Quarkonium production at SPS energies: Comovers (and other effects) at play

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Back to 2000 in Moriond…

XXXVth Rencontres de Moriond
QCD and High Energy Hadronic Interactions
Les Arcs, Savoie, France. March 18-25 2000

NON–SATURATION IN THE J/ψ SUPPRESSION AT LARGE E_T IN THE COMOVERS APPROACH

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hep-ph/0002300

INTRODUCTION

Recent data on Pb+Pb collisions at SPS energies:

NA50 Collaboration, CERN–EP–2000–013

- Anomalous J/ψ suppression: Stronger than the one obtained from nuclear absorption ($\sigma_{abs} = 7.3 \pm 0.6$ mb)

For $E_T \geq 100$ GeV the slope of the ratio $\frac{J/\psi}{DY}$ increases with increasing E_T

Interpretations

- Hadronic interpretation: Conventional physics

Comovers $\Rightarrow$ Extra J/ψ suppression due to final state interaction of the resonant J/ψ with comoving hadrons

These models exhibits a clear saturation of the ratio with increasing E_T

A. Capella *et al.*, Phys. Lett. B393 (1997) 431; Phys. Rev. C59 (1999) 395

R. Vogt, Phys. Lett. B430 (1998) 15; J. Geis *et al.*, Phys. Lett. B447 (1999) 31

For $E_T \geq 100$ GeV: Tail of the E_T distribution $\Rightarrow$ Increase in E_T due to fluctuations $\Rightarrow$ Increase in the density of comovers $\Rightarrow$ Increase in the J/ψ suppression $\Rightarrow$ Non saturation of the ratio $\frac{J/\psi}{DY}$ at large E_T

- QGP interpretation: Phase transition

Critical energy or critical density of strings $\Rightarrow$ Discontinuity in the J/ψ survival probability when the local energy density or the density of colour strings is larger than some critical value

J.–P. Blaizot and J.–Y. Ollitrault, Phys. Rev. Lett. 77 (1996) 1703

N. Armesto, M. A. Braun, E. G. Ferreiro and C. Pajares, Phys. Rev. Lett. 77 (1996) 3736

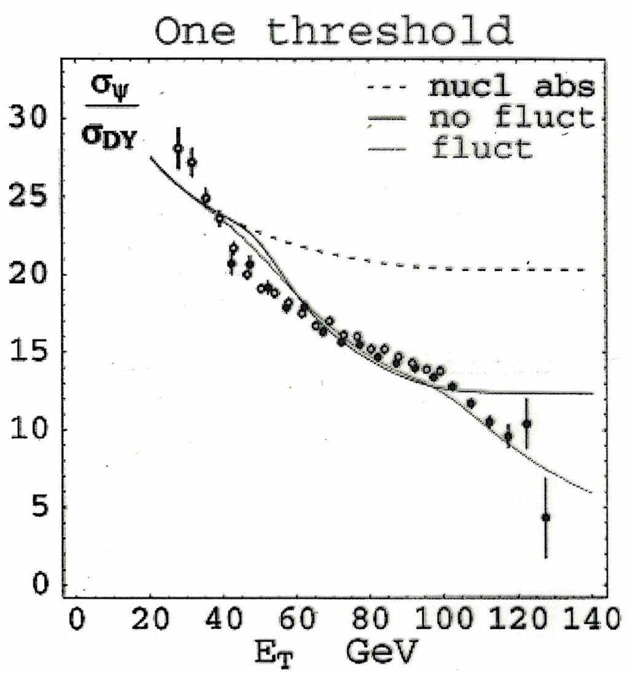
M. Nardi and H. Satz, Phys. Lett. B442 (1998) 14

Back to 2000 in Moriond…

Fit to NA50 Data (1)

(Considering deconfinement)

Blaizot, Dinh and Ollitrault PRL 85 (2000) 4012



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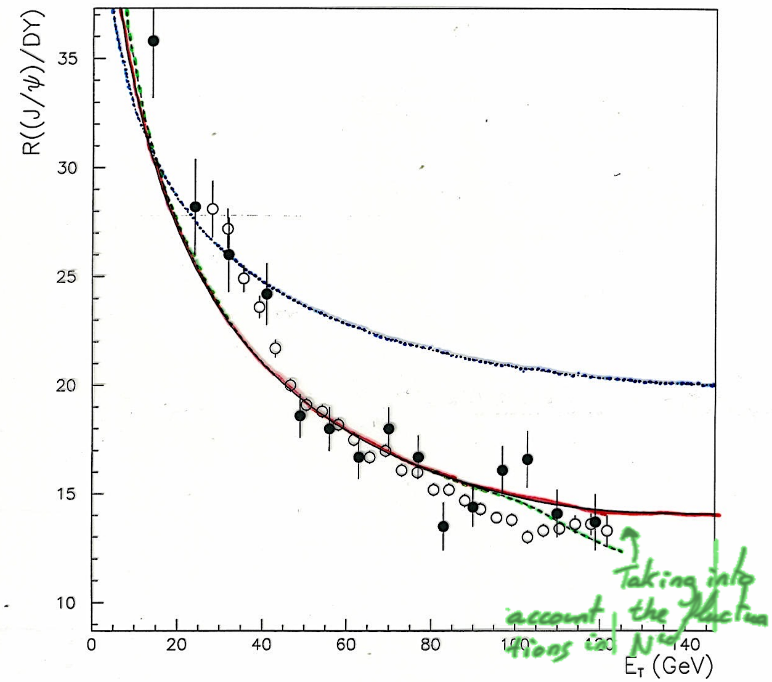
HADRONIC INTERPRETATION:

Nuclear absorption + comovers

Capella Ferreiro and Kaidalov PRL 85 (2000) 80



⇒ **DPM**: Nuclear absorption $\sigma_{abs} = 6.7$ mb + comovers $\sigma_{co} = 0.6$ mb

$R^{th} = \frac{J/\psi(a_{J/\psi})}{DY(a_{DY})}, \; a_{J/\psi} = a_{DY}$

Experimental 1996 data: Black symbols — Change of E_T scale, CERN–EP/99–13

Open symbols: $R^{exp} = (\frac{J/\psi}{MB})_{exp} * (\frac{MB(a_{MB})}{DY(a_{DY}=a_{MB})})_{th}$

⇒ **DPM**: Nuclear absorption $\sigma_{abs} = 6.7$ mb + comovers $\sigma_{co} = 0.6$ mb

$R' = R^{th} * \frac{DY(a_{DY}>a_{MB})}{DY(a_{DY}=a_{MB})}$

Back to 2000... ...

CONCLUSIONS

At a special seminar on 10th February at CERN:

"The combined data coming from the 7 experiments on CERN's Heavy Ion program have given a clear picture of a new state of matter [....] We now have evidence of a new state of matter where quarks and gluons are not confined"

"While all the pieces of the puzzle seem to fit with a quark gluon plasma explanation, it is essential to study this newly produced matter at higher and lower temperature in order to fully characterize its properties and definitively confirm the QGP

"Proof by circumstantial evidence"

RHIC answer:

"Analyzed independently, none of the CERN experiments is definitive. But taken together, they provide circumstantial evidence"

"Direct measurements will only be possible at RHIC"

Back to 2000…

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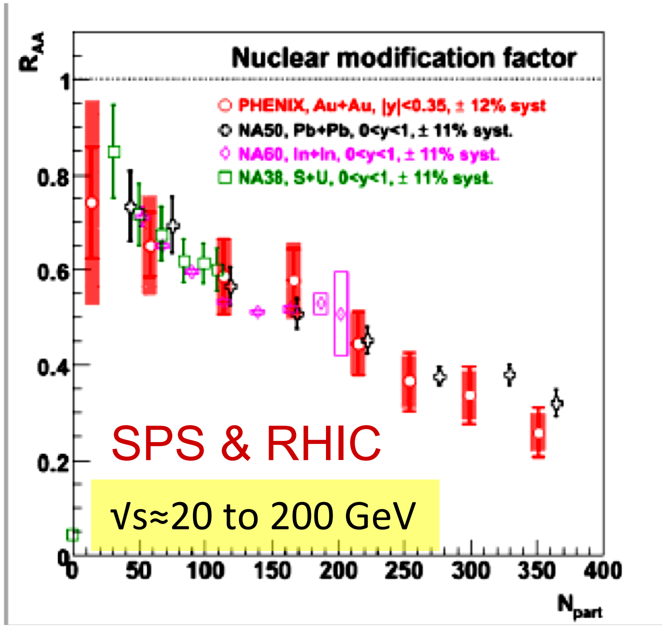
6 years later…

