# Cronin effect in d+Au collisions from mid- to forward rapidity

**Alberto Accardi** **(Columbia U.)**

Based on **A.A., M.Gyulassy, nucl-th/0308029 v2**
and many stolen transparencies from QM2004

(many thanks to: R.Debbe, A.Frawley, C.Klein-Boesing,
F.Mathatias, M.Murray, P.Steinberg, K.Schweda, Z.Yin;
and apologies to those I am missing)

**Lawrence Berkeley Laboratories, January 20th, 2004**

# Outline

**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 - $\eta$=0: no CGC!**

**Part III - $\eta \geq 1$: Colorful dynamics or boring blackness?**

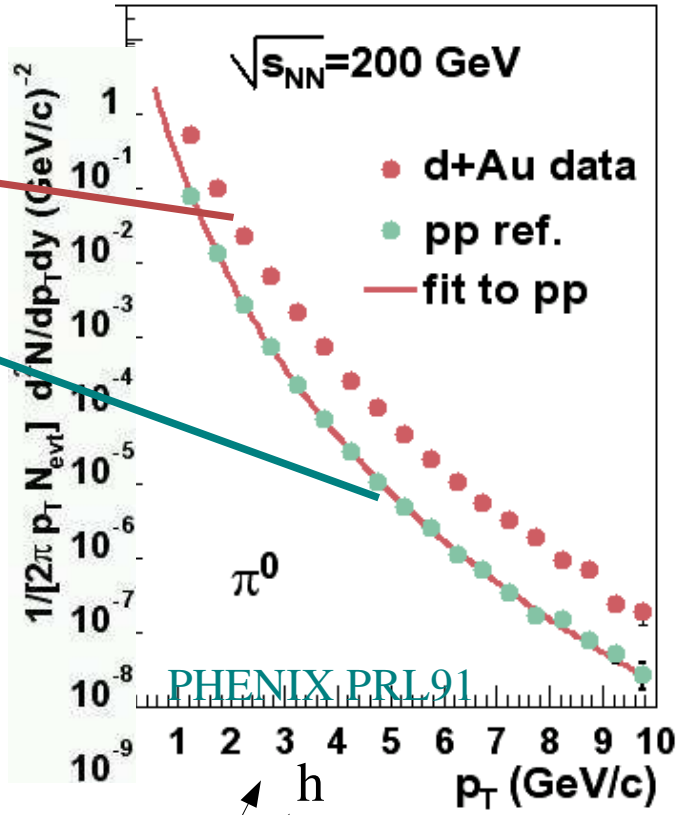
**Part IV - Many new data from QM2004!**

# Cronin ratio of inclusive spectra

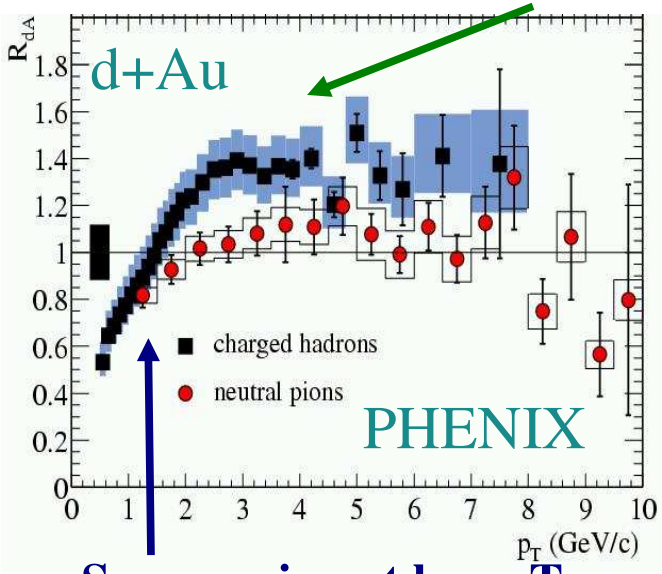
$$R_{AB}(p_T) = \frac{d^2 N^h_{AB} / dp_T d\eta}{T_{AB}\, d^2 \sigma^h_{NN} / dp_T d\eta}$$

**Binary collision scaling**

**p+p reference**

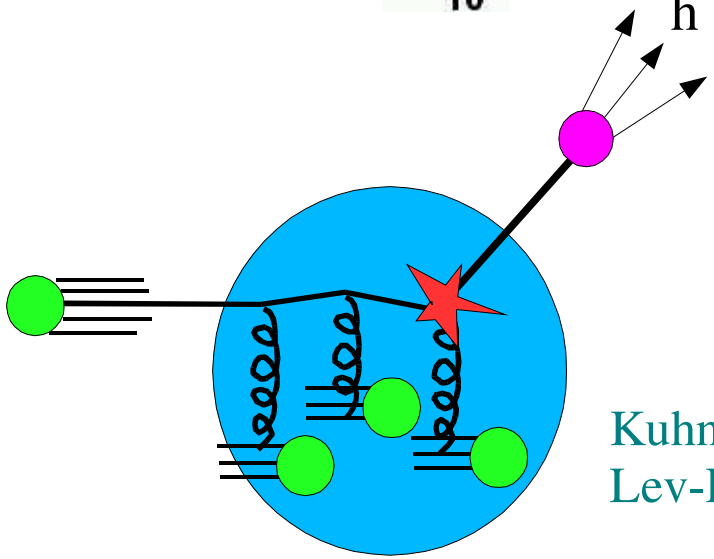



**Enhancement at moderate-pT**




**Suppression at low pT**

(same pattern at Fermilab)




Kuhn '76; Kryzwicky '79;
Lev-Petersson '83;

# Theoretical models for hA

**Glauber-Eikonal models**

**- hard partonic -**

Kuhn '76; Kryzwicky '79; Lev-Petersson '83;
Vitev, M.Gyulassy
A.A., M.Gyulassy

**Soft partonic rescatterings**

**- soft partonic -**

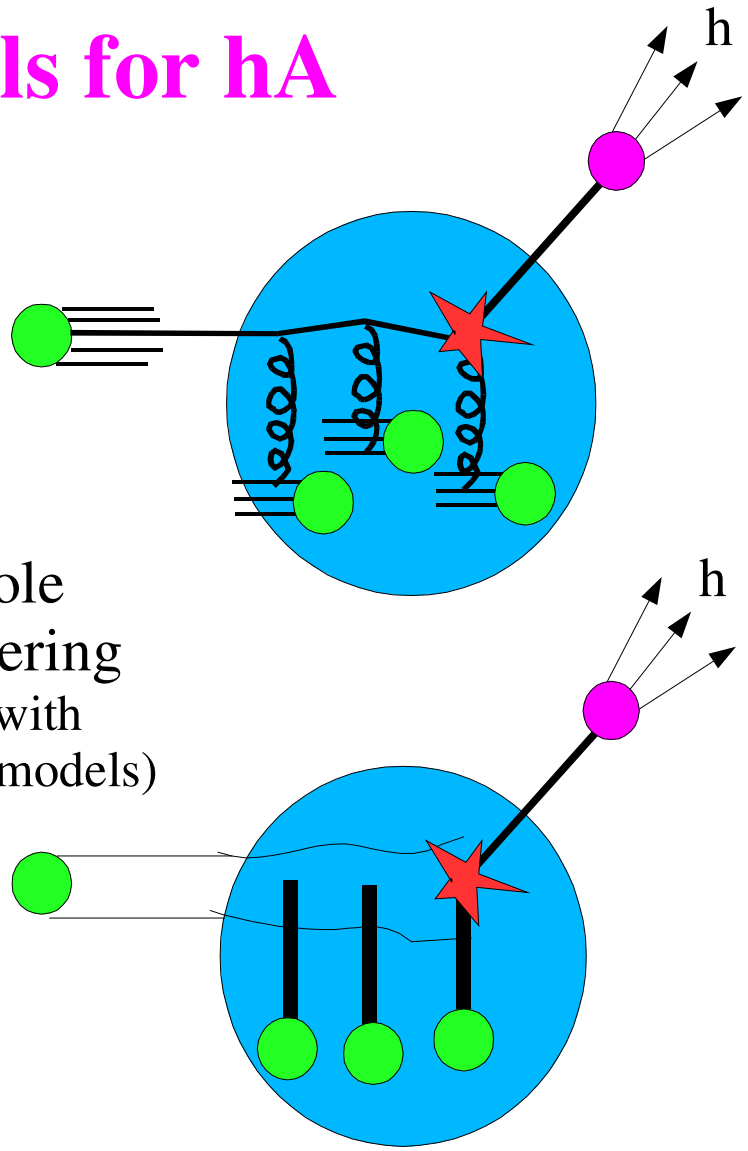
B. Kopeliovich et al.

