J/ψ and hot nuclear matter effects at SPS energy

- J/ψ suppression in AA collisions
  - Physics motivations
  - Review of AA results
  - Discussion on CNM extrapolations

- Charmonium vs open charm
  - Preliminary results from NA60

E. Scomparin – INFN (Torino)

First Retequarkonii Workshop, October 25th-28th 2010, Nantes France

Basics

PHYS. LETT. B, in press

BROOKHAVEN NATIONAL LABORATORY

June 1986 BNL-38344

J/ψ SUPPRESSION BY QUARK-GLUON PLASMA FORMATION

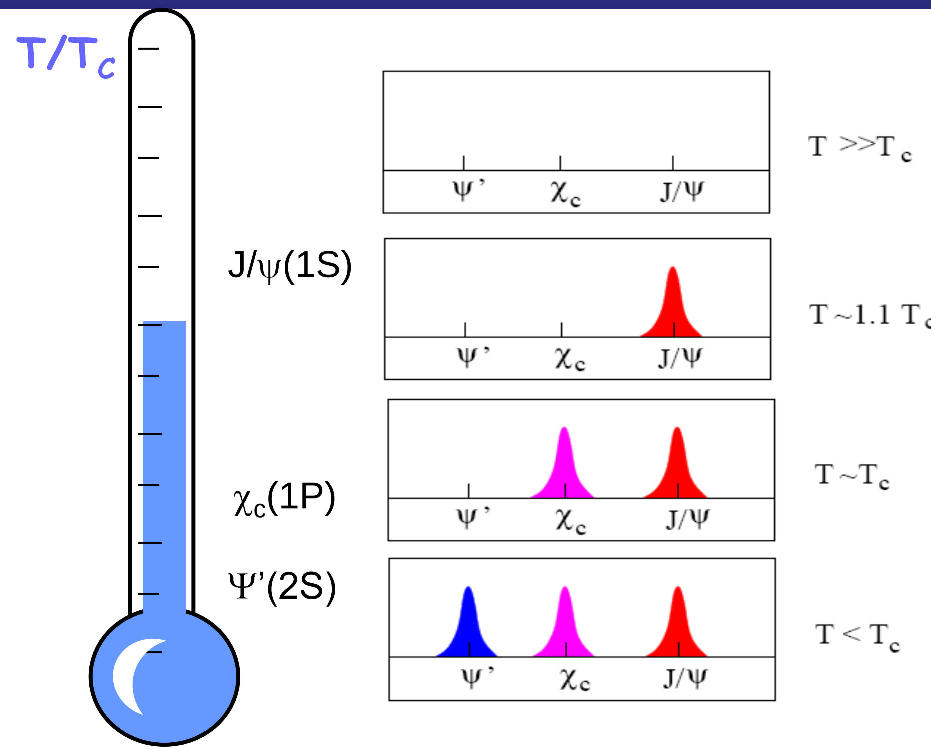
ABSTRACT

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.

This manuscript has been authored under contract number DE-AC02-76CH00016 with the U.S. Department of Energy. Accordingly, the U.S. Government retains a non-exclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

Phys.Lett. B178 (1986) 416

- Charmonia suppression has been proposed, more than 20 years ago, as a signature for QGP formation
- Sequential suppression of the resonances is a thermometer of the temperature reached in the collisions

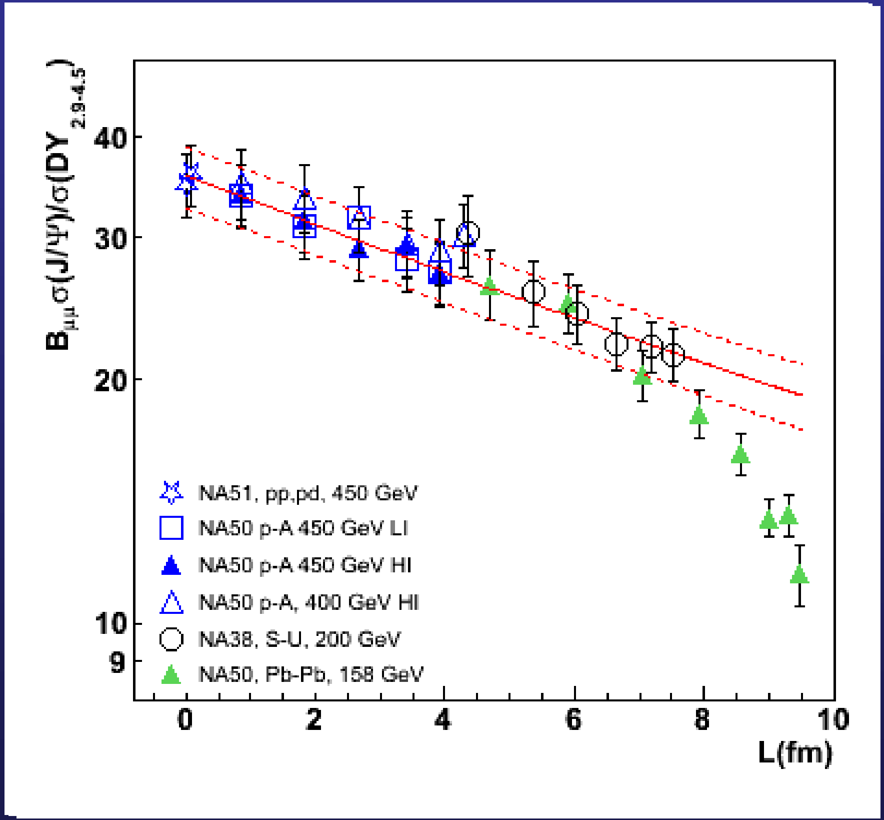


First came NA38/NA50.....

- Quantify suppression studying the J/ψ/DY ratio vs L, for various systems
- pA at 400/450 GeV → extrapolate to lower energies,

  Assume $\sigma_{abs}^{J/\psi}$ (158 GeV) = $\sigma_{abs}^{J/\psi}$ (400/450 GeV)

  Normalization $(\sigma^{J/\psi}/\sigma^{DY})_{pp}$: phenomenological rescaling



NA38

S-U 200 GeV/nucleon

M.C. Abreu et al., PLB449(1999)128

→ cold nuclear matter effects explain the observed suppression

NA50

Pb-Pb 158 GeV/nucleon

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

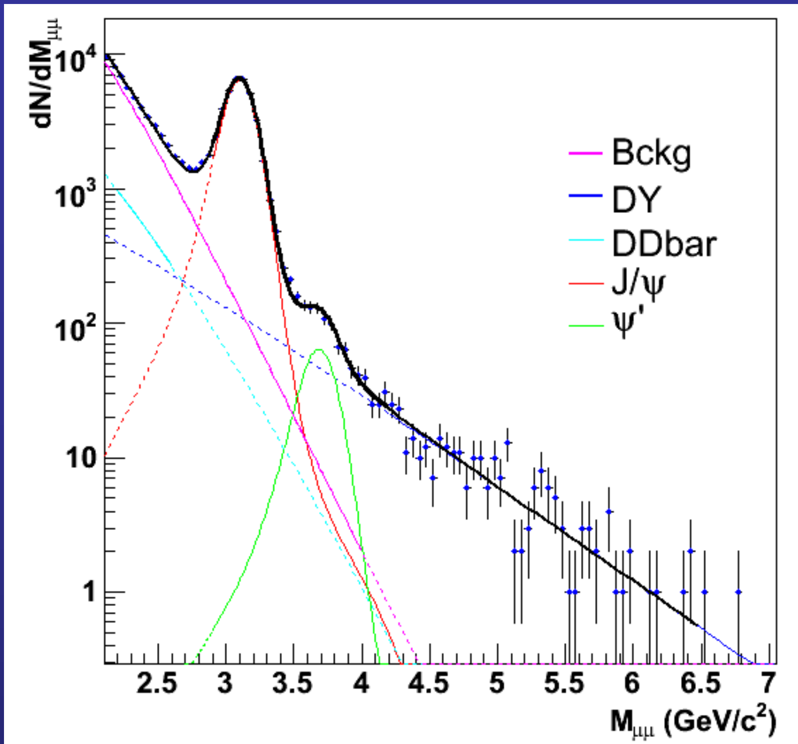
→ anomalous suppression, increasing with centrality

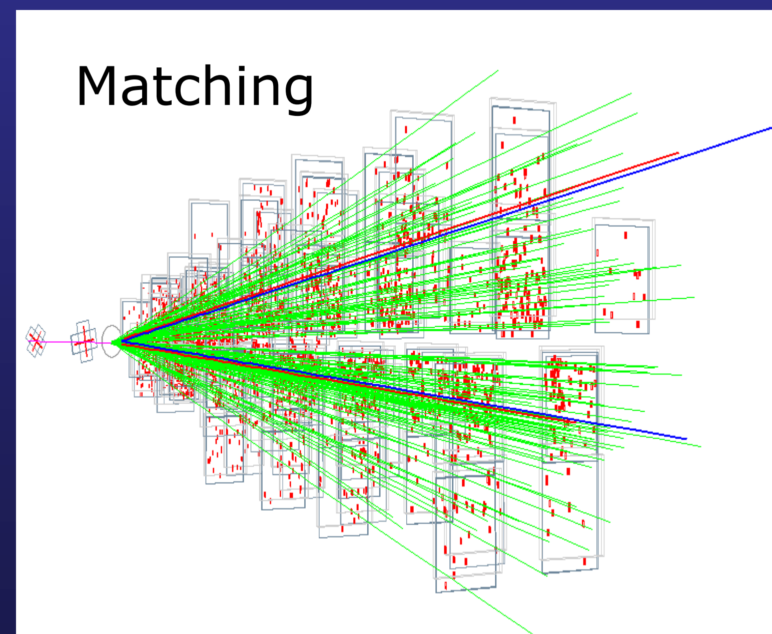
~8% error on the calculated CNM reference

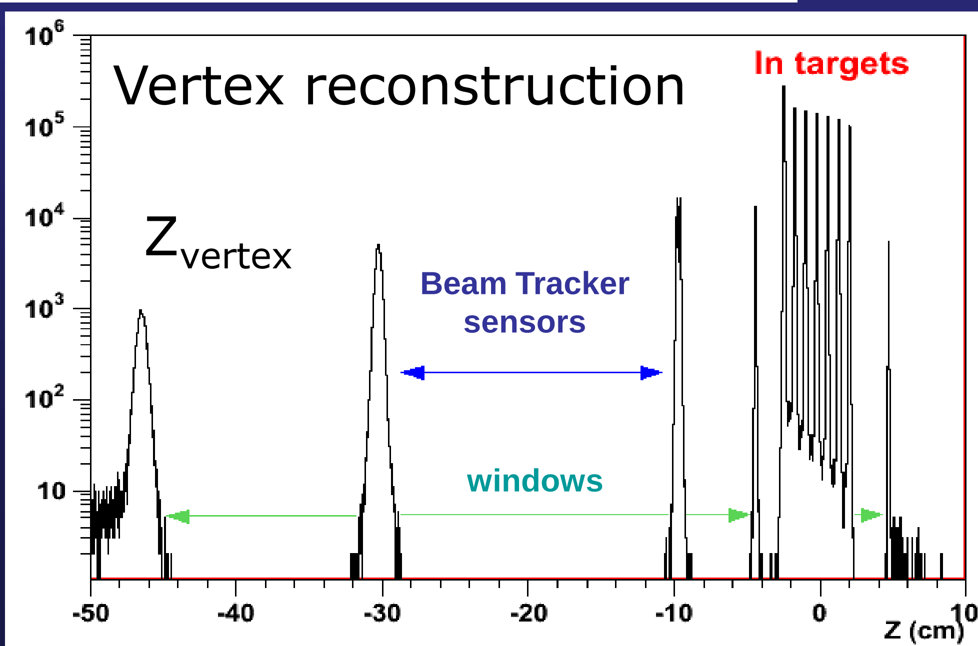
...then enters NA60

In-In collisions
at 158 GeV/nucleon

- After quality cuts →
  $N_{J/\psi}$ ~ 45000 (no matching)
  ~ 29000 (with muon matching)





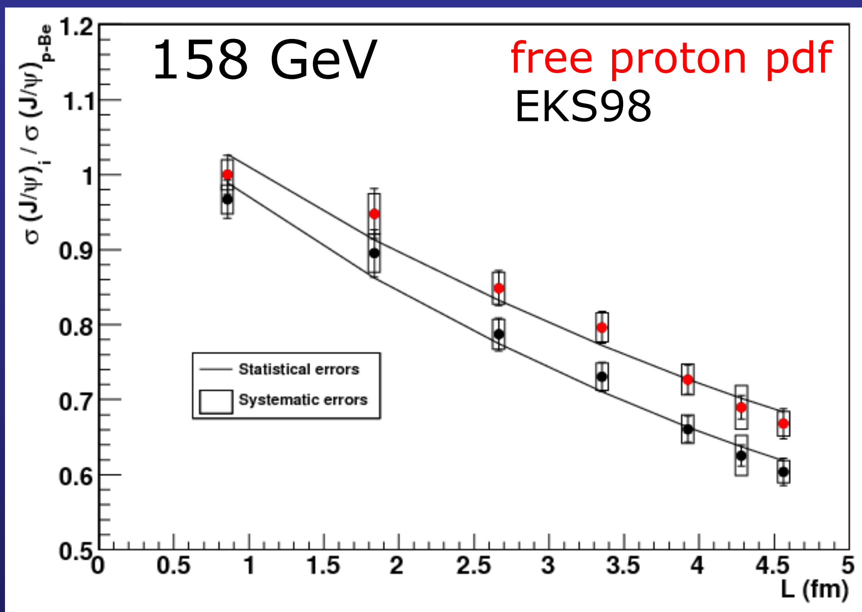


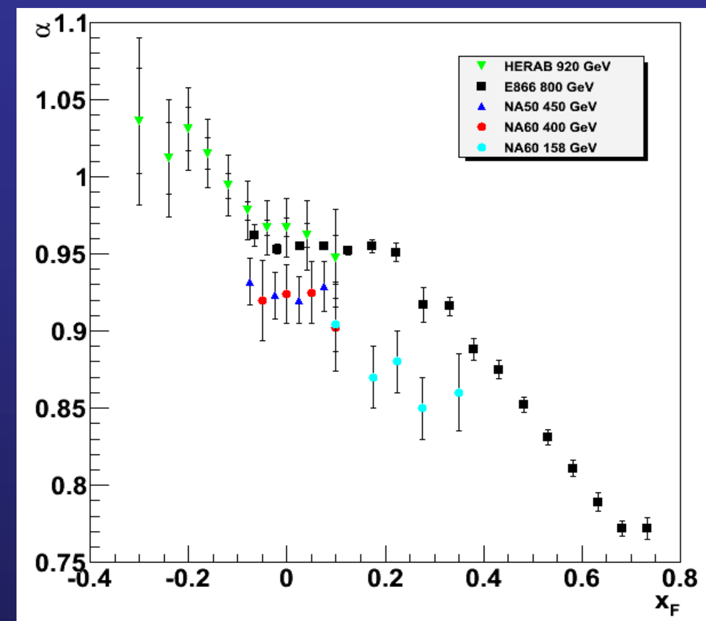
σ_z ~ 200 μm along the beam direction
(~ 10 - 20 μm in the transverse direction)

pA data in a slide.....

