Cronin Effect at Different Rapidities at FERMILAB and at RHIC

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in collaboration with:
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George Fai – Kent State University;

4th Budapest Winter School on
Heavy Ion Collision
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Nuclear Effects at High-Energy/1 – Cronin Effect, $R_{AA'}$

(a) Discovery of Cronin effect:

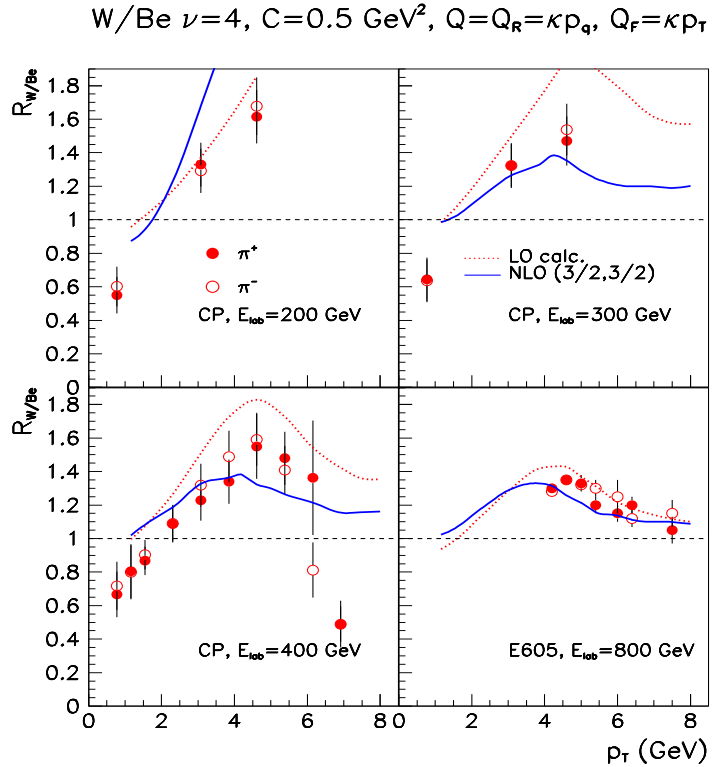
increased particle production in

3 GeV $< p_T <$ 6 GeV range (1975)

"increased" means more particles

are produced in pA than expected

from N_{bin} scaled pp collisions



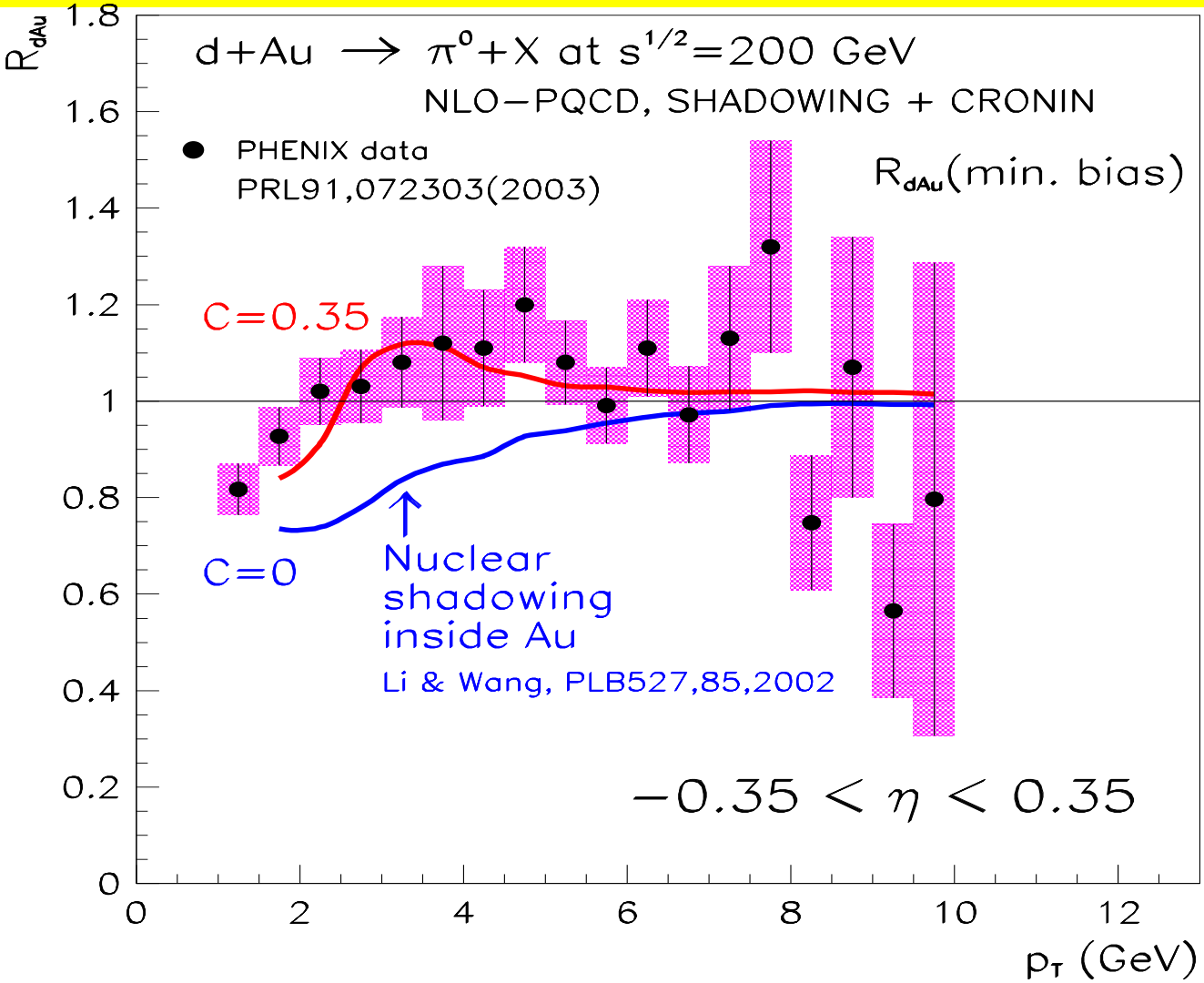
Nuclear modification factor

→ measuring Cronin effect:

$$R_{AA} = \frac{1}{N_{bin}} \frac{\mathrm{d}N_{AA}/\mathrm{d}y\ \mathrm{d}^2p_T}{\mathrm{d}Npp/\mathrm{d}y\ \mathrm{d}^2p_T}$$

D. Antreasyan *et al.* Phys. Rev. **D19**, 764 (1979)
C.N. Brown *et al.* Phys. Rev **C54**, 3195 (1996)
Y. Zhang *et al.* Phys. Rev **C65**, 034903 (2002)

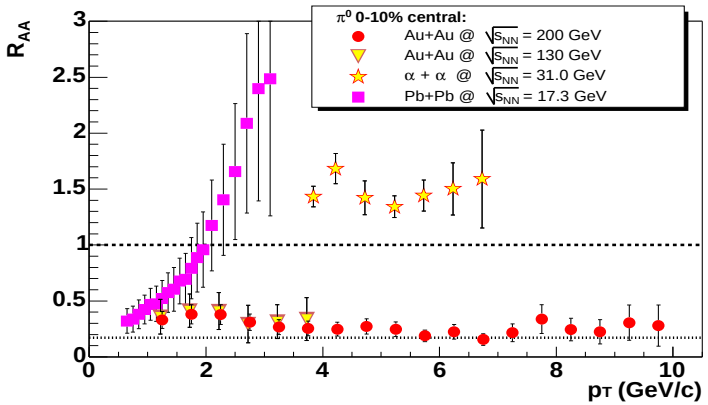
Cronin Effect – Nuclear Modification Factor

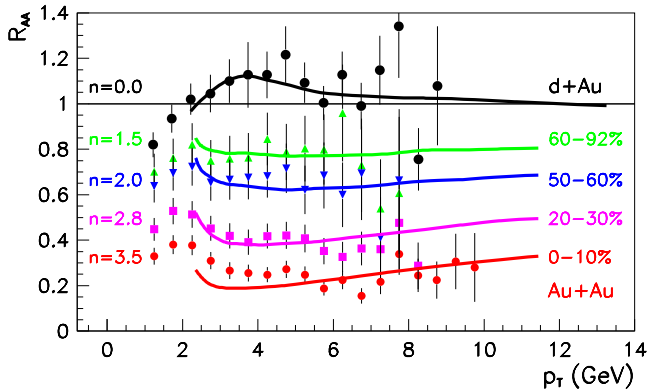


$$R^{\pi}_{AA'} := \frac{d\sigma^{AA'\to\pi}/d^3p\,(\text{"shadowing+multiscattering"})}{d\sigma^{AA'\to\pi}/d^3p\,(\text{"NO nuclear effect"})}$$

Nuclear Effects at High Energies/2 – at RHIC

(b) $R_{AA'}$ and π spectra in $AuAu$ and dAu by PHENIX, $y = 0$

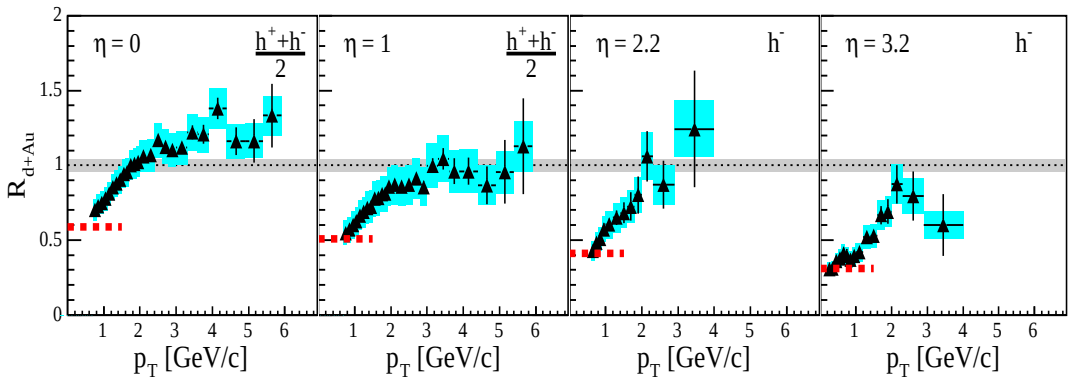




See P.Lévai's talk

Suppression in π spectra in $AuAu$ at RHIC $\Longrightarrow$ QGP
Test: NO Suppression in dAu at RHIC $\Longrightarrow$ Jet-quenching

(c) Suppression in h^+, h^- spectra in dAu by BRAHMS, $\eta > 0$



Conventional or new nuclear effect?

Questions and Program

0. Nuclear effects at high energies? – History
Does initial <u>or</u> final state eff. generate π suppression?

Hadronic model: $\Longrightarrow$ final state effects

Partonic model: $\Longrightarrow$ initial state effects (stronger shadowing)
$\Longrightarrow$ final state effects (jet quenching)

I. pQCD calculations – with nuclear shadowing only?

II. Cronin effect in pQCD improved parton model
Multiple scattering in saturated Glauber picture ?

k_T-broadening $\rightarrow$ Cronin effect reproduction at $\boxed{y = 0}$

R_{dAu} results for dAu PHENIX data

III. dAu PHOBOS, BRAHMS and STAR data at $\boxed{\eta > 0}$

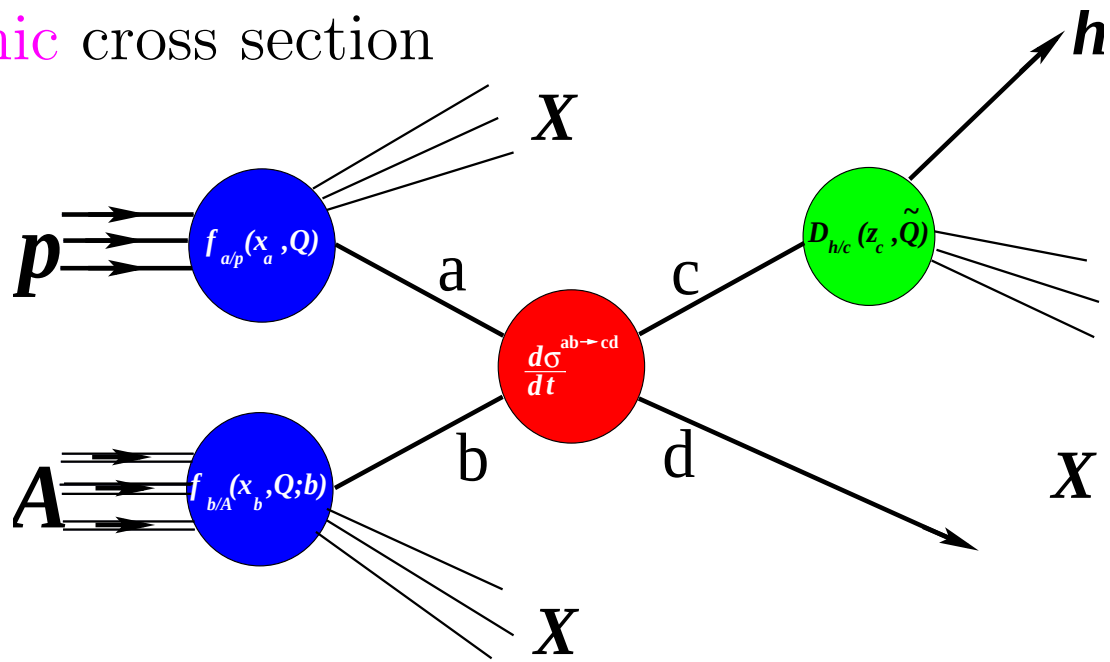
I/1. pQCD Improved Parton Model for pA Collisions

$$E_\pi \frac{\mathrm{d}\sigma_\pi^{pA}}{\mathrm{d}^3 p_\pi} \sim f_{a/p}(x_a, Q^2; k_T) \otimes f_{b/A}(x_b, Q^2; k_T, b) \otimes \frac{\mathrm{d}\sigma^{ab\to cd}}{\mathrm{d}\hat{t}} \otimes \frac{D_{\pi/c}(z_c, \widehat{Q}^2)}{\pi z_c^2}.$$

