Heavy quarkonium production at RHIC/LHC

E. Scomparin (INFN Torino, Italy)

"The spectroscopy program at EIC and future accelerators"
ECT*, Trento, December 19-21 2018

- The role of quarkonium states as a tool for
  - Probing the Quark-Gluon Plasma
  - Probing cold nuclear matter
  - Probing the initial state of the collisions

- What did we learn at collider (and fixed-target!) energy ?
- Can we get a coherent physics picture from experimental results ?

- Are there aspects that still need to be clarified ?
- Can eA production measurements shed light on them ?

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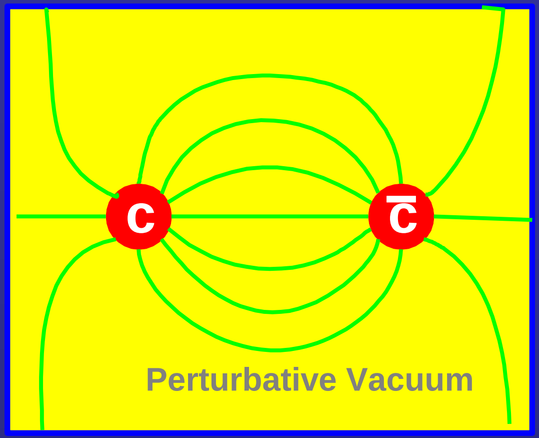
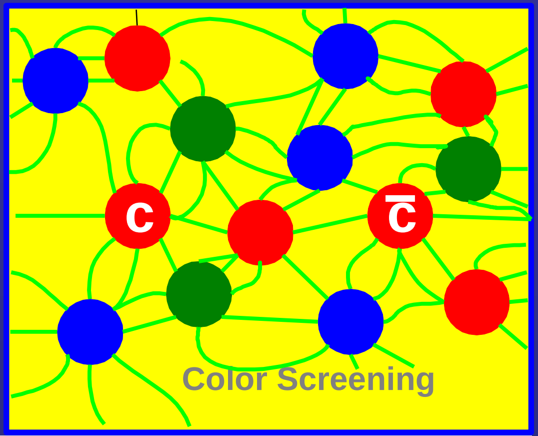
Nuclear (A-A) collisions: from color screening…

Screening of
strong interactions
in a QGP

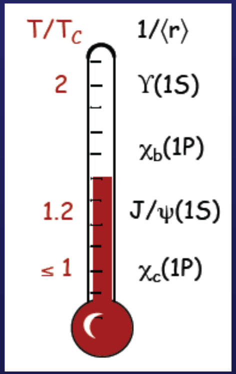
T. Matsui and H. Satz,
PLB178 (1986) 416

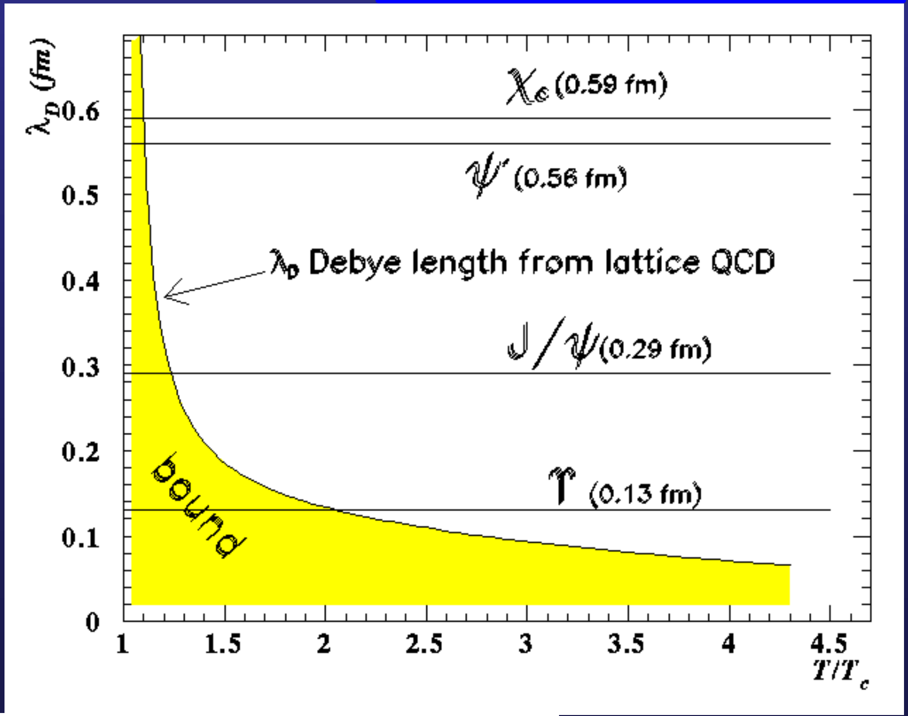




- Screening stronger at high T
- λ_D → maximum size of a bound state, decreases when T increases
- Different states, different sizes

Resonance melting



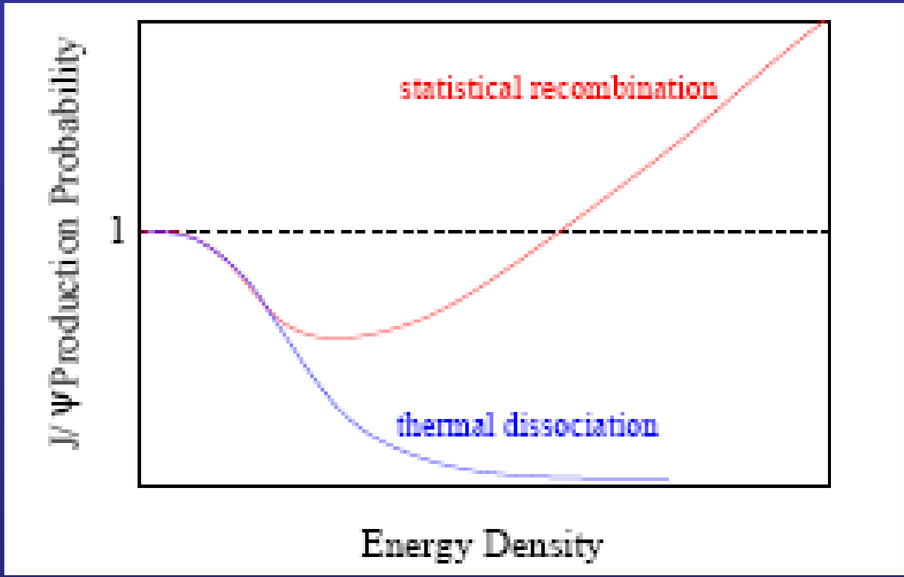


→ QGP thermometer

…to regeneration

At sufficiently high energy, the cc pair multiplicity becomes large

Central AA collisions	SPS 20 GeV	RHIC 200 GeV	LHC 5.02TeV
N_{ccbar}/event	~0.2	~10	~115



Statistical approach:

- ❑ Charmonium fully melted in QGP
- ❑ Charmonium produced, together with all other hadrons, at chemical freeze-out, according to statistical weights

Kinetic recombination:

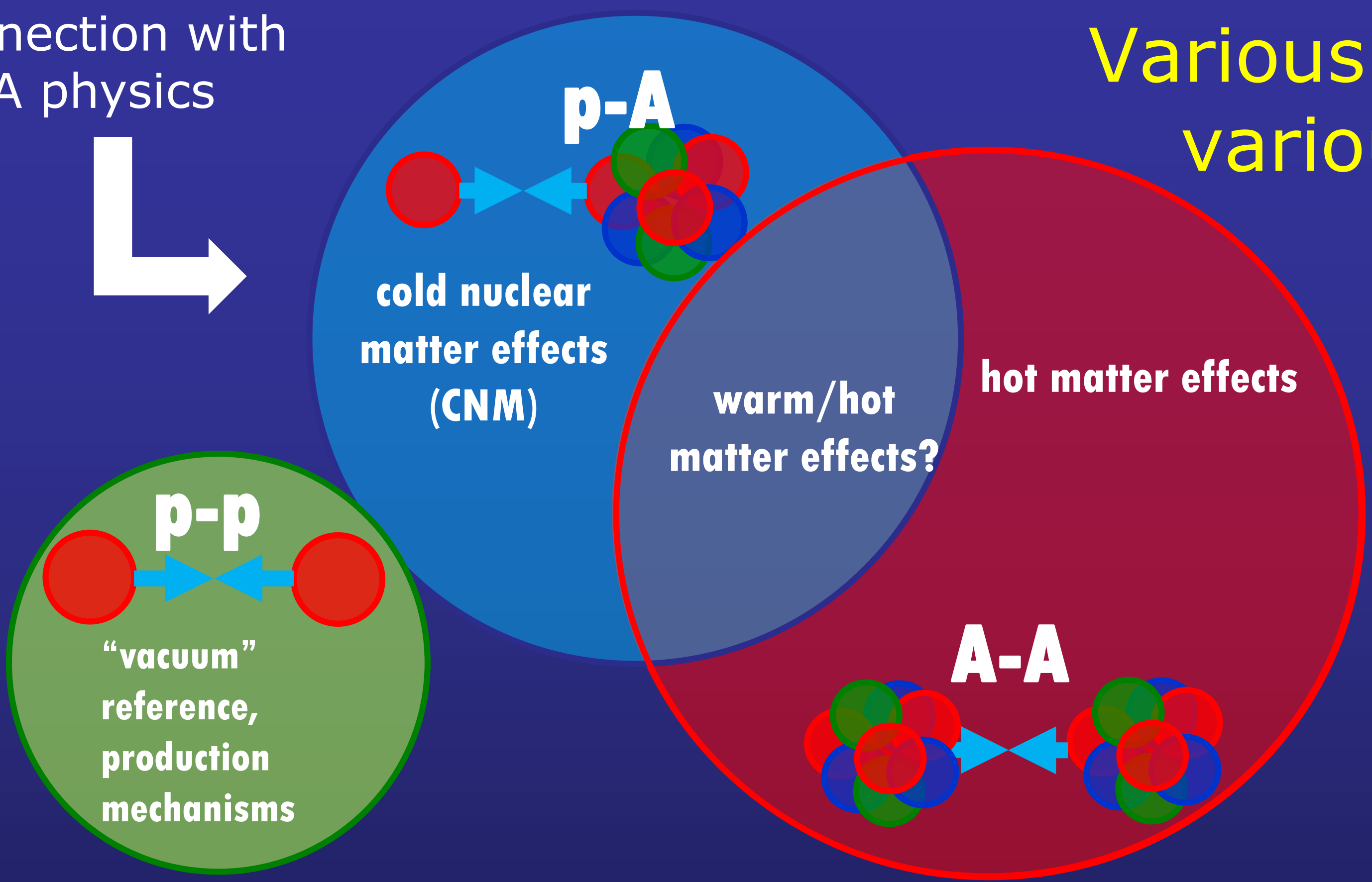
- ❑ Continuous dissociation/regeneration over QGP lifetime

P. Braun-Munzinger and J. Stachel, PLB490 (2000) 196
Thews, Schroedter and Rafelski, PRC63 054905 (2001)

Contrary to the color screening scenario this mechanism can lead to a charmonium enhancement

Various systems, various effects

Connection with eA physics



- Hot matter effects: suppression vs re-generation
- CNM: nuclear shadowing, color glass condensate, parton energy loss, resonance break-up (RHIC and fixed target energy)
- "Warm" matter effects: hadronic resonance gas

Basic quantities

One of the basic quantities when dealing with QGP physics is the **nuclear modification factor**

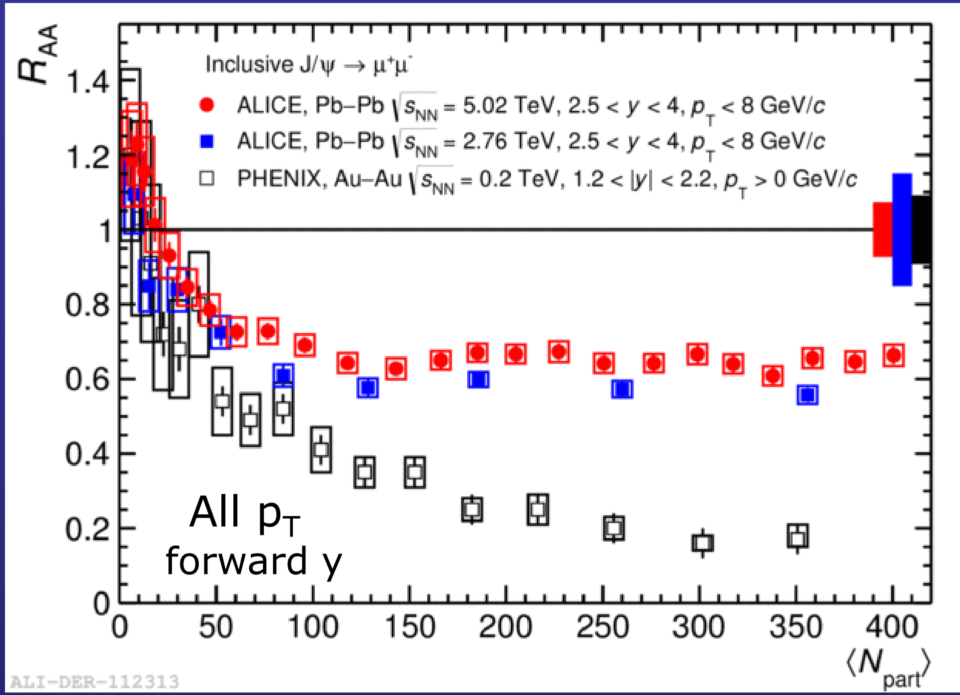
$$R_{AA}^{P}(p_T) = \frac{dN_{AA}^{P}/dp_T}{\langle N_{coll}\rangle \, dN_{pp}^{P}/dp_T}$$

