Cold nuclear effects in quarkonium production

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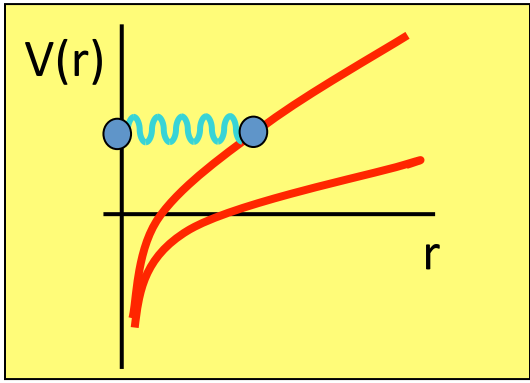
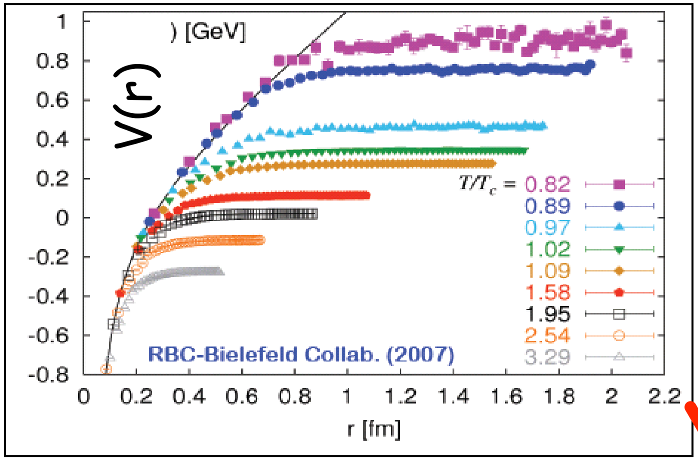
Quarkonia original motivation: Debye screening & QGP

Potential between q-anti-q pair grows linearly at large distances

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$

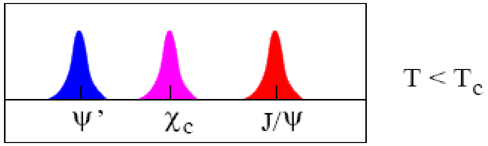


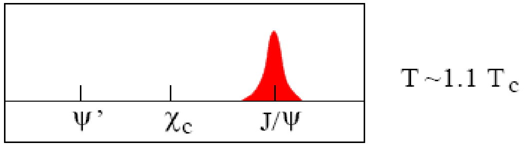
Screening of long range confining potential at high enough temperature or density.



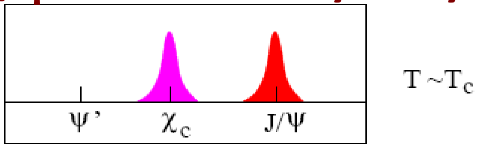
What happens when the range of the binding force becomes smaller than the radius of the state?

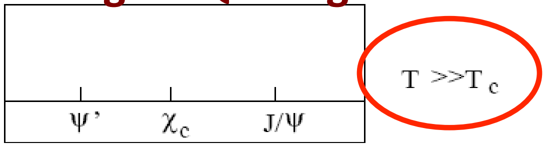
Different states "melting" at different temperatures due to different binding energies.

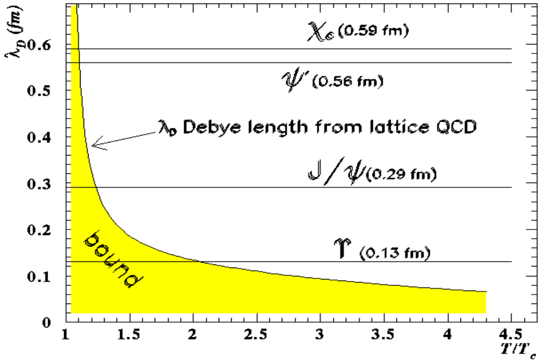




J/ψ destruction by Debye screening => QGP signature







...but the story is not so simple

- Can the melting temperature(s) be uniquely determined ?

- Are there effects that can induce an enhancement of quarkonium?

- Are there any other effects, not related to colour screening, that may induce a suppression of quarkonium states ?

- Do experimental observations fit in a coherent picture?

Charmonia/bottomonia topics

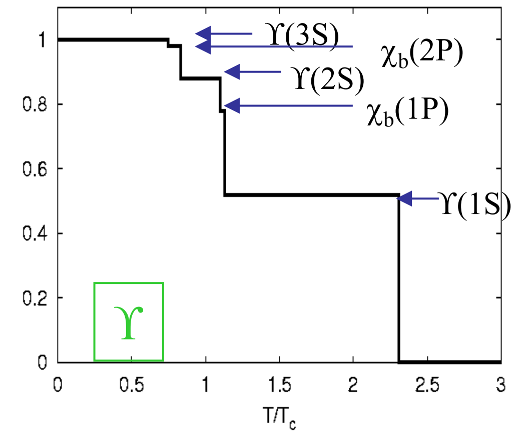
Three main topics

Sequential suppression

Charmonium → J/χ, ψ_c, $\psi(2S)$

Bottomonium Υ →(1S), Υ(2S), Υ(3S), χ_b

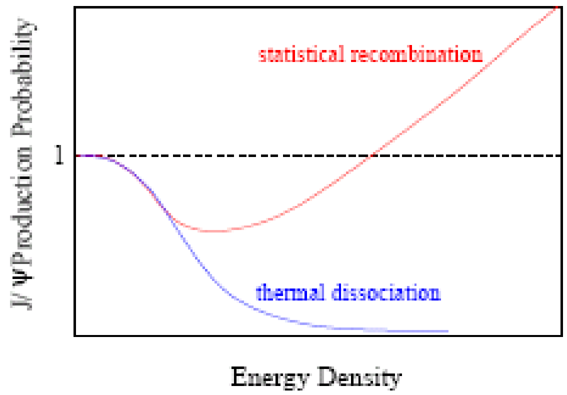
Relying on theory for connection with temperature



Two competing mechanisms

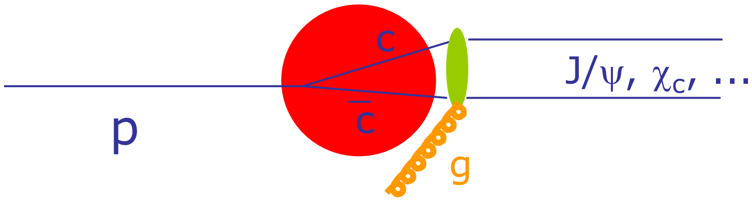
Color screening → suppression

(Re)-combination →enhancement



Cold nuclear matter effects

Shadowing, absorption, comovers
Description/understanding of underlying mechanisms difficult



Scomparin, QM2014

Present situation: Bottomonia in AA at RHIC and LHC

LHC | **RHIC**

$$R_{AA}^{\Upsilon(3S)} < R_{AA}^{\Upsilon(2S)} < R_{AA}^{\Upsilon(1S)} < R_{AA}^{\Upsilon(1S)}$$

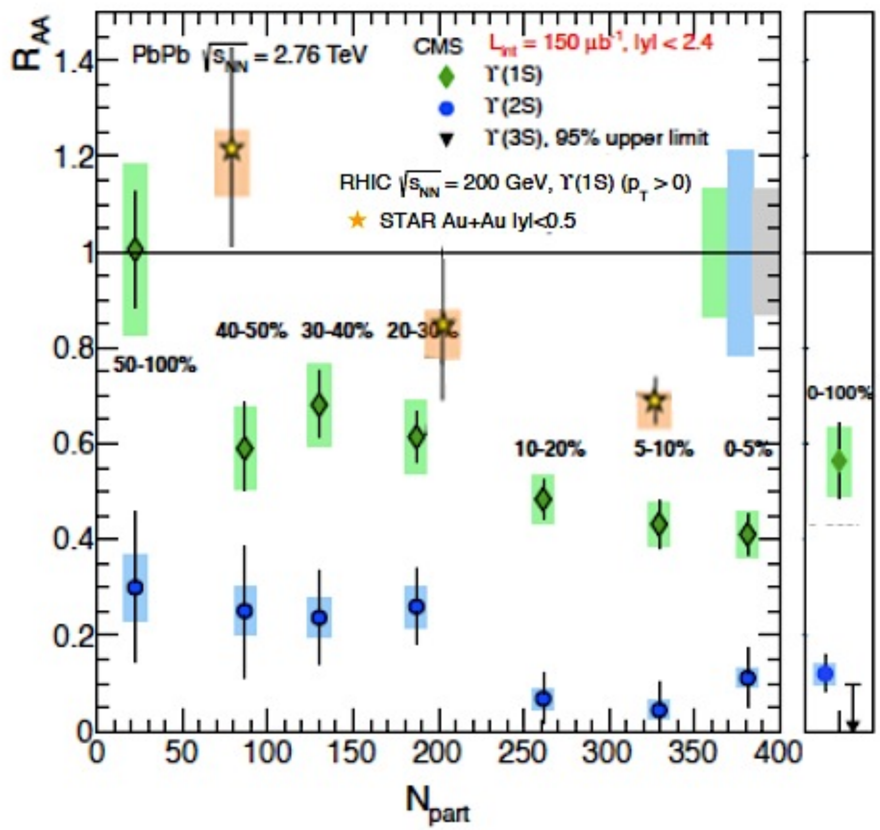
- **Centrality integrated:**

LHC

- $\Upsilon(1S)$: $0.56 \pm 0.08 \pm 0.07$
- $\Upsilon(2S)$: $0.12 \pm 0.04 \pm 0.02$
- $\Upsilon(3S)$: <0.10 at 95% CL