- For the first time NA60 has collected p-A data (p-Be,Al,Cu,In,W,Pb,U) at 158 GeV, i.e. the same energy (and rapidity) used for AA collisions

Main results:





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

2) taking into account antishadowing correction (EKS98)

$\sigma_{abs}^{J/\psi}$(158 GeV)= 9.3   0.7   0.7 mb

3) comparing α values ($\sigma_{pA} = \sigma_{pp} A^{\alpha}$) from fixed target experiments: clear dependence on x_F and beam energy

Building CNM reference from pA data

- Use pA results collected at 158 GeV, in the same kinematic and energy range as AA data

- Try to disentangle initial (antishadowing) and final state effects (absorption in nuclear matter)

- In particular, when extrapolating from pA to AA, take into account that in AA collisions gluon antishadowing affects both projectile and target

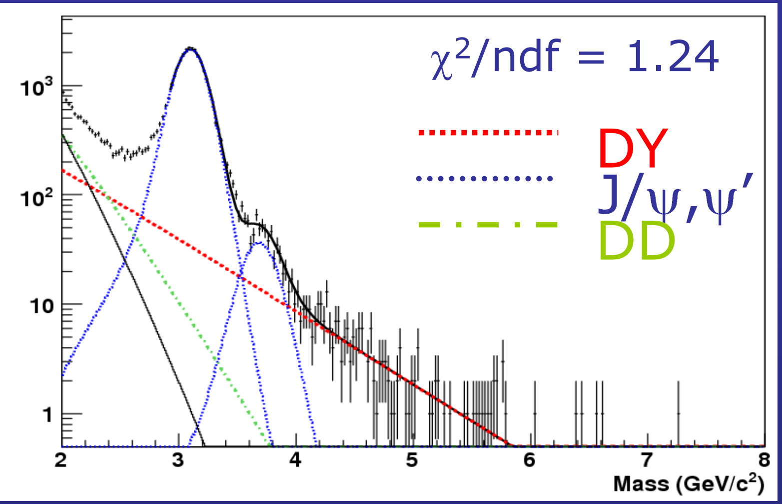
- Caveat:
  - The results on $\sigma_{abs}^{J/\psi}$(158 GeV) have small error bars
  - However, they do not have an absolute normalization
    → go through J/ψ/DY ratio, as in NA50
    - However
      - NA60 pA results have a limited high-mass DY statistics
      - Possible to extract the J/ψ/DY ratio integrated over A
      - Not possible to have (as in NA50) J/ψ/DY vs A

Building CNM reference from pA data

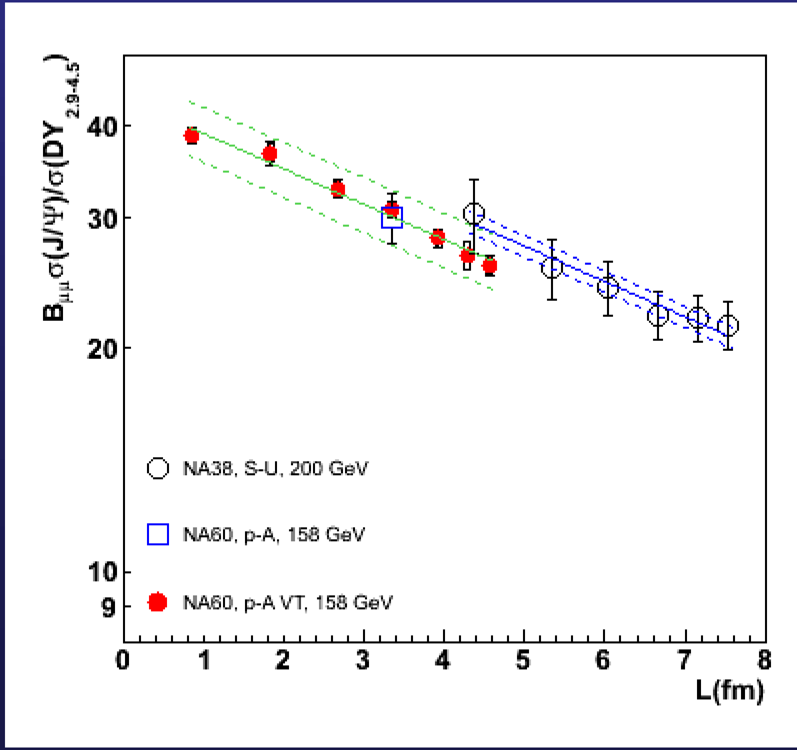
Normalize pA cross section ratio to the $(\sigma_{J/\psi} / \sigma_{DY}) |^{pA}_{158GeV}$ integrated on all the targets

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

with $2.9 < m_{DY} < 4.5$ GeV/c^2



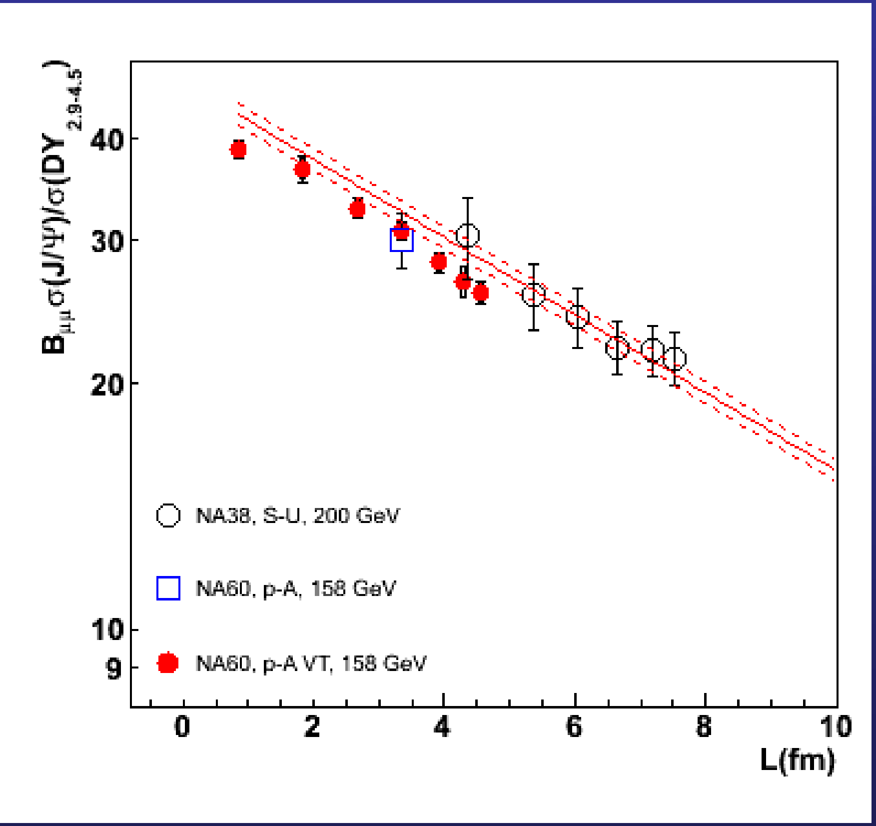
8% error on normalization
Try to reduce it using SU results
Are SU and pA compatible, for what concerns nuclear effects ?



- The answer is yes
  - Slopes are compatible within 0.3σ
  - Normalizations (after rescaling SU to 158GeV) are compatible within 1σ

Building CNM reference from pA data

- The CNM reference curve is then defined with



- normalization obtained from the weighted average of the normalizations of pA and SU data

- slope fixed from pA data

- Errors on the CNM reference curve include

- ~3% due to absolute normalization
- ~3% on average, slightly dependent on centrality, due to $\sigma^{abs}_{J/\psi}$ uncertainty (not shown)

Initial state effects: pA vs AA

- SPS energies: charmonium production probes x-region in the antishadowing region

- The extrapolation of CNM effects from pA to AA must take into account that in AA collisions the antishadowing affects both the projectile and the target nucleons

- Calculate shadowing factors, i.e. the ratio between J/ψ production cross section per NN collisions in AA and in pp, as

$$S^{J/\psi}_{InIn}(x_F) = \frac{1}{A_{In}^2}\frac{d\sigma^{InIn}_{J/\psi}/dx_F}{d\sigma^{pp}_{J/\psi}/dx_F} = \frac{1}{A_{In}^2}\frac{H_{InIn}(x_1,x_2;m^2)}{H_{pp}(x_1,x_2;m^2)}$$

- Cross sections computed at LO in the Color Evaporation Model
- Ratios should not depend too much on the choice of the underlying model

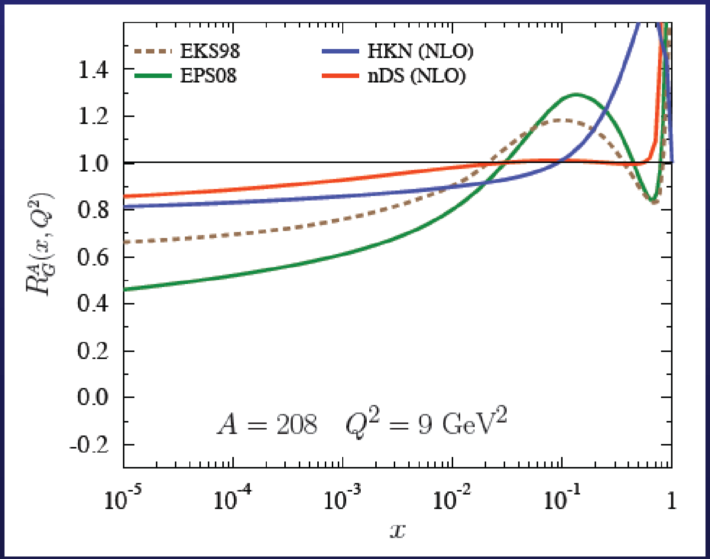
Antishadowing parameterizations

$$S^{J/\psi}_{InIn}(x_F) = \frac{1}{A^2_{In}} \frac{d\sigma^{InIn}_{J/\psi}/dx_F}{d\sigma^{pp}_{J/\psi}/dx_F} = \frac{1}{A^2_{In}} \frac{H_{InIn}(x_1, x_2; m^2)}{H_{pp}(x_1, x_2; m^2)}$$

- Gluon fusion and qq annihilation contributions to σ_{cc} are considered

$$H_{AA}(x_1, x_2; m^2) = f_g^A(x_1, m^2) f_g^A(x_2, m^2) \sigma_{gg}(m^2) + \sum_{q=u,d,s} \left(f_q^A(x_1, m^2) f_{\bar{q}}^A(x_2, m^2) \sigma_{q\bar{q}}(m^2) \right)$$

$$f_i^A(x, Q^2) = R_i^A(x, Q^2) f_i^N(x, Q^2)$$



Nuclear modification on PDF are included using EKS98 and EPS08 (EPS08 choice coincides with maximum antishadowing foreseen in EPS09)

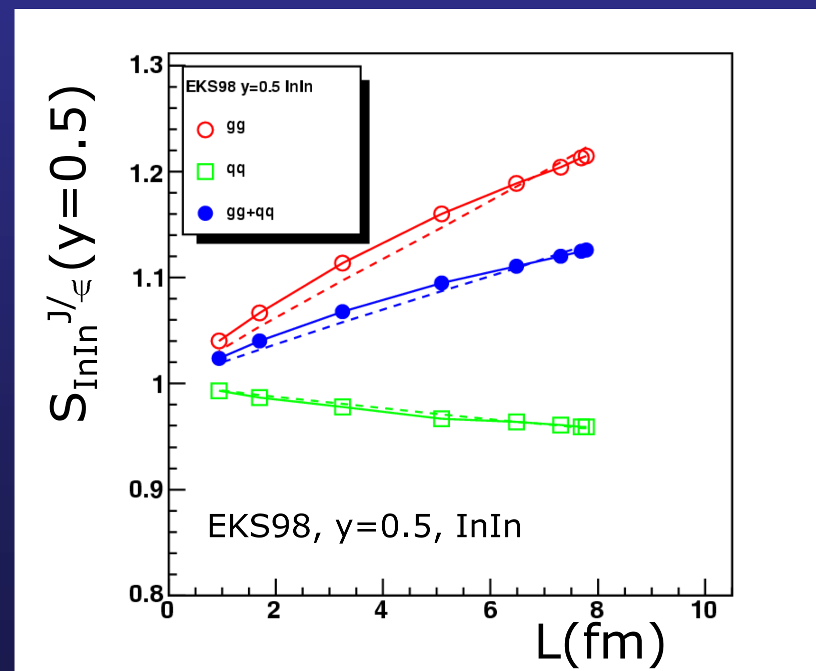
CEM formulas from R. Vogt Phys. Rep 310 (1999) 197

Shadowing spatial dependence

- Nuclear modifications depend also on the spatial location of the nucleon inside the nucleus (S.R.Klein, R.Vogt, Phys.Rev.Lett 91(2003)142301)

→ important in the study of the centrality dependence of $S^{J/\psi}$ (shadowing effects are more important for core nucleons)

- Various parametrization of the shadowing dependence on the nucleon position are considered



- proportional to the local density

(symbols, continuous line)

$$R^A_{i,\rho}(x,Q^2,\vec{r},z) = 1 + N_A\left(R^A_i(x,Q^2)-1\right)\frac{\rho_A(r,z)}{\rho_0}$$

