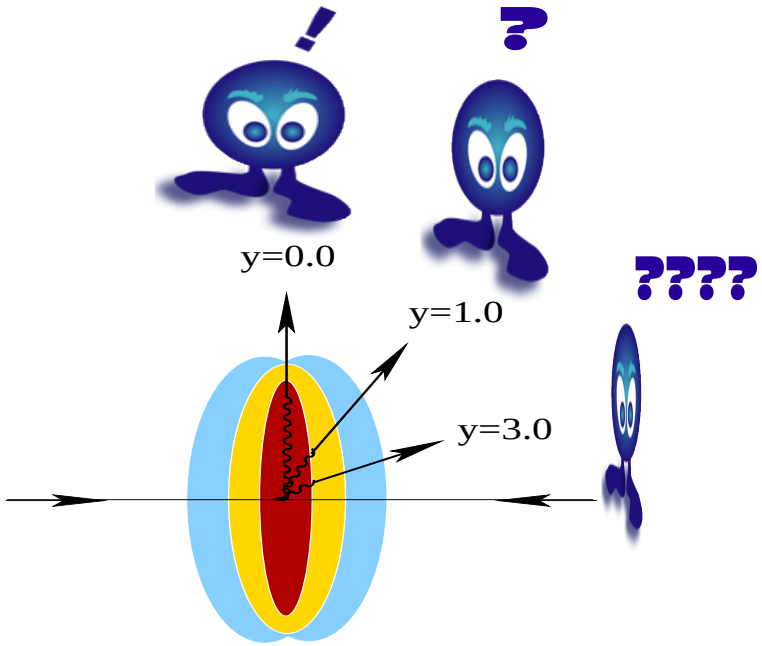
# JET TOMOGRAPHY IN THE FORWARD DIRECTIONS AT RHIC

Gergely Gábor Barnaföldi – KFKI RMKI




in collaboration with:
Péter Lévai – KFKI RMKI;
Gábor Papp – Eötvös University (ELTE);
George Fai – Kent State University;

HoT Quarks – 2006
15-20. May 2006 – Villasimius, Sardinia, Italy

# Motivation: Connecting of opacity to other parameters

**0. Good description of $\pi$ production in $(pA)dAu$ collisions**

- Baseline: $pp$ results for intrinsic-$k_T$, $\langle k_T^2 \rangle$
- HIJING shadowing + Multiscattering + Sat. Galuber model

INITIAL STATE EFFECTS $\Longrightarrow$ OK

**I. Opacity parameter in different reaction**

- System size dependence

  Centrality dependence in $AuAu$ collisions

  Comparing $AuAu$ and $CuCu$ collisions
- No rapidity dependence? Really? $\Longrightarrow$ 2D tomography?
- Energy dependence? $\Longrightarrow$ $\sqrt{s}$, $\varepsilon$, etc

$\Longrightarrow$ TESTING FINAL STATE EFFECTS

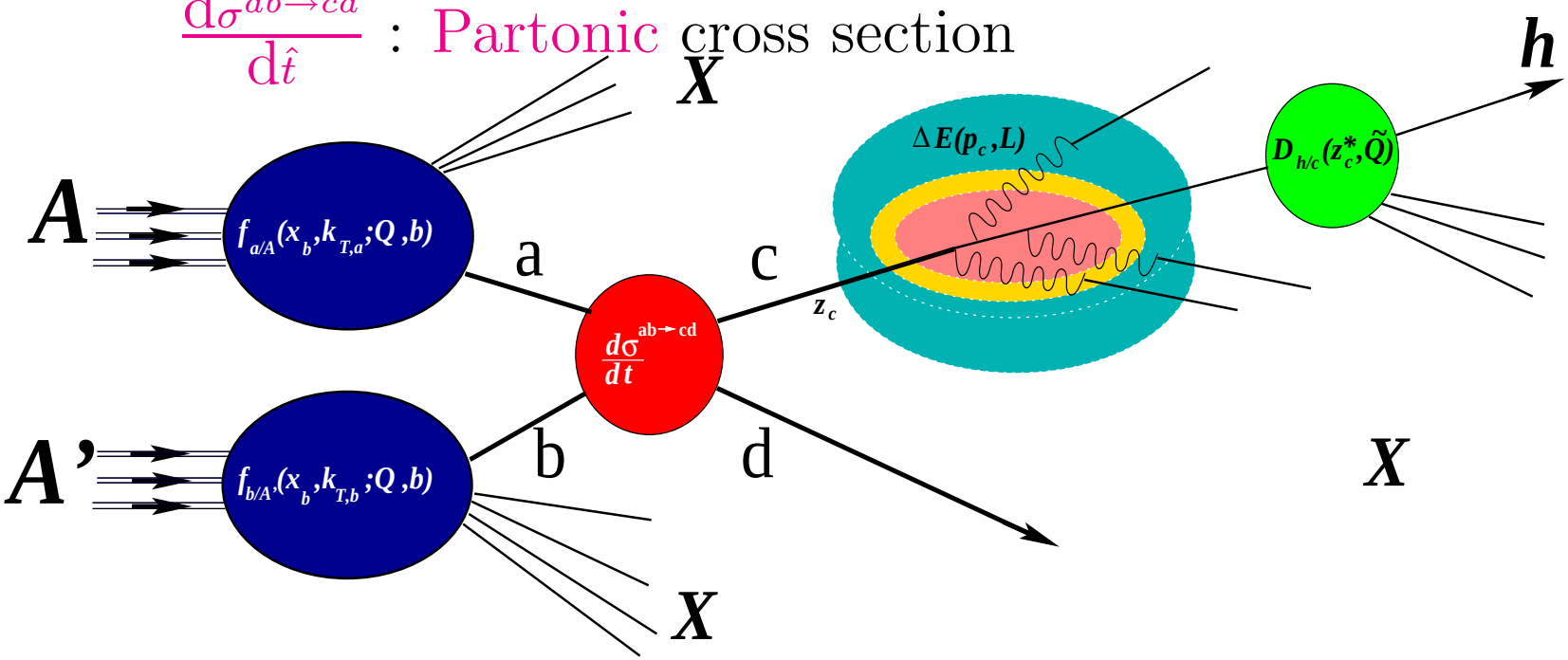
# I/1. pQCD Improved Parton Model for $AA'$ Collisions

$$E_\pi \frac{\mathrm{d}\sigma_\pi^{AA'}}{\mathrm{d}^3 p_\pi} \sim f_{a/A}(x_a, Q^2; k_T) \otimes f_{b/A'}(x_b, Q^2; k_T) \otimes \frac{\mathrm{d}\sigma^{ab\to cd}}{\mathrm{d}\hat{t}} \otimes \frac{D_{\pi/c}(z_c, \widehat{Q}^2)}{\pi z_c^2}.$$

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

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

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



# I/2. Non-abelian Jet Energy Loss – Jet-Quenching

Energy loss of jets in hot, dense non-Abelian plasma:

— energy loss in a THICK plasma - BDMS, LCPI

— energy loss in a THIN plasma - GLV method

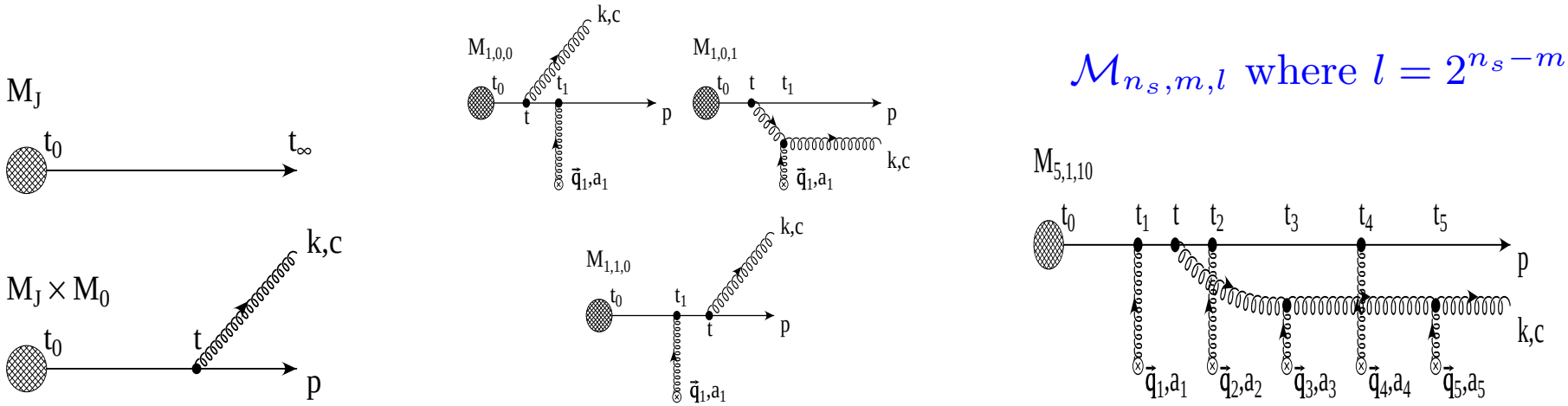
## Medium induced radiative energy loss - for thin plasma: $L \sim \lambda_g$

Gyulassy – Lévai – Vitev, Phys. Rev. Lett. **85**, 5535; Nucl. Phy s. **B594**, 371

GLV: time-ordered pQCD (Feynman diagramms)

+ OPACITY expansion ($N = 1, 2, 3, ...$)

+ kinematical cuts



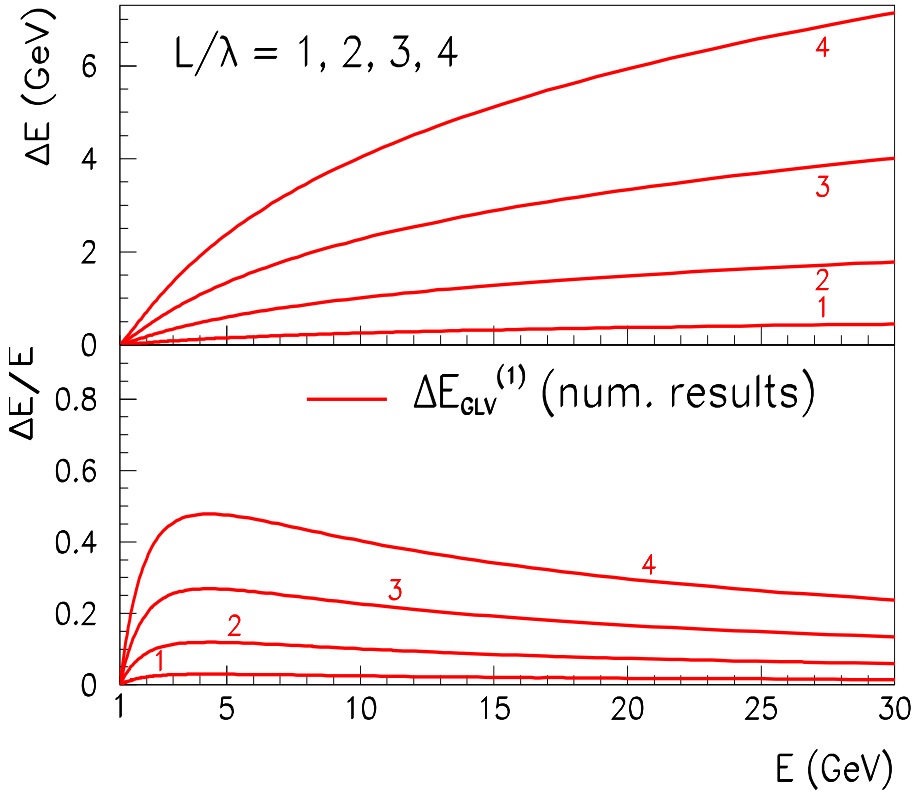

$\mathcal{M}_{n_s,m,l}$ where $l = 2^{n_s - m} - 1$

# I/3. Calculations of Relative Energy Loss – Results

## Energy dependence of GLV jet energy loss

$$\Longrightarrow \Delta E_{GLV} \approx \Delta E^{(1)}_{GLV} \approx \frac{C_R \alpha_s}{N(E)} \frac{L^2 \mu^2}{\lambda_g} \log \frac{E}{\mu}$$

- **$\Delta E$ is $E$-dependent**
  $N(E)$ is a numerical function,
  $N(E) \longrightarrow 4$ at $E \longrightarrow \infty$.
- **$\approx$ E-independent $\Delta E/E$**
  in $3 <$ GeV $E < 10$ GeV
- **Opacity $n = L/\lambda$**
  BUT WHAT IS OPACITY?



