QUARKONIUM 2016

Trento, March 1st 2016

J/ψ production in p-A collisions from SPS to LHC

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Outlook:

pA J/ψ results as:

- tool to understand cold nuclear matter effects
- reference for AA

from SPS to LHC experiments

Experimental landscape

Facility	Experiment	System	$\sqrt{s_{NN}}$ (GeV)	y_{cms} range	Data taking
SPS	NA50	p-Be,Al,Cu,Ag,W,Pb	27	-0.4<y<0.6	1996-2000
			29	-0.5<y<0.5	
	NA60	p-Be,Al,Cu,In,W,Pb,U	17	0.3<y<0.8	2004
			27	-0.1<y<0.3	
FNAL	E866	p-Be, Fe, W	39	-0.6<y<2.5*	~1996
HERA	HERA-B	p-C, Ti, W	42	-1.5<y<0.8*	2002
RHIC	PHENIX, STAR	d-Au	200	-2.2<y<2.4	>2003
		p-Al, Au		$1.2<\lvert y\rvert<2.2$	2015
LHC	ALICE	p-Pb	5020	-4.46<y<3.53	2013
	ATLAS			-2.87<y<1.94	
	CMS			-2.87<y<1.93	
	LHCb			-5.0<y<-2.5 1.5<y<4.0	

* computed at $p_T = 0$

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Fixed target experiments

- several A targets

Experimental landscape

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FNAL	E866	p-Be, Fe, W	39	$-0.23<y<2.5$	~1996
HERA	HERA-B	p-C, Ti, W	4		
RHIC	PHENIX, STAR	d-Au	20		
		p-Al, Au			
LHC	ALICE	p-Pb	5020		2013
	ATLAS				
	CMS			$-2.87<y<1.93$	
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Collider experiments
- usually p vs a single beam specie
- forward and backward y range might be covered

Experimental landscape

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Large number of target nuclei

Experimental landscape

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Two energies in the same experiment

Experimental landscape

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Largest x_F coverage

$-0.10<x_F<0.93$

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Coverage up to negative x_F

$-0.34 < x_F < 0.14$

Experimental landscape

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- very high energies
- complementary kinematic ranges

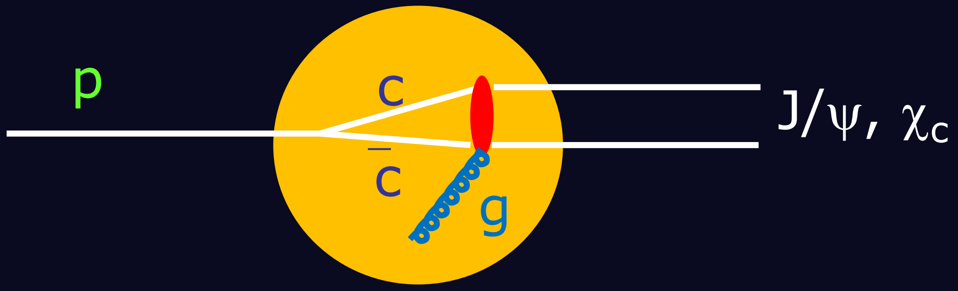
Quarkonium production in pA

The study of the interaction of the cc pair with the nuclei provides:

Constraints to production models

→ the strength of this interaction may depend on the $c\bar{c}$ quantum states and kinematics

(R.Vogt, Nucl.Phys. A700,539 (2002), B.Z. Kopeliovich et al, Phys. Rev.D44, 3466 (1991))



Tool to investigate cold nuclear matter effects

→ complicated issue, interplay of many competing mechanisms as shadowing, energy loss, break-up in the medium…

Reference to disentangle genuine QGP effect in AA collisions

→ Approach followed at SPS, RHIC and LHC

How is J/ψ studied in pA?

- Varying the amount of nuclear matter crossed by cc pair (studying J/ψ production as a function of A or centrality)
- Selecting the kinematics of the quarkonium states e.g. selecting events where resonance is formed inside or outside the nucleus
- Comparing the behavior of different resonances

"Effective" quantities are defined to evaluate the size of CNM effects

① $$\sigma^{pA}_{J/\psi} = \sigma^{pp}_{J/\psi} \cdot A \cdot e^{-\langle \rho L \rangle \sigma_{abs}}$$

← the larger σ_{abs}, the more important the nuclear effects

② $$\sigma^{pA}_{J/\psi} = \sigma^{pp}_{J/\psi} \cdot A^{\alpha}$$

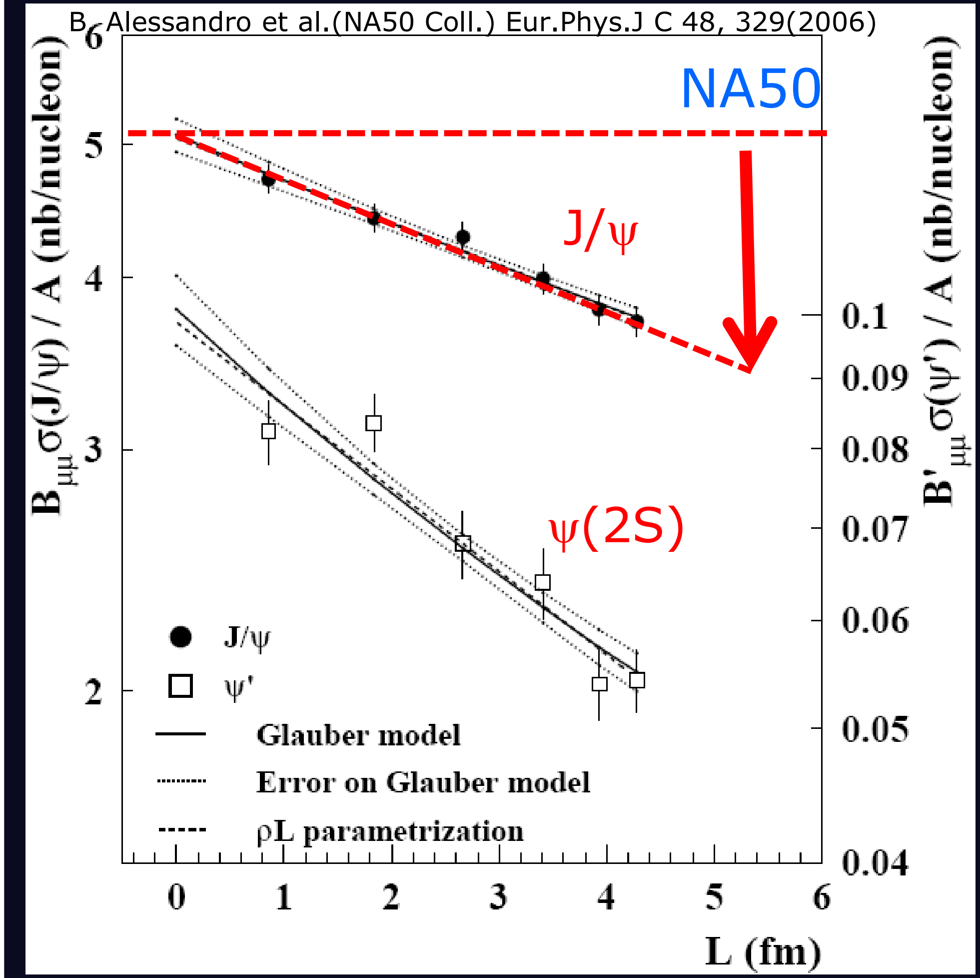
← $\alpha = 1$ → no nuclear effects
$\alpha \neq 1$ → nuclear effects

③ $$R^{pA}_{J/\psi} = \frac{\sigma^{pA}_{J/\psi}}{A \cdot \sigma^{pp}_{J/\psi}}$$

← $R_{pA} = 1$ → no nuclear effects
$R_{pA} \neq$ → nuclear effects

J/ψ in pA at SPS

A significant reduction of the yield per NN collision is observed



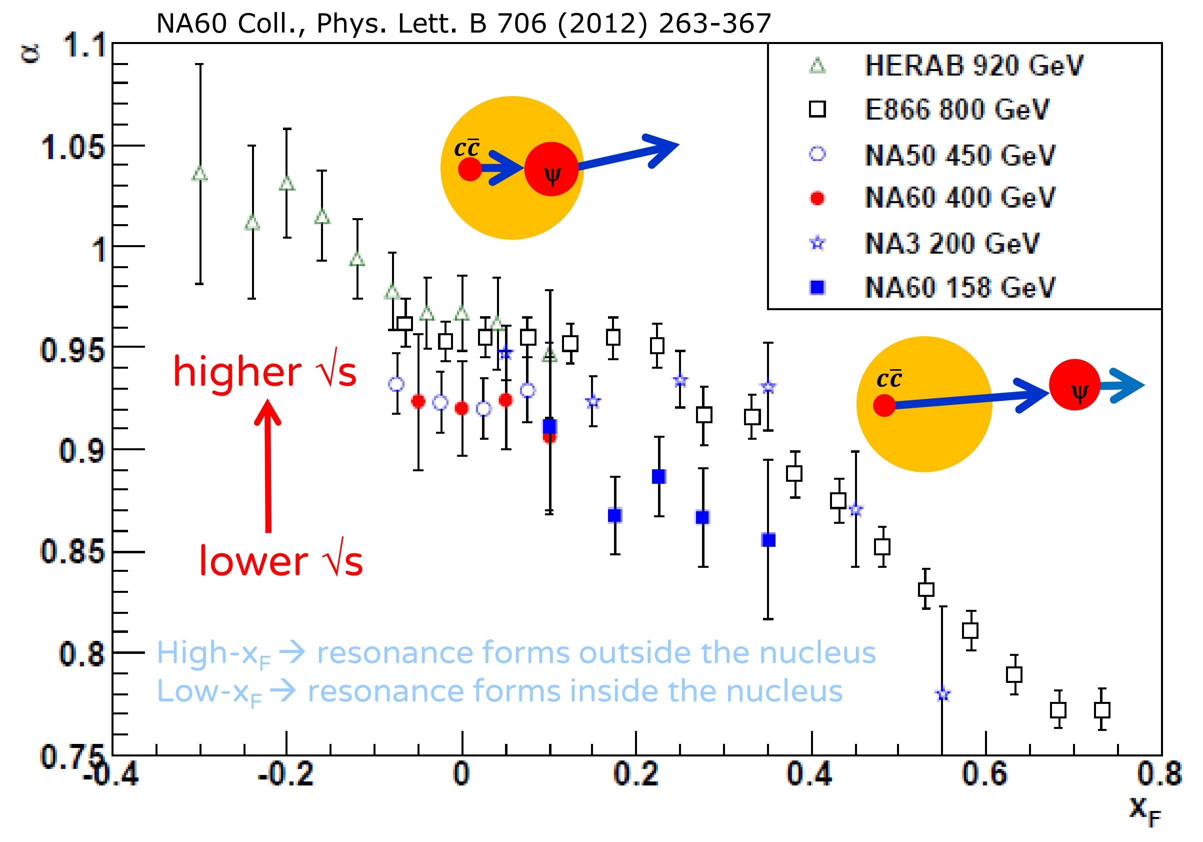
- Early studies interpreted this reduction as due to “nuclear absorption”
- Stronger absorption for the less bound state ψ(2S) at mid-*y*

→ Nucleus crossing time (τ~0.3 fm/c) comparable or larger than charmonium formation time:
→ fully formed resonances traversing the nucleus

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

J/ψ production vs x_F

- Compilation of fixed target results, collected at different √s and kinematical regions



NA60 Coll., Phys. Lett. B 706 (2012) 263-367

higher √s

lower √s

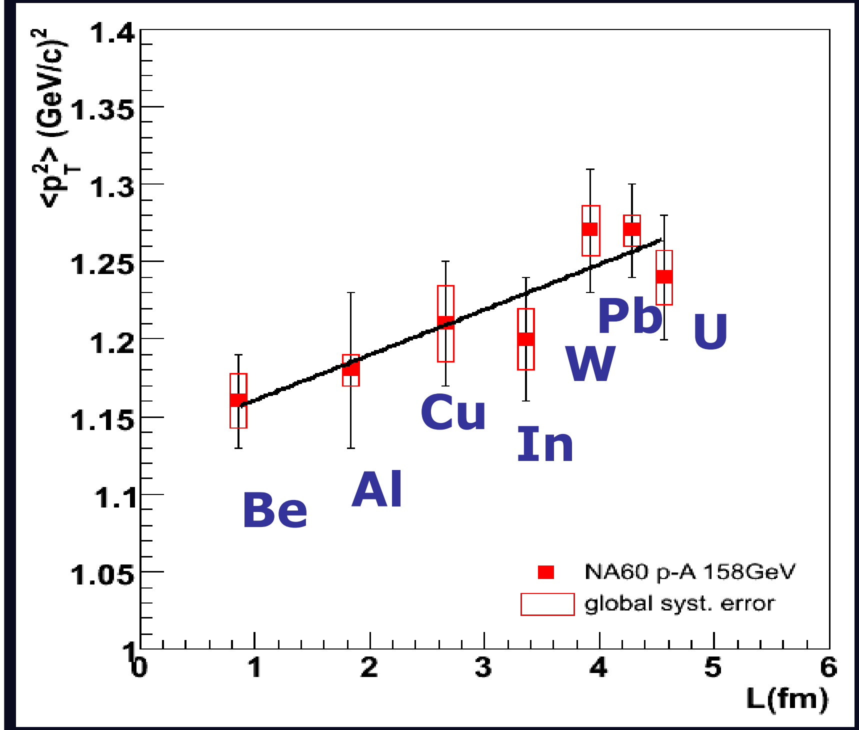
High-x_F → resonance forms outside the nucleus
Low-x_F → resonance forms inside the nucleus

- J/ψ yield in pA is modified with respect to pp collisions
- α strongly decreases with x_F
- for a fixed x_F, CNM are stronger at lower √s

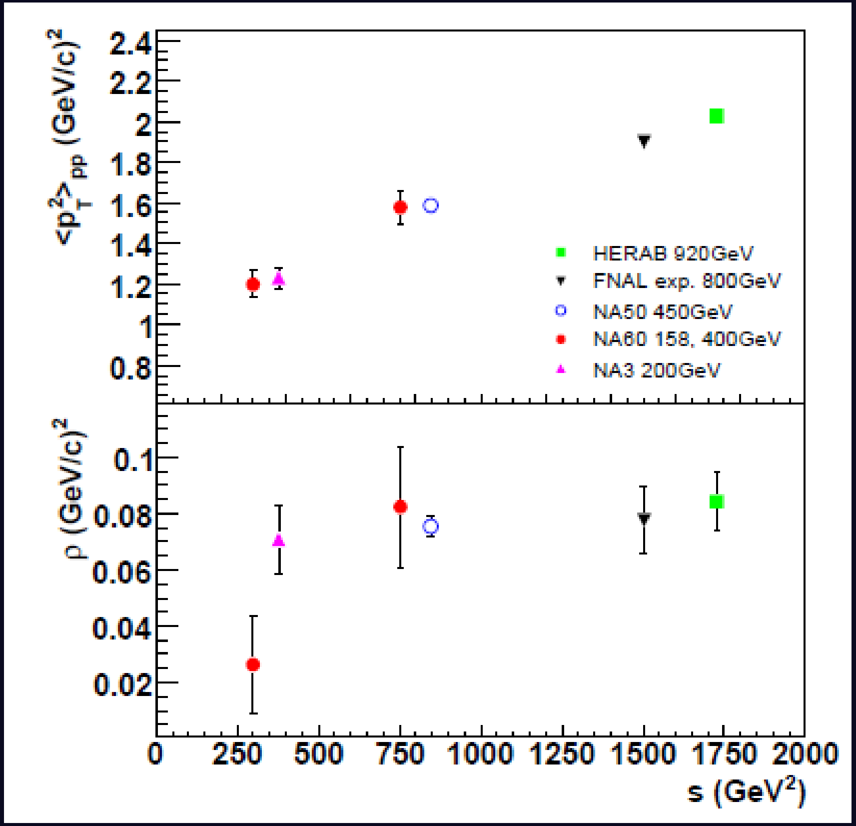
Theoretical description over the full x_F range very complicate!

