Cronin effect vs. geometric shadowing in dA collisions: pQCD vs. CGC

Alberto Accardi (Columbia U.)

Based on **A.A., M.Gyulassy, nucl-th/0308029 v2**

Part I - Minijet production in pA collisions: Glauber-Eikonal models

- pQCD + Glauber rescatterings of partons
- From pp to pA collisions
- Geometric shadowing and saturation

Part II - =0: no CGC!

Part III - 1: Colorful dynamics or boring blackness?

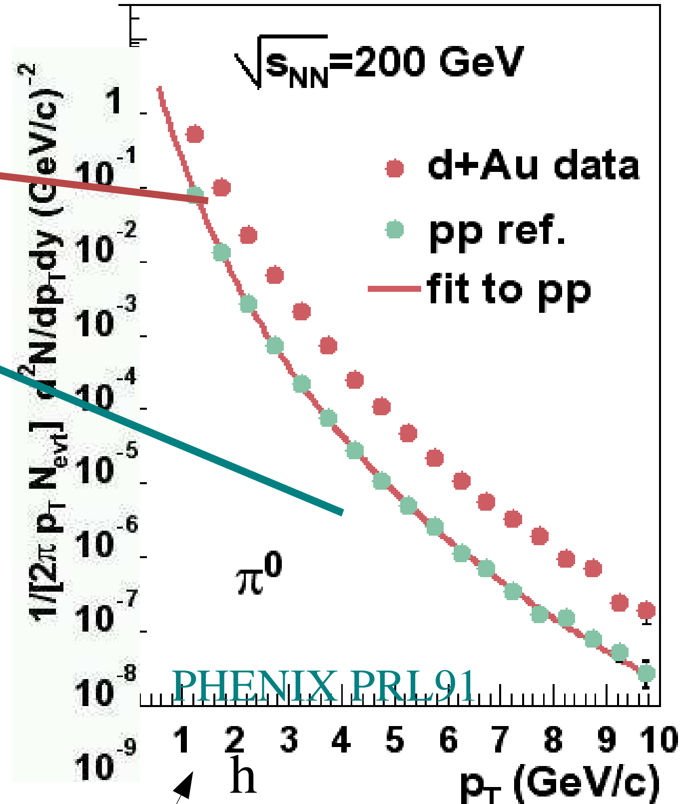
Part I

Glauber-Eikonal models:
pQCD + partonic rescatterings

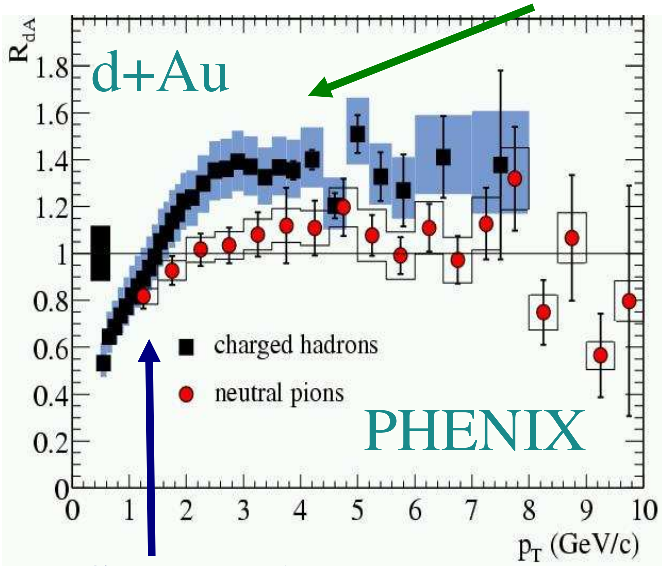
Cronin ratio of inclusive spectra

$$R_{AB}(p_T) = \frac{d^2 N^h_{AB} / dp_T\, d\eta}{T_{AB}\; d^2\sigma^h_{NN} / dp_T\, d\eta}$$

Binary collision scaling p+p reference

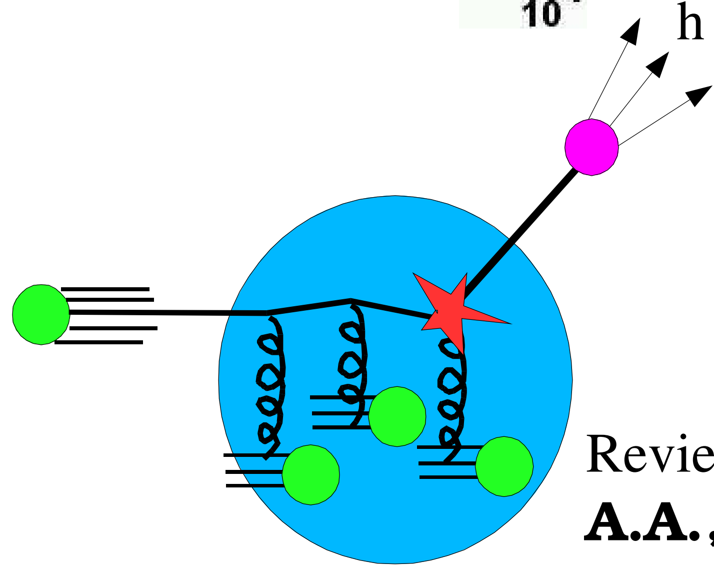


Enhancement at moderate-pT



Suppression at low pT

(same pattern at Fermilab)



Review and refs.:

A.A., hep-ph/0212148

First act: pp collisions

Single scattering = LO in pQCD

renormalization scale

fragmentation scale

$$\frac{d\sigma^{pp}}{d^2p_t} = \int dx \sum_i f_{i/h}(x, Q_p^2) \underbrace{K \int dx' \sum_j f_{j/A}(x', Q_p^2) \frac{d\sigma^{ij}_{pQCD}}{d^2p_T}}_{= d\sigma^{iN}/d^2p_T} \int dz D_{i\to h}(z, Q_h^2)$$

K-factor (simulates NLO)

IR regulator

where $$\frac{d\sigma^{iN}}{d^2p_T} \approx K \int_{\frac{4p_T^2}{x\sqrt{s}}}^{1} dx' \, f_{j/A}(x', Q^2) \frac{C^{ij}}{(p_T^2 + p_0^2)^2} \propto \frac{1}{(p_T^2 + p_0^2)^{2+n}}$$ = parton-nucleon cross section

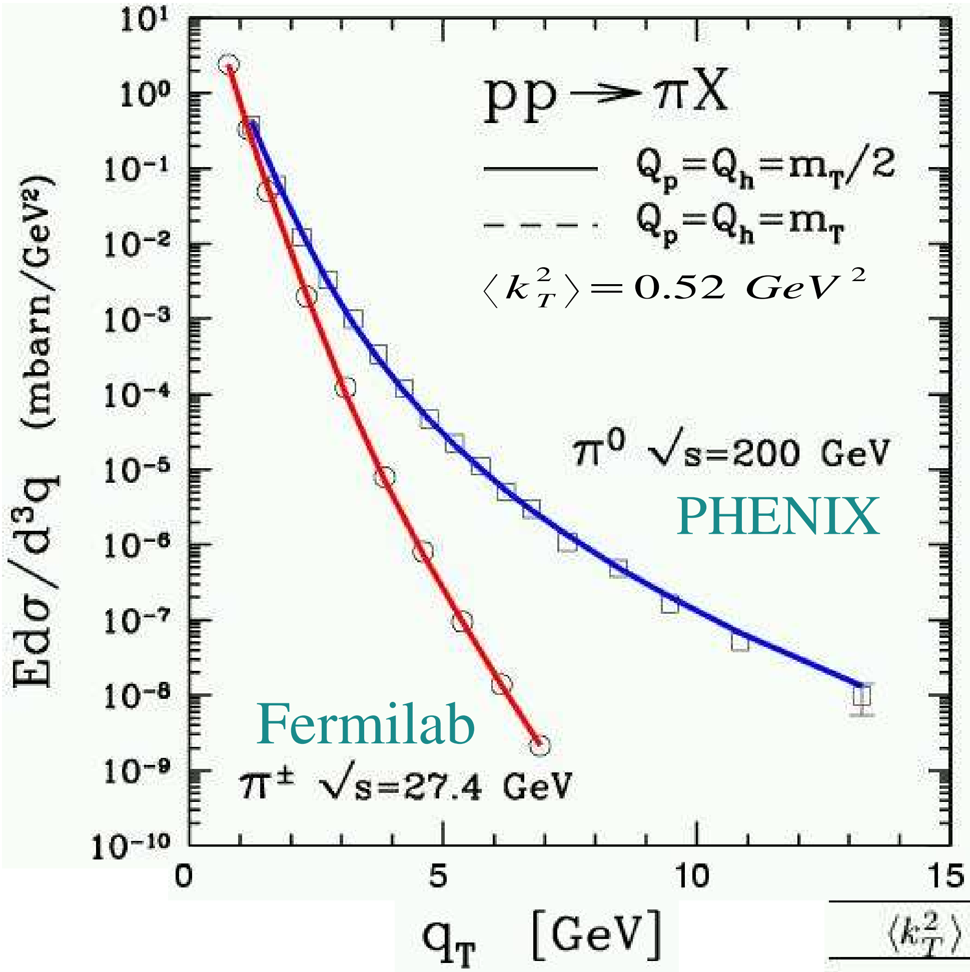
a) CHOOSE the scales: $Q_p = Q_h = m_T/2$ (or $Q_p = Q_h = m_T$)