colour dipole
multi scattering
(connection with
"saturation" models)

**Glauber-Eikonal Approximated**

**- hard partonic/hadronic -**

X.N. Wang et al.
P.Levai et al.
G.Fai, X.F.Zhang

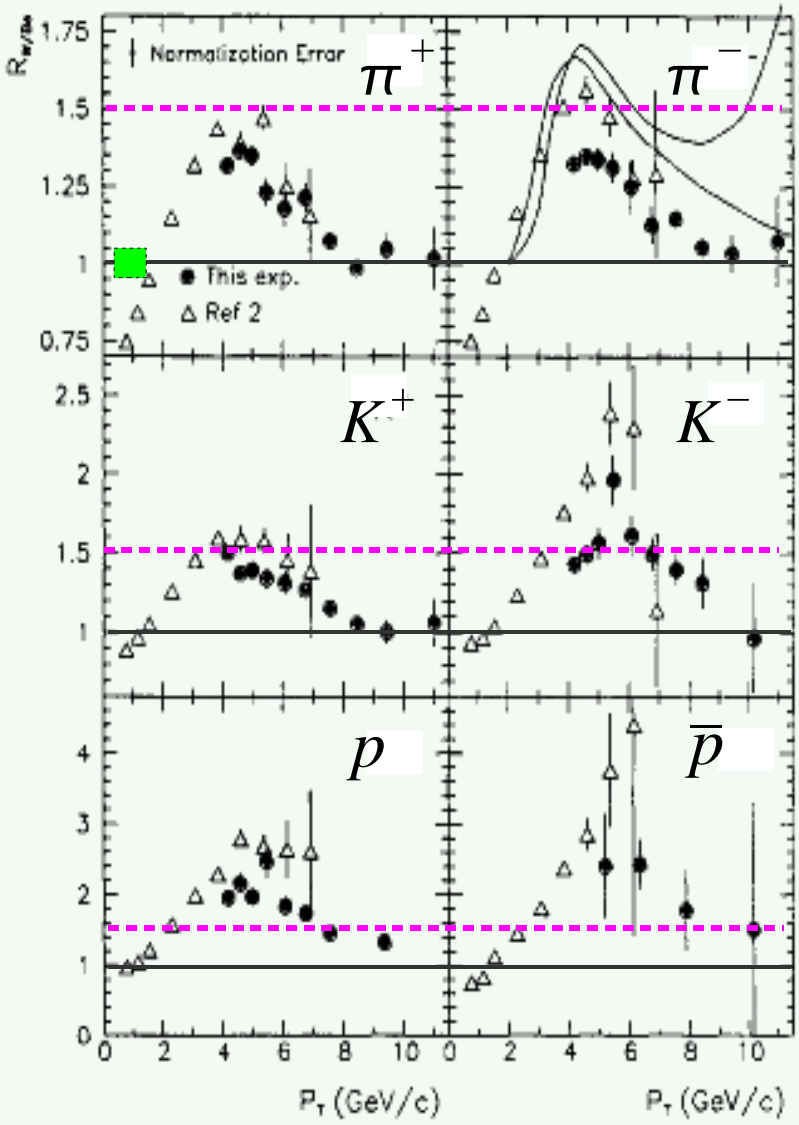



A.A. and M.Gyulassy, **nucl-th/0308029**
Review and refs.: **A.A. hep-ph/0212148**

# The pre-RHIC era: data and predictions for pA coll's

## Fermilab 27-39 GeV

Antreasyan et al. '79; Straub et al. '92

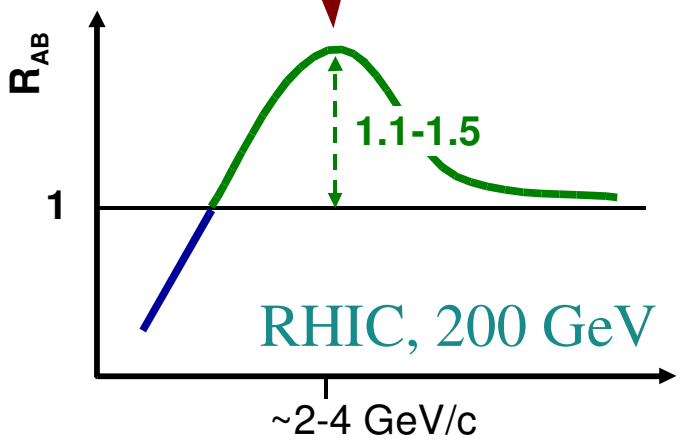



A.A., hep-ph/0212148

Table 3 – Cronin effect at $\eta$=0: comparison of theoretical models. $p_M$ is expressed in GeV.

| $\sqrt{s}$ | model | charged pions $p_M$ | charged pions $R_M$ | Ref. | partons $p_M$ | partons $R_M$ | Ref. |
|---|---|---|---|---|---|---|---|
| 27.4 GeV $pW/pBe$ data: Ref. [22] | Soft | 4.0 | 1.55* | [3] | | | |
| | Soft-saturated | 4.5*; 4.4$^\odot$ | 1.46*; 1.46$^\odot$ | [24] | 5.1*; 5.1$^\odot$ | 1.50*; 1.51$^\odot$ | [24] |
| | Color dipole | 4.5 | 1.43±0.08$^\otimes$ | [5] | | | |
| | Hard AT | | | | 6 ± 0.8$^\dagger$ | 1.1$^\flat$; 1.4$^\natural$ | |
| | Hard GV | 4 | 1.4 | [7] | | | |
| 200 GeV $pAu/pp$ | Soft | 3.5 | 1.35±0.2$^\sharp$ | [3] | | | |
| | Soft-saturated | 2.9*; 2.7$^\odot$ | 1.15*; 1.47$^\odot$ | [24] | 4.4*; 4.2$^\odot$ | 1.29*; 1.70$^\odot$ | [24] |
| | Color dipole | 2.7 | 1.1 | [5] | | | |
| | Hard AT | | | | 7±1$^\dagger$ | 1.25$^\flat$; 1.2$^\natural$ | |
| | Hard GV | 3.0 | 1.3 | [7] | | | |
| 5500 GeV $pPb/pp$ | Soft | 3.5 | 1.08±0.02$^\sharp$ | [25] | | | |
| | Soft-saturated | 2.4*; 2.2$^\odot$ | 0.78*; 1.36$^\odot$ | [24] | 4.2*; 4.2$^\odot$ | 0.91*; 1.60$^\odot$ | [24] |
| | Color dipole | 2.5 | 1.06 | [5] | | | |
| | Hard AT | | | | 11±1.3$^\dagger$ | 2.1$^\flat$; 1.2$^\natural$ | |
| | Hard GV | ≈ 40$^\diamond$ | 1.05$^\diamond$ | [7] | | | |

With HIJING shadowing [12]. $^\odot$ Without shadowing. $^\otimes$ Error estimated by varying dE/dz within error bars [23].
Central value with multiple scattering effects only; error estimated by using different shadowing parametrizations.
Numerical errors mainly. $^\flat$ Using $\mu = 1.5$ GeV. $^\natural$ Using $\mu = 0.060 + 0.283 \log(\sqrt{s})$, see text.
$^\diamond$ Completely dominated by EKS98 shadowing and anti-shadowing; result considered not reliable as yet, see text.



# Saturation models - a broad category

**MV model ("classical" YM)**

Kovchegov

Dumitru, Gelis, Jalilian-Marian

Jalilian-Marian, Nara, Venugopalan

**MV model plus BK nonlinear evolution**

Kovchegov, Tuchin

Albacete et al.

