Fall meeting of the GDR PH-QCD: nucleon and nucleus structure studies with a LHC fixed-target experiment and electron-ion colliders (18-21 octobre 2011)

Cold nuclear matter effects on quarkonium production @ RHIC and LHC

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Work done in collaboration with

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EPJC61 (2009), PLB680 (2009), PRC81 (2010), NPA855 (2011)

Introduction: motivation

- A lot of work trying to understand **A+A** data (since $J/\psi \equiv$ QGP signal)

Quarkonium as a hint of deconfinement | QGP probe

- 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 probe

- In fact, the question is even more fundamental: **p+p** data

we do not know the specific production kinematics at a partonic level:

(2→2,3,4) vs (2→1)

Quarkonium as a hint of QCD | QCD probe

Introduction : contents

Our goal:

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

3 ingredients:

•J/ψ partonic production mechanism

•Shadowing

•Nuclear absorption

• Results on J/ψ production @ RHIC and LHC

To extend our study to ϒ CNM effects :

•*fractional* energy loss

•*gluon* EMC effect

• Results on ϒ production @ RHIC

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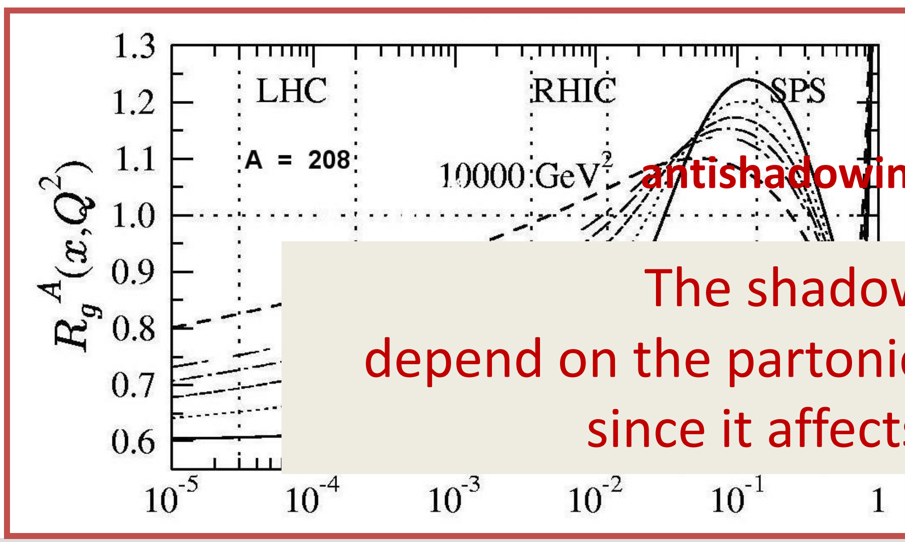
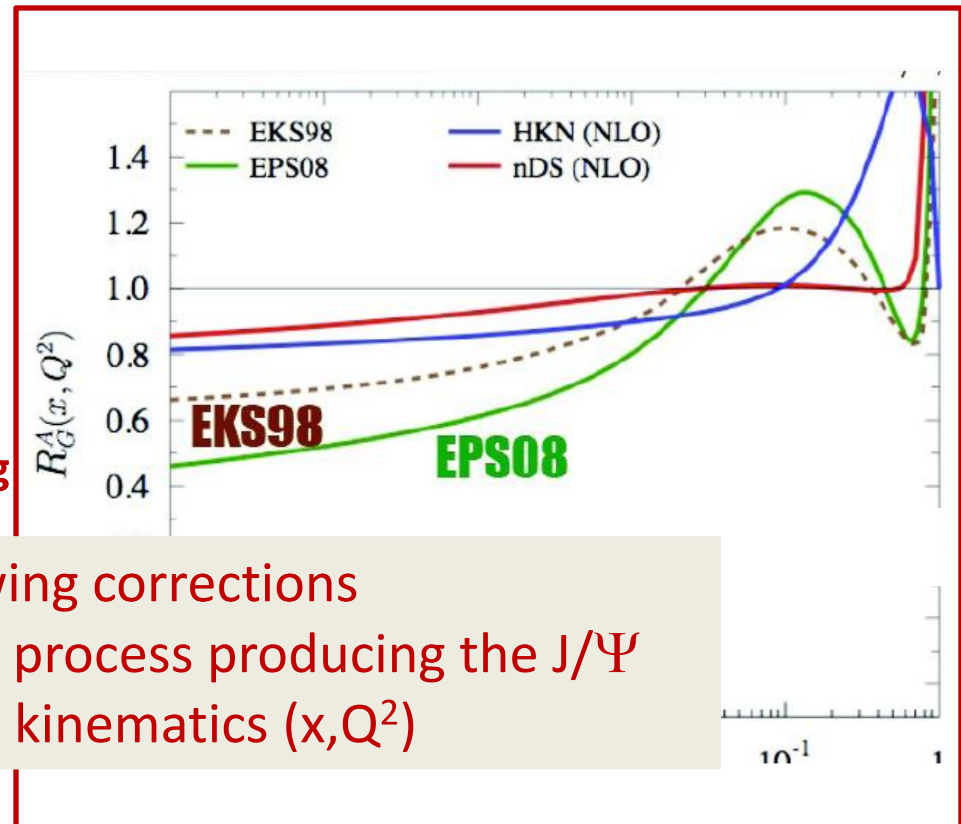
Shadowing: an initial cold nuclear matter effect

- 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)

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)

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

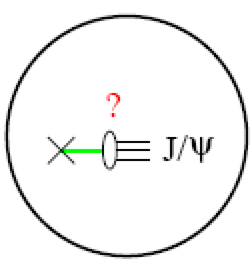
nuclear matter density (ρ) — break-up cross section (σ_{abs}) — path length (L)

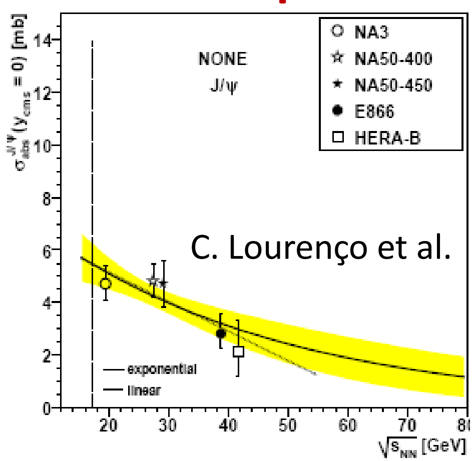
Energy dependence

- **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**

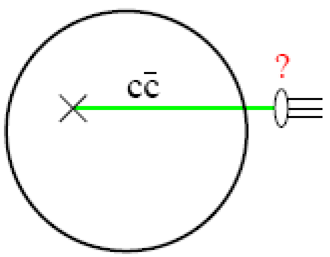
In terms of formation time:

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





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



Rapidity dependence of nuclear absorption? σ_{abs} @ mid y < σ_{abs} @ forward y?