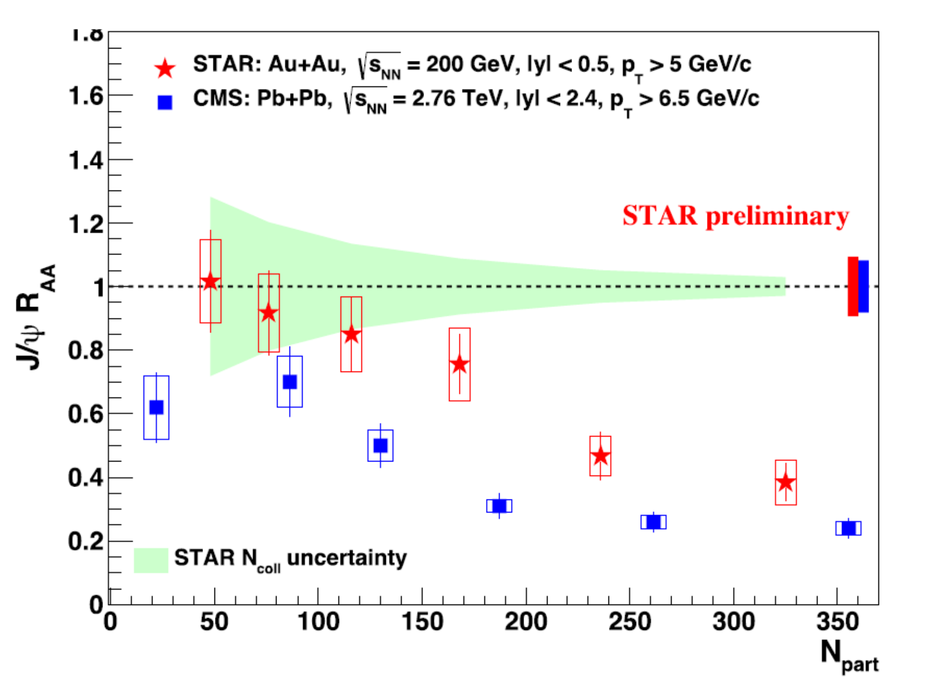
or equivalently

$$R_{AA}^{P}(p_T) = \frac{dN_{AA}^{P}/dp_T}{\langle T_{AA}\rangle \, d\sigma_{pp}^{P}/dp_T} \qquad \text{with} \qquad \langle T_{AA}\rangle = \frac{\langle N_{coll}\rangle}{A^2 \sigma_{inel}^{pp}}$$

R_{AA} <1 → suppression
R_{AA} >1 → enhancement

J/ψ in Pb-Pb/Au-Au: LHC and RHIC results





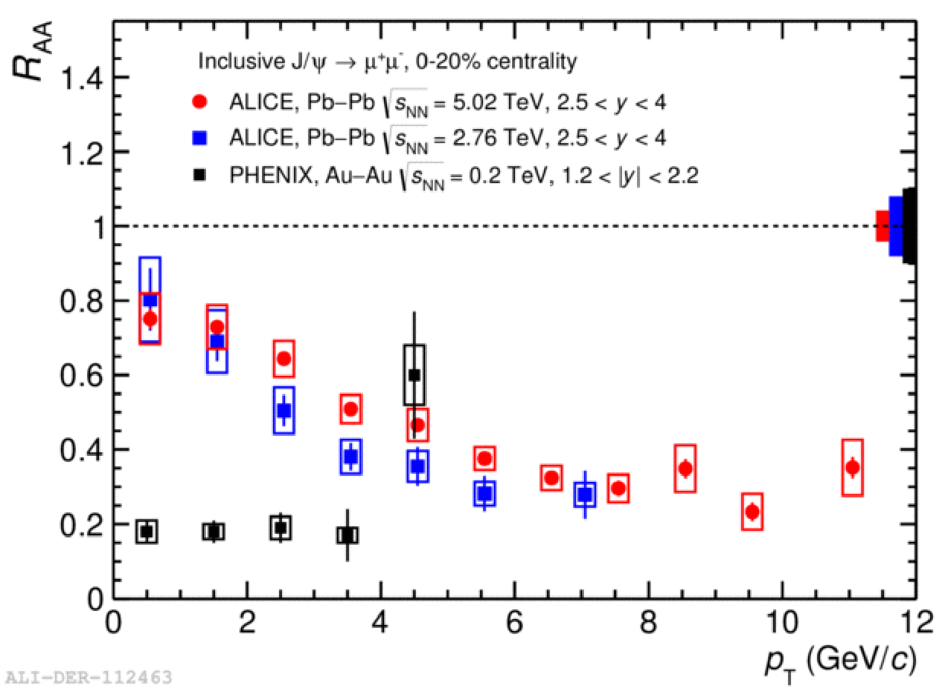
J.Adam et al, ALICE PLB766(2017) 212

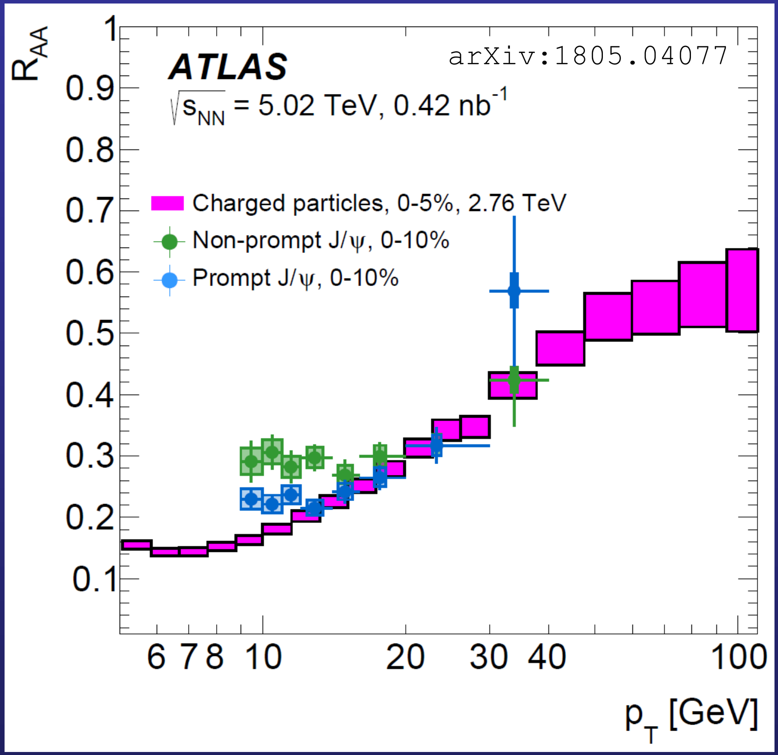
- Results vs centrality (number of participant nucleons N_{part})
  - All p_T: **larger R_{AA} values** (less suppression) at LHC
  - High p_T: **smaller R_{AA} values** (more suppression) at LHC

Possible interpretation:
- **RHIC** energy → **suppression** effects dominate
- **LHC** energy → **suppression + regeneration**

J/ψ in Pb-Pb/Au-Au: LHC and RHIC results

Transverse momentum dependence of R_{AA}



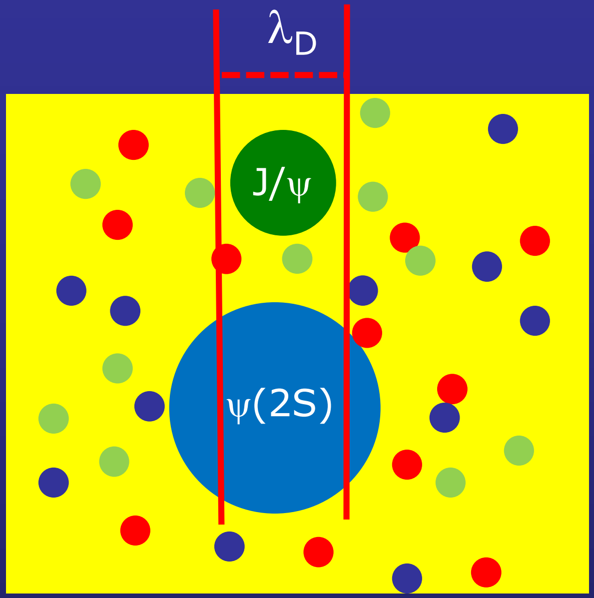


- ❑ Bulk of charm quark production occurs at low p_T
- ❑ R_{AA} rises at low p_T at LHC energy
  → **strong indication for regeneration**

- ❑ Very high p_T, hint for a rise of R_{AA}, as for charged hadrons
  → **Parton energy loss at play ?**

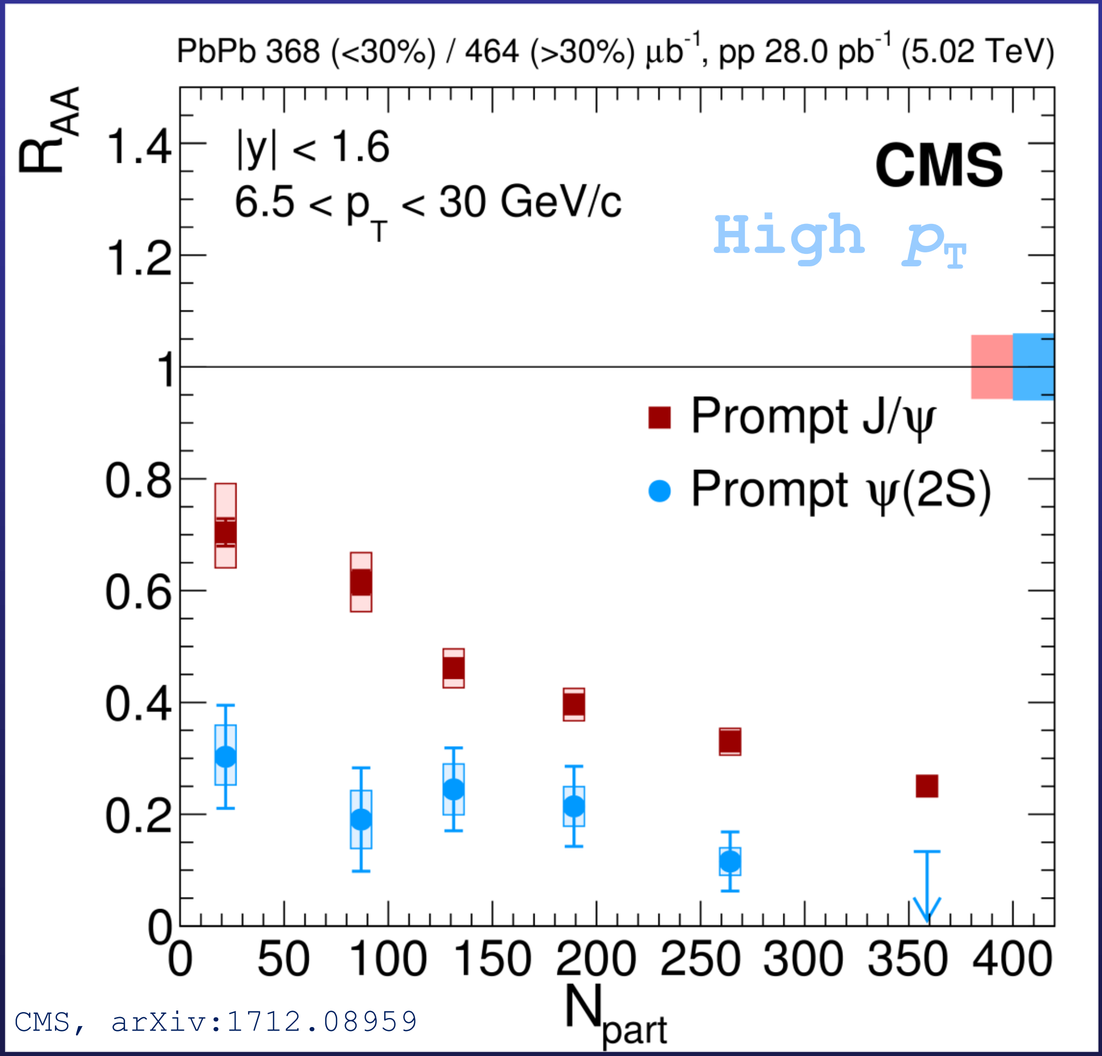
$\psi(2S)$ in Pb-Pb

- Binding energy ~$(2m_D - m_\psi)$ → **$\psi(2S)$ ~ 60 MeV, J/ψ ~ 640 MeV**



Evidence for **stronger $\psi(2S)$ suppression**

Recombination effects more subtle



Bottomonium (LHC)

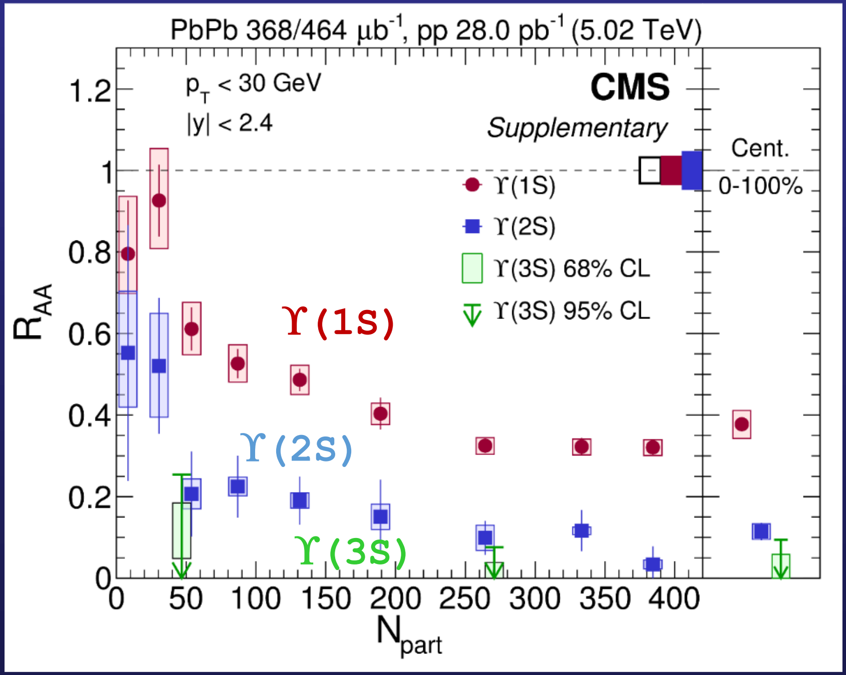
- Three states with different sensitivity to the medium with respect to charmonium