- Given the strong x_F and √s dependence, pA data used as reference for AA collisions should be collected in the same kinematical domain

J/ψ production vs p_T



- $<p_T^2>$ increasing with the A of the target nuclei
  → interpreted as Cronin effect



- p_T broadening can be parametrized as

$$<p_T^2>= <p_T^2>_{pp}+ \rho\,(A^{1/3}-1)$$

- slope ρ is almost energy independent (apart from very low √s)
- $<p_T^2>_{pp}$ increases with √s

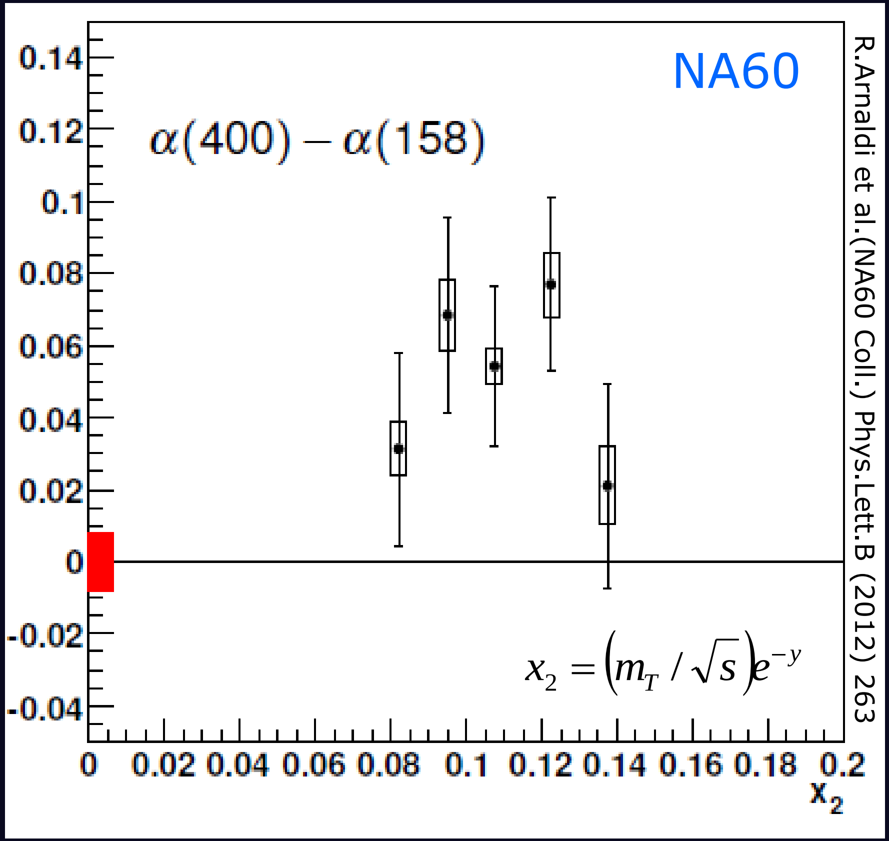
Disentangling CNM effects

- Assume dominant effects are shadowing and cc breakup at mid-y

- Shadowing in the target nucleus depends only on x_2 (2→1approach)

- J/ψ break-up depends on $\sqrt{s}_{J/\psi\text{-N}}$ which is a function of x_2

$$\sqrt{s_{J/\psi N}} \sim m_{J/\psi}\sqrt{\frac{1+x_2}{x_2}}$$



R.Arnaldi et al.(NA60 Coll.) Phys.Lett.B (2012) 263

If parton shadowing and final state absorption were the only relevant mechanisms

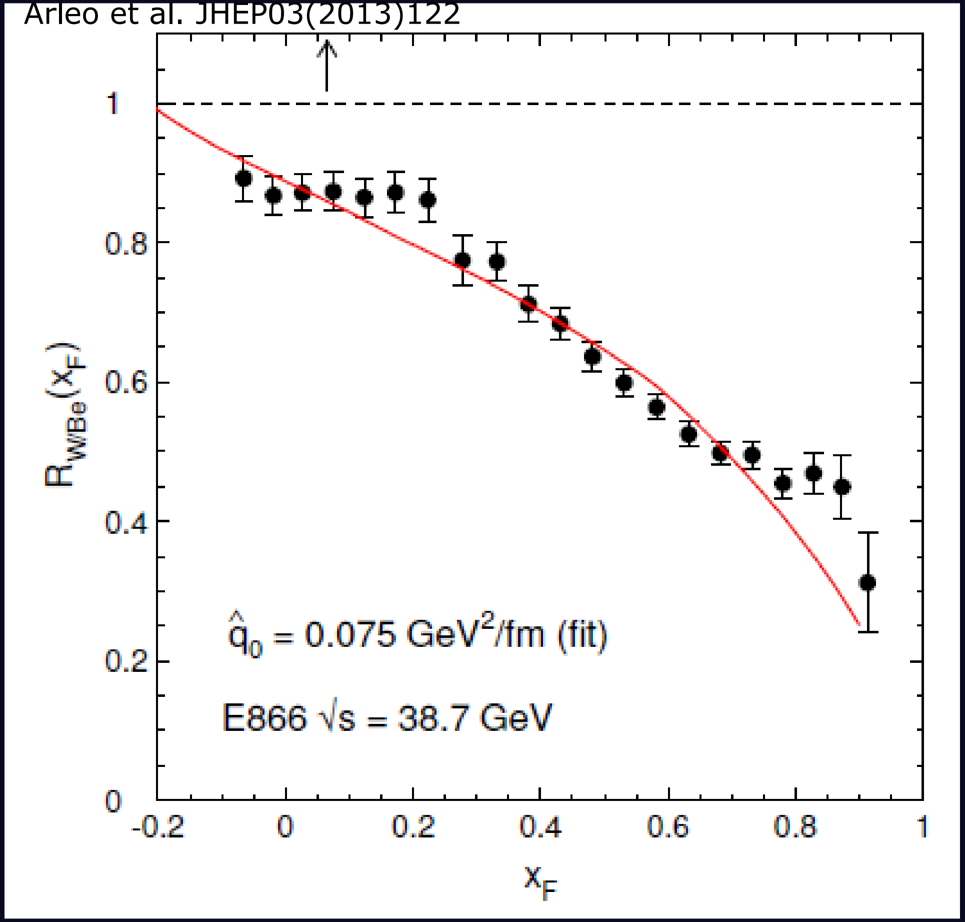
- α should not depend on √s at constant x_2 … and this is clearly not the case

- Other effects different from shadowing and cc breakup?
- Role of energy loss?

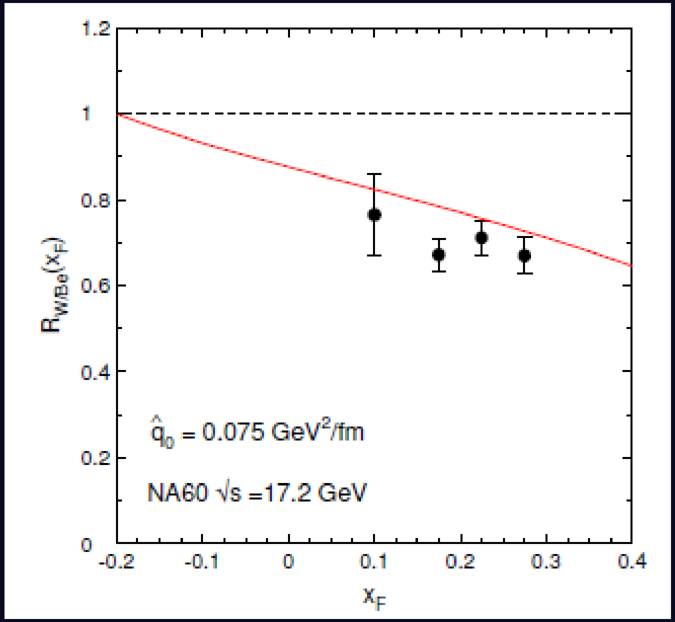
Disentangling CNM effects

- The increase of the J/ψ suppression towards high x_F might be interpreted as due to energy loss

Arleo et al. JHEP03(2013)122

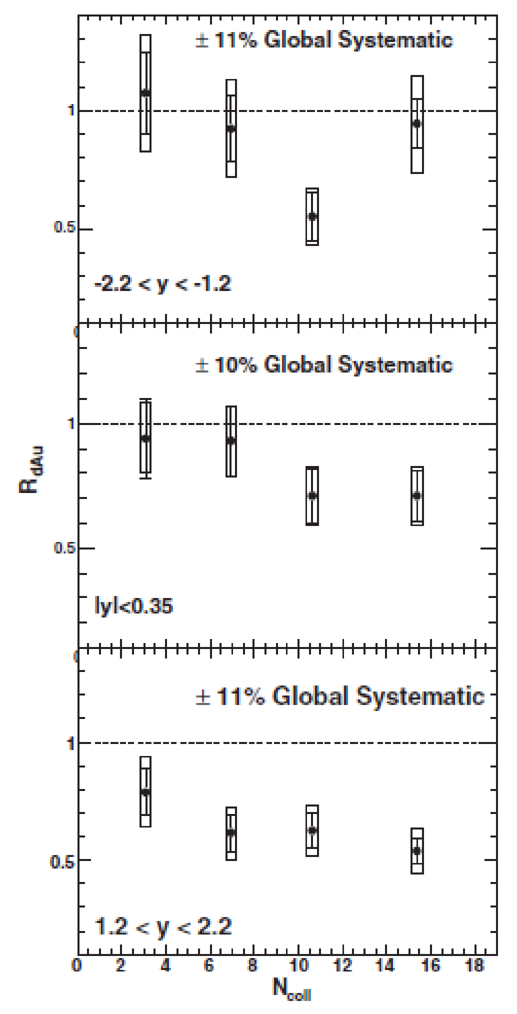


- Coherent energy loss (Arleo et al.) describes the observed trend over a large x_F range

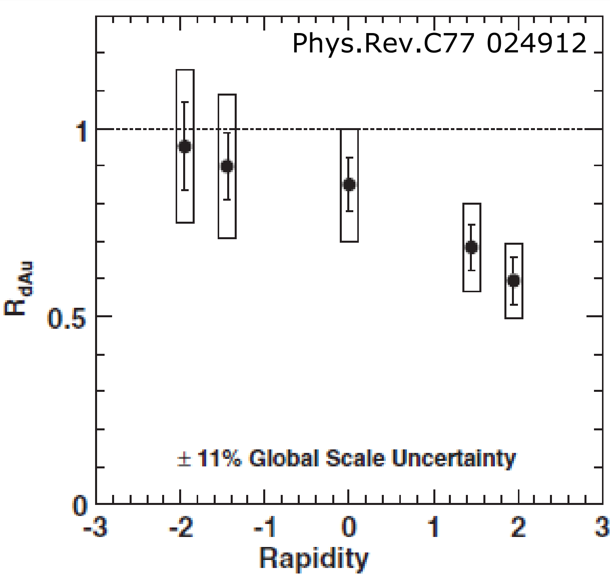


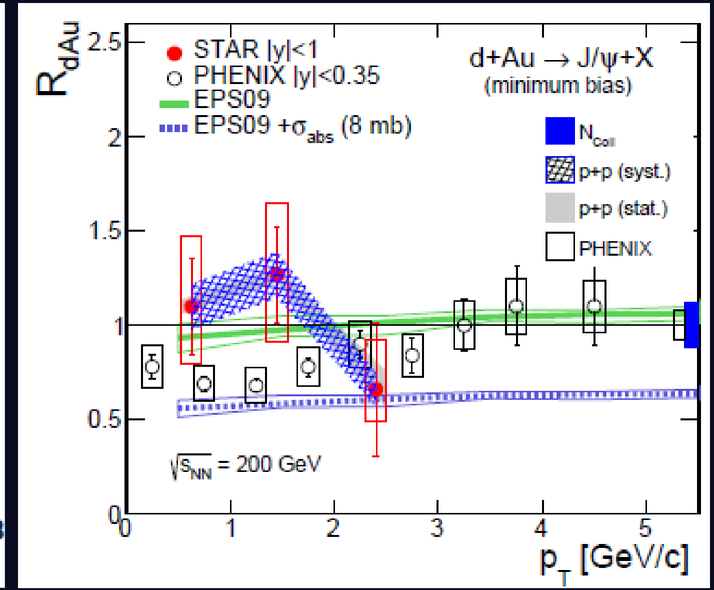
Moving to higher energies: RHIC

- Different approach wrt to fixed target experiments
  → Proton/deuteron on a single nucleus species and events selected on impact parameter



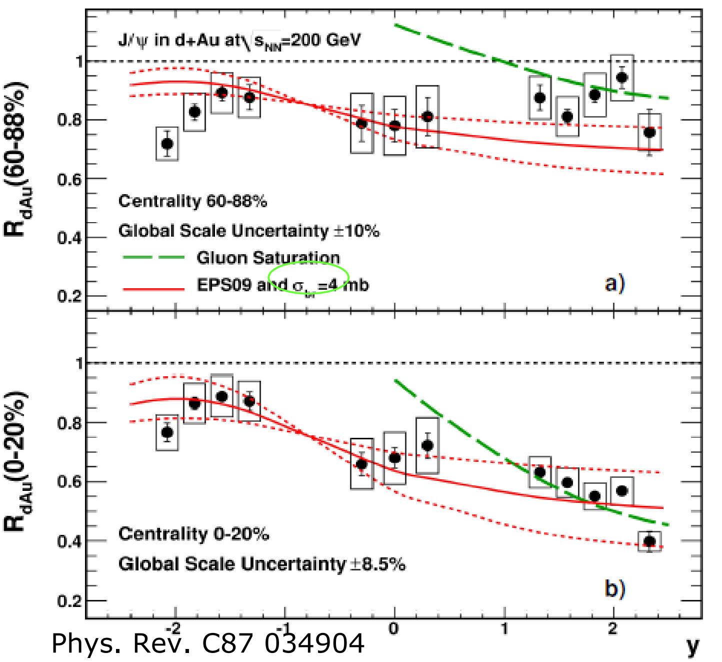
- R_{dAu} studied versus centrality, y and p_T





- J/ψ yields are suppressed in d-Au

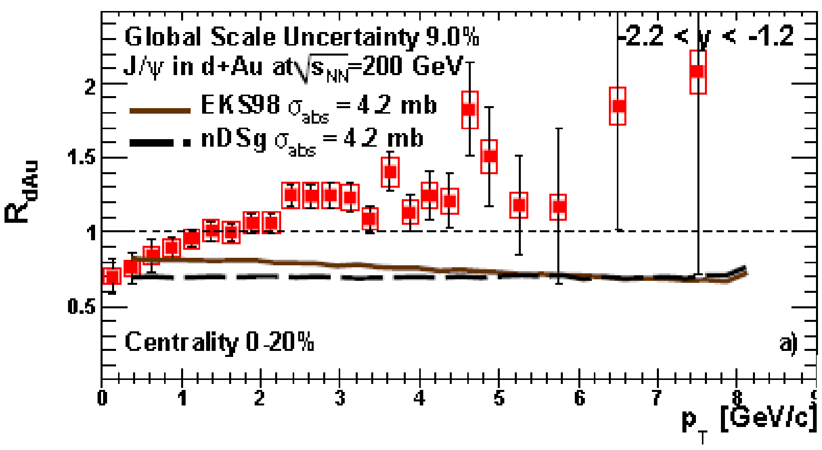
CNM effects at RHIC

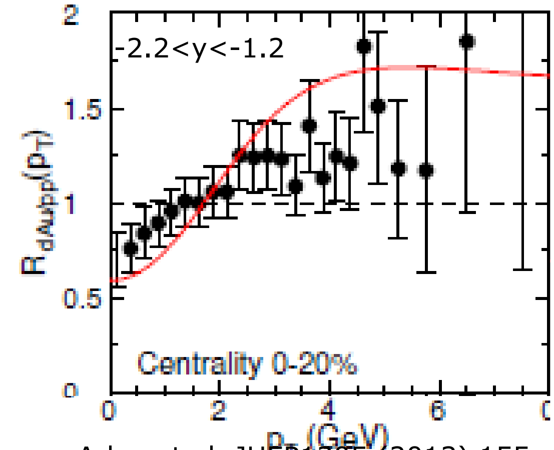


Phys. Rev. C87 034904

Disentangling CNM mechanisms is challenging

- shadowing + cc break-up describe R_{dAu} vs y, but meets some difficulties for R_{dAu} vs p_T
- coherent energy loss contribution induces a less flat R_{dAu} dependence on p_T





Arleo et al. JHEP1305 (2013) 155

Which CNM effects at LHC?