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

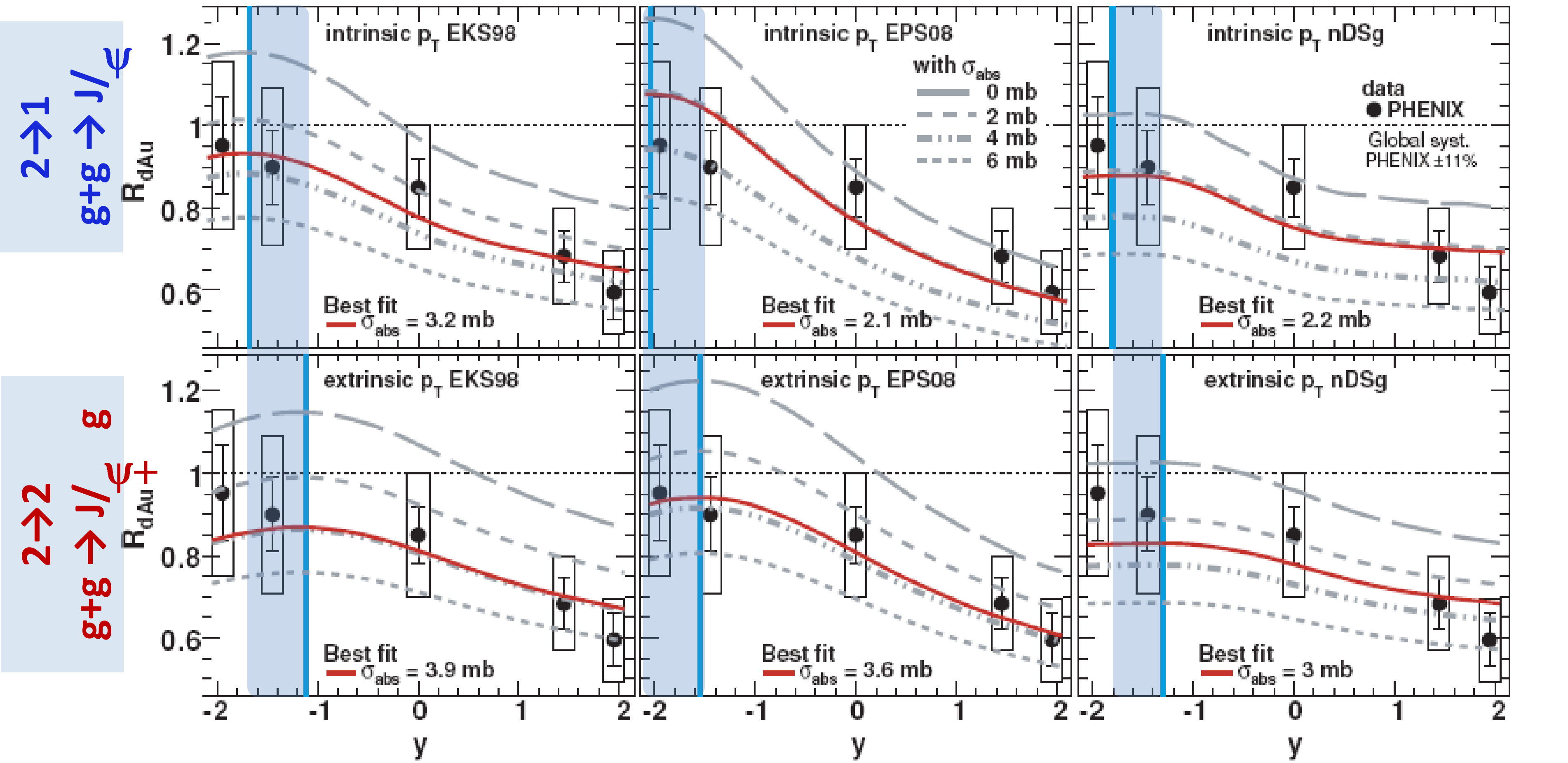
g+g → J/ψ+g, gg,ggg,… **2→2, 3, 4**

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

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

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

Results d+Au @ RHIC: J/ψ rapidity dependence of R_{dAu}



- shadowing depends on the partonic process: 2→1 or 2→2 arXiv:0912.4498
- antishadowing peak shifted toward larger y in the extrinsic case
- in order to reproduce data @ RHIC: **nuclear absorption**

σ_{abs} extrinsic > σ_{abs} intrinsic the kinematics matter for the extraction of σ_{abs}

Fit of σabs with EKS, EPS and nDS(g) from RdAu and RCP

σabs and χ^2 from **RdAu**	**EKS**		**EPS**		**nDS(g) LO**	
intrinsic	**3.20**	0.9	**2.11**	1.1	**2.21**	1.6
extrinsic	**3.90**	1.1	**3.60**	0.5	**3.00**	1.4

σabs int < σabs ext

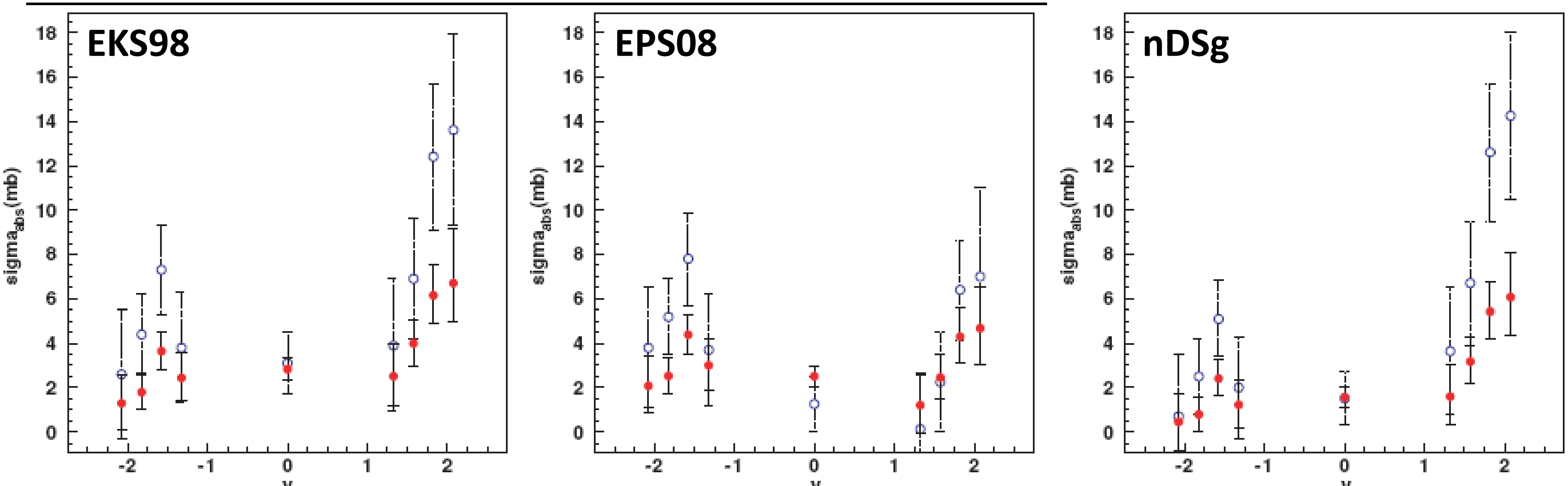
σabs from **RCP**	$y < 0$	$y = 0$	$y > 0$	All y
EKS98 Int.	5.2 ± 1.2	3.1 ± 1.3	9.5 ± 1.4	N/A
EKS98 Ext.	2.5 ± 0.5	3.2 ± 0.5	4.8 ± 0.7	3.2 ± 0.4
EPS08 Ext.	3.2 ± 0.5	2.5 ± 0.5	3.1 ± 0.6	2.9 ± 0.3
nDSg Ext.	1.4 ± 0.5	1.6 ± 0.5	4.0 ± 0.7	2.2 ± 0.3

σabs (y)?

Intrinsic: increase of σabs with y

Extrinsic: softer increase of σabs

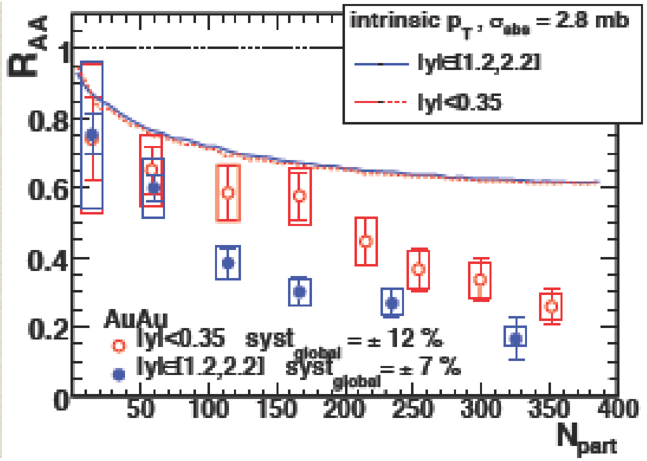
a constant behavior cannot be ruled out (see EPS08). We assume cte σabs



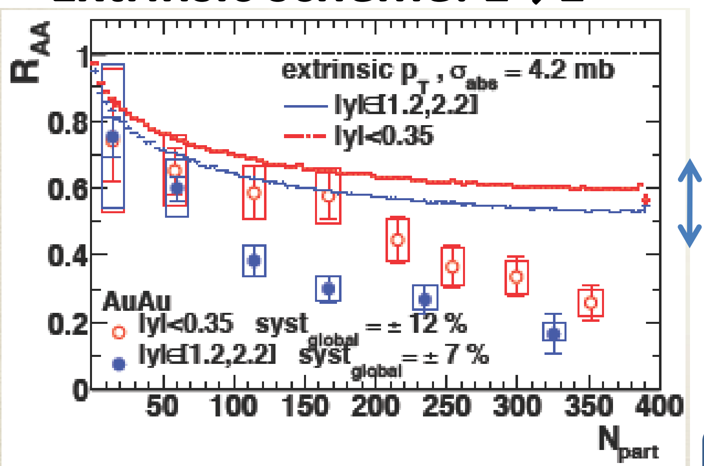
Results Au+Au @ RHIC: J/ψ centrality and y dependence