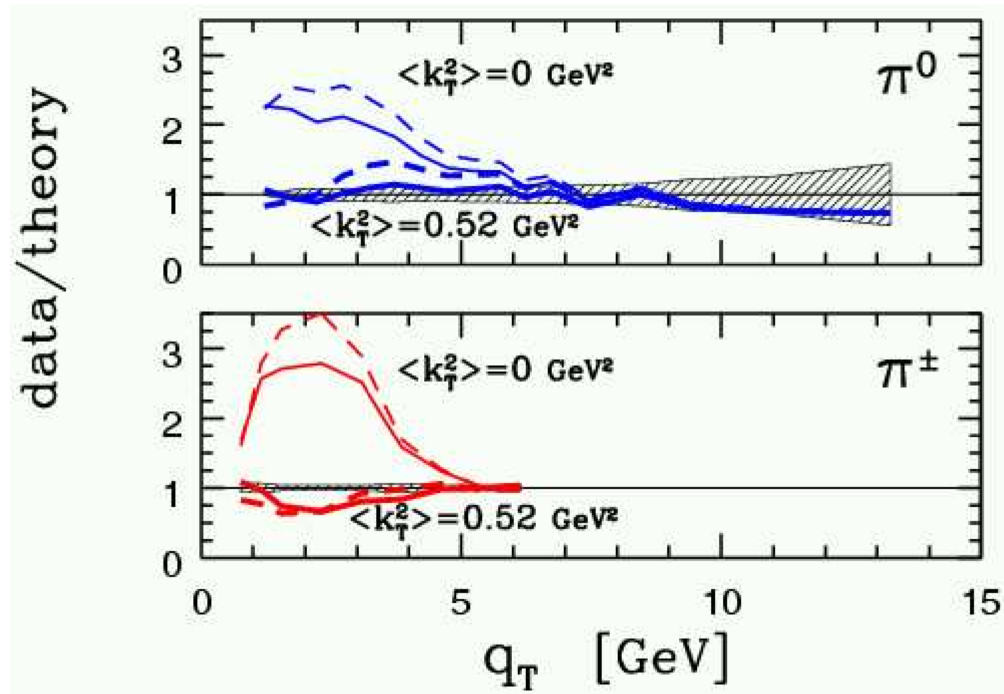
b) Intrinsic $\langle k_T^2 \rangle = 0.52\ \mathrm{GeV}^2$ from PHENIX and low-E *pp* data

c) FIT **K=K(s)** to the **high-pT** tail of the hadron spectrum (χ^2 fit - sensitive to the choice of scales)

d) FIT **p0 = p0(s)** to the **low-pT** hadron spectrum

Results of the fit





Fit procedure: Eskola, Honkanen '02

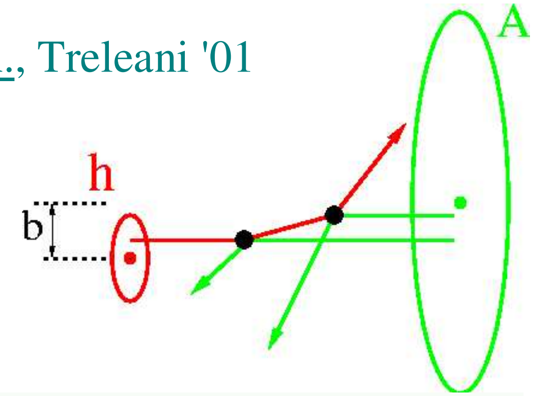
$\langle k_T^2 \rangle$	$Q_p = Q_h$	$\sqrt{s} = 27.4$ GeV	$\sqrt{s} = 200$ GeV
0.52 GeV^2	$m_T/2$	$p_0 = 0.70 \pm 0.1$ GeV $K = 1.07 \pm 0.02$	$p_0 = 1.0 \pm 0.1$ GeV $K = 0.99 \pm 0.03$
	m_T	$p_0 = 0.85 \pm 0.1$ GeV $K = 4.01 \pm 0.08$	$p_0 = 1.2 \pm 0.1$ GeV $K = 2.04 \pm 0.12$
0 GeV^2	$m_T/2$	$p_0 = (0.70 \pm 0.1$ GeV$)$ $K = 3.96 \pm 0.11$	$p_0 = (1.0 \pm 0.1$ GeV$)$ $K = 1.04 \pm 0.06$
	m_T	$p_0 = (0.85 \pm 0.1$ GeV$)$ $K = 13.4 \pm 0.4$	$p_0 = (1.2 \pm 0.1$ GeV$)$ $K = 2.04 \pm 0.12$

from PHENIX prelim. (nucl-ex/0306031)

Second act: pA collision and Cronin effect

Multiple parton scattering Calucci, Treleani '90-'91 & A.A., Treleani '01

Assuming: generalized collinear factorization
factorization of the n-body cross-section
only elastic parton scatterings



$$\frac{d\sigma^{iA}}{d^2p_t} = K\sum_{n=1}^{\infty}\frac{1}{n!}\int d^2b\int d^2k_1\cdots d^2k_n \times \underbrace{\frac{d\sigma^{iN}}{d^2k_1}T_A(b)\times\cdots\times\frac{d\sigma^{iN}}{d^2k_n}T_A(b)}_{\text{n-fold parton rescattering}}\ e^{-\sigma^{iN}(p_0)T_A(b)} \times \delta^{(2)}\left(\sum \mathbf{k}_i - \mathbf{p_t}\right)$$

unitarity factor (probability conserv.)

and: $$\frac{d\sigma^h_{pA}}{d^2p_t} = \sum_i f_{i/p}\otimes\frac{d\sigma^{iA}}{d^2p_t}\otimes D_{i\to h} + A\sum_j f_{j/A}\otimes\frac{d\sigma^{jp}}{d^2p_t}\otimes D_{j\to h}$$

- **pA = unitarized multiple parton scatterings on free nucleons**
- **Spectra in pp coll. as limiting case (high-pT or A->1)** $$\frac{d\sigma^h_{pA}}{d^2p^h_T}\xrightarrow[p_T\to\infty]{} A\,\frac{d\sigma^h_{pp}}{d^2p^h_T}$$
- **No extra free parameters**

Geometric shadowing & Cronin effect

Integrated parton yield (dominated by low-p_T)

$$\frac{d\sigma^{iA}}{d^2b\,d\eta} \approx 1 - e^{\underbrace{-T_A(b)\sigma^{iN}(\eta;p_0,K)}_{\text{opacity}}} \leq 1$$

unitarity

opacity = i_A(b,)

(average no. of scatterings)

Two limits:

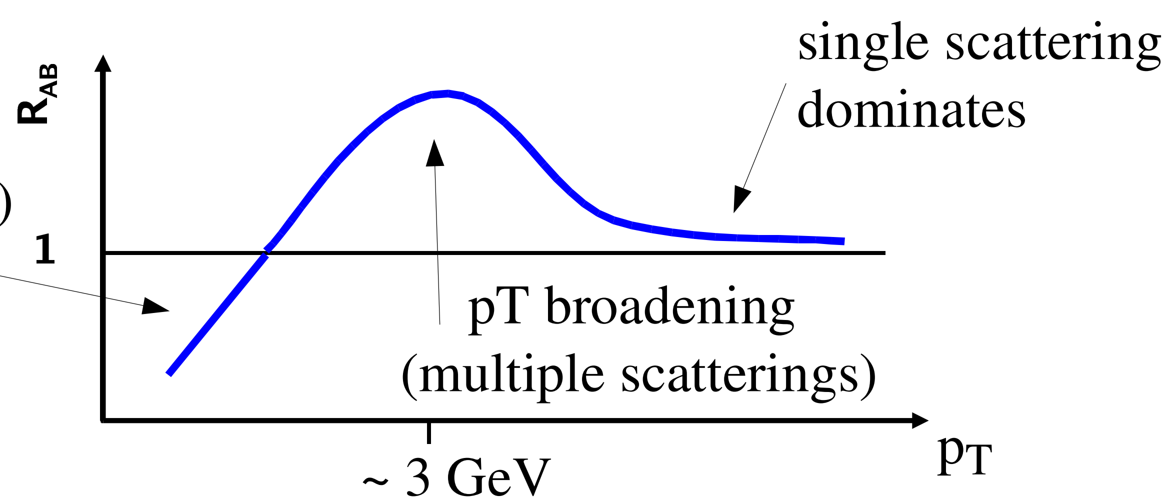
1) low-opacity $\chi \langle\langle 1 \Longrightarrow \frac{d\sigma^{iA}}{d^2b\,d\eta} \approx T_A\sigma^{iN}$ collision scaling (single semihard scattering)

2) high-opacity $\chi \gtrsim 1 \Longrightarrow \frac{d\sigma^{iA}}{d^2b\,d\eta} \langle\langle 1 \lesssim T_A\sigma^{iN}$ geometric shadowing

<u>Sum of 2 effects:</u>

a) momentum conservation
(spectrum shifted to higher p_T)

b) geometric shadowing



NOTE: "Dynamical" shadowing NOT included (no geom.scaling, no EKS98, ...)

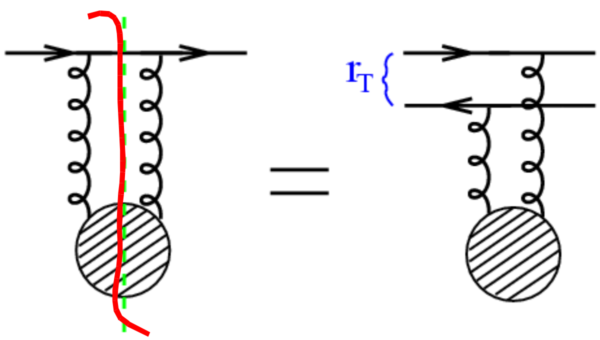
Dipole representation:
Glauber-Eikonal pQCD "is" saturation

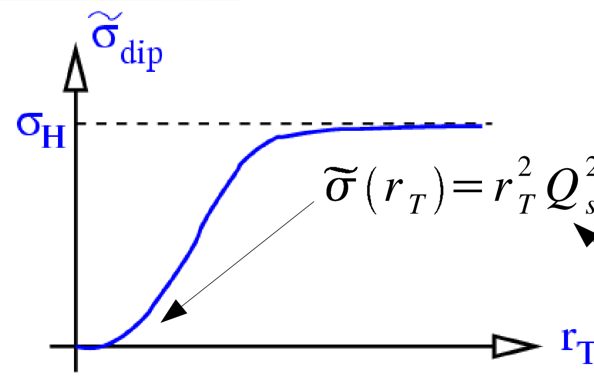
Resummation of pt-spectrum possible in coordinate-space:

$$\frac{d\sigma^{iA}}{d^2p_T} = \int \frac{d^2r_T}{4\pi^2} e^{-i\vec{k}_T\cdot\vec{r}_T}\left[e^{-\tilde{\sigma}^{iN}(r_T)T_A(b)} - e^{-\sigma^{iN}T_A(b)}\right]$$

same as saturation model by Gelis-Jal.Mar.'02

where $\tilde{\sigma}^{iN}(r_T) = \int d^2k\left[1 - e^{-i\vec{k}\cdot\vec{r}_T}\right]\frac{d\sigma^{iN}}{d^2k}$ is a dipole cross-section