- proportional to the length L of nuclear matter crossed by the parton

(dashed line)

$$R^A_{i,L}(x,Q^2,\vec{r},z) = 1 + N_A\left(R^A_i(x,Q^2)-1\right)\frac{\int dz\,\rho_A(r,z)}{\int dz\,\rho_A(0,z)}$$

The two approaches give similar results

Influence of antishadowing on AA

1) The J/ψ production cross section in pA is given by

$$\frac{1}{A}\sigma^{pA}_{J/\psi} = \sigma^{pp}_{J/\psi} \times S^{pA}_{J/\psi} \times e^{-\rho\sigma^{abs}_{J/\psi}L}$$

← final state absorption ($\sigma_{J/\psi}^{abs}$ = 8 mb in this calculation. Results of the shadowing contribution to the reference insensitive to the specific $\sigma_{J/\psi}^{abs}$)

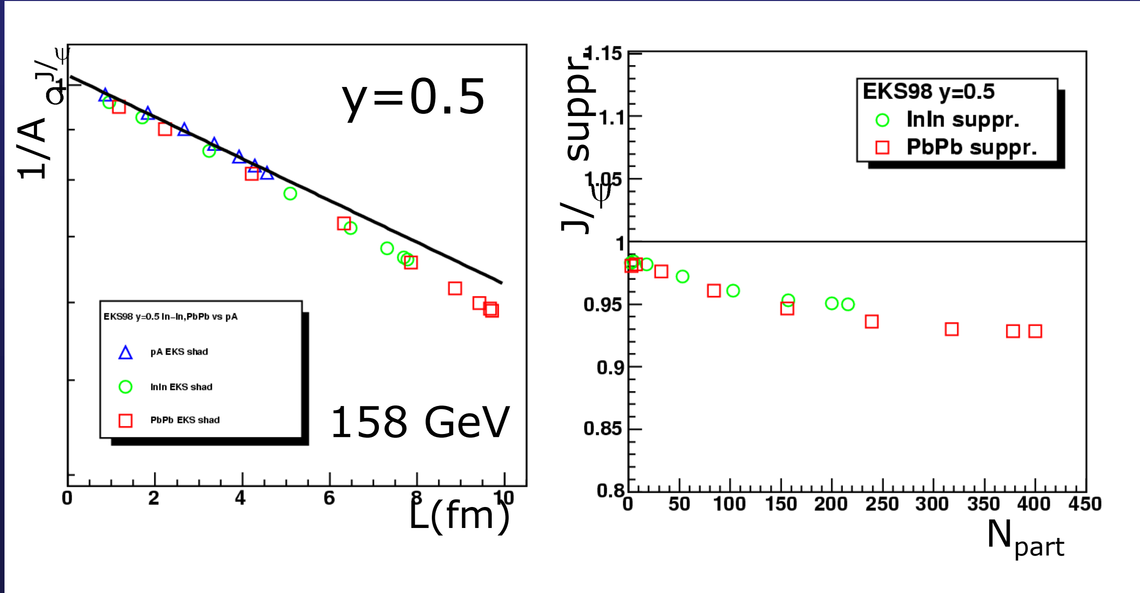
↑ shadowing

2) the nuclear absorption curve is obtained fitting $\sigma^{pA}_{J/\psi}/A$ with the $e^{-\rho\sigma L}$ behaviour and then extrapolated to AA using L scaling, neglecting shadowing (as usually done at SPS energies)

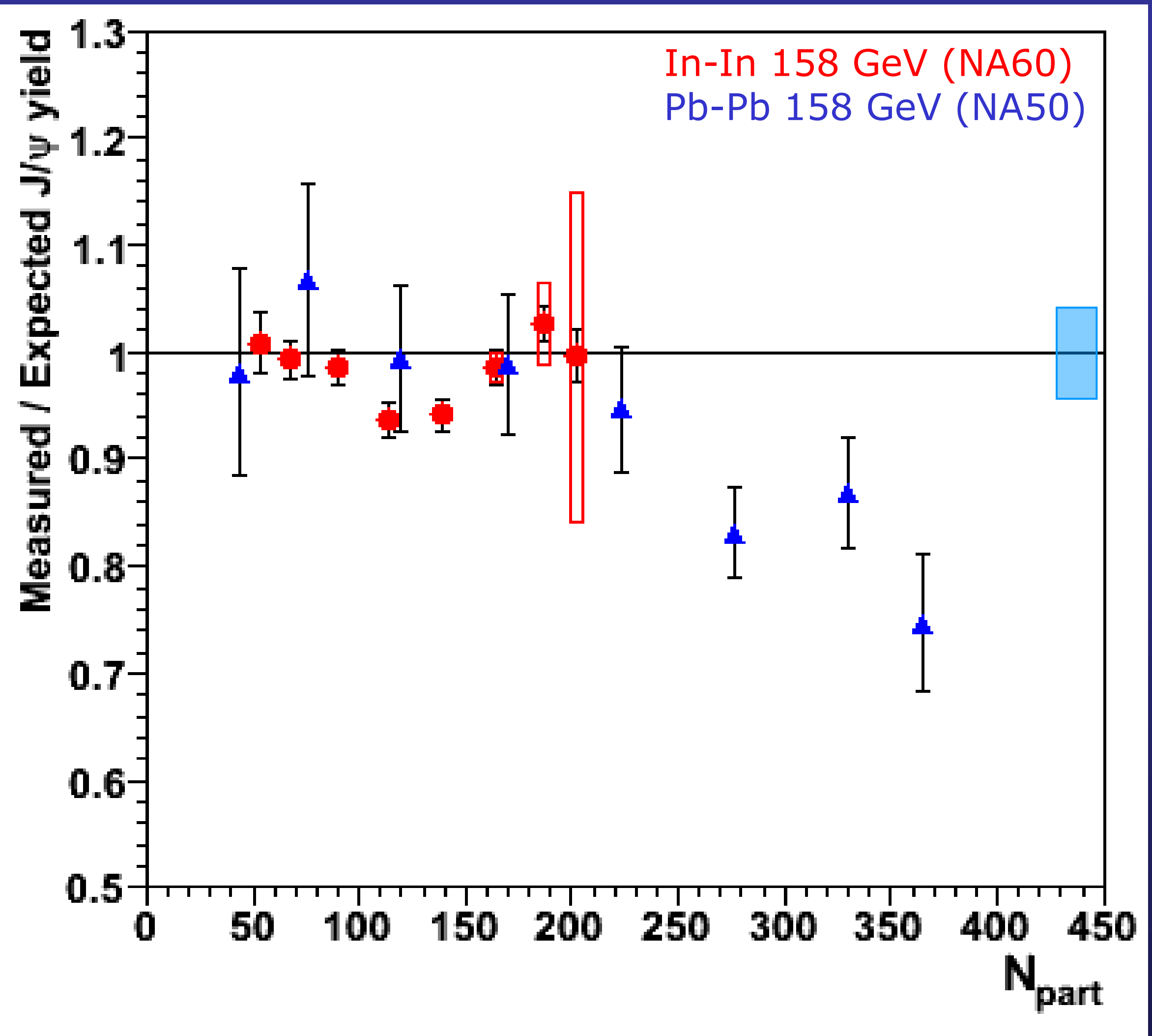
3) the fit is compared to $1/A^2\, \sigma^{AA}_{J/\psi}$, calculated with the same ingredients

→ even in absence of hot medium effects there is a difference between AA result and pA extrapolation

→ this suppression is an effect generated by neglecting AA shadowing in the reference determination



Anomalous suppression



Using the previously defined reference:

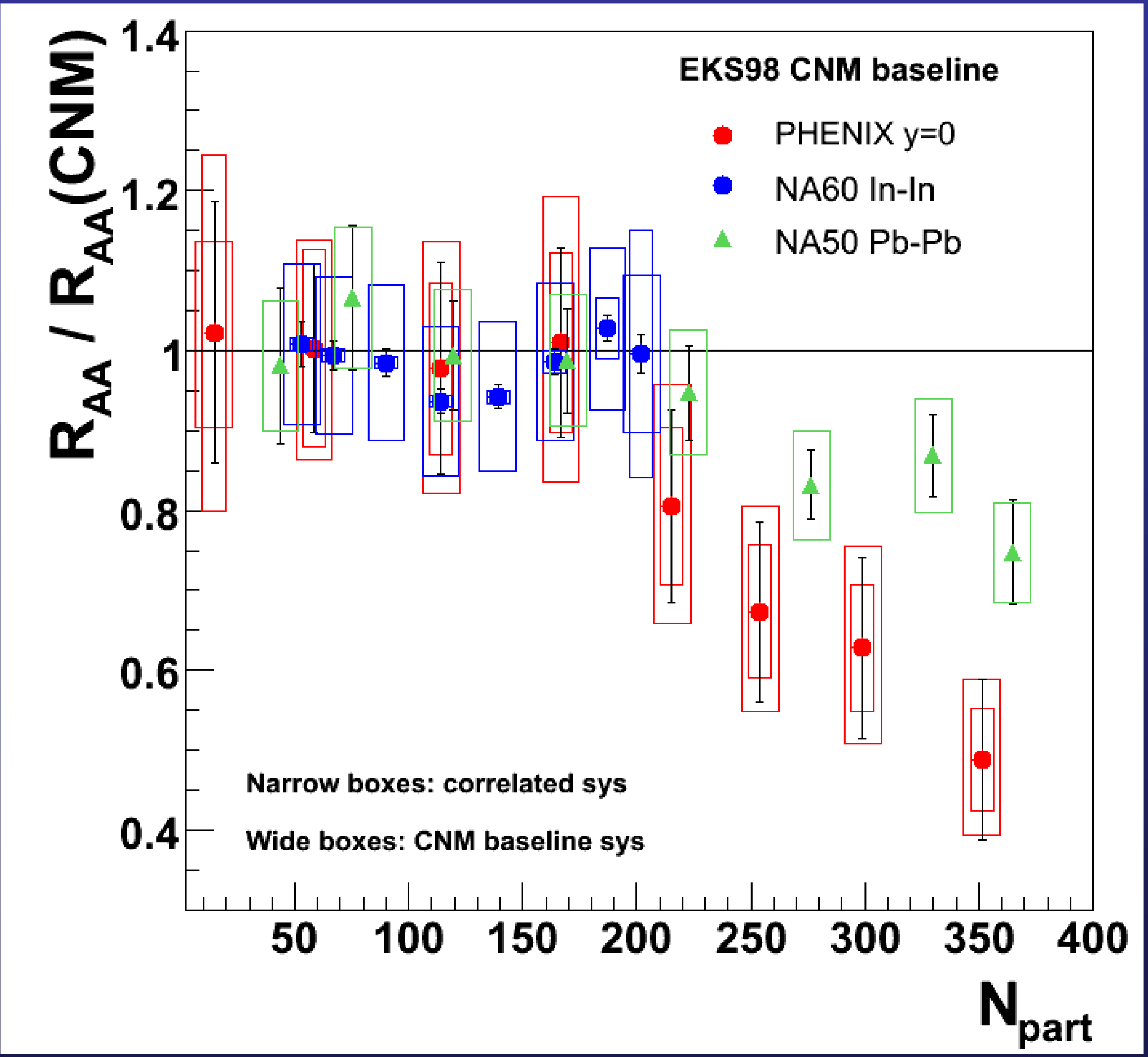
Central Pb-Pb:
→ anomalously suppressed

In-In:
→ almost no anomalous suppression

B. Alessandro et al., EPJC39 (2005) 335
R. Arnaldi et al., Nucl. Phys. A830 (2009) 345
R.Arnaldi, P. Cortese, E. Scomparin Phys. Rev. C 81 (2009), 014903

Comparison SPS vs RHIC

- Measured/Expected SPS results are compared with AuAu PHENIX R_{AA} results normalized to R_{AA}(CNM)



Both Pb-Pb and Au-Au seem to depart from the reference curve at N_{Part}~200

For central collisions more important suppression in Au-Au with respect to Pb-Pb

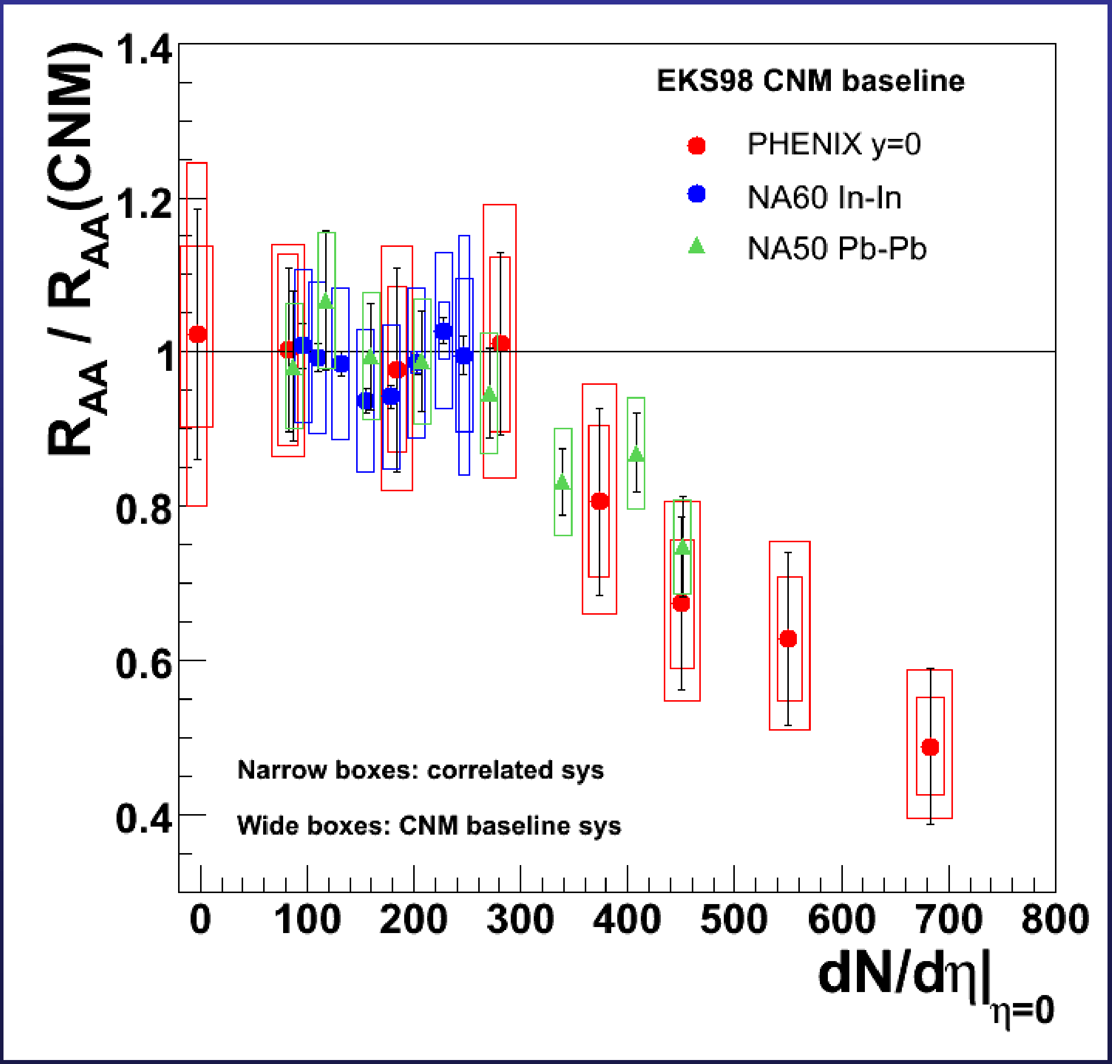
Effect of higher energy density at RHIC at constatnt N_{part} ?

