Cold Nuclear Matter Effects in pA collisions

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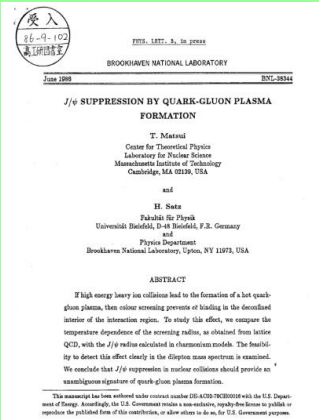
Review of pA experimental results from fixed target experiments, covering the energy range 158-920 GeV/nucleon

- Differential distributions
- Cold Nuclear Matter effects

First Rete Quarkonii Workshop, October 26th 2010, Nantes

pA and AA collisions at SPS

Quarkonia measurements at SPS is already a 25 years long story!



PHYS. LETT. B, in press

BROOKHAVEN NATIONAL LABORATORY

June 1986 BNL-38344

J/ψ SUPPRESSION BY QUARK-GLUON PLASMA FORMATION

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ABSTRACT

If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, we compare the temperature dependence of the screening radius, as obtained from lattice QCD, with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. We conclude that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation.

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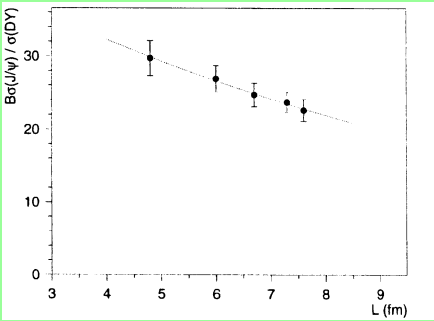
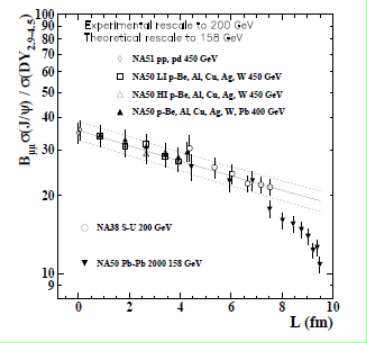
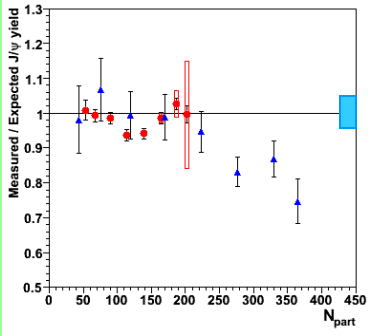
NA38



NA50



NA60



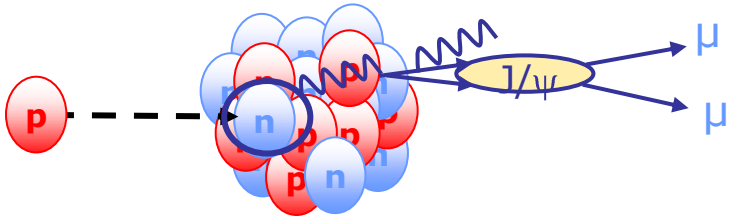
years	**1986**	**1987-1992**	**1995-2001**	**2003-2004**
system p-A	450 GeV/c	400, 450 GeV/c	158, 400 GeV/c
system A-A	S-U (200 GeV/c)	Pb-Pb (158 GeV/c)	In-In (158 GeV/c)

SPS results should be considered together with results obtained from higher energy experiments (as Hera-B, E866, RHIC)
→ improvement in the understanding of the charmonium behaviour, exploiting different energy and kinematics domains

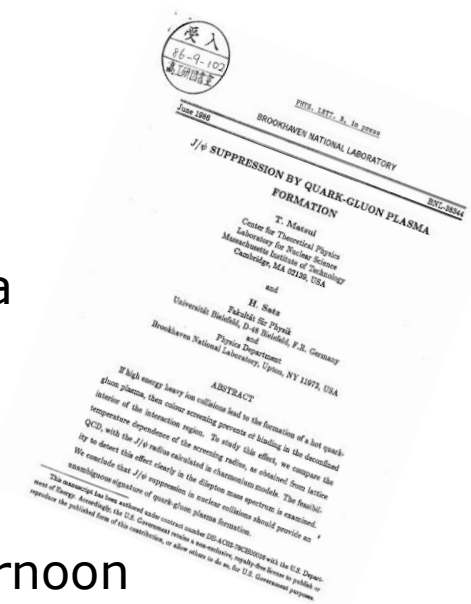
pA: Physics motivations

- the study of the interaction of the cc pair with the nuclear medium provides constraints to the production models
  → the strength of this interaction depends on the cc quantum states and kinematic
  (R. Vogt, Nucl.Phys. A700,539 (2002), B.Z. Kopeliovich et al, Phys. Rev.D44, 3466 (1991))

- allows us to study the various mechanisms affecting the J/ψ in the cold nuclear medium
  → complicate issue, because of many competing effects



- provide a reference for charmonia dissociation in a hot medium
  → approach followed at SPS and similarly at RHIC (with dAu data)


BROOKHAVEN NATIONAL LABORATORY

J/ψ SUPPRESSION BY QUARK-GLUON PLASMA FORMATION

T. Matsui

H. Satz

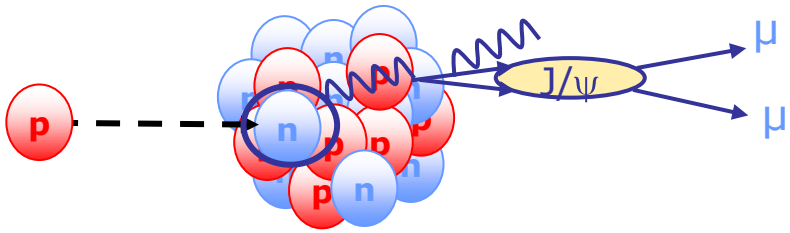
ABSTRACT

- J/ψ behaviour in AA → Enrico's talk this afternoon

Cold nuclear matter effects

- Many mechanisms affects the J/ψ behaviour in the nuclear medium

Initial state:
shadowing,
parton energy loss,
intrinsic charm



Final state:
cc dissociation
in the medium,
final energy loss

- complicate interplay between the different processes
  → to get some insight on the involved mechanisms, it's important to consider all the available p-A data sets, collected at different energies and in different kinematical regions

HERAB	**p-Cu (Ti) 920 GeV**,$-0.34<x_F<0.14$,$p_T<5$ GeV
E866	**p-Be,Fe,W 800 GeV**,$-0.10<x_F<0.93$,$p_T<4$ GeV
NA50	**p-Be,Al,Cu,Ag,W,Pb,400/450 GeV**,$-0.1<x_F<0.1$,$p_T<5$ GeV
NA3	**p-p p-Pt, 200 GeV**, $0<x_F<0.6$, $p_T<5$ GeV
NA60	**p-Be,Al,Cu,In,W,Pb,U 158/400 GeV**,$-0.1<x_F<0.35$,$p_T<3$ GeV

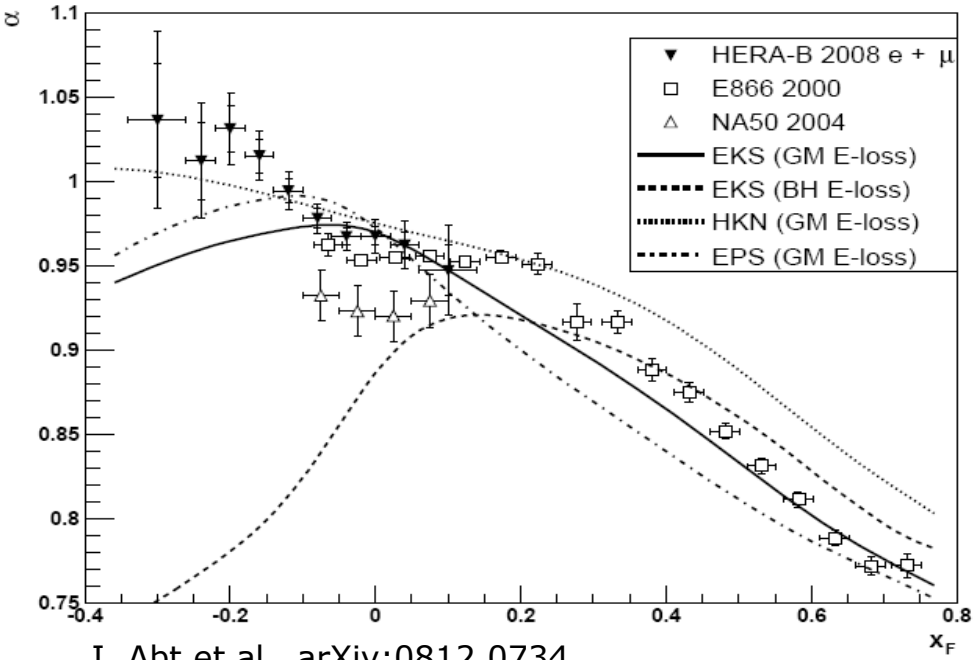
- CNM effects can be quantified in 2 ways:

$$\begin{cases} \sigma_{pA} \sim \sigma_{pp} A e^{-\rho L \sigma_{abs}} \\ \sigma_{pA} = \sigma_{pp} A^{\alpha} \end{cases}$$

→ σ_{abs} and α are "effective" quantities, including all initial/final state effects

Cold nuclear matter effects (2)

Compilation of α values vs x_F (before NA60 results):



I. Abt et al., arXiv:0812.0734

Strong x_F dependence of α

- E866 vs HERAB (similar $\sqrt{s}$)
  → agreement in the common x_F range
- E866/HERAB vs NA50
  → α decreases when decreasing $\sqrt{s}$

→ Satisfactory theoretical description still unavailable!

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

to understand the J/ψ dissociation in the hot matter (AA collisions)
→ cold nuclear matter effects have to be under control

because of the α dependence on x_F and energy
→ the reference for the AA suppression must be obtained under the same kinematic/energy domain as the AA data

NA60 pA data at 158 GeV!

NA60 pA data taking

NA60 has collected pA data at two energies:

158 GeV

- first pA data at the same energy as AA collisions.
- 3 day long data taking mainly motivated by the need of a reference taken in the same conditions as InIn (NA60) and PbPb (NA50) data
  ...but useful also to enlarge the α vs x_F systematics

CERN-SPSC-2004-012
SPSC-M-715
April 22, 2004

Request for 7 days of primary protons at 158 GeV

The NA60 Collaboration

Therefore, we conclude that we need proton data at 158 GeV, in order to establish a robust reference baseline with respect to which the Indium and Lead J/ψ suppression patterns can be directly compared, to place on more solid grounds the existence of "anomalous" effects in the heavy-ion data. The presently existing systematic errors due to the energy (and phase space) corrections and to the absence of solid evidence that the absorption cross-section remains the same from 450 to 158 GeV, are the main sources of uncertainty in the interpretation of the data collected in nuclear collisions.

