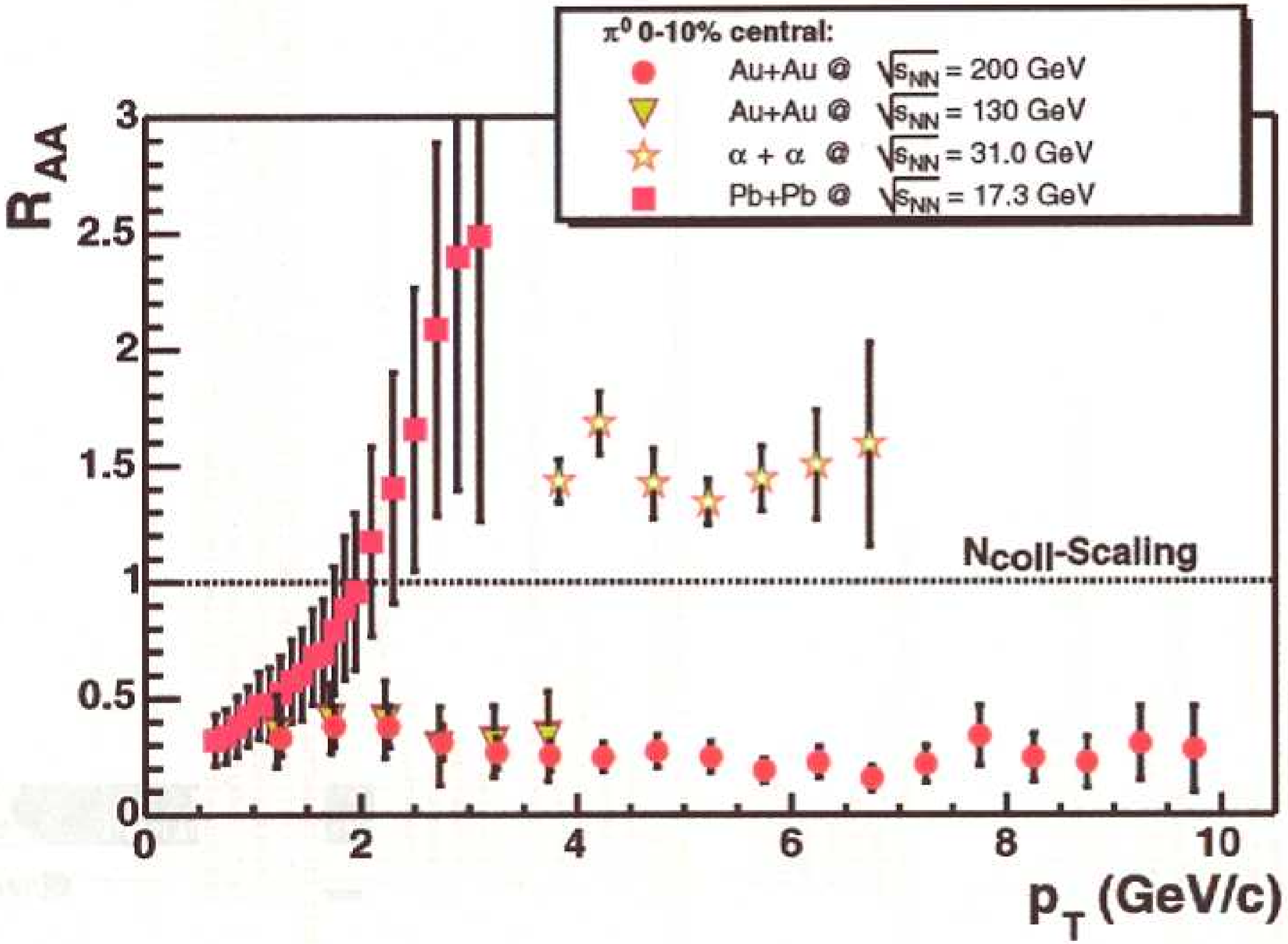
Nuclear Theory Summary of "High-$p_\perp$ Physics @ RHIC"

- Au+Au, $y=0$: consensus reached on high-$p_\perp$ suppression of single-inclusive distributions: final-state effect, presumably e-loss

- d+Au, $y=0$:
  - $dN/d\eta$ from CGC works!
  - $dN/dp_\perp$ @ $\eta=0$ requires only moderate, if any, LT shadowing + Cronin
  - $dN/dp_\perp$ @ $\eta=3$ requires strong LT shadowing → perhaps the first glimpse @ scaling regime <u>above</u> saturation regime (no consensus yet)
  - Can one identify the high-density regime @ $p_\perp \lesssim Q_s$?

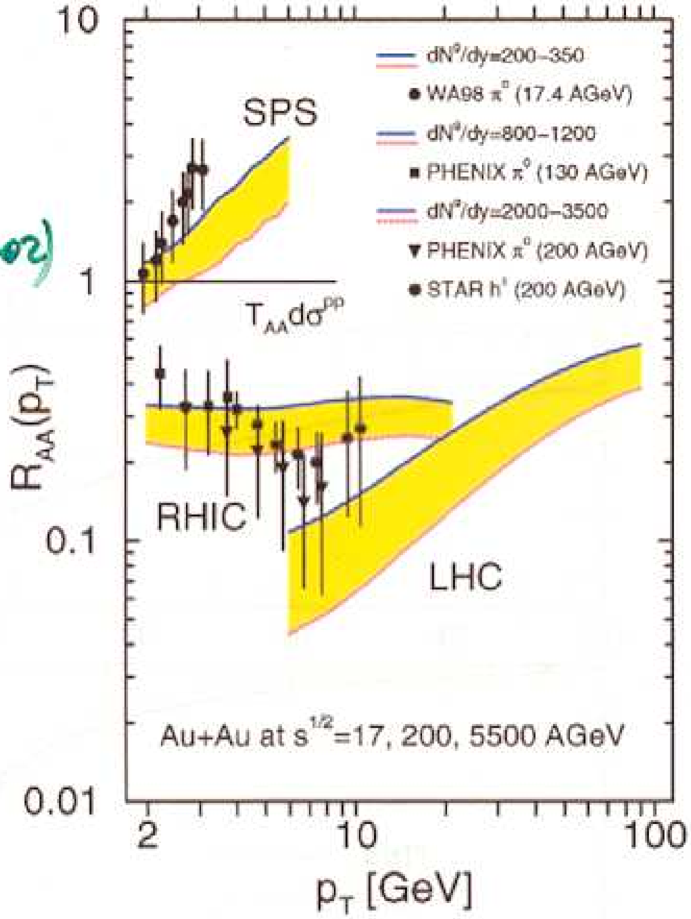
What happens at higher transverse momenta?

PHENIX and STAR extend measurements to ~ 10 GeV

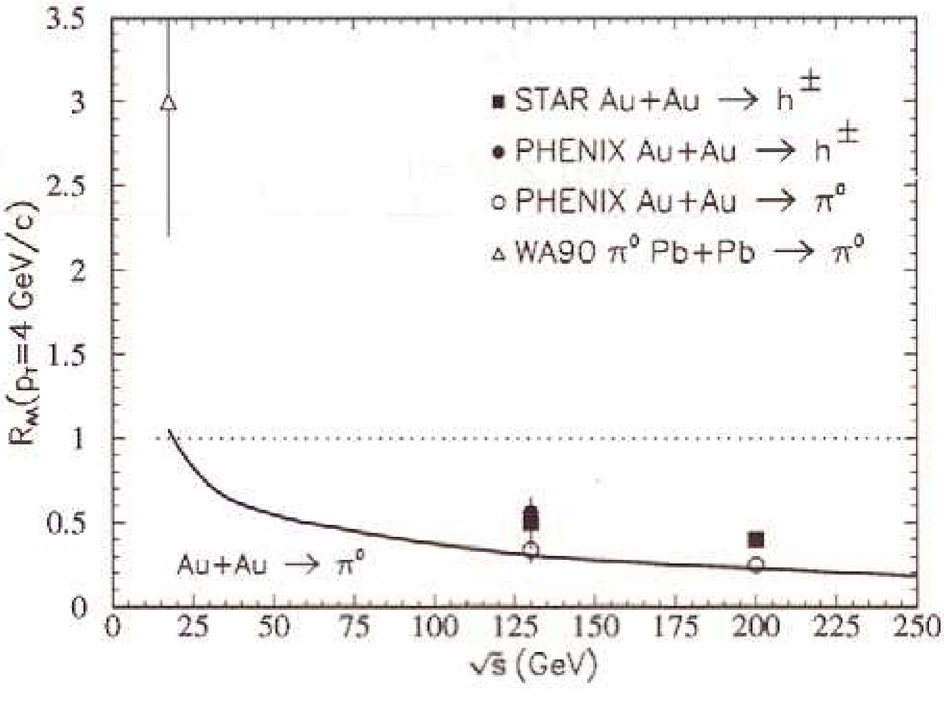


Energy Dependence of ΔE

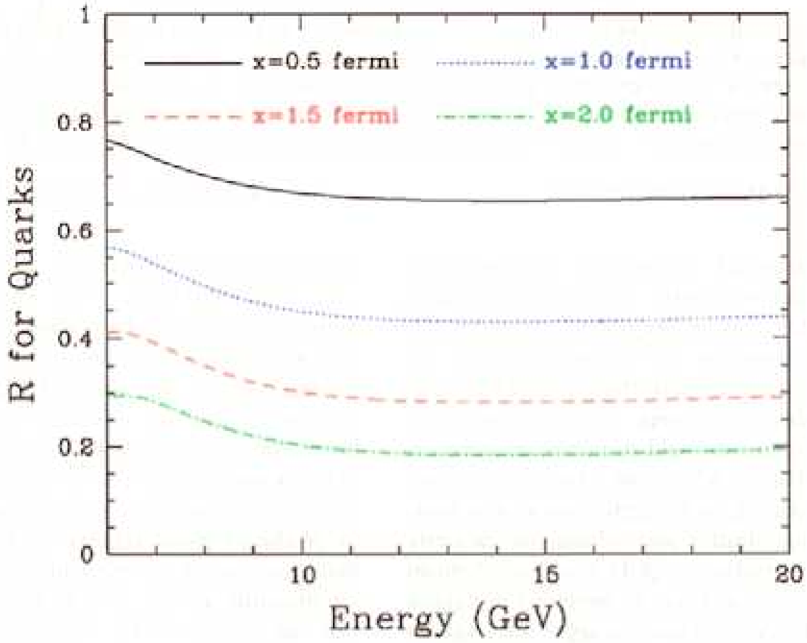
Vitev, Gyulassy
PRL 89 (2002)



