Cold nuclear matter effects on quarkonium production @ RHIC and LHC:

Fractional energy loss on Υ and J/ψ production

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in collaboration with
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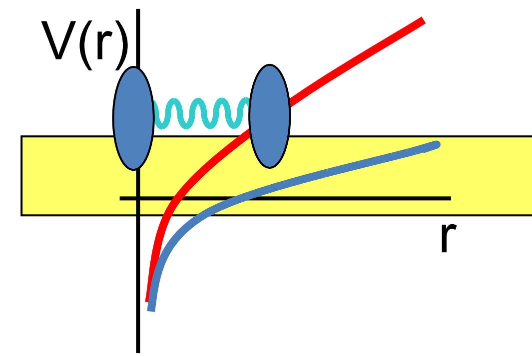
EPJC61 (2009), PLB680 (2009), PRC81 (2010), NPA855 (2011), arXiV:1110:5047

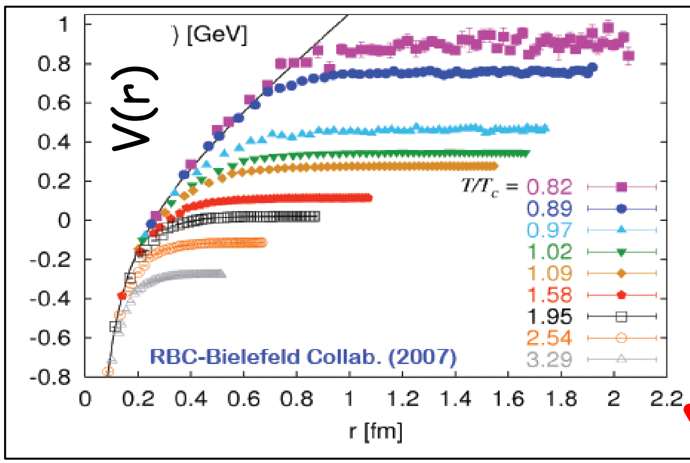
Introduction I: the intringuing story of J/ψ production

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.

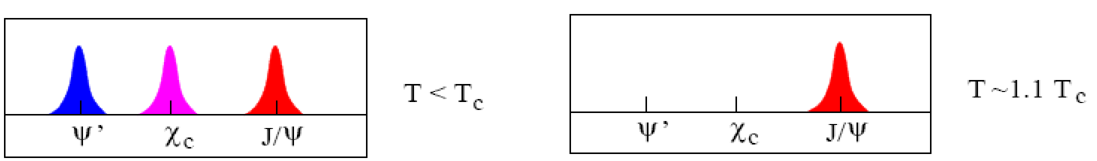


What happens when the range of the binding force becomes smaller than the radius of the state?

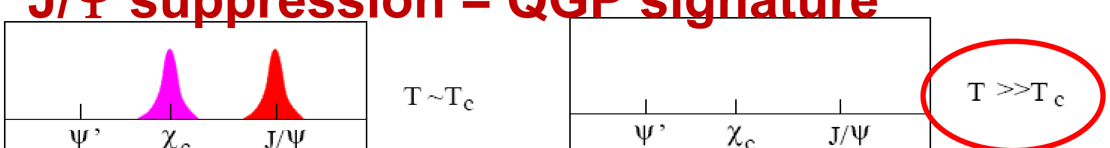
different states "melting" at different temperatures due to different binding energies.

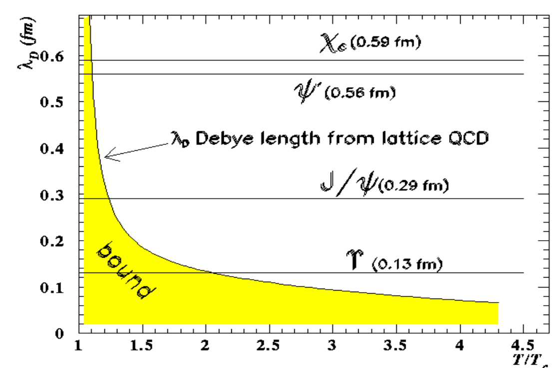
Matsui and Satz:

J/ψ destruction in a QGP by Debye screening



J/Ψ suppression = QGP signature





Introduction II: motivation

- A lot of work trying to understand **A+A** data (since J/ψ ≡ QGP signal)

Quarkonium as a hint of deconfinement — QGP

- If we focalise on **p+A** data (where no QGP is possible)
  only cold nuclear matter (CNM) effects are in play here:
  shadowing and nuclear absorption
  EMC and energy loss

Quarkonium as a hint of coherence — nPDF

- In fact, the question is even more fundamental: **p+p** data
  we do not know the specific production kinematics at a partonic level:
  $(2 \rightarrow 2,3,4)$ vs $(2 \rightarrow 1)$

Quarkonium as a hint of QCD — QCD

Introduction III: contents

Our goal:

To investigate the **CNM effects** and the impact of the specific **partonic production** kinematics

3 ingredients:

- **Quarkonium partonic production mechanism**
- **Shadowing**
- **Nuclear absorption**

• Results on J/ψ production @ RHIC and LHC

To extend our study to Υ and other CNM effects :

- ***fractional* energy loss**
- ***gluon* EMC effect**

•

• Results on Υ and J/ψ production @ RHIC

• Results on Υ @ LHC

Quarkonium supression in p+A collisions: CNM effects

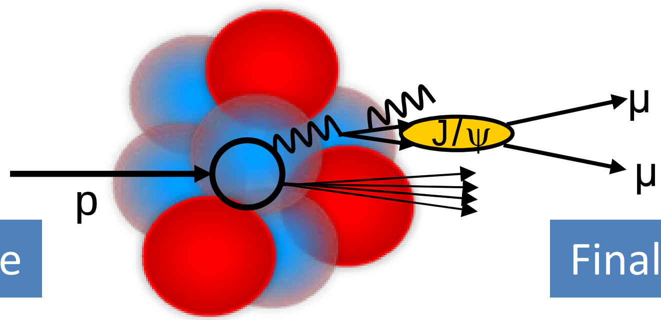
Quarkonium production is suppressed in nuclear collisions ...but for a variety of reasons

- 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
- final energy loss
- comovers

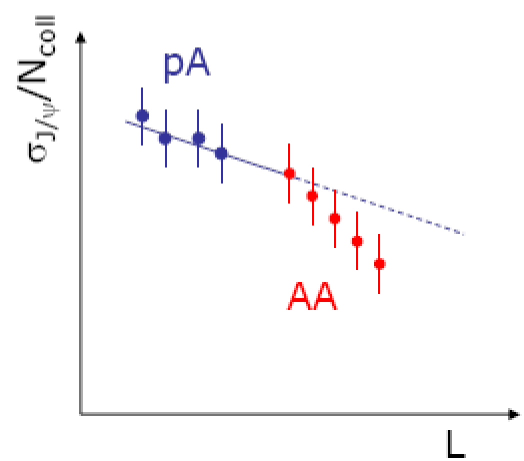
CNM effects
p+A and A+A collisions

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

It is very important to measure cold nuclear matter effects (CNM) before any claim of an “anomalous” (QGP) suppression in AA collisic

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



Quarkonium as a tool of COLD and HOT effects

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

gluon shadowing
gribov shadowing

nuclear structure functions
in nuclei ≠ superposition
of constituents nucleons

NI@SPS, IMP@RHIC

nuclear absorption

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

IMP@SPS, RHIC?

CGC

parton saturation

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

non thermal
colour connection

partonic comovers

hadronic comovers

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

suppression by a dense medium, not thermalized

Others:
EMC effect, energy loss

- **hot effects:** **w thermalisation QGP**

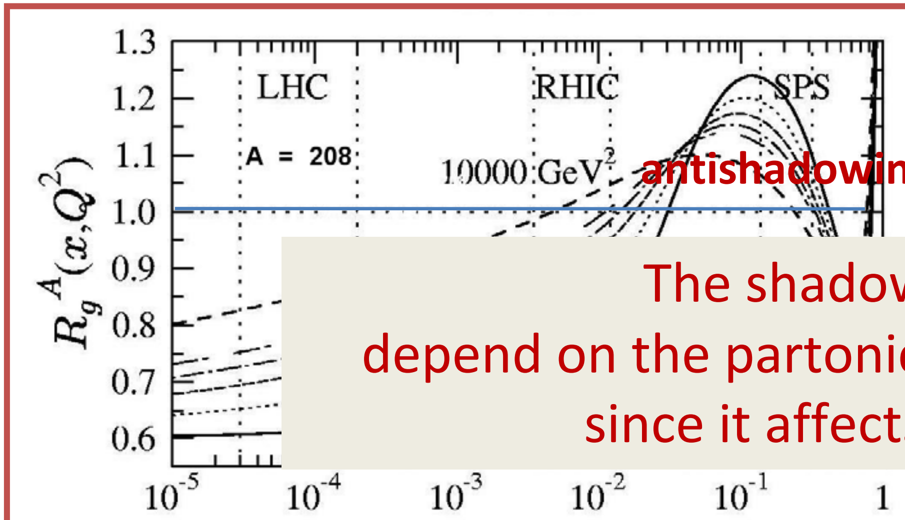
QGP   sequential suppression   recombination