- Ordered suppression
  => **Sequential melting**

- **The situation seems clear for Υ**
  less effects than on J/ψ



Present situation: Charmonia in AA at RHIC and LHC

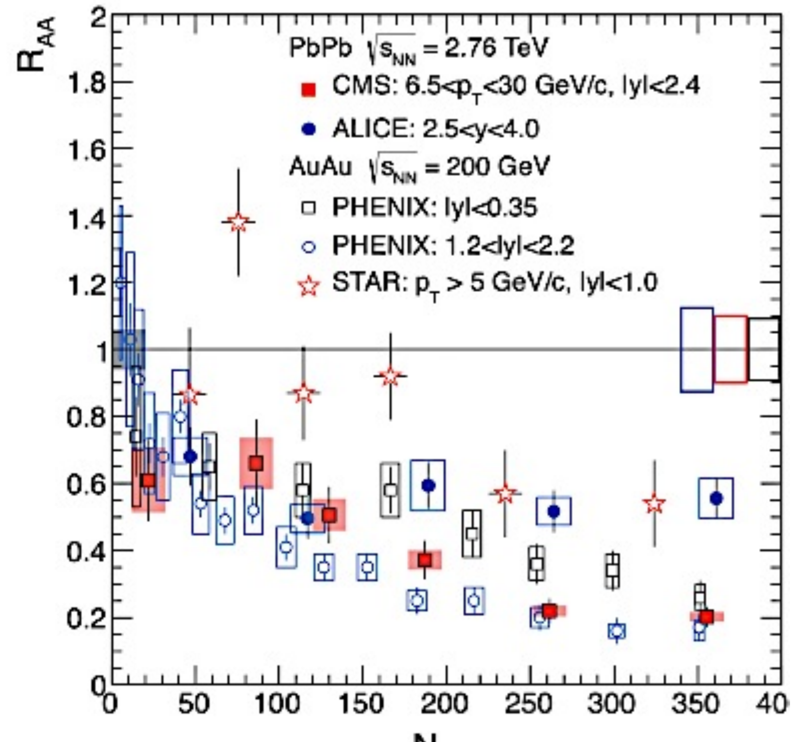
- **Suppression**, but not clear pattern/picture

- **Interplay** of **hot** and **cold** medium effects:

  shadowing, nuclear absorption, energy loss, comovers, colour screening, regeneration

- **Quarkonium in p+p** still not fully controlled theoretically

  CSM, COM, polarization..



JHEP 1205 (2012) 063
JHEP 1205 (2012) 063
PRL 98 (2007) 232301
PRC 84 (2011) 054912

Quarkonium supression in p+A collisions: CNM effects

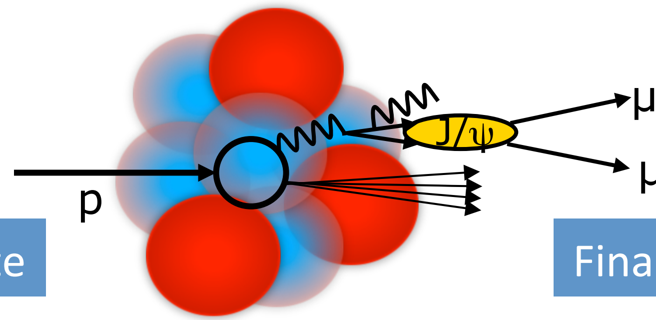
Quarkonium production is suppressed in nuclear collisions ...but for a variety of reasons

- dissociation by screening ("melting") and/or collisions in hot QGP

QGP effects
A+A collisions

- shadowing,
- saturation
- intrinsic charm

Initial state



Final state

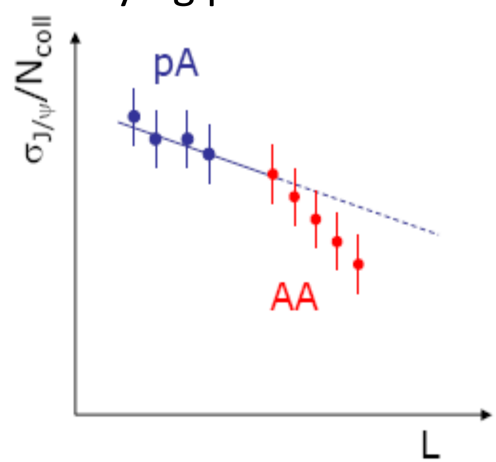
- nuclear absorption
- energy loss
- comovers

CNM effects
p+A and A+A collisions

To understand quarkonium behaviour in the hot medium, it's important to know its behaviour in the cold nuclear matter. This information can be achieved studying pA collisions

The cold nuclear matter effects present in pA collisions are of course present also in AA and can mask genuine QGP effects

CNM, evaluated in pA, are extrapolated to AA, in order to build a reference for the J/Ψ behaviour in hadronic matter



Nuclear absorption: a final cold nuclear matter effect

Particle spectrum altered by interactions with the nuclear matter they traverse
=> J/Ψ suppression due to final state interactions with spectator nucleons

- Usual parameterisation:
(Glauber model)

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

nuclear matter density — break-up cross section — path length

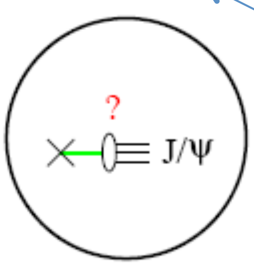
Energy dependence

- **At low energy**: the heavy system undergoes successive interactions with nucleons in its path and has to survive all of them => **Strong nuclear absorption**
- **At high energy:** the coherence length is large and the projectile interacts with the nucleus as a whole => **Smaller nuclear absorption**

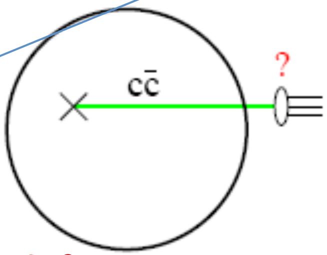
In terms of formation time:

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



Nuclear absorption small at LHC energies and smaller for ϒ than for J/ψ

Energy loss effect: Fractional energy loss

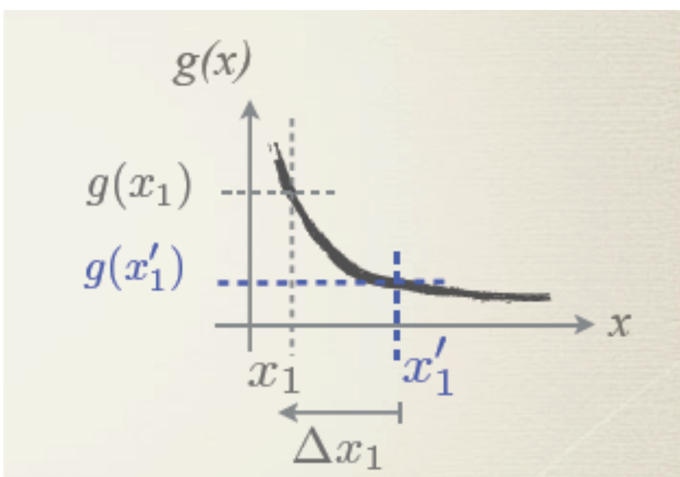
- **Radiated energy associated to a hard process => *a fractional energy loss*: $\Delta E \propto E$**

The medium-induced gluon radiation associated to large-x_F quarkonium hadroproduction:

Arleo, Peigne

- ❖**coherent radiation of the incoming parton and outgoing colored object**
- ❖**arises from large gluon formation times $t_f \gg L$**
- ❖ **scales as the incoming parton energy E**

- Due to energy loss, a hard QCD process probes the incoming PDFs at higher x, where they are suppressed, leading to nuclear suppression



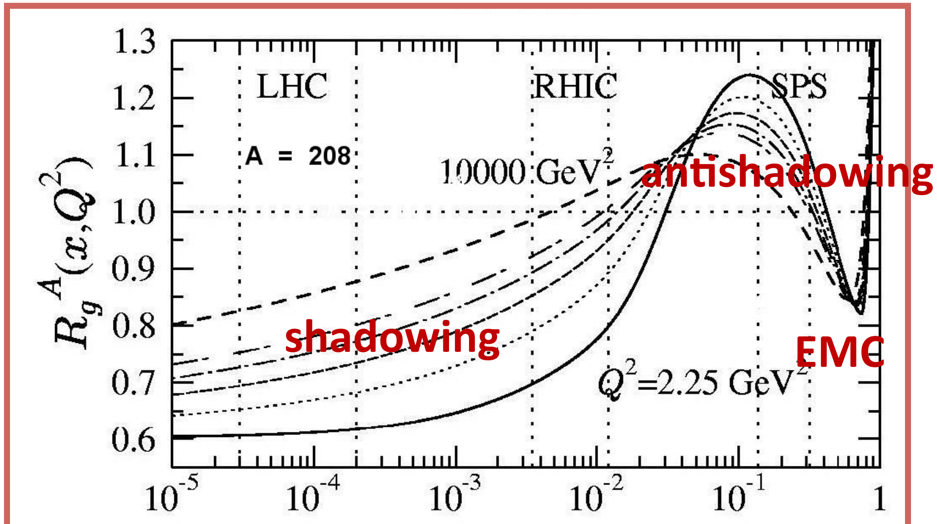
$$R_{\text{loss}}(x_1, Q^2) = \frac{g(x'_1, Q^2)}{g(x_1, Q^2)}$$

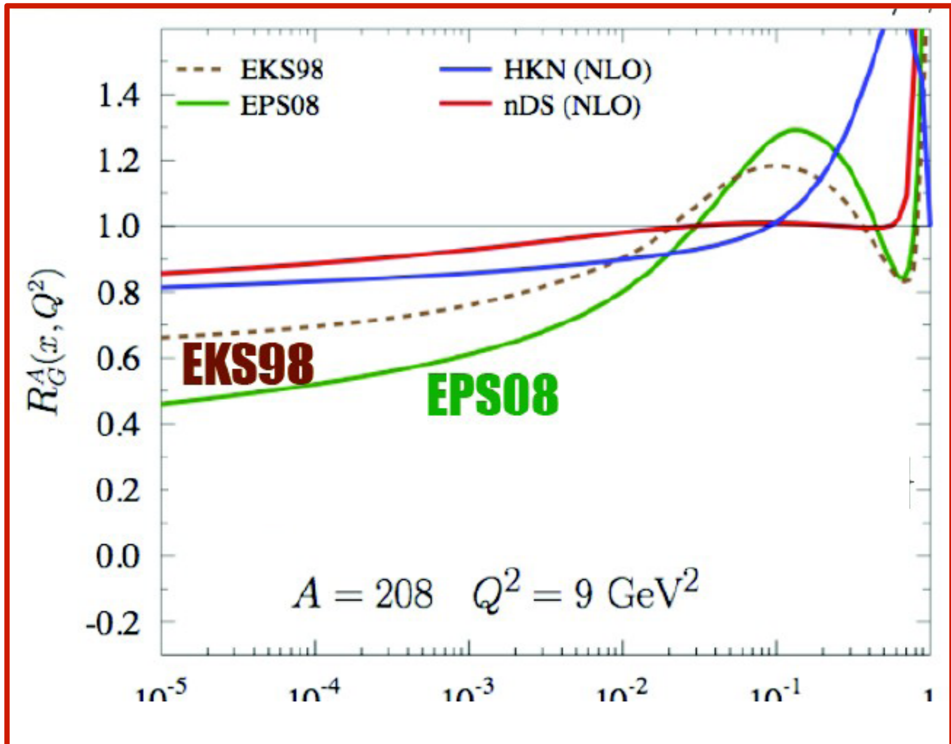
nPDFs modification: an initial cold nuclear matter effect

- Nuclear shadowing is an initial-state effect on the partons distributions
- Gluon distribution functions are modified by the nuclear environment
- PDFs in nuclei different from the superposition of PDFs of their nucleons

Shadowing effects increases with energy (1/x) and decrease with Q^2 (m_T)

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





Large uncertainties for gluons : Shape of the nPDFs, shadowing, antishadowing, EMC?