X.N. Wang,
nucl-th 0307036

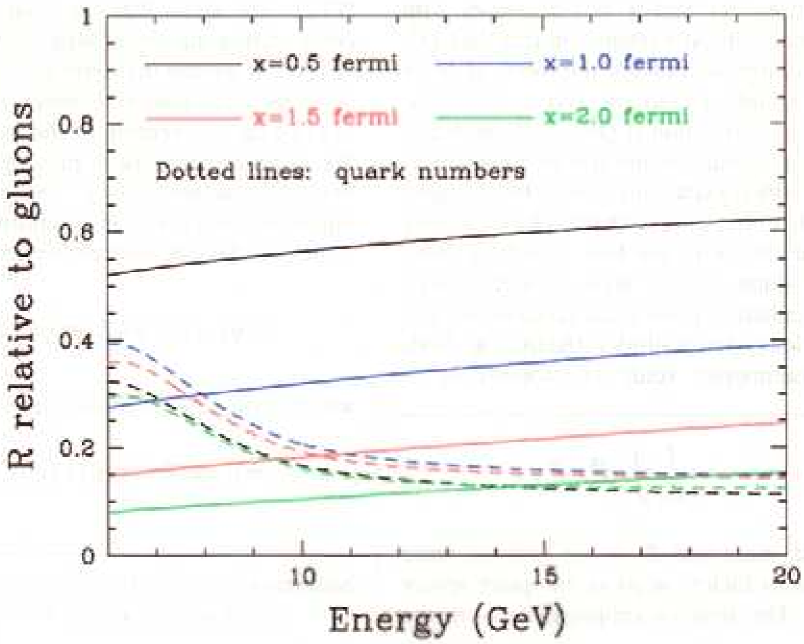


Initially Pure Quark Spectrum



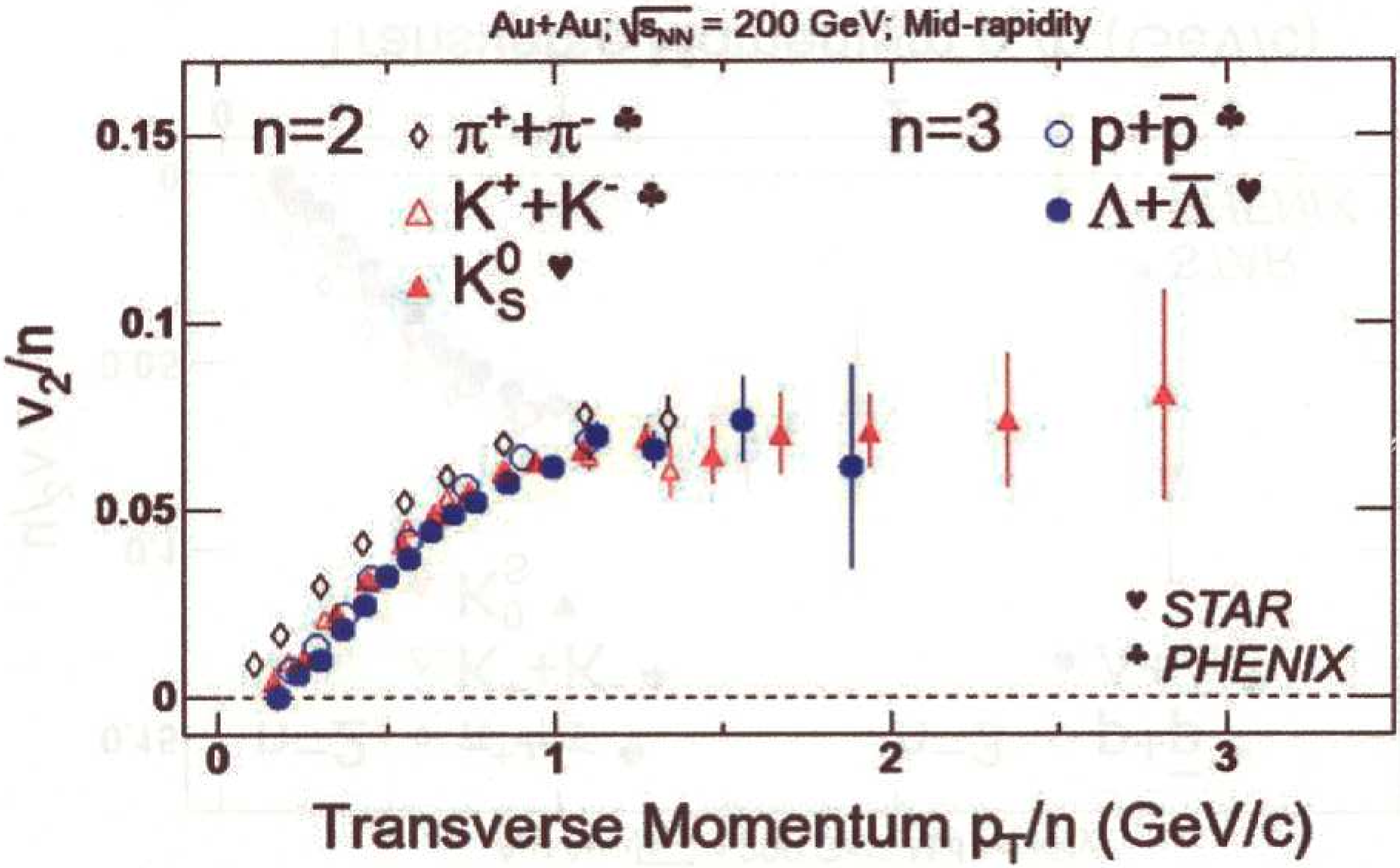
Negligible glue produced.

Initially Pure Gluon Spectrum

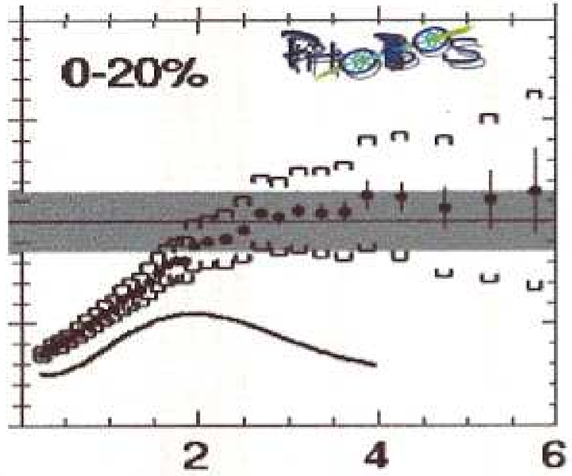


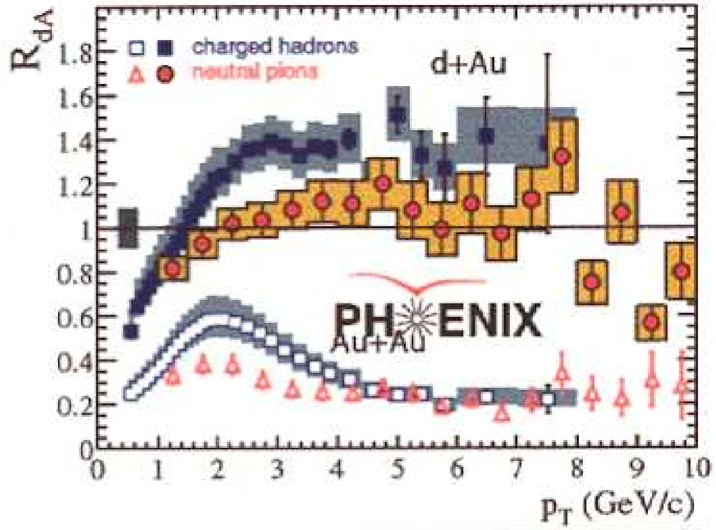
Significant quarks: eventually, quarks dominate

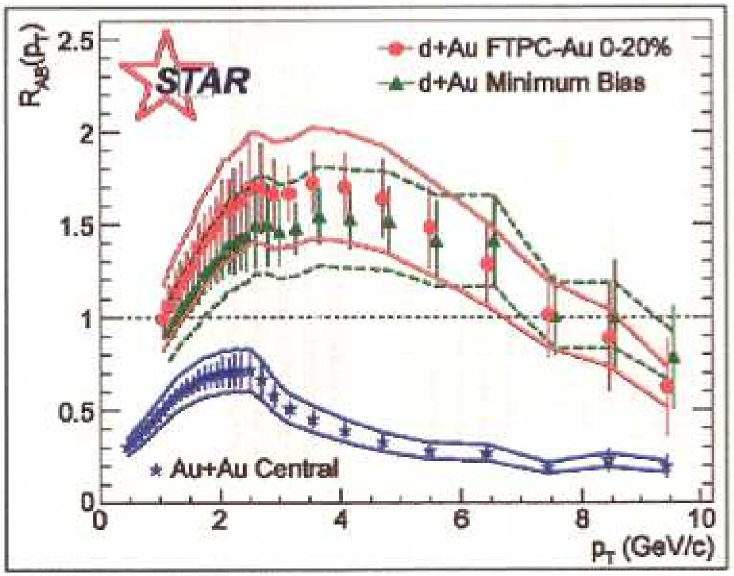
Coalescence ?