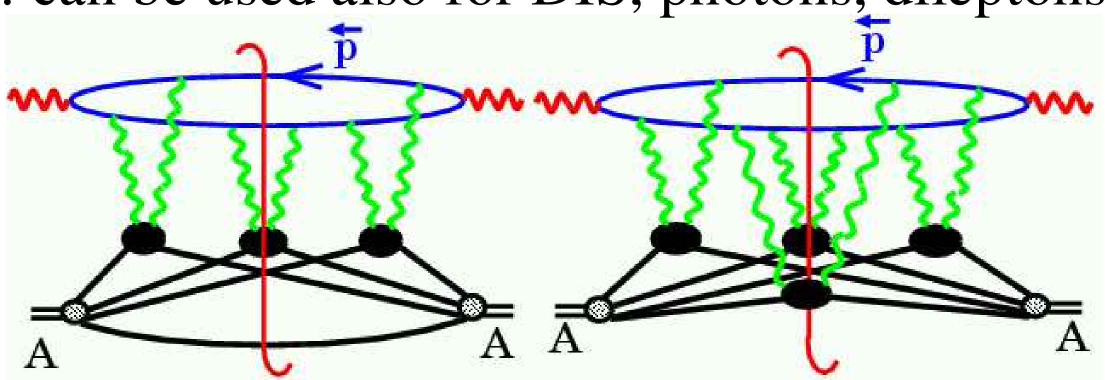




this is the saturation scale

$$\alpha_s(Q^2)\frac{8\pi N_c}{N_c - 1} x G(x;Q^2) \tau_A(b)$$

- pA collisions as multiple scatterings of a colour dipole (with DGLAP evol.)
- Universality: can be used also for DIS, photons, dileptons...

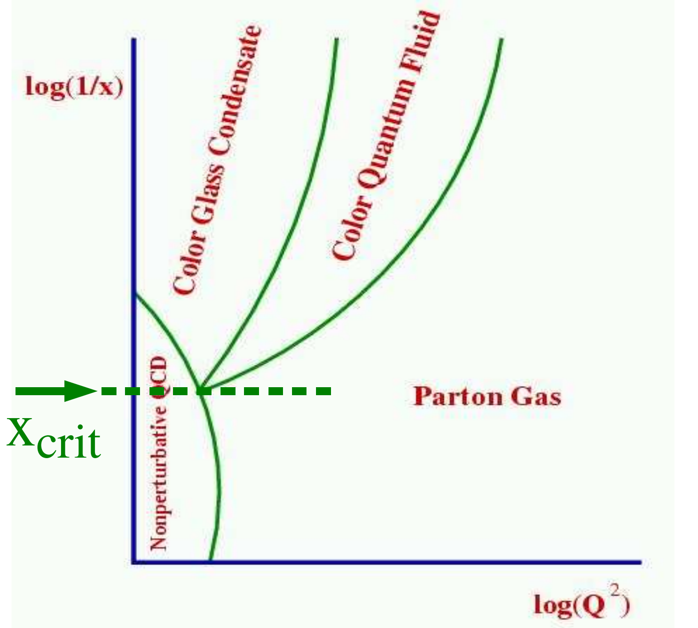


Saturation vs. Glauber-Eikonal

Saturation models: (McLerran-Venugopalan+....)

- prefactors not under control:
  y-dependence of Q_{sat}, not absolute value
  width of geom.scaling window: $Q_{gs}=Q^2_{sat}/Q_0 \overset{?}{=}$
- spectra stricly = $1/p_T^4$
- no quarks
- no kinematic limits

$\}$ can't reproduce hadron spectra in pp collisions nor in pA



Glauber-Eikonal model:

"equivalent to saturation models" - with the difference that:

- kinematics + q&g: # spectra in p+p OK
  # Cronin at low energy OK
- DGLAP evolution included in PDF's
- includes "geometric shadowing" = unitarization of DGLAP nucleons
- does not include "dynamical shadowing"

Baseline to measure dynamical shadowing and x_{crit}

Part II

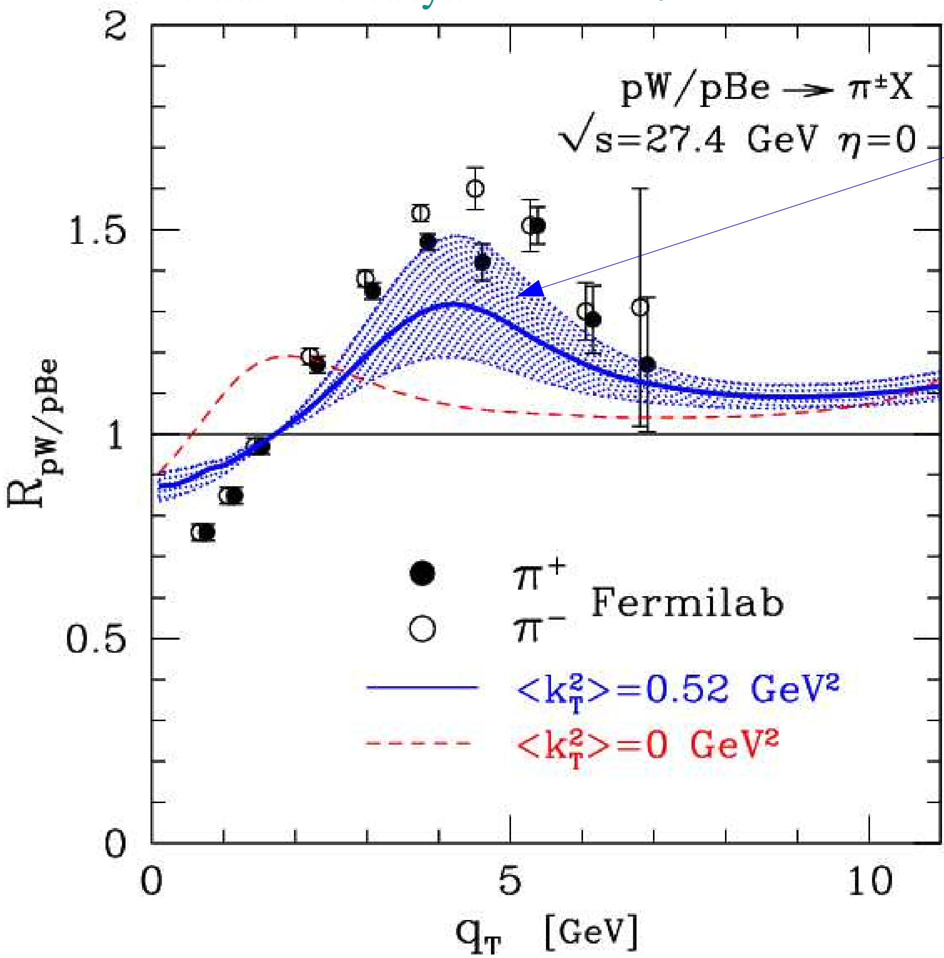
No CGC at RHIC =0

A.A. and M.Gyulassy, **nucl-th/0308029 v2**

Note: in v1 there was a bug in the kT-smearing routine. Fits and computations have been redone with correct routine

Cronin effect on pions at Fermilab

data: Antreasyan - PRD '79



theoretical error due to fit of $p_0 = 0.7 \pm 0.1$ GeV

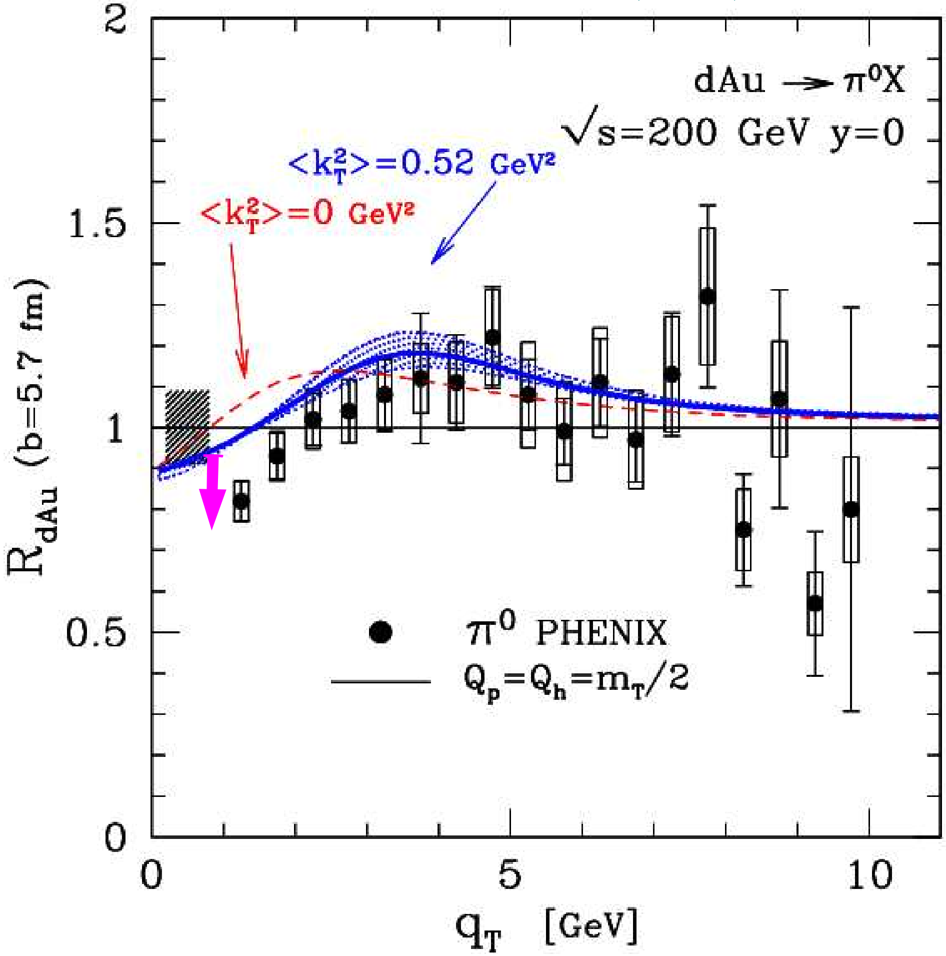
Q=mT/2 or Q=mT give similar results

We reproduce the data well.