Initial shadowing effects are important: J/ψ production in PbPb @ LHC

- Nuclear shadowing is an initial-state effect on the partons distributions
- Gluon distribution functions are modified by the nuclear environment
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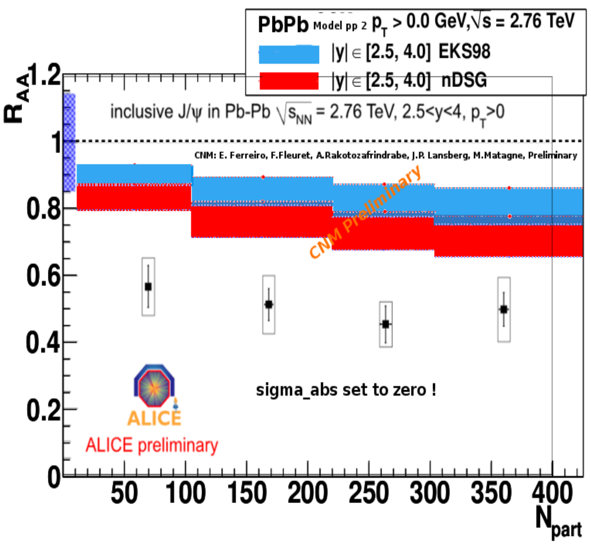
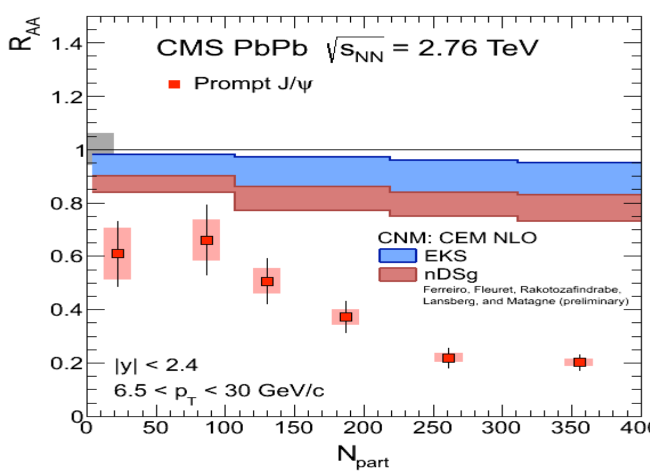
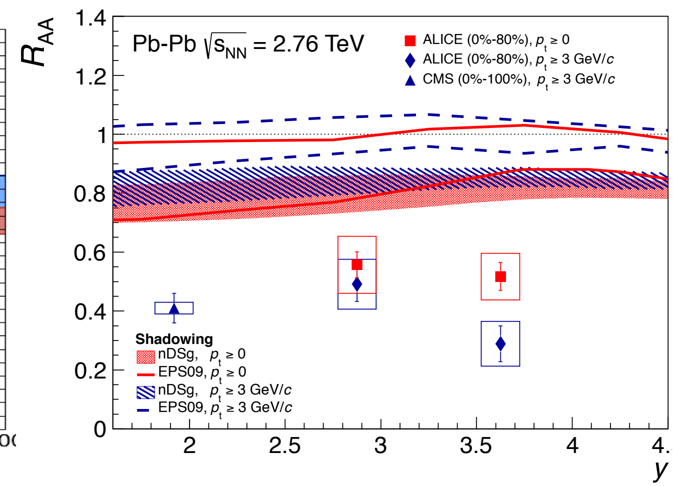


Rakotozandrabe, Ferreiro, Fleuret, Lansberg , Matagne Nucl. Phys. A855, 327 (2011)

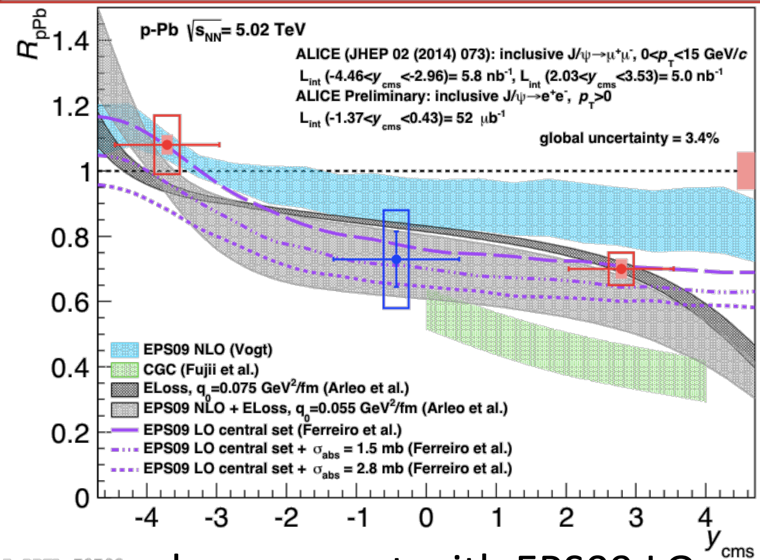


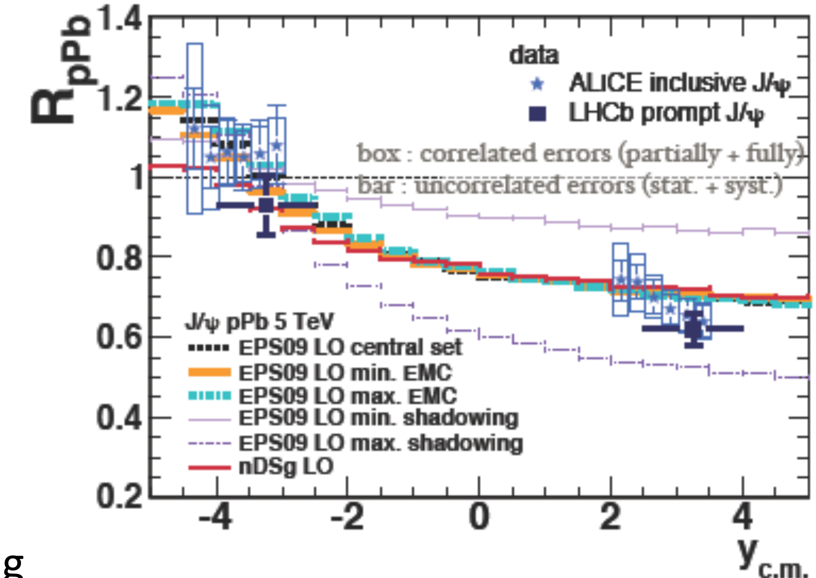


Production mechanism affects CNM effects intimately:

- Shadowing depends on momentum fraction x of the target (and projectile in AA) which is influenced by how the state was produced: 2 → 1 or 2 → 2 process
- Production can also affect other CNM effects, since singlet and octet states can be absorbed differently

Cross check: J/ψ production in pPb @ LHC



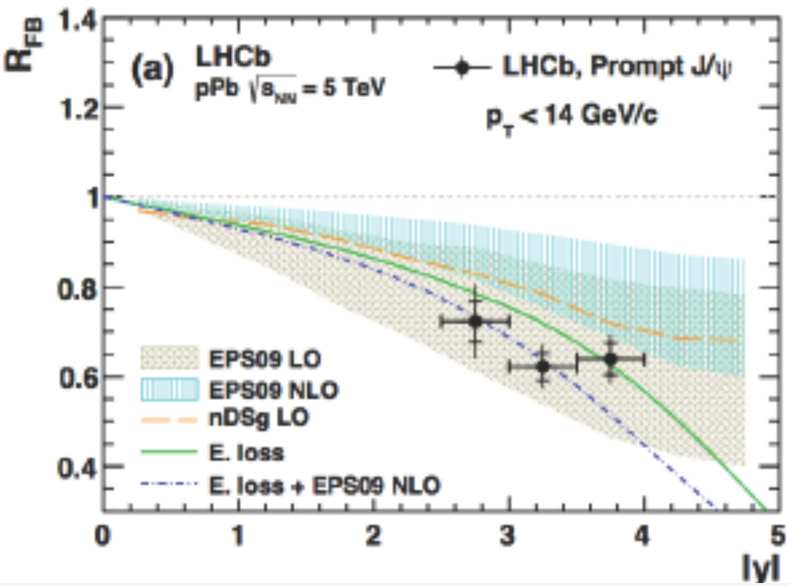


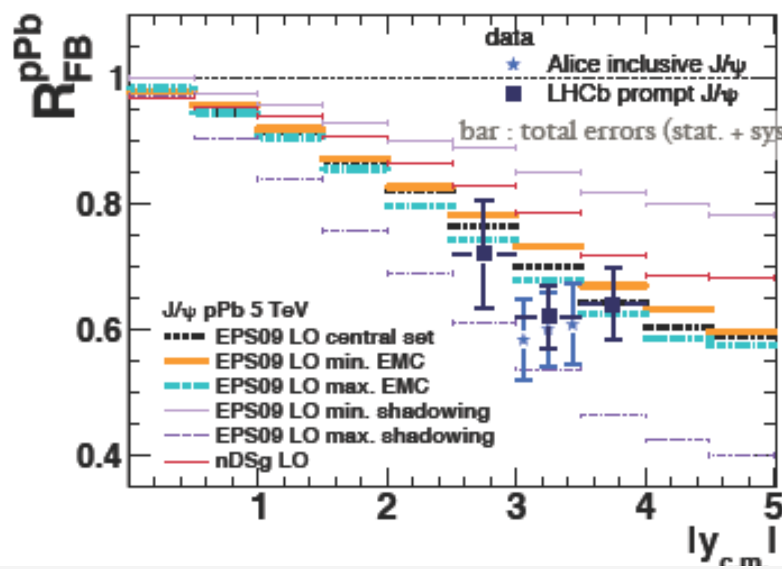
good agreement with EPS09 LO and nDSg shadowing

