Gluon Shadowing and Nuclear Modification Factor

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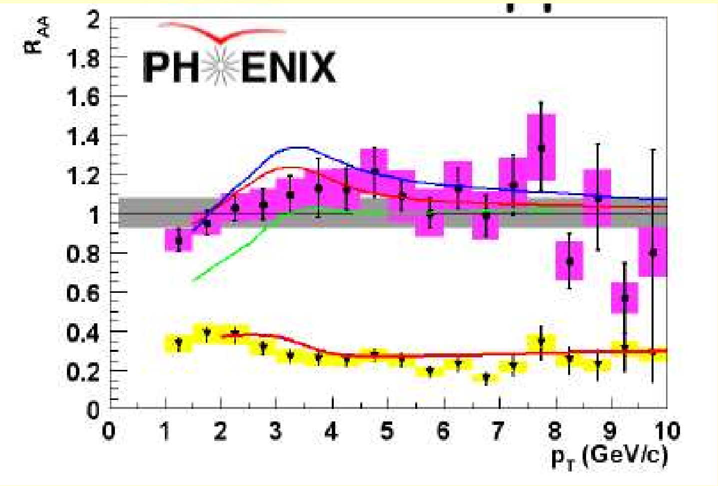
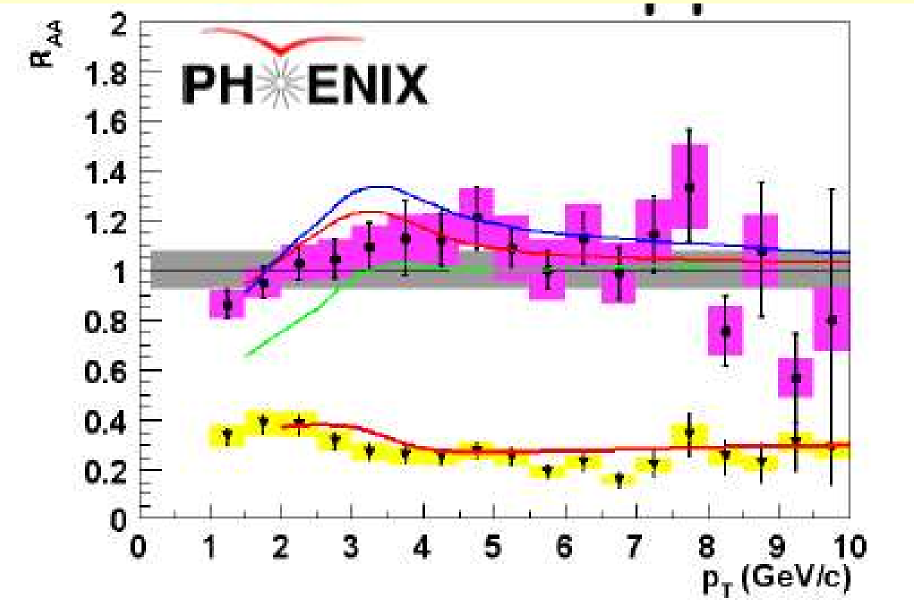
QCD at Cosmic Energies -II

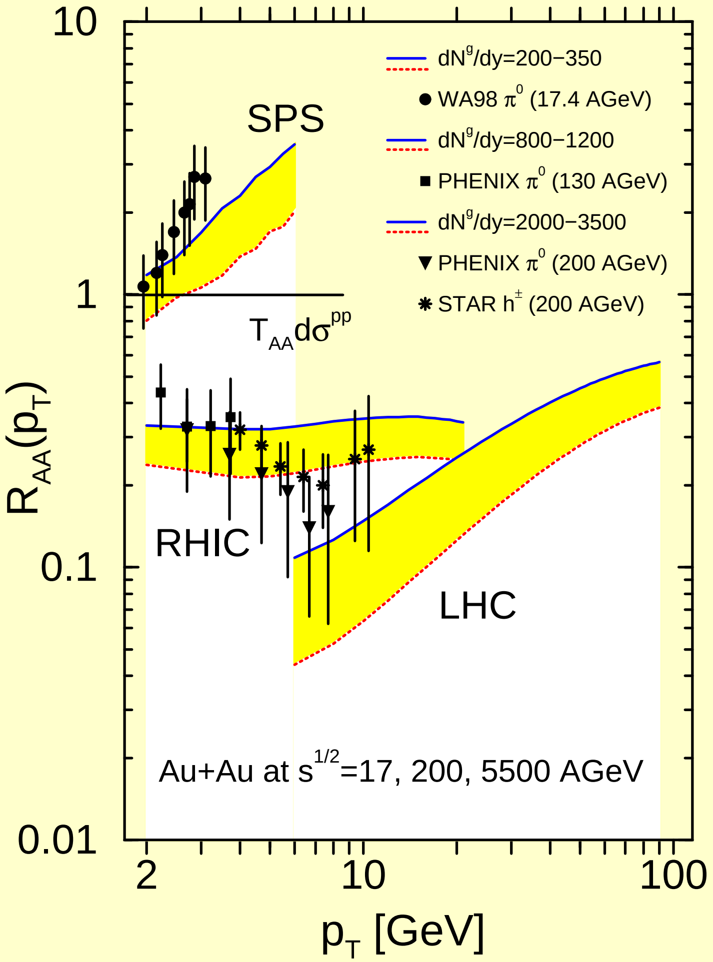
- Motivation
- Features of d+Au and Au+Au interactions at RHIC
- Nuclear modification factors R_{AA} and R_{CP}
- Shadowing at ultra-relativistic energies
- Models at our disposal: HIJING, QGSM, HSD, ...
- Conclusions



Motivation: $R_{AA}(p_T)$

M. Gyulassy, P. Levai, I. Vitev, PRL 85 (2000) 5535
A. Accardi, M. Gyulassy, nucl-th/0308029





Nuclear modification factor $\mathbf{R_{AA}}$ for $\mathbf{d+Au}$ and $\mathbf{Au+Au}$ collisions
$\mathbf{R_{dA}}$ shows interplay between different gluon shadow parameterizations and Cronin enhancement

Nuclear Modification Factors

Definitions:

$$\mathbf{R_{dAu} = \frac{d^2N/dp_T d\eta(d+Au)}{N_{coll} d^2N/dp_T d\eta(p+p)}}$$