- Large Lorentz-γ factor →short crossing time of the cc in the nuclear matter

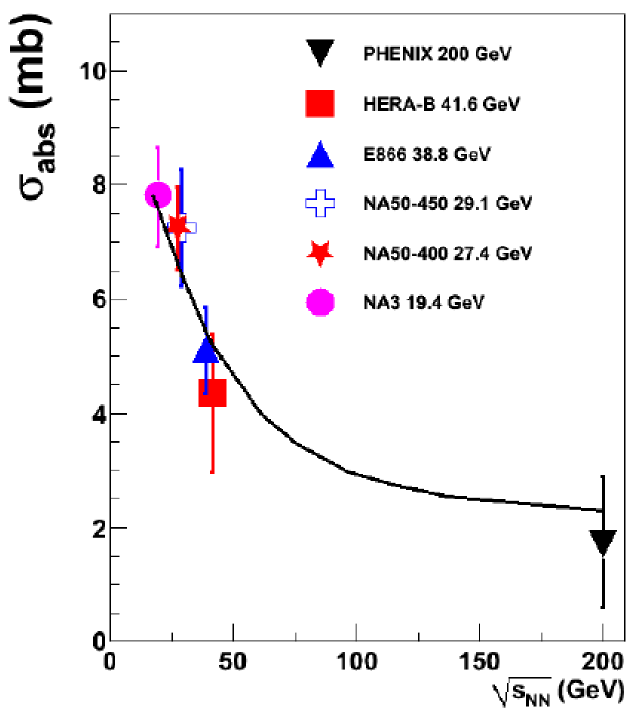
→ $c\bar{c}$ pair almost point-like after crossing the nuclear matter

→ final state effects (as cc break-up) might be negligible

$$\tau_c = \frac{\langle L \rangle}{(\beta_z \gamma)}$$

forward-y: $\tau_c \sim 10^{-4}$ fm/c
backward-y: $\tau_c \sim 7 \cdot 10^{-2}$ fm/c

D. McGlinchey, A. Frawley and R.Vogt, PRC 87,054910 (2013)



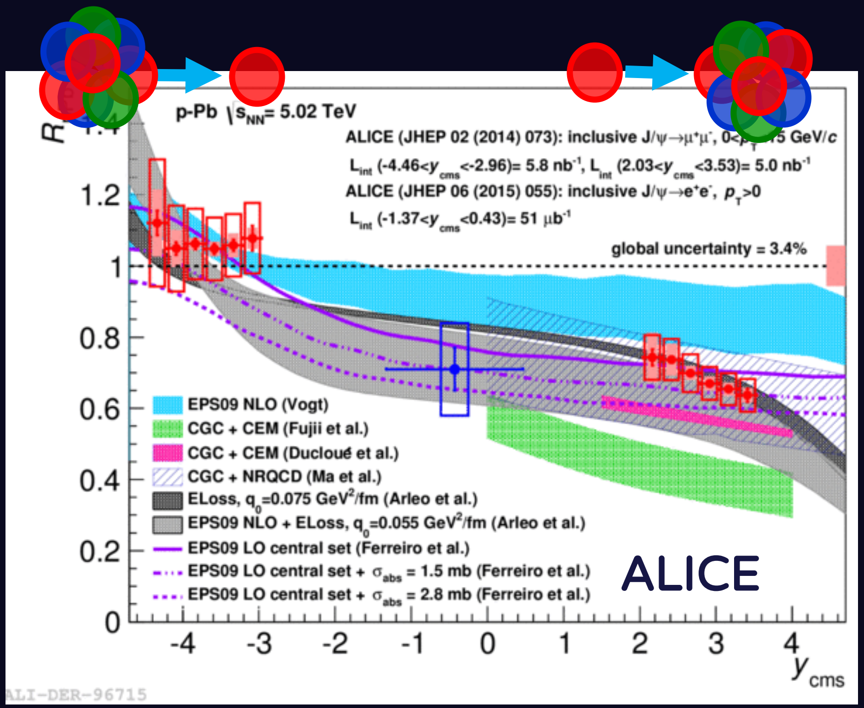
- shadowing and/or energy loss might be the dominant effects

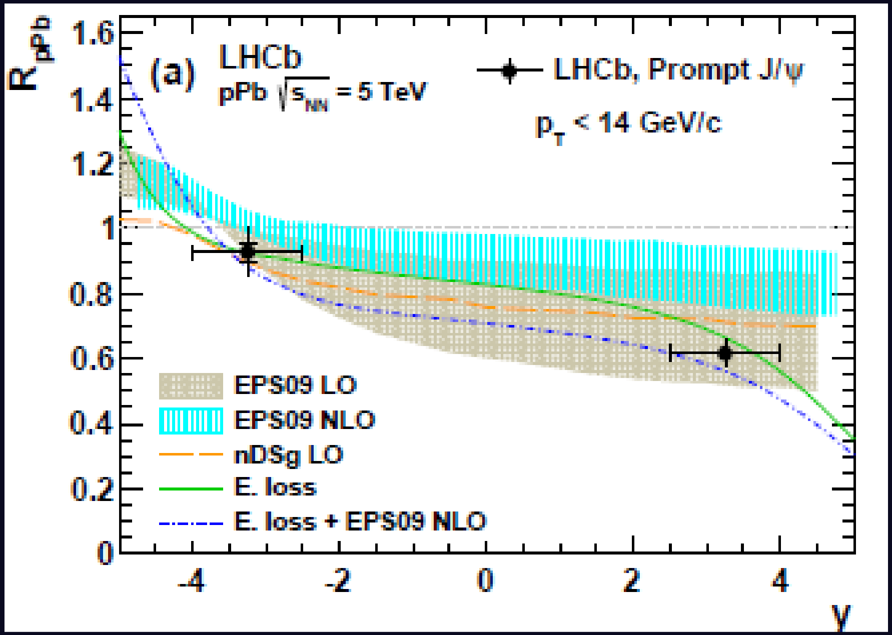
- parton saturation effects can also be investigated at low-x

LHC: J/ψ R_{pA} vs y

Pb-going p-going

➡ Broad rapidity coverage





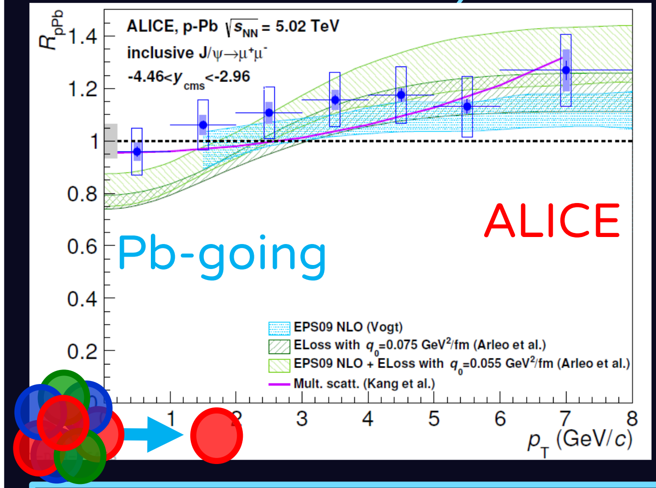
J/ψ production modified by CNM effects → R_{pA} decreases at forward *y*

➡ Theoretical predictions:

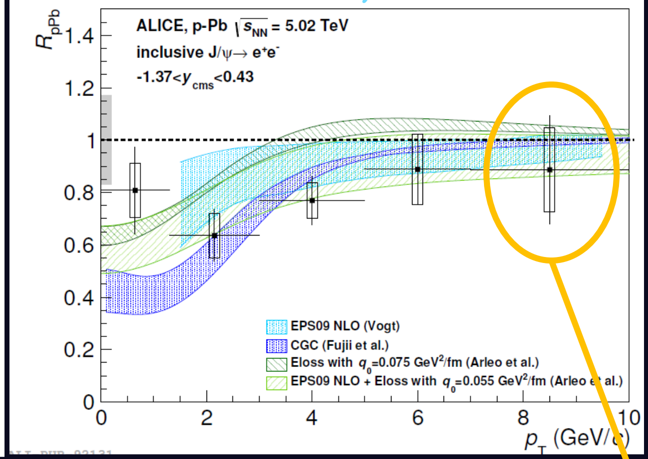
- shadowing calculations and models including coherent parton energy loss reasonably describe the data
- agreement with CGC depends on the implementation

LHC: J/ψ R_{pA} vs p_T

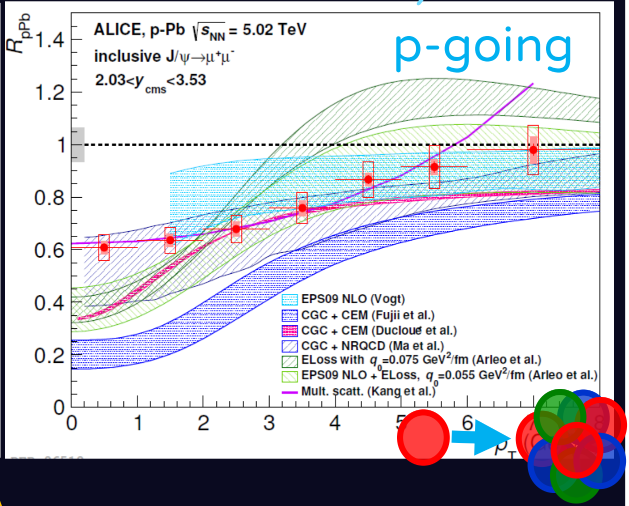
backward-*y*



mid-*y*



forward-*y*

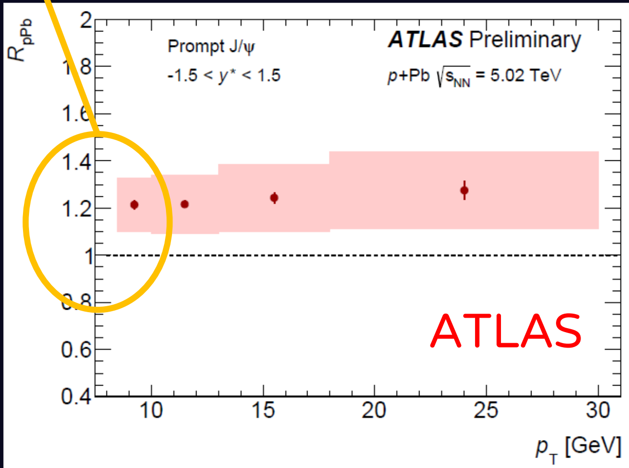


J/ψ production strongly depends of on y and p_T

- backward-*y*: R_{pA} ~1, negligible p_T dependence
- forward-*y*: R_{pA} increases with p_T
- mid-*y*: small p_T dependence, R_{pA} ~1 for p_T>3GeV/c (ALICE) and slightly larger for p_T>8GeV/c (ATLAS)

~0.7σ difference

mid-*y*

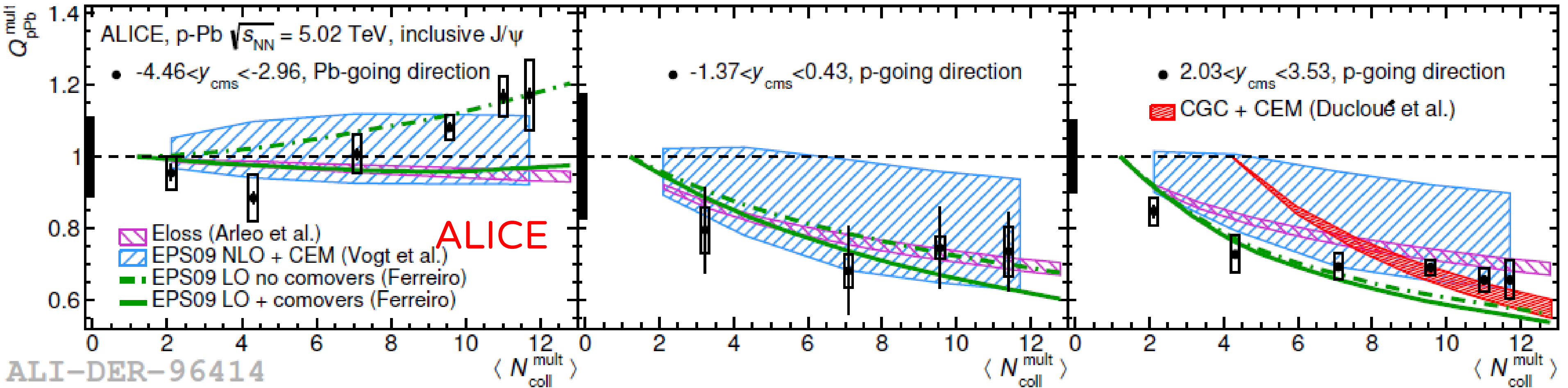


➡ shadowing and coherent parton energy loss models reasonably describe the data

➡ agreement with CGC depends on implementation

LHC: J/ψ R_{pA} vs centrality

backward-y mid-y forward-y



ALICE:

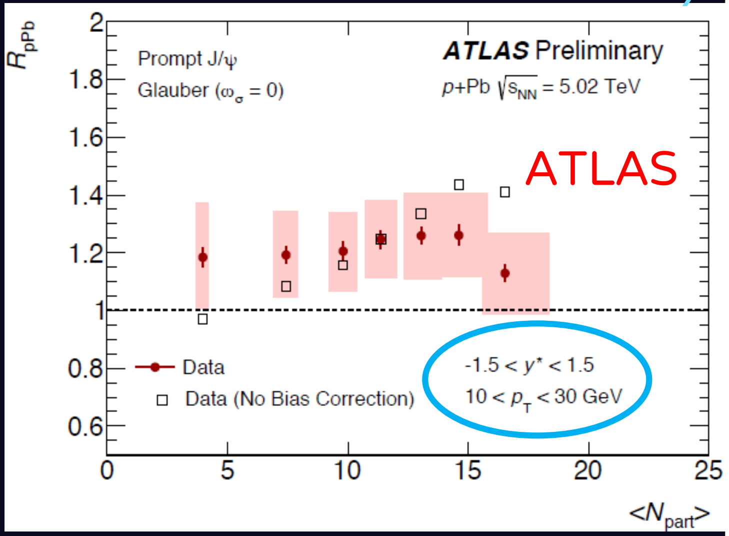
mid & fw-y: suppression increases with centrality

backward-y: hint for increasing Q_{pA} with centrality

Shadowing and coherent energy loss models in fair agreement with data

No strong comovers effect expected for J/ψ

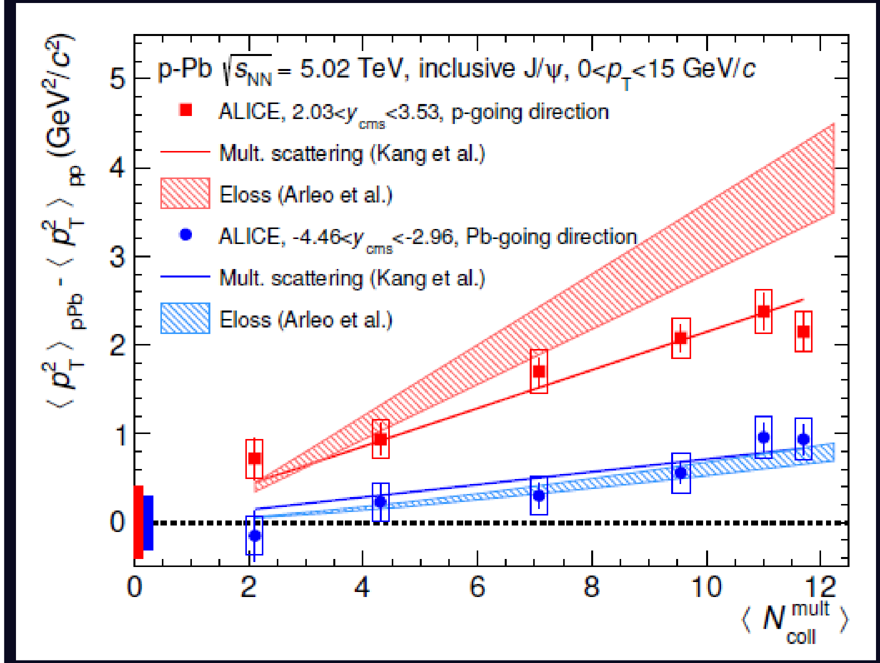
mid-y



ATLAS

Flat centrality dependence in the high p_T range

J/ψ $<p^2_T>$

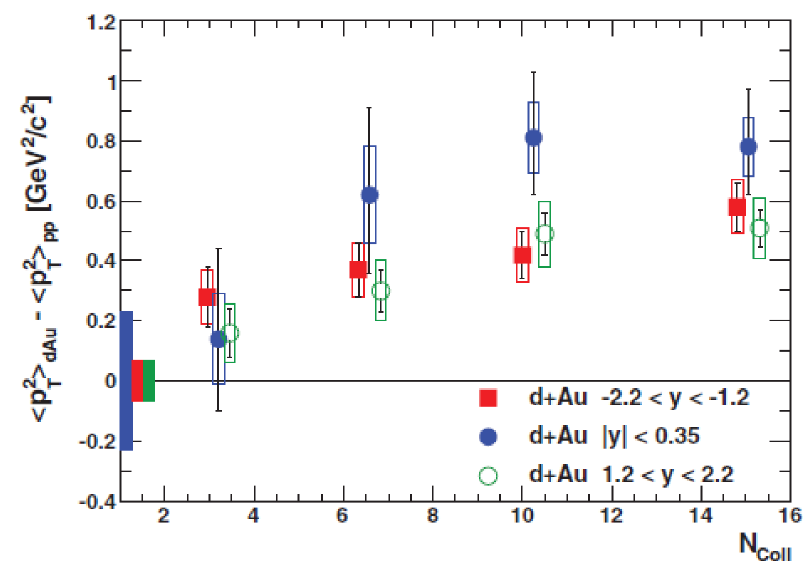


ALICE:

- the p_T broadening $\Delta<p_T^2>$ increases from peripheral to central collisions
- effect is stronger at forward y
- initial/final state parton multiple scattering model describe the results
- energy loss describes the bck-y results, but predicts a steeper trend at forward y

PHENIX:

- p_T broadening similar as the one observed by ALICE at backward-y
- large uncertainties prevent conclusions on the y dependence

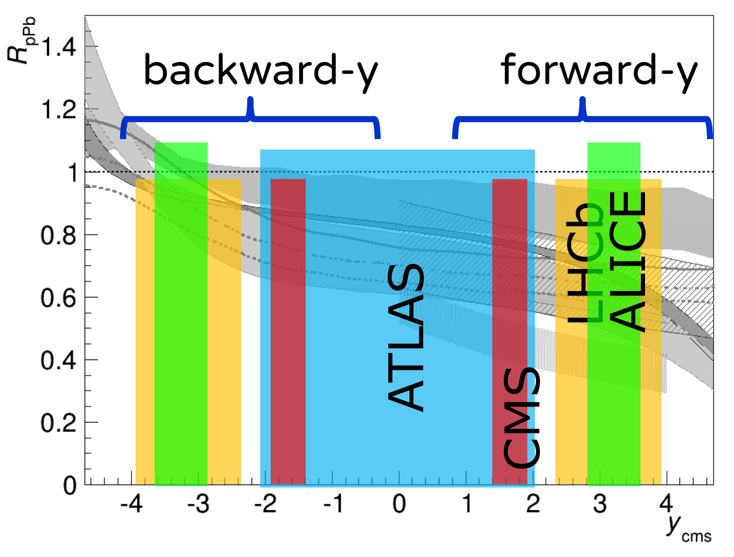


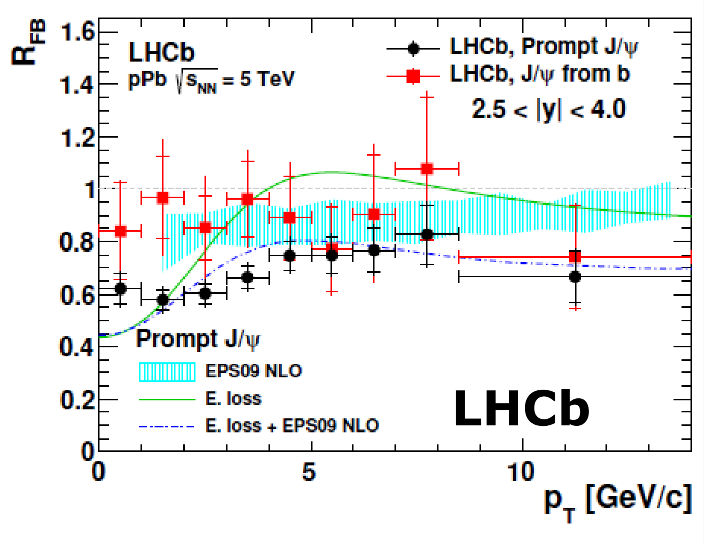
J/ψ R_{FB}

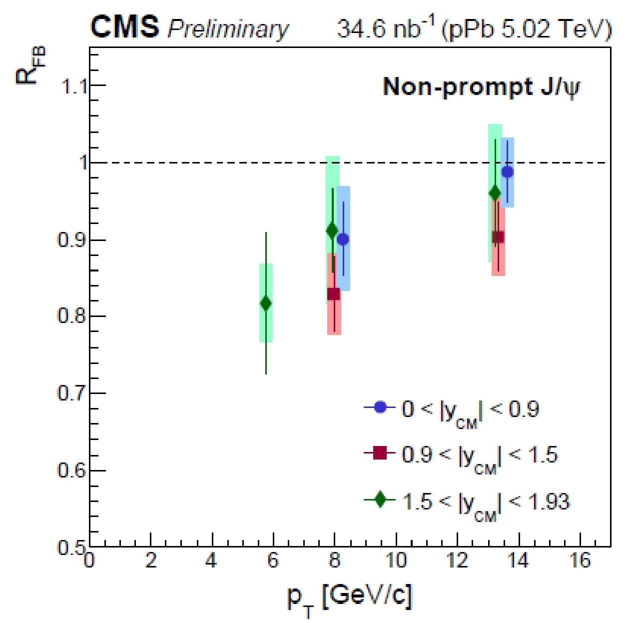
- Forw. to backw. ratio in a common y range

$$R_{FB} = \frac{Y^{forward}_{J/\psi}}{Y^{backward}_{J/\psi}}$$

→ no pp reference is needed
→ but less straightforward to interpret





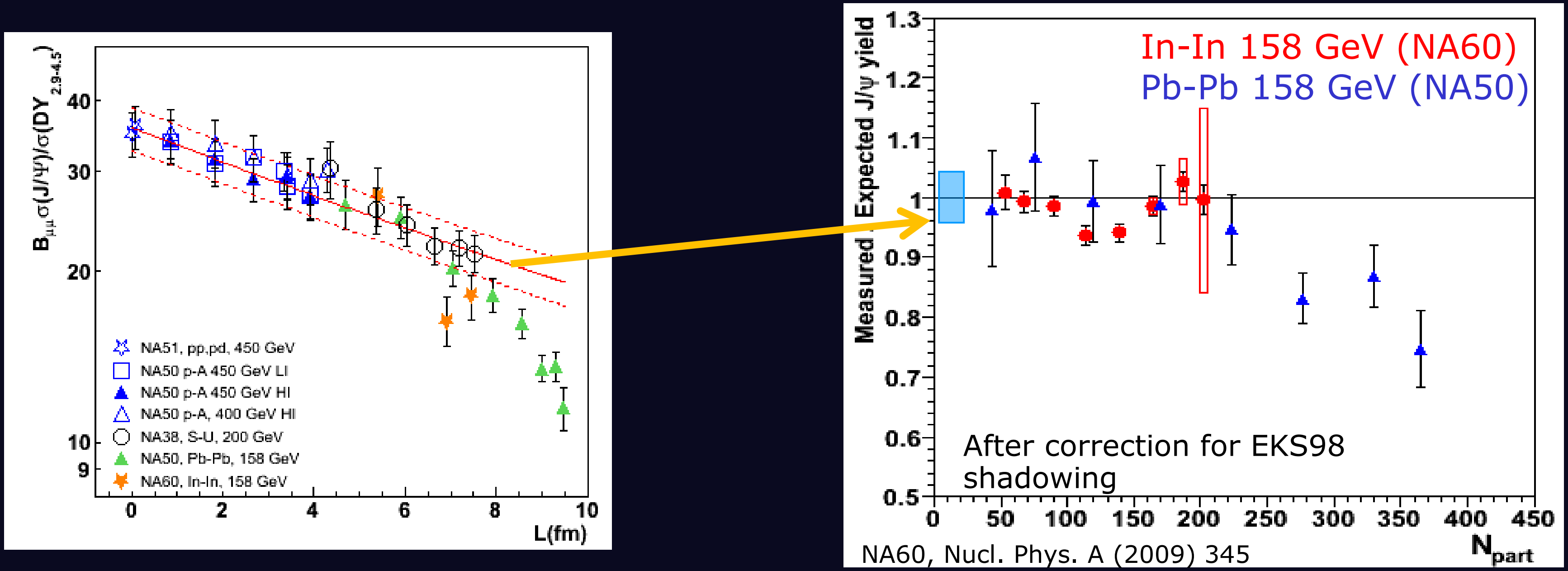


- Comparison of R_{FB} results is not straightforward:

1) strong rapidity dependence of CNM effects
2) diifferent kinematic ranges covered by the experiments

From pA to AA: SPS

➡ Once CNM effects are measured in pA, how can they be extrapolated to AA?



NA60, Nucl. Phys. A (2009) 345

SPS → the reference is built

- evaluating σ break-up in pA collisions (in the same kinematic range as AA)
- including project/target (anti)shadowing
- determining the reference centrality dependence through Glauber approach

From pA to AA: RHIC

- Same energy for AA and d-Au collisions
- Reference evaluated with several approaches as:

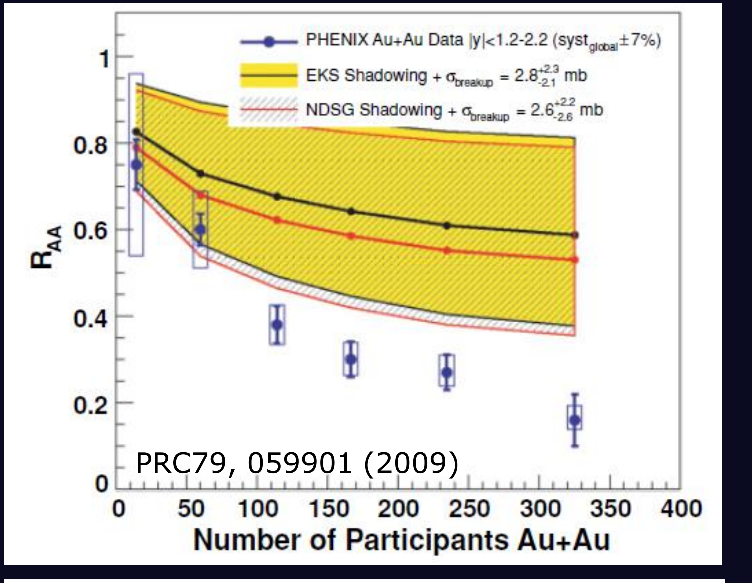
① R_{dAu} vs centrality (y) is described with various shadowing + break-up σ

Shadowing scenario + break-up σ (evaluated in pA) are then compared to AA result

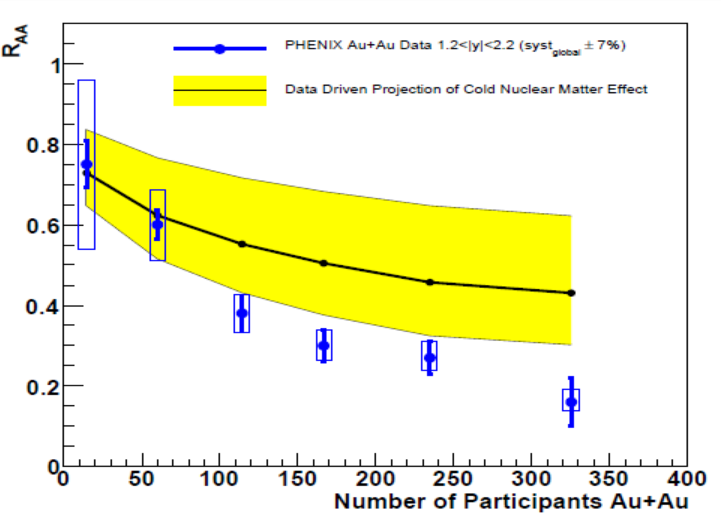
② Data-driven approach:

All CNM effects (not disentangled) depend on the radial position in the nucleus

$R_{AA} \sim R_{dAu}(-y) \times R_{dAu}(y)$



PRC79, 059901 (2009)

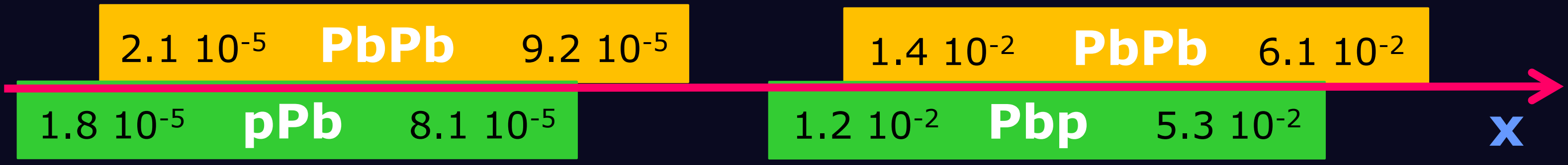


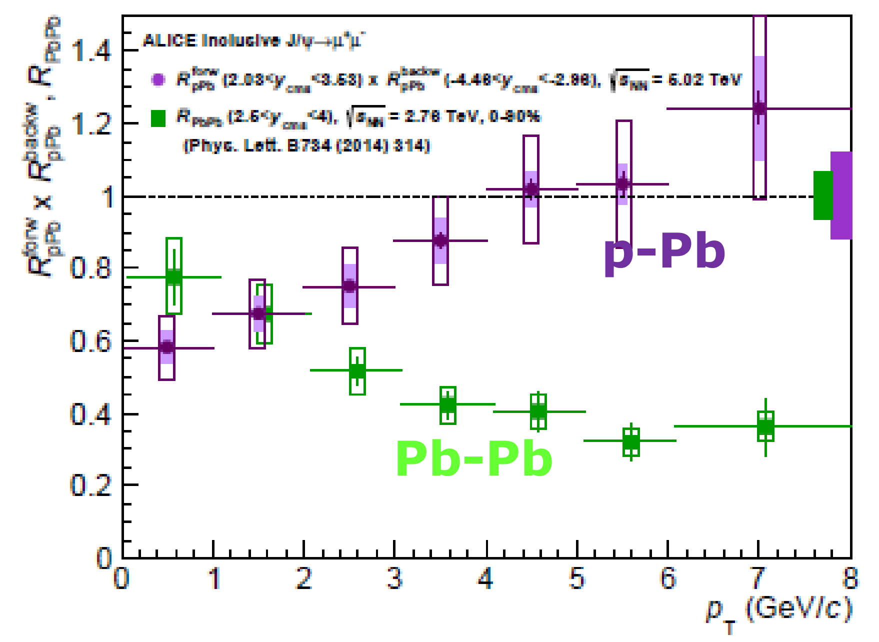
From pA to AA: LHC

Different pA and AA √s and y range

Hypothesis:

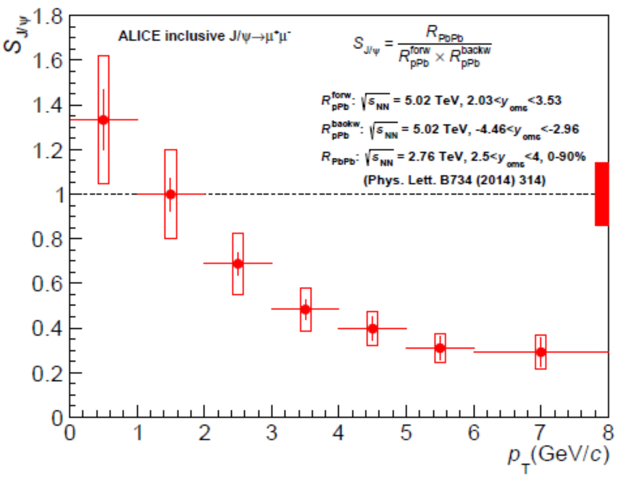
- 2→1 kinematics for J/ψ production
- CNM effects (dominated by shadowing) factorize in p-A
- CNM obtained as $R_{pA} \times R_{Ap}$ (R_{pA}^2), similar x-coverage as PbPb



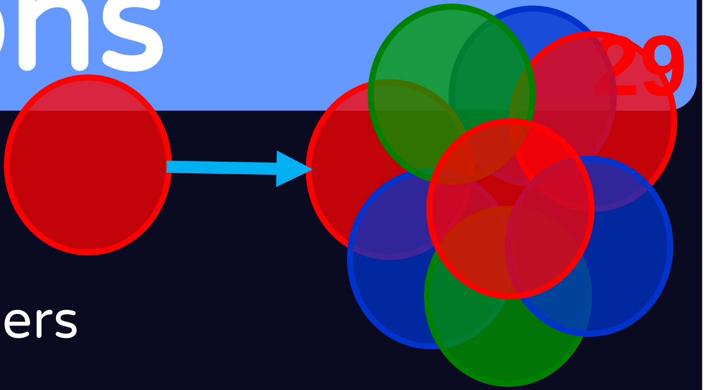


CNM effects are "removed" via

AA / pA



Conclusions



- The production of quarkonia in nuclear matter has been studied since a long time, both at fixed target and at colliders

- The J/ψ production is modified in pA (d-Au) with respect to pp, with a strong kinematic dependence

- Interplay of many cold nuclear matter effects as shadowing, energy loss and, at low √s, also cc break-up in the nucleus

  → Modeling is complicate, but progresses have been done!