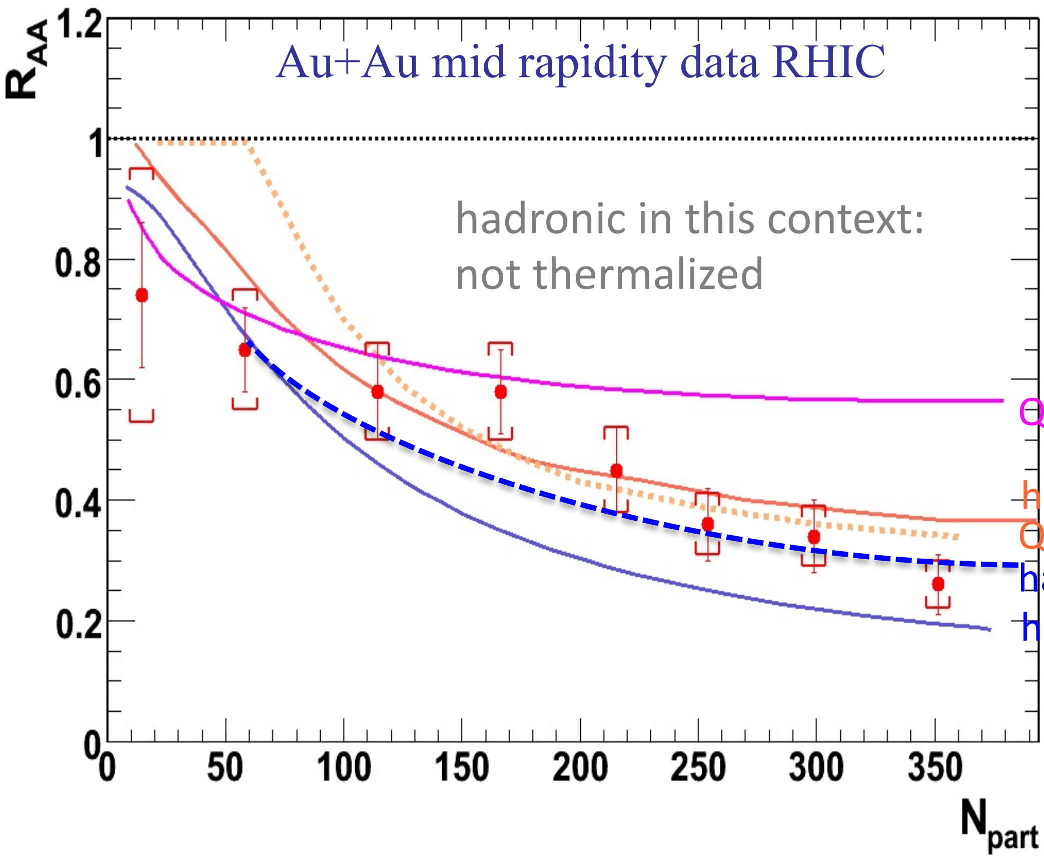
- **J/ψ suppression at RHIC:**

J/ψ are suppressed, but not as much as expected if we have complete color screening

puzzle at RHIC: same amount of suppression as at SPS



Suppression by a dense medium: Models @ SPS & RHIC



QGP & rec

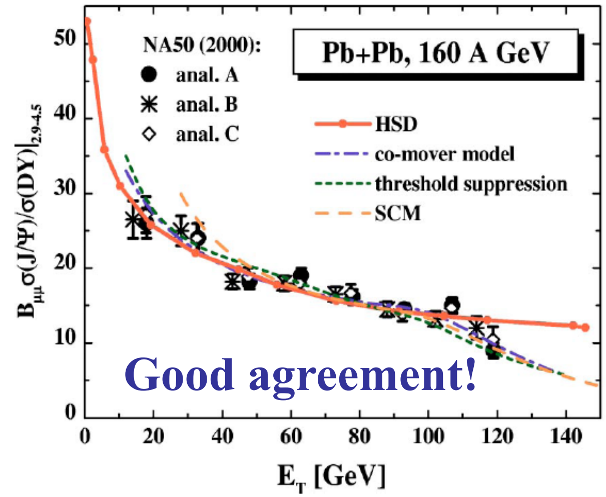
hadronic & rec

QGP & rec

hadronic & rec

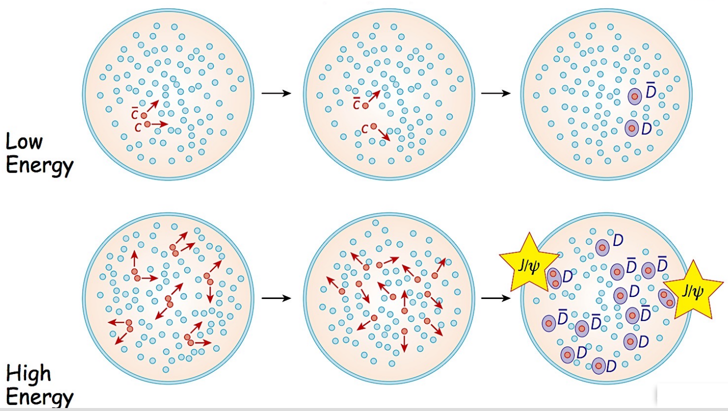
hadronic & no rec

Models at SPS



Recombination at play in both scenarios

excess of initially produced charm => new form of combinatorial charmonium production at hadronization