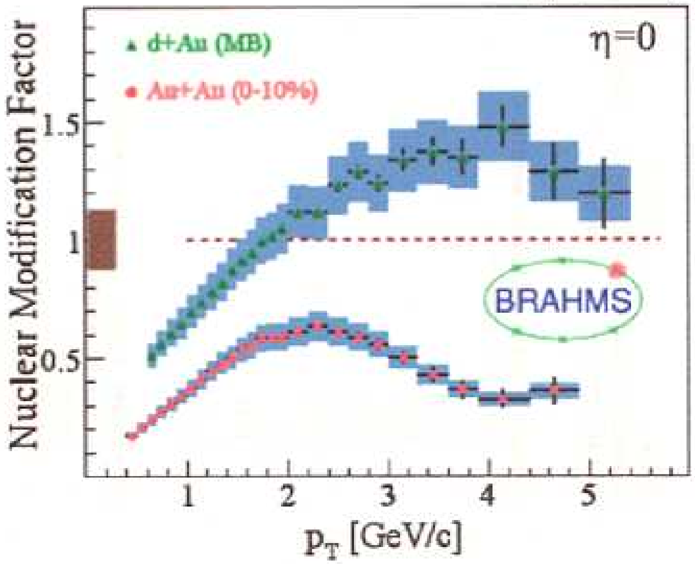


D-Au collisions: suppression or enhancement?

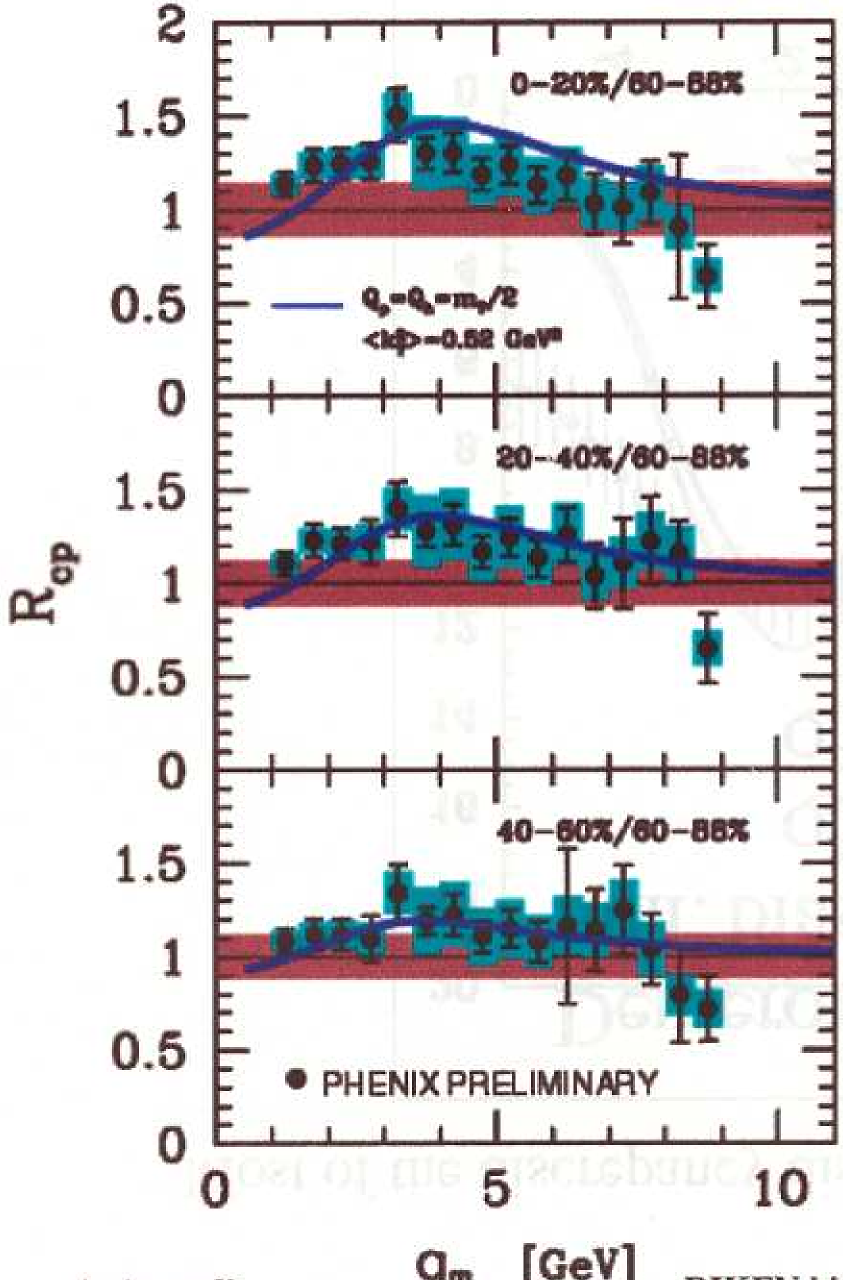








Let's use a handle: the central/peripheral ratio



In exp. data, part of ystematic errors drop out: shape and height of peak are better measured.

If dynamical shadowing is at work,
$\Longrightarrow$ stronger suppression in central than in peripheral collisions

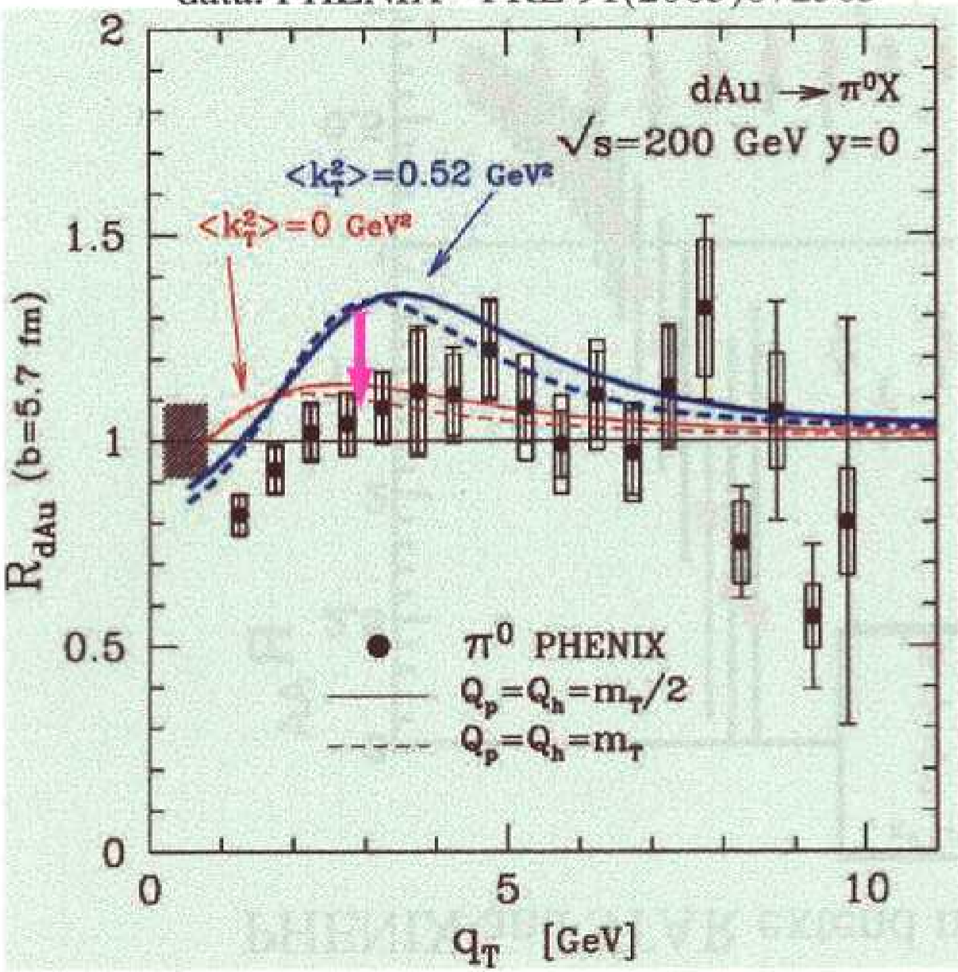
dAu $\cong$ sum of pp + unitarity
Not much room for saturation

(R_{dAu} not in so nice agreement: systematic errors need better understanding)