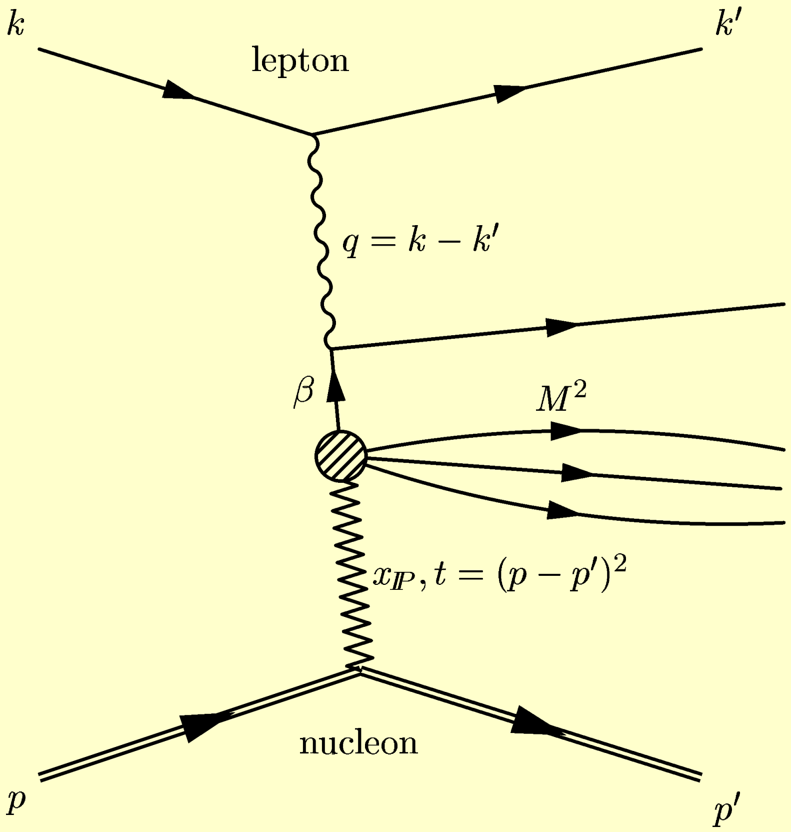
$$\mathbf{R_{AA} = \frac{d^2N/dp_T d\eta(A+A)}{N_{coll} d^2N/dp_T d\eta(p+p)}}$$

$$\mathbf{R_{CP} = \frac{N_{coll}^{peripheral} d^2N/dp_T d\eta(A+A)}{N_{coll}^{central} d^2N/dp_T d\eta(A+A)}}$$

- $\mathbf{R_{d(A)A} \neq R_{CP}}$
- $\mathbf{R_{d(A)A}}$: **isospin effects, canonical strangeness suppression**
- $\mathbf{R_{CP}}$: **collective effects in peripheral collisions, undefined collision geometry in peripheral collisions**

Shadowing

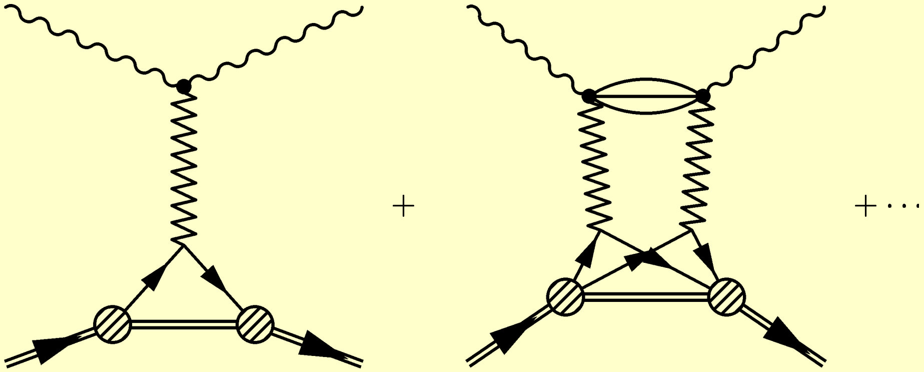
M. Arneodo, Phys. Rep. 240 (1994) 301
N. Armesto et al., EPhJ C 29 (2003) 531
L. Frankfurt, M. Guzey, M. Strikman, PRD 71 (2005) 054001



Diffractive DIS: kinematic variables in the infinite momentum frame

Shadowing: at small values of the Bjorken variable x (≤ 0.01) the structure function $\mathbf{F_2}$ per nucleon turns out to be smaller in nuclei than in a free nucleon. In the rest frame of the nucleus nuclear shadowing is a consequence of multiple scattering which in turn is related to diffraction. One can alternatively investigate the process in the infinite momentum frame (IMF), which is the case for the presented model. The usual variables for diffractive DIS are $\mathbf{Q^2}$, $\mathbf{x}$, $\mathbf{M^2}$ and $\mathbf{t}$, or $\mathbf{x_P} = \mathbf{x}/\beta$, $\beta = \frac{\mathbf{Q^2}}{\mathbf{Q^2+M^2}}$.

Shadowing and Diffraction



The first two terms (single and double re-scattering) of the multiple scattering series for the total $\gamma^* N$ cross section

We use the relation of diffraction to nuclear shadowing which arises from Gribov theory, Reggeon calculus and the AGK cutting rules together with a model for the diffractive and inclusive structure functions of the nucleons, $\mathbf{F_2}$ and $\mathbf{F_{2D}}$. First term - Glauber model; subsequent terms - due to the multiple scatterings of the excited γ^*-system that contribute negatively to the total cross section.

$$\boxed{\sigma_{\mathbf{A}} = \sigma_{\mathbf{A}}^{(\mathbf{1})} + \sigma_{\mathbf{A}}^{(\mathbf{2})} + \ldots\,,}$$

where

$$\boxed{\sigma_{\mathbf{A}}^{(\mathbf{1})} = \mathbf{A}\,\sigma_{\gamma^*\mathbf{N}}}$$

Shadowing and Diffraction

Employing the Schwimmer unitarization model, one gets

$$\sigma^{\mathrm{Sch.}}_{\gamma^* \mathbf{A}} \; = \; \sigma_{\gamma^* \mathbf{N}} \int \mathbf{d^2b} \, \frac{\mathbf{A T_A (b)}}{\mathbf{1 + (A-1) f(x, Q^2) T_A (b)}}$$

where

$$\mathbf{(x, Q^2)} \; = \; \frac{\mathbf{4}\pi}{\sigma_{\gamma^* \mathbf{N}}} \int_{\mathbf{M^2_{min}}}^{\mathbf{M^2_{max}}} \mathbf{dM^2} \, \frac{\mathbf{d}\sigma^{\mathbf{D}}_{\gamma^* \mathbf{N}}\mathbf{(t = 0)}}{\mathbf{dM^2 \, dt}} \, \mathbf{F^2_A (t_{min})}$$

$\mathbf{F_A}$ is the nuclear form factor, and $\mathbf{T_A}$ is the nuclear profile. The shadowing in nuclei is usually studied through the ratios of cross sections per nucleon for different nuclei

$$\mathbf{R(A/B)} \; = \; \frac{\mathbf{B}}{\mathbf{A}} \, \frac{\sigma_{\gamma^* \mathbf{A}}}{\sigma_{\gamma^* \mathbf{B}}}$$

Parametrization of Nuclear PDF

For the nucleon

$$\sigma_{\gamma^* \mathrm{N}} = \frac{4\pi^2 \alpha_{\mathrm{em}}}{\mathrm{Q}^2} \mathrm{F}_2(\mathrm{x}, \mathrm{Q}^2)$$