400 GeV

- bulk of the NA60 pA data taking.
- sub-sample with same set-up used at 158 GeV: useful as a cross-check (same kinematic and energy domain of the large statistics NA50 data sample)

Kinematical window where acceptance is >0 for all targets

$3.2 < y_{lab} < 3.7$

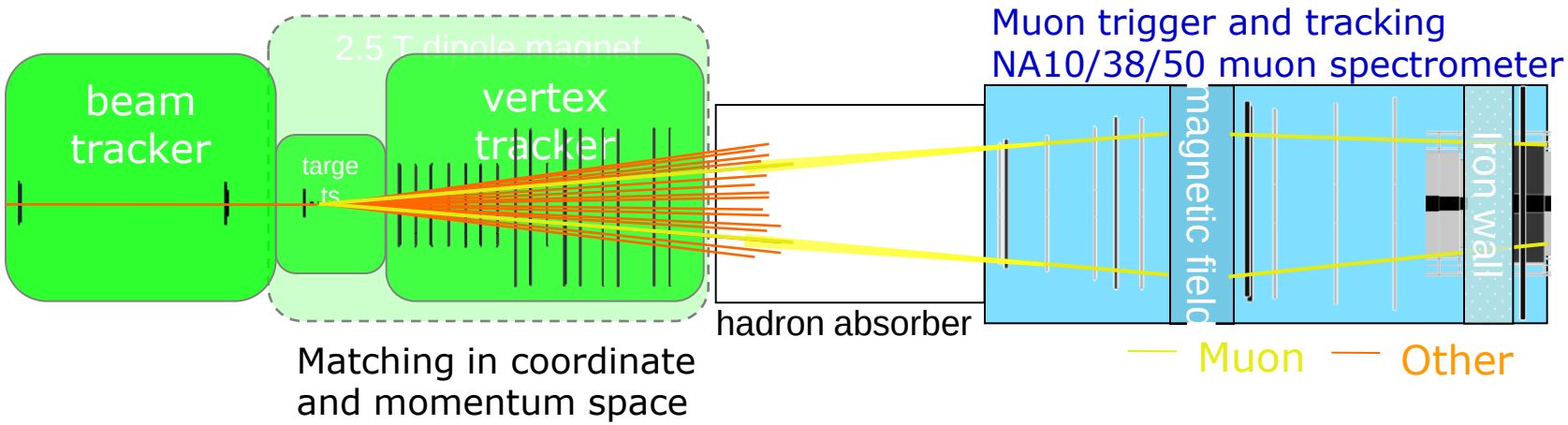
$0.28 < y_{cm} < 0.78$ (158 GeV)

$-0.17 < y_{cm} < 0.33$ (400 GeV)

$|\cos\theta_{CS}| < 0.5$

NA60 pA data

- NA60 has collected pA data using 9 nuclear targets Al, U, W, Cu, In, Be1, Be2, Be3, Pb (mixed A-order to limit possible z-dependent systematics)



- Two analysis approaches:

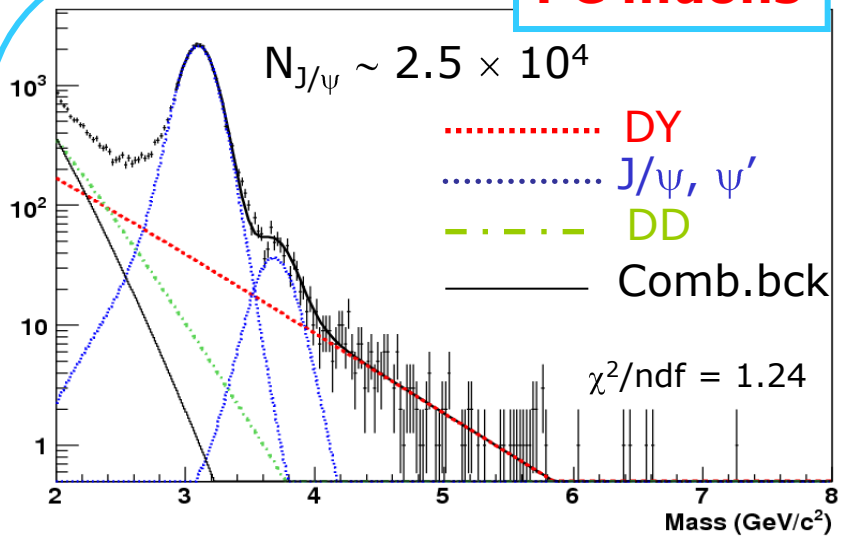
1) Do not use vertex spectrometer information (PC muons only)
   - Advantages: larger statistics, higher acceptance and detection eff.
   - Drawbacks: no target ID possible

2) Use vertex spectrometer: track matching (VT muons)
   - Advantages: accurate target ID, improved mass resolution and bck rejection
   - Drawbacks: smaller statistics (vertex spectrometer efficiency)

pA invariant mass spectra

Fit the invariant mass spectrum as a superposition of the various expected sources: Drell-Yan, J/ψ, ψ′, open charm

PC muons



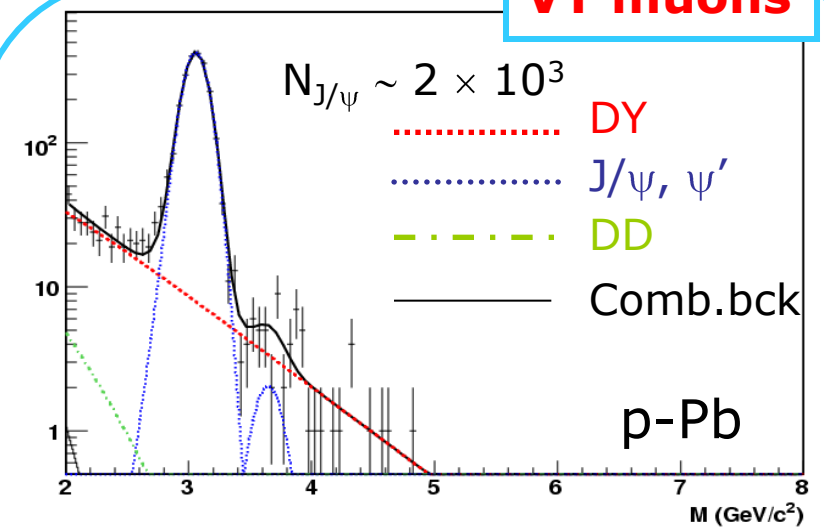
still significant statistics for high mass Drell-Yan events

→ possible to extract $B_{\mu\mu}\,\sigma_{J/\psi}/\sigma_{DY}$ averaged over all the targets

$$B_{\mu\mu}\,\sigma_{J/\psi}/\sigma_{DY} = 30.1 \pm 2.3 \pm 0.4$$

with $2.9 < m_{DY} < 4.5$ GeV/c²

VT muons



target ID available

→ fit done target by target, but...

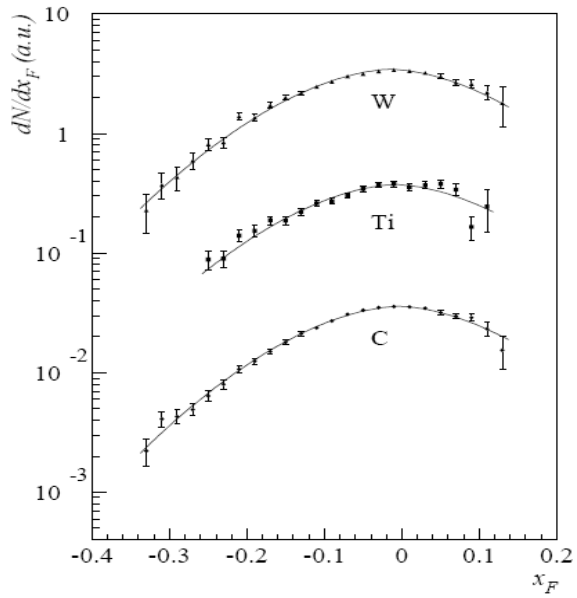
statistics now much lower

- 9 targets
- tracking/matching eff.~40-50%

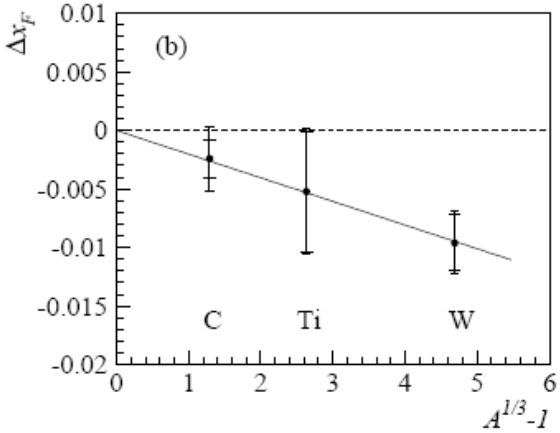
→ not enough to extract $B_{\mu\mu}\,\sigma_{J/\psi}/\sigma_{DY}$

→ evaluation of $N_{J/\psi}$ is anyway robust (huge peak over continuum)

Differential distributions: $d\sigma/dy$, $d\sigma/dx_F$

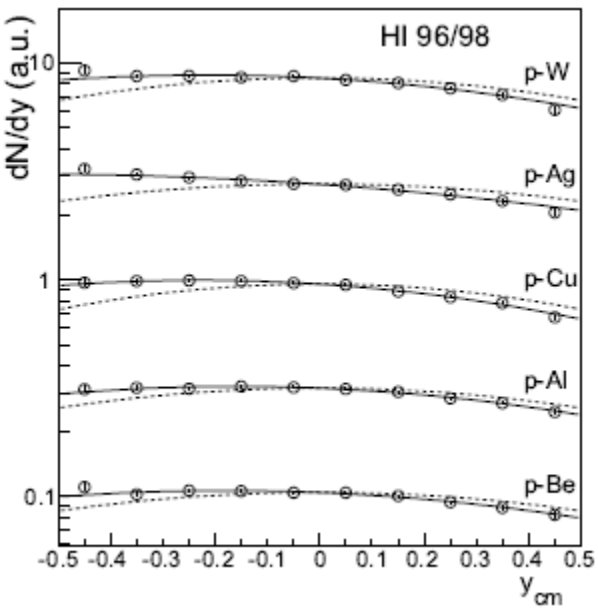


HERA-B (920 GeV)



small A-dependent backward shift of the x_F distributions (Δx_F <0.01)

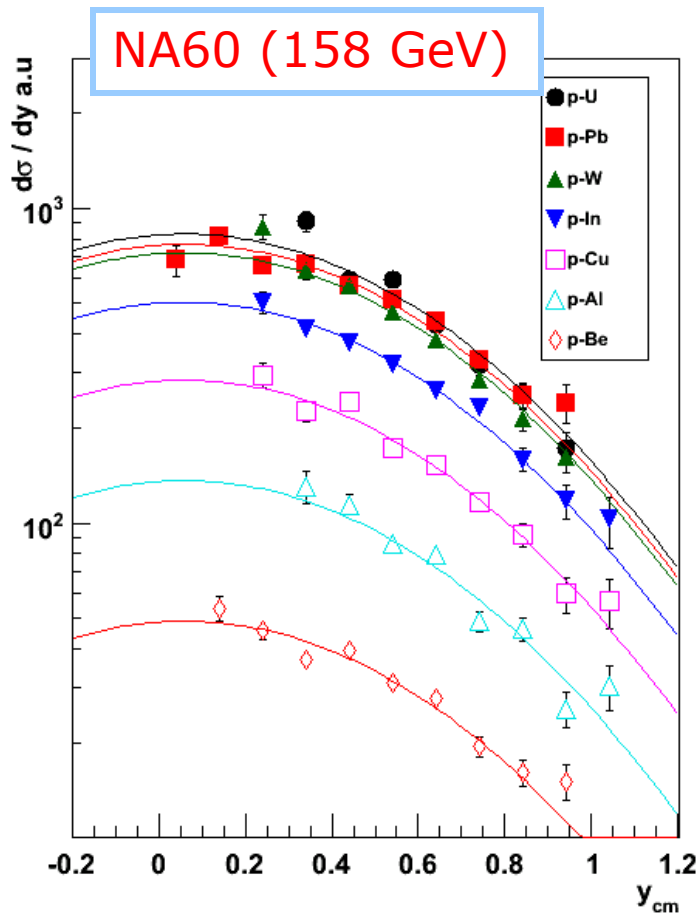
backward shift due to the energy loss of the incident parton/ccbar pair in their path through the nucleus, causing a reduction of the J/ψ x_F? (HERAB Coll., Eur. Phys. J C60(2009),525)

