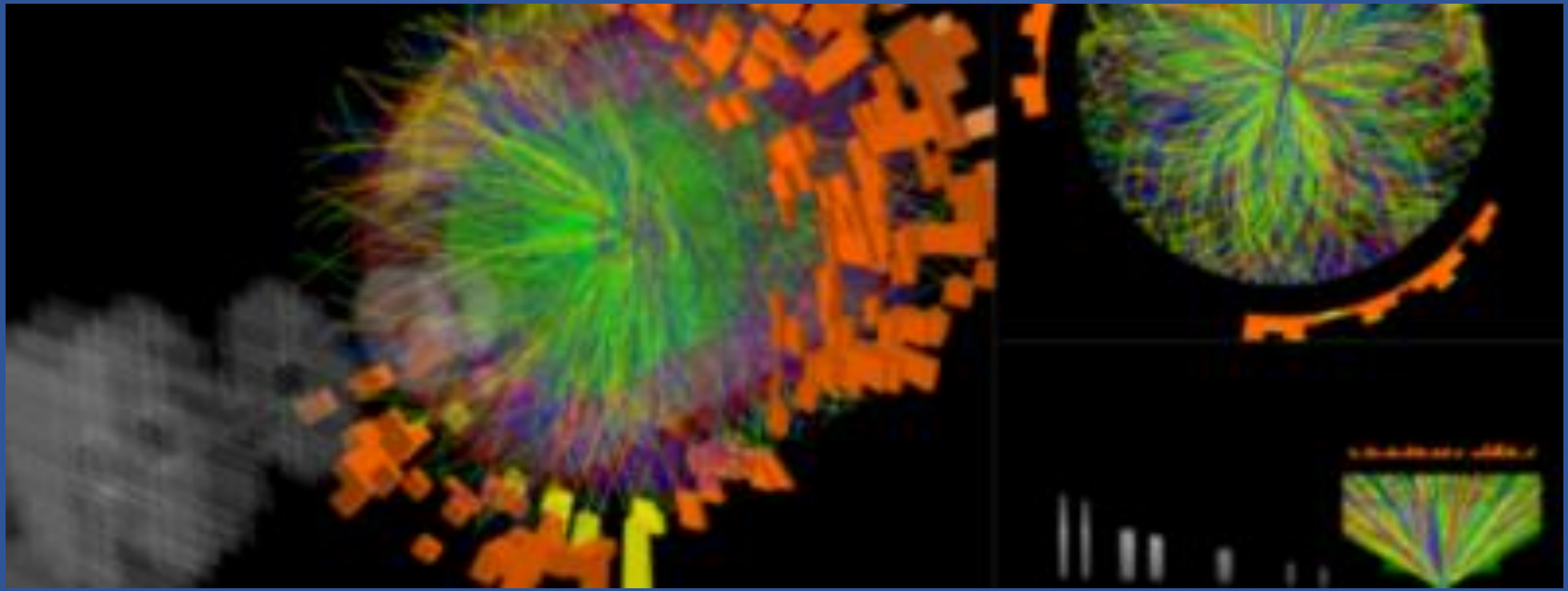
Quarkonium production at low energies: achievements and prospects

E. Scomparin – INFN Torino (Italy)



QUARK-GLUON PLASMA CHARACTERISATION WITH HEAVY FLAVOUR PROBES

TRENTO
NOVEMBER 15-19 2021

Introduction

- Quarkonium: the only **`hard probe' of QGP** investigated down to low energy ($\sqrt{s}$~20 GeV)

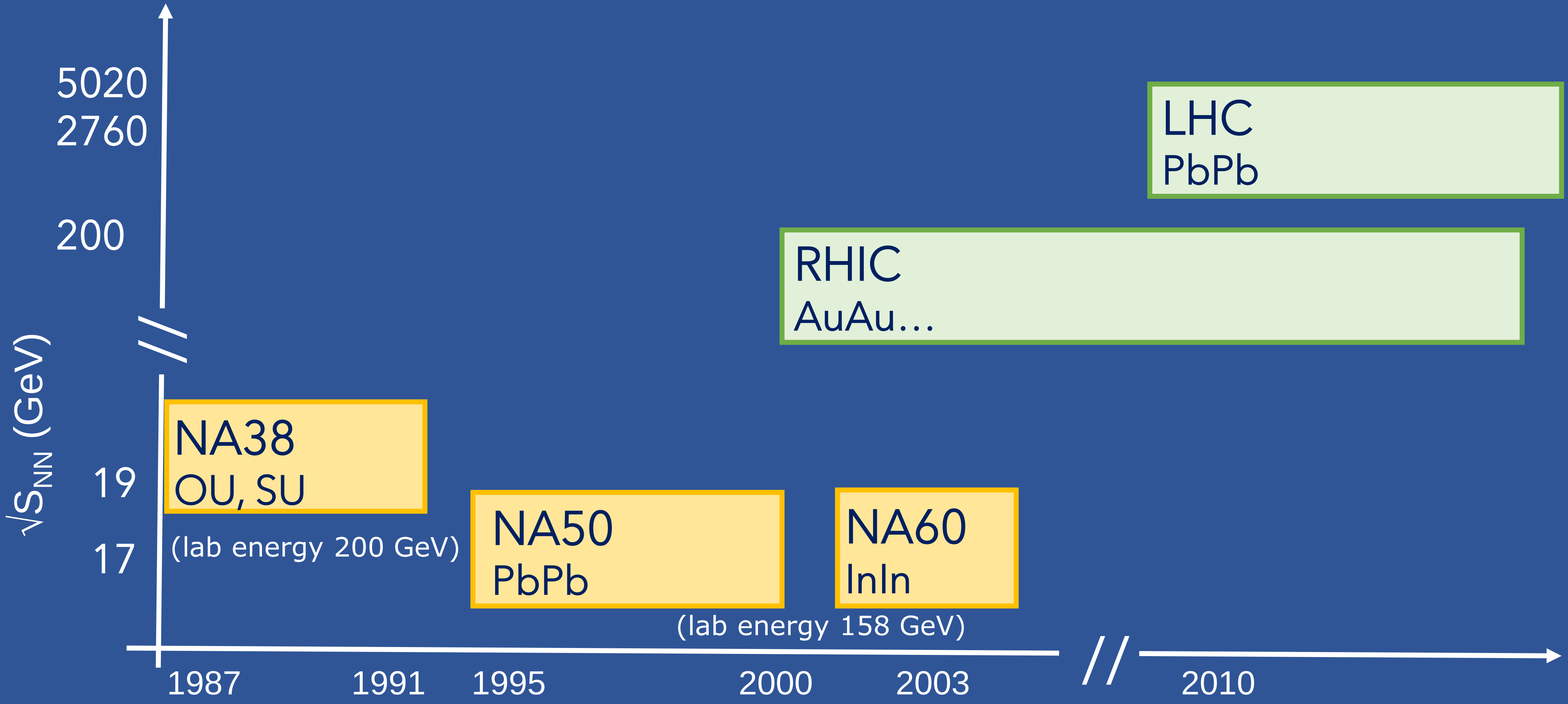
- Fixed target experiments
  - A-A @ SPS → NA38/NA50/NA60 experiments
  - p-A @ SPS, FNAL, HERA

- Ground and excited states : **J/ψ, ψ(2S)**
  - Experimental techniques and main results
  - Open points

- Prospects for (near) future measurements in A-A
  - "Threshold" energy → **CBM@SIS100** ($\sqrt{s}$ < 5 GeV)
  - "Low" SPS energy → **NA60+** project (5 < $\sqrt{s}$ < 20 GeV)

- Conclusions

Studies of charmonium production in AA



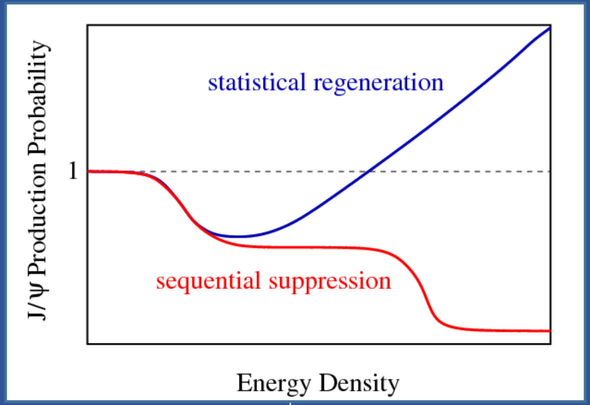
J/ψ: low vs high energy

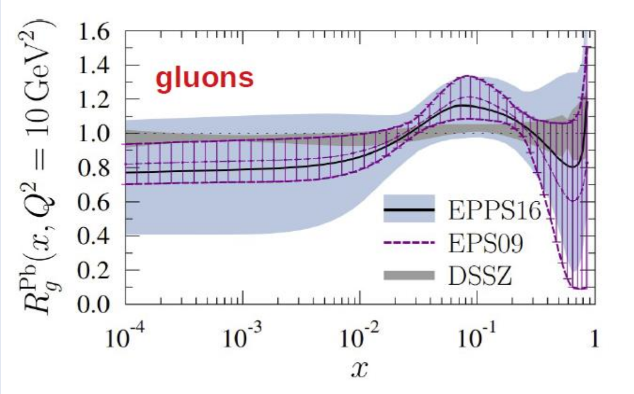
Collider (LHC)

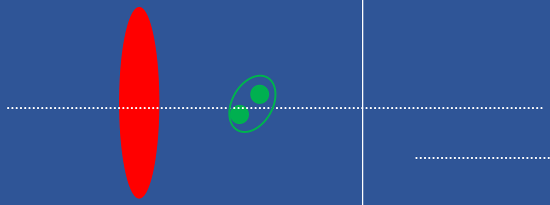
Hot matter effects: regeneration counterbalances (overcomes) suppression

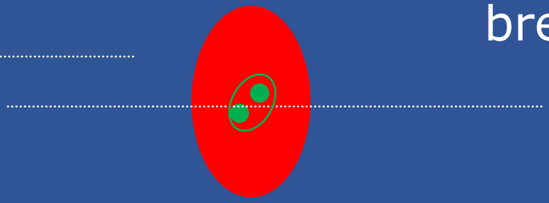
Initial state effects:
shadowing
$x \sim 10^{-5}$ ($y \sim 3$),
$x \sim 10^{-3}$ ($y = 0$),
$x \sim 10^{-2}$ ($y \sim -3$)

(Final state) CNM effects:
negligible, extremely short crossing time
$\tau = L/(\beta_z\gamma) \sim 7\ 10^{-5}$ fm/c ($y \sim 3$)
$\tau = L/(\beta_z\gamma) \sim 4\ 10^{-2}$ fm/c ($y \sim -3$)









Fixed target (SPS)

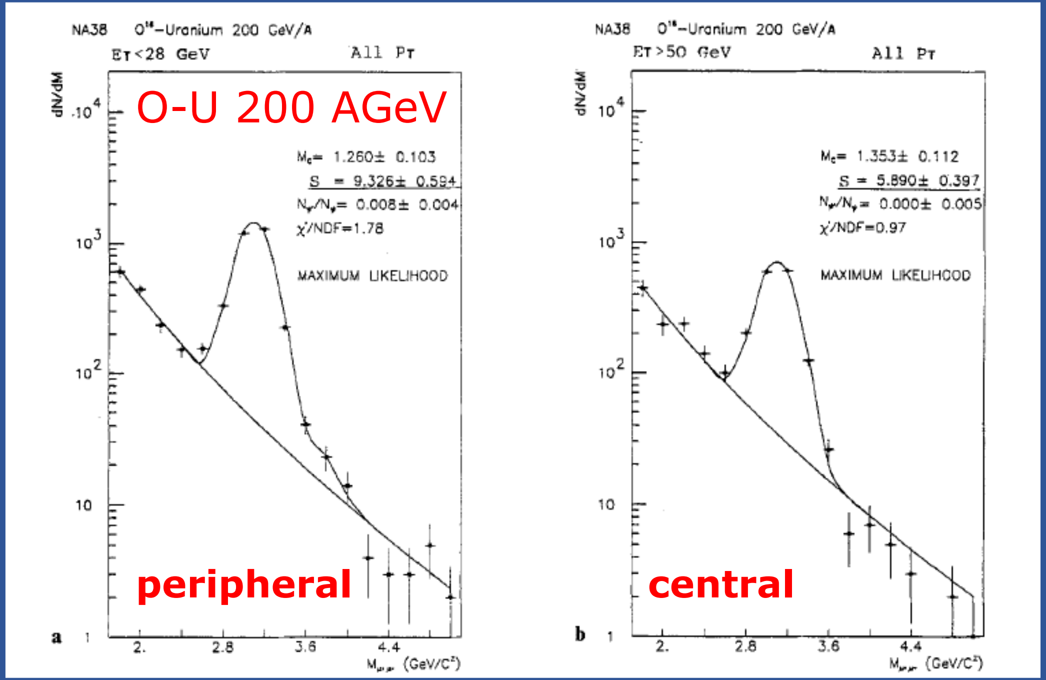
Hot matter effects:
suppression effects (if existing) dominate

Initial state effects:
moderate anti-shadowing
$x \sim 10^{-1}$ ($y = 0$)

(Final state) CNM effects:
break-up in nuclear matter can be sizeable
$\tau = L/(\beta_z\gamma) \sim 0.5$ fm/c($y = 0$)

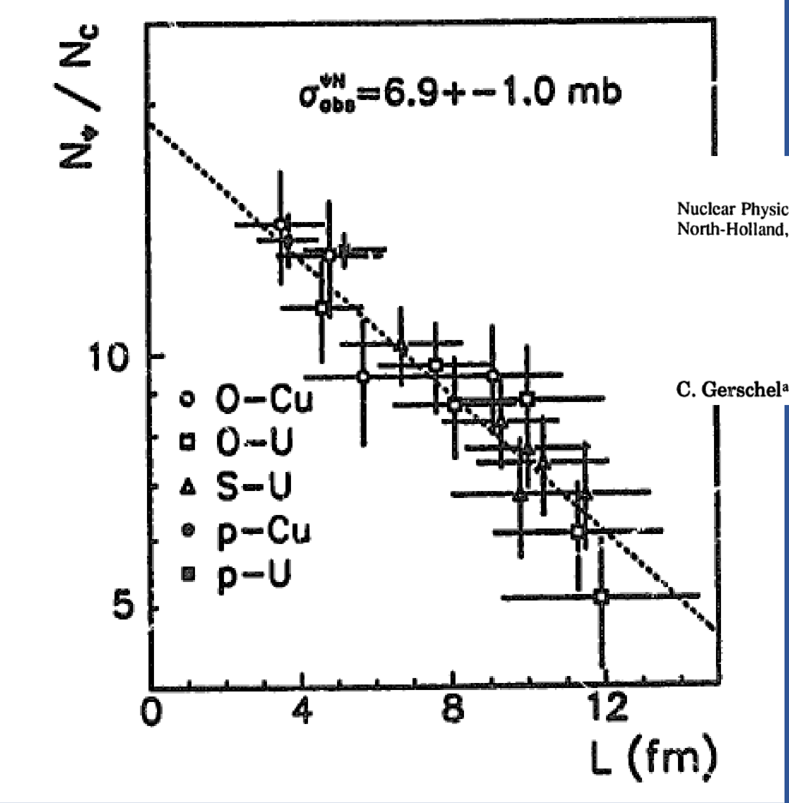
J/ψ at SPS energy: discovery of the suppression

NA38, Z. Phys. 38(1988) 117



Centrality–dependent ratio J/ψ / continuum → **evidence for suppression**

Reference process?



C. Gerschel et al., PLB207 (1988)253

Nuclear Physics A544 (1992) 513c–516c
North-Holland, Amsterdam

NUCLEAR PHYSICS A

Comparison of J/ψ-Suppression in Photon, Hadron and Nucleus-Nucleus Collisions : Where is the Quark-Gluon Plasma ?

