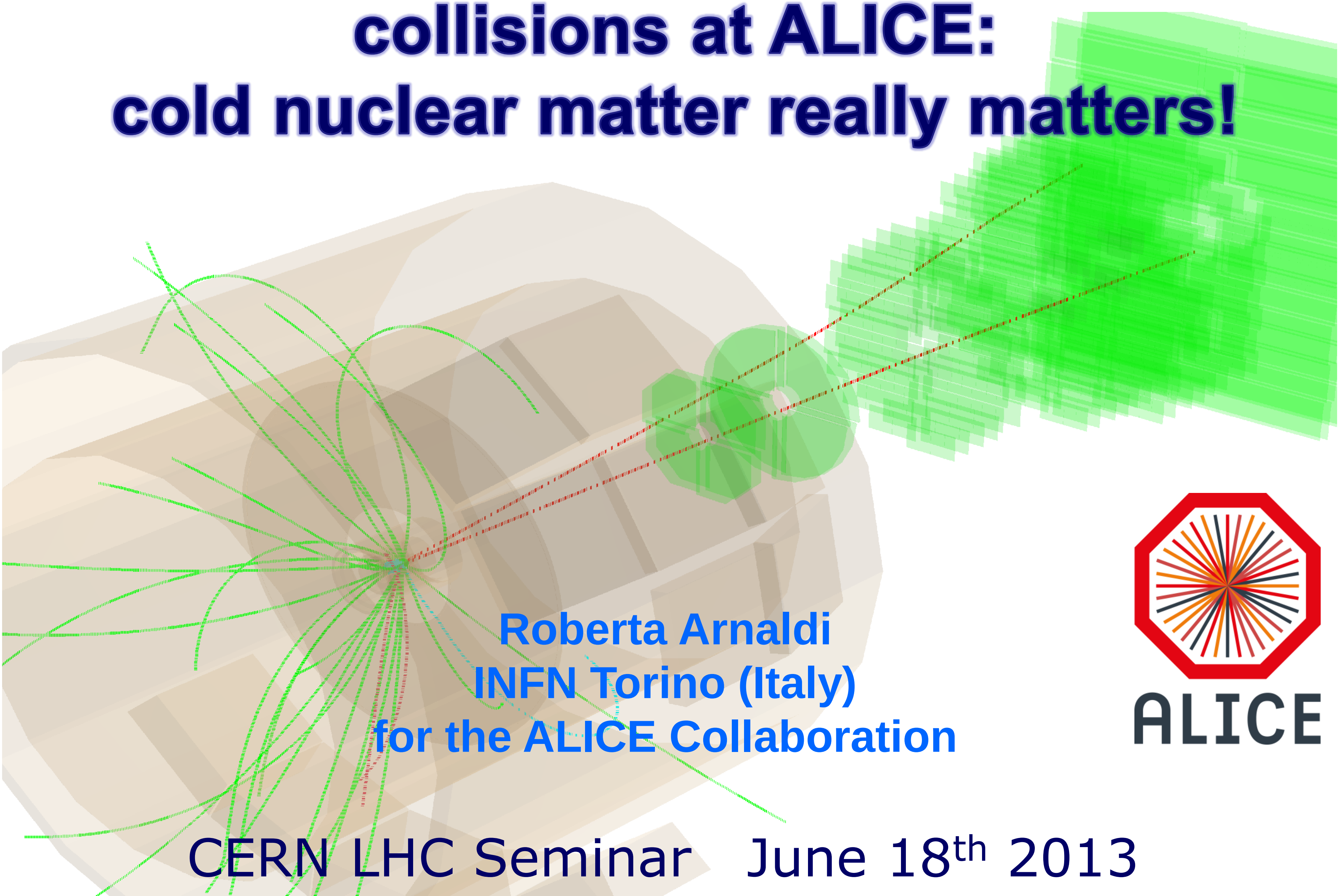
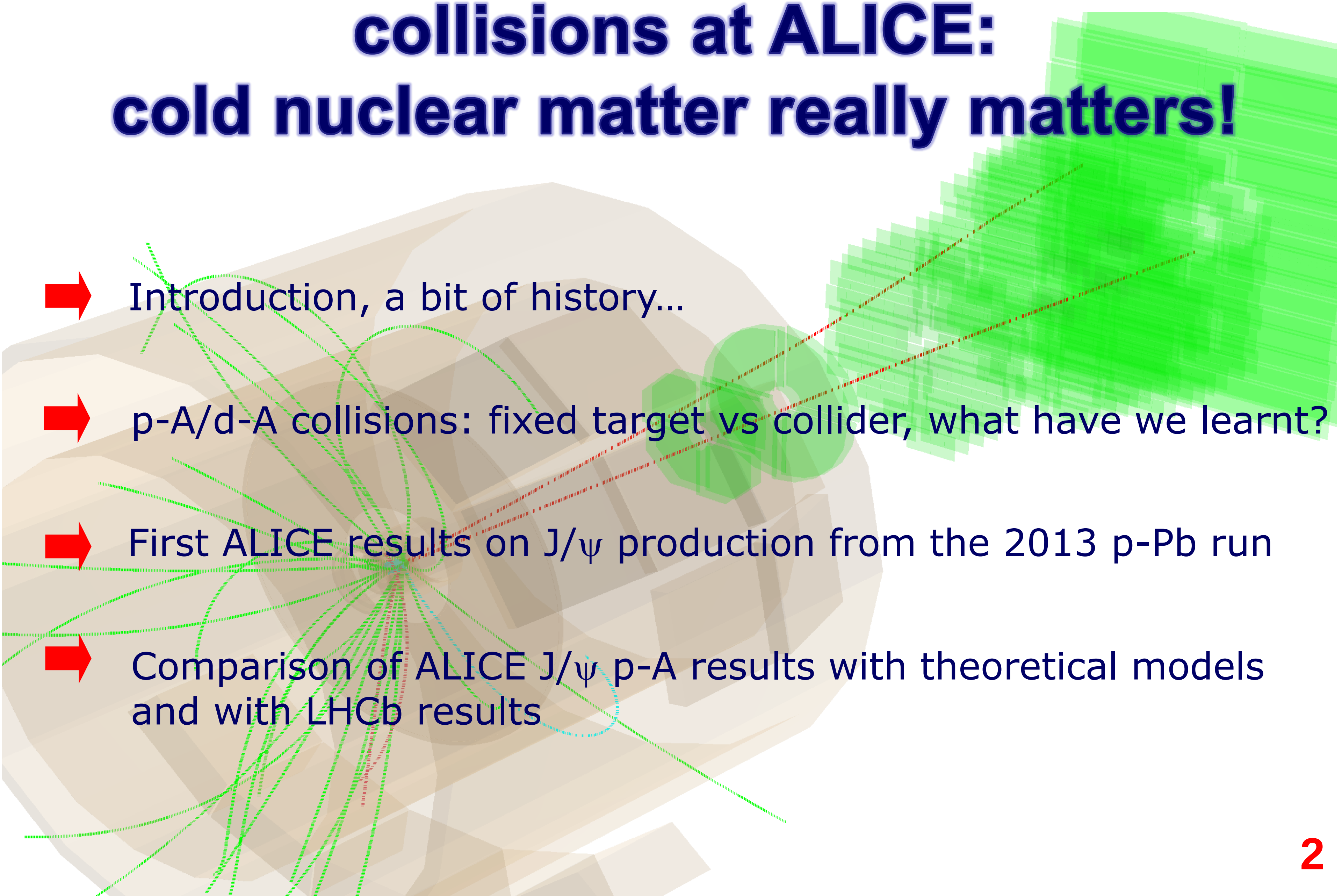
J/ψ production in proton-nucleus collisions at ALICE: cold nuclear matter really matters!



Roberta Arnaldi
INFN Torino (Italy)
for the ALICE Collaboration

CERN LHC Seminar June 18th 2013

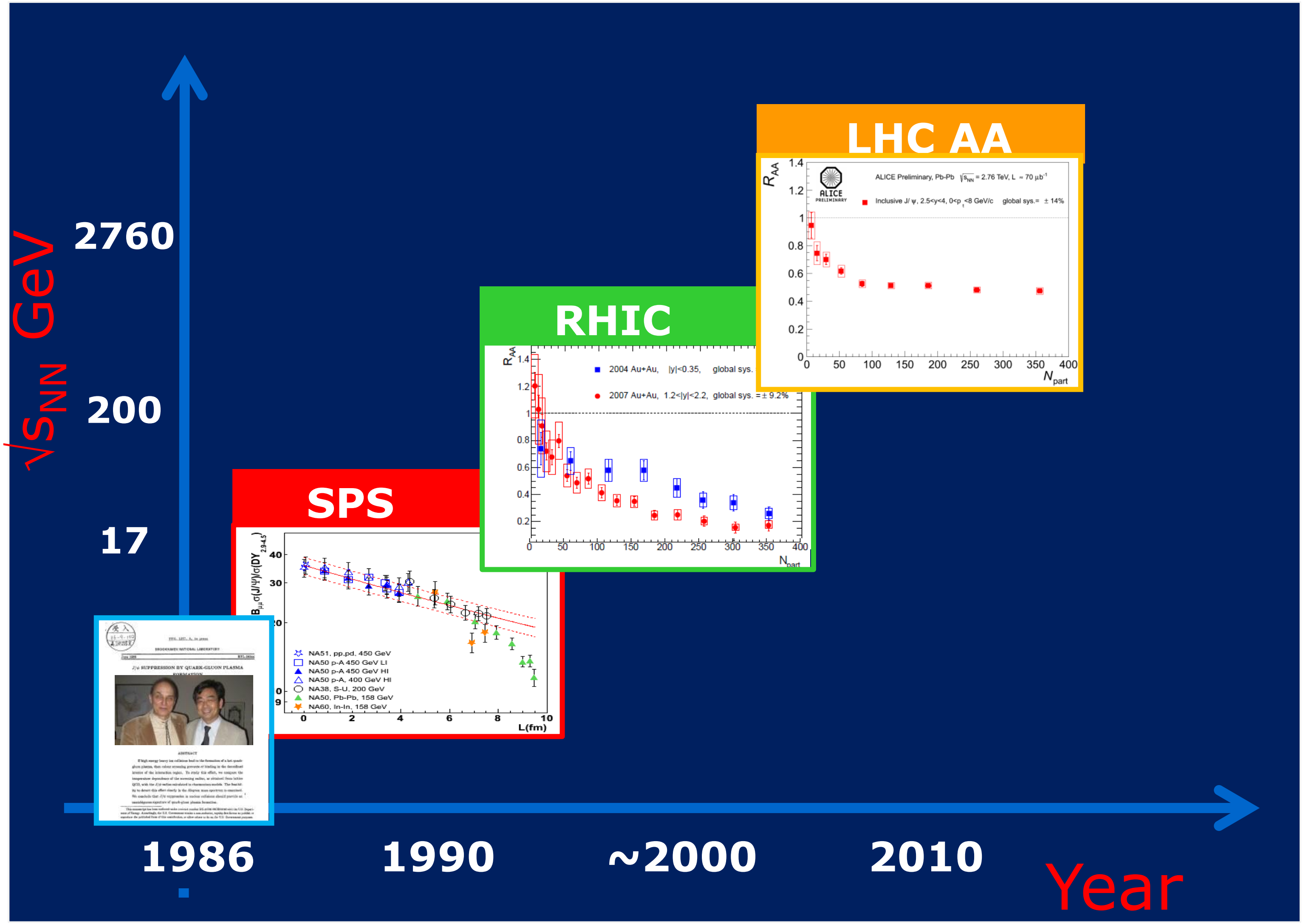
J/ψ production in proton-nucleus collisions at ALICE: cold nuclear matter really matters!



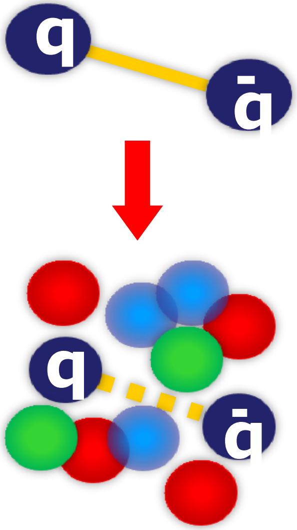
- Introduction, a bit of history…
- p-A/d-A collisions: fixed target vs collider, what have we learnt?
- First ALICE results on J/ψ production from the 2013 p-Pb run
- Comparison of ALICE J/ψ p-A results with theoretical models and with LHCb results

Quarkonium: introduction

- Quarkonium suppression has been, since 25 years, one of the most striking signatures for QGP formation in A-A collisions



From suppression to recombination in 1 slide!

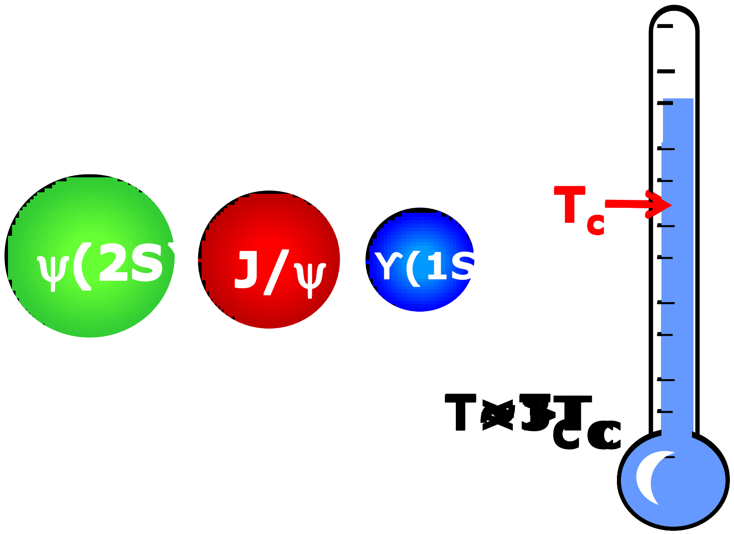


➡ In a QGP, binding of a $q\bar{q}$ pair is subject to colour screening:

- screening is stronger at high T
(screening length, i.e. maximum distance which allows the formation of a bound state, decreases with T)
- different states → different sizes

sequential melting of the states with increasing T

→ thermometer of the initial QGP temperature
(Digal,Petreczki,Satz PRD 64(2001) 0940150)



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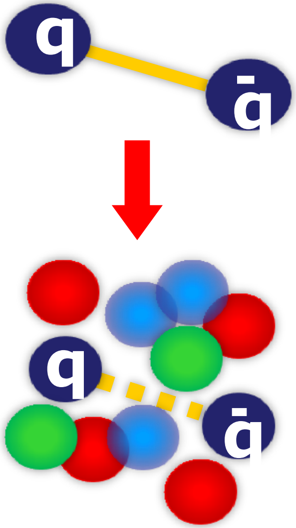
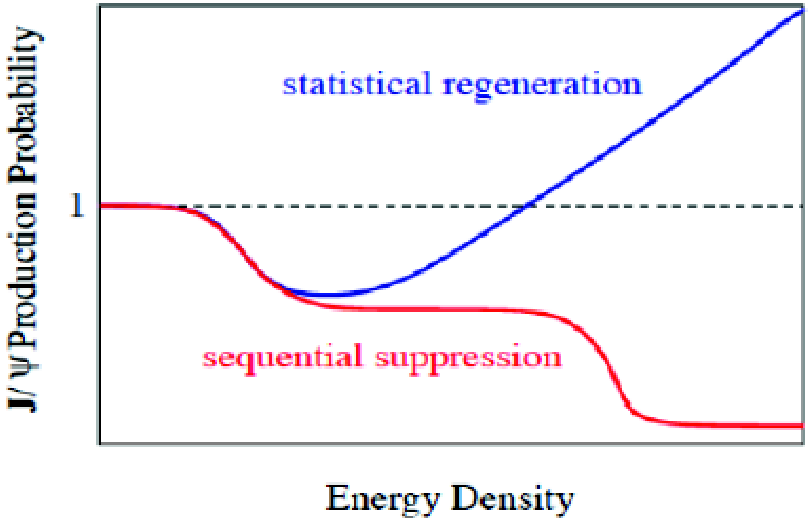


Increasing the collision energy, the $c\bar{c}$ pair multiplicity increases

In most central A-A collisions	**SPS 20 GeV**	**RHIC 200 Gev**	**LHC 2.76 TeV**
N_{ccbar}/event	**~0.2**	**~10**	**~60**

An enhancement via (re)combination of $c\bar{c}$ pairs producing quarkonia can take place at hadronization or during QGP stage



P. Braun-Muzinger and J. Stachel, Phys. Lett. B490(2000) 196, R. Thews et al, Phys.ReV.C63:054905(2001)

How can we measure medium effects?

- **Nuclear modification factor R_{AA}:**

  compare quarkonium yield in AA with the pp one, scaled by a the overlap factor T_{AA} (from Glauber model)

$$R_{AA}^{J/\psi} = \frac{Y_{AA}^{J/\psi}}{\langle T_{AA}\rangle \sigma_{pp}^{J/\psi}}$$

- If yield scales with the number of binary collisions

  → $R_{AA} = 1$

- If there are medium effects

  → $R_{AA} \neq 1$

Cold Nuclear Matter effects (CNM):

- Nuclear parton shadowing
- Parton energy loss
- $c\bar{c}$ in medium break-up

Hot Medium effects:

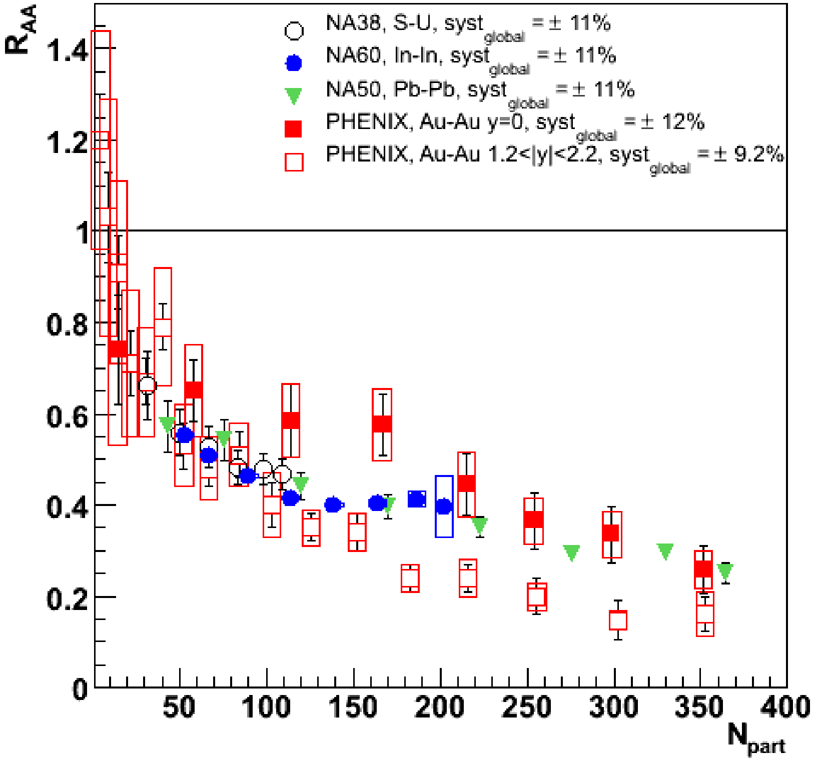
- quarkonium suppression
- enhancement due to recombination

- knowledge of CNM effects fundamental to disentangle genuine QGP induced suppression in A-A!

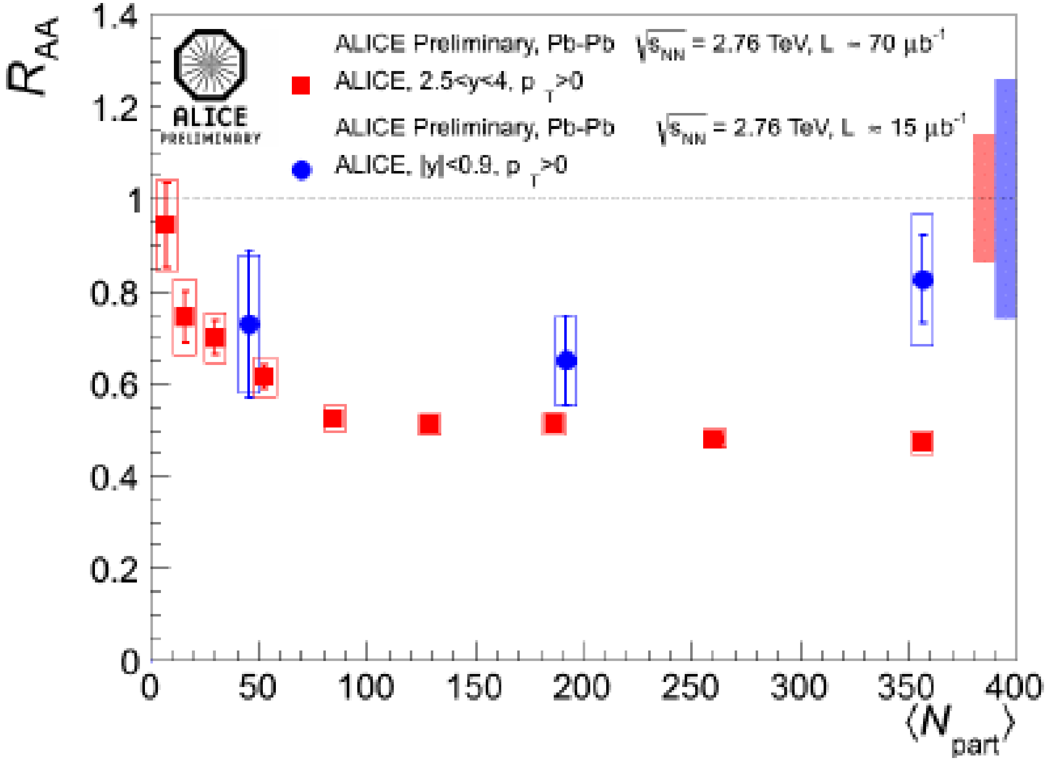
From SPS to LHC: J/ψ in AA collisions

- A reduction of the J/ψ yield wrt to pp collisions is observed at SPS (√s=17GeV), RHIC (√s=200GeV) and finally LHC (√s=2.76TeV)!