Systematic errors on the CNM reference are shown for all points

PHENIX results from T. Frawley, workshop on "Quarkonium In Hot Media:From QCD to Experiment", Seattle 2009

Comparison SPS vs RHIC

- Plot results as a function of a the multiplicity of charged particles



The relation between the charged multiplicity and N_{part} is obtained

AuAu → using PHOBOS data
(Phys.Rev.C65 061901 (2002)

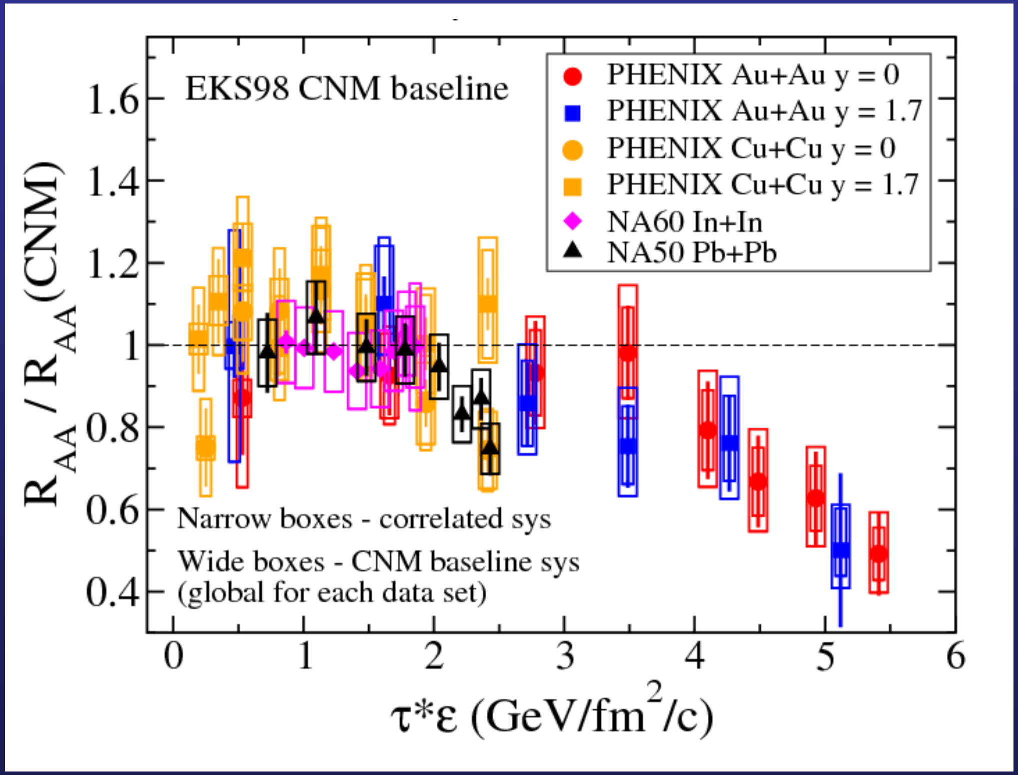
PbPb → using NA50 data
(Phys.Lett.B 530 1-4 (2002) 43-55)

Scaling between SPS and RHIC !

Comparison SPS vs RHIC

- Comparison can also be done in terms of τ * Bjorken energy density

$$\tau_0 \varepsilon = \frac{dE_T / dy}{A}$$



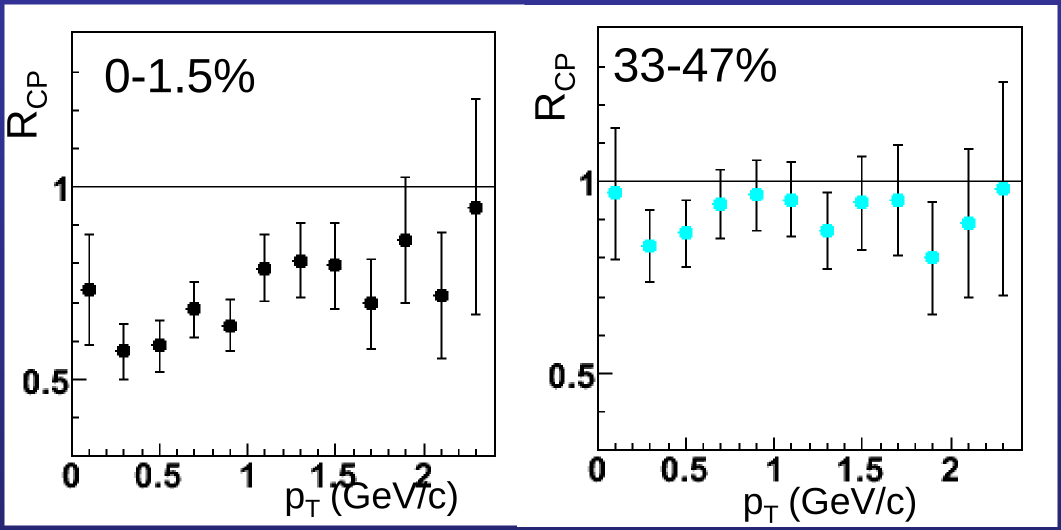
Energy density evaluation based on:

→ $dE_T/d\eta$ from WA98 data for SPS
→ no $dE_T/d\eta$ for CuCu, so AuAu data at the same N_{part} are used

Control of relative systematics not straightforward

p_T–dependence of the J/ψ suppression

NA60: In-In @158 GeV



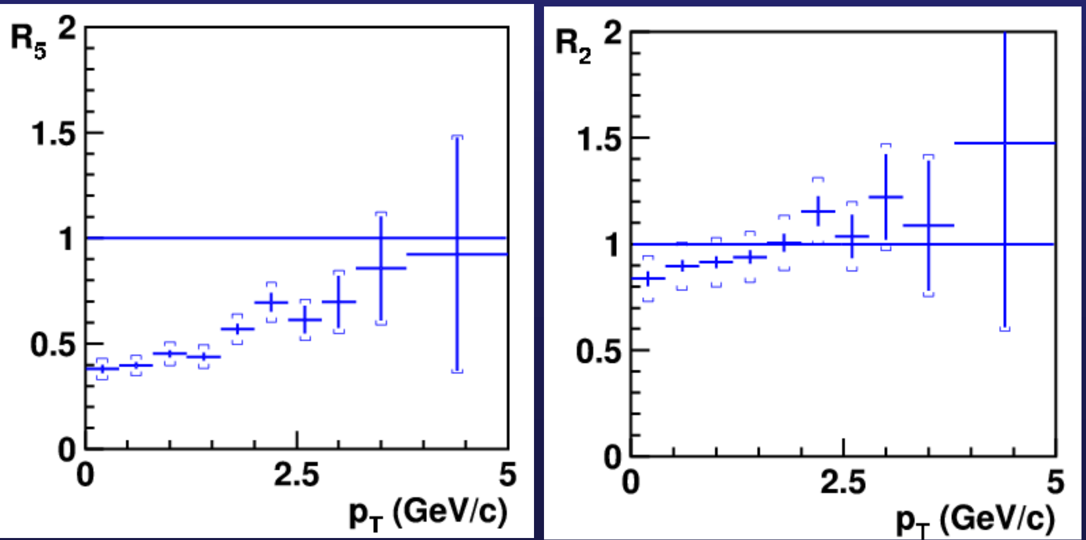
p_T dependence of the J/ψ suppression investigated at SPS energies:

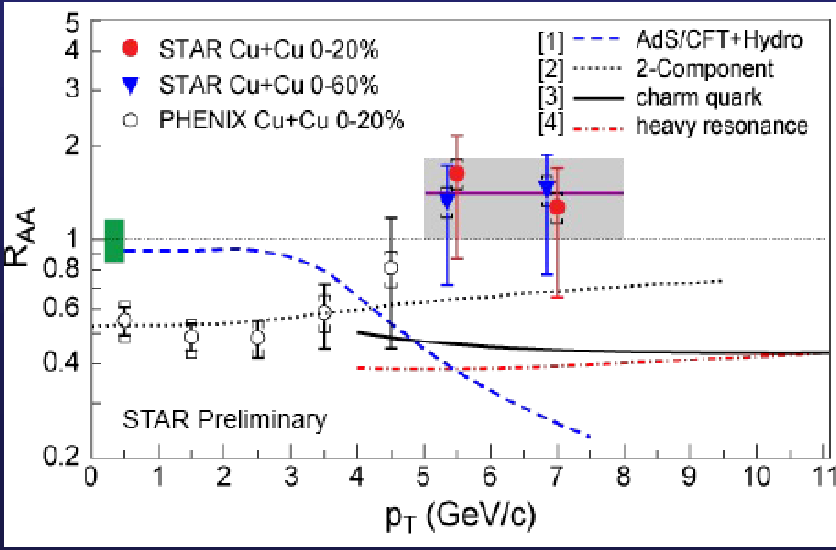
→strong p_T dependence of R_{CP}

→ only the low p_T J/ψ are suppressed !

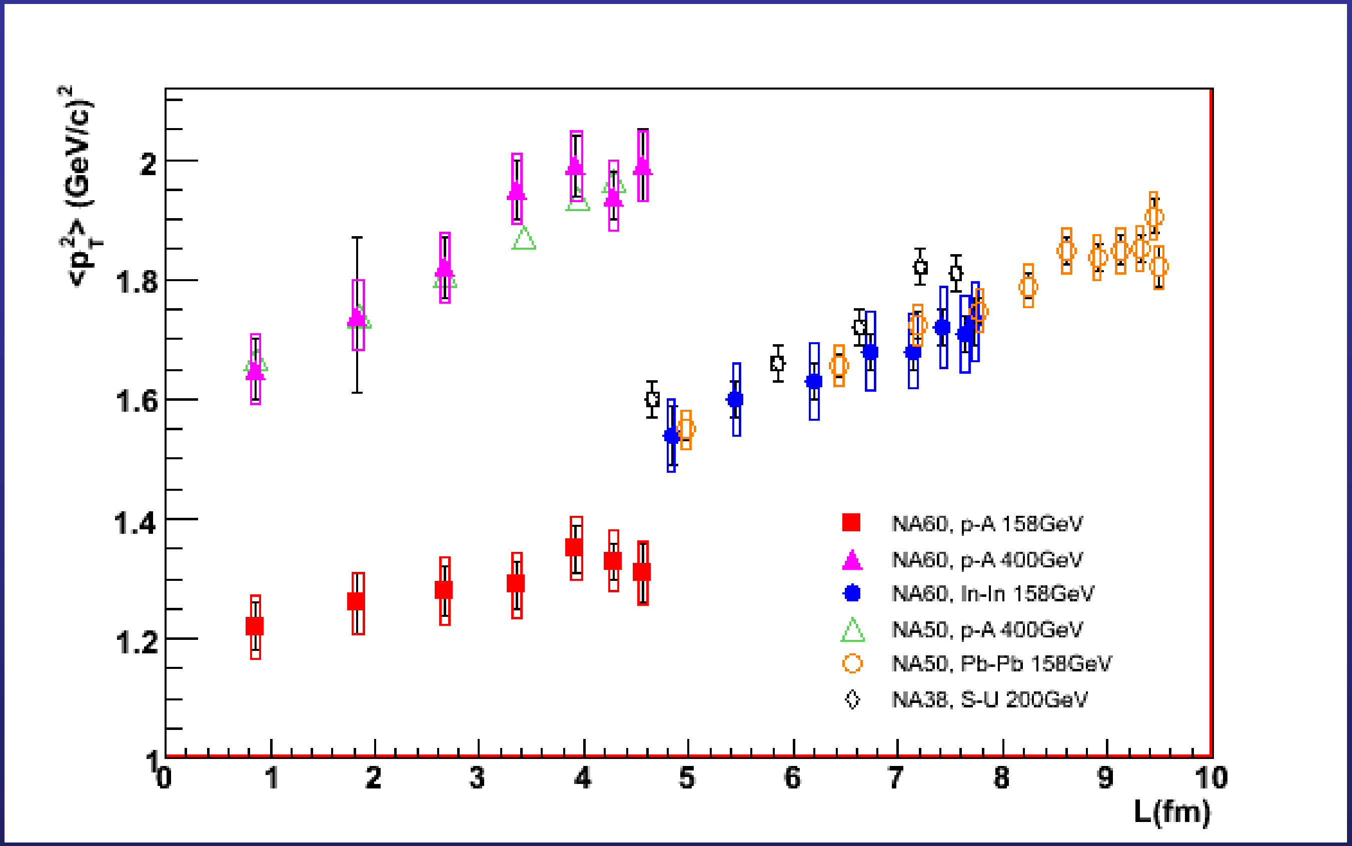
Similar to the behaviour observed at RHIC