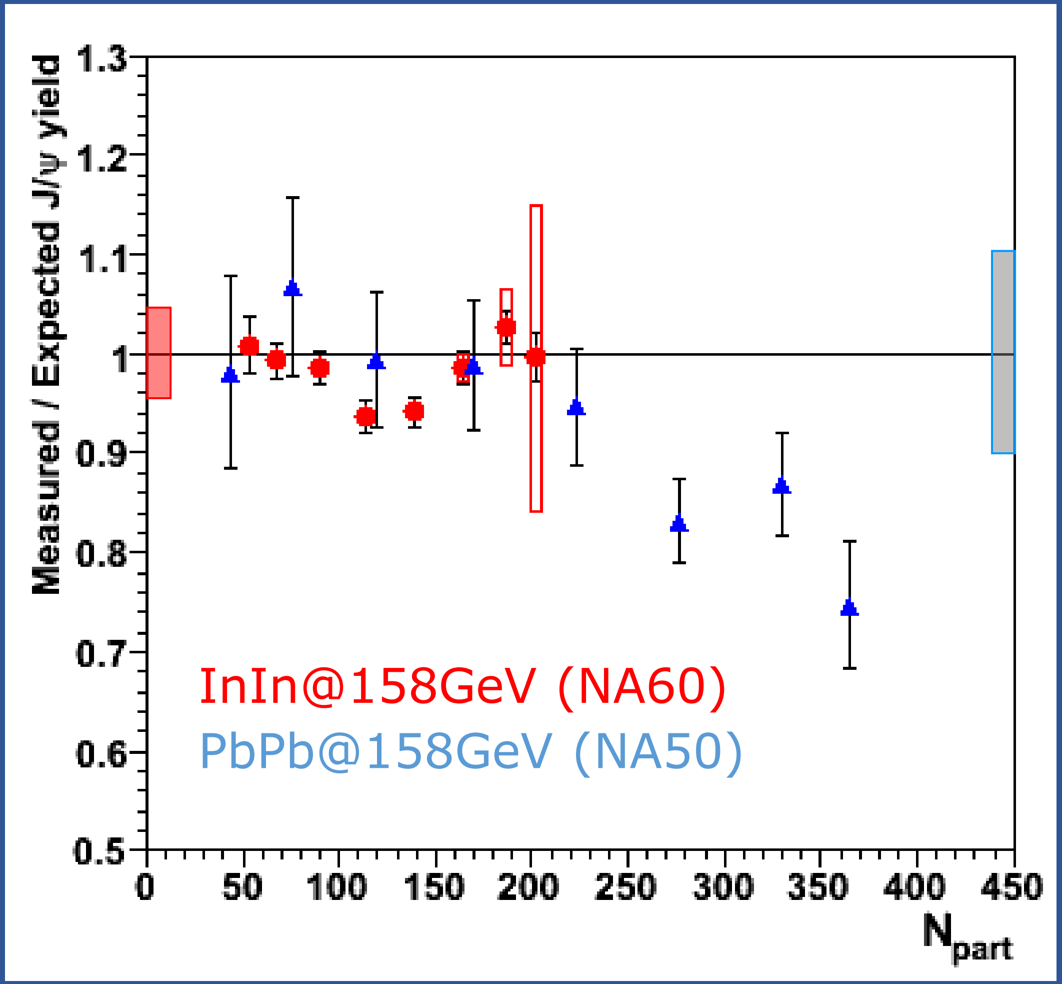
C. Gerschel[a] and J. Hüfner[b]

p-A collision results imply **significant dissociation cross sections in CNM**

→ Crucial ingredient in the interpretation of the data

→ Stimulated an intense experimental program at both CERN and FNAL

"Summary" J/ψ plot



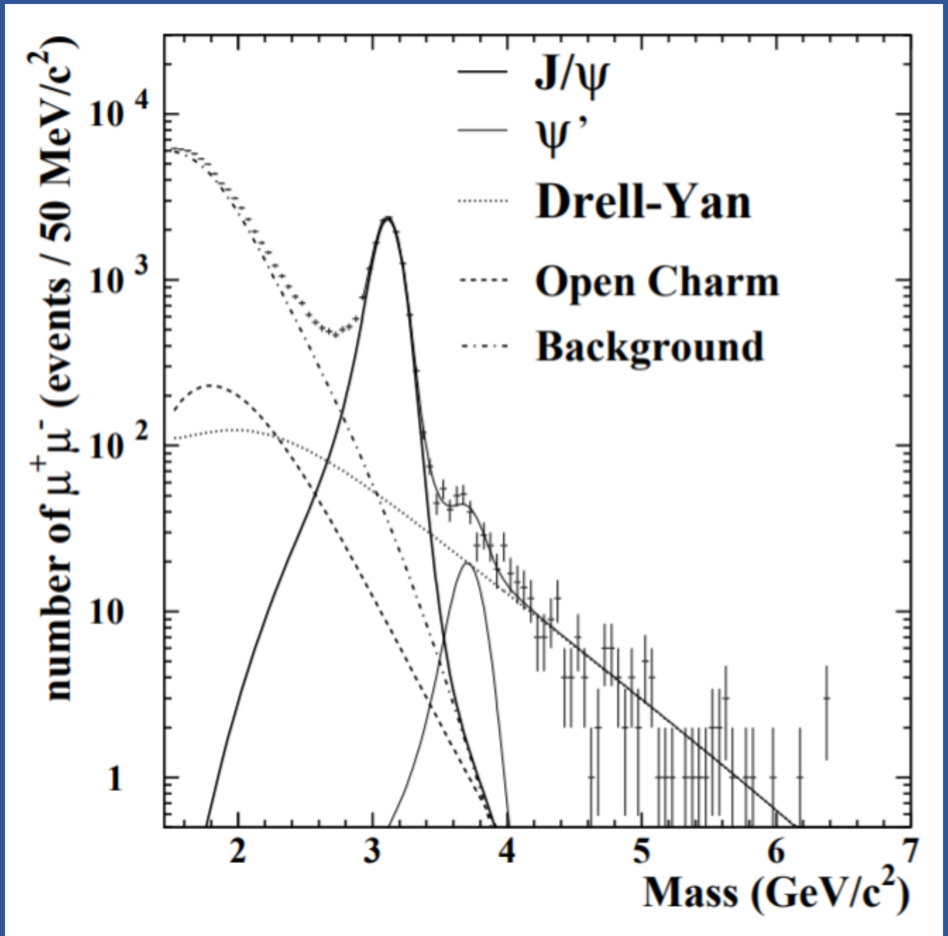
NA50, EPJC39 (2005) 335
NA60, Nucl. Phys. A830 (2009) 345
R.Arnaldi, P. Cortese, E. Scomparin Phys. Rev. C 81, 014903

- Expressed in terms of **measured J/ψ yield, normalized to an extrapolation of CNM effects**, evaluated starting from p-A results
- **Drell-Yan** reference used to extract results
- **Suppression** effects beyond CNM reach **~30%** in central Pb-Pb collision
- Qualitatively consistent with **suppression of feed-down** from ψ(2S) (measured) and χ_c (not measured)
- **In-In** result shows **small or no suppression**, with the origin of "wiggle" at intermediate centrality unclear (coupling to X(3872) via DD^* proposed in Blaschke et al., NPA927(2014) 1)

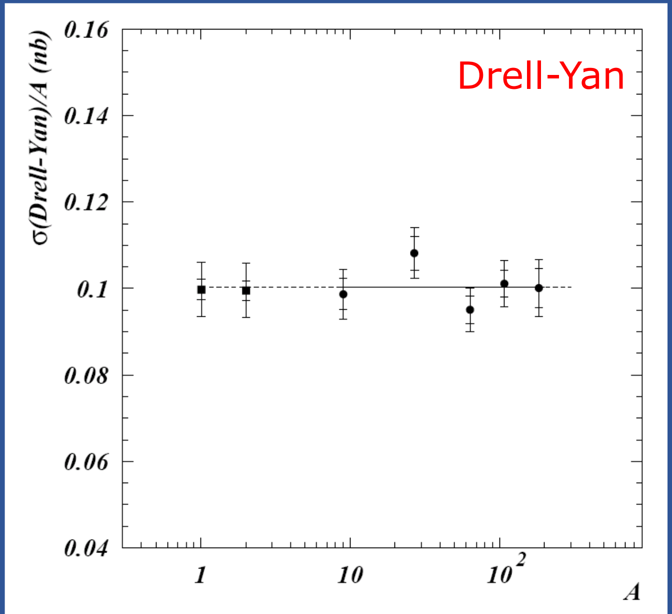
Reference processes at SPS energy

- Use **Drell-Yan as a reference**, insensitive to medium modifications

NA50, PLB553(2003)167



35<E_T<45 GeV

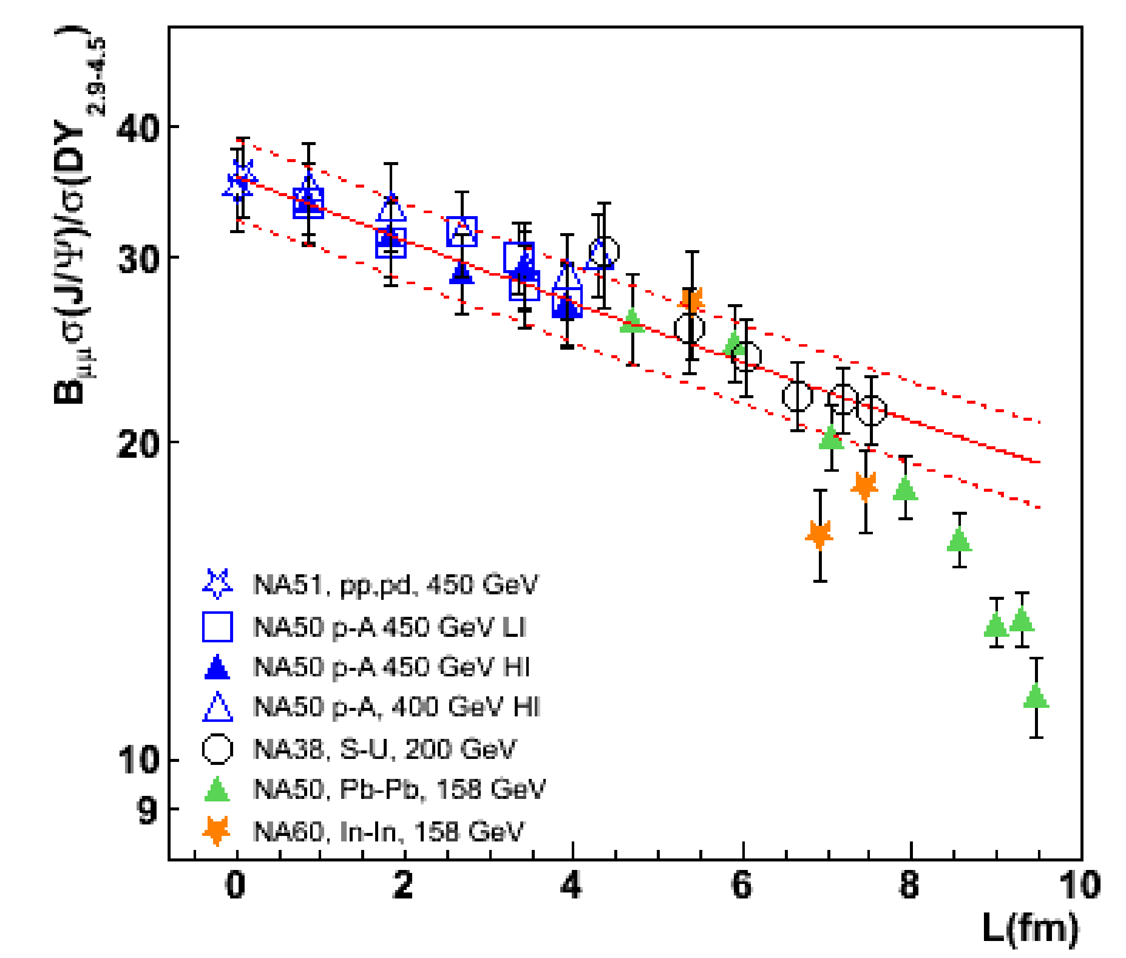


PROS:
- Both J/ψ and DY are hard processes
  → Ratio proportional to J/ψ yield per NN collision
- Luminosity and several efficiencies cancel out (μμ final state)
- Shadowing effects weak

CONS:
- Low DY statistics
  (largest NA50 sample led to 2 10^5 J/ψ, ~2 10^3 DY dimuons with M>4.2 GeV/c^2)

(DY-like reference was also built from minimum-bias sample in an attempt to increase statistical significance, with various technical difficulties)

Extrapolation of CNM effects

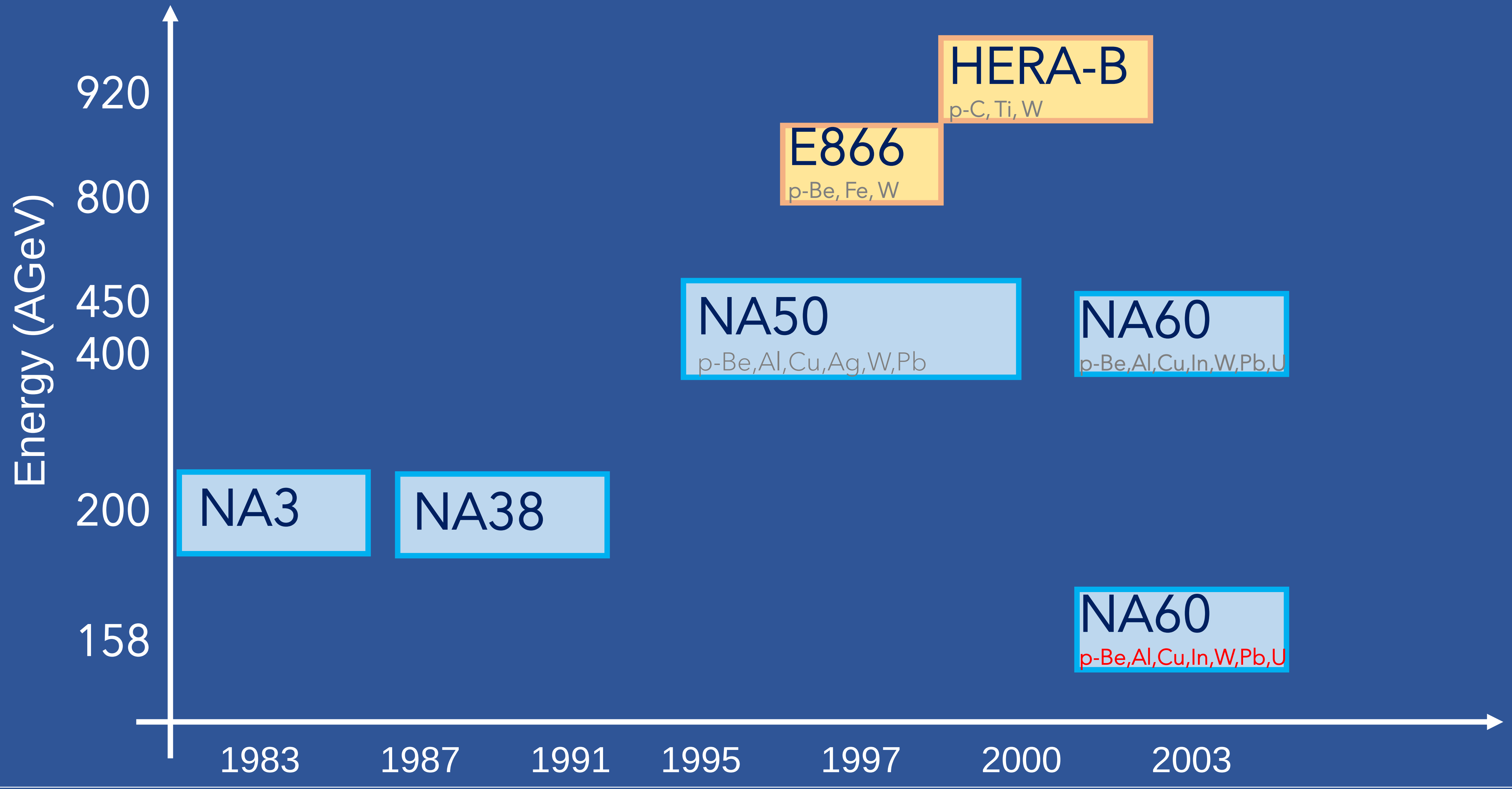


NA38 Coll., PLB449 (1999)128
NA50 Coll., EPJC39 (2005)335

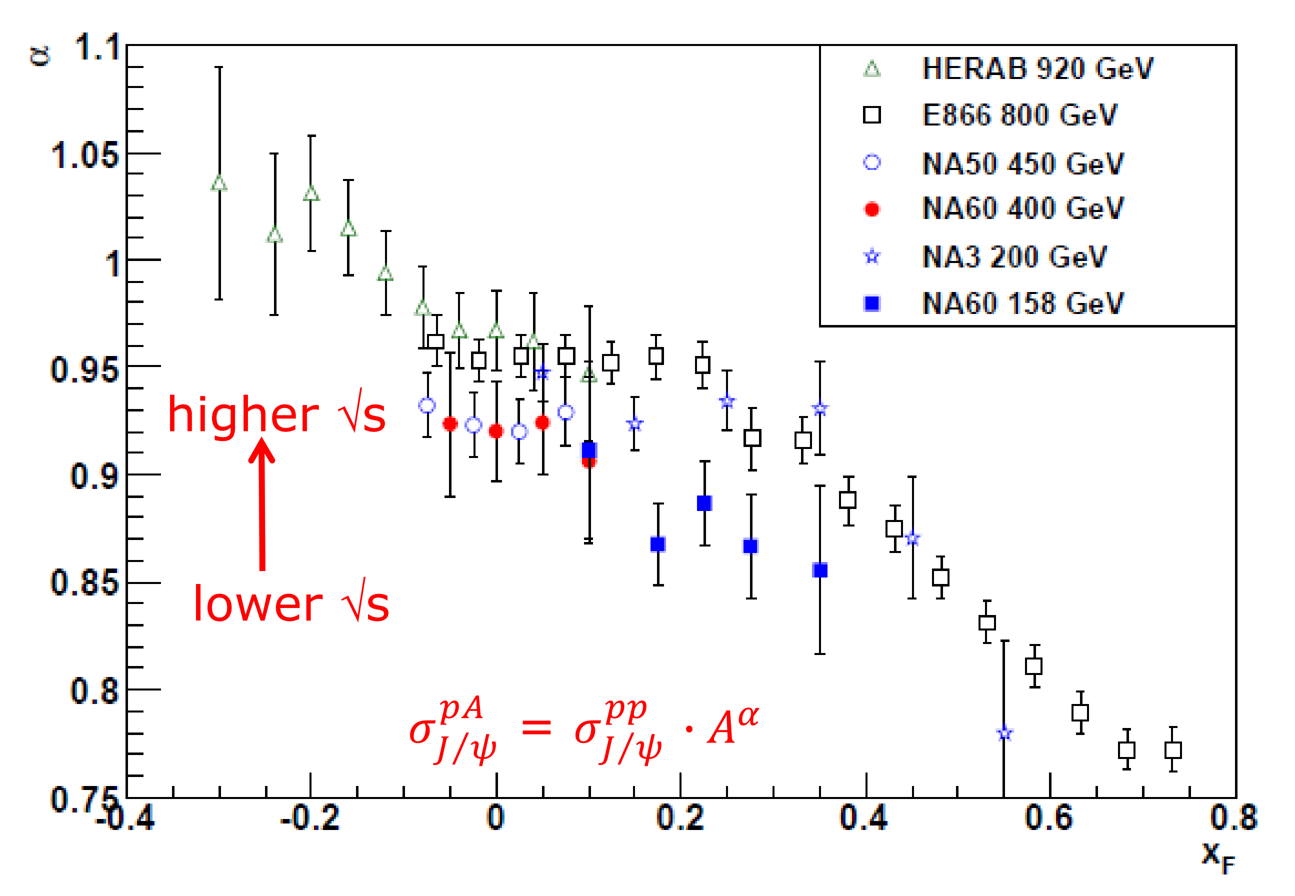
- **Use L as scaling variable**
  → average thickness of nuclear matter crossed by the cc pair
- **Exponential behaviour in pA**
  → break-up effects dominate
- **Light AA collisions (S-U)**
  → compatible with pA behaviour
- **Pb-Pb collisions**
  → breaking of L-scaling: anomalous suppression