also consistent w energy loss models w/wo EPS09NLO shadowing

EPS09 NLO and CGC calculation disfavored

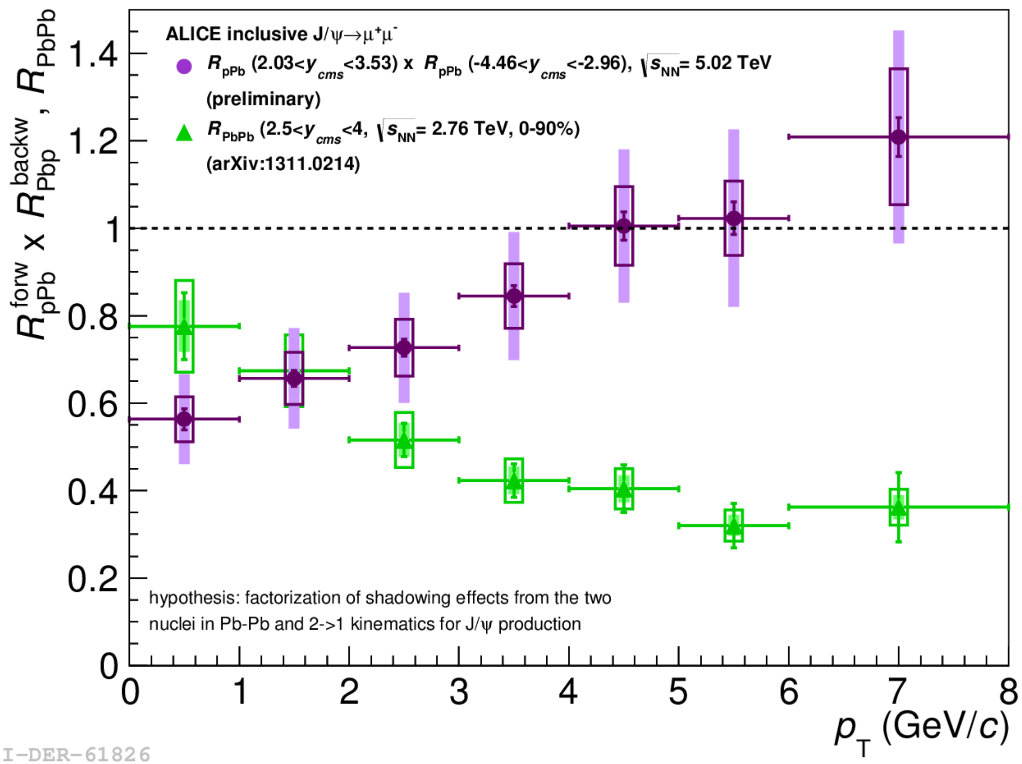
E.G.F, F. Fleuret, J.P. Lansberg, A.Rakotozafindrabe
Phys.Rev. C88 (2013) 4, 047901





CNM effects from p-Pb to Pb-Pb

Once CNM effects are measured in pA,
what can we learn on J/ψ production in PbPb?

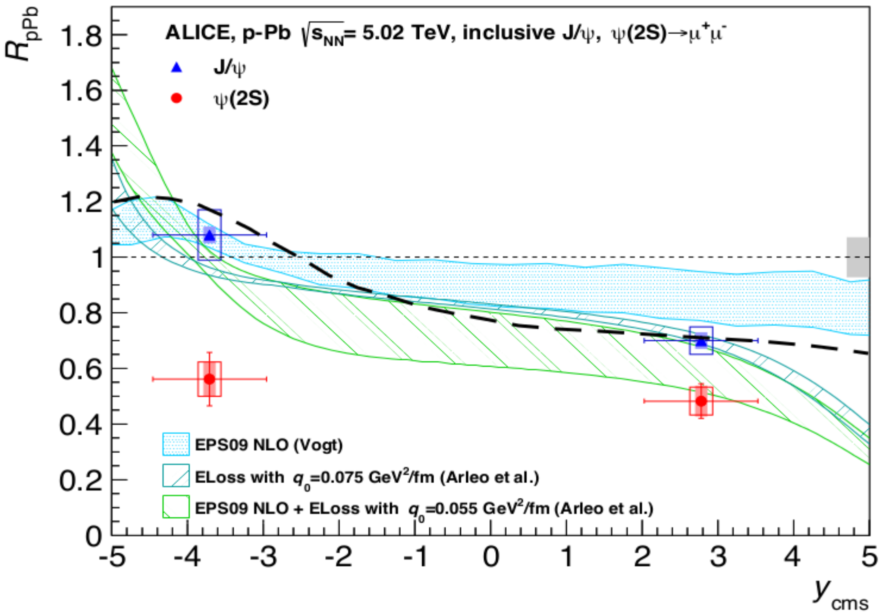


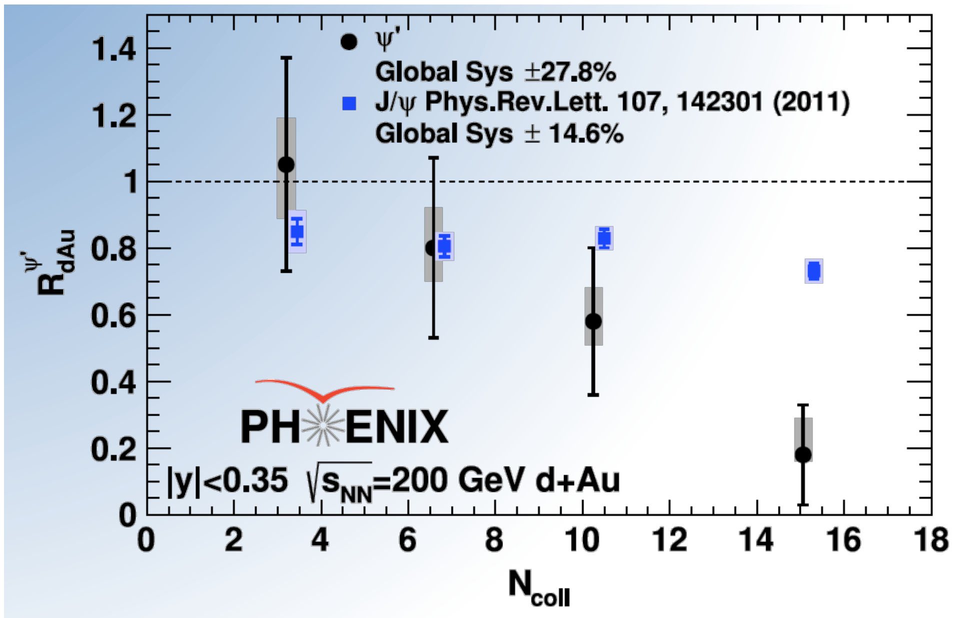
Sizeable p_T dependent suppression still visible
→ CNM effects not enough to explain AA data at high p_T

From enhancement to suppression increasing p_T
→ hint for recombination

A surprise: ψ(2S) in dAu @ RHIC and pPb @LHC

- A strong decrease of the ψ(2S) production, relative to J/ψ, is observed in
  p+Pb at LHC   d+Au at RHIC





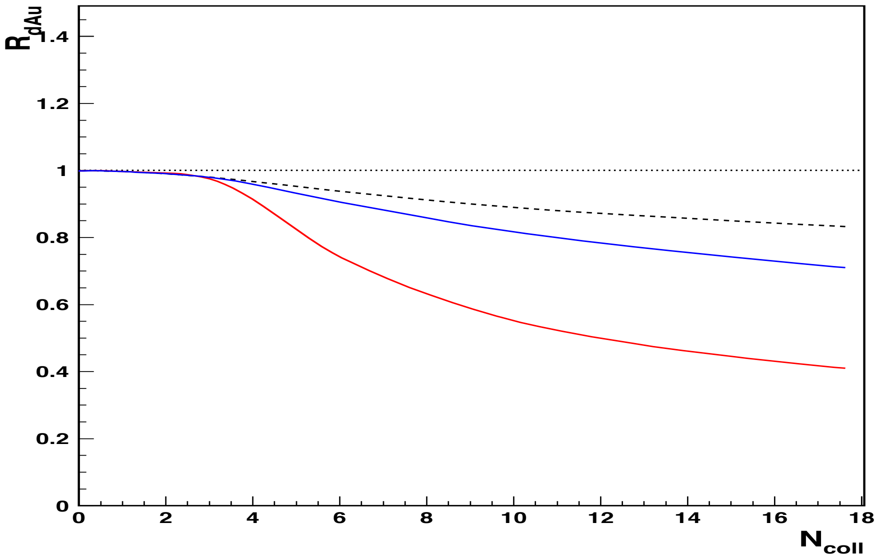
Same initial CNM effects (shadowing –similar m_T-, energy loss, nuclear absorption - charmonium formation time $t_f = \gamma\, \tau.$ < R_A -) for both J/ψ and ψ(2S)
=> theoretical predictions in disagreement with ψ(2S) results