mid-y & forward-y

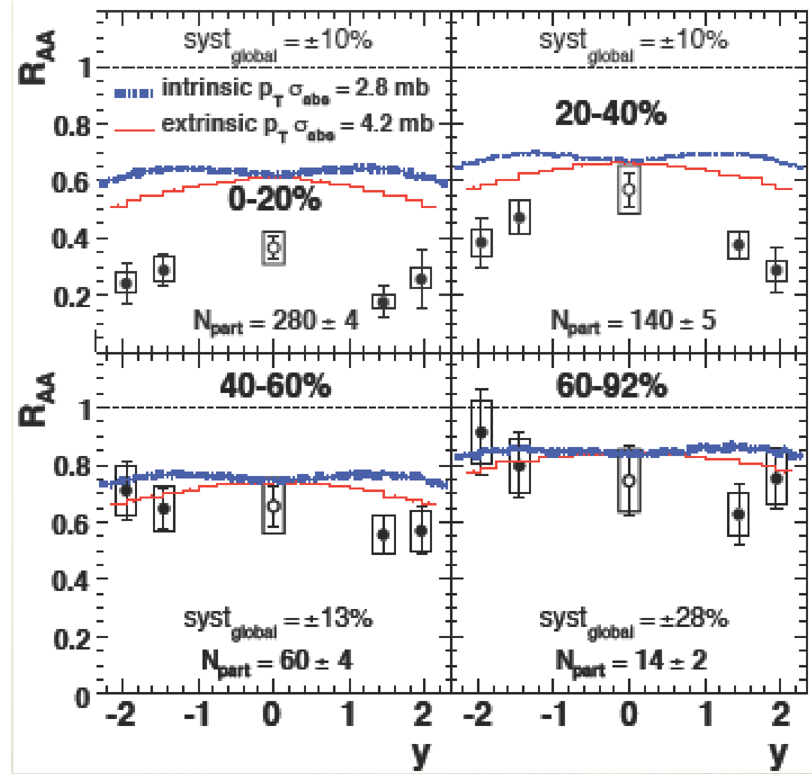
Intrinsic scheme: 2→1



Extrinsic scheme: 2→2



2→1 & 2→2 process



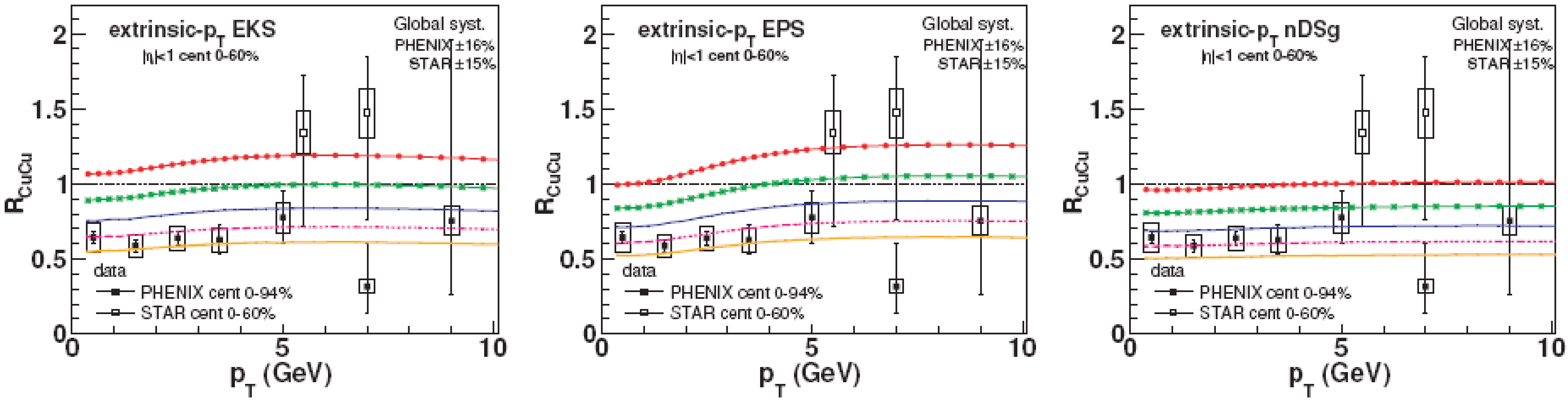
Extrinsic scheme : **R_{AA} @ forward y < R_{AA} @ mid y**

Hot Nuclear matter effects of course needed, but…

Less need for recombination effects @ RHIC

Results A+A @ RHIC: J/ψ transverse momentum dependence

Extrinsic scheme: σ_{abs}= 0, 2, 4, 6 mb in 3 shadowing models



R_{AA} increases with P_T partially matching the trend of PHENIX and STAR data

Growth of R_{AA} not related to Cronin :
it comes from the increase of x with p_T

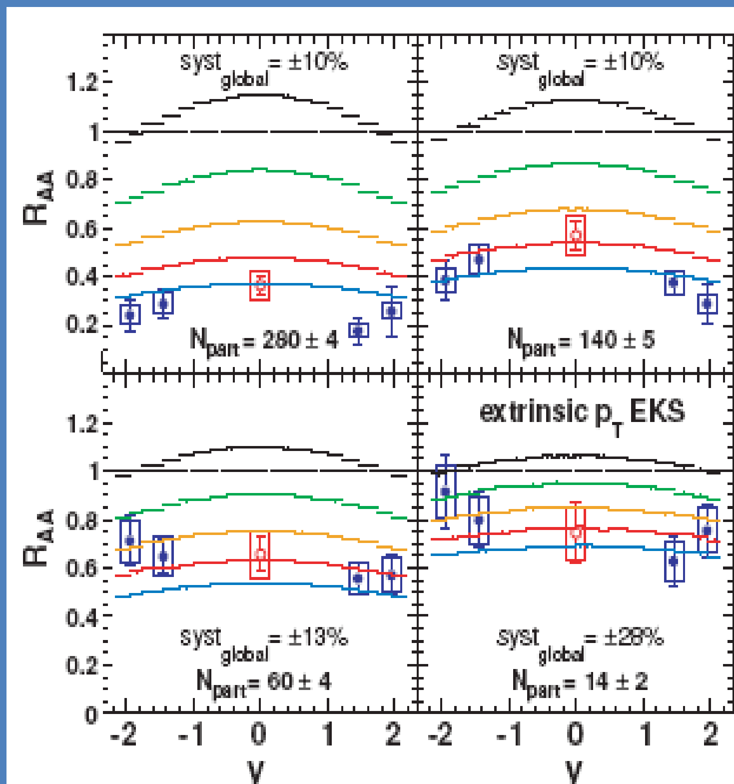
$$x_\perp \propto \left(m_{J/\psi}^2 + p_\perp^2\right)^{1/2}$$

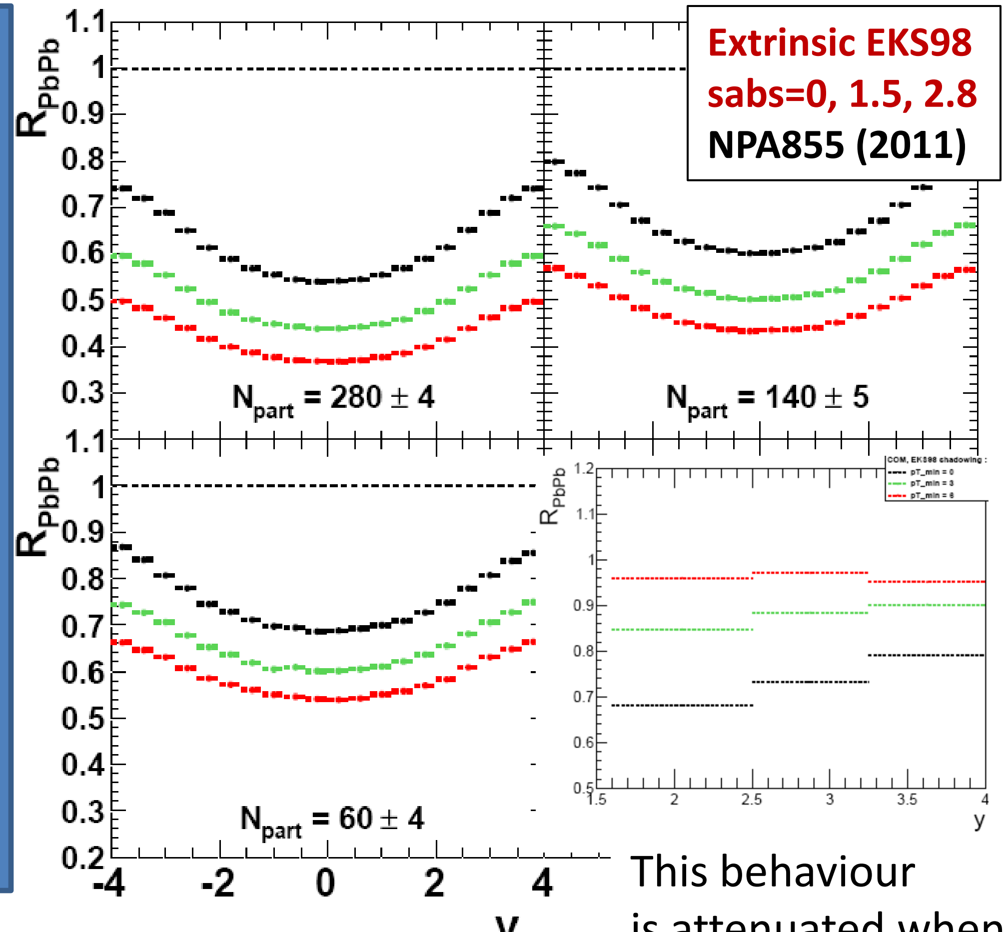
Less shadowing effects when increasing p_T

p_T matters!!!

Work in progress: J/ψ @ LHC rapidity dependence (2 → 2)

RHIC





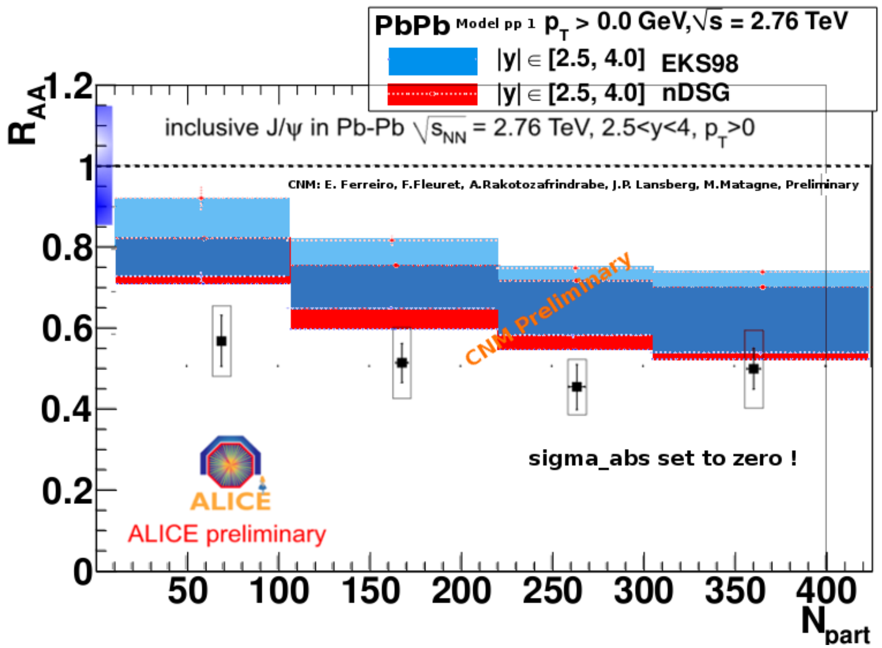
This behaviour is attenuated when going to higher p_T

