Review of experimental results on quarkonium production

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Exploring high-μ_B matter with rare probes, ECT*, 14 October 2021

Review of experimental results on quarkonium production → *focus on fixed target experiments*

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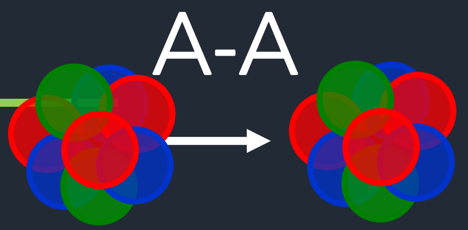
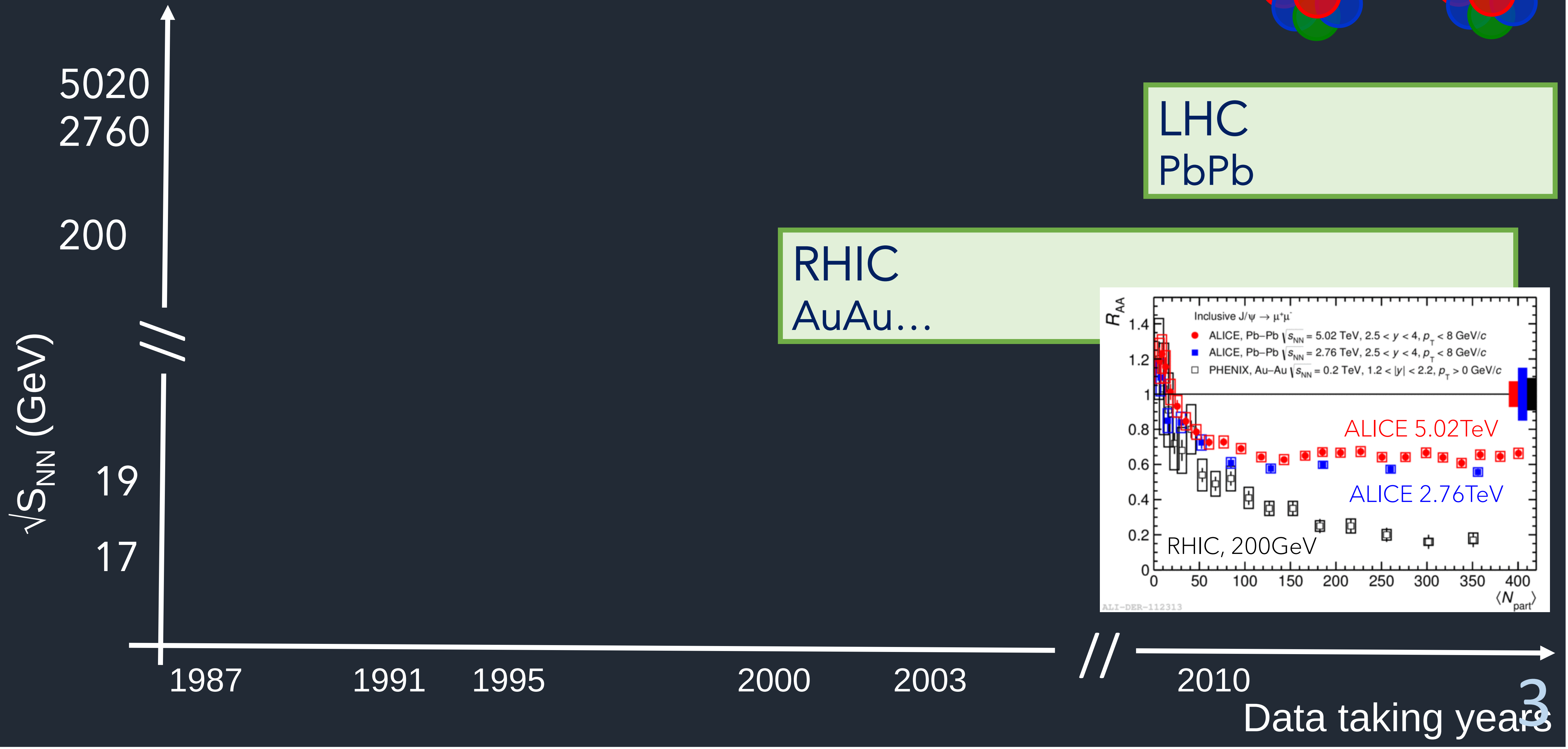
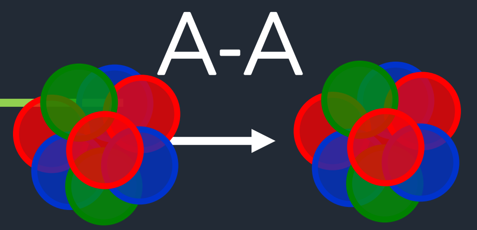
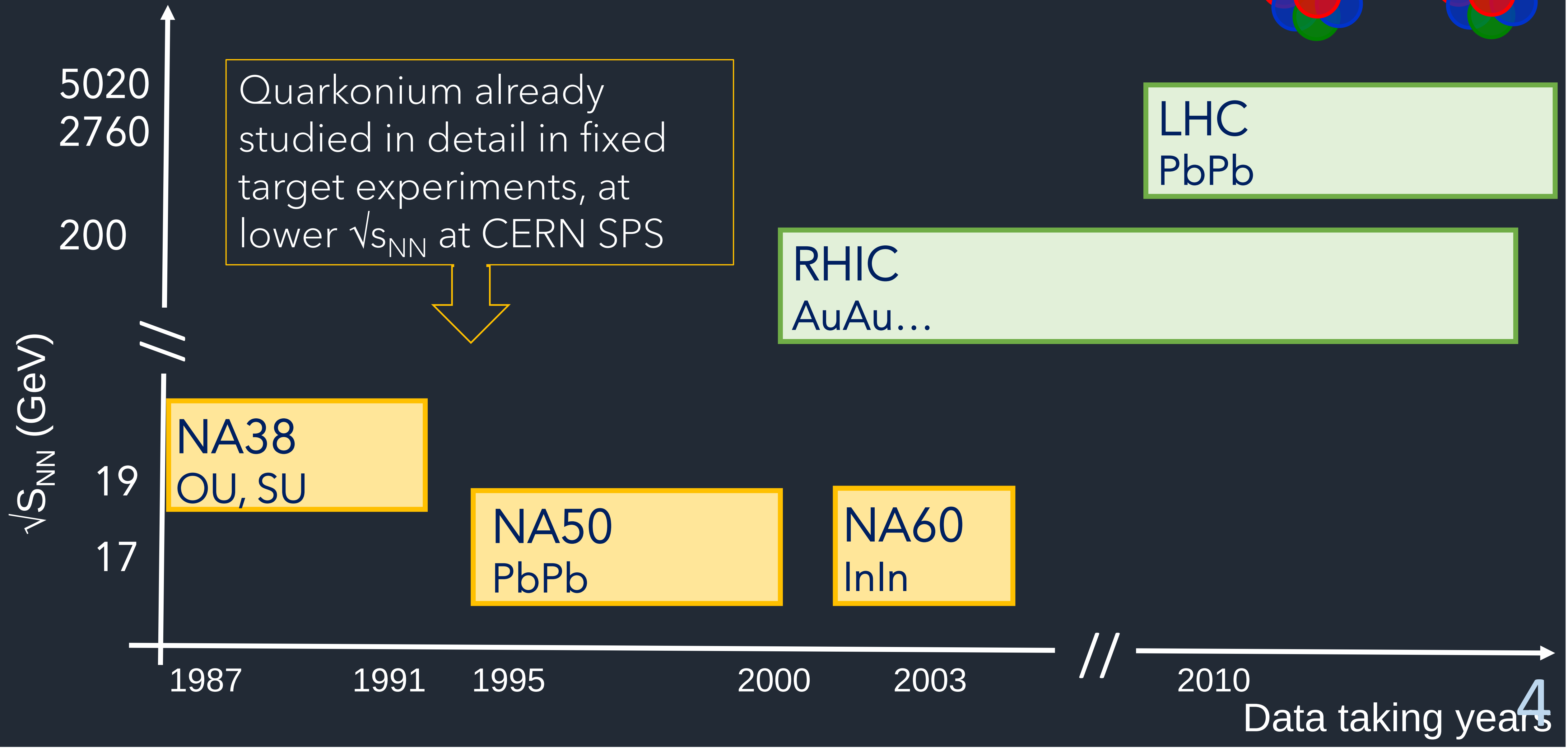
Quarkonium in AA





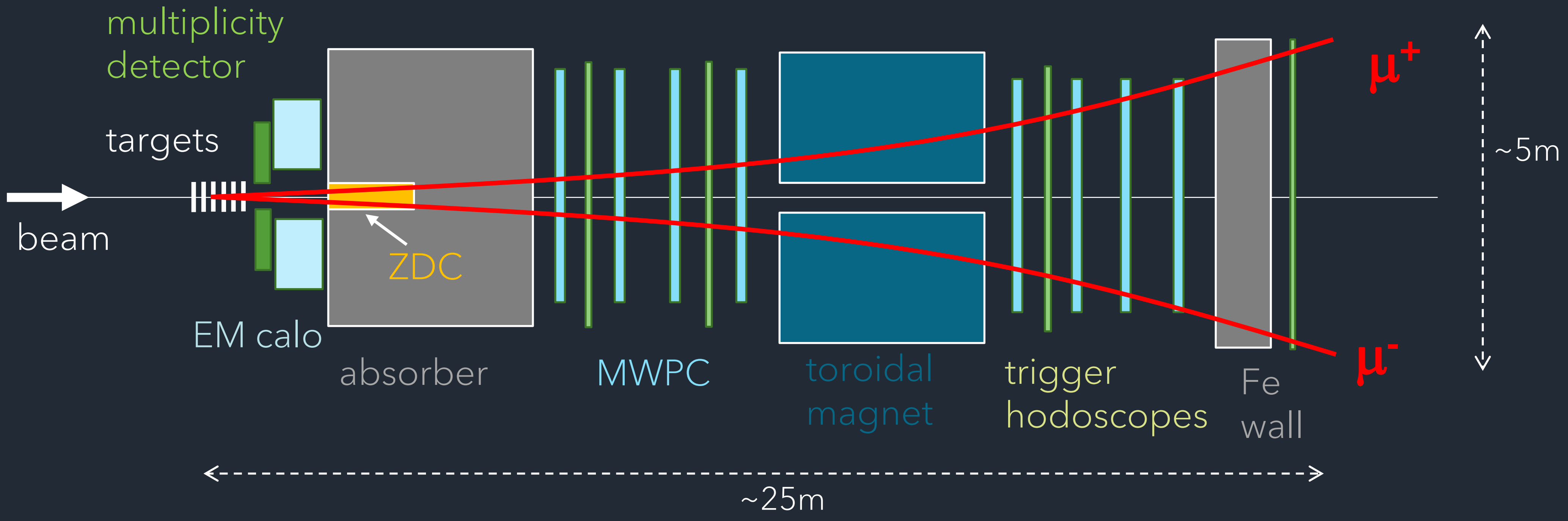
Quarkonium in AA





NA38/NA50

Study of muon pairs vs centrality of the collisions

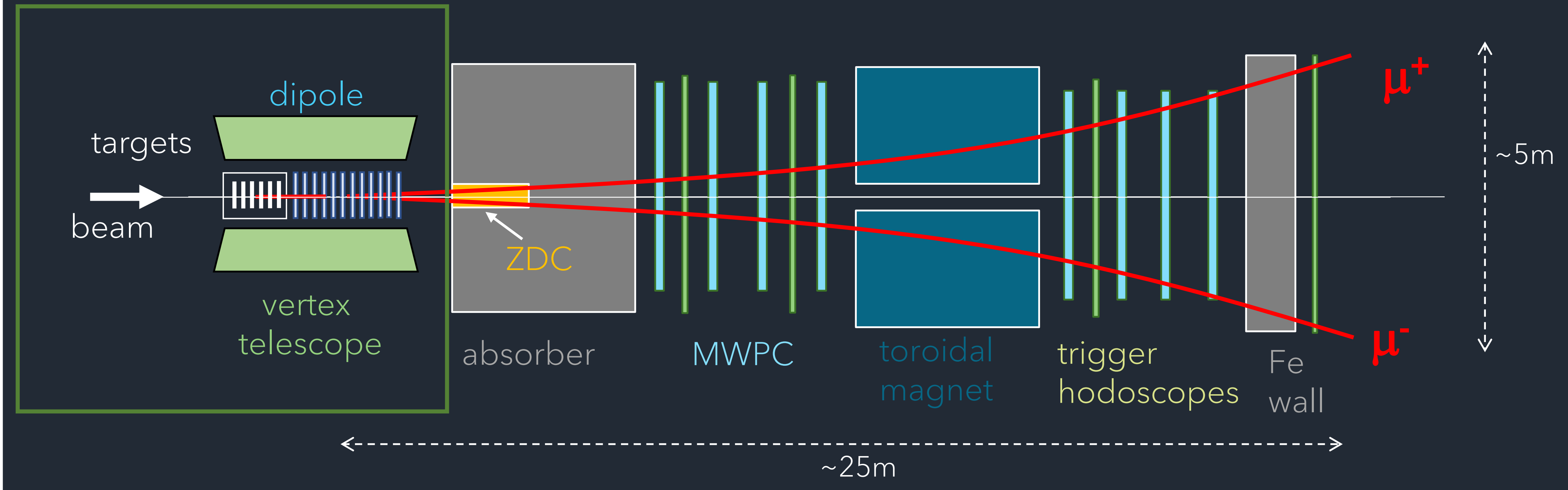


(not to scale)

NA60

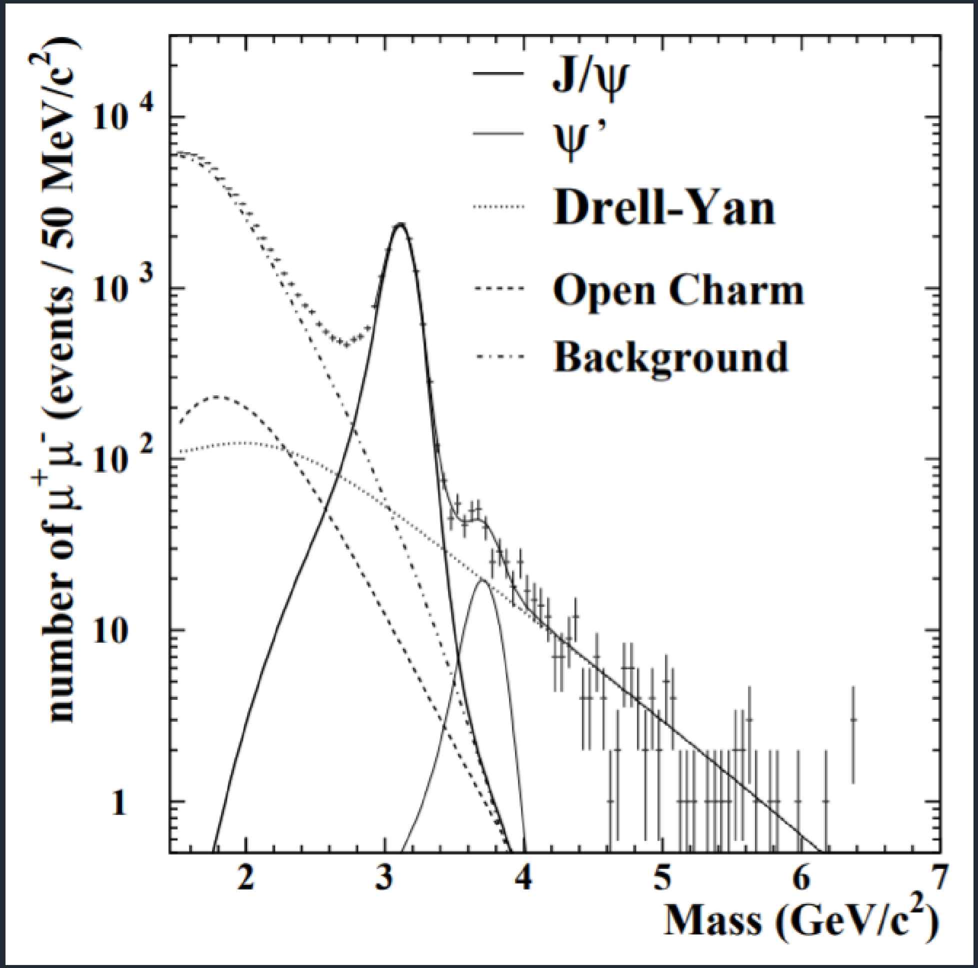
Upgraded vertex region
with vertex telescope

- improved dimuon kinematics
- improved mass resolutions
- reduced combinatorial background



(not to scale)

Analysis techniques in NA50/NA60



1 J/ψ/DY

DY is the reference, since not sensitive to medium modifications

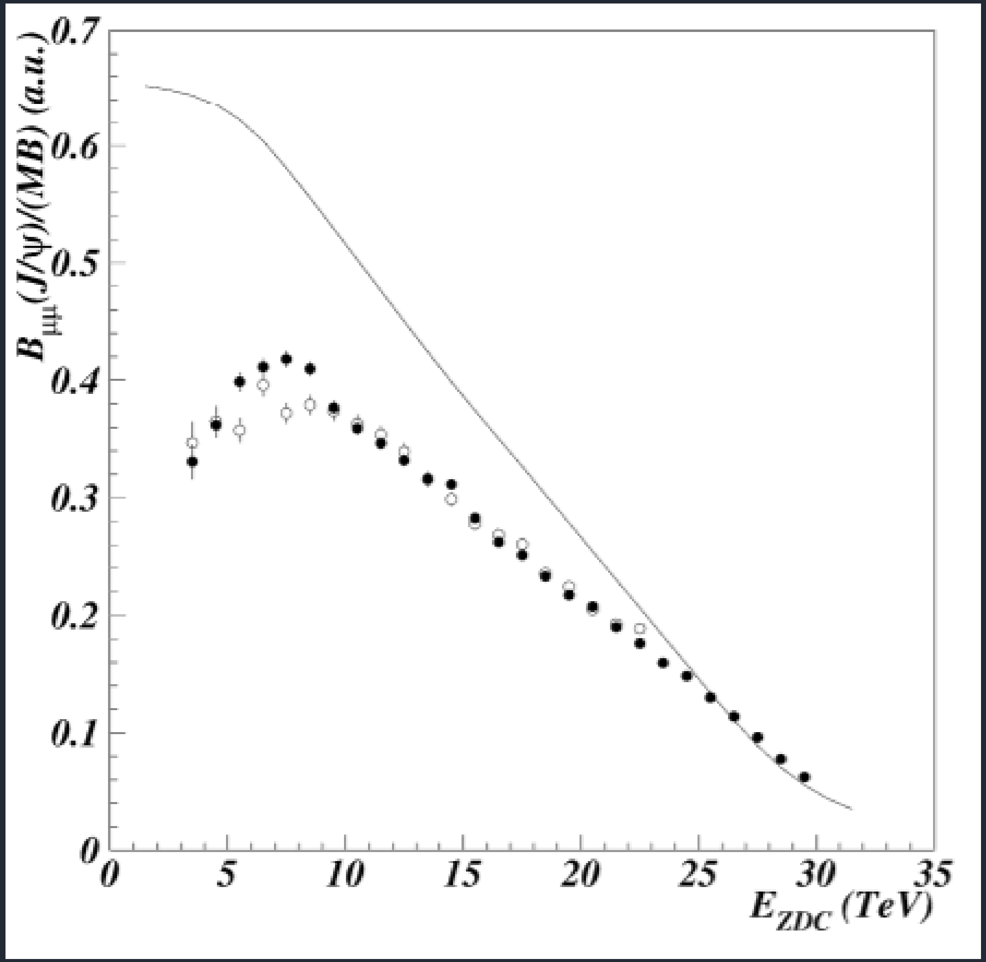
PROS:

Both J/ψ and DY are hard processes
→ systematic uncertainties cancel out

CONS:

Low DY statistics
(200000 J/ψ, ~2000 DY with M>4.2 GeV/c^2)

Analysis techniques in NA50/NA60



NA50 Coll., PLB521 (2001) 195

2 J/ψ/MB, J/ψ/DY*

DY* = "Fake" DY built from the MB spectrum, weighted by N_{Coll}

PROS:
Large statistics reference

CONS:
Larger systematics, due to different trigger (dimuon and MB) involved

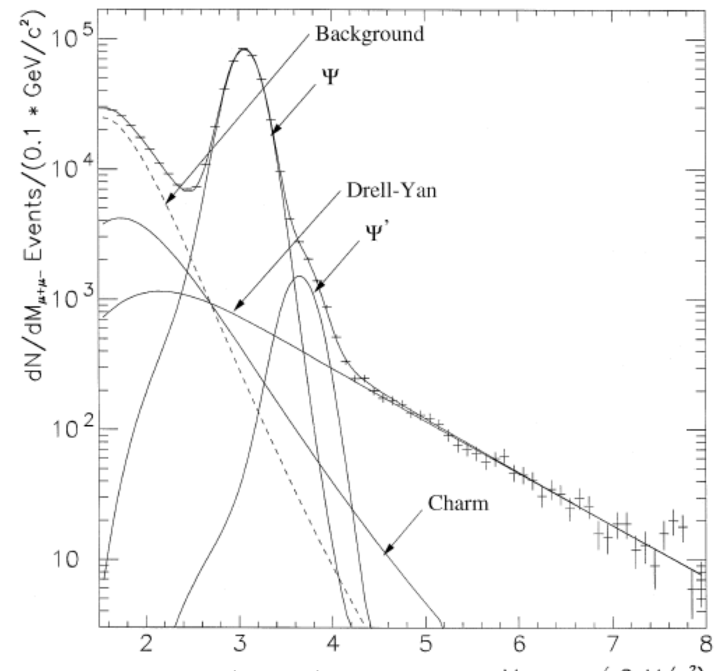
Analysis techniques in NA50/NA60

At SPS J/ψ was not studied via R_{AA} → limits on pp reference

- not available at 158 GeV
  → SPS usually running at top energy, i.e. 400/450 GeV
- p target not easily available