$f_{a/A}(x_a, Q^2; k_T, b)$: Parton Dist. Function (PDF), at scale Q^2

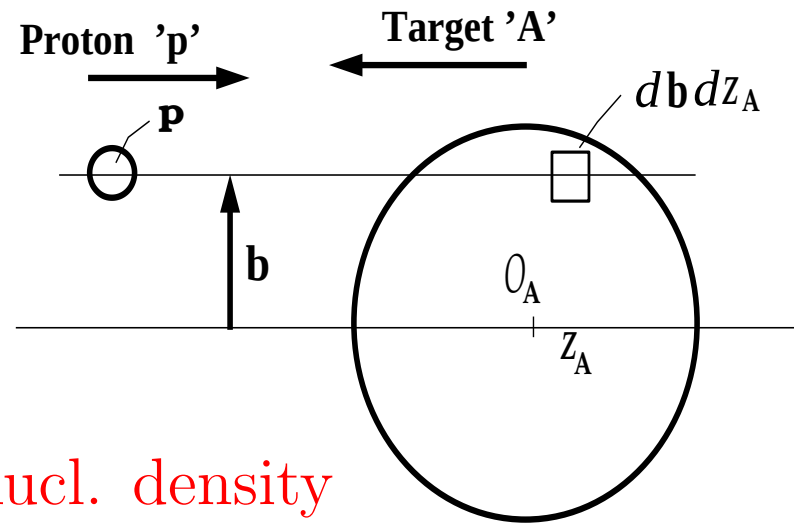
$D_{\pi/c}(z_c, \widehat{Q}^2)$: Fragmentation Function for π (FF), at scale $\widehat{Q}^2$

$\frac{\mathrm{d}\sigma^{ab\to cd}}{\mathrm{d}\hat{t}}$: Partonic cross section



I/2. Collision Geometry and Shadowing in $pA \to \pi$

$$E_\pi \frac{\mathrm{d}\sigma_\pi^{pA}}{\mathrm{d}^3 p} = \int \mathrm{d}^2 b\, t_A(b) \int \ldots f_{a/A}\left(x_a, Q^2; \ldots\right) \ldots$$



(a) **Nuclear thickness function:**

$t_A(b) = \int dz\, \rho(b,z)$ and normalized as:

$$A = \int_0^{b_{max}} t_A(b) \mathrm{d}^2 b \text{ , where } \rho(b,z) \text{ nucl. density}$$

(b) **Nuclear Shadowing – modified PDFs inside nucleus**

$$f_{a/A}\left(x, Q^2; b\right) = S_a^A(x,b) \left[\frac{Z}{A} f_{a/p}\left(x, Q^2\right) + \left(1 - \frac{Z}{A}\right) f_{a/n}\left(x, Q^2\right)\right]$$

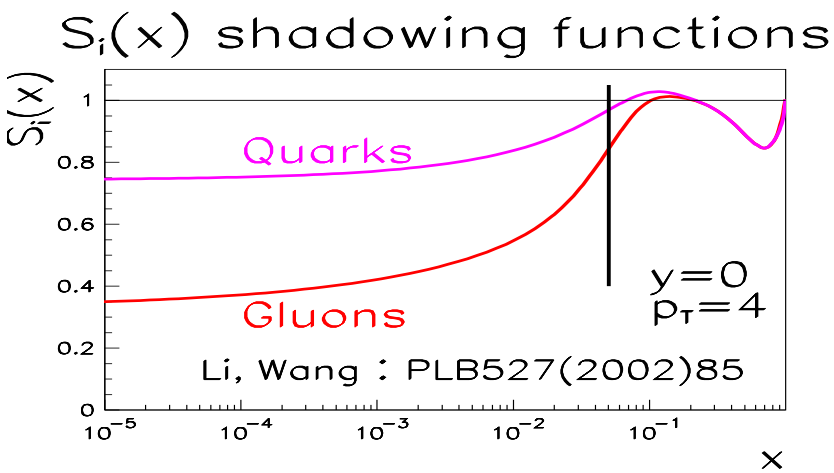
$S_a^A(x,b)$: b-dependent or independent shadowing function;
HIJING: S. Li, X.-N. Wang: Phys.Letts. **B527**,85(2002)
A atomic- and Z the proton number

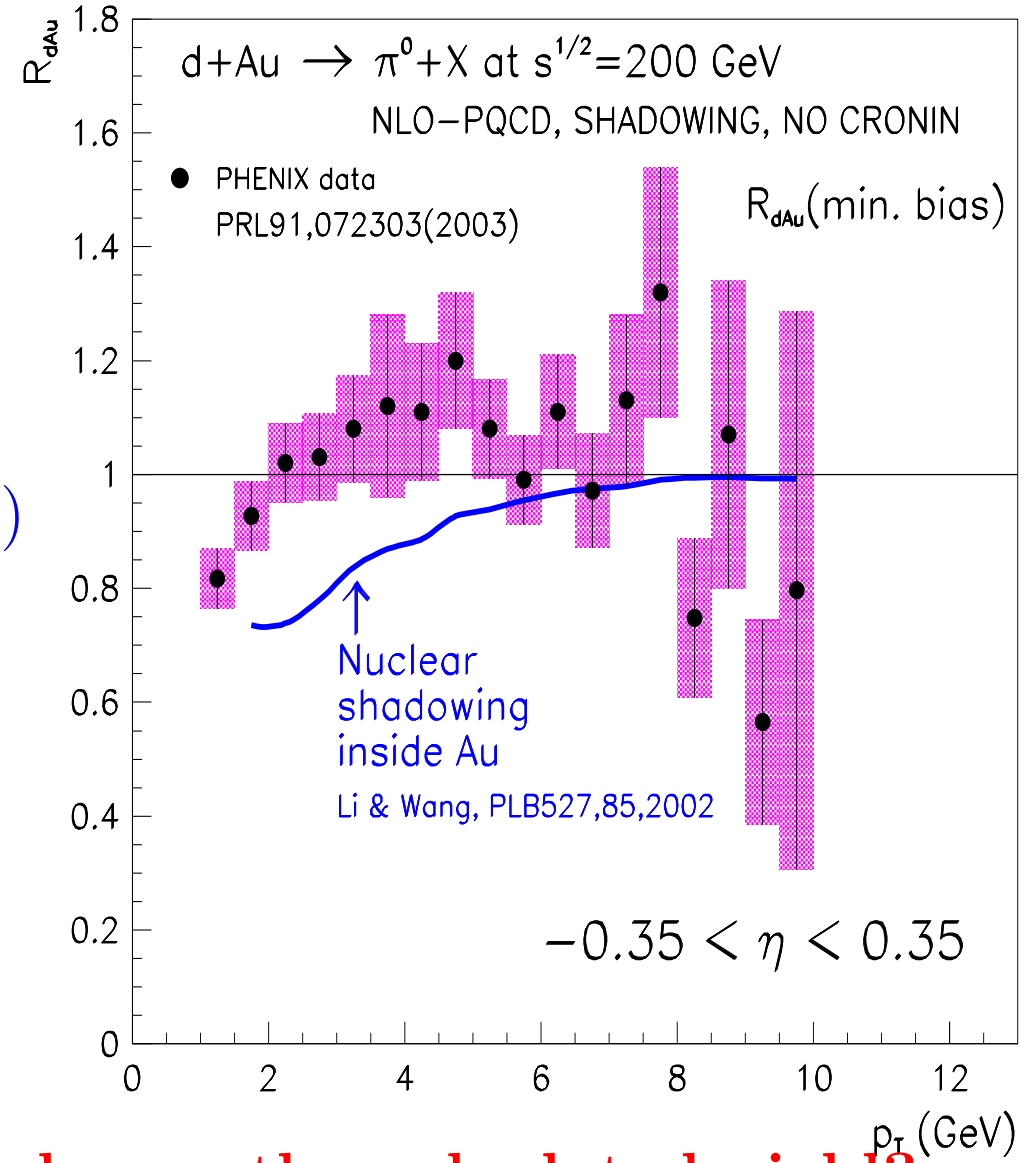
I/3. Nuclear Modification Factor for dAu at $\sqrt{s}$ =200 GeV

- **PHENIX data** at $\boxed{y = 0}$

Phys. Rev. Lett. **91**, 072303 (2003)

- **Shadowing inside nucleus** is small effect at PHENIX at $y = 0 \Longleftrightarrow$ we are at moderate-x region ($\langle x \rangle \sim 0.05$)





Is multiscattering able to enhance the calculated yield?

II/1. Theoretical Model – Reproduction of Cronin Effect

Introducing intrinsic k_T for colliding partons

Phenomenological assumption: PDFs are modified

1 dimensional PDFs are changed to 1+2 dimensional ones

$$\mathrm{d}x\, f_{a/p}(x, Q^2) \longrightarrow \mathrm{d}x\, \mathrm{d}^2 k_T\; g_{pp}(\vec{k}_T)\; f_{a/p}(x, Q^2)$$

where $g(\vec{k}_T)$ is a Gauss distribution function :

$$g_{pp}(\vec{k}_T) = \frac{e^{-\vec{k}_T^2/\langle k_T^2\rangle}}{\pi\langle k_T^2\rangle} \quad \text{and} \quad \langle k_T^2\rangle = \frac{4\langle k_T\rangle^2}{\pi}$$

Baseline $\langle k_T^2\rangle$ values for pp: Phys. Rev. **C65** 034903 (2002)

$\langle k_T^2\rangle \sim$ value agrees with measured values by PHENIX,

II/2. Reproducing Cronin Effect – Multiple Scattering

Saturated NN collison numbers (in $pA \to \pi$)

- improve the Glauber model:

$$E_\pi \frac{\mathrm{d}\sigma_\pi^{pA}}{\mathrm{d}^3 p} = \int \mathrm{d}^2 b \; t_A(b) E_\pi \frac{\mathrm{d}\sigma_\pi^{pp}(\langle k_T^2 \rangle_{pA}, \langle k_T^2 \rangle_{pp})}{\mathrm{d}^3 p}$$

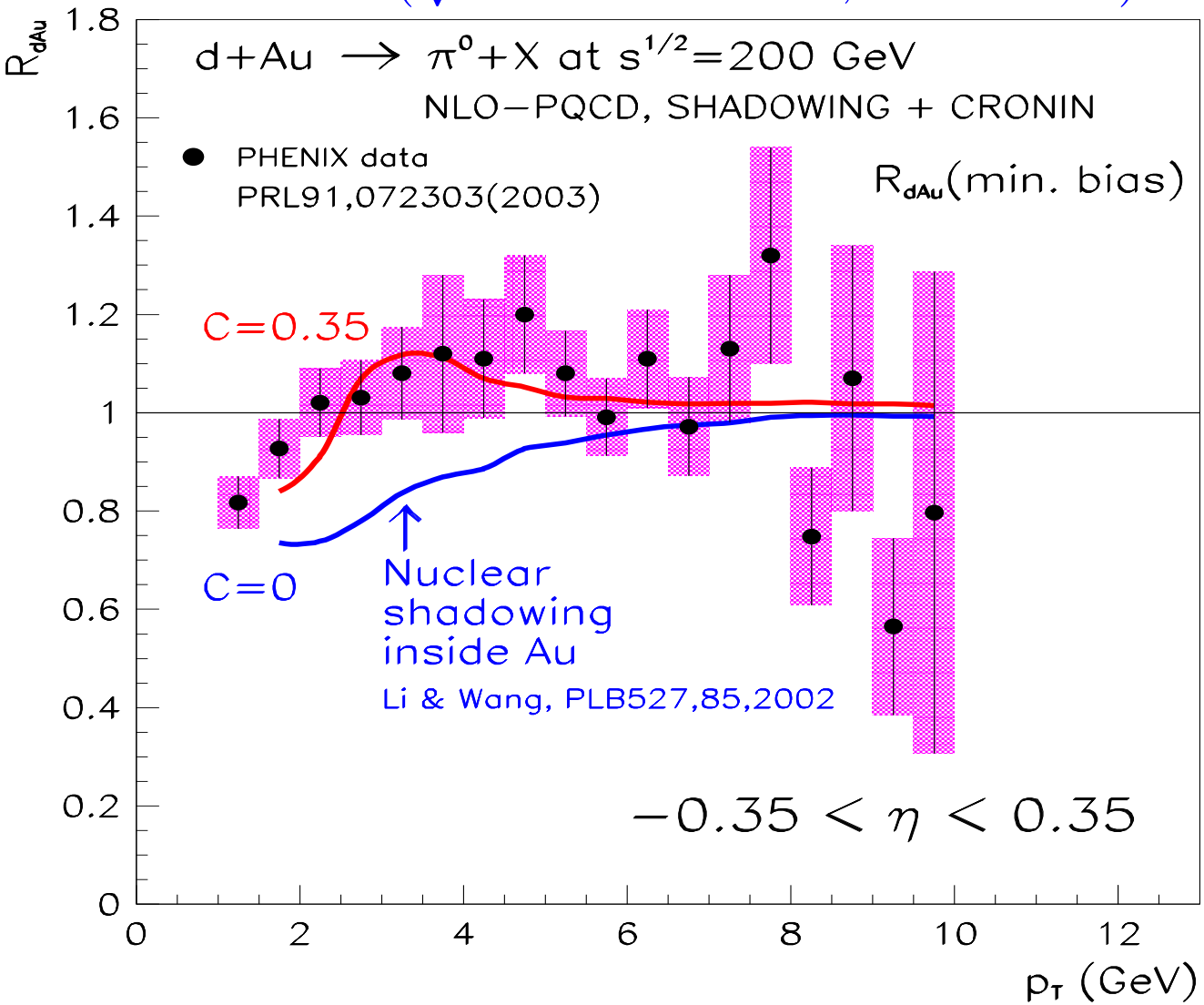
$$\langle k_T^2 \rangle_{pA} = \langle k_T^2 \rangle_{pp} + C \; h_{pA}(b)$$

Total broadening = pp baseline + nuclear broad.

