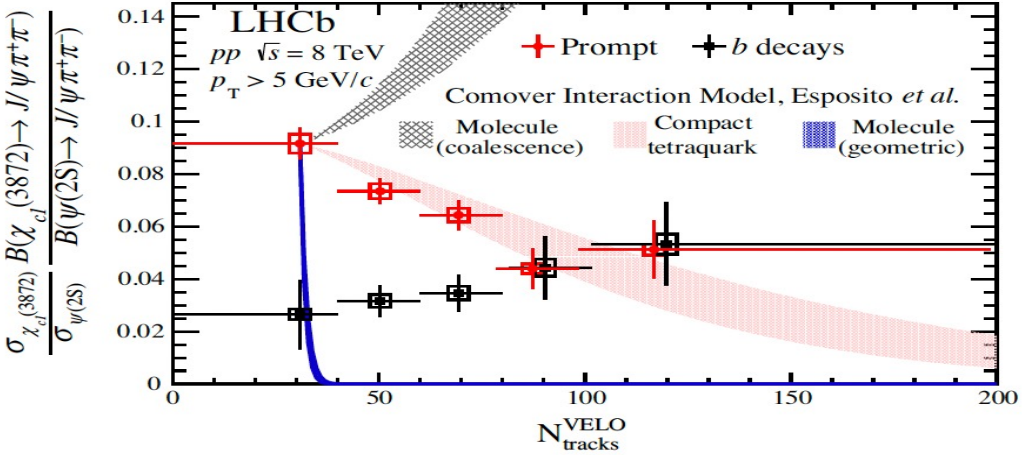




consistent with a suppression of the excited Υ states at high charged-particle multiplicity.

Application of final state comover interaction to spectroscopy in pp collisions





Work in progress: developing an in-medium potential for X(3872) AA

with Nestor Armesto, Miguel Escobedo & Victor Lopez Pardo

Relation between in-medium and vacuum potential:

$$V(\mathbf{p}) = \frac{V_{\text{vac}}(\mathbf{p})}{\varepsilon(\mathbf{p}, m_D)}$$

momentum or coordinate space

$$V(\mathbf{r}, m_D) = (V_{\text{vac}} * \varepsilon^{-1})(\mathbf{r}, m_D)$$

with the permittivity from HTL perturbation theory:

$$\varepsilon^{-1}(p, m_D) = \frac{p^2}{p^2 + m_D^2} - i\pi T \frac{p m_D^2}{(p^2 + m_D^2)^2}$$

$$\varepsilon^{-1}(r, m_D) = \frac{\delta(r)}{4\pi r^2} - \frac{m_D^2 e^{-m_D r}}{4\pi r} - i\frac{m_D T}{4\sqrt{\pi} r} G_{1,3}^{2,1}\left(\begin{matrix} -\frac{1}{2} \\ \frac{1}{2}, \frac{1}{2}, 0 \end{matrix} \middle| \frac{1}{4} m_D^2 r^2 \right)$$

In-medium potential general formula:

$$V(r, m_D) = C(m_D) + 4\pi \int^r \mathrm{d}r' \frac{\partial V(r', 0)}{\partial r'} \int^{r'} \mathrm{d}r'' r''^2 \varepsilon^{-1}(r'', m_D)$$

We use Lafferty & Rothkopf method: Generalized Gauss law

Work in progress: developing an in-medium potential for X(3872) AA

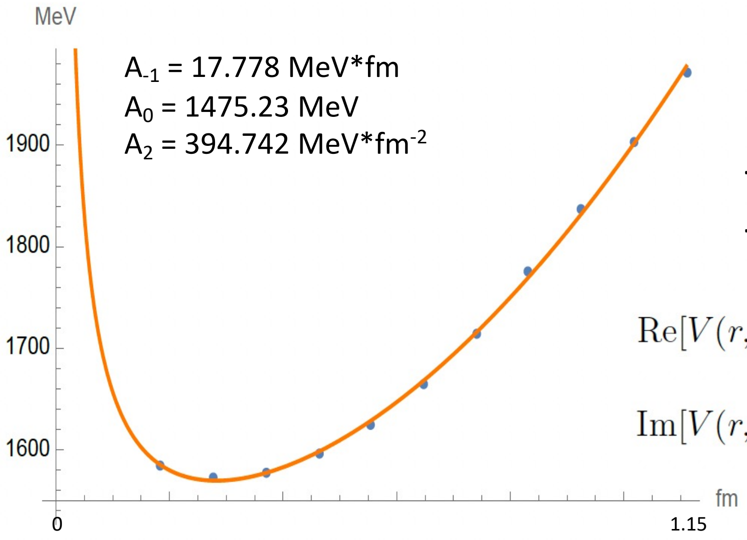
with Nestor Armesto, Miguel Escobedo & Victor Lopez Pardo

Using the vacuum potential:

Inspired on the one of the hybrid Π_u^-

$$V(r,0) = \frac{A_{-1}}{r} + A_0 + A_2 r^2$$

O. Philipsen et al. "Precision computation of hybrid static potentials in SU(3) lattice gauge theory". Phys Rev D, 99, 034502 (2020)