- Limited recombination and no B feed-down (but large feed-down from excited states)
  → Interesting for **sequential suppression studies**

Binding Energy (MeV):
ϒ(1S): ~1100 ϒ(2S): ~500
ϒ(3S): ~200

Strong suppression of all ϒ(nS) when increasing centrality

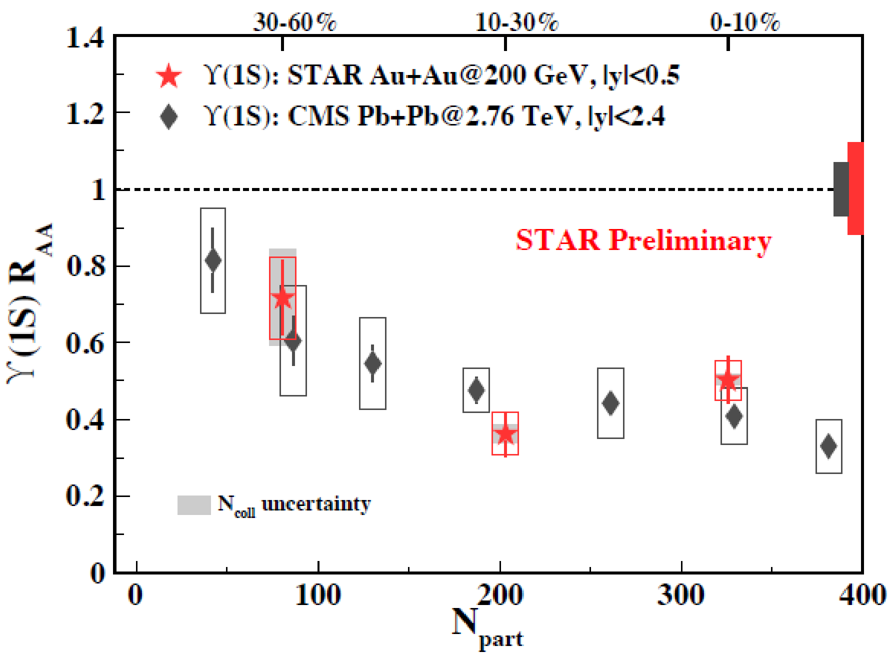
~ factor 2 for ϒ(1S)
~ factor 9 for ϒ(2S)

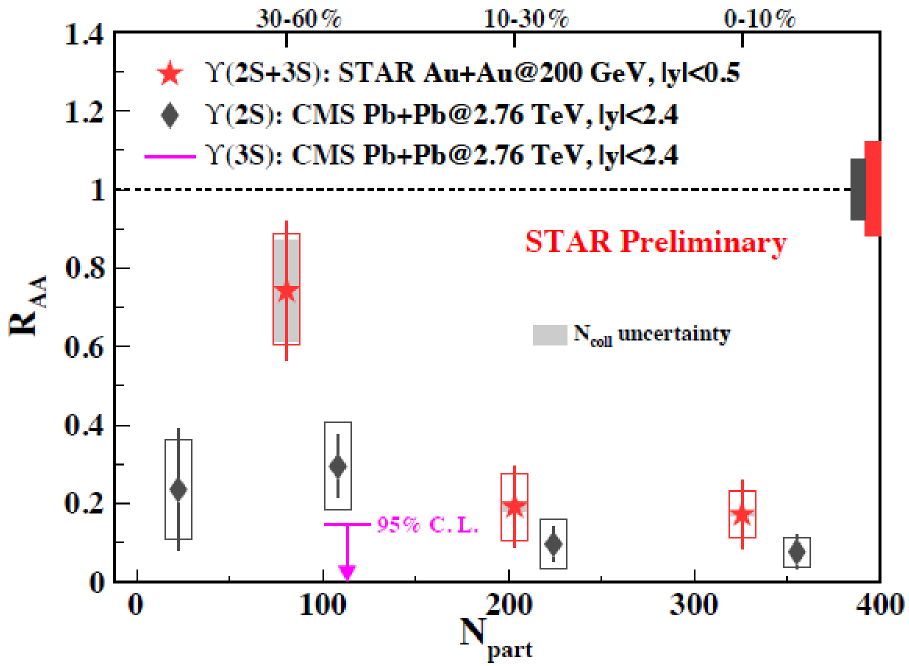


➡ Lower R_{AA} values for excited states compatible with sequential suppression

Suppression of directly produced ϒ(1S) ?
Feed down contribution ~ 30%

Bottomonium (RHIC)

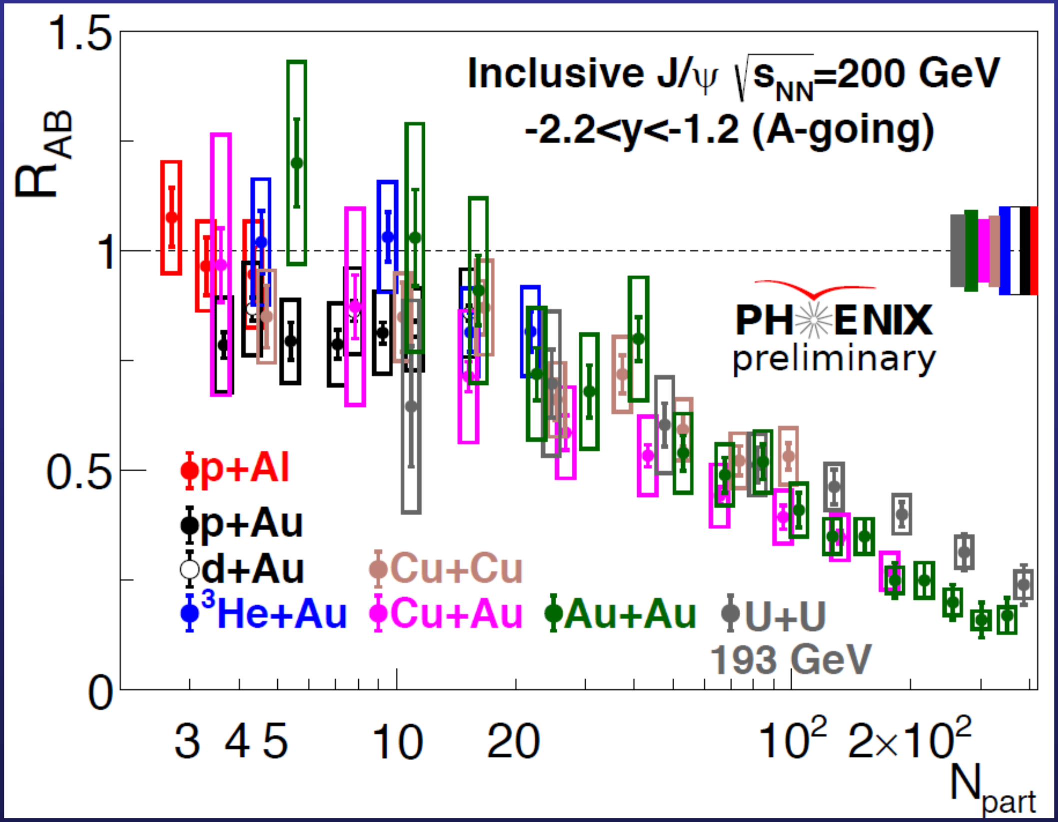




- ❑ **Evidence for suppression of the 3 ϒ states** ALSO at RHIC energy
- ❑ Hints for ϒ(2S)+ϒ(3S) less suppressed up to semi-central events and then compatible with CMS for central → effect related to energy density ?
- ❑ ϒ(1S) identical at RHIC and LHC → dominated by feed-down ?

A-A suppression is only part of the story

- Consider the rich data sets collected e.g. at RHIC energy (smaller recombination effects)
- Suppression **sets in for pA and smoothly increases towards AA** collisions

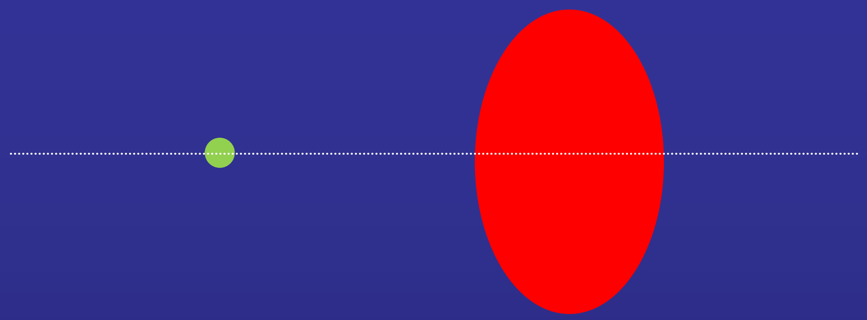


Non-QGP effects are present! Likely related to **cold nuclear matter**

Accurate studies of the behaviour of quarkonia in CNM are mandatory for a quantitative interpretation of the data

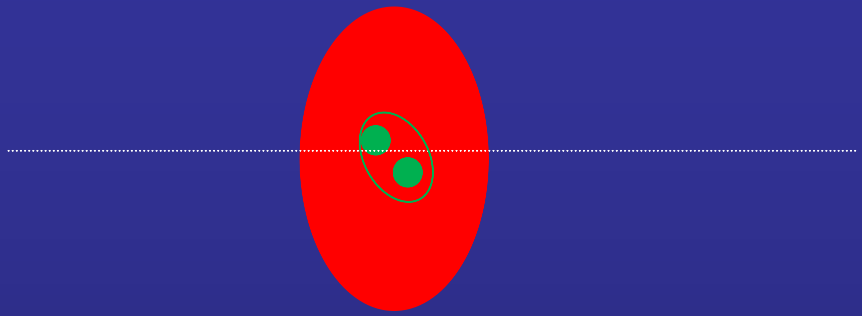
Study of **pA collisions** represents up to now the prime source of information

p-A collisions and CNM effects



Low-energy collisions
cc pair may form inside nucleus
→ can be dissociated
→ low hadronic multiplicity

p-A collisions and CNM effects



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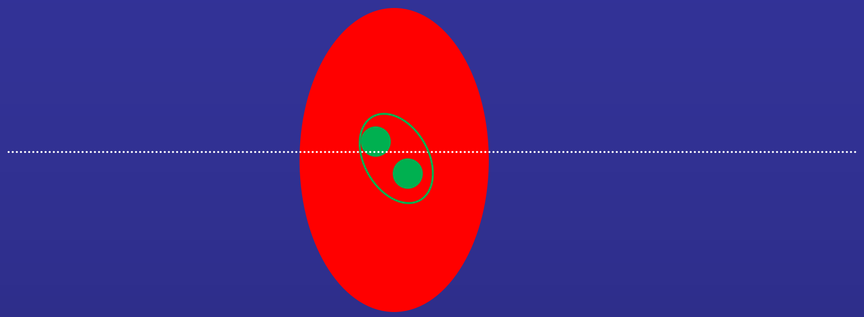

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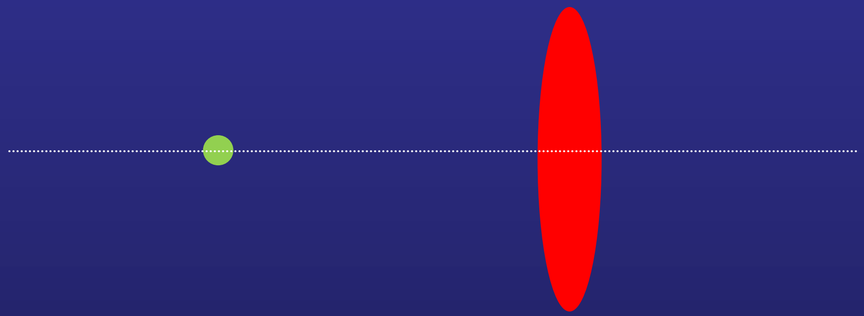
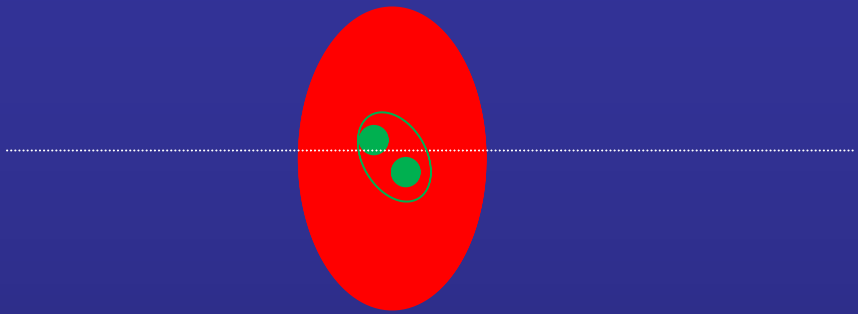