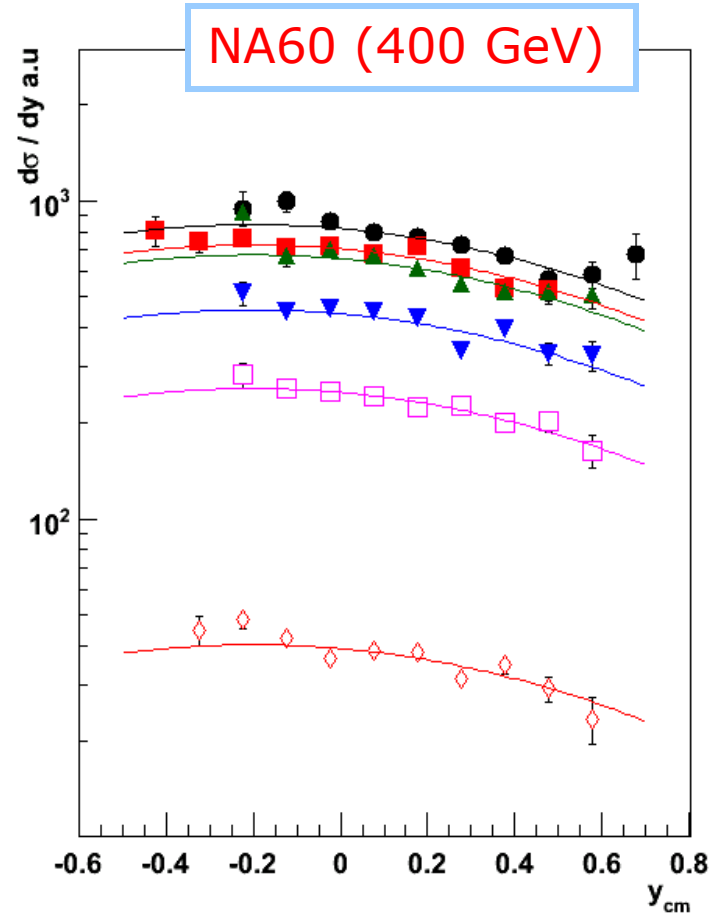


NA50 (400 GeV)

strong, A-independent, backward shift (Δy=0.2, corresponding to Δx_F= 0.045, larger than the one observed by HERA-B)

NA60 differential distributions: dσ/dy





- gaussian fit gives
  μ_y=0.05 0.05,
  σ_y=0.51 0.02
  NA60 Coll., Nucl.Phys.A830(2009)345

- peak position not well constrained
  Imposing μ_y=-0.2 (NA50, 400 GeV)
  → σ_y=0.81 0.03 (NA50 got 0.85)

- Seem to confirm NA50 result, but data probably not precise enough to quantitatively investigate rapidity shift

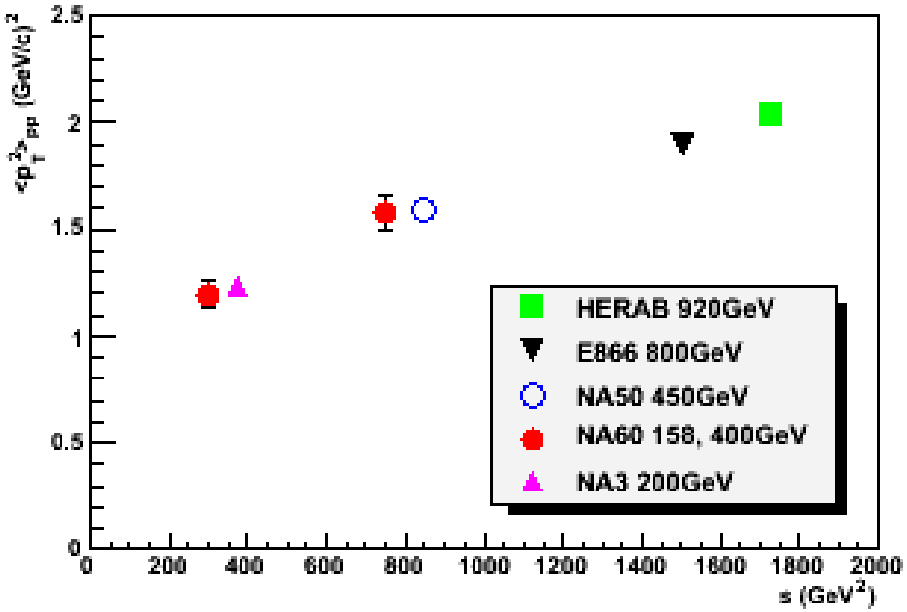
p_T evolution vs $\sqrt{s}$

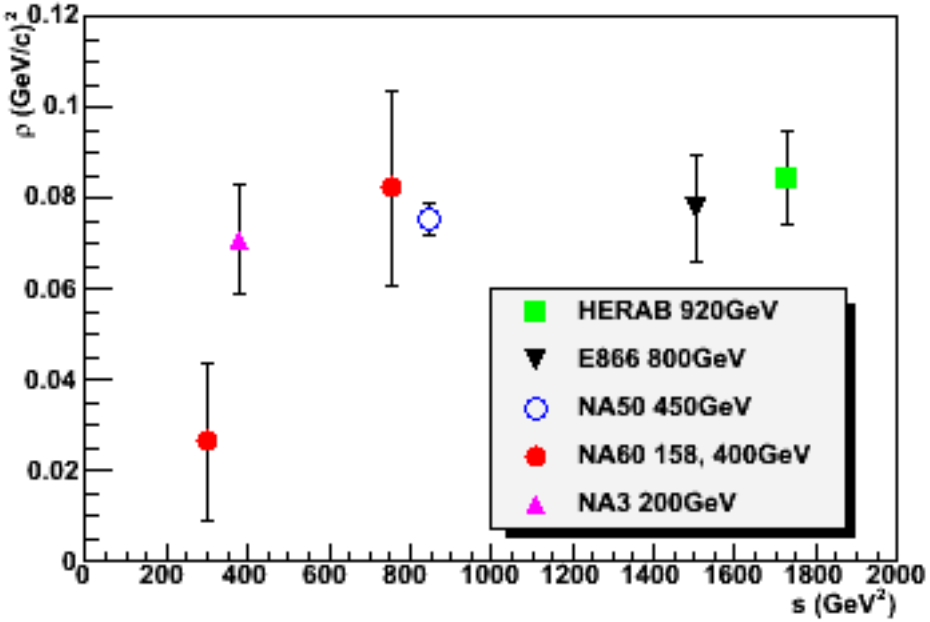
- J/ψ p_T broadening, interpreted as initial state gluon multiple scattering (Cronin effect)

- Fit $\langle p_T^2 \rangle$ for various nuclei as

$$\langle p_T^2 \rangle = \langle p_T^2 \rangle_{pp} + \rho\,(A^{1/3}-1)$$

α L, the lenght of nuclear matter crossed by the J/ψ





- $\langle p_T^2 \rangle_{pp}$ shows a linear increase vs s

- nearly flat behaviour with a decrease at low s

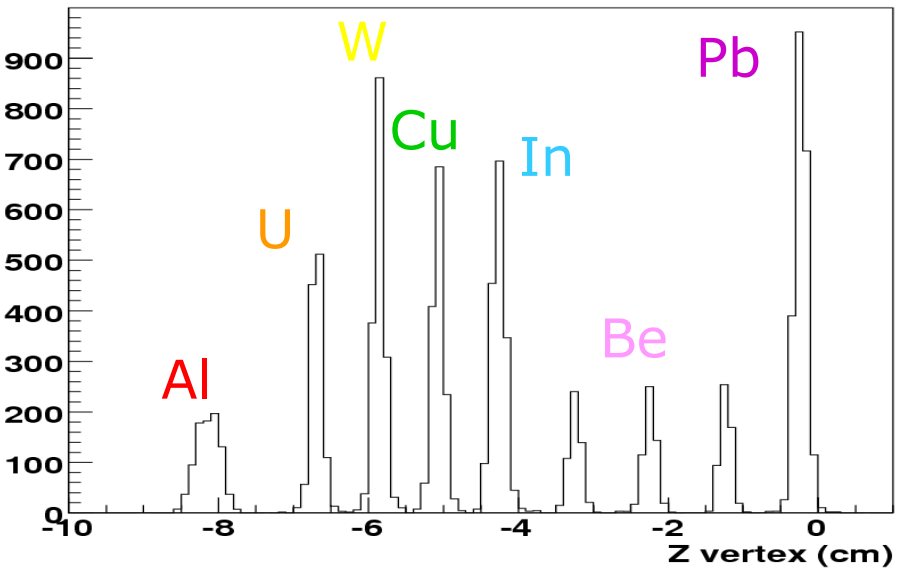
(NA60 Coll., Nucl.Phys.A830(2009)345)

Cross section ratios

Not enough DY statistics to extract (as in NA50) $B_{\mu\mu}\,\sigma_{J/\psi}/\sigma_{DY}$ target by target

Estimate of nuclear effects through relative cross sections:

$$\frac{\sigma_A^{J/\psi}}{\sigma_{Be}^{J/\psi}} = \frac{\dfrac{N_A^{J/\psi}}{N_A^{inc} \times N_A^{targ} \times A_A \times \varepsilon_A}}{\dfrac{N_{Be}^{J/\psi}}{N_{Be}^{inc} \times N_{Be}^{targ} \times A_{Be} \times \varepsilon_{Be}}}$$



all targets simultaneously on the beam

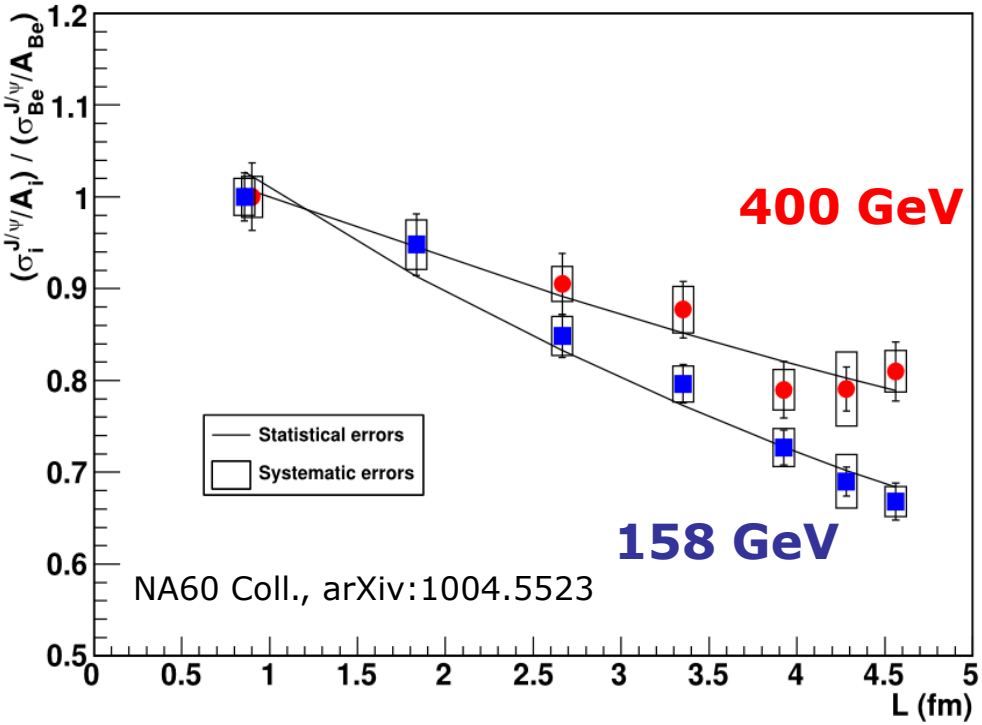
→ beam luminosity factors N_i^{inc} cancel out (apart from a small beam attenuation factor) → no systematic errors

→ acceptance and recostruction efficiencies do not completely cancel out (these quantities and their time evolution are computed for each target)

→ each target sees the vertex spectrometer under a (slightly) different angle: kinematic window is restricted, to reduce systematic

Relative correction vs. A

From the A dependence of the relative J/ψ cross sections, we observe:



→ an increasing suppression of the J/ψ yield as a function of A

→ a larger suppression at 158GeV

using a Glauber fit to extract σ_{abs}

158 GeV:

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

400 GeV:

$\sigma_{abs}^{J/\psi}$ = 4.3 0.8 0.6 mb

very good agreement with NA50 (4.6 0.6mb)

shadowing neglected for the moment…

systematic errors due to :