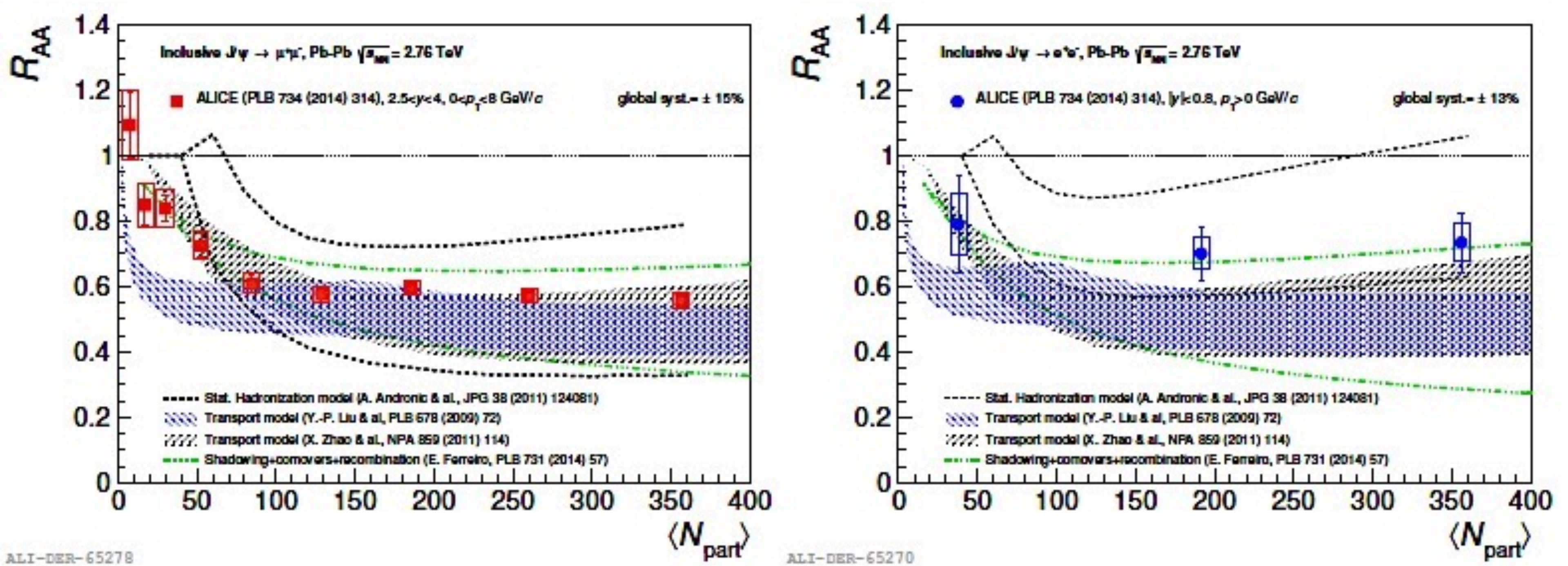


- ______ **transport**, Grandchamp et al, PRL 92, 212301 (2004).
- ______ **HSD**, E.L.Bratkovskaya et al., PRC 71, 044901 (2005).
- ---------- **SCM**, A.Andronic et al., nucl-th/0701079.
- _______ **comover**, A.Capella and E..Ferreiro hep-ph/0610313

Present situation: J/ψ production @ LHC

The originally proposed J/ψ suppression signature of QGP formation has evolved into a more complex problem where both suppression & regeneration (or statistical hadronization) mechanisms need to be considered

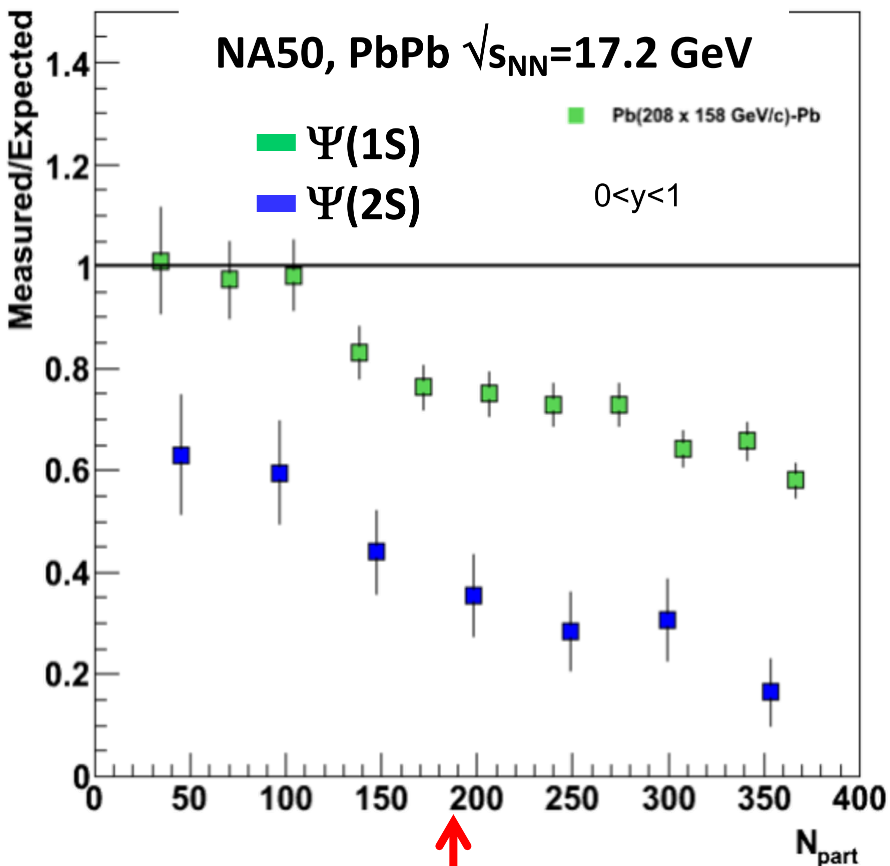
Main ingredients:
- suppression (either color screening, or in-medium dissociation)
- recombination (either in-medium or at phase boundary)
- Initial cold nuclear matter effects (shadowing and/or energy loss)

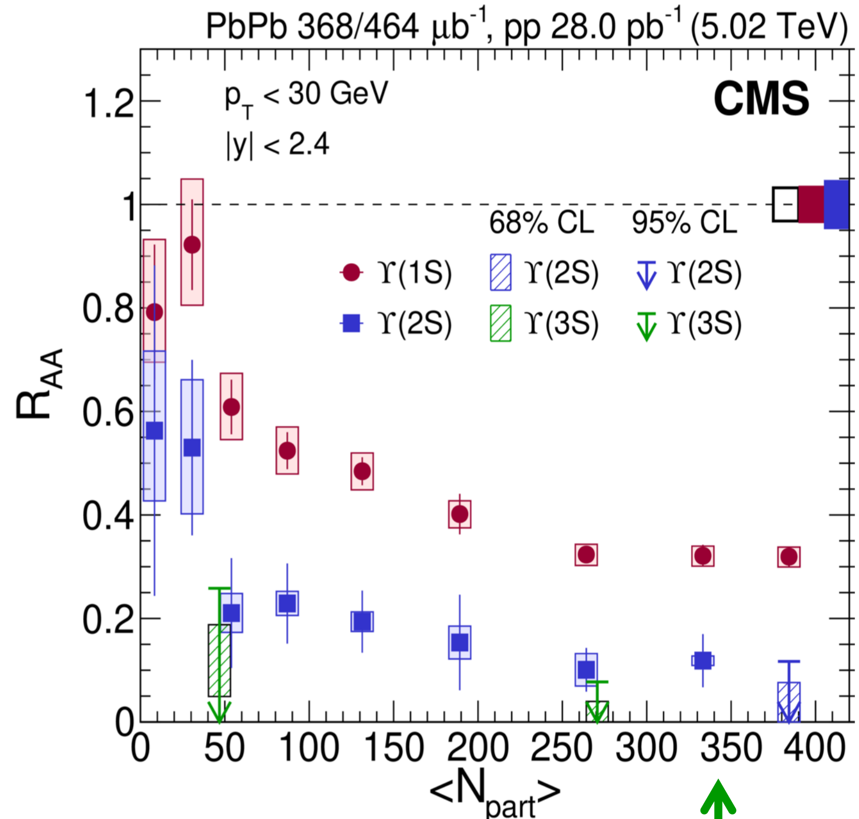


Inclusive J/ψ R_{PbPb} versus Event Centrality @ LHC

J/ψ production seems *at least qualitatively* understood

Some analogies: : J/ψ production @ SPS vs ϒ @ LHC





Charmonia @ SPS **bottomonia @ LHC**

Sequencial suppression? Comover scenario?

Quarkonium production at low & high energies: Effects at play

Many physics effects of specific interest are involved:

- Modification of the gluon flux *initial-state effect*
  - Modification of PDF in nuclei — nPDF shadowing
  - Gluon saturation at low x — CGC

- Quarkonium-hadron interaction *final-state effect*
  - Break up in the nuclear matter — Nuclear absorption
  - Break up by comoving particles — Comover interaction

- Quarkonium-high density matter interaction *final-state effect*
  - Quarkonium dissociation — QGP-like effects