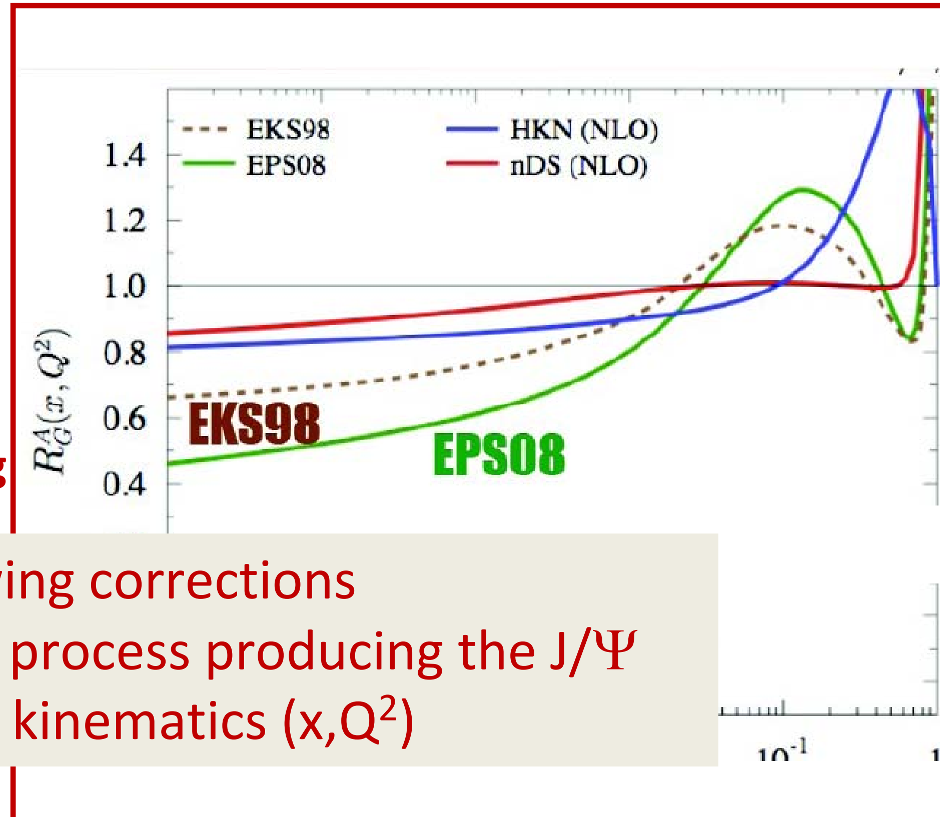
Shadowing: an initial cold nuclear matter effect

- 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)

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





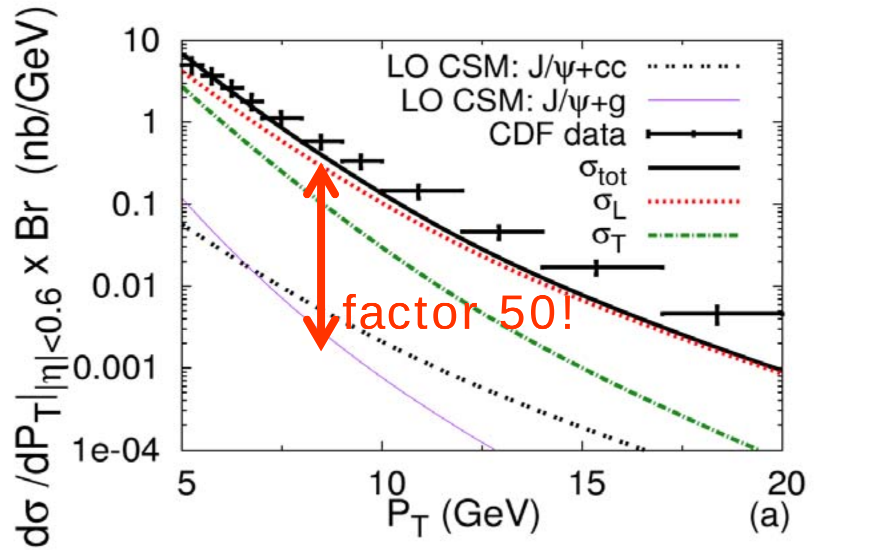
The shadowing corrections
depend on the partonic process producing the J/Ψ
since it affects kinematics (x,Q^2)

J/ψ production mechanisms at partonic level

- **First proposed: CSM @ LO**

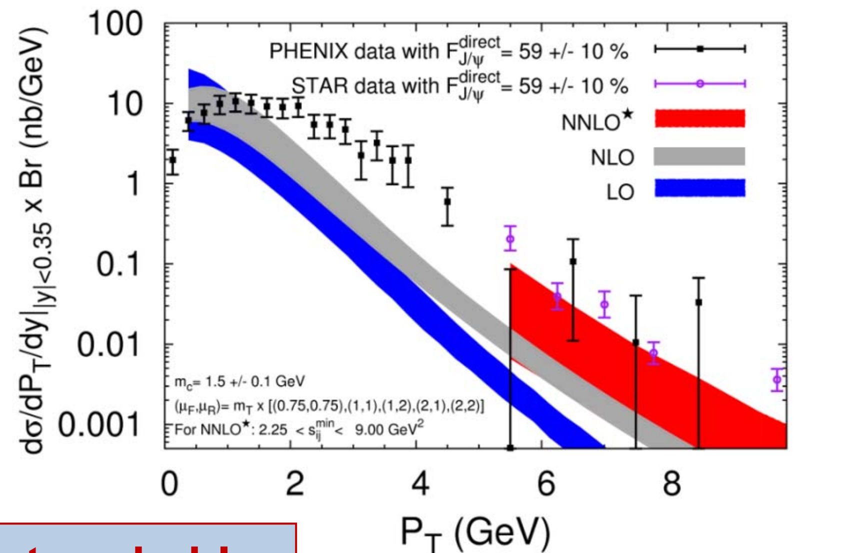
–perturbative creation of the ccbar pair in *color singlet state* with subsequent binding to J/ψ with same quantum numbers
–hard gluon emission

But CDF results on J/ψ direct production revealed a striking discrepancy wrt LO CSM



- **Second proposed: COM @ LO**

– uses NRQCD formalism to describe the non-perturbative hadronization of the ccbar color octet to the color singlet state via soft gluon emission



The agreement improves in NRQCD approach but it does not describe polarization

Recently many step forwards (NLO and NNLO corrections…)

Most probably: CS+CO @ NLO

On the kinematics of J/ψ production: two approaches

- CNM -shadowing- effects depends on J/ψ kinematics (x,Q^2)
- J/ψ kinematics depends on the production mechanism =>

Investigating two production mechanisms (including **p_T** for the J/ψ):

g+g ⟶ J/ψ

2⟶1

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

- intrinsic scheme: the **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 low p_T

g+g ⟶ J/ψ+g, gg,ggg,…

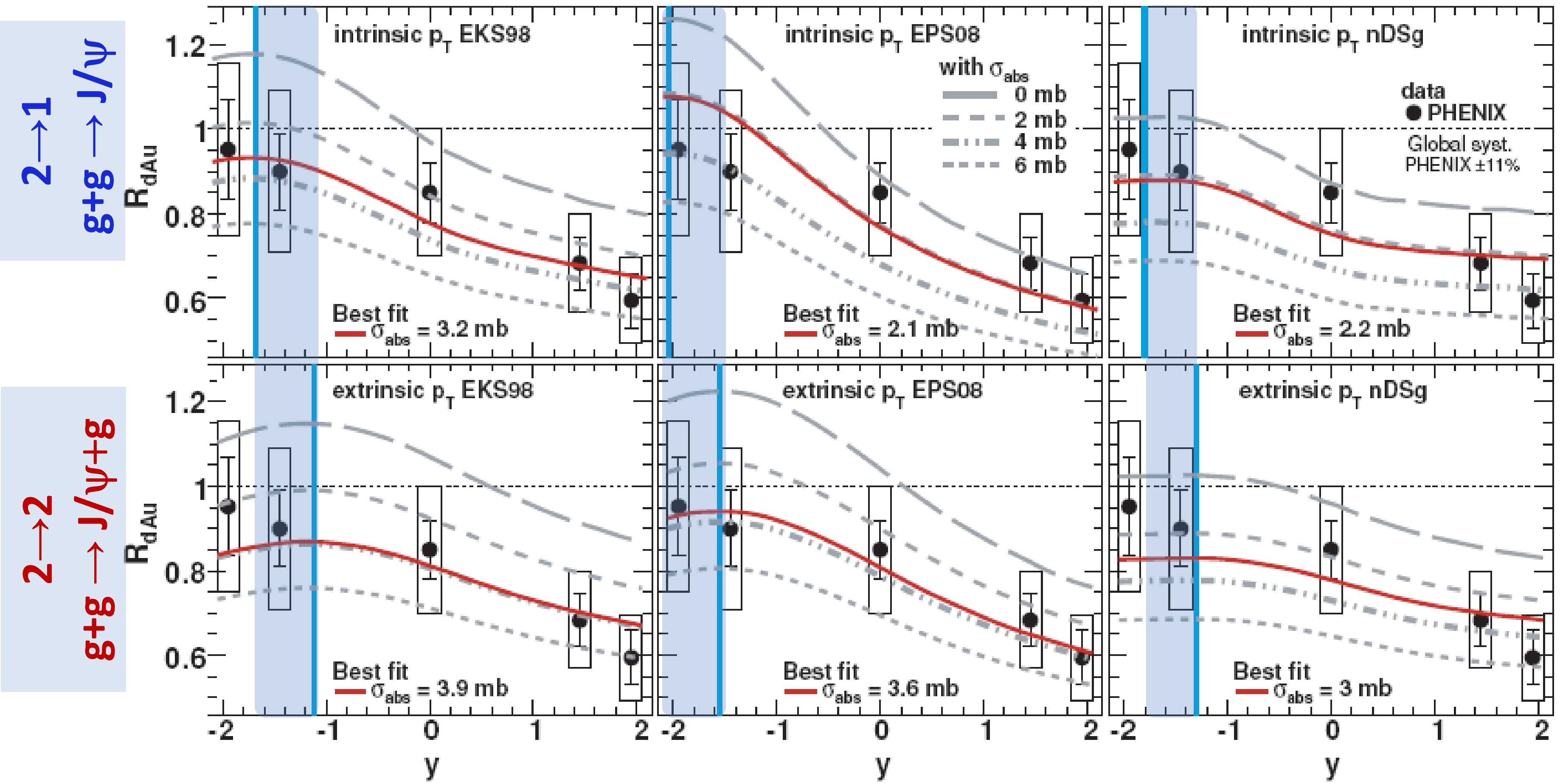
2⟶2, 3, 4

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

- extrinsic scheme: the **p_T** of the J/ψ is balanced by the outgoing parton(s)
  - ❖COM (NLO, NNLO),
  - ❖CSM (LO, NLO, NNLO)