- **Caveats**
  - Assume √s-independence of nuclear effects
  - Extrapolation of shadowing effects is more complex
    → to be taken into account

Initial state and CNM effects at fixed target



p-A results at fixed target: a complex environment



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

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**

Superposition of several effects

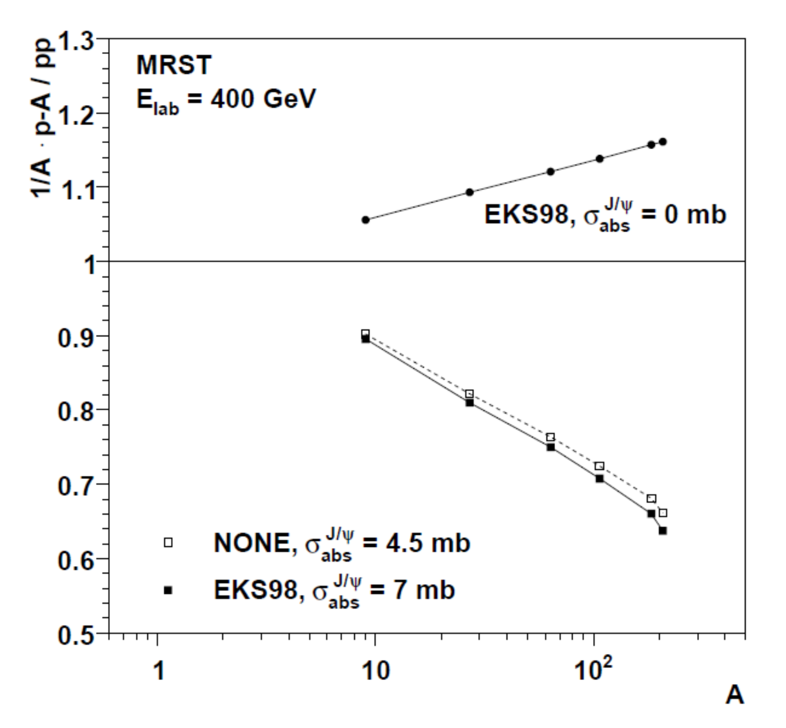
Shadowing
Nuclear break-up
Energy loss (at large x_F)

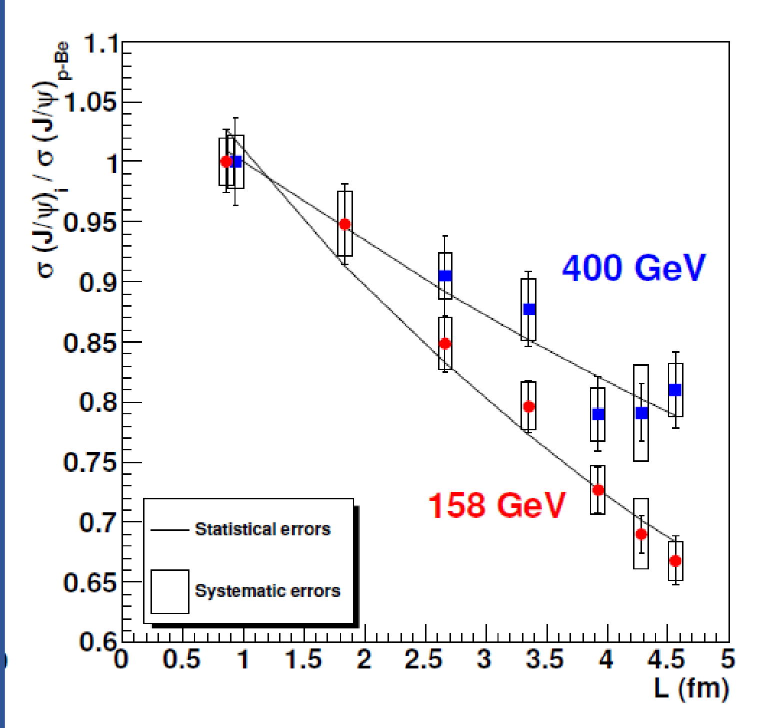
No consistent theory description over the whole x_F range

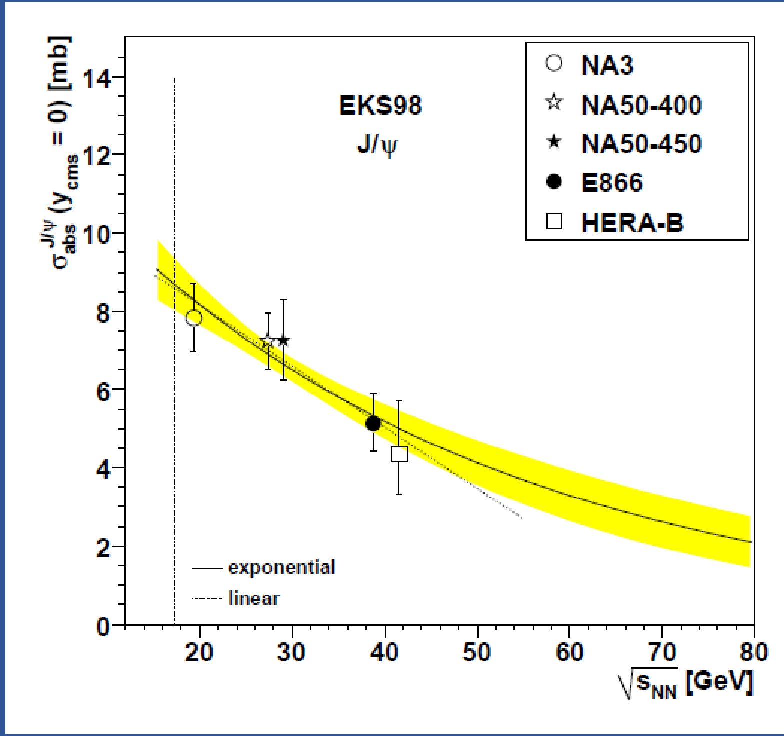
Attempting a parameterization of CNM

NA60, Phys.Lett.B 706 (2012) 263

Lourenco, Vogt, Woehri, JHEP 0902:014,2009







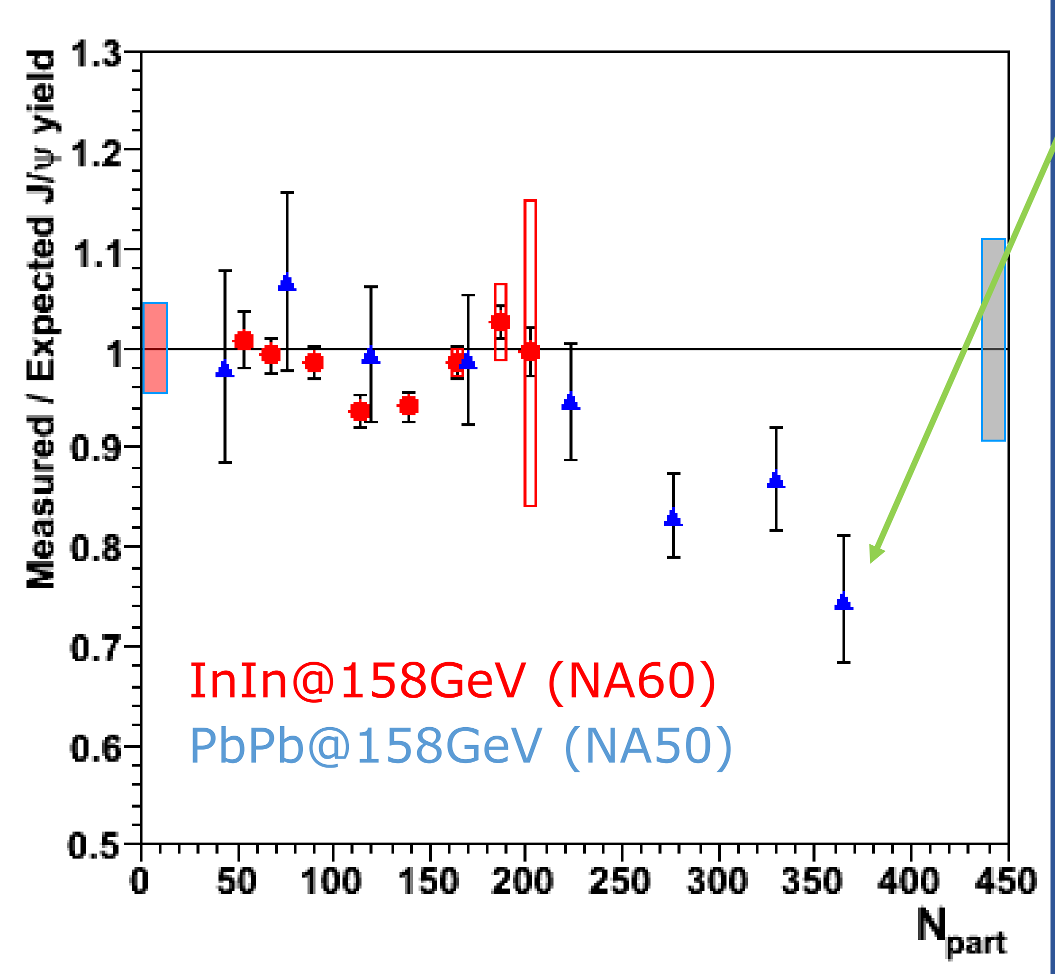
"Competition" between (anti)shadowing and nuclear break-up

Relative J/ψ cross sections
Evidence for **√s-dependence**

$\sigma^{J/\psi}_{abs}$~10 mb at low √s

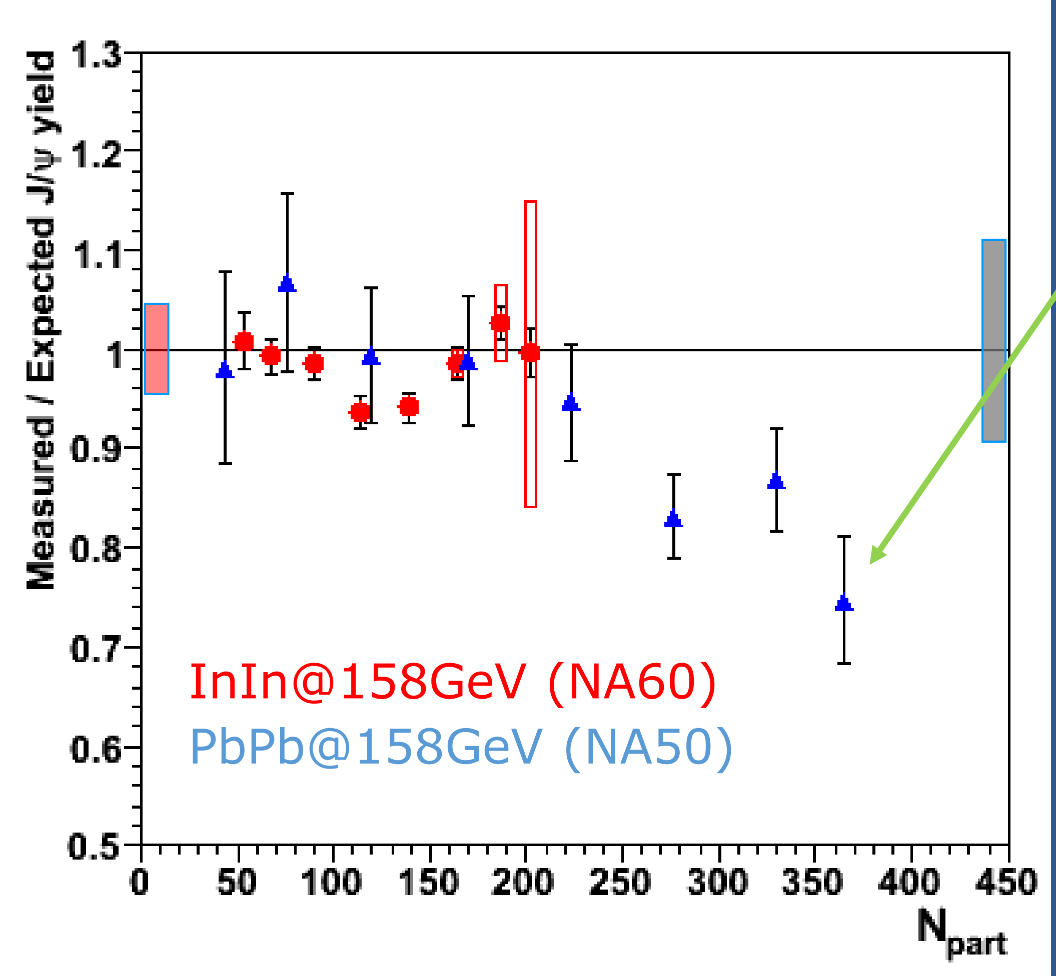
→ **CNM effects to become dominant in A-A** at sufficiently low collision energy

Prospects for new measurements at SPS energy



1 Improve accuracy in PbPb measurements at top SPS energy → results now limited by DY statistics

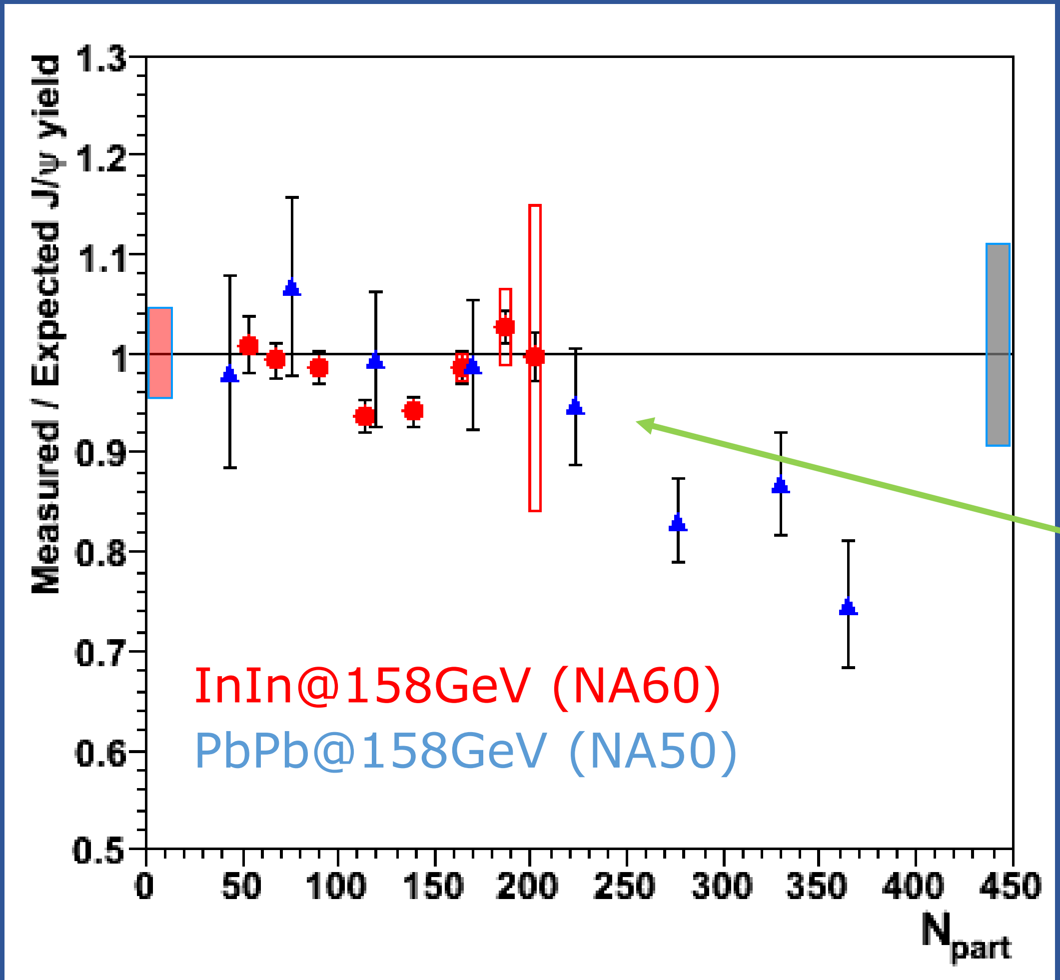
Prospects for new measurements at SPS energy