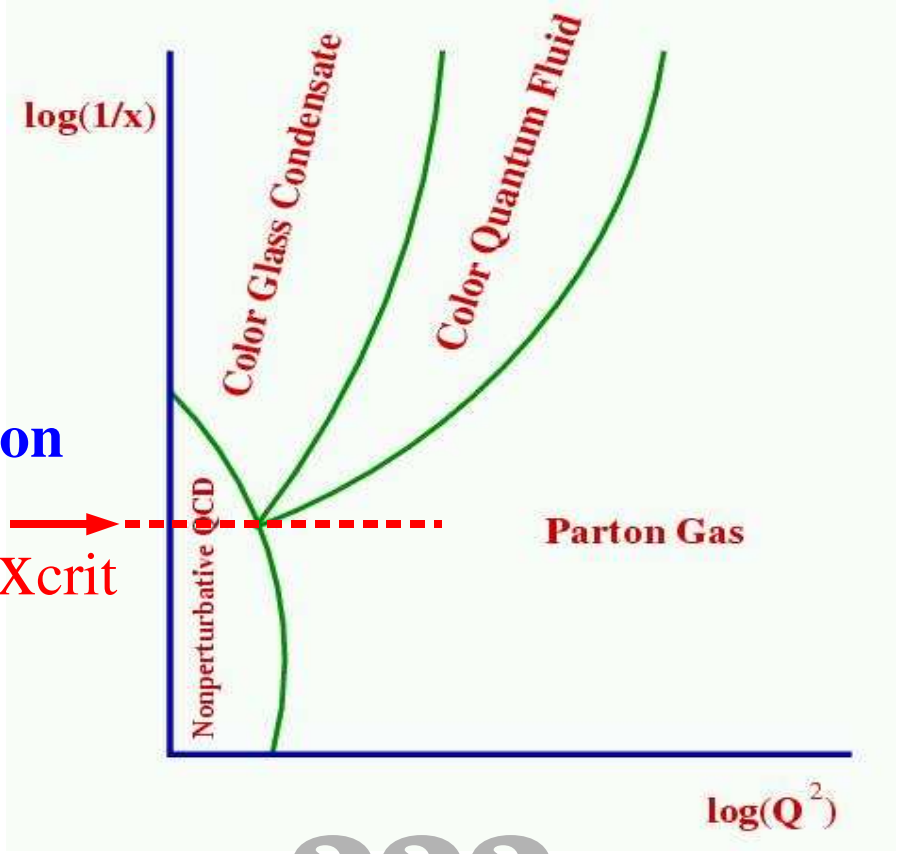
**CGC = MV + quantum evolution**

Iancu, Itakura, McLerran + ...

**CGC inspired models**

Kharzeev, Levin, McLerran

Kharzeev, Kovchegov, Tuchin




**??? QUESTIONS...**

**How small is xcrit?**

**Where does RHIC stand?**

# Part I

# Glauber-Eikonal models:
# pQCD + partonic rescatterings

# 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

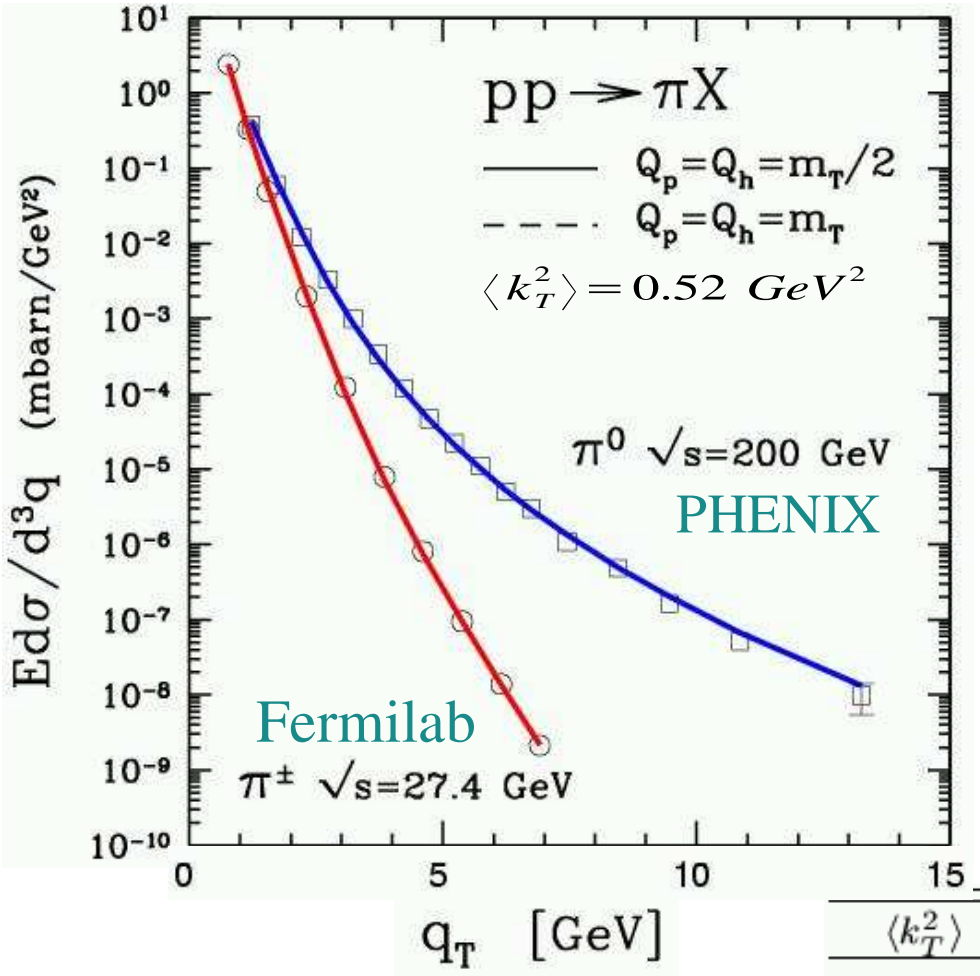
a) CHOOSE the scales: $\mathbf{Q_p = Q_h = m_T/2}$ (or $\mathbf{Q_p = Q_h = m_T}$)

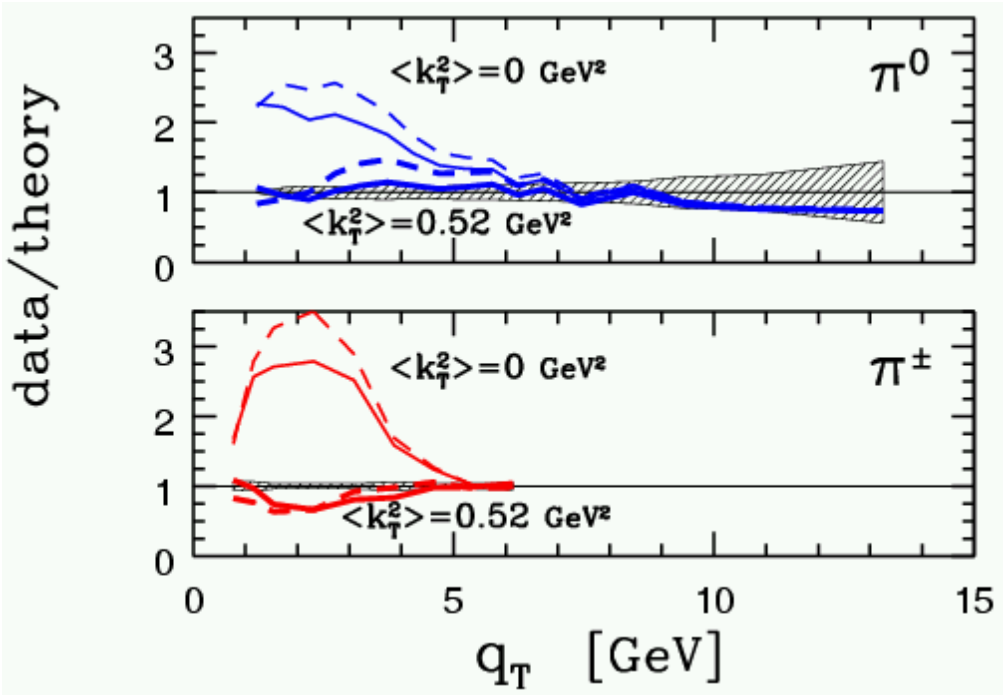
b) Intrinsic $\langle k_T^2 \rangle = 0.52$ GeV$^2$ from PHENIX and low-E *pp* data

c) FIT **K=K(s)** to the **high-pT** tail of the hadron spectrum
($\chi^2$ 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