See details in PR**C65** 034903 (2002) and `hep-ph/0212249`

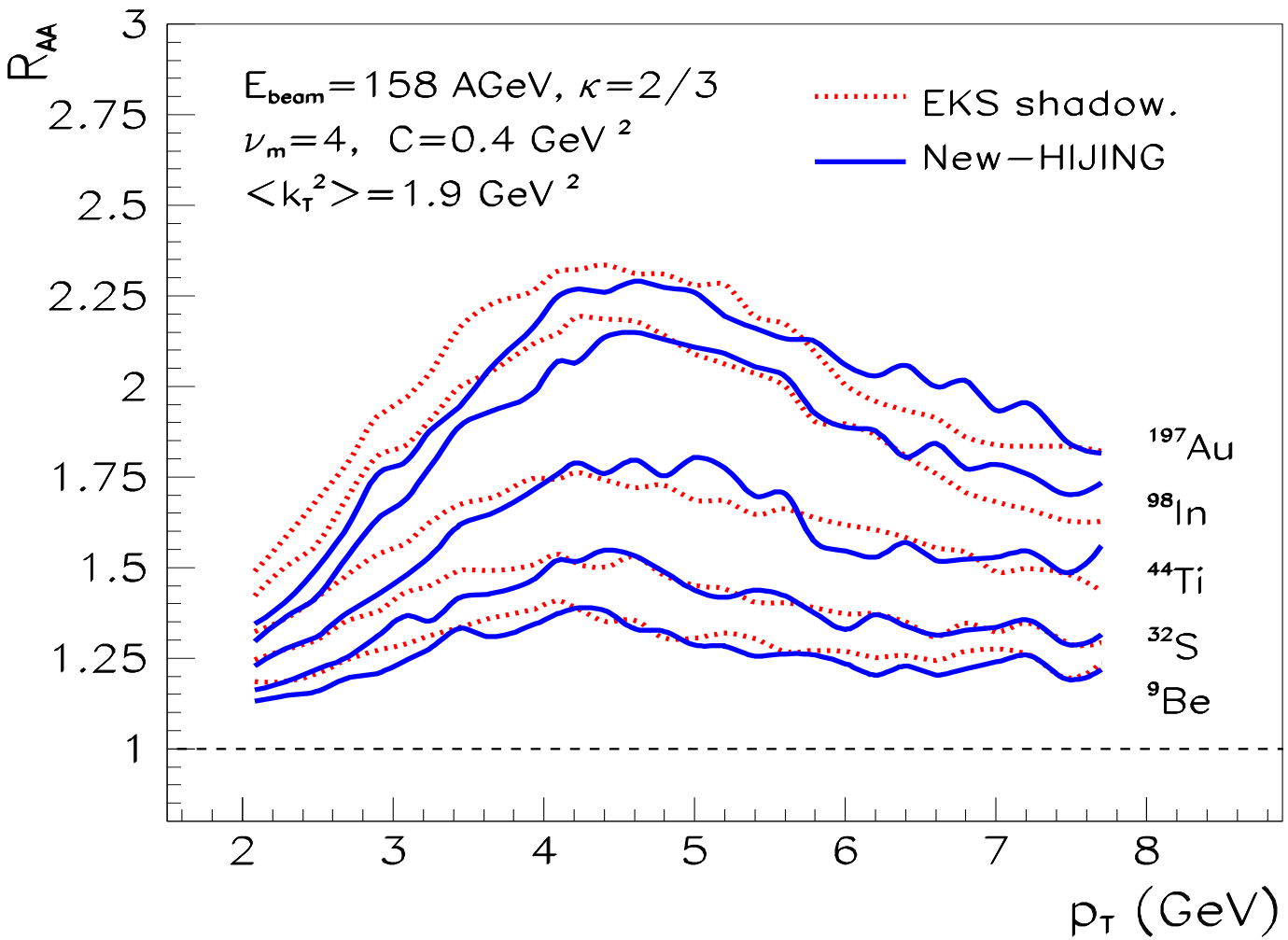
$h(\nu_A(b) - 1)$: number of effective NN collisions $\nu_{max} = 3 - 4$
C : (average mom. broadening)^2 / coll. $C \approx 0.35$ GeV^2
$t_A(b)$: nuclear thickness function

Cronin Effect with shadowing and multiscattering in dAu collision at PHENIX ($\sqrt{s} = 200$ AGeV, min. bias)



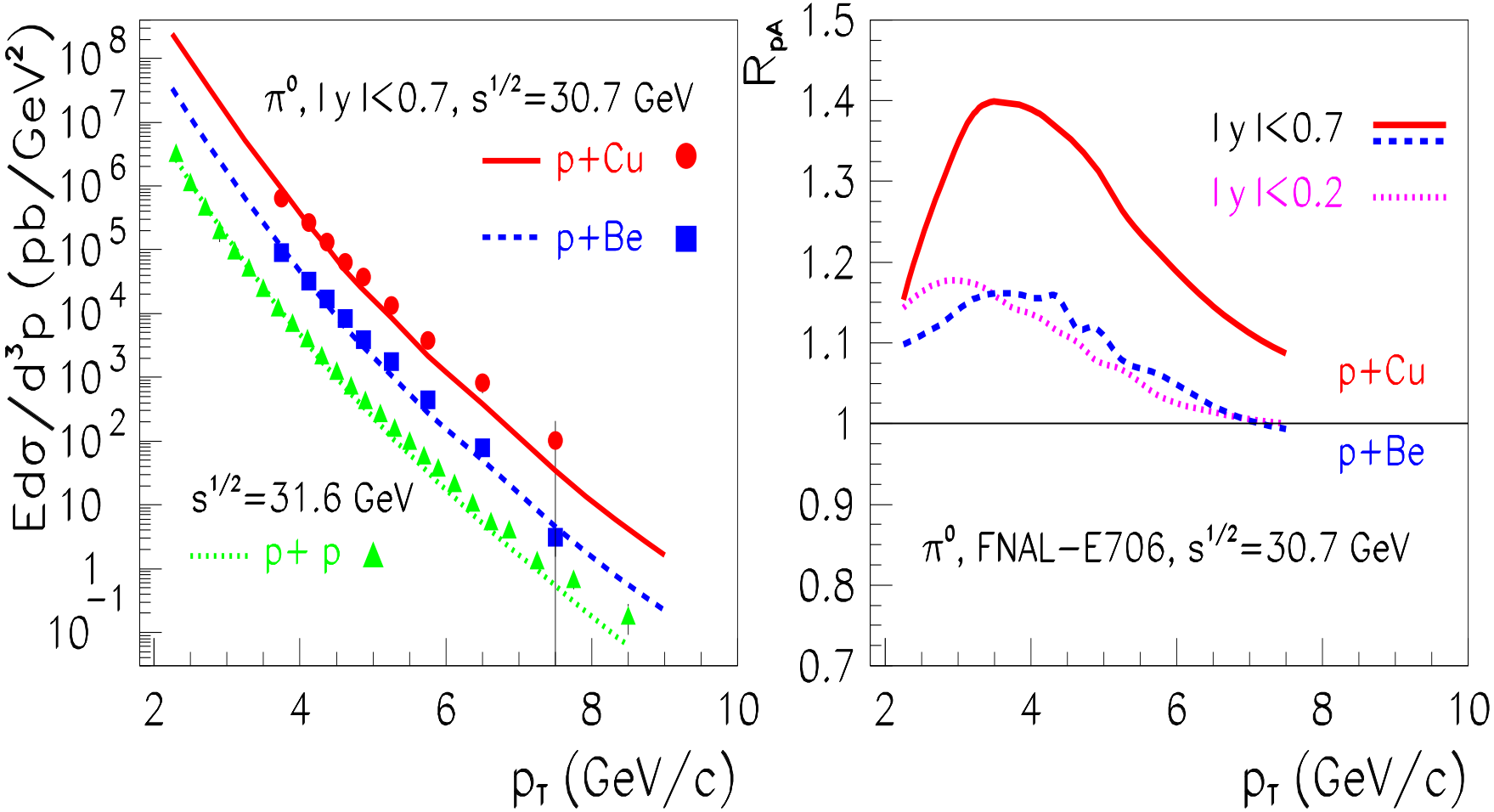
HIJING (b-indep.) shadowing, $\nu_{max} = 4$, $C_{sat} = 0.35$, $y = 0$

Cronin effect for π^0 at midrapidity in different pA collisions at CERN SPS energies



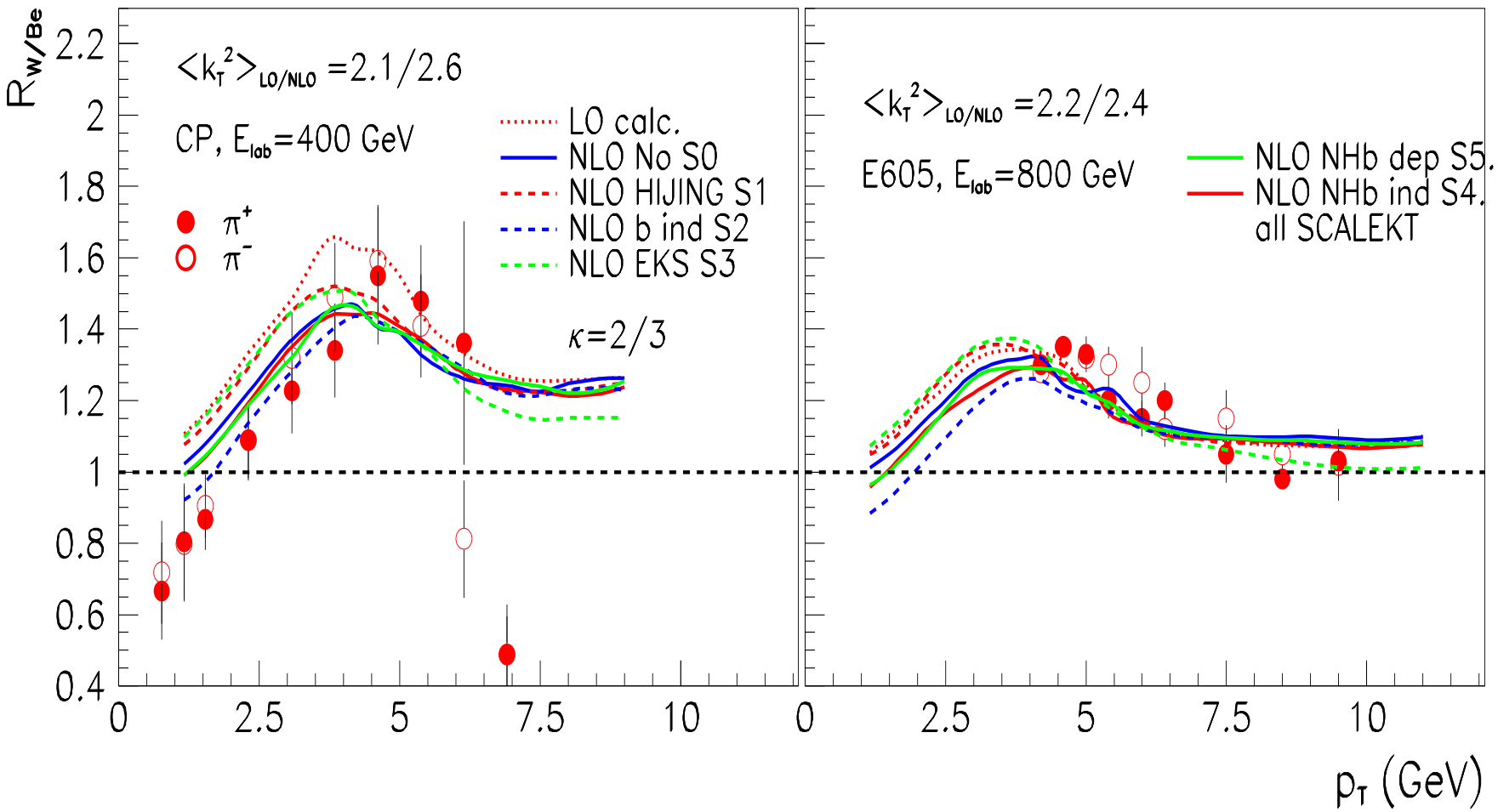
G.G. Barnaföldi *et al.*: Proc. of. 10th ICNRM (2003)

Cronin effect for π^0 at midrapidity in pBe and pCu collision at FNAL E706



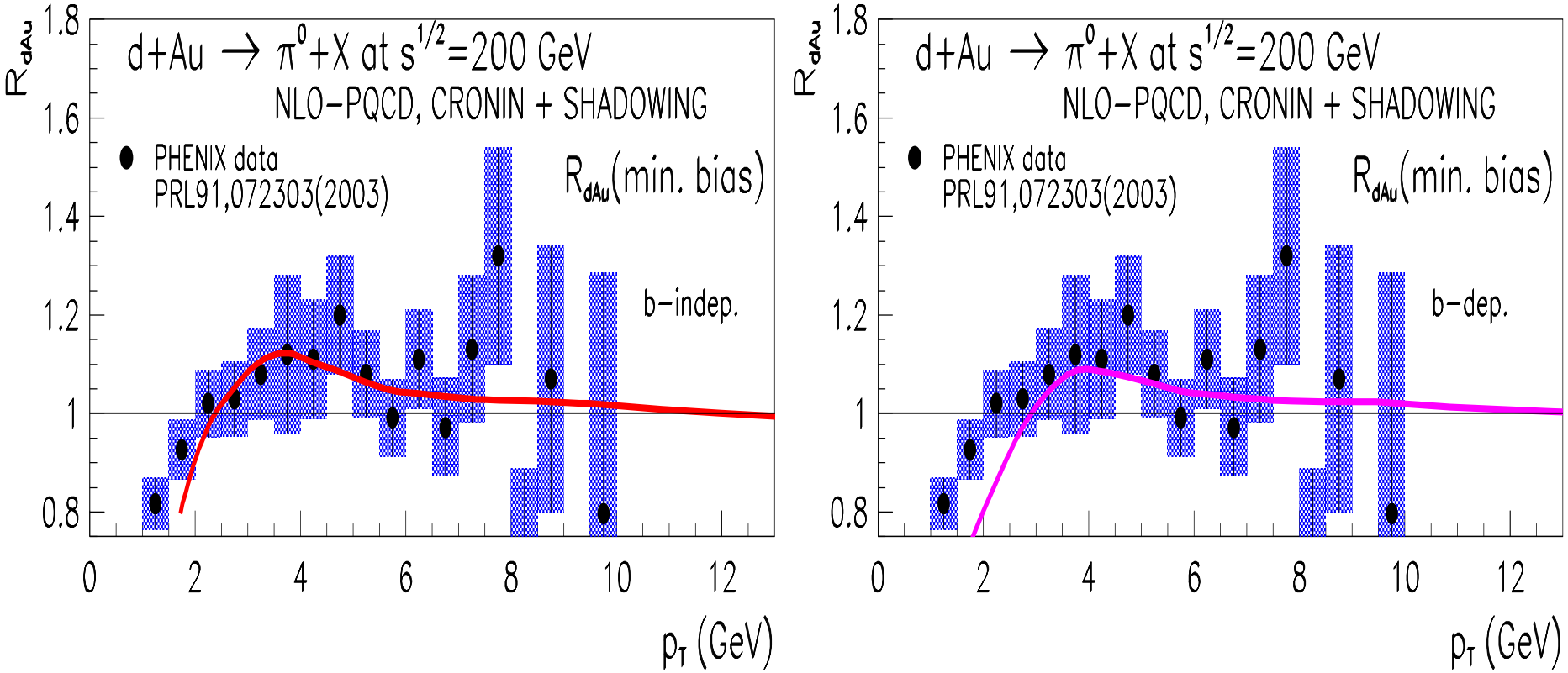
G.G. Barnaföldi *et al.*: APH NS (2004)