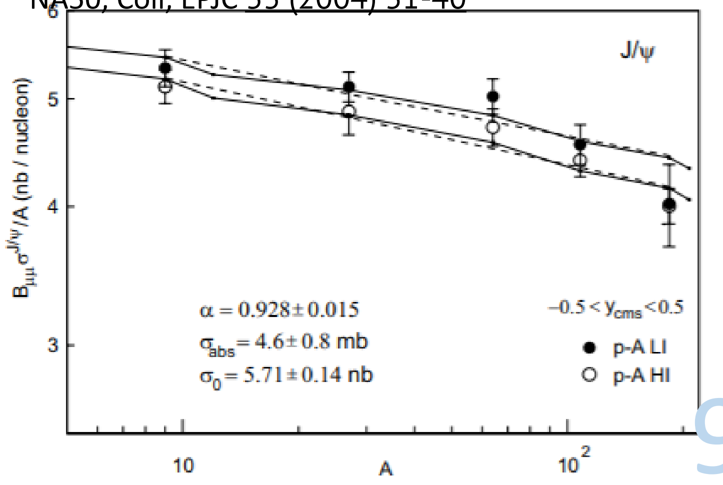
NA51: pp collisions using 1.2m liquid H_2 target at 450GeV
→ broad J/ψ resolution ~175 MeV due to multiple scattering in the absorber + poor vertex constraint
→ $B\sigma(J/\psi) = 5.50 \pm 0.01 \pm 0.36$ nb → ~7% uncertainty

NA50: J/ψ in pA collisions
→ extrapolate A-dependence to A=1, having Be as lightest target
→ ~3% uncertainty on the extrapolated pp cross section

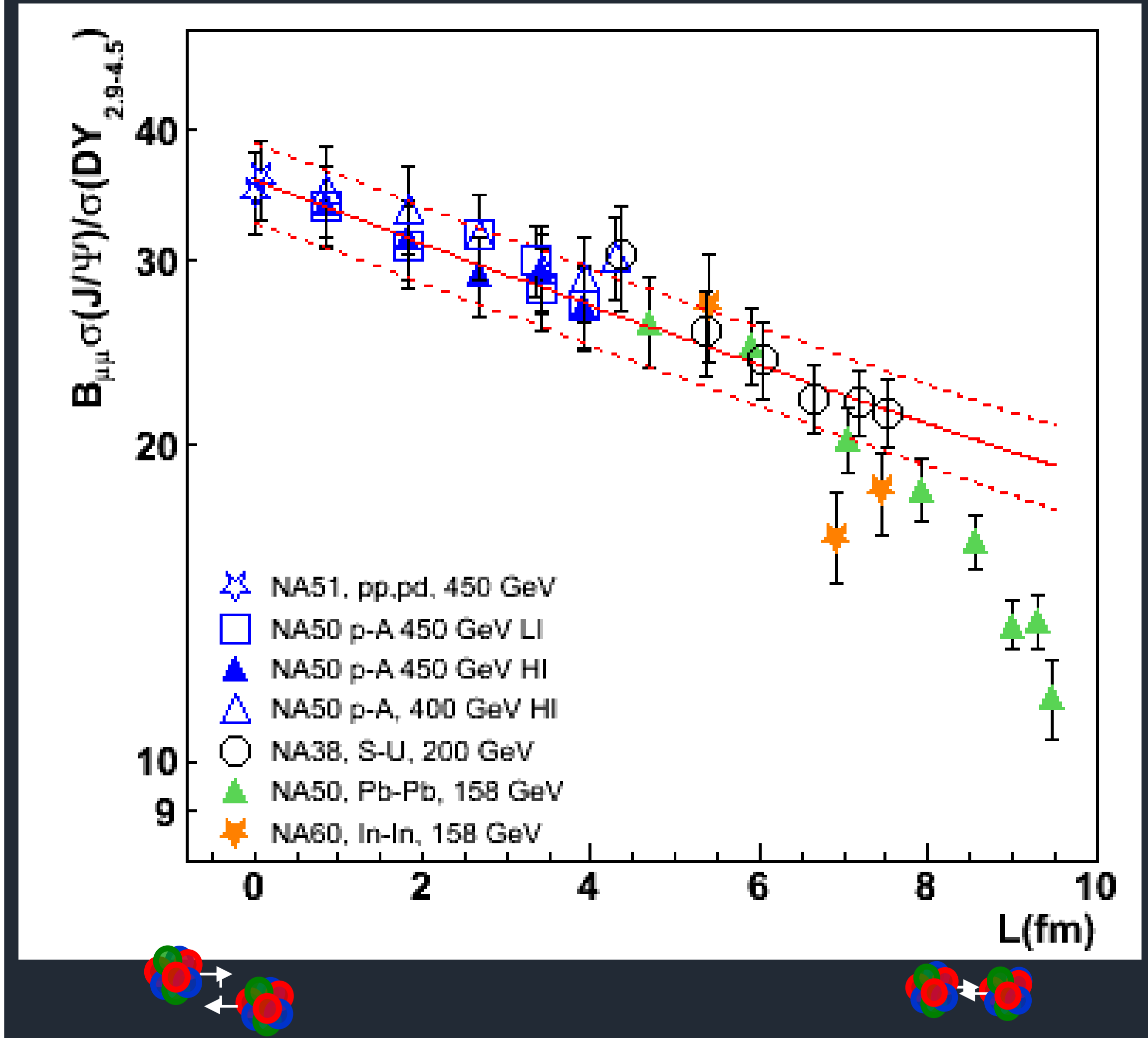


NA51, PLB438 (1998)35

NA50, Coll, EPJC 33 (2004) 31-40



J/ψ/DY in NA50



NA38 Coll., PLB449(1999)128
NA50 Coll.,EPJC39 (2005)335

pA (NA50)

- define the behavior due to CNM effects

SU (NA38)

- cold nuclear matter effects explain the observed suppression

PbPb (NA50)

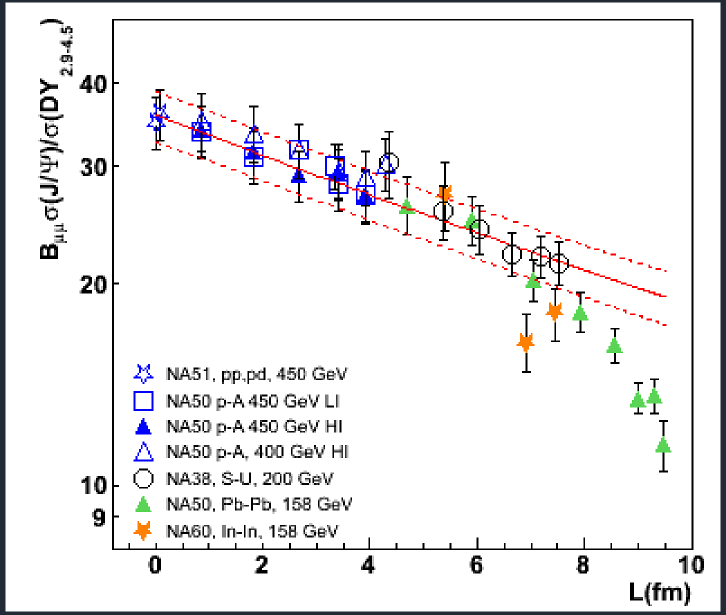
- decreasing trend vs centrality
- anomalous suppression in central collisions

evidence for QGP formation in central PbPb

CNM effects on J/ψ

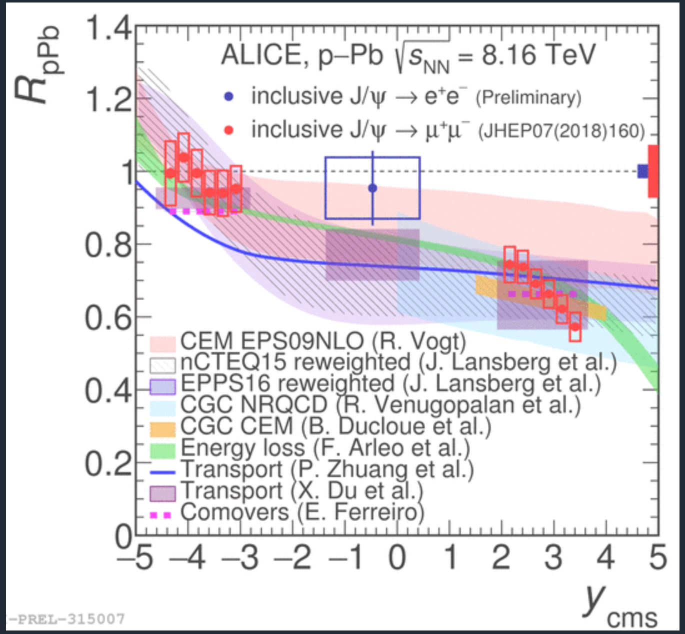
J/ψ suppressed already in cold nuclear matter
→ sizable CNM effects
→ precise pA measurements are crucial

as a reference for the hot matter effects



- SPS: ratio "measured/expected" was the standard approach
- LHC: approach not yet fully exploited

useful to disentangle CNM effects

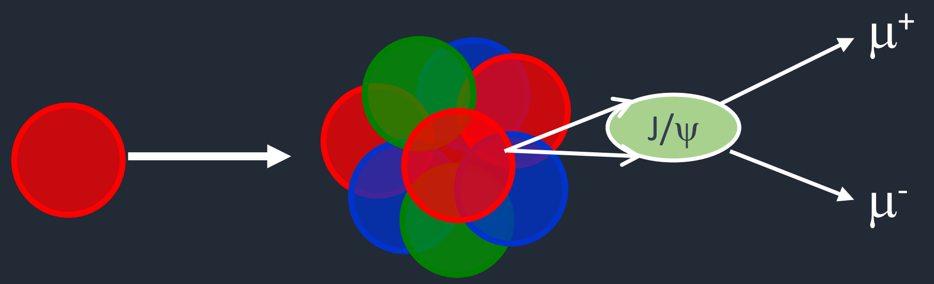


- LHC: attempts to separate CNM effects
- SPS: CNM effects usually described by effective quantities

Quarkonium in pA

1. Many mechanisms affect the J/ψ behavior in the nuclear medium

Initial state:
- shadowing,
- parton energy loss …

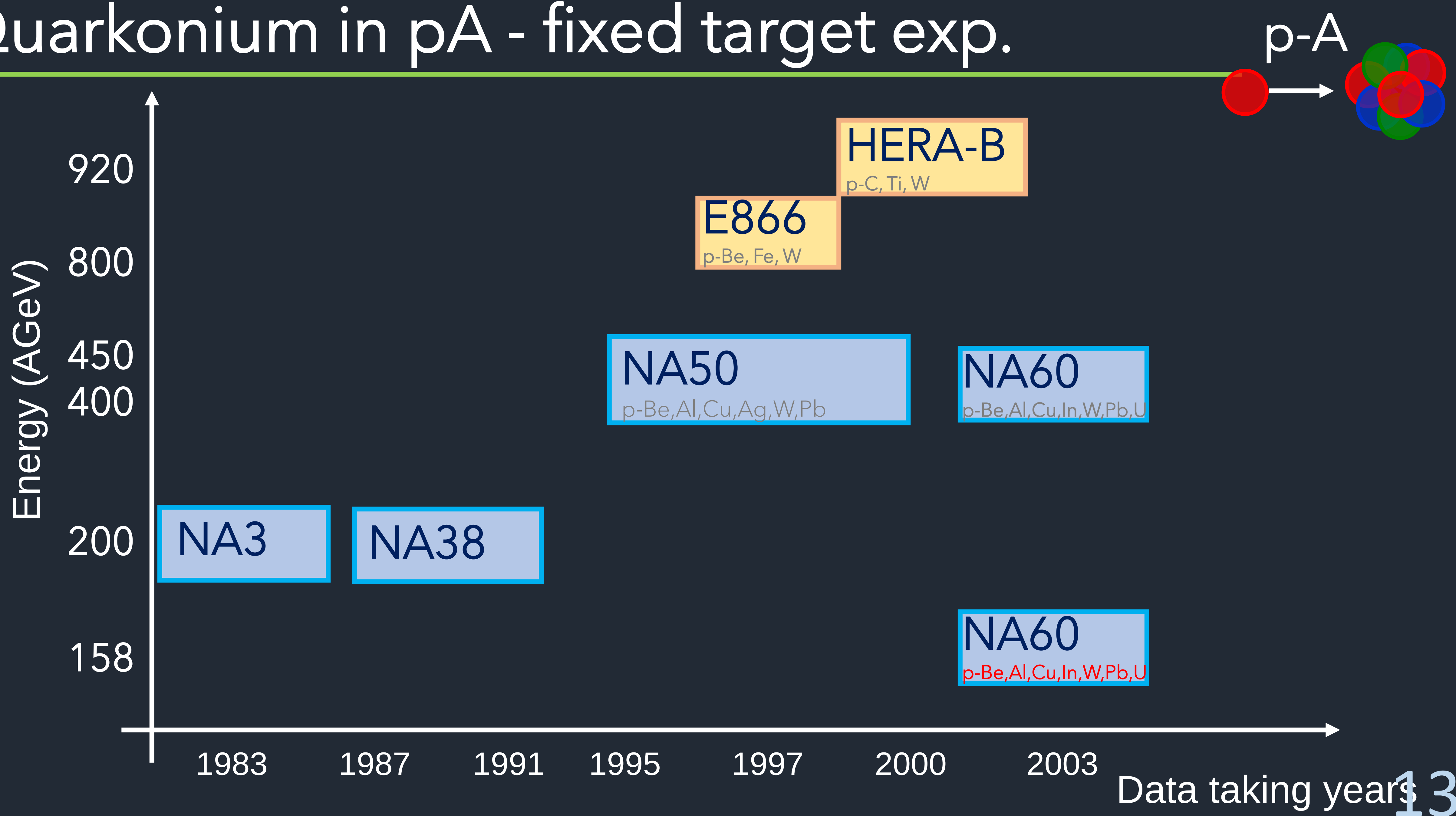


Final state:
- resonance break-up in the medium,
- final energy loss…

2. Complicate interplay between the different processes

→ consider all together the available pA data sets, collected at different energies and in different kinematical regions

Quarkonium in pA - fixed target exp.

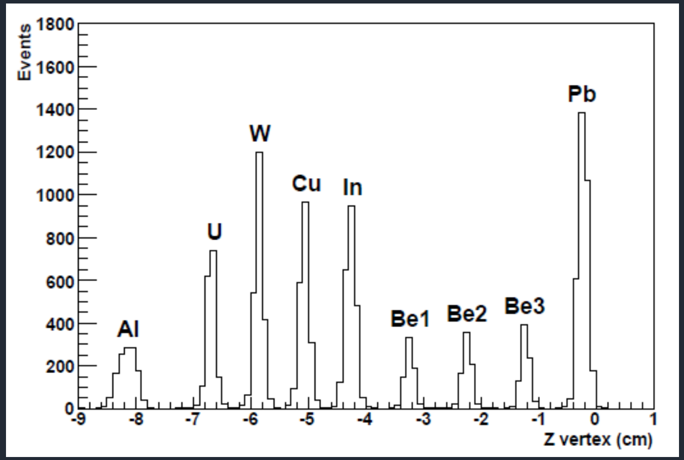


How was the J/ψ studied in pA?

J/ψ production vs A, i.e. varying the amount of nuclear matter crossed by cc pair

⇩

size of CNM effects defined by "effective" quantities



NA60 Coll. PLB706, 4-5, 263-267

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

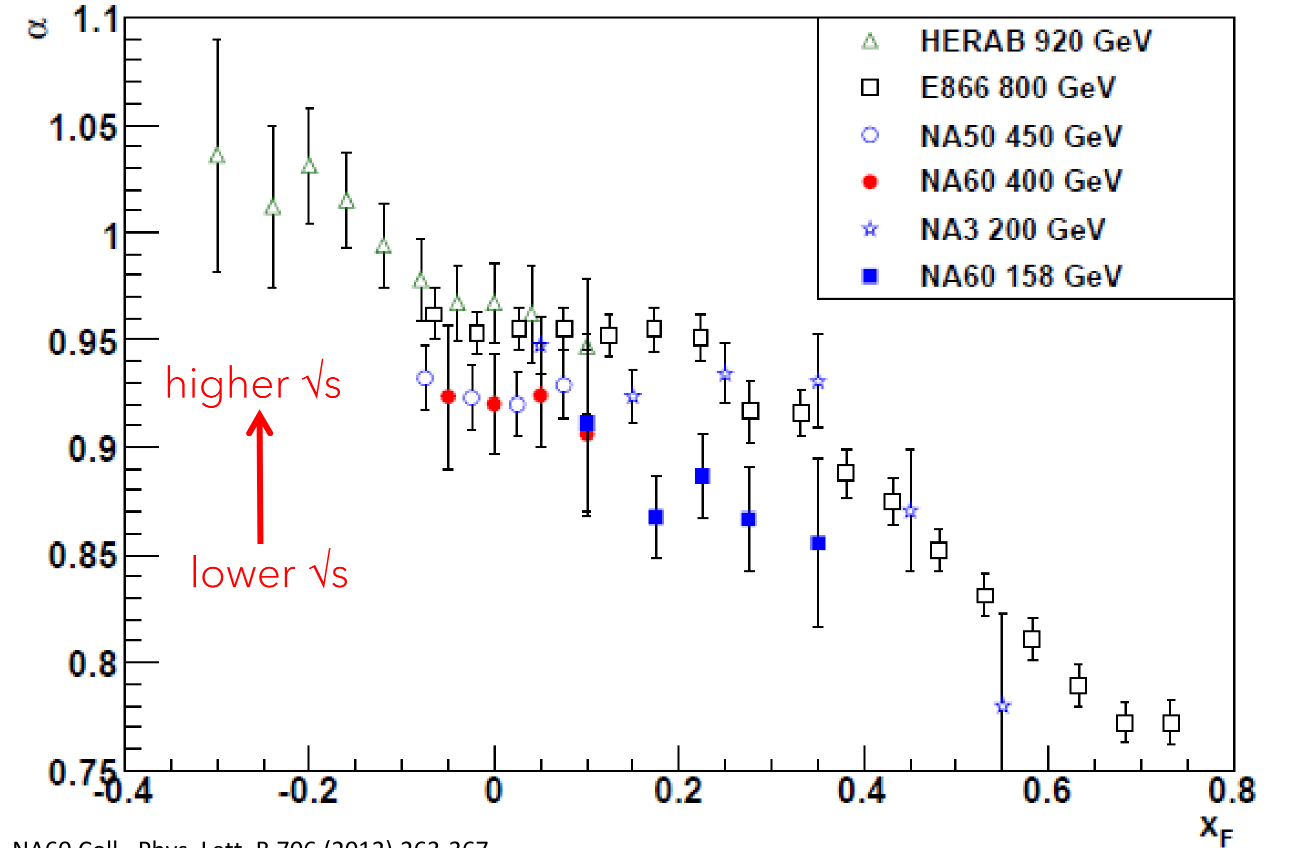
3. $R^{pA}_{J/\psi} = \dfrac{\sigma^{pA}_{J/\psi}}{A \cdot \sigma^{pp}_{J/\psi}}$ ← $R_{pA} = 1$ → no nuclear effects; $R_{pA} \neq$ → nuclear effects

↓

not used at SPS energies

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

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

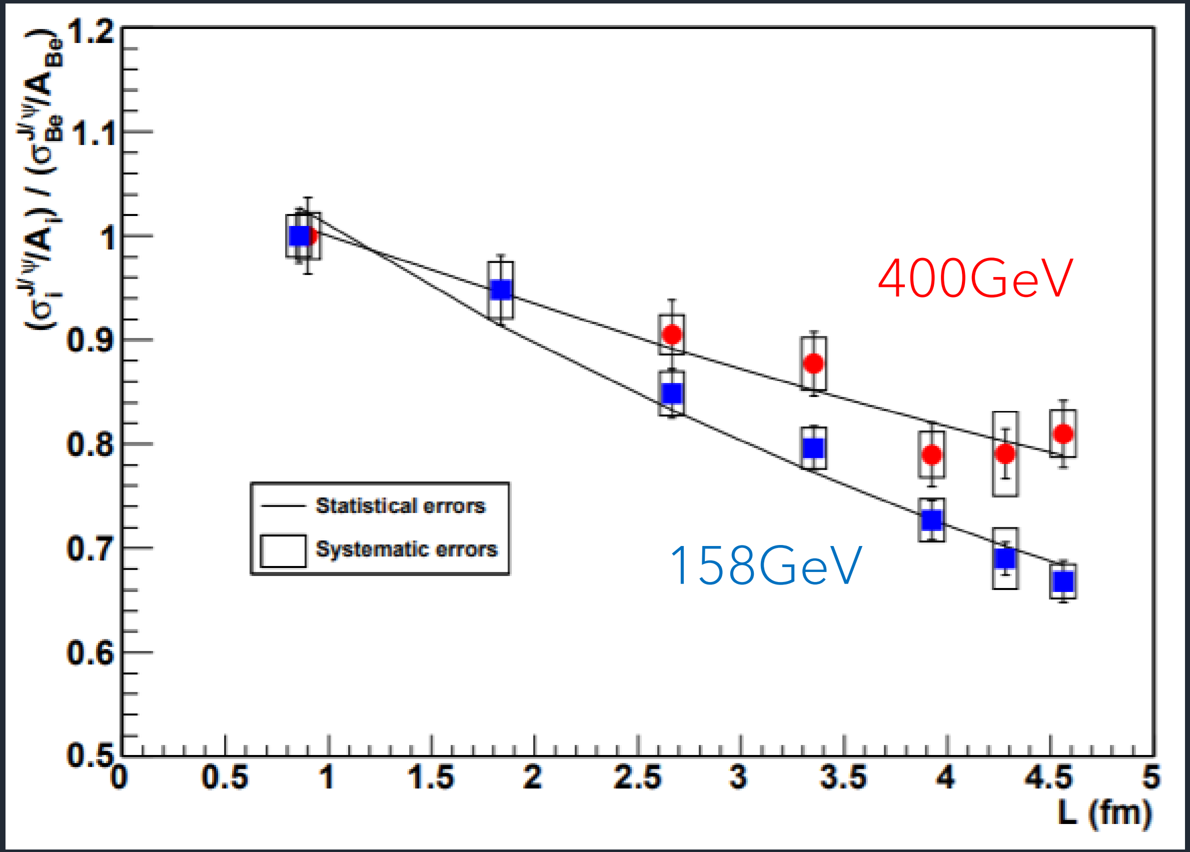
J/ψ yield in pA is modified with respect to pp, with a significant kinematic dependence