Eur.Phys.J.C71:1534,2011

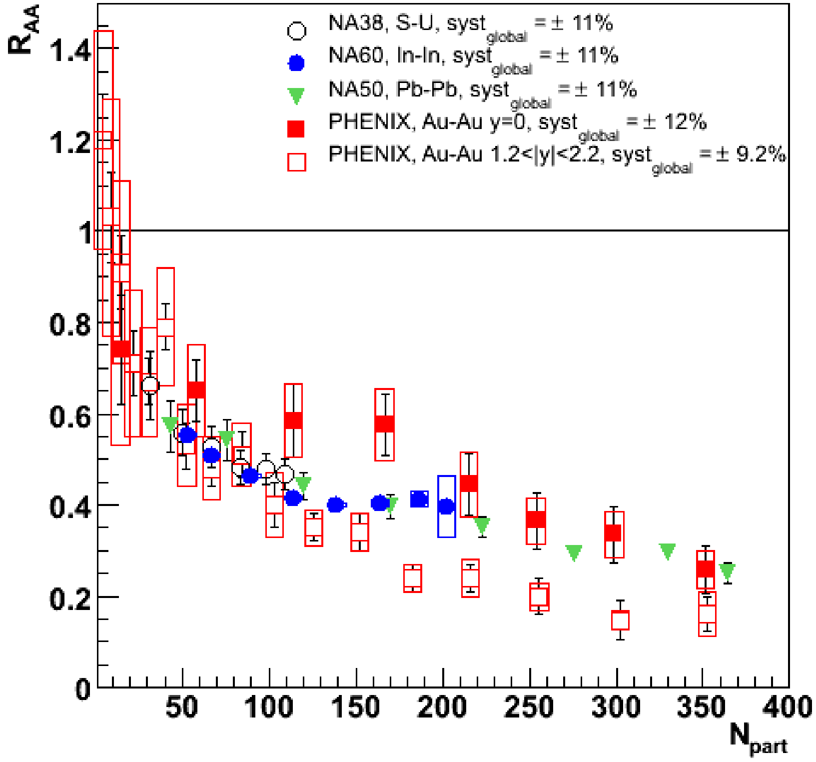


E. Scomparin, NPA 904-905, 202-209 (2013)

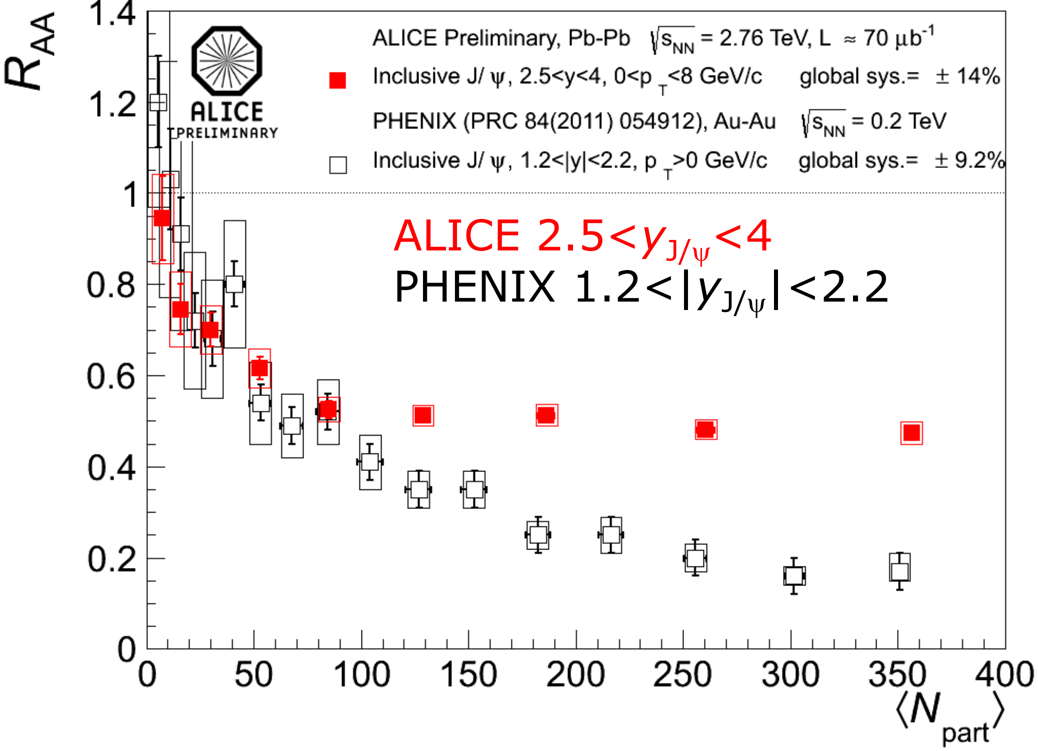


From SPS to LHC: J/ψ in AA collisions

- A reduction of the J/ψ yield wrt to pp collisions is observed at SPS (√s=17GeV), RHIC (√s=200GeV) and finally LHC (√s=2.76TeV)!
  - Decrease of suppression at LHC (low p_T J/ψ) could be a sign of (re)combination!



Eur.Phys.J.C71:1534,2011

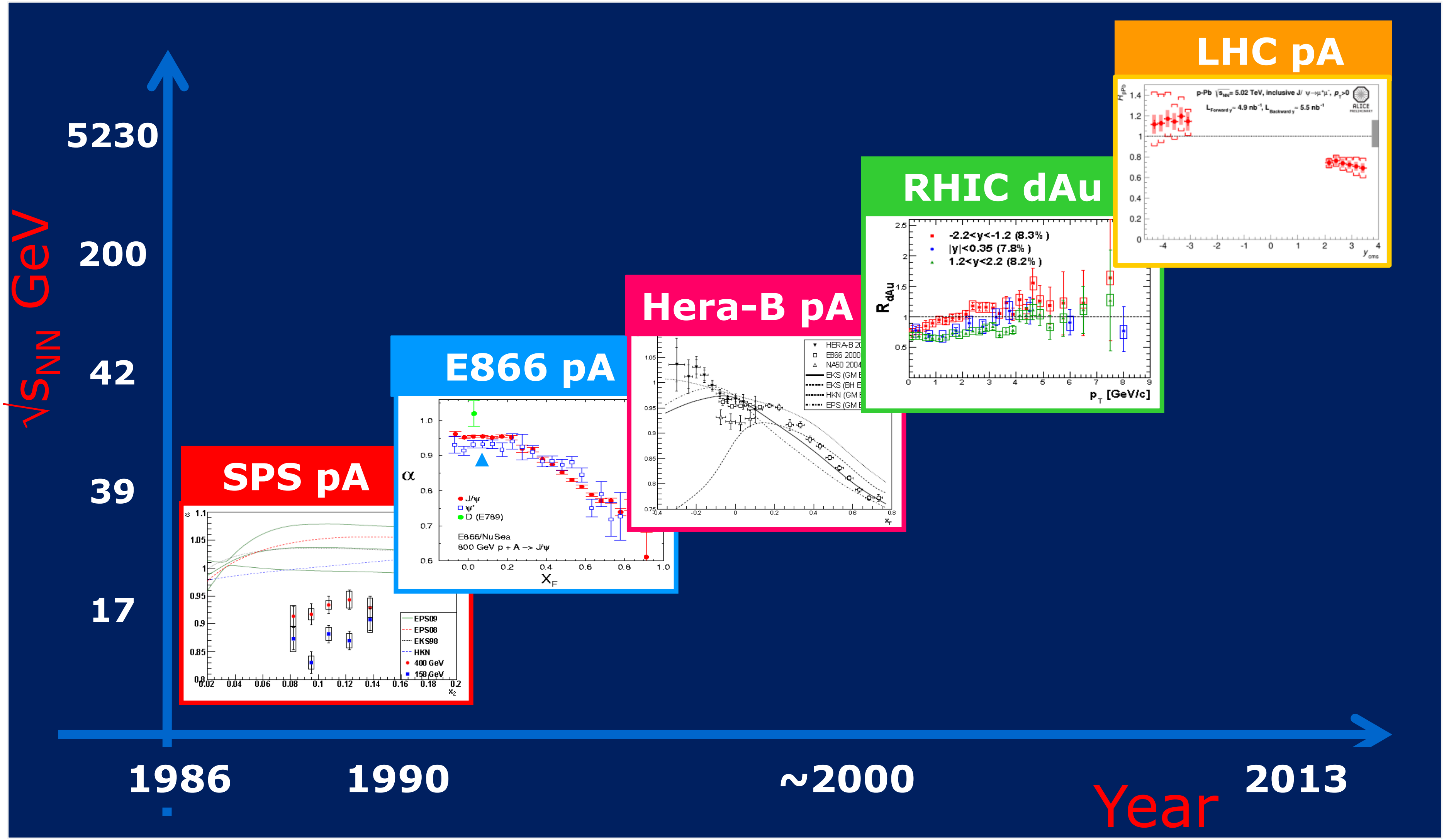


E. Scomparin, NPA 904-905, 202-209 (2013)

- To correctly interpret the results, hot and cold medium effects should be separated → need infos on quarkonium production in p-A collisions!

Quarkonium in p-A collisions

- … in parallel with the QGP search in heavy-ion collisions…a large wealth of data has been collected also in p-A collisions!

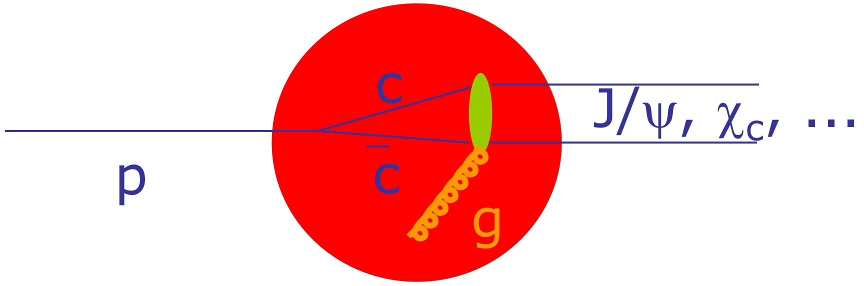


What can we learn by studying quarkonium in pA?

Production models:

the study of the interaction of the cc pair with the nuclei provides constraints to the 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))



Initial/final state nuclear effects:

J/ψ behaviour in cold nuclear matter (CNM) can be investigated

→ complicated issue, interplay of many competing mechanisms

Initial state
shadowing/saturation,
initial state energy loss,
intrinsic charm

Final state
cc in-medium dissociation
final state energy loss

Reference for understanding dissociation in a hot medium

knowledge of J/ψ behaviour in p-A to disentangle genuine QGP effects in A-A

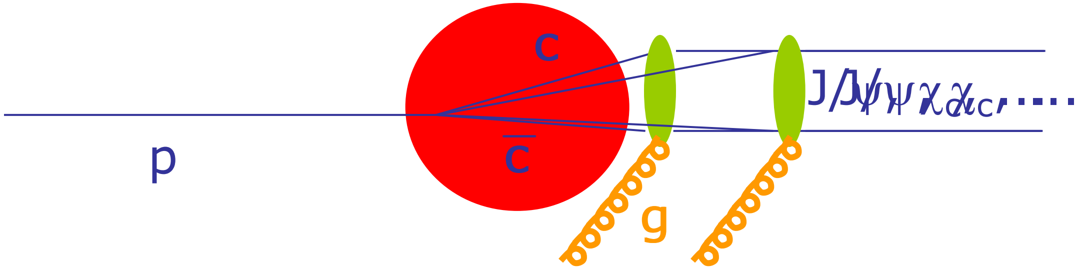
→ approach followed at SPS (p-A) and similarly at RHIC (d-Au data)

How can quarkonium be studied in p-A?

Varying the amount of nuclear matter crossed by cc pair

i.e. performing systematic studies as a function of A (or centrality)

→ the thickness of nuclear matter seen by the $c\bar{c}$ pair (or the fully formed resonance) changes



Selecting the kinematics of the quarkonium states

i.e. selecting events where resonance is formed inside or outside the nucleus

Study vs x_F is particularly relevant

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

Studying different resonances

→ they correspond to different mixtures of intermediate color octet/singlet states and may be affected differently by the nuclear medium

→ sizeable feed-down contribution to be taken into account

What do experiments measure?

- Use various target nuclei (or a single nucleus defining centrality classes) to study the CNM dependence on the thickness of nuclear matter

- Define “effective” quantities to evaluate size of CNM effects, without disentangling the different contributions

- These effects can be quantified in terms of the α parameter

$$\sigma_{pA}^{\psi} = \sigma_{pp}^{\psi} A^{\alpha}$$

$\alpha = 1$ → no nuclear effects
$\alpha < 1$ → nuclear effects

- ...through the so-called “absorption cross section”

$$\sigma_{pA}^{\psi} = A\sigma_{pp}^{\psi} e^{-\rho\sigma_{abs}^{\psi}L}$$

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

(L is the length of nuclear matter crossed by the $c\bar{c}$ pair)

- or, finally, in terms of nuclear modification factor R_{pA}

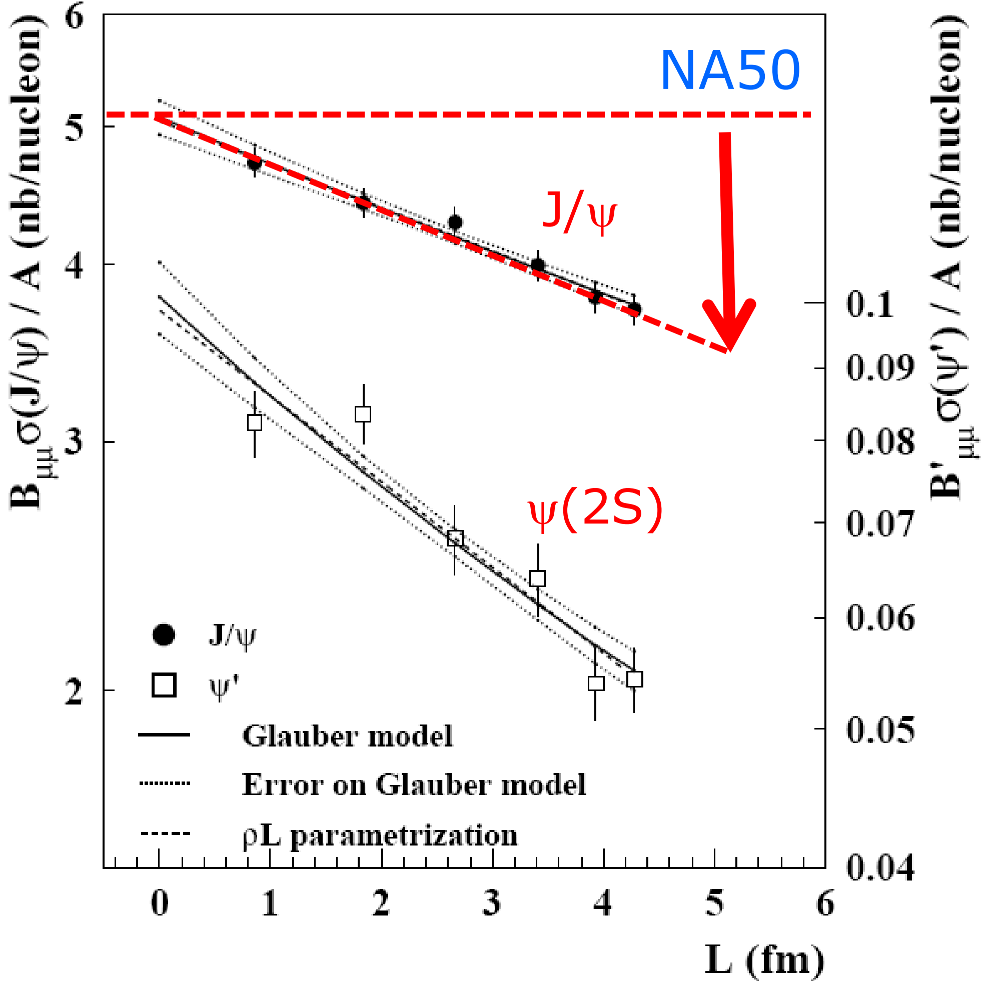
$$R_{pA} = \frac{1}{\langle N_{coll} \rangle} \frac{\sigma_{pA}^{\psi}}{\sigma_{pp}^{\psi}}$$

$R_{pA} \neq 1$ → nuclear effects

Quarkonium results at SPS

- A significant reduction of the yield per NN collision is observed

B. Alessandro et al.(NA50 Coll.) Eur.Phys.J C 48, 329(2006)



- Early studies interpreted this reduction as mainly due to "nuclear absorption"

- Stronger absorption for less bound state ψ(2S) at mid-*y*
  → Nucleus crossing time comparable or larger than charmonium formation time: fully formed resonances traversing the nucleus!

- Fitting with $\sigma_{pA} \sim \sigma_{pp} A e^{-\rho L \sigma_{abs}}$

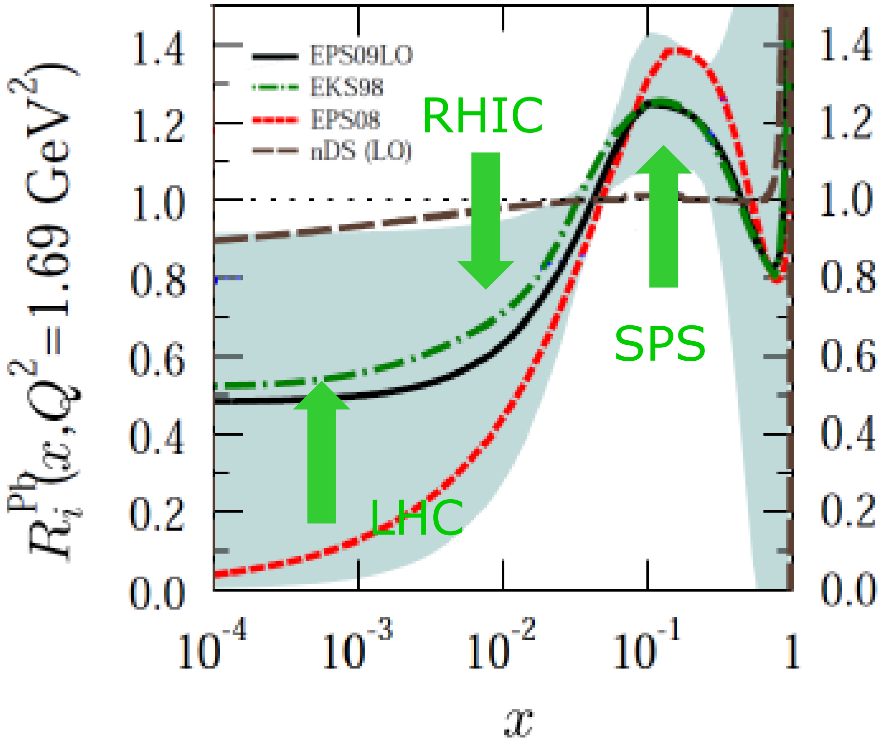
we get: $$\begin{cases} \sigma_{abs}^{J/\psi} = 4.5 \pm 0.5 \ \text{mb} \\ \sigma_{abs}^{\psi'} = 8.3 \pm 0.9 \ \text{mb} \end{cases}$$

- However nuclear absorption cannot be the only involved mechanism!

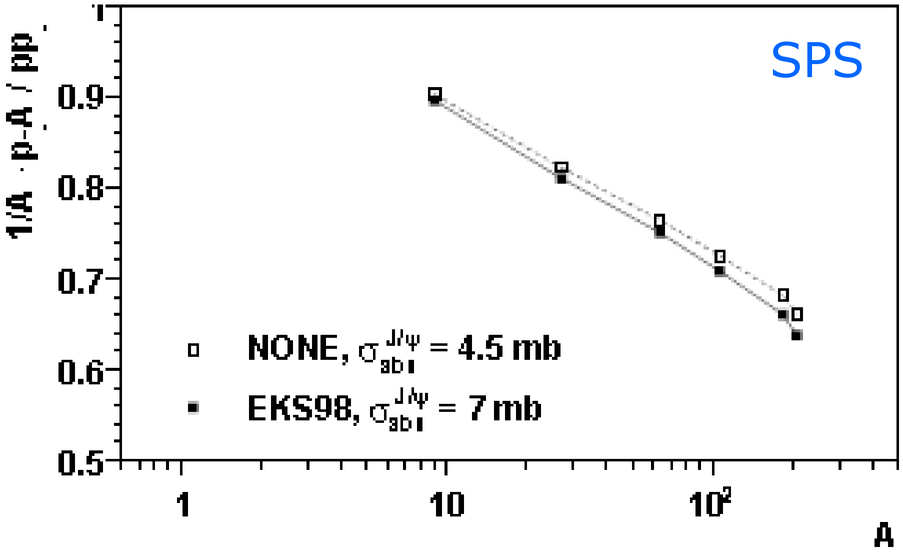
Nuclear shadowing

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!

Can we consider only shadowing + cc break-up?

- Assume dominant effects to be shadowing and cc breakup at mid-*y*

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

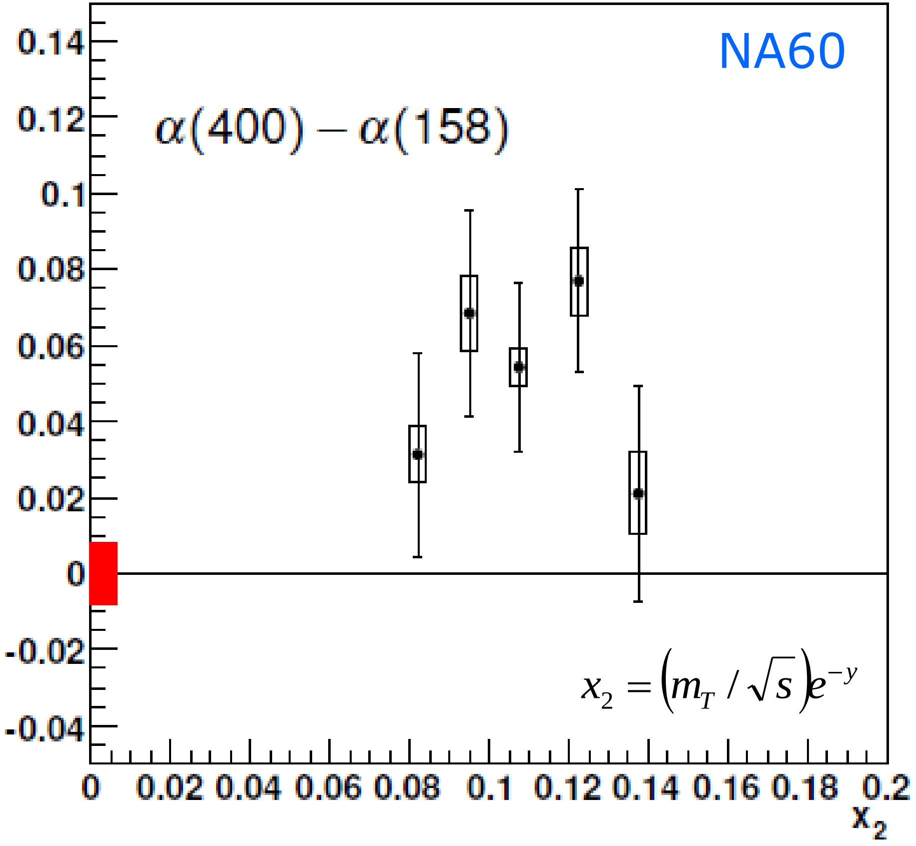
- J/ψ break-up depends on $\sqrt{s}_{J/\psi\text{-}N}$ which can be expressed as a function of x_2

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

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

- α should not depend on $\sqrt{s}$ at constant x_2 … and this is clearly not the case

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



- Other effects different from shadowing and cc breakup?