$R_{W/Be}(p_T)$ for π^+ and π^- at midrapidity at CP and CCOR



Weak dependence on shadowing at lower energies

Cronin effect with b-independent (left) and b-dependent (right) shadowing in dAu collision at PHENIX (Min. Bias)

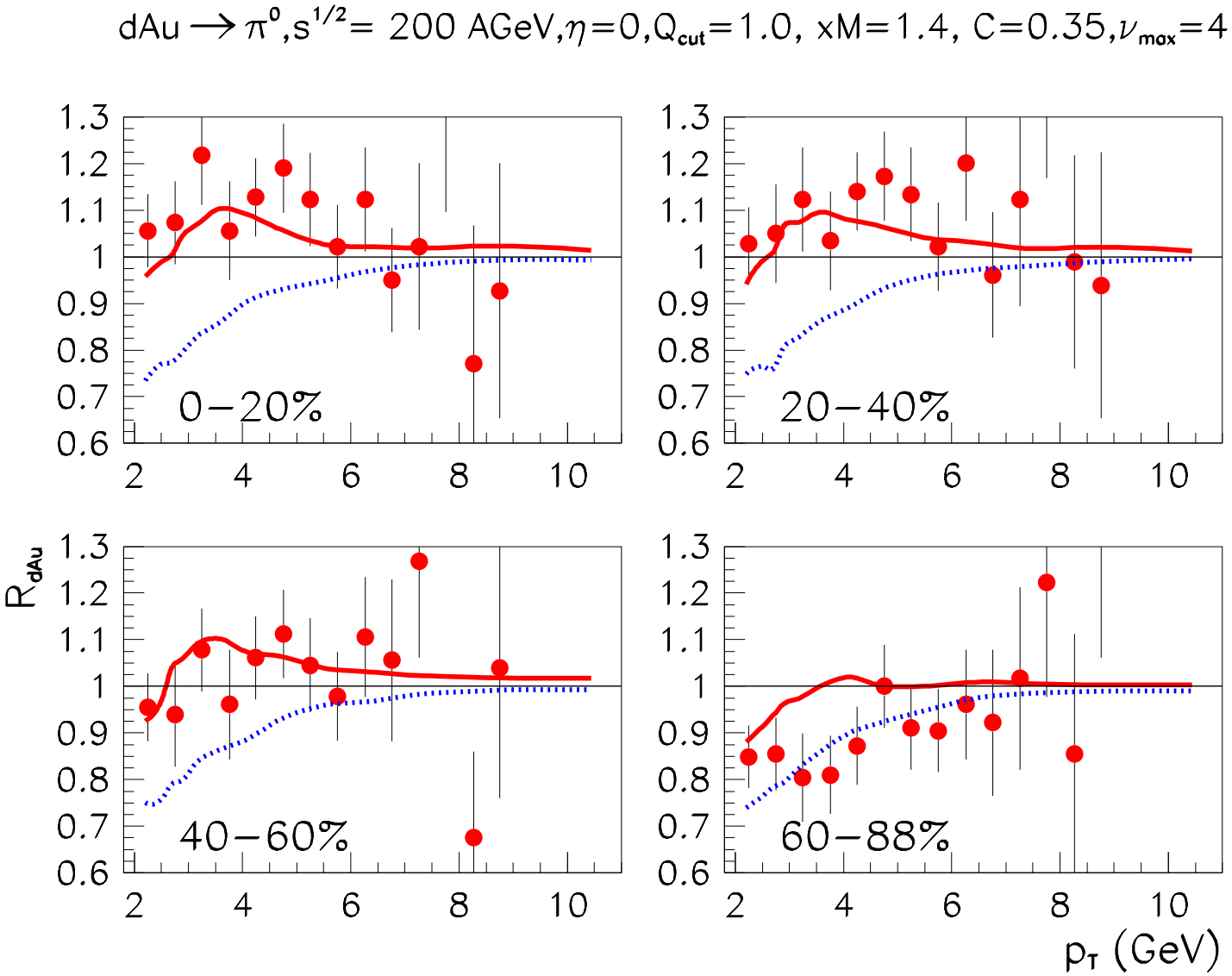


NO quenching is assumed $\Longrightarrow$ NO suppression in dAu

MINIMUM BIAS reproduction $\Longrightarrow$ OK

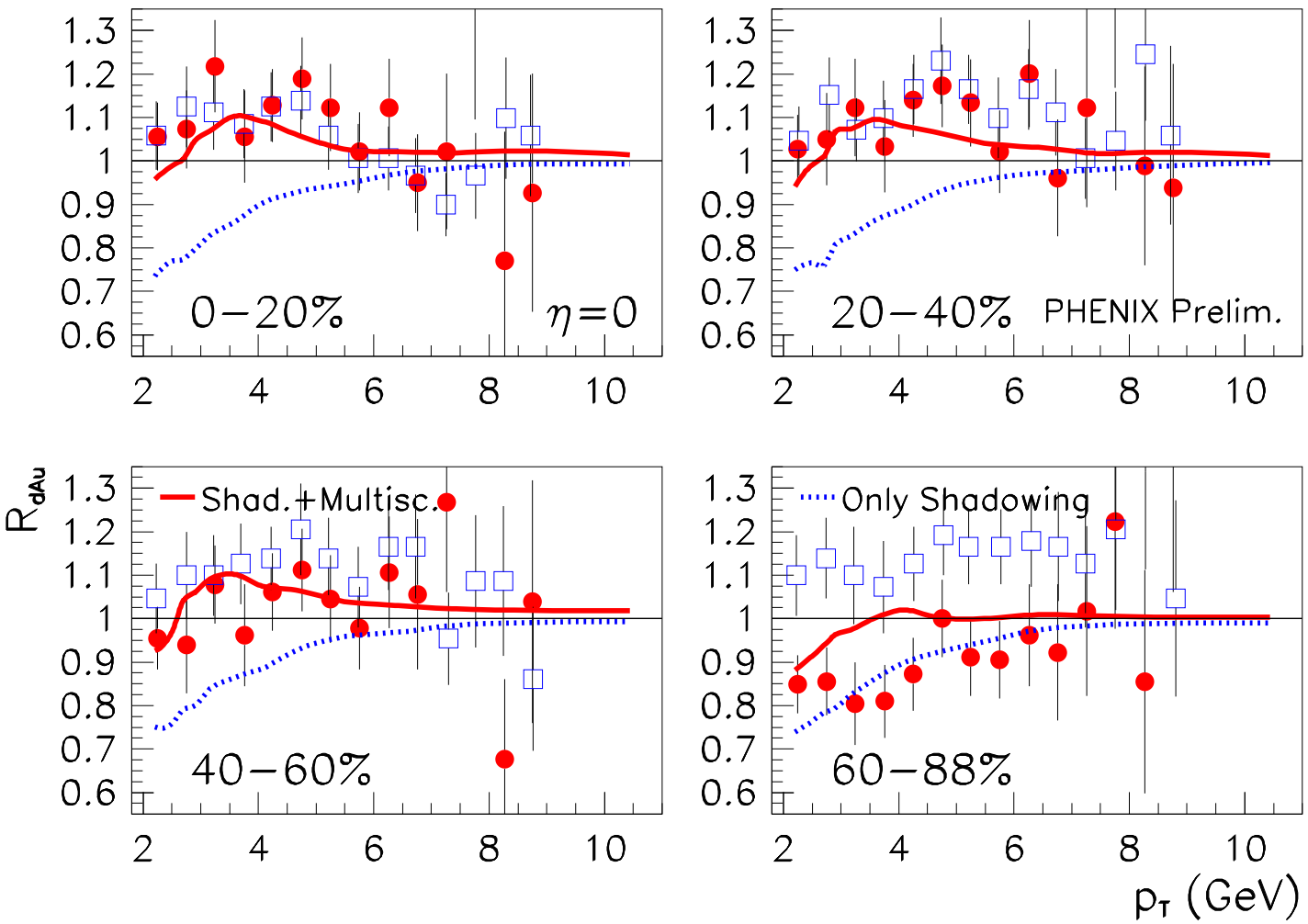
See details in: P. Lévai, G. Papp, G.G. Barnaföldi, G. Fai: `nucl-th/03006019`

Cronin effect in different Centralities in *dAu* collision (QM '04)



G.G. Barnaföldi *et al.*: J. Phys. G30, S1125

Cronin effect in different Centralities in dAu collision at PHENIX



Preliminary (latest) data from PHENIX – APS NDP meeting

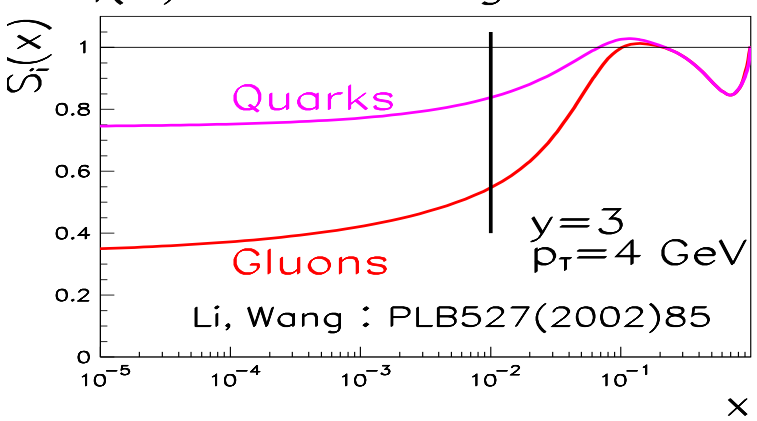
III. Calculations with Shadowing at Larger Rapidity

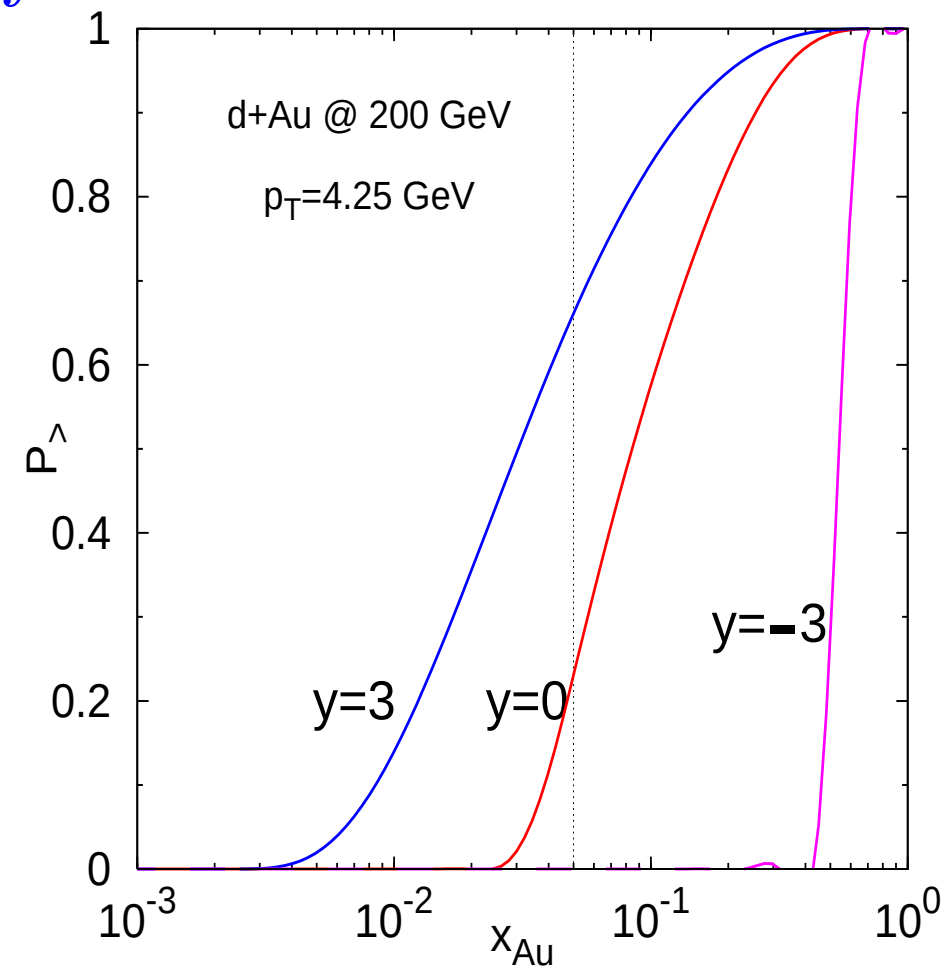
- **Cumulative probability**

$$P_{>}(x_{Au}) = \frac{\int_0^{X_{Au}} \mathrm{d}\sigma(x')\mathrm{d}x'}{\int_0^1 \mathrm{d}\sigma(x')\mathrm{d}x'}$$