(valid at small x), where $\mathrm{F}_2(\mathrm{x}, \mathrm{Q}^2)$ is the nucleon structure function. The relation between the diffractive cross section and the diffractive structure function is provided by a model

$$\left. \frac{\mathrm{d}\sigma^{\mathrm{D}}_{\gamma^* \mathrm{N}}(\mathrm{Q}^2, \mathrm{x_P}, \beta)}{\mathrm{dM}^2\, \mathrm{dt}} \right|_{\mathrm{t}=0} = \frac{4\pi^2 \alpha_{\mathrm{em}}\, \mathrm{B}}{\mathrm{Q}^2\, (\mathrm{Q}^2 + \mathrm{M}^2)}\, \mathrm{x_P}\, \mathrm{F}^{(3)}_{2\mathrm{D}}(\mathrm{Q}^2, \mathrm{x_P}, \beta)$$

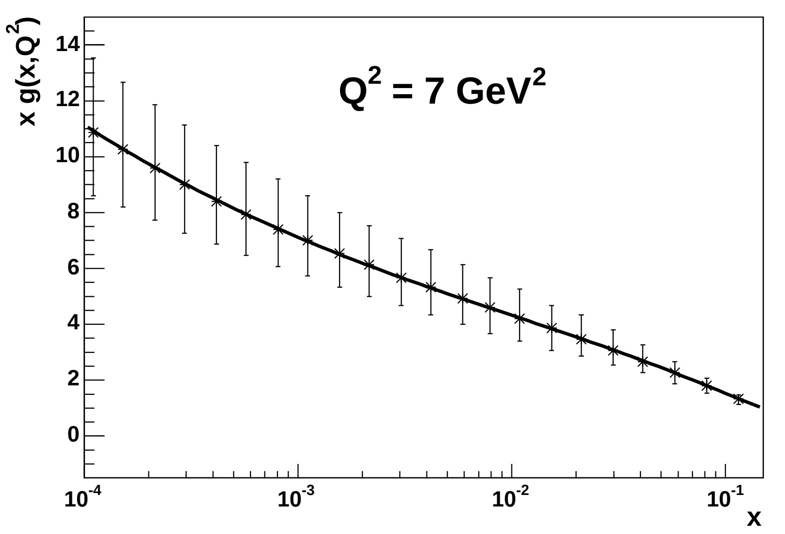
where Regge factorization has been assumed.

Then,

if the HERA hard diffractive information is not used, there are no constrains on the gluon shadowing (M. Strikman, Small-x Workshop)

Parametrization of Nuclear PDF

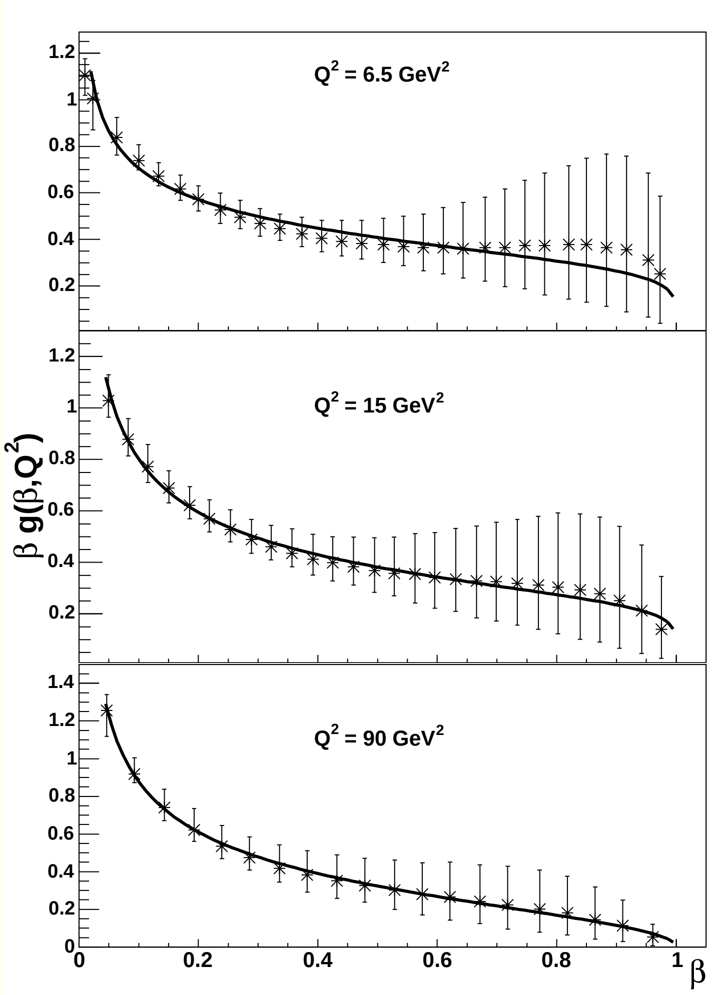
The gluonic nuclear parton distribution functions for nucleon and Pomeron have recently been measured at the HERA experiment



Fit to ZEUS data: distribution of gluons in the proton

Parametrization

$$\boxed{Ax^b(1-x)^c}$$

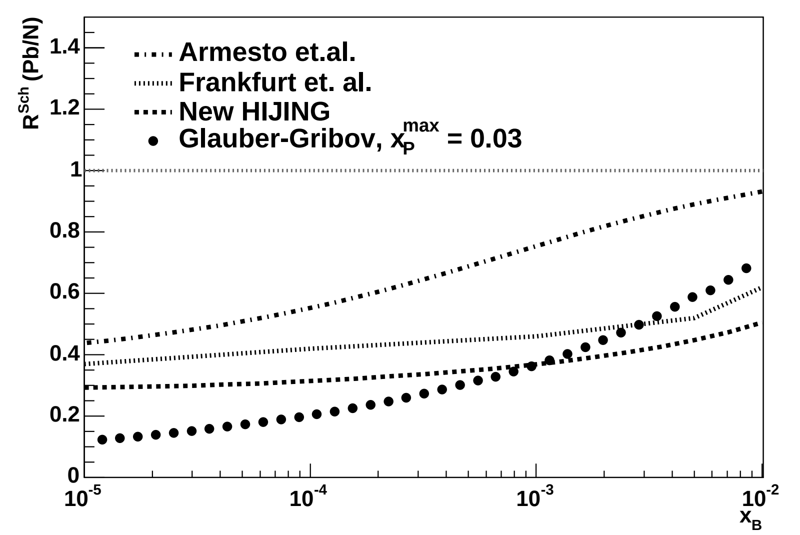


Fit to H1 data: distribution of gluons in the Pomeron

Gluon Shadowing

$$\mathbf{f(x,Q^2) = 4\pi \int_x^{x_P^{max}} dx_P\, B(x_P)\, \frac{F_{2D}^{(3)}(x_P,Q^2,\beta)}{F_2(x,Q^2)}\, F_A^2(t_{min.})}$$

where $B(x_P) = 0.184 + 0.02 \ln \frac{1}{x_P}$ **fm^2, $\alpha(t) = 1.173 + 0.26\,t$ GeV^{-2}, and calculations are made for two values of x_P^{max}: 0.1 and 0.03.**