1. Improve accuracy in PbPb measurements at top SPS energy → results now limited by DY statistics

2. Access excited quarkonium states in AA
to confirm that 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

Prospects for new measurements at SPS energy



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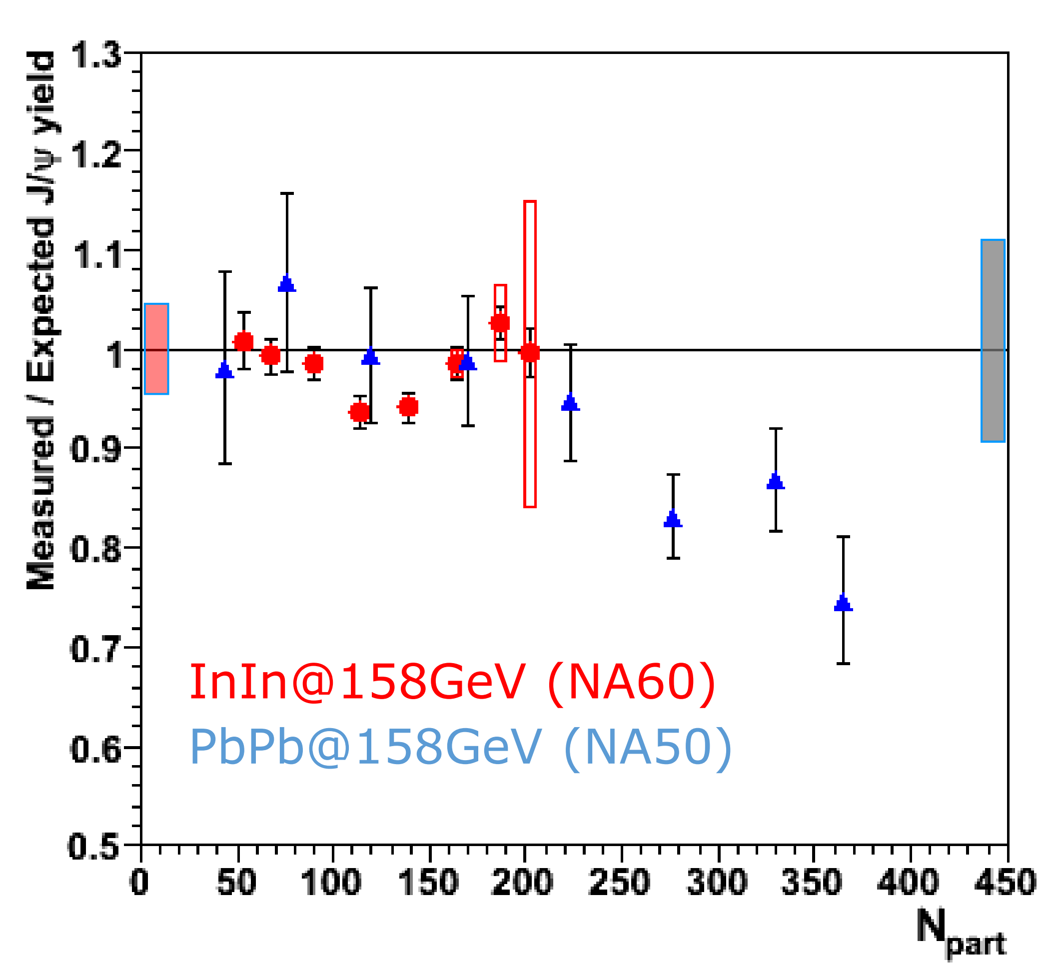
3. **Energy dependence of the anomalous suppression**
studying J/ψ production below top SPS energies

Prospects for new measurements at SPS energy



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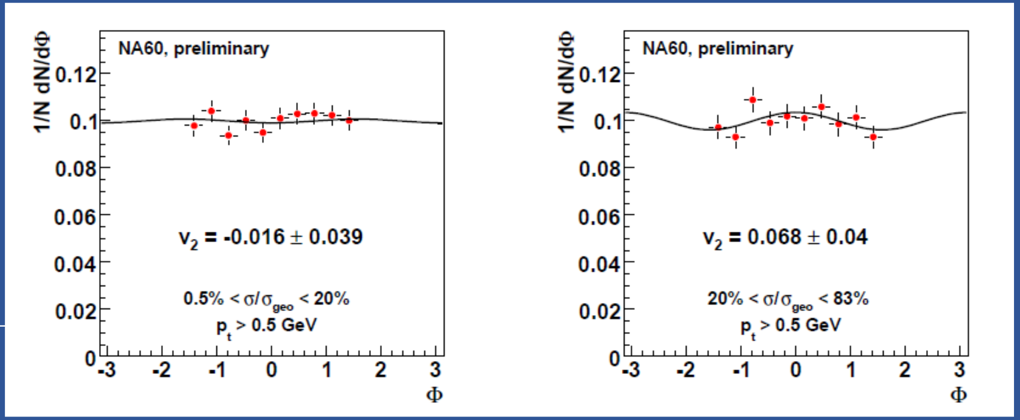
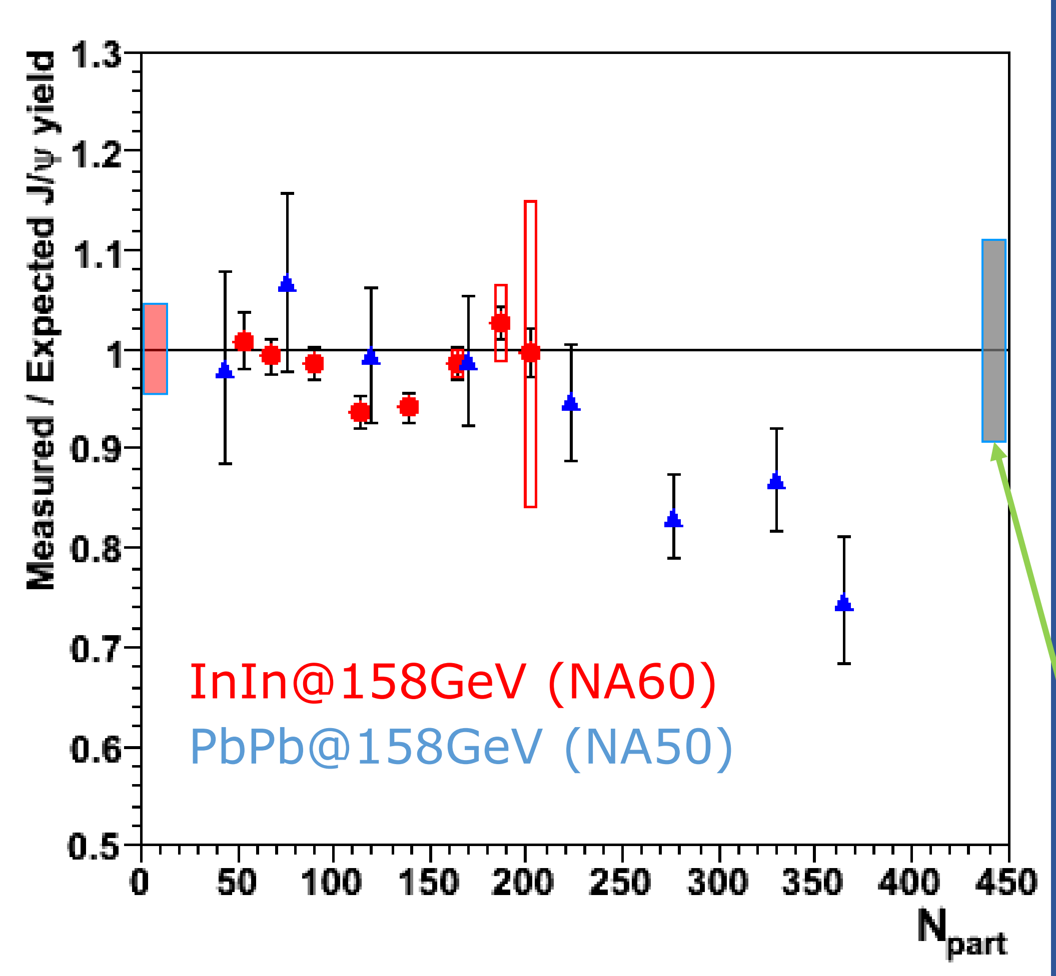
3. **Energy dependence of the anomalous suppression**
   studying J/ψ production below top SPS energies

4. Study elliptic flow, sensitive to medium properties

NA60, J.Phys.G32:S51-S60,2006



Prospects for new measurements at SPS energy



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3. **Energy dependence of the anomalous suppression**
studying J/ψ production below top SPS energies

4. Study elliptic flow, sensitive to medium properties

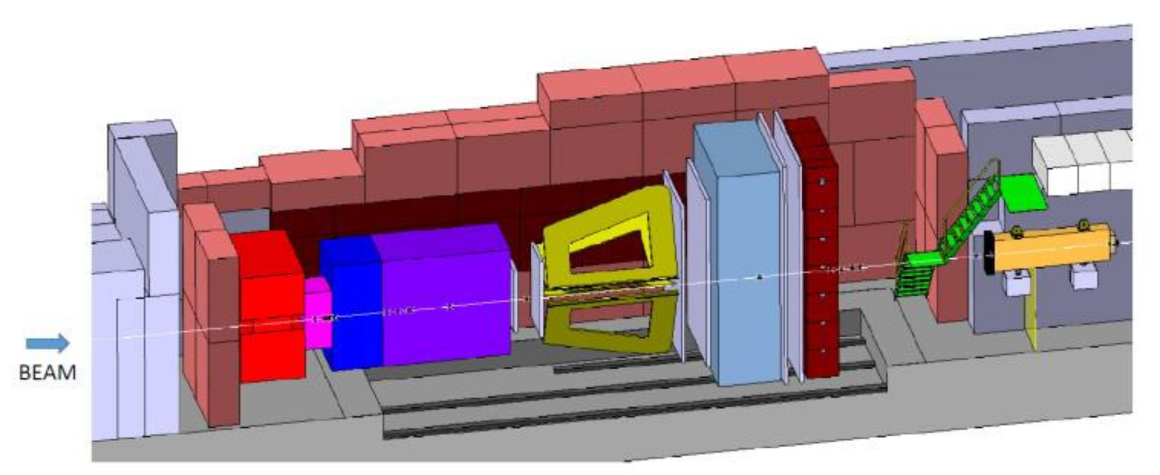
5. Precise pA reference at the same energy as AA,
currently ~12% uncertainty (158 GeV data taking was ~4 days at I_{beam}= 5e8 p/s)

Quarkonium production at low SPS energy: NA60+

Study of hard and electromagnetic processes at CERN-SPS energies

Perform an energy scan in $\mathbf{E_{lab}}$ **= 20 – 158 GeV**

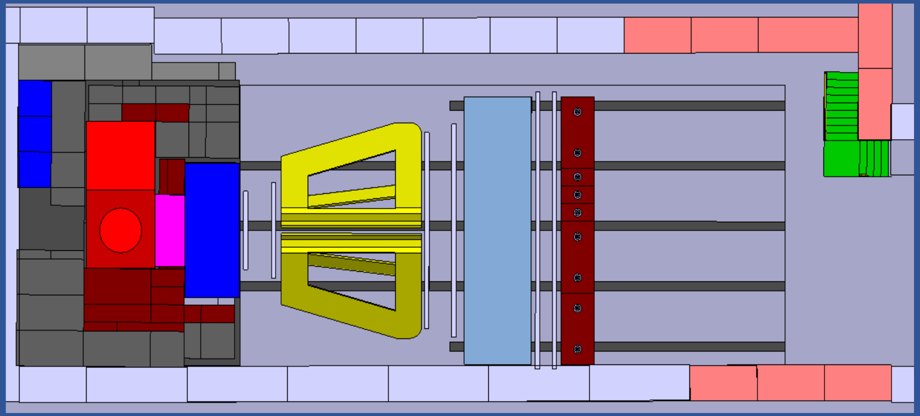
→ **quarkonium production not studied below top SPS energies!**



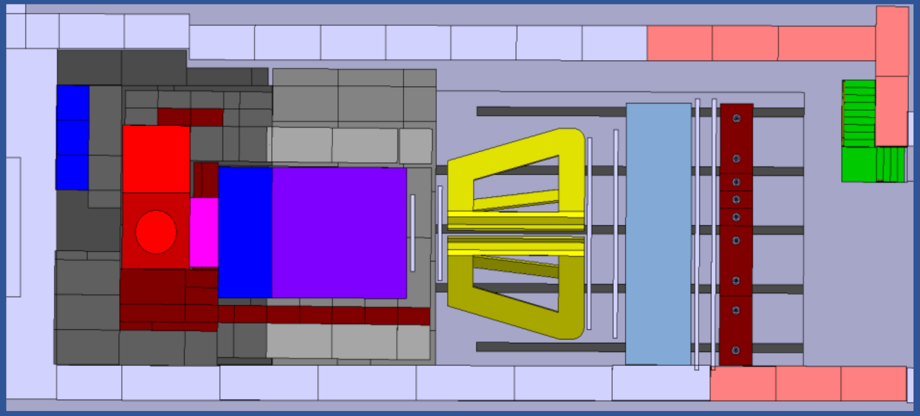
- Decreasing √s:
  - **High-μ_B QGP effects on quarkonium**
    → needs theory guidance
  - **Onset of χ_c and ψ(2S) deconfinement**
    → be correlated to T measurement via thermal dimuons
  - **Stronger CNM effects**
    → to be accounted for with pA data taking at the same √s

More details on the project
Webpage → https://na60plus.ca.infn.it/
Expression of Interest → https://cds.cern.ch/record/2673280

Performing an energy scan at SPS energies



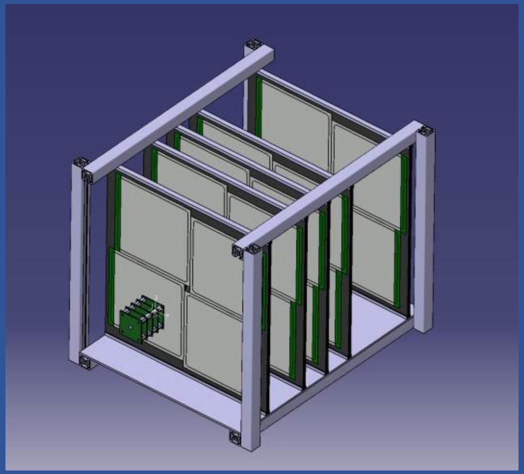
Top view (low-energy setup)

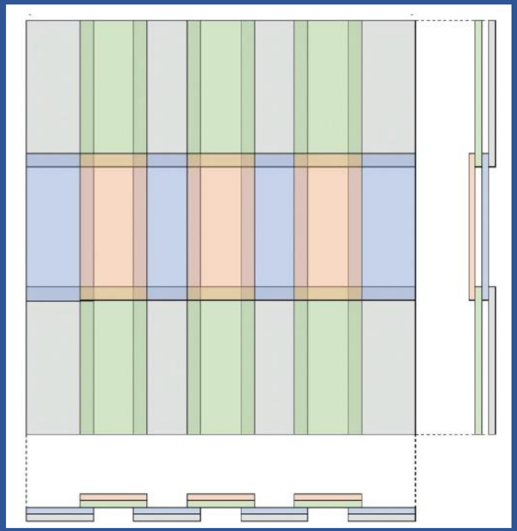


Top view (high-energy setup)