At low-p_T, theory overestimates data

Cronin effect on pions at PHENIX   =0

data: PHENIX - PRL 91(2003)072303



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

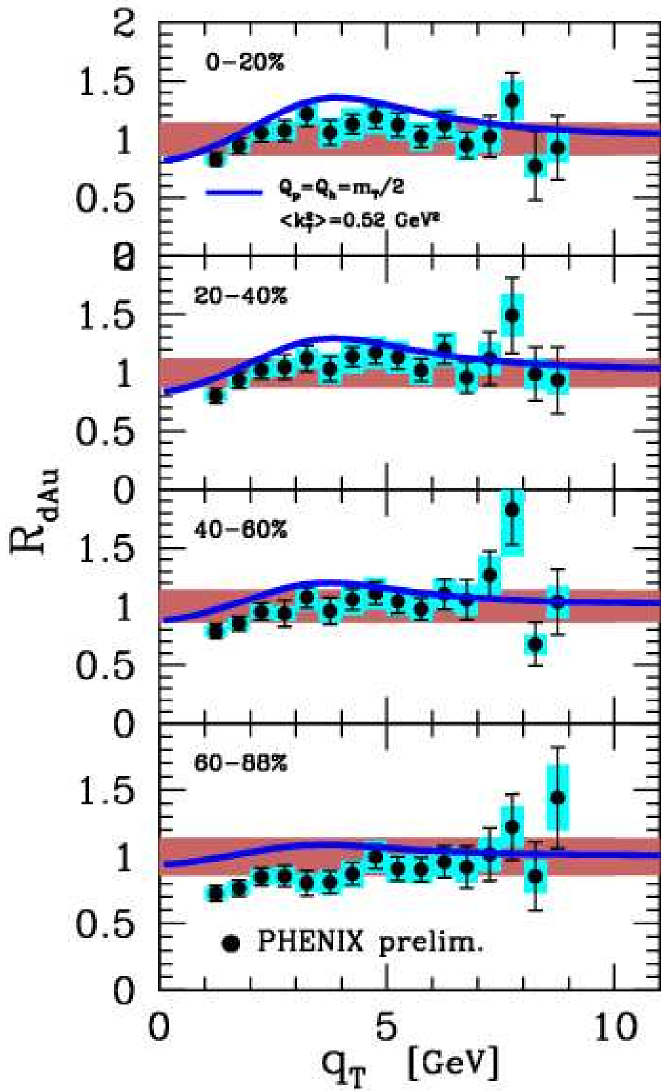
Computation compatible with data inside <u>exper.</u> and <u>theor. errors</u>

Tends to overestimate data at low pT

⇒ **Possible indication of (small) dynamical shadowing ?**
(but... also at Fermilab energy?)
Non-perturbative dynamics?

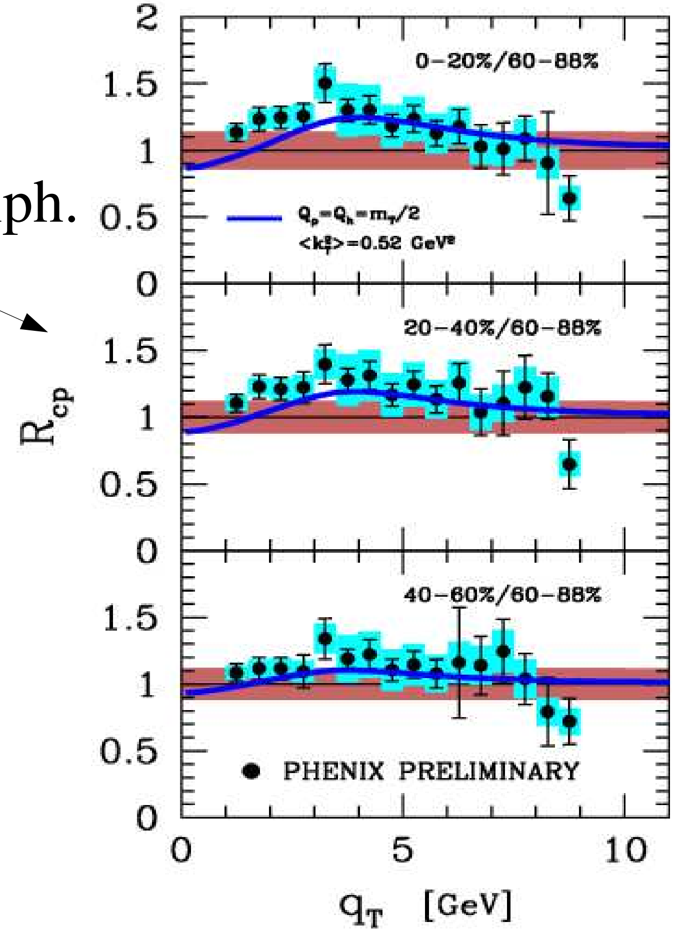
Centrality dependence

If dynamical shadowing at work, $\Longrightarrow$ stronger suppression in central



d+Au/p+p

central/periph.



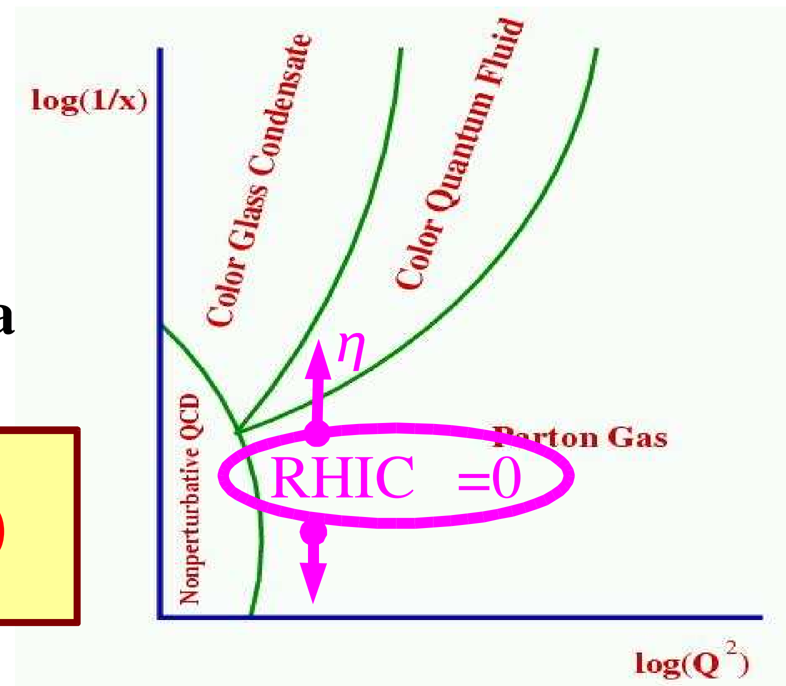
prelim. data: T.Awes, DNP Tucson Nov'03

dAu multiple scatt. + unitarity: no dynamical shadowing

Conclusions - 1

The Glauber-Eikonal model (= pQCD + rescatterings) allows to compute pA collisions starting from pp spectra

- dAu unitarity + sum of free nucleons
  = "geometric shadowing + Cronin"
- can find "dynamical shadowing"
  by comparing GE baseline with exp. data



There is no CGC at RHIC =0

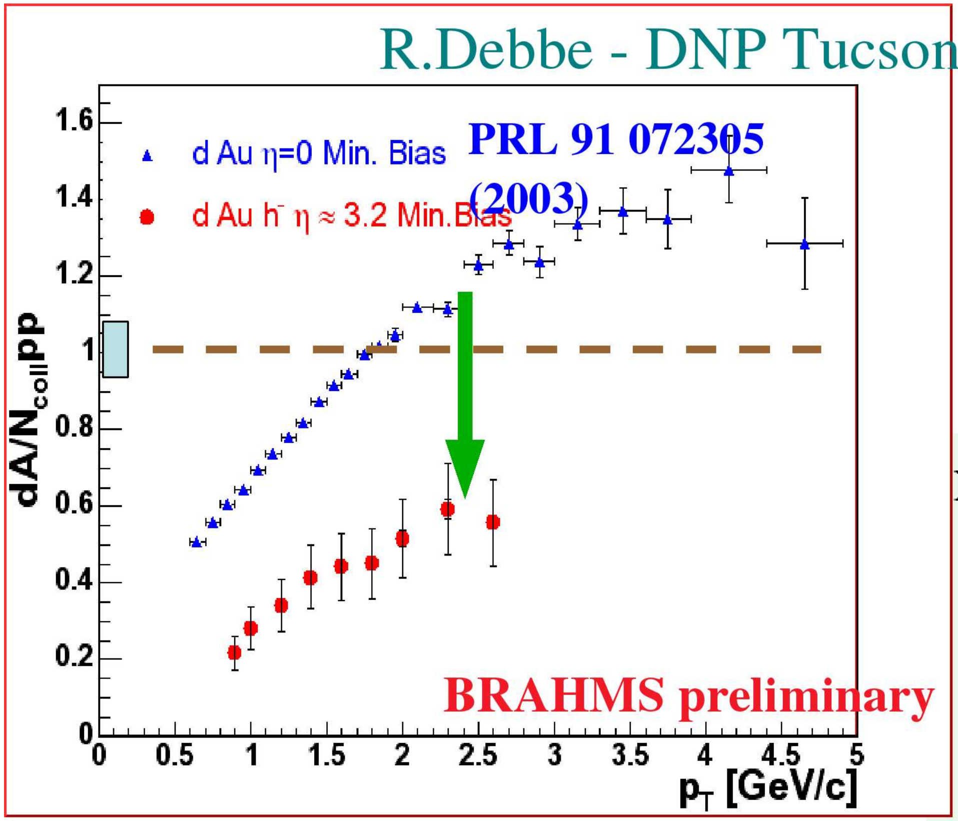
what about =3?

Part III

Forward :

Colorful dynamics or boring blackness?

What about = 3.2 ?