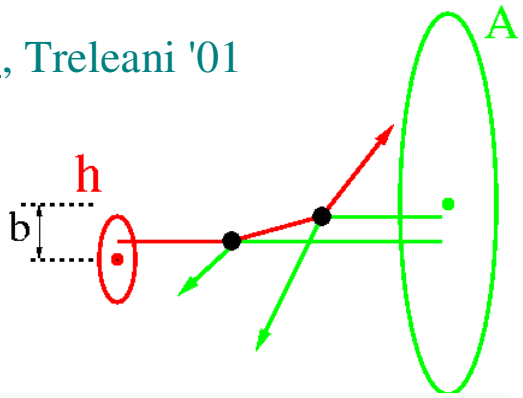
| $\langle k_T^2 \rangle$ | $Q_p = Q_h$ | $\sqrt{s} = 27.4$ GeV | $\sqrt{s} = 200$ GeV |
|---|---|---|---|
| 0.52 GeV$^2$ | $m_T/2$ | $p_0 = 0.70 \pm 0.1$ GeV<br>$K = 1.07 \pm 0.02$ | $p_0 = 1.0 \pm 0.1$ GeV<br>$K = 0.99 \pm 0.03$ |
| | $m_T$ | $p_0 = 0.85 \pm 0.1$ GeV<br>$K = 4.01 \pm 0.08$ | $p_0 =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

**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




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

n-fold parton rescattering

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)** $\frac{d\sigma^{h}_{pA}}{d^2p_T^h} \underset{p_T\to\infty}{\to} A\frac{d\sigma^{h}_{pp}}{d^2p_T^h}$
- **No extra free parameters**

# Geometric shadowing & Cronin effect

Integrated parton yield (dominated by low-$p_T$)

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

unitarity

opacity $\chi=\chi^i_A(b,\eta)$ (average no. of scatterings)

Two limits:

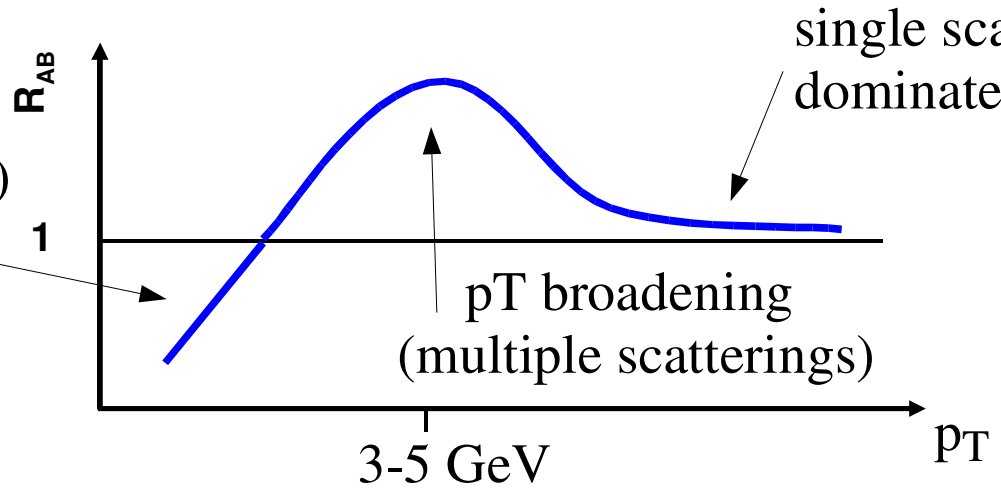
1) low-opacity $\chi \langle\langle 1 \Longrightarrow \frac{d\sigma^{iA}}{d^2b d\eta} \approx T_A\,\sigma^{iN}$ collision scaling (single semihard scattering)

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

Sum of 2 effects:

a) momentum conservation (spectrum shifted to higher $p_T$)

b) geometric shadowing




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

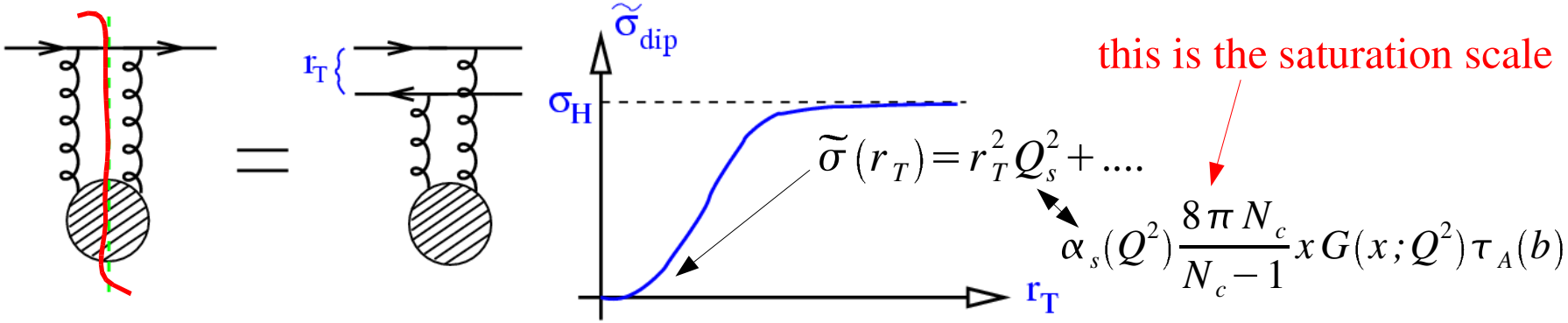
# Dipole representation: Glauber-Eikonal pQCD "is" saturation

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

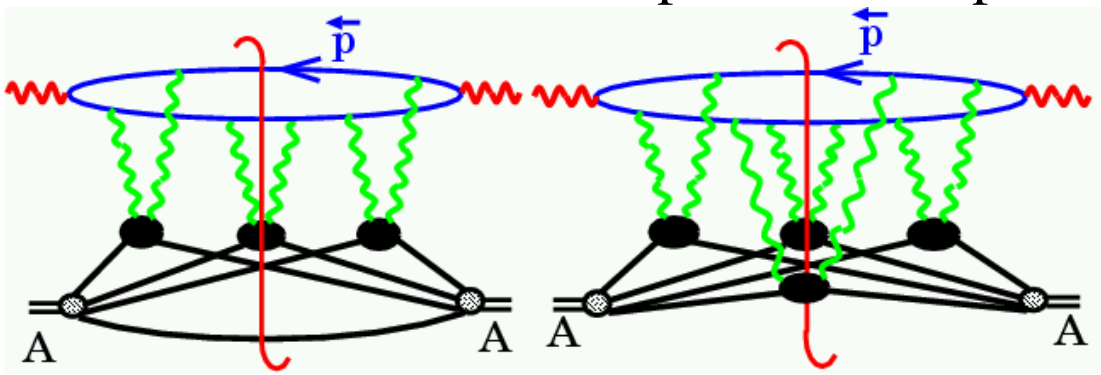



$$\tilde{\sigma}(r_T) = r_T^2 Q_s^2 + \ldots.$$

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...