Exp. data $\longrightarrow$ T.Awes, DNP Tucson

Cronin effect on pions at PHENIX

data: PHENIX - PRL 91(2003)072303



Beware: Theoretical errors ~10% at the peak.
Large experimental systematic errors

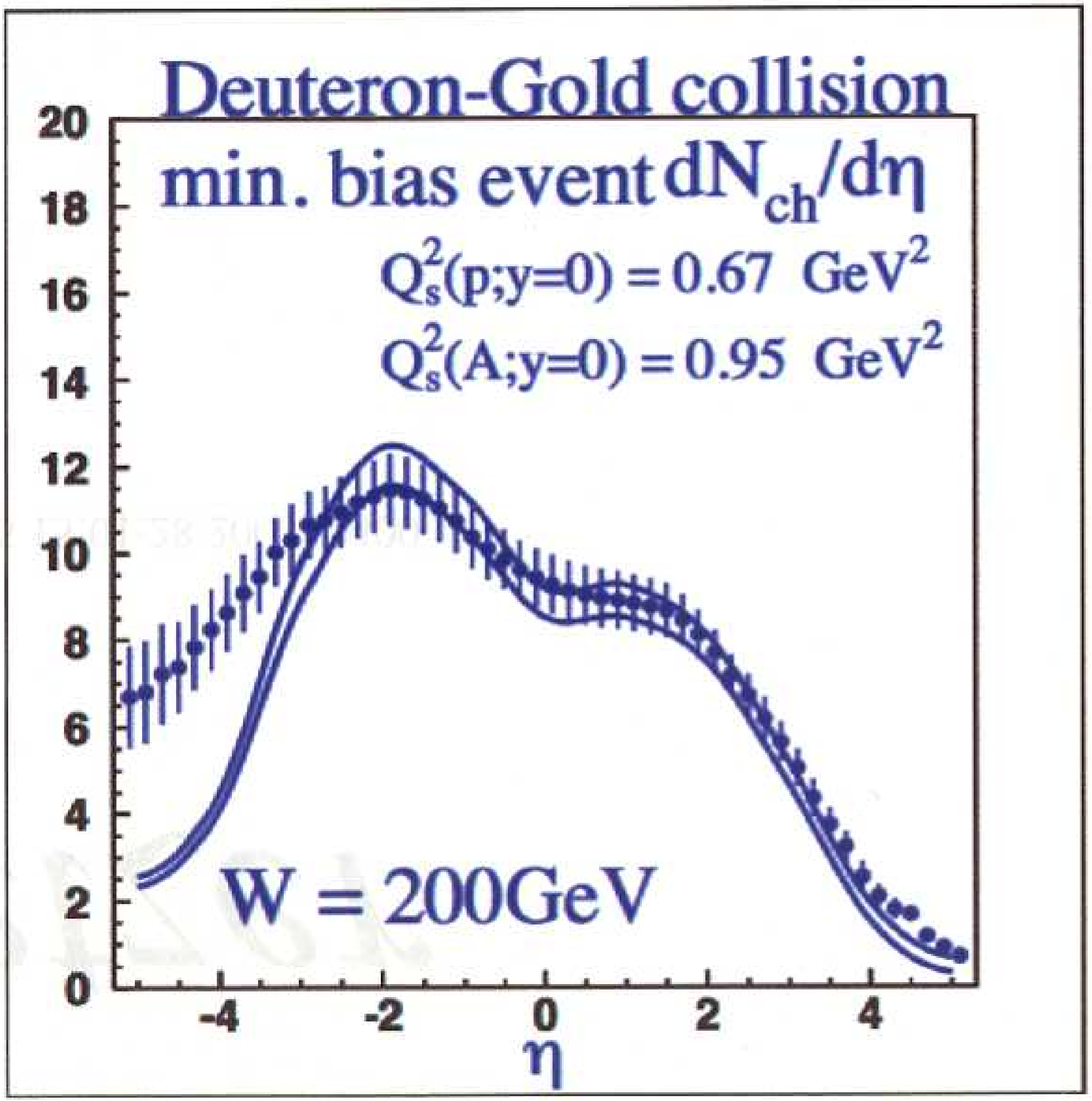
Computation compatible with data inside exper. and theor. errors

Tends to overestimate the data

⇒ **Possible indication of dynamical shadowing**

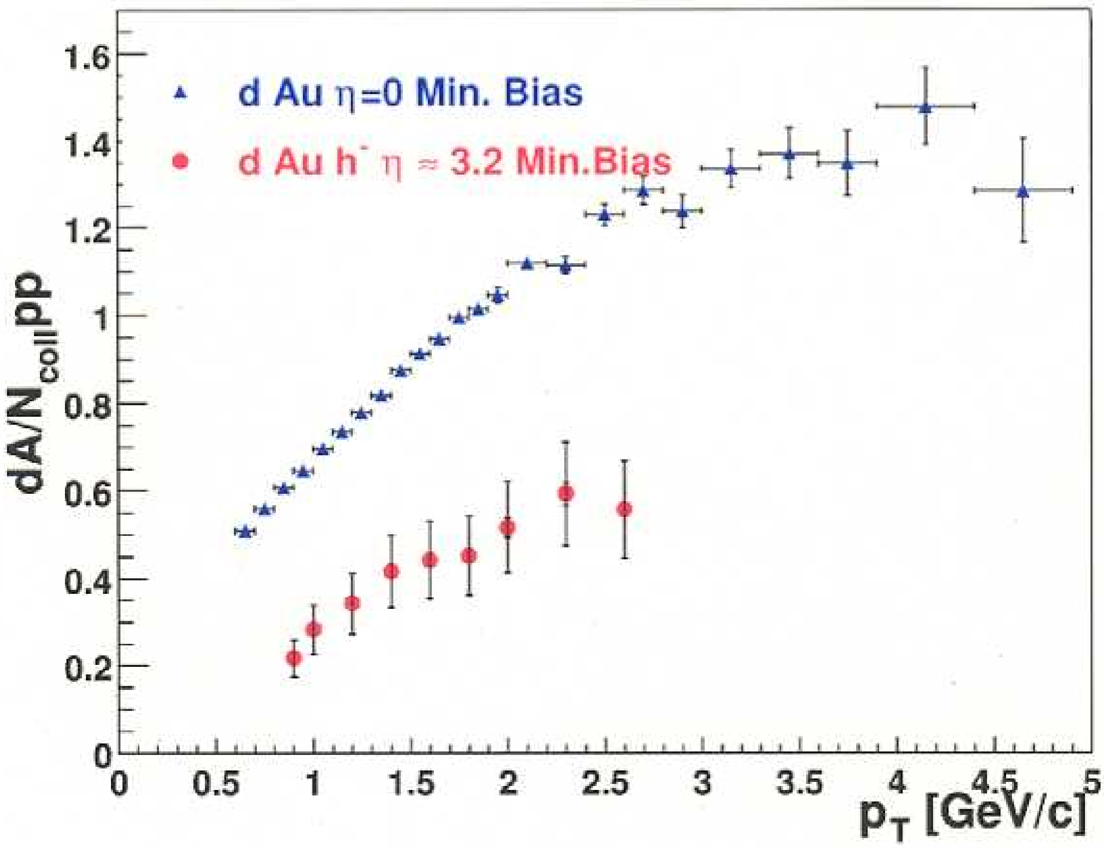
However:
radiative and collisional en. loss. (here neglected) may slightly suppress the spectrum at low p_T, barring shadowing...

Most of the discrepancy disappears; Au fragmentation still a problem



pA and the CGC

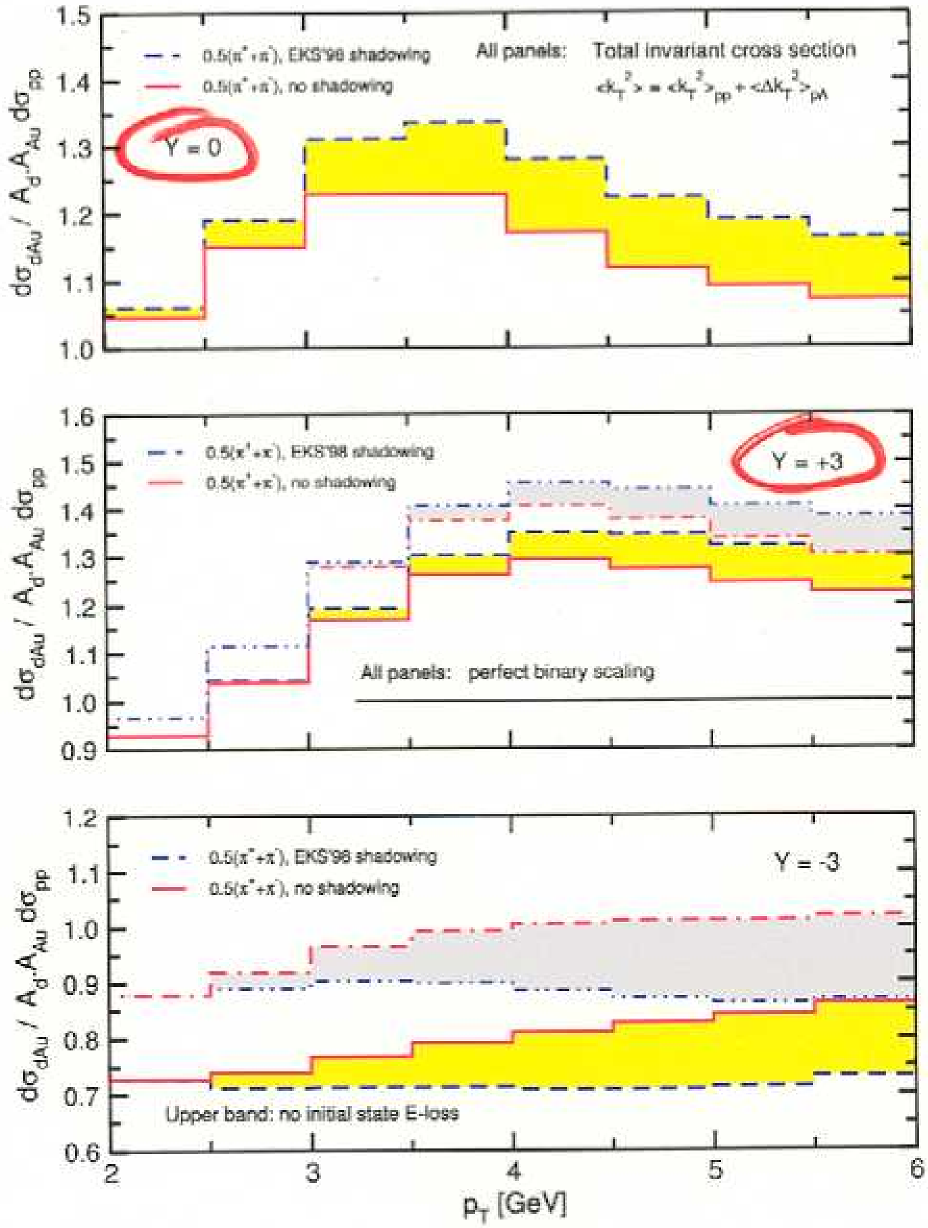
- Preliminary data
- Strong suppression: evolution?