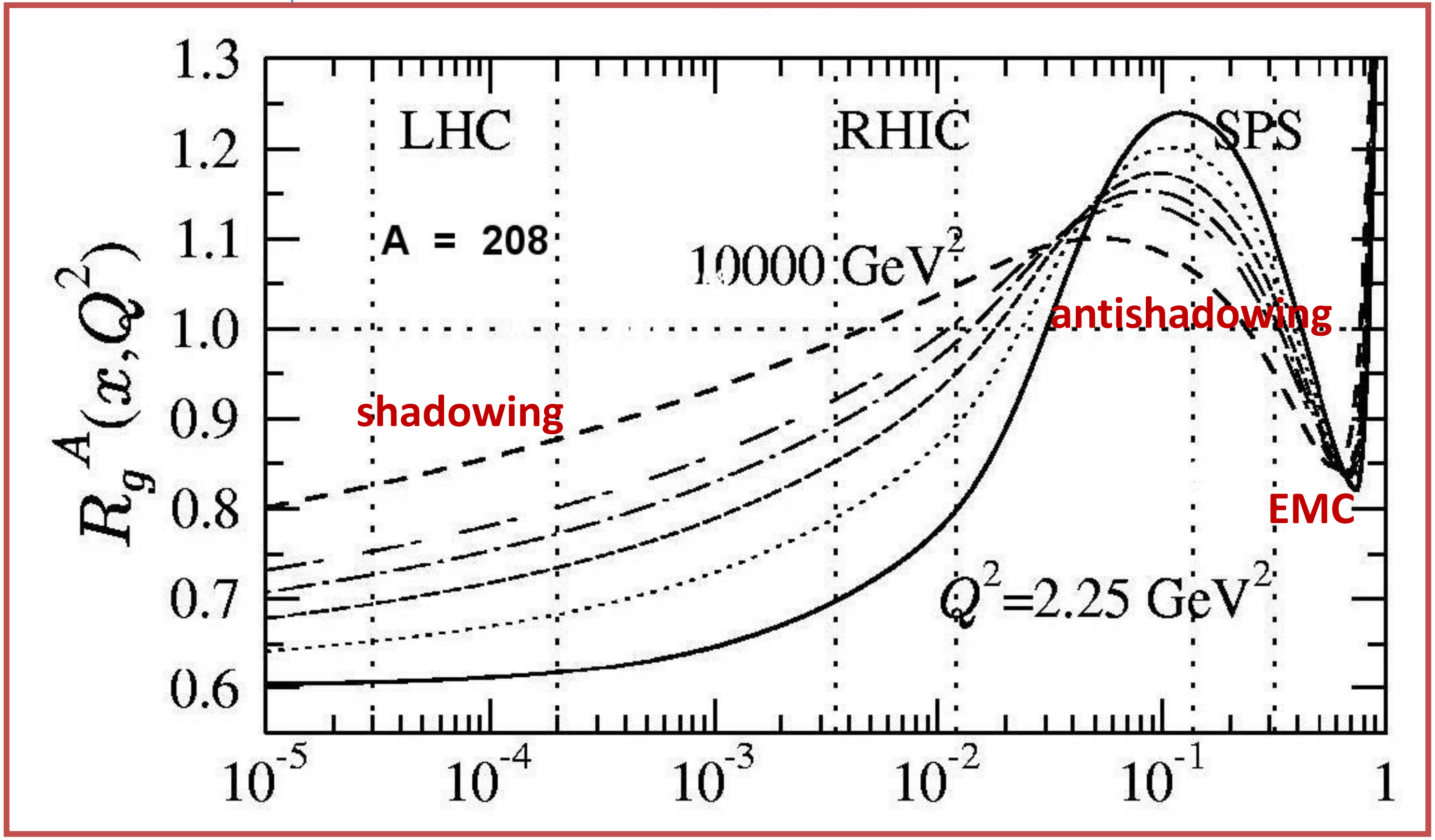
- Others: intrinsic charm? Coherent energy loss? …

Initial effects: nPDF modification

- Gluon distribution functions are modified by the nuclear environment

- Ideal place to look for it: pA collisions

$$R_i^A(x,\mu_f) = \frac{f_i^A(x,\mu_f)}{A f_i^{nucleon}(x,\mu_f)}\ ,\quad f_i = q, \bar{q}, g$$



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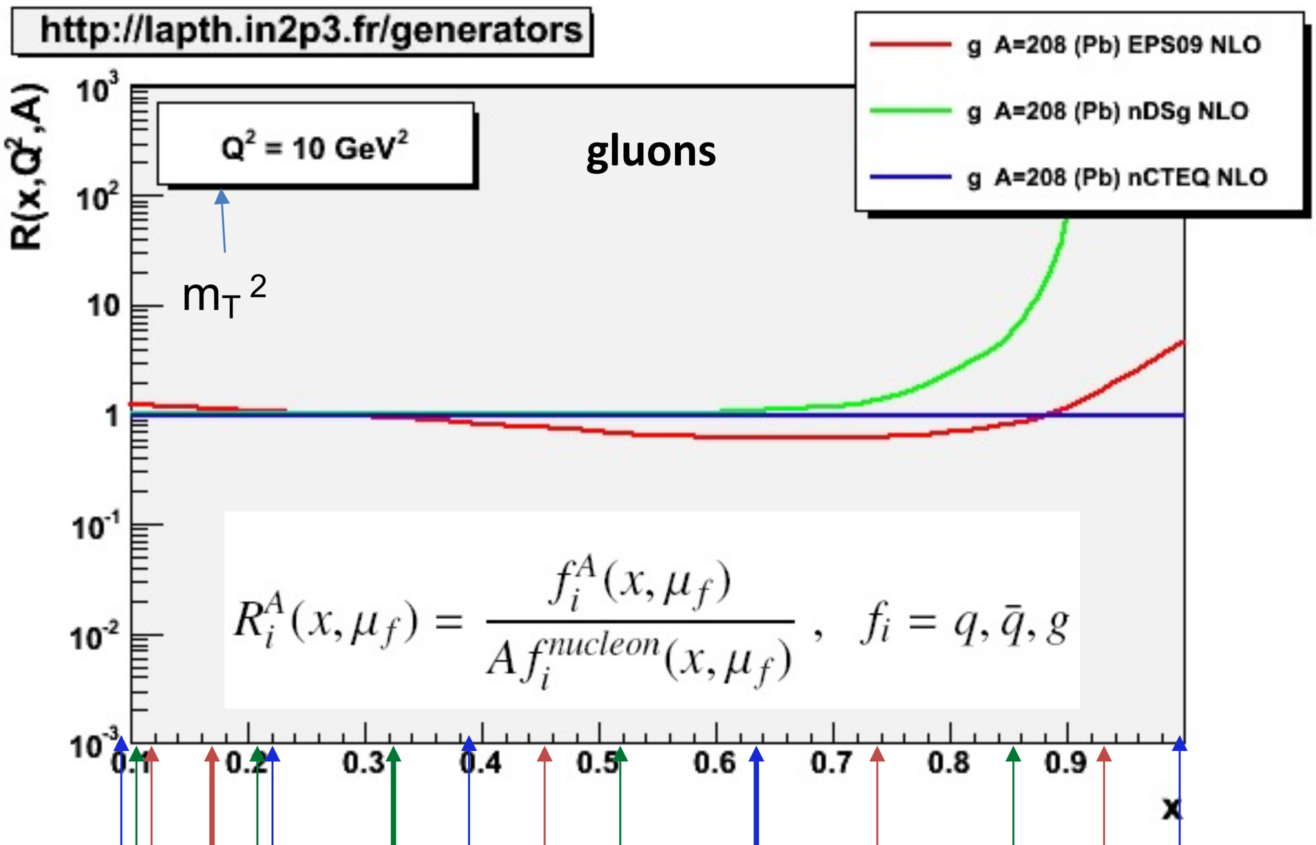