  → However, size of uncertainties prevents a clear assessment of the role of the various contributions

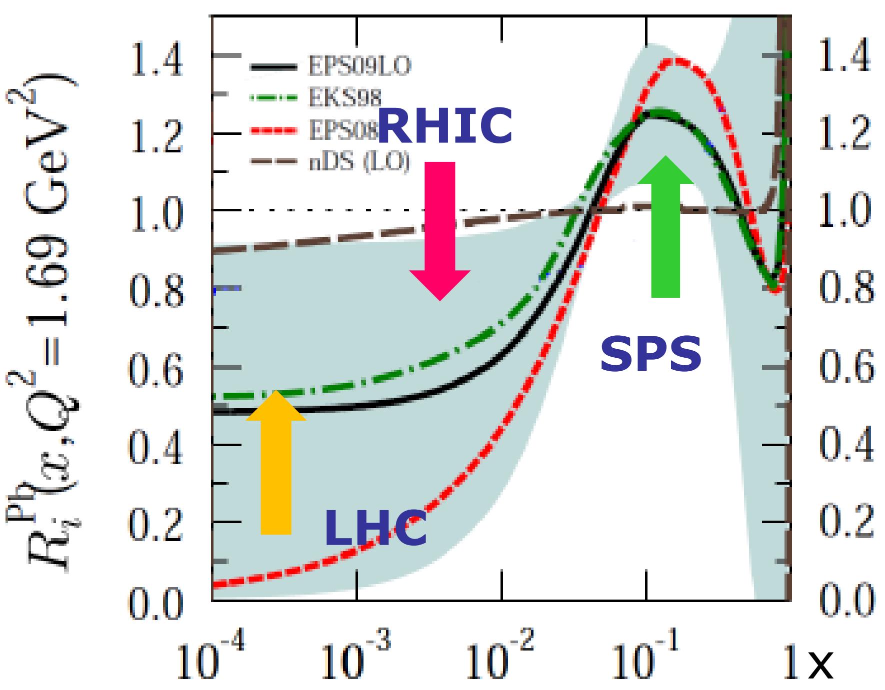
backup slides

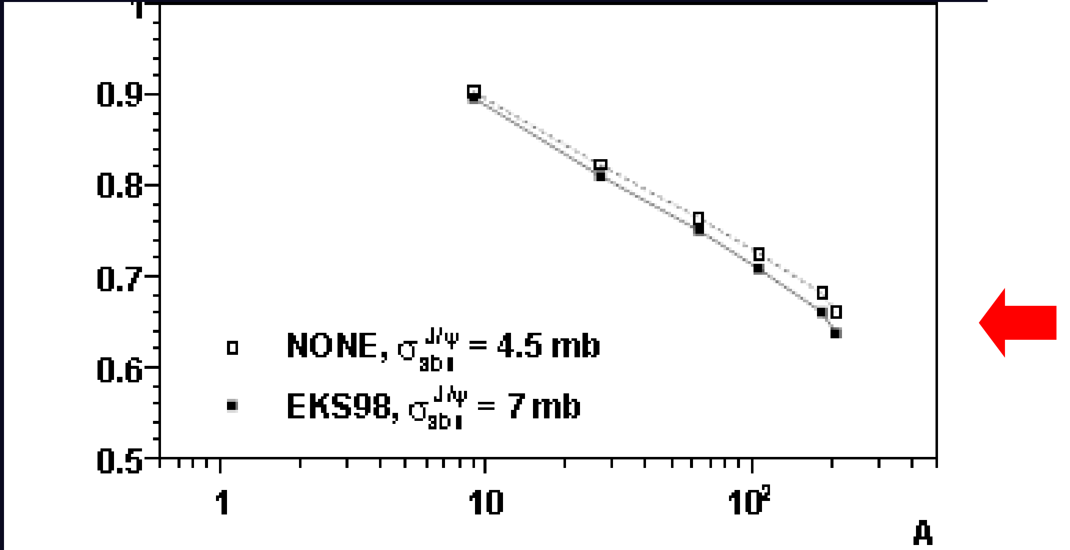
J/ψ in pA

Facility	Experiment	System	$\sqrt{s_{NN}}$ (GeV)	x_F range	Data taking
SPS	NA50	p-Be,Al,Cu,Ag,W,Pb	27	$-0.14<x_F<0.10$	1996-2000
			29	$-0.10<x_F<0.10$	
	NA60	p-Be,Al,Cu,In,W,Pb,U	17	$0.05 <x_F<0.40$	2004
			27	$-0.07<x_F<0.12$	
FNAL	E866	p-Be, Fe, W	39	$-0.10 <x_F<0.93$	~1996
HERA	HERA-B	p-C, W	42	$-0.34 <x_F<0.14$	2002
RHIC	PHENIX, STAR	d-Au	200	$-0.1 <x_F<0.2$ $0.05 < \lvert x_F \rvert <0.14$	>2003
		p-Al, Au			2015
LHC	ALICE	p-Pb	5020	$-0.05<x_F<0.02$	2013
	ATLAS			$-0.01<x_F<-0.004$	
	CMS			$-0.01<x_F<-0.004$	
	LHCb			$-0.09<x_F<-0.007$ $0.003<x_F<-0.03$	

CNM effects: shadowing

- PDF in nuclei are strongly modified with respect to those in a free nucleon
- Various parameterizations developed in the last ~10 years Significant spread in the results, in particular for gluon PDFs
- From parton densities enhancement to suppression, moving towards higher energy!

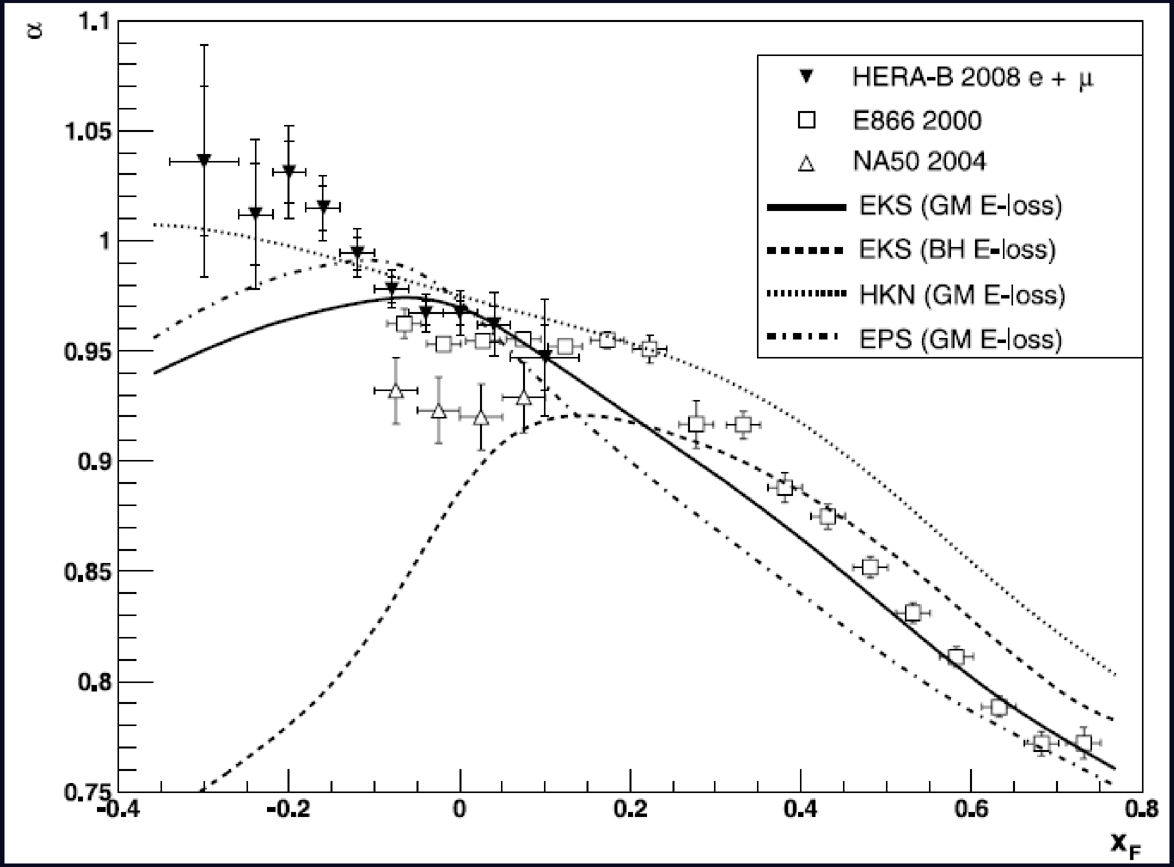




Value of absorption cross section σ_{abs} depends whether PDFs are taken into account or not!

J/ψ production vs xF

Compilation of fixed target results:



$$\sigma^{pA}_{J/\psi} = \sigma^{pp}_{J/\psi} \cdot A^{\alpha}$$

J/ψ production is modified by the medium already in pA collisions

α strongly decreases with xF

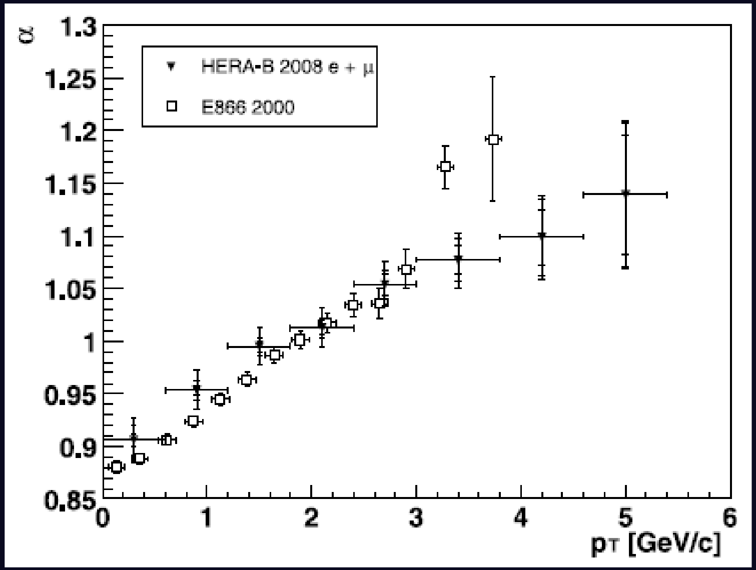
for a given x_F, CNM are stronger at lower √s

Satisfactory theoretical description still unavailable!

High-x_F → resonance forms outside the nucleus
Low-x_F → resonance forms inside the nucleus

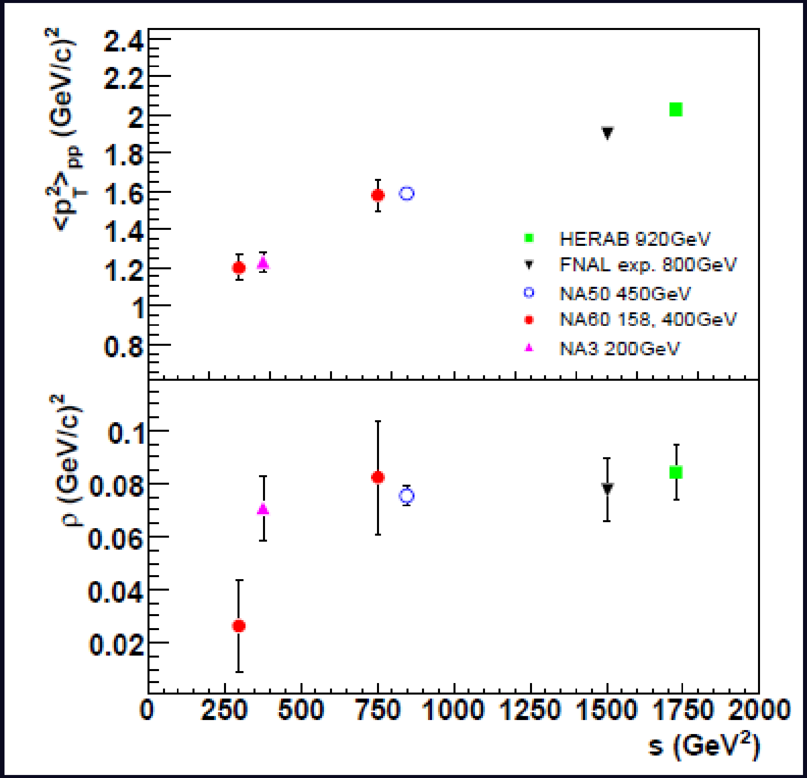
J/ψ production vs p_T

- The J/ψ suppression is stronger at low pT
- Increase of α with p_T interpreted in terms of Cronin effect



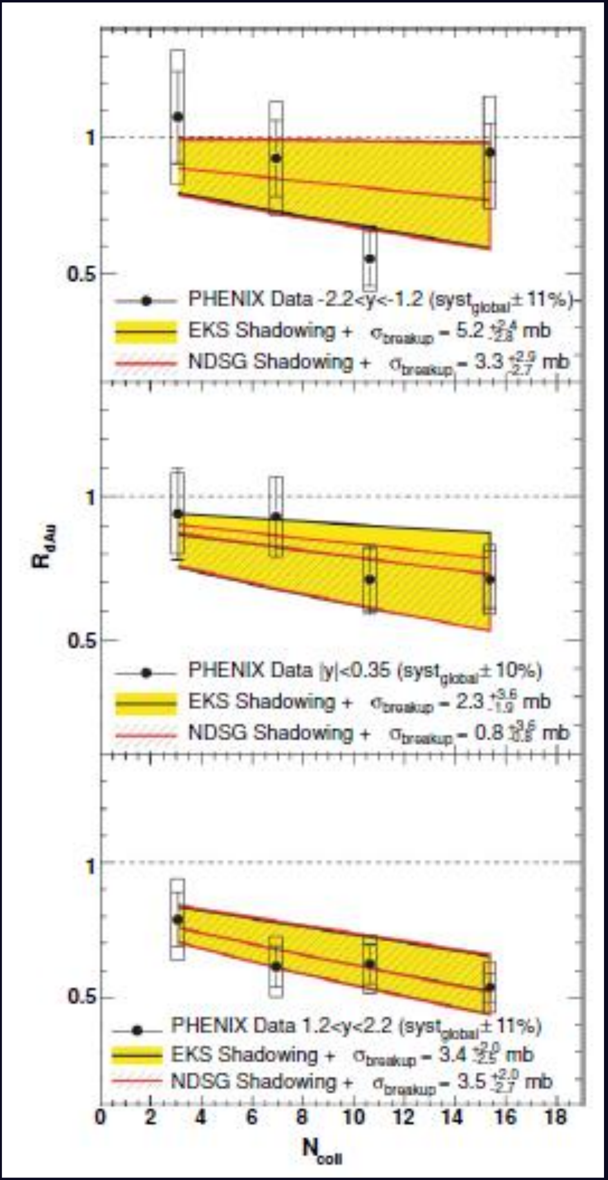
A broadening of pT as a function of A is observed:

$<p_T^2> = <p_T^2>_{pp} + \rho\,(A^{1/3}-1)$

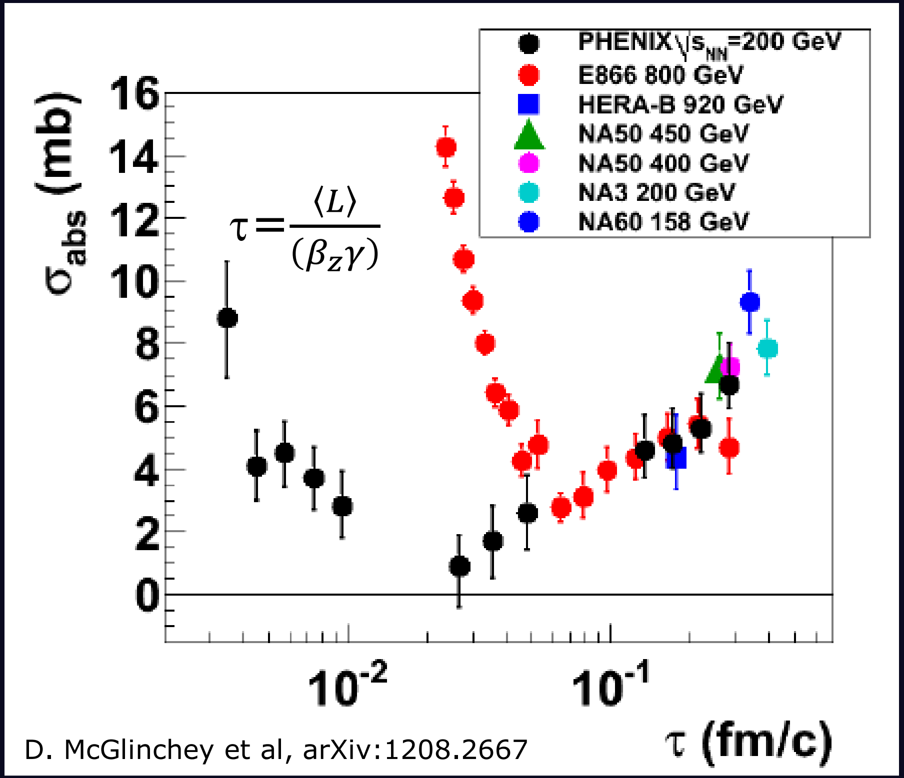


Slope ρ is almost energy independent (apart from very low √s) while $<p_T^2>$pp increases with √s

Moving to higher energies: RHIC



➡ Results might be described including shadowing and a rapidity-dependent σ_{abs}

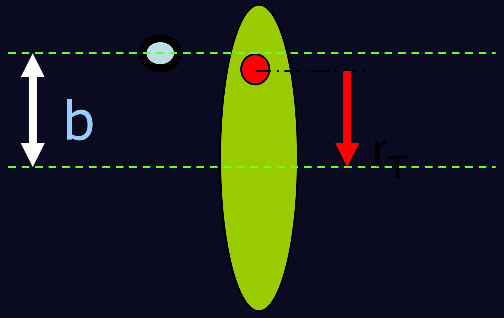


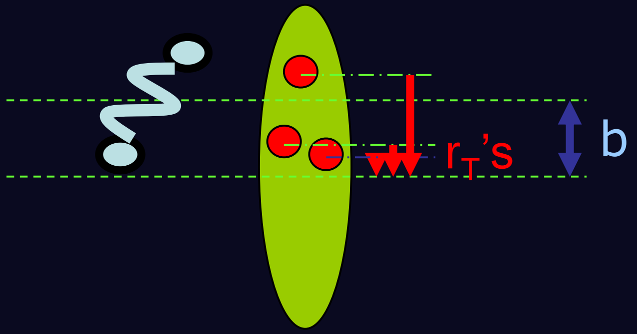
D. McGlinchey et al, arXiv:1208.2667

Moving to higher energies: RHIC

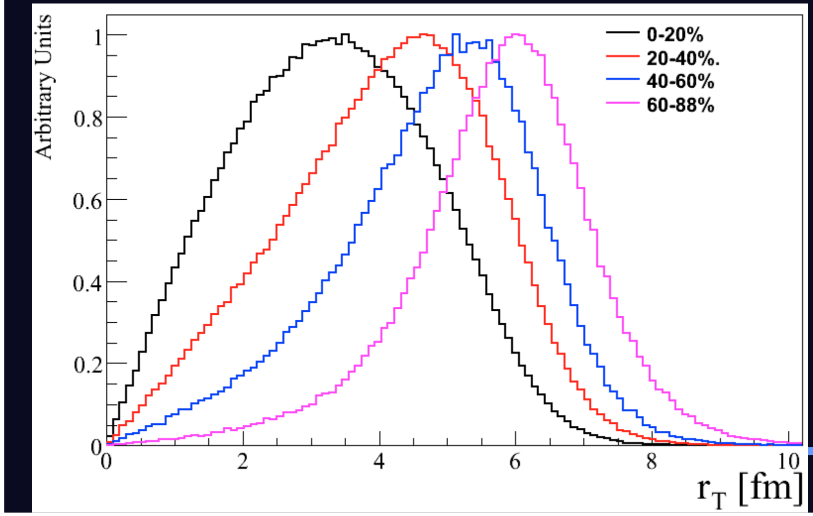
- Different approach wrt to fixed target experiments:

Instead of accelerating several different nuclei
→ Use one single nucleus species and select on impact parameter





p-A: $r_T \sim b$



d-Au: due to the size of the deuteron (<r>~2.5fm) the distribution of transverse positions of the collisions are not very well represented by impact parameter

→ overlap of the centrality classes

d-Au rapidity range

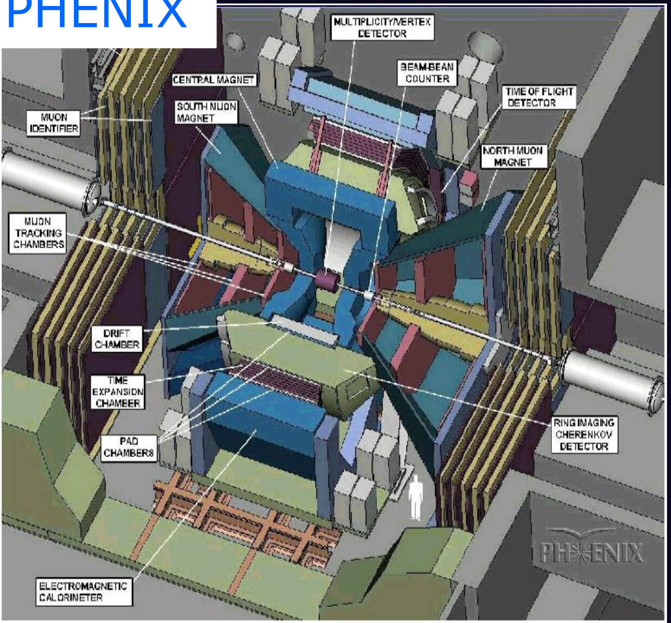
- Regions corresponding to very different strength of shadowing effects have been studied:

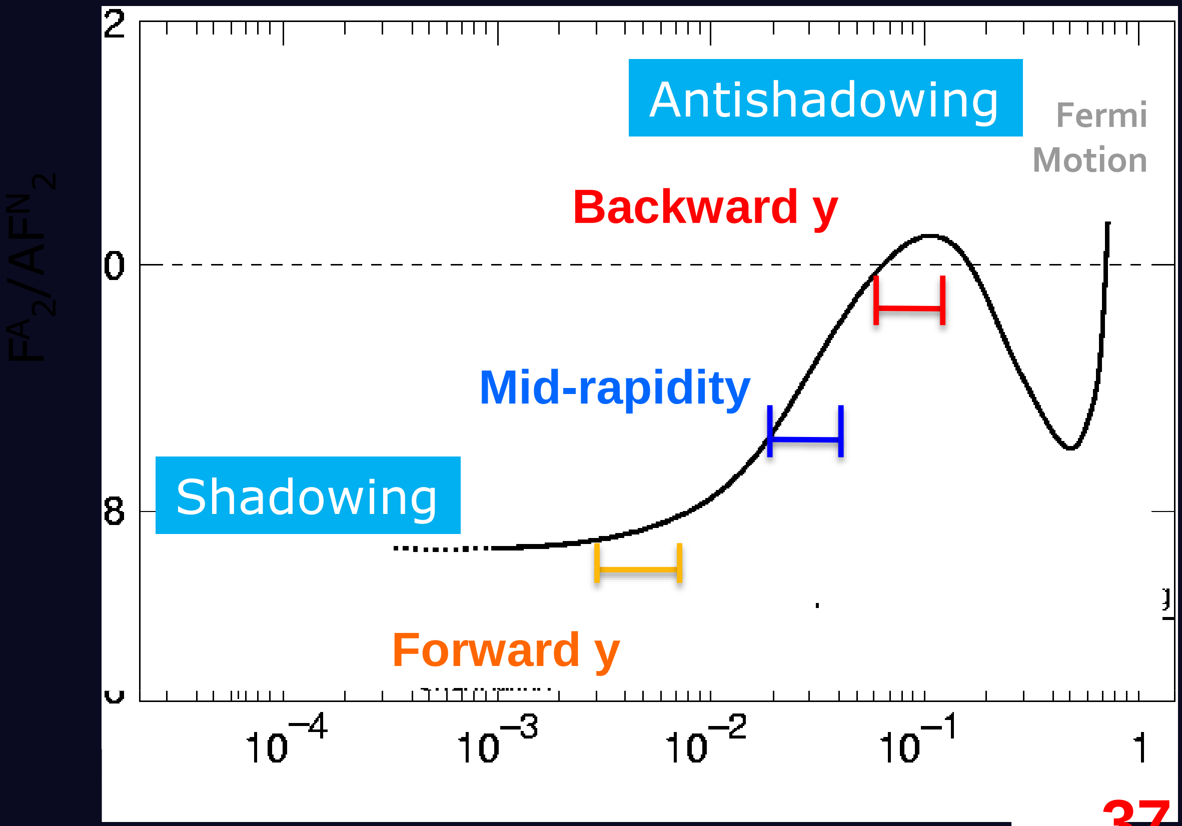
  $-2.2<y<-1.2$, $|y|<0.35$, $1.2<y<2.2$

  → good test of our understanding of the physics!

forward y	x~0.005
mid y	x~0.03
backward y	x~0.1

PHENIX



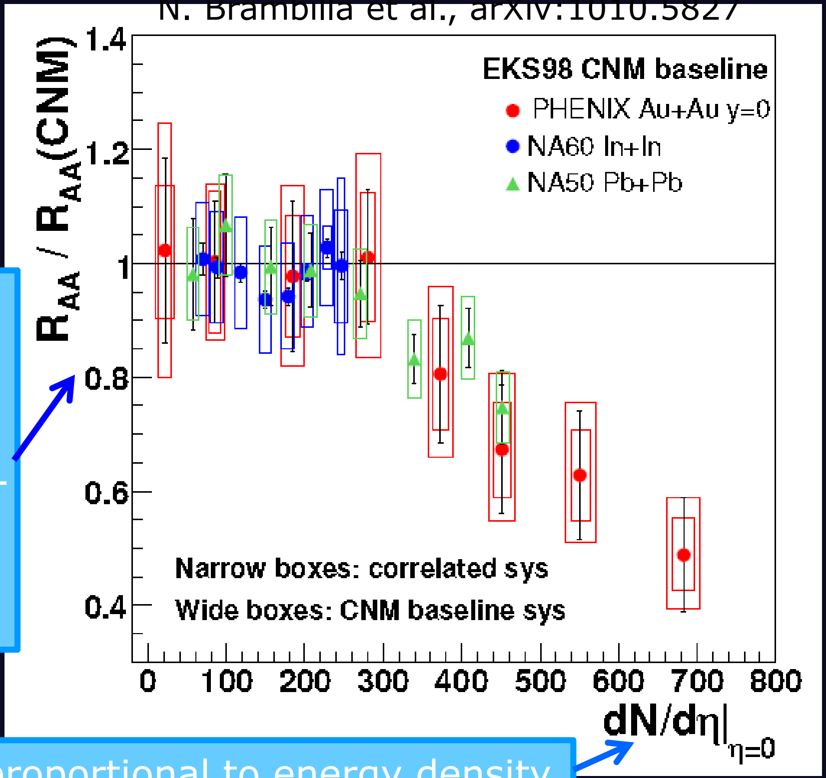


From p-A to A-A…

- Even if disentangling the different CNM mechanisms is a complicate issue…

…CNM, evaluated in p-A, can be extrapolated to A-A to build a reference for the J/ψ behaviour in hadronic matter!

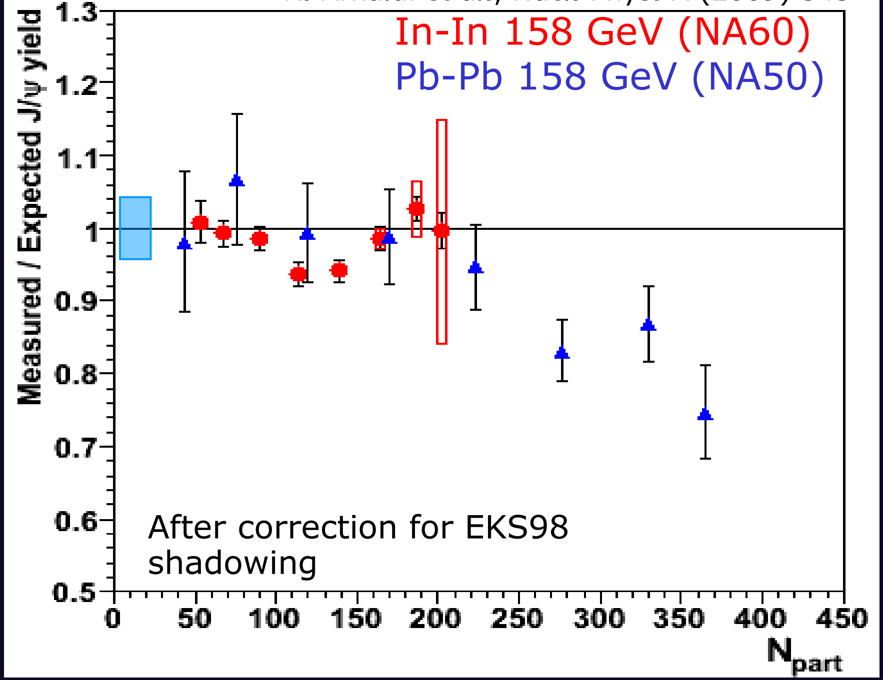
N. Brambilla et al., arXiv:1010.5827



R_{AA} normalized to CNM expectations

~ proportional to energy density

B. Alessandro et al., EPJC39 (2005) 335
R. Arnaldi et al., Nucl. Phys. A (2009) 345

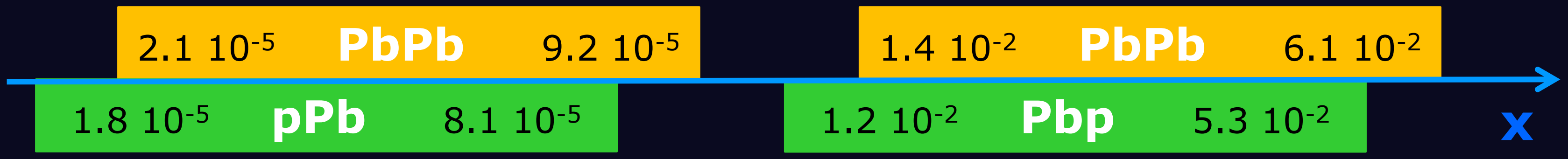


- Clear suppression is indeed observed on top of CNM effects!

From p-Pb to Pb-Pb…

- p-Pb results will provide information on the size of CNM effects in Pb-Pb
  - Pb-Pb: $2.5<|y_{CMS}|<4$, $\sqrt{s_{NN}} = 2.76$TeV
  - p-Pb: slightly different kinematic domain and energy
    $2.04<y_{CMS}<3.54$, $2.96<y_{CMS}<4.46$, $\sqrt{s_{NN}} = 5.03$TeV

…but Bjorken x regions shifted by only ~10%.
In a 2→1 production mechanism (at p_T~0):



$2.1\ 10^{-5}$ **PbPb** $9.2\ 10^{-5}$

$1.8\ 10^{-5}$ **pPb** $8.1\ 10^{-5}$

$1.4\ 10^{-2}$ **PbPb** $6.1\ 10^{-2}$

$1.2\ 10^{-2}$ **Pbp** $5.3\ 10^{-2}$

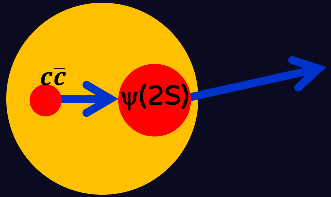
x

- Work in progress to quantify size of CNM effects in Pb-Pb results!