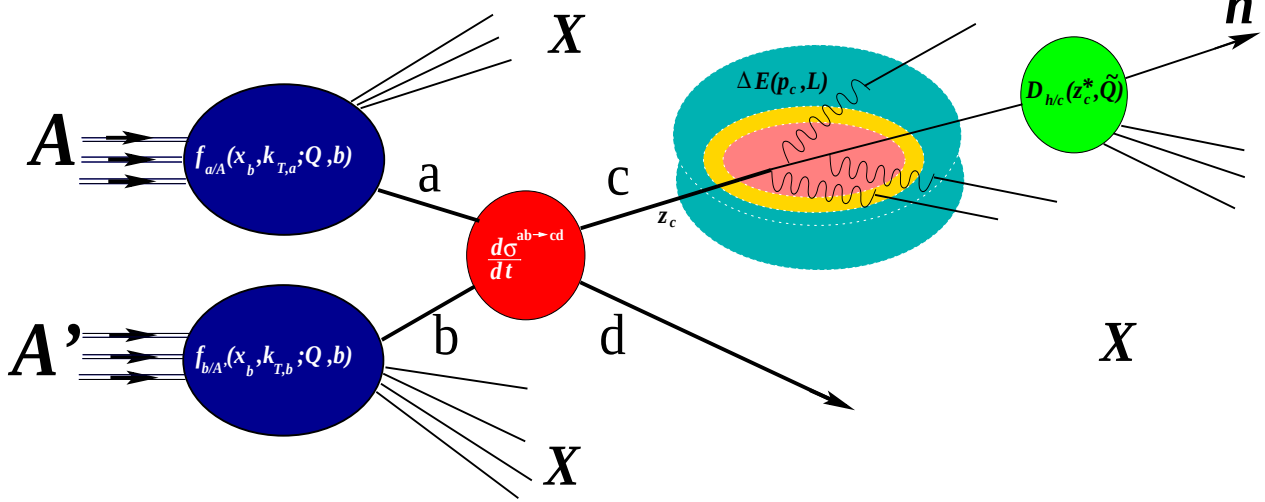
# I/4. $\pi$-suppression in $AuAu$ collisions at RHIC energies

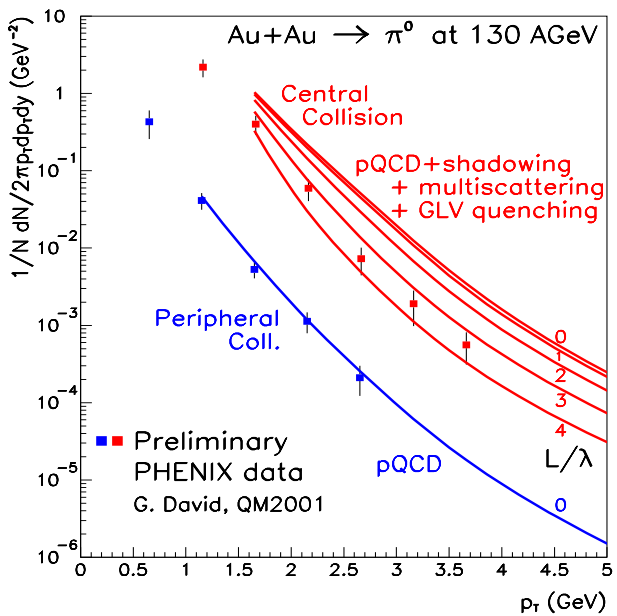
GLV jet-quenching in thin plasma approximation $L \sim \lambda_g$ :

$$\Delta E_{GLV} \sim \frac{L^2\mu^2}{\lambda_g} \log \frac{E}{\mu}$$

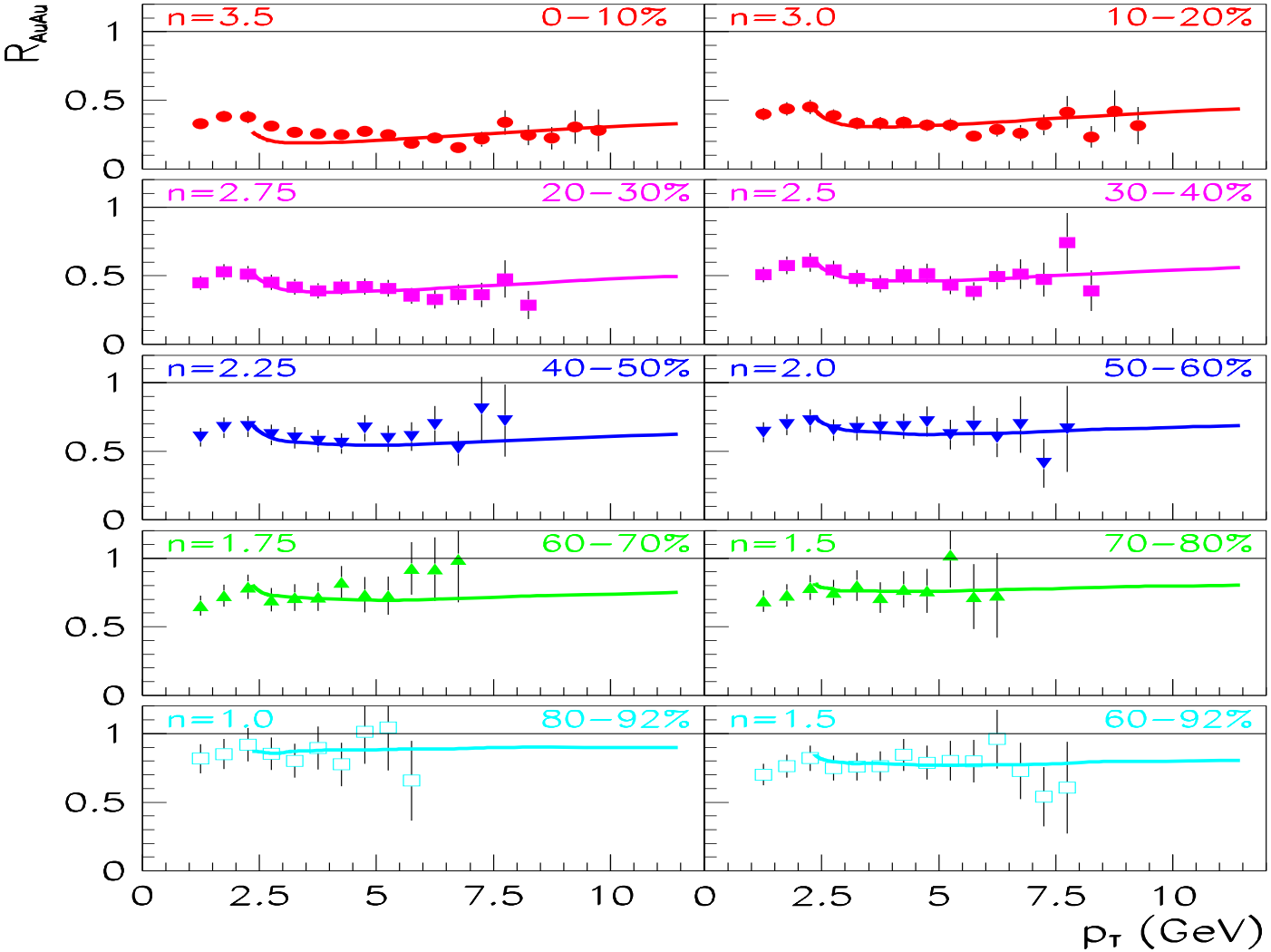
Energy loss of jet decreases the $p_c$ momenta of $c$ before fragmentation:

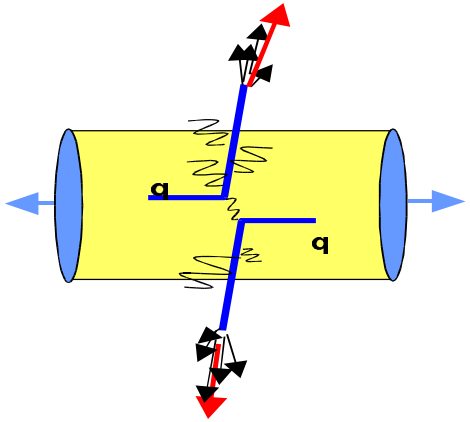
$$\frac{D_{\pi/c}\left(z_c,Q'^2\right)}{\pi z_c^2} \rightarrow \frac{z_c^*}{z_c}\,\frac{D_{\pi/c}\left(z_c^*,Q'^2\right)}{\pi z_c^2}, \quad \text{where} \quad z_c^* = \frac{z_c}{1-\Delta E/p_c},$$