High-energy collisions
cc pair forms outside nucleus
→ not dissociated in the nucleus
→ May interact with "medium"

p-A collisions and CNM effects



Low-energy collisions

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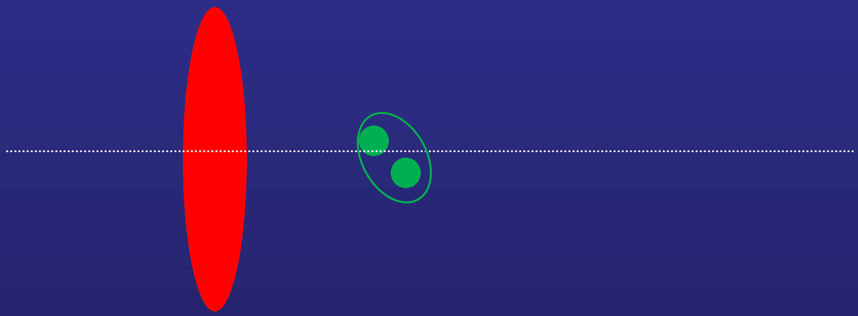

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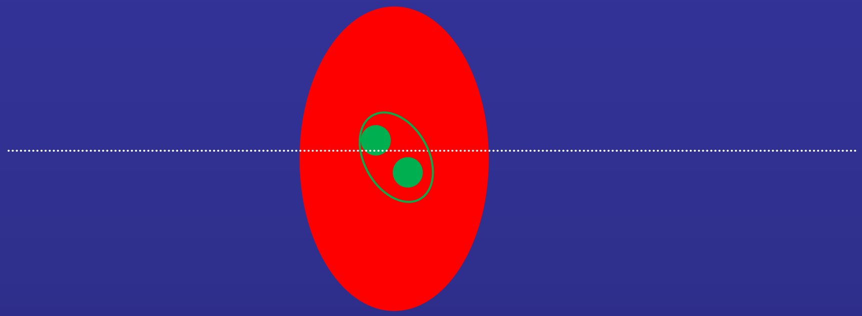
p-A collisions and CNM effects



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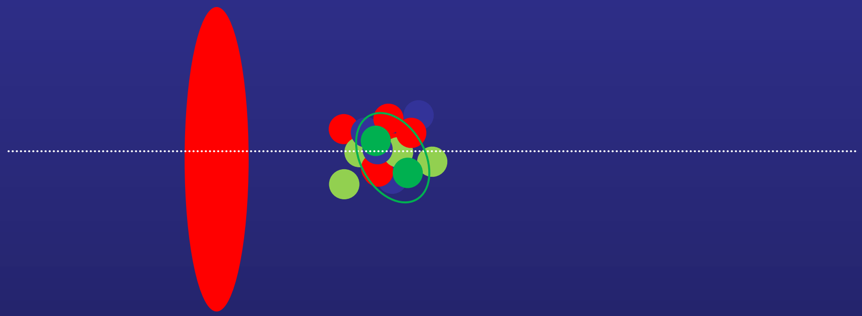
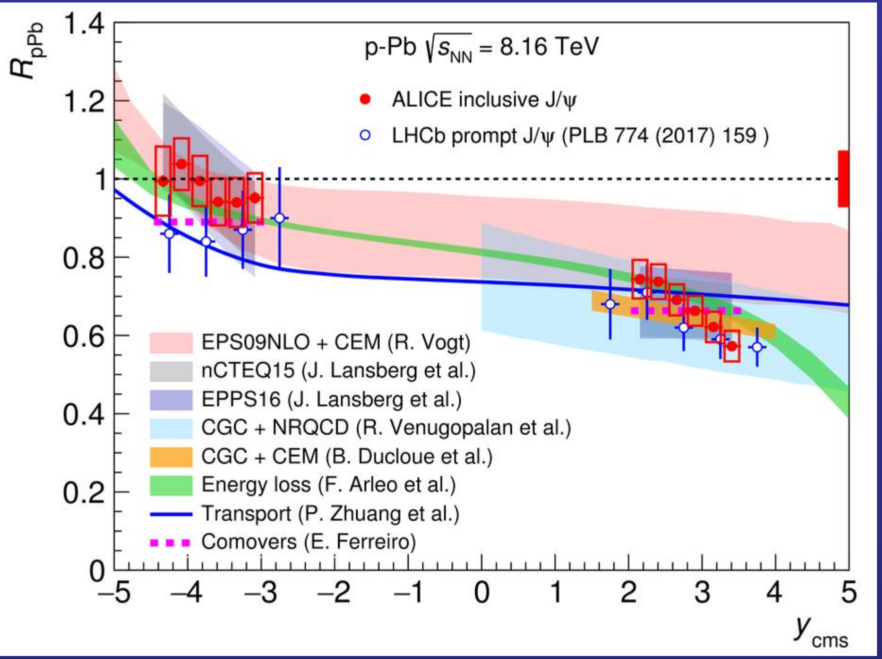


High-energy collisions
cc pair forms outside nucleus
→ not dissociated in the nucleus
→ May interact with "medium"

- ❑ Important ingredient for the interpretation of A-A results
- ❑ Study of various QCD-related mechanisms
  (shadowing, coherent parton energy loss, CGC, …)

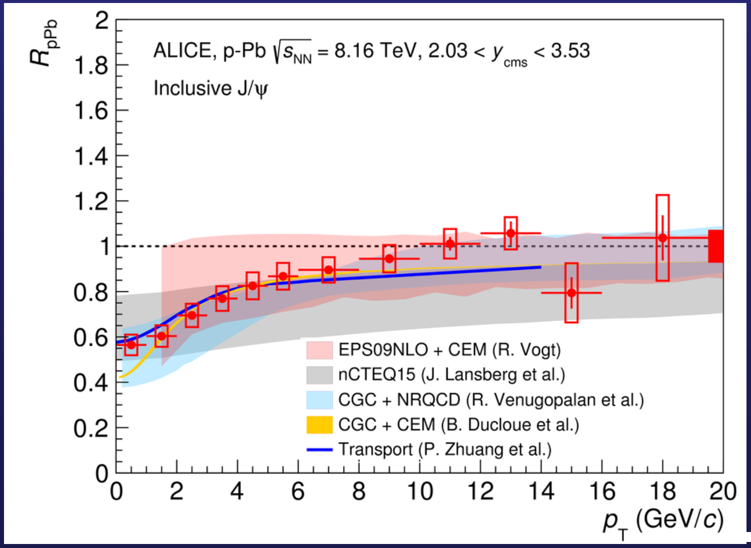
High-energy regime: LHC

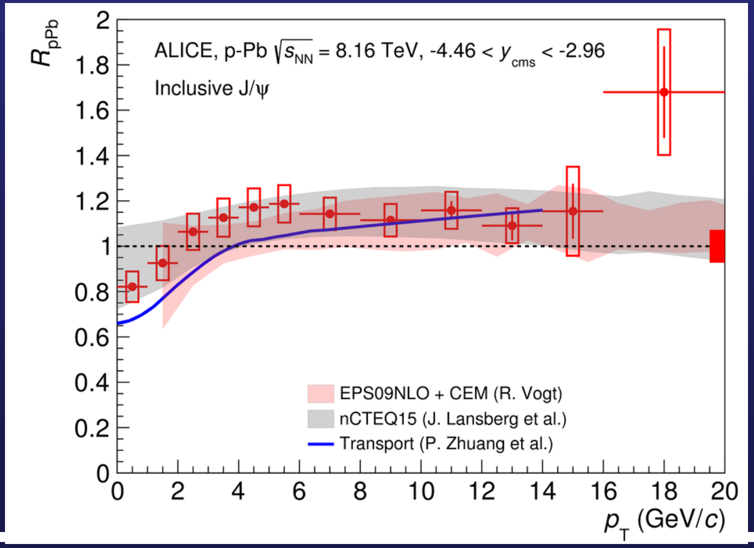
In pA collisions, CNM effects affect J/ψ production mainly at forward-y and low p_T



Good agreement between data and models based on shadowing, CGC, energy loss

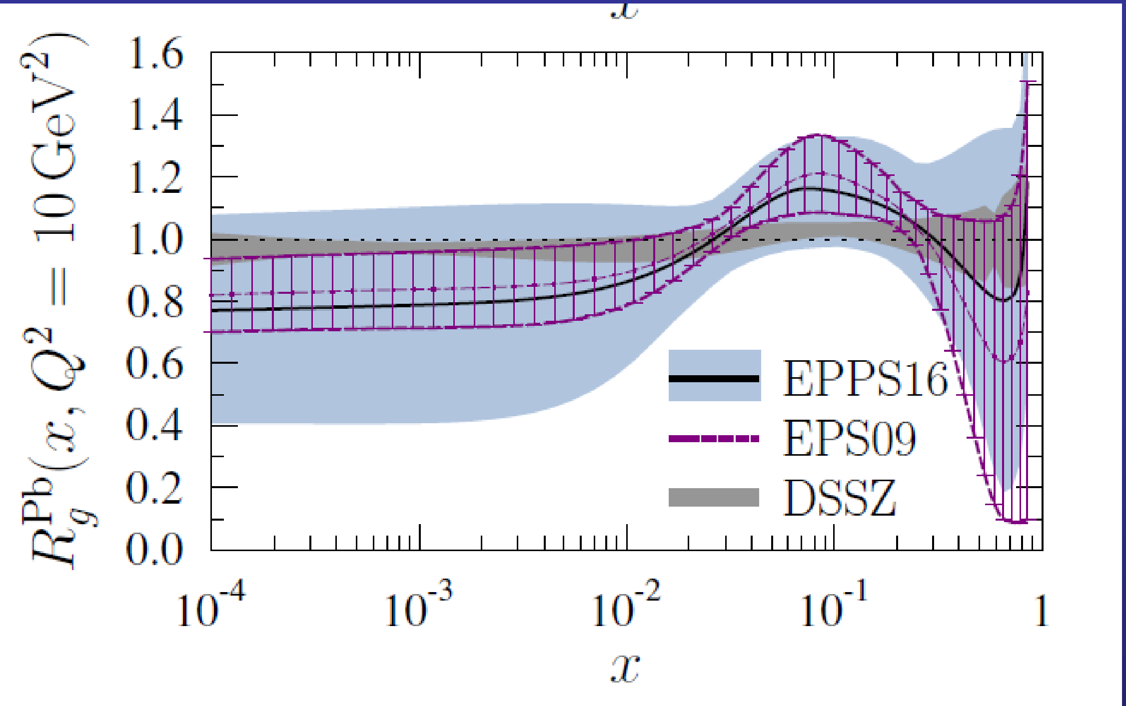
Size of theory uncertainties (mainly shadowing) still prevents a more quantitative comparison





Shadowing uncertainties

K. Eskola et al, arXiv:1612.05741

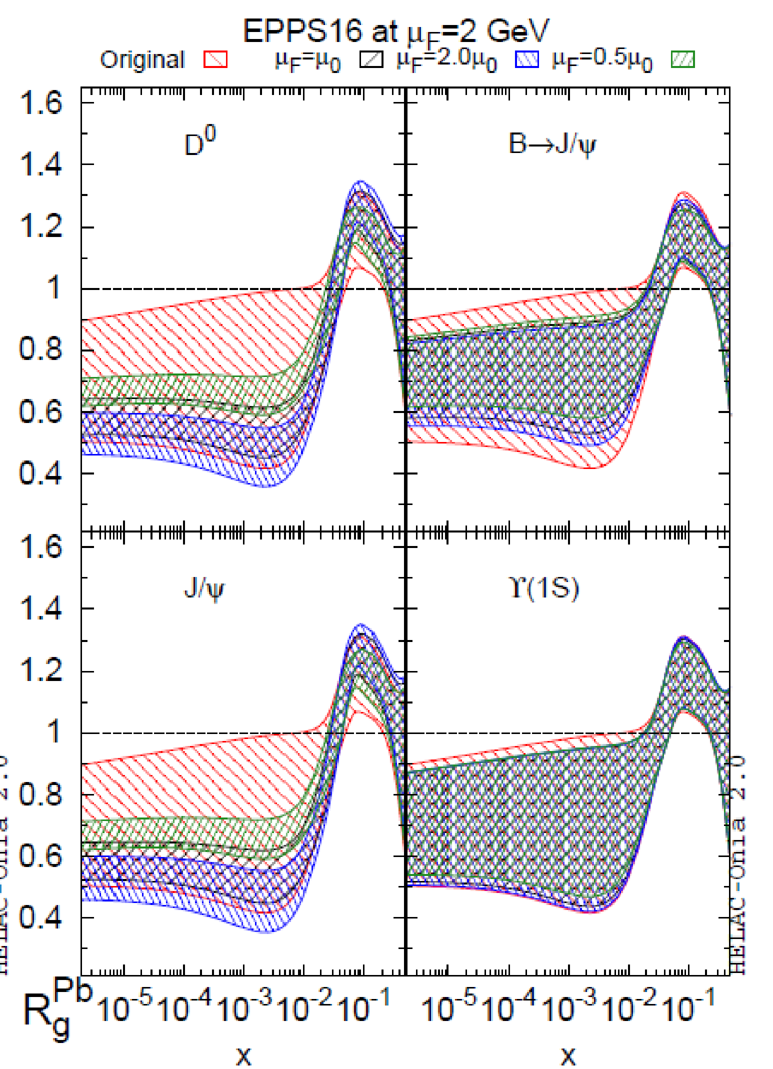


❑ "Tendency" in modern fits of nPDF towards a **strong increase of uncertainties**
→ See **EPPS16** parameterization

❑ Can EIC measurements help our knowledge in the relevant x range(s) ?