NA50: Pb-Pb @158 GeV





J/ψ p_T distributions in NA50/NA60: AA vs pA



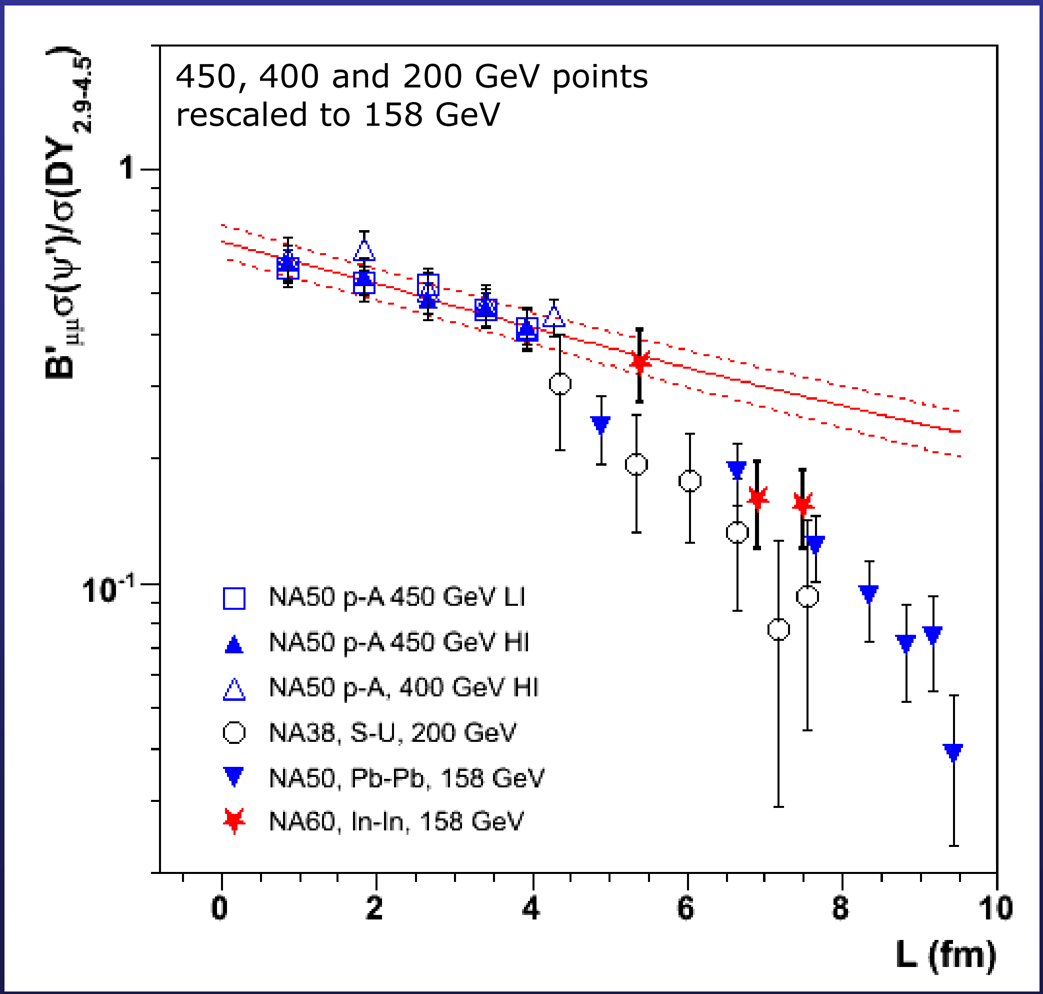
- Systematic errors
  - → ~ 4% for the NA60 points
  - → <1% for the NA38 points
  - → ~ 2% for the NA50 points

- Linear increase of $\langle p_T^2 \rangle$ vs L for p-A and A-A, slope smaller in p-A at 158 GeV
- L scaling broken between p-A and A-A
- Initial state parton scattering cannot be the only source of transverse momentum broadening. Final state effects ?

- "Control experiment": pA at 400 GeV: comparison NA60/NA50 is OK

ψ' suppression in p-A and A-A

- ψ'/DY values for nuclear collisions (S-U, In-In, Pb-Pb) in good relative agreement



- $\sigma^{abs}_{\psi'}$ for p-A collisions at 158 GeV not available (statistics per target too low)

- Fit of pA 400/450 GeV data
  → $\sigma^{abs}_{\psi'}$ =7.3   1.6 mb

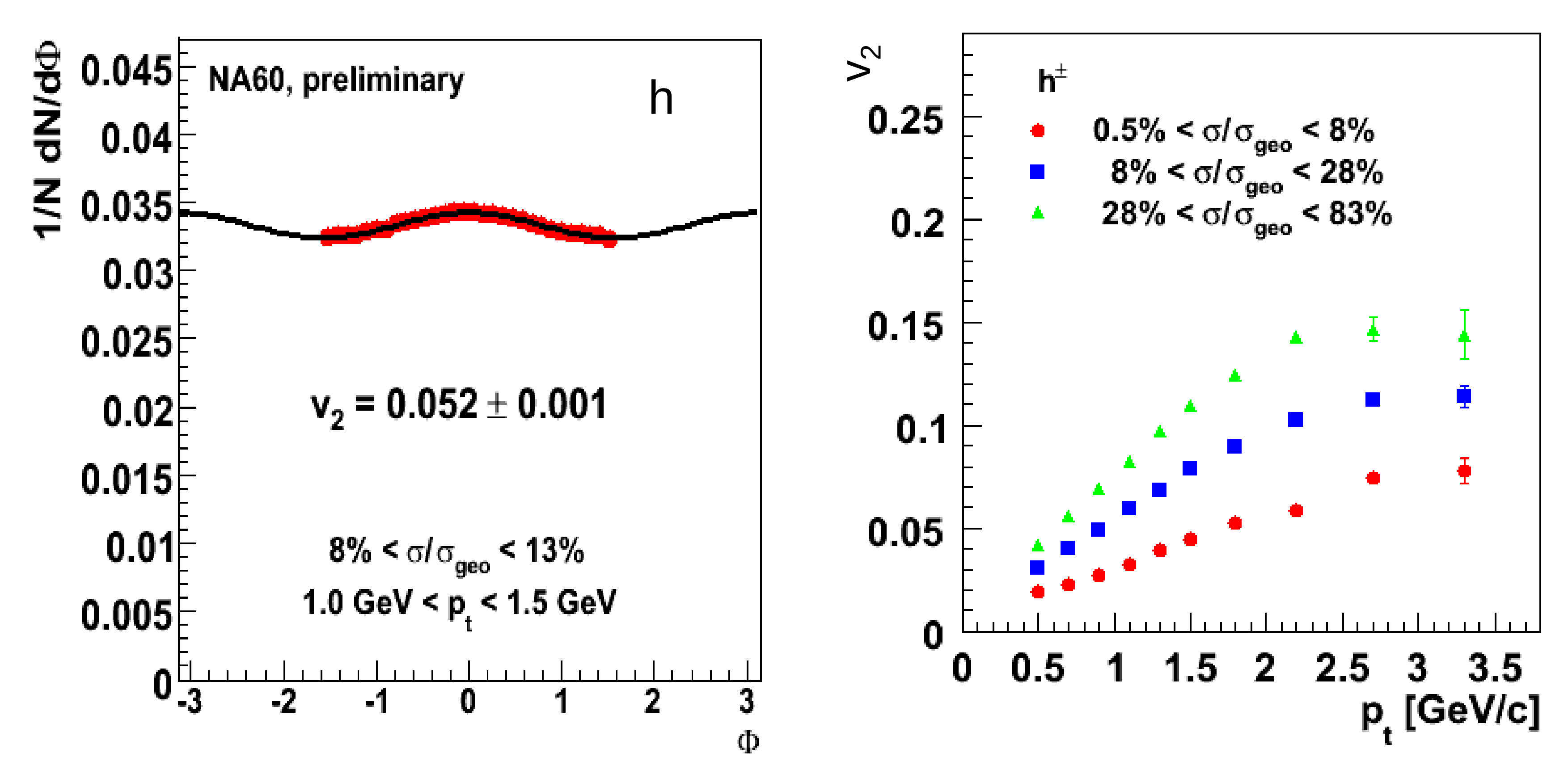
- Fit of S-U, Pb-Pb data
  → $\sigma^{abs}_{\psi'}$ =19.2   2.4 mb

- Even if (as for the J/ψ)
  $\sigma^{abs}_{\psi'}$(158 GeV)> $\sigma^{abs}_{\psi'}$(400 GeV)
  an additional suppression in A-A wrt p-A is likely to be present

v_2 measurements for J/ψ

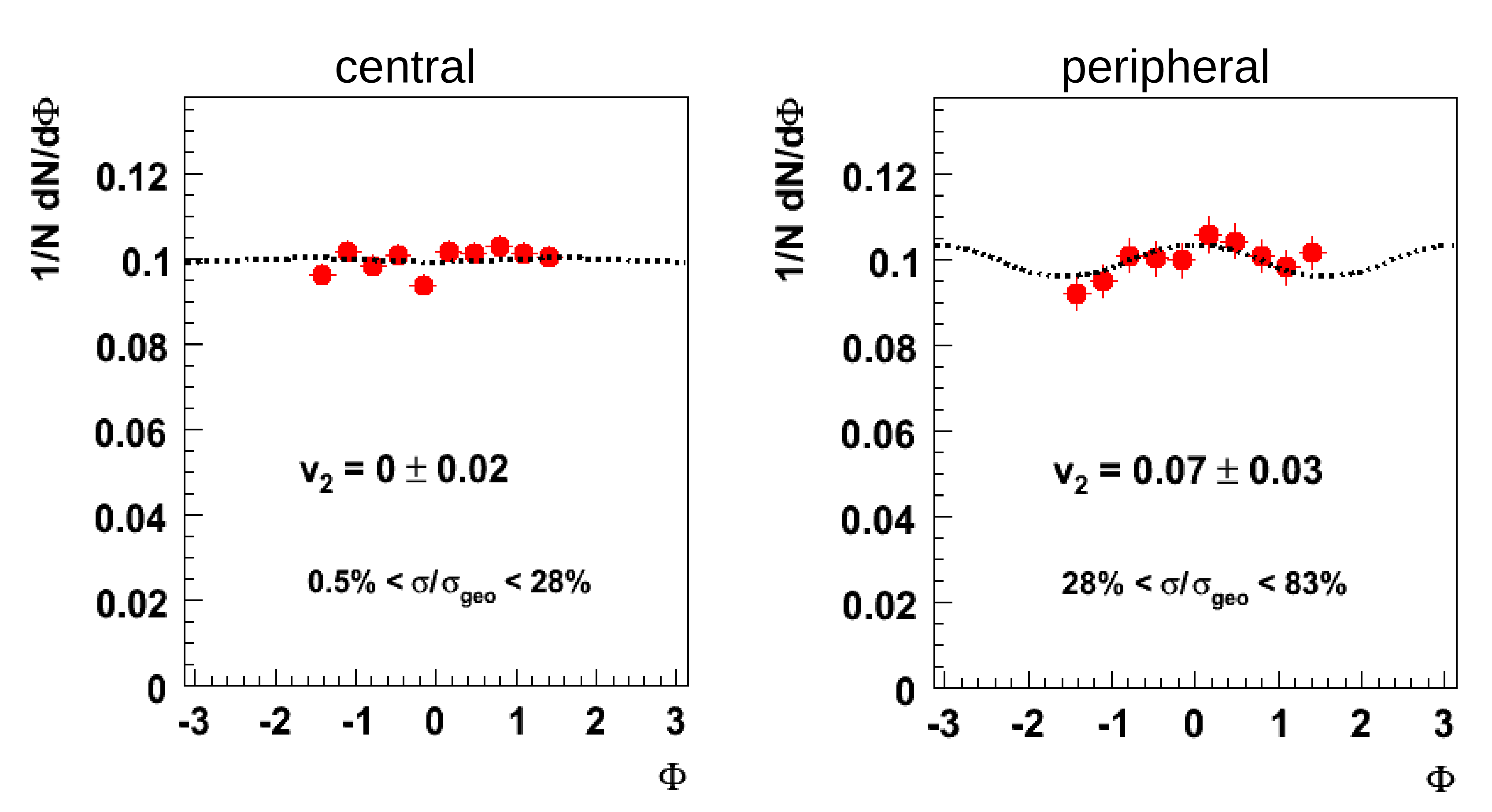
- NA60 acceptance: ~ $0 < y_{cm} < 1$
- Determination from charged particle tracks as measured in the vertex tracker

v_2 for charged particles



J/ψ azimuthal anisotropy

- Limited statistics (<30000 J/ψ events) prevents a fine binning in N_{part}/p_T
- Define 2 broad centrality classes

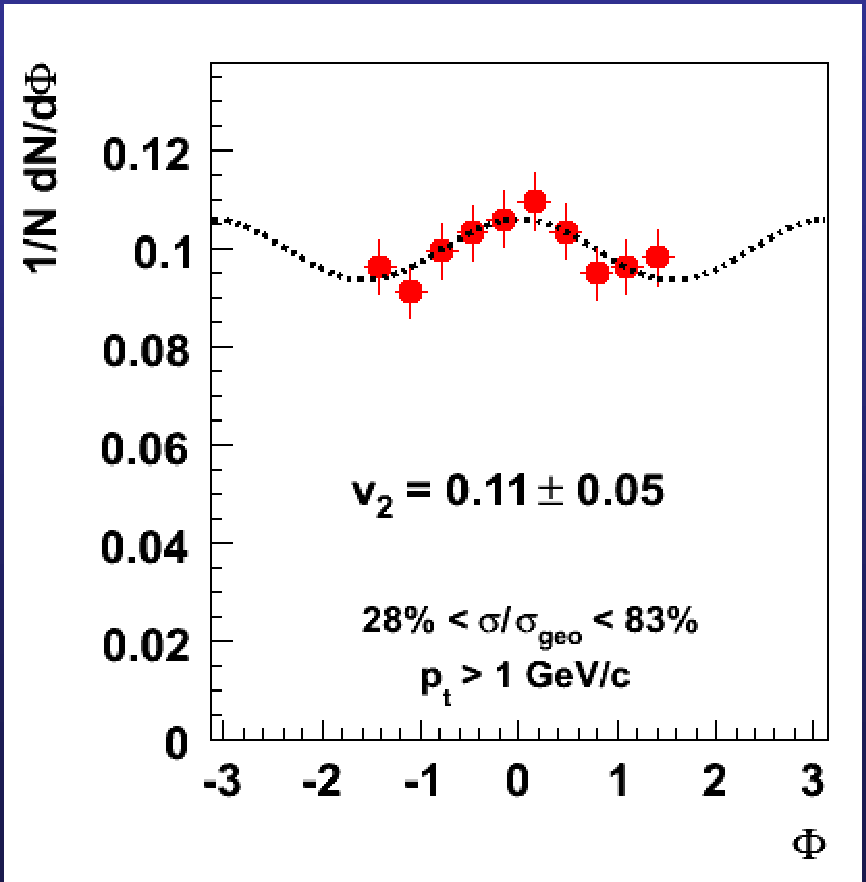


v_2 consistent with zero for central events, $v_2 > 0$ (2.3σ) for peripheral

J/ψ azimuthal anisotropy

- Introduce a rough p_T binning

Centrality	p_t<1GeV/c	p_t>1GeV/c
0.5% < σ/σ_{geo} < 28%	0.00 0.03	-0.01 0.03
28% < σ/σ_{geo} < 83%	0.03 0.05	0.11 0.05