- α strongly decreases with x_F
- for a fixed x_F, stronger CNM at lower √s

given the strong x_F and √s dependence, pA reference should be measured in the same kinematical domain as AA

J/ψ in pA@ 158 GeV

NA60 collected for the first time pA data at the same energy as AA, i.e.158 GeV



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

$\sigma_{abs}^{J/\psi}$ (158 GeV) = 7.6 ± 0.7 ± 0.6 mb

$\sigma_{abs}^{J/\psi}$ (400 GeV) = 4.3 ± 0.8 ± 0.6 mb

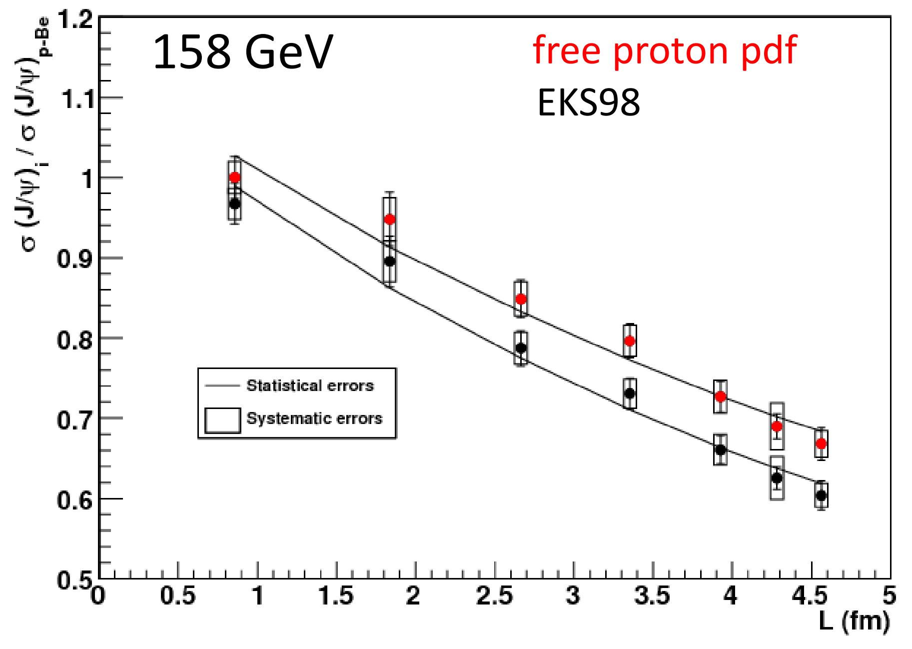
stronger cold nuclear matter effects at 158 GeV

NA60 Coll. PLB706, 4-5, 263-267

J/ψ in pA@158GeV

First attempt to disentangle CNM effects

At SPS energies: shadowing + nuclear break-up (crossing time > formation time)



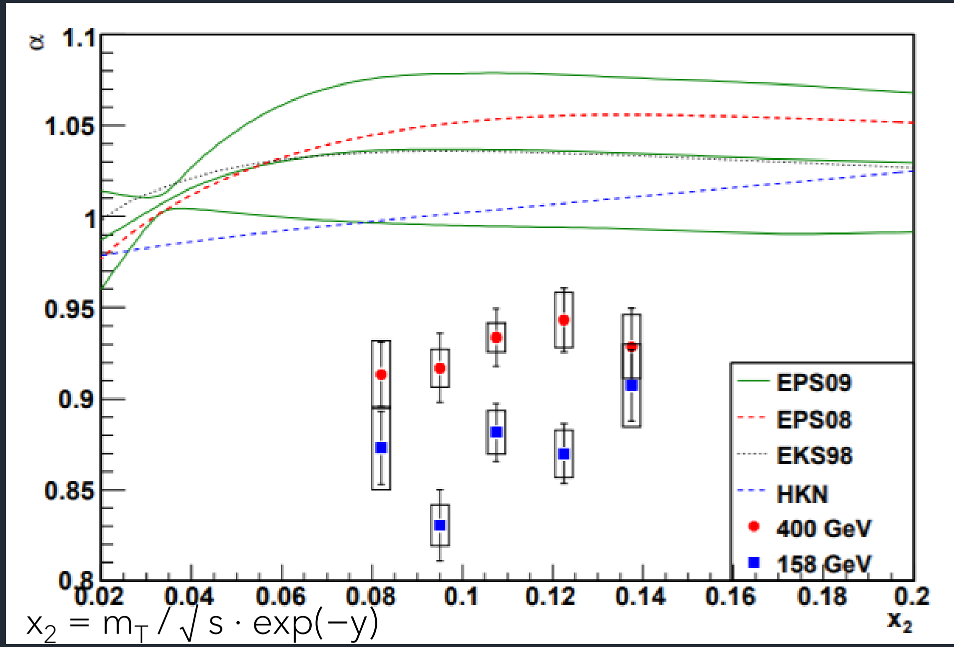
nuclear break-up vs. (anti)shadowing

$\sigma_{abs}^{J/\psi} = 7.6 \pm 0.7 \pm 0.6$ mb

⇩

$\sigma_{abs}^{J/\psi} = 9.3 \pm 0.7 \pm 0.7$ mb

with EKS98 shadowing correction



NA60 Coll. PLB706, 4-5, 263-267

compare results at the two energies. At a given x_2

- same shadowing expected
- same J/ψ break-up in the medium expected
- other effects at play?

From pA to AA – new reference curve

NEW reference curve is extrapolated from pA to AA:

NEW σ_{abs} shows an energy/kinematical dependence

reference now obtained in pA at the same energy/kinematical range as the AA data (OLD reference curve was based on 400/450GeV pA data)

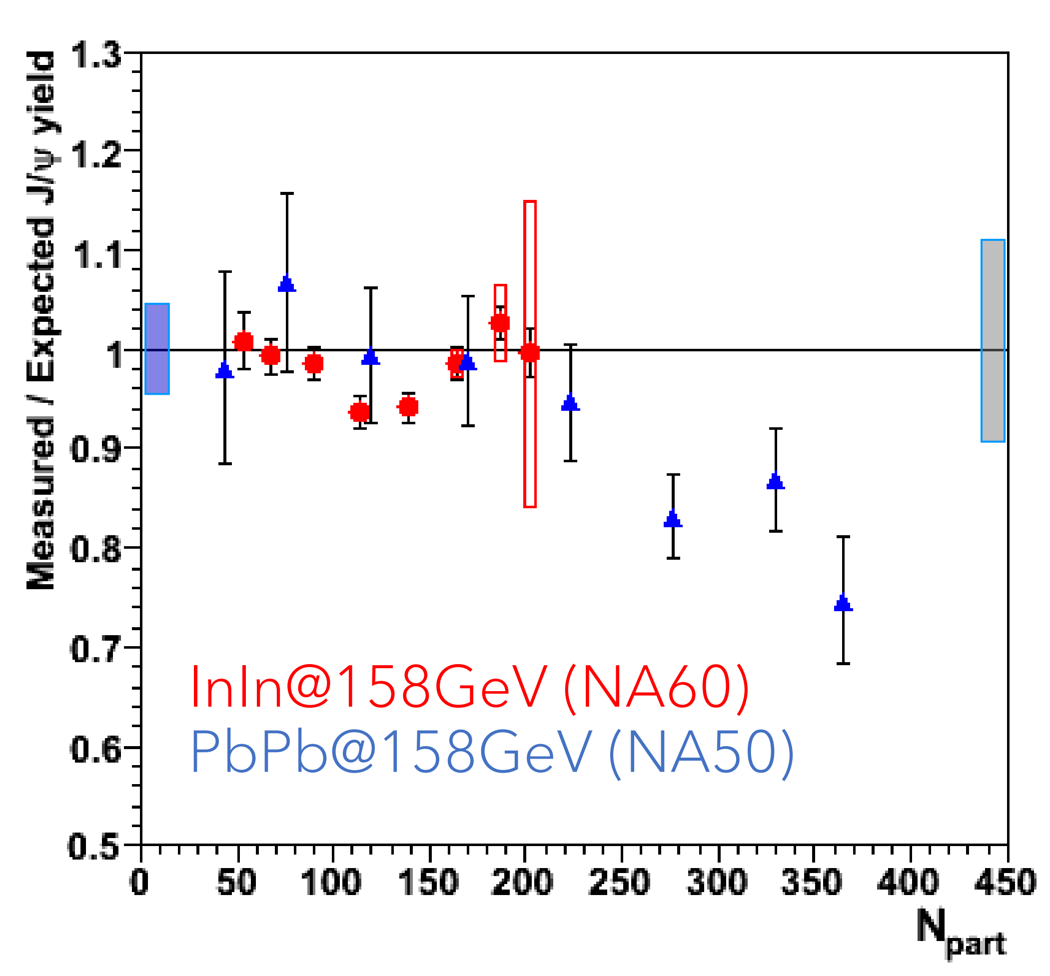
NEW in AA, shadowing affects both projectile and target

projectile and target antishadowing taken into account in the reference determination

centrality dependence of the reference

obtained within a Glauber approach

J/ψ measured/expected



SPS results now based on the pA reference curve at 158 GeV (same energy as AA)

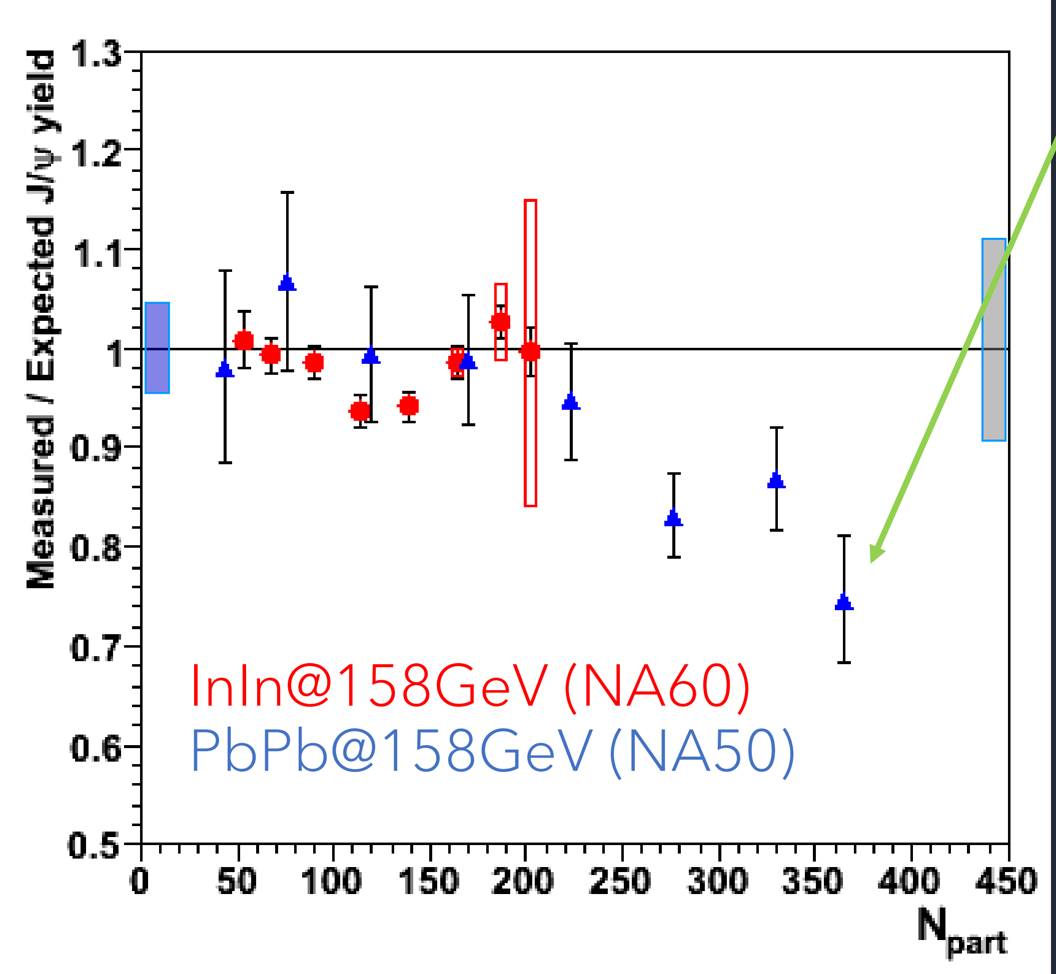
- Central Pb-Pb
  J/ψ anomalously suppressed

- In-In
  almost no anomalous suppression

Size of J/ψ suppression quantitatively consistent with melting of ψ(2S) and χ_c

B. Alessandro et al., EPJC39 (2005) 335
R. Arnaldi et al., Nucl. Phys. A (2009) 345
R.A.rnaldi, P. Cortese, E. Scomparin Phys. Rev. C 81, 014903

What can still be improved?



1 accuracy in PbPb measurements, similar to the NA60 one

so far, results limited by low DY statistics

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

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

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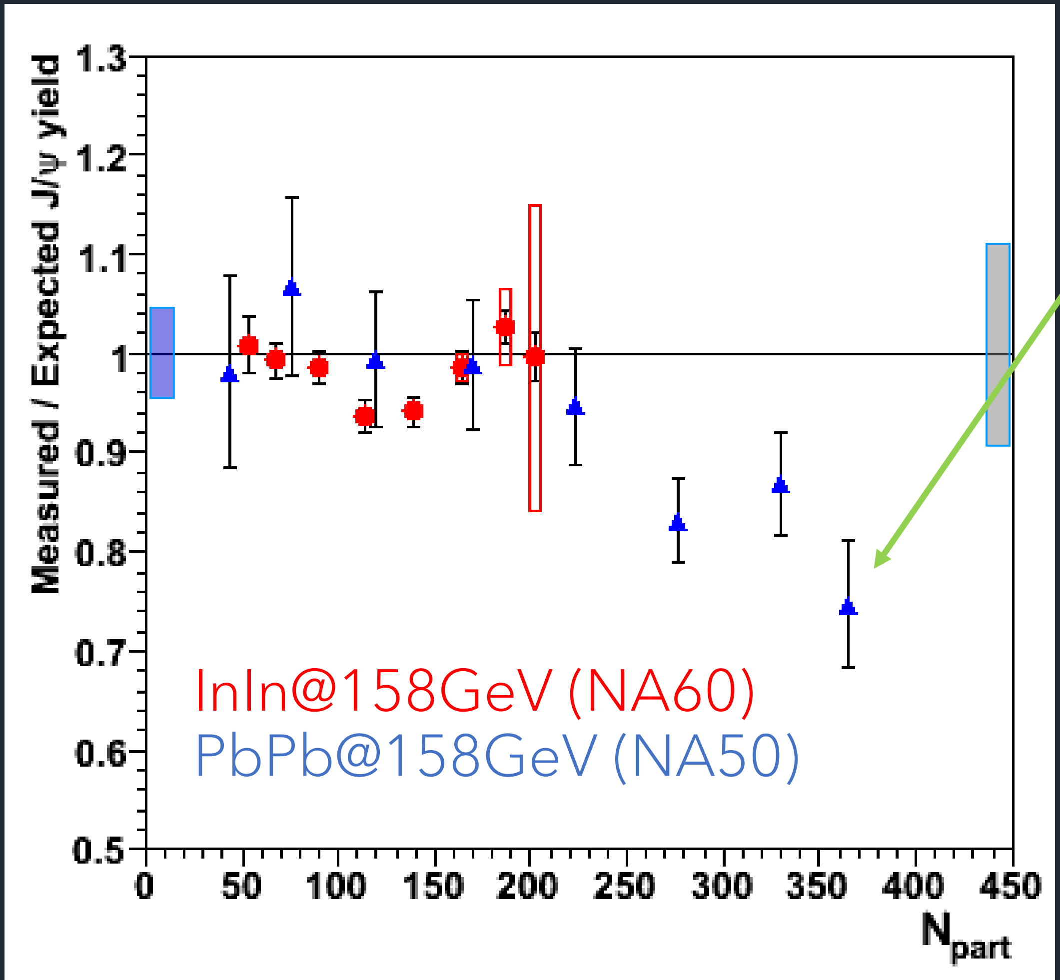

1. accuracy in PbPb measurements, similar to the NA60 one

2. access to excited quarkonium states in AA

to understand if the J/ψ suppression is accounted for by the melting of ψ(2S) and χ_c

- investigate their suppression
- study their impact on the J/ψ through feed down

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

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

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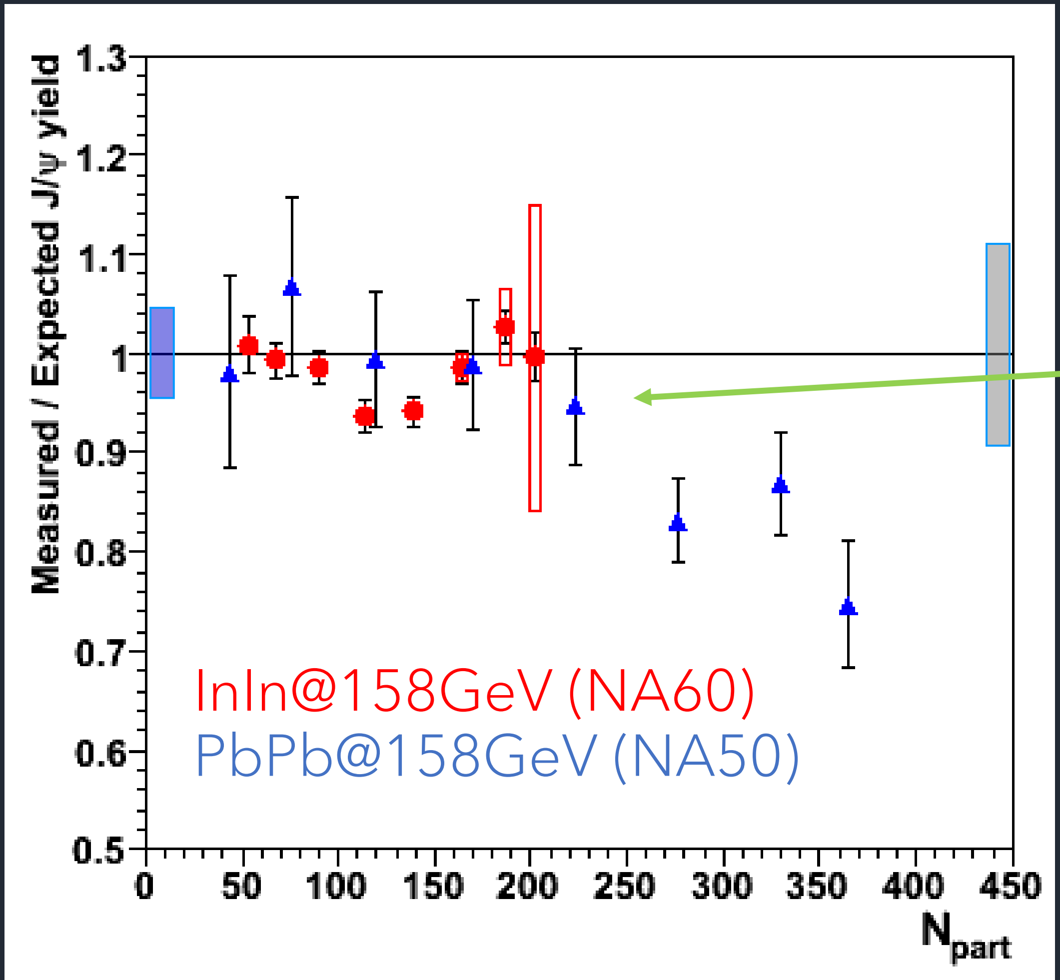

1. accuracy in PbPb measurements, similar to the NA60 one
2. access to excited quarkonium states in AA
3. energy dependence of the anomalous suppression onset

studying J/ψ production below top SPS energies

B. Alessandro et al., EPJC39 (2005) 335
R. Arnaldi et al., Nucl. Phys. A (2009) 345
R.A.rnaldi, P. Cortese, E. Scomparin Phys. Rev. C 81, 014903