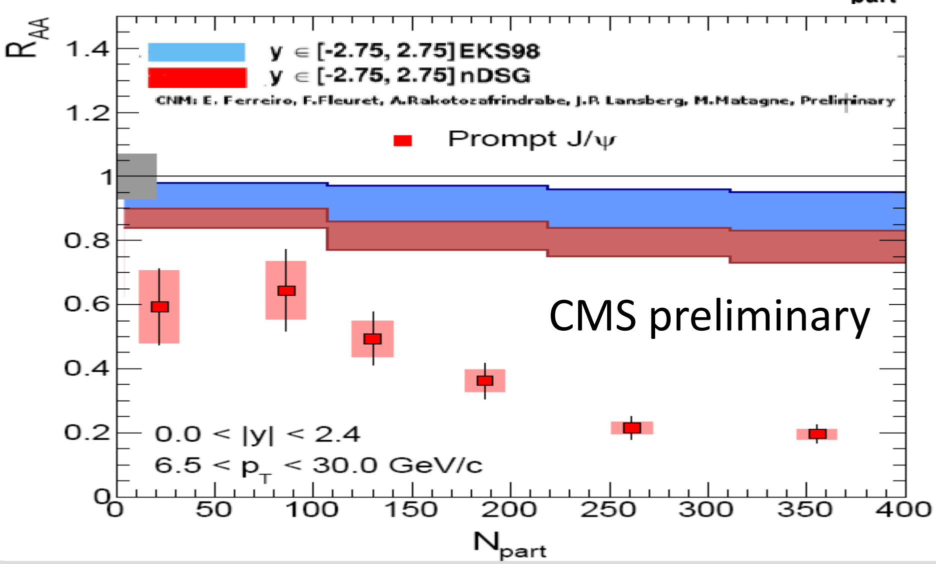
Opposite CNM R_{AA} behaviour vs rapidity @ RHIC and LHC:

- At RHIC=> stronger suppression at forward y
- At LHC => stronger suppression at mid y

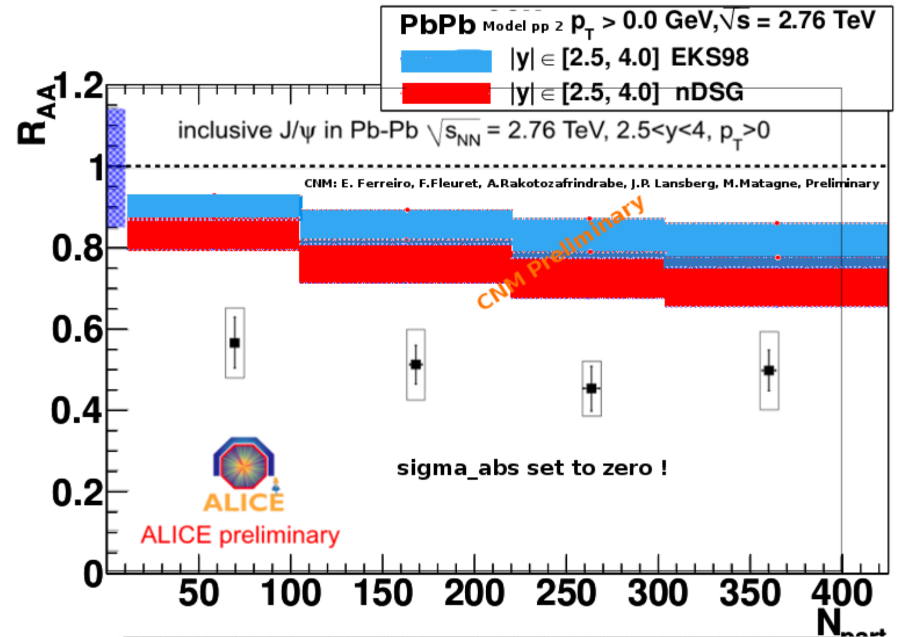
Work in progress: J/ψ @ LHC centrality dependence (2 → 2)

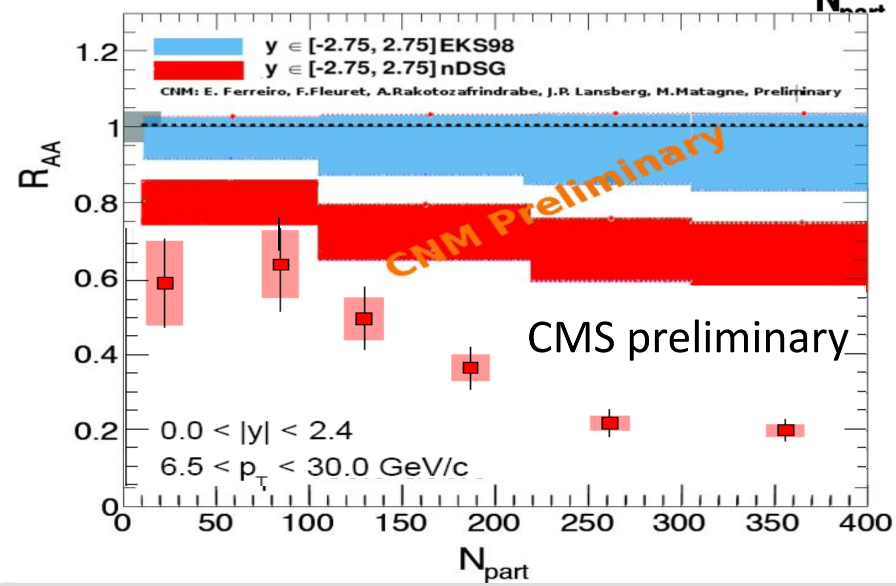
"CEM NLO" before k_T smearing





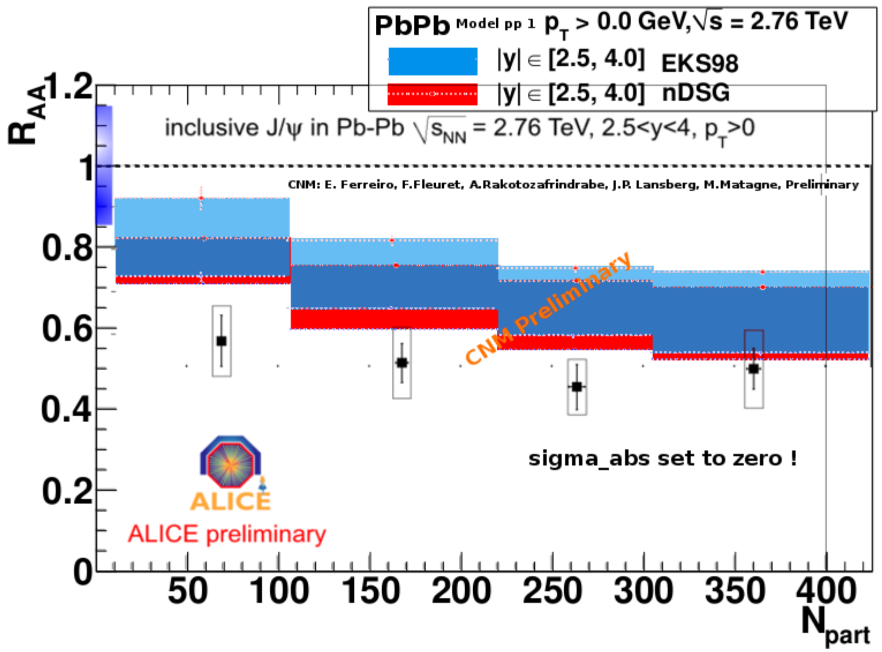
"Traditional" 2 → 2



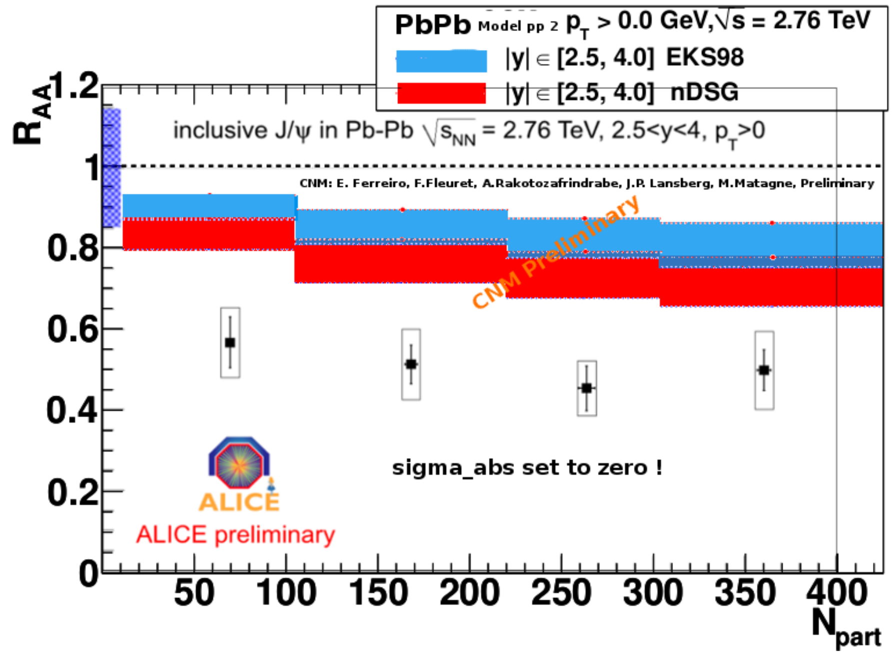


Work in progress: J/ψ @ LHC centrality dependence (2 → 2)