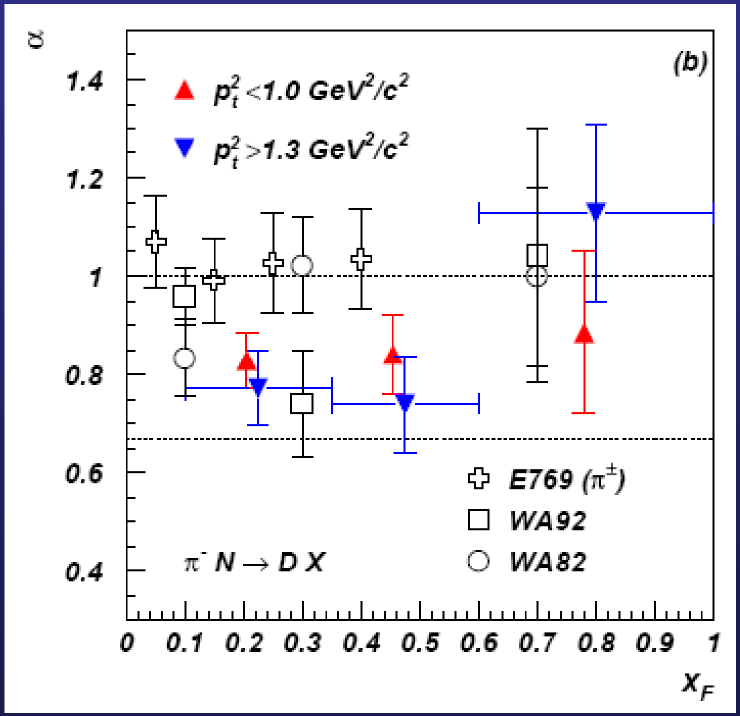


- In spite of the relatively low statistics, we see an anisotropy for peripheral events, concentrated at high p_T
- Hardly a signal of elliptic flow (charm collective motion), since at SPS
  - N_{cc} is low (no recombination)
  - Difficult to have charm thermalisation
- Effect likely to be connected with anisotropic absorption in QGP/nuclear matter

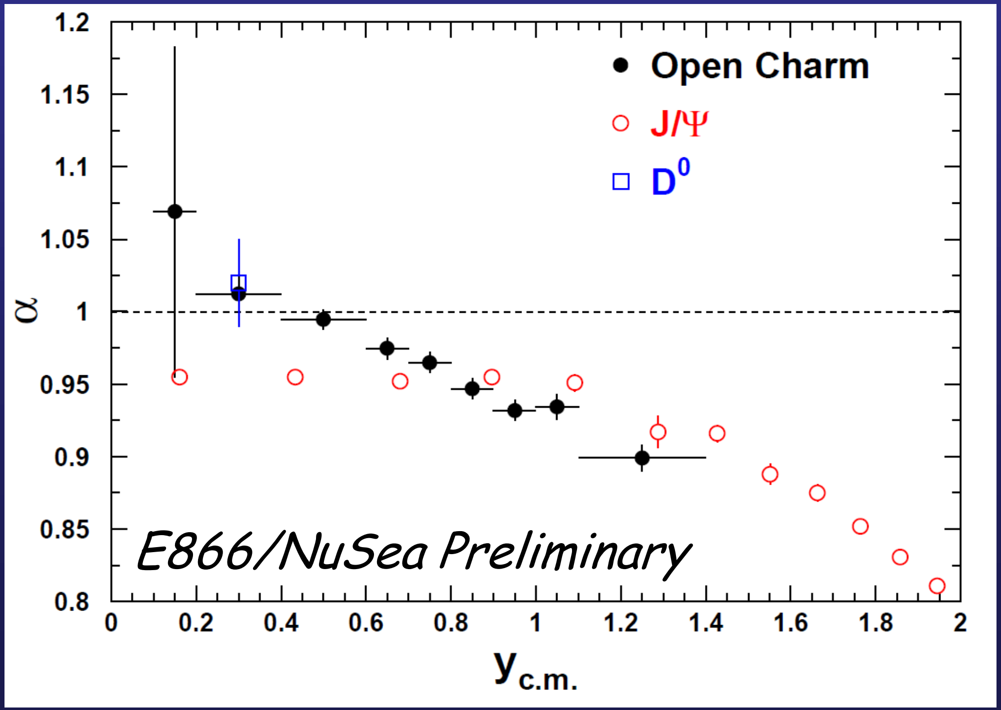
Open charm production in p-A collisions

- Open charm shares initial state effects with charmonium
  → a measurement of open charm in p-A collisions may help in understanding J/ψ suppression

- Recent results from SELEX and E866 suggest rather strong nuclear effects on open charm



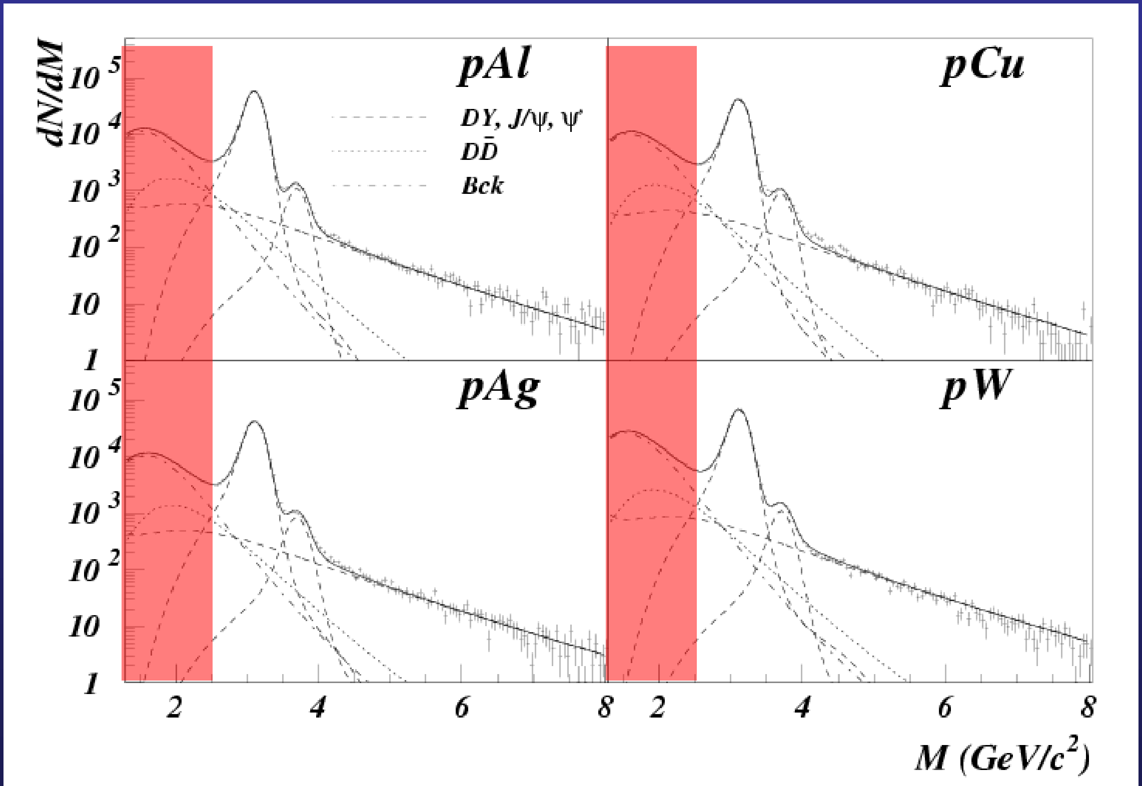
A. Blanco et al. (SELEX), EPJC64(2009) 637



M. Leitch (E866), workshop on "Heavy Quarkonia Production in Heavy-Ion Collisions", ECT* 2009

Open charm dimuons in p-A: NA60

- NA50 tried to evaluate DD production studying the IMR in pA
  → Large background levels (S/B ~0.05 at $m_{\mu\mu}$ = 1.5 GeV/c^2)



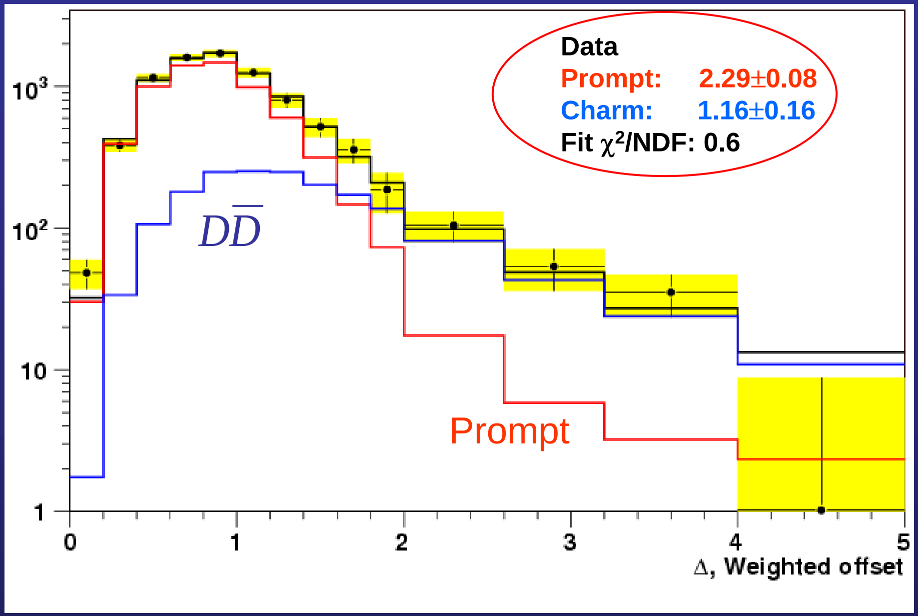
NA50 had to impose a constant DD/DY vs A (i.e. $\alpha_{DD} = \alpha_{DY} \sim 1$)

M.C. Abreu et al., EPJC14(2000) 443

- NA60 is much better placed, thanks to the muon matching
  → S/B is ~60 times more favourable

IMR in NA60: pA collisions

- Best option: separate DD and DY in the IMR using the offset information, obtained in the vertex detector



- Successfully done for In-In collisions

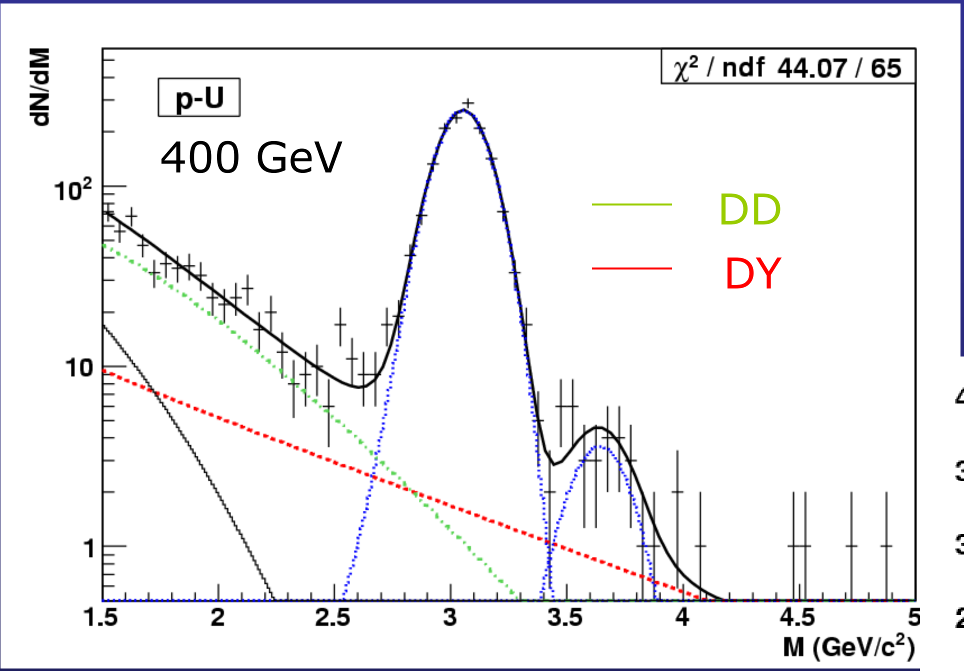
(R. Arnaldi et al., EPJC59(2009)607)

- In p-A because of the smaller multiplicity, accuracy on vertex determination is smaller

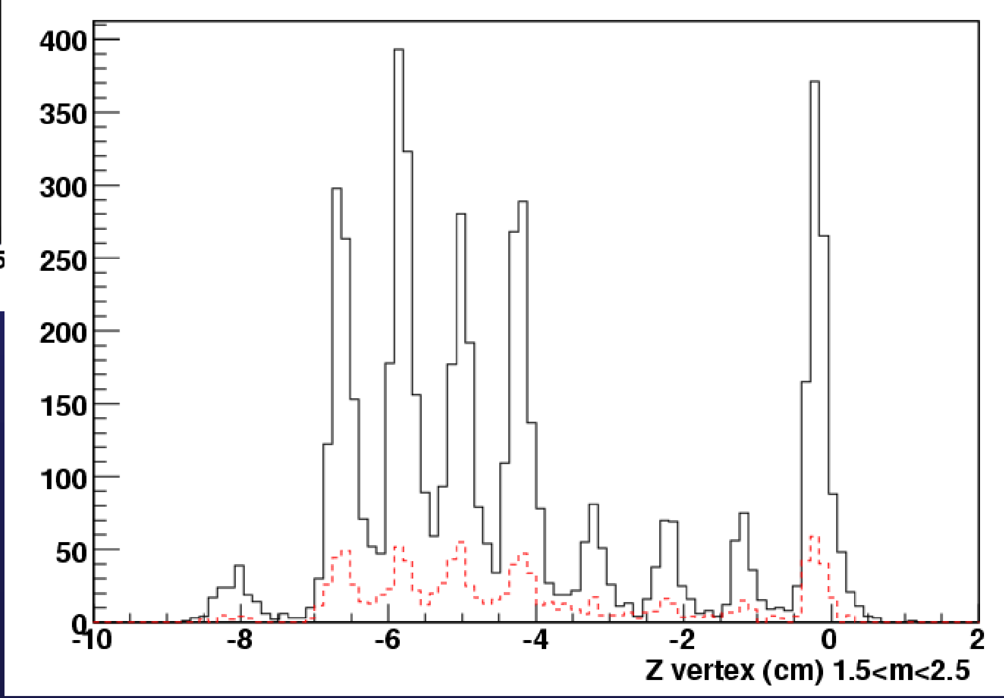
- Possible solution
  - Use the ratios ψ/DY from NA50 to fix the DY contribution (not well constrained in NA60 because of the small statistics)
  - Fit the IMR as DD+DY, after subtracting the small comb. bckgr.