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

How partonic kinematics affects CNM: J/ψ in d+Au @ RHIC



E. G. Ferreiro, F. Fleuret, J. P. Lansberg and A. Rakotozafindrabe PRC 81 (2010) 064911

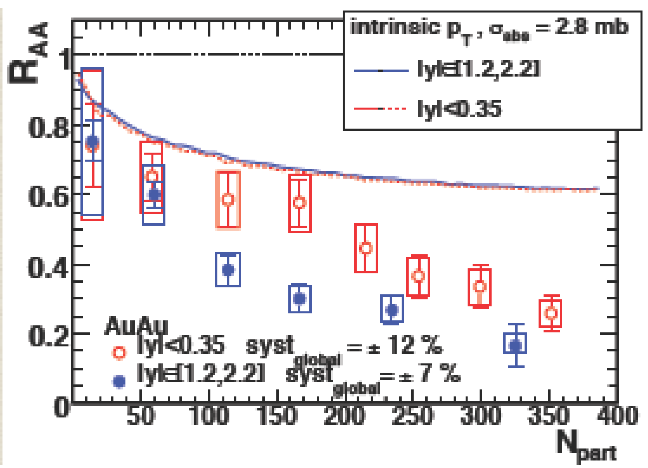
- shadowing depends on the partonic process: **2→1** or **2→2**
- in order to reproduce data @ RHIC: **nuclear absorption**

σabs extrinsic > σabs intrinsic   the kinematics matter for the extraction of σabs

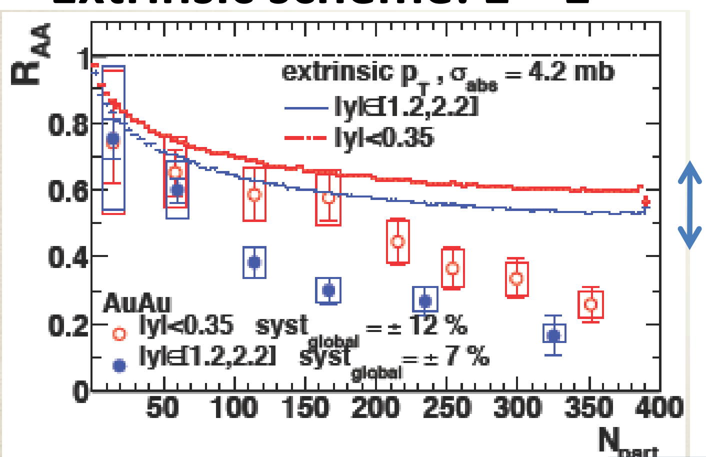
How partonic kinematics affects CNM: J/ψ in Au+Au @ RHIC

mid-y & forward-y

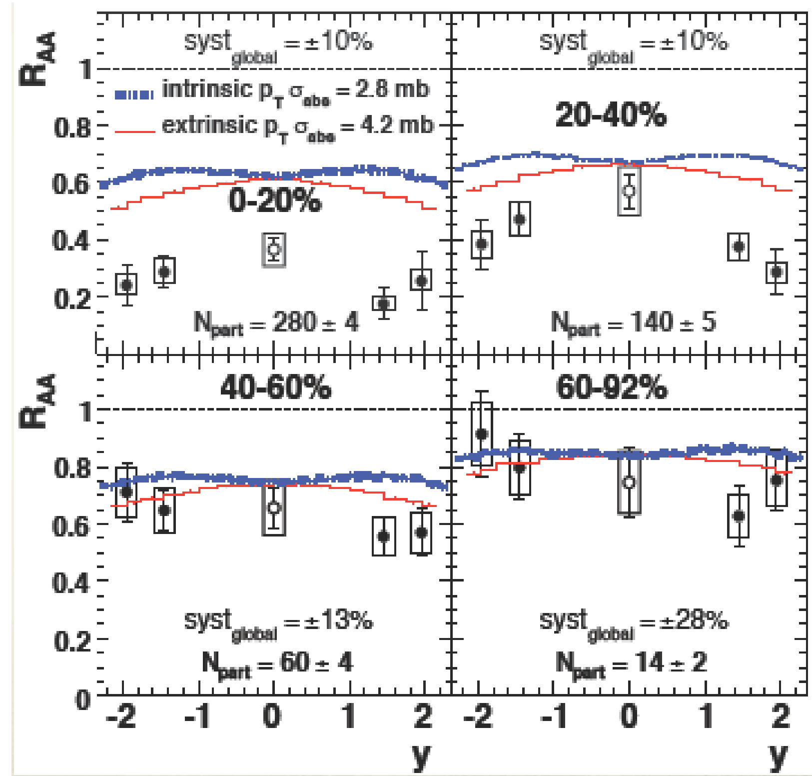
Intrinsic scheme: 2→1



Extrinsic scheme: 2→2



2→1 & 2→2 process

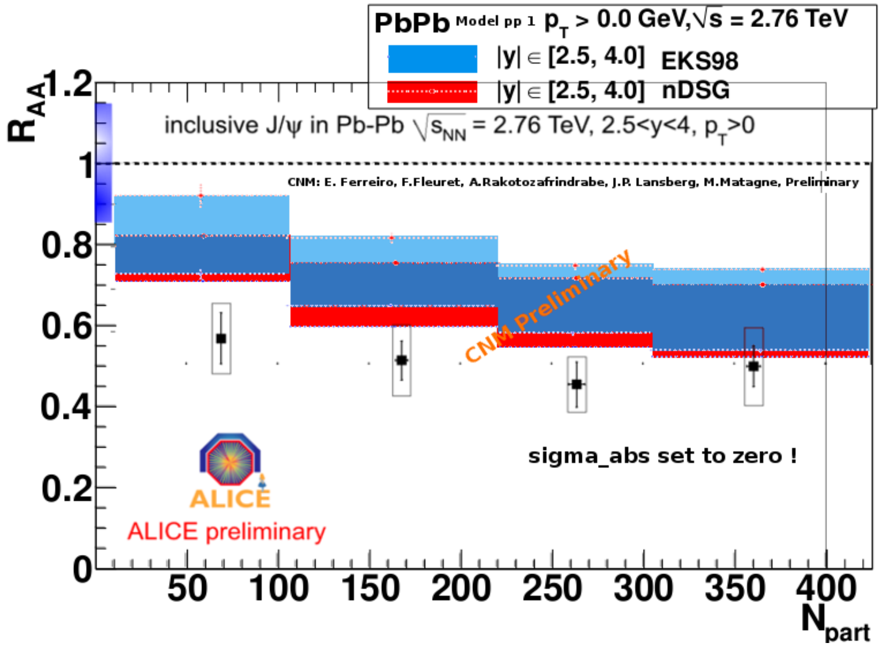


Hot Nuclear matter effects of course needed, but…
by considering the correct partonic kinematics

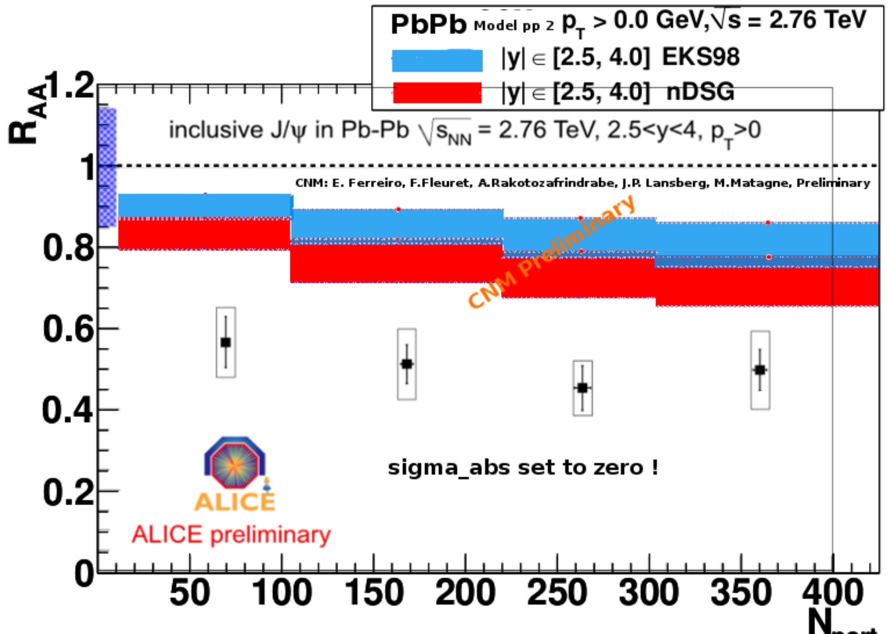
CNM effects could explain the mid/forw @ RHIC