pA: the conventional apparaoach

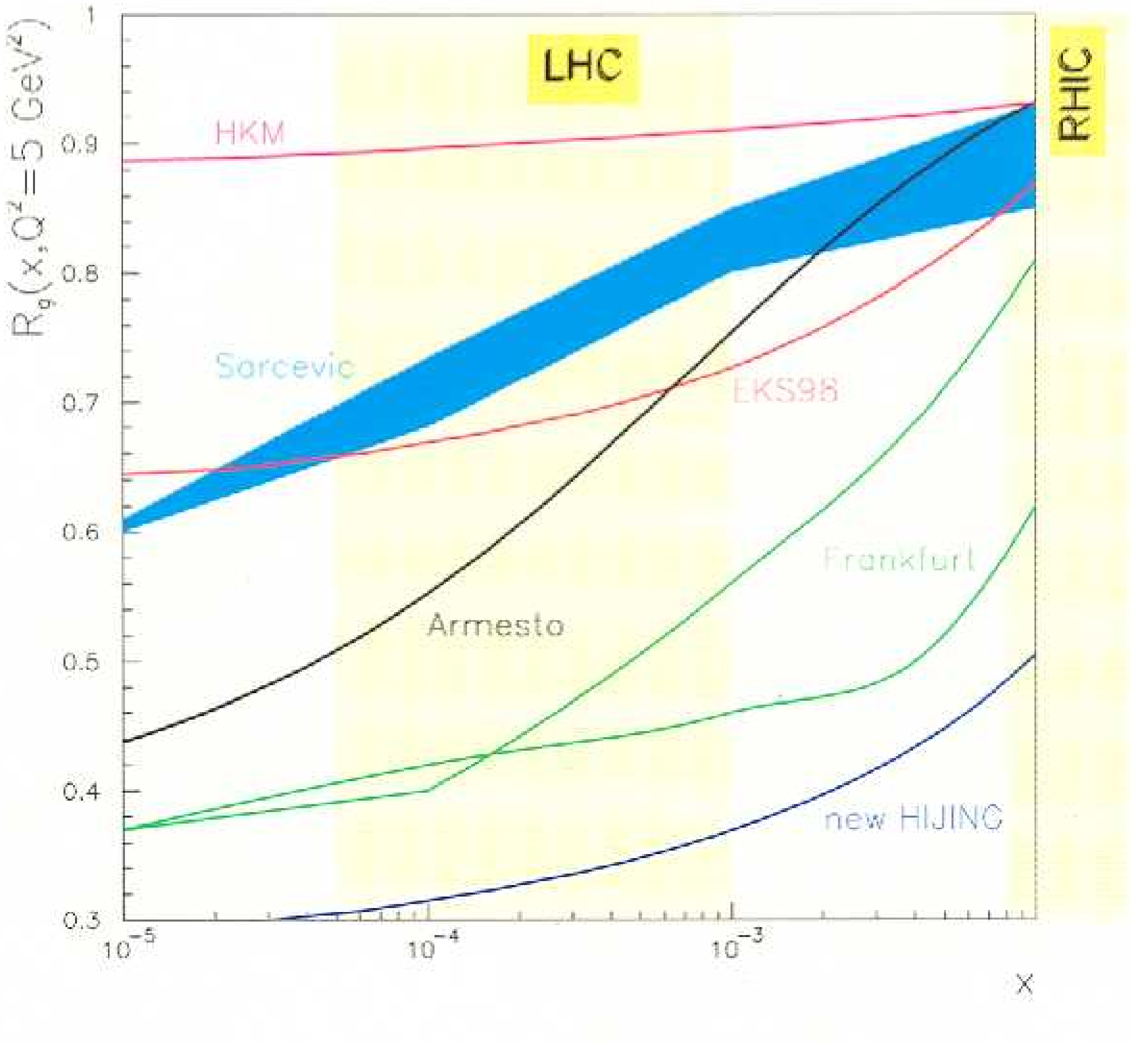
- The forward rapidity region

Vitev



Conventional approach to PA

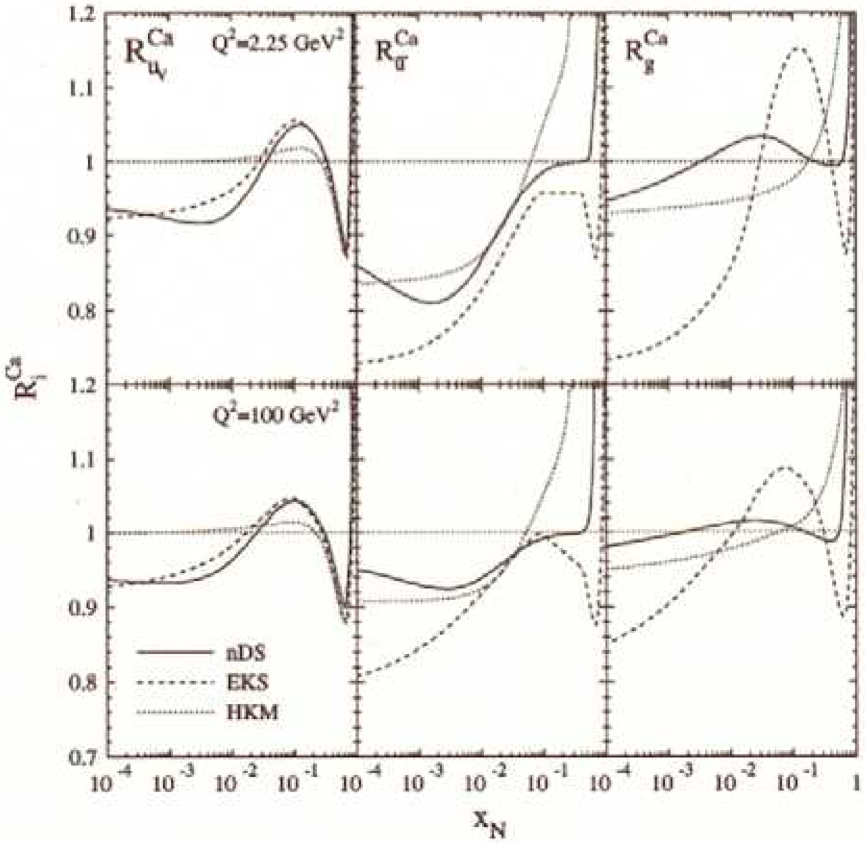
- Shadowing
  - Parameterization: initial condition + DGLAP
  - Calculation: use relation to diffraction



From N. Armesto and C.A. Salgado (hep-ph/0301200)