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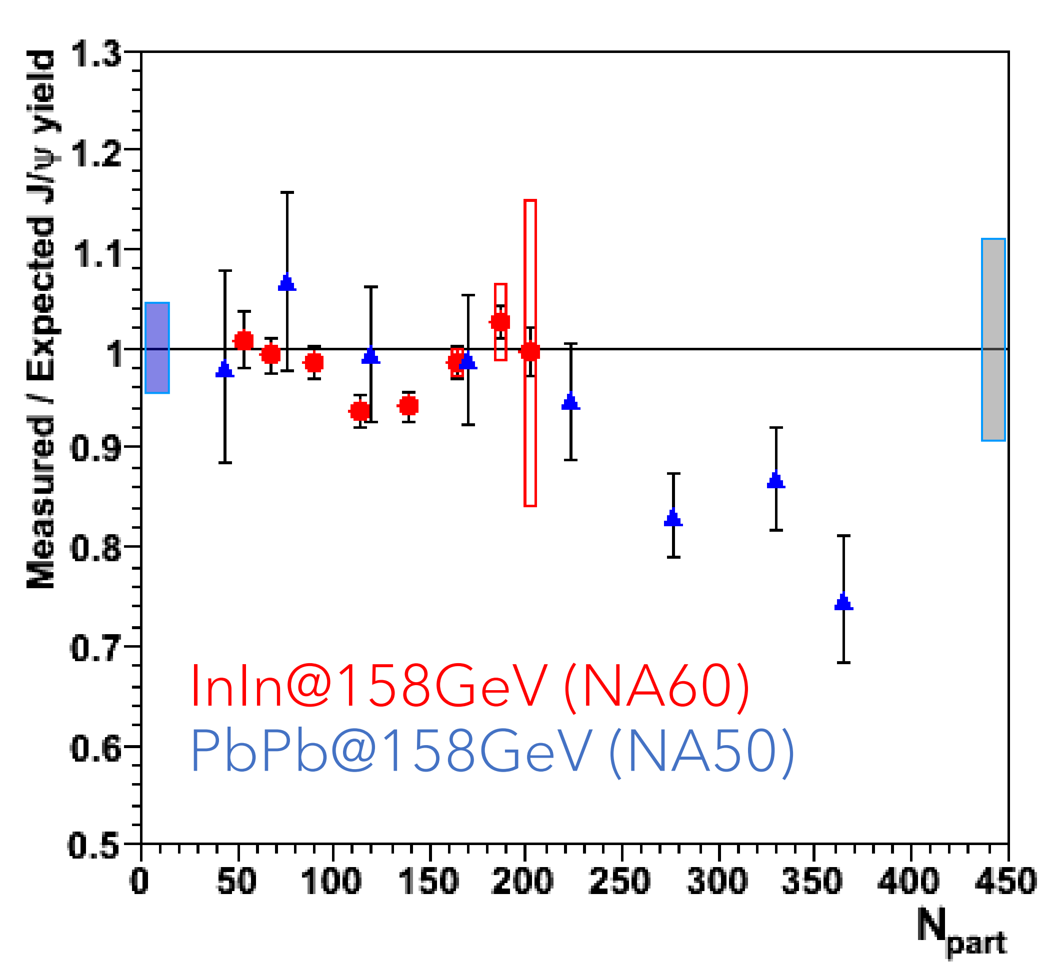
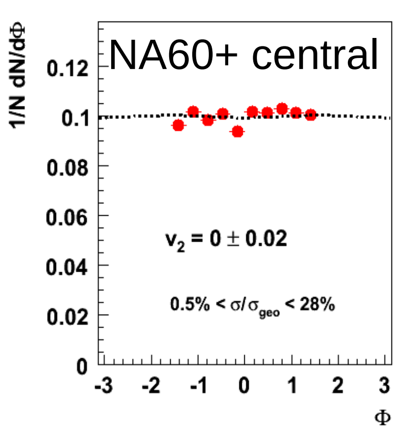
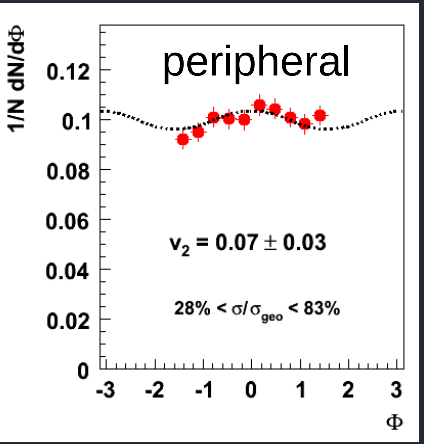


1. accuracy in PbPb measurements, similar to the NA60 one
2. access to excited quarkonium states in AA
3. energy dependence of the anomalous suppression onset
4. study other observables as v_2
turned out to provide complementary information at LHC





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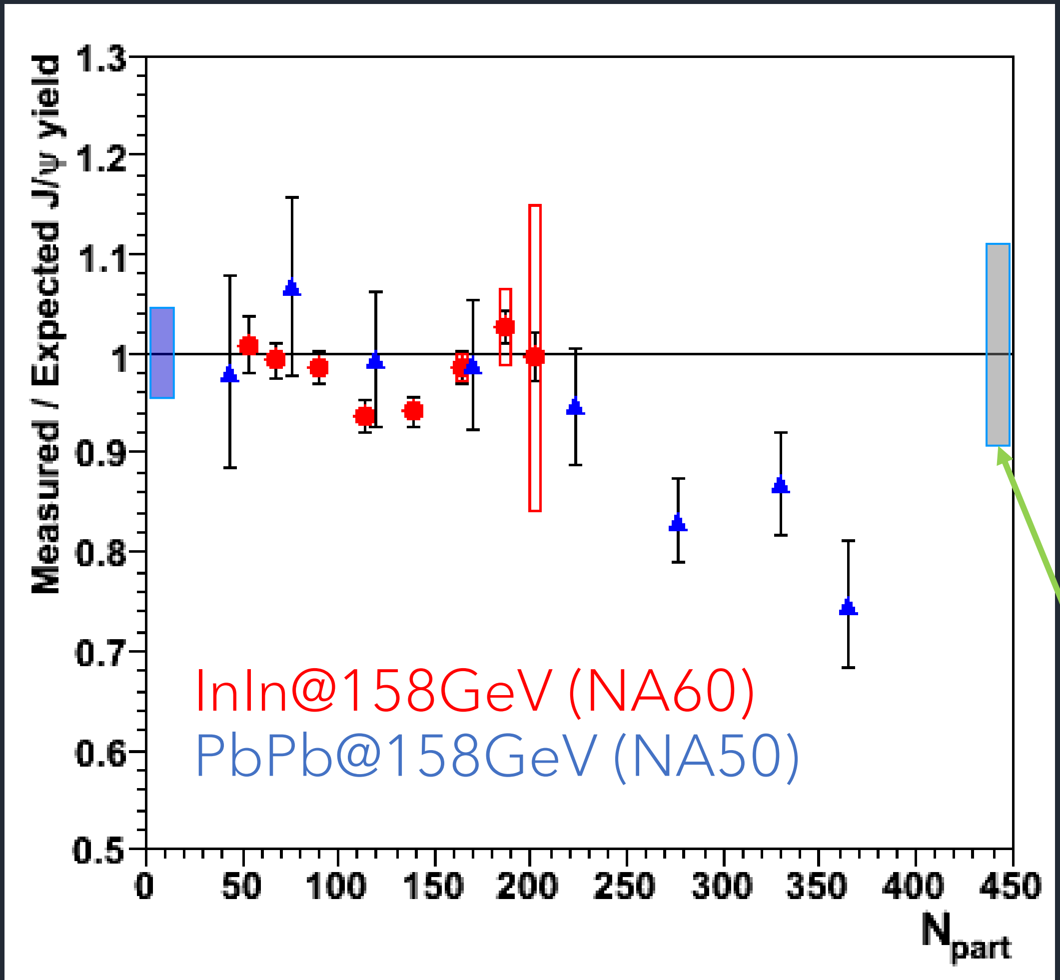


1. accuracy in PbPb measurements, similar to the NA60 one
2. access to excited quarkonium states in AA
3. energy dependence of the anomalous suppression onset
4. study other observables as v_2
5. the precision of the pA reference
   - crucial to have pA and AA at the same energy
   - ~12% uncertainty (158 GeV data taking was ~4 days at I_{beam}= 5e8 p/s)
   - important to disentangle shadowing from nuclear break-up

B. Alessandro et al., EPJC39 (2005) 335
R. Arnaldi et al., Nucl. Phys. A (2009) 345
R.A.rnaldi, P. Cortese, E. Scomparin Phys. Rev. C 81, 014903

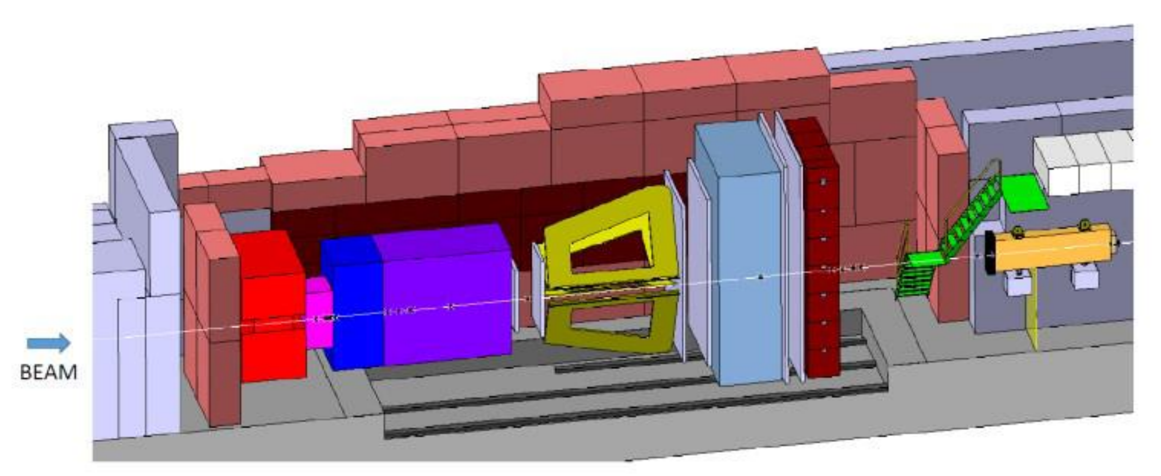
Quarkonium in NA60+

NA60+ aims to answer to these questions with an energy scan between

E_{lab} = 40 – 158 GeV

→ quarkonium production not studied below top SPS energies!

Alessandro De Falco on Monday

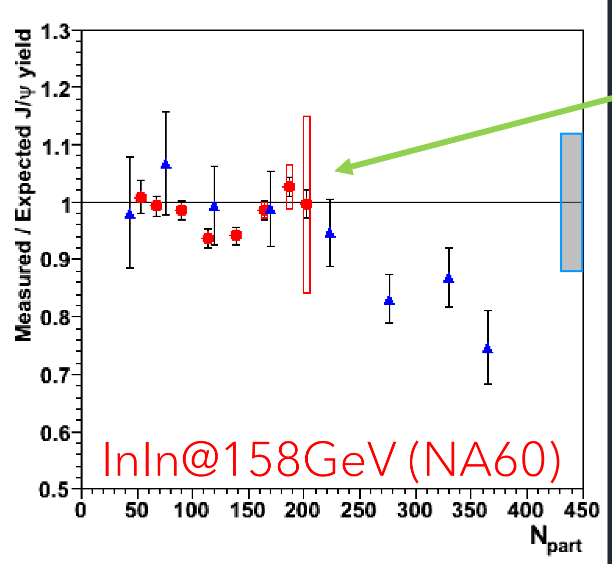


Decreasing in √s:

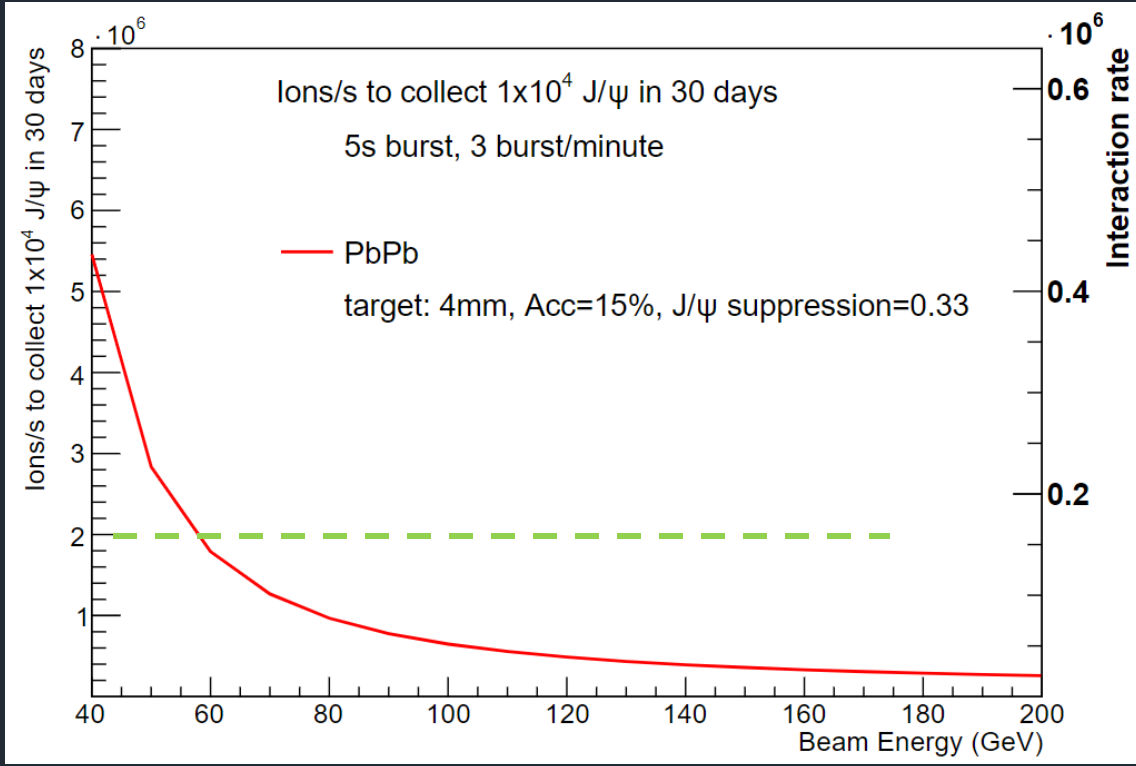
- high μ_B QGP effects on quarkonium
  → still need theory guidance
- onset of χ_c and $\psi(2S)$ deconfinement
  → can be correlated to T measurement via thermal dimuons
- stronger CNM effects
  → to be accounted for with pA data taking at the same √s

J/ψ in NA60+, AA collisions

High luminosity is needed to cope with the low production cross sections at low √s



AA: precise NA60 data (InIn at 158 GeV) correspond to 3 x 10^4 J/ψ



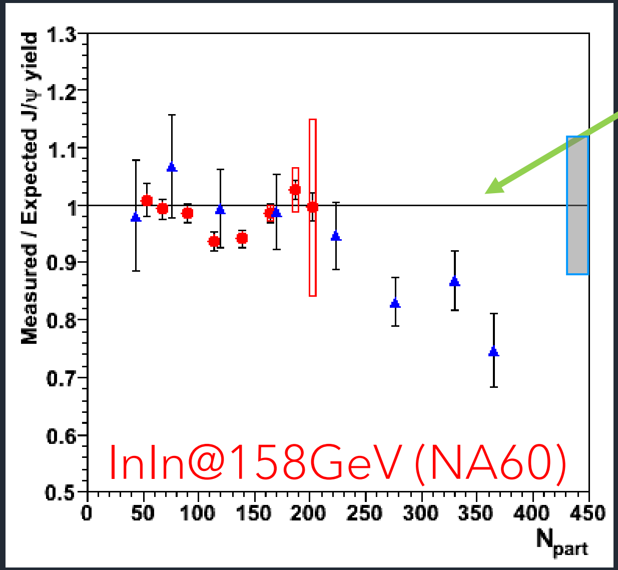
NA60+ CERN-SPSC-2019-017 ; SPSC-EOI-019

With I_{beam}~2x10^6 Pb/s and 1 month of data taking NA60+ can aim to

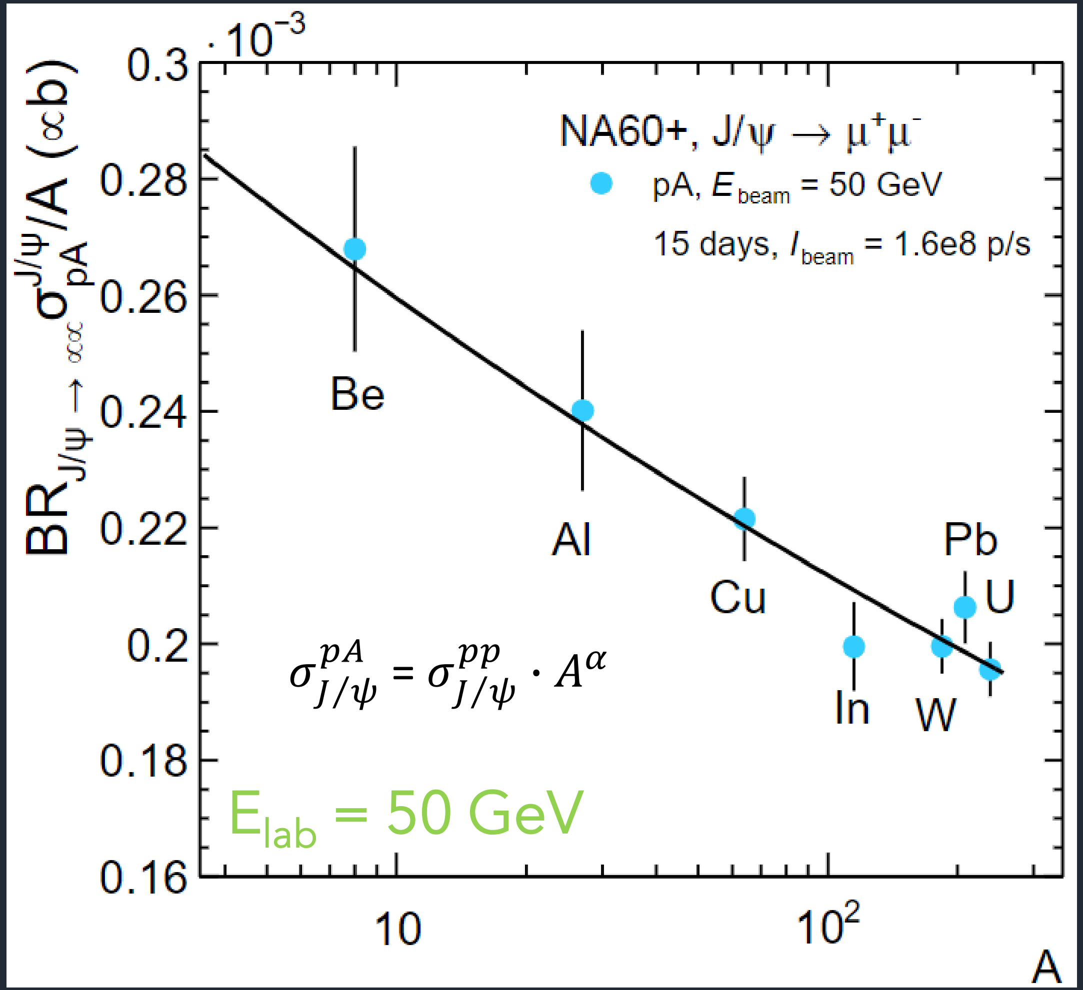
- ~10^4 J/ψ at 50 GeV
- ~5 10^4 J/ψ at 158 GeV

J/ψ in NA60+, pA collisions

High luminosity is needed to cope with the low production cross sections at low $\sqrt{s}$



pA: NA60 data taking at 158 GeV was ~1.5×10^4 J/ψ

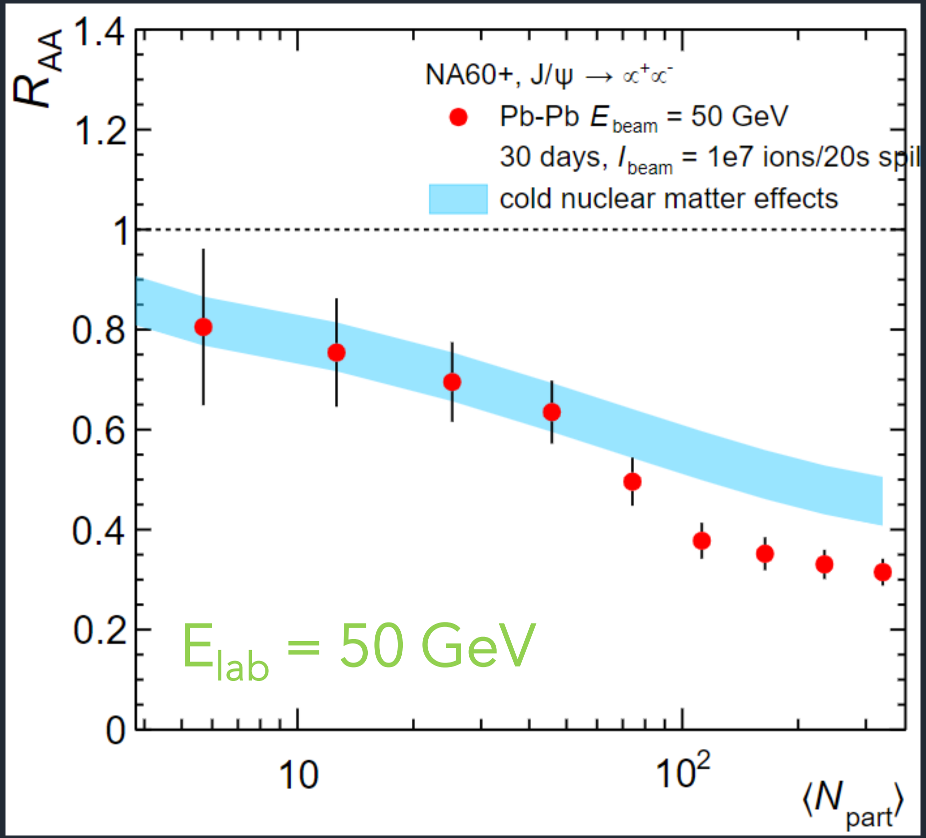


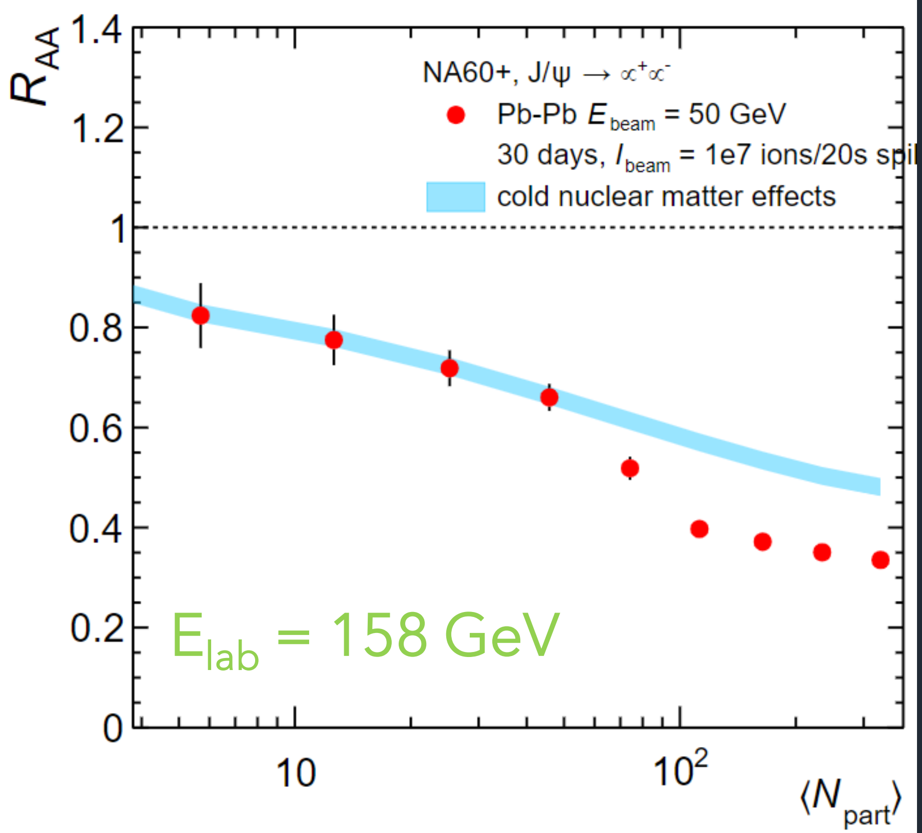
In 15 days of data taking at 1.6×10^8 p/s NA60+ should collect