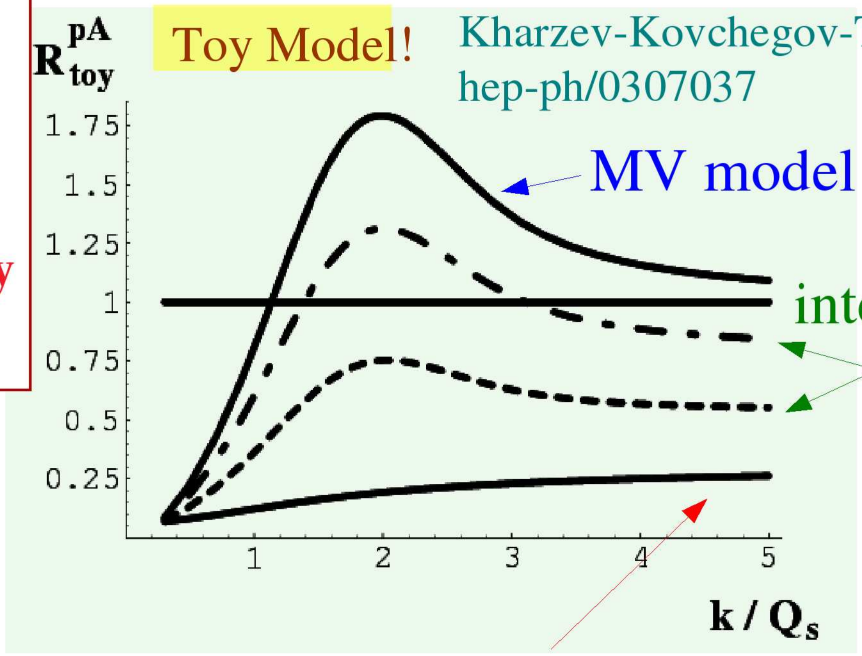
"Suppression" of η=3 spectrum:

1) Colorful dynamics ??? KKT'03

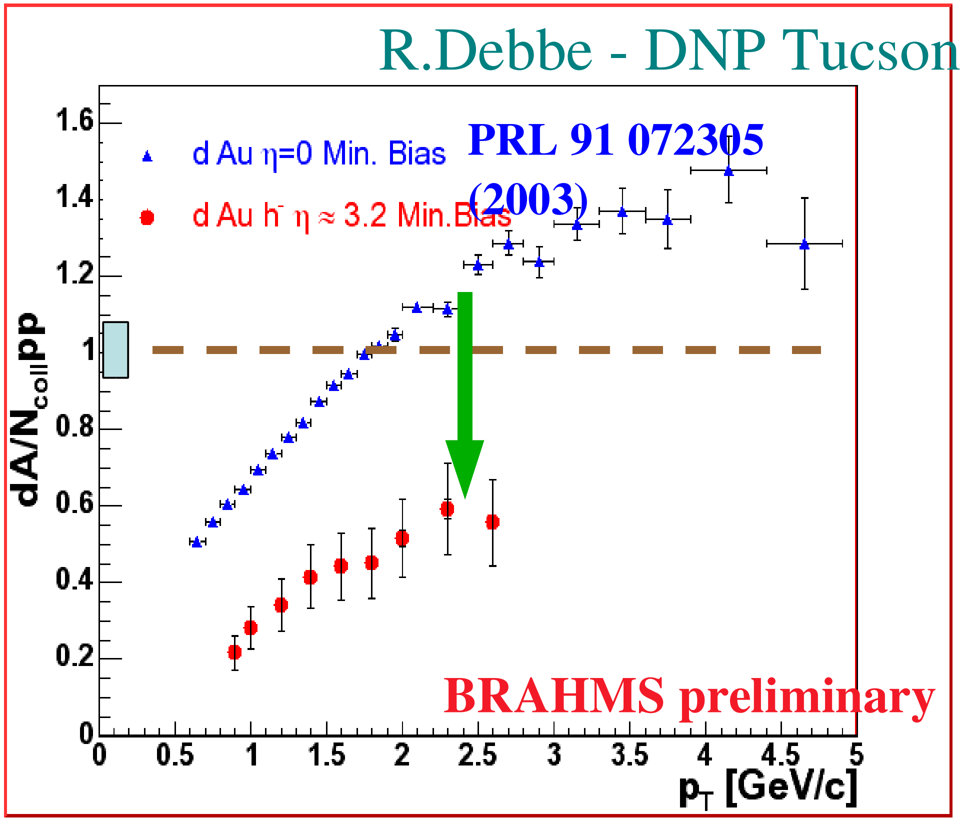
DGLAP → BFKL+ sat. bound. cond's

= anomalous scaling

"=" CGC



What about = 3.2 ?



"Suppression" of η=3 spectrum:

1) Colorful dynamics ???

DGLAP → BFKL+ sat. bound. cond's

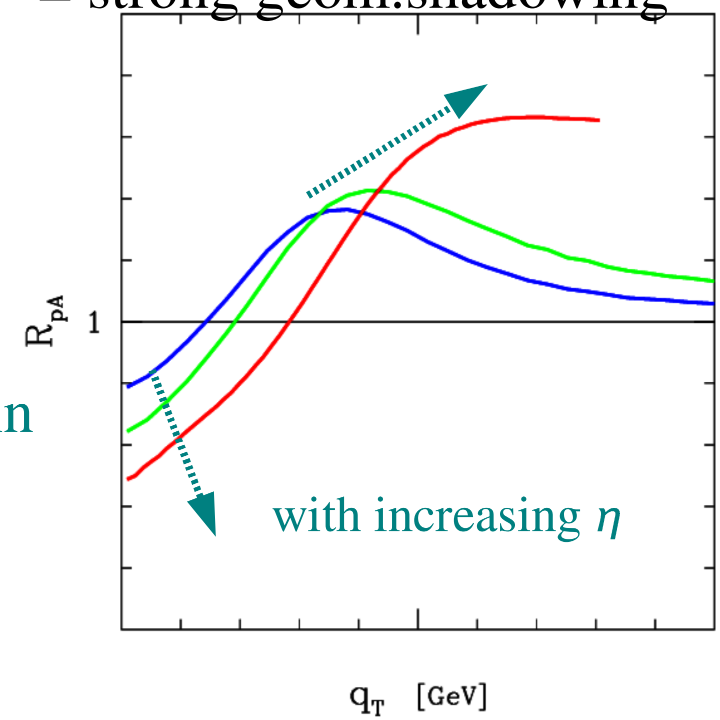
= anomalous scaling

"=" CGC

2) Boring blackness ??? A.A, Gyulassy

DGLAP + black nucleus + unitarity

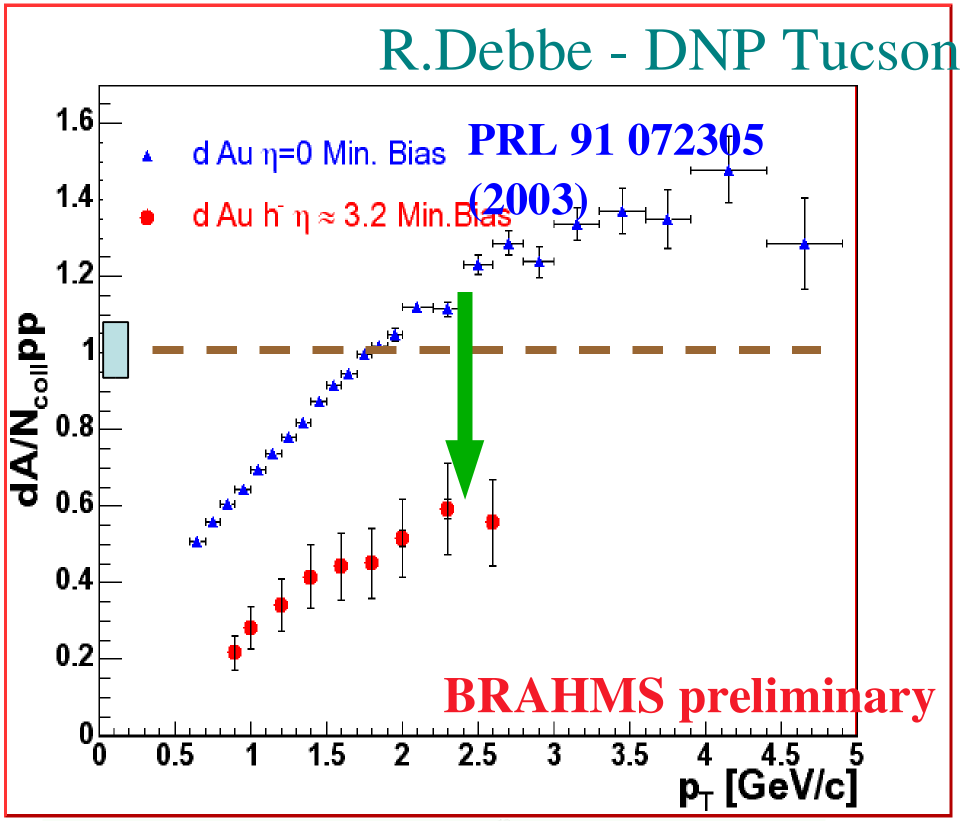
= strong geom.shadowing



NOTE: same qualitative result as in "classical" MV model

(Dumitru-Gelis-JalilianMarian)

What about = 3.2 ?



"Suppression" of η=3 spectrum:

1) Colorful dynamics ???

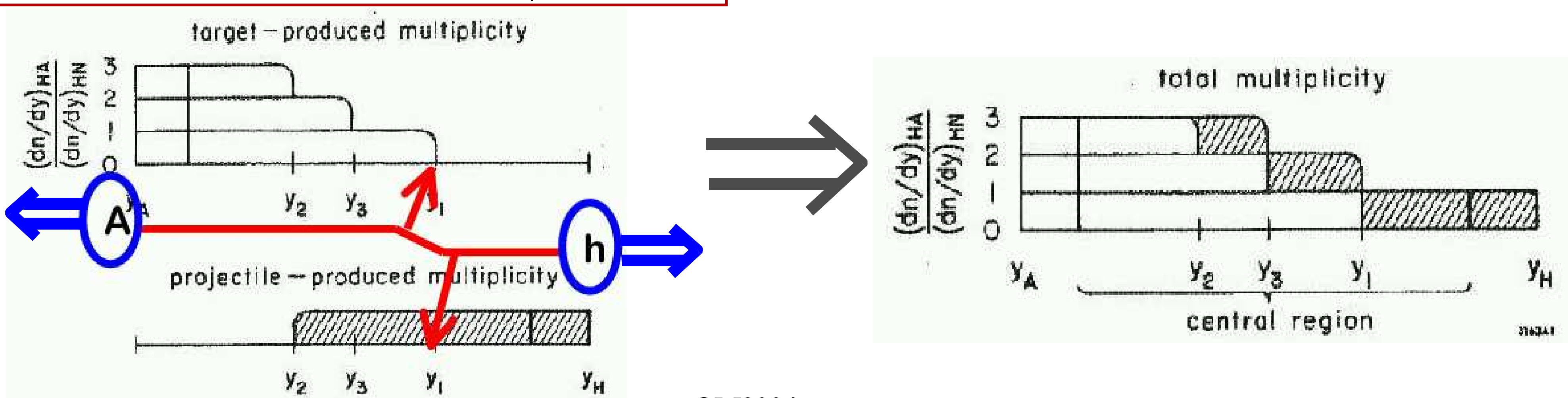
DGLAP → BFKL+ sat. bound. cond's
= anomalous scaling
"=" CGC

2) Boring blackness ???