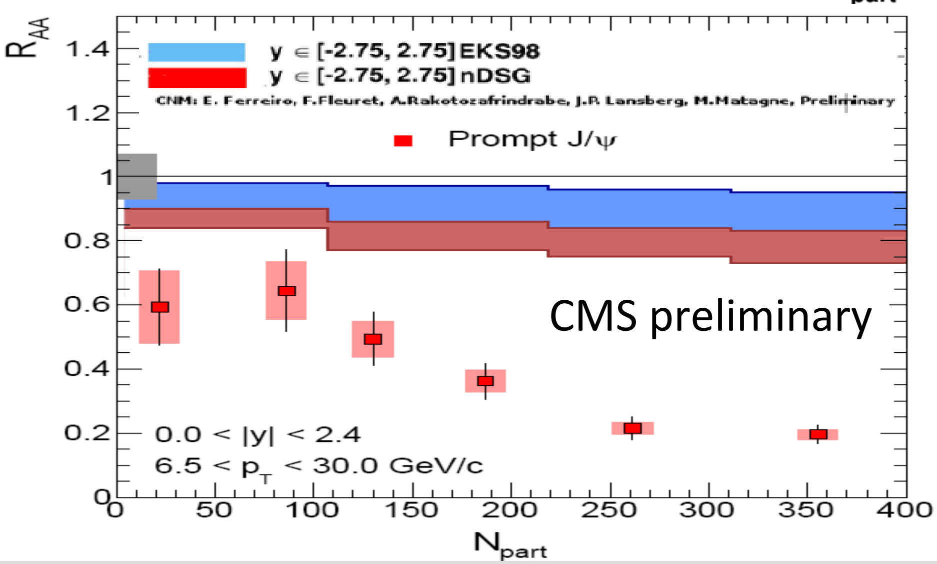
Going to higher energy: J/ψ in Pb+Pb @ LHC

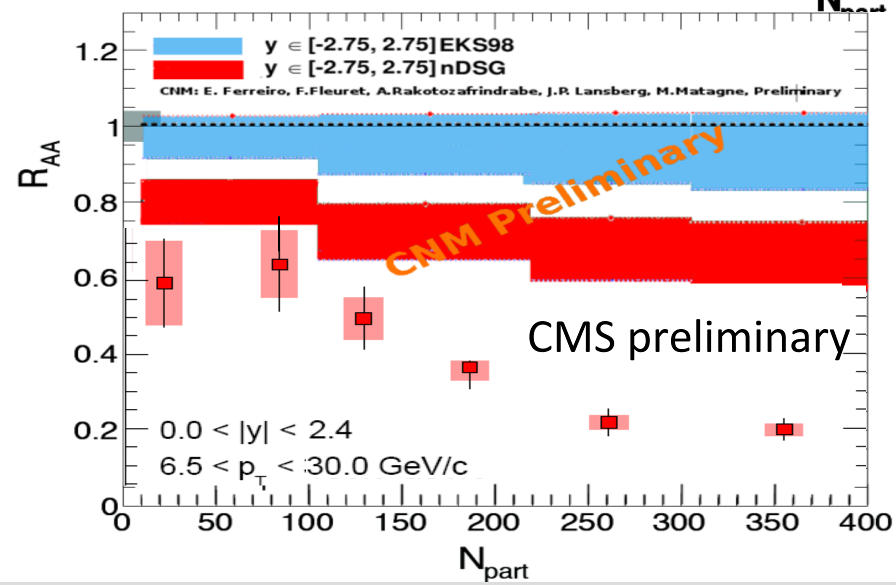
"CEM NLO" before k_T smearing



"Traditional" 2 → 2

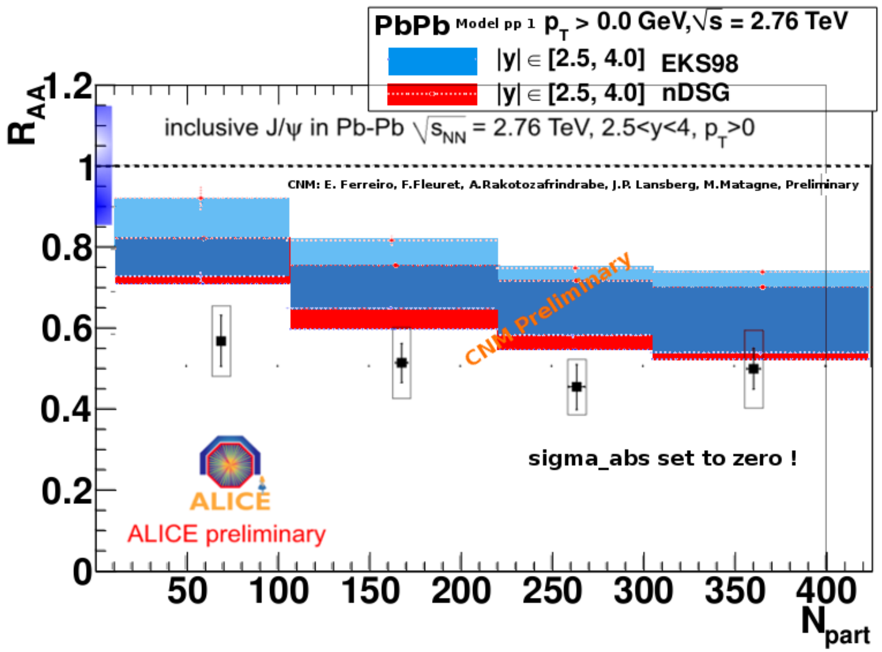




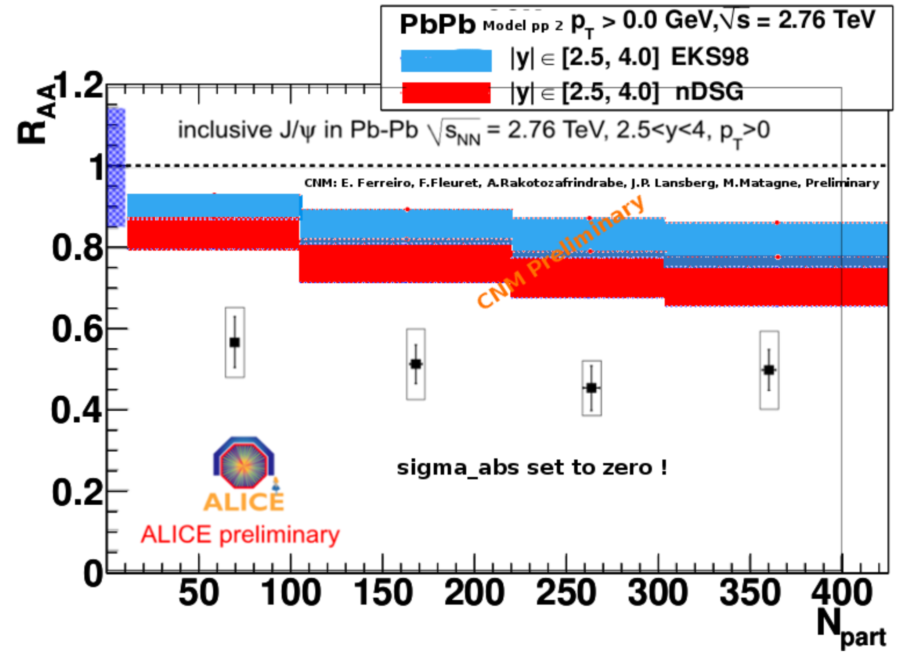


Going to higher energy: J/ψ in Pb+Pb @ LHC

“CEM NLO” before k_T smearing

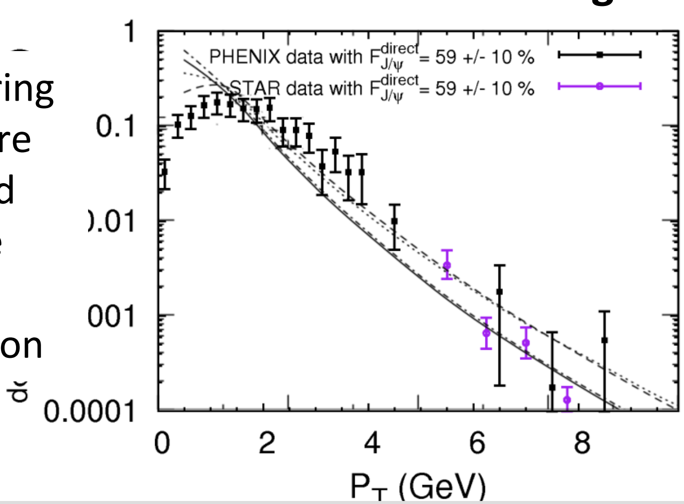


“Traditional” 2 → 2



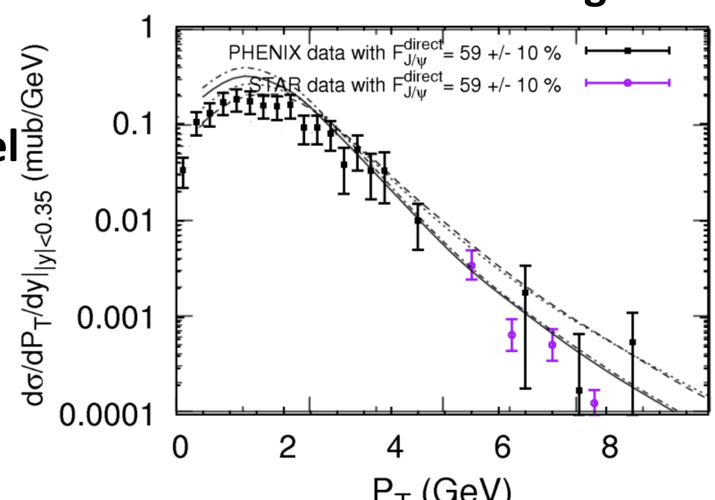
kt smearing procedure is applied after the (x_1,x_2) integration