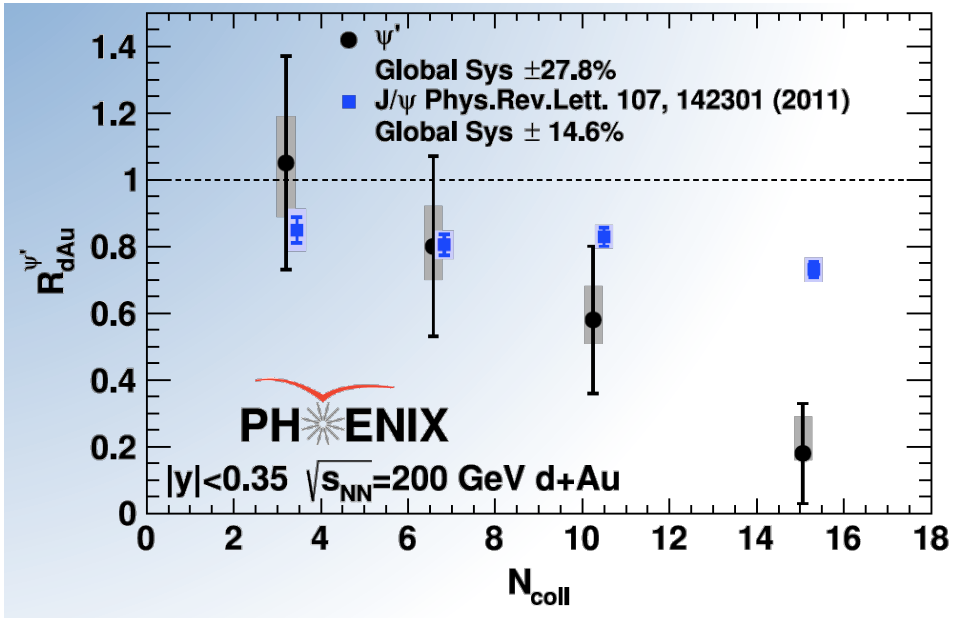
Final state effects related to the medium created in the p-Pb collisions?: co-moving medium

ψ(2S) and J/ψ in dAu @ RHIC: comover scenario

$$\tau \frac{\mathrm{d}N_{J/\psi}}{\mathrm{d}\tau}\,(b,s,y) \;=\; -\sigma_{co} N^{co}(b,s,y) N_{J/\psi}(b,s,y)$$

$$S^{\rm co}(b,s) \;= \exp\left[-\sigma_{\rm co} N^{\rm co}(b,s,y)\ln\left(N^{\rm co}(b,s,y)/N_{pp}(0)\right)\right]$$



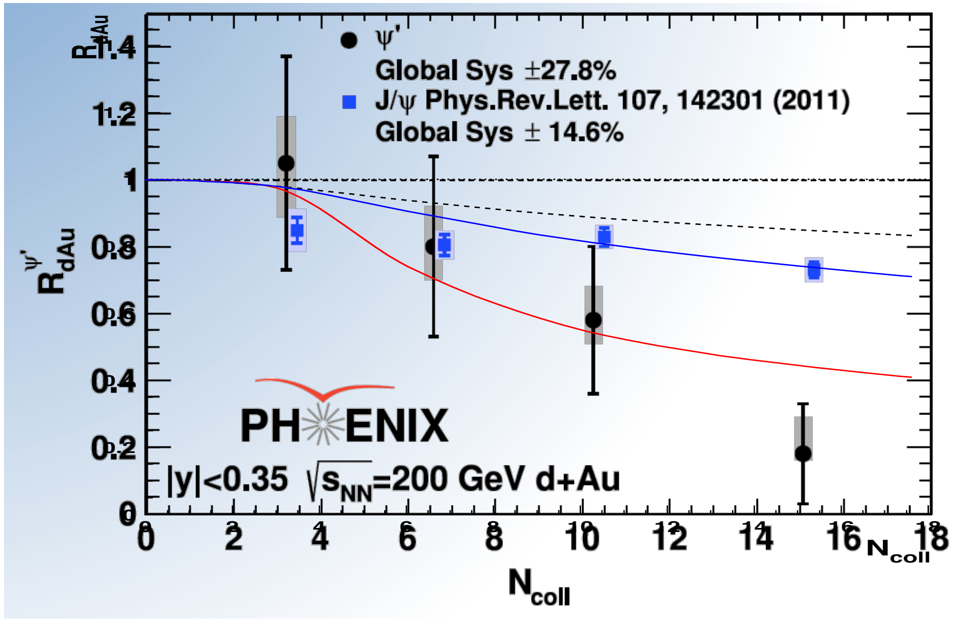


ψ(2S) and J/ψ in dAu @ RHIC: comover scenario

$$\tau \frac{dN_{J/\psi}}{d\tau}(b,s,y) = -\sigma_{co} N^{co}(b,s,y) N_{J/\psi}(b,s,y)$$

$$S^{co}(b,s) = \exp\left[-\sigma_{co} N^{co}(b,s,y) \ln\left(N^{co}(b,s,y)/N_{pp}(0)\right)\right]$$

- Identical shadowing for ψ(2S) and J/ψ
- J/ψ suppression due to the combined effect of shadowing and comover dissociation
- ψ (2S) suppression due to the combined effect of shadowing and stronger comover dissociation



$\sigma_{co-\psi(2S)} > \sigma_{co-J/\psi}$

$\sigma_{co-\psi(2S)}$ = 6 mb, $\sigma_{co-J/\psi}$ = 0.65 mb
(identical to the ones used at SPS & LHC)
PLB430 (1998), PRL 85 (2000) 2080, PLB731 (2014) 57

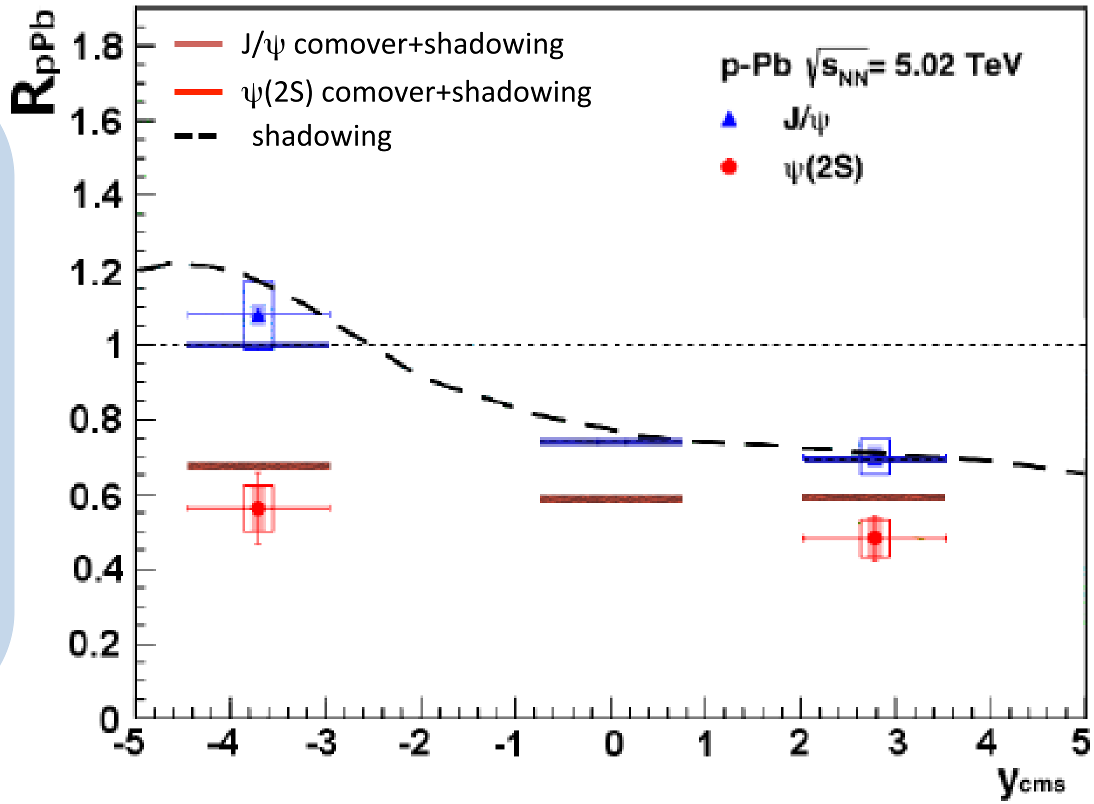
ψ(2S) and J/ψ in pPb @ LHC: comover scenario

$$\tau \frac{\mathrm{d}N_{J/\psi}}{\mathrm{d}\tau}(b,s,y) = -\sigma_{co} N^{co}(b,s,y) N_{J/\psi}(b,s,y)$$

$$S^{co}(b,s) = \exp\left[-\sigma_{co} N^{co}(b,s,y) \ln\left(N^{co}(b,s,y)/N_{pp}(0)\right)\right]$$

Charmonium interaction with comoving particles:

- Comovers dissociation affects more strongly the loosely bound ψ(2S) than the J/ψ
- Comovers density larger at backward rapidity



E. Ferreiro arXiv:1411.0549

What have we learnt from J/ψ production in pPb and PbPb @ LHC?