Gluon shadowing for Pb at $Q^2 = 6.5(5)$ GeV^2

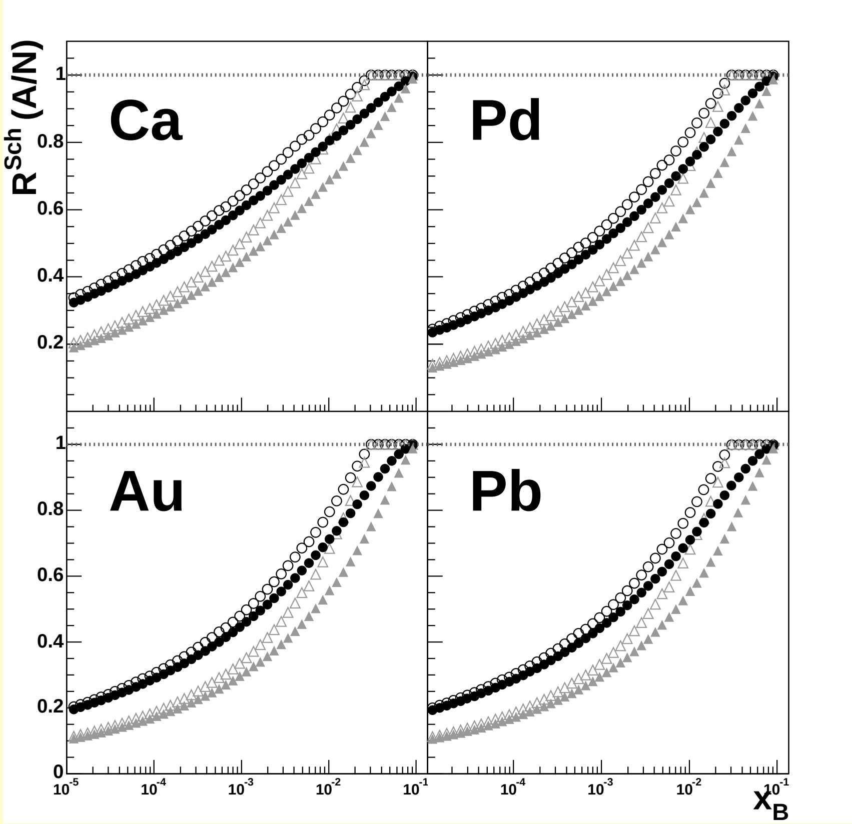
Two different nuclear density profiles $T_A(b)$ were used: (i) hard-sphere profile and (ii) Woods-Saxon density profile.

The shadowing due to gluons in the nucleus is much stronger than for quarks for small $x \sim 10^{-2}$ (Frankfurt, Strikman; Kaidalov). High-p_T particles and jets are produced by both quarks and gluons, however at very high energies and in the central rapidity region gluons dominate, because their distribution in nucleons is larger than those for quarks and the cross section of interaction is larger also.

Gluon Shadowing: Calculations

Hard spheres:

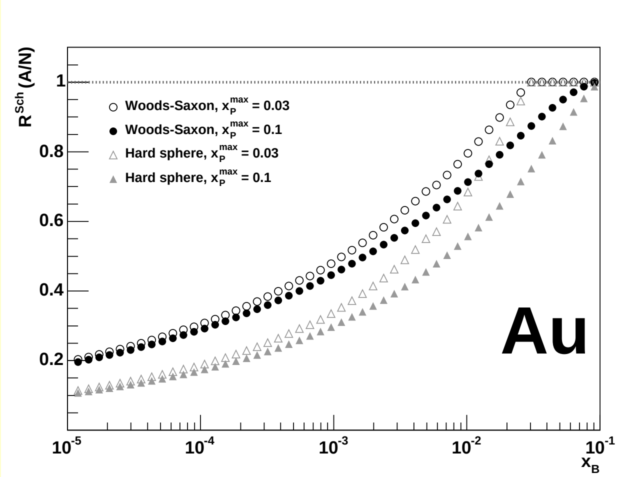
$$\mathbf{T_A(b) = \frac{3}{2\pi R_A^3}\sqrt{R_A^2 - b^2}}$$



Gluon shadowing for Ca, Pd, Au, Pb at $Q^2 = 6.5$ GeV^2

Woods-Saxon:

$$\mathbf{T_A(b) = \int_{-\infty}^{\infty} dz \, \frac{\rho_0}{\left(1 + e^{\frac{r-c}{a}}\right)}}$$



Gluon shadowing for Au at $Q^2 = 6.5$ GeV^2

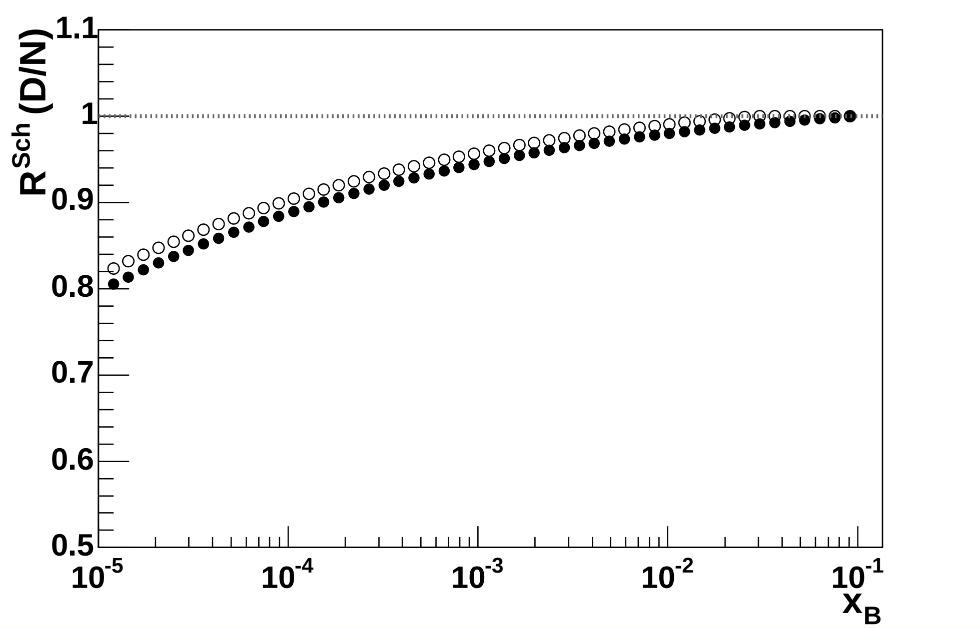
Gluon Shadowing Effects for Deuteron

We employ the following formulas for calculation of the shadowing in deuteron:

$$\sigma_{d}^{(1)} = 2\,\sigma_{\gamma* N}$$

$$\sigma_{d}^{(2)} = -2\int_{-\infty}^{t_{min}} dt \int_{M^2_{min}}^{M^2_{max}} dM^2\, \frac{d\sigma^{D}_{\gamma* N}(t=0)}{dM^2\, dt} F_D(t)$$

where $F_D(t) = e^{at}$, $a = 40$ GeV^{-2}



Unitarity effects in d+Au collisions

Corrections to the Glauber model:

Multiplicity is modified by the shadowing factor γ_A

$$\frac{dn_{A_1A_2}}{dy} = n_{A_1A_2}(b)\,\frac{dn_{NN}}{dy}\gamma_{A_1}\gamma_{A_2}$$

where

$$\gamma_{A_1} = \int d^2b \frac{T_A(b)}{1 + F(x,Q^2)T_A(b)}$$

The corrected kinematic values for x for the projectile particle and the target are found through

$$x_{p(t)} = c\frac{p_T}{\sqrt{s}}e^{\pm y*}$$

we assume that most of the high-p_T particles come from jets c times more energetic than the measured one. Multiplicity reduction:

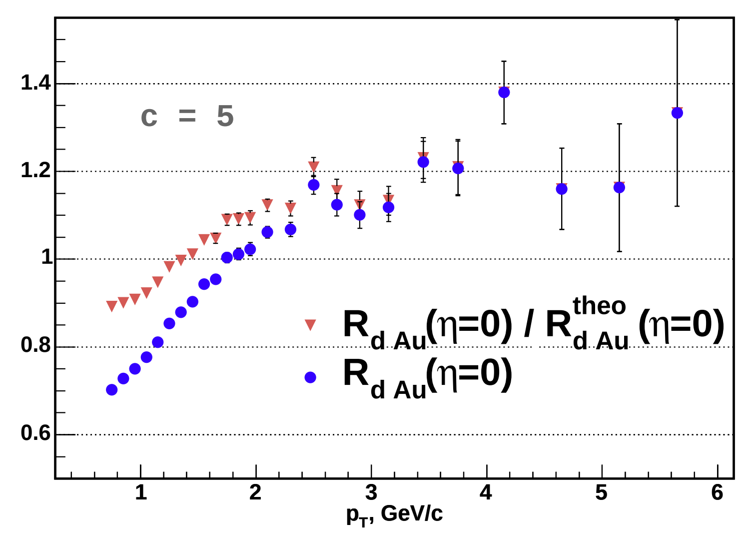
$$R_{dAu} = R_d(x_p)R_{Au}(x_t)$$

Nuclear Modification Factor

$$\mathbf{R_{dAu}} = \frac{\mathbf{1}}{\langle \mathbf{N}_{coll} \rangle} \frac{\mathbf{d^2N^{d+Au}/dp_T\, d}\eta}{\mathbf{d^2N^{p+p}_{\mathit{inel}}/dp_T\, d}\eta}$$

Normalization

$$\mathbf{R^{\mathit{norm}}_{dAu}} = [\mathbf{R^{\mathit{exp}}_{dAu}}/\mathbf{R^{\mathit{theo}}_{d-Au}}]_{\eta=\mathbf{0}}$$



Shadowing effect for d+Au collisions at mid-rapidity

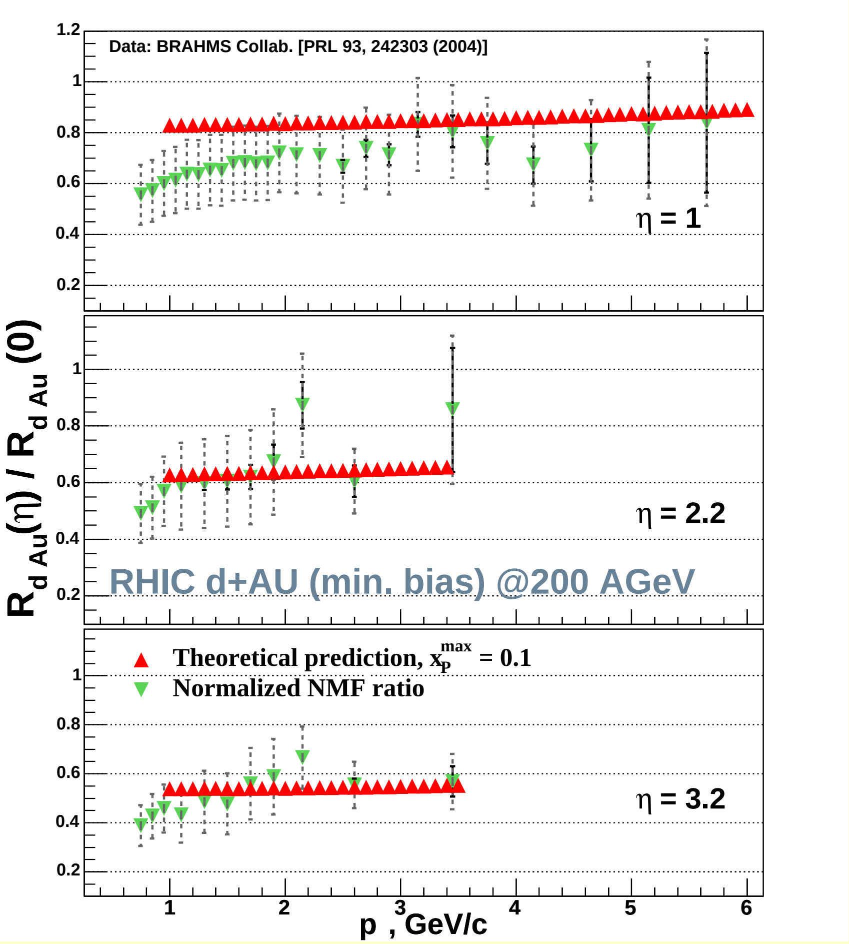
There is almost no shadowing at $\eta = \mathbf{0}$ for $\mathbf{p_T} > \mathbf{2}$ GeV/c.