without kt smearing



underlying partonic model

with kt smearing

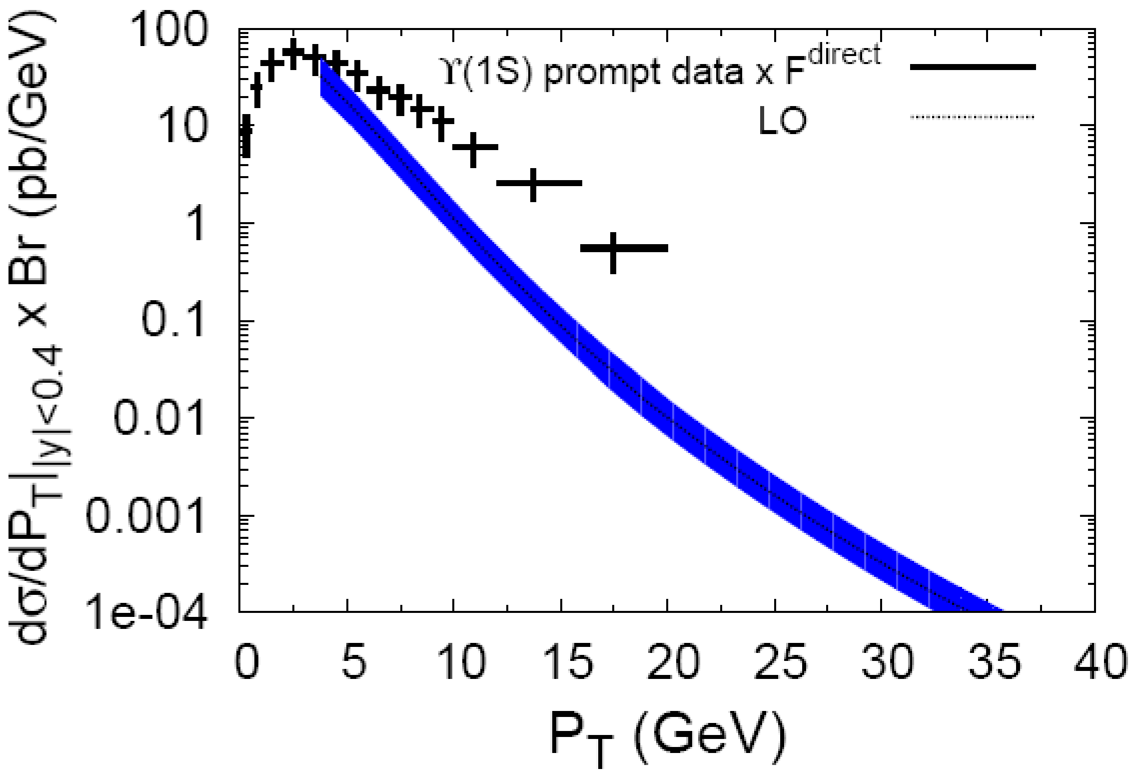


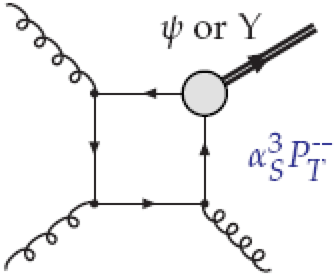
Something new… searching for other CNM effects

- **Gluon** EMC effect
- **Fractional** energy loss

Remainder: QCD corrections for Υ in p+p @ Tevatron

P. Artoisenet, J. Campbell, J.P. Lansberg, F. Maltoni, PRL 101 (2008) 152001.





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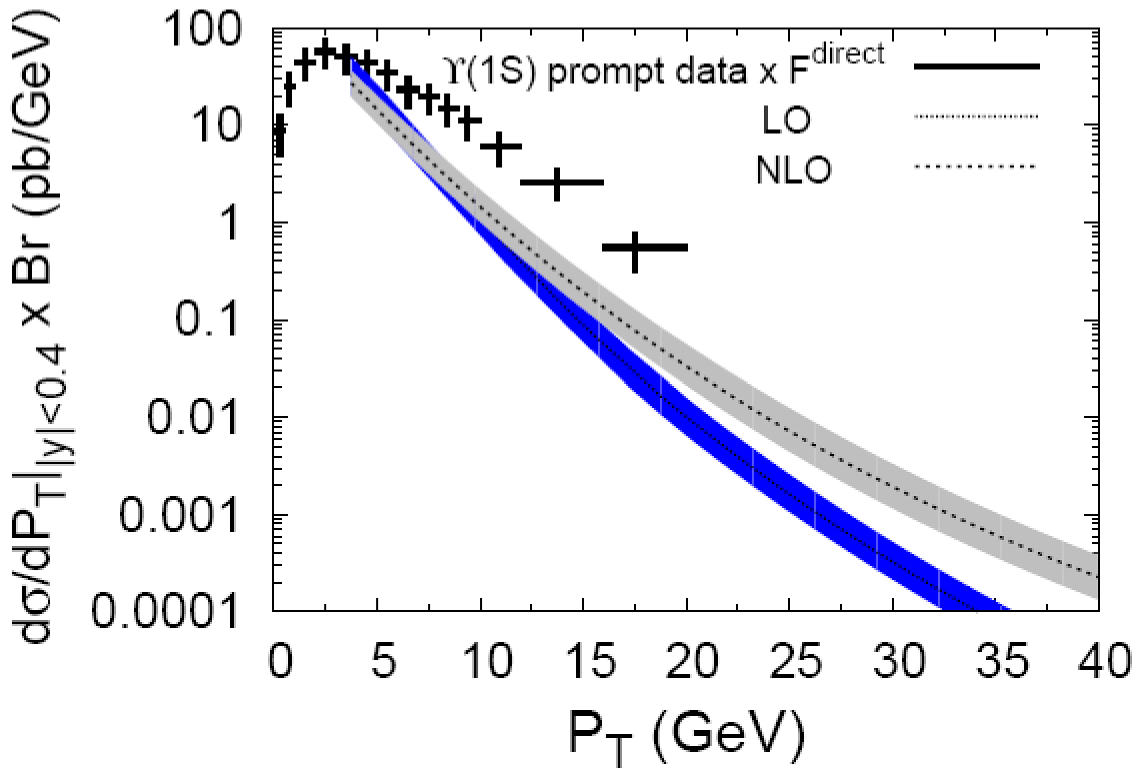