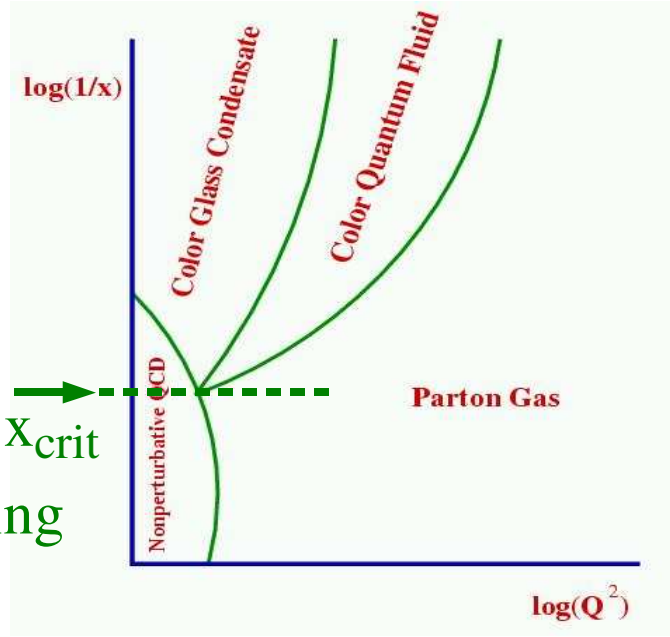
# Saturation vs. Glauber-Eikonal

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

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

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

- anomalus scaling as source of dynamical shadowing




## 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 (instead of BFKL as in CGC)
- includes "geometric shadowing" = unitarization of DGLAP nucleons
- does not include "dynamical shadowing"