Initial state energy loss

- Energy loss of the incoming parton producing the $c\bar{c}$ pair

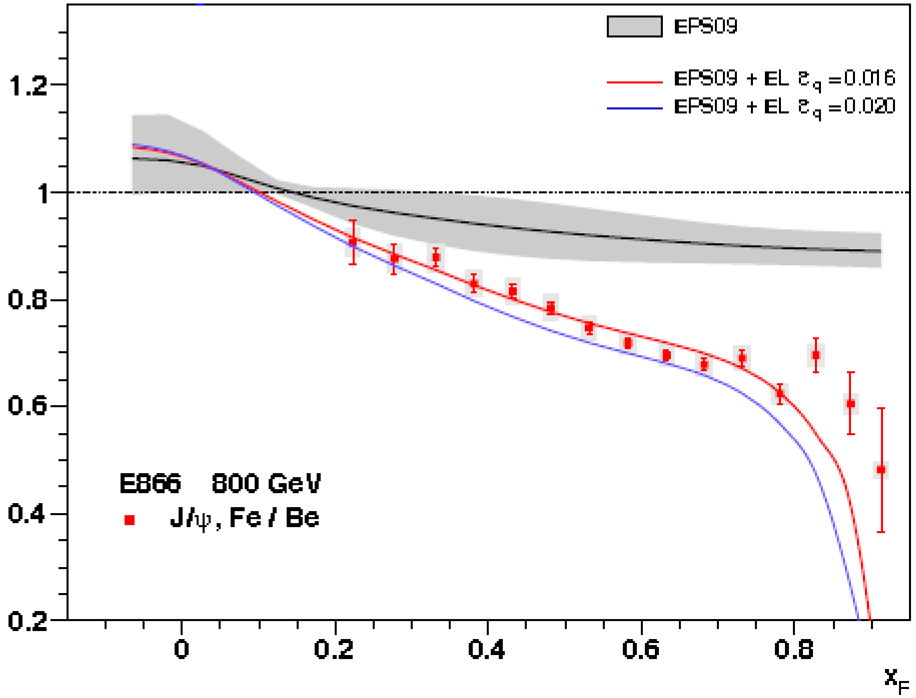
Common approach: constant fraction of the parton energy is lost in each collision → x_1 shift

$$x_1 = \left(m_T / \sqrt{s}\right) e^y$$

$$x_1' = x_1 \left(1 - \varepsilon_{q(g)}\right)^{N_{coll} - 1}$$

$\varepsilon_{q(g)}$: fractional en. loss

H.K.Woehri, "3 days of Quarkonium production...", Palaiseau 2010



- Effect most important for fast partons → large x_F

- Suppression increases towards high x_F

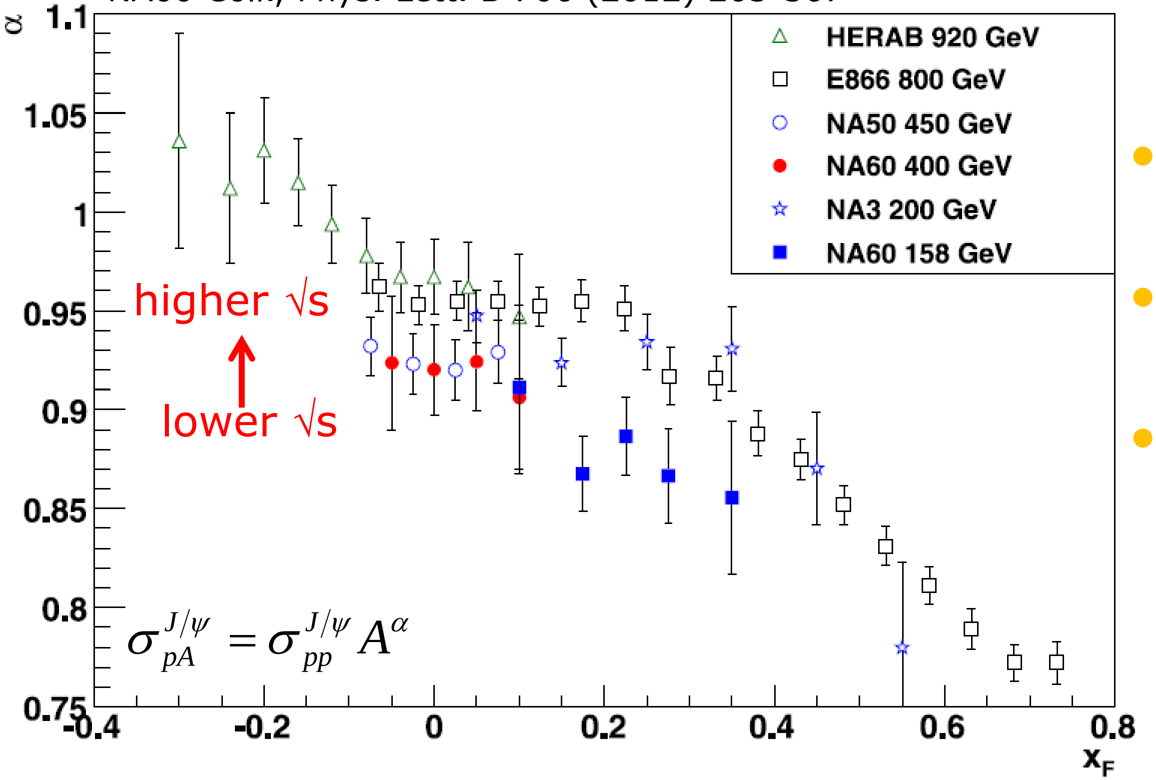
ε_q =0.002 (small!) seems enough to reproduce Drell-Yan results, but a larger (~factor 10) energy loss is required to reproduce large-x_F J/ψ depletion from E866!

- New theoretical approaches (Peigne', Arleo): coherent energy loss, may explain small effect in DY and large for charmonia

CNM effects in p-A: summary

Important to consider all available p-A data, collected at different energies and in different kinematical regions

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



- J/ψ yield in p-A is modified with respect to pp collisions
- Strong x_F dependence of suppression
- For a fixed x_F, stronger nuclear effects at lower √s

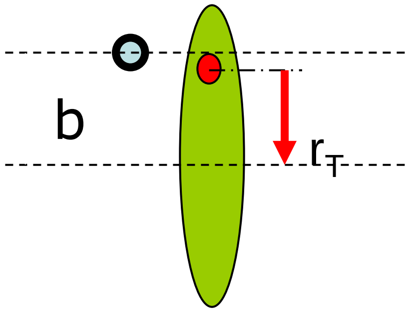
Theoretical description over the full x_F range still meets difficulties!

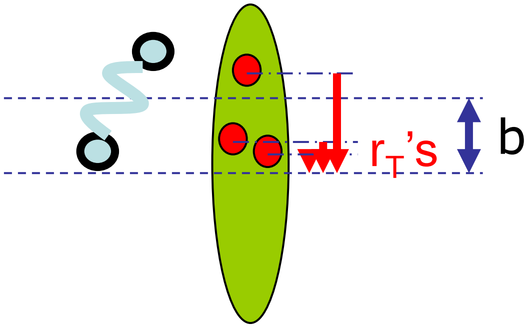
Given the strong x_F and √s dependence, pA data used as reference for AA collisions should be collected in the same kinematical domain

Moving to higher energies: d-Au at RHIC

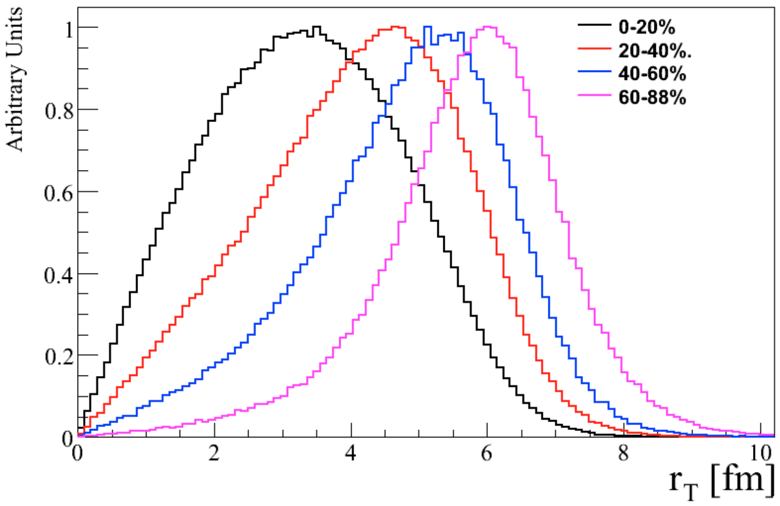
Much larger √s at colliders!
Different approach wrt to fixed target experiments:

Instead of accelerating several different nuclei
→ Use one nucleus 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

Centrality classes overlaps

Also shadowing estimates are less precise (need b-dependence)

d-Au rapidity range

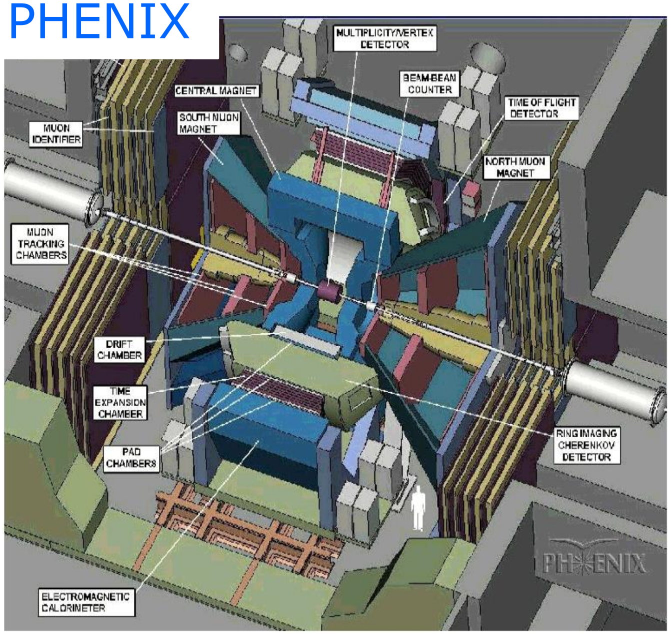
Regions corresponding to very different strength of shadowing effects have been studied:

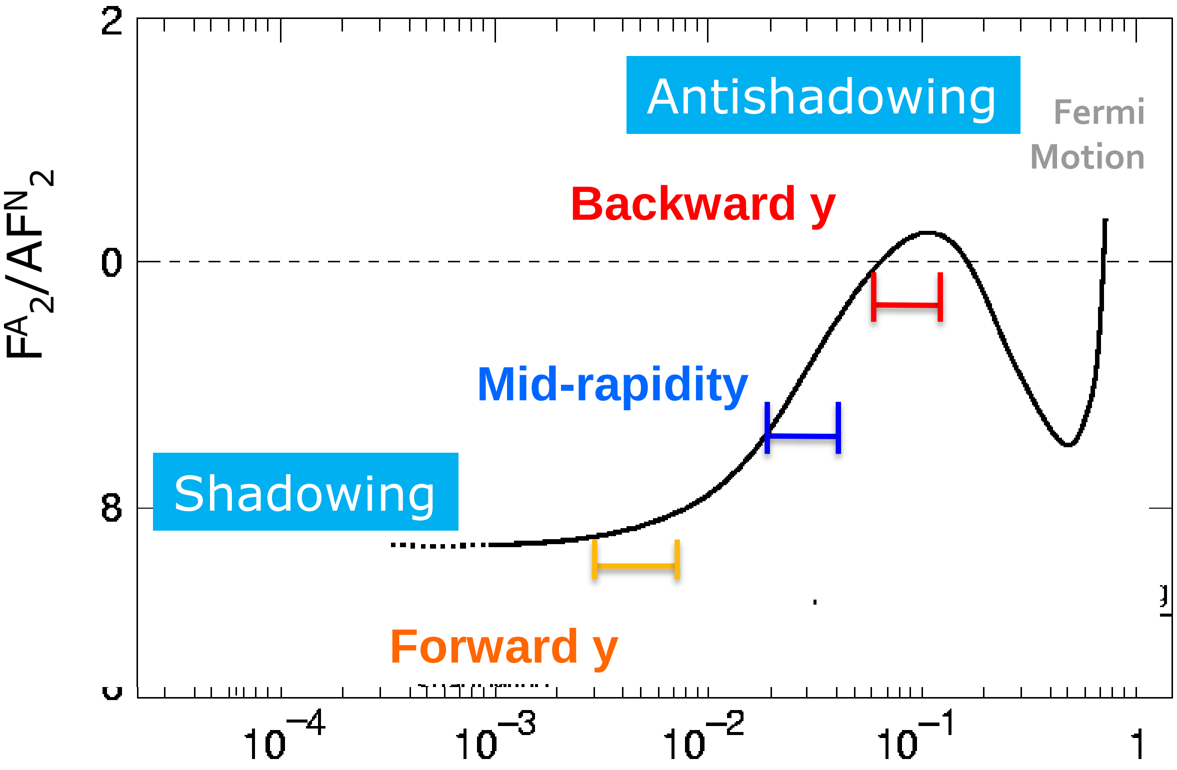
$-2.2<y<-1.2$, $|y|<0.35$, $1.2<y<2.2$

→ good test of our understanding of the physics!

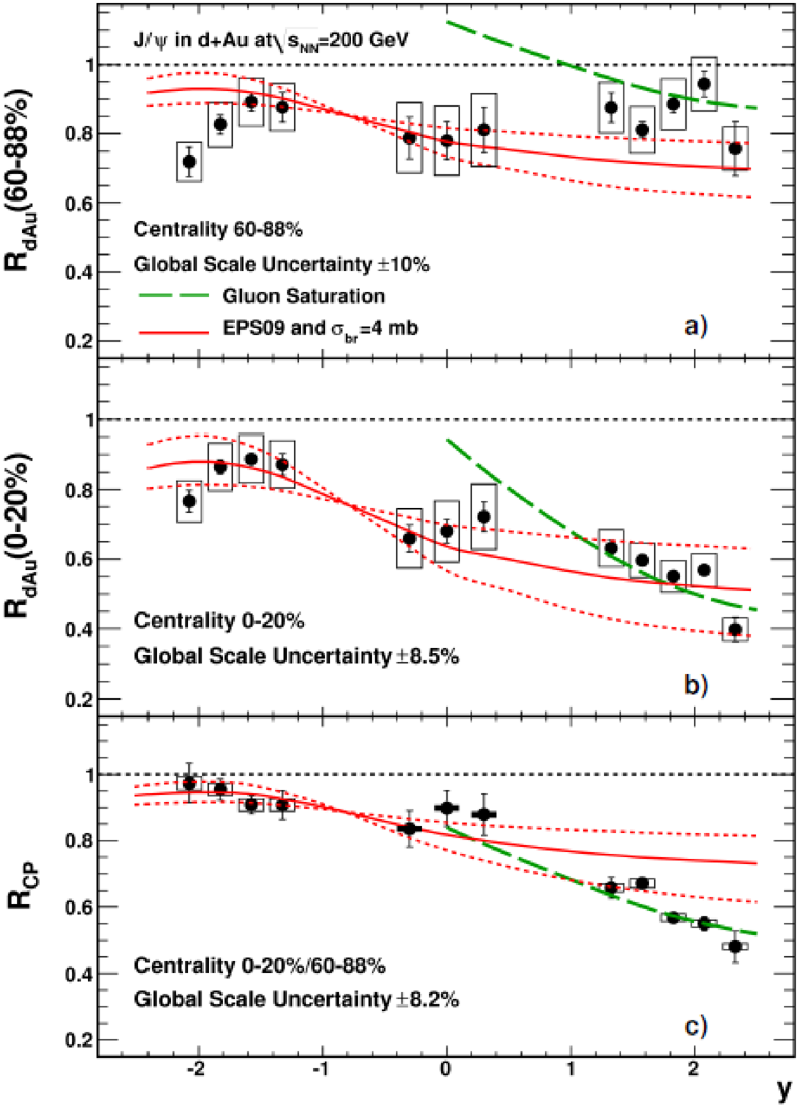
forward y	x~0.005
mid y	x~0.03
backward y	x~0.1

PHENIX



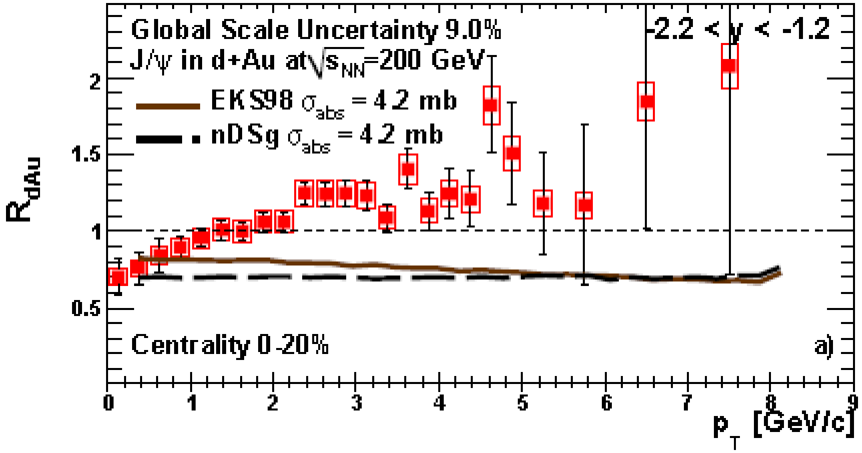


A selection of PHENIX results



Phys. Rev. C 87 034904 (2013)

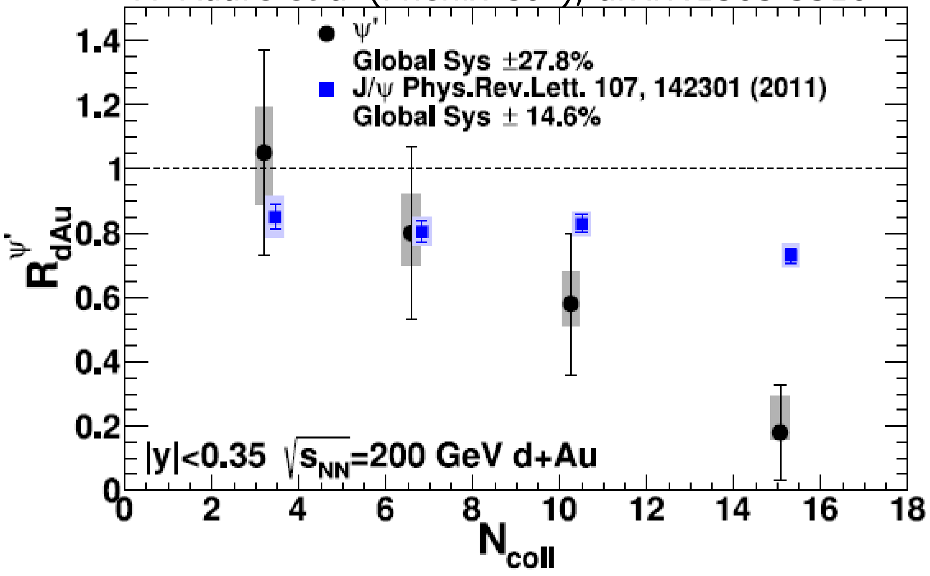
- R_{dAu} is studied versus centrality, y and p_T
  - disentangling CNM mechanisms is challenging
- description in terms of shadowing + cc break-up is reasonable for R_{dAu} vs y, but it meets some difficulties for R_{dAu} vs p_T



$\psi(2S)$ suppression in d-Au

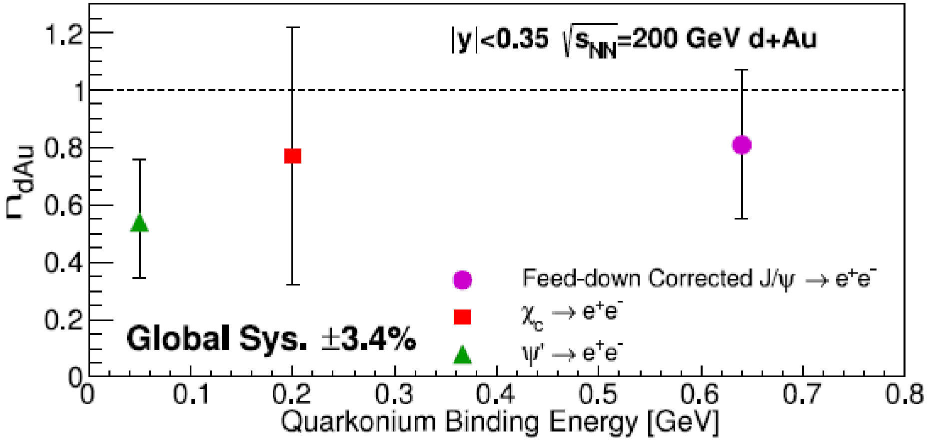
- At RHIC energy, the time spent traversing the nucleus is shorter than the J/ψ and $\psi(2S)$ formation time
  - → final meson state should form outside the nucleus
  - → absorption effects of pre-resonance state expected to be similar
  - → shadowing effects should be very similar for J/ψ and $\psi(2S)$

- However in contrast with these observations


A. Adare et al.(Phenix Coll), arXiv:1305.5516

- much stronger $\psi(2S)$ suppression in central collisions wrt J/ψ!

- More suppression for less bound states



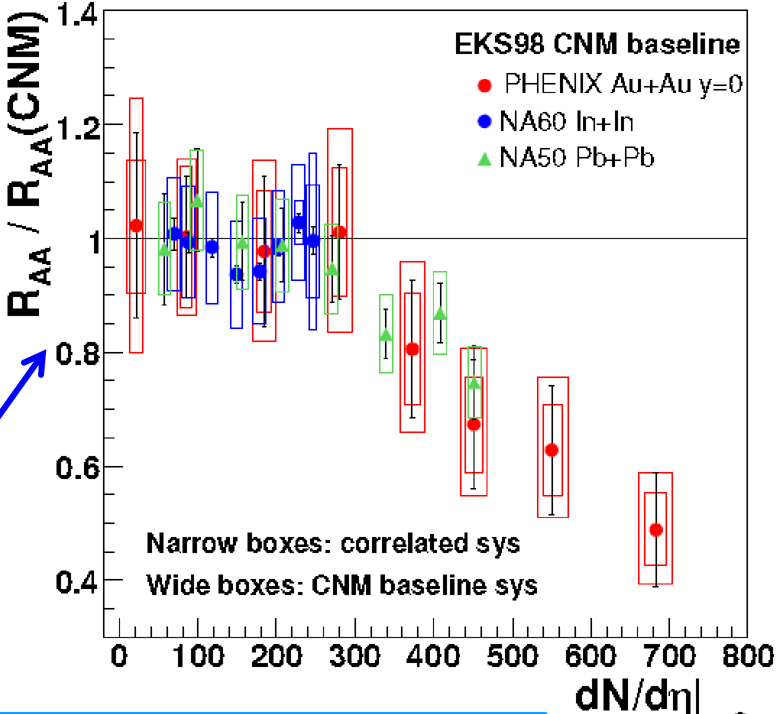
- Is there a process affecting differently the J/ψ and the $\psi(2S)$ at RHIC energy?

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

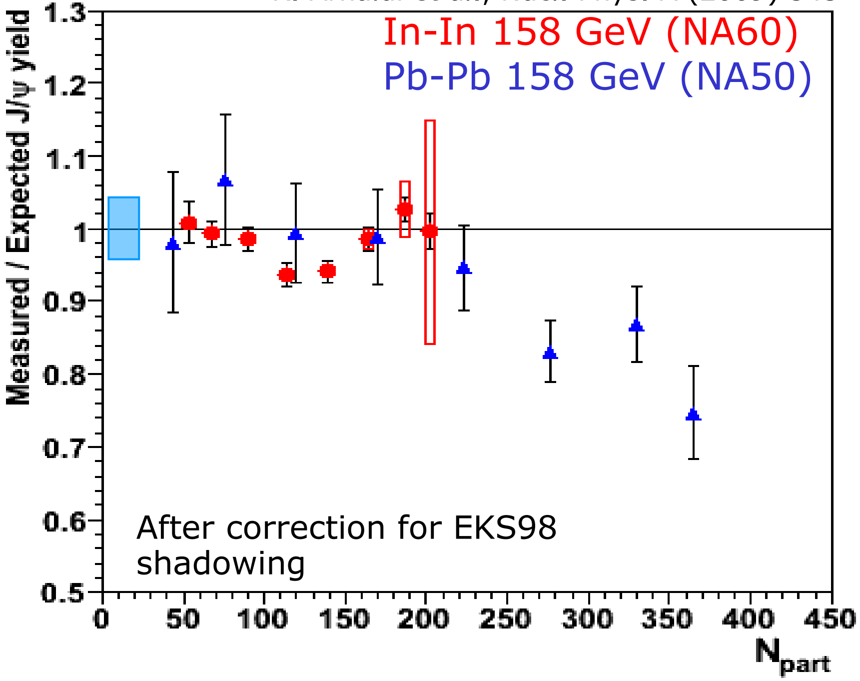


R_{AA} normalized to CNM expectations

~ proportional to energy density

B. Alessandro et al., EPJC39 (2005) 335

R. Arnaldi et al., Nucl. Phys. A (2009) 345

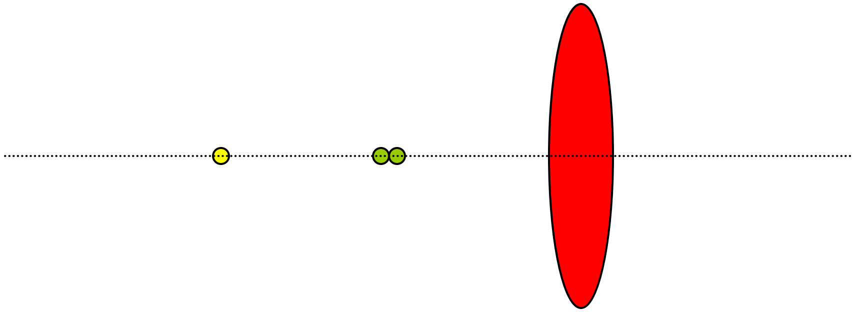


- Clear suppression is indeed observed on top of CNM effects!