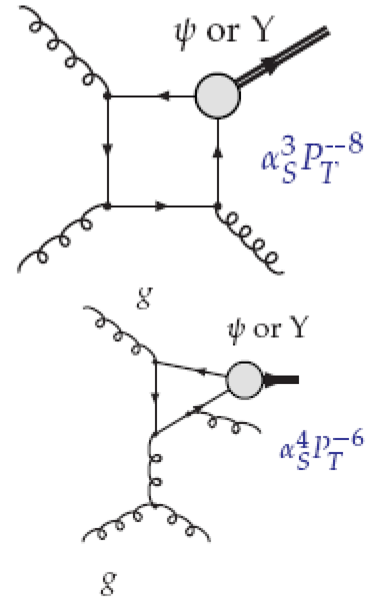

Remainder: QCD corrections for ϒ in p+p @ Tevatron

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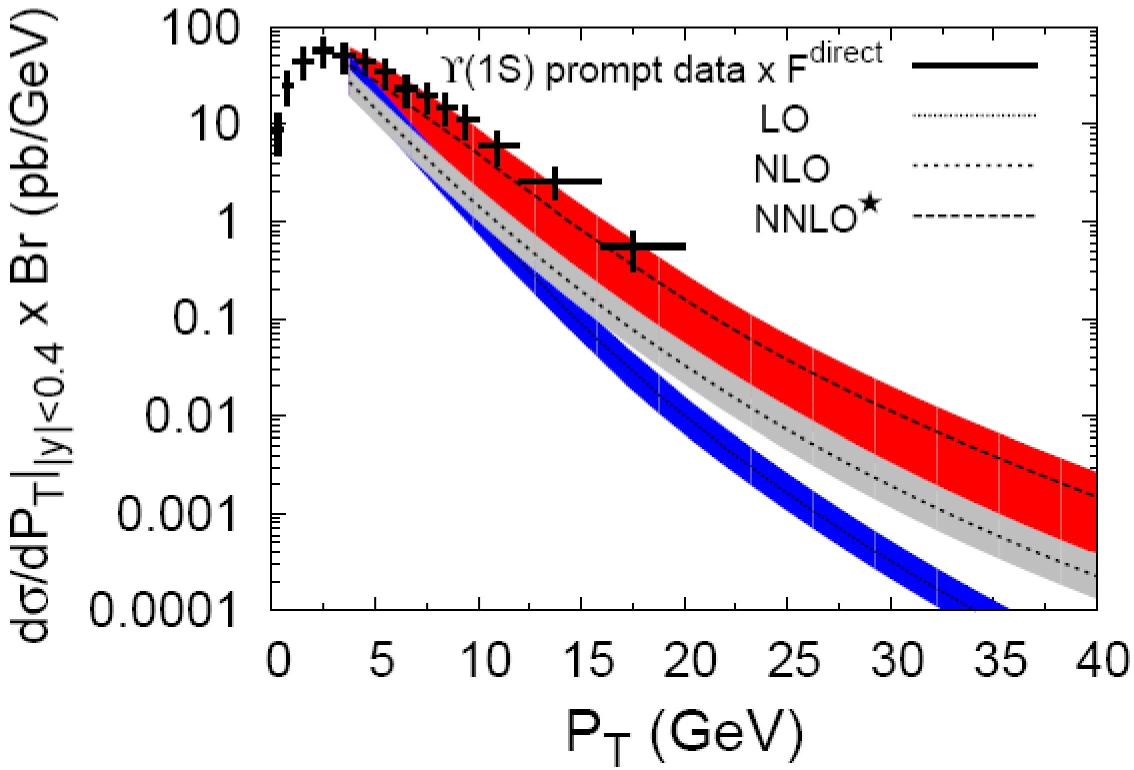
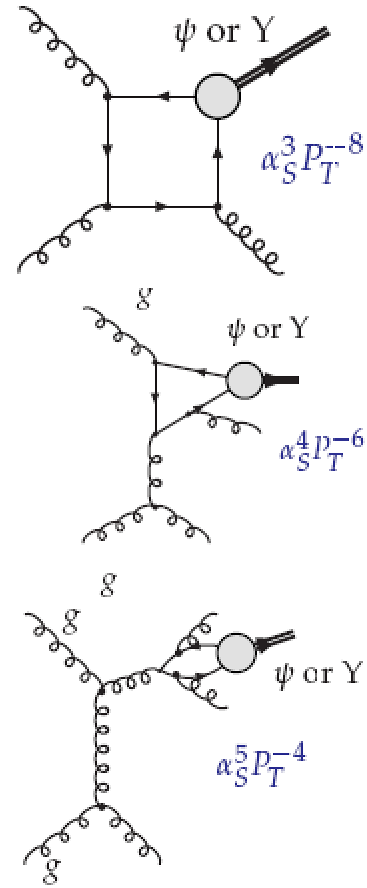




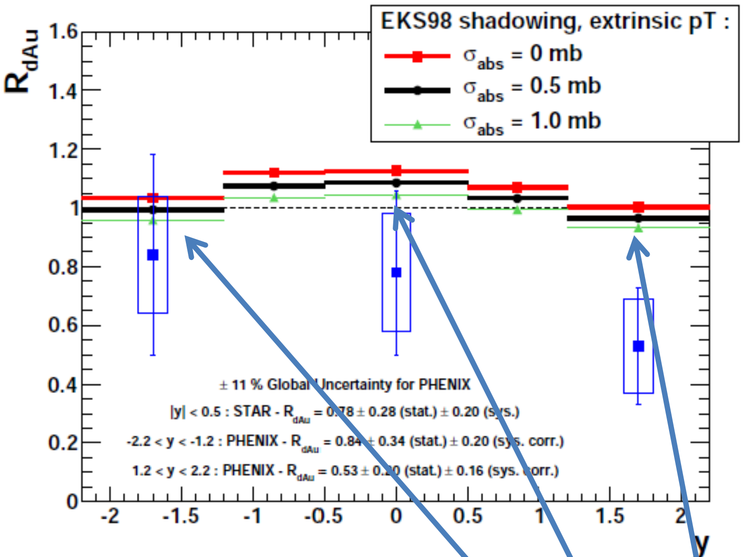
CSM LO sufficient to describe low pT data

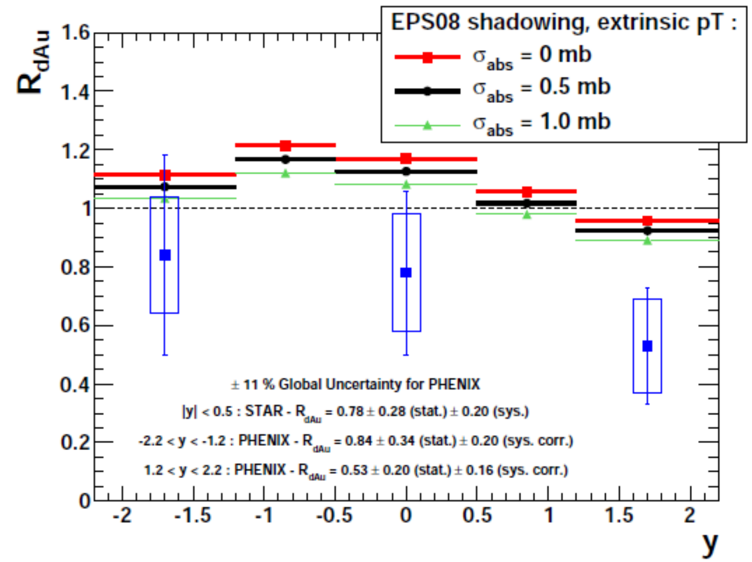
ϒ vs J/ψ :

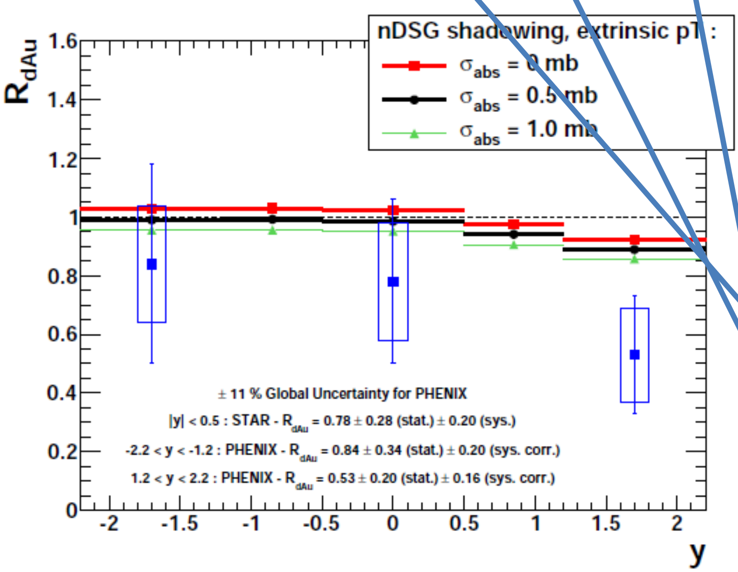
- better th. control on the prod. process (larger mQ)
- smaller uncertainty on σ_{abs} (since small)

Searching new CNM effects: ϒ in d+Au @ RHIC

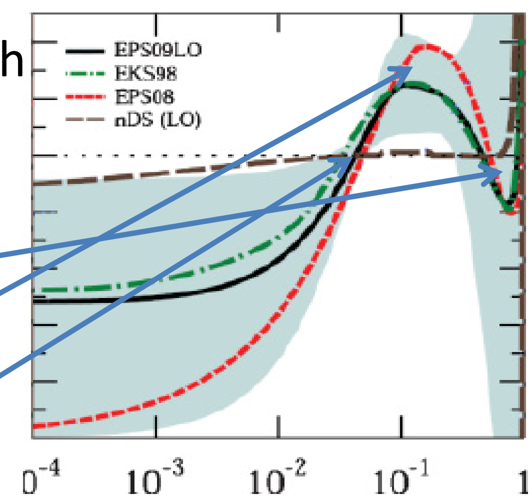
Extrinsic scheme: σ_{abs}=0 mb, σ_{abs}= 0.5mb , σ_{abs}= 1 mb in 3 shadowing models







- backward: ok within uncertainties
- central: reasonable job
- forward : clearly too high