– substantial contribution from higher-x region

$S_i(x)$ shadowing functions

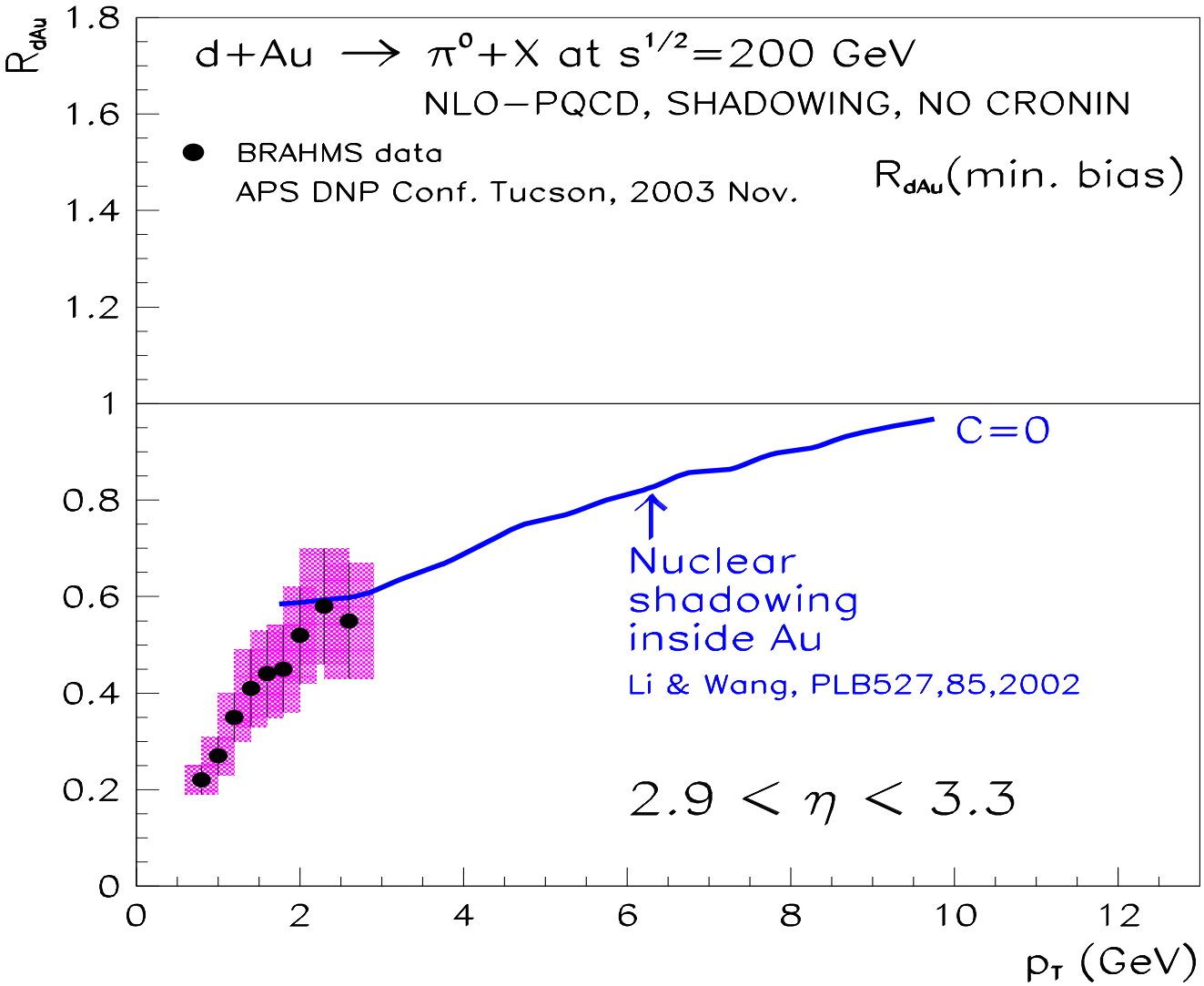




$p_T = 4$ **GeV and** $y = 0 \Longrightarrow \sim 5\%$ **suppression**

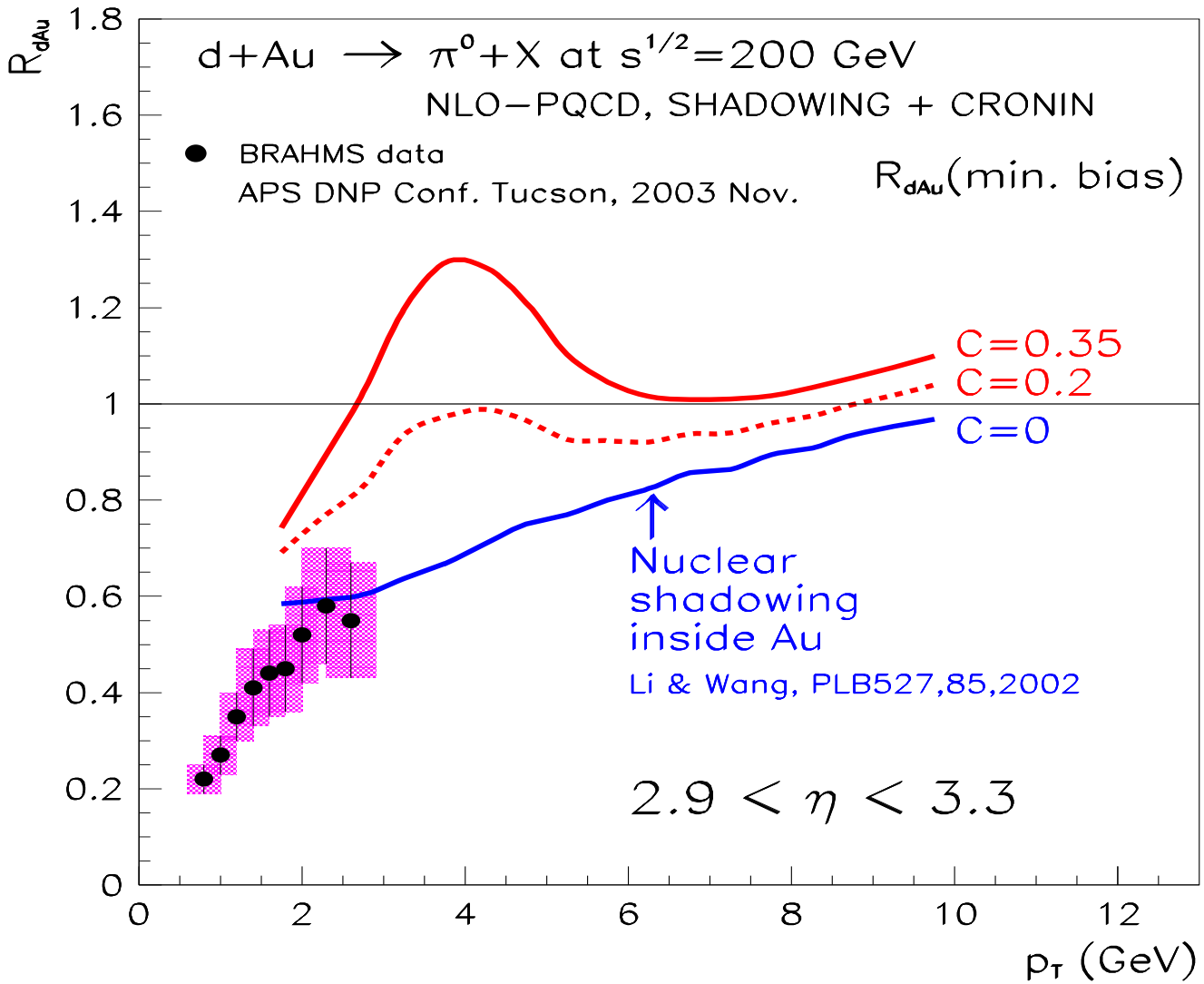
$p_T = 4$ **GeV and** $y = 3 \Longrightarrow \sim 30\%$ **suppression**

BRAHMS data in dAu collision at $\sqrt{s} = 200$ AGeV (min. bias) calculation with shadowing only (QM '04)



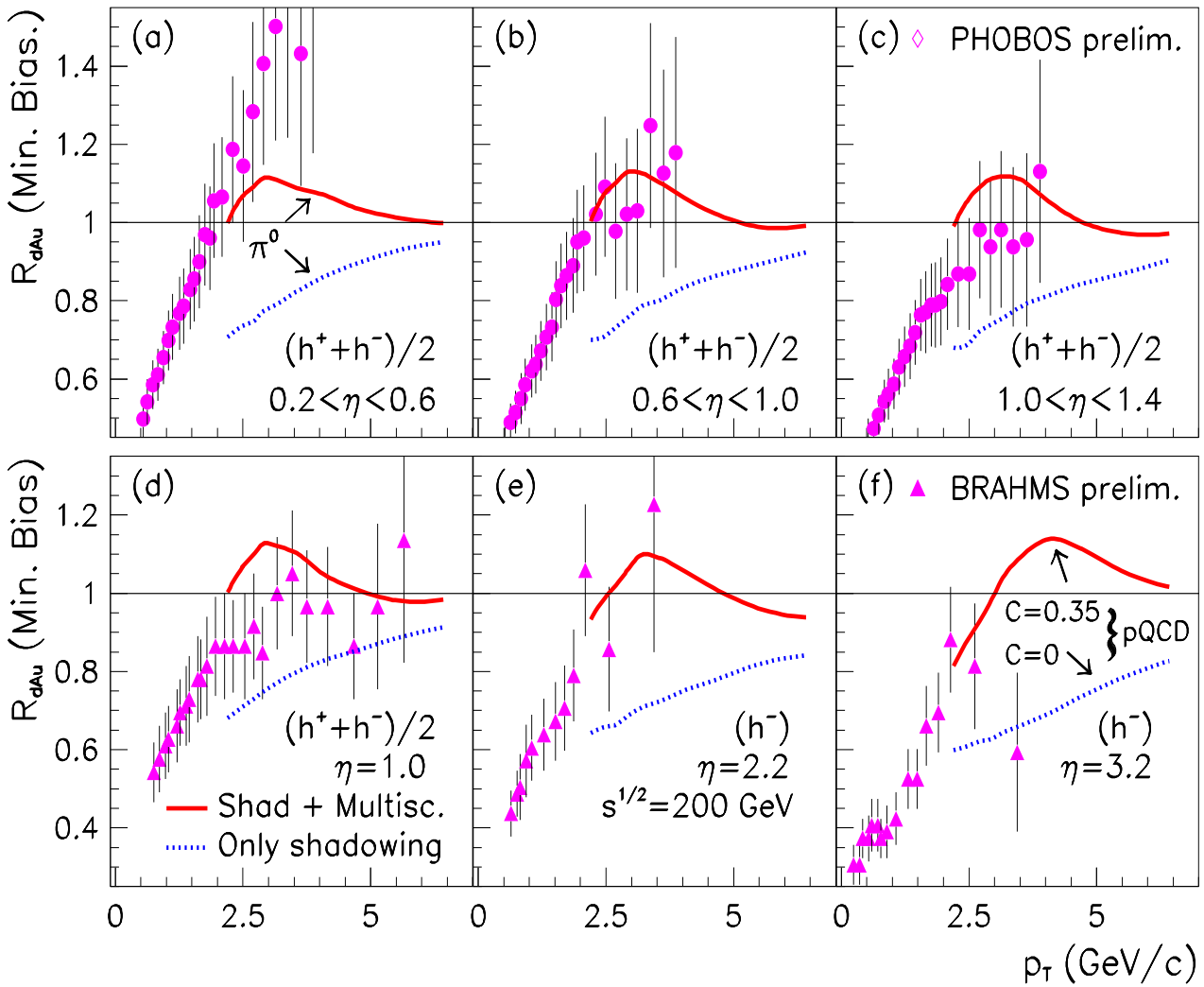
HIJING (b-indep.) shad., NO Cronin ($C_{sat} = 0$), $y = 3$

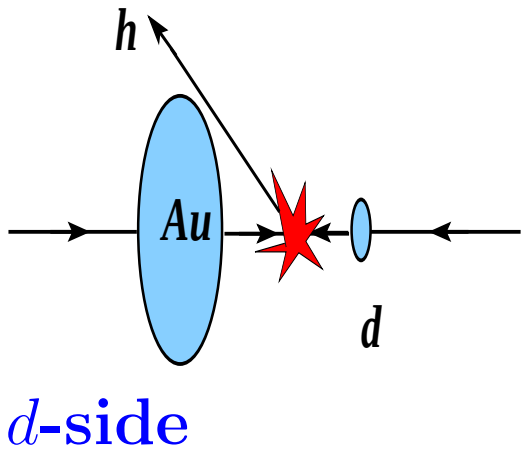
BRAHMS data in dAu collision at $\sqrt{s} = 200$ AGeV (min. bias) calculation with shadowing + CRONIN (QM '04)

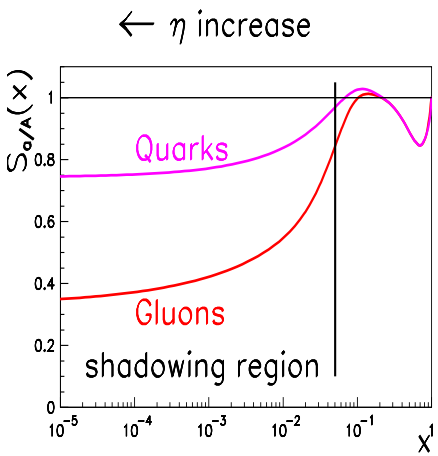


HIJING (b-indep.) shad., $\nu_{max} = 4$, $C_{sat} = 0 - 0.35$, $y = 3$

Cronin on min. bias $dAu \to \pi^0$ at PHOBOS and BRAHMS $\eta > 0$







BRAHMS data: `nucl-ex/0403005` **and PHOBOS data:** `nucl-ex/0406017`

Summary – Outlook

Goal: Reproducing the Cronin effect in $pA(dAu) \to \pi$

I. Cronin effect reproduction at $\boxed{y = 0}$

- **Baseline: pp results for intrinsic-k_T, $\langle k_T^2 \rangle$**
- **Shadowing functions (HIJING, EKS, etc.)**
- **Multiple scattering with saturated Glauber picture**

  $\Longrightarrow$ **Midrapidity data are well reproduced**

  $\Longrightarrow$ **NO suppression, NO need for extra shadowing**

  $\Longrightarrow$ **Agreement between Theory vs. Data**

II. Results for $dAu \to \pi$ at $\boxed{\eta > 0}$

- **Determining the efficiency of multiscat. at $\eta > 0$,**
- **Looking forward to (π) experimental data at high-p_T**