❑ x intervals for J/ψ production for p-Pb collisions at LHC energy (ALICE)
$2\times10^{-5} < x < 8\times10^{-5}$ (forward y, **p-going**)
$6.1\times10^{-4} < x < 3\times10^{-3}$ (central y)
$10^{-2} < x < 5\times10^{-2}$ (backward y, **Pb-going**)

Re-weighting nPDFs

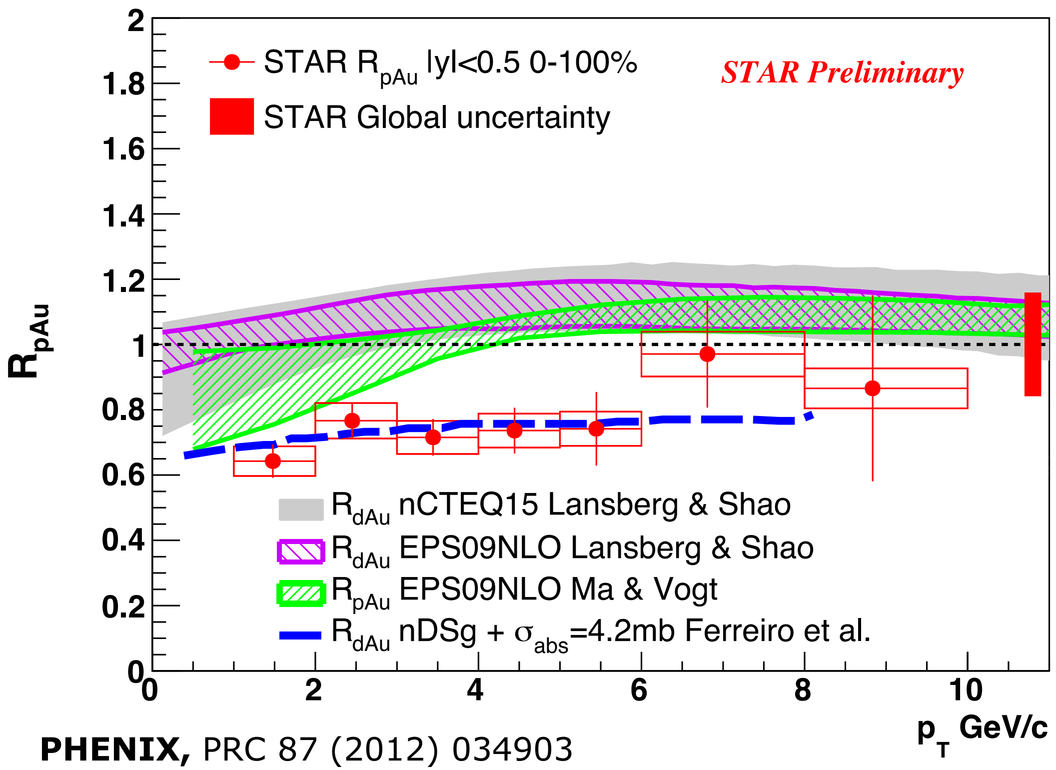


- Interesting developments towards a **"re-weighting" of nPDF**, taking into account LHC results on heavy flavours (Kusina, Lansberg et al., arXiv:1712.07024)

→ Can quarkonium (and open heavy quark) measurements in p-A be directly used to **constrain the nuclear PDFs** ?

- Limited knowledge of modifications of gluon structure functions represents a serious problem in the evaluation of CNM effects in A-A collisions

RHIC: J/ψ production in p-A (mid-y)

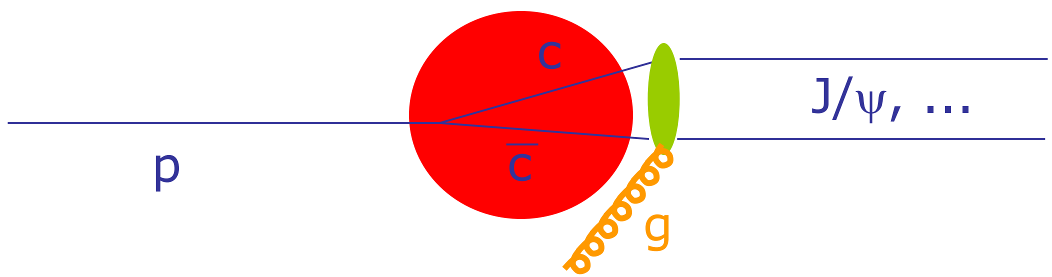


PHENIX, PRC 87 (2012) 034903

Significant suppression observed for J/ψ

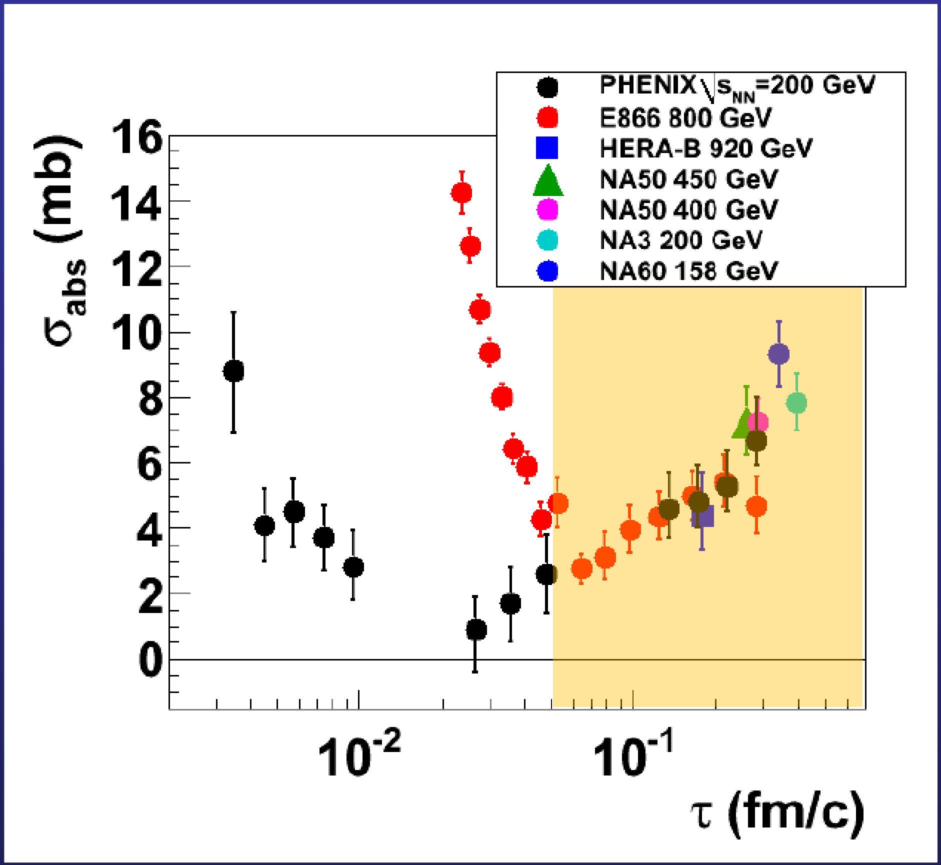
It clearly **exceeds shadowing effects**

Adding a break-up component in the models helps in reproducing data



Formation time likely longer than crossing time
→ Interaction of the (pre)-resonant state

Formation/crossing times



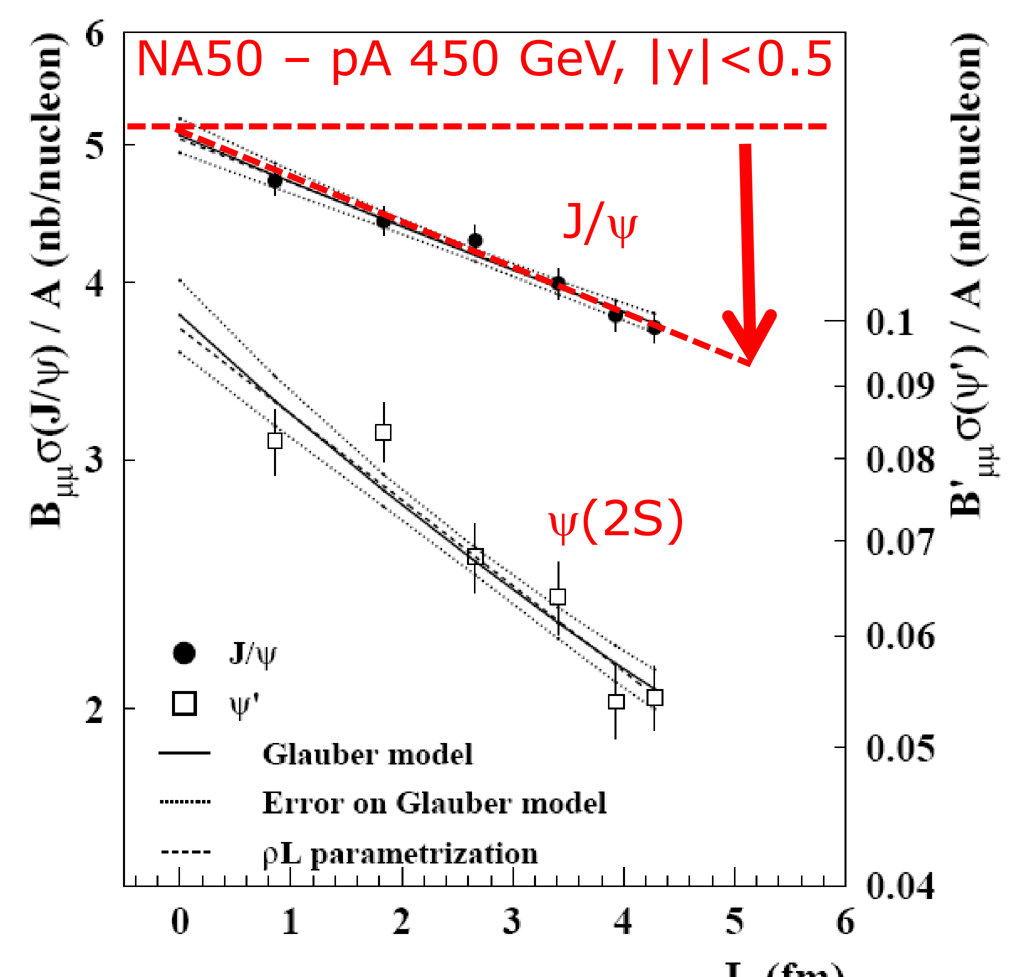
When crossing times exceed τ_c~ 0.05 fm/c a steady increase of the strength of suppression effects is seen

Visible at
RHIC → backward y
Fixed target → central y

(for τ_c <~ 0.05 fm/c other effects dominate, energy loss etc…)

→ Effect possibly related to the **increase in the size of the cc pair while crossing CNM**

Fixed target: J/ψ vs ψ(2S)



NA50, Eur.Phys.J C 48, 329(2006)

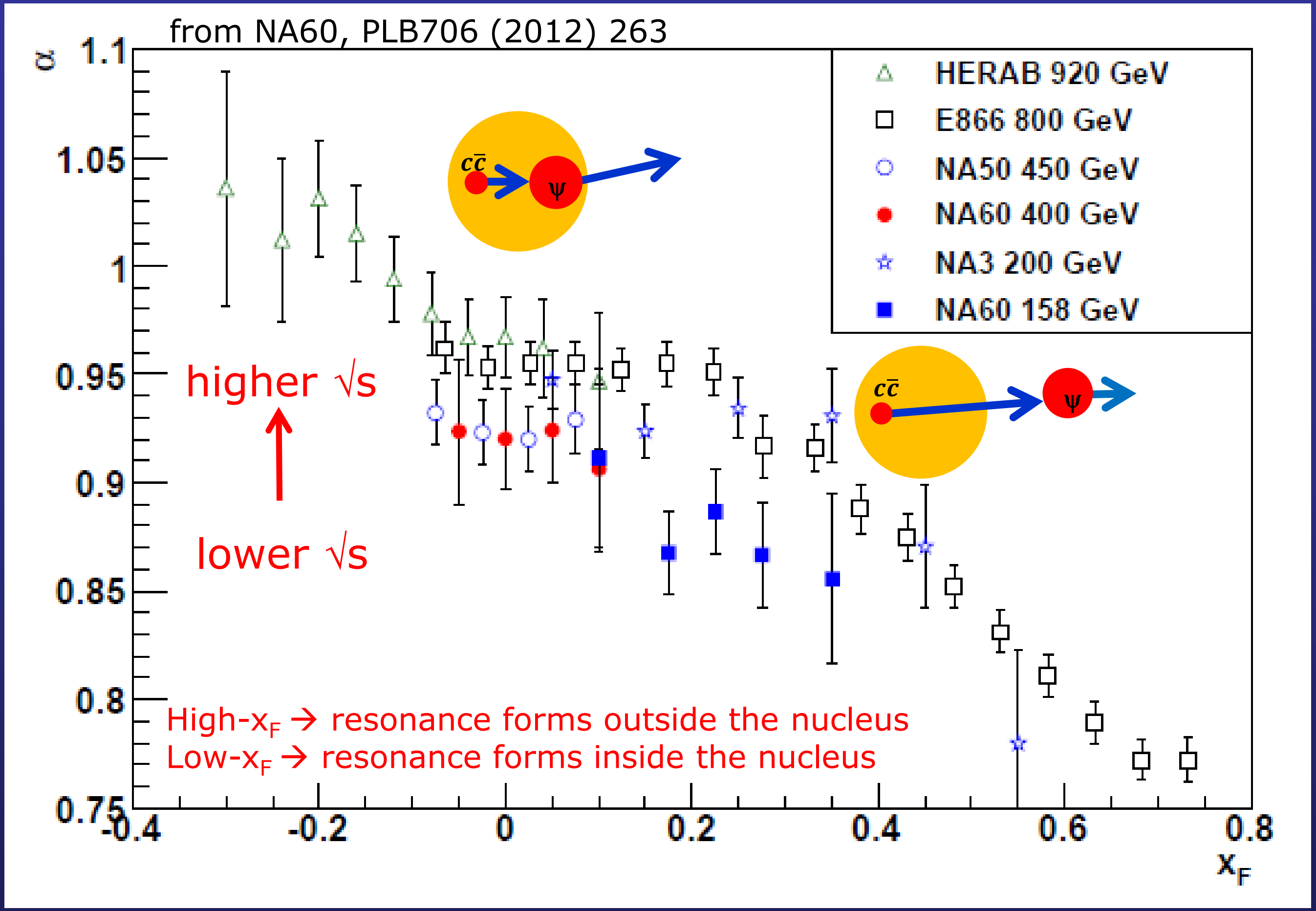
L: thickness of nuclear matter crossed by cc