A vertex spectrometer coupled to a muon spectrometer

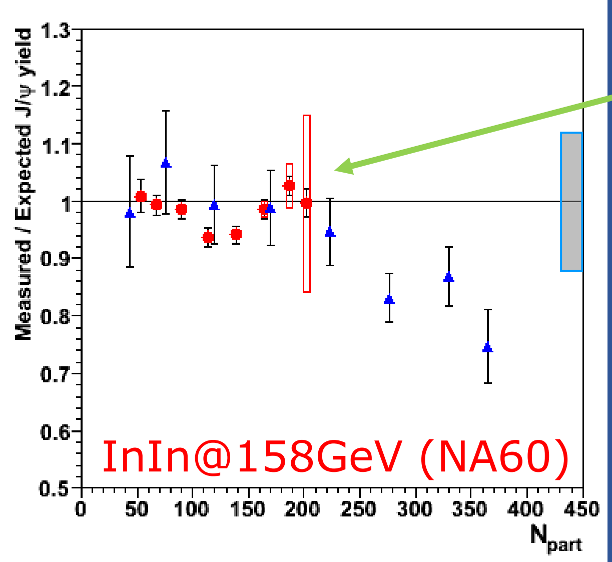
Vary spectrometer length and muon absorber thickness according to collision energy



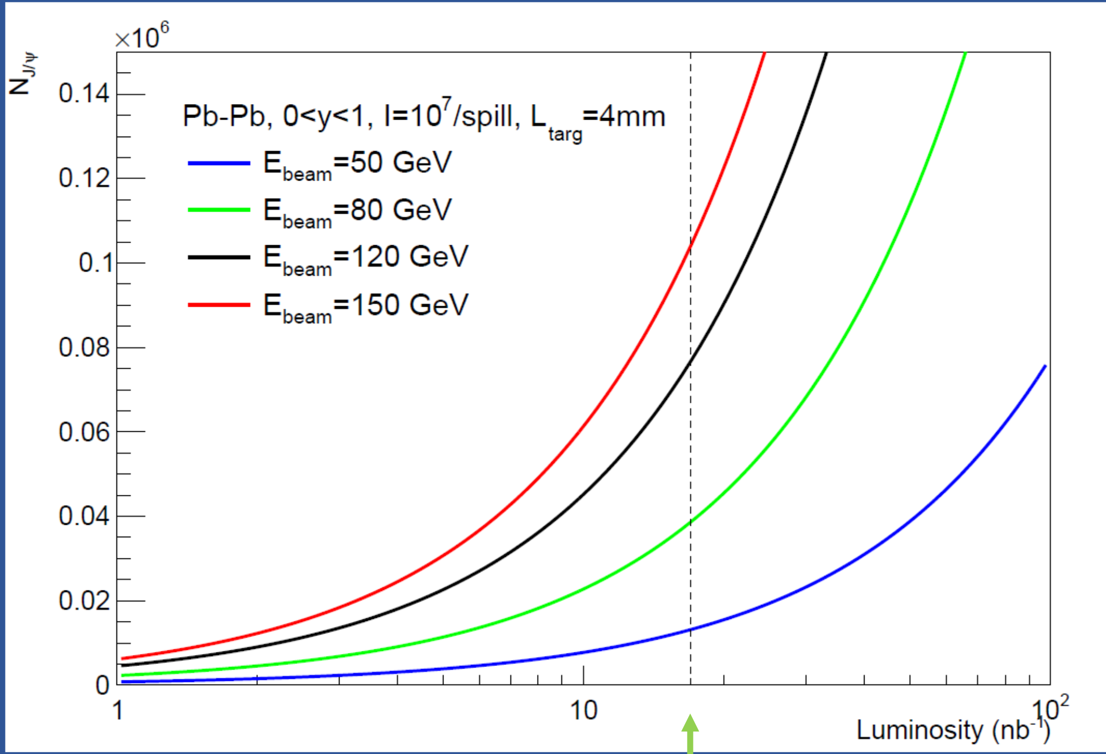


R&D in progress
Preparing LoI

NA60+ J/ψ, Pb-Pb collisions



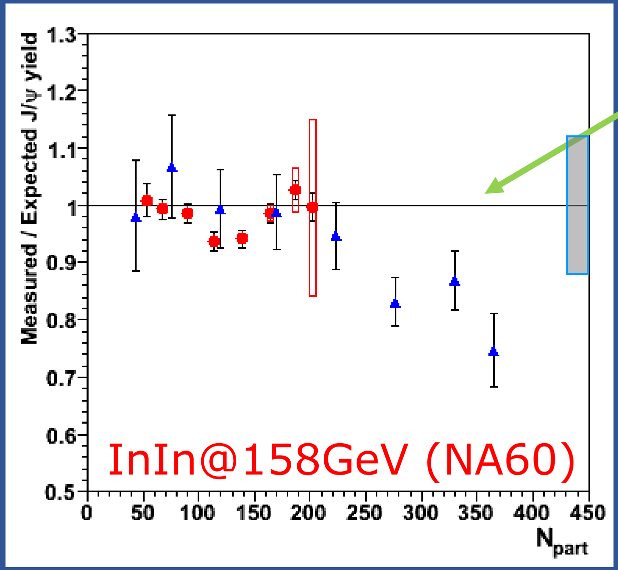
NA60 sample
(InIn at 158 GeV)
~ 3 x 10^4 J/ψ



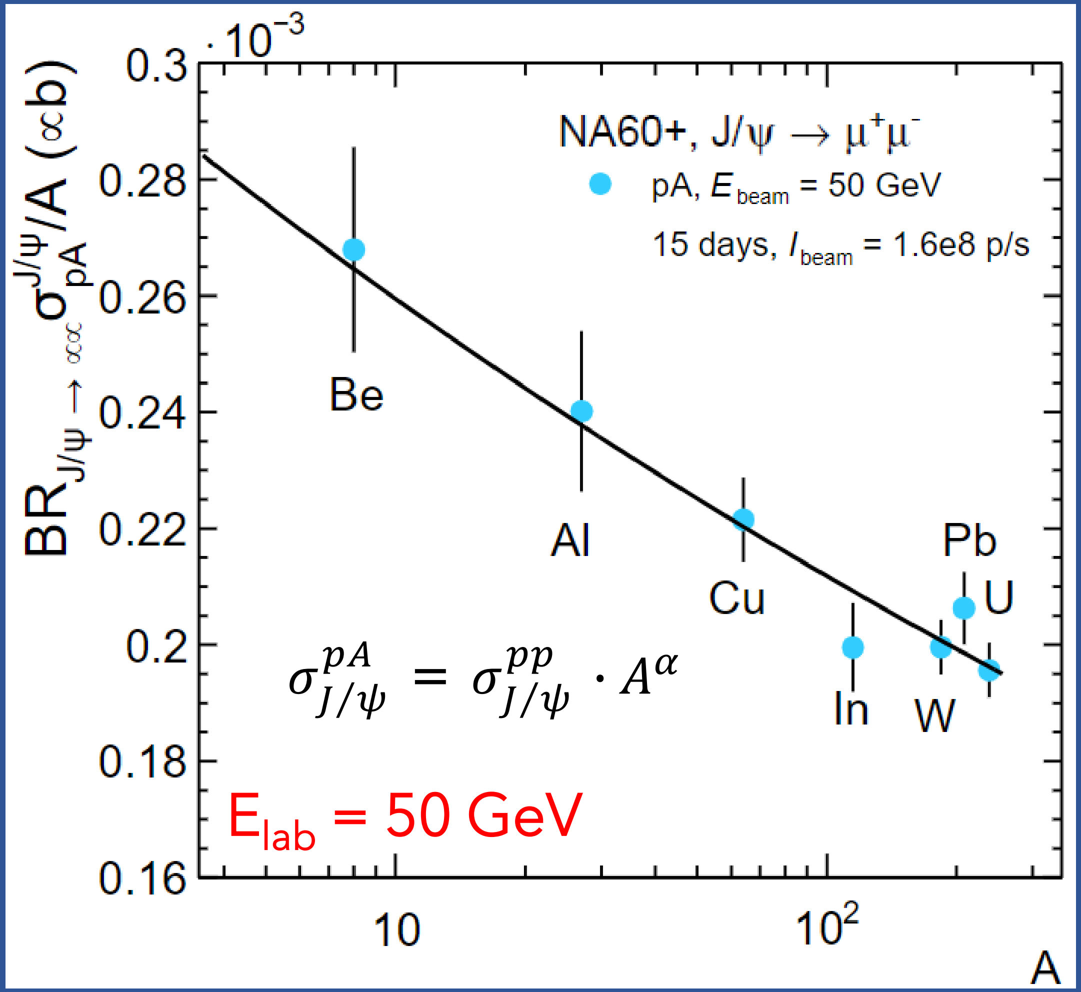
- With I_{beam}~10^7 Pb/20s spill, 4mm Pb target and 1 month of data taking → **L_{int} =17 nb^{-1}** NA60+ can aim at
  - **~O(10^4) J/ψ at 50 GeV**
  - **~O(10^5) J/ψ at 158 GeV**

- N.B.: a factor 3 overall suppression (CNM + QGP) is assumed in these estimates

NA60+ J/ψ, p-A collisions



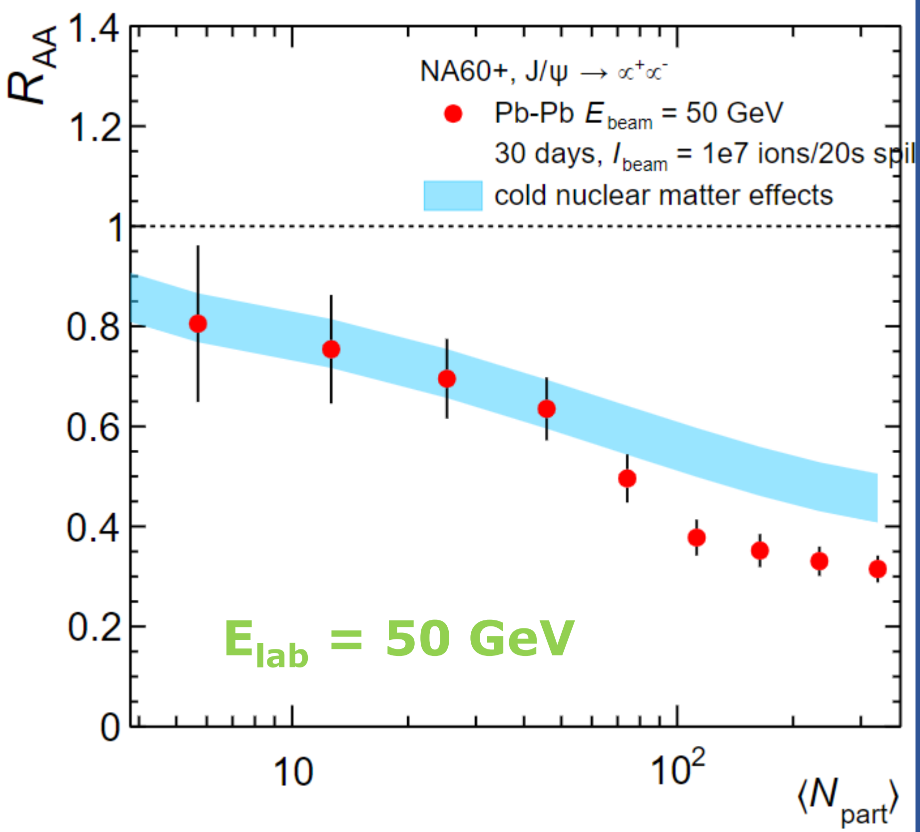
NA60 sample
(pA at 158 GeV)
~1.5 x 10^4 J/ψ

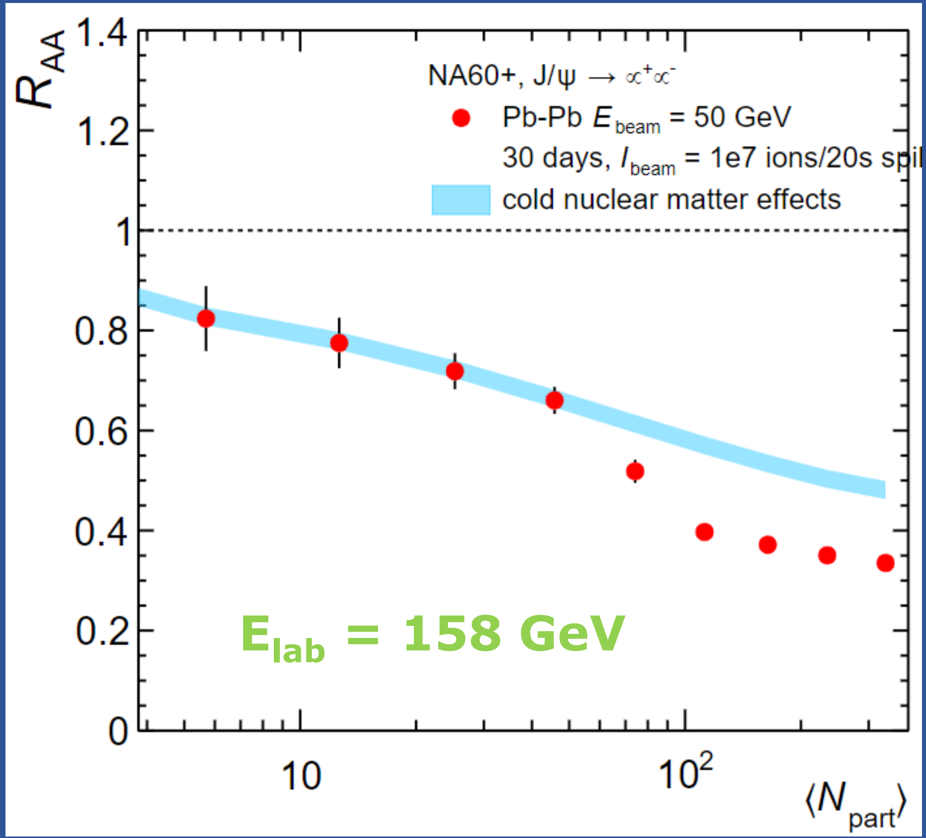


- With I_{beam}~8x10^8 p/20s spill, 7 targets with total interaction length 10% and 0.5 months of data taking NA60+ can aim at
  - **~6000 J/ψ at 50 GeV**
  - **~50000 J/ψ at 158 GeV**

- pp collisions unpractical
  → Use a system of several targets simultaneously exposed to the p beam

NA60+, R_{AA} estimate





- Based on
  - 30 days PbPb I_{beam} = 1e7/spill
  - 15 days pA I_{beam} = 8e8/spill

Assume only CNM effects for N_{part}<50 and 20% extra suppression in Pb-Pb for N_{part}>50

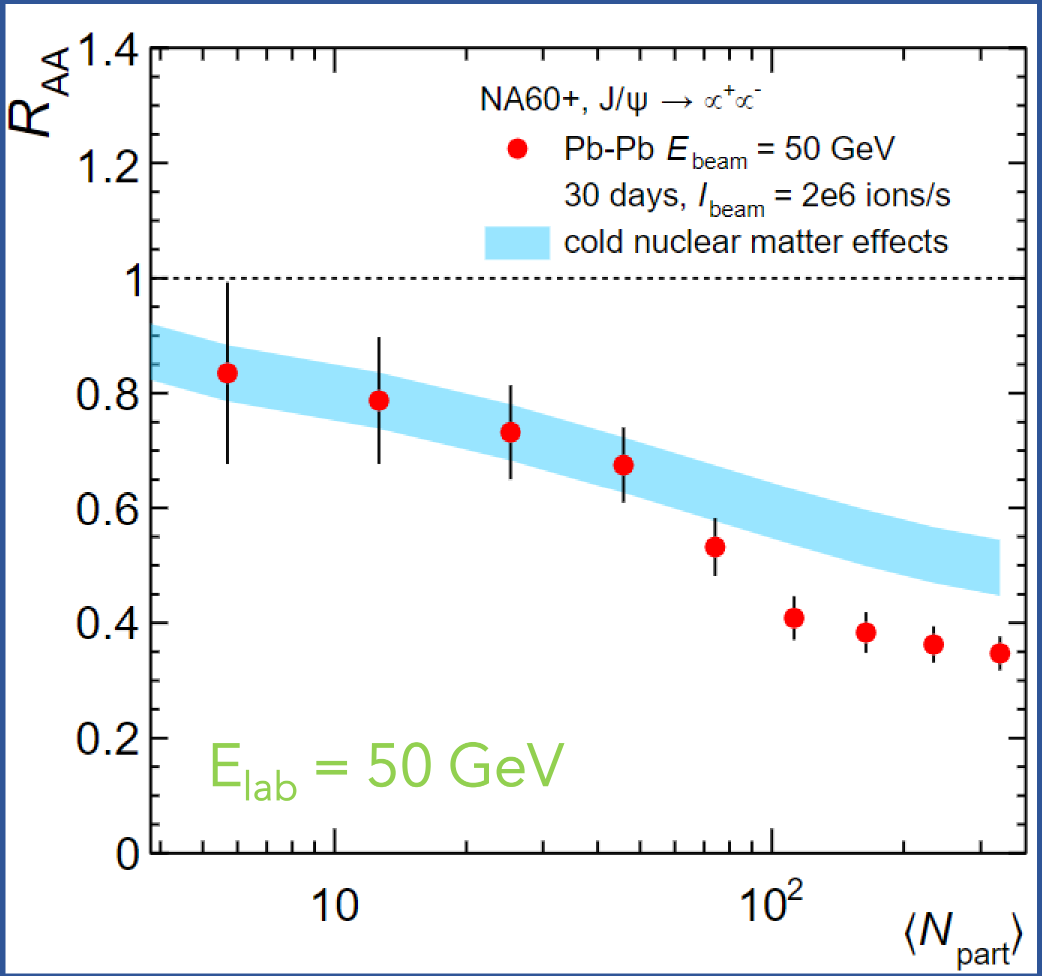
→ **Precise evaluation of anomalous suppression within reach even at low energy**