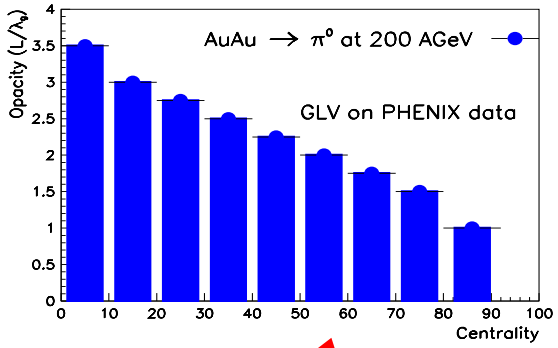


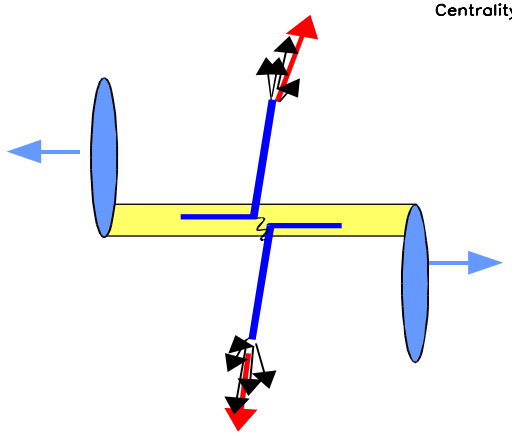



# Jet-tomography in $AuAu$ Collisions at PHENIX $(y = 0)$

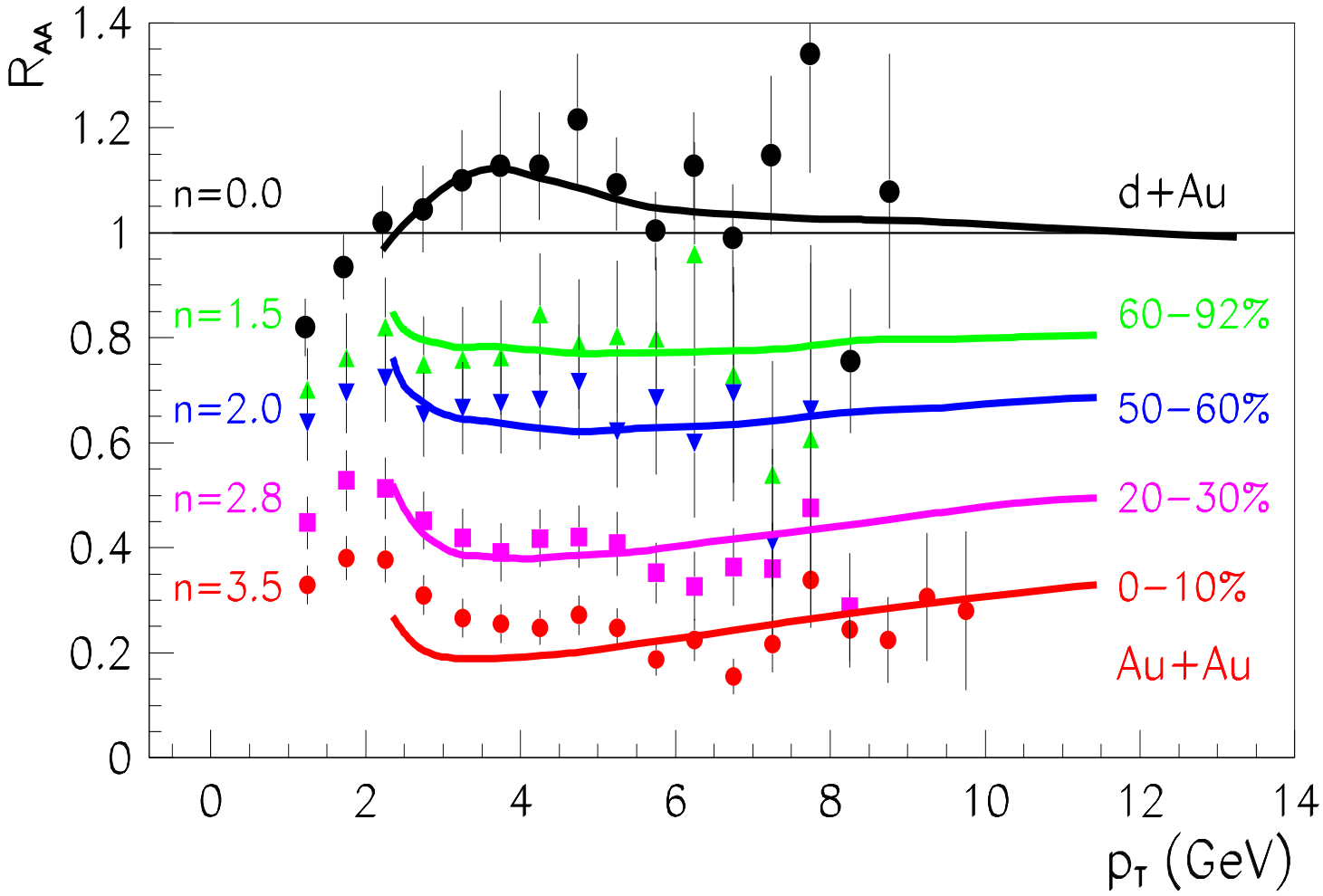


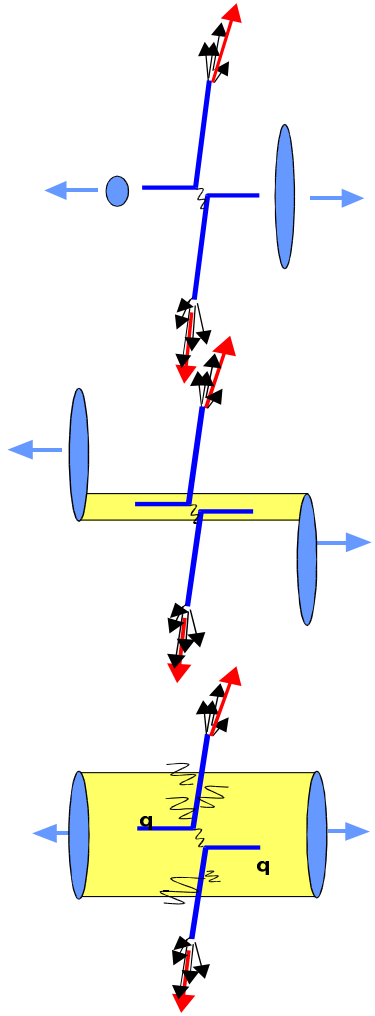



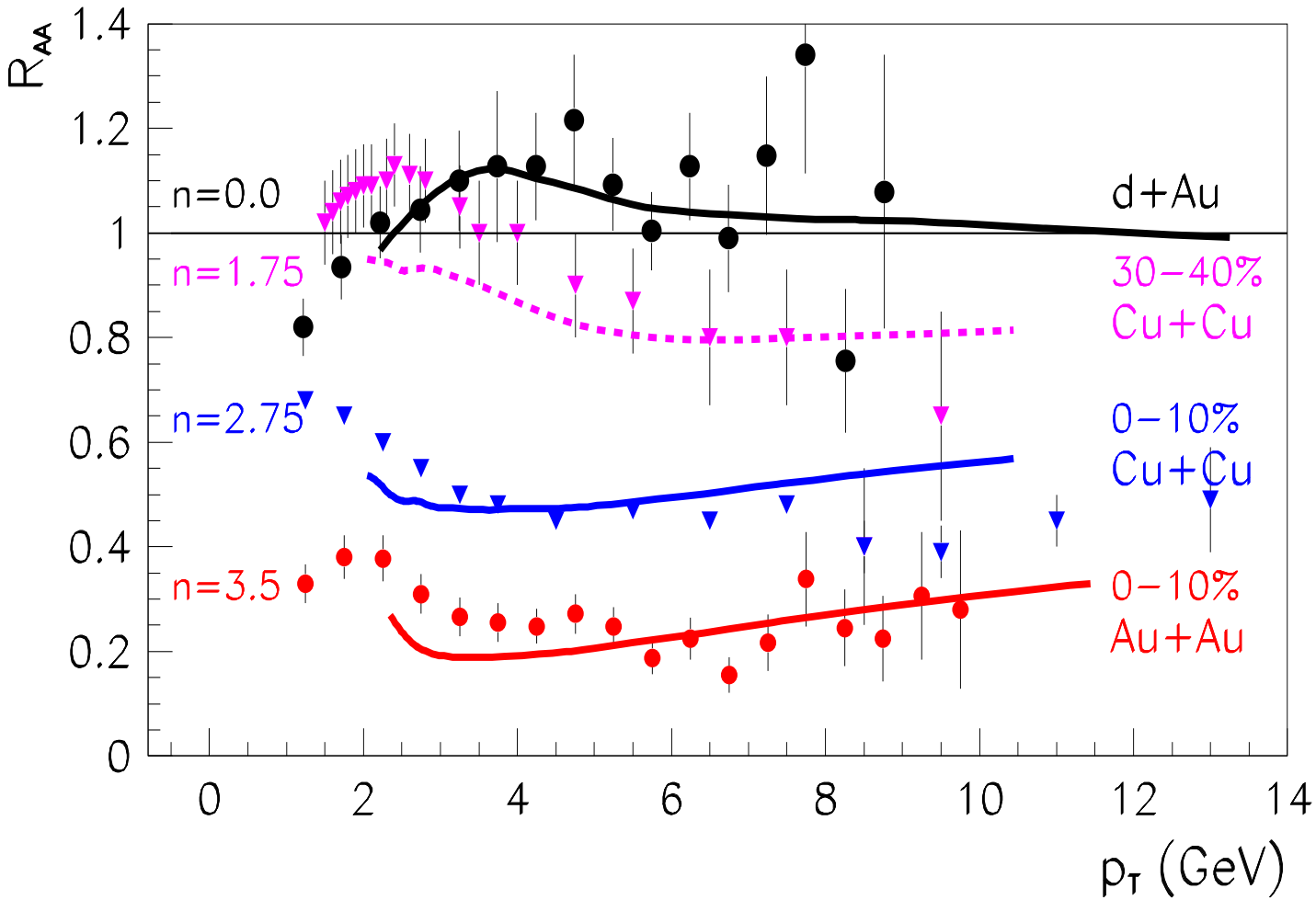
# Jet tomography in $AuAu$ and $dAu$ collision at PHENIX




Prog. in Part. and Nucl. Phys. **52** 2 (2004), Eur. Phys. J. **C33** S609 (2004)