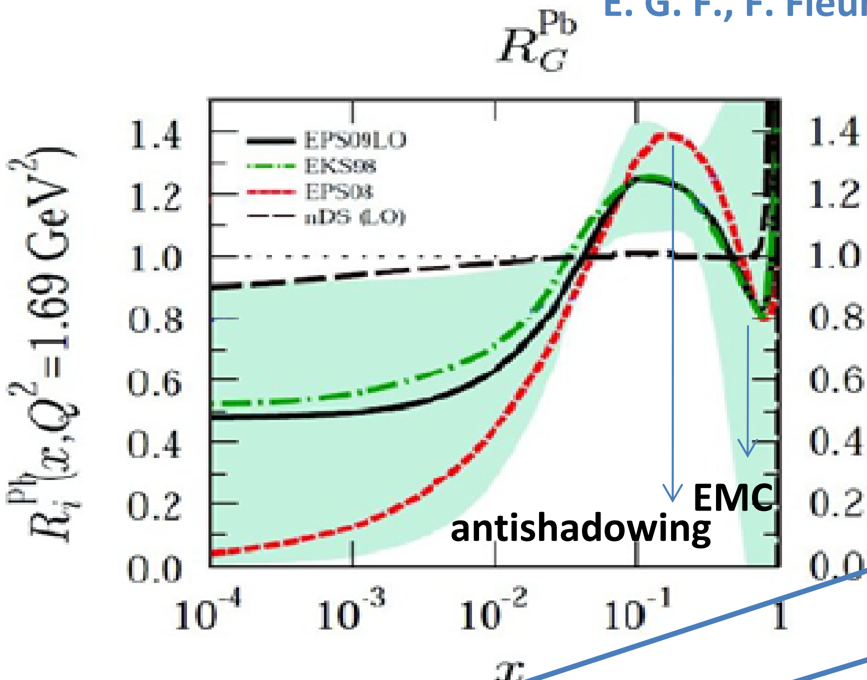
Physical interpretation

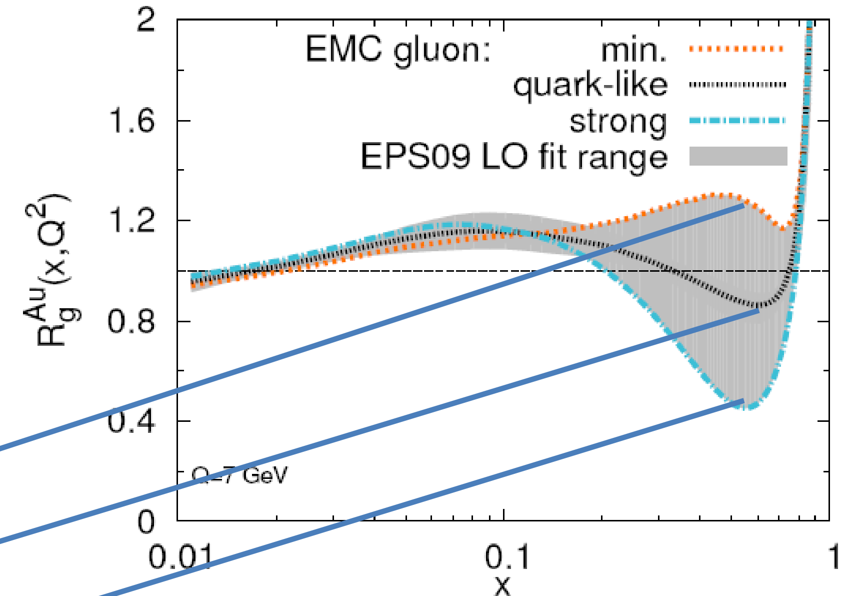
- backward: EMC effect
- central: antishadowing
- forward : shadowing≈1

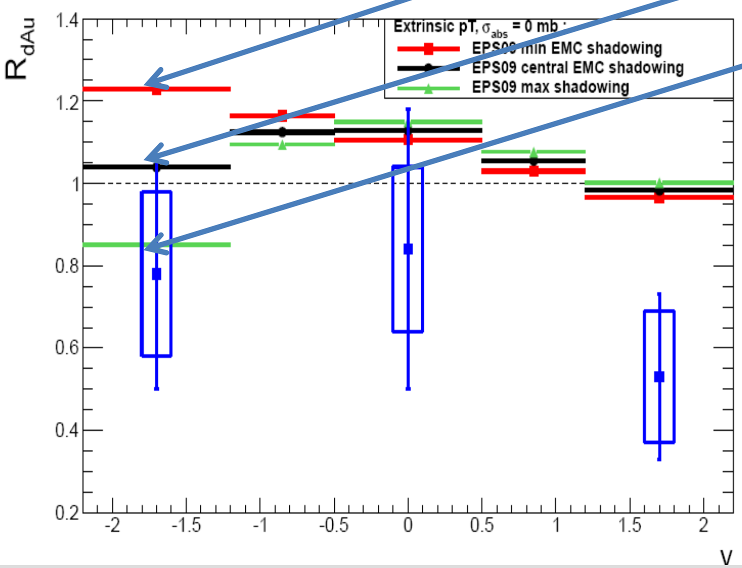
energy loss is needed

Gluon EMC effect

E. G. F., F. Fleuret, J. P. Lansberg and A. Rakotozafindrabe arXiV:1110:504







Let us try to increase the suppression of *g(x)* in the EMC region, thr shadow incert.:

we have used three of the EPS09 LO sets: one with a quark-like EMC gluon suppression, and the two limiting curves

Works better for backward region

What about the forward region?

Energy loss effect: Radiative energy loss

- **Basic 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
  => Δ E is limited and does not scale with E (Brodsky-Hoyer)

- **At RHIC and LHC** (contrary to SPS), typical partons (for x1 ~ 10^{-2}) have energies of the order of hundreds of GeV in the nucleus rest frame
  => radiative energy loss has a negligible effect on the parton x_1

Energy loss effect: Fractional energy loss

• Still, in order to explain large x_F data at RHIC, it would be useful to have

***=> a fractional energy loss*: Δ E α E**

(Old idea by Gavin Milana, thought to be ruled out by LPM bound)

• Recently (Arleo, Peigner, Sami arxiv:10006.0818) 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**.

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 Gavin-Milana 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.

Coherent energy loss effect

Arleo, Peigner, Sami arxiv:1006.0818
Arleo HP2012

(i) Incoherent radiation in the initial/final state

Radiation of gluons with large formation times cancels out in the induced gluon spectrum, leading to $t_f \sim L$

$$\Delta E \propto \hat{q} L^2$$

- Hadron production in nuclear DIS and Drell-Yan in p A collisions
- Jets and hadrons produced in hadronic collisions at large angle

(ii) Coherent radiation (interference) in the initial/final state

Induced gluon spectrum dominated by large formation times

$$\Delta E \propto \frac{\sqrt{\hat{q} L}}{M} E$$

- Production of light and open heavy-flavour hadrons at forward rapidities in the medium rest frame (nuclear matter or QGP)
- Production of heavy-quarkonium if color neutralisation occurs on long time-scales $t_{\text{octet}} \gg t_{\text{hard}}$

Energy loss effect @ RHIC

$$\Delta E/E = \Delta x_1/x_1 \simeq N_c \alpha_s \sqrt{\Delta \langle p_T^2 \rangle}/M_T$$

E. G. F., F. Fleuret, J. P. Lansberg and A. Rakotozafindrabe arXiV:1110:5047

Independently of the gluon PDF parameterization, this energy loss will induce

For ϒ

a suppression of 80% - 90% at mid y

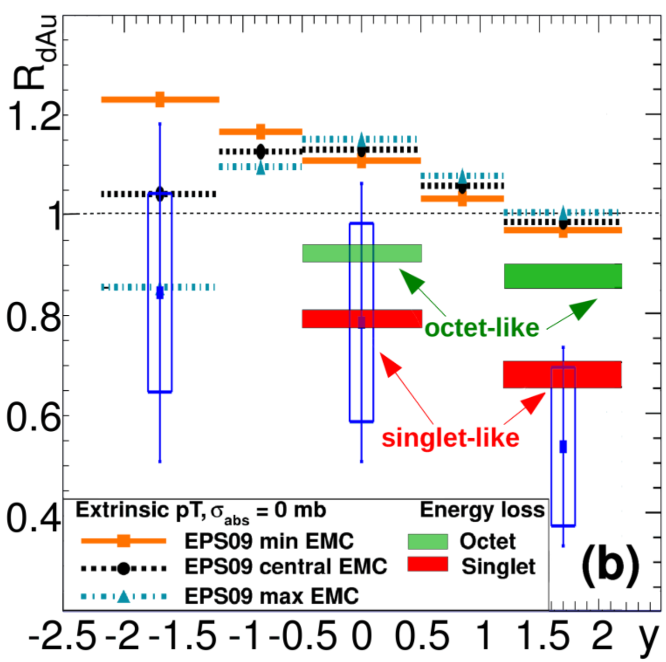
a suppression of 65% -85%at forward y

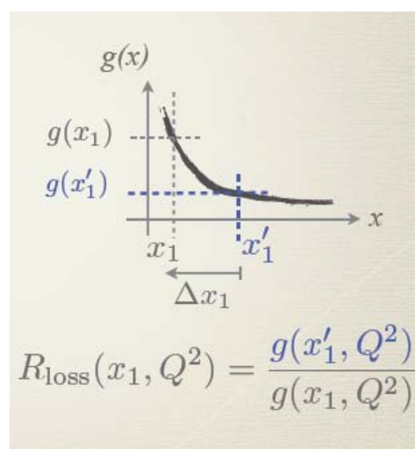
For J/ψ

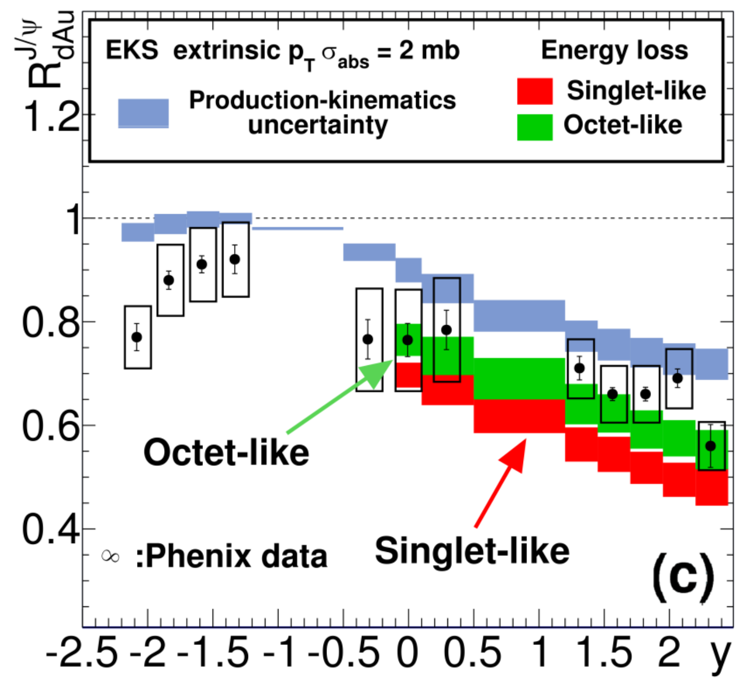
a suppression of 80% - 90% at mid y

a suppression of 70% -80%at forward y

Due to t_f of the order of nuclear size, this energy loss is not applicable in the backward y