  $\Longrightarrow$ **Consistency with exp. data at $\eta > 0$**

Related Publications

G.G. Barnaföldi; P. Lévai; G. Papp; G. Fai

Proc. of Erice '03 hep-ph/0312384 **(2003)**

Proc. of ICNRM '03 nucl-th/0307062 **(2003)**

R_{dAu} **at RHIC** nucl-th/0306019 **(2003)**

Submitted to Heavy Ion Phys. nucl-th/0206006 **(2002)**

Phys. Rev C65, 034903 (2002) hep-ph/0109233

Nucl. Phys A698, 627 (2002) hep-ph/0104021

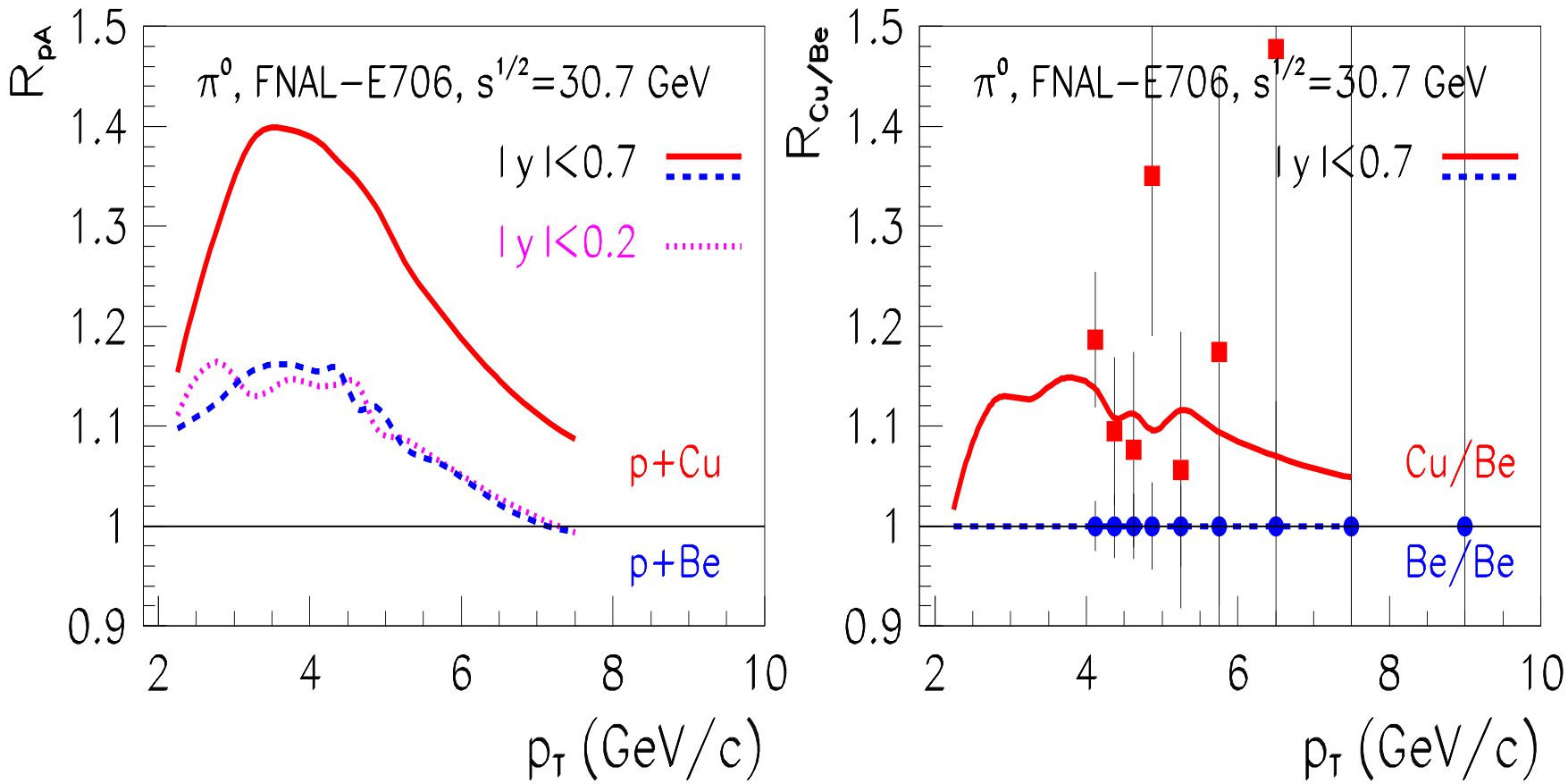
Nucl. Phys A698, 631 (2002) hep-ph/0104035

JHEP PRHEP-hep2001/242 (2001) hep-ph/0111211

Acta. Phys. Polonica. B32, 4069 (2001)

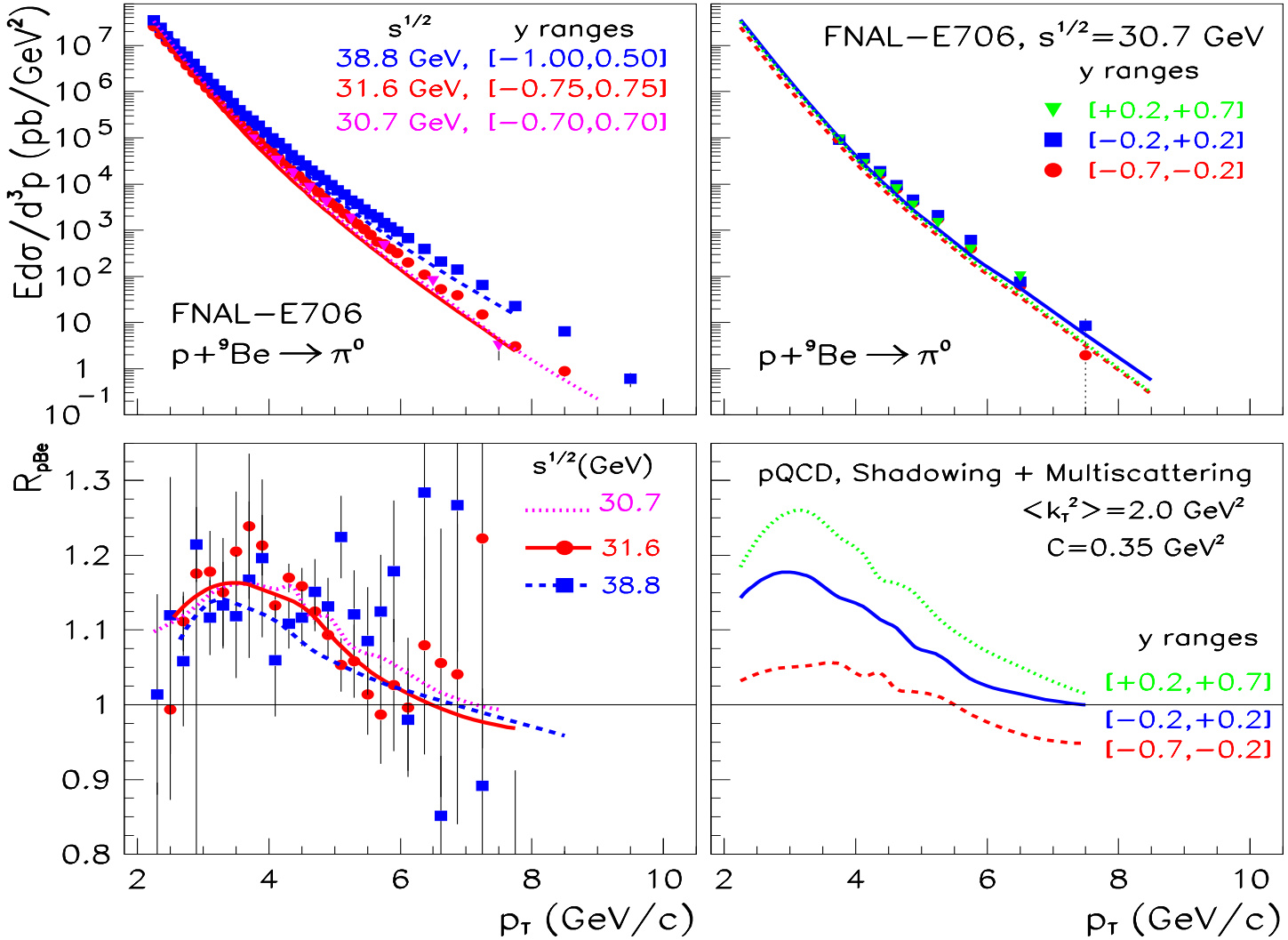
Proc. of ISMD '02 (2003) nucl-th/0212111

Cronin effect at midrapidity in pBe and pCu collision at FNAL E706



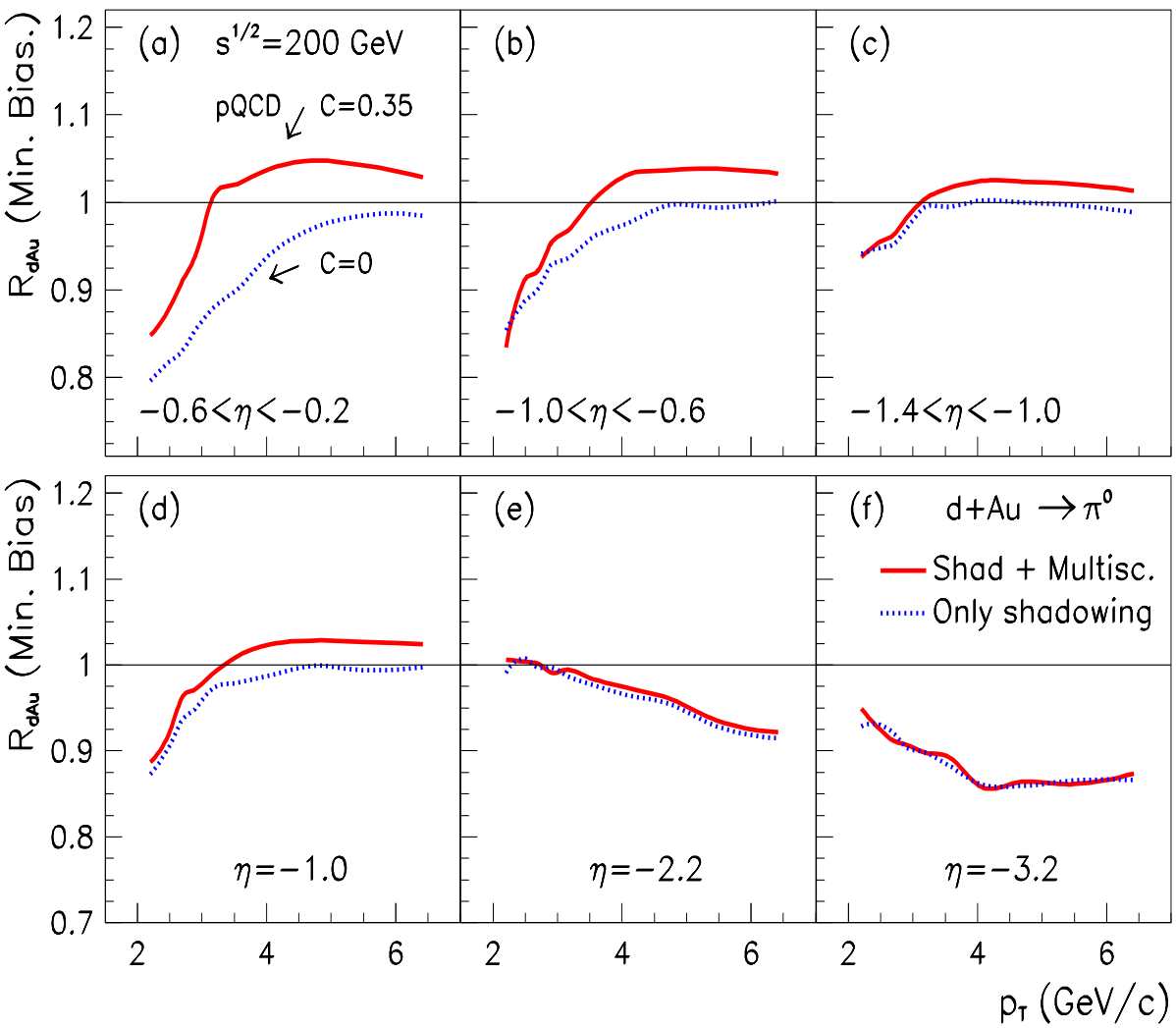
G.G. Barnaföldi *et al.*: APH NS (2004)

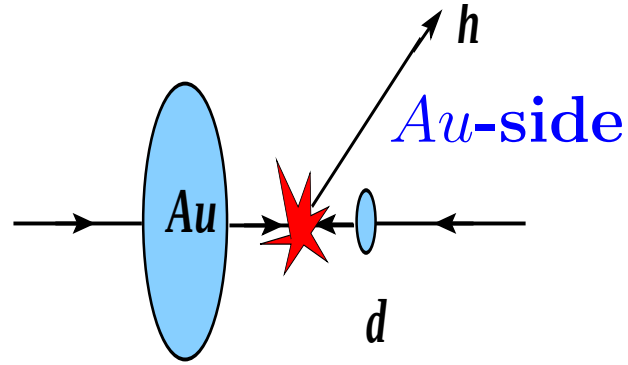
Cronin effect in the close-to-midrapidity region in pA collision at FNAL-E706



G.G. Barnaföldi *et. al*: APH NS (2004)

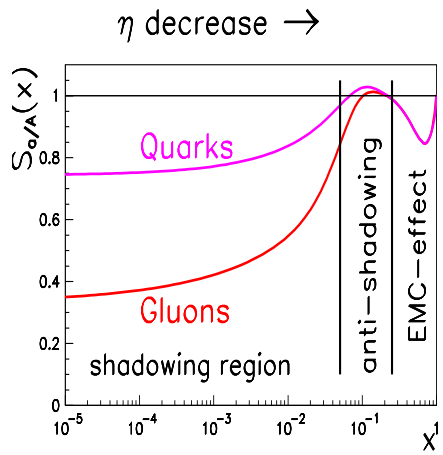
Cronin on min. bias $dAu \to \pi^0$ as inverted, $\eta < 0$