# Calculated $R_{AA}^{\pi^0}$ for Central $AuAu$ and $CuCu$ Collisions




**In the smaller**

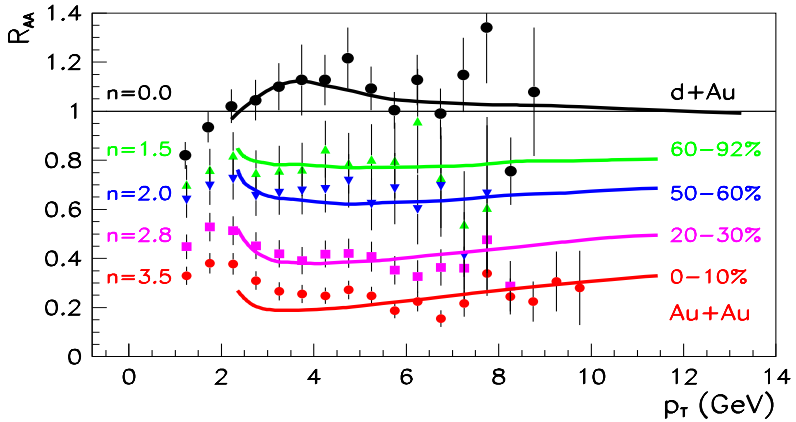
**$CuCu$ system**

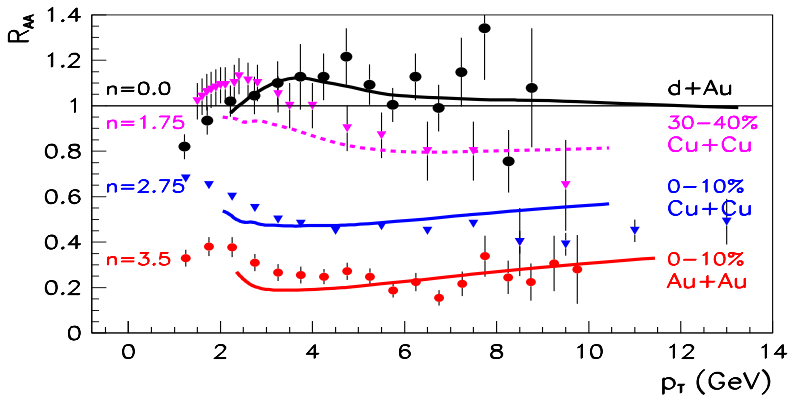
**$L/\lambda$ is less $\sim 0.75$**

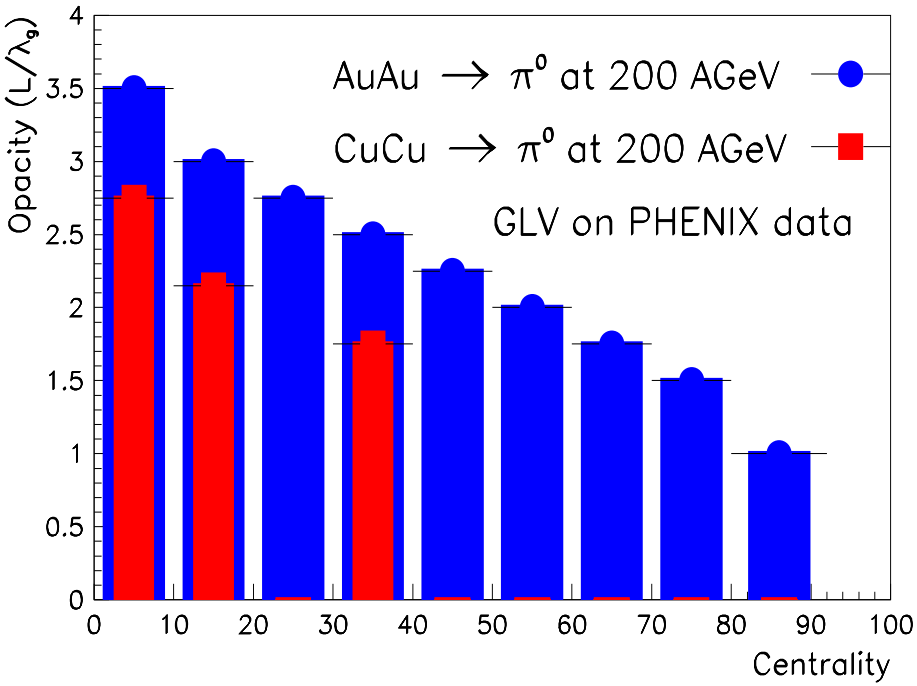
**than in $AuAu$.**

$AuAu$,$dAu$ and central $CuCu$ data for $\pi^0$ by PHENIX, mid-central $CuCu$ by STAR

# System size dependence ($A$) of $R_{AA}^{\pi^0}$ for $AuAu$ and $CuCu$




See also H. Büsching's talk

$AuAu$,$dAu$ and central $CuCu$ data for $\pi^0$ by PHENIX, mid-central $CuCu$ by STAR

# Comparing $\pi^0$ data in $AuAu$ at $\eta = 3.1$ and $y = 0$

$AuAu$ at BRAHMS $\eta = 3.1$ and PHENIX $y = 0$

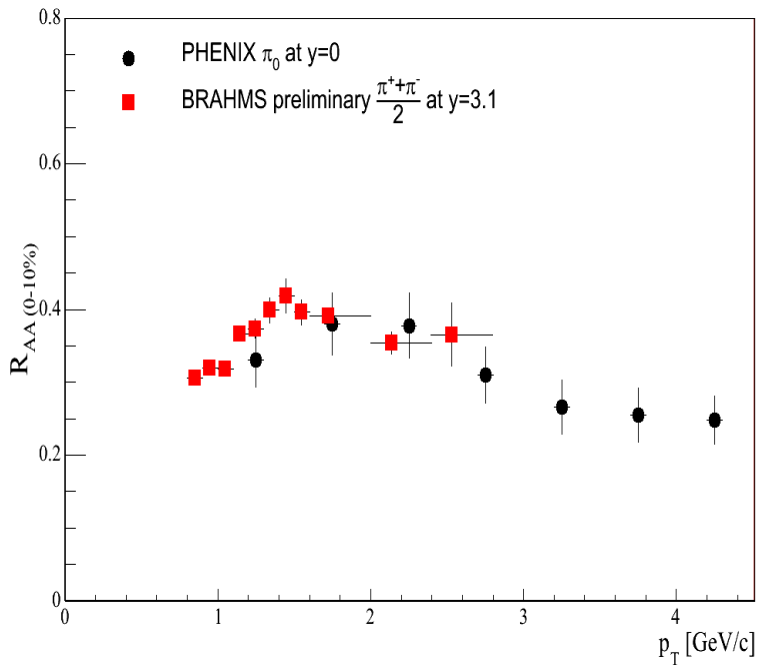
Larger shadowing in $dAu$ at $\eta > 0$

Additional (exp.) information:

– $R_{AuAu}(y = 0) \approx R_{AuAu}(y > 0)$

– $R_{CP} \geq R_{AA'}$

– **QM '06 BRAHMS results**

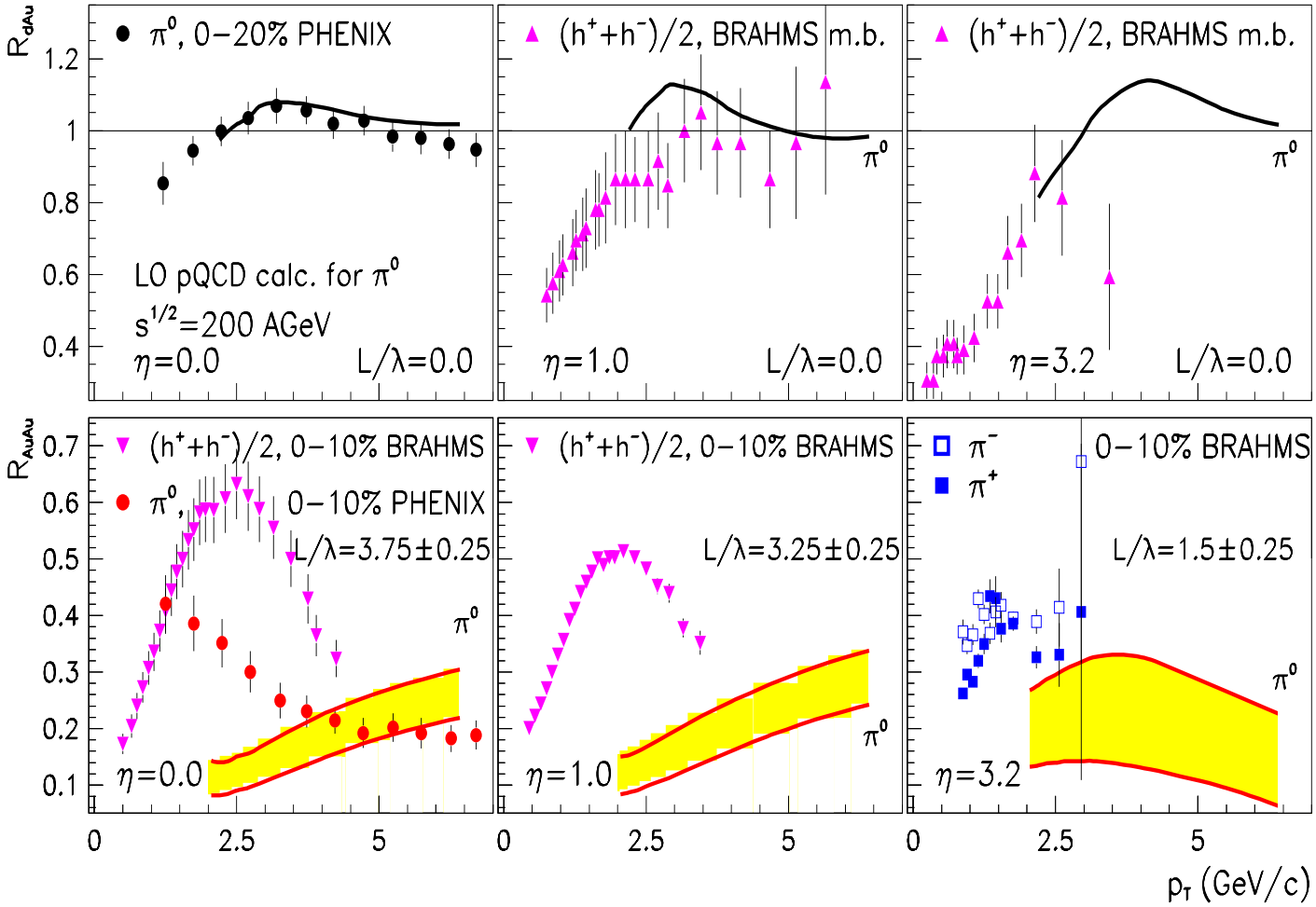



$\Longrightarrow$ **Shadowing effect is stronger**

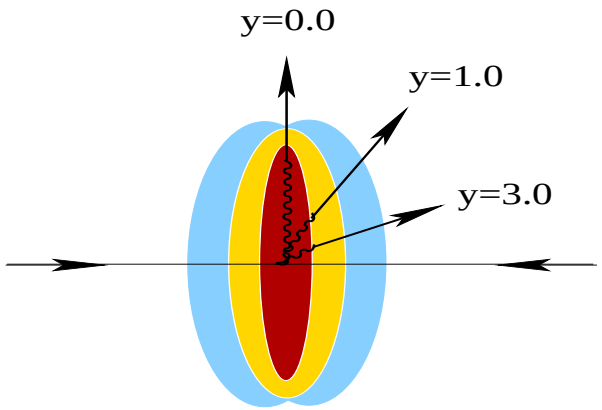
$\Longrightarrow$ **Travelling length getting smaller as going more forward**

$\Longrightarrow$ **Smaller $L/\lambda$ can be extracted in the forward $\pi$ production**