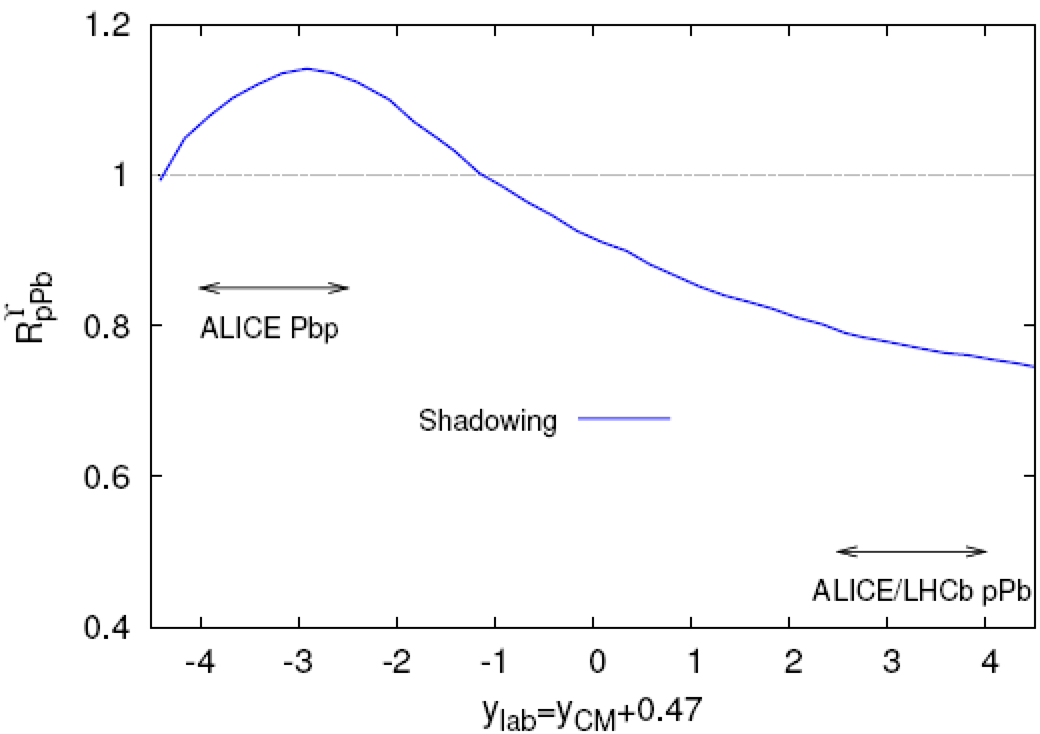




Work in progress: ϒ production @ LHC

- **Shadowing** effect is not small

Remember that in PbPb collisions at y = 0 shadowing effect is squared compared to pPb



Work in progress: Υ production @ LHC

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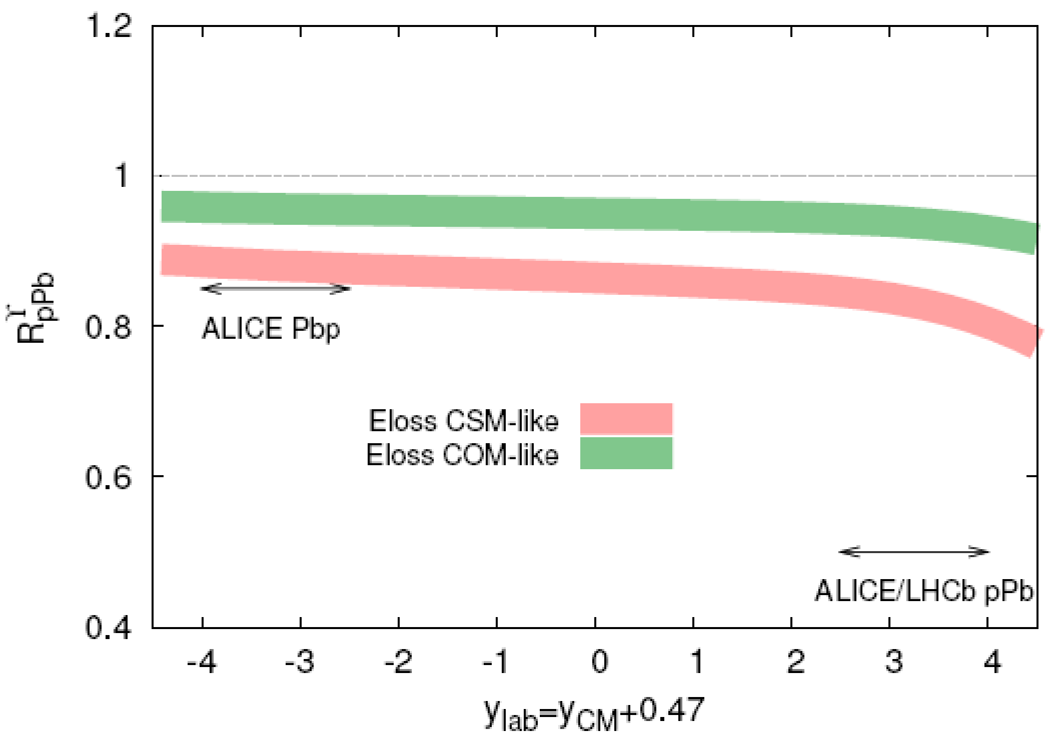
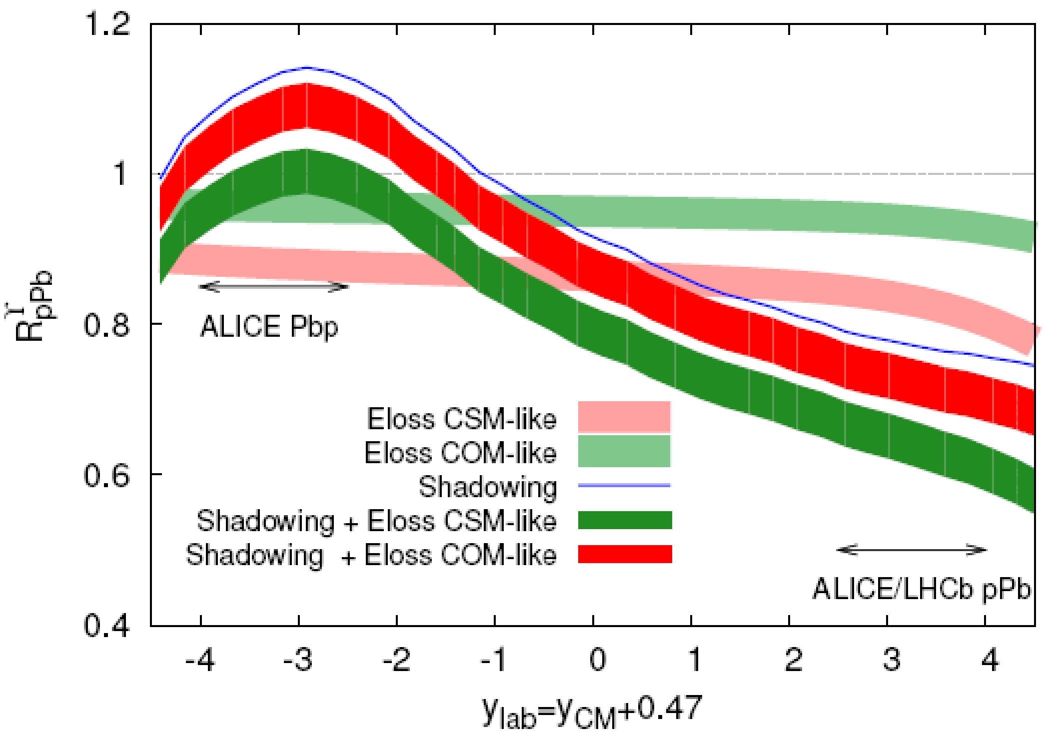


- **Energy loss** also likely matters

Work in progress: ϒ production @ LHC

- **Shadowing** effect is not small

Remember that in PbPb collisions at y = 0 shadowing effect is squared compared to pPb



- **Energy loss** also likely matters
- Overall, **nuclear matter effects** are not small

they should be accounted when analysing PbPb data

Conclusions

- We have studied the influence of specific partonic kinematics

  within 2 schemes: intrinsic ($2\longrightarrow 1$) and extrinsic ($2\longrightarrow 2$) p_T
  for different shadowings
  including nuclear absorption and different partonic models

- for J/ψ
  d+Au collisions @ RHIC
  A+A collisions @ RHIC and LHC
  CNM strong effects at both energy

- for ϒ in d+Au collisions @ RHIC:
  EMC effect in the backward region
  fractional energy loss in the central & forward region
- energy loss can also affect J/ψ @ RHIC
- work in progress: ϒ production @ LHC

http://phenix-france.in2p3.fr/software/jin/index.html