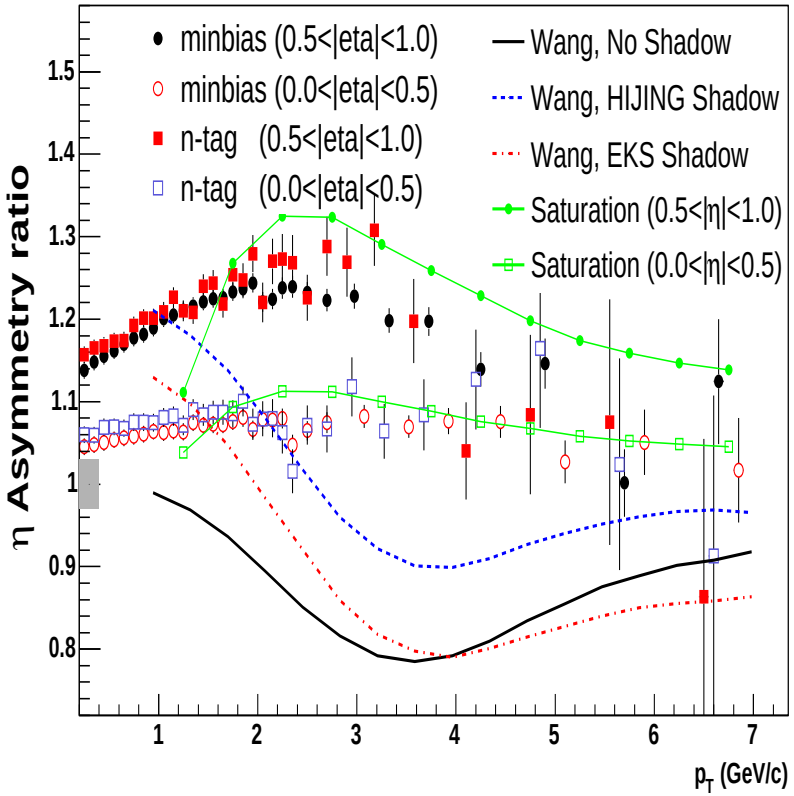


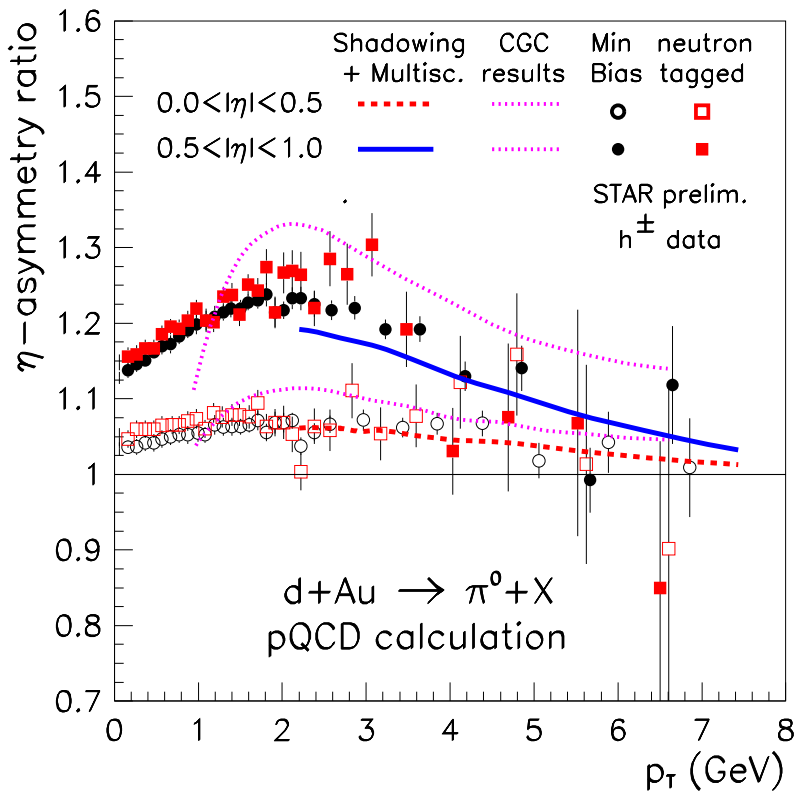
Au-side

NO relevant multiscatt. in d.



η Asymetry Ratio in $dAu \to \pi^0$ at STAR



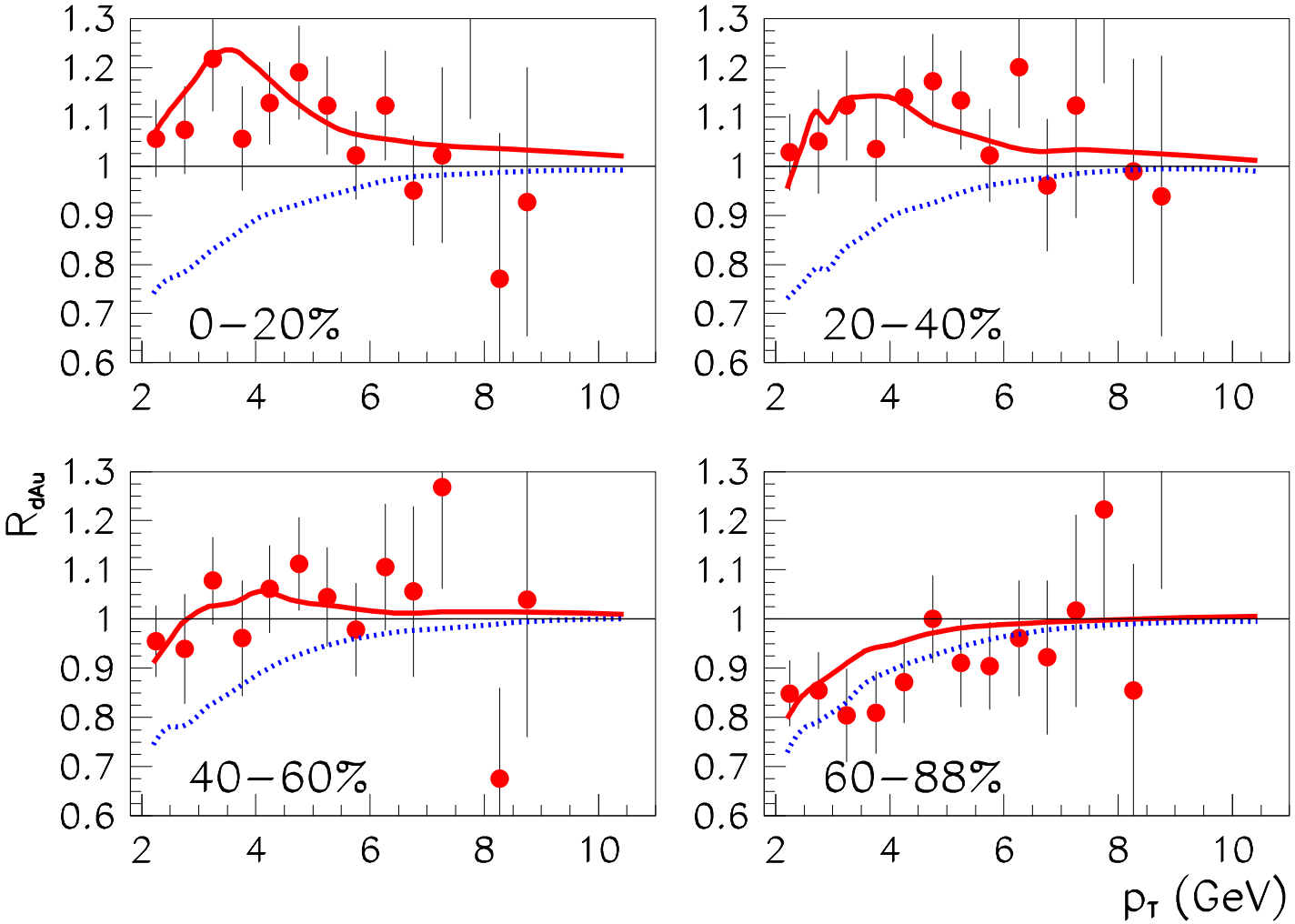


$$\eta^{\pi}(\textbf{asymetry ratio}) := \frac{d\sigma^{Au+d\to\pi}/d^3p\,(\textbf{Au-side})}{d\sigma^{Au+d\to\pi}/d^3p\,(\textbf{d-side})}$$

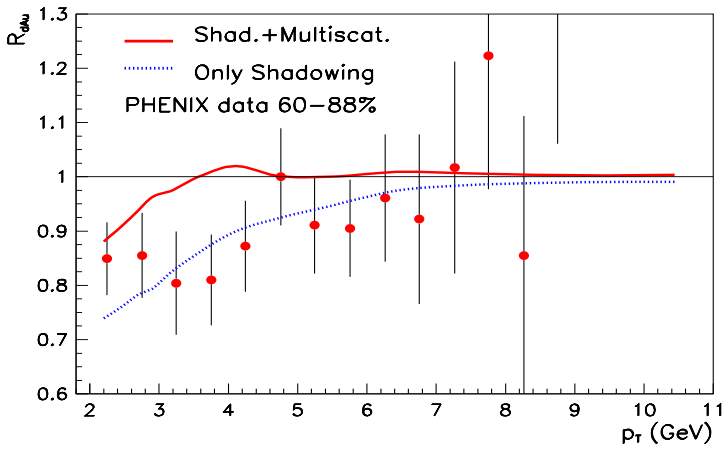
New STAR data: `nucl-ex/0408016`

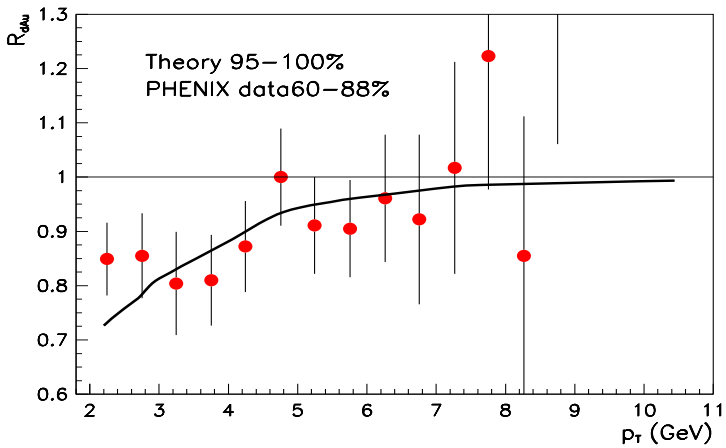
Cronin effect in different Centralities in dAu collision at PHENIX

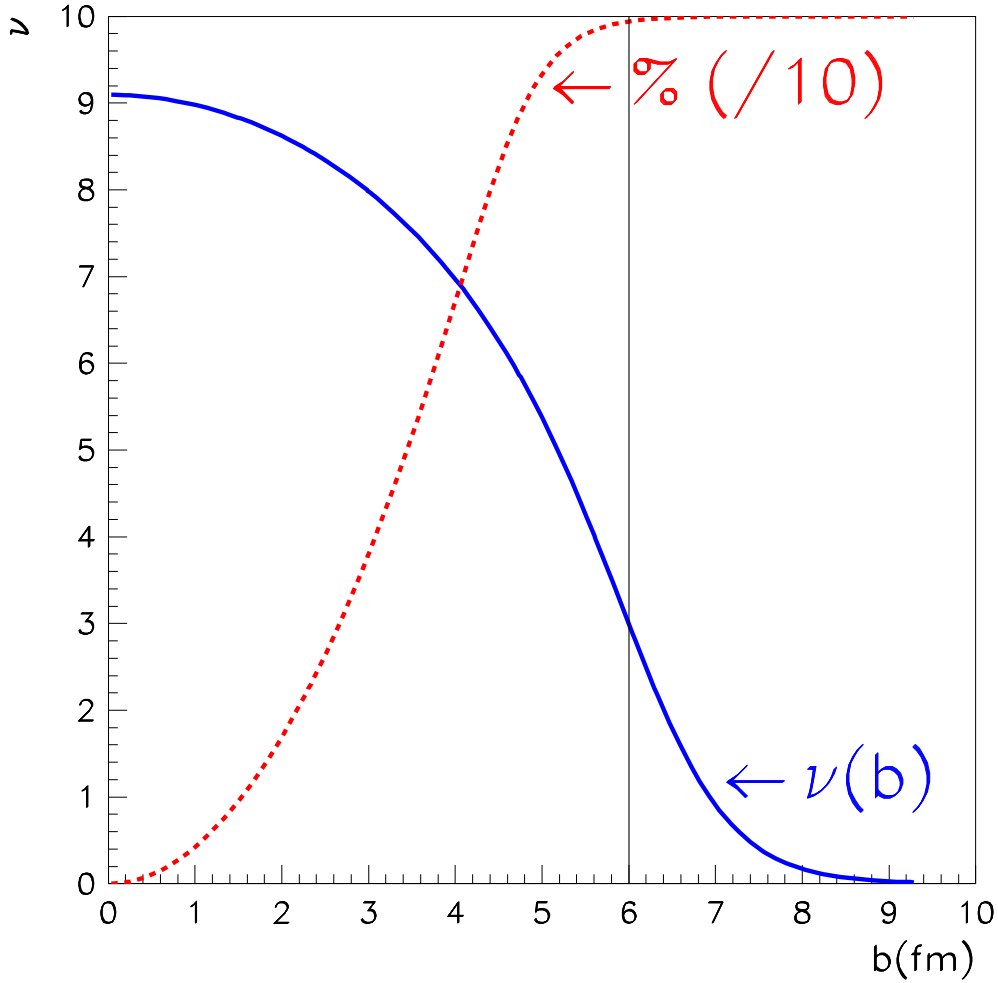
dAu $\rightarrow \pi^0$, $s^{1/2}$= 200 AGeV, η=0, Q_{cut}=20.0, xM=1.4, C=0.2, ν_{max}=9



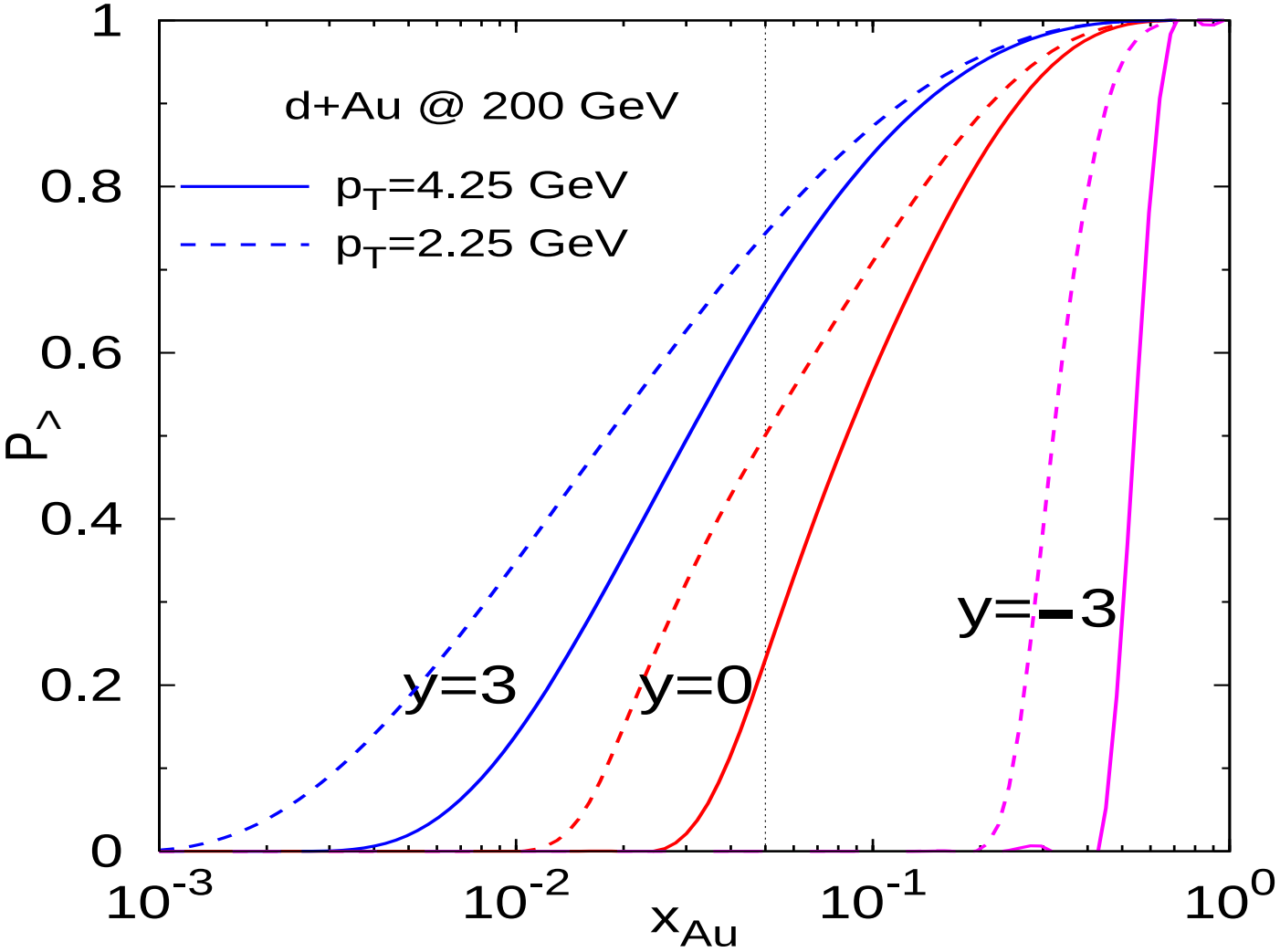
Effect of Wood – Saxon tail in peripheral dAu collision at PHENIX