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}

Quantifying hot matter effects



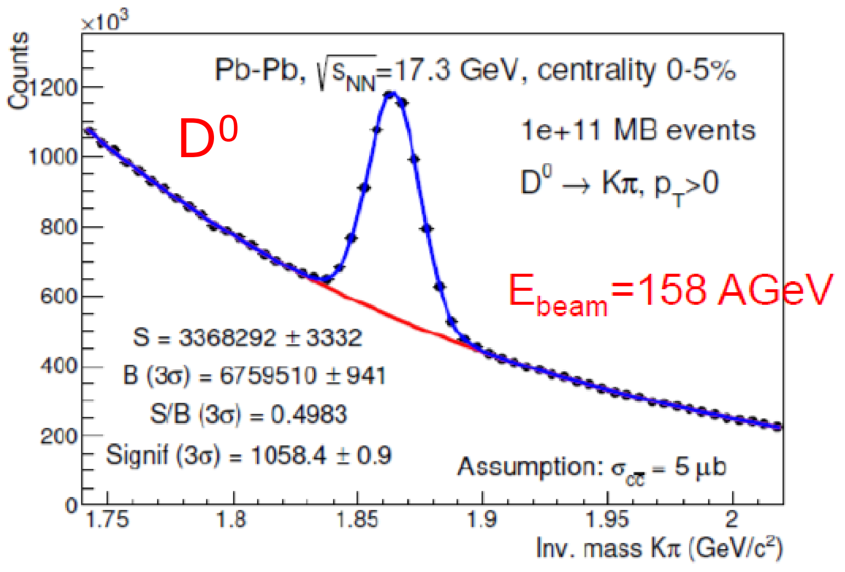
Which observables could be used?

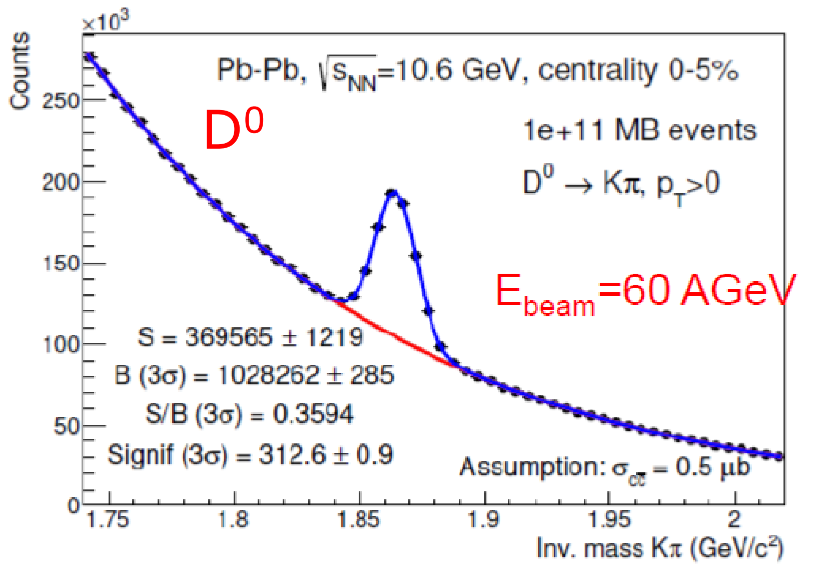
- **R_{AA}** based on pp extrapolated from pA results at the same √s (<5% uncertainty)
- **R_{AA}/R_{pA}** ~ measured/expected à la NA50/60
  → useful to compare results at various √s, since CNM are energy dependent
- **Drell-Yan**
  very much limited by statistics at high mass (x100 less wrt J/ψ for $m>m_{J/\psi}$)
- **J/ψ/(total charm)?**
  potentially accessible via hadronic charm measurements

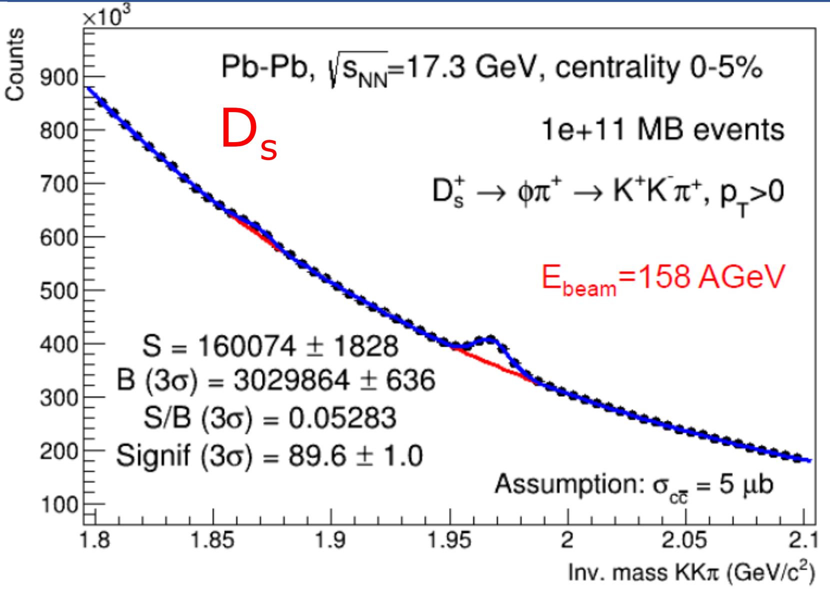
Prospects for open charm measurements

F. Prino, ECT*

- Measurement of hadronic decays of open charm (vertex spectrometer, no PID): **D^0, D_s**





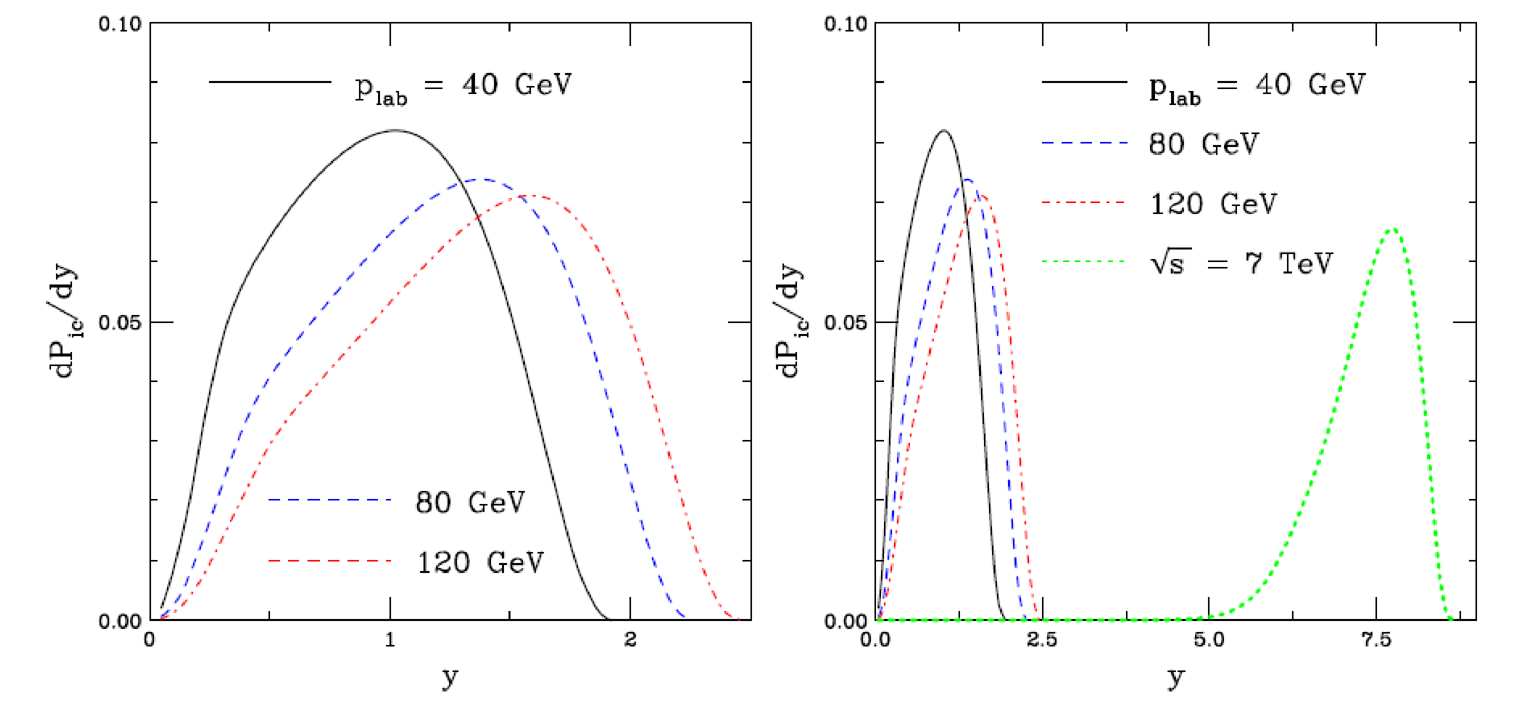


- Assume 10^{11} MB collisions (can be collected in ~1 month at 200kHz interaction rate)
- Measurements of **D^+ meson** expected to be within reach
  → longer lifetime (larger displacement) and higher abundance than D_s meson
- Studies ongoing for **Λ_c performance**
  → short lifetime, more challenging separation of decay vertex
  → Study also reconstruction of decays with a neutral strange hadron in the decay products

Low-$\sqrt{s}$ J/ψ: studying intrinsic charm

- Intrinsic charm component of the hadron wavefunction **|uudc$\bar{c}$>**
- Leads to **enhanced charm production** in the forward region

- Hints from several experiments, but **no conclusive results**
- At colliders, forward x_F pushed to very high rapidity, difficult to measure
  → fixed-target configurations more appropriate

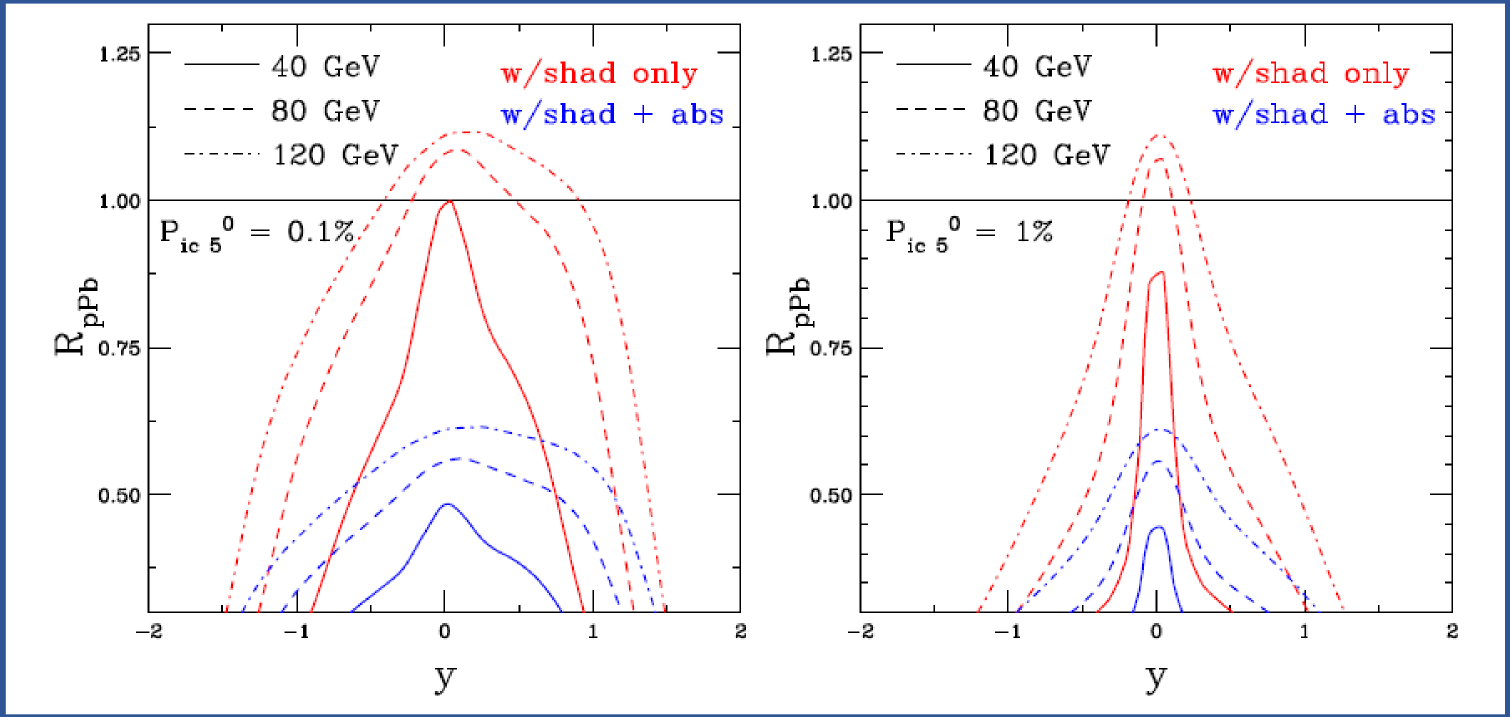


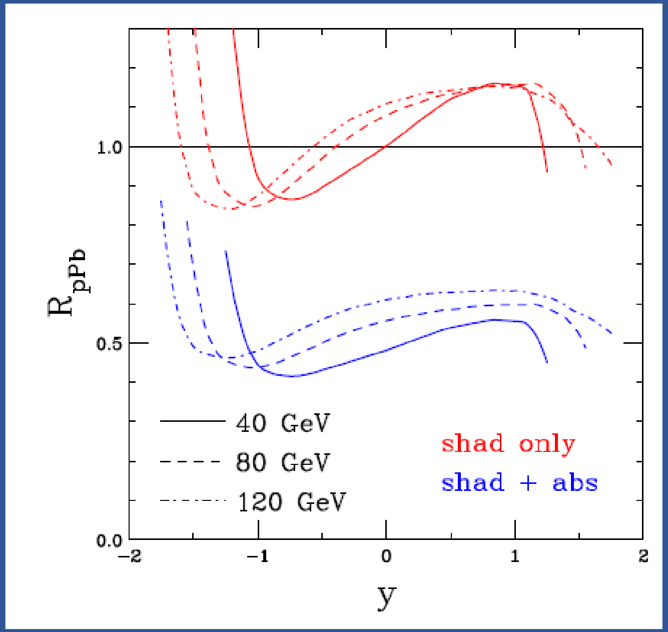
Assumed intrinsic charm content varied between 0.1% and 1%

R. Vogt, talk at ECT* workshop "Exploring high-muB matter with rare probes", october 2021

Low-√s J/ψ: energy dependence in p-Pb

p-Pb collisions
- EPPS shadowing
- σ_{abs} = 9,10,11 mb at E_{lab}=120, 80, 40 GeV
- P_{ic} varied between 0.1 and 1%