DGLAP + black nucleus + unitarity
= strong geom.shadowing

3) Non-perturbative physics ???

Baryon number conservation?

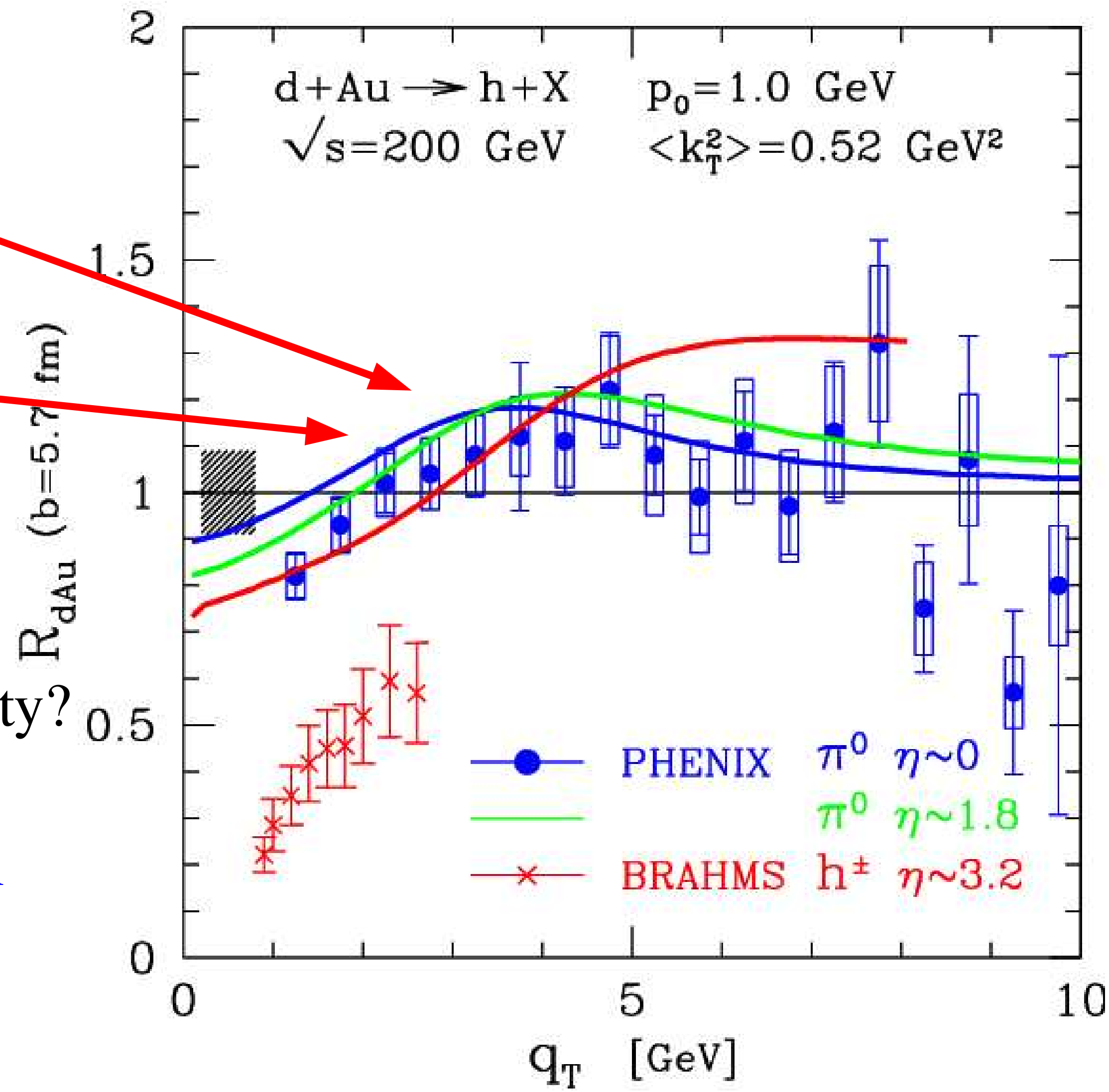


GE model: computation

No available data for pp coll's at forward rapidity ⇒ we take **same parmeters as for η=0:**

- $p_0(\eta>0) = p_0(\eta=0) = 1.0$ GeV
- $K(\eta>0) = K(\eta=0) = 1$

η	**0**	**1.8**	**3.2**
χ	**0.74**	**0.85**	**0.95**



Data are much lower than theory:

Is this a CGC ????

...or are we underestimating opacity?

p_0 and K may change with η:

The nucleus may be blacker than extrapolated from mid-rapidity.

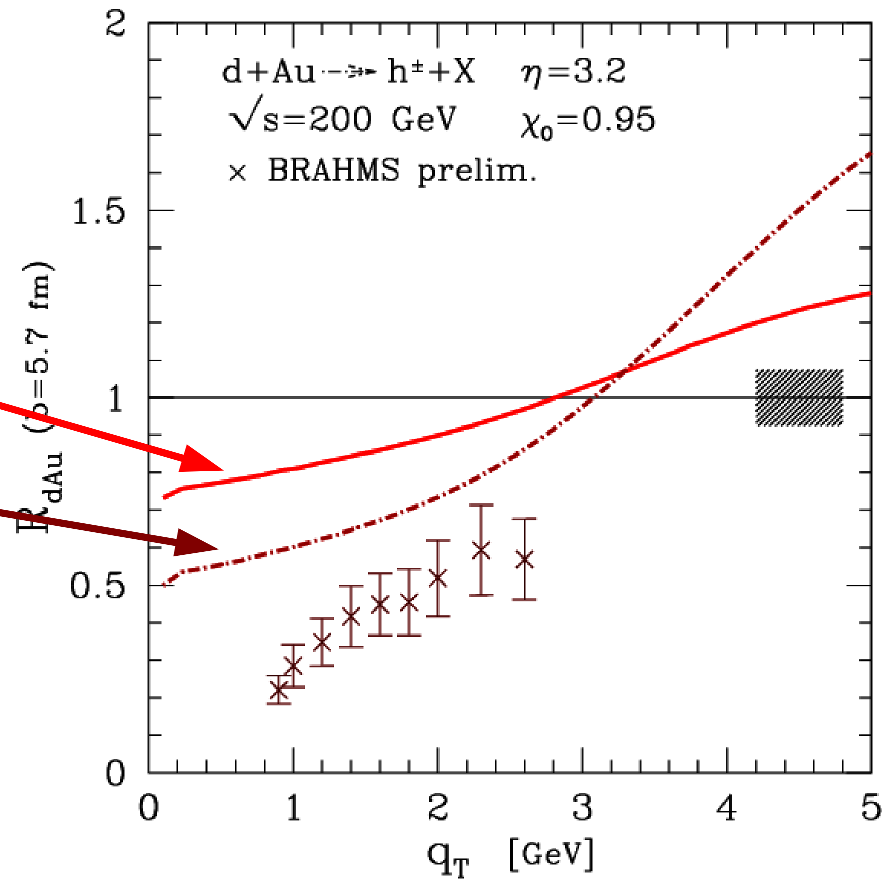
Using p_0 and K fitted in pp at =0, we have $_0$=0.95 at =3.2.
This may be underestimated, though, and must be checked in p_T-spectrum in pp collisions at η=3.2

But even with =3 $_{0,}$ data lie below the computation:

There seems to be some dynamical shadowing!

= $_0$

=3 $_0$



Conclusions - 2

Given knowledge of pp spectra, the Glauber-Eikonal model (= pQCD + rescatterings) allows to compute pA collisions

- can find "dynamical shadowing" by comparing GE baseline with exp. data

There is no CGC at RHIC $\eta=0$

Something interesting is there at $\eta=3.2$

The End

CGC toy model

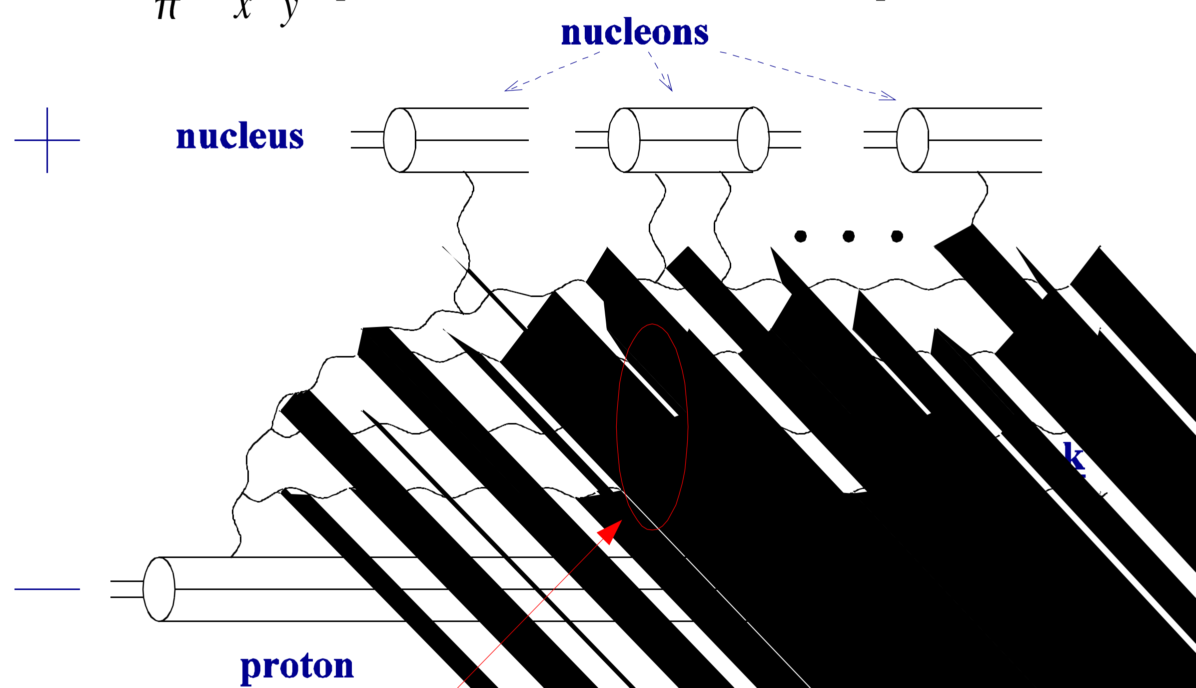
Classical YM gluon production cross section is given by