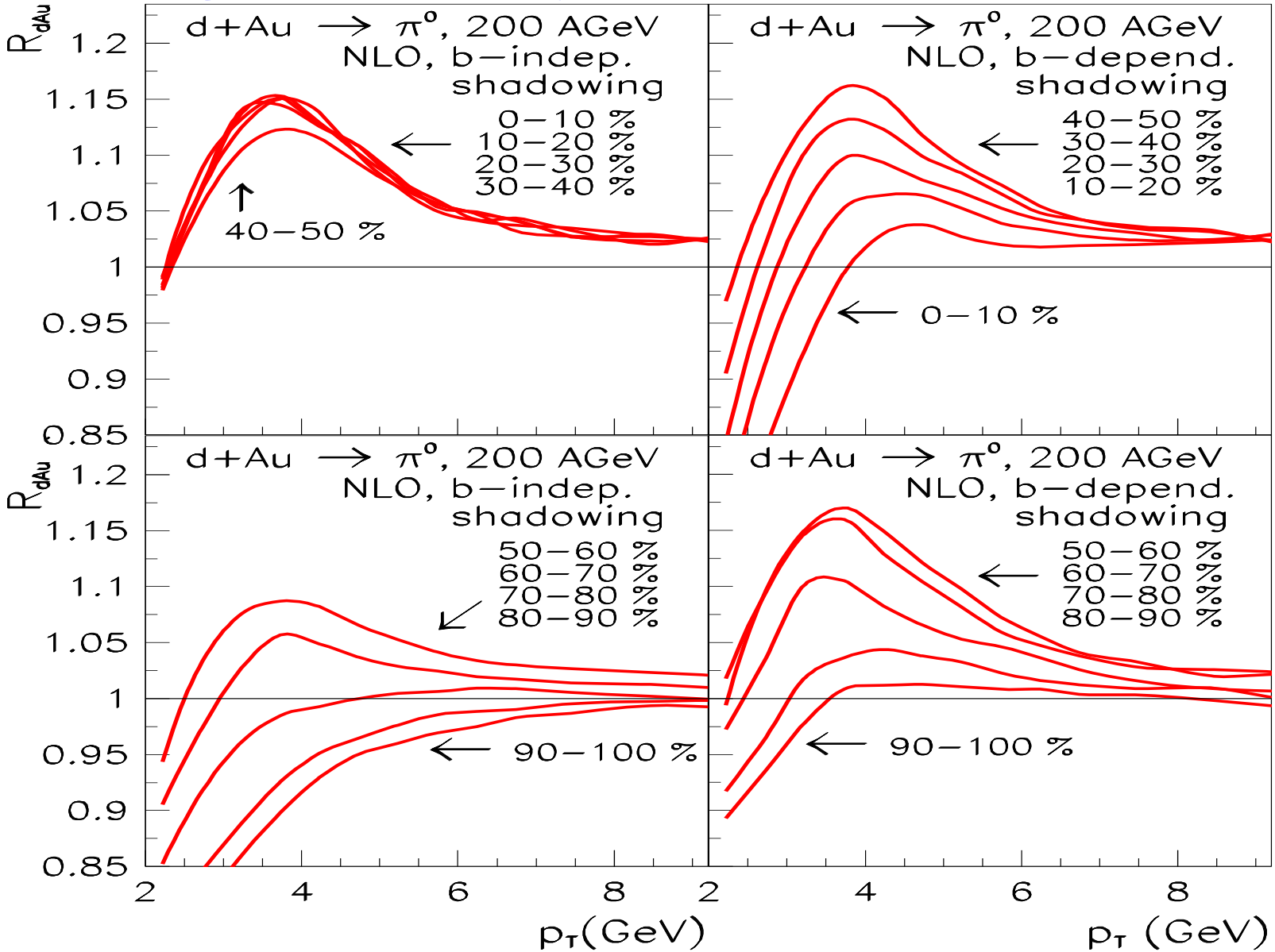




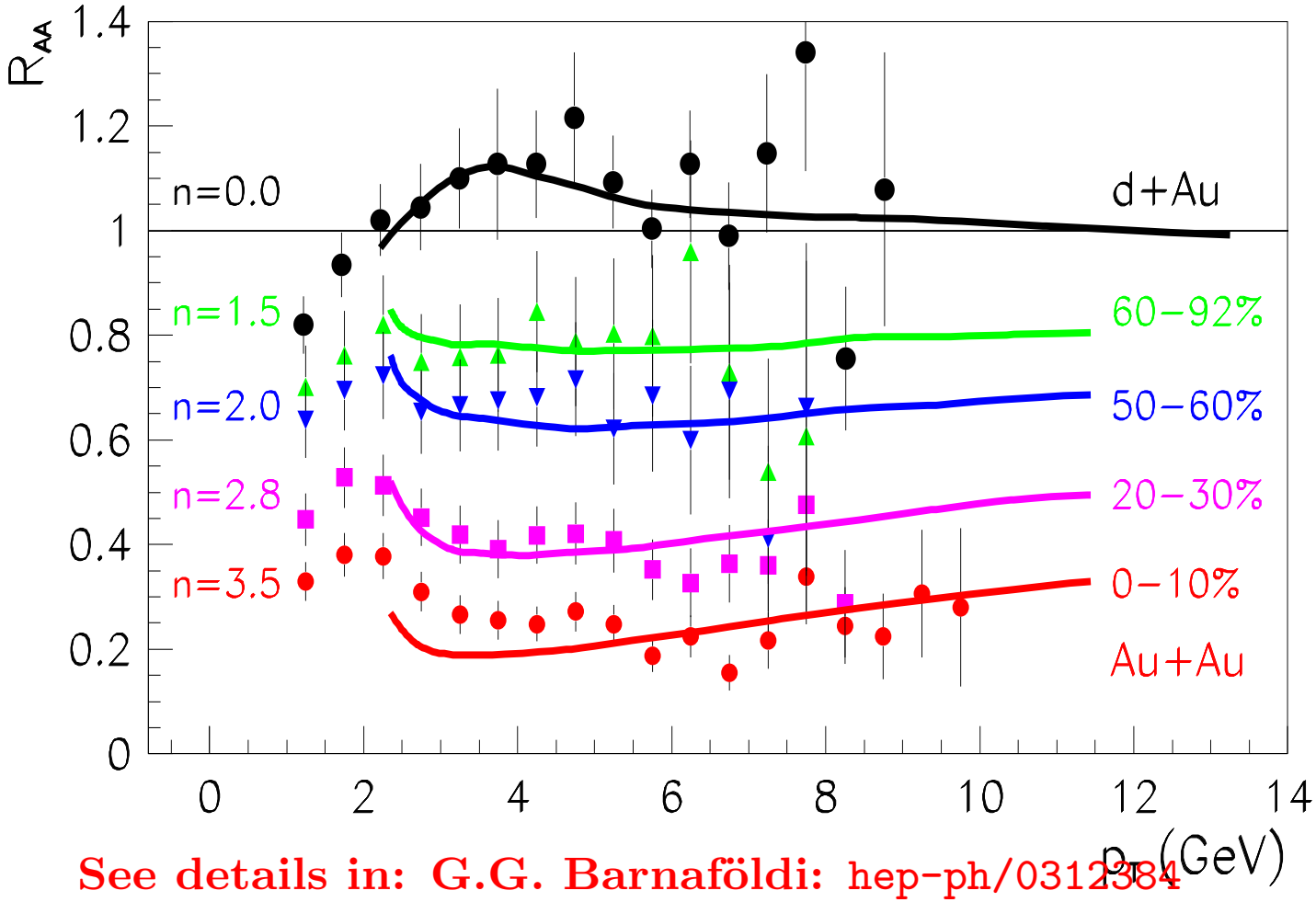
Cumulative probability for dAu collision at different rapidities

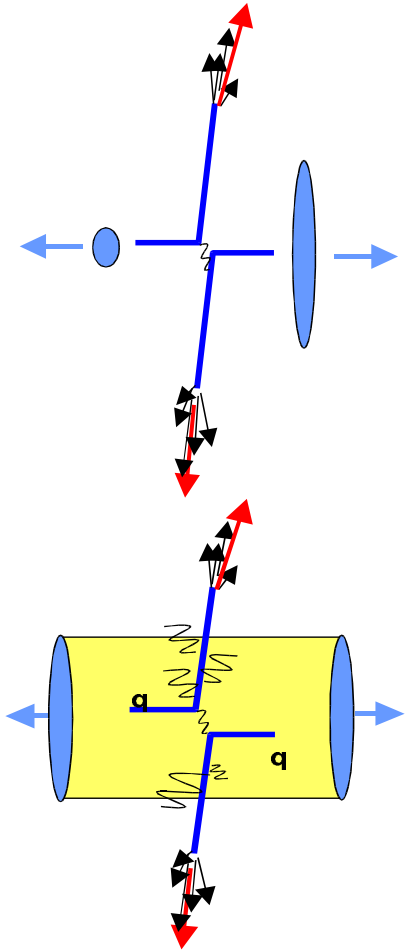


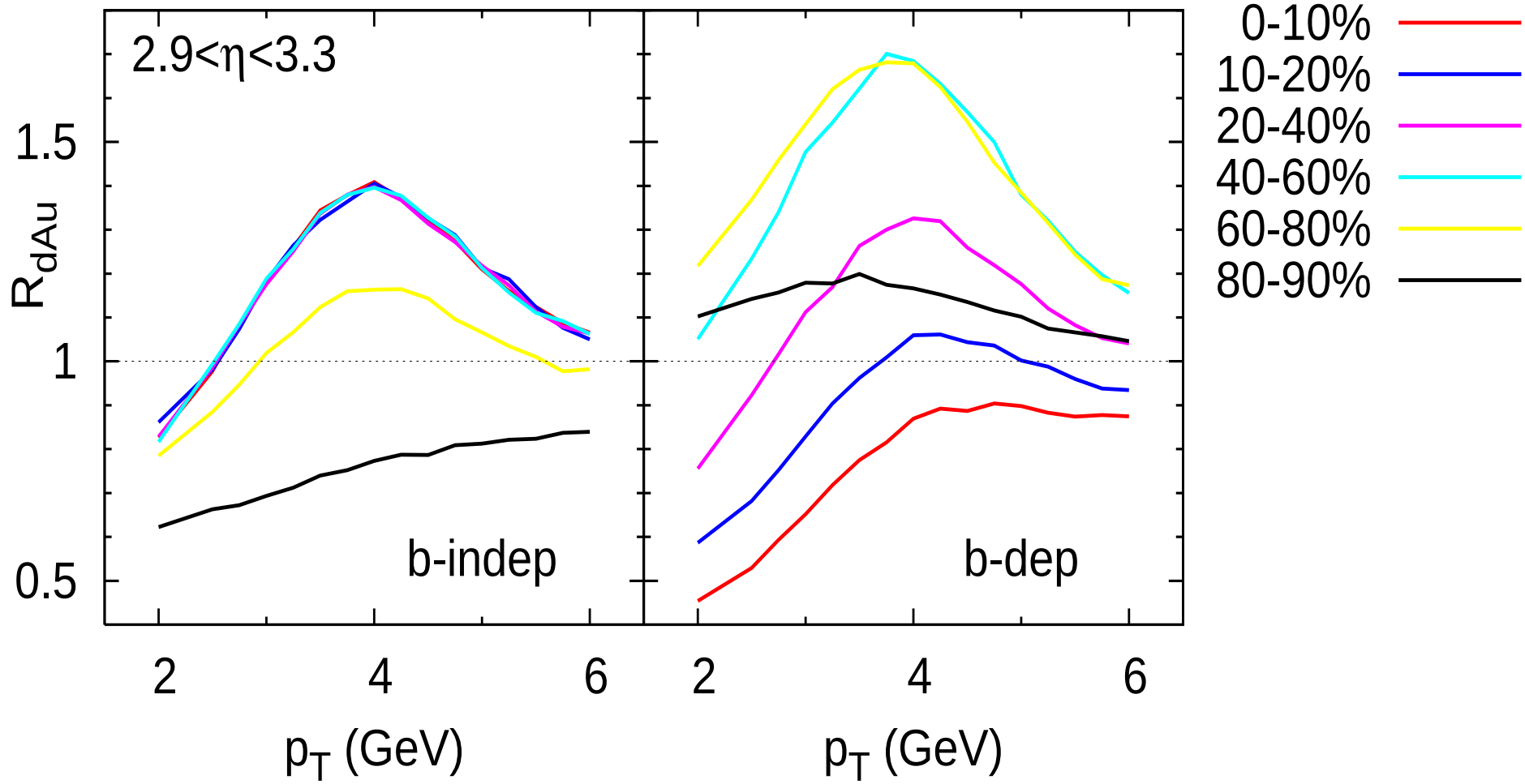
Cronin effect with b-indep. (left) and b-dep. (right) shadowing vs. centrality in dAu collision at PHENIX



Jet tomography in $AuAu$ and dAu collision at PHENIX





See details in: G.G. Barnaföldi: hep-ph/0312384

Cronin effect with b-independent (left) and b-dependent (right) shadowing vs. centrality in dAu collision at BRAHMS