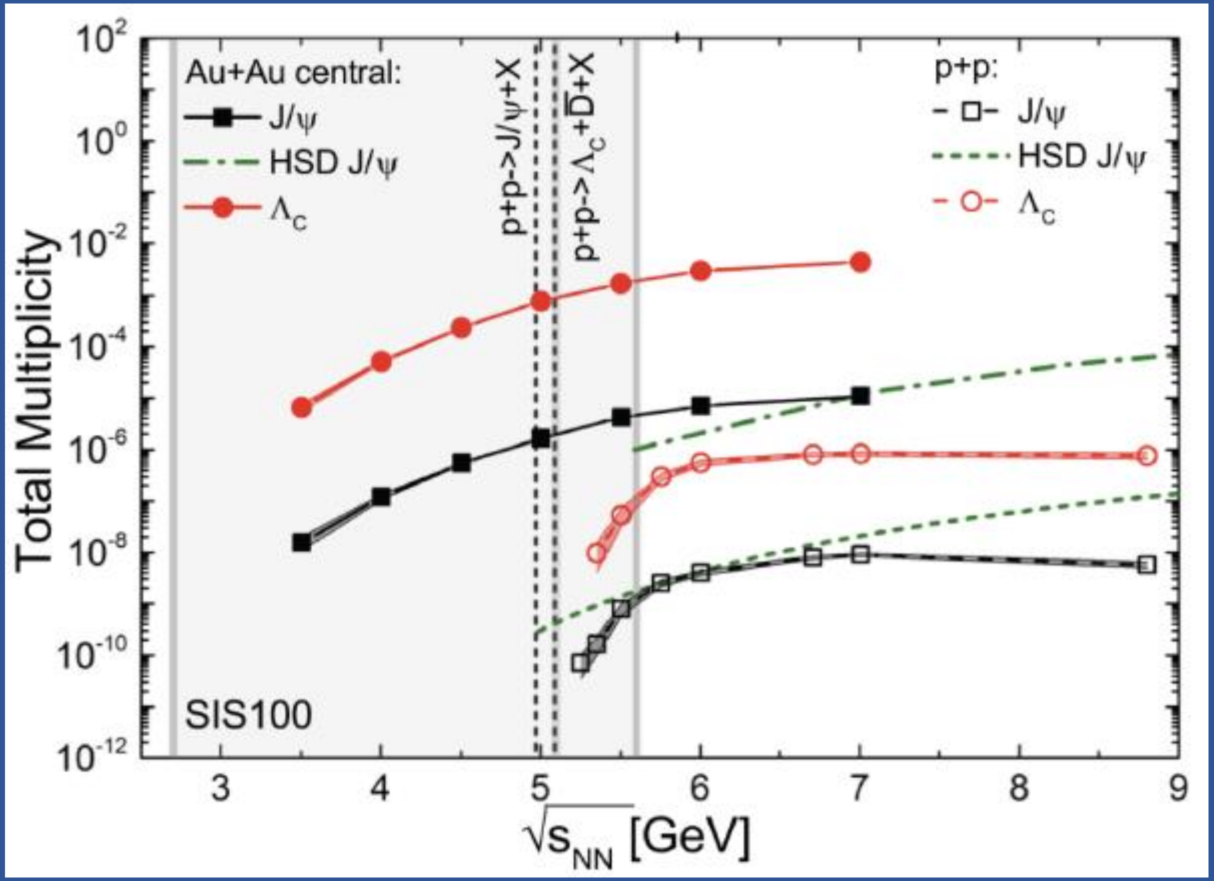
(w/o intrinsic charm)

- **R_{pPb} is overwhelmed by intrinsic charm**, even at midrapidity with P_{ic}=0.1%
- N.B.: all calculations are preliminary

Quarkonium at CBM: threshold production

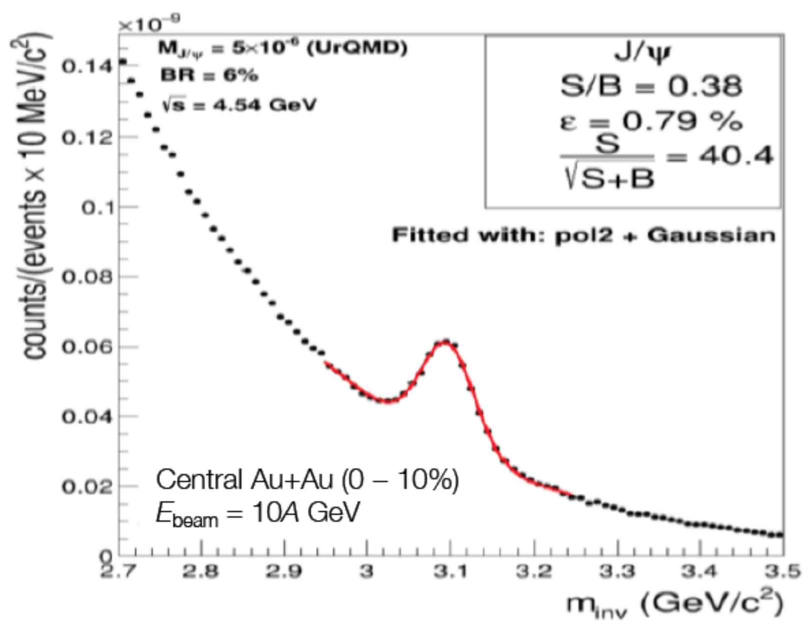
- **Sub-threshold production** (rare but feasible) via multiple collision processes
- Production threshold might be exceeded with SIS100 beam of N=Z nuclei
- Both $\mu^+\mu^-$ and e^+e^- decay channels accessible
- Needs **very large interaction rates** → 10 MHz (50 times NA60+)
- Beam intensities → 10^9/s A, 10^{11}/s p

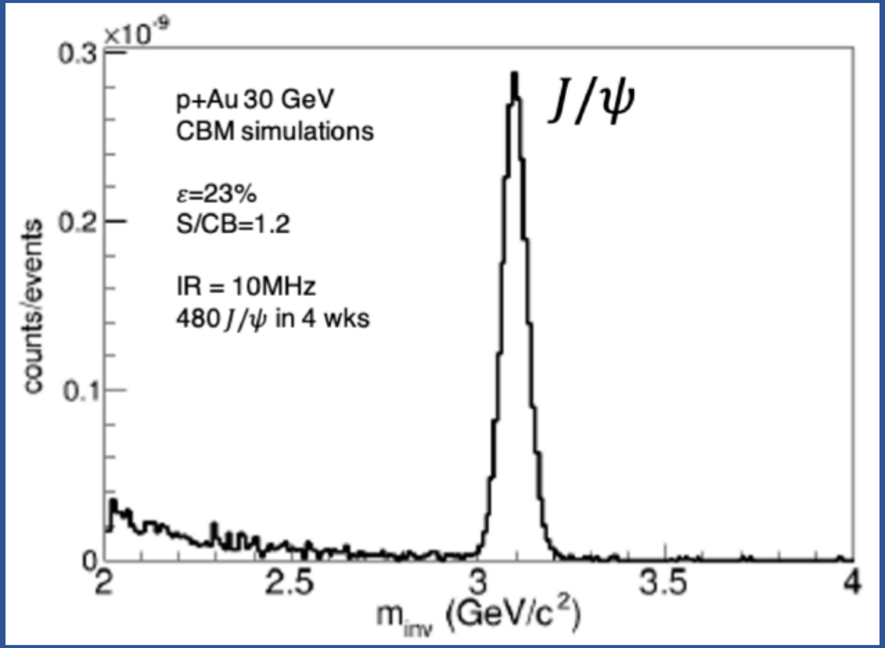
Au-Au Ca-Ca pp

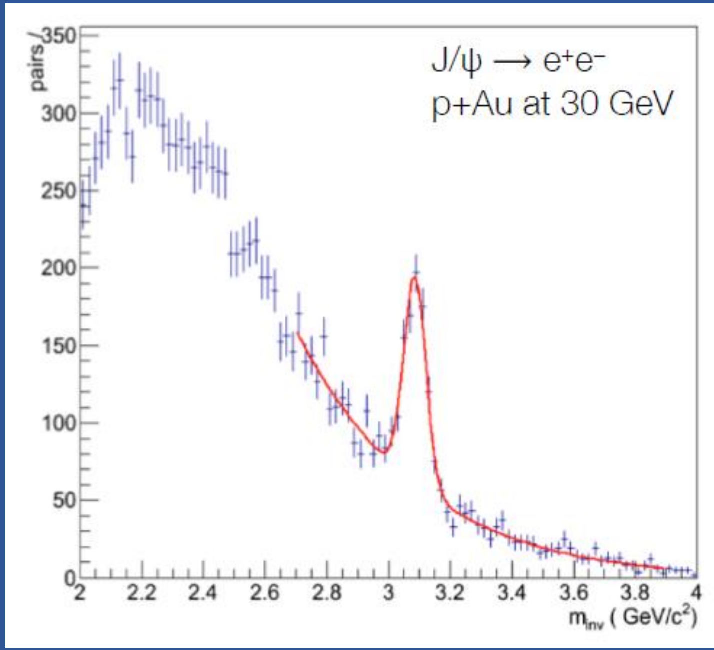


J. Steinheimer et al, Phys. Rev, C95 (2017) 014911

Quarkonium at CBM: physics performance







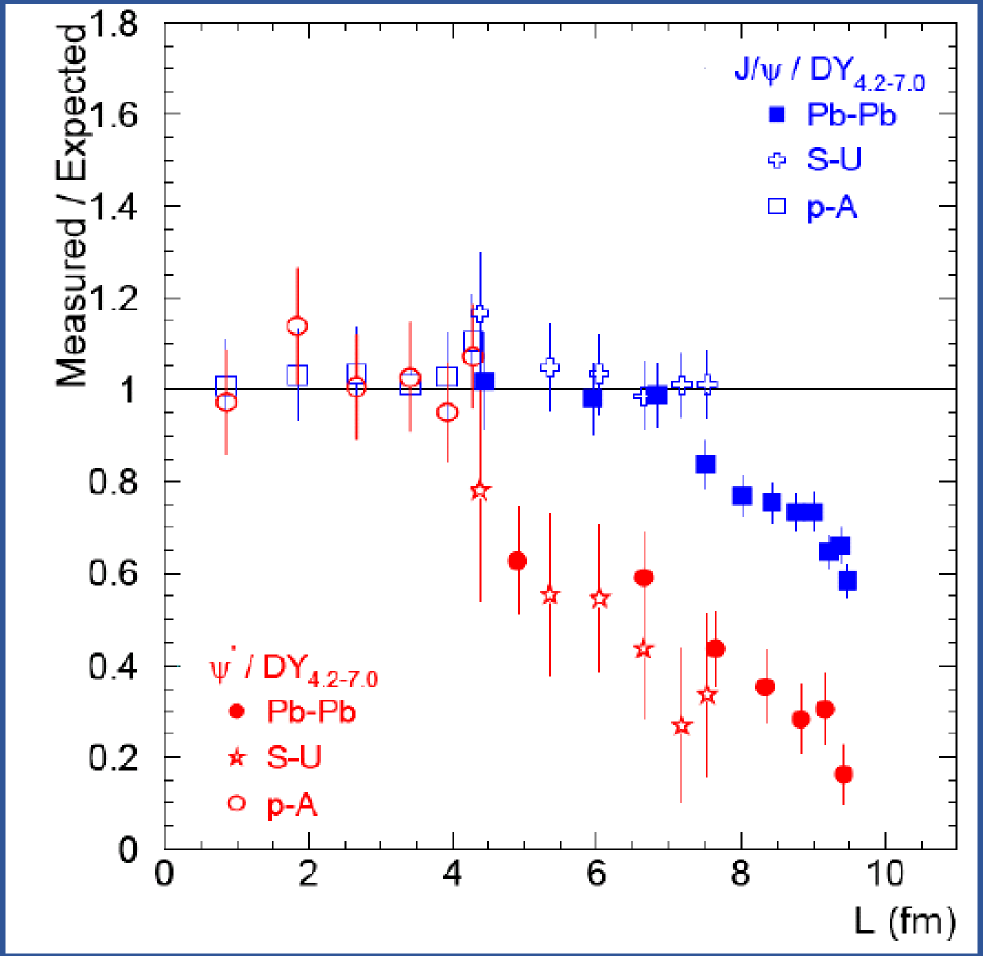
J/ψ→μμ
AuAu ~30k J/ψ in 4 weeks at 10 MHz interaction rate
pAu ~500 J/ψ in 4 weeks at 10 MHz interaction rate

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

pA → lower statistics, but very clean signal

Excited charmonium states: $\psi(2S)$, χ_c

NA50, EPJC39 (2005) 335, EPJC49 (2007) 559



- ❑ Clear **ordering in the suppression** when moving from J/ψ to $\psi(2S)$
- ❑ The first **discovery of sequential suppression!**
  → Later confirmed by CMS in the Υ sector
- ❑ Typical yields in the dilepton channel
  → Lower by a factor ~100

No measurement of CNM on $\psi(2S)$ available at E_{lab}=158 GeV → not enough stat for NA60

N.B. here (weaker) CNM effects tuned at 450 GeV were used → bias!

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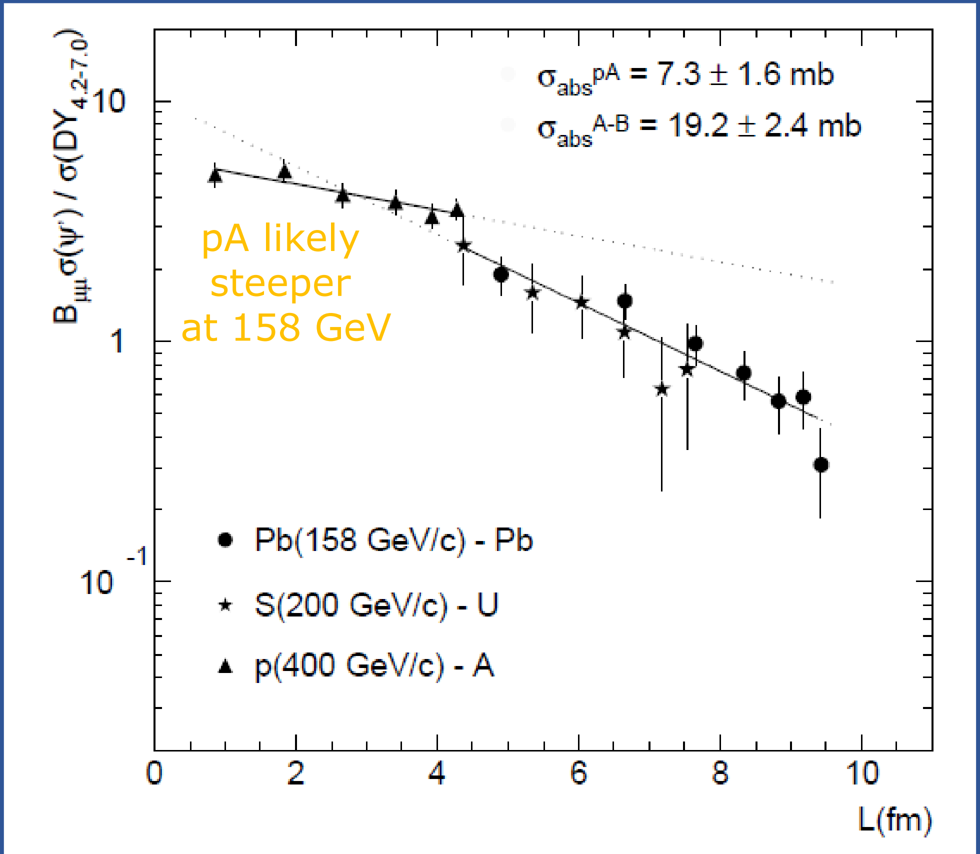

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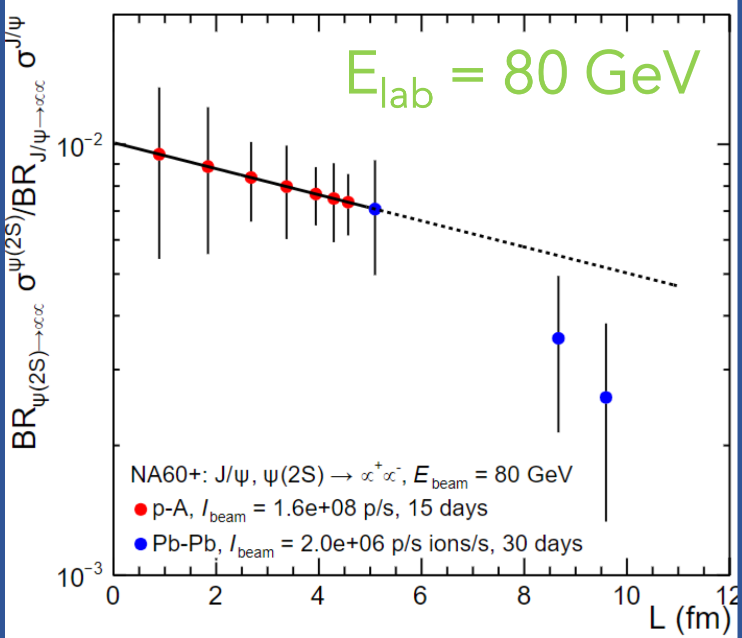
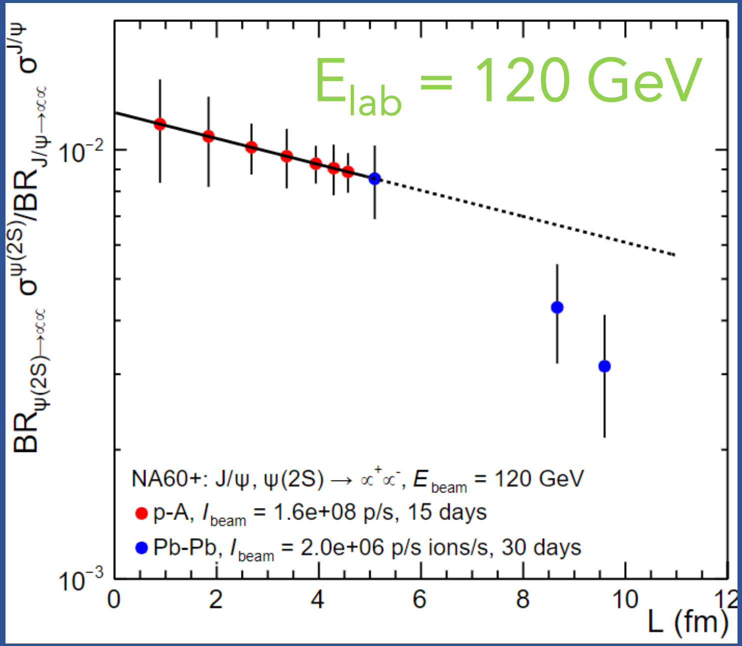
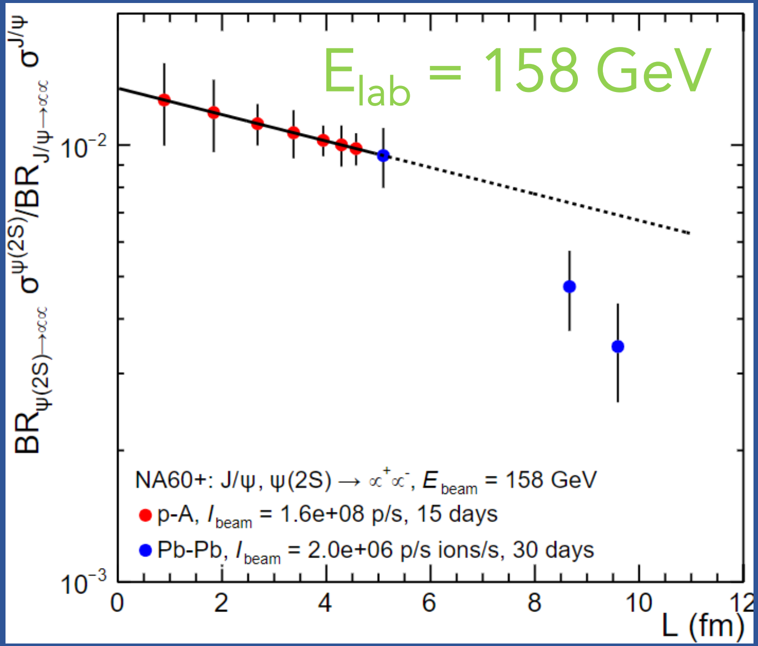
Prospects for ψ(2S) measurements in NA60+