J/ψ production seems at least **qualitatively understood**

- **Initial cold nuclear matter** effects can be described with shadowing/energy loss
- Production in HI collisions is described by a combination of

  suppression (either color screening, or in-medium dissociation)
  recombination (either in-medium or at phase boundary)

Challenge will be to discriminate between these possible scenarios

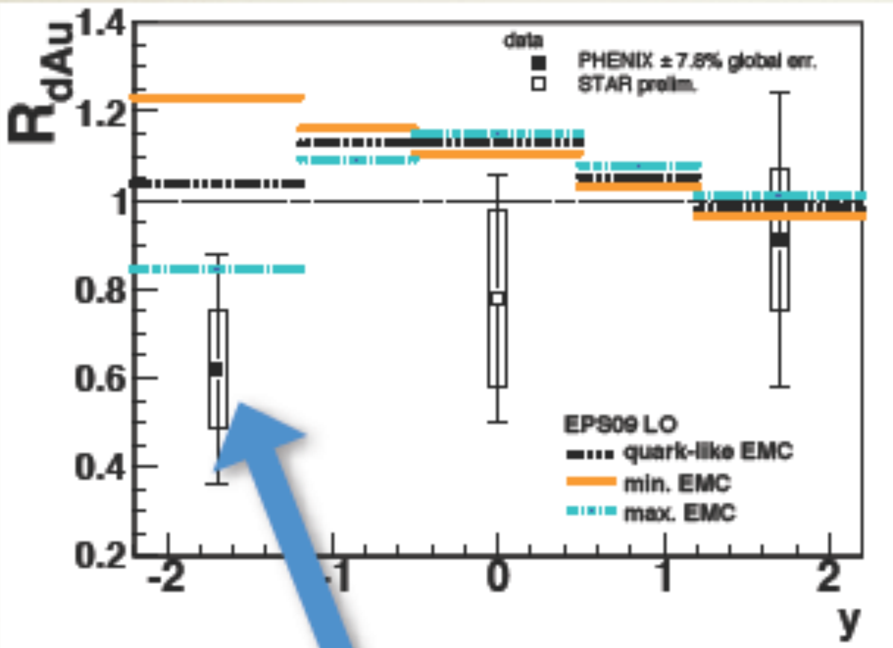
What is the **state of the art for ψ(2S)?**

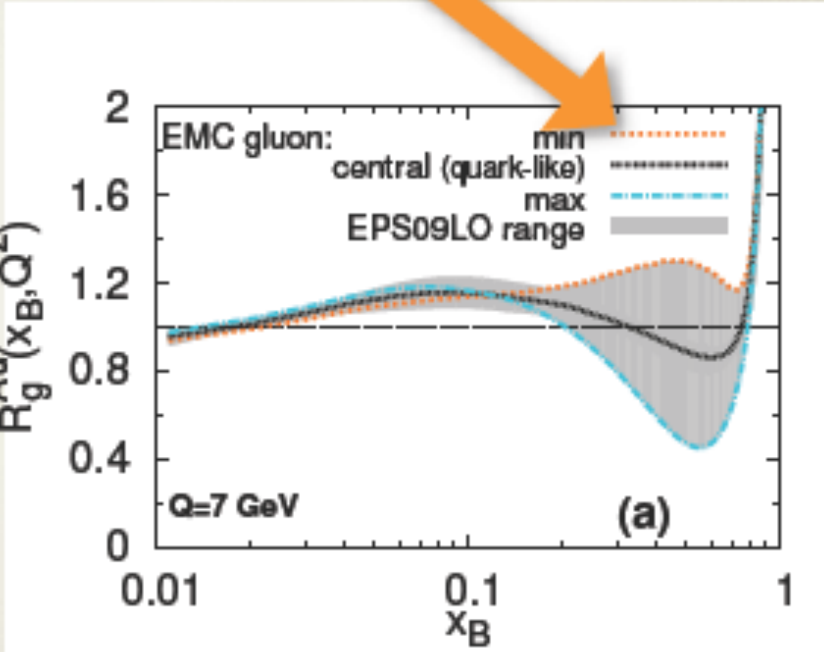
- **Initial cold nuclear matter effects** (shadowing/ energy loss) are considered to be the same for than for the J/ψ
- **In-medium effects** depending on density (comovers) are able to distinguish between J/ψ and ψ(2S)

ϒ in dAu @ RHIC: gluon EMC effect

Let us focus in the **EMC region** and pick the EPS09 sets that are the limiting cases in this region :

min. disfavoured





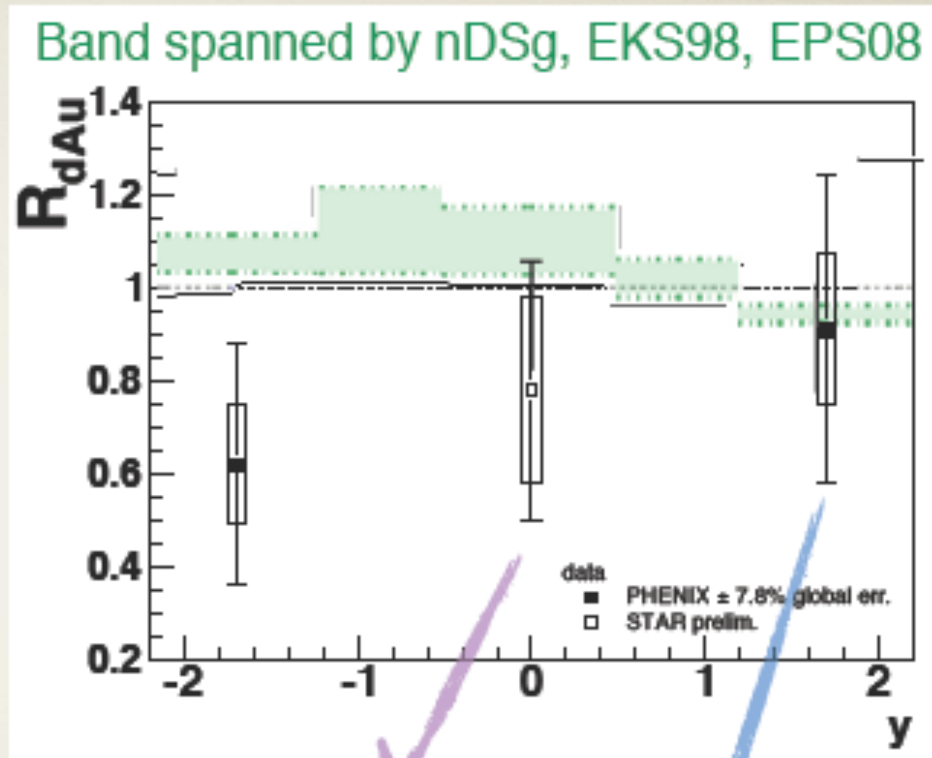
EMC effect stronger for g than for *q* ?

E. G. Ferreiro, F. Fleuret, J. P. Lansberg, N. Matagne and A. R. EPJ C (2013) 73:2427

ϒ in dAu @ RHIC: shadowing

E. G. Ferreiro, F. Fleuret,
J. P. Lansberg, N. Matagne and A. R.
EPJ C (2013) 73:2427

ϒ could be a nice tool to **check antishadowing** (still under debate)



absence of antishadowing ?

entering shadowing

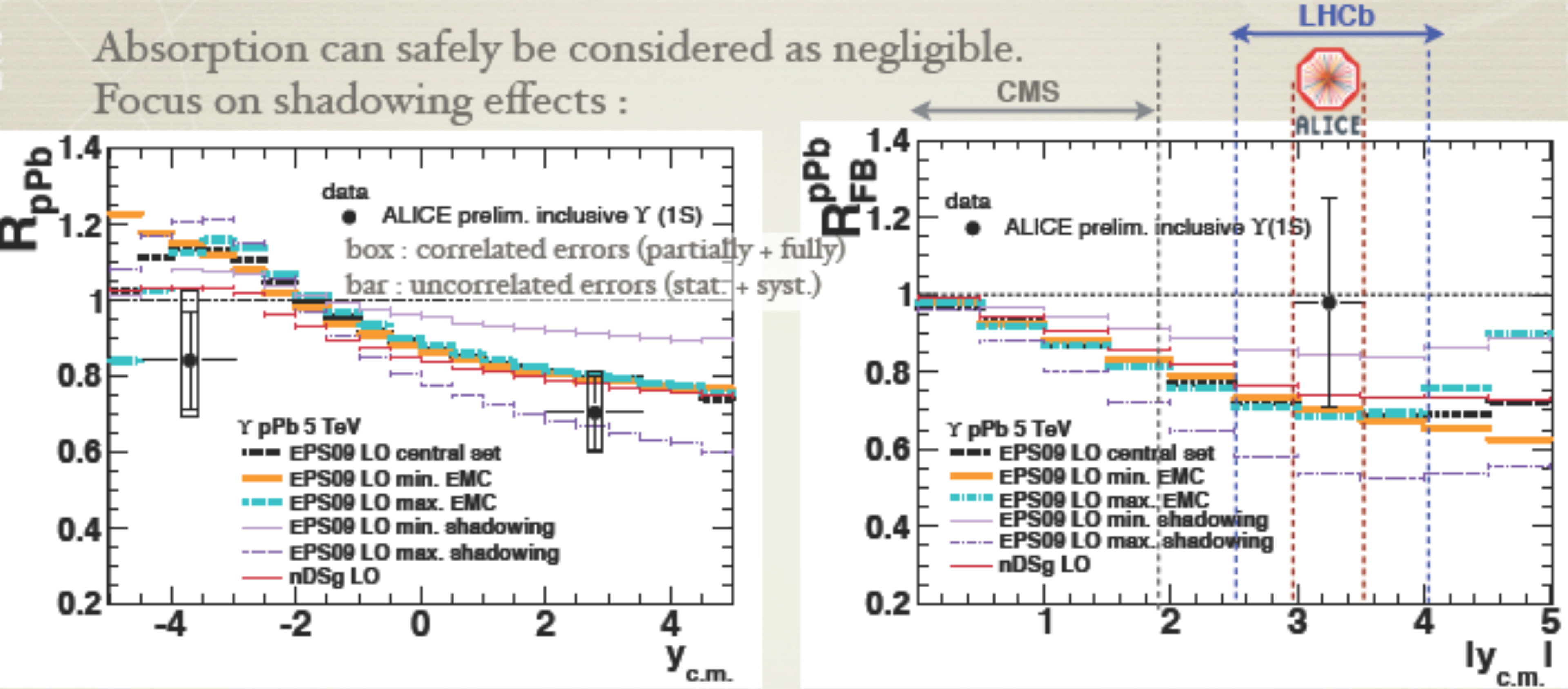
Data:

STAR Preliminary, Nucl. Phys. A855 (2011) 440, PRD 82 (2010) 012004.

PHENIX Preliminary, PoS DIS2010 (2010) 077.

ϒ in pPb @ LHC: shadowing

Absorption can safely be considered as negligible.
Focus on shadowing effects :



- Experiments probe the shadowing and antishadowing regions. The interesting **EMC region** will be **out of reach**.
- More precision needed at backward-y to conclude about antishadowing.

What have we learnt from quarkonia production @ LHC?