Open charm dimuons in p-A: NA60

- Take ψ/DY ratios from EPJC48(2006)329 (NA50) to fix the DY contribution



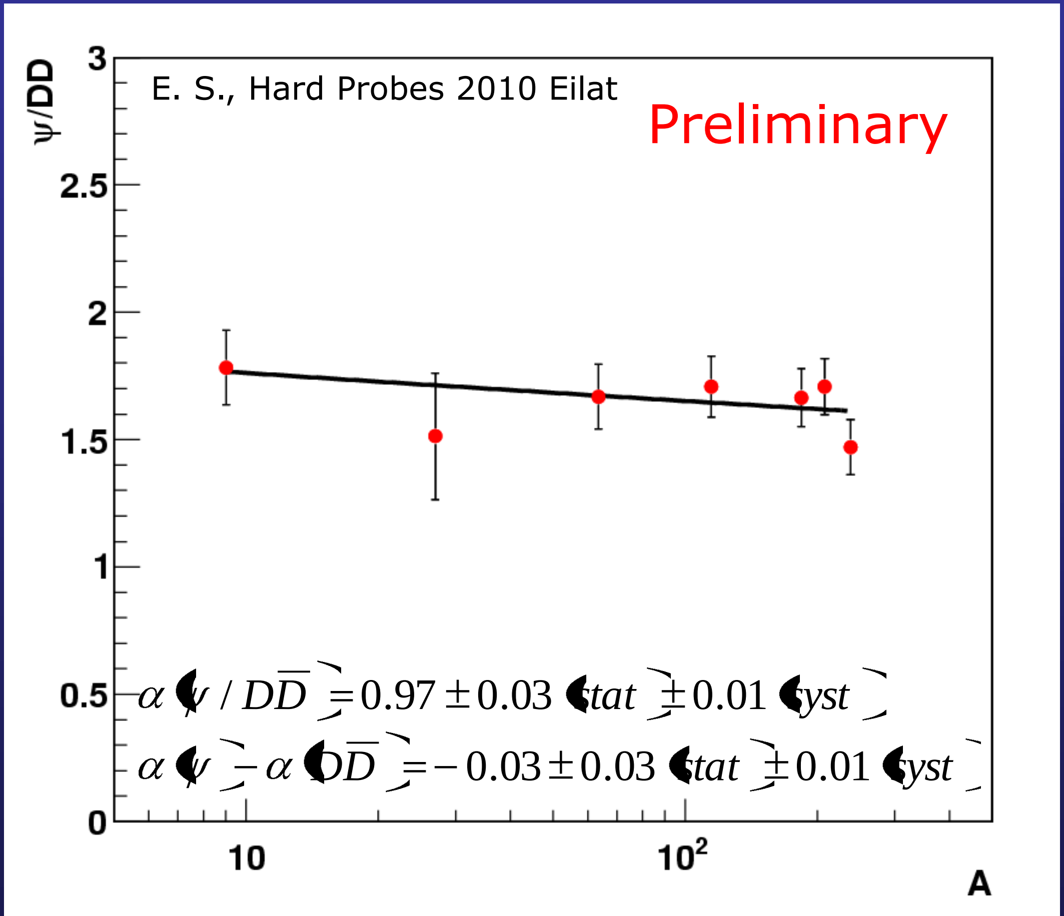
- Good resolution on the longitudinal position of the vertex in the IMR (no problem in target assignment)



- Results given for the 400 GeV sample only (at 158 GeV DD contribution much smaller than DY)

Open charm dimuons in p-A: results

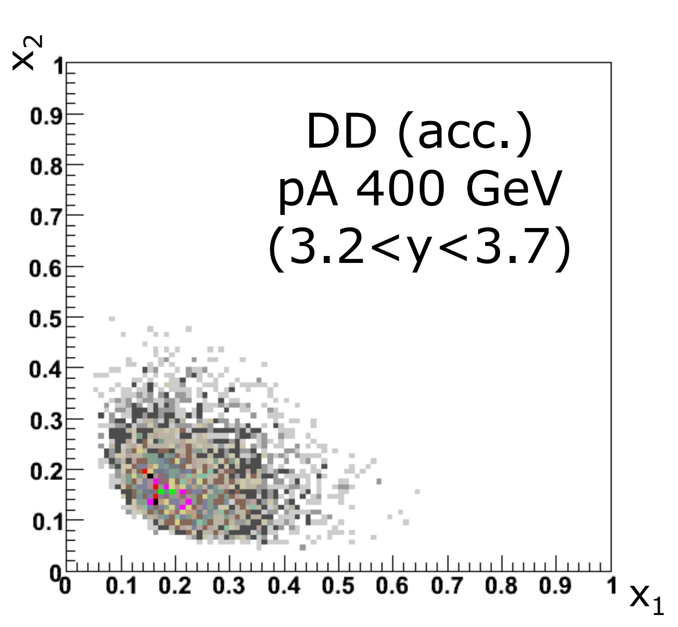
- Kinematic range: $3.2<y_{lab}<3.7$ $(-0.17<y_{cm}<0.33)$
- Study the ratio ψ/DD (reduce systematic errors)

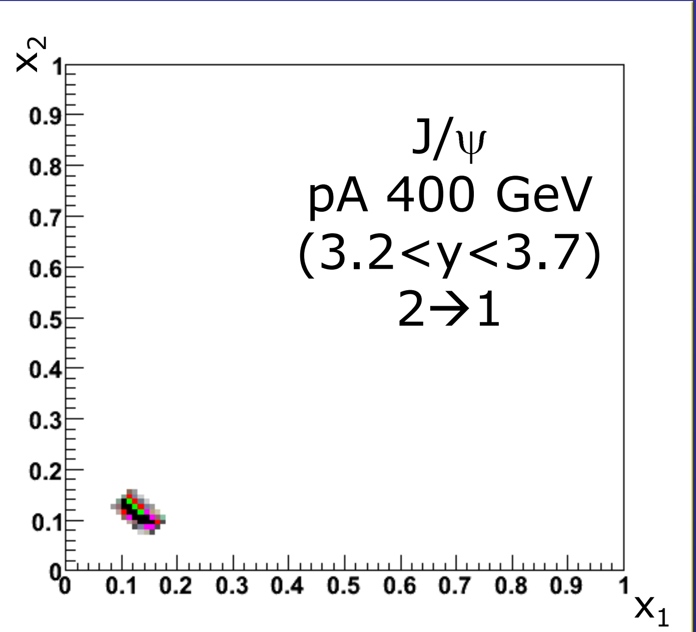


- Systematic errors
  - Fit starting point
  - Track χ^2
  - ψ/DY (norm. and $\alpha_{J/\psi}$)
  - Background normalization

- Using the measured $\alpha_{J/\psi}$ value one gets $\alpha_{DD} = 0.96\pm0.03$
- Anti-shadowing would suggest $\alpha_{DD} > 1$

Open charm kinematics

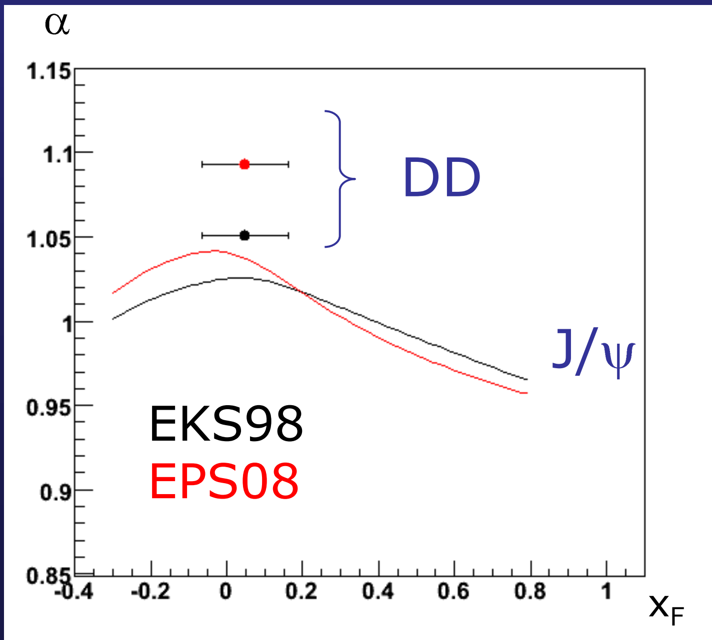




- Calculate the expected α for DD pairs decaying into muons in the NA60 acceptance (400 GeV protons)

- Antishadowing for DD should be even stronger than for the J/ψ
- If DD has little final state interactions its α should be significantly larger than that of the J/ψ (initial state energy loss should be the same)....

...but the difference we see in data is rather small



Conclusions

- J/ψ suppression studies at the SPS: large statistics for both A-A and p-A collisions

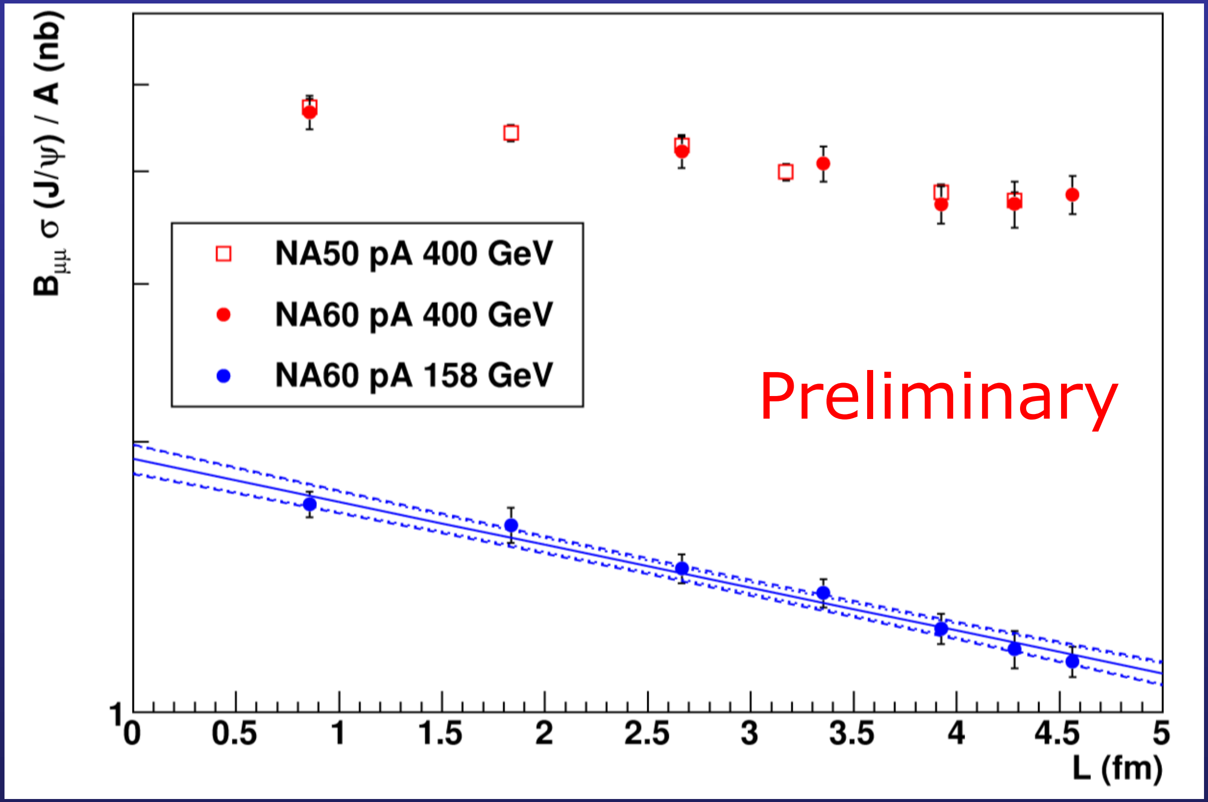
- Pb-Pb data exhibit a significant suppression beyond CNM effects
- In-In (and S-U) data show almost no anomalous suppression

- Comparison between SPS and RHIC results in terms of anomalous suppression: good (qualitative) agreement in terms of energy density

- Preliminary results from open charm production in pA at the SPS: J/ψ more suppressed than DD, but measured α_{DD} disagrees with anti-shadowing expectations