(Kovchegov, Mueller, hep-ph/9802440)

$$\frac{d}{d^2k\,dy} = \frac{1}{(2\pi)^2}\int d^2b\,d^2x\,d^2y\,e^{i\underline{k}\cdot(\underline{x}-\underline{y})}\,\frac{C_F}{\pi^2}\,\frac{\underline{x}\cdot\underline{y}}{x^2y^2}\left[N_G(x)+N_G(y)-N_G(\underline{x}-\underline{y})\right]$$

With the (classical) gluon-gluon dipole-A forward scattering amplitude

$$N_G(x, Y=0) = 1 - e^{-x^2Q_s^2/4}$$



The rules accomplishing the inclusion of quantum corrections are

Proton's LO wave function ⇒ Proton's BFKL wave function and $N(x, Y=0) \Rightarrow N($

where the dipole-nucleus amplitude N satisfy Balitski-Kovchegov eqn.

The toy model (Kharzev-Kovchegov-Tuchin, hep-ph/0307037)

energy, giving $\ln 1/(z_T \Lambda)$ in Eq. (117). We will model the gluon dipole amplitude at high energy by a Glauber-like unitary expression

$$\boxed{N_G^{toy}(z_T, y) = 1 - e^{-z_T\, Q_s(y)},} \qquad \begin{array}{c} Q_s(y) \approx Q_{s0}\, e^{2.44\, \overline{\alpha}_s\, y} \\ \text{(Mueller-Triantafyllopoulos)} \end{array} \tag{118}$$

which mimics the onset of anomalous dimension $\lambda = 1$ by the linear term in the exponent. The saturation scale $Q_s(y)$ in Eq. (118) is some increasing function of y which can be taken from Eq. (79) or from Eq. (83). Indeed the amplitude in Eq. (118) has an incorrect small-z_T behavior, scaling proportionally to z_T instead of z_T^2 as shown in Eq. (14). If Eq. (118) is used in Eq. (117) it would lead to an incorrect high-k_T behavior of the resulting cross section. We therefore argue that Eq. (118) is, probably, a reasonable model for N_G inside the saturation and extended geometric scaling regions $(1/z_T \sim k_T < k_{\rm geom})$, but should not be used for very small z_T / high k_T $(1/z_T \sim k_T > k_{\rm geom})$.

Substituting Eq. (118) into Eq. (117) and integrating over z_T yields

$$\boxed{\begin{aligned} \frac{d\sigma_{toy}^{pA}}{d^2k\, dy} = \frac{\alpha_s C_F}{\pi^2} \frac{S_A}{k_T^2} \frac{Q_s}{k_T^2 + Q_s^2} \Bigg[-Q_s(k_T^2 + Q_s^2) + \sqrt{k_T^2 + Q_s^2} \Bigg(2Q_s^2 + \gamma\, k_T^2 + k_T^2 \ln \frac{2(k_T^2 + Q_s^2)}{k_T\, \Lambda} \\ + \frac{k_T^2}{2} \ln \frac{\sqrt{k_T^2 + Q_s^2} - Q_s}{\sqrt{k_T^2 + Q_s^2} + Q_s} \Bigg) \Bigg], \end{aligned}} \tag{119}$$

where γ is the Euler's constant and $Q_s = Q_s(y)$. Corresponding gluon production cross section for pp is obtained by expanding Eq. (119) to the lowest order at high k_T and substituting Λ instead of Q_s and S_p instead of S_A:

$$\boxed{\frac{d\sigma_{toy}^{pp}}{d^2k\, dy} = \frac{\alpha_s C_F}{\pi^2} \frac{S_p\, \Lambda}{k_T^3} \left(\ln \frac{2\, k_T}{\Lambda} + \gamma \right).} \tag{120}$$

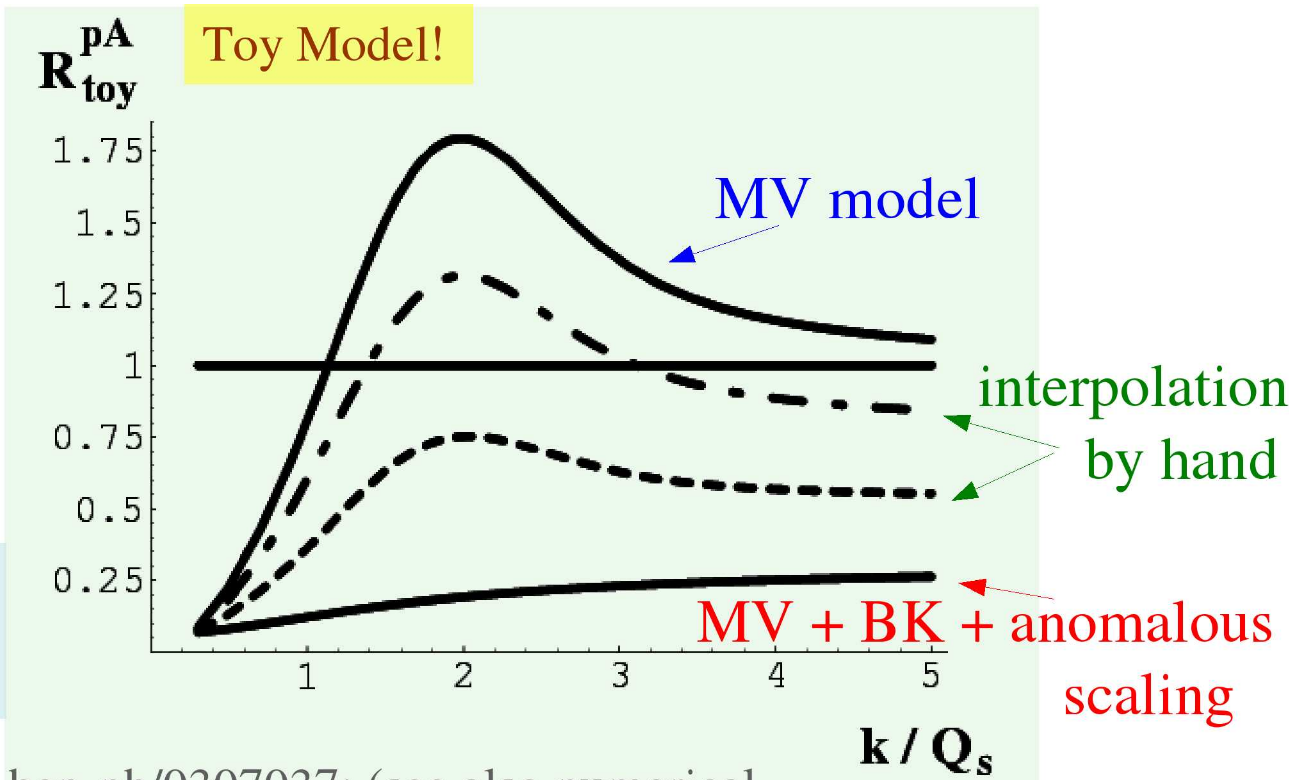
Toy-model prediction

Y.Kovchegov - RIIKEN BNL "high-pT" workshop - Dec 2003

Our analysis shows that as energy/rapidity increases the height of the Cronin peak decreases. Cronin maximum gets progressively lower and eventually disappears.

- Corresponding R^{pA} levels off at roughly at

$$R^{pA} \sim A^{-1/6}$$



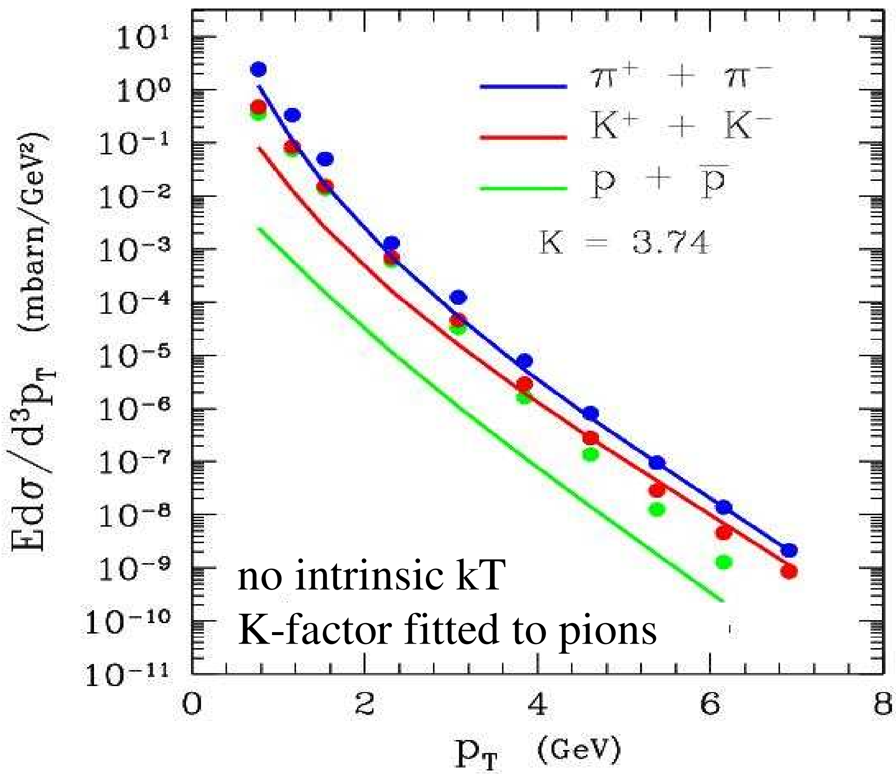
D. Kharzeev, Yu. K., K. Tuchin, hep-ph/0307037; (see also numerical simulations by Albacete et al. hep-ph/0307179 and Baier et al. hep-ph/0305265 v2.)