“CEM NLO” before k_T smearing

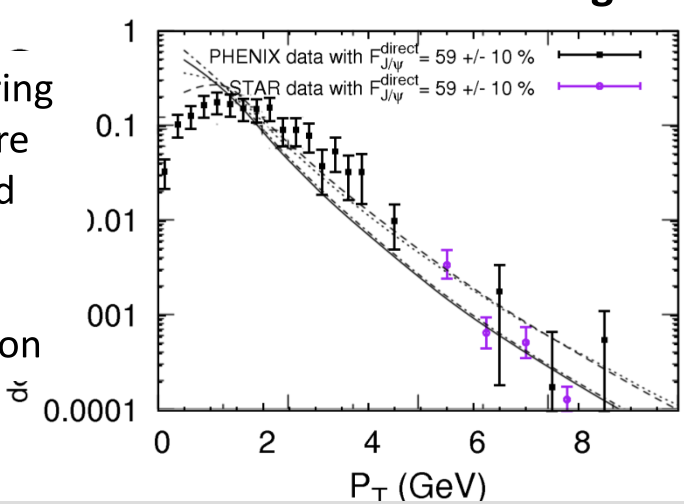


“Traditional” 2 → 2



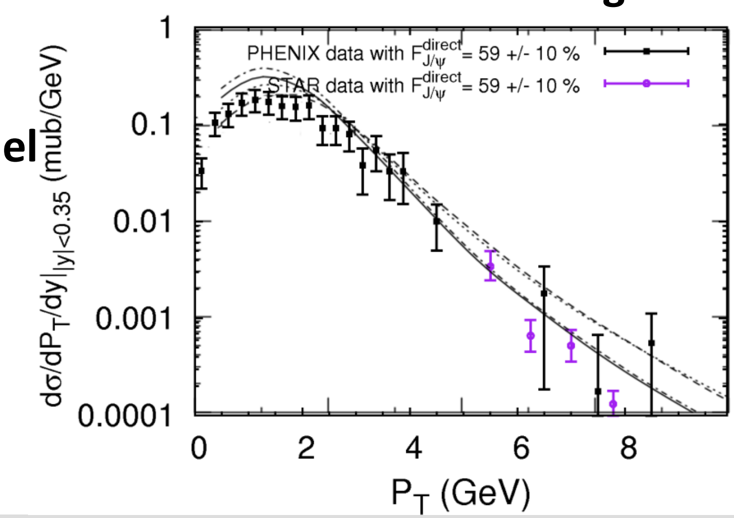
kt smearing procedure is applied after the (x_1,x_2) integration

without kt smearing

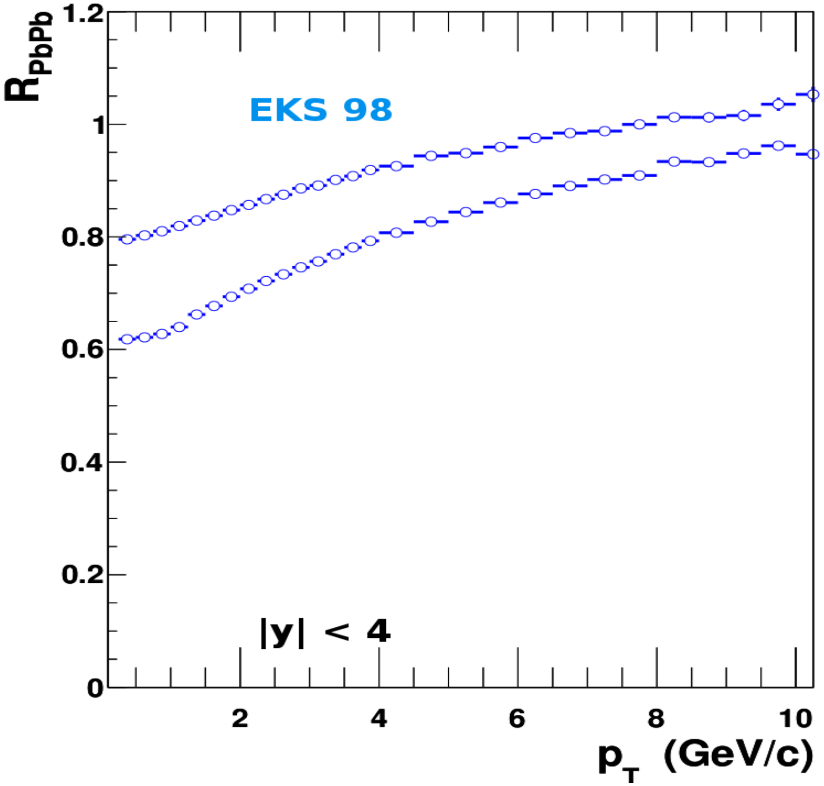


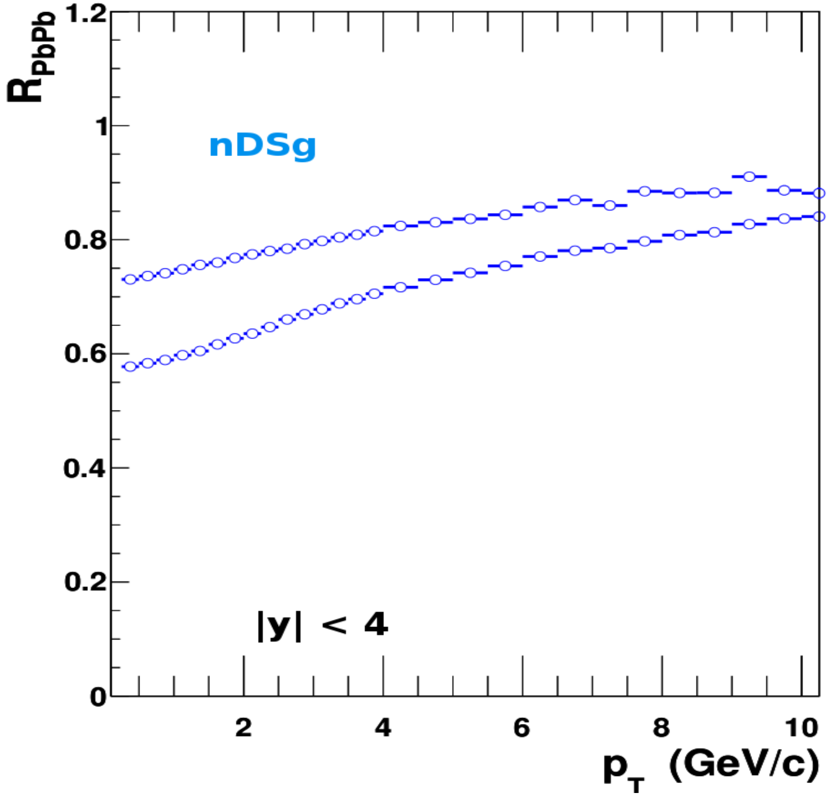
underlying partonic model

with kt smearing



Work in progress: J/ψ @ LHC pT dependence (2 → 2)





Shadowing decreases with increasing pT

Stronger variation for EKS than nDSg

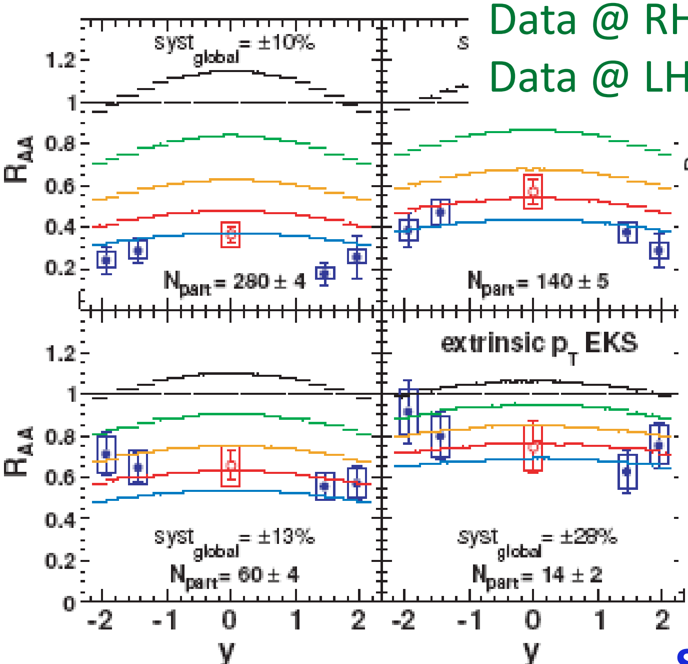
EKS: 25-40%

nDSg: 15-30%

p_T matters!!!