- target thicknesses (<1.5%)
- J/ψ y distribution (<1.5%)
- reconstruction eff. calculation (<3%)

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

158 GeV:

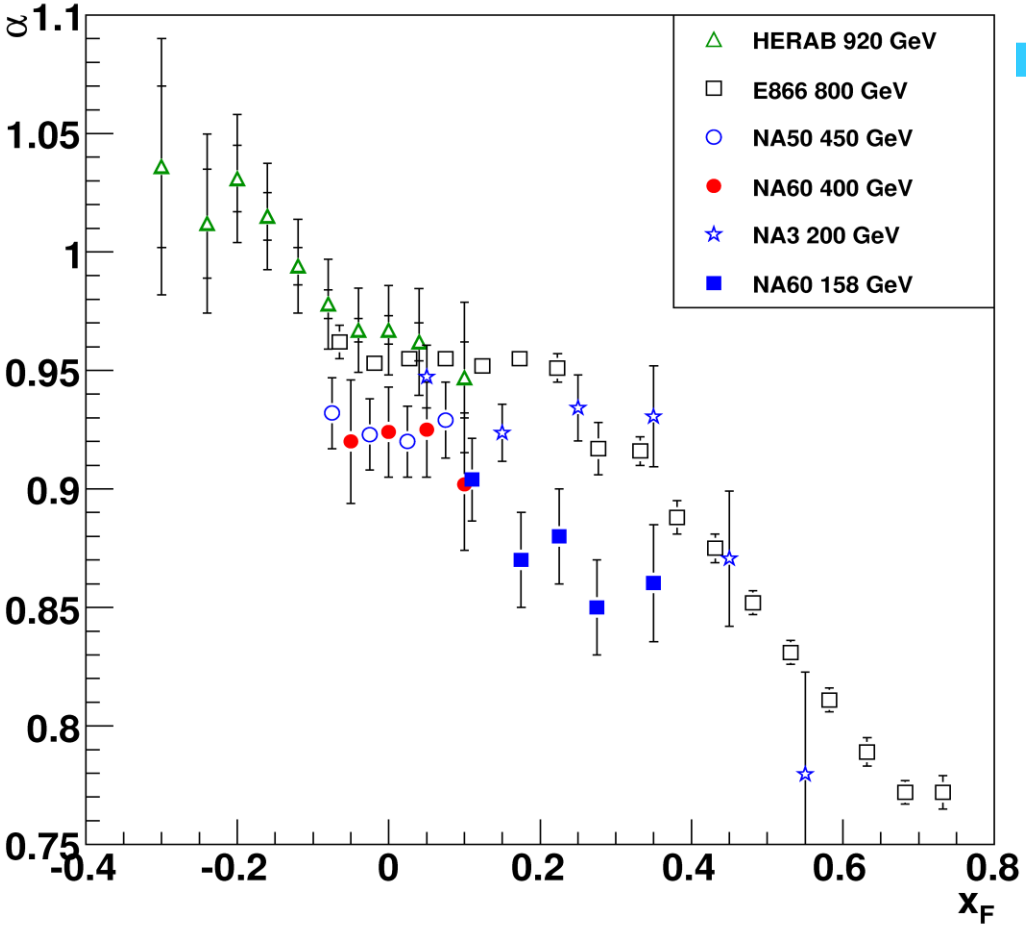
α = 0.882 0.009 0.008

400 GeV:

α = 0.927 0.013 0.009

α vs. x_F

NA60 pA results can be compared with α values from other experiments (HERAB, E866, NA50 and NA3)



In the region close to x_F=0, increase of α with $\sqrt{s}$

NA60 400 GeV

→ very good agreement with NA50

NA60 158 GeV:

→ smaller α, hints of a decrease towards high x_F ?

→ discrepancy with NA3

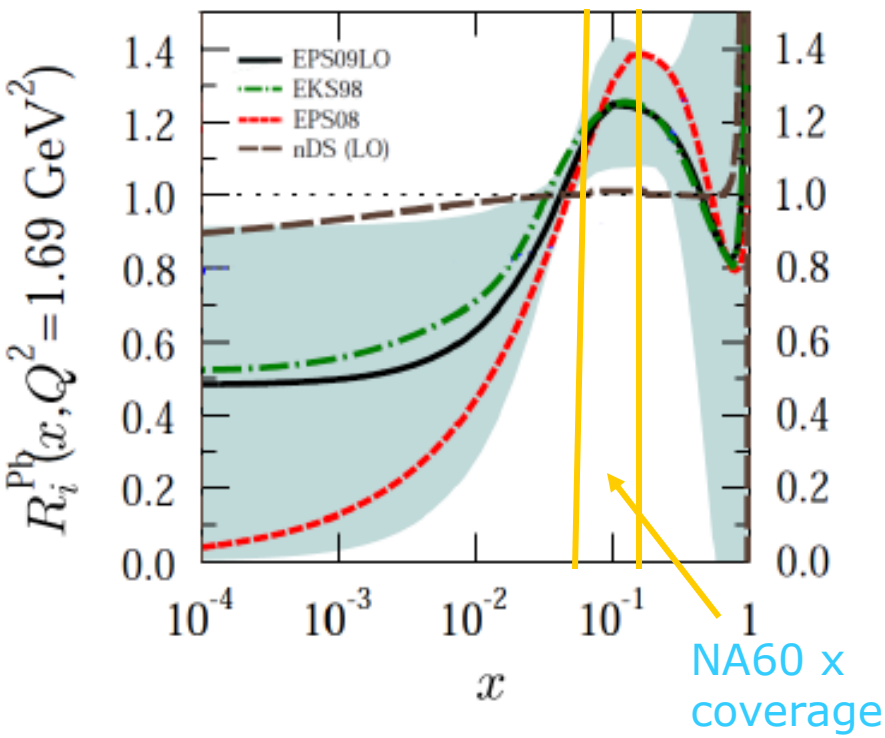
Systematic error on α for NA60 points ~0.01

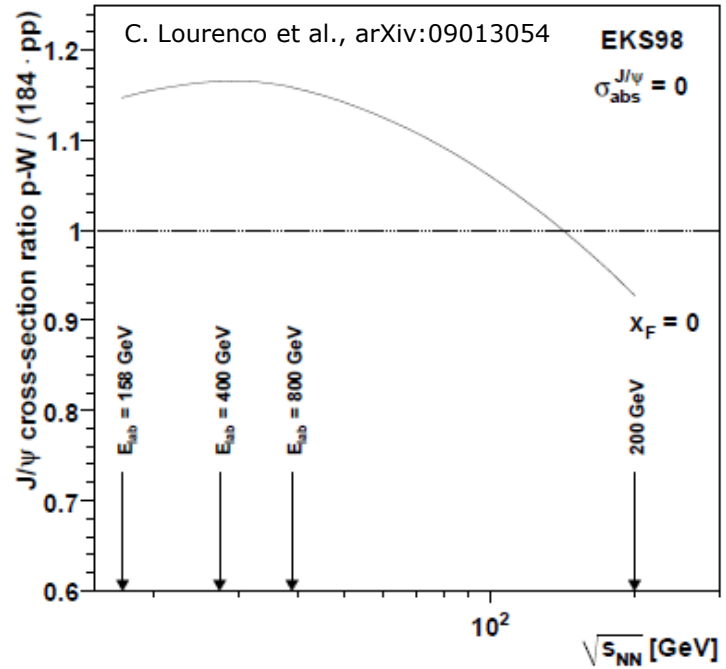
Shadowing

- Interpretation of results not easy
  → many competing effects affect J/ψ production/propagation in nuclei
  - anti-shadowing (with large uncertainties on gluon densities!)
  - final state absorption…

  → need to disentangle the different contributions

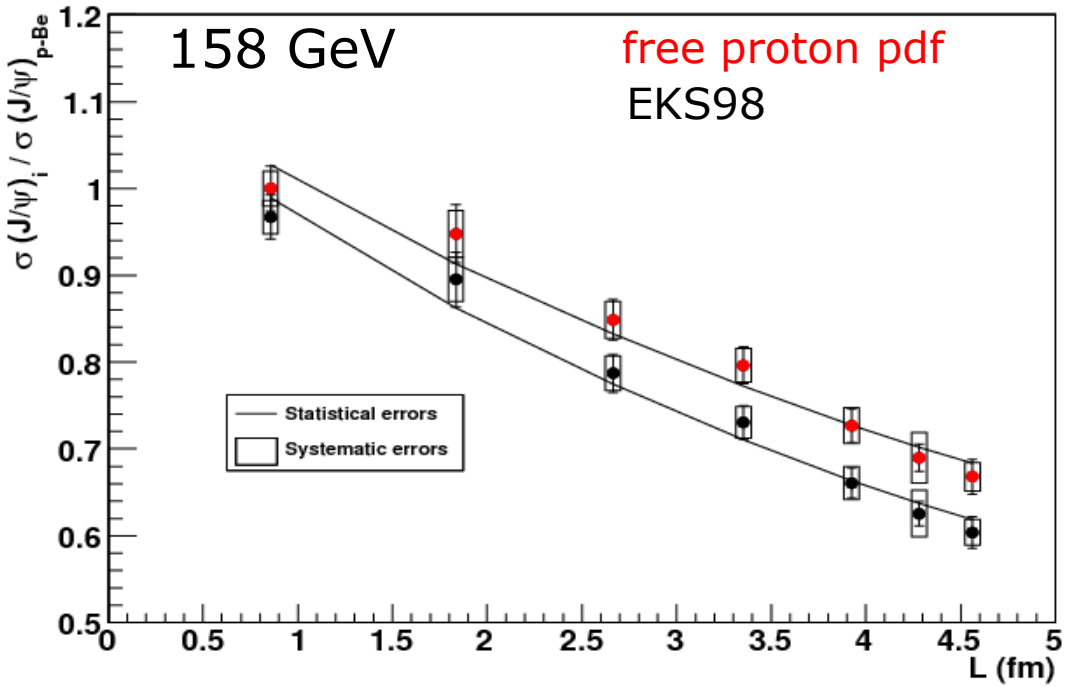
- Size of shadowing-related effects may be large and should be taken into account when comparing results at different energies





Anti-shadowing contribution

We have evaluated (and corrected for) the (anti)shadowing effect expected for our data points, within the EKS98 and EPS08 scheme



$\sigma_{abs}^{J/\psi}$ (158 GeV):

without antishadowing= 7.6 0.7 0.6 mb

with antishad.(EKS98)= 9.3 0.7 0.7 mb

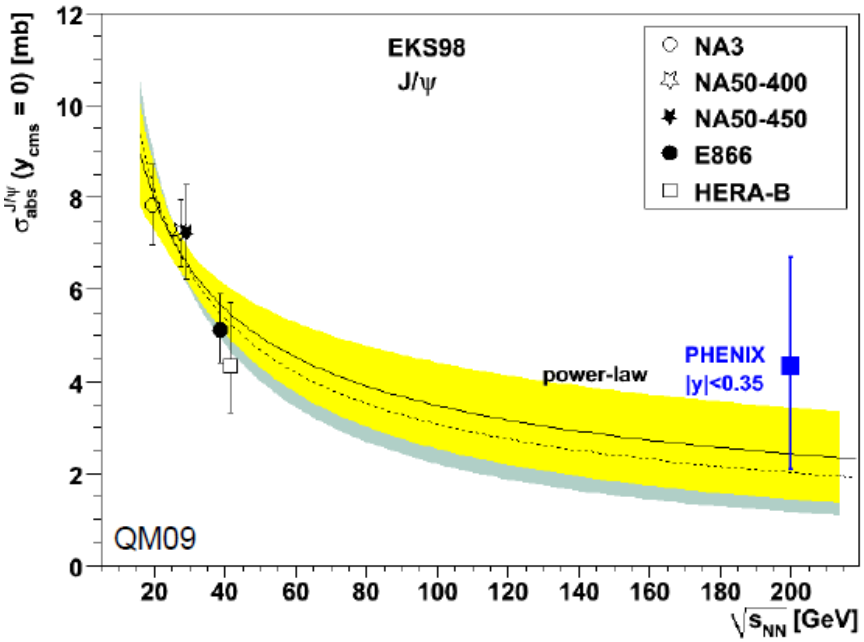
with antishad.(EPS08)= 9.8 0.8 0.7 mb

Significantly higher than the "effective" value

Kinematic dependence of nuclear effects

- Apart from shadowing, other effects not very well known, as parton energy loss, intrinsic charm may complicate the picture even more