J/ψ production seems at least qualitatively understood

Initial cold nuclear matter effects can be described with shadowing and/or energy loss

Production in HI collisions is described by a combination of

- suppression (either color screening, or in-medium dissociation)
- recombination (either in-medium or at phase boundary)

High density medium,
Not necessarily thermalized

Challenge will be to discriminate between these possible scenarios

What is the state of the art for ψ(2)?

Crucial to distinguish among the models

Note that cold nuclear matter effects (shadowing and/or energy loss) are considered to be the same for than for the J/ψ

Nevertheless, in-medium effects depending on density (comovers) would be able to distinguish between them

ϒ(2S) and (3S) are strongly suppressed at LHC.
ϒ(1S) suppression is the same at RHIC and LHC, consistent with higher mass excited states suppression
No recombination, but some shadowing effects

COLD or HOT effects?

•cold effects: **wo thermalisation NO QGP**

gluon shadowing

nuclear structure functions in nuclei $\neq$ superposition of constituents nucleons

nuclear absorption

multiple scattering of a pre-resonance c-cbar pair within the nucleons of the nucleus

CGC

parton saturation

non-lineal effects favoured by the high density of partons become important and lead to eventual saturation of the parton densities

-

comovers

dissociation of the c-cbar pair with the dense medium produced in the collision **partonic or hadronic**

Others: Cronin effect
energy loss

•hot effects: **w thermalisation QGP** **A+A**

QGP sequential suppression recombination

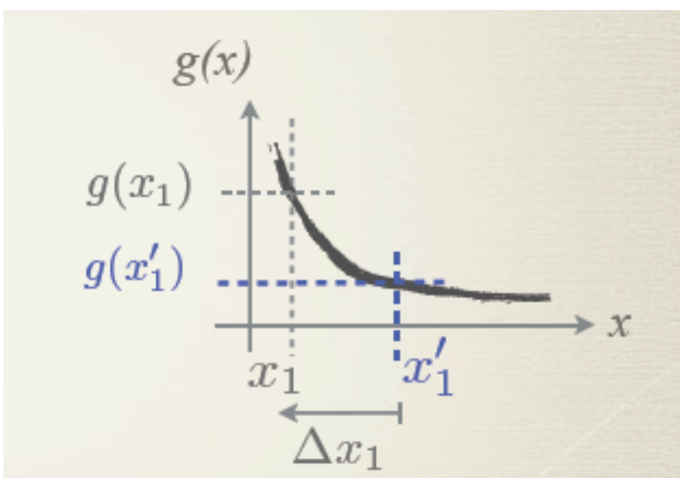
Energy loss effect: Fractional energy loss

- **Radiated energy associated to a hard process => *a fractional energy loss*: $\Delta E \; \alpha \; E$**

The medium-induced gluon radiation associated to large-x_F quarkonium hadroproduction:

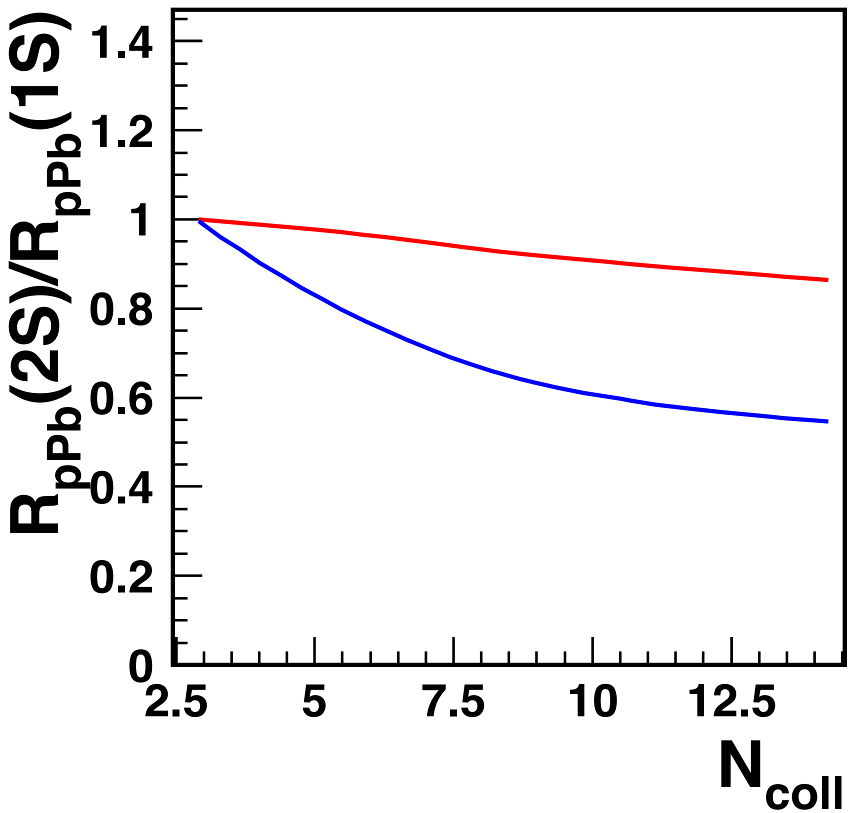
- **coherent radiation of the incoming parton and outgoing colored object**
- **arises from large gluon formation times $t_f >> L$**
- **scales as the incoming parton energy E**

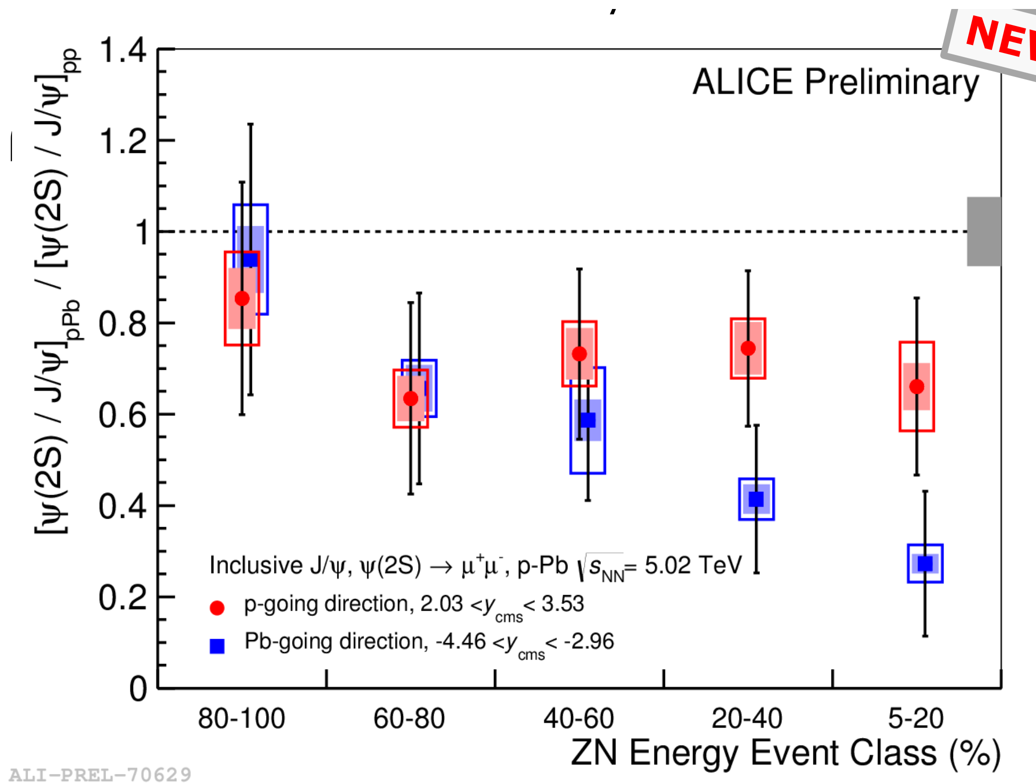
- Due to energy loss, a hard QCD process probes the incoming PDFs at higher x, where they are suppressed, leading to nuclear suppression



$$R_{\text{loss}}(x_1, Q^2) = \frac{g(x_1', Q^2)}{g(x_1, Q^2)}$$

ψ(2S) and J/ψ in pPb @ LHC: comover scenario





Identical shadowing effects for ψ(2S) and J/ψ

[ψ(2S) / J/ψ] < 1 due to comover interactions, that affects strongerly the ψ(2S)

This effect is more important in the backward region, since the density of comovers is higher there

Some nPDF parameterizations on the market

EKS98: K. J. Eskola, V. J. Kolhinen and P. V. Ruuskanen, Nucl. Phys. B 535 (1998) 351
[arXiv:hep-ph/9802350];
K. J. Eskola, V. J. Kolhinen and C. A. Salgado, Eur. Phys. J. C 9 (1999) 61
[arXiv:hep-ph/9807297].

nDS: D. de Florian and R. Sassot, Phys. Rev. D 69, 074028 (2004)
[arXiv:hepph/0311227].