# Jet-tomography in $AuAu$ Collisions at Large $\eta$

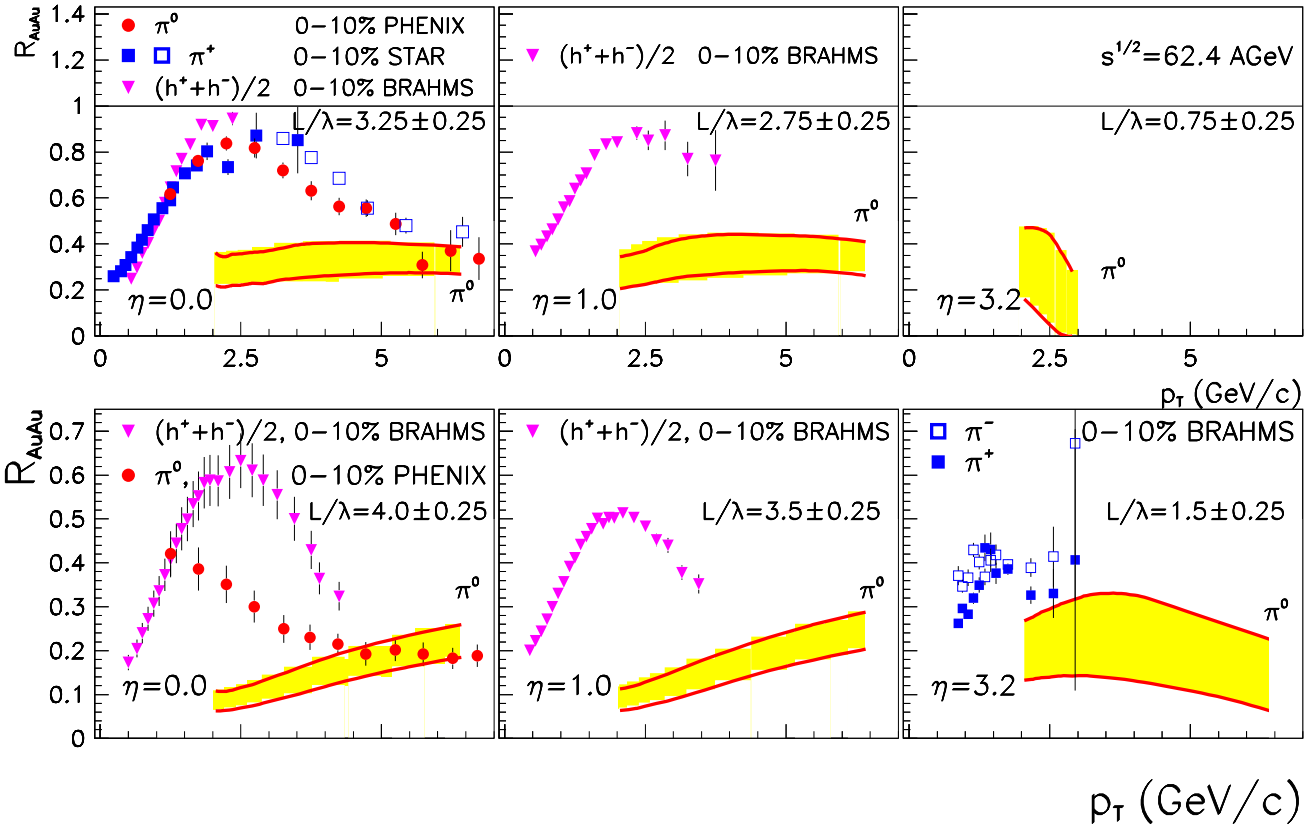



**In the forward directions $L/\lambda$ is smaller, due to less matter.**




$AuAu$, $dAu$ data for $\pi^0$ by PHENIX and $h^\pm$ and $\pi^+$,$\pi^-$ by BRAHMS

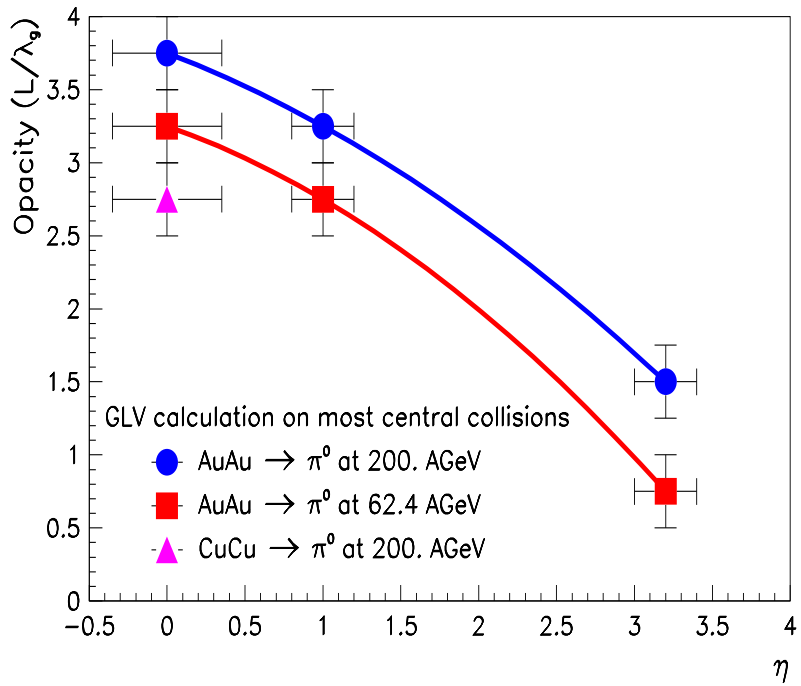
# Jet-tomography in $AuAu$ Collisions at 62.4 and 200 $A$GeV




**Decreasing $\sqrt{s}$**

**the $L/\lambda$ is**

**smaller,**




**Getting close to compare**

**geometrical and $\varepsilon$ properties**

# Summary – Outlook

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

Goal: Extracting the $L/\lambda_g$ values in $AA'$ in all direction

**Results for $\pi^0$ in $AuAu$ and $CuCu$ at $\boxed{\eta = 0}$ and $\boxed{\eta > 0}$**

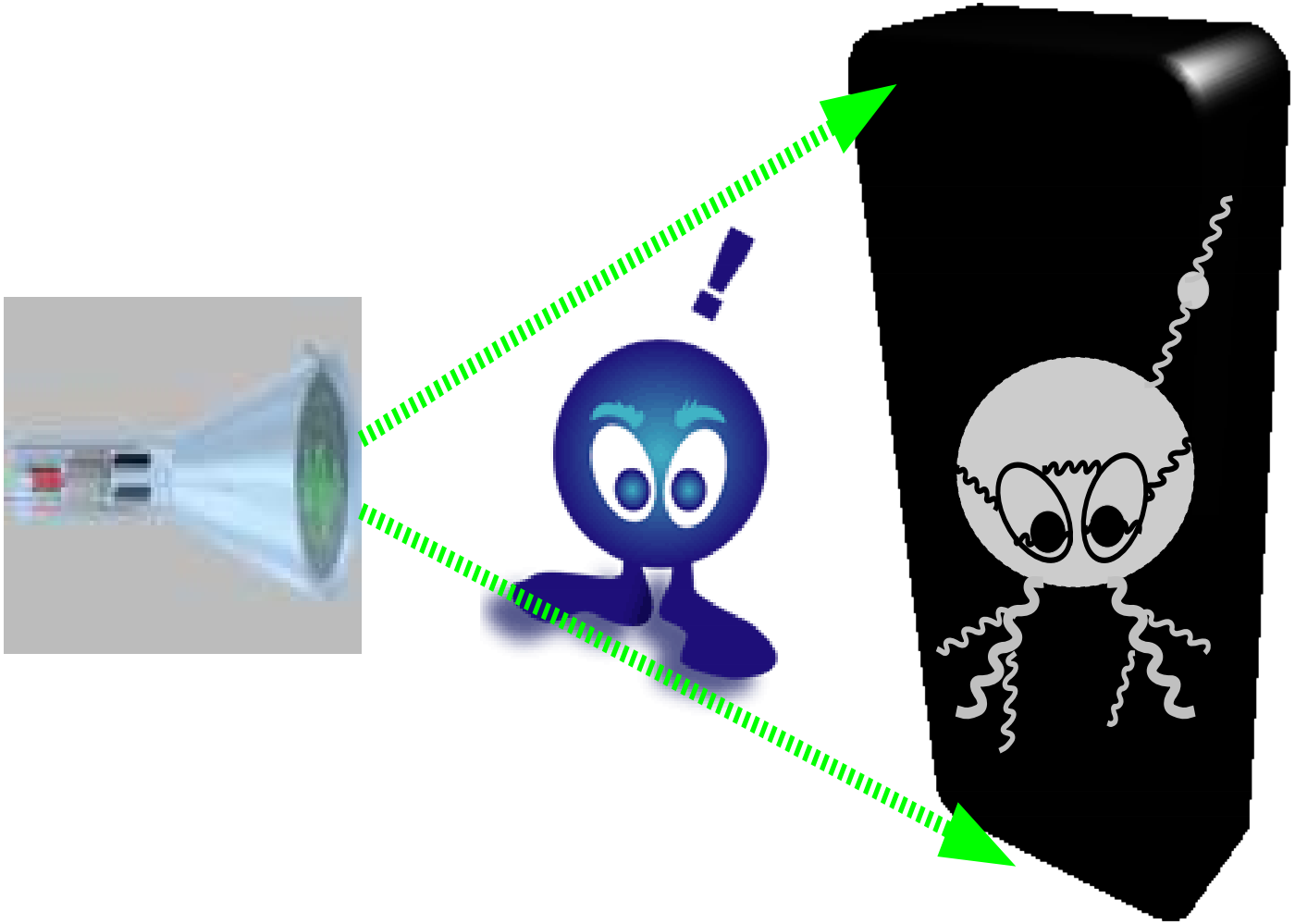
– GLV jet-quenching with opacity parameter $n = L/\lambda$

$\Longrightarrow$ As we expected, $R_{AA}(\eta > 0)$ needs smaller $L/\lambda$.

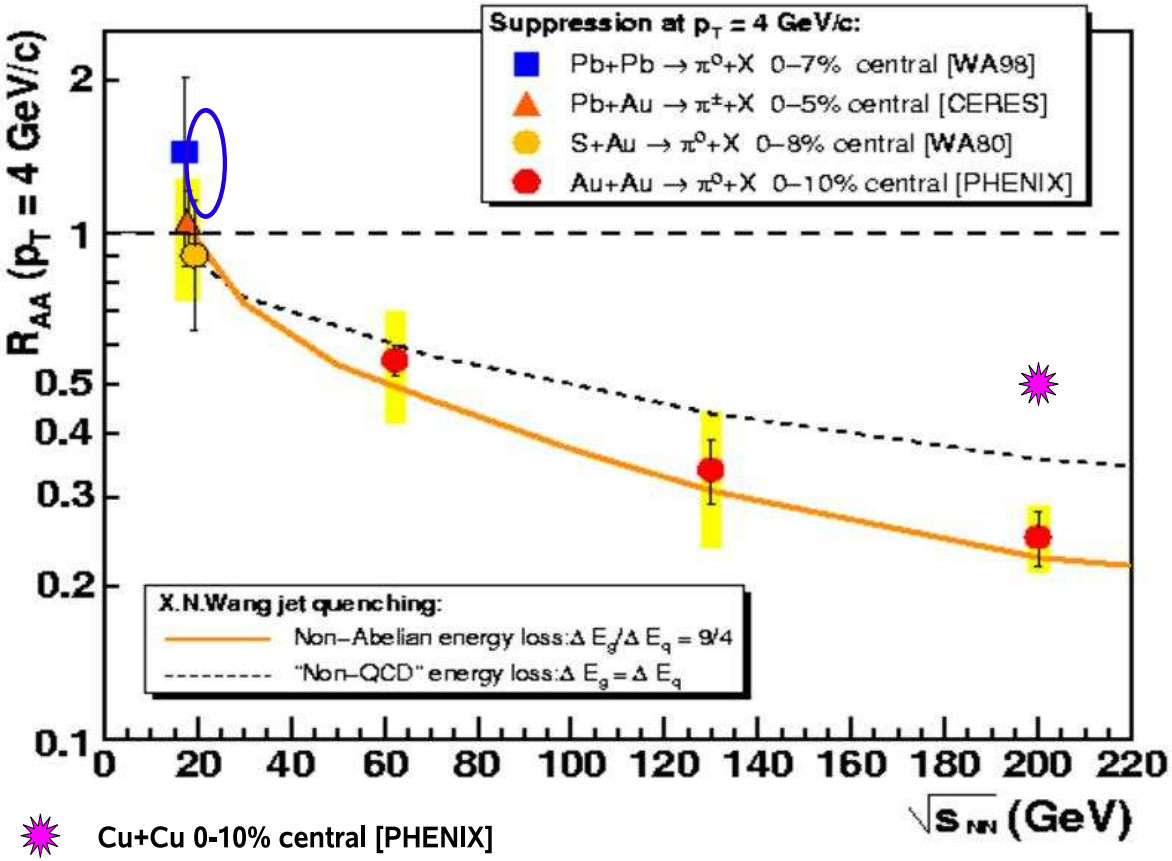
$\Longrightarrow$ System size and $\sqrt{s}$ dependence of $L/\lambda$.