(1982) Comparison to other LO distributions

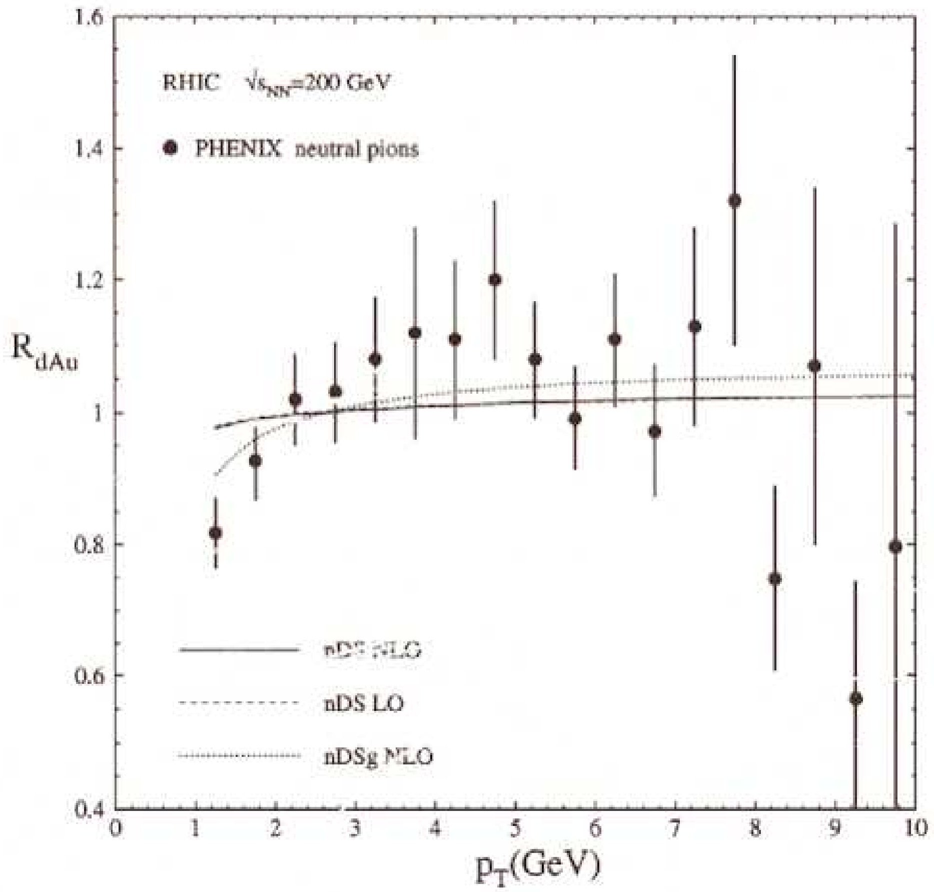
- EKS: no χ^2 analysis but comparison to almost same set of data
  K.J. Eskola, V.J. Kolhinen and C.A. Salgado (1999)
  K.J. Eskola, V.J. Kolhinen and P.V. Ruuskanen (1998)
- HKM: no Drell-Yan and Q^2 dependent Sn data
  M. Hirai, S. Kumano, and M. Miyama (2001)



- $\chi^2 \sim 630$ for EKS (large contribution from Q^2 dependent Sn data) and larger for HKM if full data set included
- Differences between sets ⇒large for gluon and sea quark distributions
- Differences between LO and NLO ratios not negligible ⇒not convenient to use LO ratios to compute NLO observables!

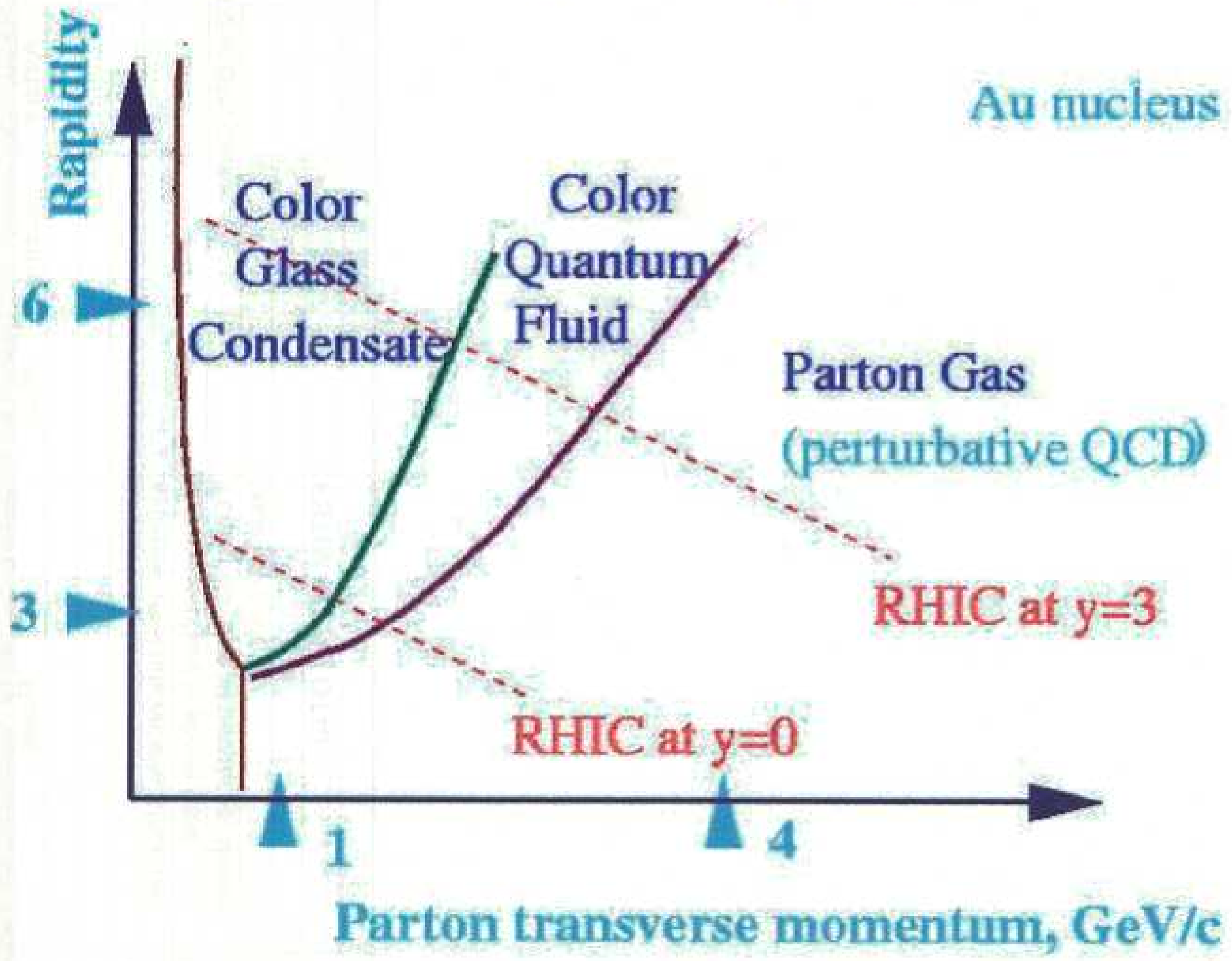
Pion production at RHIC

- 'high-p_T' π^0 production at PHENIX with $\sqrt{s_{NN}} = 200$ GeV and central rapidity
- Ratio $R_{dAu} = \sigma_{dAu}/\sigma_{pp}$ using frag.fnct. Kretzer (2000)

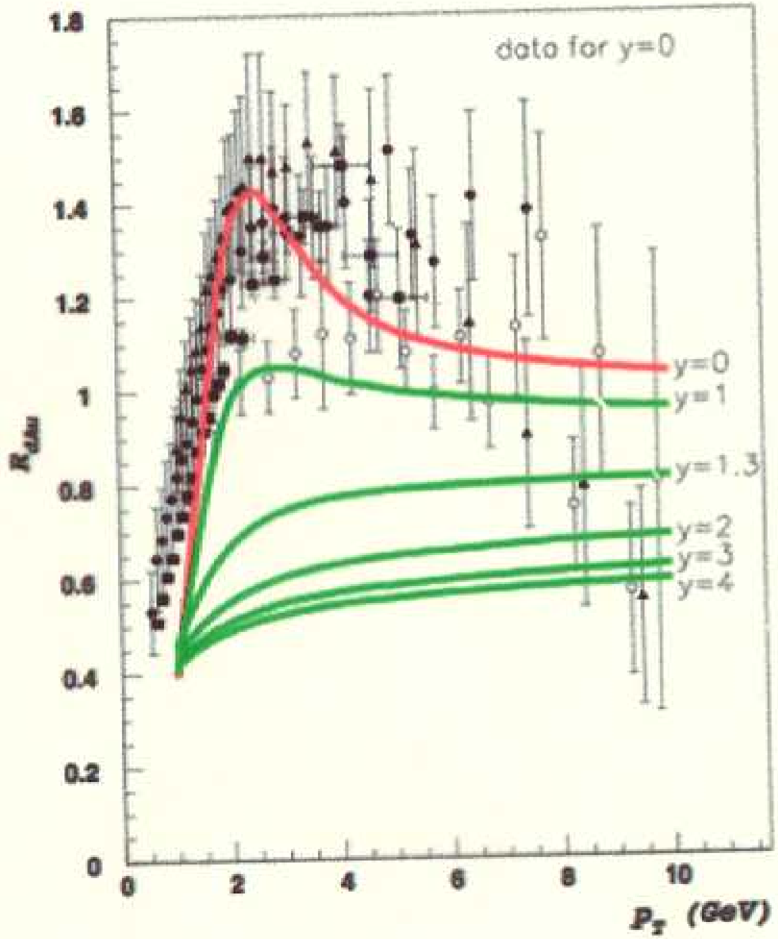


- NLO corrections almost 'cancel' in the ratio (but not in the cross-section!) ⇒Perturbative stability of sets
- Result shows dependence on (Au) gluon density ⇒see R_{dAu} computed using nDSg set
- Still data not precise enough to draw any conclusion or include in a global fit
- Similar results for larger rapidity: more shadowing at $p_T < 2$ GeV but never $R_{dAu} < 0.8$

Phase diagram of high energy QCD and RHIC



Color Glass Condensate: confronting the data



The effects of quantum
Evolution in the CGC
set in very rapidly

<u>RHIC energy is ideal</u>

talk by K. Tuchin/Yu.Kovchegov

DK, Yu. Kovchegov, K. Tuchin,
To appear

Forward Quark Jets from Protons Shattering the Color Glass Condensate

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Physics Department, Brookhaven National Lab, Upton, New York 11973
(Received 4 April 2002; published 24 June 2002)

We consider the single-inclusive minijet cross section in pA at forward rapidity within the color glass condensate model of high energy collisions. We show that the nucleus appears black to the incident quarks except for very large impact parameters. A markedly flatter p_t distribution as compared to QCD in the dilute perturbative limit is predicted for transverse momenta about the saturation scale, which could be as large as $Q_s^2 \simeq 10$ GeV^2 for a gold nucleus boosted to rapidity ~ 10 (as at the BNL-RHIC).