**Baseline to measure dynamical shadowing and $x_{crit}$**

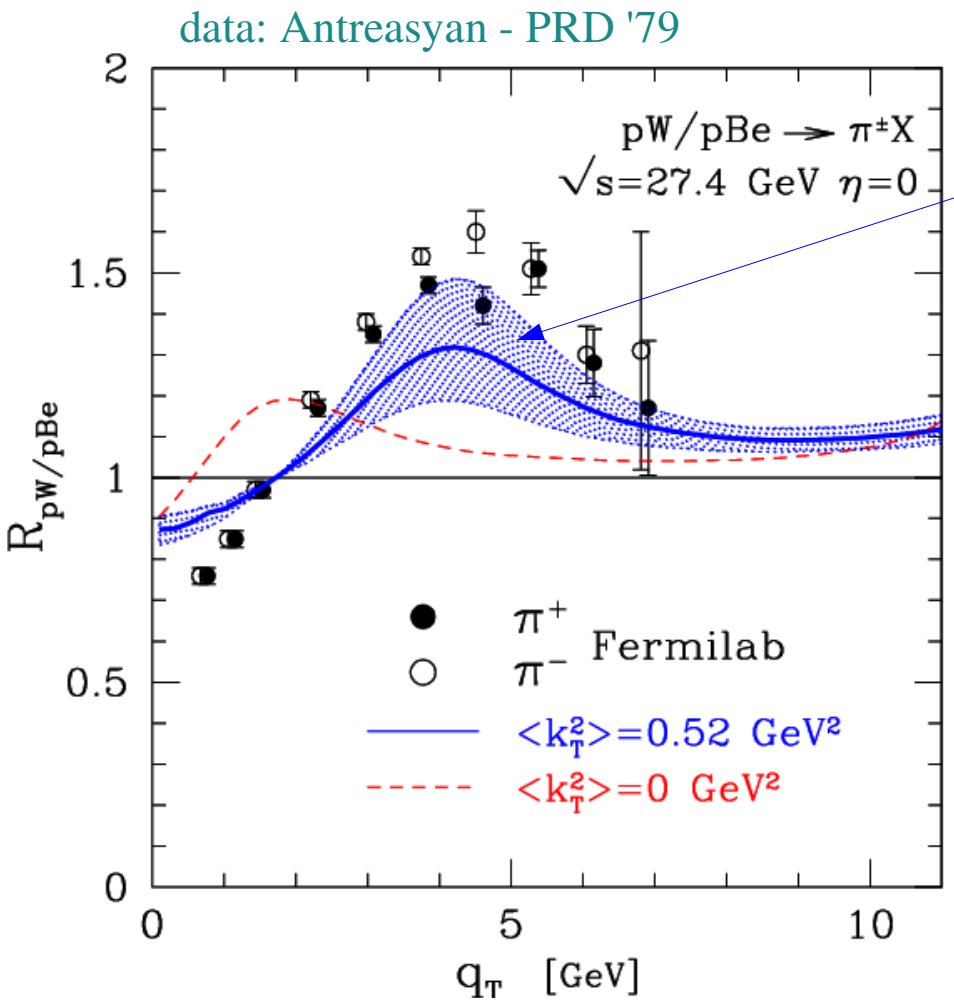
# Part II

# No CGC at RHIC $\eta$=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




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

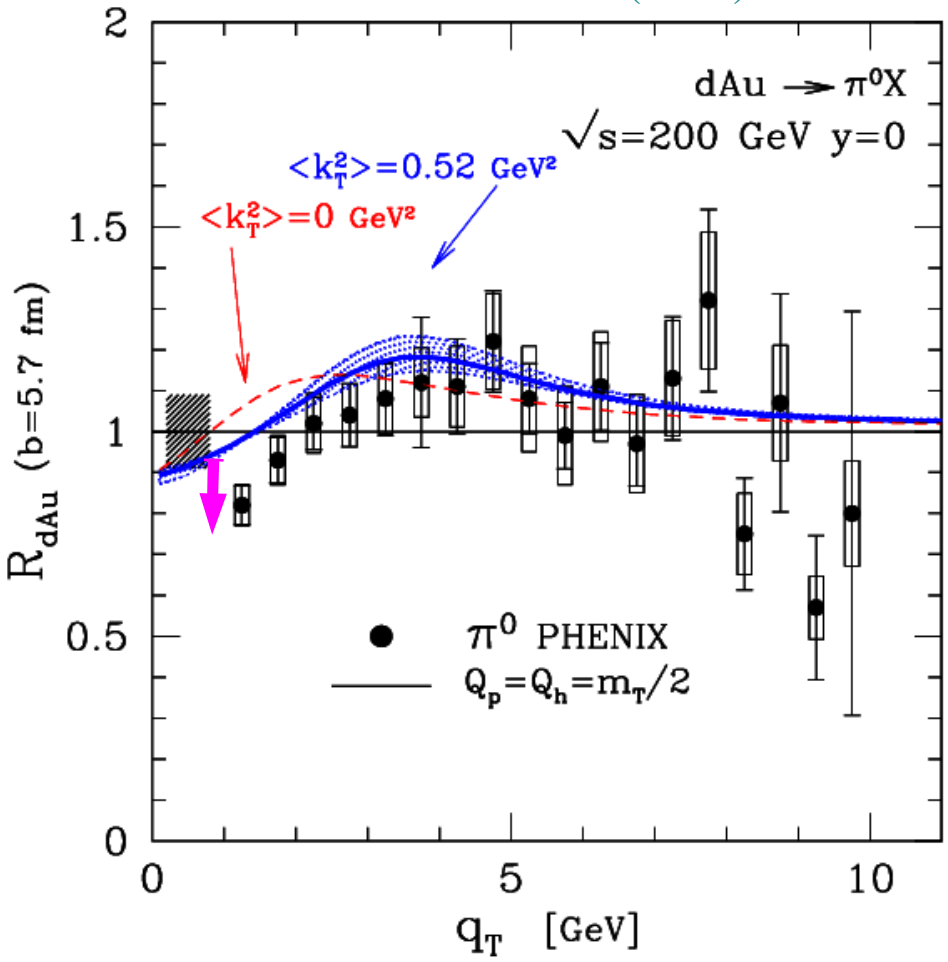
Q=mT/2 or Q=mT give similar results

**We reproduce the data well.**

At low-$p_T$, theory overestimates data

# Cronin effect on pions at PHENIX $\eta$=0

data: PHENIX - PRL 91(2003)072303




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

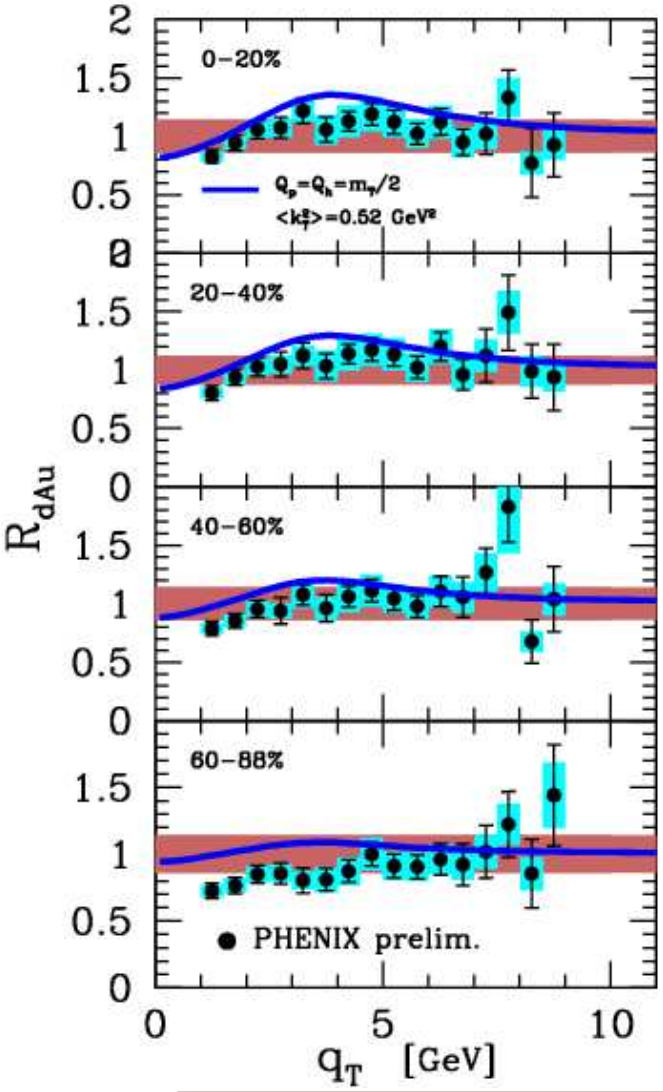
Computation compatible with data inside exper. and theor. errors

**Tends to overestimate data at low pT**

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

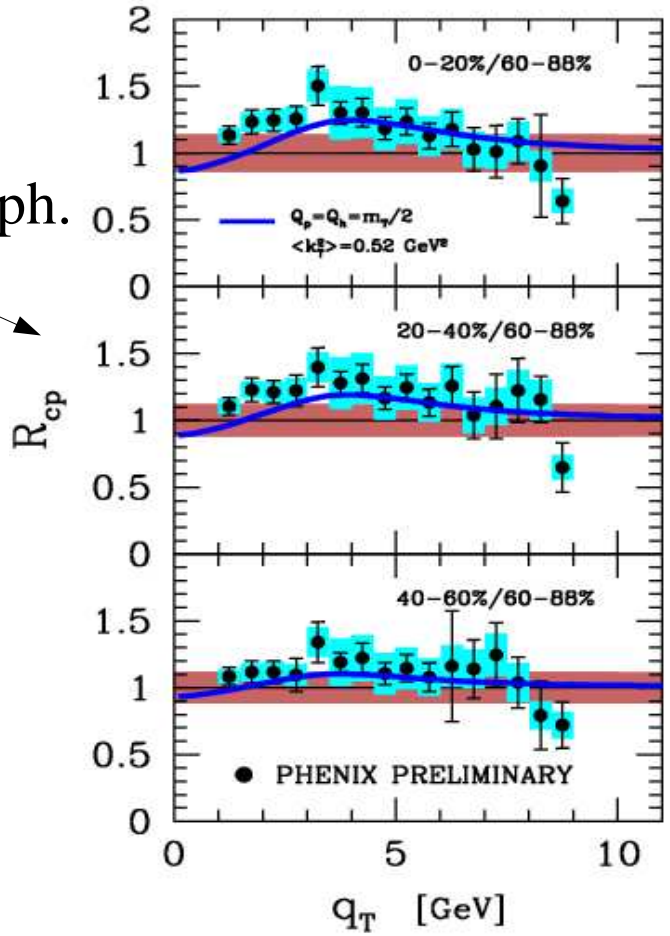
# Centrality dependence

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




d+Au/p+p

central/periph.