ψ(2S) production in pA

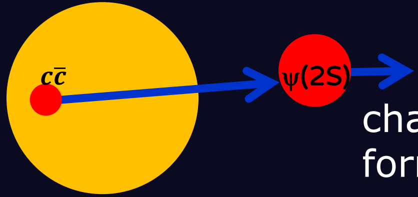
- Being more weakly bound than the J/ψ, the ψ(2S) is an interesting probe to have further insight on the charmonium behaviour in pA
- Low energy ψ(2S) p-A results from NA50, E866 and HERA-B:

<u>mid-*y* (x_F~0)</u>:
ψ(2S) suppression stronger than J/ψ one, interpreted via pair break-up
→ fully formed resonances traversing the nucleus



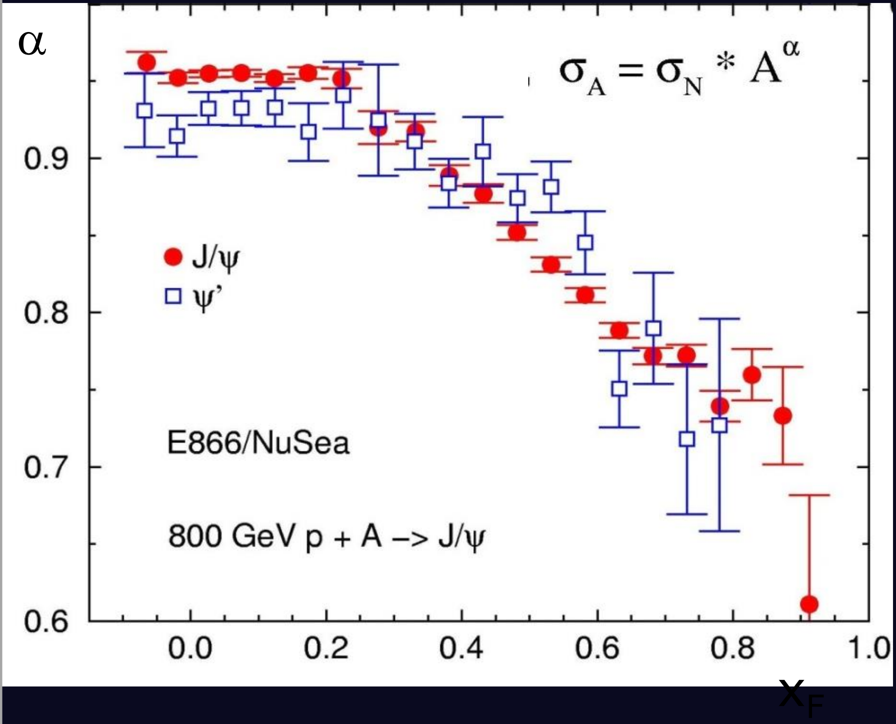
charmonium
formation time<crossing time

<u>forward-*y* (high x_F)</u>:
suppression becomes identical
→ dominated by energy loss



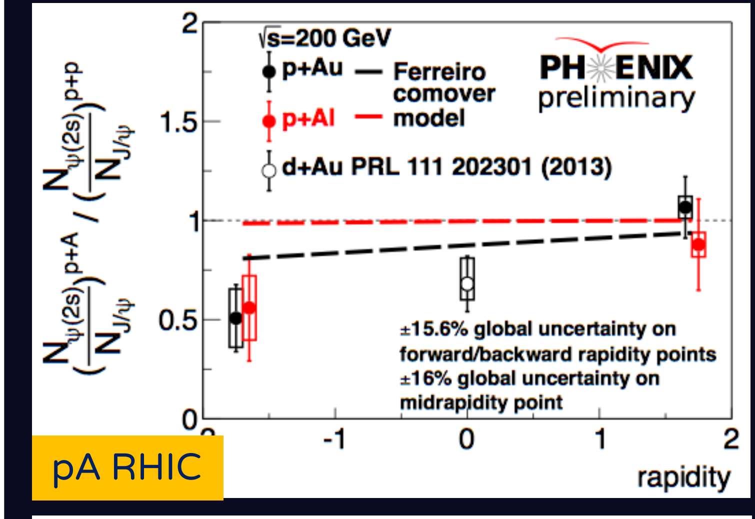
charmonium
formation time>crossing time

E866 Collab., PRL 84 (2000) 3256

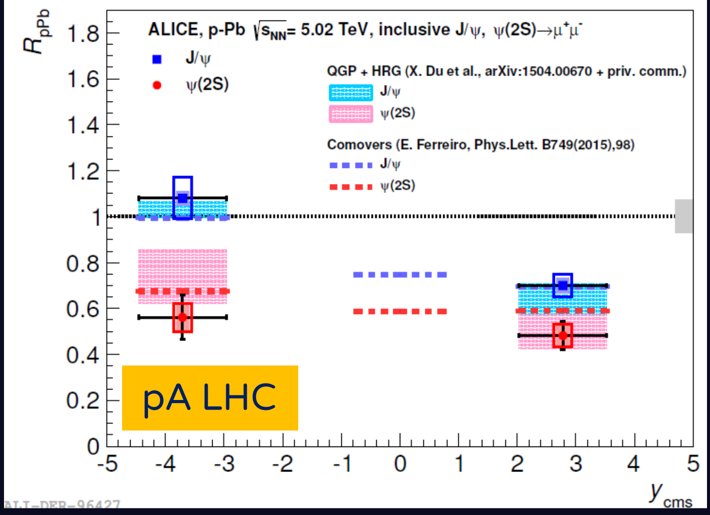


Comparison to theoretical models

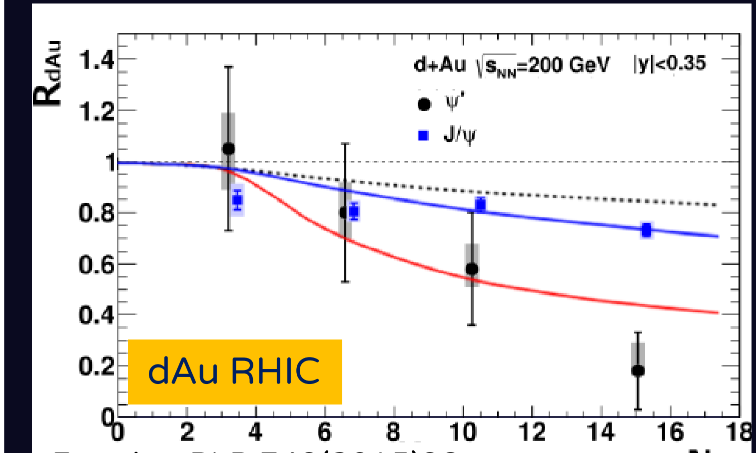
QGP+hadron resonance gas (Rapp) or comovers models (Ferreiro) reasonably describe both J/ψ and ψ(2S) suppression at RHIC and LHC



pA RHIC

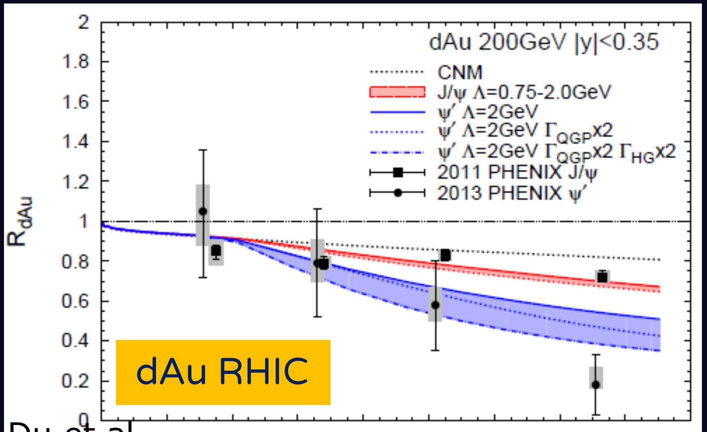


pA LHC



dAu RHIC

Ferreiro, PLB 749(2015)98



dAu RHIC

Du et al.
arXiv:1504.00670

J/ψ

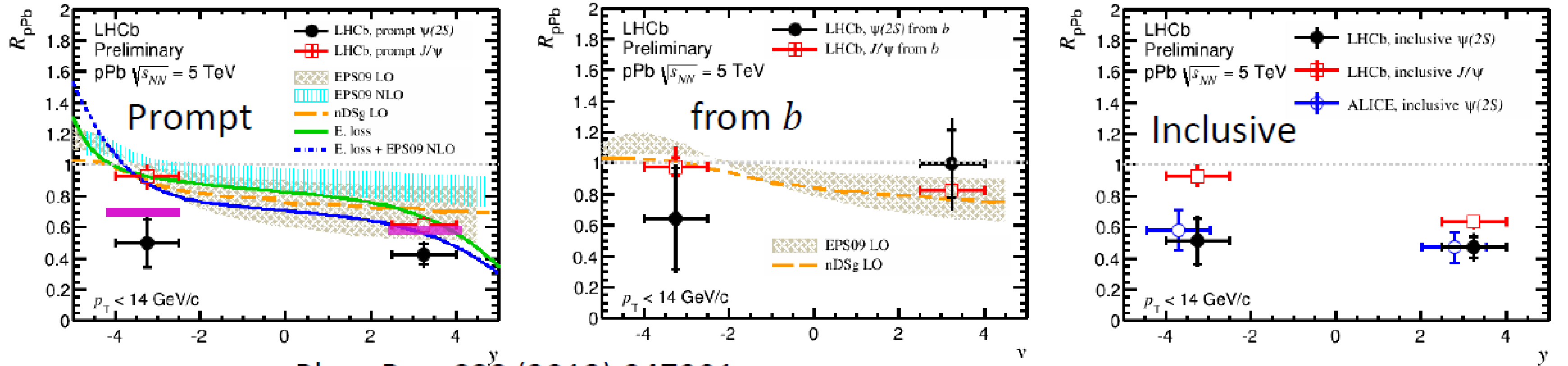
→ small suppression beyond CNM effects

ψ(2S)

→ strongly affected by comovers due to its larger size

→ comovers more important in the A-going direction

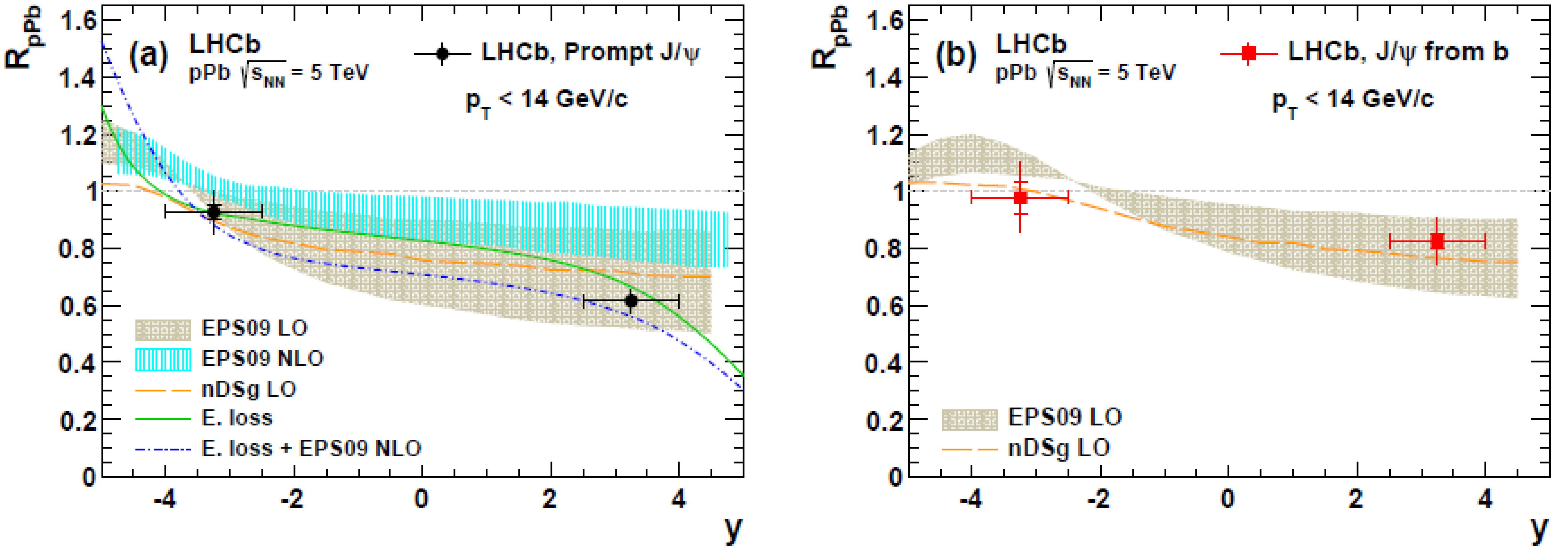
J/ψ RpA inclusive and prompt



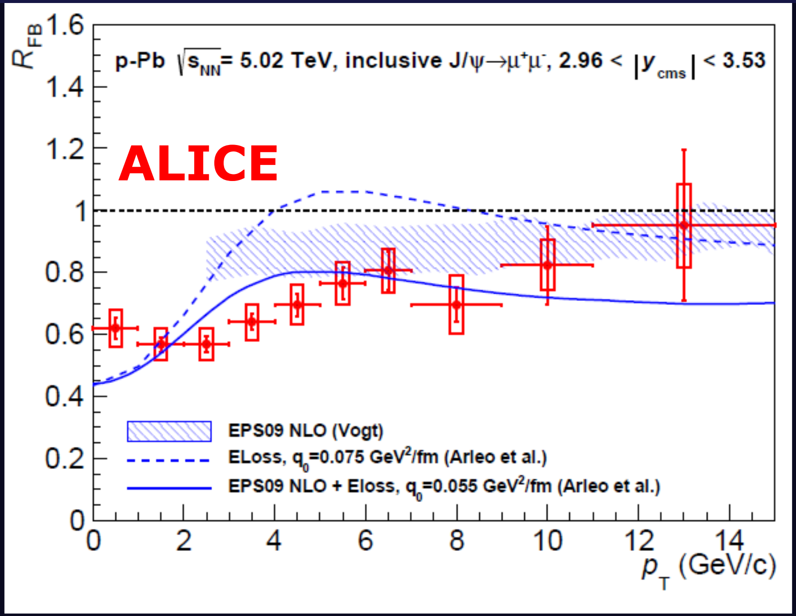
▨	**EPS09 LO**	Phys. Rev. C88 (2013) 047901
▥	**EPS09 NLO**	Int. J. Mod. Phys. E22 (2013) 1330007
— —	**nDSg LO**	Phys. Rev. C88 (2013) 047901
—	**E. loss**	JHEP 03 (2013) 122

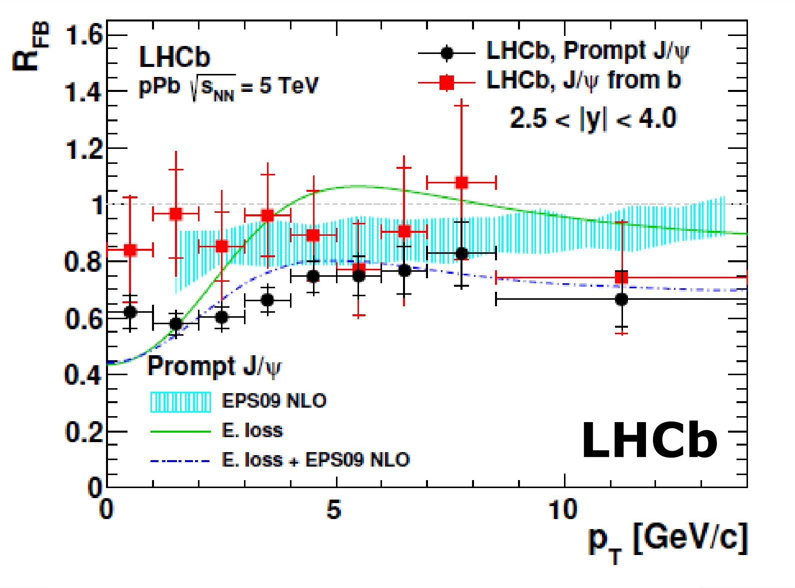
▨ **EPS09 LO**
— — **nDSg LO** Nucl.Phys.A926 (2014) 236