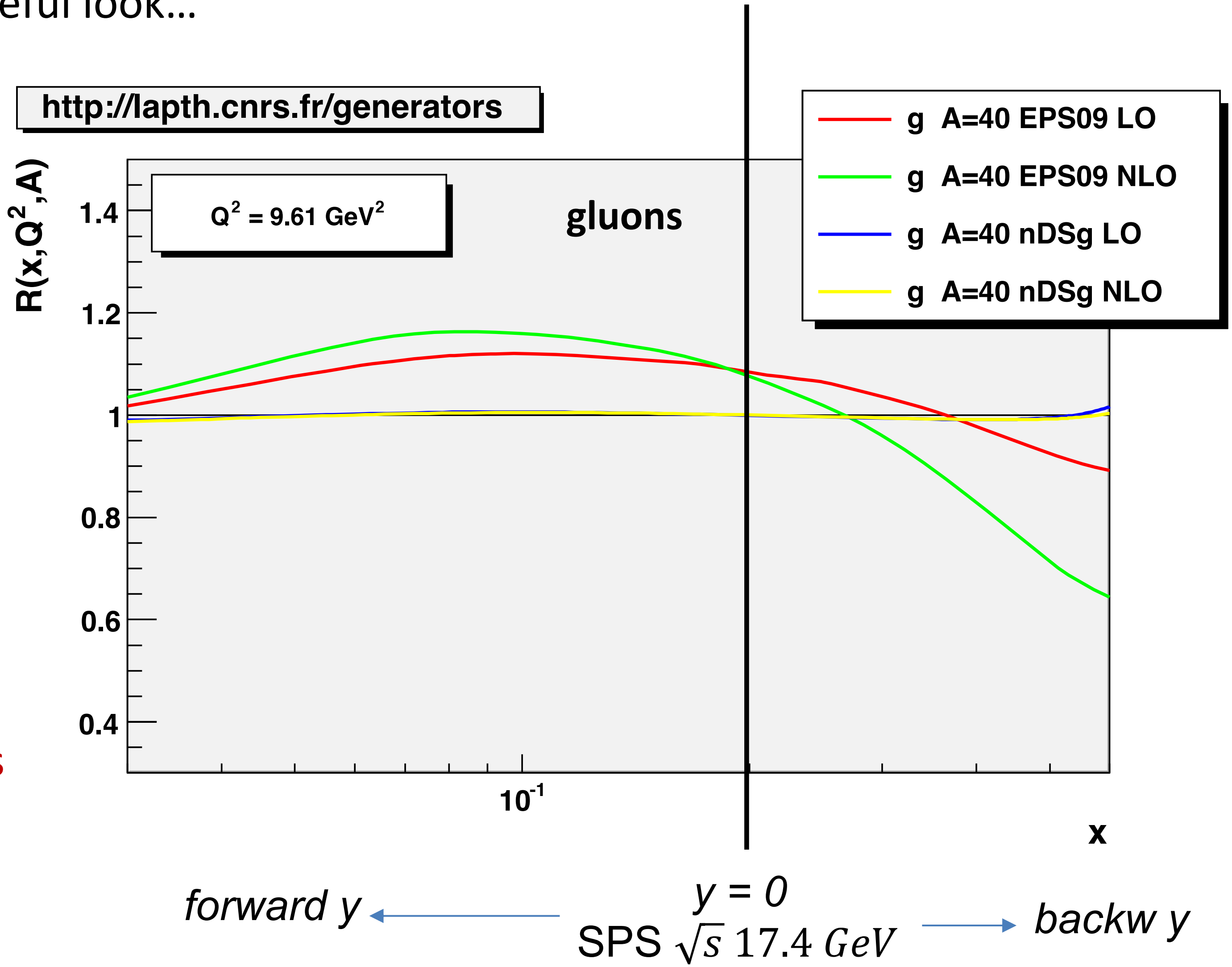
$\sqrt{s} = 5\ GeV$ $y = 1.75$ 1 0.5 0 -0.5

$\sqrt{s} = 10\ GeV$ $y = 1$ 0.5 0 -0.5 -1

$\sqrt{s} = 20\ GeV$ $y = 0.5$ 0 -1 -1.5 -1.75

Initial effects: nPDF modification

- A more careful look…



This effect can be relevant at SPS energies

Initial effects: saturation CGC

Saturation scale

$$Q_{sA}^2 = A^{\frac{1}{3}} \times 0.2 \times \left(\frac{x_0}{x}\right)^{\lambda} (\text{in unit of GeV}^2),$$

with $\lambda \sim 0.2 \div 0.3$ and with $x_0 = 0.01$

sets the minimum momentum fraction below which one expects non-linear effects to be significant in the evolution of the parton distribution

ϒ @ RHIC

y	$Q_{s\mathrm{Au}}$(GeV)	$\frac{Q_{s\mathrm{Au}}}{m_\Upsilon}$	y	$Q_{s\mathrm{Au}}$(GeV)	$\frac{Q_{s\mathrm{Au}}}{m_\Upsilon}$
-2.0	$\lesssim 1$	–	0.0	$\lesssim 1$	–
-1.5	$\lesssim 1$	–	+1.5	$1.0 \div 1.1$	0.1
-1.0	$\lesssim 1$	–	+2.0	$1.1 \div 1.2$	0.1

J/ψ and ψ' @ RHIC

y	$Q^{\psi'}_{s\mathrm{Au}}$(GeV)	$\frac{Q^{\psi'}_{s\mathrm{Au}}}{m_{\psi'}}$	$Q^{J/\psi}_{s\mathrm{Au}}$(GeV)	$\frac{Q^{J/\psi}_{s\mathrm{Au}}}{m_{J/\psi}}$
-2.2	< 1	–	< 1	–
-1.2	~ 1	–	~ 1	–
0	$1.0 \div 1.1$	0.3	$1.0 \div 1.1$	0.35
1.2	$1.3 \div 1.4$	$0.35 \div 0.4$	$1.4 \div 1.5$	$0.45 \div 0.5$
2.2	$1.6 \div 1.9$	$0.4 \div 0.5$	$1.7 \div 2.0$	$0.55 \div 0.65$

Saturation scale always well below the typical energy scale of the process *m*

=> one does not expect any specific saturation effect on ϒ or J/ψ production in collisions @ SPS

=> shadowing of gluons as encoded in the nPDF fits based on the collinear factorisation should give a reliable account of the possible physics

J/ψ, ψ' and ϒ @ SPS:
Qs<1 for all rapidities

This effect is not relevant for SPS energies

Final effects: Nuclear absorption through break-up cross section

The bound states may be destroyed by inelastic scatterings with nucleons if they are formed in the nuclear medium. One expect

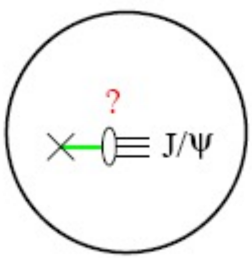
$\sigma_{\text{break-up}} \propto r^2_{\text{meson}}$

$S_{abs} = \exp(-\rho\sigma_{\text{break-up}}L)$

- In order to interact with nuclear matter => $t_f \leq R$
- In the meson rest frame: $\tau_f = \frac{2M_{c\bar{c}}}{(M^2_{2S} - M^2_{1S})} \approx$ 0.3÷0.4 fm
- t_f has to be considered in the rest frame of the target nucleus => $t_f = \gamma\, \tau_f$

Low energy: $t_f = \gamma(x_2)\,\tau_f \ll R$

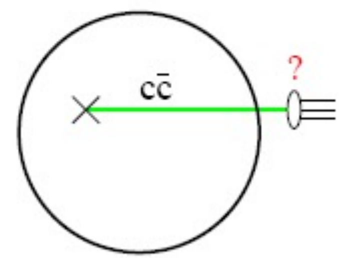
High energy: $t_f = \gamma(x_2)\,\tau_f \gg R$



Formation time depends on the boost

$\gamma = \cosh(y - y^A_{\text{beam}})$ => At y=0:

$\gamma_{SPS} = 9.2$



It takes $t_f \approx 3$ fm/c at SPS for a quarkonium to form and to become distinguishable from its excited states $t_f \sim R$

Nuclear absorption, negligeable at LHC, can be relevant at low energies

- It depends on y (boost increases with rapidity)
- It can be different for ground and excited states (but effectively of the same order)

Final effects: Comover interaction model

- In a comover model: suppression from scatterings of the nascent ψ with comoving medium of partonic/hadronic origin **Gavin, Vogt, Capella, Armesto, Ferreiro … (1997)**

- Stronger comover suppression where the comover densities are larger. For asymmetric collisions as proton-nucleus, stronger in the nucleus-going direction