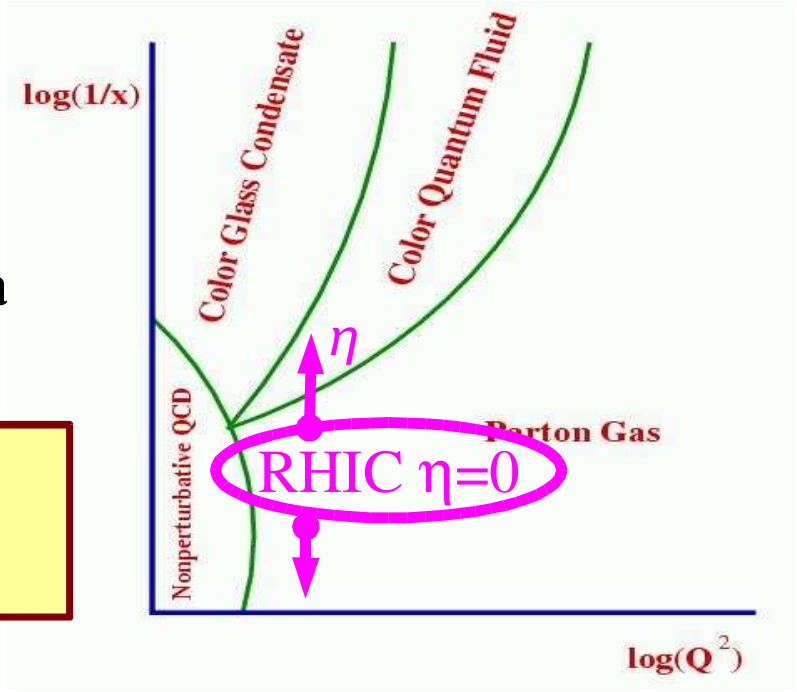

prelim. data: T.Awes, DNP Tucson Nov'03

**dAu $\cong$ 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**



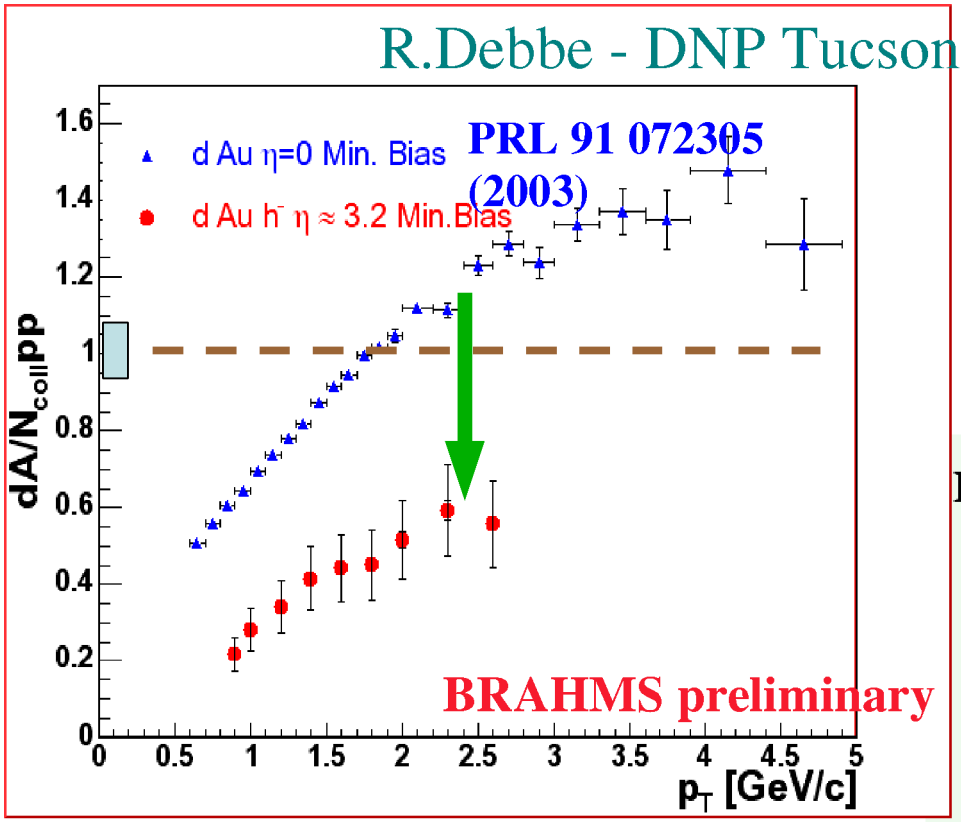

**There is no CGC at RHIC η=0**

**what about η=3?**

# Part III

# Forward $\eta$:
# Colorful dynamics or boring blackness?

# What about η = 3.2 ?



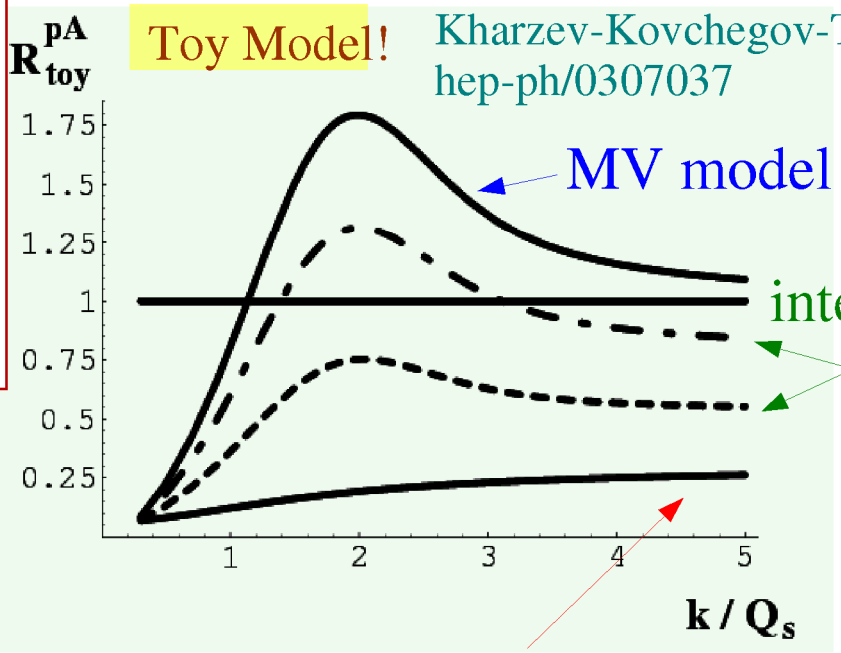

**"Suppression" of $\eta$=3 spectrum:**

1) Colorful dynamics ??? KKT'03

DGLAP → BFKL+ sat. bound. cond's

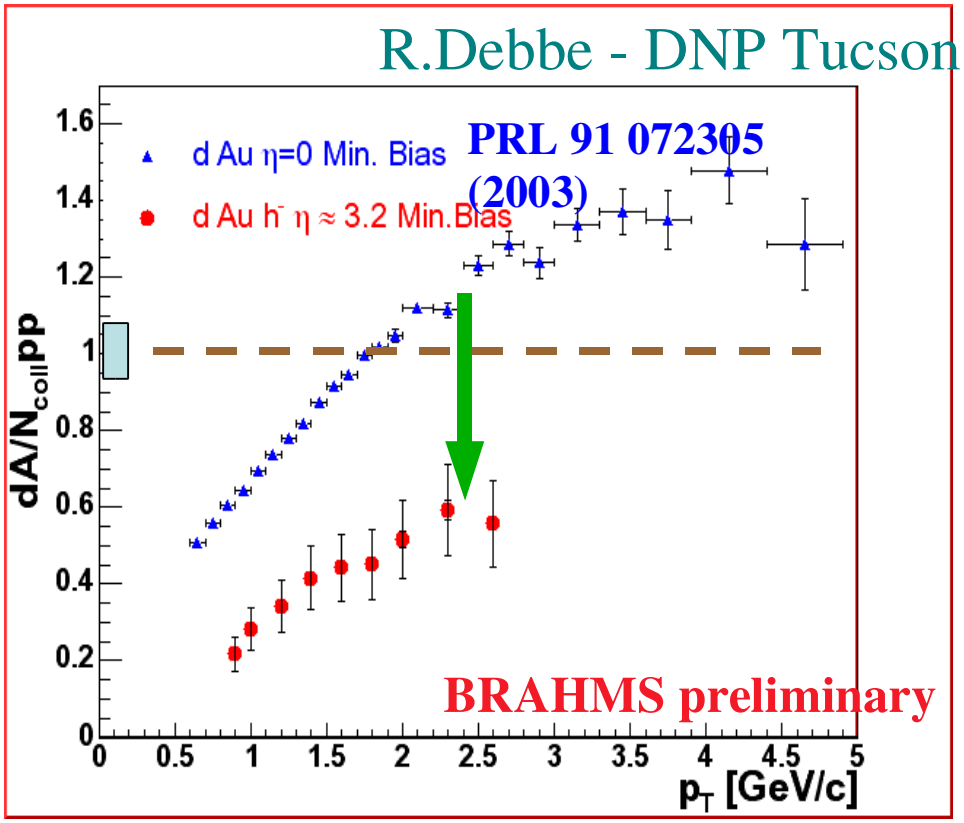
= anomalous scaling

"=" CGC




MV + BK + anomalous scaling

# What about η = 3.2 ?




**"Suppression" of $\eta$=3 spectrum:**

1) Colorful dynamics ???