Which CNM at LHC?

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

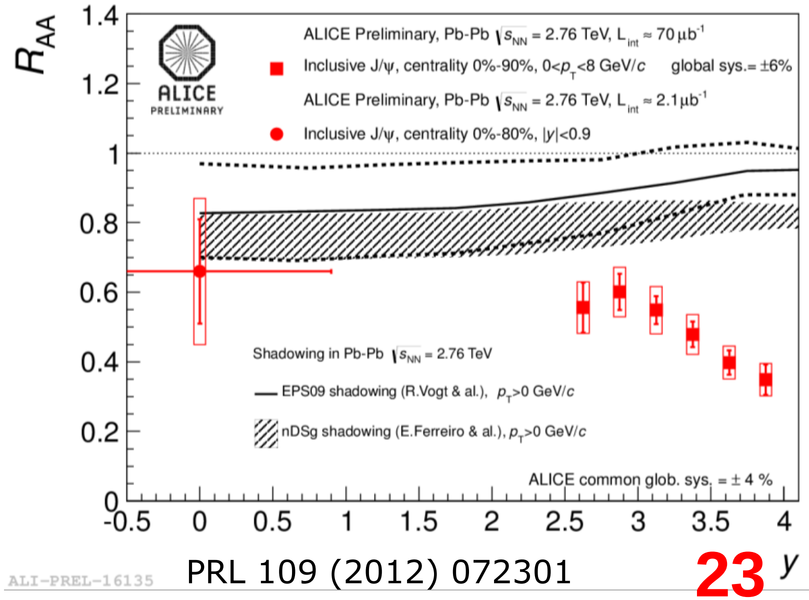
  → $c\bar{c}$ pair may still be almost point-like after crossing the nuclear matter
  → final state effects might be negligible



- Dominant effects should be shadowing and/or energy loss

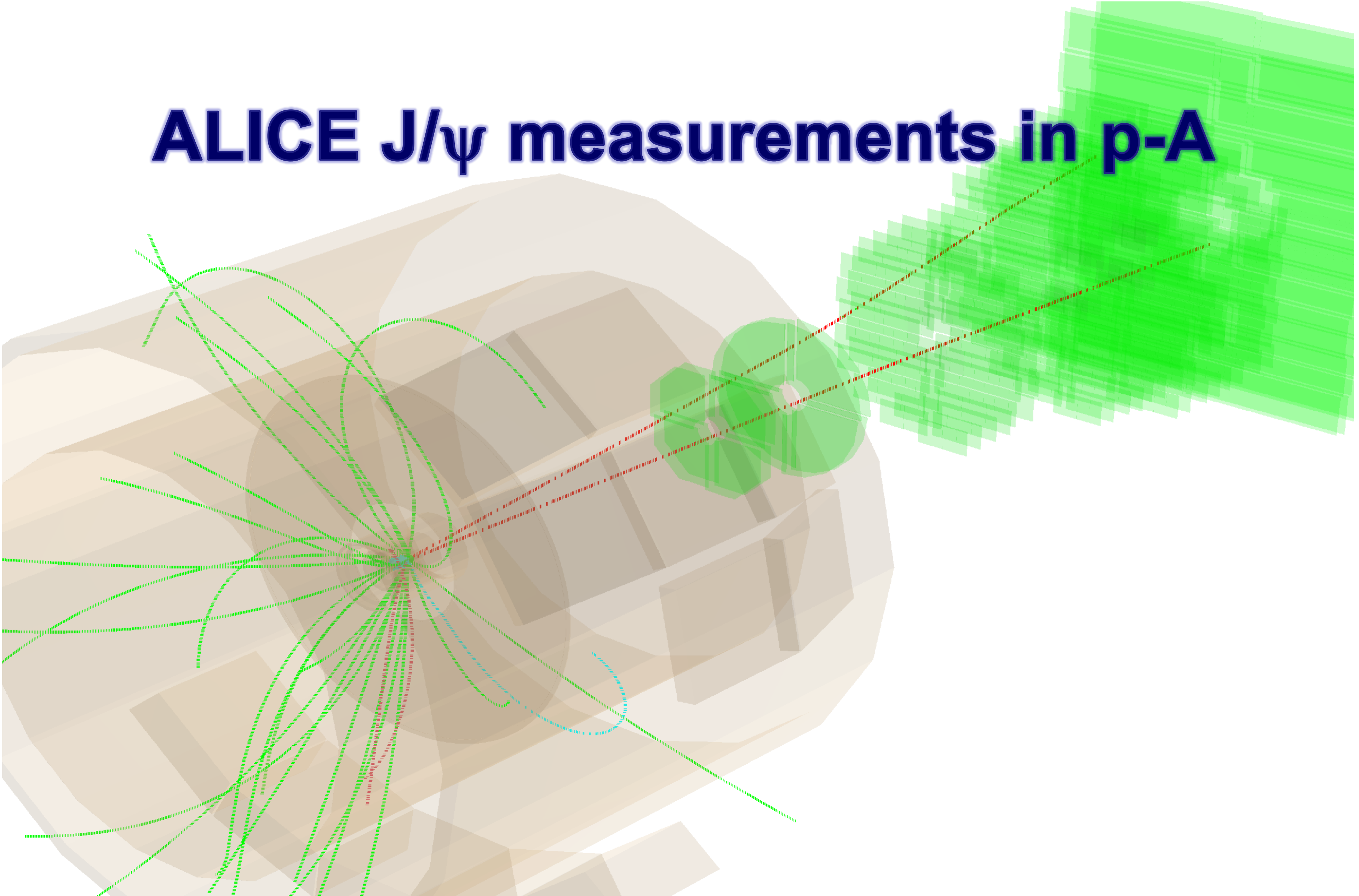
  - low-x probed region:
    → parton saturation effects can also be investigated
  - sizeable shadowing effects

    → use J/ψ to constrain low-x gluon nPDF and reduce uncertainties



PRL 109 (2012) 072301

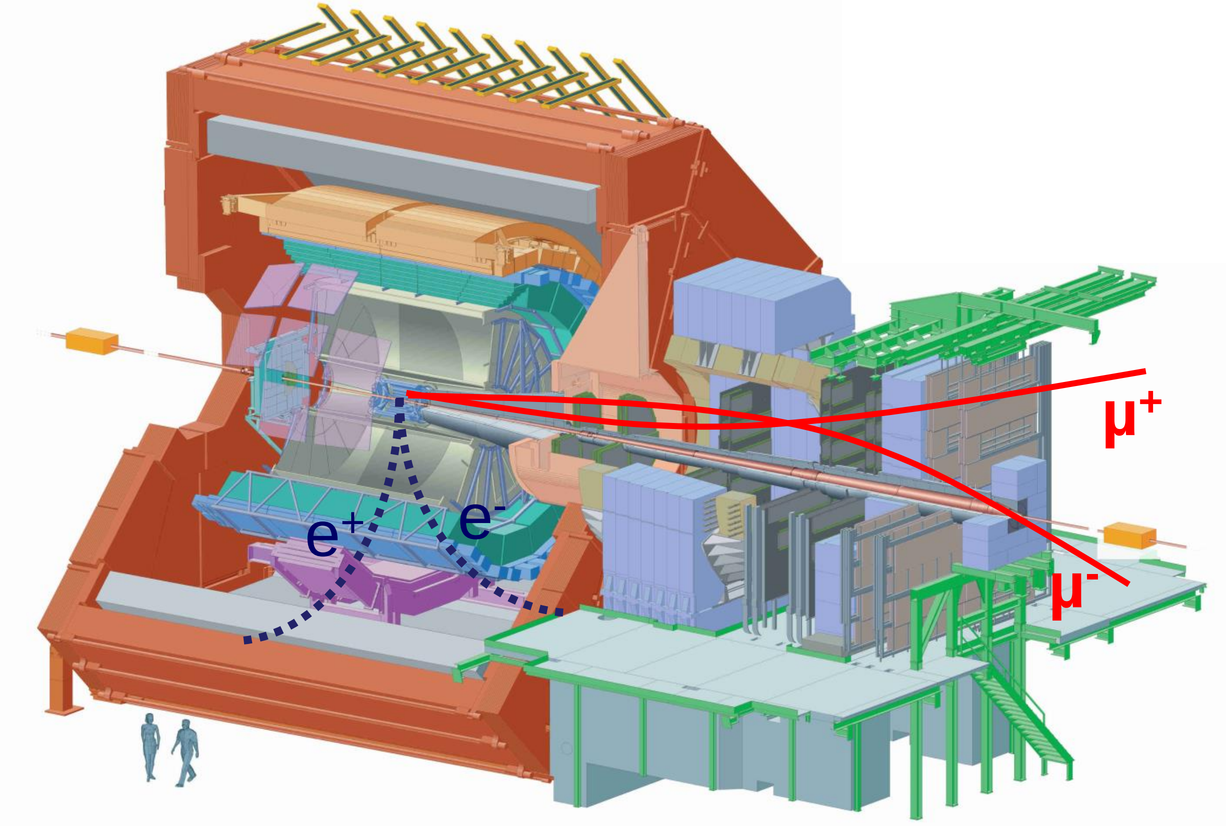
ALICE J/ψ measurements in p-A



Quarkonium measurement in ALICE

Quarkonium in ALICE can be measured in two ways:

Central Barrel $(\lvert y_{LAB} \rvert < 0.9)$ **$J/\psi \rightarrow e^+e^-$**	**Forward muon arm** $(2.5 < y_{LAB} < 4)$ **$J/\psi \rightarrow \mu^+\mu^-$**
Electrons tracked using ITS and TPC Particle identification: TPC, TOF, TRD	Muons identified and tracked in the muon spectrometer



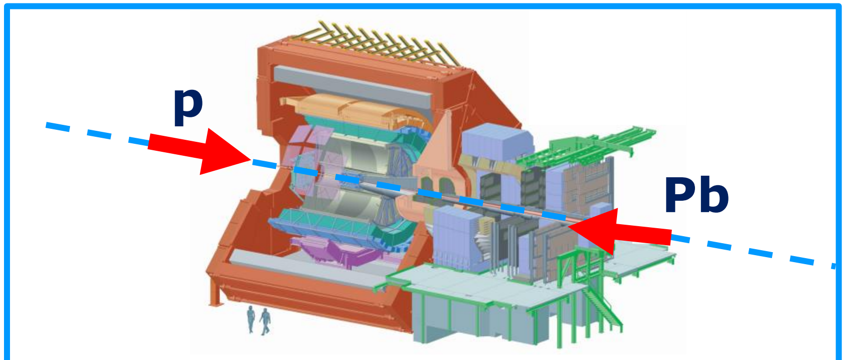
- Acceptance coverage in both *y* regions down to zero p_T
- ALICE results presented in this talk refer to inclusive J/ψ production in the $\mu^+\mu^-$ decay channel

p-A collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

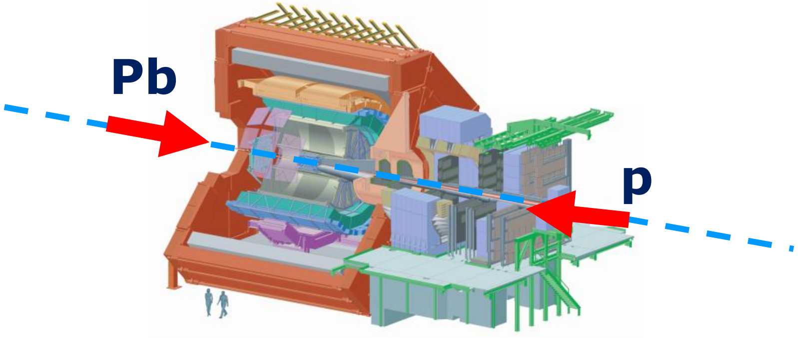
- Results from data collected in January/February 2013

- **Beam energy: $\sqrt{s_{NN}}$ = 5.02 TeV**
  Energy asymmetry of the LHC beams (E_p = 4 TeV, E_{Pb}= 1.58 A·TeV)
  → rapidity shift Δy= 0.465 in the proton direction

- **Beam configurations**:
  Data collected with two beam configurations: p-Pb and Pb-p in the range $2.5<y_{LAB}<4$



$2.03<y_{CMS}<3.53$



$-4.46<y_{CMS}<-2.96$

- **Integrated luminosity used for this analysis:**
  p-Pb ($2.03<y_{CMS}<3.53$) ~ 4.9 nb^{-1}
  p-Pb ($-4.46<y_{CMS}<-2.96$) ~ 5.5 nb^{-1}

Physics observables

Nuclear effects on J/ψ production can be parameterized via:

$$Y_{pPb}^{J/\psi} = \frac{N_{J/\psi}}{(A \times \varepsilon) N_{MB}}$$

Nuclear modification factor R_{pA}:

$$\boxed{R_{pPb}^{J/\psi} = \frac{Y_{pPb}^{J/\psi}}{\langle T_{pPb} \rangle \sigma_{pp}^{J/\psi}}}$$

Pros:
The full coverage of the ALICE muon spectrometer $2.5<y_{LAB}<4$ can be exploited
Cons:
Rely on an estimate of the $\sigma^{J/\psi}_{pp}$ reference at $\sqrt{s_{NN}}=5.02$TeV

Forward to backward ratio R_{FB}:

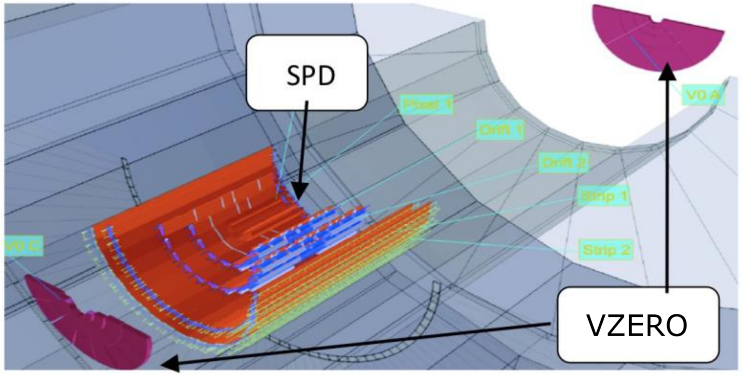
$$\boxed{R_{FB} = \frac{Y_{J/\psi}^{Forward}}{Y_{J/\psi}^{Backward}}}$$

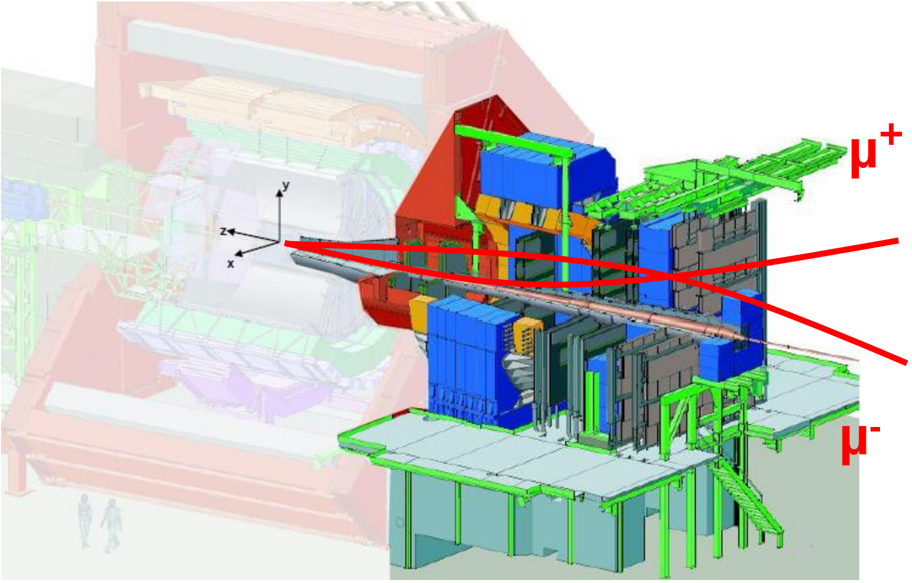
Pros:
Does not depend on the estimate of the $\sigma^{J/\psi}_{pp}$ reference at $\sqrt{s_{NN}}=5.02$TeV
Cons:
The forward and backward yields have to be computed in the common (restricted) y_{CMS} range $2.96< |y_{CMS}|< 3.53$

Event selection

Event selection:

- Rejection of beam gas and electromagnetic interactions (VZERO and ZDC)
- SPD used for vertex determination





Trigger:

- Dimuon trigger: coincidence of a minimum bias (MB) interaction with two opposite sign muon tracks detected in the trigger chambers of the Muon Spectrometer.
- MB trigger efficiency ~99% for NSD events

Muon track selection:

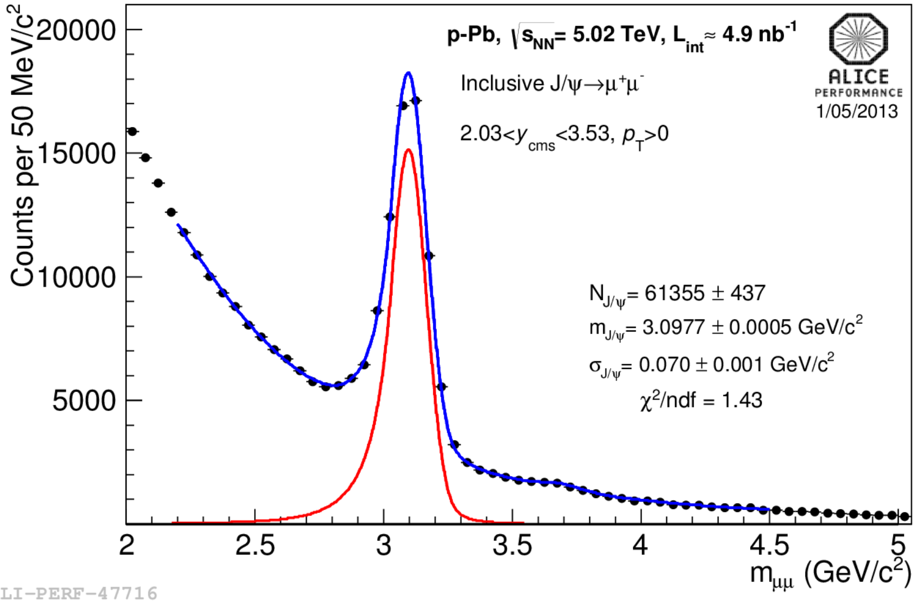
- Muon trigger matching
- $-4<\eta_\mu<-2.5$
- $17.6<R_{abs}<89$ cm
  (R_{abs}= track radial position at the absorber end)
- $2.5<y^{\mu\mu}_{LAB}<4$

$J/\psi \rightarrow \mu^+\mu^-$ signal

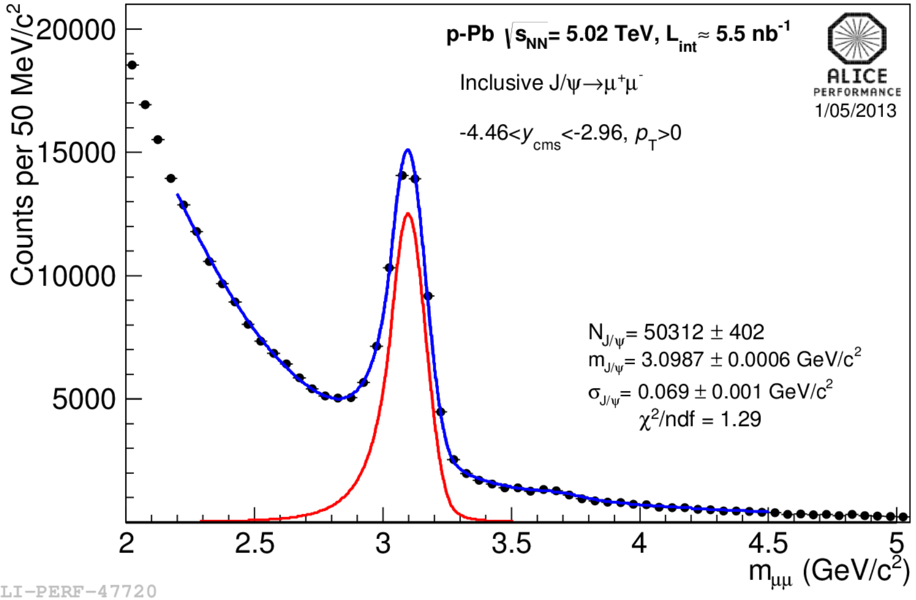
- J/ψ yield extracted fitting the opposite sign dimuon invariant mass spectrum with a superposition of signal and background shapes

- Signal: shape described by an extended Crystal Ball function or other pseudo-gaussian phenomenological shapes

  Background: several functions tested, as a variable width gaussian or combinations of exponential x polynomial functions



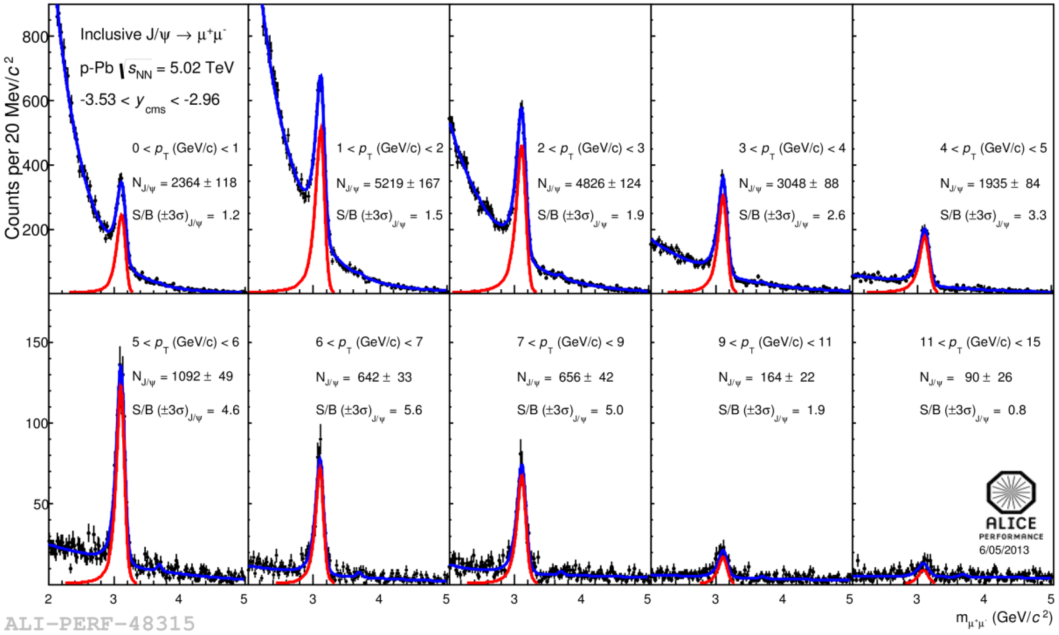
ALI-PERF-47716



ALI-PERF-47720

$J/\psi \rightarrow \mu^+\mu^-$ signal

- J/ψ yield extracted fitting the opposite sign dimuon invariant mass spectrum with a superposition of signal and background shapes:



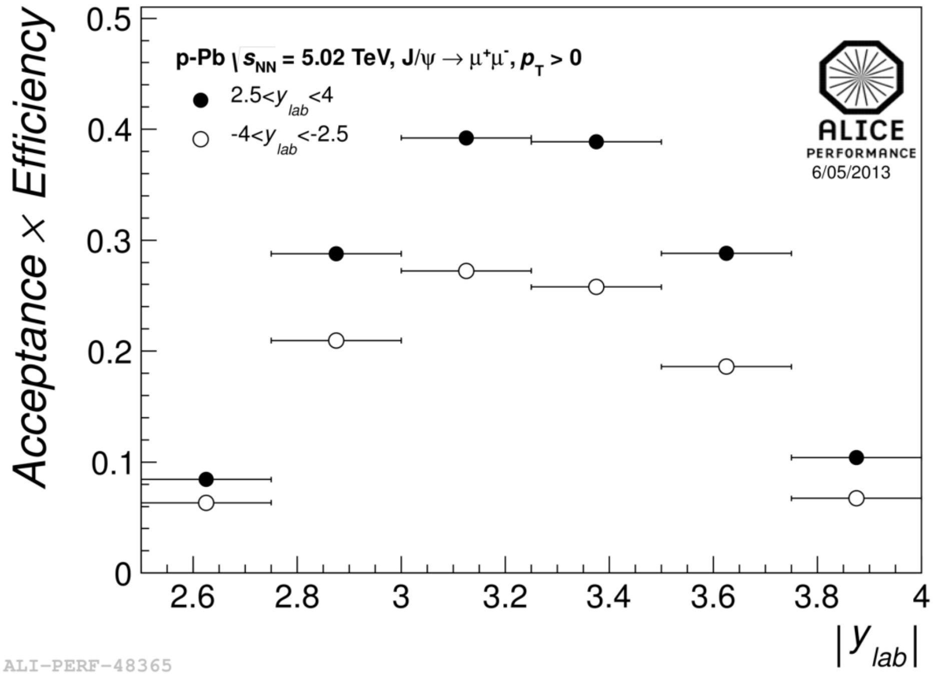
- Signal: shape described by an extended Crystal Ball function or other pseudo-gaussian phenomenological shapes

  Background: several functions tested, as a variable width gaussian or combinations of exponential x polynomial functions

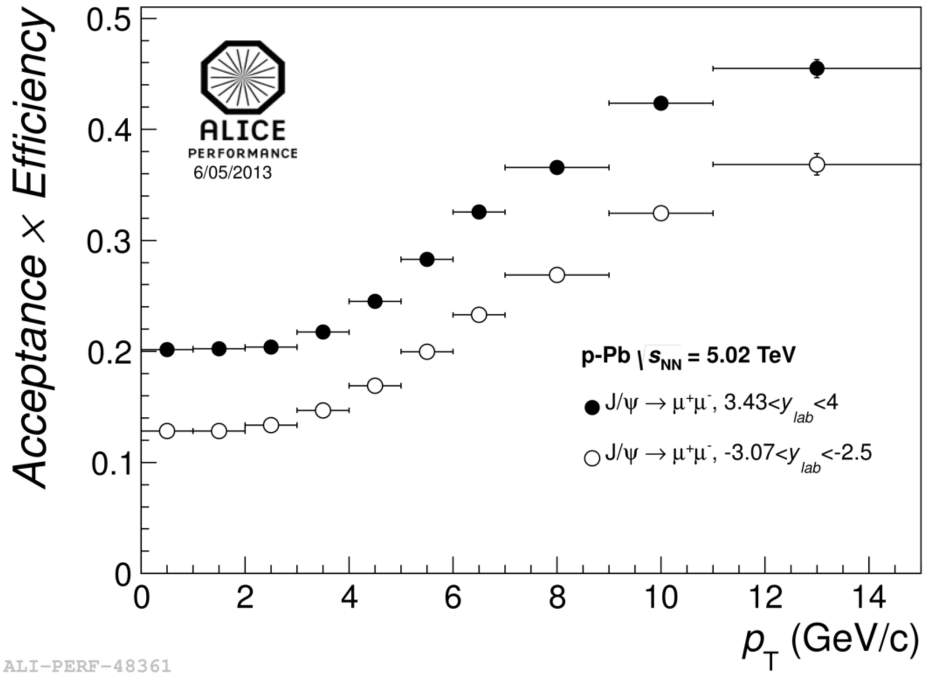
- Thanks to the large collected statistics, J/ψ yields can be extracted also in kinematic bins (y, p_T)

J/ψ acceptance x efficiency

Acceptance x efficiency computed with pure signal simulations, using as input J/ψ y and p_T kinematical distributions tuned on p-Pb data



ALI-PERF-48365



ALI-PERF-48361

Average J/ψ Acc. x Eff (dominated by geometrical acceptance):

- ~25% in $2.03<y_{CMS}<3.53$
- ~17% in $-4.46<y_{CMS}<-2.96$

(the lower acceptance x efficiency value for $-4.46<y_{CMS}<-2.96$ is due to a time-dependent detector efficiency)

Systematic uncertainties

➡ Summary of the systematic uncertainties for R_{pA} (or R_{FB})

Source of systematic uncertainty	
Signal extraction	1-4%
Acceptance inputs	1-3.5%
Trigger efficiency	3%
Tracking efficiency	4-6%
Matching efficiency	1%
Normalization dimuon-MB trigger	1%
Nuclear overlap function T_{pA}	3.5%
pp reference @ y=0, $\sqrt{s_{NN}}$ = 5.02TeV	10-15%
y-dependence of pp reference @ $\sqrt{s_{NN}}$ = 5.02TeV	10-20%
Total syst. uncertainty (excluding pp ref)	**~7-12 %**

(ranges correspond to values obtained in y or p_T bins)

The pp reference at √s = 5.02 TeV

- pp data at √s = 5.02 TeV are not available
  - reference cross section $\sigma_{J/\psi}^{pp}$ obtained through an interpolation procedure (based on F. Bossu’ et al., arXiv:1103.2394)
  - $\sigma_{J/\psi}^{pp}$ energy and rapidity dependence interpolated from CDF (√s = 1.96 TeV), PHENIX (√s = 200 GeV), ALICE, LHCb (√s = 2.76 and 7TeV) and CMS (√s = 7TeV) data

- **Energy dependence: pp cross section ad mid-rapidity**
  - Interpolation based on a phenomenological shape (power-law) gives, at √s = 5.02 TeV

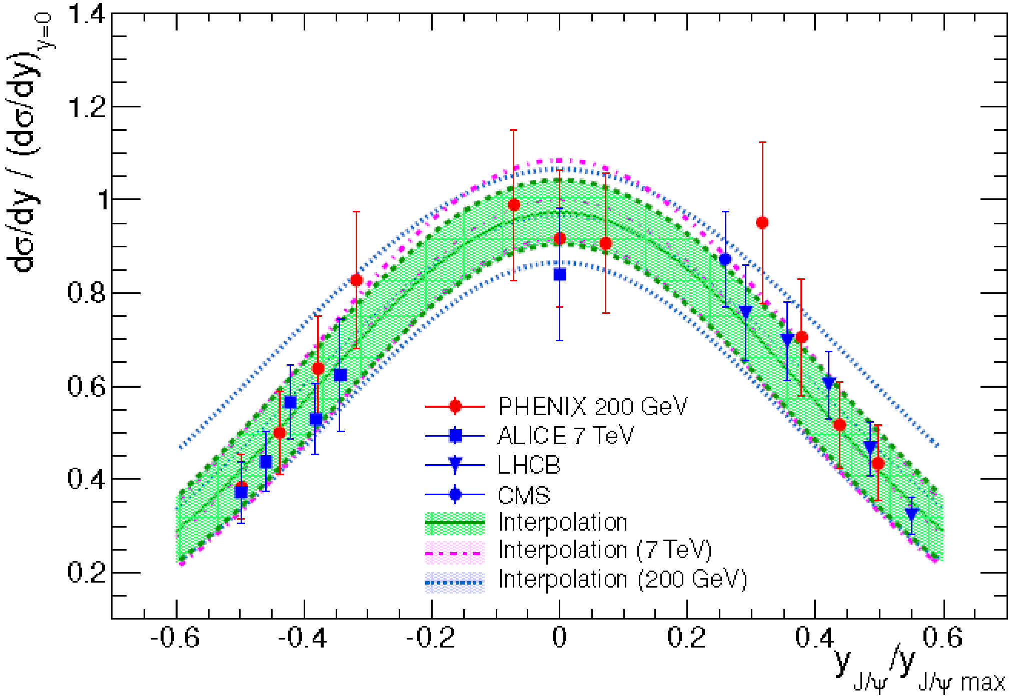
$$BR \times \left.\frac{d\sigma^{pp}}{dy}\right|_{y=0} = 362 \pm 6(stat) + 55(syst) - 37(syst)\,nb$$

  - Systematic uncertainties evaluated fitting test distributions obtained moving data points according to a Gaussian distribution with a width corresponding to 2.5 × their systematic uncertainties (randomly for uncorrelated ones, same direction for correlated ones)
  - Results are in agreement with FONLL and LO CEM calculations

The pp reference at √s = 5.02 TeV

Rapidity dependence

- phenomenological approach, based on the observation that PHENIX, ALICE and LHCb and CMS results on $(d\sigma^{pp}/dy)/d\sigma^{pp}/dy|_{y=0}$ vs $y_{J/\psi}/y_{J/\psi,\max}$ are independent on √s



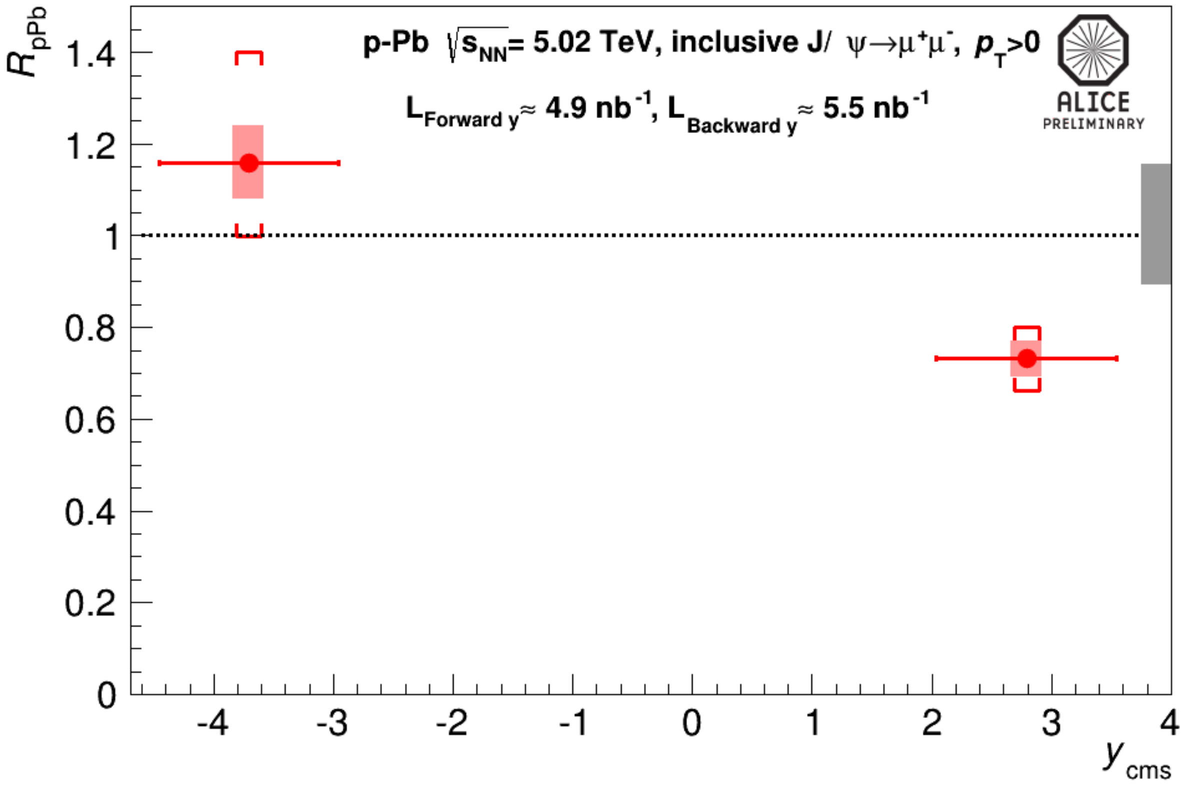
- The distribution is fitted with a gaussian shape

- Systematic uncertainties obtained with the same procedure adopted for the mid-*y* result. The chosen 2.5 sigma cut accommodate results based on FONLL and LO CEM calculations

$$BR \times d\sigma^{pp}_{J/\psi} \Big/ dy \left(2.03 < y_{CMS} < 3.53\right) = 231 + 41(syst) - 32(syst)\, nb$$

$$BR \times d\sigma^{pp}_{J/\psi} \Big/ dy\, (-4.46 < y_{CMS} < -2.96) = 159 + 40(syst) - 27(syst)\, nb$$

Nuclear modification factor: R_{pA}



- R_{pA} decreases towards forward *y*

Uncertainties:

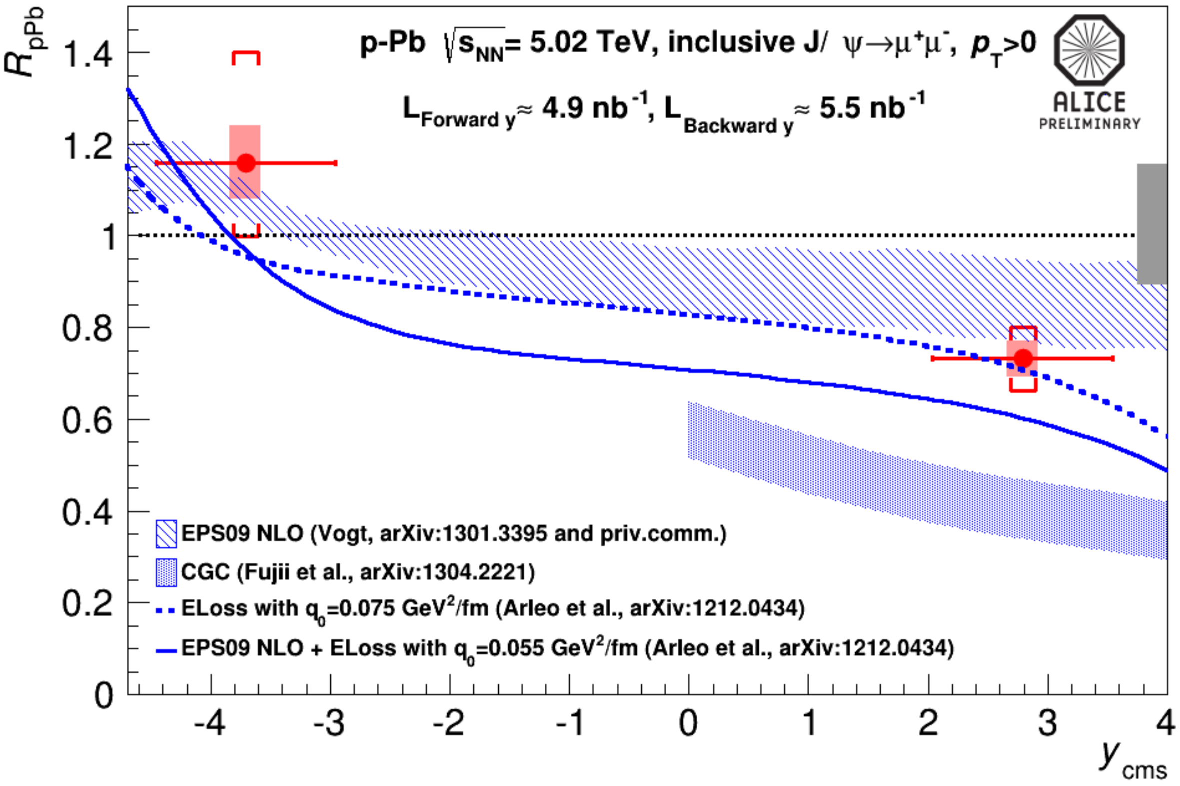
- uncorrelated (box around points)
- partially correlated ([])
- 100% correlated (grey box)

- dominant error source is due to the normalization to pp collisions

R_{pA} (2.03<y_{CMS}<3.53)=
0.732 ± 0.005(stat) ± 0.059(syst) + 0.131(syst. ref) – 0.101(syst.ref)

R_{pA} (-4.46<y_{CMS}<-2.96)=
1.160 ± 0.010 (stat) ± 0.096(syst) + 0.296(syst. ref) – 0.198(syst.ref)

Nuclear modification factor: R_{pA}



- R_{pA} decreases towards forward *y*

Uncertainties:

- uncorrelated (box around points)
- partially correlated ([])
- 100% correlated (grey box)

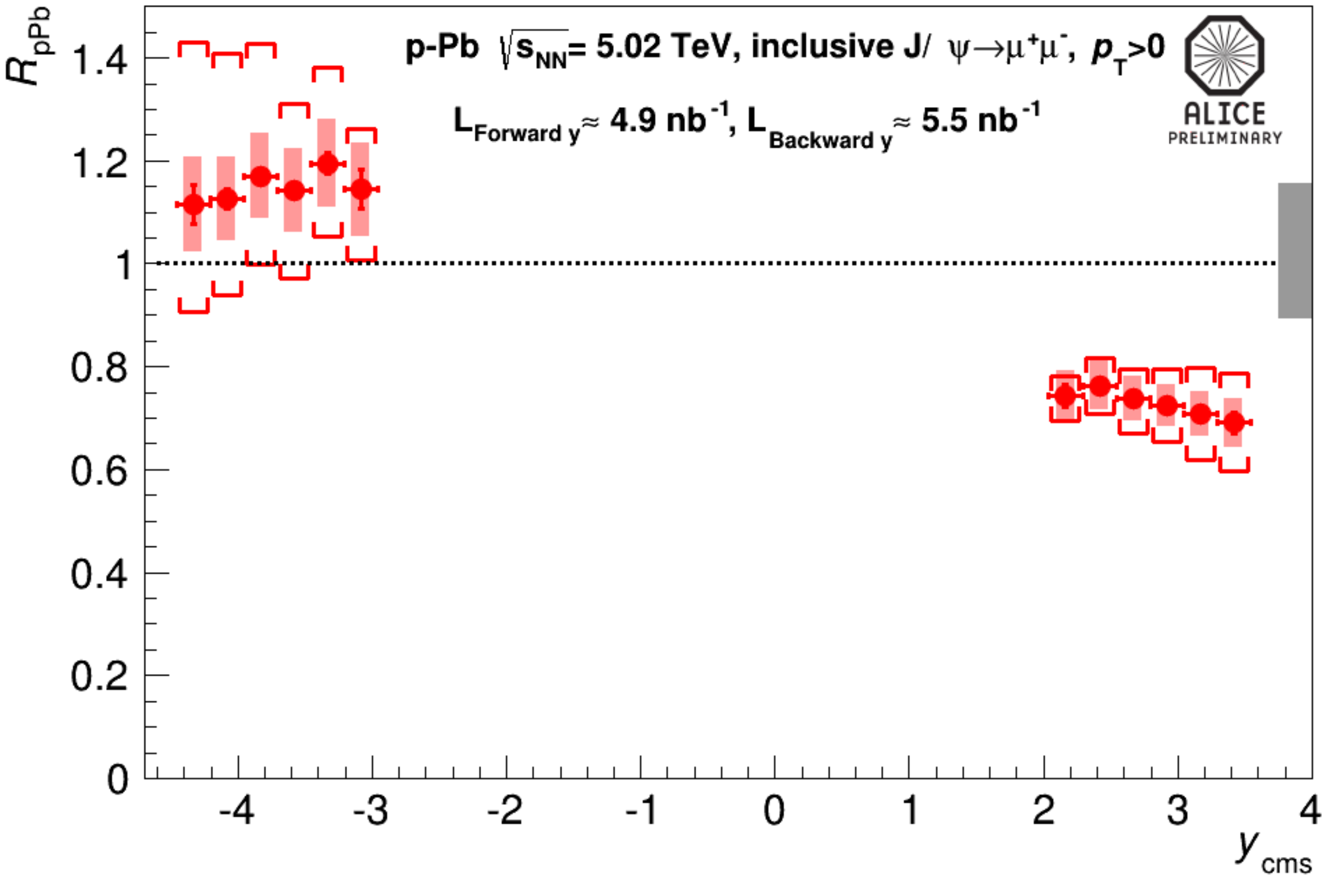
- dominant error source is due to the normalization to pp collisions

- Comparison with theoretical predictions shows reasonable agreement with:
  - shadowing EPS09 NLO calculations (R. Vogt)
  - models including coherent parton energy loss contribution (F. Arleo et al)

while CGC description ($Q^2_{S0,A}$ = 0.7-1.2 GeV/c^2, H. Fujii et al) seems not to be favoured

R_{pA} and R_{Ap} vs rapidity

Due to the large collected statistics, we can study the *y* dependence of R_{pA}

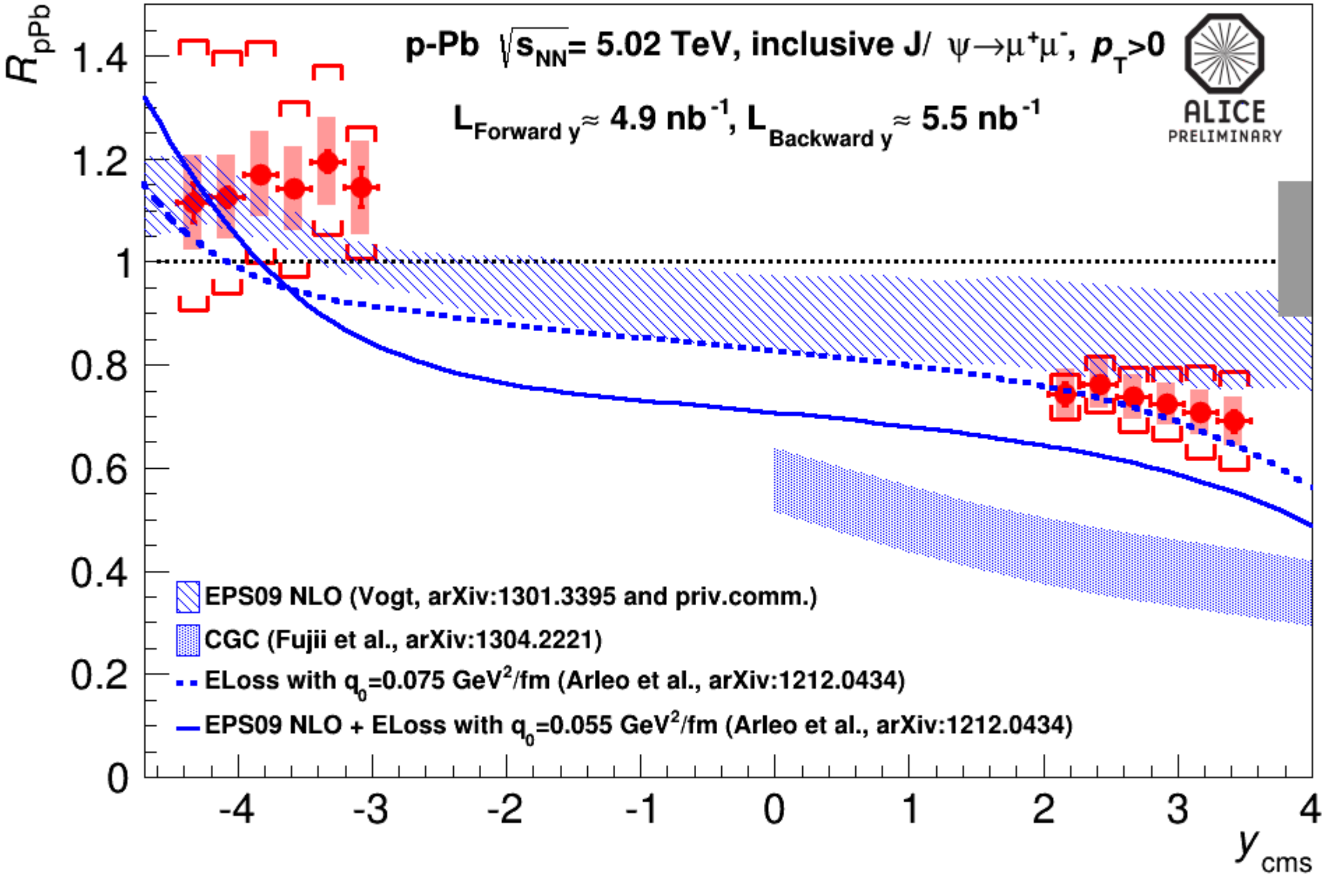


Uncertainties:

- uncorrelated (box around points)
- partially correlated ([])
- 100% correlated (grey box)

R_{pA} and R_{Ap} vs rapidity

- Due to the large collected statistics, we can study the y dependence of R_{pA}



Uncertainties:

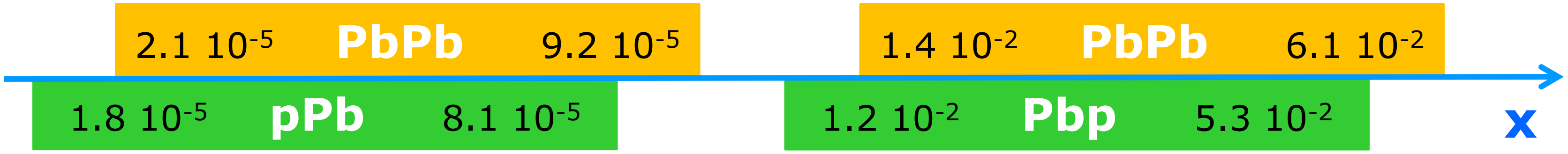
- uncorrelated (box around points)
- partially correlated ([])
- 100% correlated (grey box)

- At backward y, models including coherent parton energy loss show a slightly steeper pattern than the one observed in data
- Results are dominated by uncertainties on the pp reference

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

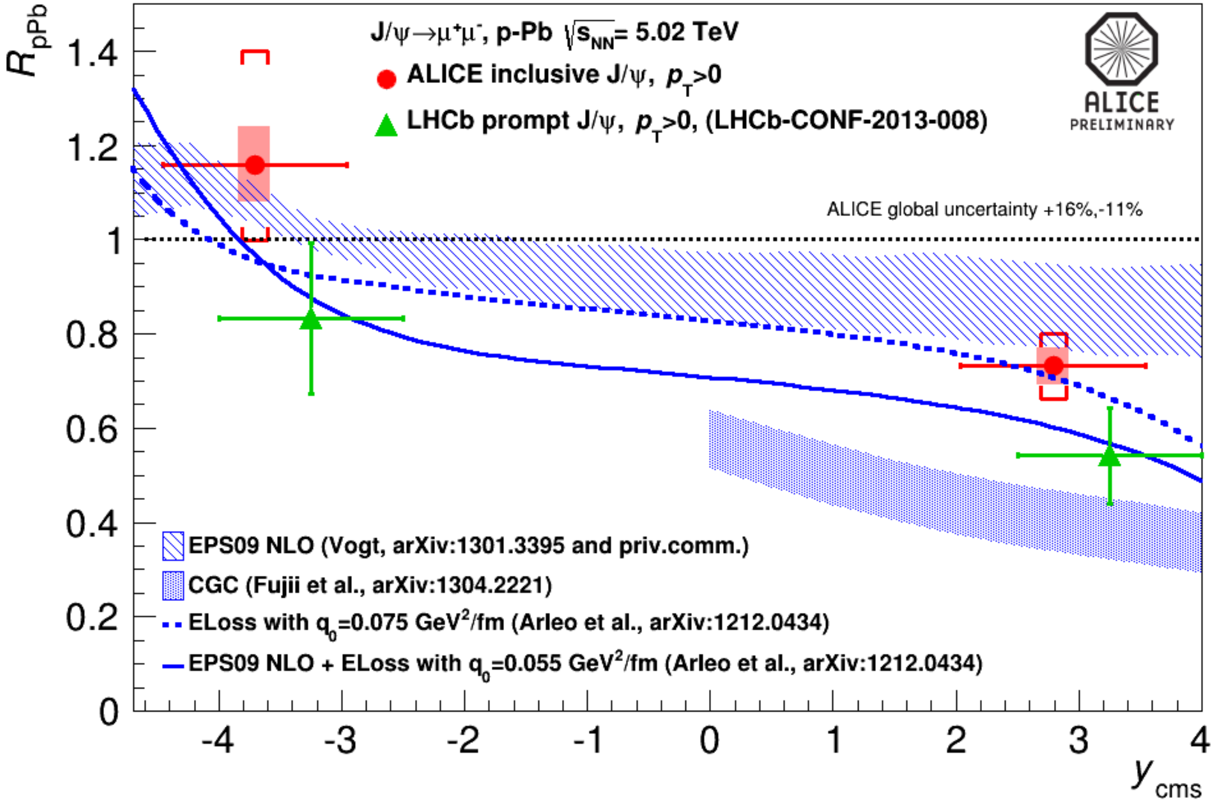
- Work in progress to quantify size of CNM effects in Pb-Pb results!

Comparison with LHCb results

- ALICE inclusive R_{pA} is compared to LHCb result for prompt J/ψ

LHCb-CONF-2013-008

- difference between inclusive and prompt R_{pA} evaluation is within few percent

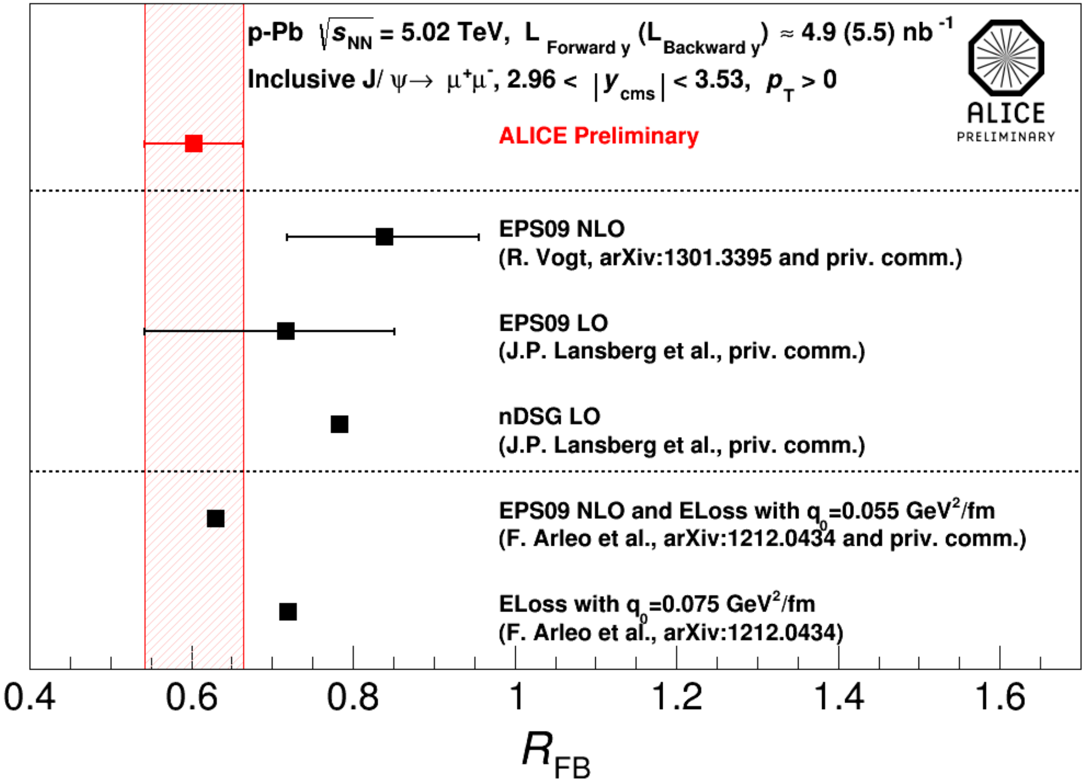


- Comparison ALICE vs LHCb at the edge of the systematic uncertainties

Forward to backward ratio: R_{FB}

- To be free of the uncertainty on the pp reference the forward to backward ratio of the nuclear modification factors (R_{FB}) is studied in the range $2.96<|y_{CMS}|<3.53$

$$R_{FB} = 0.60 \pm 0.01\ (\text{stat}) \pm 0.06\ (\text{syst})$$



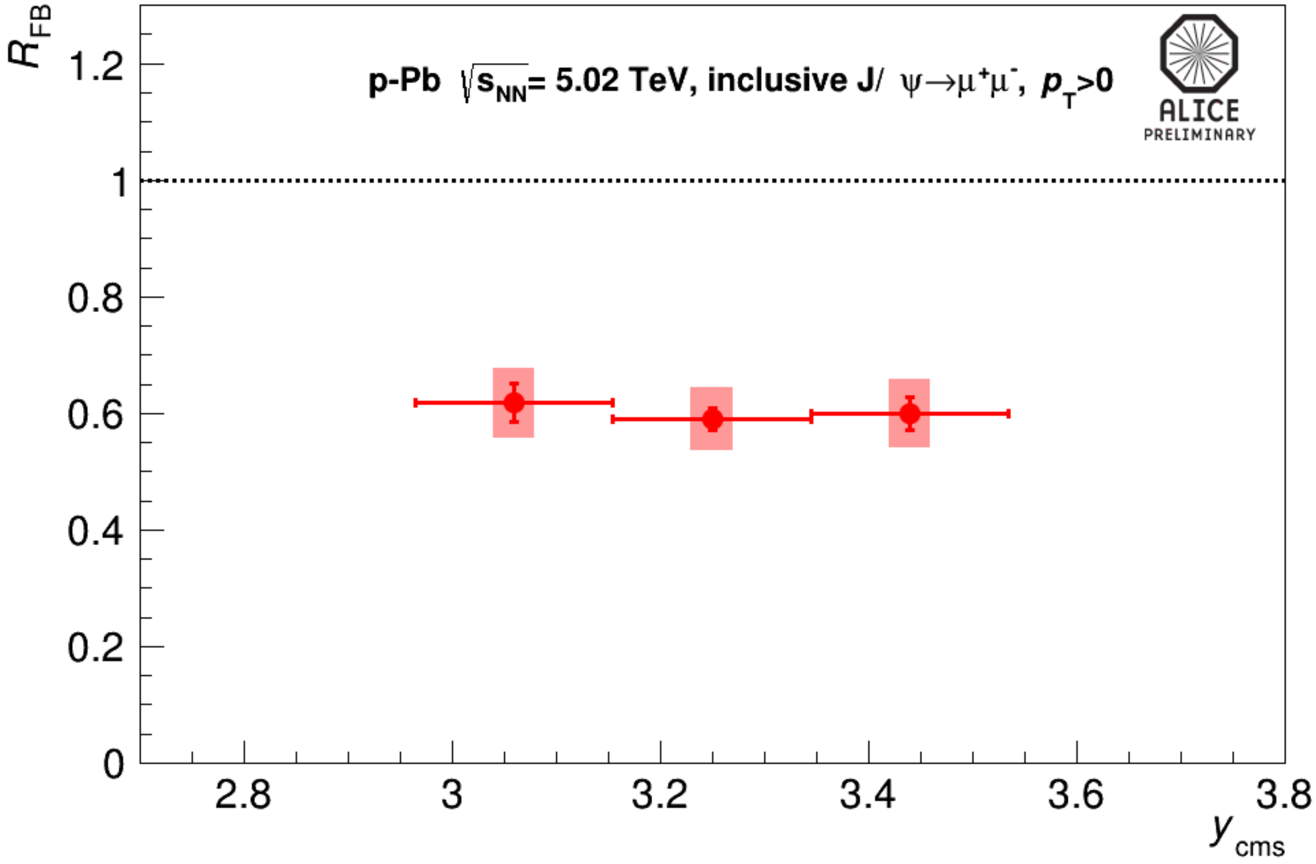
- limiting the *y* range implies a reduction of the J/ψ statistics → compensated by a sizable decrease of the systematic uncertainty wrt R_{pA} (from 20-25% to 10%)

- Agreement between data and model including energy loss contribution is rather good, while pure shadowing R_{FB} seems to slightly overestimate the data

- R_{FB} comparison with models may be less significant that in the case of R_{pA} and R_{Ap} separately

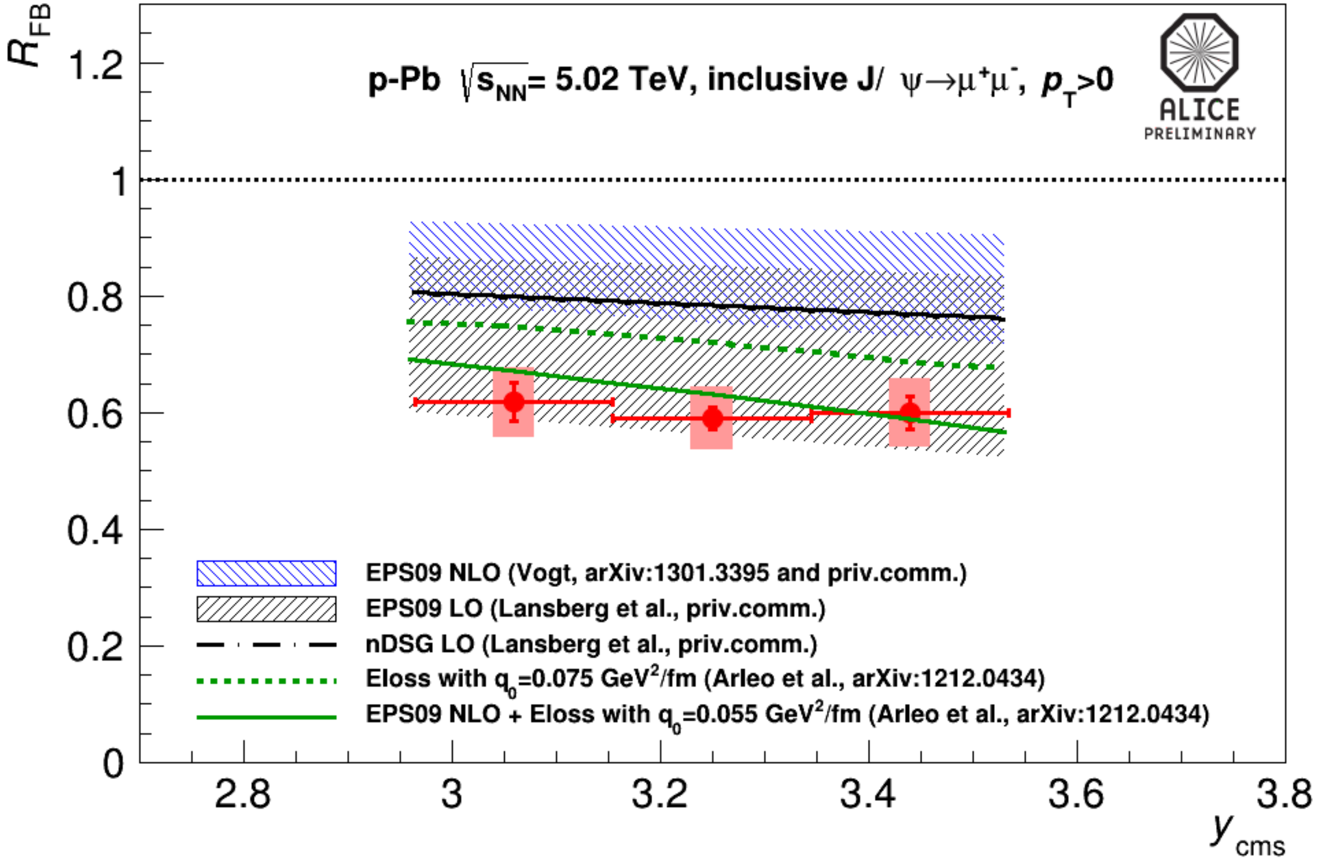
R_{FB} versus rapidity

- The R_{FB} rapidity dependence has also been investigated



R_{FB} versus rapidity

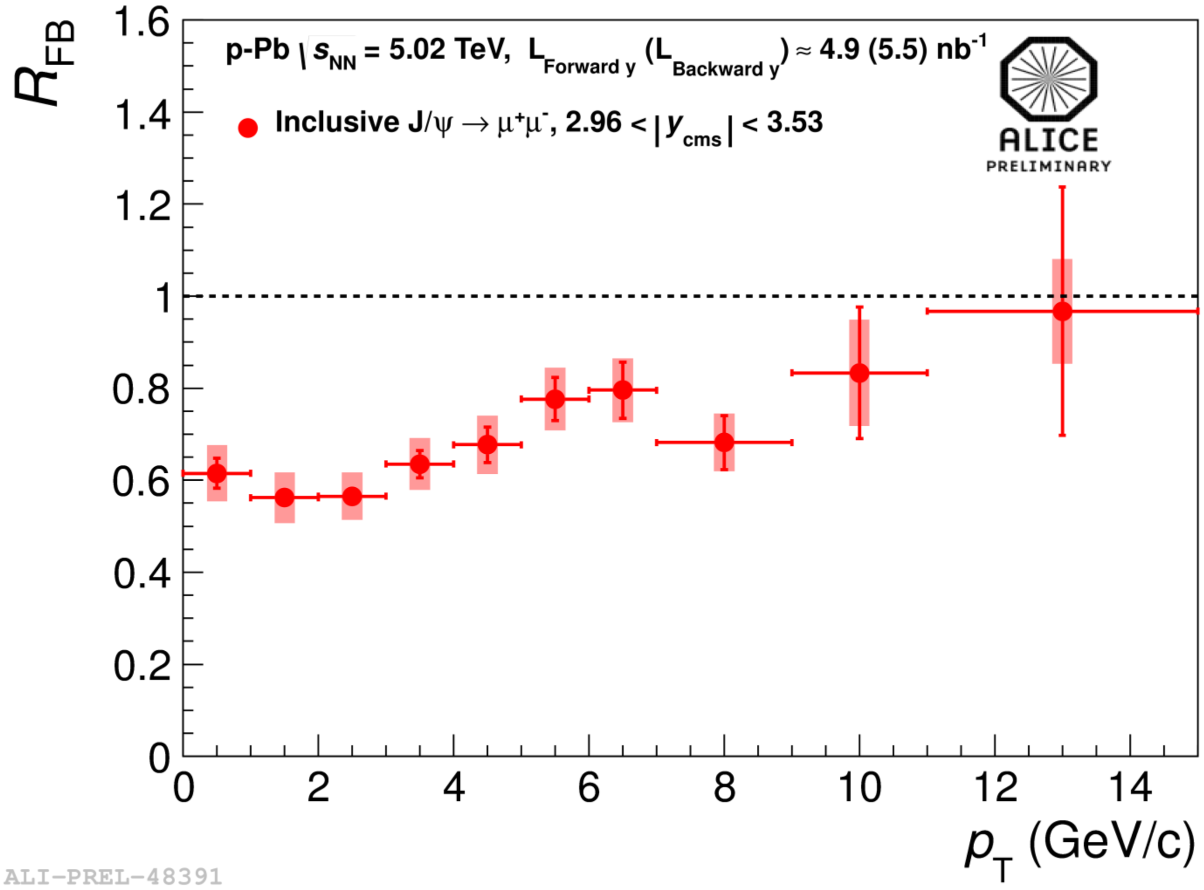
- The R_{FB} rapidity dependence has also been investigated



- comparison with theoretical models confirms previous observations done on the *y*-integrated results
- Calculations including both shadowing and energy loss seem consistent with the data

R_{FB} versus p_T

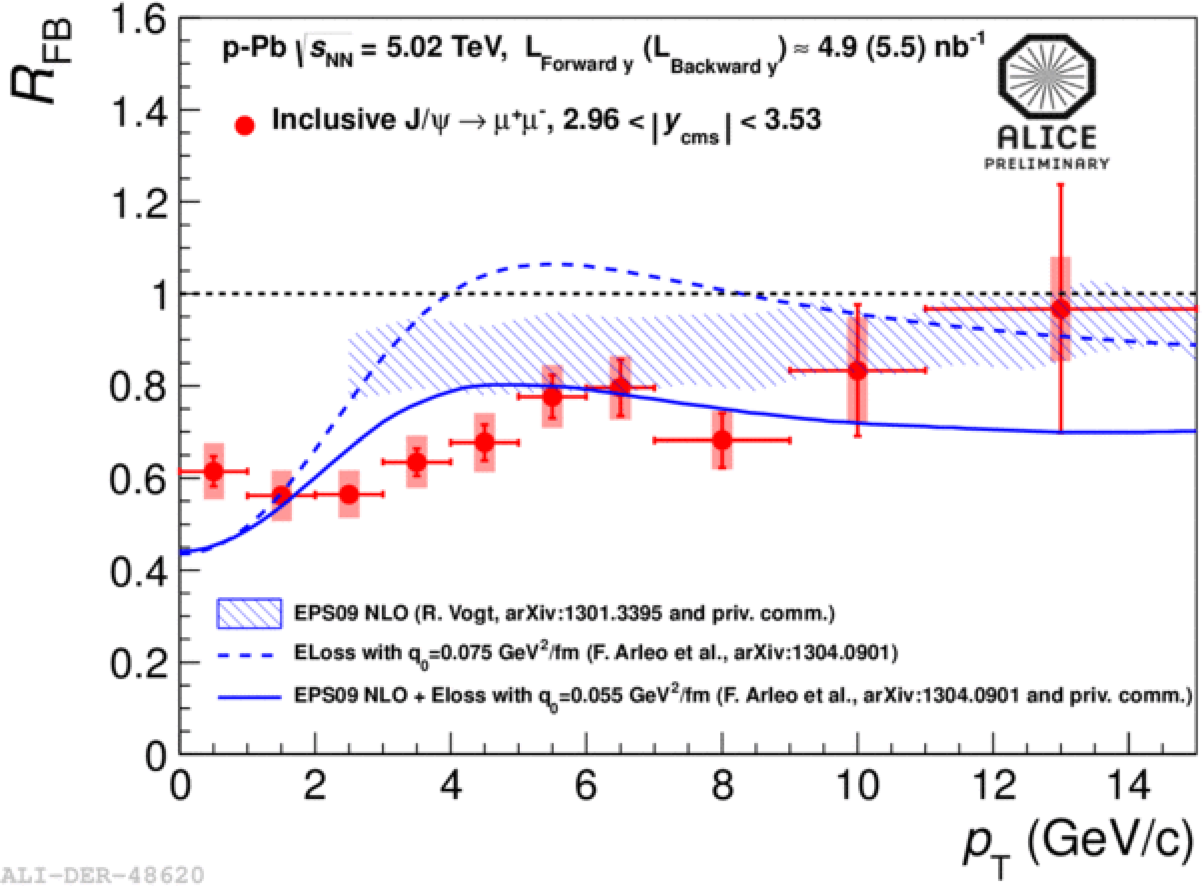
- The R_{FB} p_T dependence is studied in the range $0<p_T<15$ GeV/c



- The R_{FB} ratio shows a p_T dependence with a stronger suppression at low p_T

R_{FB} versus p_T

- The R_{FB} p_T dependence is studied in the range $0<p_T<15$ GeV/c



ALI-DER-48620

- The R_{FB} ratio shows a p_T dependence with a stronger suppression at low p_T

- theoretical predictions including energy loss show strong nuclear effects at low p_T, in fair agreement with the data