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

Expectations based on
- 30 days PbPb, I_{beam} = 1e7 ions/spill (assuming larger suppression for ψ(2S) than J/ψ)
- 15 days pA, I_{beam} = 8e8 p/spill



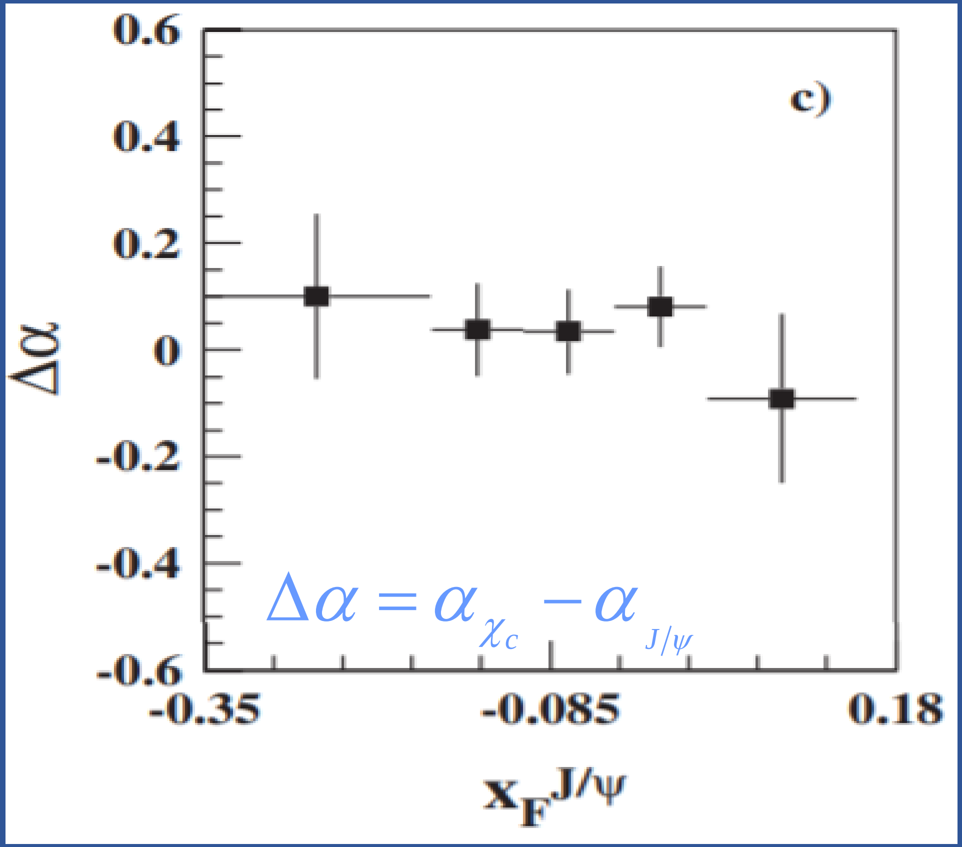




- ❑ **ψ(2S)/ψ measurement looks feasible down to E_{lab} = 120 GeV**
- ❑ **Lower E_{lab} would require larger beam intensites/longer running times**

χ_c measurements

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



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

- 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 observed 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 $\Delta\alpha=0.05\pm0.04$), but more accurate results are needed

- Non-trivial measurement, needs detection of low-momentum photon (<1 GeV)
  → conversion or calorimetry

Conclusions

- Charmonium measurements in A-A at fixed target energy have provided in the past
  → **Evidence for J/ψ suppression** beyond CNM effects
  → **Ordering of J/ψ and ψ (2S) suppression** according to binding energy

- **p-A studies** have shown a superposition of various effects with **increasing size** at small collision energy

- **No information exists below top SPS energy** ($\sqrt{s_{NN}}$=17 GeV)

- Prospects for measurements
  - Low SPS energy → **NA60+** project
  - Threshold region → **CBM** experiment

- Aims
  - Detecting **threshold for hot matter effects** on charmonia and correlate with **temperature** information obtained with thermal dimuon production
  - Search evidence for new effects → **intrinsic charm**

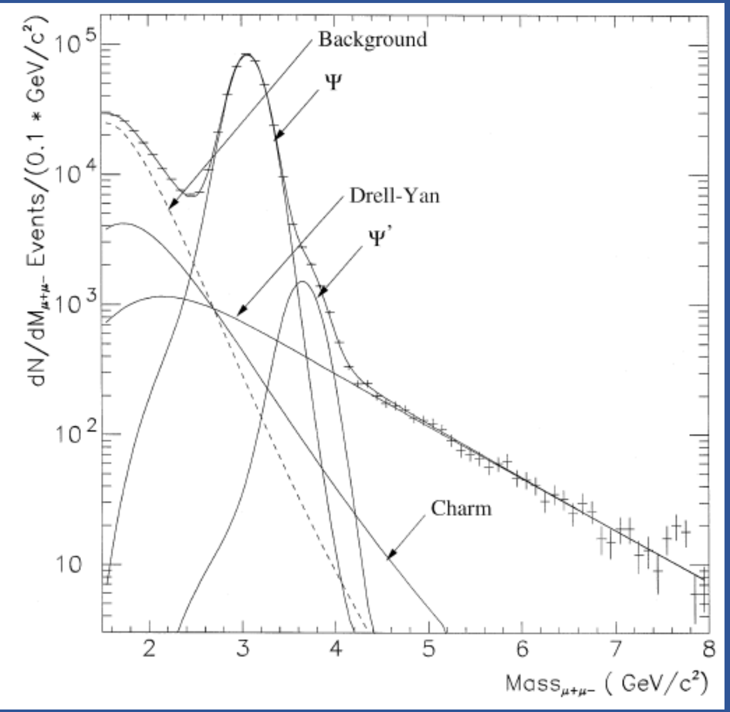
Backup

Why was R_{AA} not used ?

- Historical reasons (in pre-RHIC era)

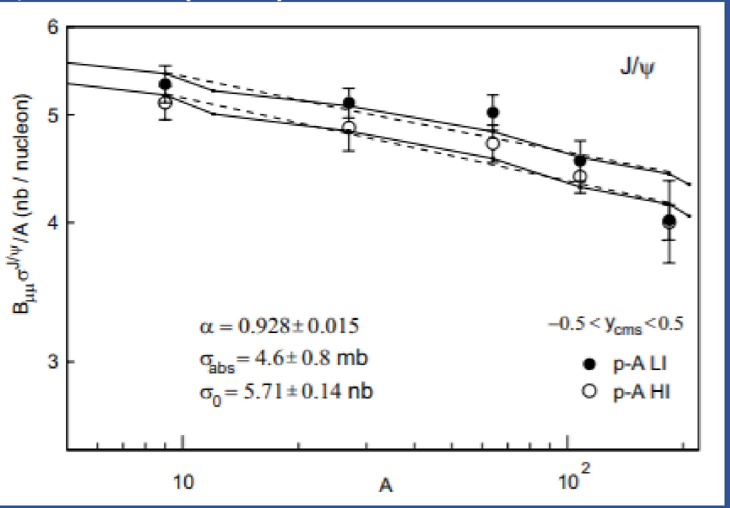
- Possibility of using
  - A **"direct" pp reference**
  - An **extrapolation of pA results**

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 ± 0.01 ± 0.36 nb → ~7% uncertainty



NA51, PLB438 (1998)35

NA50, EPJC 33 (2004) 31-40



NA50: J/ψ in pA collisions at 400 GeV
→ extrapolate A-dependence to A=1, having Be as lightest target
→ ~3% uncertainty on the extrapolated pp cross section

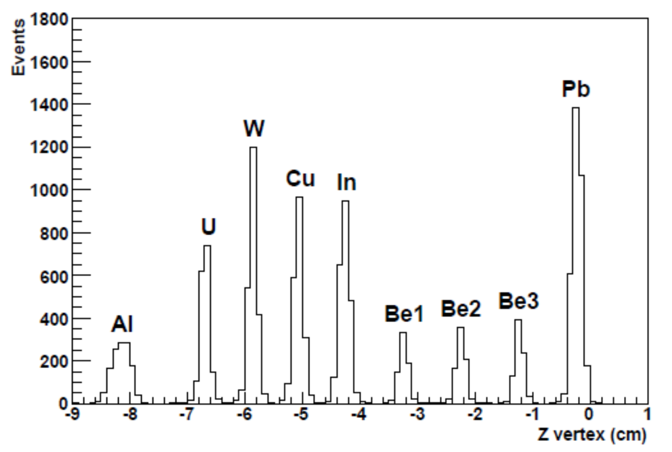
- Use of R_{AA} would have been in principle possible

p-A results at fixed target: a complex environment

- ❑ J/ψ production vs A, i.e. varying the amount of nuclear matter crossed by cc pair
- ❑ Advantage → do not deal with centrality selection in p-A

⇩

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

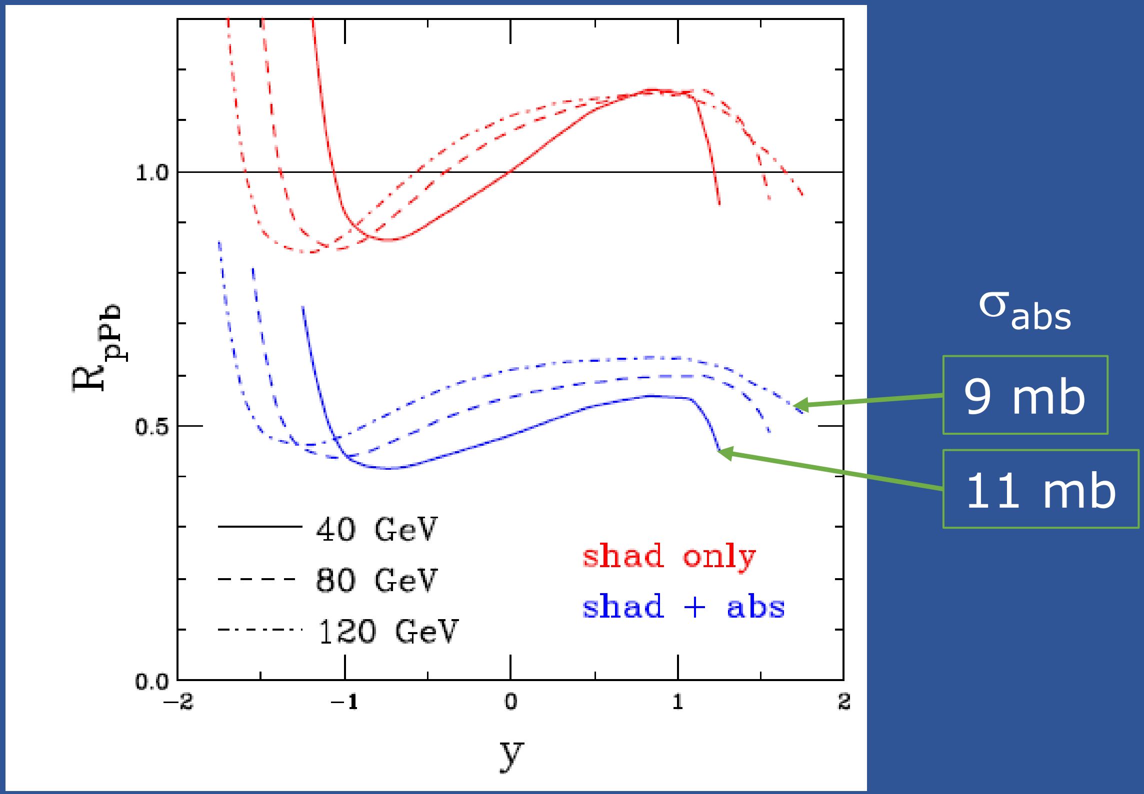
2 $\sigma^{pA}_{J/\psi} = \sigma^{pp}_{J/\psi} \cdot A^{\alpha}$ ← α = 1 → no nuclear effects; α ≠ 1 → nuclear effects

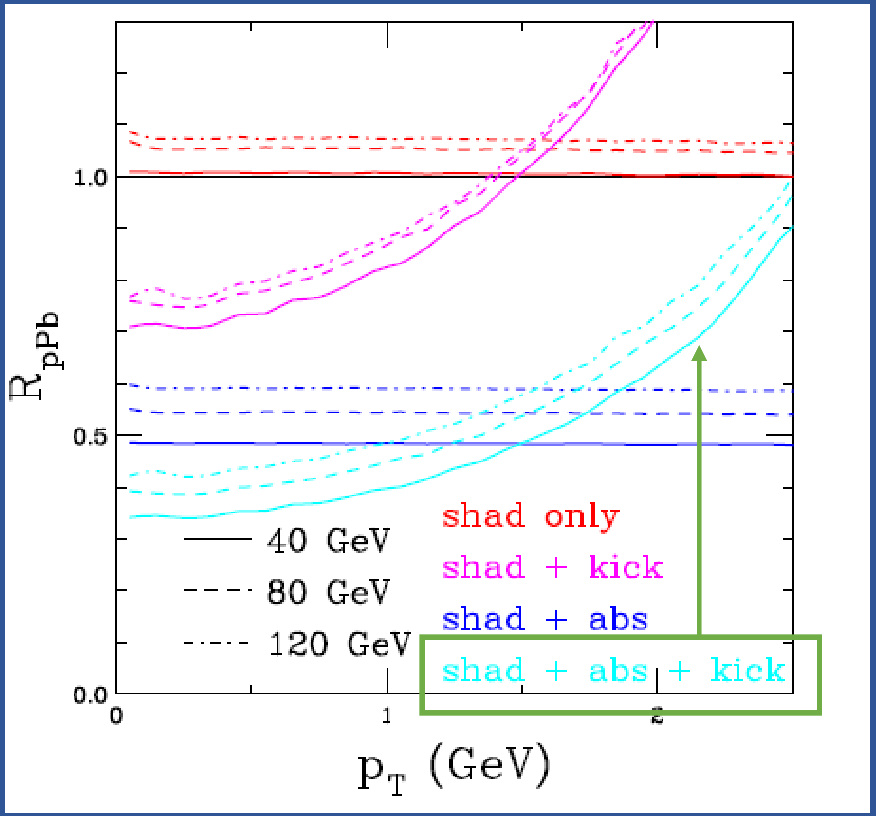
3 $R^{pA}_{J/\psi} = \frac{\sigma^{pA}_{J/\psi}}{A \cdot \sigma^{pp}_{J/\psi}}$ ← R_{pA} = 1 → no nuclear effects; R_{pA} ≠ 1 → nuclear effects

not used at fixed target

Extrapolation of CNM effects from pA to AA can be delicate → various effects superimposed

Moving to lower $\sqrt{s}$





Factor >2 suppression due to shadowing and break-up at low SPS energy

Expect **strong p_T dependence** due to collision broadening