It is posible to calculate the real and imaginary parts of the in-medium potential according to the general formula:

$$\mathrm{Re}[V(r,m_D)] = \mathrm{Re}[C(m_D)] + \int^r \mathrm{d}r' \frac{\partial V(r',0)}{\partial r'} e^{-m_D r'}(m_D r' + 1),$$

$$\mathrm{Im}[V(r,m_D)] = \mathrm{Im}[C(m_D)] - \int^r \mathrm{d}r' \frac{\partial V(r',0)}{\partial r'} \frac{\sqrt{\pi} m_D T}{2} r'^2 G^{2,1}_{1,3}\left(\begin{matrix} \frac{1}{2} \\ \frac{1}{2}, \frac{1}{2}, -1 \end{matrix} \middle| \frac{1}{4} m_D^2 r'^2 \right)$$

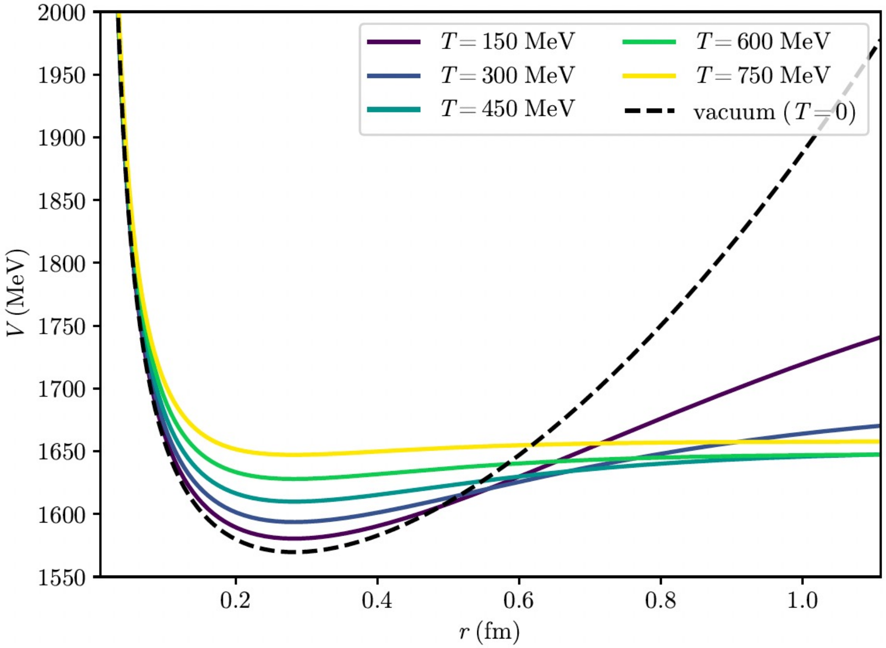
with the prescription that $C(m_D)$ must ensure that $V(r,m_D) = V_{\mathrm{vac}}(r)$ up to $\mathcal{O}(m_D)$.

Work in progress: developing an in-medium potential for X(3872) AA

with Nestor Armesto, Miguel Escobedo & Victor Lopez Pardo

We obtain, for the in-medium real potential:

$$\mathrm{Re}[V(r, m_D)] = A_{-1}\left(m_D + \frac{e^{-m_D r}}{r}\right) + A_0 + A_2\left[\frac{6}{m_D^2}(1 - e^{-m_D r}) - \left(2r^2 + \frac{6r}{m_D}\right)e^{-m_D r}\right]$$