- Shadowing effects small
- Significantly different suppression on ψ(2S) and J/ ψ
- **Stronger absorption for the weakly bound ψ(2S),** at mid-*y*
- Nucleus crossing time comparable or larger than charmonium formation time: **fully formed resonances** cross the nucleus

$$\sigma^{pA}_{J/\psi} = \sigma^{pp}_{J/\psi} \cdot A \cdot e^{-\langle\rho L\rangle\sigma_{abs}}$$

$$\begin{cases} \sigma_{abs}{}^{J/\psi} = 4.5 \pm 0.5 \text{ mb} \\ \sigma_{abs}{}^{\psi(2S)} = 8.3 \pm 0.9 \text{ mb} \end{cases}$$

Fixed target: SPS + Tevatron + HERA



Parameterize nuclear effects via $\sigma_{J/\psi}(A)=\sigma_0 A^{\alpha}$

Strong dependence of α on x_F

At fixed x_F, α increases when $\sqrt{s}$ increases

- ❑ **High x_F** → no final state effects, possibly initial state energy loss ?
- ❑ **Low x_F** → α >1, interpretation not straightforward (but interesting region)

Quarkonium production in medium: status

- 30-year long effort, what do we know today

- In **heavy-ion collisions** (Au-Au, Pb-Pb) J/ψ is suppressed
- Competition between dissociation (color screening) and recombination
- From fixed target to collider energy
  - **SPS** → suppression observed
  - **RHIC** → suppression similar to SPS, possible compensation of dissociation and recombination
  - **LHC** → strong recombination, due to large cc multiplicity (~100 pairs per central event)

- Understanding **non-QGP effects** necessary for a quantitative assessment

- Cold nuclear matter (CNM) effects strong at all energies, various regimes
- **p-A studies have shown**
  - **LHC** → dominated by shadowing (role of energy loss and CGC ?)
  - **RHIC** → superposition of shadowing + break-up effects
  - **SPS** → dominated by break-up of the (pre)resonant state

Quarkonium production: prospects and EIC

- Do not expect by definition any direct info on hot matter effects at EIC
- May expect improvement on **understanding of CNM effects**

- Main question (on my side)
  - Can the more **quantitative handle on kinematics** allow a selection of certain physics processes involving quarkonia and occurring in CNM?

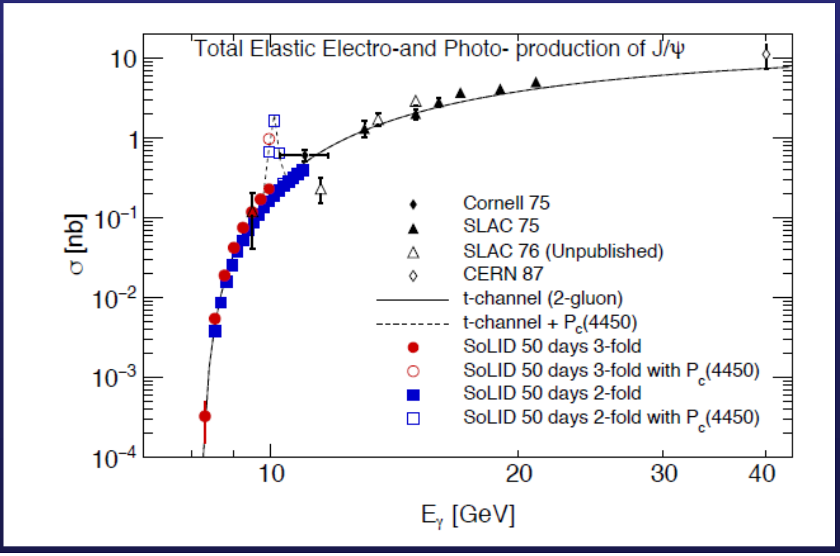
In particular

- Study of the formation (and propagation!) of the fully formed **resonance inside the nucleus**
  → addresses relevant physics issues, as the different interaction strength of (precursor) color octet/singlet states
  → If several states can be measured (J/ψ, χ_c,..) they may react differently to CNM due to the different mixture of **octet and singlet states** in their pre-resonant state → test of NRQCD approach

Charmonia propagation in CNM

- Requires, in hadronic collisions, central/backward-y coverage at moderate (fixed target) energies, data exist from SPS, Tevatron, HERA-B for central y, but not for backward y
  → **Can it be studied at EIC** (e.g. via electroproduction, likely not too far from threshold, or via backward-y J/ψ detection at higher W) ?

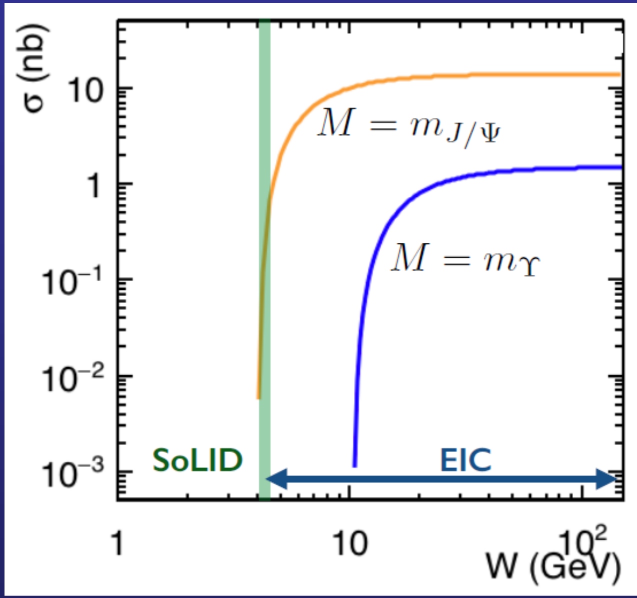
- Measurements of J/ψ production close to threshold were already proposed with the 12 GeV e beam of JLab (ep collisions)
  → SoLID, GlueX
  Extension/inclusion to eA may present interest in this respect

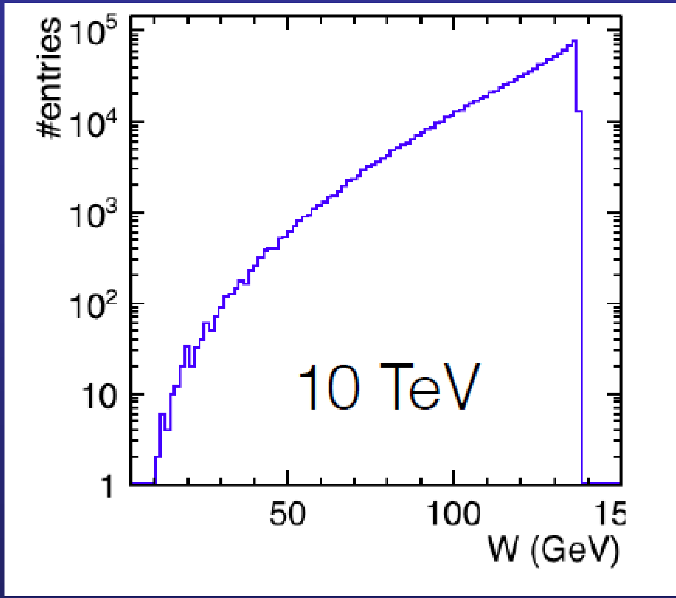


From Joosten and Meziani, arxiv:1802.02616

Charmonia propagation in CNM

Measurement of J/ψ and ϒ production close to threshold **are also considered at the EIC**





Corresponds to 20 GeV e on 250 GeV p

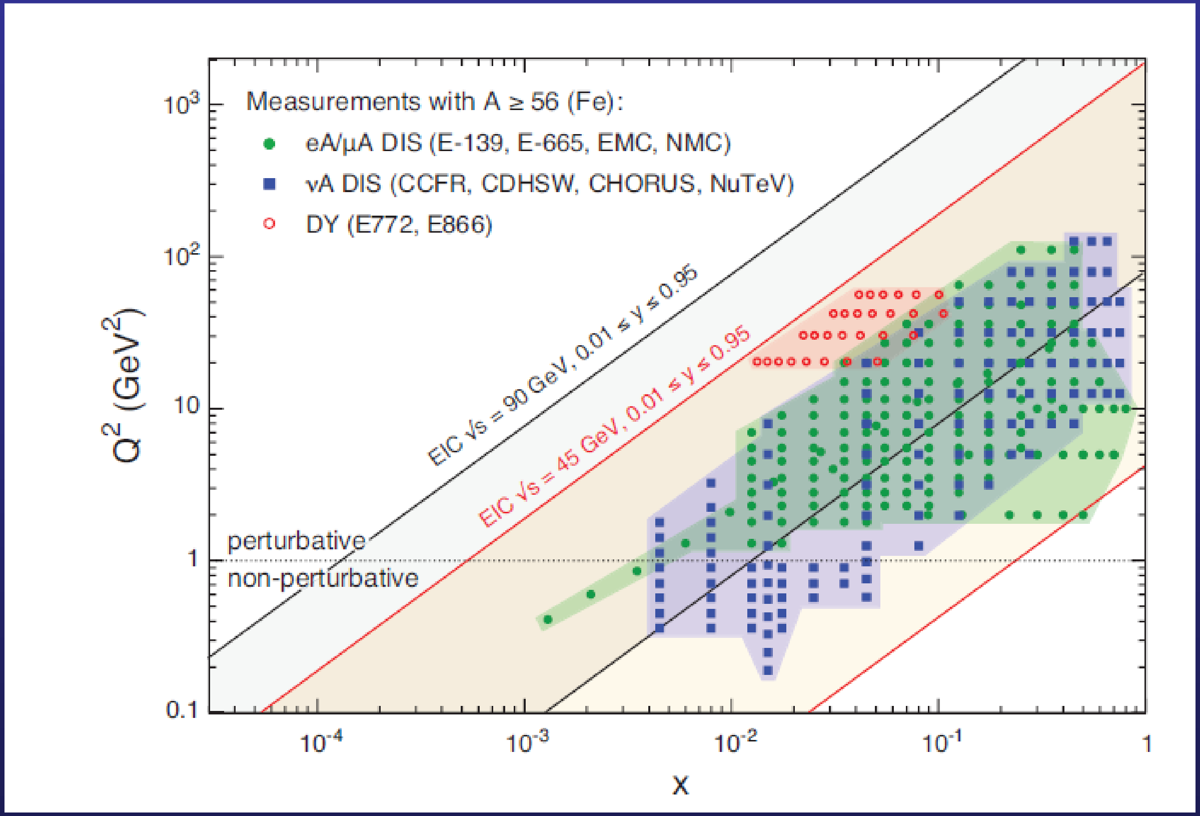
Strong increase of yields with W

$\tau_c = \langle L \rangle / (\beta_z \gamma)$ — $\beta_z = \tanh y_{cc}^{rest}$, $\gamma = E_{cc}/m_{cc}$; $E_{cc} = m_{T,cc} \cosh y_{cc}^{rest}$

It should be possible to work out the kinematic details in such a way to have full **control on the propagation time of quarkonia** in CNM

Charmonium and nPDFs

- Initial state effects are crucial for the interpretation of collider data (both p-Pb and Pb-Pb collisions!) on charmonia



Charmonium and nPDFs

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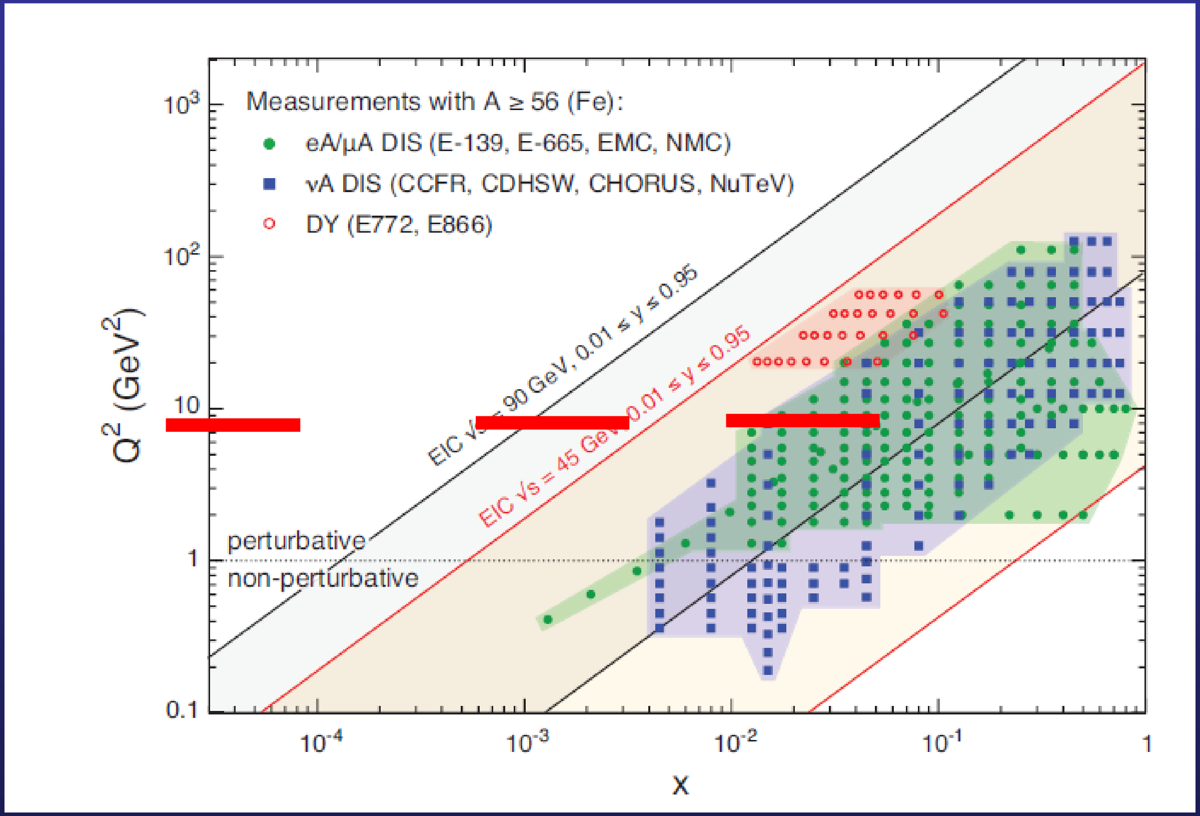