CNM effects: Comparing A+A results @ RHIC and LHC

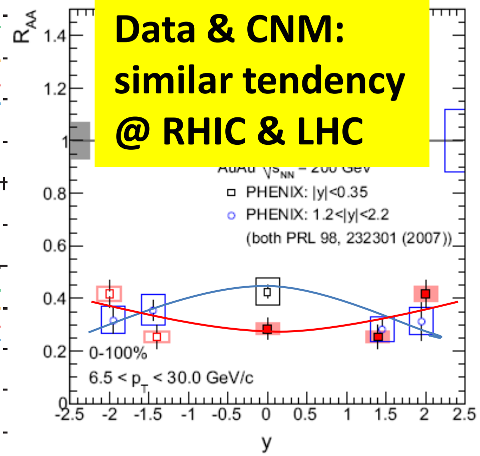
RHIC



Opposite CNM behaviour vs y

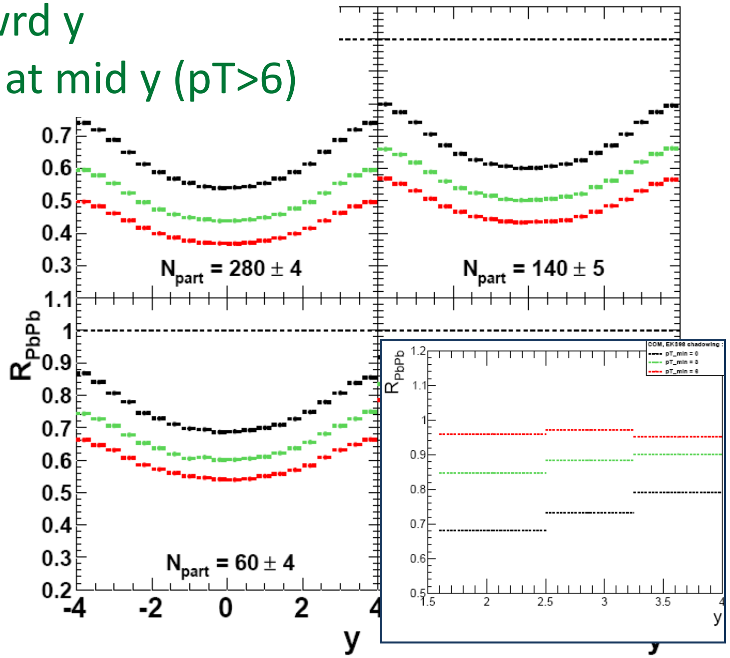
Data @ RHIC: stronger supp. at frwrd y

Data @ LHC: stronger suppression at mid y (pT>6)

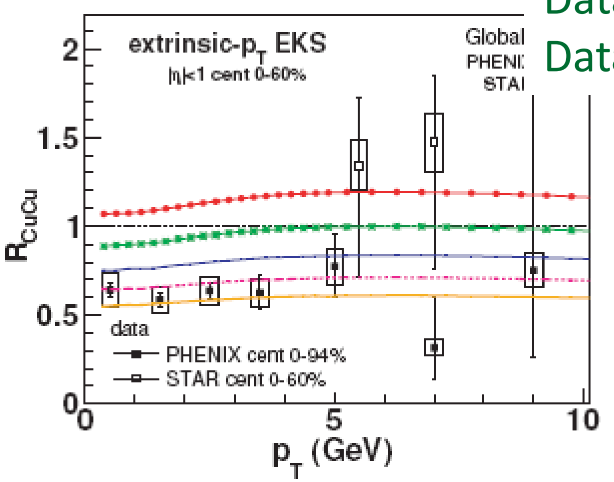


Data & CNM: similar tendency @ RHIC & LHC

LHC



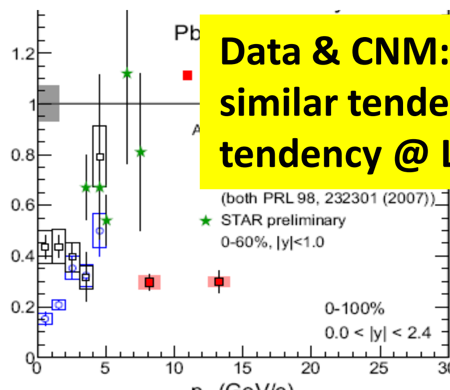
RHIC



Same CNM behaviour vs p_T

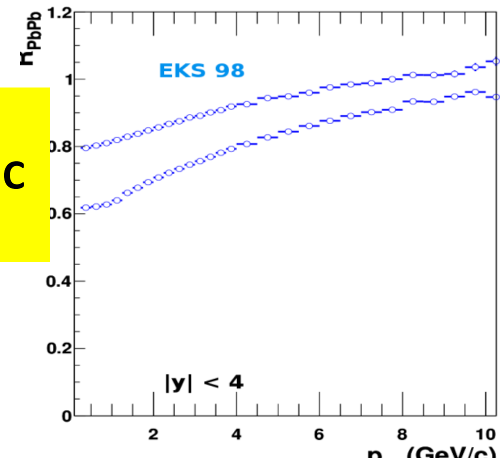
Data @ RHIC: stronger supp. at low p_T

Data @LHC: similar suppression with p_T ?

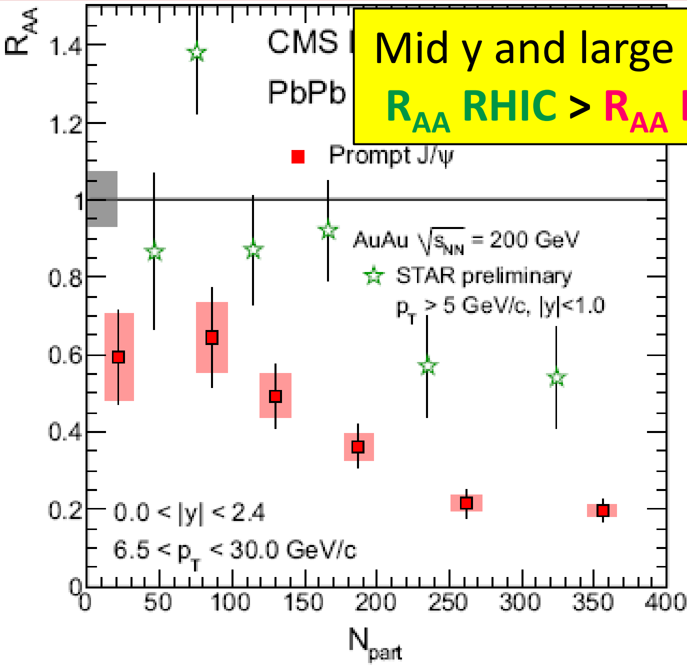


Data & CNM: similar tendency @RHIC tendency @ LHC?

LHC

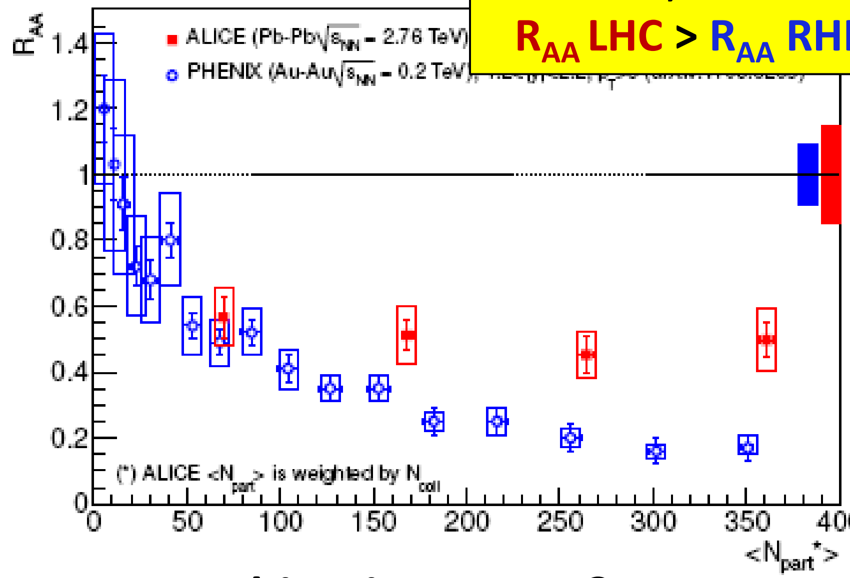


Comparing A+A experimental results @ RHIC and LHC



Mid y and large p_T

R_{AA} RHIC > R_{AA} LHC



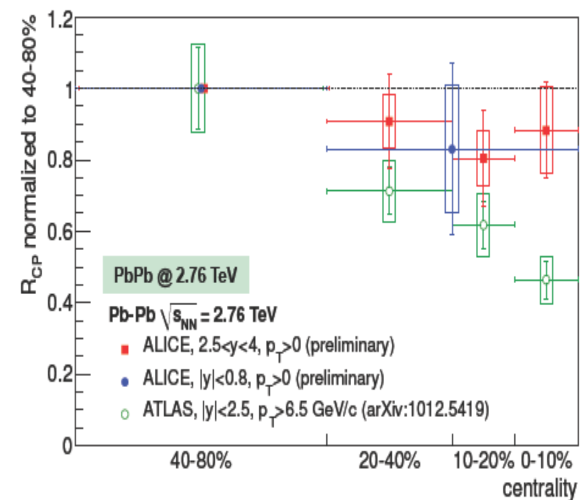
Forward y and low p_T

R_{AA} LHC > R_{AA} RHIC

Recombination at LHC?
(stronger at mid y and p_T=0)

ALICE data at mid y needed!