New result: J/ψ cross section in pA

- J/ψ production 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

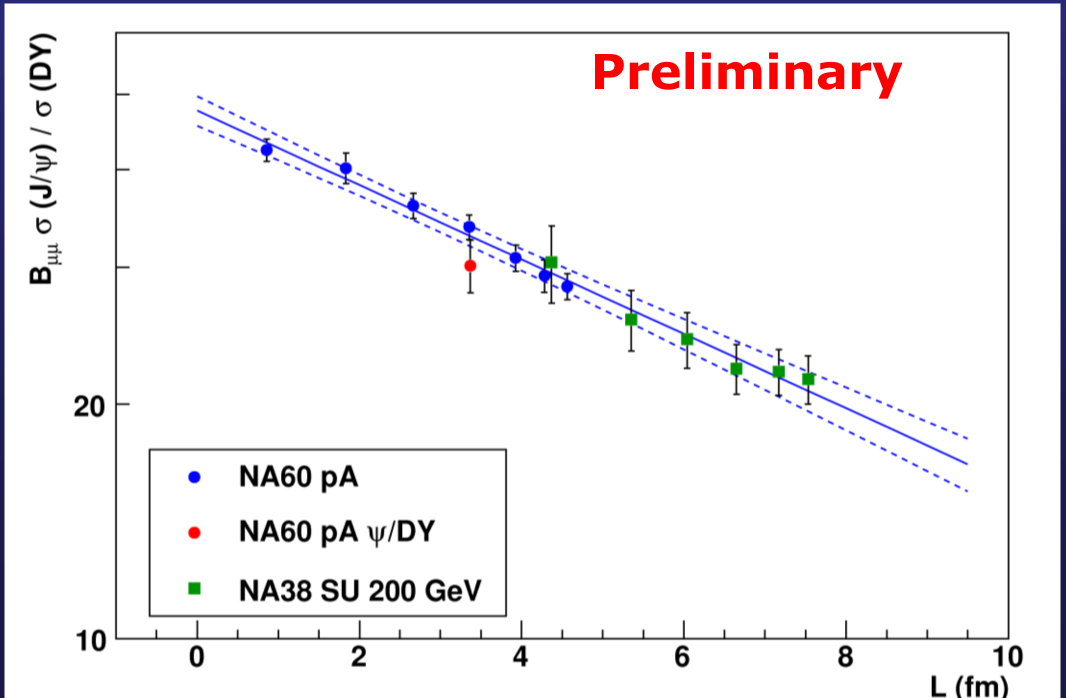
New reference using J/ψ cross sections

- Alternative approach for the normalization of the pA reference curve based on the pA J/ψ absolute cross section
- To fully profit from this approach, a measurement of the absolute J/ψ cross section in In-In would be needed. For the moment…
  - J/ψ/DY values are obtained rescaling the DY cross section measured at 450 GeV by NA50 (not enough statistics at 158 GeV)
  - Main advantage: no assumption on SU, since it is not used anymore in the fit

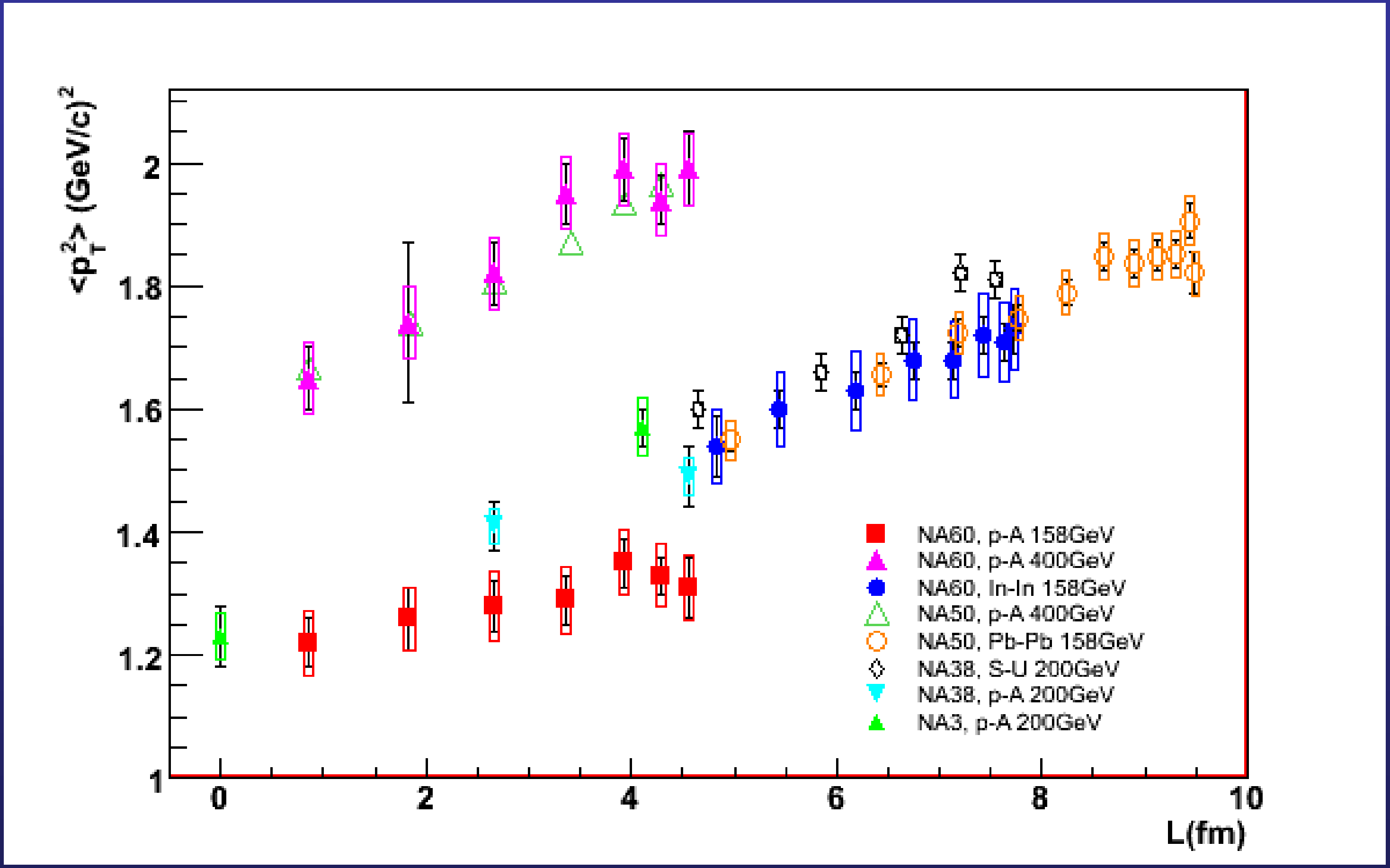
No practical consequence on anomalous J/Ψ suppression

⬇

difference with previous CNM reference ~1% well within errors



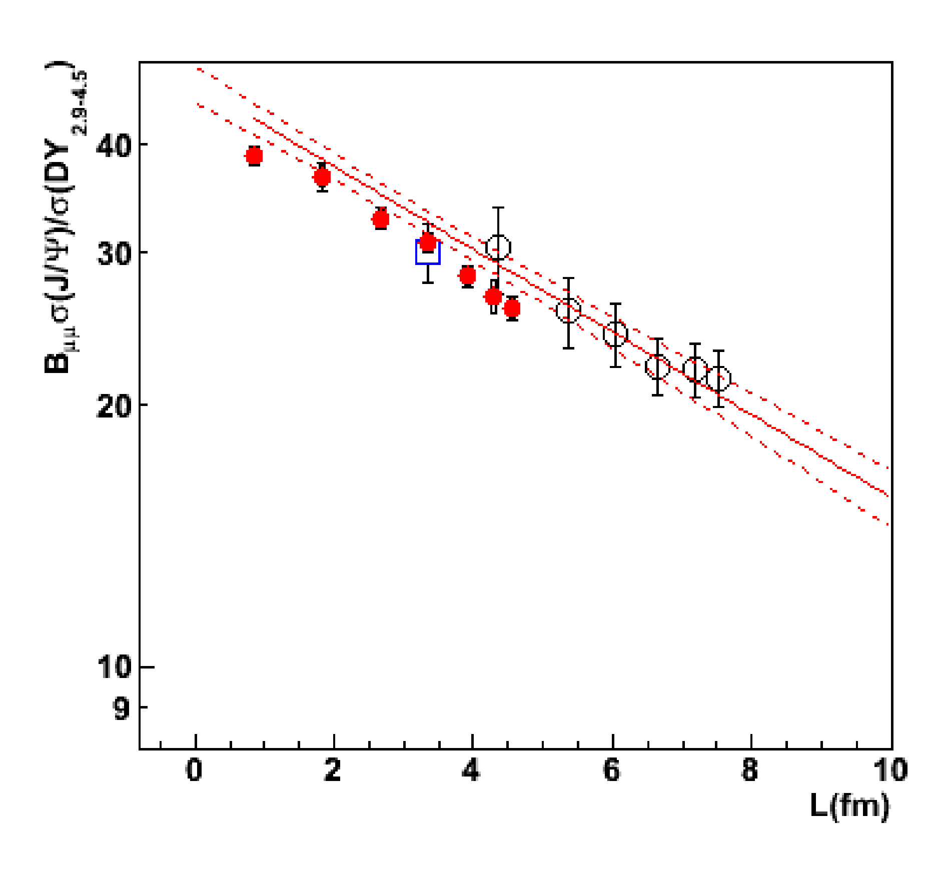
p_T spectra: some more data points

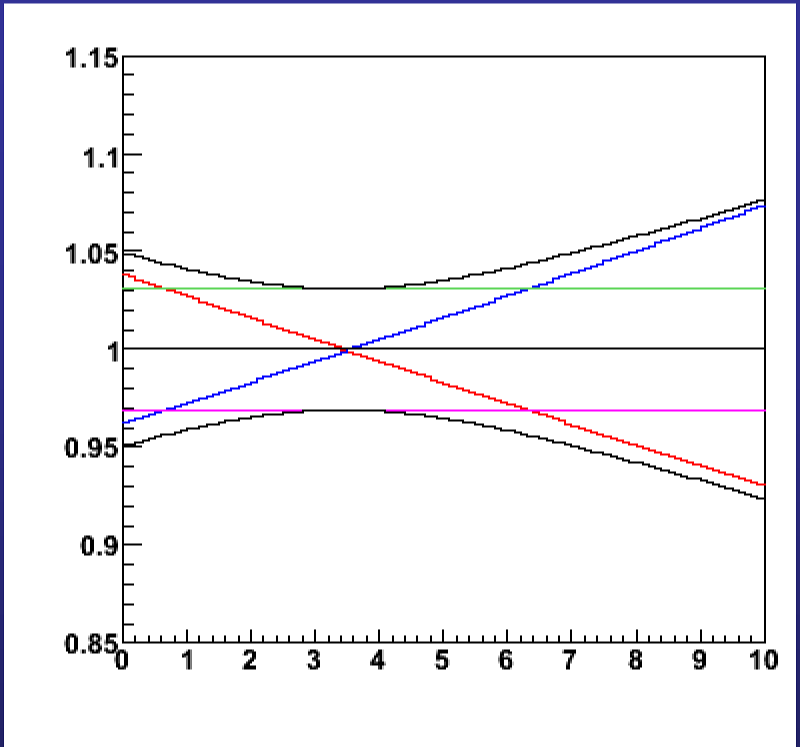


Systematic errors explicitly quoted, when available

- In the literature, one can find a few more measurements of $\langle p_T^2 \rangle$ in this energy range (NA3, NA38 at 200 GeV)

- These experiments seem to suggest a higher $\langle p_T^2 \rangle$ (~ 15%) with respect to the NA60 points → now checking relative systematics in detail



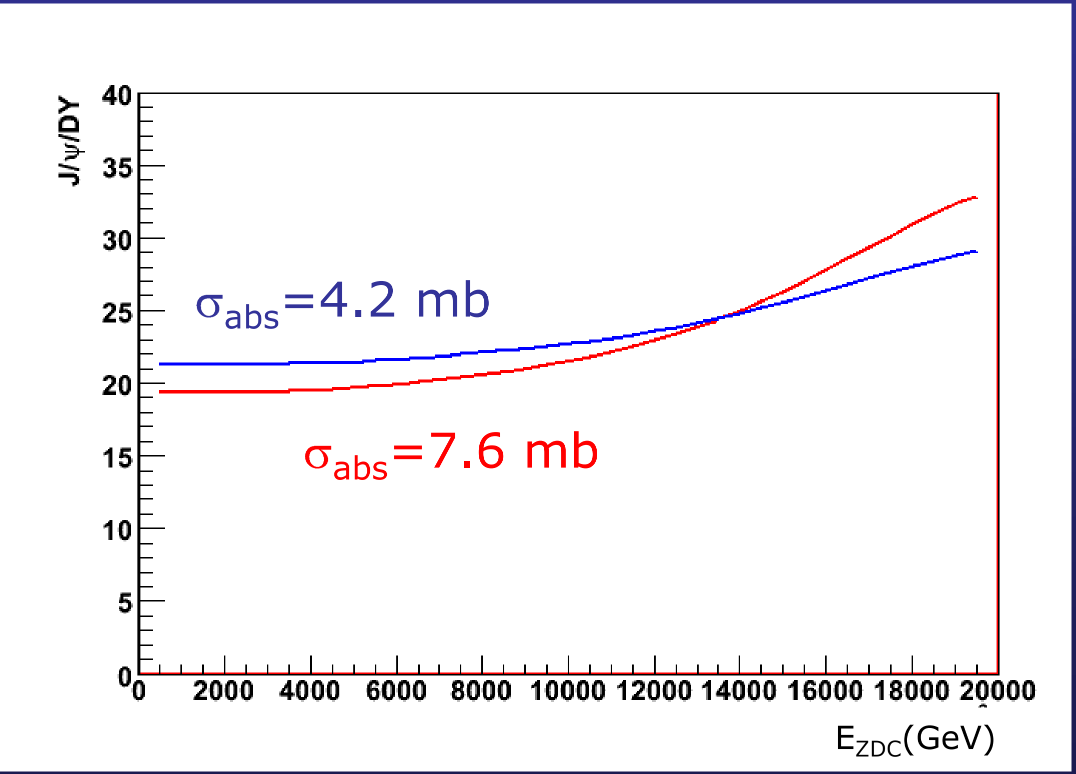


Assuming maximum correlation
between the errors on the
normalization and sigmaabs

$\sigma_{abs}^{J/\psi}$ and normalization

In order to obtain the AA reference curve vs. centrality, $(\sigma_{J/\psi} / \sigma_{DY})\ |^{pp}_{158GeV}$ is needed

→ obtained extrapolating $(\sigma_{J/\psi} / \sigma_{DY})\ |^{pA,SU}_{158GeV}$ to A=1 (i.e. L=0)



Moving from the 400/450GeV based reference to the 158GeV based reference, both σ_{abs} and $(\sigma_{J/\psi} / \sigma_{DY})\ |^{pp}_{158GeV}$ have changed