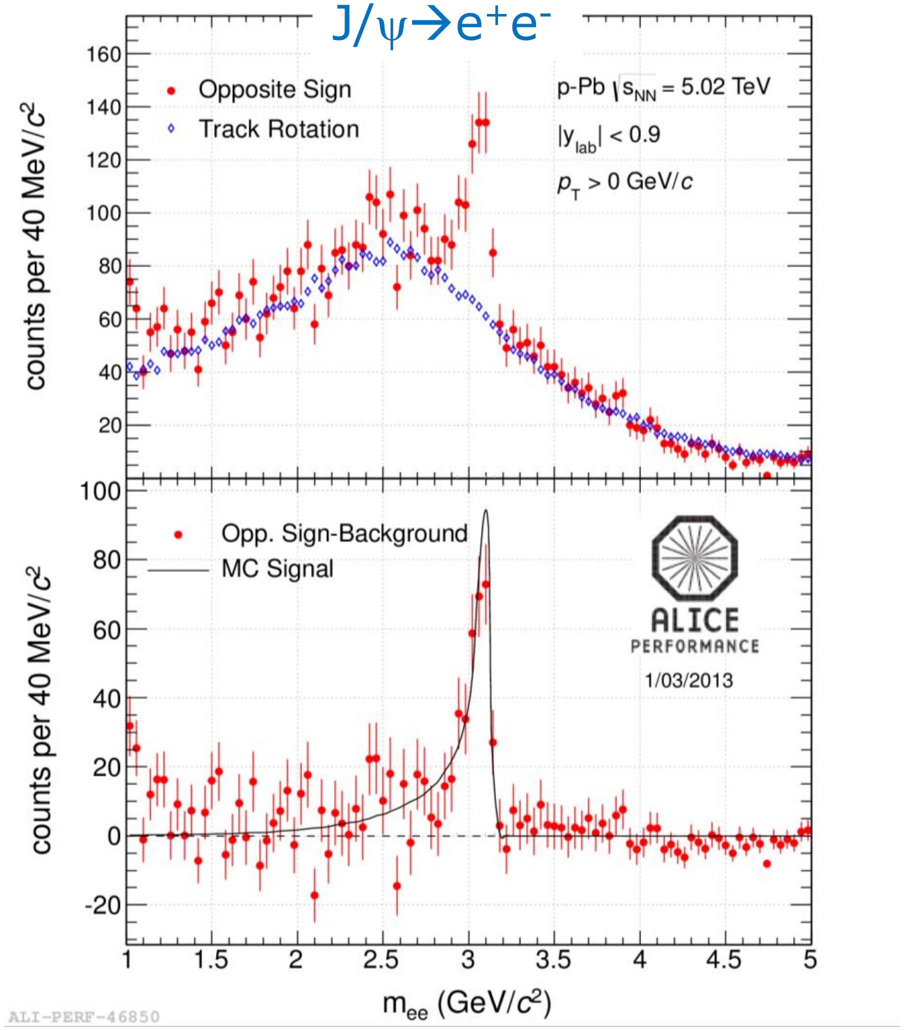
- ...but the observed p_T dependence is a bit smoother than the one expected in coherent energy loss models

Conclusions…

- The production of quarkonia in nuclear matter has been now studied for a long time, both at fixed target and at colliders
  - Many competing effects have been singled out
    → Modeling is complicate, but progresses have been done!
  - New LHC energy domain
    → different mixture of initial/final state effects
    → study still unexplored low x-range
- First ALICE results on J/ψ production from p-Pb collisions at $\sqrt{s}$=5.02 TeV:
  - R_{pA} result shows an increasing suppression of the J/ψ yield towards forward y
  - R_{FB} ratio decreases at low p_T in fair agreement with models including coherent energy loss contribution
  - pure nuclear shadowing and/or energy loss seem to reasonably describe the data, indicating that final state absorption may indeed be negligible at LHC energies

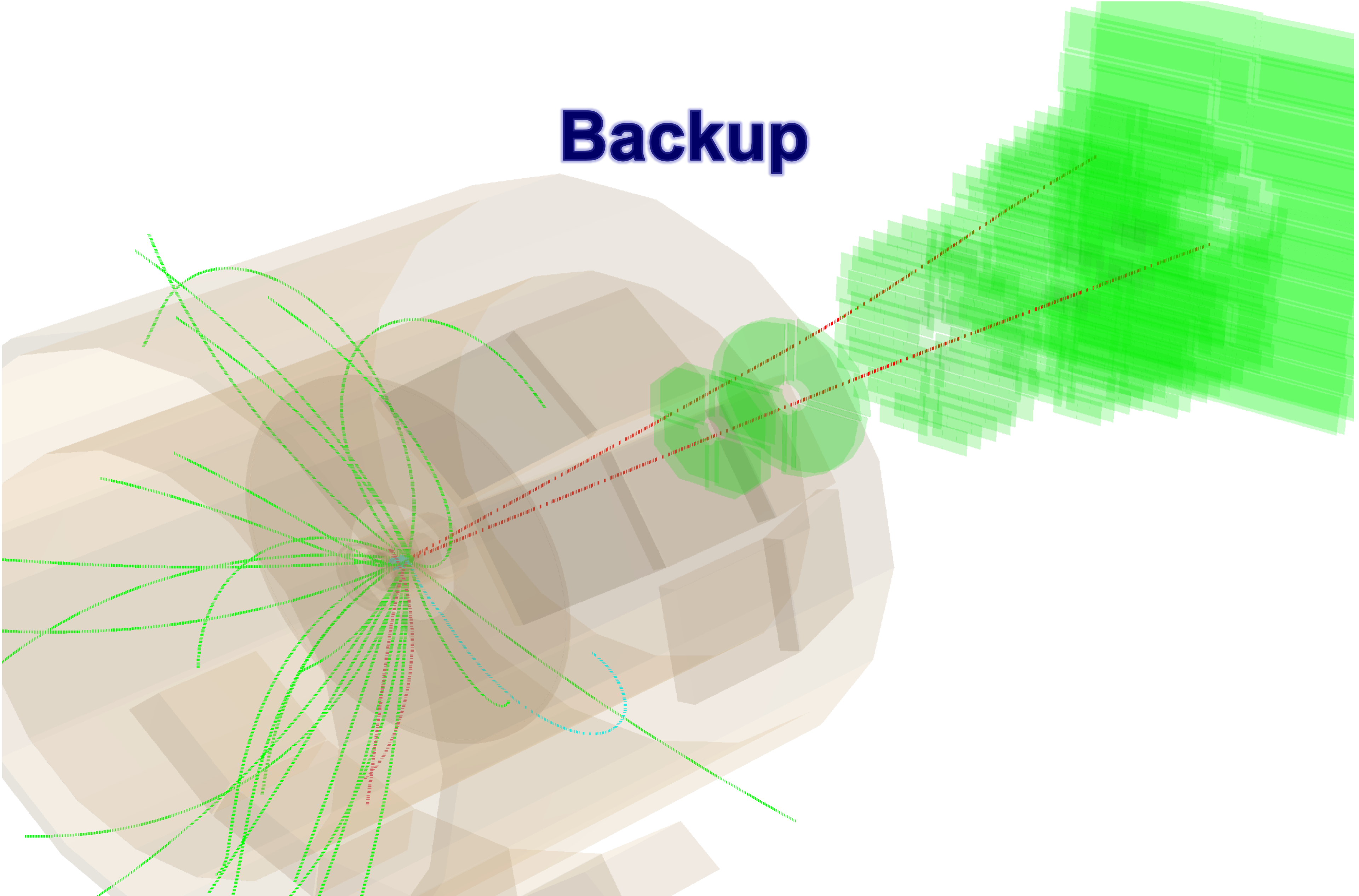
…and prospects

Many more results still to be extracted from the 2013 p-A data!



- Centrality dependence of the J/ψ nuclear modification factor and R_{FB}
- $\psi(2S)$ and bottomonia production in p-Pb
- J/ψ studies at mid-rapidity in the e^+e^- channel and lots more…

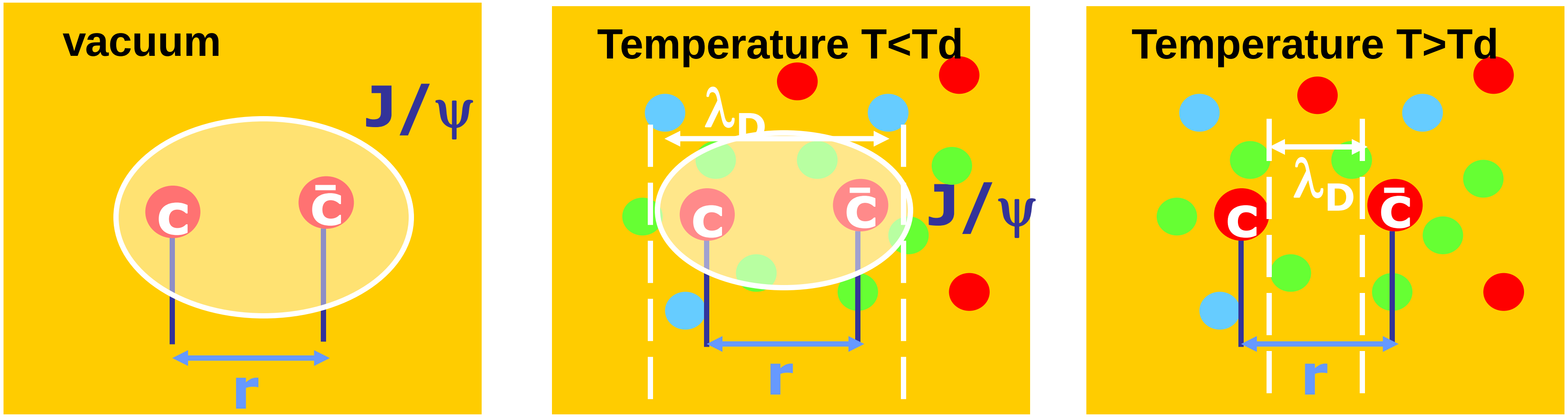
Thank you
and…
stay tuned!



Backup

Quarkonium suppression

- Binding of a $q\bar{q}$ pair is subject to the effects of colour screening
  - → screening is stronger at high T
  - → screening radius $\lambda_D(T)$ (i.e. maximum distance which allows the formation of a bound state) decreases with T

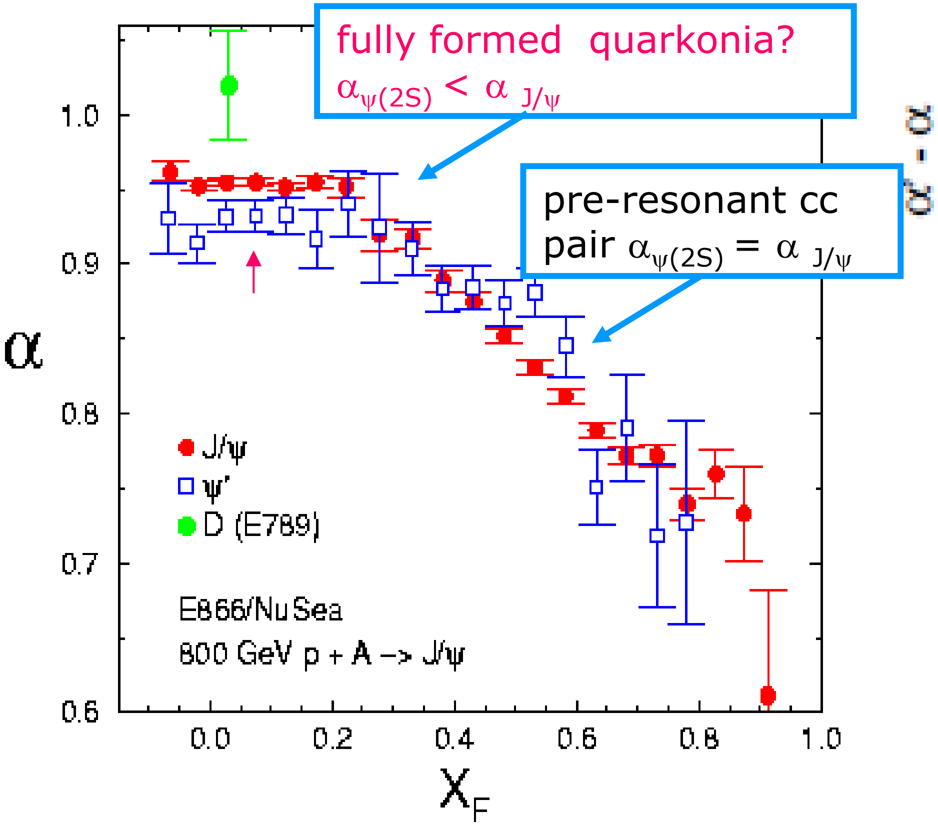


At a given T:

if resonance radius < $\lambda_D(T)$ → resonance can be formed

if resonance radius > $\lambda_D(T)$ → no resonance is formed

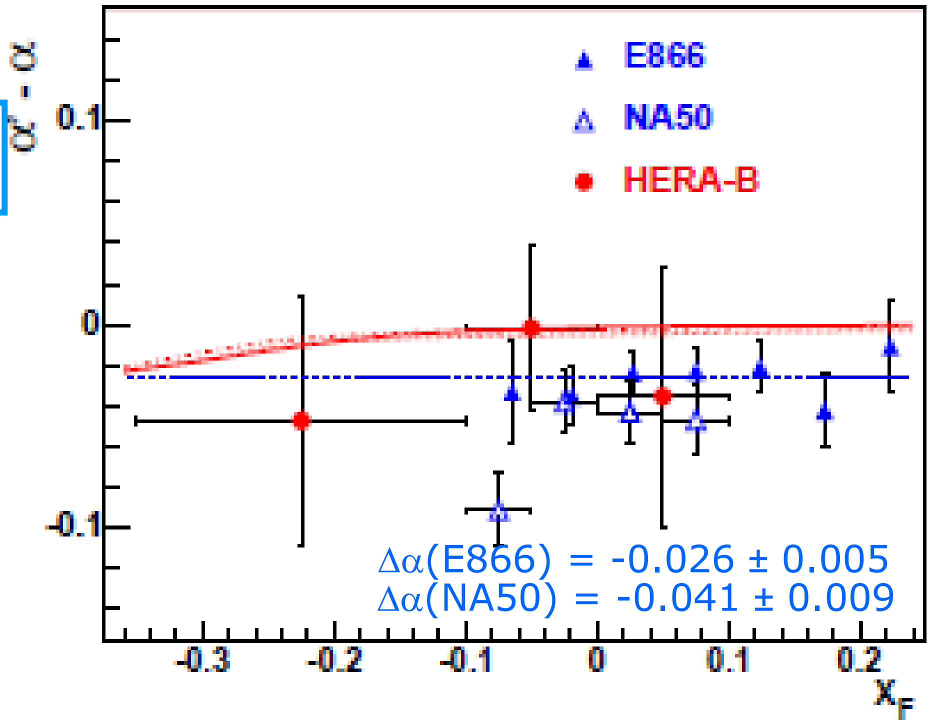
CNM effects on other resonances: $\psi(2S)$



fully formed quarkonia?
$\alpha_{\psi(2S)} < \alpha_{J/\psi}$

pre-resonant cc pair $\alpha_{\psi(2S)} = \alpha_{J/\psi}$

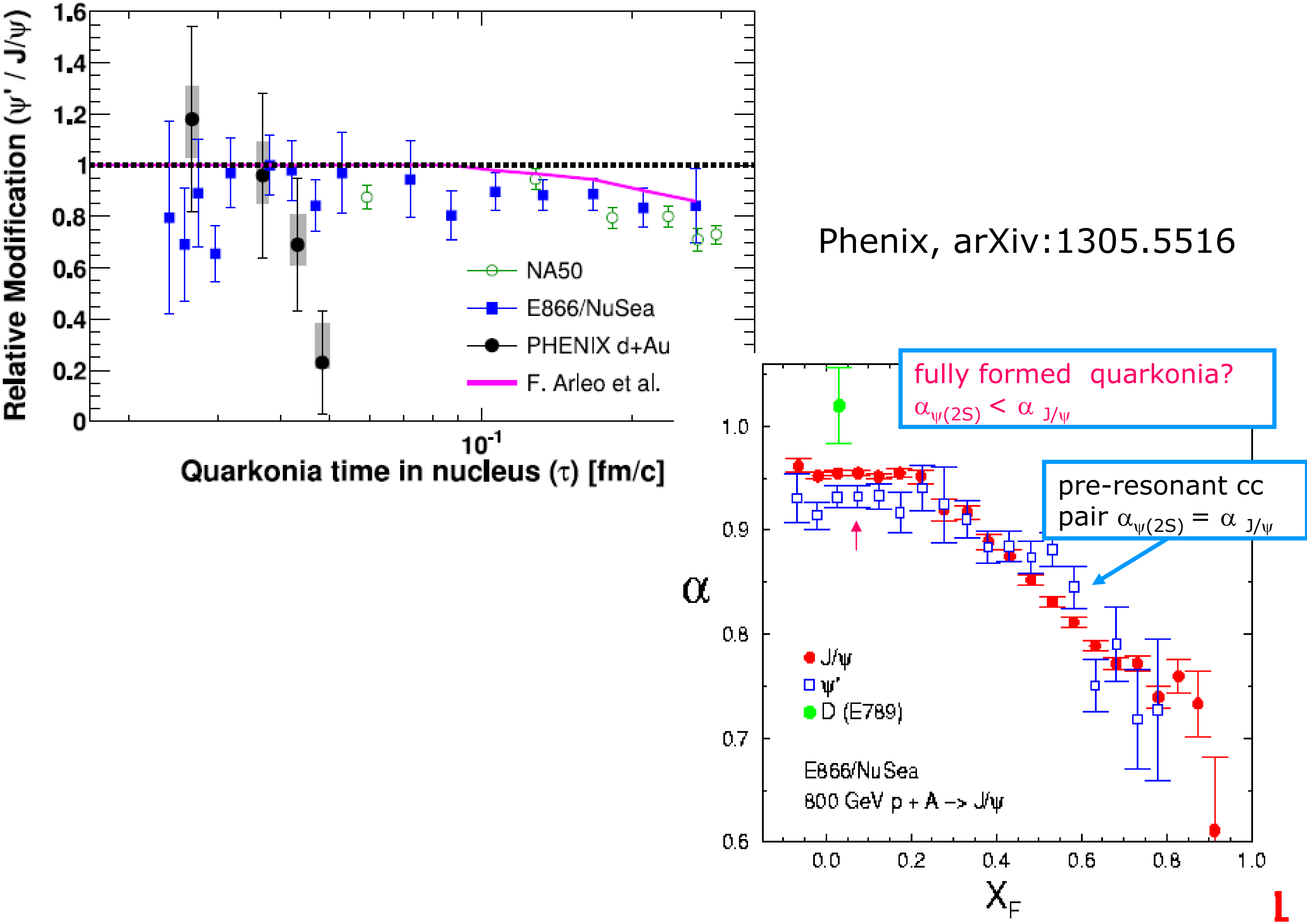
HERA-B Coll. Eur.Phys.J.C49:545-558,2007



$\Delta\alpha(E866) = -0.026 \pm 0.005$
$\Delta\alpha(NA50) = -0.041 \pm 0.009$

From the high statistics E866 and NA50 samples:

- Stronger absorption for $\psi(2S)$ in the region $x_F<0.25$
  Effect not scaling with $r^2_{J/\psi}/ r^2_{\psi(2S)} \rightarrow$ only a fraction of the resonances formed in the nucleus
- at higher x_F, $\psi(2S)$ and J/ψ α values are closer (E886)

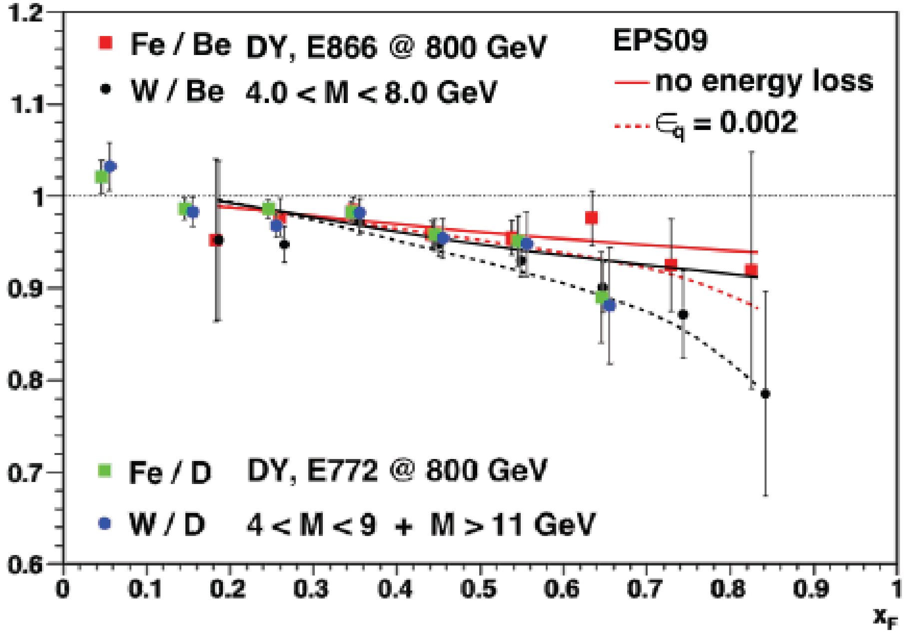


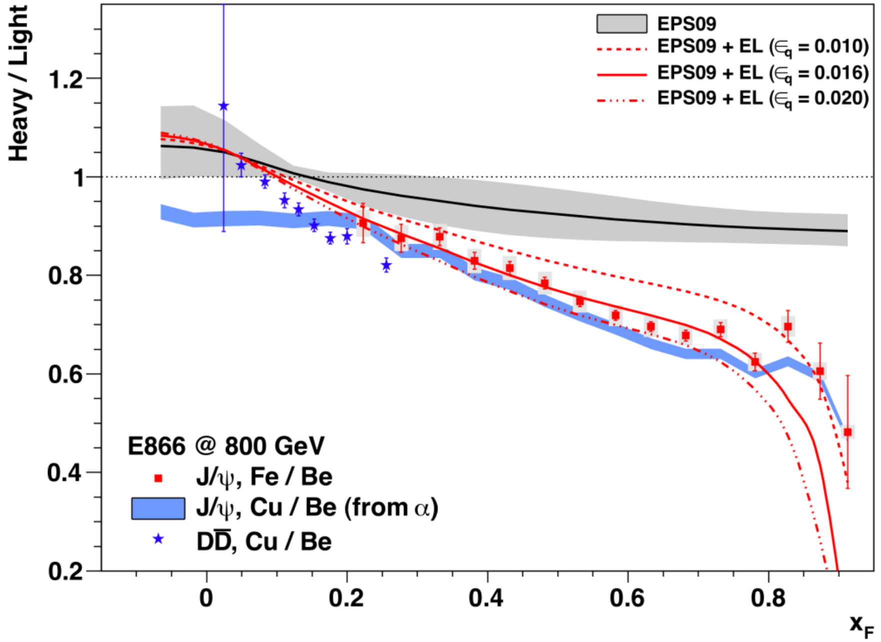
Phenix, arXiv:1305.5516

fully formed quarkonia?
$\alpha_{\psi(2S)} < \alpha_{J/\psi}$

pre-resonant cc pair $\alpha_{\psi(2S)} = \alpha_{J/\psi}$

Initial state energy loss





- Energy loss of incident partons → shifts x_1

H.K.Woehri, "3 days of Quarkonium production…", Palaiseau 2010

√s of the parton-parton interaction changes (but not shadowing)

$$x_1' = x_1\left(1-\varepsilon_{q(g)}\right)^{N_{coll}-1}$$

$\varepsilon_{q(g)}$: fractional energy loss

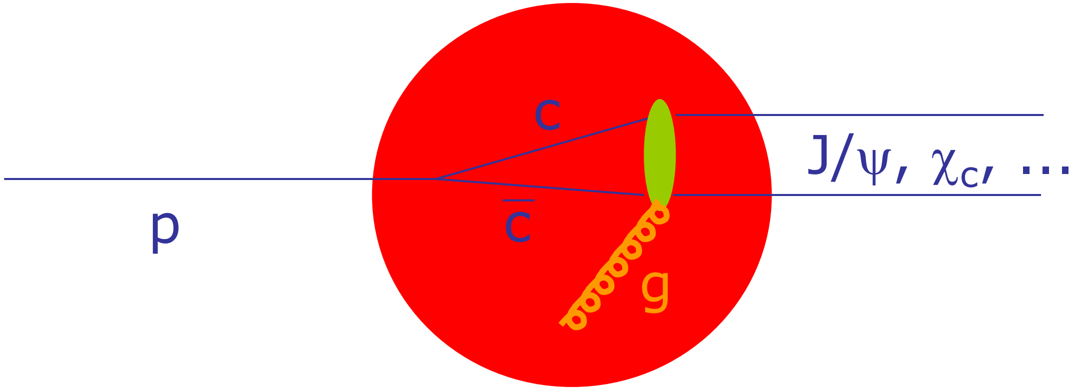
ε_q =0.002 (small!) seems enough to reproduce Drell-Yan results
But a much larger (~factor 10) energy loss is required to reproduce large-x_F J/ψ depletion from E866!