DOI: 10.1103/PhysRevLett.89.022301 PACS numbers: 24.85.+p, 12.38.–t, 13.85.–t

QCD correctly predicted logarithmic violations of Bjorken scaling in deep-inelastic electron-proton scattering at very large Q^2, i.e., at very short distances [1]. Asymptotic freedom provides the theoretical basis for the successful applications of perturbative QCD to hard scattering, short distance phenomena. However, the region of QCD phase space where the field strengths are strong is largely unexplored. This is where one expects that cross sections become comparable to geometric sizes of hadrons and nuclei (the "black limit") and where the unitarity limit is reached. A perturbative QCD based mechanism for unitarization of cross sections is provided by gluon saturation effects [2,3]. A semiclassical approach to gluon saturation and QCD in the high energy limit (small x) was developed in [4–7] and applied to high energy heavy ion collisions at RHIC [8–11].

Large nuclei provide an ideal environment to study gluon saturation and unitarization effects since the gluon density per unit transverse area is larger by a factor of $A^{1/3}$ due to the Lorentz contraction of the nucleus. The scale associated with the high gluon density, the saturation scale Q_s, grows with energy and A and decreases with increasing impact parameter. At a resolution less than Q_s^2, the color field carries large occupation numbers, of order of the inverse QCD coupling constant $1/\alpha_s$. Thus, the gluons in the nuclear wave function at $Q^2 < Q_s^2$ condense. The local color charge density in the transverse plane is a stochastic variable which eventually has to be averaged over (see below). Also, the large x (hard) gluons evolve slowly and so appear frozen to the low x (soft) gluons. Therefore, the high gluon density state of high energy QCD at $Q^2 \lesssim Q_s^2$ is called a "color glass condensate" [7].

The Relativistic Heavy-Ion Collider (RHIC) at BNL will soon allow experimental study of proton-gold or deuteron-gold collisions at a center-of-mass energy of $\sqrt{s} \sim 200$–300 GeV. We suggest that the saturation regime of QCD can be probed at RHIC by measuring the inclusive cross section in p + Au (or d + Au) collisions (in this regard, see also [11,12]). In particular, in the forward region, i.e., close to the rapidity of the proton beam, the saturation scale Q_s can become quite large due to renormalization group evolution in rapidity [6,7]. Thus, we predict significant modifications of the p_t distribution of produced pions relative to leading twist perturbation theory at transverse momenta as large as several GeV. A modification of the *longitudinal* distribution of leading hadrons produced by electrons scattering inelastically from a black target has been predicted previously [13]. Here, we focus on the transverse distribution in the forward region from $p + A$ scattering, which will be analyzed experimentally in the near future at RHIC.

At large rapidity, we consider the quark-nucleus elastic and total scattering cross sections. (In turn, towards midrapidity gluon production becomes the dominant contribution to the cross section in the color glass condensate model [11].) We argue that the total quark-nucleus scattering cross section may be related to the single inclusive hadron (jet) cross section in proton-nucleus collisions by using the collinear factorization theorem on the proton side. Let p^μ (q^μ) be the momentum of the incoming (outgoing) quark. We assume the quark is moving along the left branch of the light cone such that $p^- \gg p^+ = p_t^2/2p^-$. The starting point is the scattering amplitude (for brevity, we do not write polarization indices explicitly)

$$\langle q(q)_{\rm out} | q(p)_{\rm in}\rangle = \langle {\rm out}| b_{\rm out}(q) b^\dagger_{\rm in}(p) |{\rm in}\rangle, \quad (1)$$

which, using the LSZ formalism [14] can be written as

$$\langle {\rm out}| b_{\rm out}(q) b^\dagger_{\rm in}(p) |{\rm in}\rangle = -\frac{1}{Z_2}\int d^4x\, d^4y\, e^{-i(px-qy)} \bar{u}(q)[i\overrightarrow{\partial_y} - m]\langle {\rm out}|T\psi(y)\bar\psi(x)|{\rm in}\rangle[-i\overleftarrow{\partial_x} - m]u(p), \quad (2)$$

where m is the quark mass and Z_2 is the fermion wave function renormalization factor. $u(p)$ is the quark spinor with momentum p. The fermion propagator G_F in the background of the classical color field is

$$\langle {\rm out}|T\psi(y)\bar\psi(x)|{\rm in}\rangle = -i\langle {\rm out}|{\rm in}\rangle G_F(y,x). \quad (3)$$

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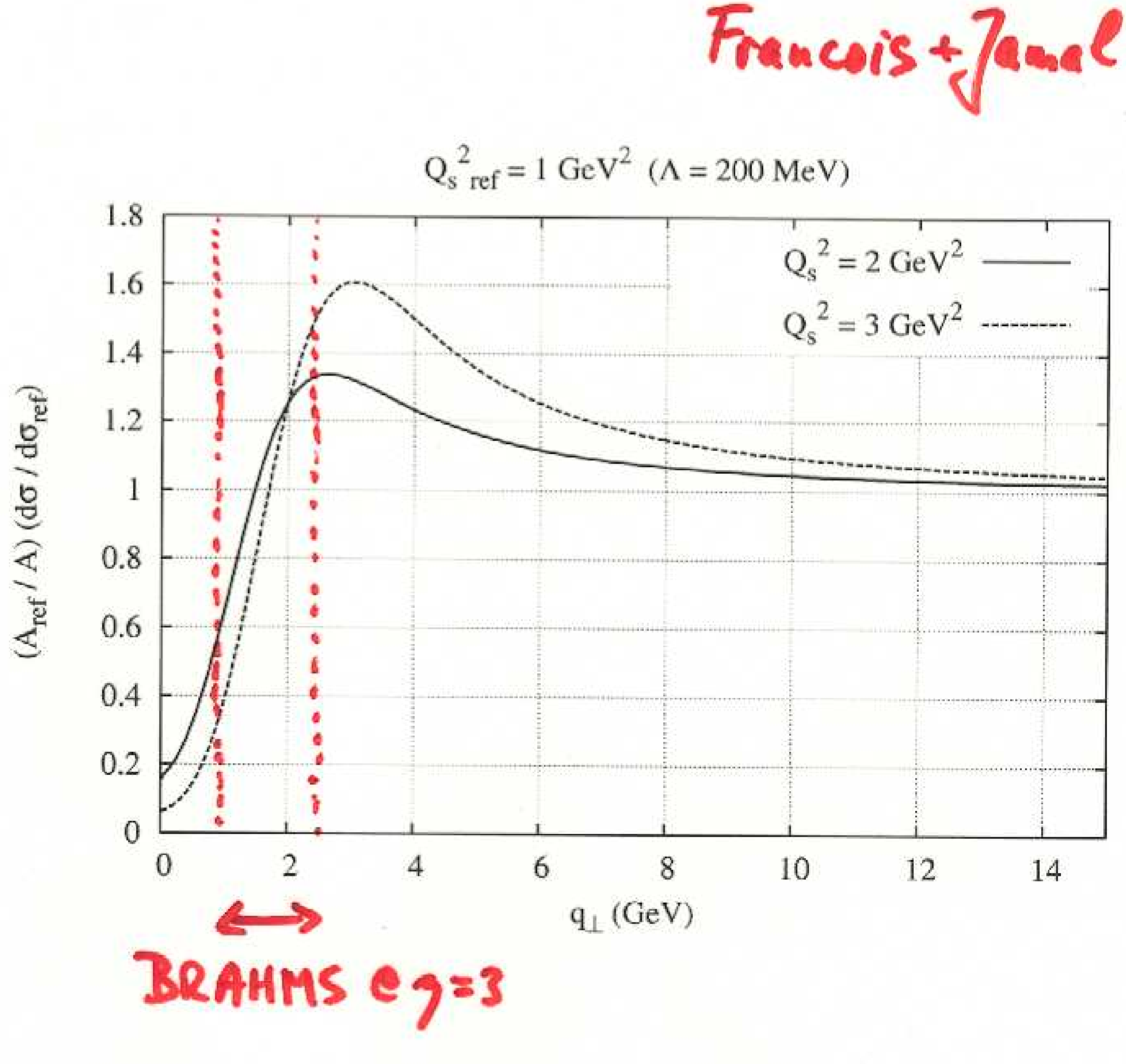
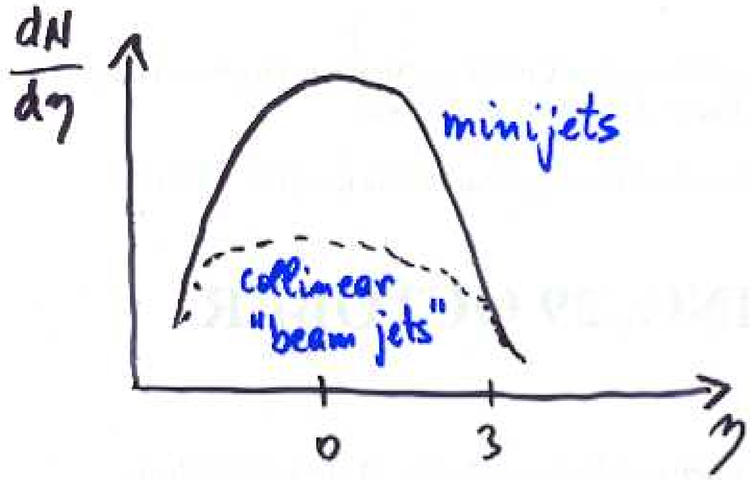
pA and the CGC:classical

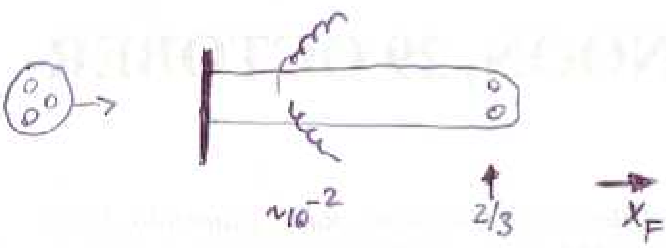
- Shadowing + Cronin



BRAHMS suppression @ $\eta = 3$ due to soft physics?