- E_{lab} = 50GeV ~6000 J/ψ
- E_{lab} = 158GeV ~50000 J/ψ

NA60+ CERN-SPSC-2019-017 ; SPSC-EOI-019

J/ψ in NA60+, pA and AA collisions





Based on

- 30 days PbPb
  I_{beam} = 2e6 Pb/s
- 15 days pA
  I_{beam} = 1.6e8 p/s

assuming only CNM effects for N_{part}<50 and 20% suppression for N_{part}>50

→ Precise evaluation of anomalous suppression within reach even at low E_{lab}

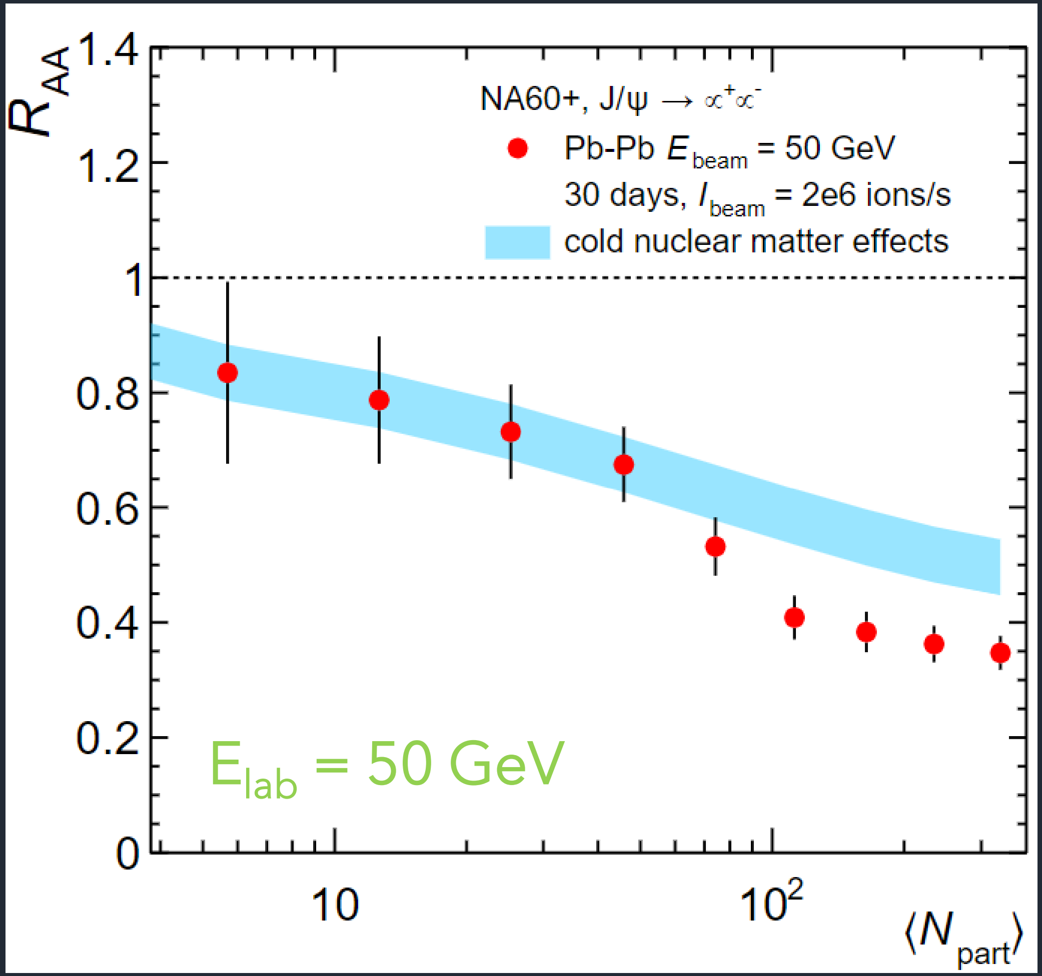
In 15 days of data taking at 1.6 x 10^8 p/s the uncertainties on the pA reference are:

E_{lab} = 50GeV
- ~15% on σ_{abs}
- ~5% on σ_{pp}

E_{lab} = 158GeV
- ~6% on σ_{abs}
- ~2% on σ_{pp}

NA60+ CERN-SPSC-2019-017 ; SPSC-EOI-019

J/ψ in NA60+, observables

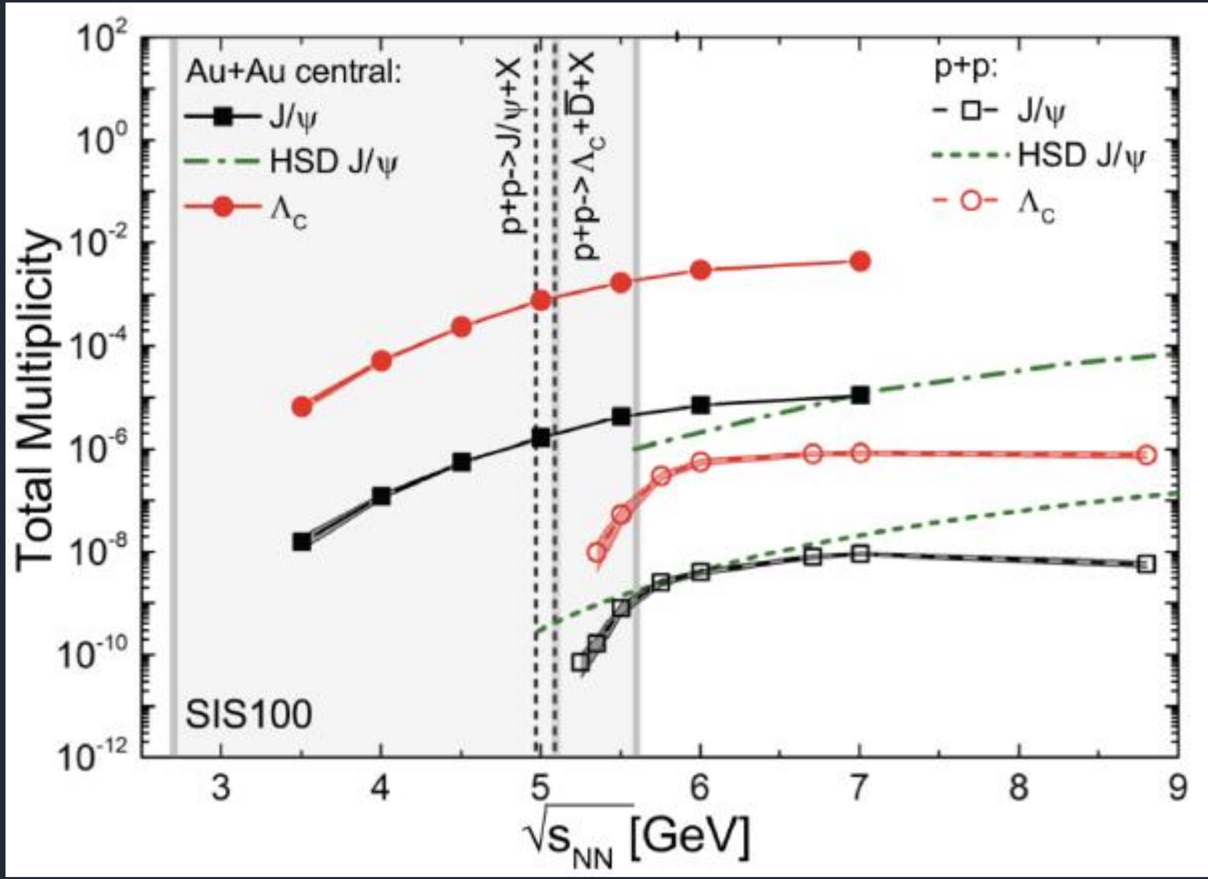


Which observables can we use?

- R_{AA} based on pp extrapolated from pA results at the same √s (<5% uncertainty)
- R_{AA}/R_{pA} ~ measured/expected à la NA50/60
  → useful to compare results at various √s, since CNM are energy dependent
- no need of Drell-Yan?
  very much limited by statistics (x100 less wrt J/ψ)
- J/ψ/(DDbar)?
  suppression of J/ψ + enhancement DDbar?

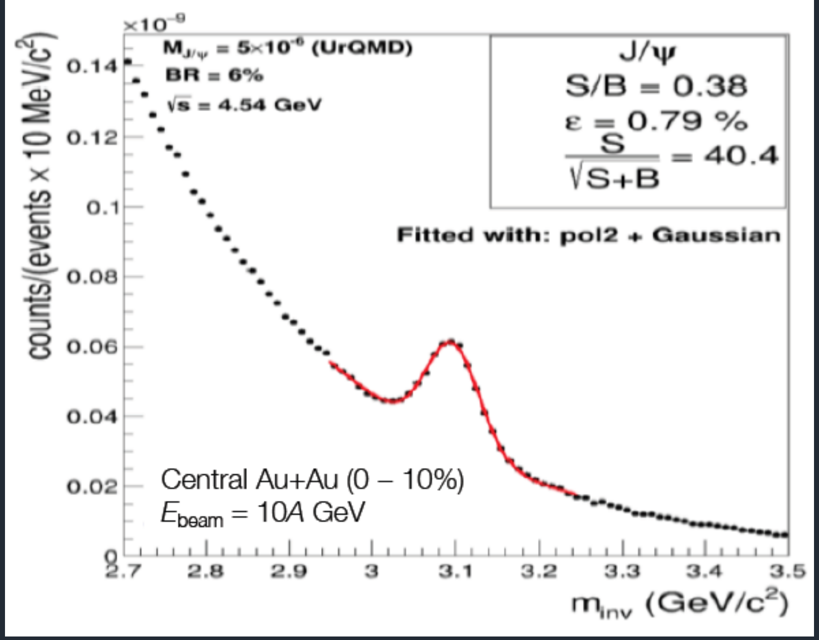
Quarkonium in CBM

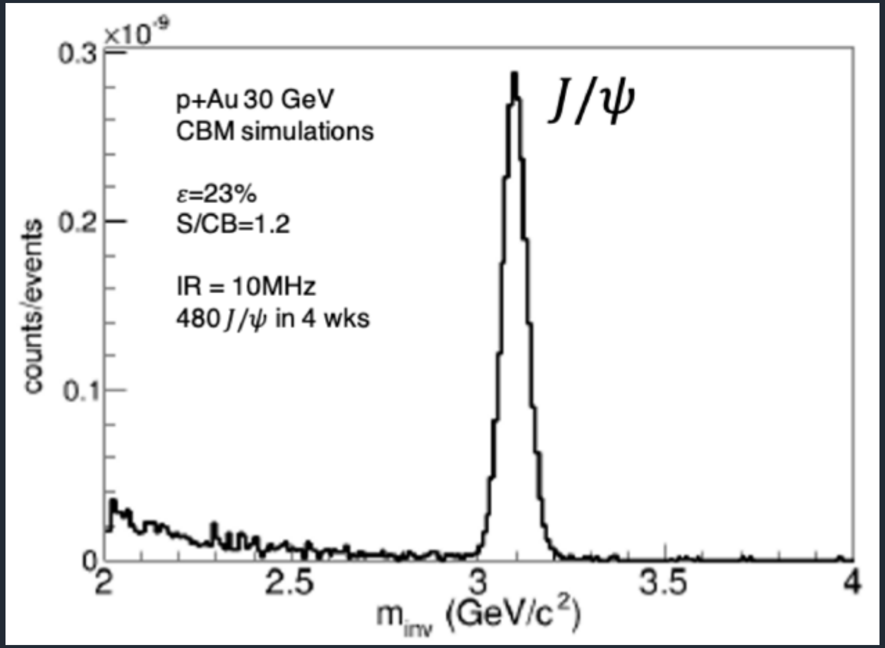
- Sub-threshold production (rare but feasible)
- Production threshold might be exceeded with SIS100 beam of N=Z nuclei
- Both $\mu^+\mu^-$ and e^+e^- decay channels accessible

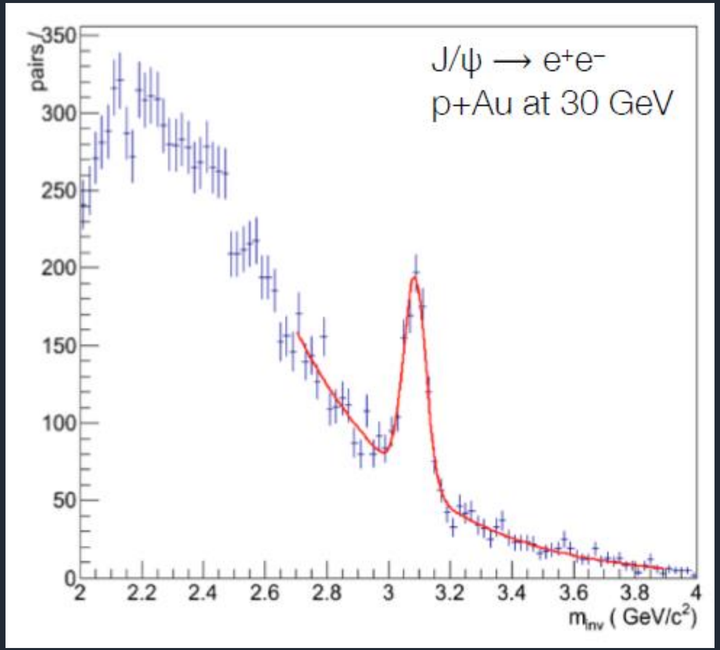


J. Steinheimer et al, Phys. Rev, C95 (2017) 014911

Quarkonium in CBM







J/ψ→μμ

AuAu ~30k J/ψ in 4 weeks at 10 MHz interaction rate

pAu ~500 J/ψ in 4 weeks at 10 MHz interaction rate

J/ψ→ee

pAu ~450 J/ψ in 4 weeks at 10 MHz int. rate

pA → lower statistics, but very clean signal

C. Blume on Monday

Other quarkonium states

Measurements of other quarkonium states allow us to investigate

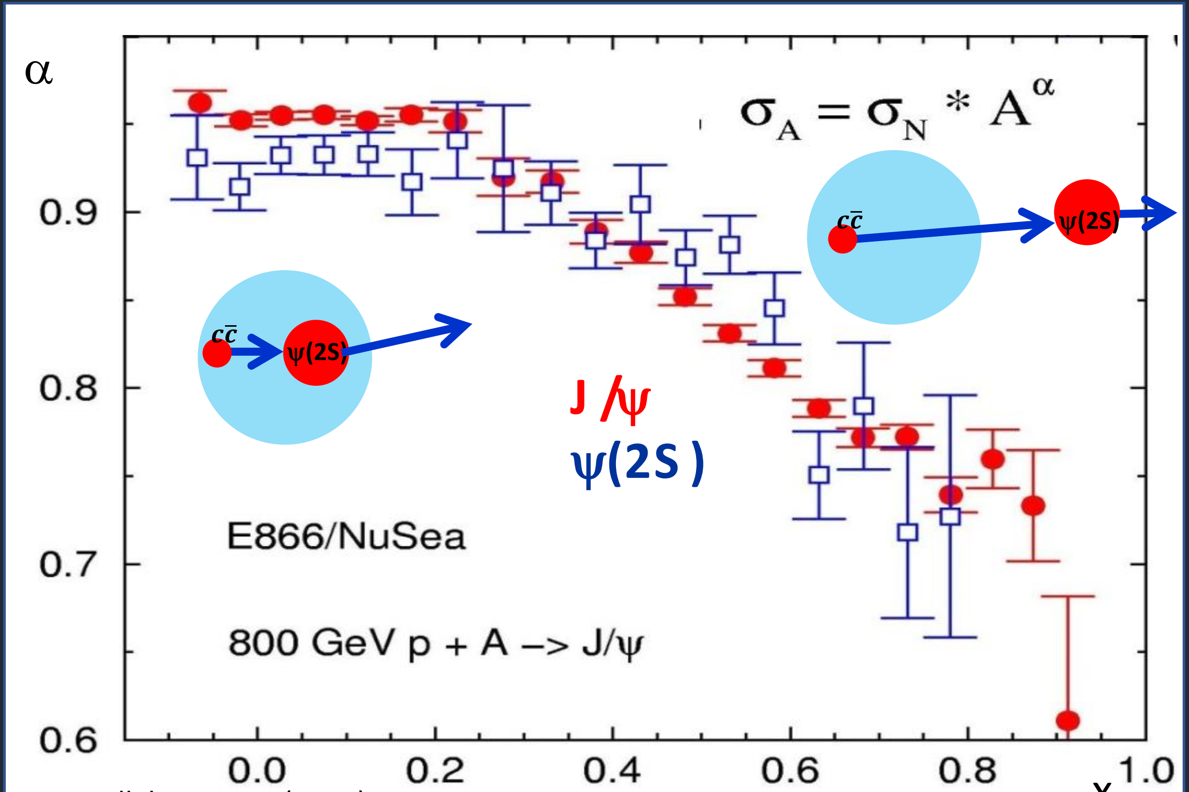
- the mechanisms behind their in medium modification
- their impact on the J/ψ suppression (via feed-down)

At fixed target experiments, still room for improvements for excited charmonium states in both pA and AA

	Fixed target	
	AA	pA
J/ψ		
$\psi(2S)$	X	X
χ_c		~

ψ(2S) in pA collisions in fixed target

ψ(2S) production is modified by CNM effects depending on its kinematic



E866 Collab., PRL 84 (2000) 3256

mid-y (x_F~0):

ψ(2S) suppression stronger than J/ψ one,
→ break-up of fully formed resonance traversing the nucleus

charmonium formation time
<
crossing time

fw-y (high x_F):