If recombination, R_{AA} at mid y > R_{AA} at forward y (p_T>0)



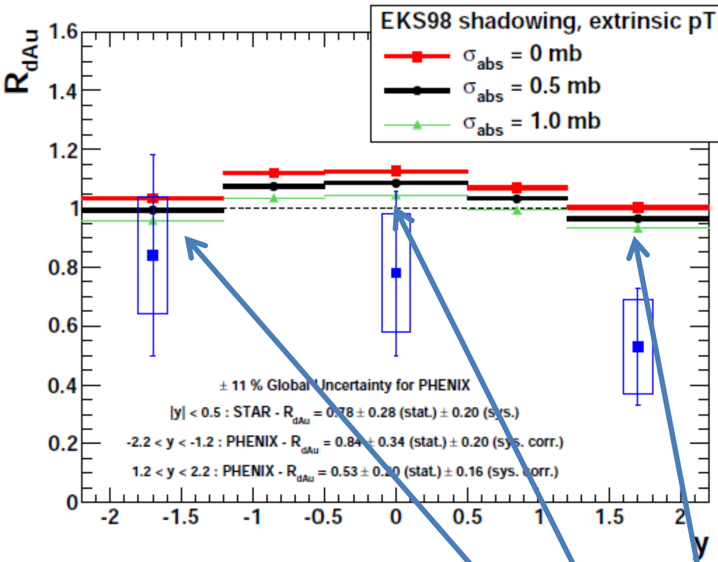
Place for recombination effects @ LHC

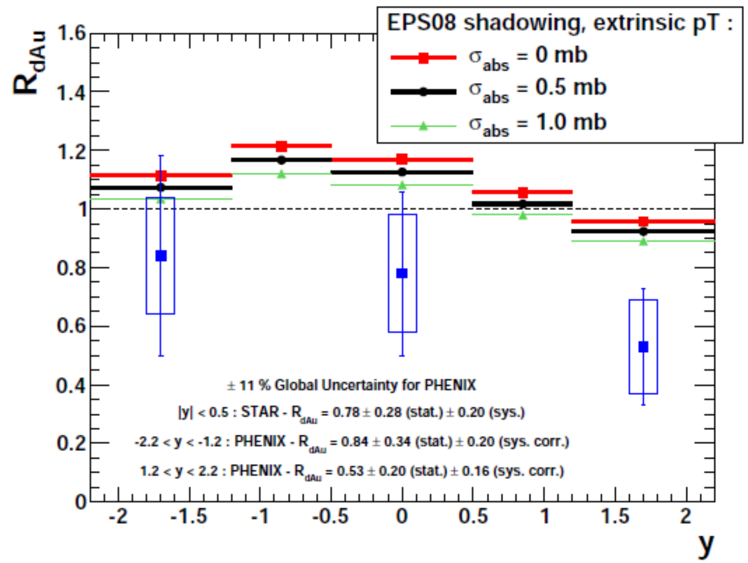
Other CNM effects: Υ rapidity dependence in dAu @ RHIC

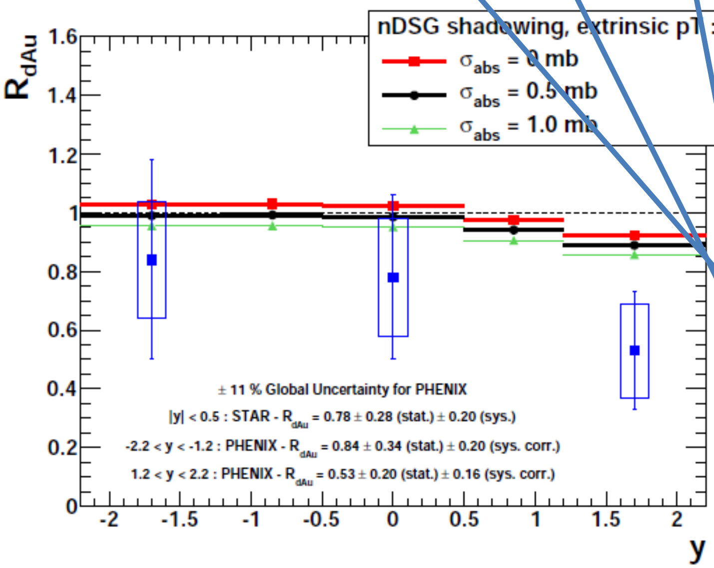
- **Gluon** EMC effect
- **Fractional** energy loss

Other CNM effects: Υ rapidity dependence in dAu @ RHIC

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





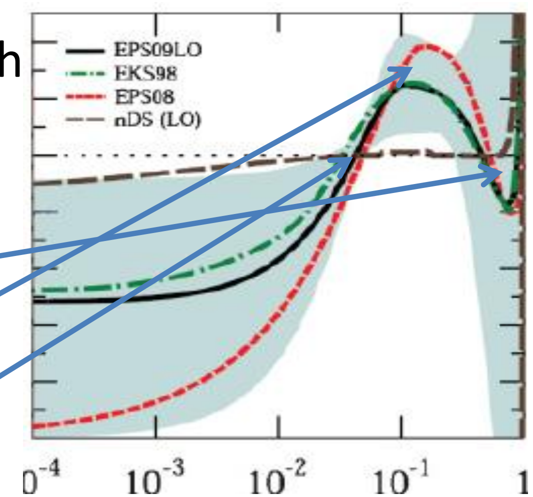


- backward: ok within uncertainties
- central: reasonable job
- forward : clearly too high

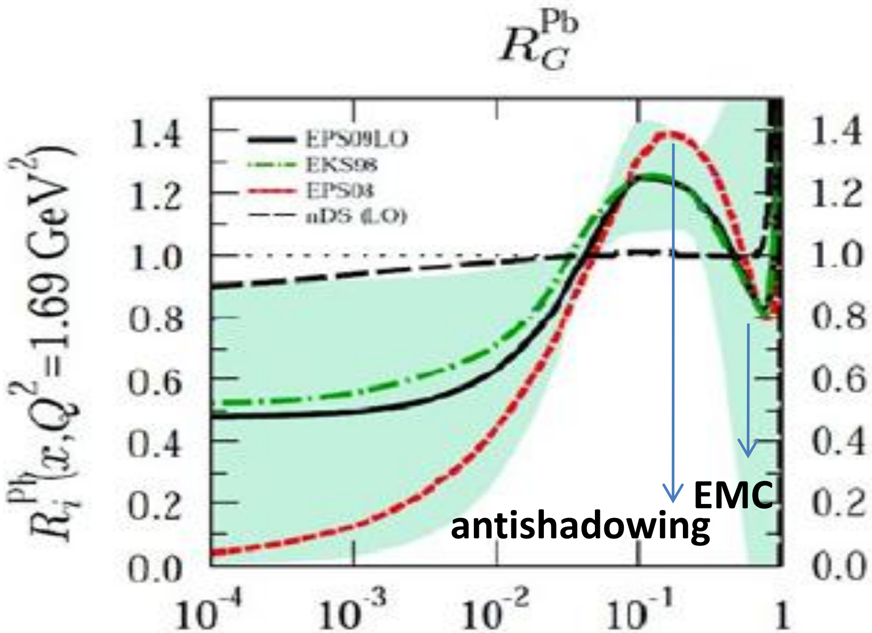
Physical interpretation

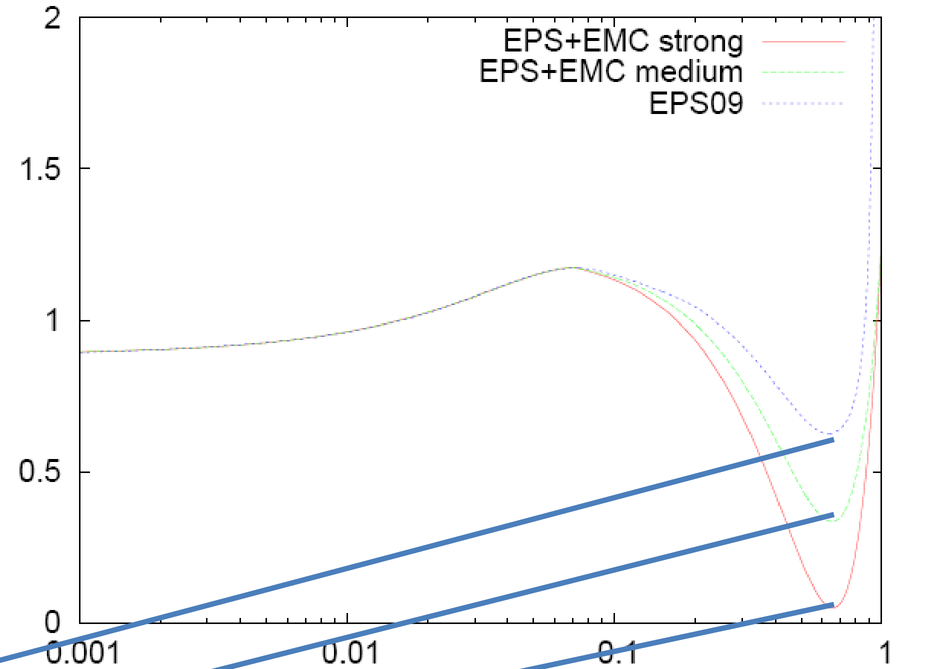
- backward: EMC effect
- central: antishadowing
- forward : shadowing≈1