- First attempts of a systematic study recently appeared
  (C. Lourenco, R. Vogt and H.Woehri, JHEP 0902:014,2009, INT Seattle workshop 2009, F. Arleo and Vi-Nham Tram Eur.Phys.J.C55:449-461,2008, arXiv:0907.0043)



- No coherent picture from the data
  → no obvious scaling of α or σ_{abs} with any kinematical variable

- Clear tendency towards stronger absorption at low $\sqrt{s}$

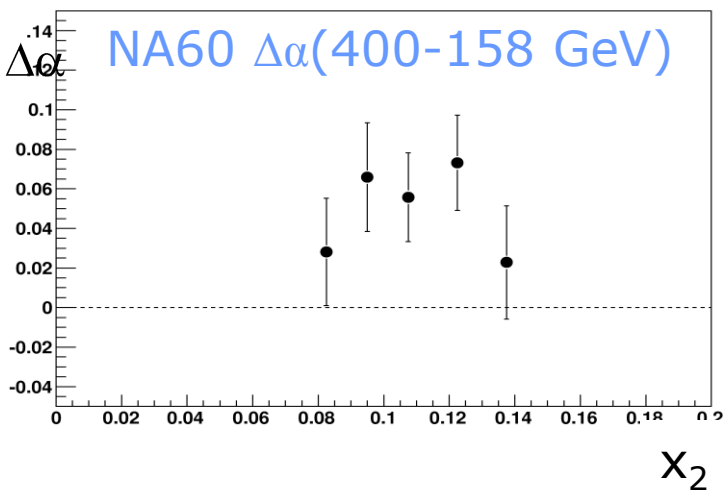
α vs. x_2

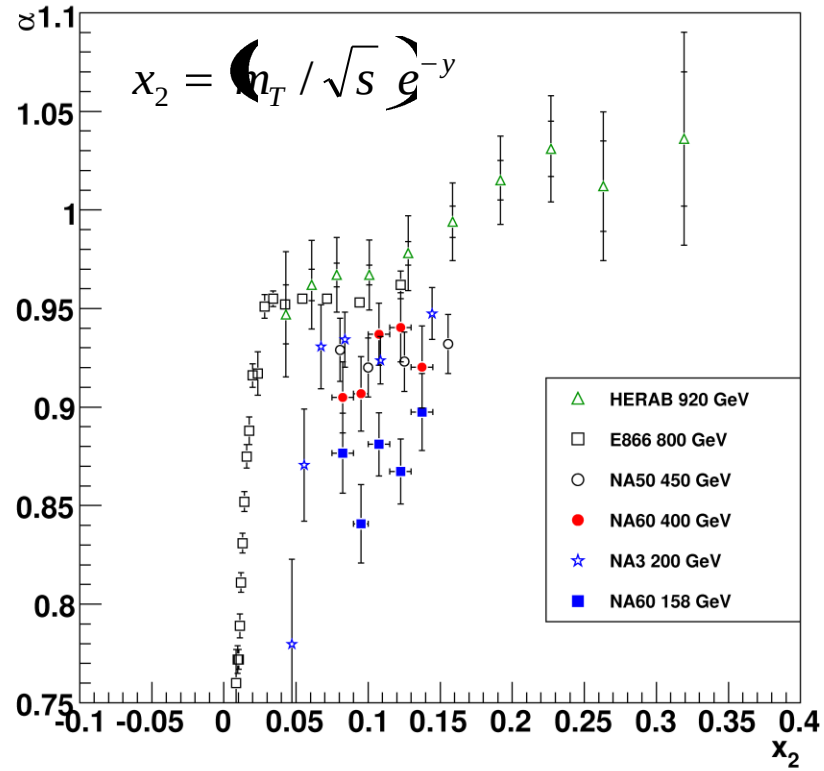
- Shadowing effects (in the 2→1 approach) and final state absorption

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

- if parton shadowing and final state absorption were the only relevant mechanisms
  - → α should not depend on √s at constant x_2

- Let's consider the NA60 data (two energies in the same experimental conditions)
  - → reduced systematics on Δα





- Δα ≠ 0 in the explored x_2 region
  - → clearly other effects are present

J/ψ polarization

- important tool to investigate production models and their ingredients
- extremely debated topic because of inconsistencies between theoretical models and experimental data

- Study the full angular distribution

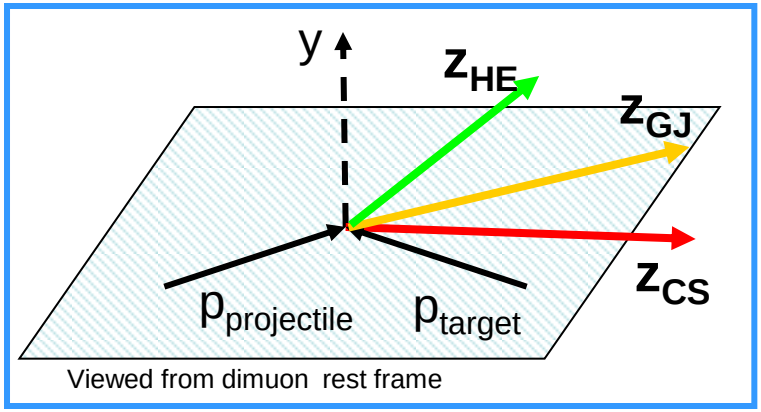
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta\, d\phi} = \left(1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi\right)$$

In literature, for J/ψ hadroproduction the μ, ν terms were usually neglected

- the knowledge of the full angular distribution (and therefore of λ, μ, ν) allows to analytically calculate λ′, μ′, ν′ in another reference frame (→this is not the case if only λ is measured)

Reference frame

- Recents studies have pointed out the importance of the choice of the polarization frame (E. Braaten et al arXiv:0812.3727, P. Faccioli et al. arXiv:0902.4462).
  - The degree of polarization may depend on the chosen frame
  - Polarization results can be compared only if the same frame is adopted



- Commonly used reference frames:

Collins-Soper

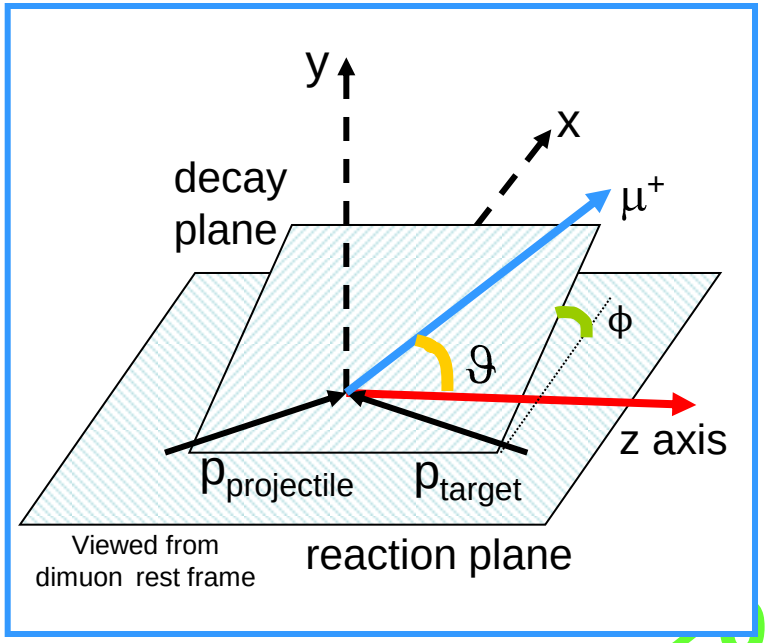
z axis parallel to the bisector of the angle between beam and target directions in the J/ψ rest frame

Helicity

z axis coincides with the J/ψ direction in the target-projectile center of mass frame

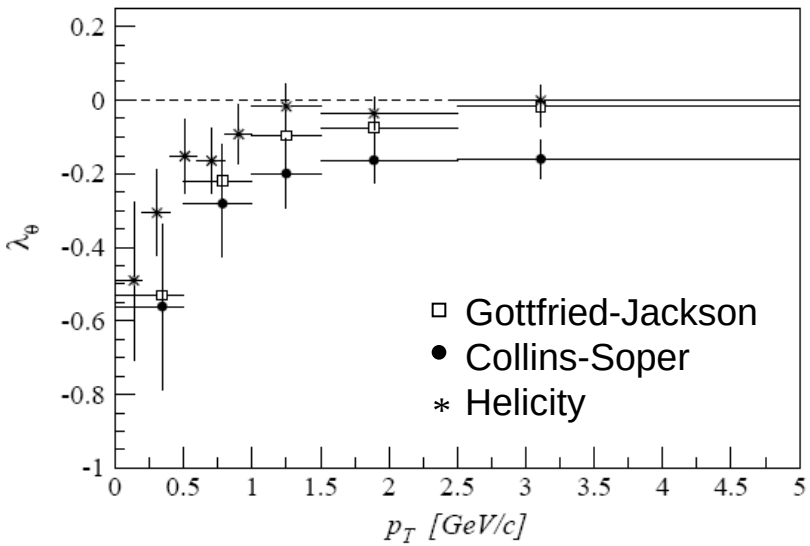
Gottfried-Jackson

z axis parallel to the beam momentum in the J/ψ rest frame



J/ψ polarization in pA

HERA-B

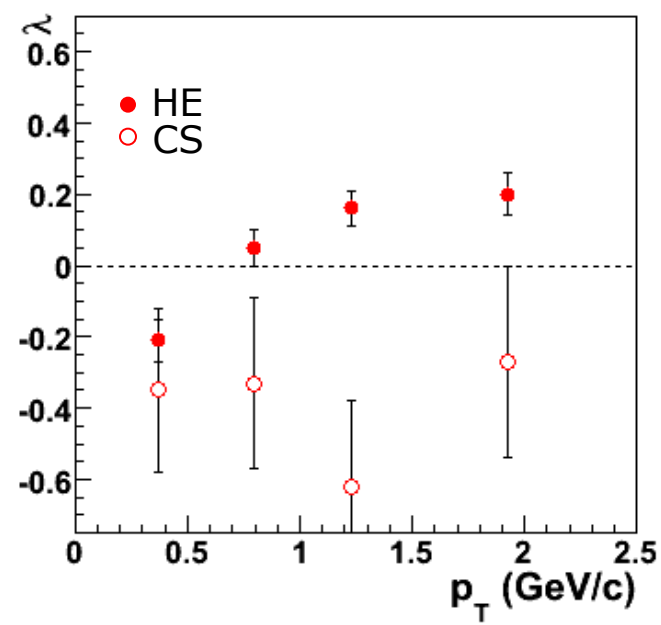


- Full J/ψ angular distribution has been measured (I. Abt et al. arXiv:0901.1015)
  - Clear hierarchy for the values of the decay angular parameters measured in the different frames