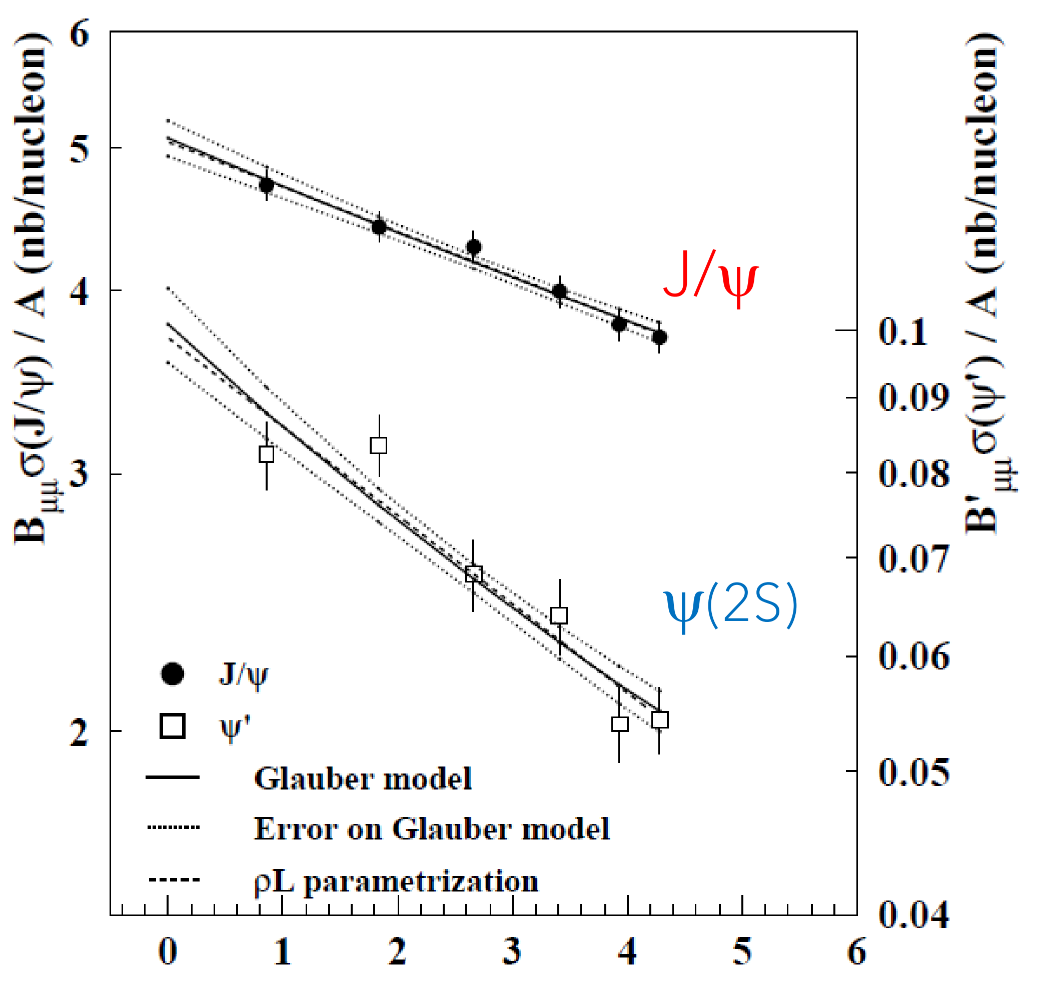
suppressions roughly identical
→ dominated by energy loss

charmonium formation time
>
crossing time

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

McGlinchey, Frawley, Vogt
PRC 87 054910

ψ(2S) in pA collisions at SPS



NA50 Coll. EPJC48 (2006) 329

At SPS, ψ(2S) suppression stronger than the J/ψ

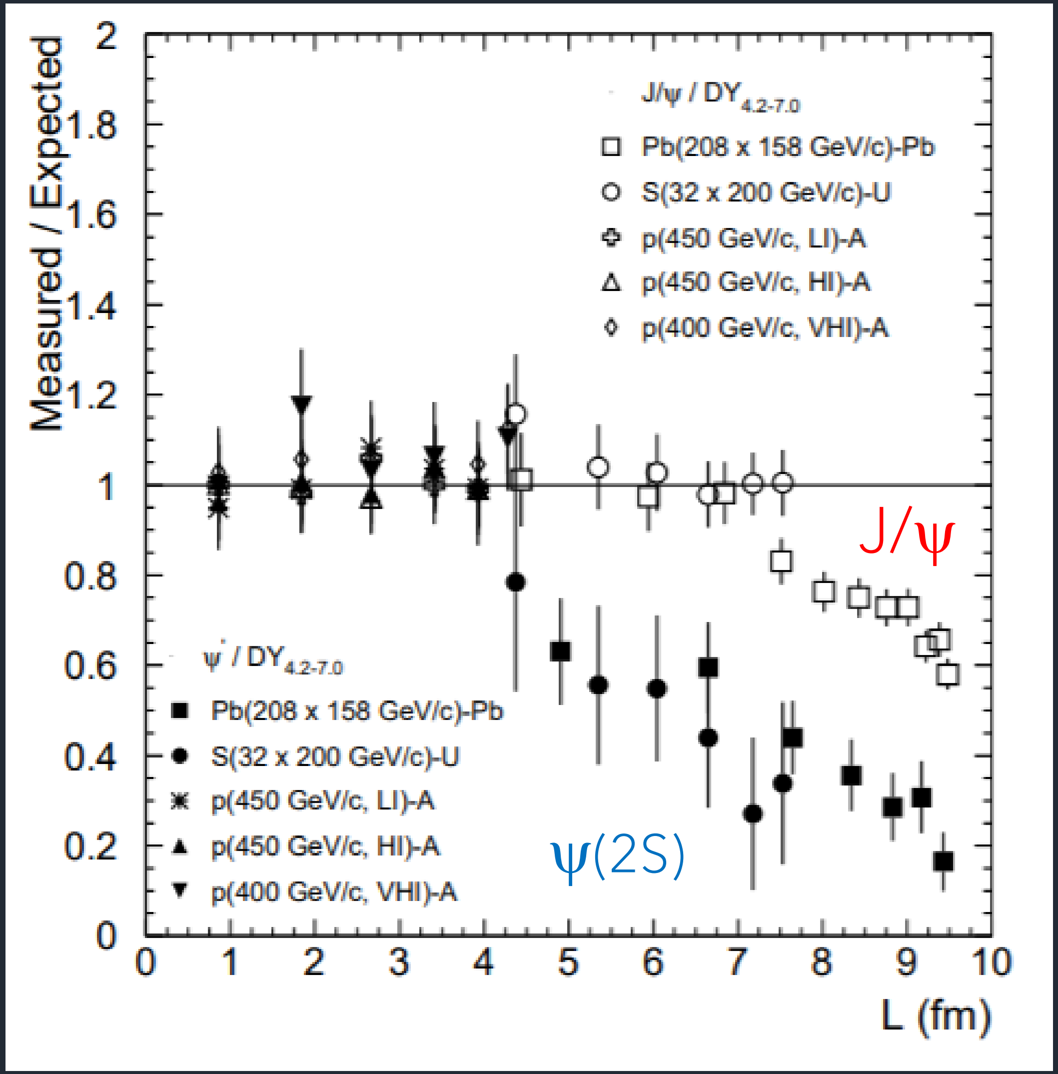
$\sigma_{abs}^{J/\psi}$ (400 GeV) = 4.6 ± 0.6 mb
$\sigma_{abs}^{\psi(2S)}$ (400 GeV) = 10.1 ± 1.5 mb

Fully formed ψ(2S) crosses the nuclear matter

- formation time ~0.1 fm/c
- crossing time ~0.3 fm/c

→ being weakly bound it is easily broken

ψ(2S) in PbPb collisions at SPS

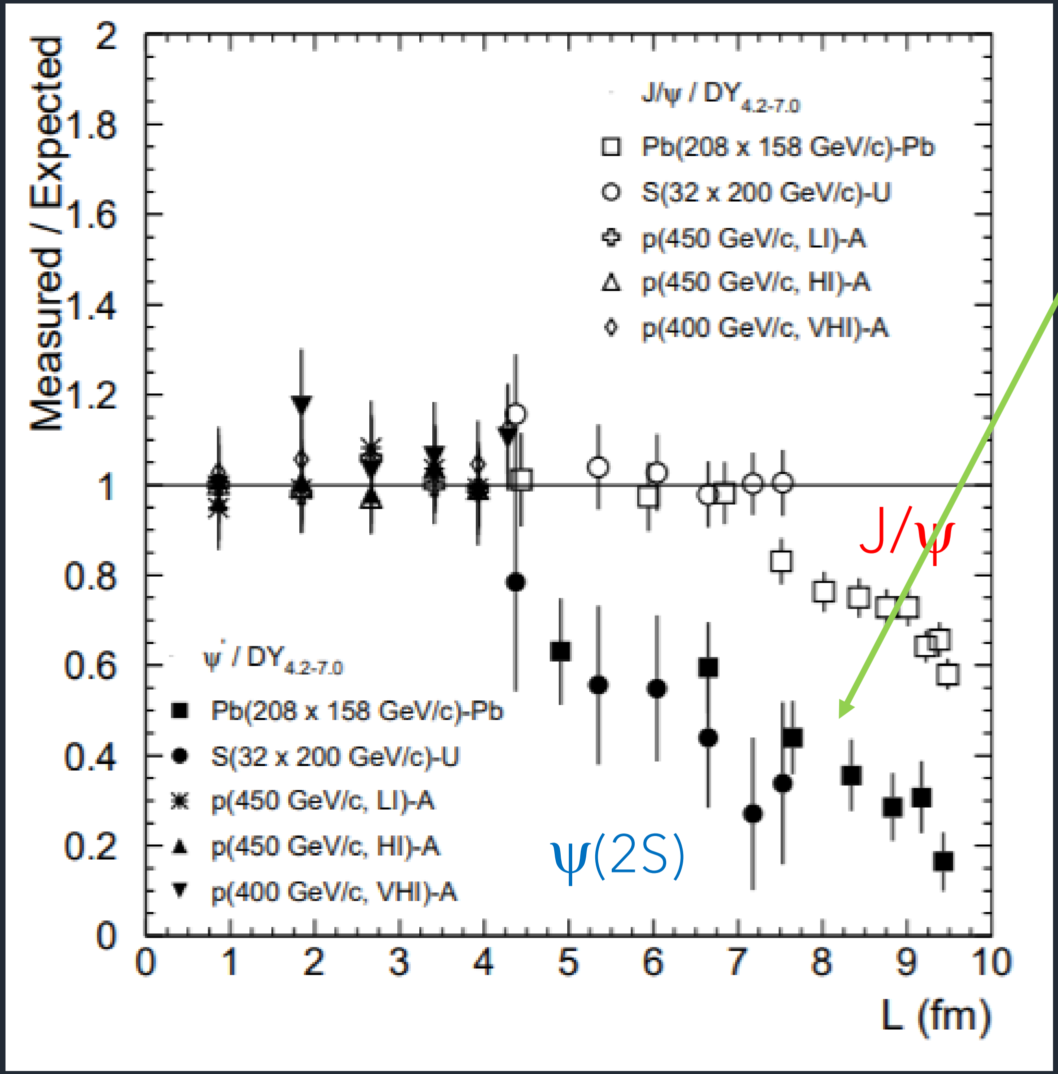


- Also in AA, ψ(2S) anomalous suppression is stronger than the J/ψ one
- sets in earlier, at lower energy densities (1.5 GeV/fm^3 wrt ~2.5 GeV/fm^3 for the J/ψ)
- ψ(2S) suppressed already in SU collisions

Not enough statistics for ψ(2S) results by NA60 in InIn

NA50 Coll., Eur.Phys.J. C49:559-567, 2007

What next on ψ(2S) at lower energies?

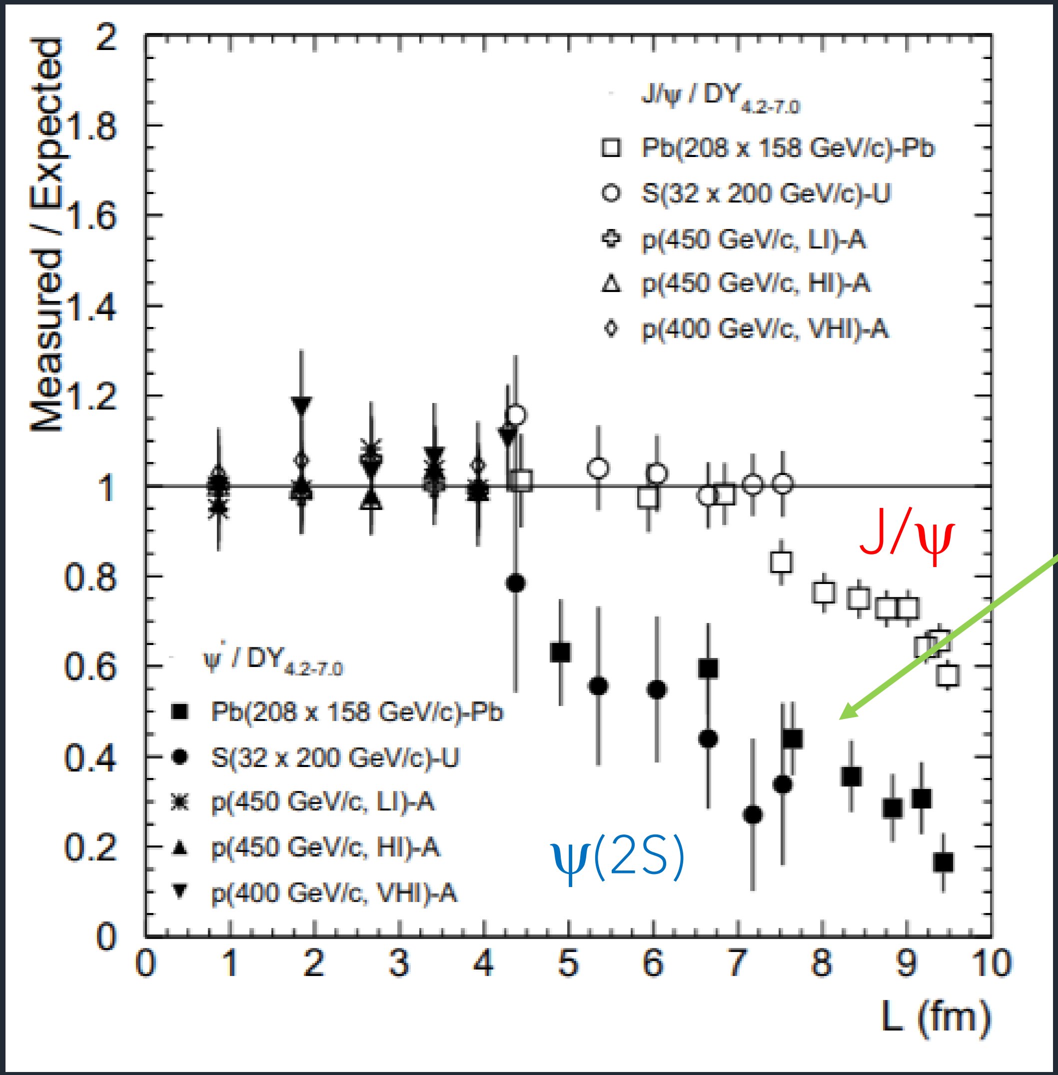


No precision data à la NA60 on the ψ(2S)

1. important to reach an accuracy similar to the J/ψ

NA50 Coll., Eur.Phys.J.C49 559-567, 2007

What next on ψ(2S) at lower energies?



NA50 Coll., Eur.Phys.J. C49 559-567, 2007

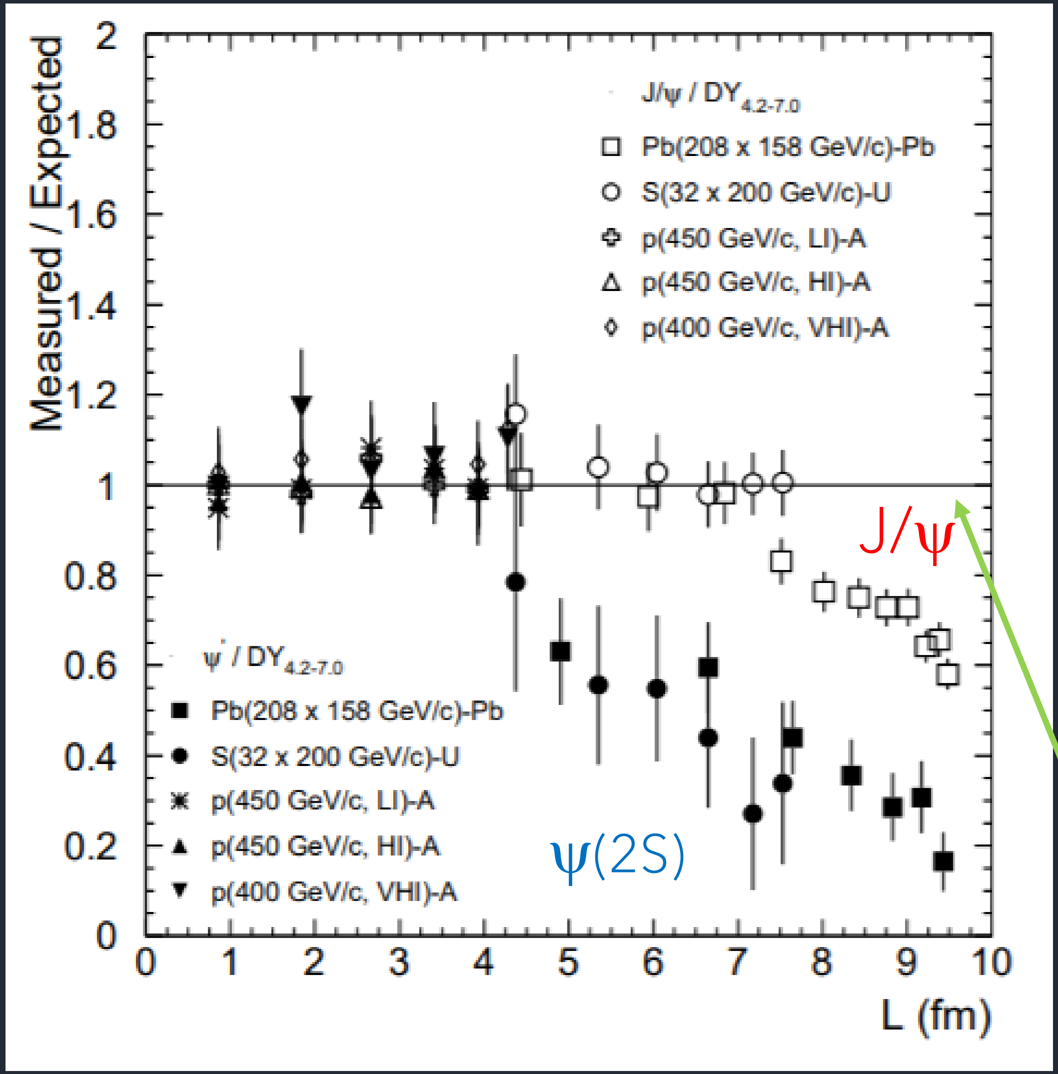
No precision data à la NA60 on the ψ(2S)

1. important to reach an accuracy similar to the J/ψ

Onset of the suppression

2. investigate energy dependence of the onset (and the impact on the J/ψ) studying PbPb collisions at lower $\sqrt{s_{NN}}$

What next on ψ(2S) at lower energies?



NA50 Coll., Eur.Phys.J. C49 559-567, 2007

No precision data à la NA60 on the ψ(2S)

1. important to reach an accuracy similar to the J/ψ

Onset of the suppression

2. investigate energy dependence of the onset, studying PbPb collisions at lower $\sqrt{s_{NN}}$

No pA data at 158GeV

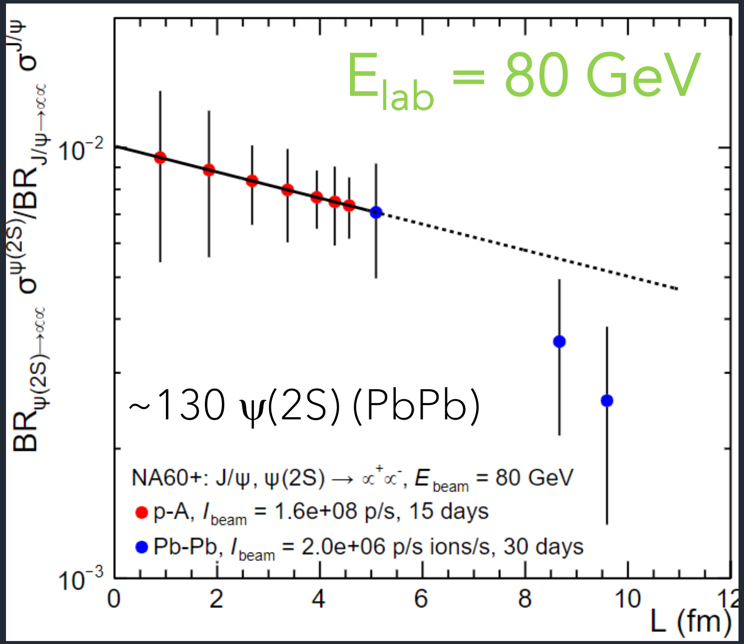
3.
- crucial to measure pA reference in the same kinematic range as AA, as now done for /ψ
- disentangling shadowing from nuclear break-up should help to shed further light

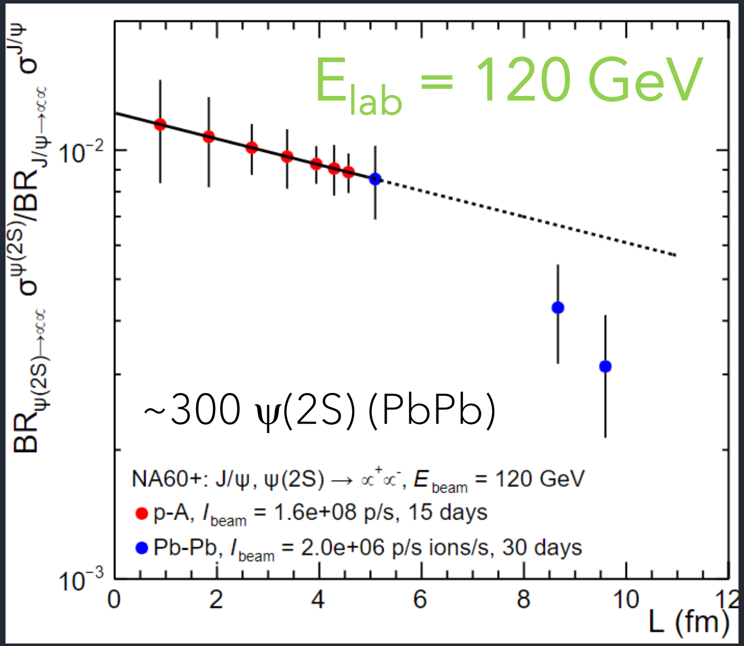
$\psi(2S)$ in NA60+, pA and AA collisions

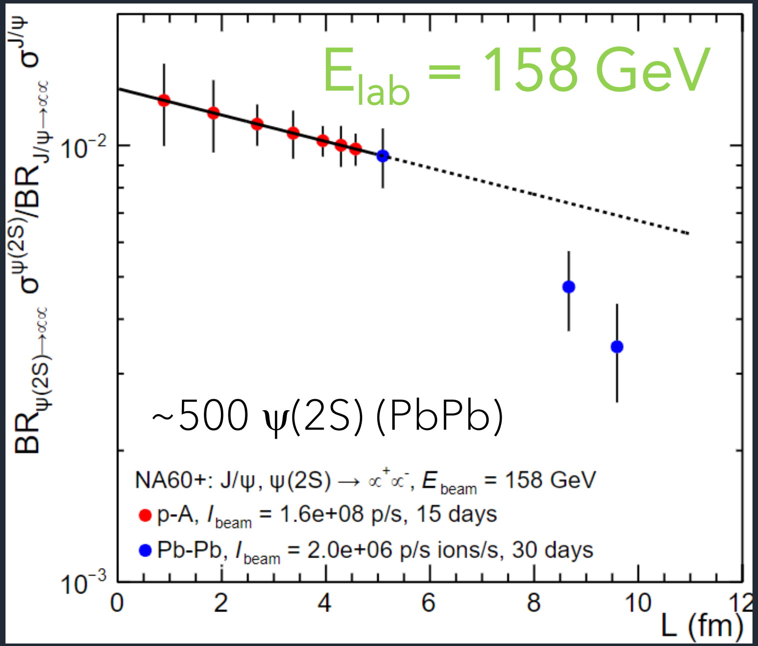
Good charmonium resolution (~30 MeV for the J/ψ) will help $\psi(2S)$ measurements