- ❑ LHC x-range covered by EIC acceptance **except at forward rapidity**

Charmonium and nPDFs

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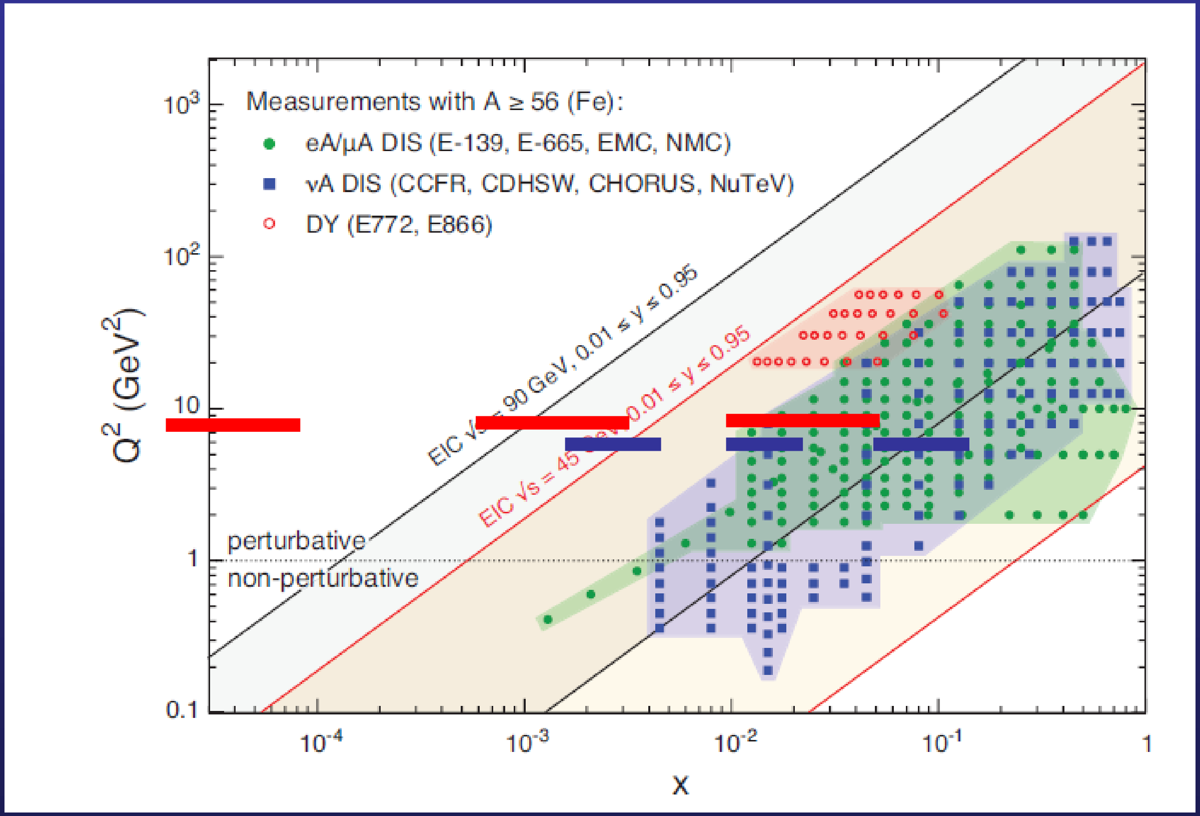

- ❑ LHC x-range covered by EIC acceptance **except at forward rapidity**
- ❑ RHIC x-range **well within** EIC acceptance

Charmonium and nPDFs

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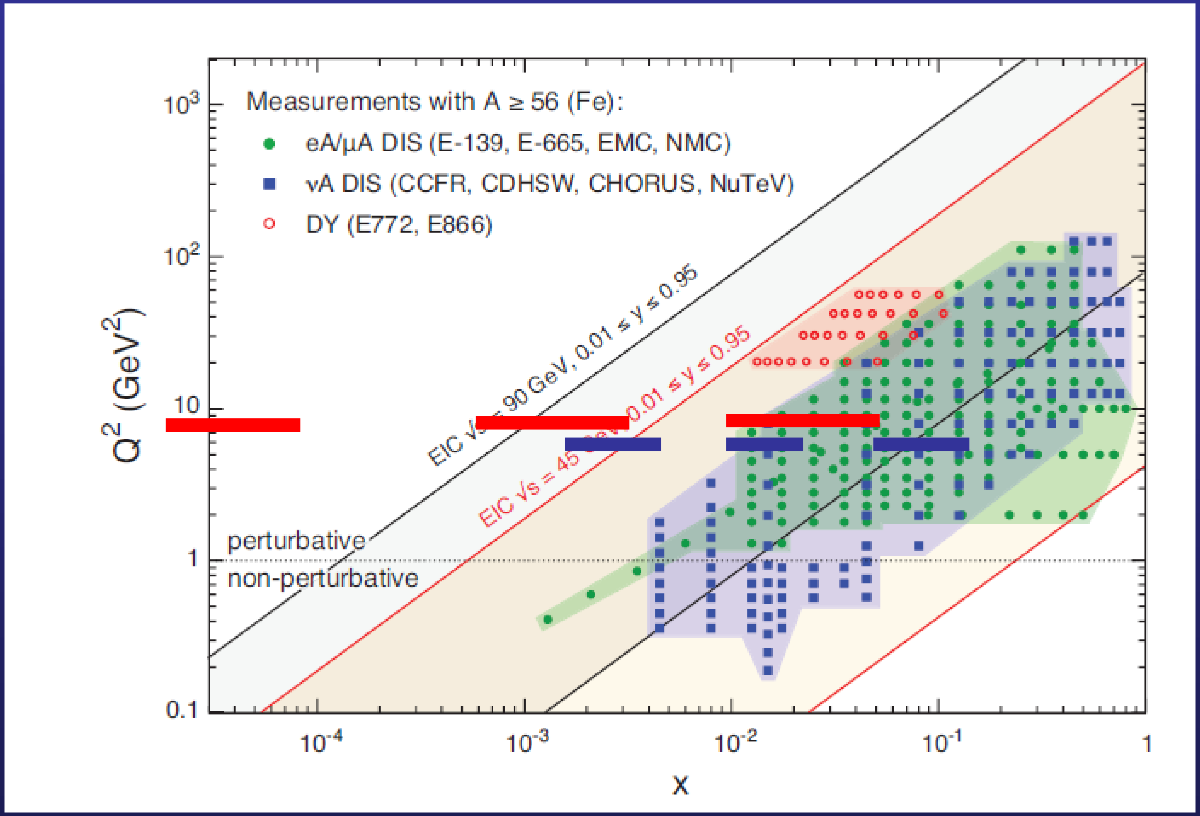


Can we expect improvements of our knowledge of nPDFS even in domains not directly covered at EIC energy ?

- ❑ LHC x-range covered by EIC acceptance **except at forward rapidity**
- ❑ RHIC x-range **well within** EIC acceptance

Conclusions

- Quarkonium represents in many respects an **ideal probe of "QCD matter",** both deconfined (QGP) and confined (nucleus)

- At the same time, after many years of investigations, there are **still open issues** in quarkonium physics

- Restricting to the topics discussed here
  - A quantitative understanding of **quarkonium results related to QGP** formation requires a (very) **good knowledge of CNM effects**
  - Although the latter can be investigated via p-A collisions, there is still **no precise control** over the involved mechanisms and in the corresponding calculations

- **Quarkonium studies in e-nucleus collisions (EIC),** thanks to the more selective control of kinematics (Q^2, ν) and the possibility of measuring various cc/bb states, may help clarifying the open questions, such as the behavior of (pre)resonant states in nuclear matter and their connection to color octet/singlet states in the production process
  → to be worked out also with theory guidance

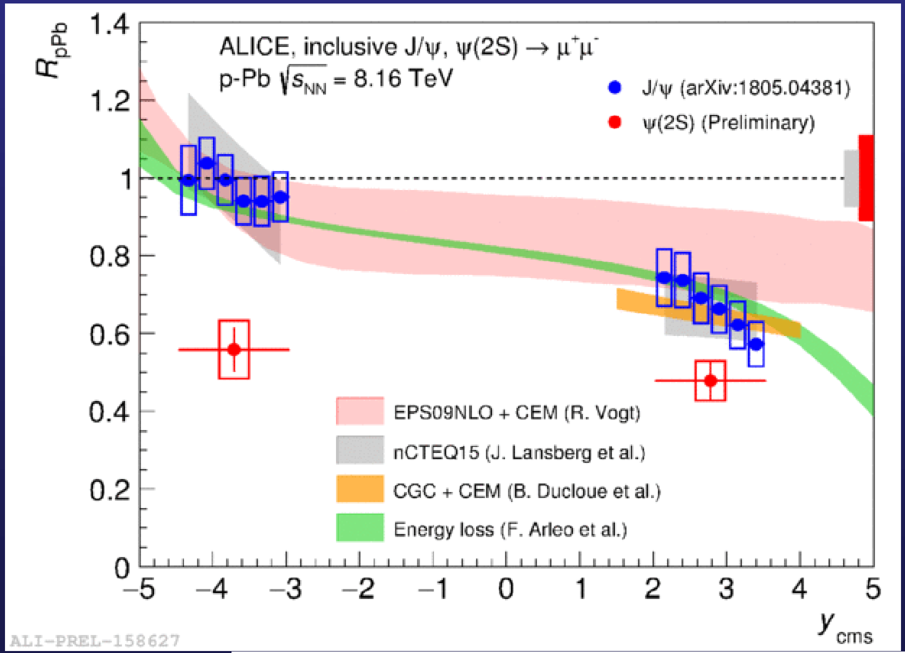
Backup

$\psi(2S)$

- At LHC energy, all produced charmonium states have **no final state effects in nuclear matter**, due to the very **short crossing time** of the cc pair

$$\tau_c = \langle L \rangle / (\beta_z \gamma) \begin{cases} \tau_c\ (2.<y<3.5) \sim 10^{-4}\ \text{fm/c} \\ \tau_c\ (-4.5<y<-3) \sim 7\ 10^{-2}\ \text{fm/c} \end{cases}$$

- One would therefore expect **similar suppression effects** for all charmonium states. This is clearly **not the case!**



The extra-suppression for the $\psi(2S)$ can be due to a dissociation of this weakly bound state by the **produced system of strongly interacting particles** (QGP?)

ψ(2S) suppression vs particle density

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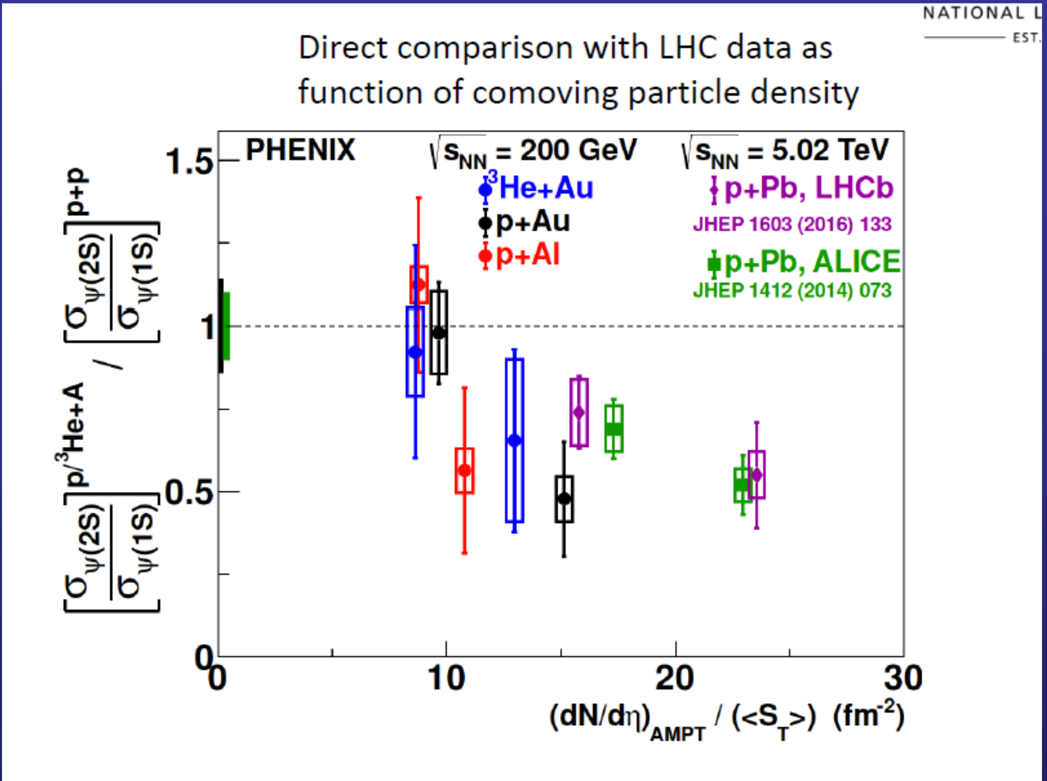
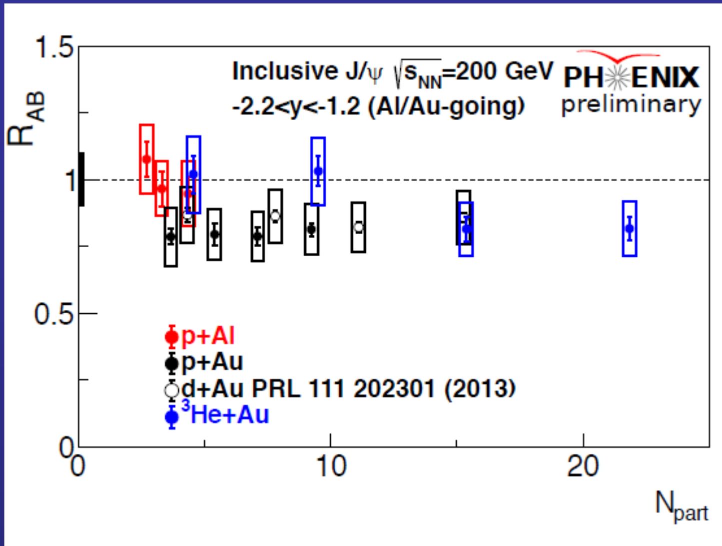