$$|\lambda_{HE}| < |\lambda_{GJ}| < |\lambda_{CS}|$$

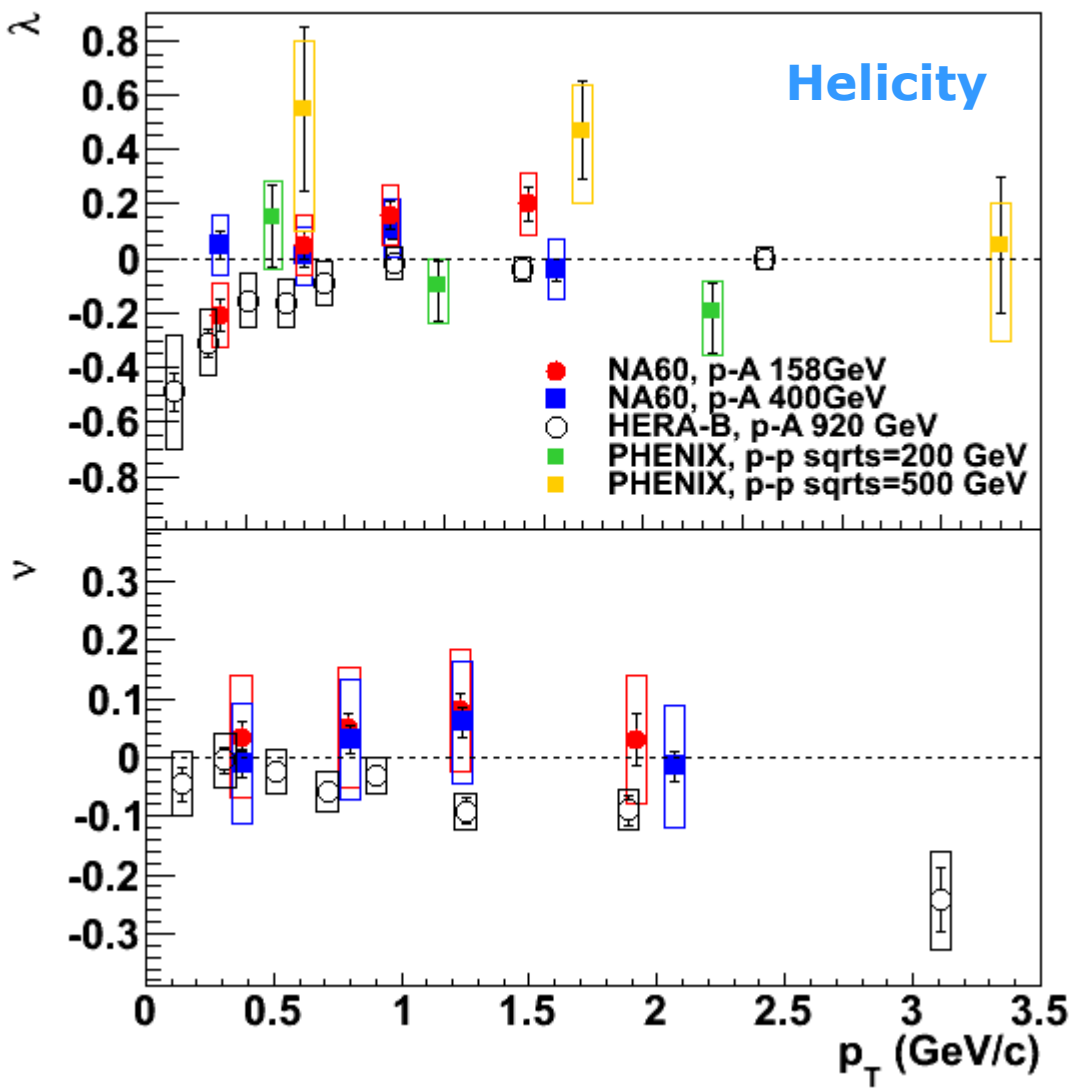
  - Polarization depends on the J/ψ p_T

NA60 p-A 158 GeV



- λ_{CS} tends to be negative and larger in absolute value with respect to λ_{HE}
- large errors for λ in the CS frame (acceptance large only at small $|\cos\theta_{CS}|$)

J/ψ polarization in pA: helicity



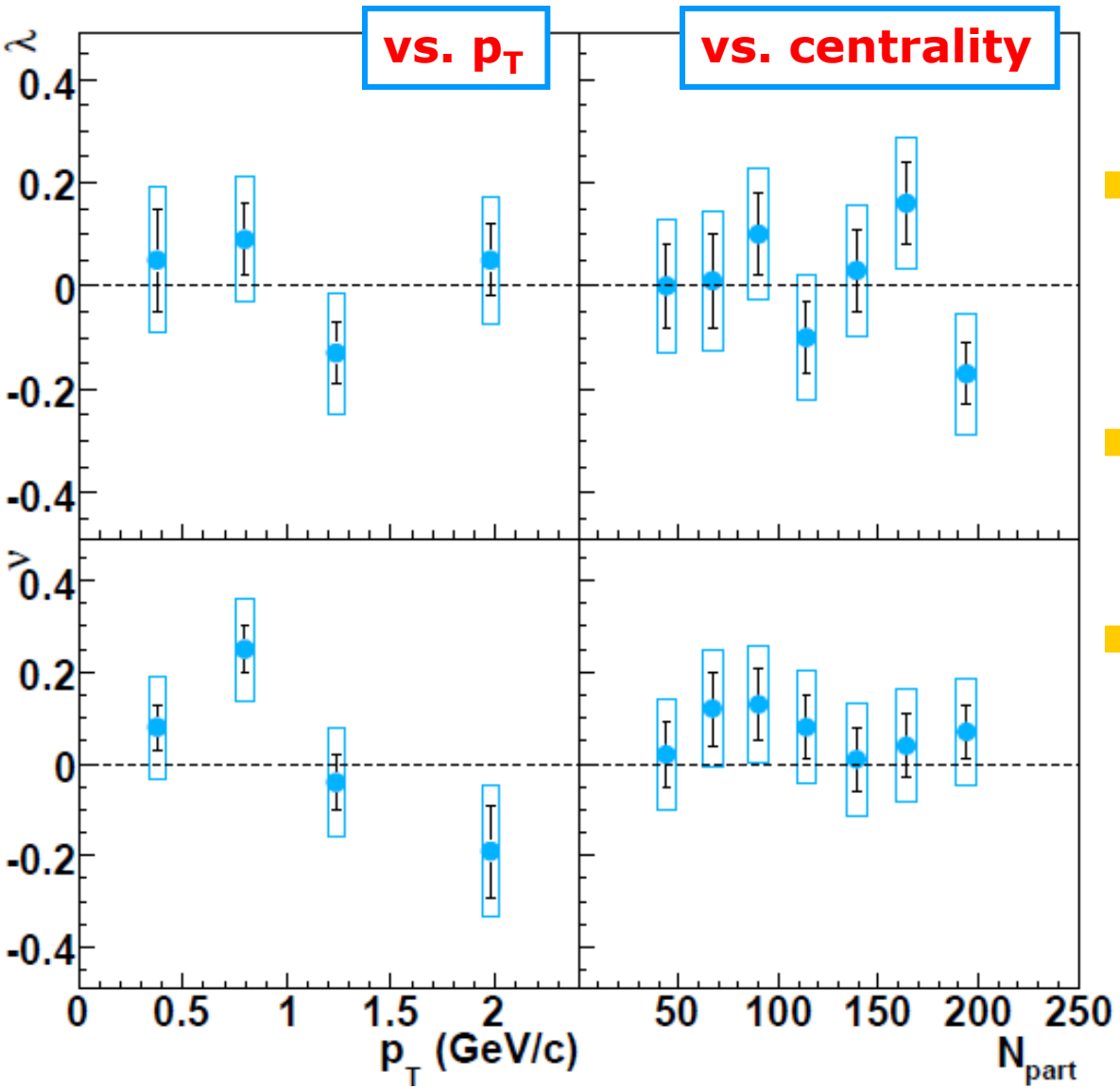
...mixing pp and pA results...

- μ compatible with zero everywhere
- no large differences between NA60, HERAB and PHENIX
- new preliminary PHENIX data at 500GeV compatible with this trend?

significant amount of studies at collider energy...but no much guidance at fixed target

J/ψ polarization in In-In

First full measurement of the J/ψ angular distribution in nuclear collisions



Polarization is rather small everywhere: no p_T or centrality dependence

Positive azimuthal coefficient at low p_T?

Polarization in AA may be influenced by the hot medium
→quantitative predictions needed!
(D.Kharzeev Phys. Rev. C68 061902 (2003))

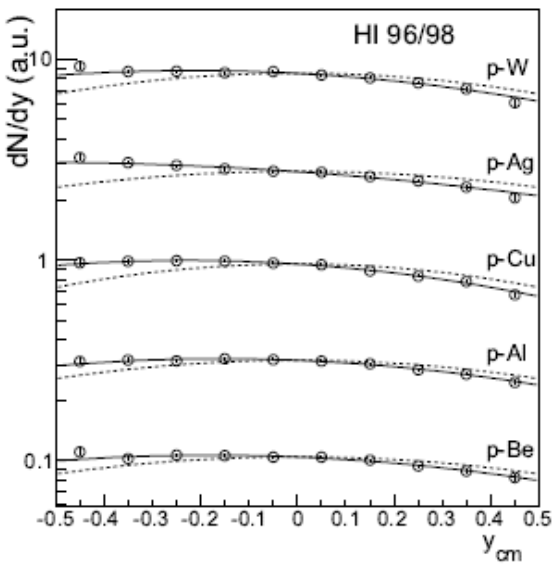
Conclusions

- NA60 data complement the set of fixed target pA and AA available results, covering the energy range 158 < Energy < 920 GeV
  - Many steps forward thanks to new high precision data
  - Complicate interplay of the various initial and final cold nuclear matter effects affecting the J/ψ
  - No clear scaling of α with x_F or x_2 → other mechanisms should be present, apart from shadowing and final state absorption
  - Nuclear effects are more important at lower energies
- The understanding of the CNM effects is important to provide a reference for the J/ψ behaviour in AA collisions
  - pA data collected at the same energy as AA data (158 GeV)

Backup

Differential distributions: dσ/dy

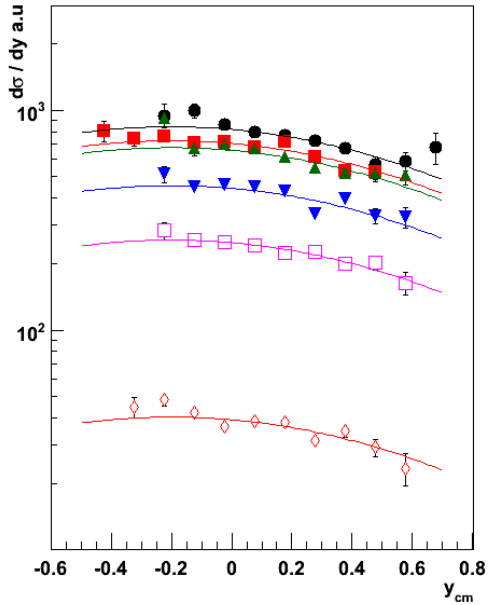
NA50 (400 GeV)



strong, A-independent, backward shift (Δy=0.2, corresponding to Δx_F= 0.045).