Expectations based on
- 30 days PbPb, I_{beam} = 2e6 ions/s
- 15 days pA, I_{beam} = 1.6e8 p/s

(assuming larger suppression for $\psi(2S)$ than J/ψ)





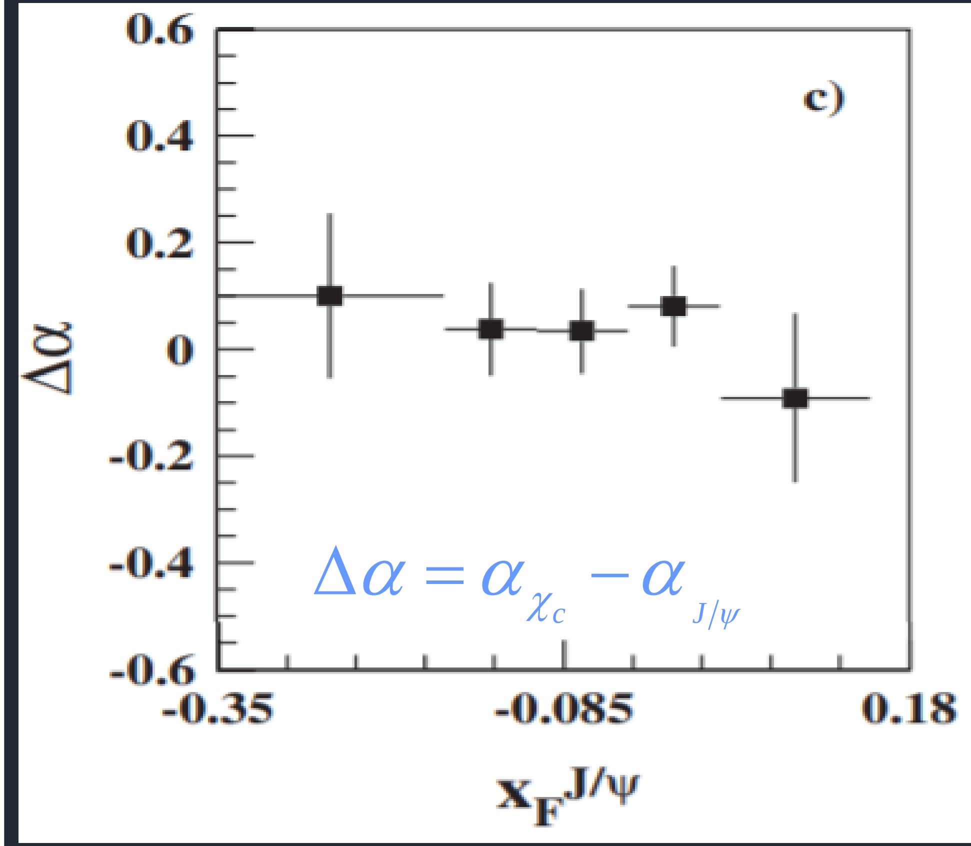


$\psi(2S)/\psi$ measurement down to E_{lab} = 120 GeV

Lower E_{lab} would require larger beam intensites/longer running times

χ_c at fixed target

~25% of the J/ψ comes from the χ_c decay
→ $\alpha(\chi_c)$ important to understand the J/ψ suppression



- χ_c not measured at SPS (no AA data)
- available results at HERA-B, pA@ 920 GeV (large χ_c sample: ~15000 χ_c $-0.35<x_F^{J/\psi}<0.15$)

HERA-B observes no significant difference between $\alpha(\chi_c)$ and $\alpha(J/\psi)$

→ similar "global" CNM effects on both resonances in the covered kinematical range (average value $\Delta\alpha=0.05\pm0.04$)

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

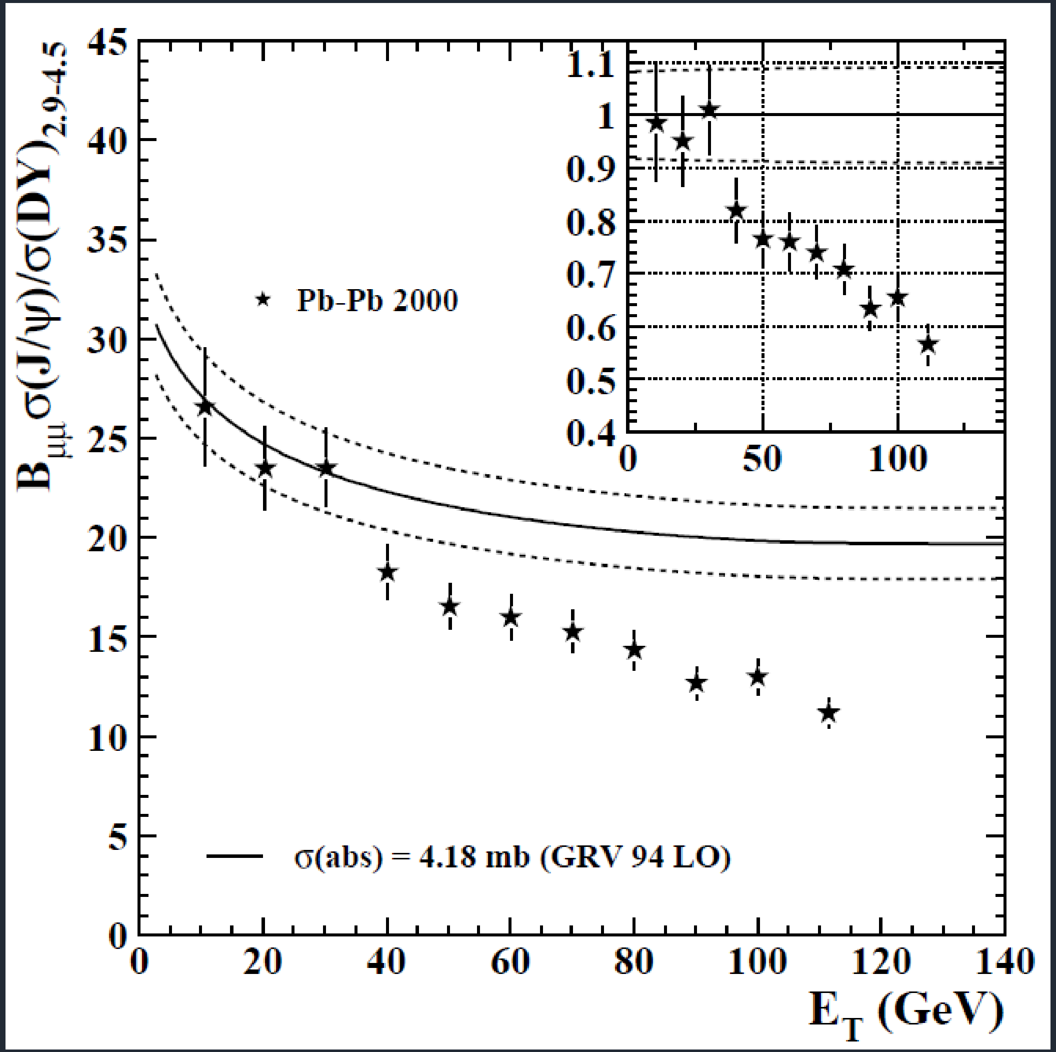
Outlook and conclusions

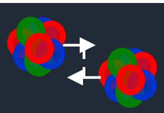
- Quarkonium still a very interesting topic after ~30 years, not only at LHC! Very much promising also at lower energies
- Solid results on J/ψ from past experiments at top SPS energies
- Data even at lower energies should help understanding the J/ψ behaviour in the medium:
    - high precision needed
    - pA and AA data at same energy
    - update analysis approaches (R_{AA}? disentagle CNM effects…)
    - access to higher charmonia states?

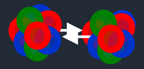
Looking forward to new quarkonium results in the next years!

Backup

J/ψ/DY in PbPb collisions







J/ψ/DY shows

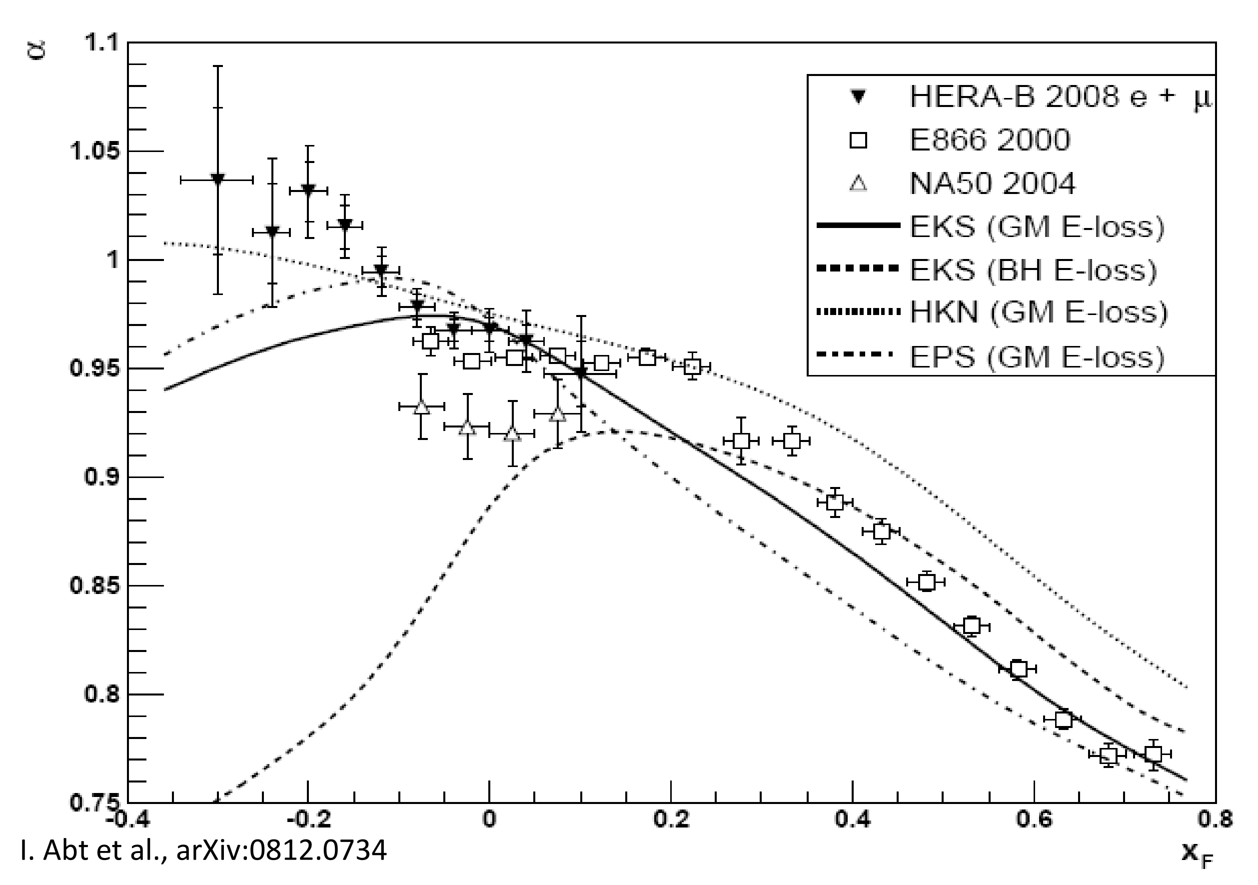
- a decreasing trend vs centrality
- a departure from expected behaviour if only cold nuclear effects are present
  → tuned on pA collisions

Evidence for QGP formation in central PbPb

references

J/ψ production vs x_F

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



J/ψ yield in pA is modified with respect to pp, with a significant kinematic dependence

- α strongly decreases with x_F
- for a fixed x_F, stronger CNM at lower √s

Theoretical description over the full x_F range very complicate!

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

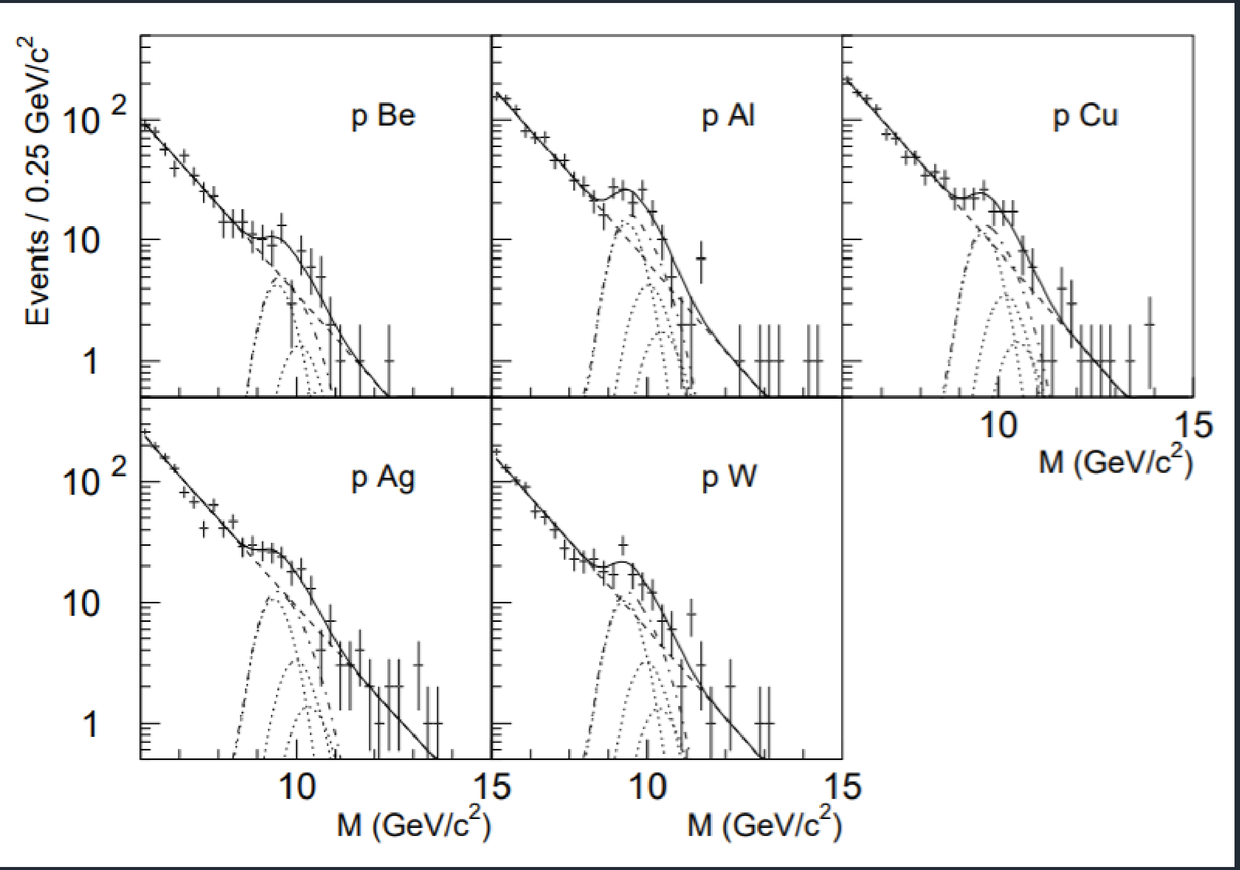
Υ at fixed target

AA collisions

no measurements available

pA collisions

- not all experiments have enough resolution to separate the Υ states
- result accuracy limited by Υ statistics



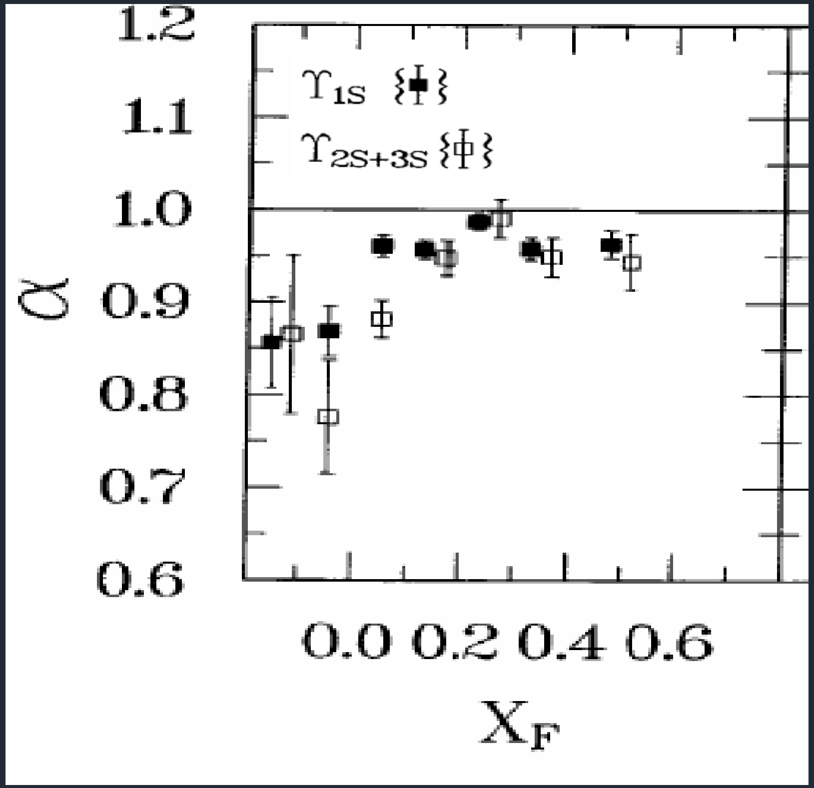
NA50 Coll., Phys.Lett.B635:260-269,2006

Υ in pA at fixed target

E772 (pA@800GeV)

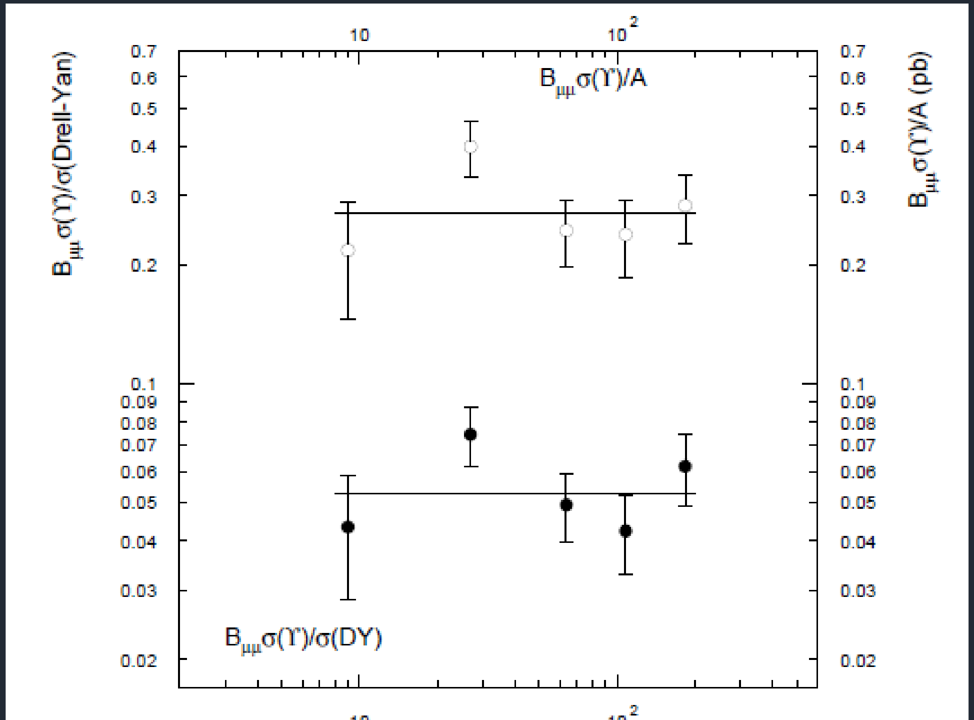
similar α for Υ(1S) and Υ(2S+3S) in $0<x_F<0.6$

α (Υ(1S))= 0.962 ± 0.006 α (Υ(2S+3S))= 0.948 ± 0.012



E866, Phys. Rev. Lett. 66(1991) 2285

NA50 (pA@450GeV)



NA50 Coll. Phys. Lett. B635(2006) 260

No strong CNM effects on Υ(1S+2S+3S) at $x_F \sim 0$

α (Υ(1S+2S+3S))= 0.98 ± 0.10

Results not accurate enough to evaluate the x_F and $\sqrt{s}$ α dependence

From pA to AA – new reference curve

NEW reference curve is extrapolated from pA to AA:

σ_{abs} shows an energy/kinematical dependence

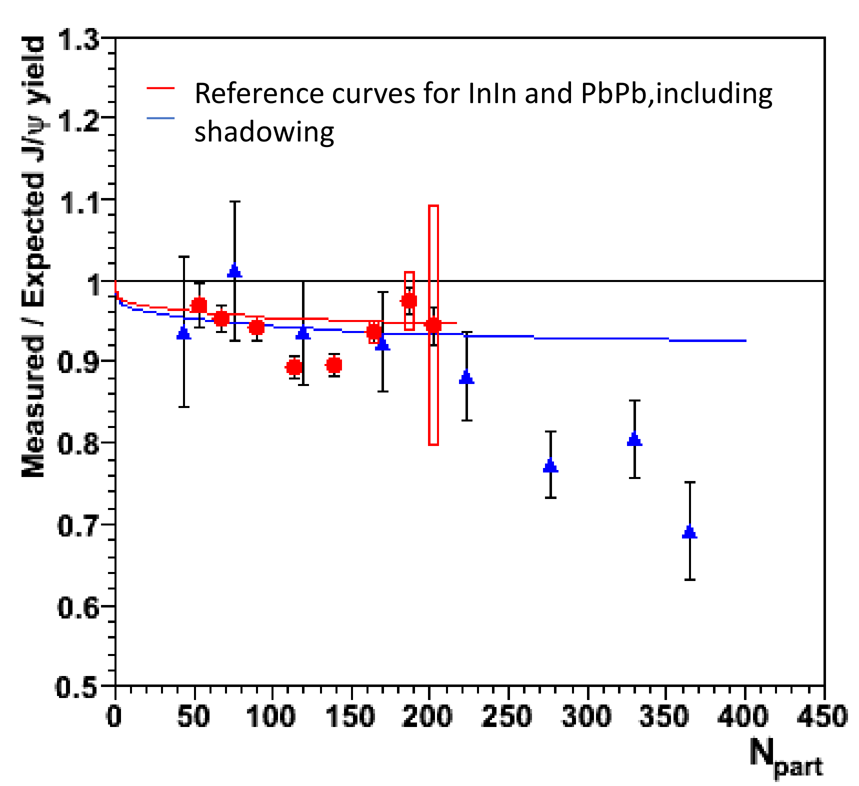
reference now obtained in pA at the same energy/kinematical range as the AA data

in AA, shadowing affects both projectile and target

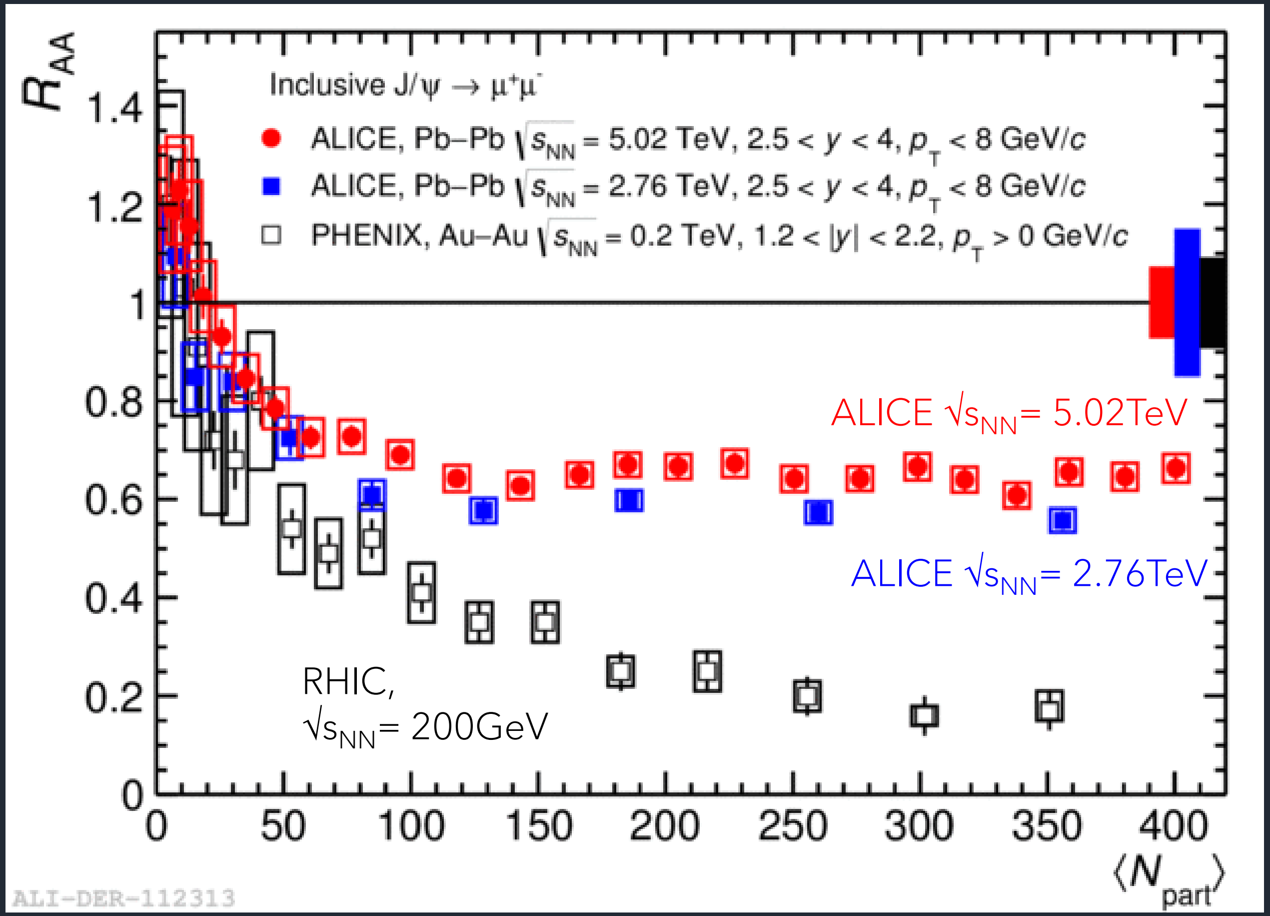
projectile and target antishadowing taken into account in the reference determination

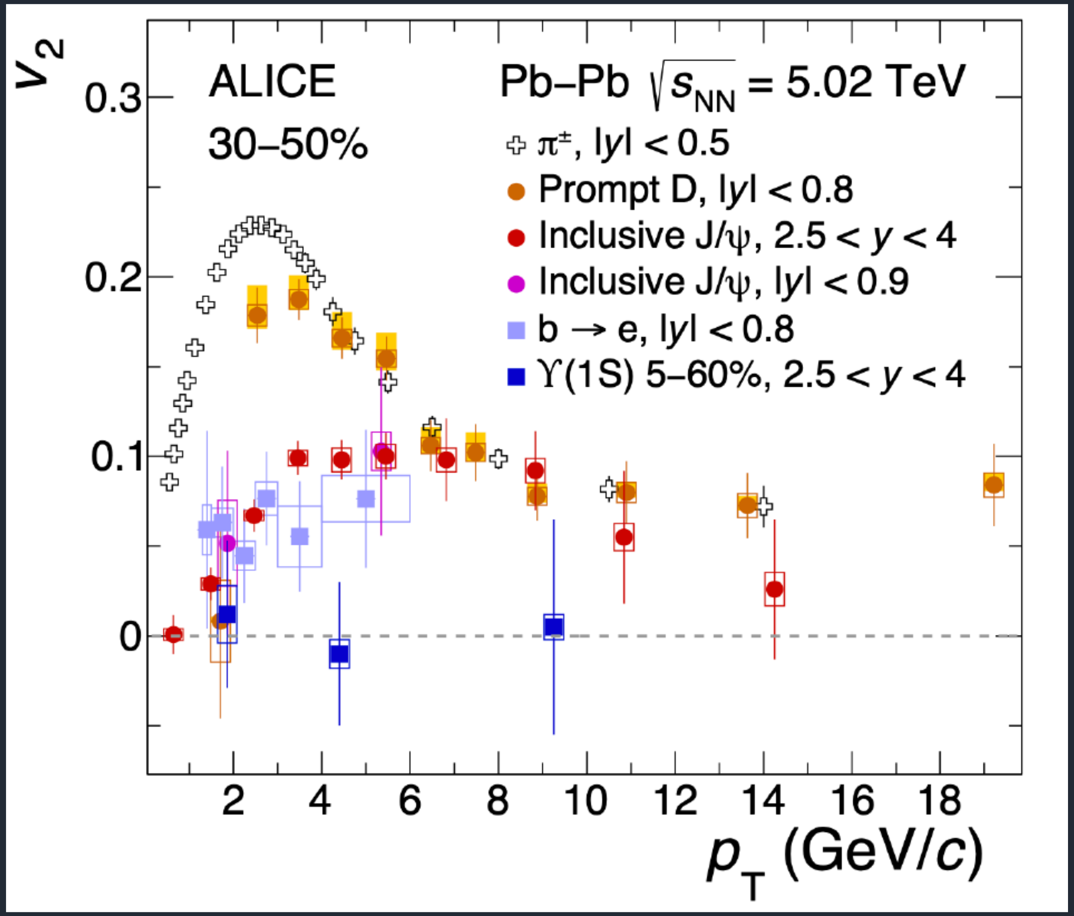
centrality dependence of the reference

obtained within a Glauber approach



J/ψ measurements at high energies

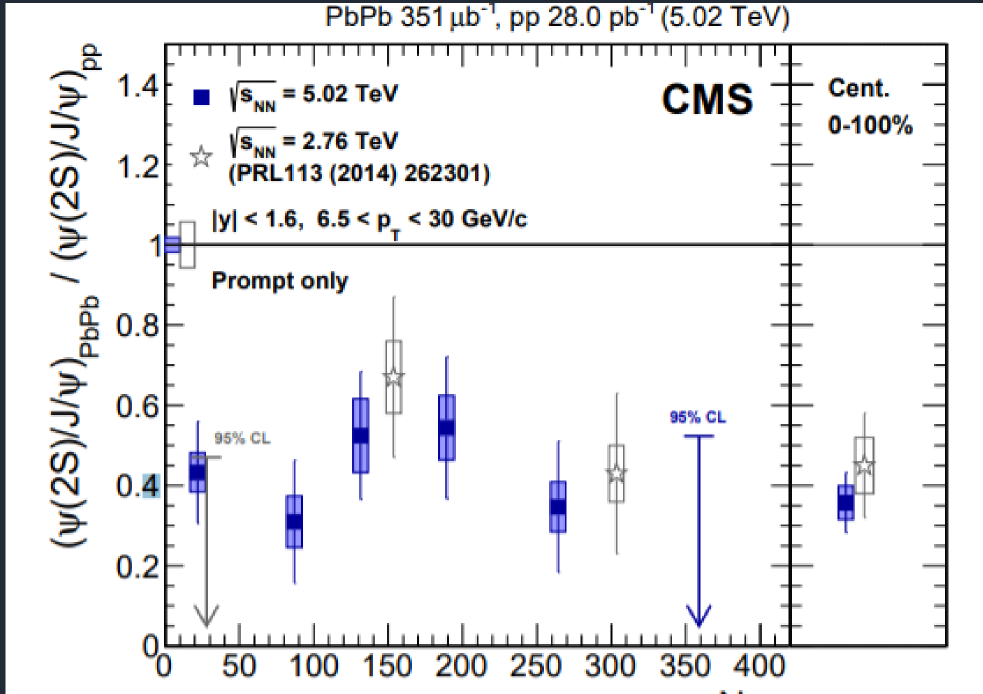




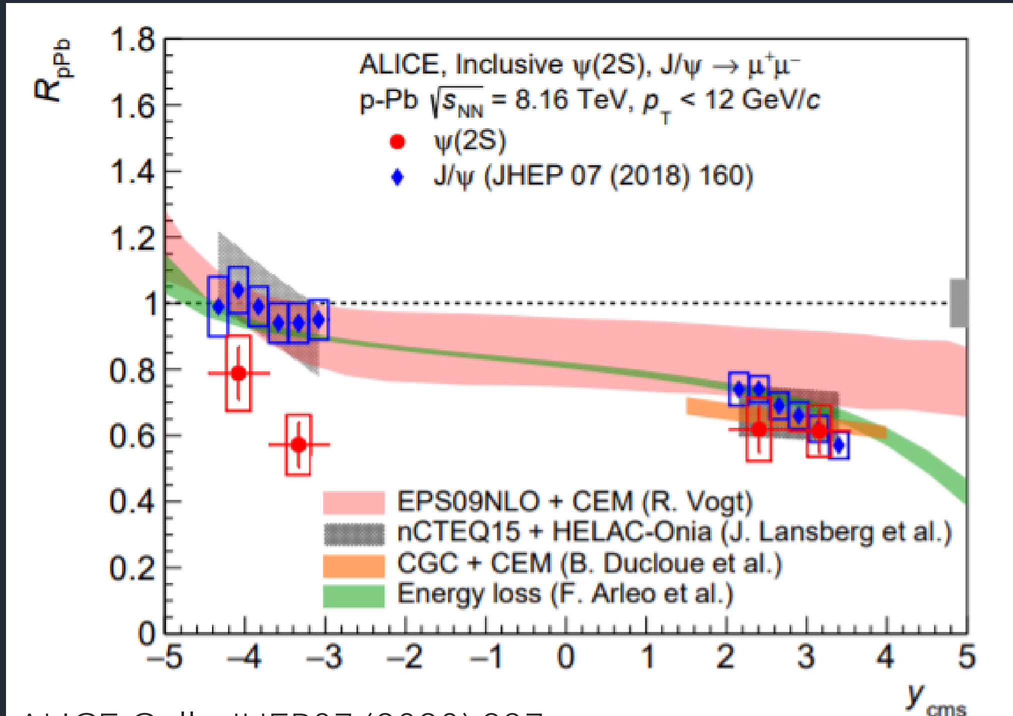
High precision data at colliders indicate

- interplay between J/ψ suppression and regeneration
- significant J/ψ elliptic flow originating from charm thermalized in the medium

ψ(2S) at LHC



CMS Coll., PRL 118 (2017) 162301



ALICE Coll., JHEP07 (2020) 237

PbPb collisions:

ψ(2S) suppression stronger than the J/ψ one

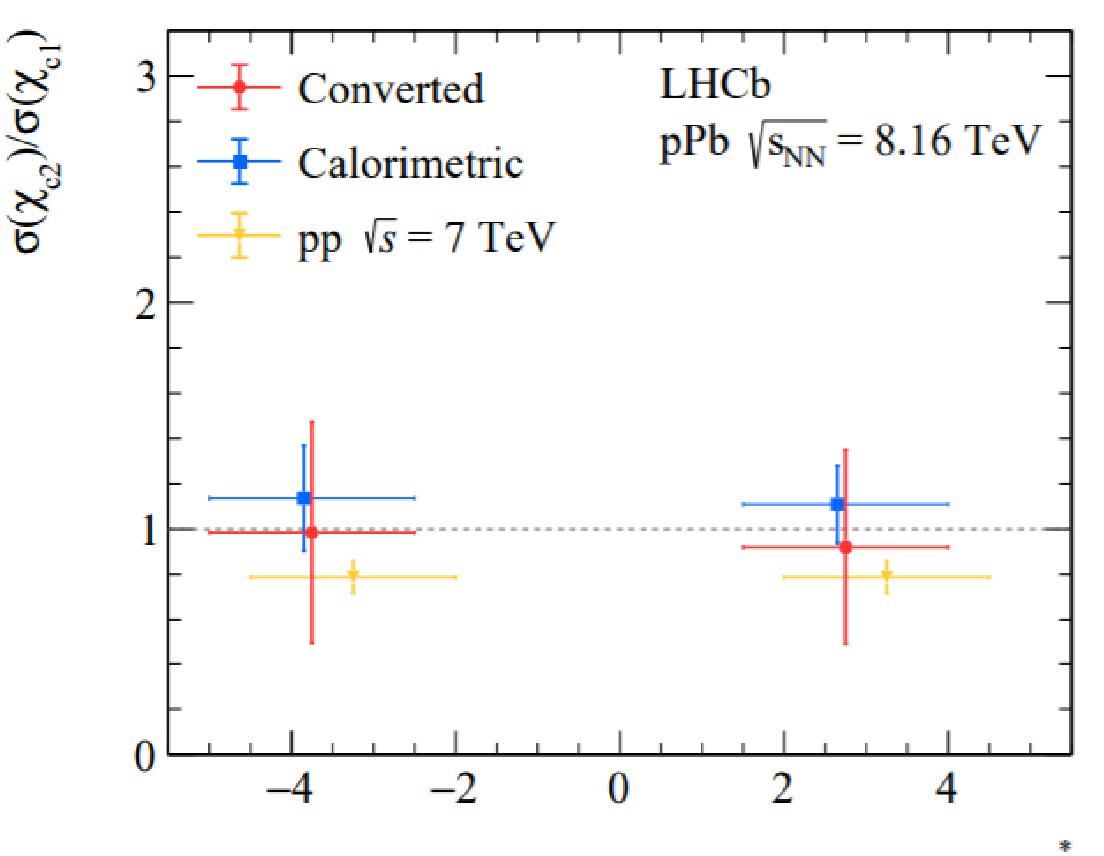
pPb collisions:

ψ(2S) suppression stronger than the J/ψ one at backward-y and beyond standard CNM mechanisms
→ suggestive of hot matter effects

χ_c at LHC

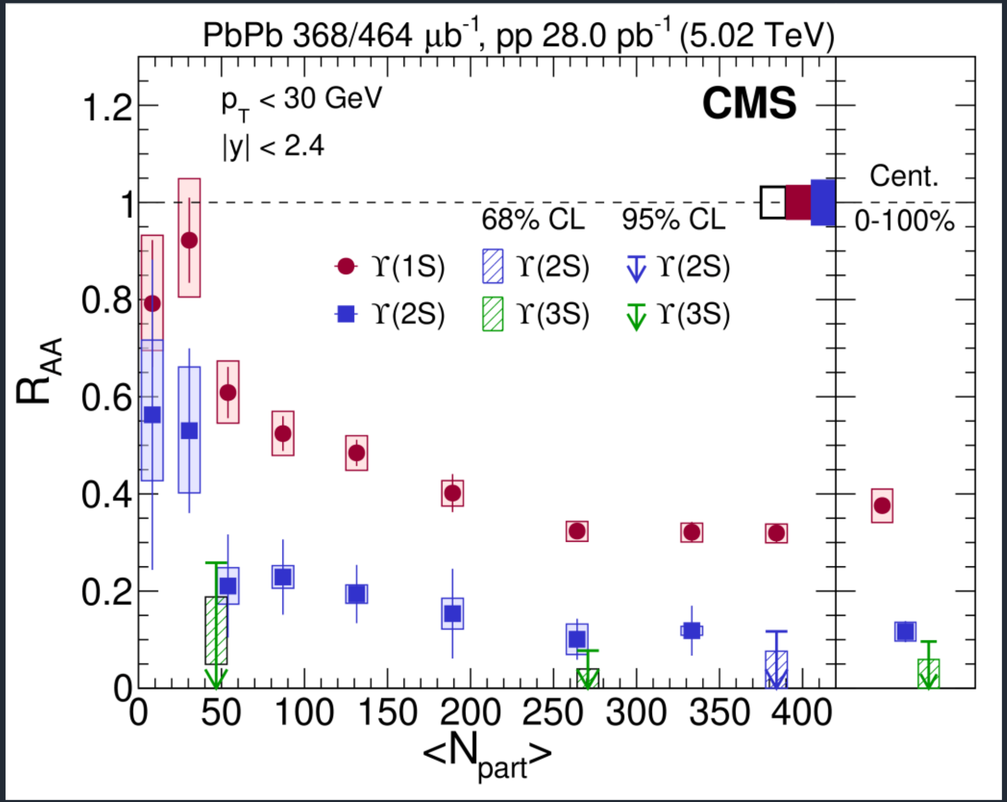
AA:
no measurements so far

pA:
χ_{c1} and χ_{c2} similarly affected by nuclear effects, within the uncertainties

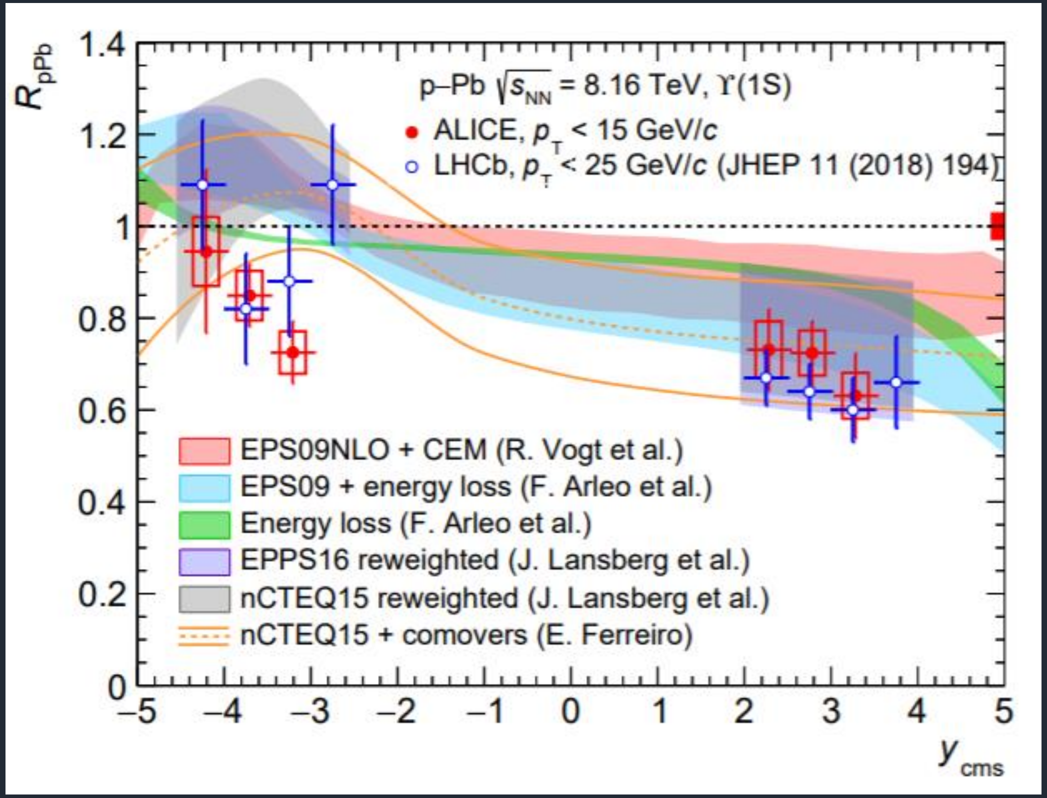


LHCb Coll.. Phys. Rev. C 103, 064905 (2021)

ϒ at LHC



CMS Coll. Phys. Lett. B790 (2019) 270



ALICE Coll. Phys. Lett. B 806 (2020) 135486

AA collisions

first bottomonium measurements
→ clear mass ordering in the suppression pattern

pA collisions:

ϒ(1S) modification accounted for by shadowing
Still larger uncertainties on excited states