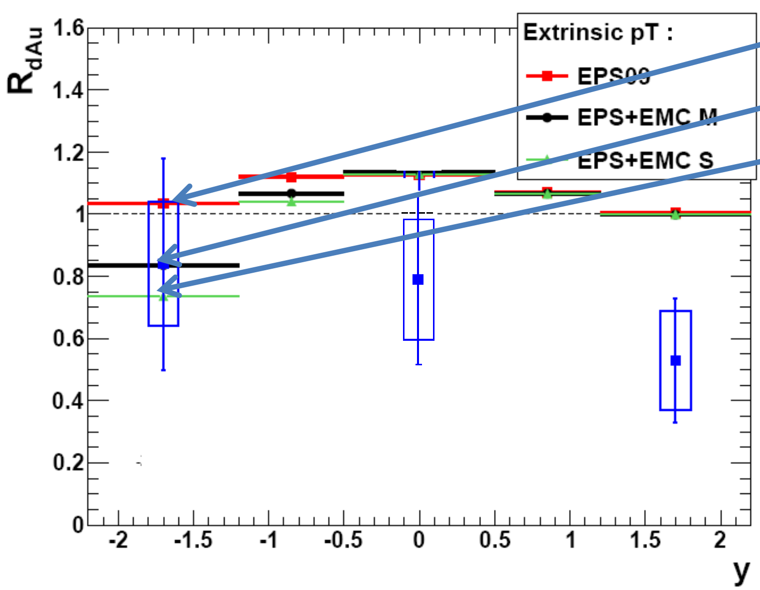
  energy loss is needed



Work in progress: EMC effect



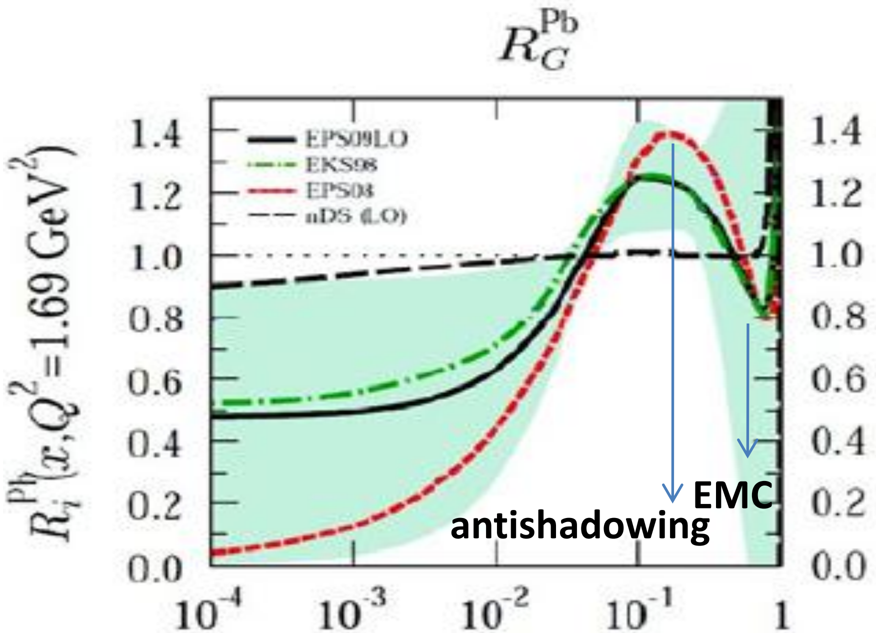


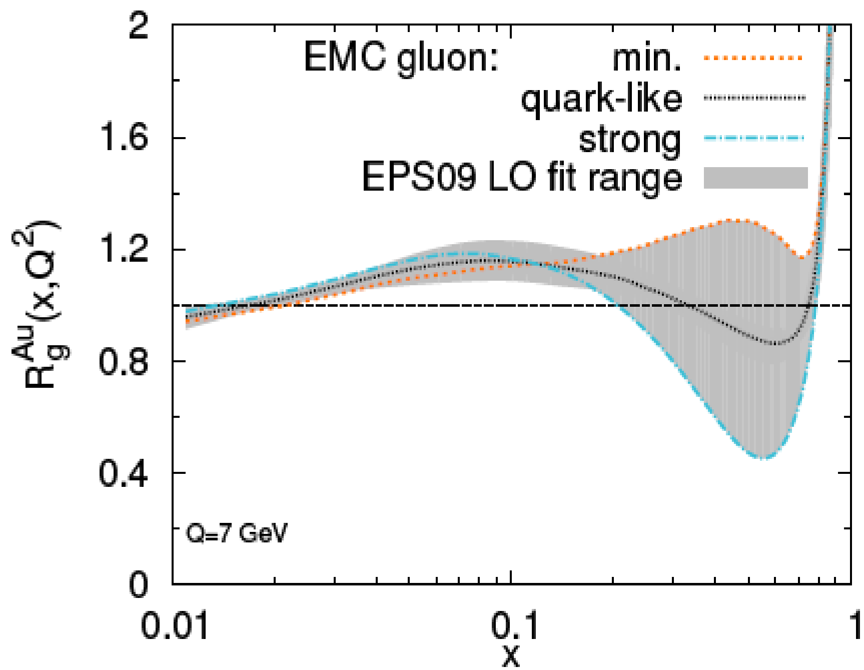


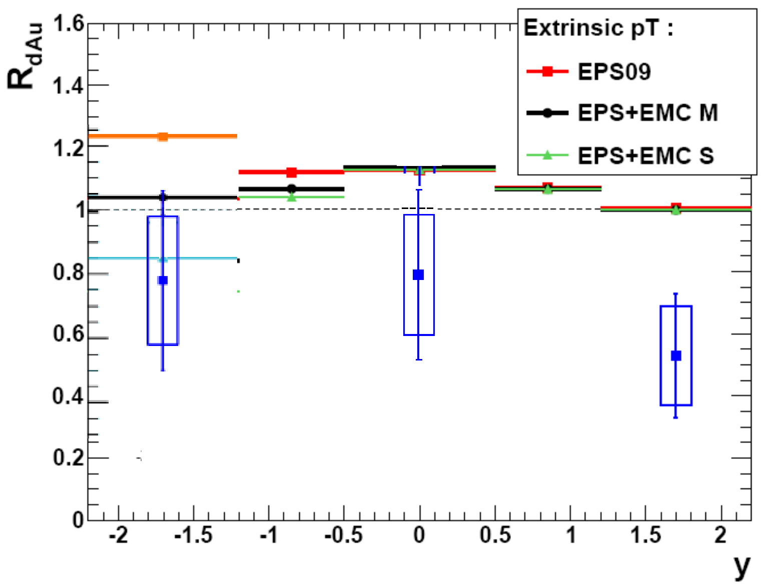
Let us try to increase the suppression of *g(x)* in the EMC region, keeping momentum conservation : $\int xg(x)\,dx$ = Cte

Works better for backward region

Work in progress: EMC effect







Let us try to increase the suppression of *g(x)* in the EMC region,
by using the maximum and minimum of EPS09

Works better for backward region

Work in progress: Energy loss effect

- **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

Work in progress: Energy loss effect

• 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:1006.0818) 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**

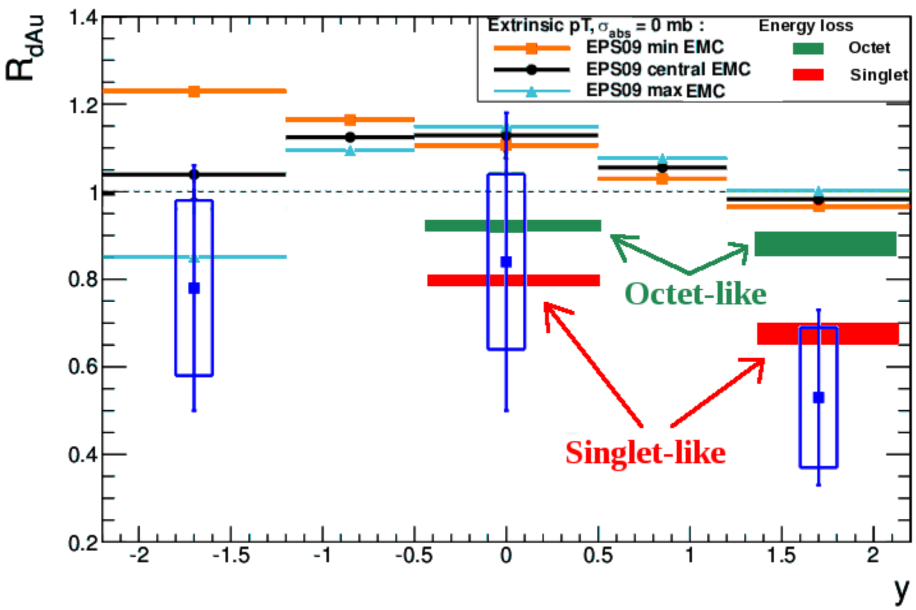
Thus, the Gavin-Milana assumption of an "energy loss" scaling as E turns out to be qualitatively valid for quarkonium production provided this "energy loss" is correctly interpreted as the radiated energy associated to the hard process (quarkonium production process), and **not** as the energy loss of independent incoming and outgoing color charges (of an independent parton suddenly produced)

• Note that space effect through Sudakov suppression can also induce a fractional energy loss but for x_1 > 0.5 (Kopeliovich))

Work in progress: Energy loss effect

$$\Delta E|_{\text{ind, large } x_F} \sim N_c \alpha_s \, \hat{\omega} \sim N_c \alpha_s \frac{\sqrt{\Delta q_\perp^2}}{M_\perp} \cdot E$$

$$\Delta x_1 = \frac{\Delta E}{E} \sim N_c \alpha_s \frac{\sqrt{\Delta q_\perp^2}}{M_\perp}$$



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

Note that, independently of the gluon PDF parameterization, this energy loss will induce a minimum suppression of 90% up to a maximum one of 60% in the forward region

Conclusions

- We have studied the influence of specific partonic kinematics

  within 2 schemes: intrinsic (2→ 1) and extrinsic (2→2) p_T
  for different shadowings: EKS98, EPS08, nDSg
  including nuclear absorption and different partonic models

- for J/ψ

  A+A collisions @ RHIC: R_{AA} forward y < R_{AA} mid y as CNM in 2→2
  A+A collisions @ LHC: R_{AA} forward y > R_{AA} mid y as CNM in 2→2

but… R_{AA} forward y @ LHC > R_{AA} forward y @ RHIC

Place for recombination effects,
to be checked with ALICE data (p_T>0) at mid y

- for ϒ in d+Au collisions @ RHIC:

  EMC effect in the backward region
  fractional energy loss in the central & forward region

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