$\Longrightarrow$ Extracting $L/\lambda$ in central and peripherical collisions.

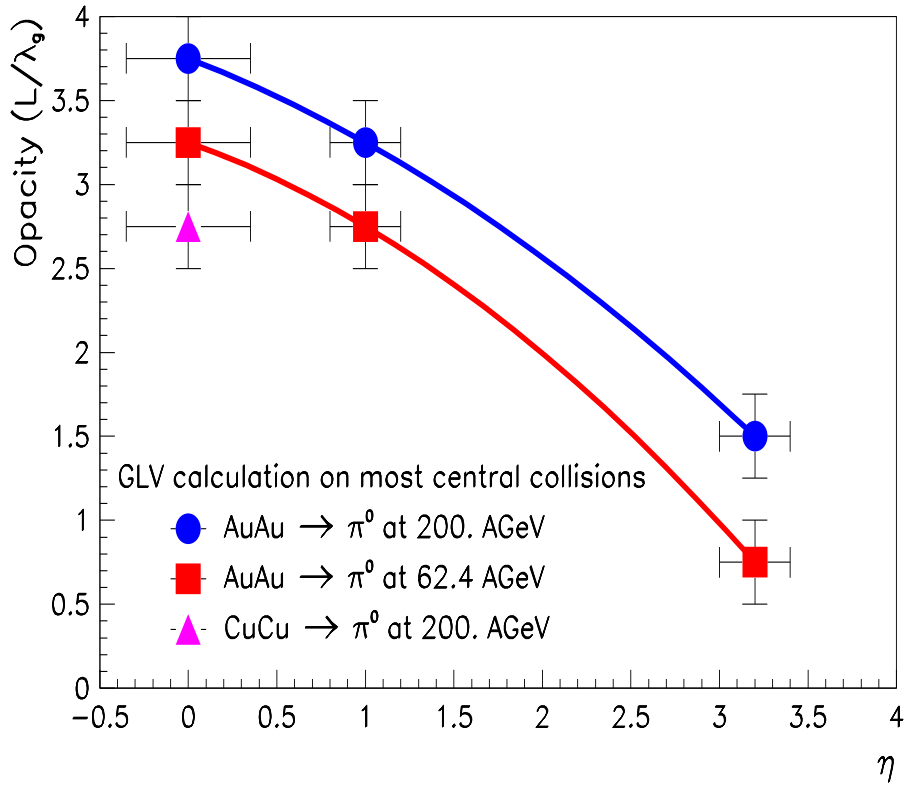
# T O M O G R A F F I T I



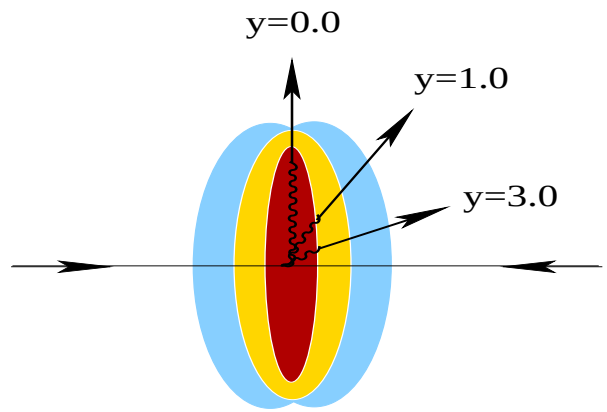
# Energy (Density) Dependence of the Suppression




Cu+Cu 0-10% central [PHENIX]

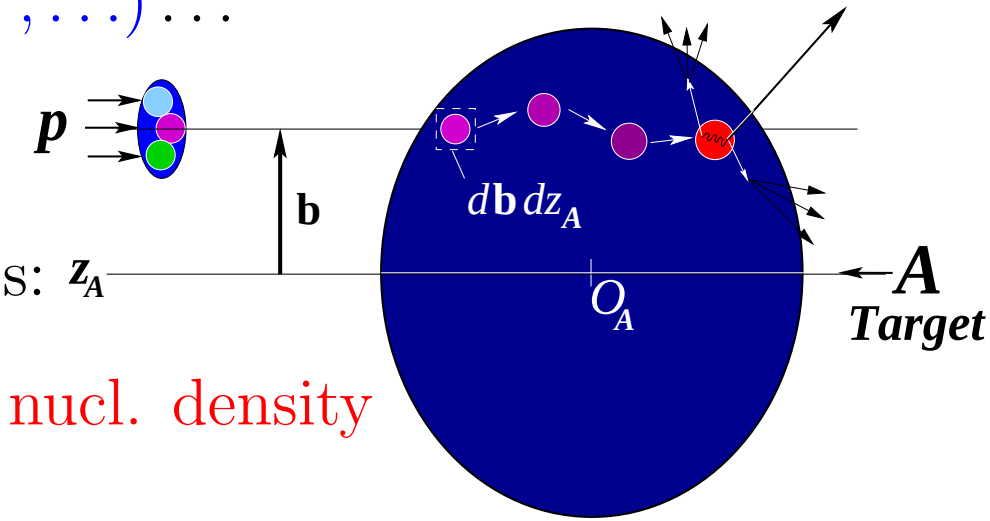



| Reaction | $\sqrt{s_{NN}}$ (GeV) | $\epsilon_{Bj}$ (GeV/fm$^3$) |
|---|---|---|
| $S+S$ | $17,3$ | $\gtrsim 1,3$ |
| $S+Au$ | $19,4$ | $\gtrsim 2.6$ |
| $Pb+Pb$ | $17,3$ | $\gtrsim 3.2$ |
| $Pb+Au$ | $17,3$ | $\gtrsim 3.0$ |
| $Au+Au$ | $62.4$ | $\gtrsim 3.7$ |
| $Au+Au$ | $130$ | $\gtrsim 4.4$ |
| $Au+Au$ | $200$ | $\gtrsim 5.0$ |



# I/1. 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:**

$t_A(b) = \int dz\, \rho(b,z)$ normalized a s: $A = \int_0^{b_{max}} t_A(b) \mathrm{d}^2 b$ , where $\rho(b,z)$ 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/2. (b) Phenomenological introduction of intrinsic $k_T$

## 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 :

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

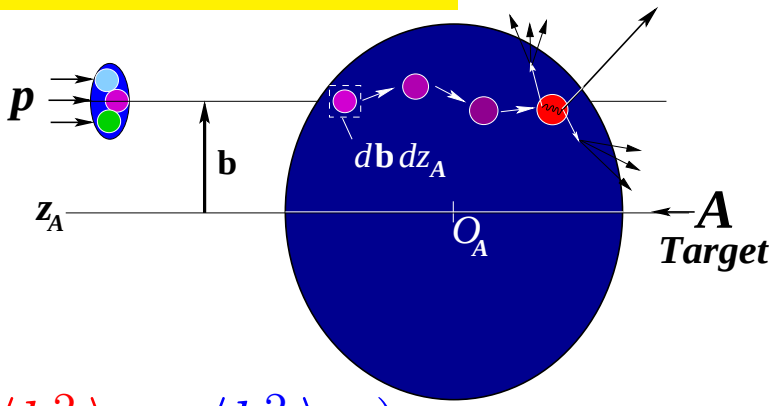
Baseline $\langle k_T^2\rangle$ values for $pp$: Phy s. Rev. **C65** 034903 (2002)

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

# I/3. (b) Multiple Scattering – Cronin Effect

**Improve Glauber model:**

**assuming saturation in the number of $NN$ collisons**




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

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

**Total broadening = $pp$ baseline + nuclear broadening**

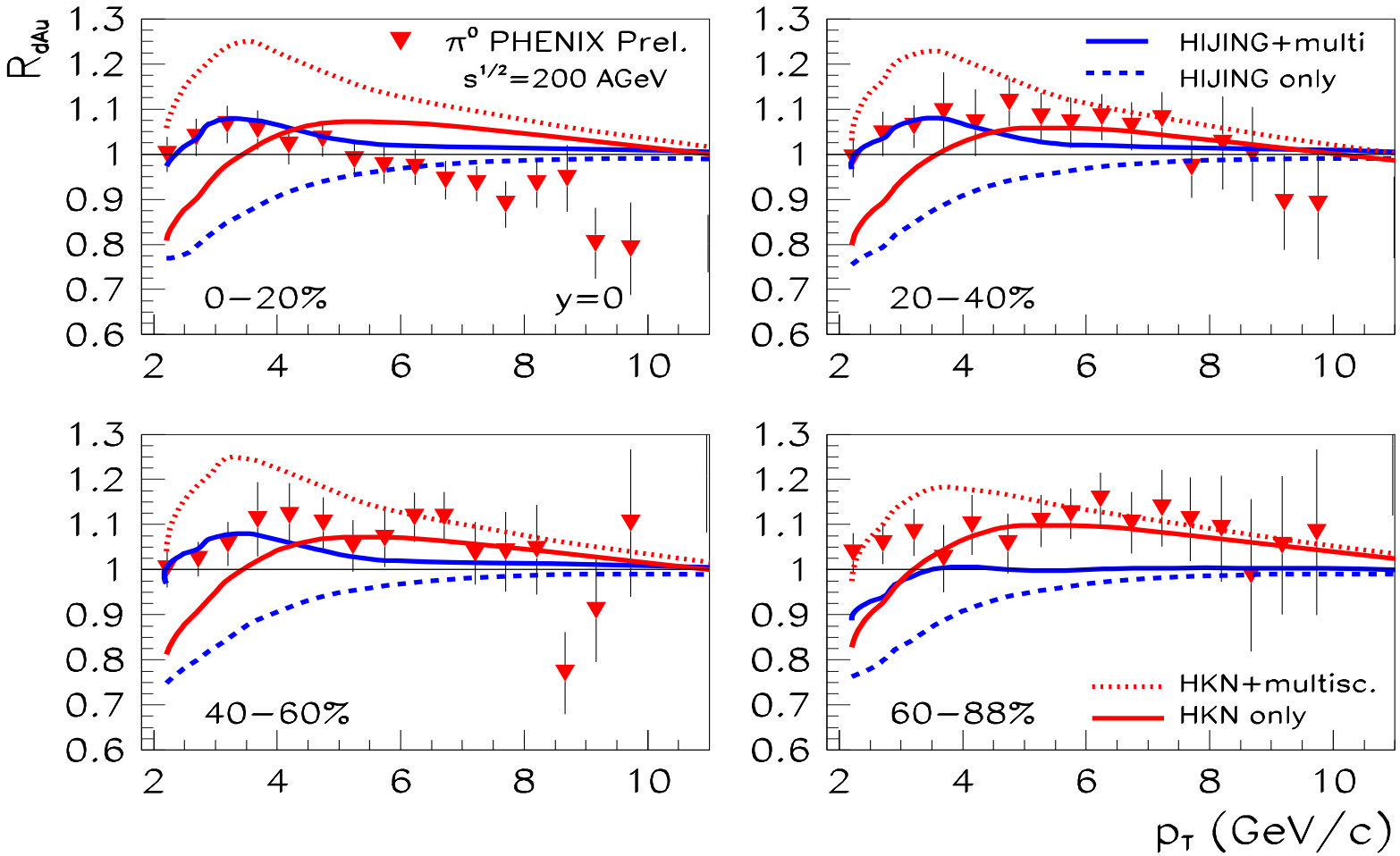
See details in PR**C65** 034903 (2002) and `hep-ph/0212249`