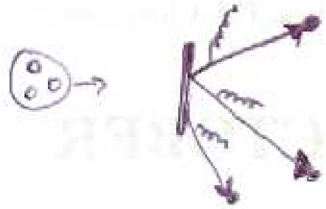


Gyulassy, Vitev, Wang, ...



leading particles $p_\perp \sim \Lambda_{QCD}$

→ leading baryon effect

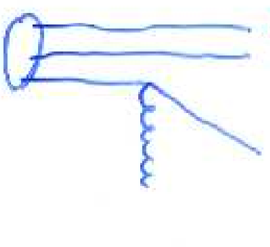


leading particles $p_\perp \sim Q_s$

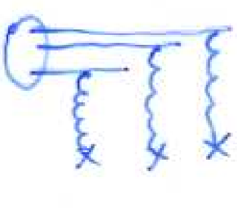
→ projectile proton "shatters"
no leading particle "recombination",
no leading baryon

→ $\langle p_\perp \rangle$ should be larger than for pp
@ $x_F \gtrsim 0.1$

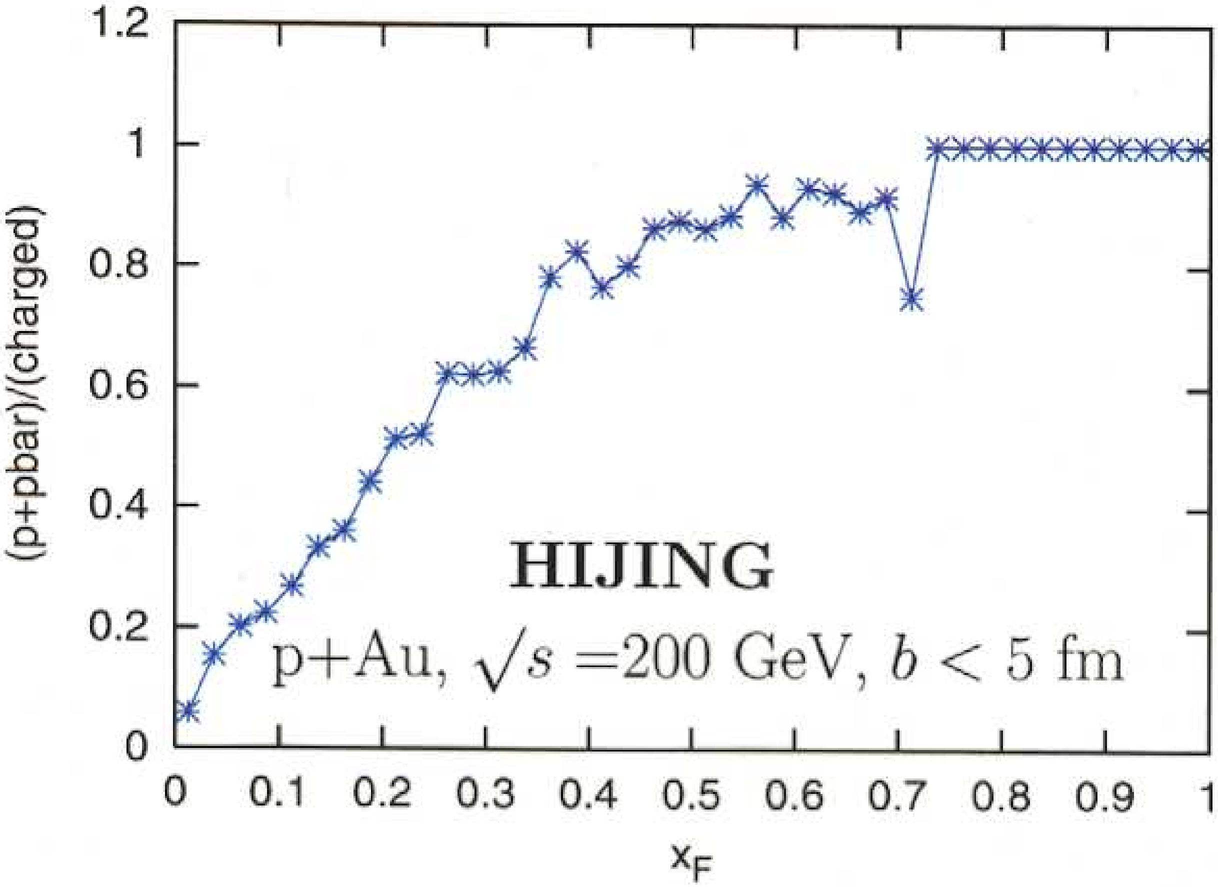
(but careful with kinematic boundaries...)

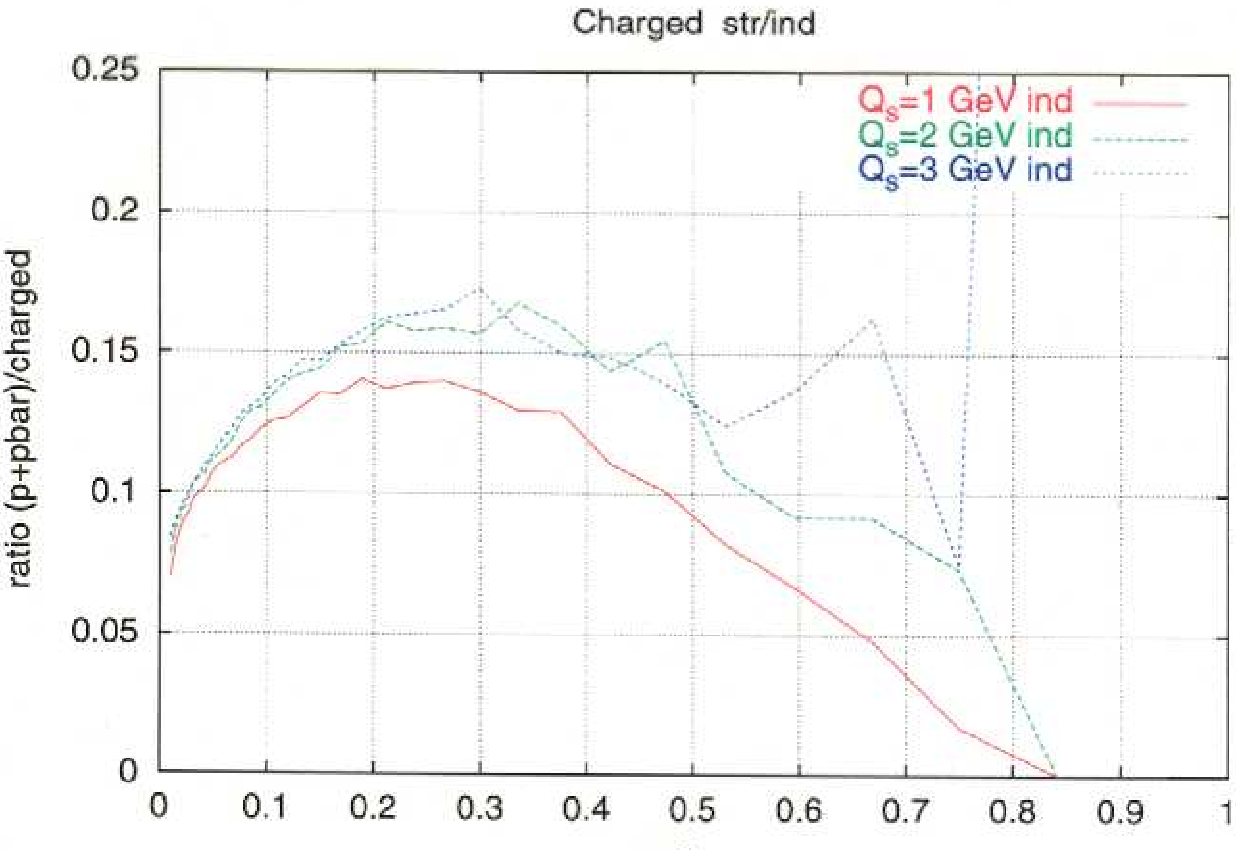


← leading "remnant"
→ baryon



complete breakup
→ mesons





Work in progress with Hajo Drescher + Mark Strikman