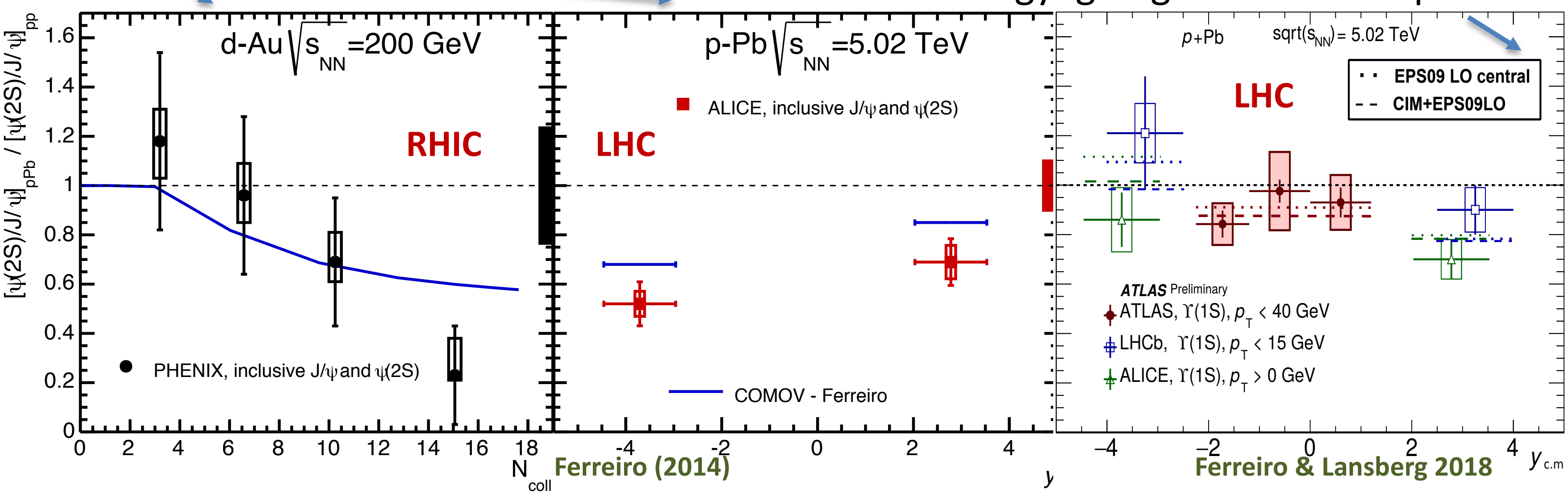
- Rate equation governing the charmonium density:

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

$$S^{co}_{\psi}(b,s,y) \;=\; \exp\left\{-\sigma^{co-\psi}\,\rho^{co}(b,s,y)\,\ln\left[\frac{\rho^{co}(b,s,y)}{\rho_{pp}(y)}\right]\right\}$$

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

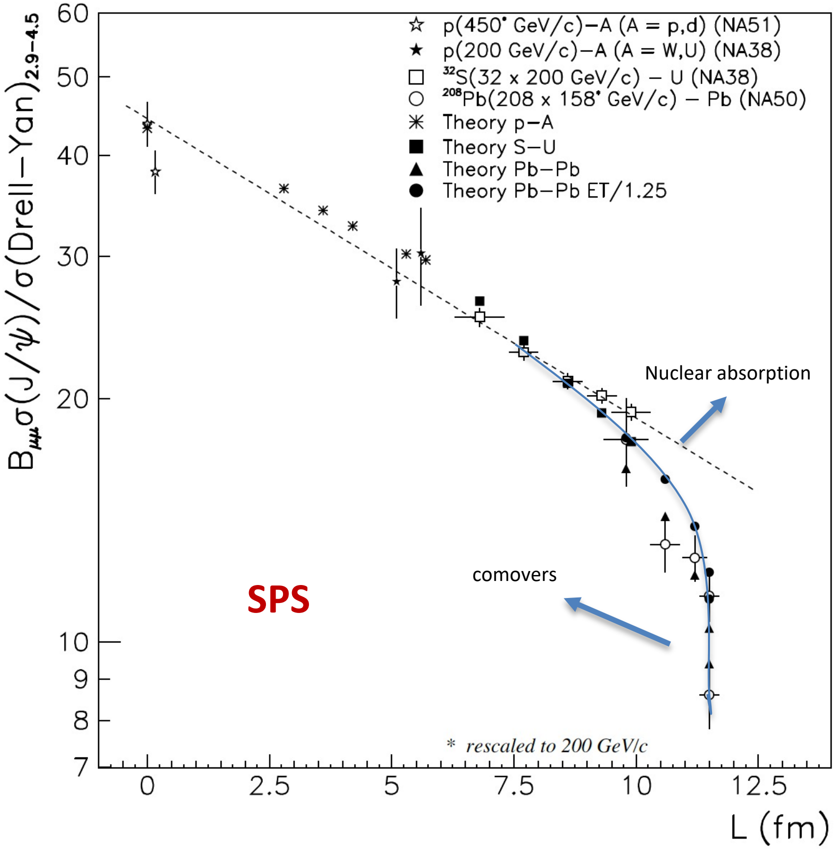
- New strategy: going to a microscopic level

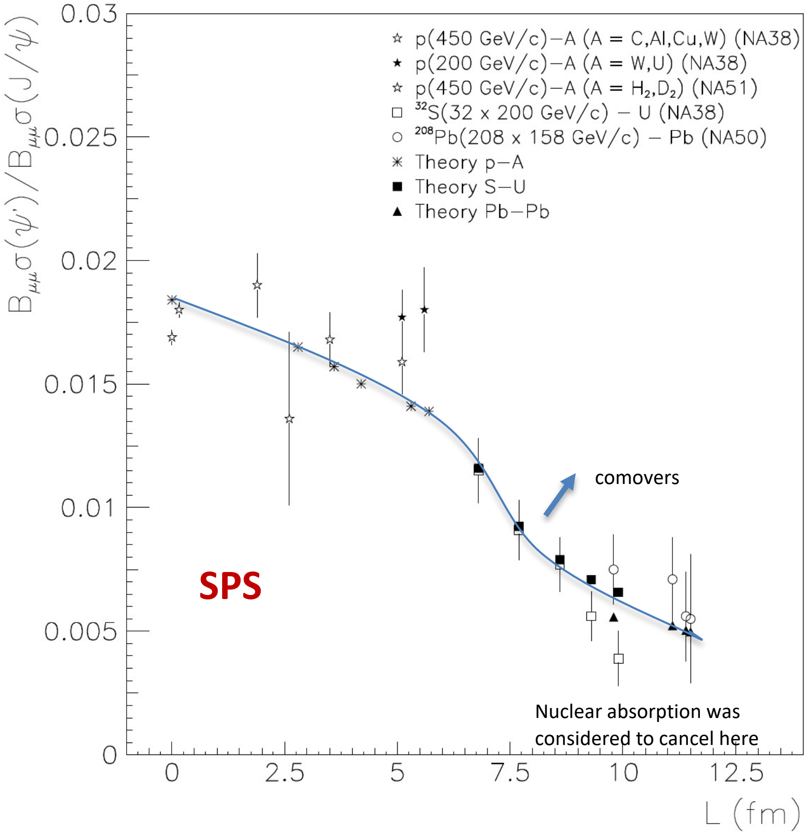


Nuclear absoption not at play

Final effects: Comover interaction model

- Back to 2000:





$\sigma^{\text{co-}J/\psi}$ 0.6 mb $\quad$ $\sigma^{\text{co-}\psi'}$ 6 mb $\quad$ σ_{abs} 4-7 mb