$h(\nu_A(b)-1)$ : number of effective NN collisions $\nu_{max} = 3-4$

$C$ : (average mom. broadening)$^2$ / coll. $C \approx 0.35$ GeV$^2$

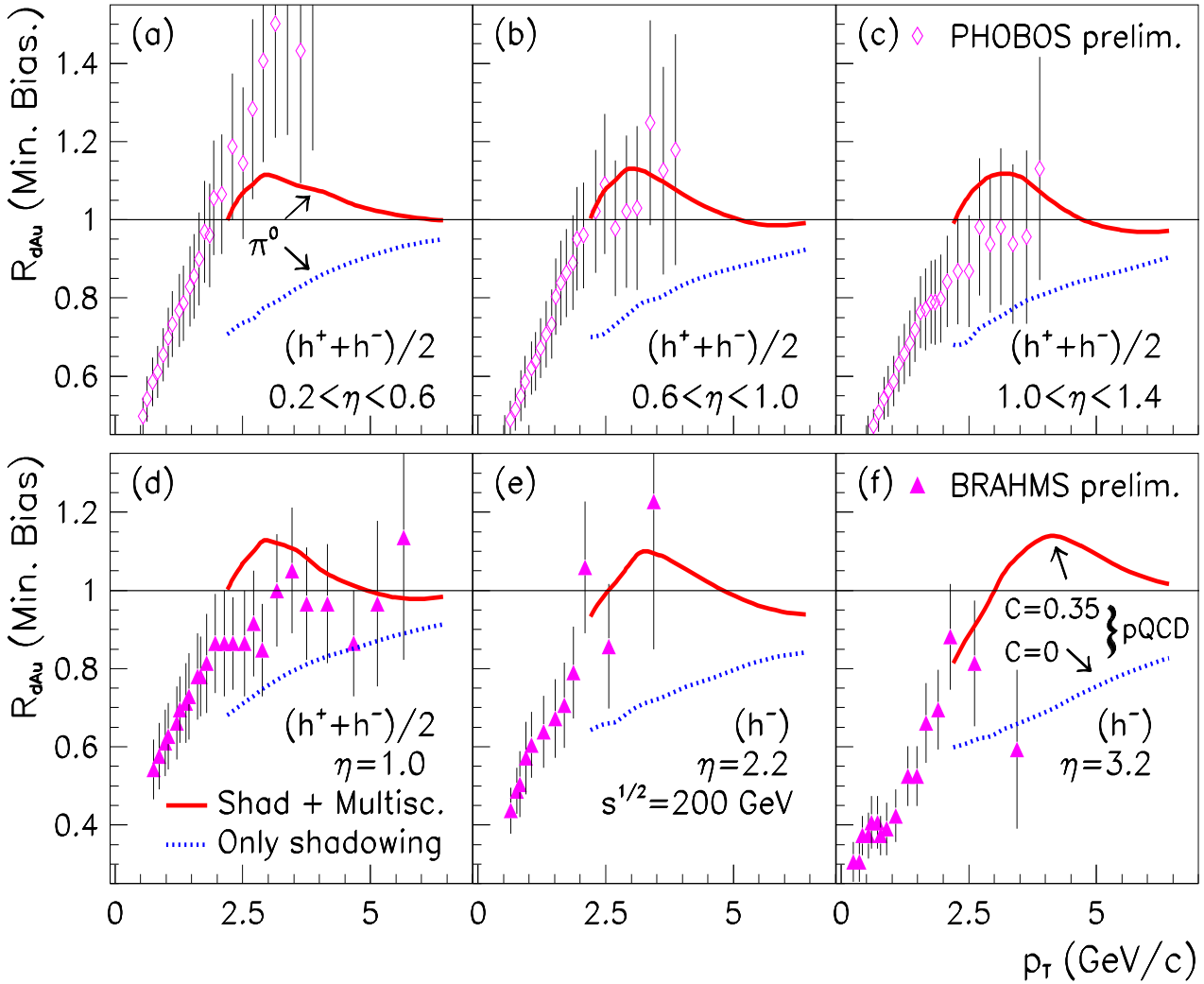
$t_A(b)$ : nuclear thickness function

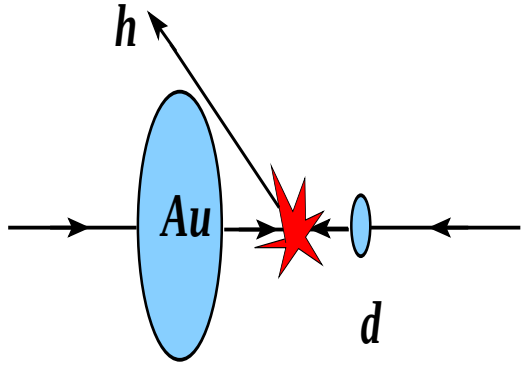
# Cronin effect in different Centralities in $dAu$ collision at PHENIX



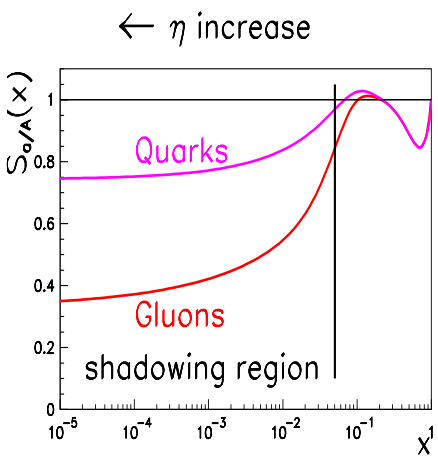

G.G. Barnaföldi *et al.*: to be published...