The next step is to find the effect of shadowing for forward rapidities. The data sets at $\eta = \mathbf{1},\ \mathbf{2.2},\ \mathbf{3.2}$ should be normalized properly

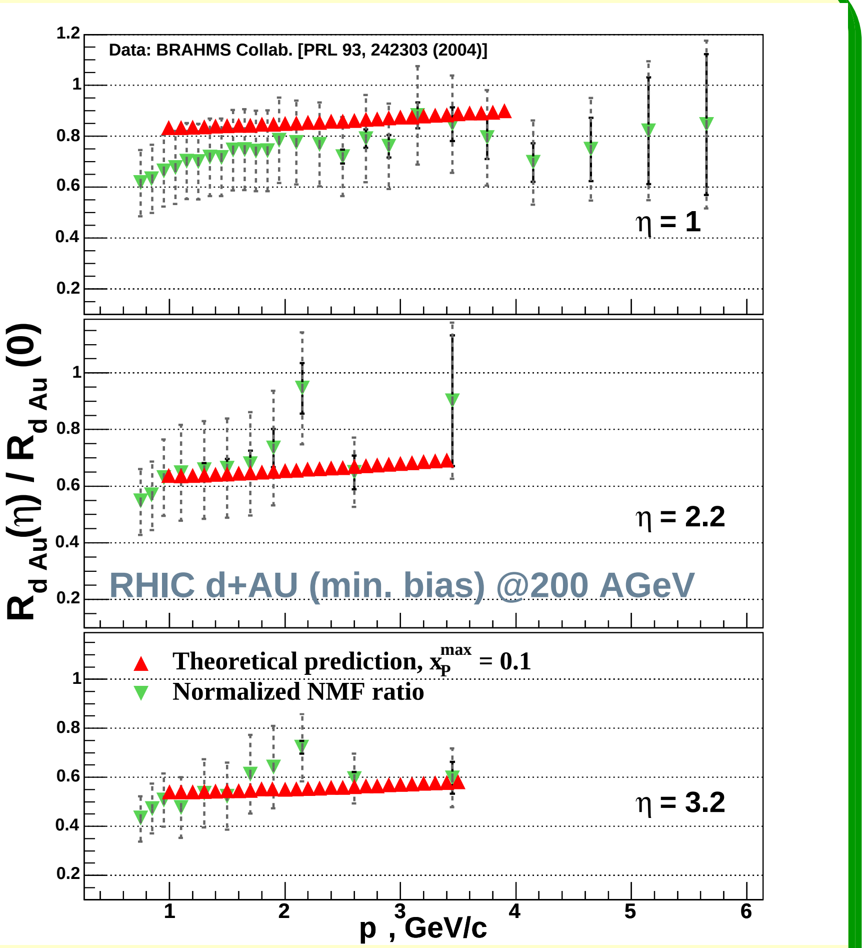
$$\mathbf{R}_{\mathit{shadowing}} = \frac{[\mathbf{R_{dAu}}]_{\eta=\mathbf{1},\,\mathbf{2.2},\,\mathbf{3.2}}}{\mathbf{R^{\mathit{norm}}_{dAu}}}$$

For the sake of simplicity, we assume that the Cronin and other effects have no rapidity dependence. We use $\mathbf{x^{max}_P} = \mathbf{0.1}$ and the Woods-Saxon nuclear density profile in the calculations.

Results: Comparison with BRAHMS data



$\mathbf{c = 3}$



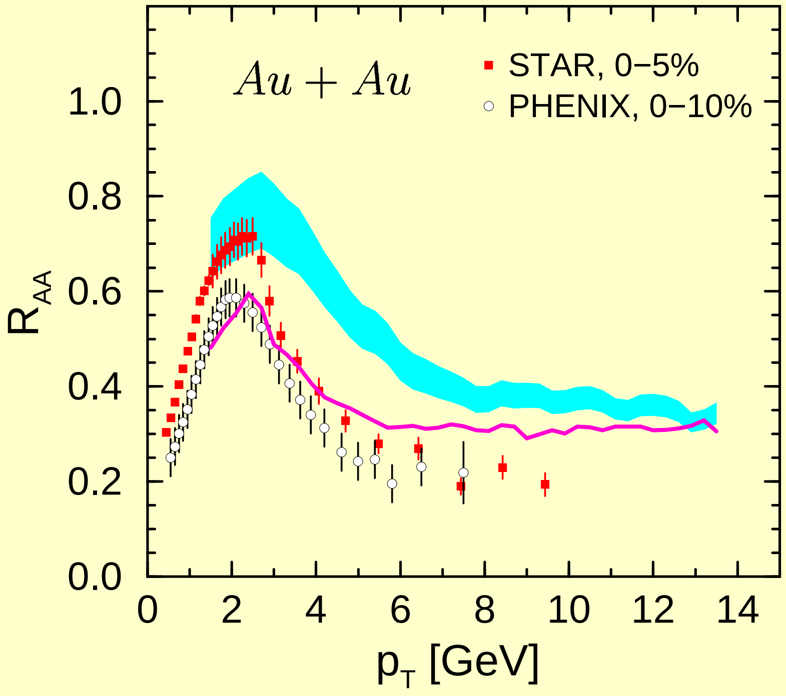
$\mathbf{c = 5}$

It appears that the choice of c does not affect the result. Suppression of the nuclear modification factor at forward rapidities is mostly due to gluonic shadowing in the nuclei

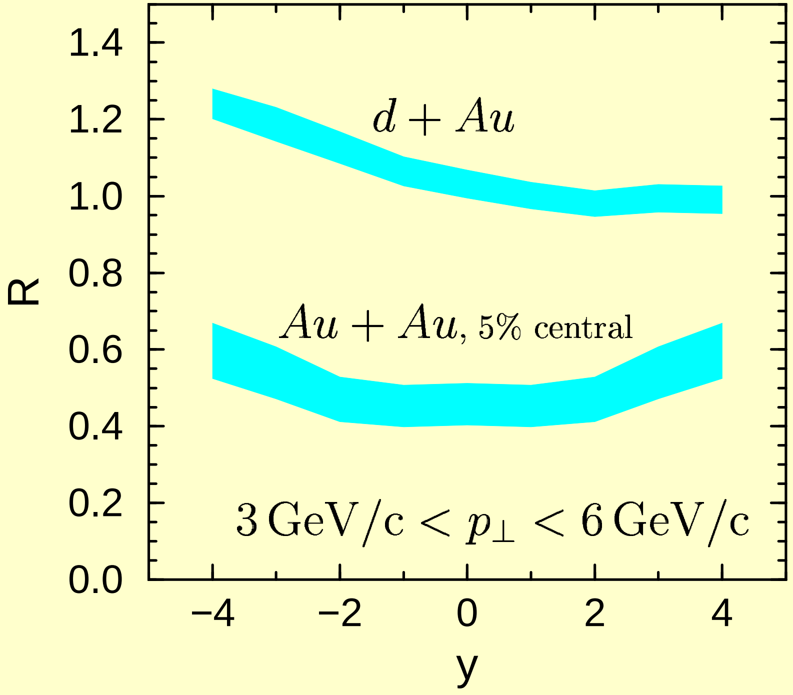
HSD results

W. Cassing, K. Gallmeister, and C. Greiner hep-ph/0311358;
hep-ph/0403208

$$R_{AA}(p_T) = \frac{1/N_{AA}^{event}\ d^2N_{AA}/dydp_T}{\langle N_{coll}\rangle/\sigma_{pp}^{inelas}\ d^2\sigma_{pp}/dydp_T}$$



The hatched band - with Cronin effect; the solid line - without.



The hatched bands indicate the uncertainty due to the Cronin effect.

Large suppression is due to (pre-)hadronic FSI ?!