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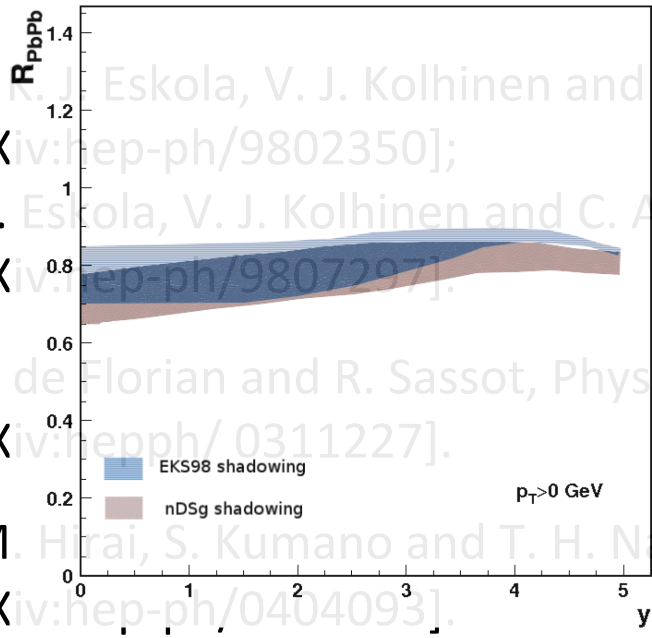
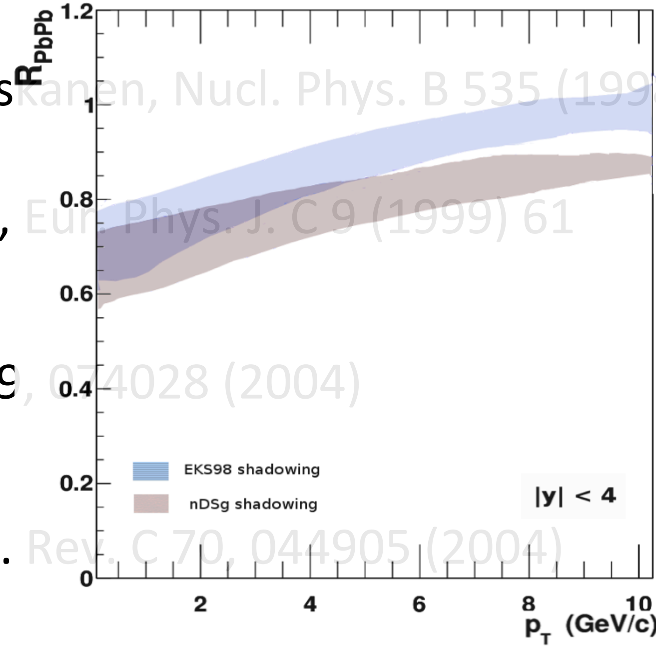
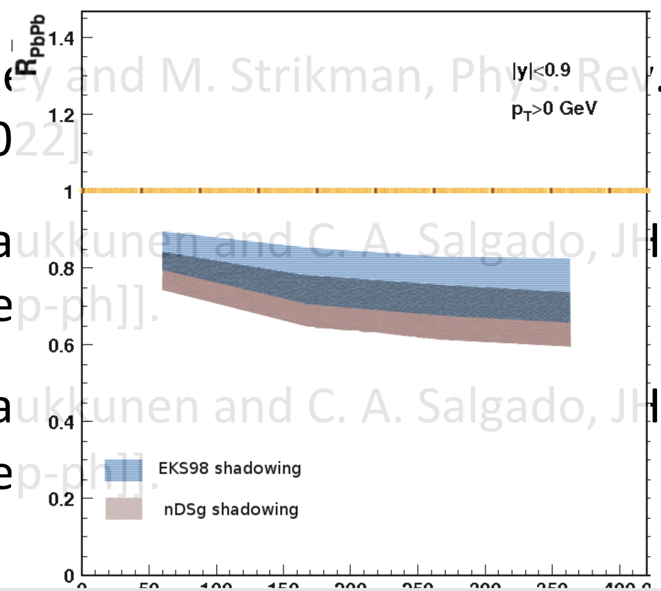






Quarkonium production issues: two approaches

Production mechanism affects CNM effects intimately:

- Shadowing depends on momentum fraction x of the target (and projectile in AA) which is influenced by how the state was produced: 2 → 1 or 2 → 2 process
- Production can also affect other CNM effects, since singlet and octet states can be absorbed differently

g+g → J/ψ **2→1**

$$x_{1,2} = \frac{m_T}{\sqrt{s_{NN}}} \exp(\pm y)$$

- intrinsic scheme: the $\mathbf{p_T}$ of the J/ψ comes from initial partons
  - ❖Not relevant for, say, p_T>3 GeV
  - ❖Only applies if COM(LO, α_s^2) is the relevant production mechanism at lowp_T

g+g → J/ψ+g, gg,ggg,… **2→2, 3, 4**

$$x_2 = \frac{x_1 m_T \sqrt{s_{NN}} e^{-y} - M^2}{\sqrt{s_{NN}}(\sqrt{s_{NN}} x_1 - m_T e^{y})}$$

- extrinsic scheme: the $\mathbf{p_T}$ of the J/ψ is balanced by the outgoing parton(s)
  - ❖CSM, COM (NLO, NNLO)

for a given y, larger x in extrinsic scheme => modification of shadowing effects

In fact, the 2-> 2 scenario is common to CSM (LO) and COM (NLO)

Energy loss effect: Fractional energy loss

- **Usual idea:** An energetic parton traveling in a large nuclear medium undergoes multiple elastic scatterings, which induce gluon radiation **=> *radiative energy loss* (BDMPS)**
- **Intuitively:** due to parton energy loss, a hard QCD process probes the incoming PDFs at higher x, where they are suppressed, leading to nuclear suppression
- **The problem:** This energy loss is subject to the LPM bound (Brodsky-Hoyer)
  => Δ E is limited and does not scale with E =>negligible effect at RHIC and LHC
- **Recently** (Arleo, Peigner, Sami) it has been probed that the **notion of radiated energy associated to a hard process is more general than the notion of parton energy loss**.
  => *a fractional energy loss*: Δ E α E

The medium-induced gluon radiation associated to large-x_F quarkonium hadroproduction:

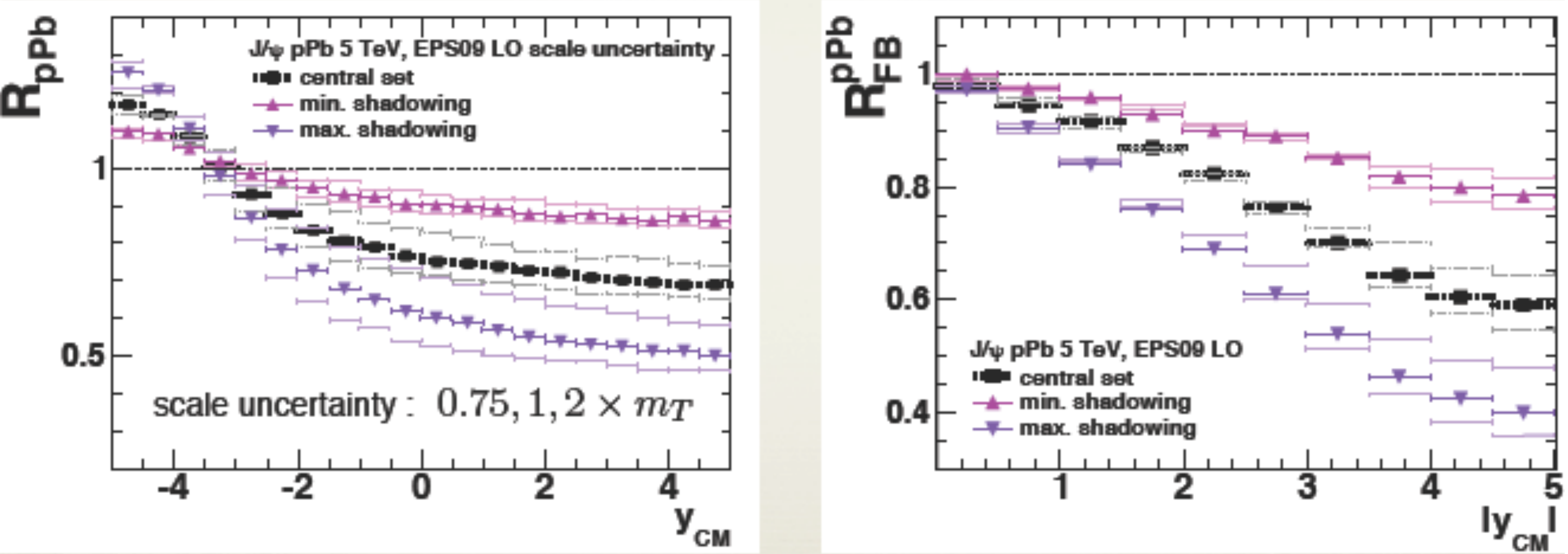
- **arises from large gluon formation times t_f >> L**
- **scales as the incoming parton energy E**
- **cannot be identified with the usual energy loss**
- **qualitatively similar to Bethe-Heitler energy loss**
- **the Brodsky-Hoyer bound does not apply for large formation times**

Thus, the assumption of an “energy loss” scaling as E turns out to be qualitatively valid for quarkonium production provided this “energy loss” is correctly interpreted as the radiated energy associated to the hard process, and not as the energy loss of independent incoming and outgoing color charges.

COMMENT 1: **Scale uncertainty**

- What enters the evaluation is $R_g^A(x, \mu_F)$
- What value to take for μ_F ?
- In DIS, $\mu_F \leftrightarrow Q$ (Q is measured).
- For quarkonia ? $\mu_F = M$, m_c , m_T ?

E. G. Ferreiro, F. Fleuret, J. P. Lansberg and A. R. arXiv:1305.4569



The scale uncertainty must be added on top the EPS09 error evaluation.

COMMENT 2: **Saturation?**

Saturation scale

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

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

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

ϒ @ RHIC

y	Q_{sAu}(GeV)	$\frac{Q_{sAu}}{m_\Upsilon}$	y	Q_{sAu}(GeV)	$\frac{Q_{sAu}}{m_\Upsilon}$
-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

ϒ @ LHC

y	Q_{sPb} (GeV)	$\frac{Q_{sAu}}{m_\Upsilon}$	y	Q_{sPb}(GeV)	$\frac{Q_{sPb}}{m_\Upsilon}$
-4.0	$\lesssim 1$	–	+2.0	$1.6 \div 1.9$	0.2
-2.0	$\lesssim 1$	–	+4.0	$1.9 \div 2.5$	$0.2 - 0.25$
0.0	$1.3 \div 1.4$	0.15			

J/ψ and ψ' @ RHIC

y	$Q^{\psi'}_{sAu}$(GeV)	$\frac{Q^{\psi'}_{sAu}}{m_{\psi'}}$	$Q^{J/\psi}_{sAu}$(GeV)	$\frac{Q^{J/\psi}_{sAu}}{m_{J/\psi}}$
-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_Υ

=> one does not expect any specific saturation effect on ϒ production in p(d)A collisions @ RHIC &LHC or in J/ψ @ RHIC

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

Some place for CGC on J/ψ @ LHC:
$Q_{spPb}^{J/\psi}$ = 2.3 GeV at y=0
=3.8 GeV at y=2
=6.5 GeV at y=4