Larger wrt the A-dependent one observed by HERA-B (Δx_F <0.01)

NA60 (400 GeV)



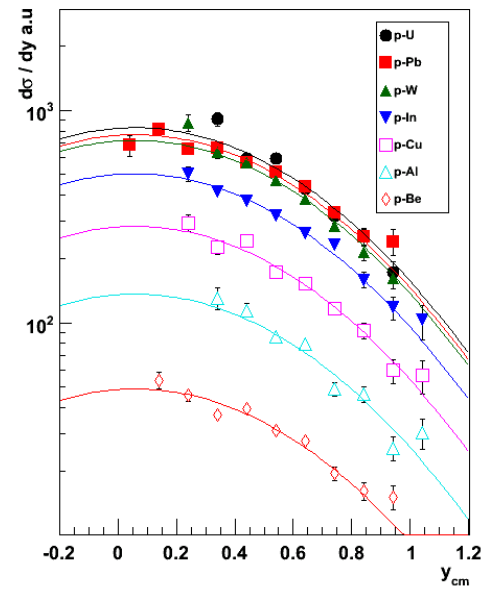
peak position not well constrained

Imposing μ_y=-0.2 (NA50, 400GeV)

→ σ_y=0.81 0.03

(NA50 got 0.85)

NA60 (158 GeV)



from a gaussian fit

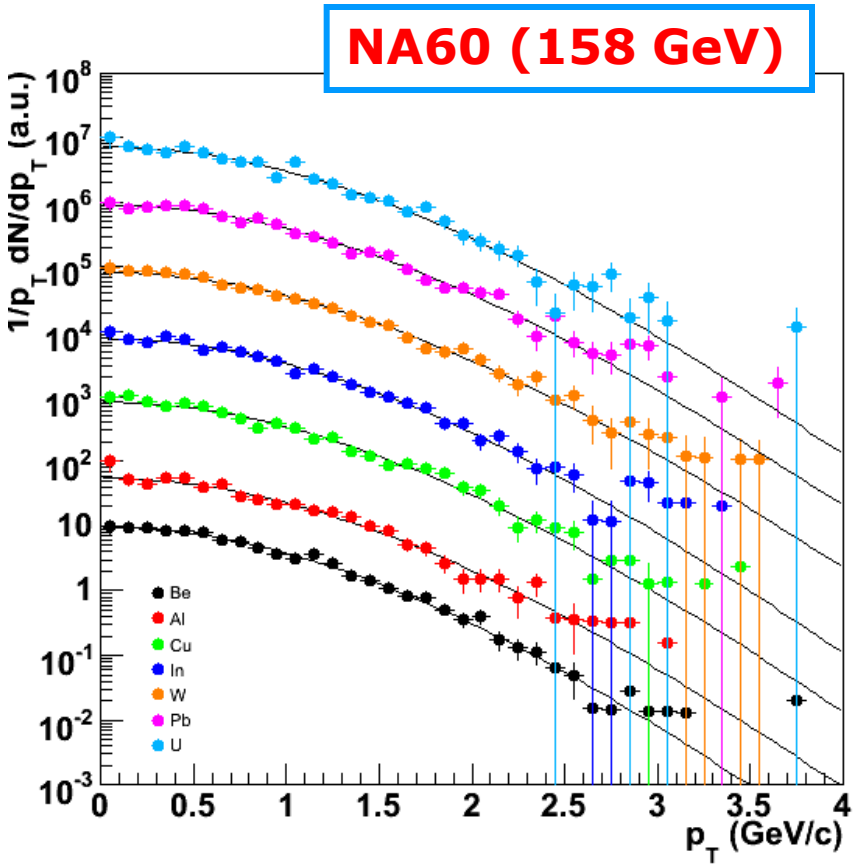
μ_y=0.05 0.05,

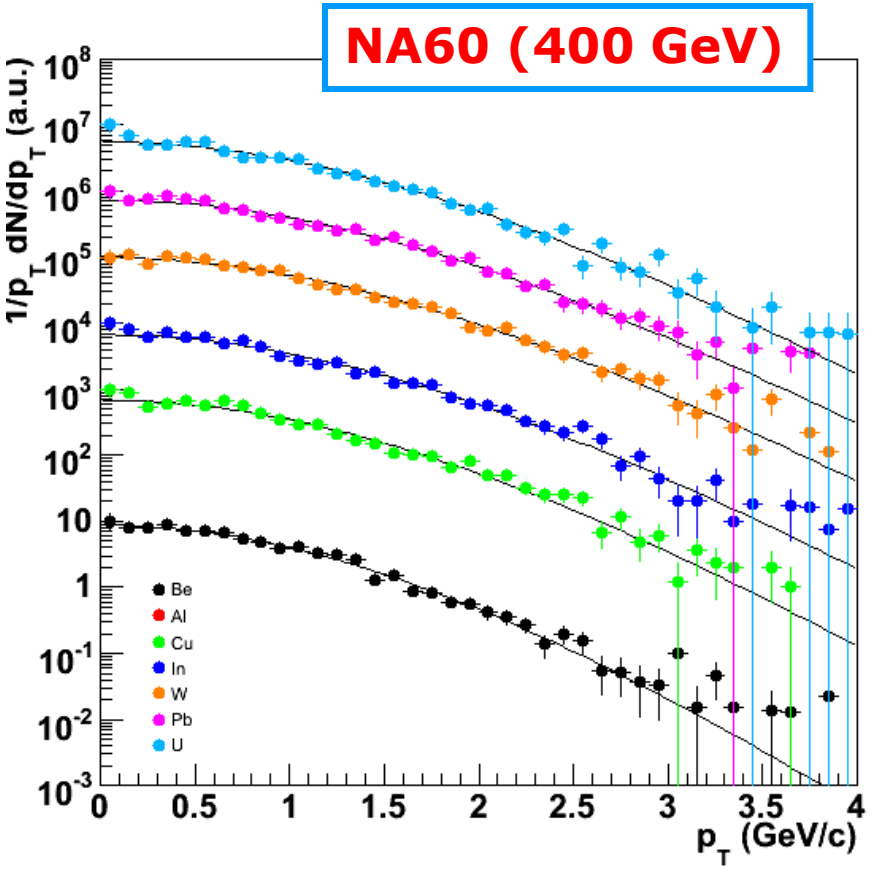
σ_y=0.51 0.02

→ y distribution is narrower wrt 400 GeV, as expected

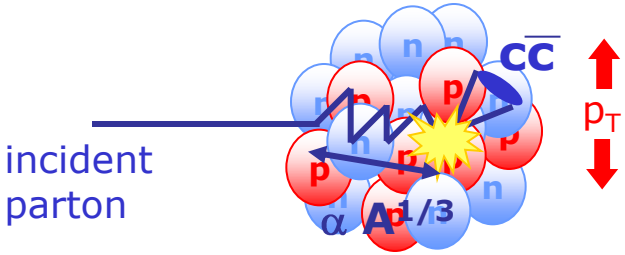
➡ NA60 results seem to confirm NA50 result, but data not precise enough to quantitatively investigate rapidity shift

Differential distributions: $d\sigma/dp_T$

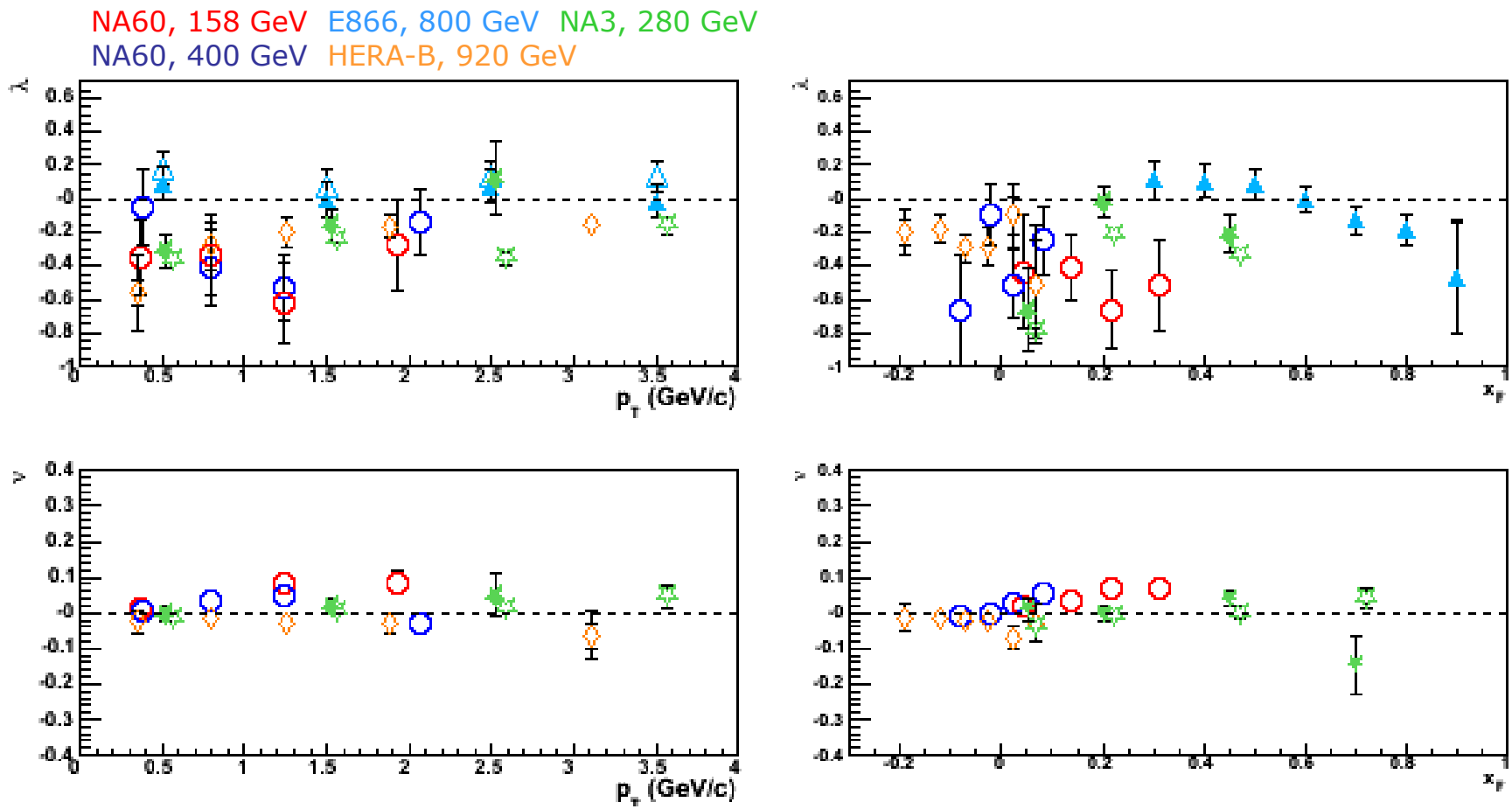




➡ p_T broadening, interpreted as initial state gluon multiple scattering (Cronin effect), observed at both 158 and 400 GeV



J/ψ polarization in pA: CS



- Results from other experiments are available:

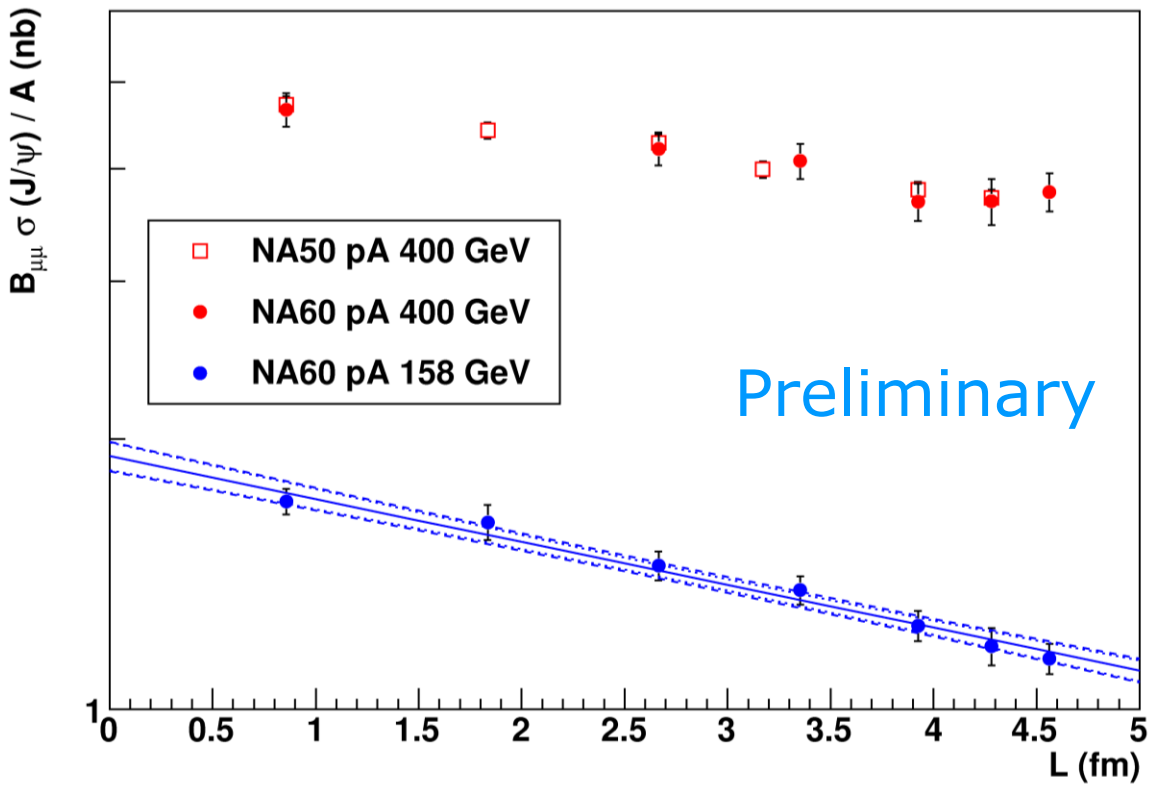
E866 p-A @ 800 GeV
(T. Chang et al. Phys. Rev. Lett 91, 211801 (2003))