HIJING and QGSM

Heavy Ion Jet INteraction Generator:

- NN interactions: PYTHIA (perturbative QCD) and Lund FRITIOF (longitudinal strings)
- String fragmentation: Lund JETSET
- Jet quenching: is assumed via an energy loss $\mathbf{dE/dz}$ of partons traversing the produced dense matter
- $A + A$ collisions: Glauber geometry
- No secondary rescattering

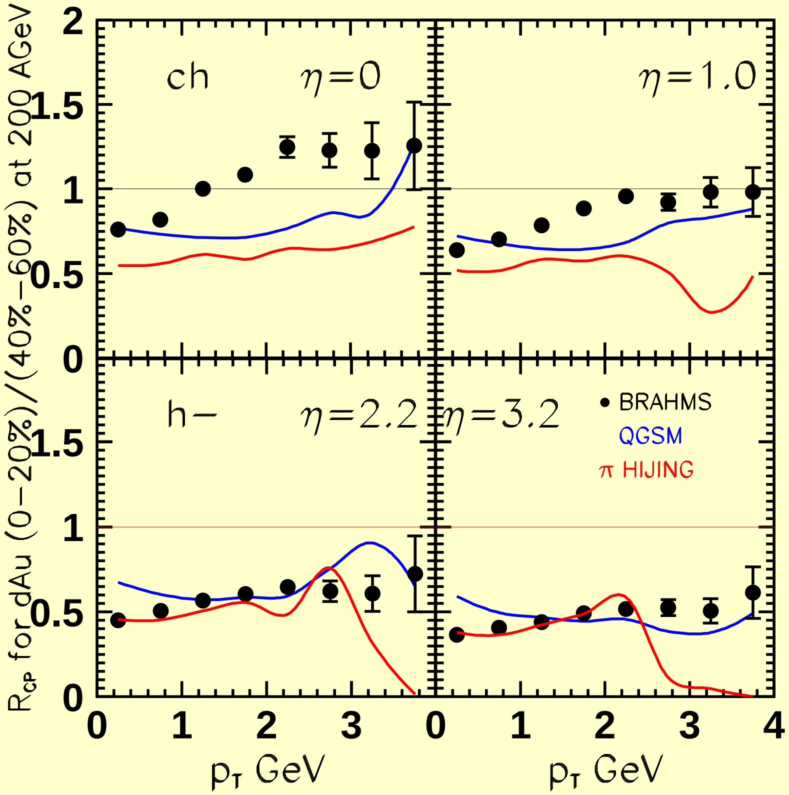
Quark-Gluon String Model:

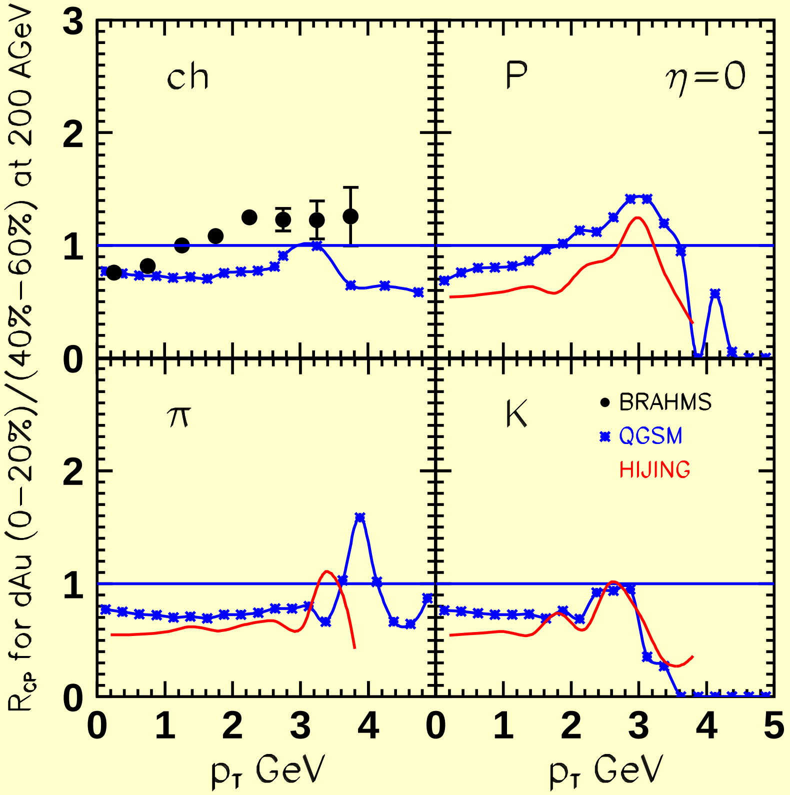
- NN interactions: color exchange (GRT)
- String fragmentation: Field-Feynman mechanism (independent jets)
- $A + A$ collisions: secondary interactions of the produced hadrons with primary target or projectile nucleons and with secondary hadrons
- The newly produced particles can interact after a certain formation time τ_0. It comes from the uncertainty principle

$$\tau_0 \geq \frac{\hbar}{\mathbf{m_T}}$$

However, for composite particles (hadrons) this is an open and model dependent issue.