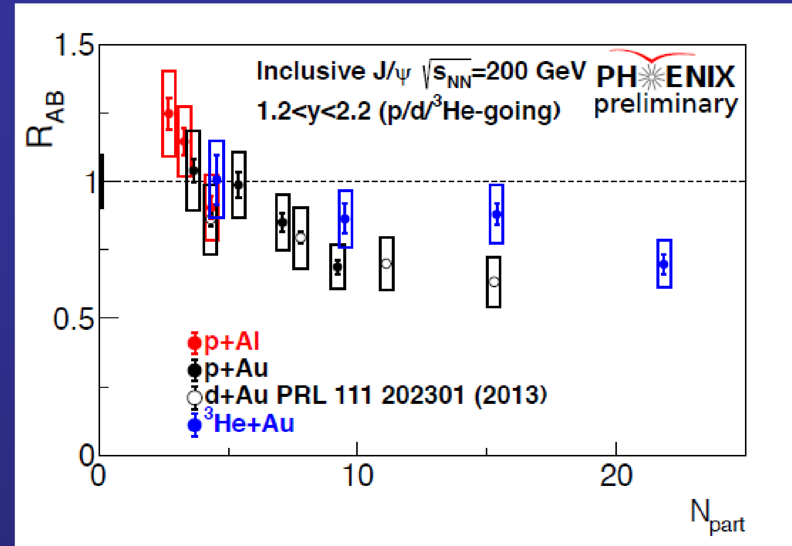
$$< S_T >= 4\pi\sqrt{< x^2 >< y^2 > - < xy >^2}$$

from Glauber model

- Within large uncertainties, indication for a **suppression effect proportional to the density of the produced particles**

RHIC: small systems forward/backward y

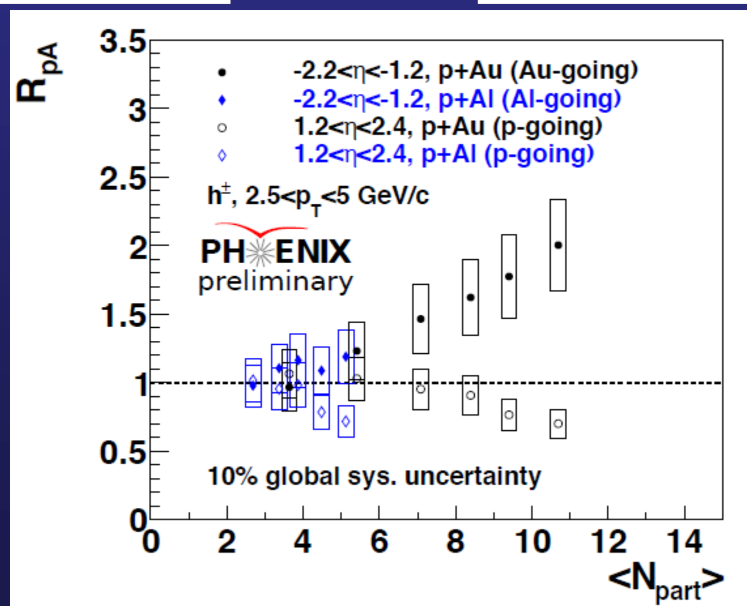




Backward y

→ suppression

- Possibly due to final state effects (larger hadronic multiplicity and no shadowing or small antishadowing expected)



Forward y

→ suppression

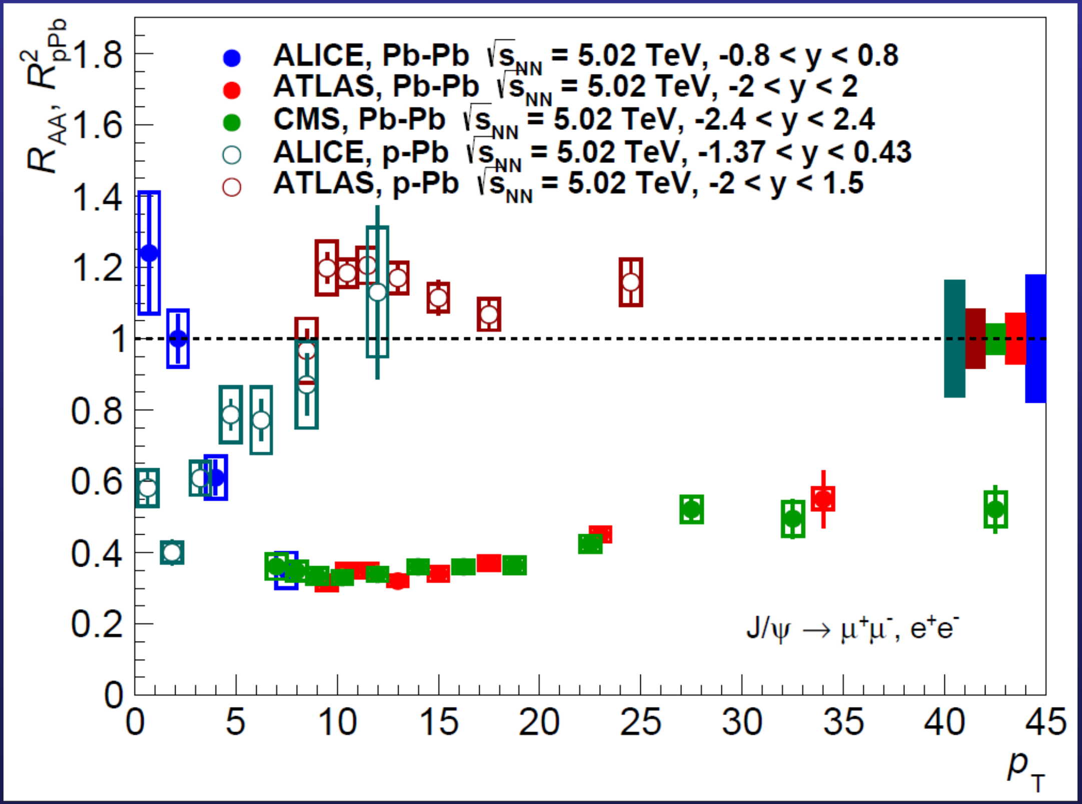
- Likely due to initial state effects (smaller hadronic multiplicity, weaker final state effects expected)

p-A results and CNM in A-A

- No "exact" way to extrapolate the measurement of CNM effects in p-A towards the conditions of A-A collisions
→ semi-empirical criteria were developed

- For example, in case of shadowing dominance for CNM (LHC energy) one has **$R_{PbPb}^{CNM}=R_{pPb}^2$**

- After accounting for CNM effects one observes a **strong J/ψ enhancement** at low p_T



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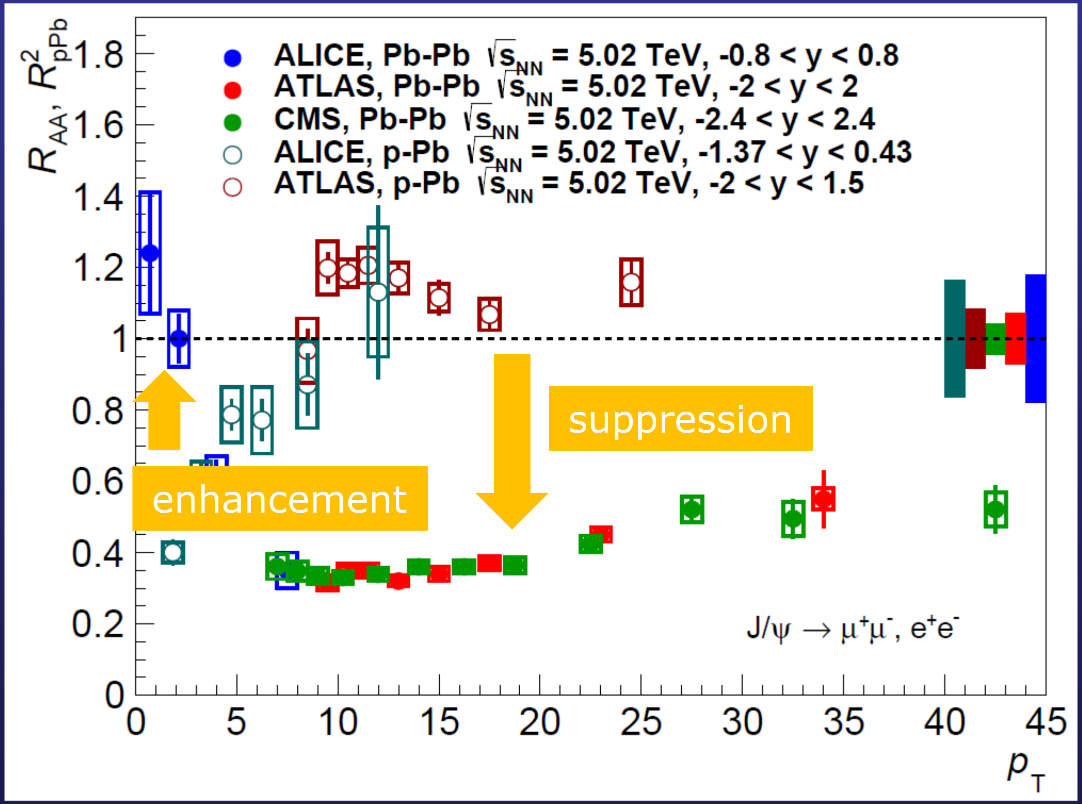
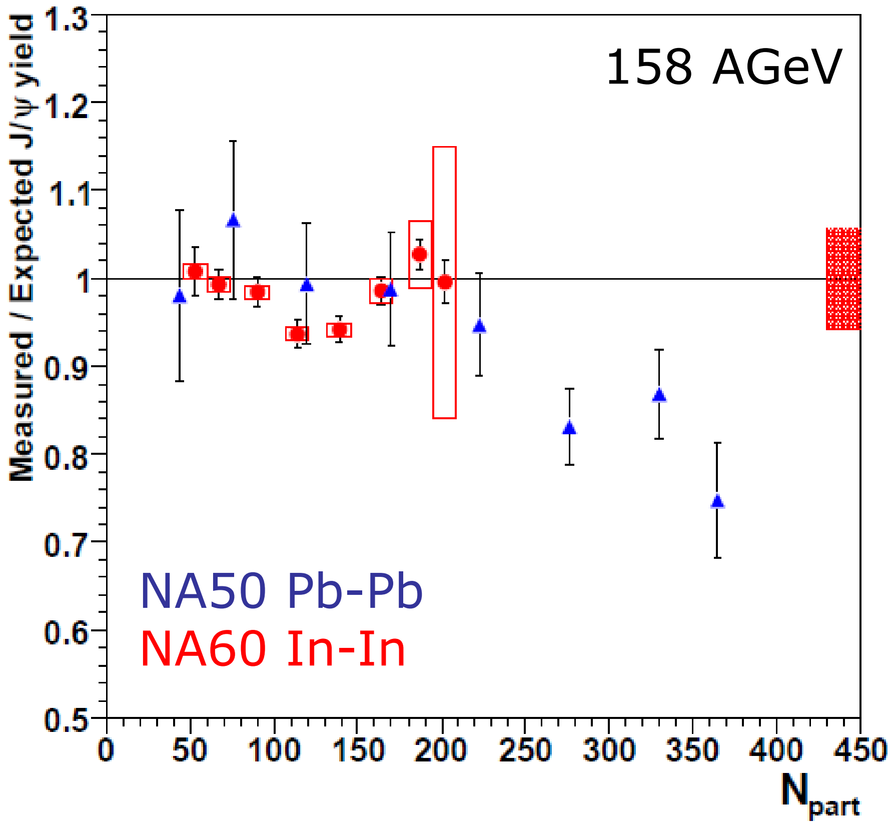


p-A results and CNM in A-A (fixed target)

- Fixed-target: CNM **dominated by break-up** at central-y
- Use a simple parameterization of p-A results in terms of $\sigma_{abs}^{J/\psi}$ and extrapolate to A-A



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- Non-CNM effects relatively weak, choice of the p-A reference data is crucial
  → Same √s and kinematics

- **Evidence for anomalous J/ψ suppression** at fixed-target energy (25-30% in central Pb-Pb)