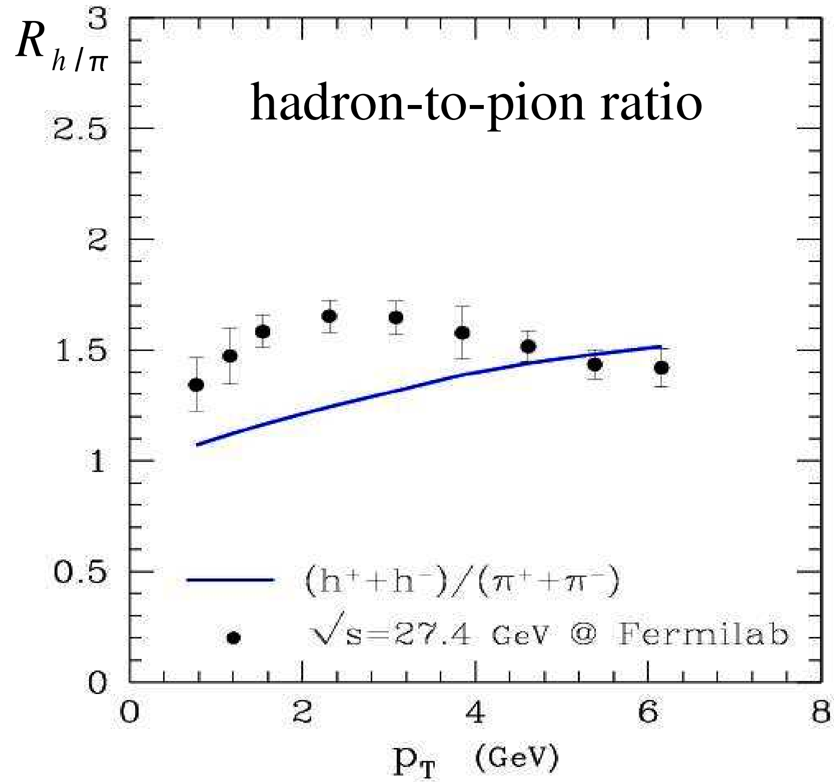
At high energy / rapidity R^{pA} at the Cronin peak becomes a decreasing function of both energy and centrality.

My (A.A.) question: Can this toy model be used to conclude about "Discovery of CGC" in BRAHMS data???

Back to pp at Fermilab: mesons vs. baryons

Fermilab 27 GeV - Antreasyan et al. '79



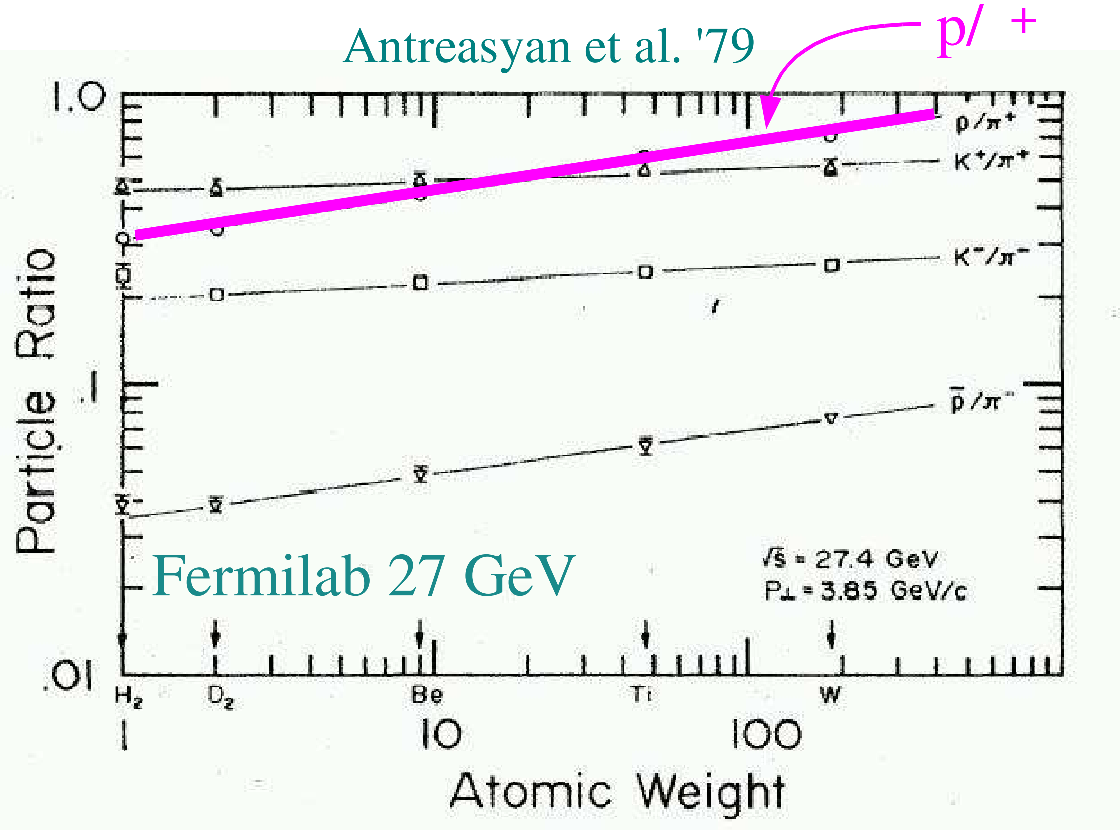


* fairly well described
* *K* slightly underestimated at low-p_T

BUT...

baryons are missed in pQCD + indep. fragmentation already in pp collisions

From pp to pA at Fermilab

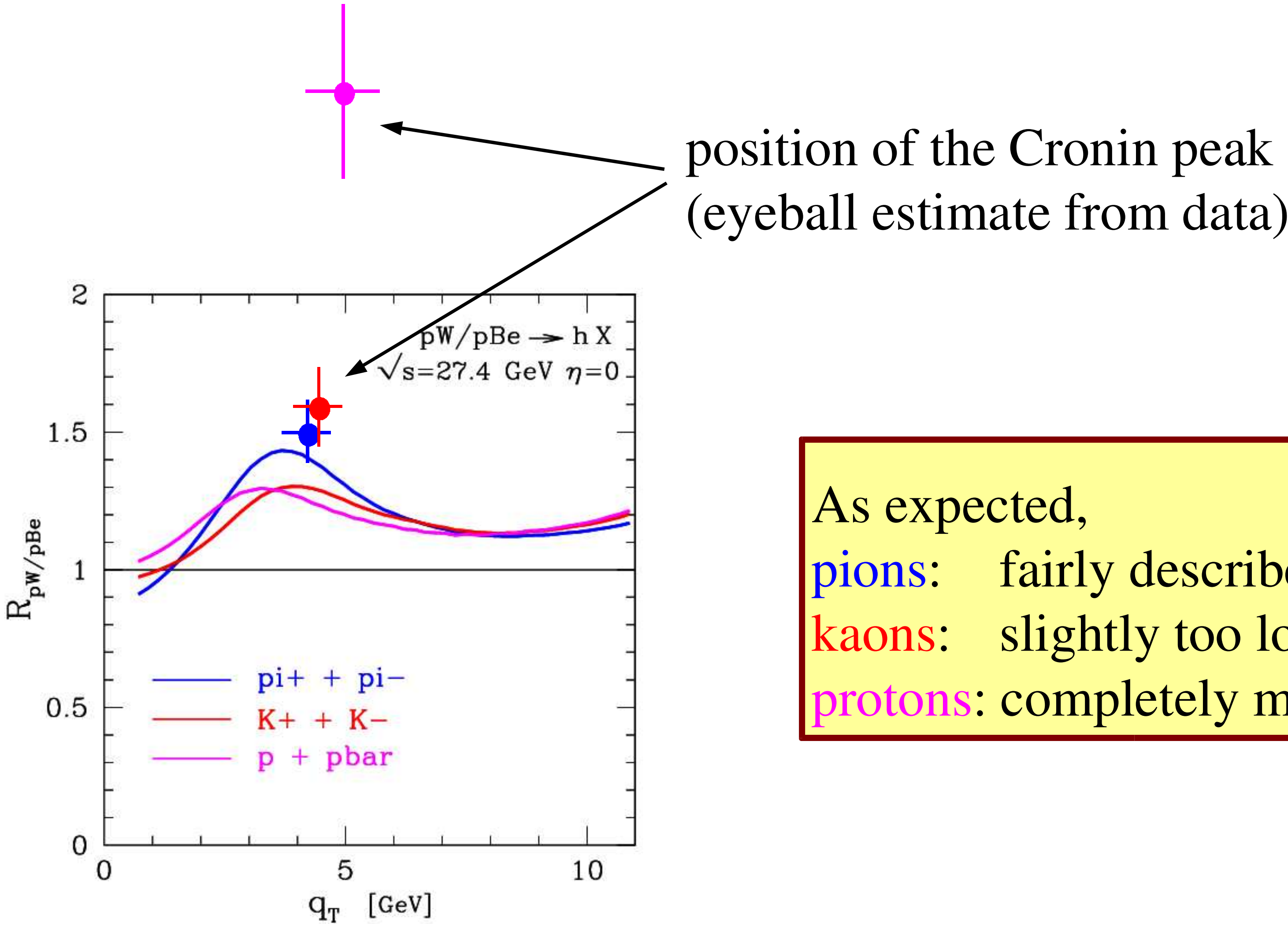


Baryons are even worse in pA collisions....

Baryon excess - possible solutions:

- <u>different k_T-broadening</u> for baryons and mesons Fai,Zhang '03
- new mechanism: <u>hadronization by parton recombination at small p</u>T
  Greco et al. '03 - Bass et al. '03
  (already in pp coll's? what about 2 part's corr's?)

Flavour dependence of Cronin effect at Fermilab



As expected,
pions: fairly described
kaons: slightly too low
protons: completely missed

different hadronization mechanism for baryons and mesons