Comparison with BRAHMS data

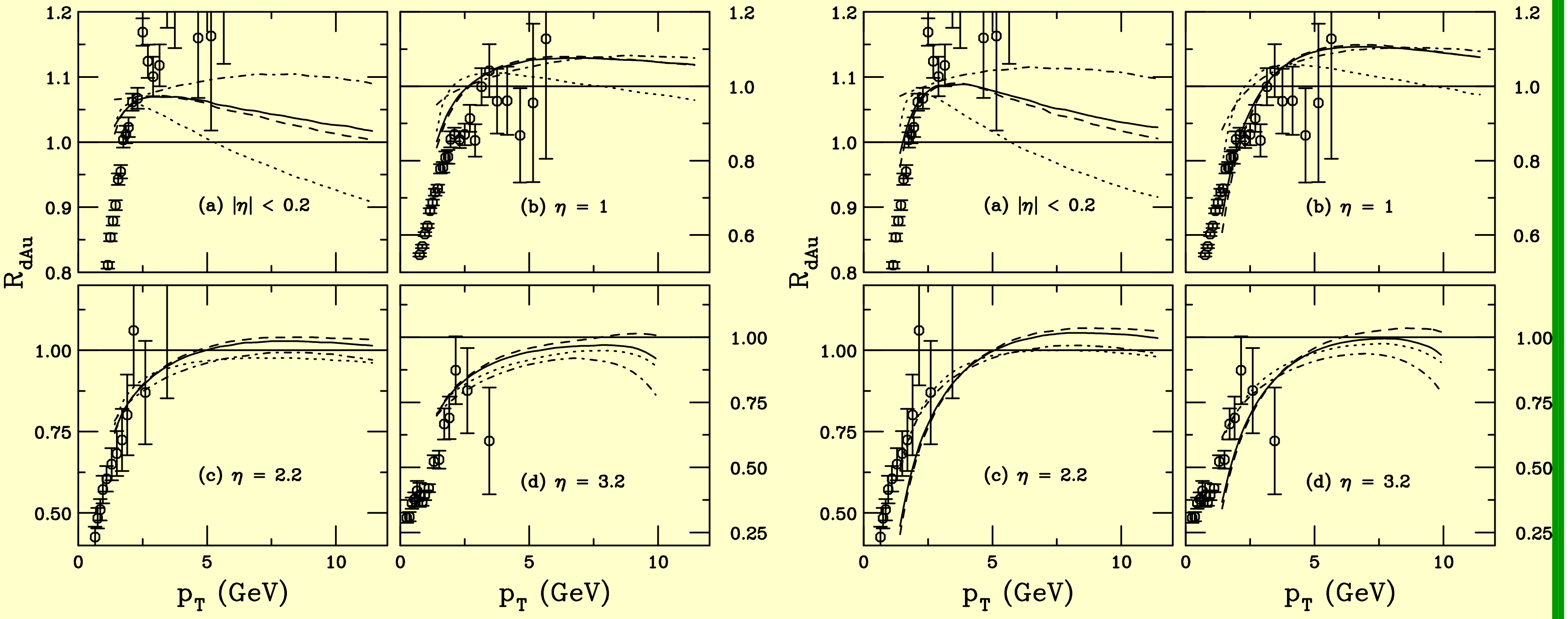




- **Models reproduces data at $\eta \geq 1$, but not at the midrapidity**
- **Rescattering effects seem to play minor role (?!)**
- **Nuclear modification factors $\mathbf{R_{CP}}$ are different for different hadron species**
- **NB: HIJING v1.3.6 - no jet quenching and no shadowing**

Shadowing: calculations vs BRAHMS data

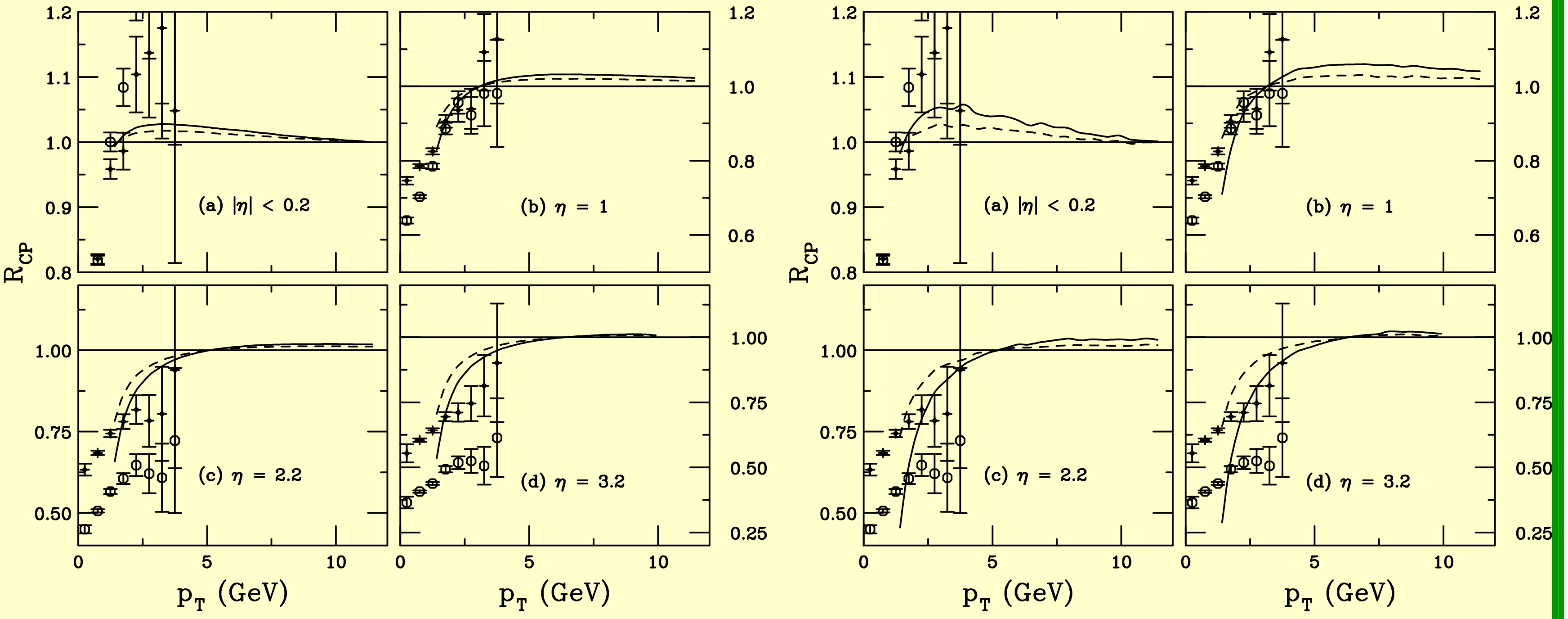
BRAHMS Collaboration, I. Arsene et al., nucl-ex/0403005
R. Vogt, hep-ph/0405060



R_{dAu} for charged pions (dashed) and kaons (dot-dashed) as well as protons and antiprotons (dotted) and the sum over all charged hadrons (solid) for deuteron-gold collisions at $\sqrt{S_{NN}} = 200$ GeV as a function of p_T. The results for homogeneous shadowing with the **EKS98** parameterization (left plot) and with the **FGS** parameterization (right plot) are compared to the BRAHMS data

Shadowing: calculations vs BRAHMS data

BRAHMS Collaboration, I. Arsene et al., nucl-ex/0403005
R. Vogt, hep-ph/0405060



R_{CP} for charged hadrons in deuteron-gold collisions at $\sqrt{S_{NN}} = 200$ GeV as a function of p_T. The results for $S_{FGS,WS}$ (left panel) and for $S_{FGS,\rho}$ (right panel) are compared to the BRAHMS data. (central/periph. - solid line; semi-cen./per. - dashed line)

R_{dAu}, calculated with leading-twist shadowing, especially employing the **FGS** parameterization, agrees rather well with the BRAHMS data.

Conclusions and Prospects

- The gluonic nPDF's are extracted from recent HERA experiment data
- It is found that at energies of RHIC and higher the gluon shadowing strongly dominates over the quark one
- **d+Au** data from RHIC confirm a small amount of shadowing at $\eta = 0$ and large p_T
- The nuclear modification factor in **d+Au** forward rapidity region at RHIC is calculated within Gribov-Regge field theory. Theoretical results are in good agreement with BRAHMS data. This suggests that the nuclear modification factor can be explained solely by gluonic shadowing
- The agreement with the data is due to the unitarity constraints on the diffractive processes at high x; no additional effects have been added in the mode
- None of the models (microscopic or macroscopic) is able to describe the whole variety of measured signals