NA3 π-A @ 280 GeV
(J. Badier et al., ZPC20 (1983) 101)

- λ_{CS} tends to be negative and larger in absolute value with respect to λ_{HE}

New result: pA J/ψ cross sections

- New result on absolute J/ψ cross sections for pA data

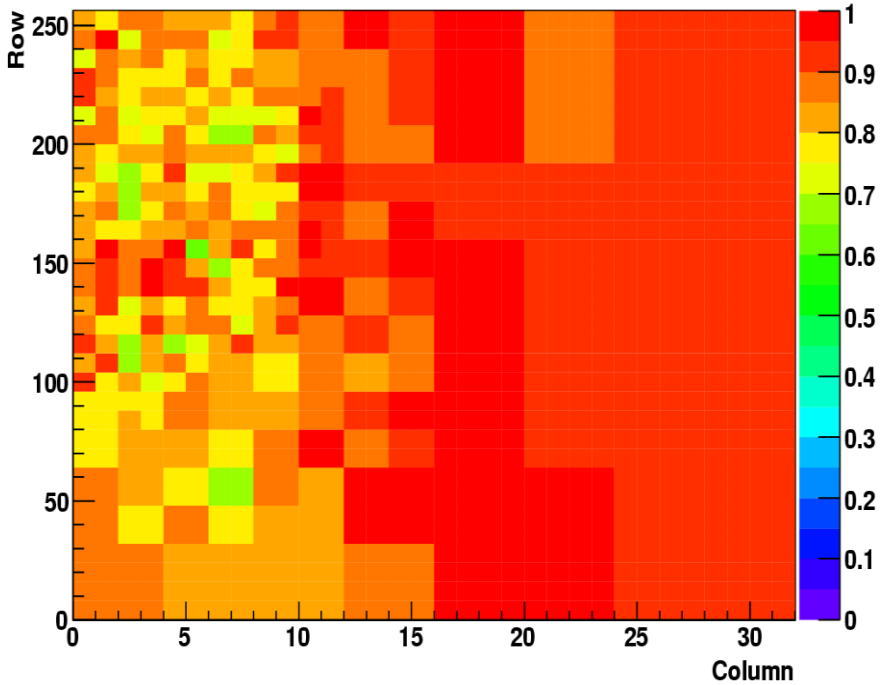


- Systematic error on (absolute) luminosity estimation quite high
  - Relative luminosity estimate between 158 and 400 GeV much better known (~2-3% systematic error)
  - Normalize NA60 400 GeV cross section ratios to NA50 results
- 158 GeV cross sections constrained by the relative normalization

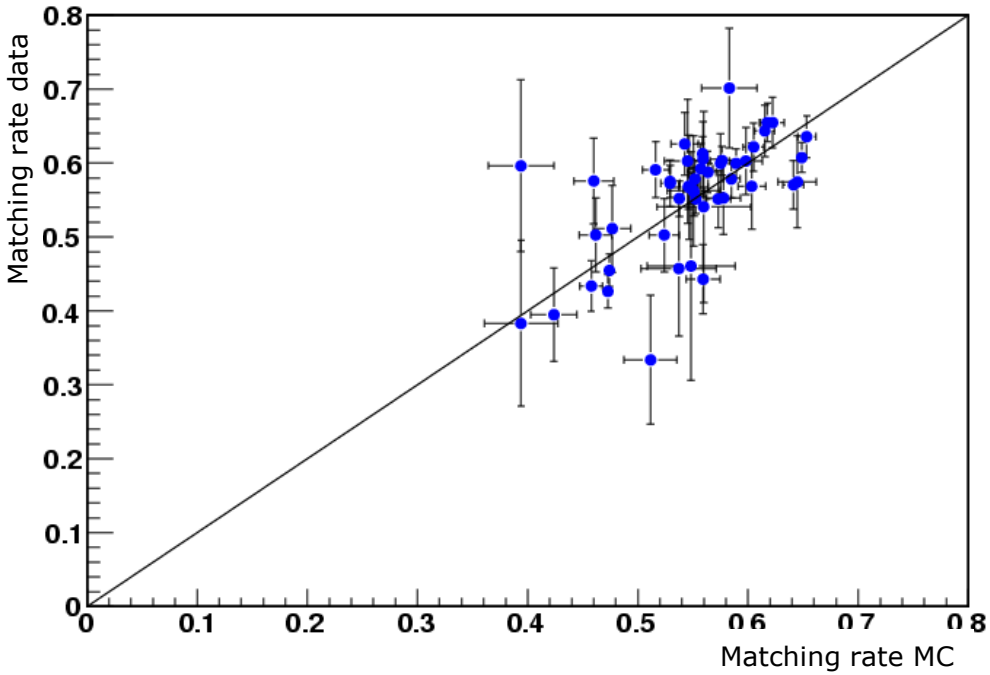
Efficiency correction

- Reconstruction efficiency does not cancel in the ratio

- Estimation based on a Monte-Carlo approach
  - Inject realistic VT efficiencies (follow their time evolution)
  - Finest granularity (regions of ~0.2mm^2 where statistics is enough)
  - Use "matching efficiency" and its time evolution as a check of the goodness of the procedure

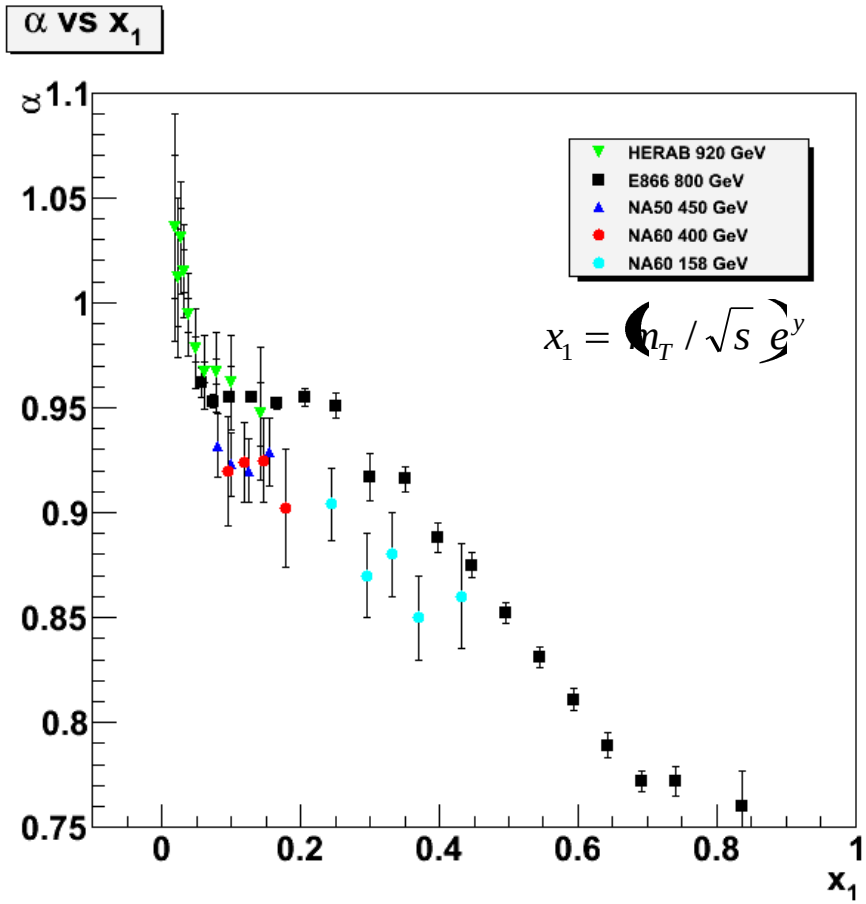


Efficiency map
(4th plane, sensor 0)



Matching efficiency

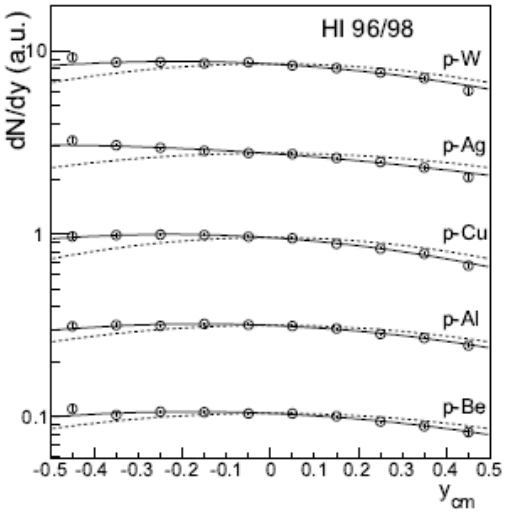
α vs. x_1



➡ α pattern vs x_1 at lower energies resembles HERA-B+E866 but systematically lower

Differential distributions: $d\sigma/dy$, $d\sigma/dx_F$

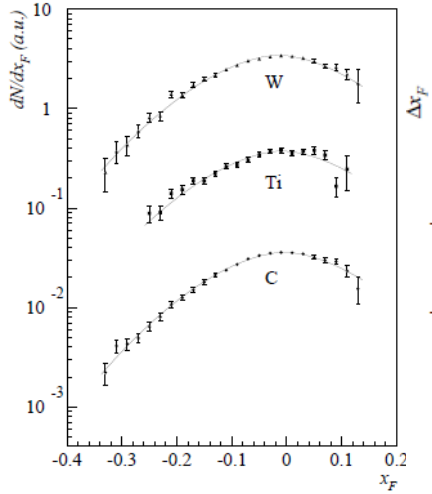
NA50(pA@400GeV)

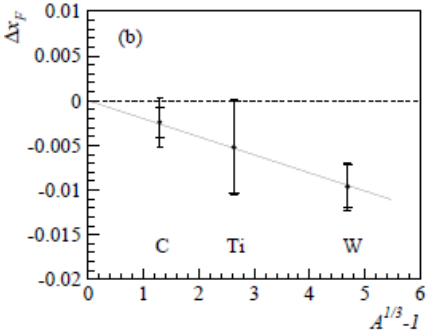


NA50 Coll., Eur. Phys. J C48(2006),329

strong, A-independent, backward shift
(Δy=0.2 → Δx_F= 0.045)

HERAB(pA@920GeV)

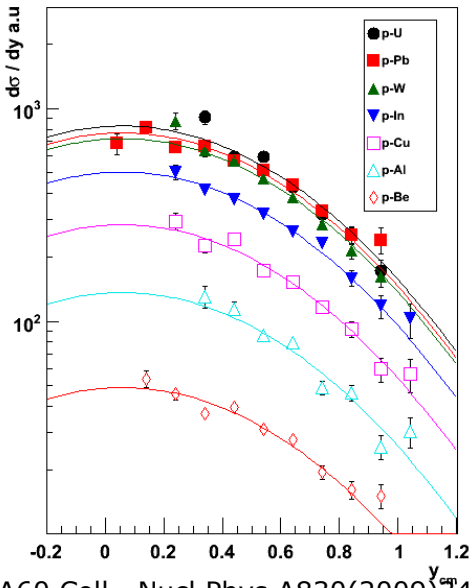




HERAB Coll., Eur. Phys. J C60(2009),525

A-dependent backward shift (Δx_F <0.01) smaller than the observed by NA50

NA60 (pA@158 GeV)



NA60 Coll., Nucl.Phys.A830(2009)345

from a gaussian fit
μ_y=0.05 0.05,
σ_y=0.51 0.02

➡ Backward shift due to the energy loss of the incident parton/ ccbar pair in their path through the nucleus, causing a reduction of the J/ψ x_F? (HERAB Coll., Eur. Phys. J C60(2009),525)