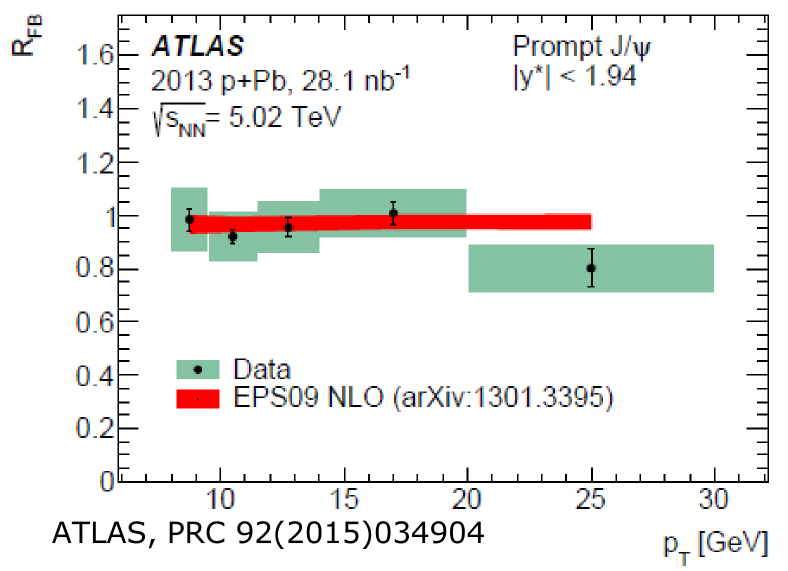
▬ **Comover** Phys. Lett. B749 (2015) 98



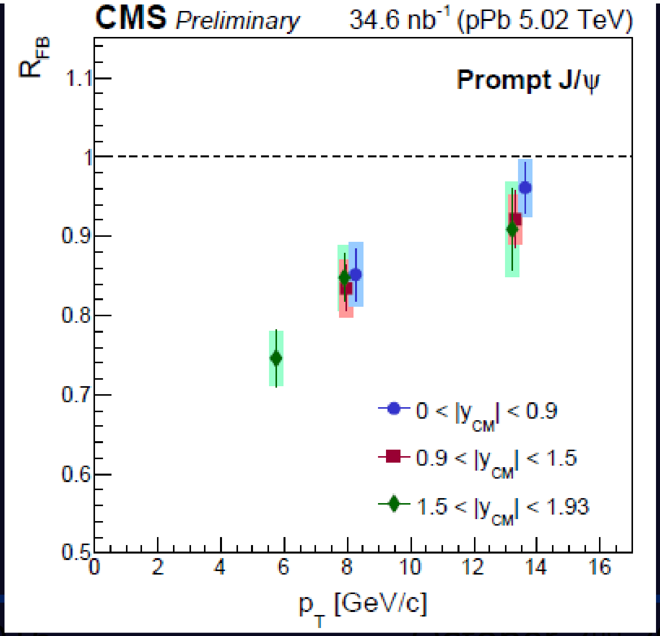
J/ψ forward-to-backward ratio

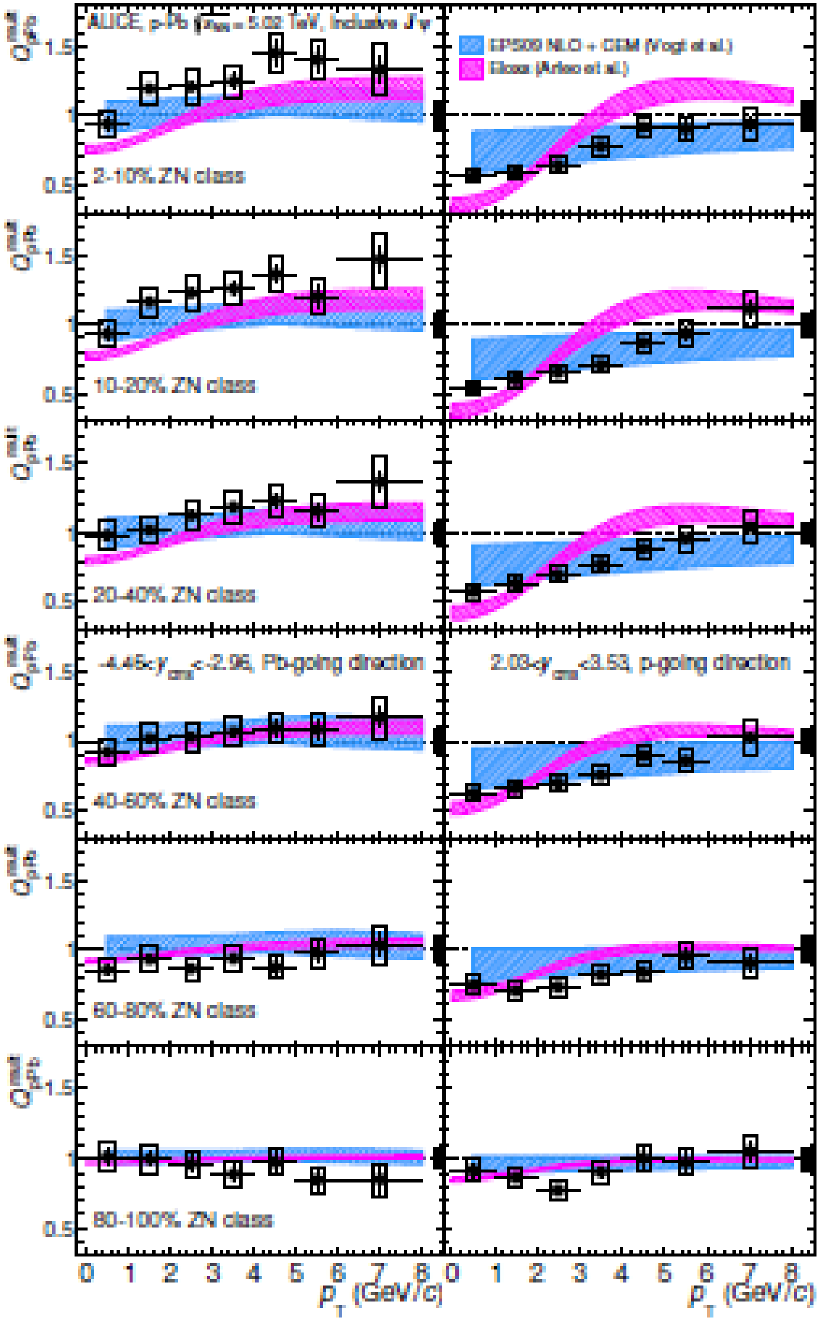




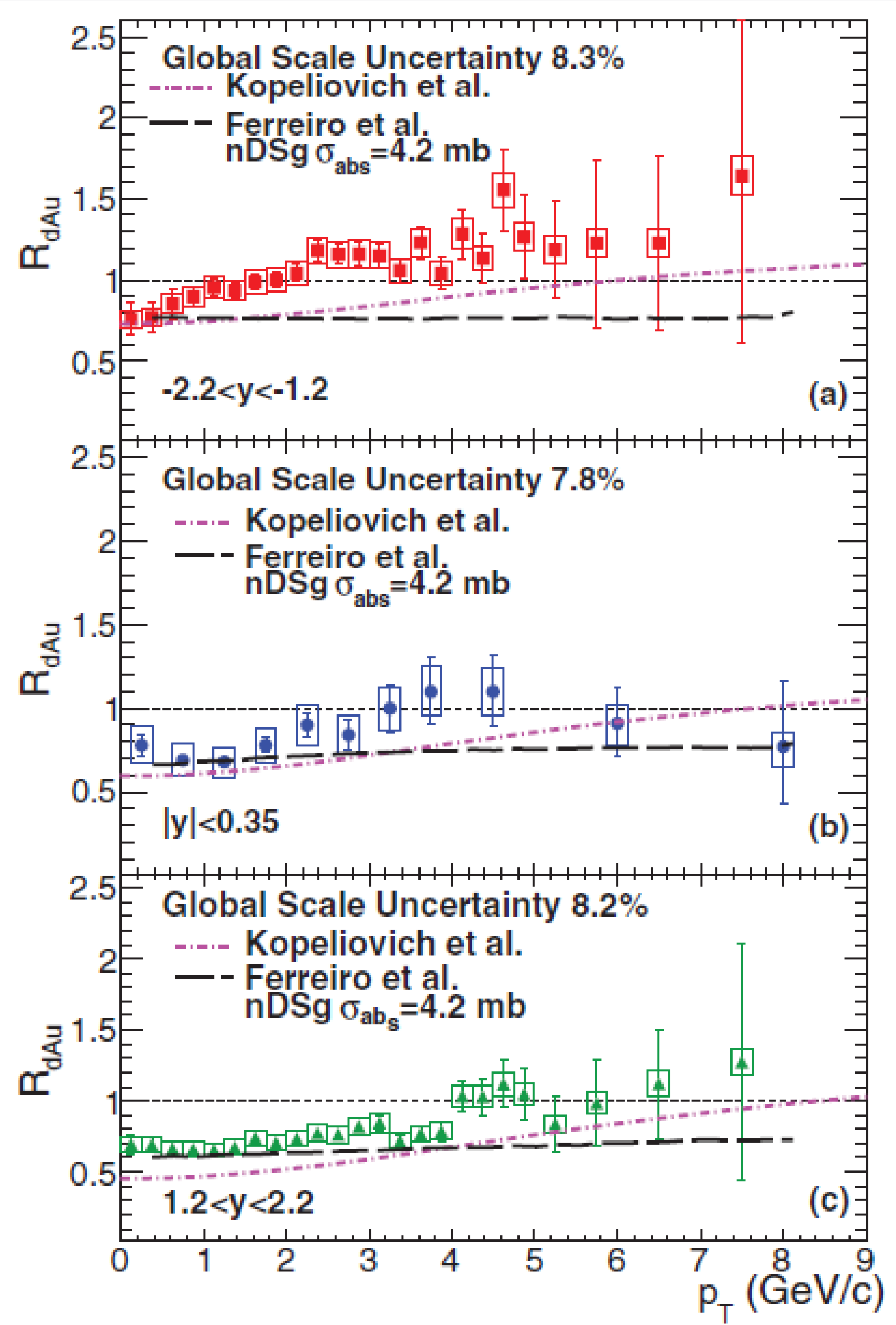


ATLAS, PRC 92(2015)034904

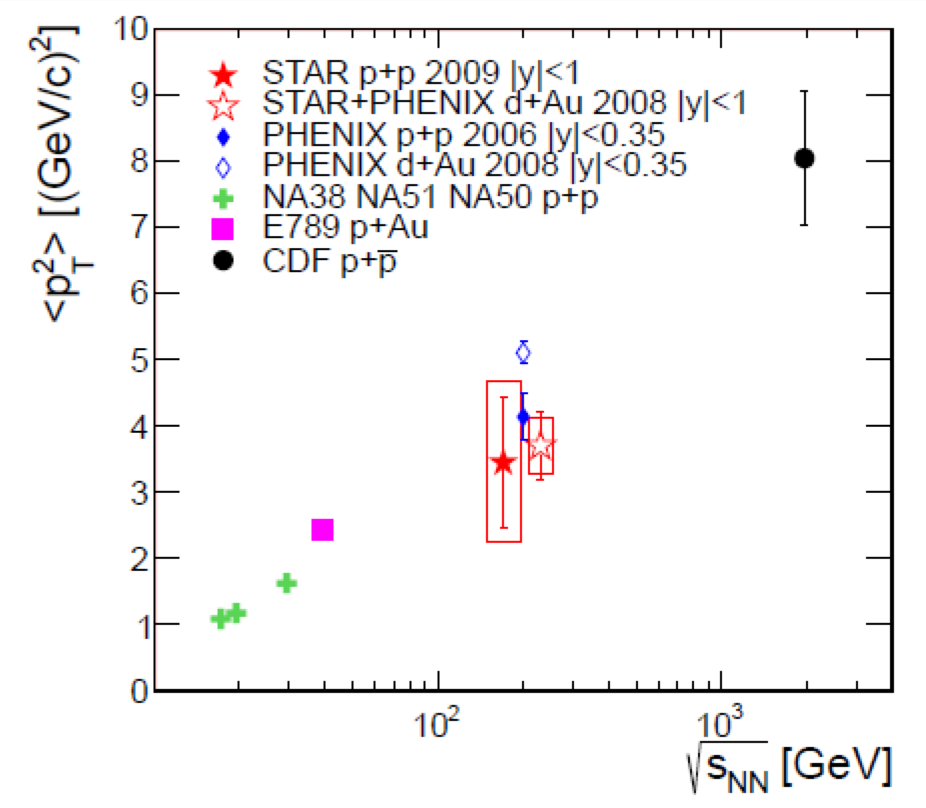


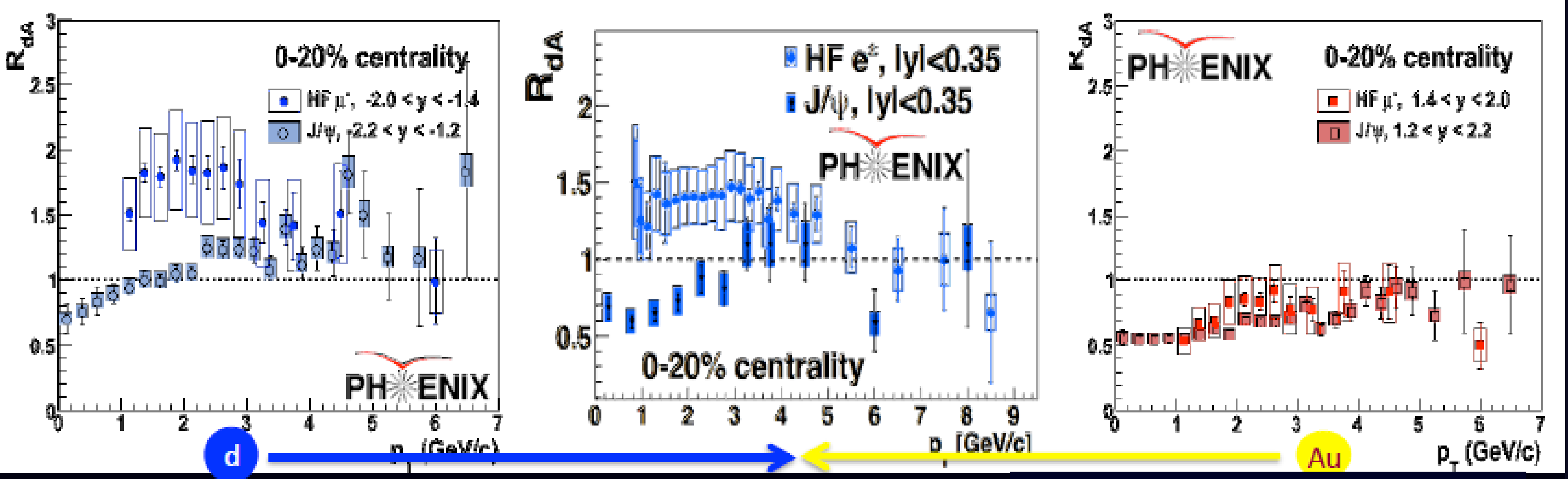


Differential results might provide constraints to theoretical calculations



Global Scale Uncertainty 8.3%
Kopeliovich et al.
Ferreiro et al.
nDSg σ_{abs}=4.2 mb
-2.2<y<-1.2
(a)
Global Scale Uncertainty 7.8%
Kopeliovich et al.
Ferreiro et al.
nDSg σ_{abs}=4.2 mb
|y|<0.35
(b)
Global Scale Uncertainty 8.2%
Kopeliovich et al.
Ferreiro et al.
nDSg σ_{ab_s}=4.2 mb
1.2<y<2.2
(c)
R_{dAu}
R_{dAu}
R_{dAu}
0.5
1
1.5
2
2.5
0
1
2
3
4
5
6
7
8
9
p_T (GeV/c)


STAR p+p 2009 |y|<1
STAR+PHENIX d+Au 2008 |y|<1
PHENIX p+p 2006 |y|<0.35
PHENIX d+Au 2008 |y|<0.35
NA38 NA51 NA50 p+p
E789 p+Au
CDF p+p̄
$<p_T^2>$ [(GeV/c)^2]
0
1
2
3
4
5
6
7
8
9
10
10^2
10^3
$\sqrt{s_{NN}}$ [GeV]


R_{dA}
0-20% centrality
HF μ^-, -2.0 < y < -1.4
J/ψ, -2.2 < y < -1.2
PHENIX
p_T (GeV/c)
R_{dA}
HF $e^{\pm}$, |y|<0.35
J/ψ, |y|<0.35
PHENIX
0-20% centrality
p_T [GeV/c]
R_{dA}
PHENIX
0-20% centrality
HF μ^-, 1.4 < y < 2.0
J/ψ, 1.2 < y < 2.2
p_T (GeV/c)
d
Au