Final effects: Comover interaction model

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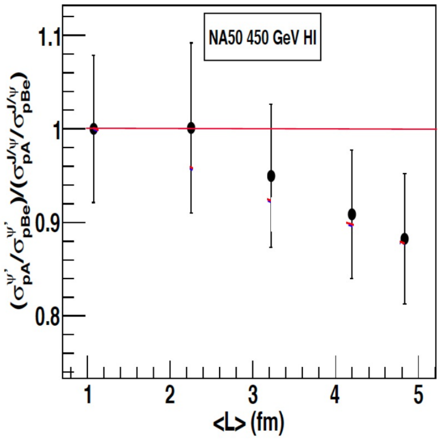
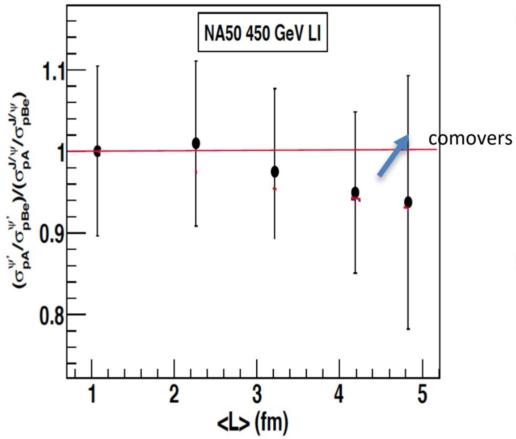
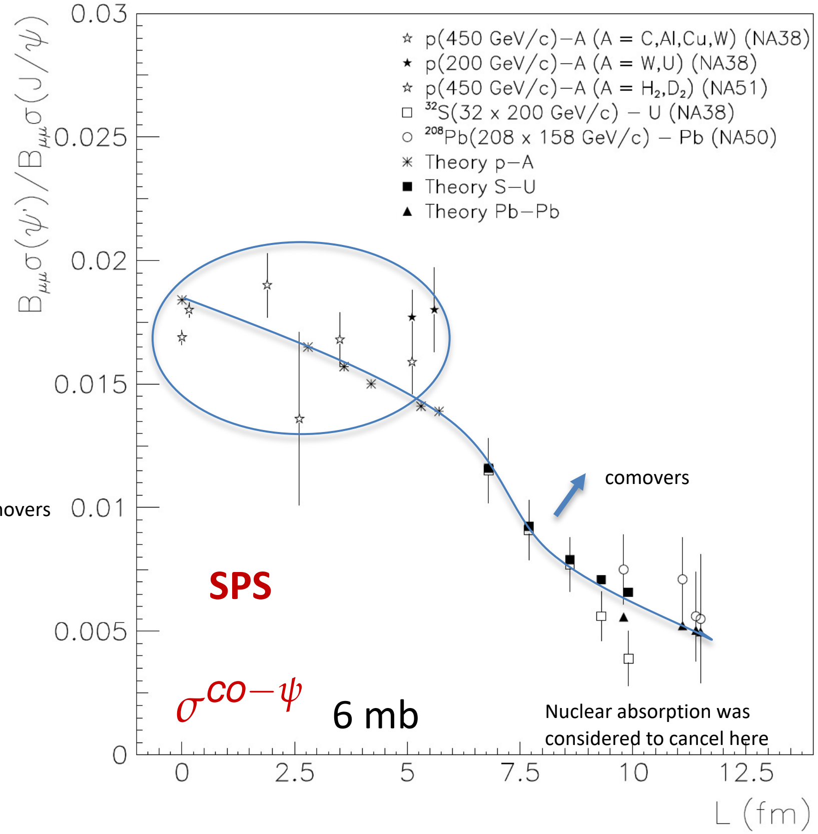






$\sigma^{\text{co-}J/\psi}$ 0.6 mb $\sigma^{\text{co-}\psi'}$ 6 mb σ_{abs} 4-7 mb

Comover interaction cross section

- New strategy: going to a microscopic level

E.G.F., J.P. Lansberg JHEP 10 (2018)

[the feed-downs are taken into account]

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

$\sigma^{\mathcal{Q}}_{\mathrm{geo}} \simeq \pi r^2_{\mathcal{Q}}$, where $r_{\mathcal{Q}}$ is the quarkonium Bohr radius

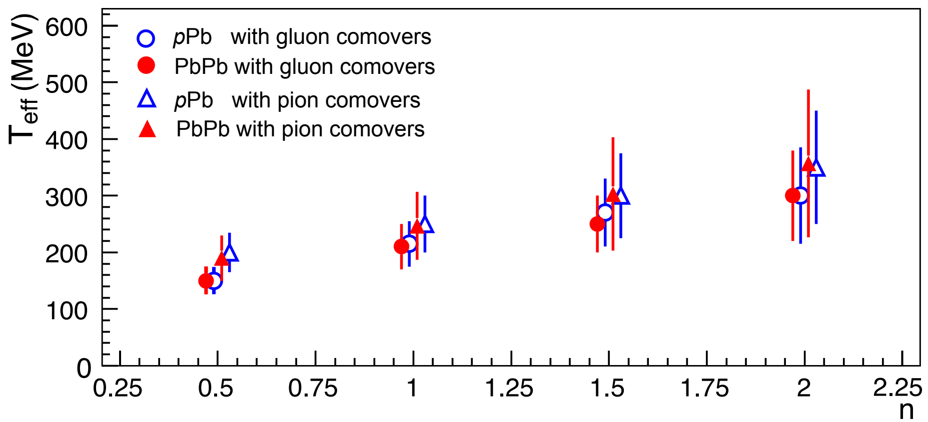
$E^{\mathcal{Q}}_{\mathrm{thr}} = 2M_B - M_{\mathcal{Q}_{1,i}}$, *i.e.* the threshold energy

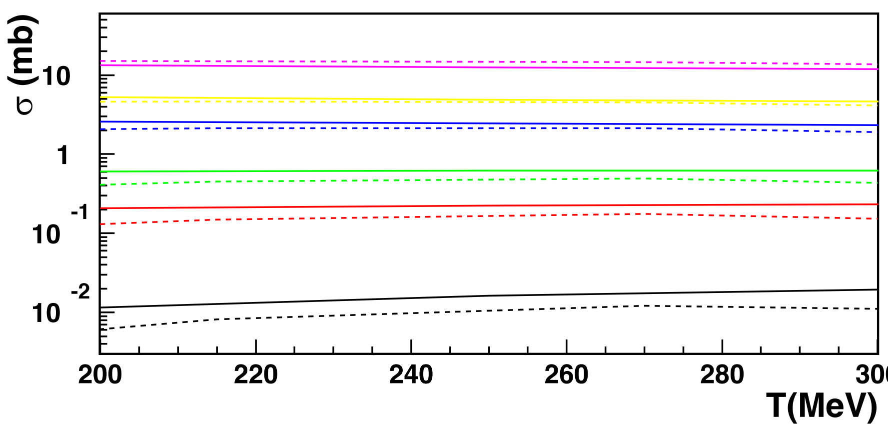
$E^{co} = \sqrt{p^2 + m^2_{co}}$ energy of the comovers

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

Bose-Einstein distribution

$$\mathcal{P}(E^{\mathrm{co}}; T_{\mathrm{eff}}) \propto \frac{1}{e^{E^{\mathrm{co}}/T_{\mathrm{eff}}} - 1}$$





Using pPb CMS and ATLAS data at 5.02 TeV we fit T_{eff} and n. Also with PbPb CMS data

By varying n between 0.5 and 2, we obtain T_{eff} in the range from 200 to 300 MeV

Dissociation cross-sections for the bottomonium family in a comover medium made of pions (continuous line) or gluons (discontinuous line).
From down to up: 1S, 1P, 2S, 2P, 3S, 3P

Comover "propaganda" plot

Taking cross-sections:

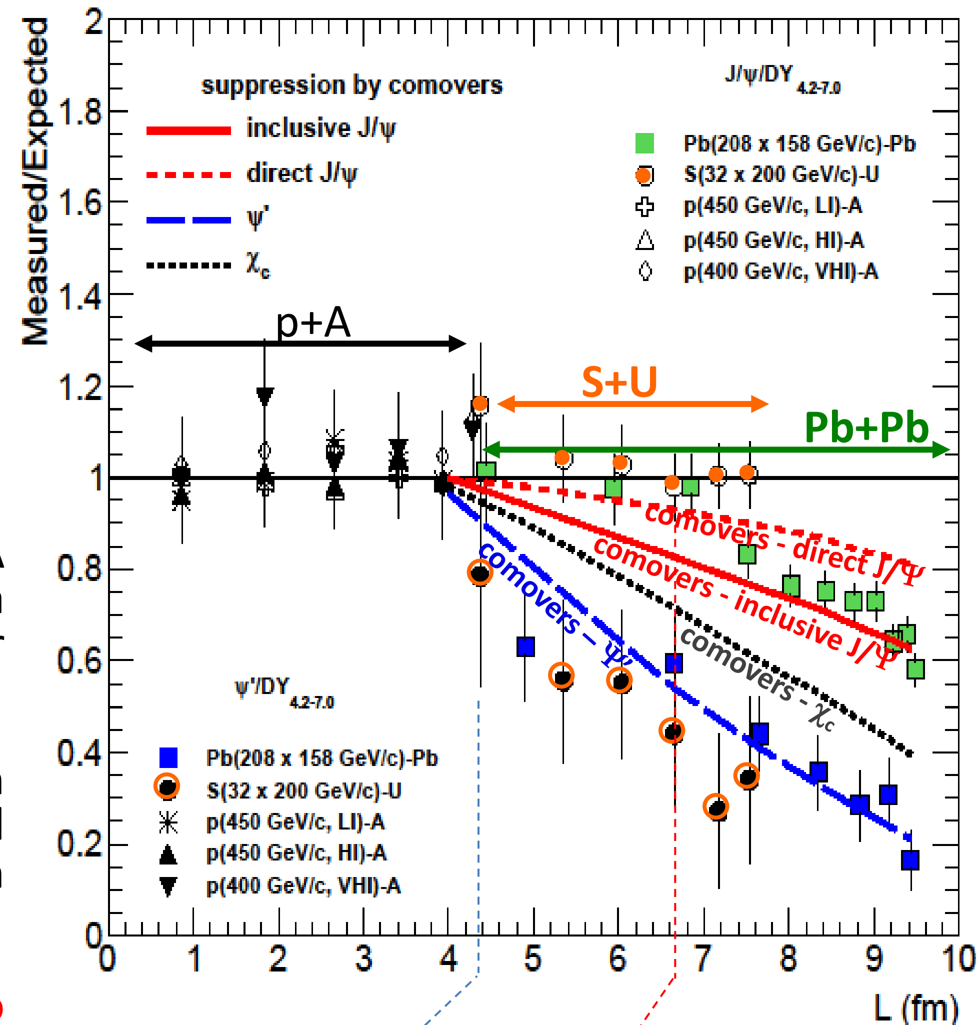
- **comovers-direct J/Ψ = 0.2 mb**
- **comovers – χ_c = 1.0 mb**
- **comovers – Ψ' = 2.0 mb**

and considering feed-downs

60% direct J/Ψ
+ 30% $\chi_c \rightarrow J/\Psi+\gamma$
+ 10% Ψ' → J/Ψ + X

Inclusive J/Ψ yield

From Frédéric Fleuret in ECT* 2013:



L (fm)	4.37	4.90	6.65	7.65	8.83	9.43
ε (GeV/fm³)	1.04	1.24	2.04	2.53	3.19	3.76

- Measuring together J/Ψ, Ψ' and χ_c in p+A collisions with several targets will give a thorough control of Cold Nuclear Matter effects
- Measuring together J/Ψ, Ψ' and χ_c in A+A collisions at SPS energies will (dis)prove sequential suppression scenario.
- Testing sequential suppression scenario at SPS is crucial to fully understand RHIC and LHC results.

Comover "propaganda" plot

Taking cross-sections:

- **comovers-direct J/Ψ = 0.2 mb**
- **comovers – χ_c = 2.0 mb**
- **comovers – Ψ' = 5.0 mb**

and considering feed-downs

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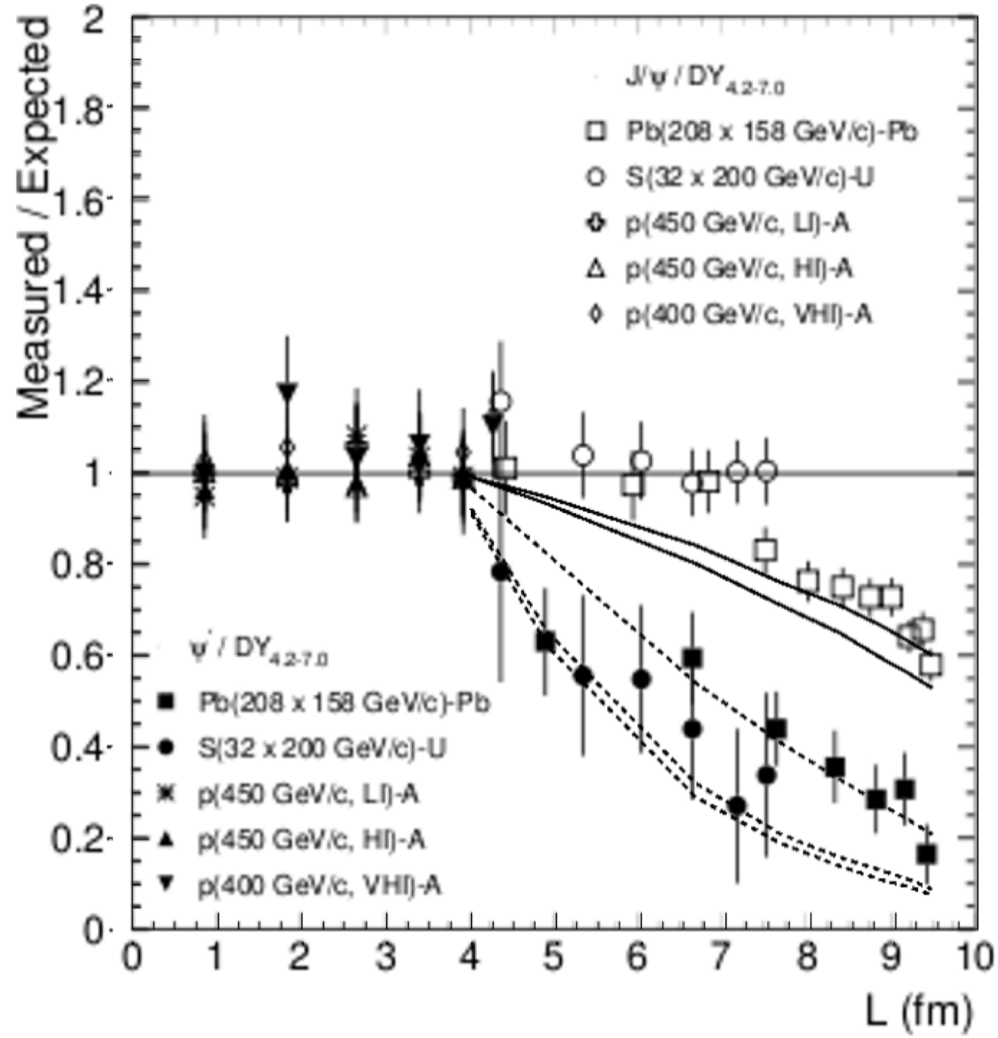
Inclusive J/Ψ yield



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Conclusions/wish list

- Measurement of excited states are required
  - Feed-downs can be important
  - Direct ground state measurements?

- Use pA SPS data to determine the absoptive cross section
  - If posible at rapidities where nPDFs modification is expected to be small
    Becareful: antishadowing, EMC effects…
    can affect our understanding of the nuclear absorption
  - Do effects cancel on excited-over-ground states?
    (For initial effects yes, for final not sure)
  - Comover effect on the groud state not expected to be important in pA
    Nevertheless it can affect through feed-downs

- Use AA SPS data to determine the presence of other final-state effects
  - At lowest SPS energies the screening scenario is not expected (low energy density)