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



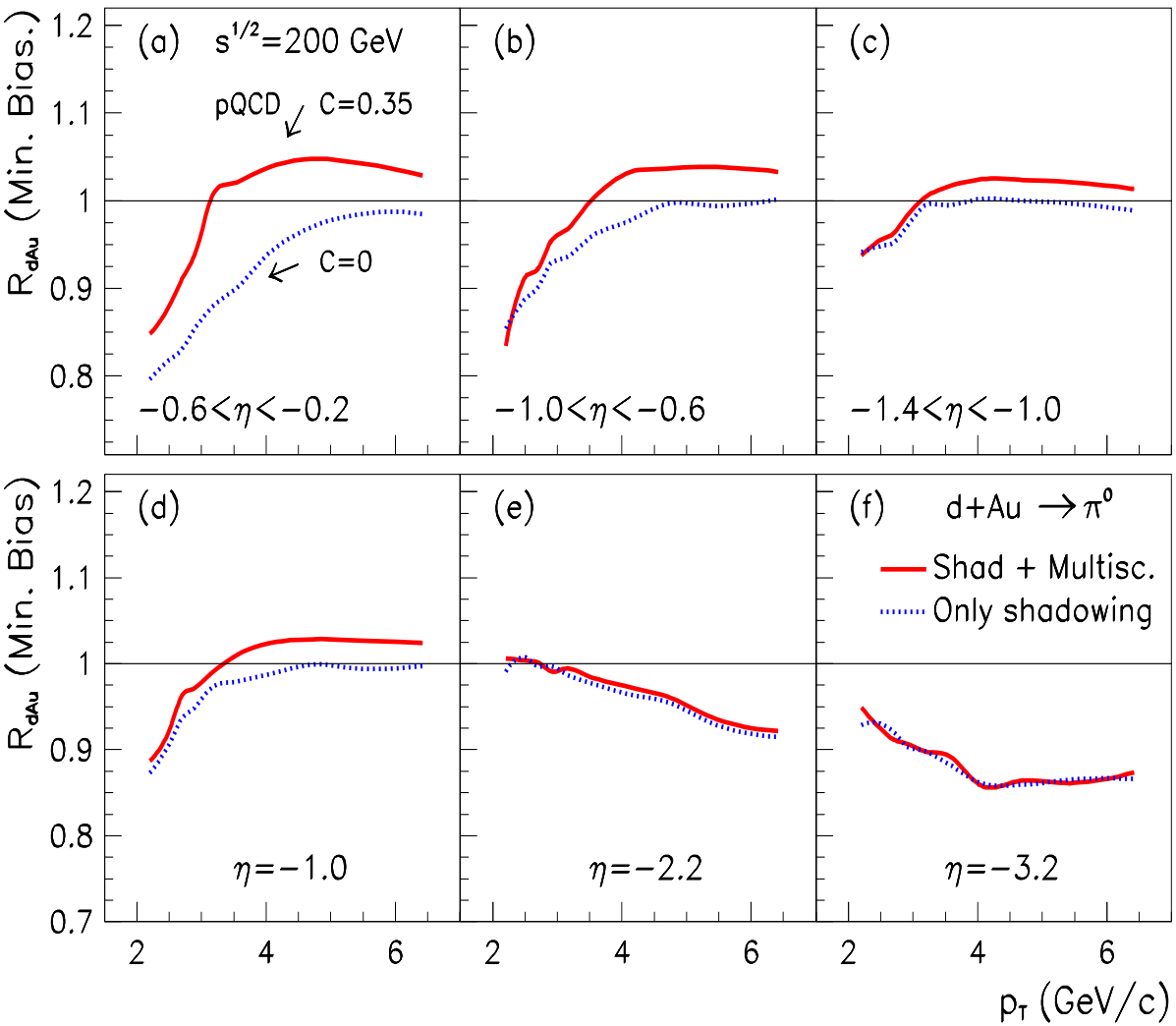



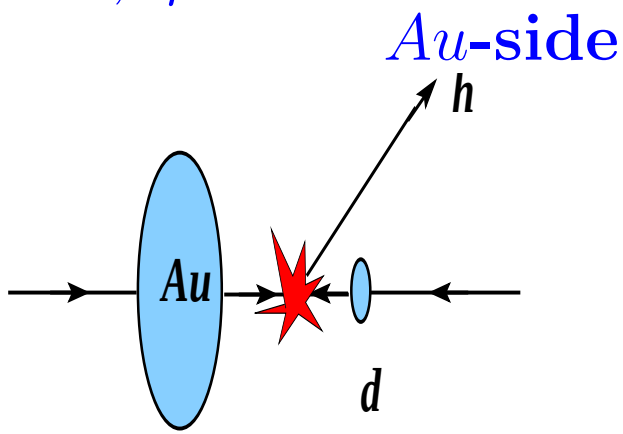

**$d$-side**



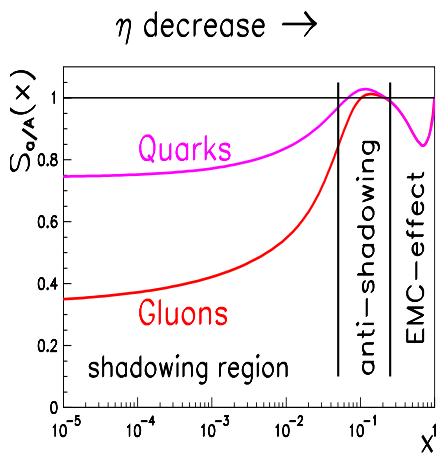

**BRAHMS data:** `nucl-ex/0403005` **and PHOBOS data:** `nucl-ex/0406017`

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

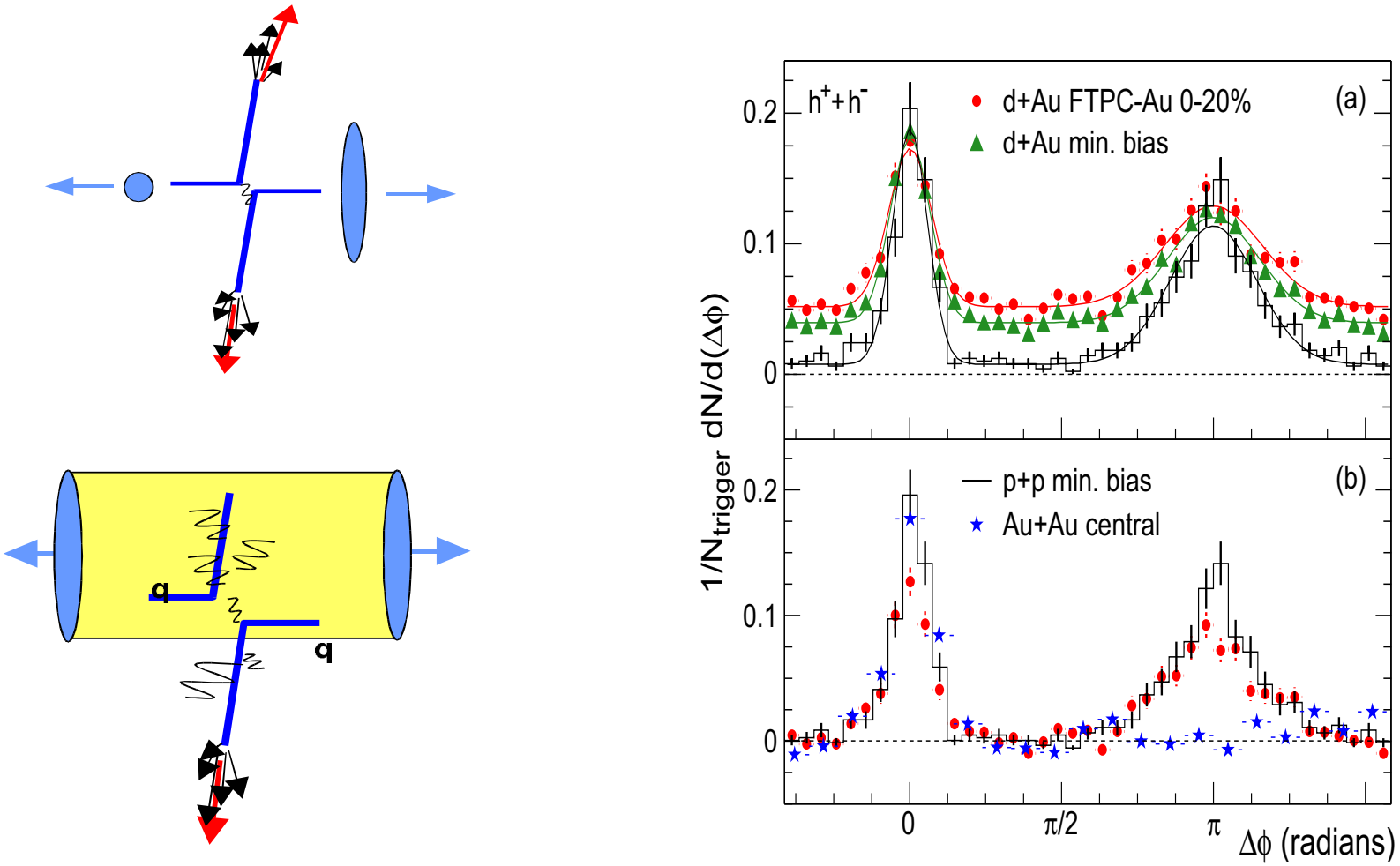



**NO relevant multiscatt. in $d$.**

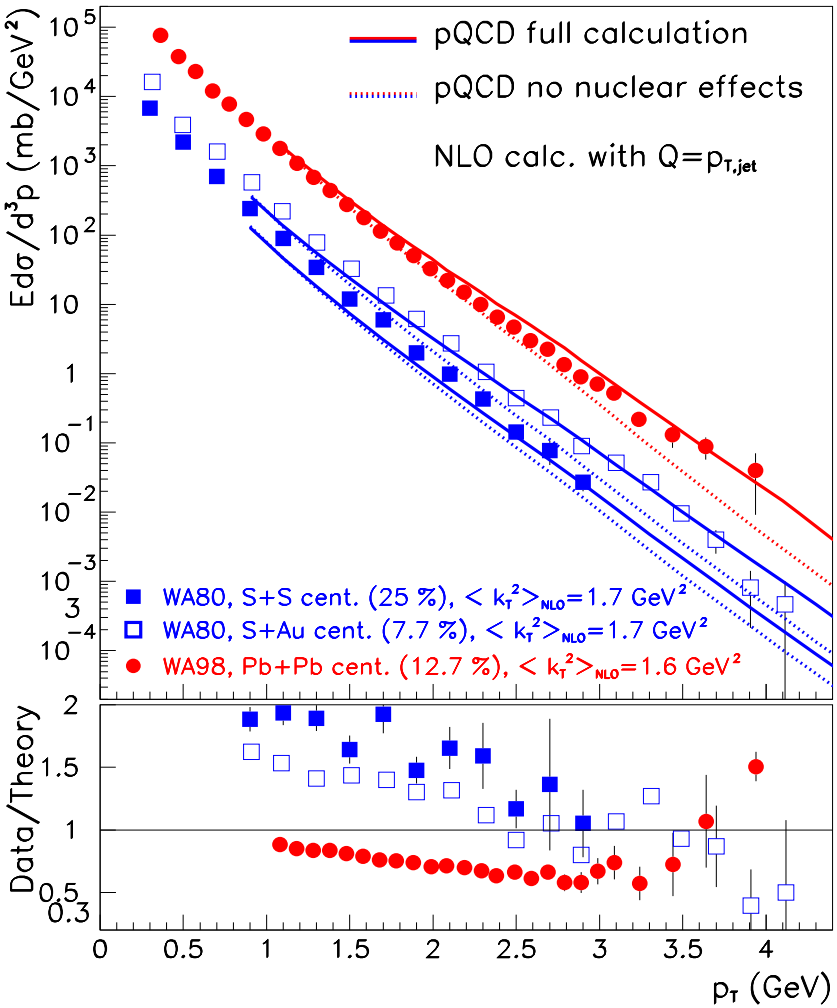


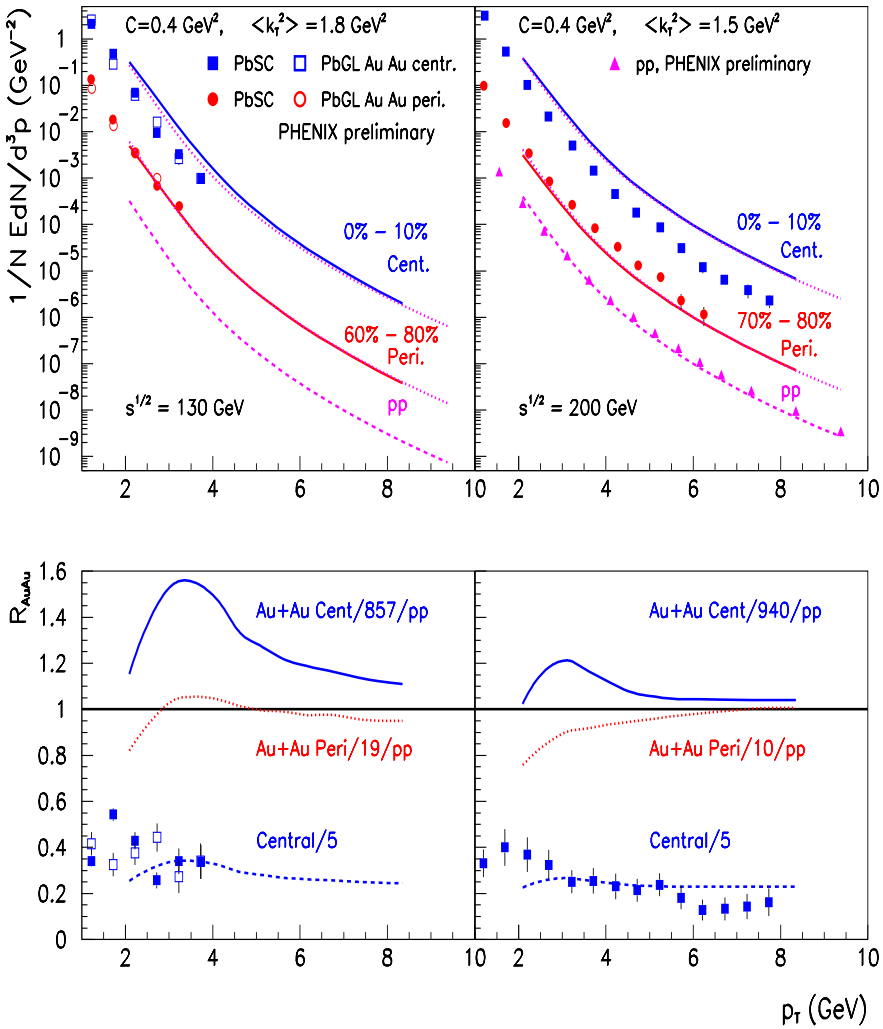
# I/3. Jet-Jet Correlation in $d + Au$ and $Au + Au$




Jet-jet back-to-back correlation data from STAR experiment displays strong jet suppression in $Au + Au$ collision (nucl-ex/0306024)

# Results: $\pi$ Spectra in $AA'$ Collisions at SPS and RHIC




Proc. of ISMD'02, 145 (2002), APH NS Heavy Ion Phys. **18**, 79 (2003)