- New theoretical approaches (Peigne', Arleo): coherent energy loss, may explain small effect in DY and large for charmonia

Quarkonium production in p-A

➡ Quarkonium production: a two-step process

- Perturbative QCD production of the cc pair
- Non-perturbative binding (color neutralization)



➡ What happens when all (or part) of this process occurs inside the nuclear medium ?

➡ Can the interaction of the “pre-resonant” state with the nucleus significantly depend on its properties (color octet, color singlet...) ?

➡ Can we learn anything on production from the disappearance of bound states, due to the interaction with nuclear matter ?

Comparing different resonances

- Different resonances correspond to different mixtures of intermediate color octet/singlet states
  - Resonances could be affected in a different way by the nuclear medium → compare nuclear effects on various quarkonium states

- If the resonance hadronizes inside the medium, it is expected to interact with

$$\sigma_{\psi}^{abs} \propto r_{\psi}^{2} \qquad \Rightarrow \sigma_{\psi(2S)}^{abs} \approx 3.7\sigma_{\psi}^{abs}, \quad \sigma_{\chi_c}^{abs} \approx 2.4\sigma_{\psi}^{abs}$$

- When measuring various resonances, understanding of feed-down fractions is essential
  - For the J/ψ, one has

$$R(\psi(2S)) = (8.1 \pm 0.3)\% \qquad R(\chi_c) = (25 \pm 5)\%$$

from various pA measurements, extrapolated to L=0,
P. Faccioli et al., JHEP 10 (2008) 004

J/ψ production in fixed target experiments

To get some insight on the CNM mechanisms
→ important to consider all the available p-A data, collected at different energies and in different kinematical regions

Let’s start discussing what have we learnt up to now!

Fixed target experiments:

HERAB **p-C (Ti) 920 GeV**, $-0.34<x_F<0.14$, $p_T<5$ GeV
(I. Abt et al., arXiv:0812.0734)

negative x_F range

E866 **p-Be,Fe,W 800 GeV**, $-0.10<x_F<0.93$, $p_T<4$ GeV
(M. Leitch et al., PRL84(2000) 3256)

wider x_F coverage

NA50 **p-Be,Al,Cu,Ag,W,Pb,400/450 GeV**, $-0.1<x_F<0.1$, $p_T<5$ GeV
(B. Alessandro et al., EPJC48(2006) 329)

NA3 **p-p p-Pt, 200 GeV**, $0<x_F<0.6$, $p_T<5$ GeV
(J. Badier et al., ZPC20 (1983) 101)

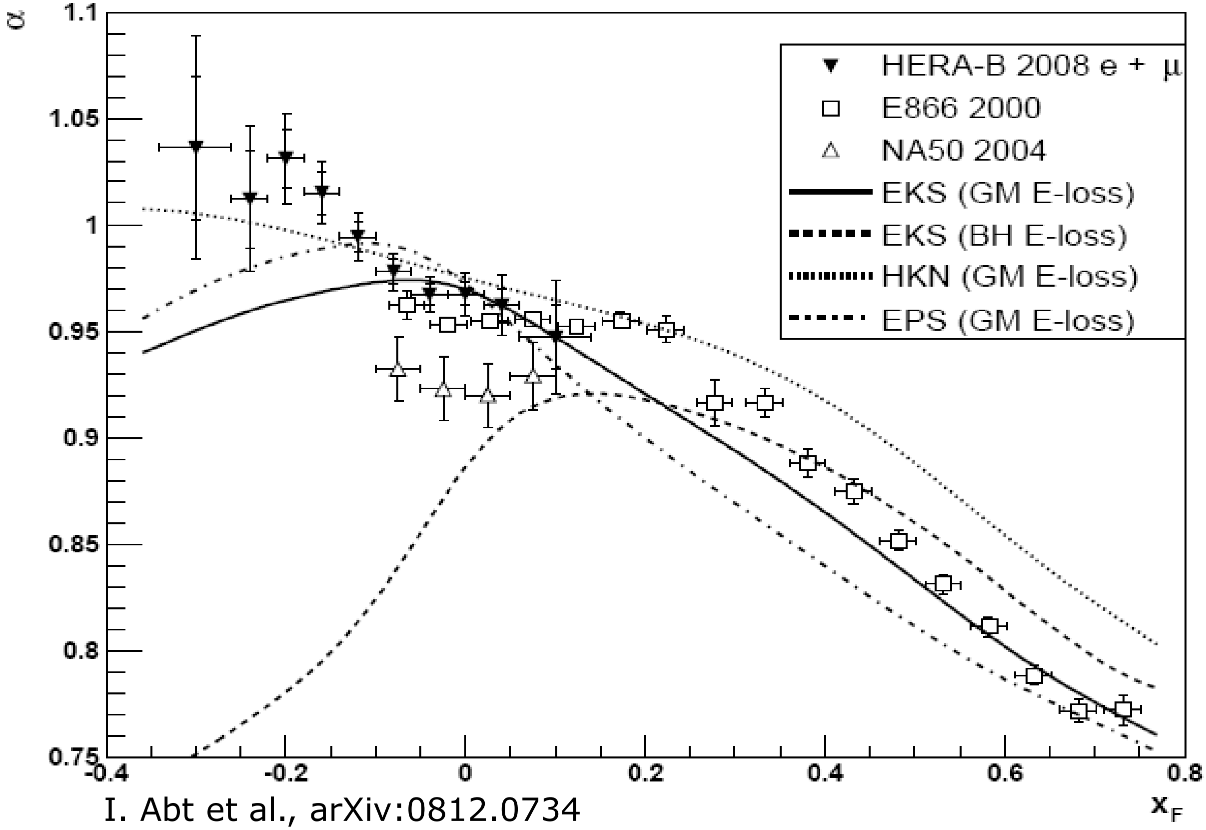
large number of nuclei

NA60 **p-Be,Al,Cu,In,W,Pb,U 158/400 GeV**, $-0.1<x_F<0.35$, $p_T<3$ GeV
(E. Scomparin et al., Nucl. Phys. A 830 (2009) 239)

2 energies in the same experiment

Cold nuclear matter effects

From a compilation of fixed target results of J/ψ α vs x_F:



I. Abt et al., arXiv:0812.0734

Theoretical description over the full x_F range still meets difficulties!

(R. Vogt, Phys. Rev. C61(2000)035203, K.G.Boreskov
A.B.Kaidalov JETP Lett. D77(2003)599)

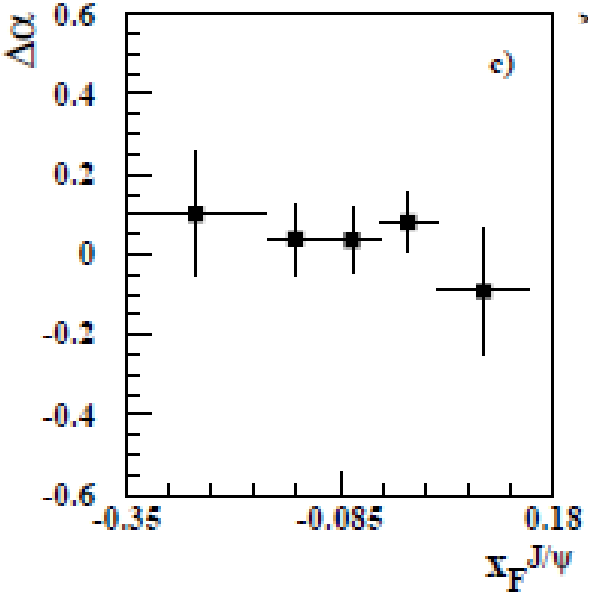
CNM effects on other resonances: χ_c

- The CNM issue is complicated by the fact that ~30% of the J/ψ come from the feed-down of higher charmonium states ($\psi(2S)$, χ_c)
  - The nuclear medium might affect J/ψ, $\psi(2S)$, χ_c in a different way (shadowing contribution should be similar)
  - Unfortunately, less accurate results on $\psi(2S)$, χ_c

Nuclear effects on χ_c are studied through

$$\Delta\alpha = \alpha_{\chi_c} - \alpha_{J/\psi}$$

HERA-B, Phys.Rev.D79:012001,2009



- No significant difference between $\alpha(\chi_c)$ and $\alpha(J/\psi)$ is observed, within the large errors → similar "global" CNM effects on both resonances in the covered kinematical range (average value $\Delta\alpha=0.05\pm0.04$)

- CEM and NRQCD differ in the prediction for the behaviour of the charmonia states vs. x_F, but large errors do not allow to distinguish among the models (R. Vogt, Nucl. Phys. A 700(2002) 539)

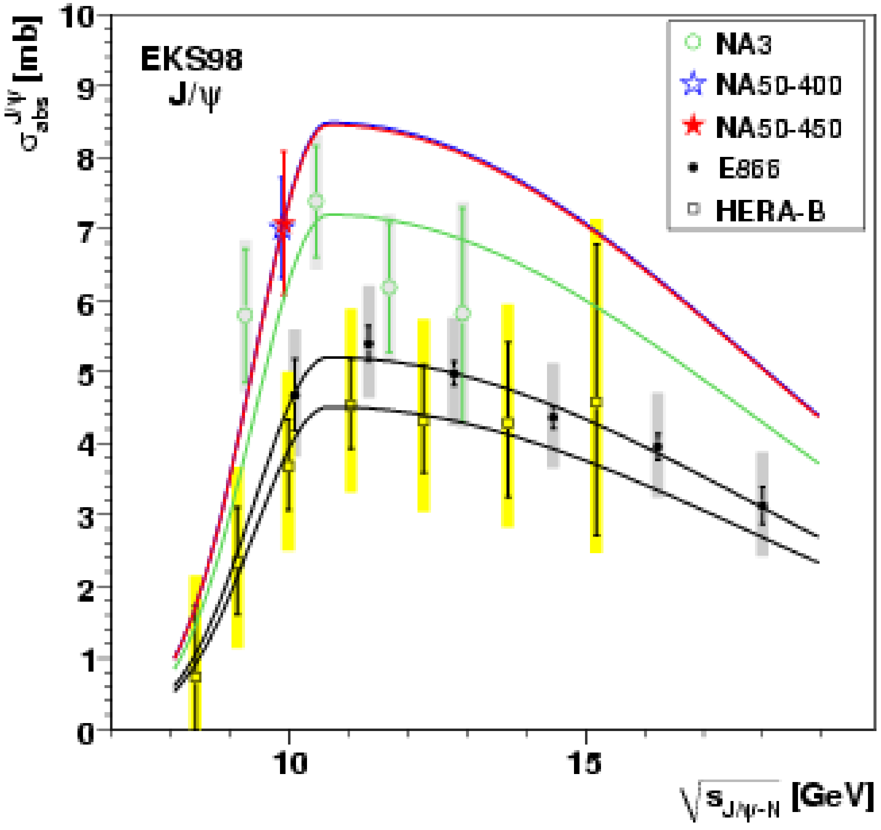
Can we consider only shadowing + cc break-up?

Assume dominant effects to be shadowing and cc breakup

1st approach:

→ correct the results for shadowing (2→1 kinematics), using EKS98
→ cc break-up cross section should depend only on $\sqrt{s_{J/\psi\text{-}N}}$

C. Lourenco, R. Vogt and H.K.Woehri, JHEP 02(2009) 014



Even after correction, there is still a significant spread of the results at constant $\sqrt{s_{J/\psi\text{-}N}}$

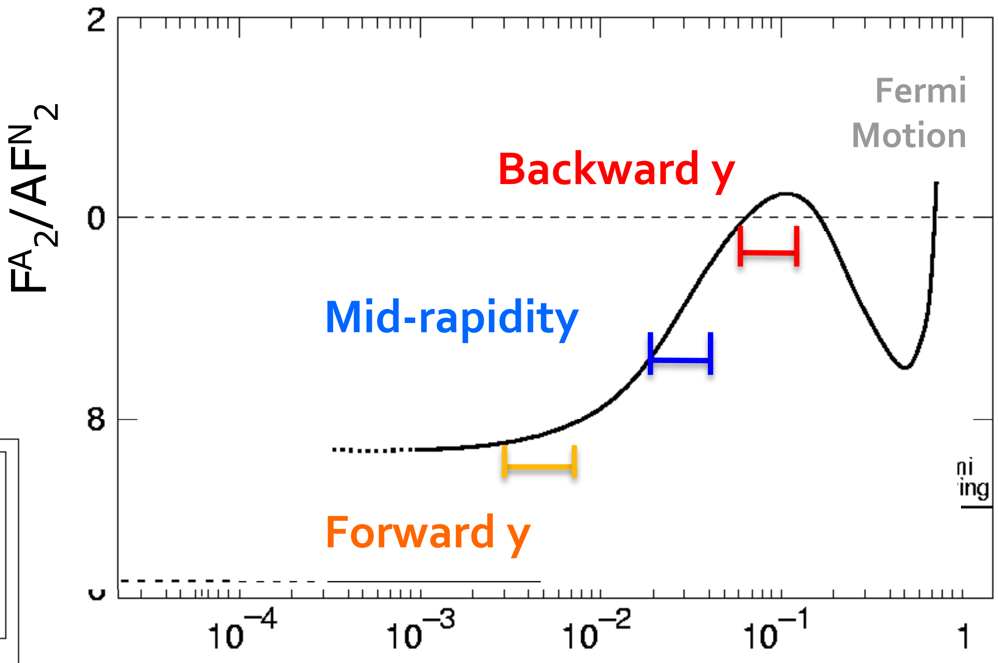
Other effects different from shadowing and cc breakup?

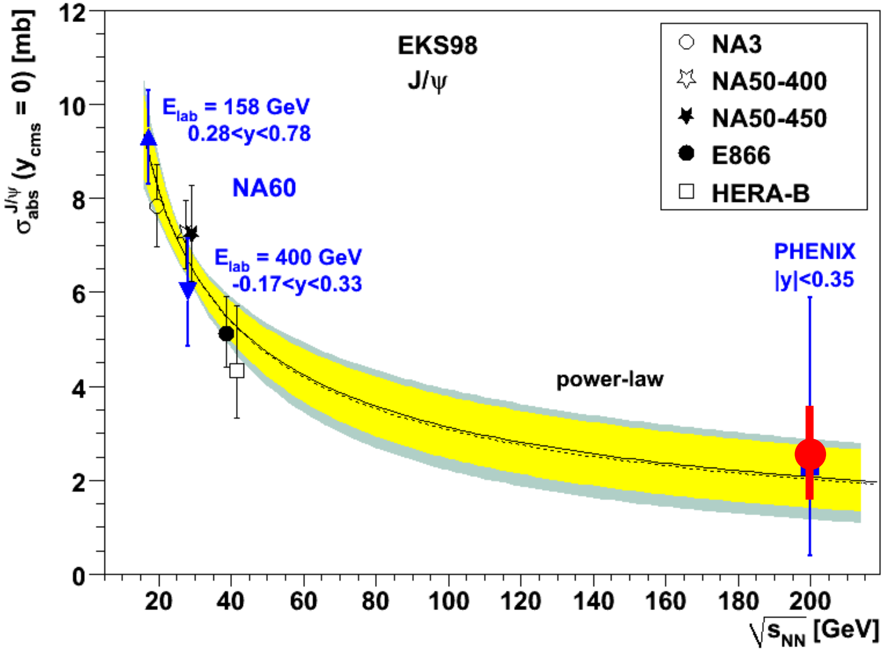
J/ψ in d-Au

Results obtained by the PHENIX experiment in a wide rapidity range

→ Different shadowing regions probed

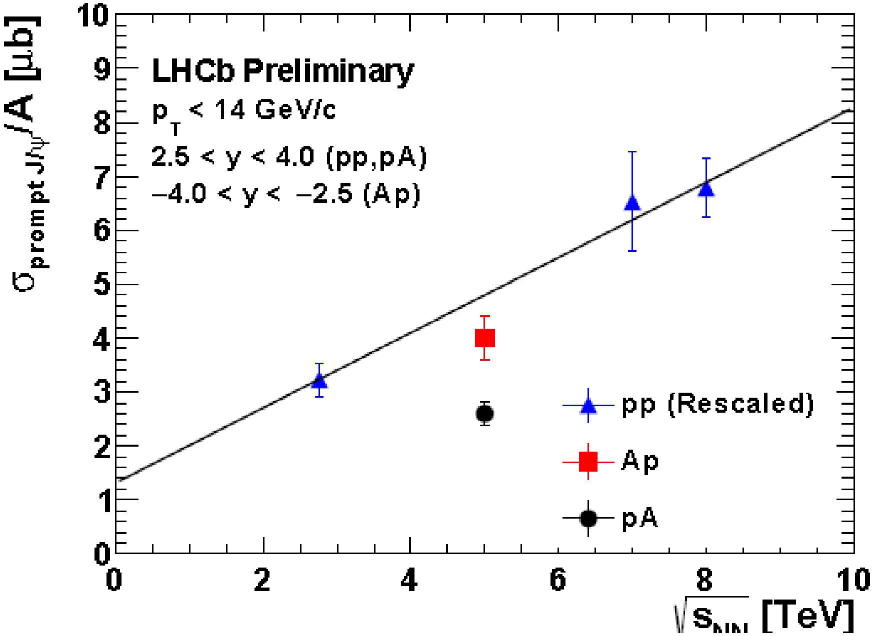
forward y	x~0.005
mid y	x~0.03
backward y	x~0.1

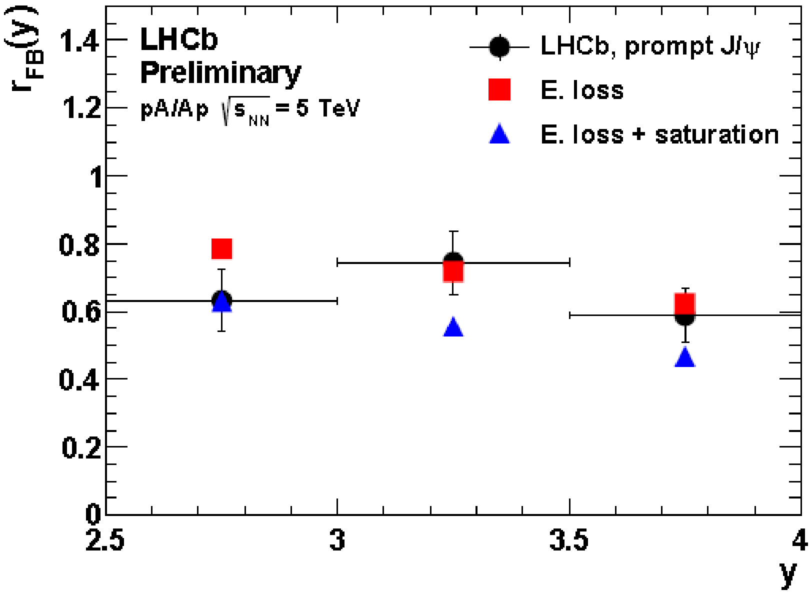




The tendency for weaker nuclear effects when increasing √s holds also at collider energy
(C. Lourenco et al, JHEP 0902:014 (2009))

LHCb





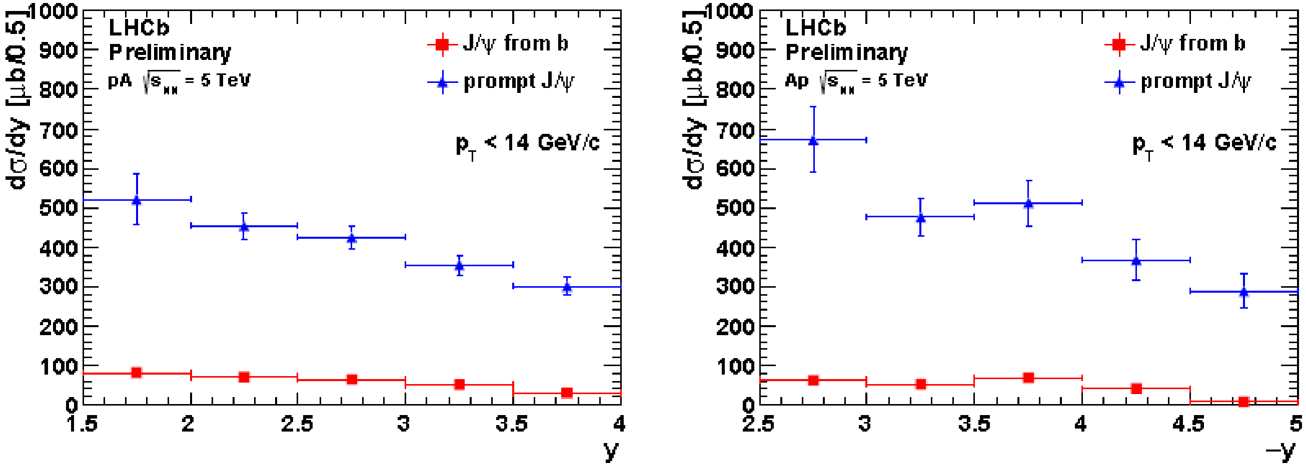
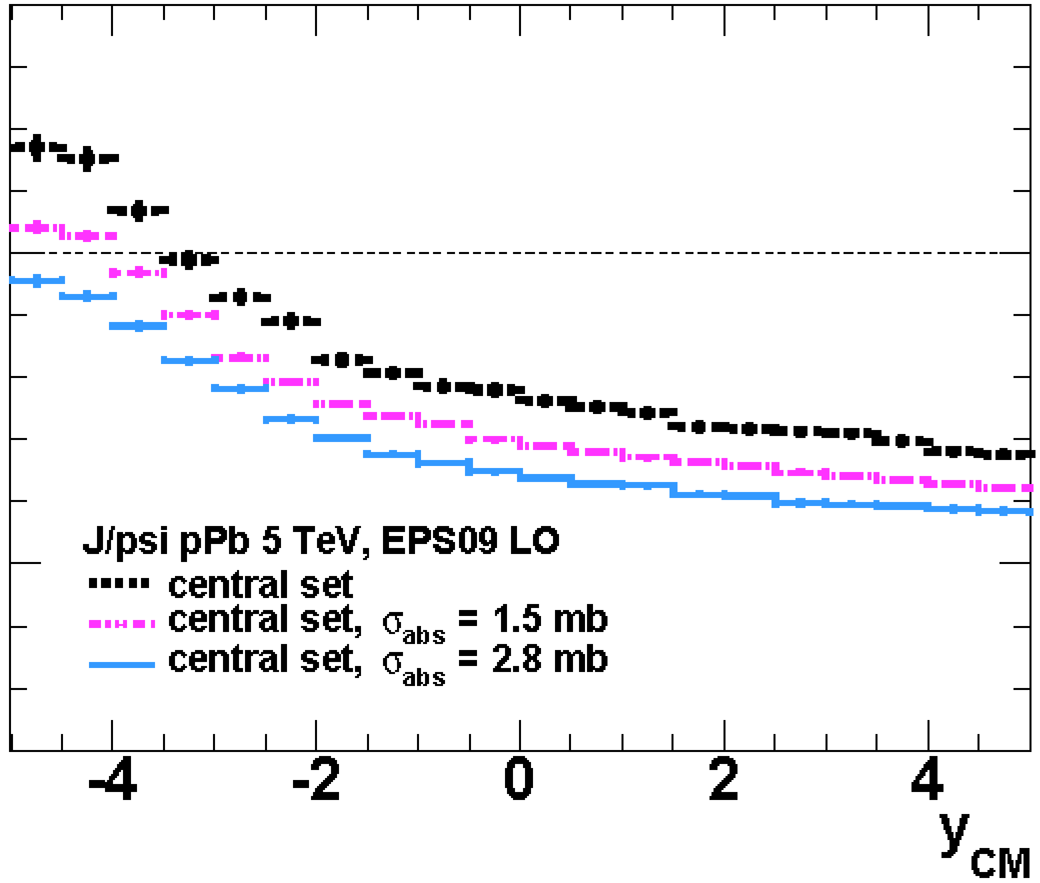


Figure 5: Differential cross-sections fro prompt J/ψ mesons and J/ψ from b-hadrons as functions of y in (left) pA and (right) Ap collisions, $p_{\mathrm{T}} < 14$ GeV/c.

Other models



(d) EPS09 LO with σ_{abs}

E. Ferreiro et al:
arXiv:1305:4569