Work in progress: developing an in-medium potential for X(3872) AA

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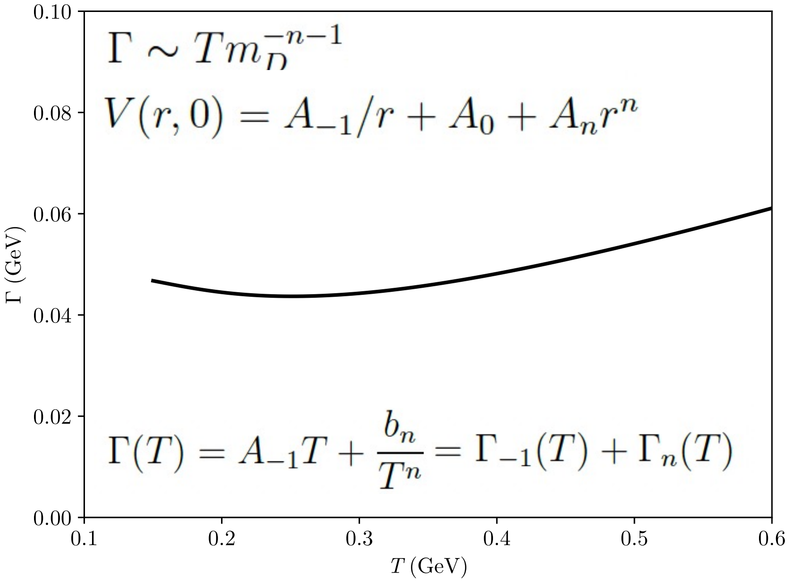
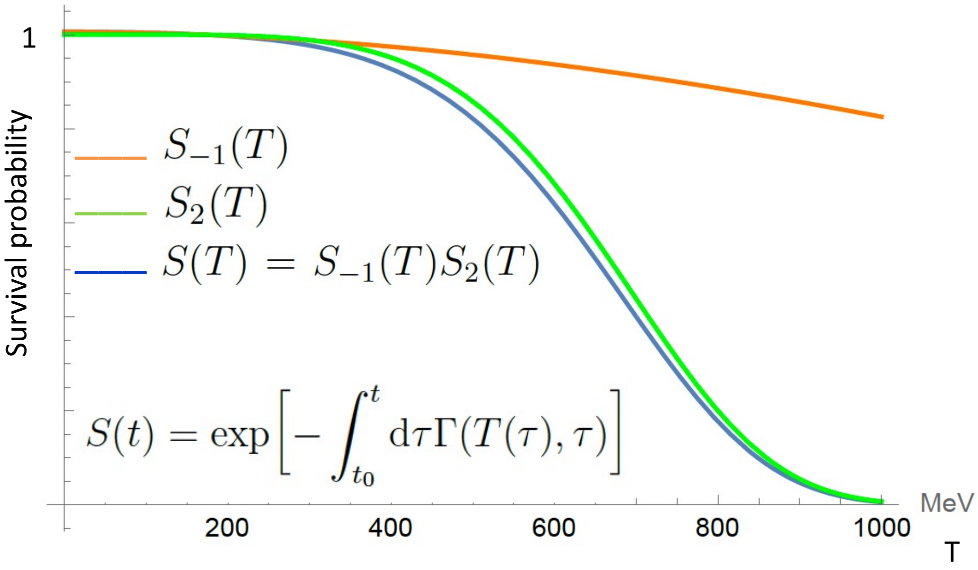
For the imaginary part, we perform a regularization that allows us to obtain a general decay rate for power vacuum potentials: $V_n(r,0) \propto r^n$ $\quad \lim_{r\to\infty} \mathrm{Im}[V_n(r,m_D)] \propto \frac{T}{m_D^{n+1}}$





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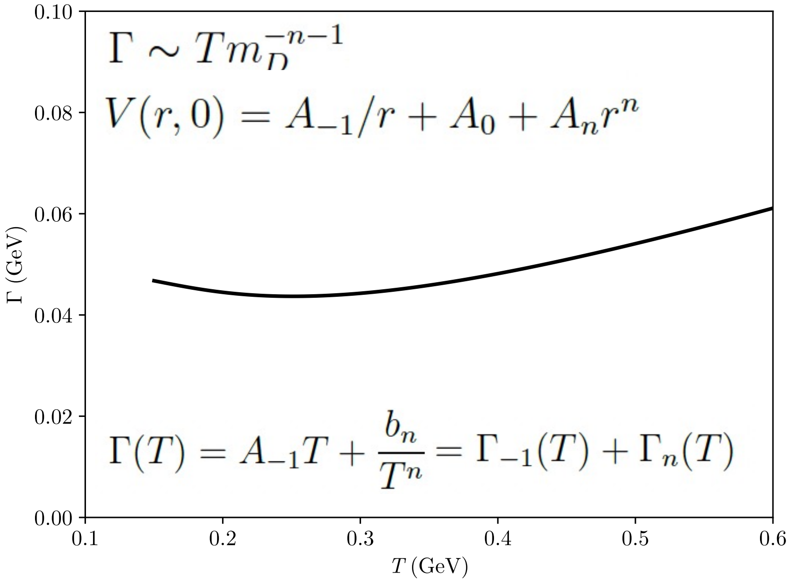

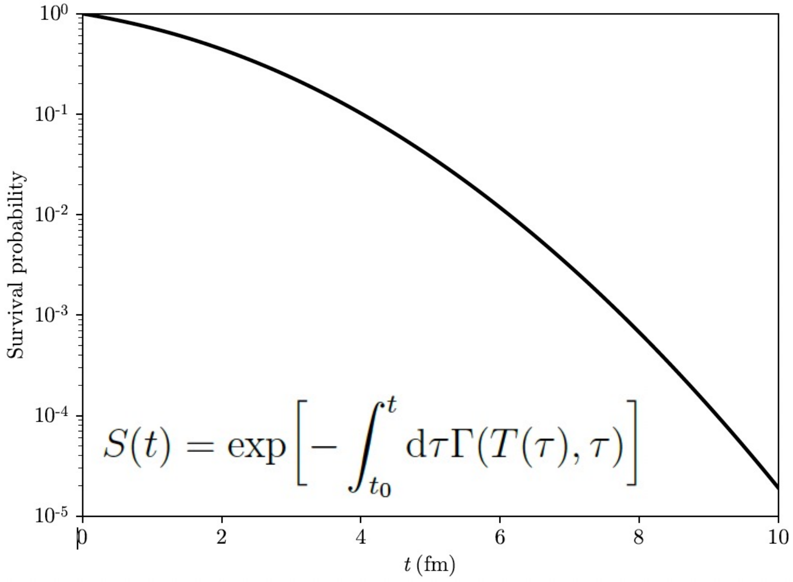

Final remarks

- **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?