DGLAP → BFKL+ sat. bound. cond's

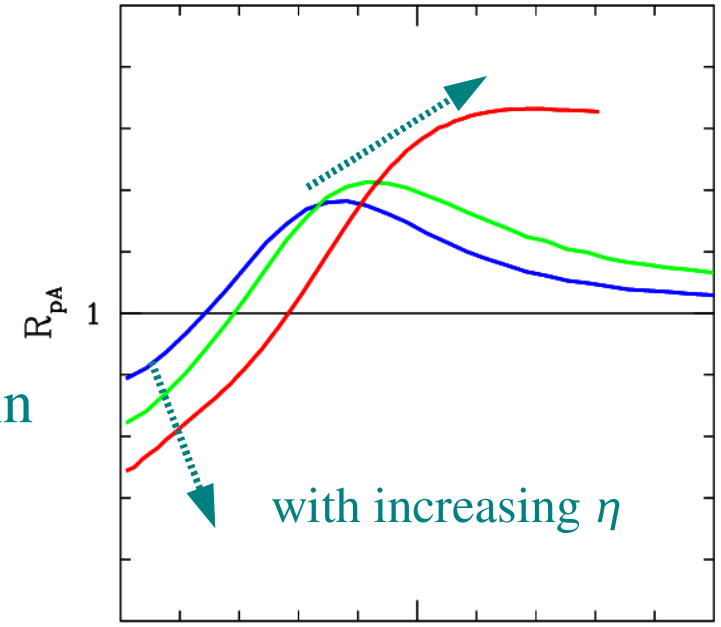
= anomalous scaling

"=" CGC

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

DGLAP + black nucleus + unitarity

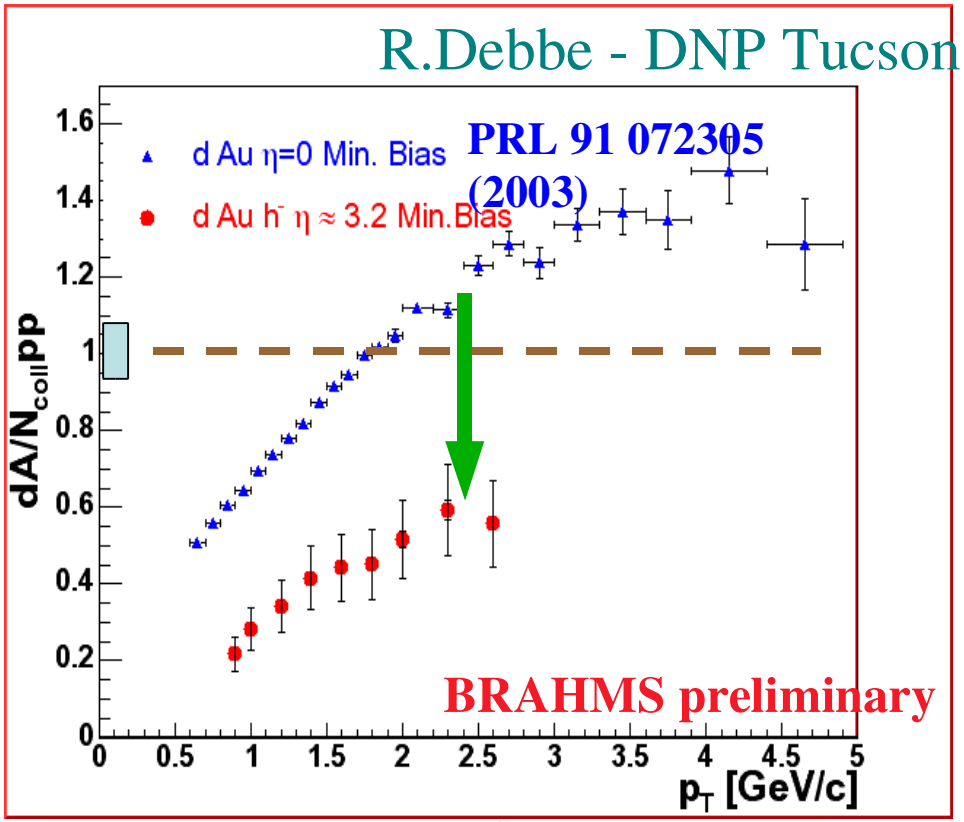
= strong geom.shadowing




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

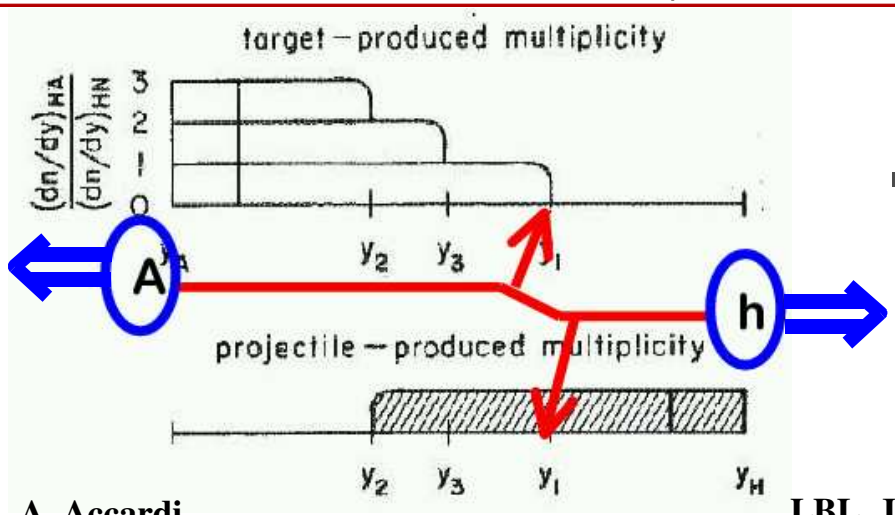
(Dumitru-Gelis-JalilianMarian)

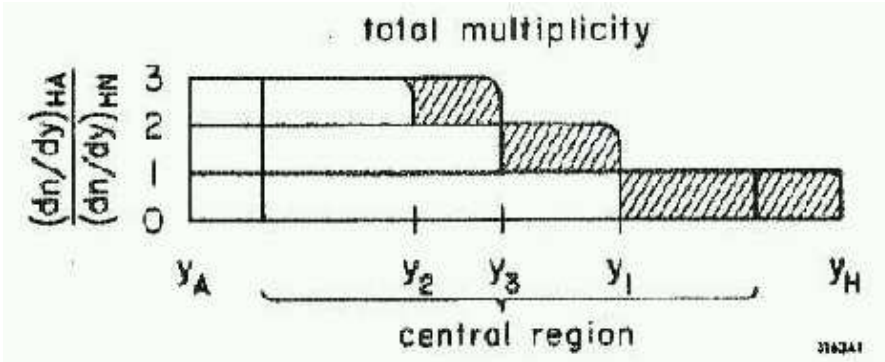
# What about η = 3.2 ?




**"Suppression" of $\eta$=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 $\eta$=0:**

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

| $\eta$ | 0 | 1.8 | 3.2 |
|---|---|---|---|
| $\chi$ | 0.74 | 0.85 | 0.95 |

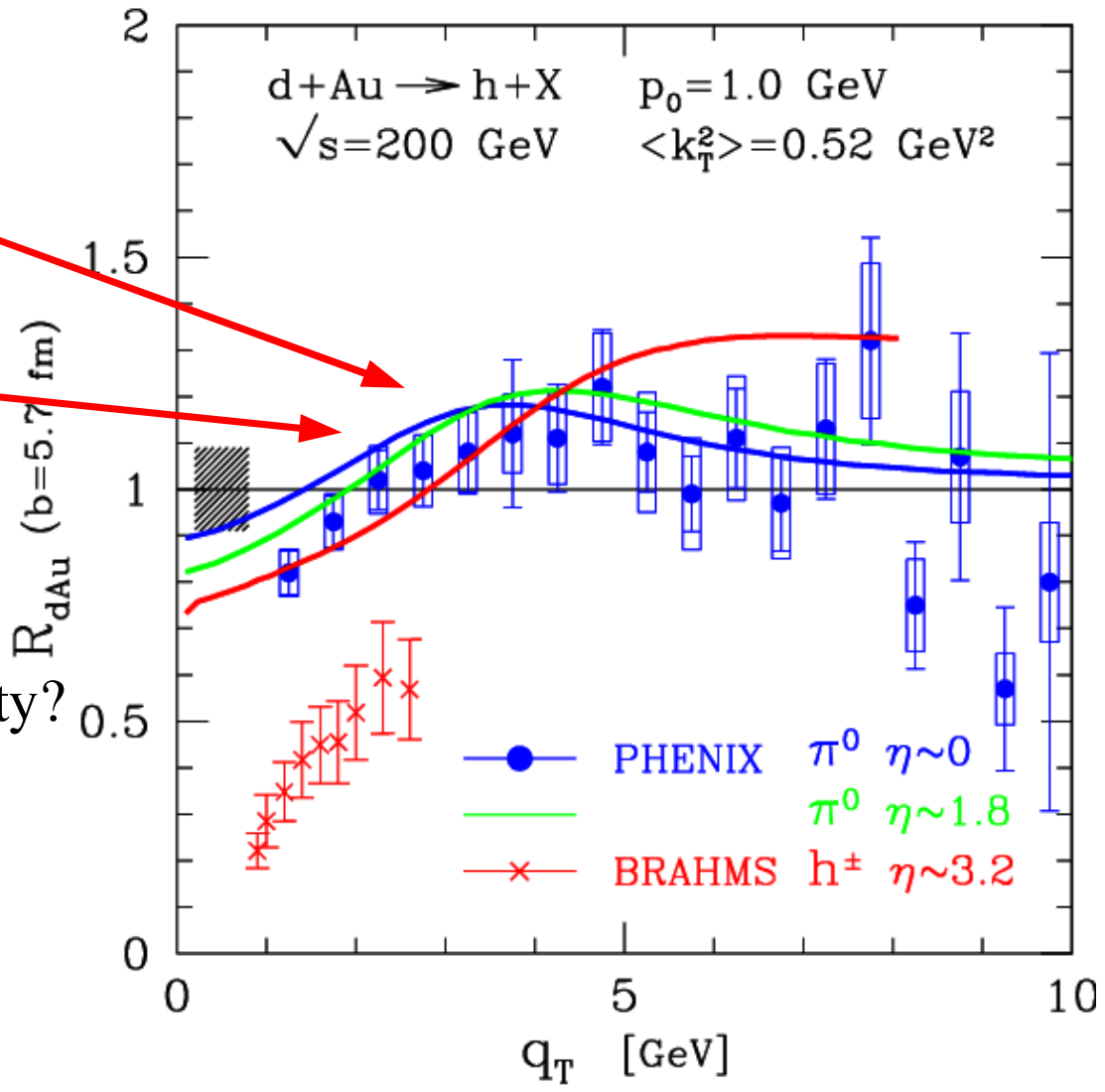
Data are much lower than theory:

Is this a CGC ????

...or are we underestimating opacity?

**$p_0$ and K may change with $\eta$:**

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



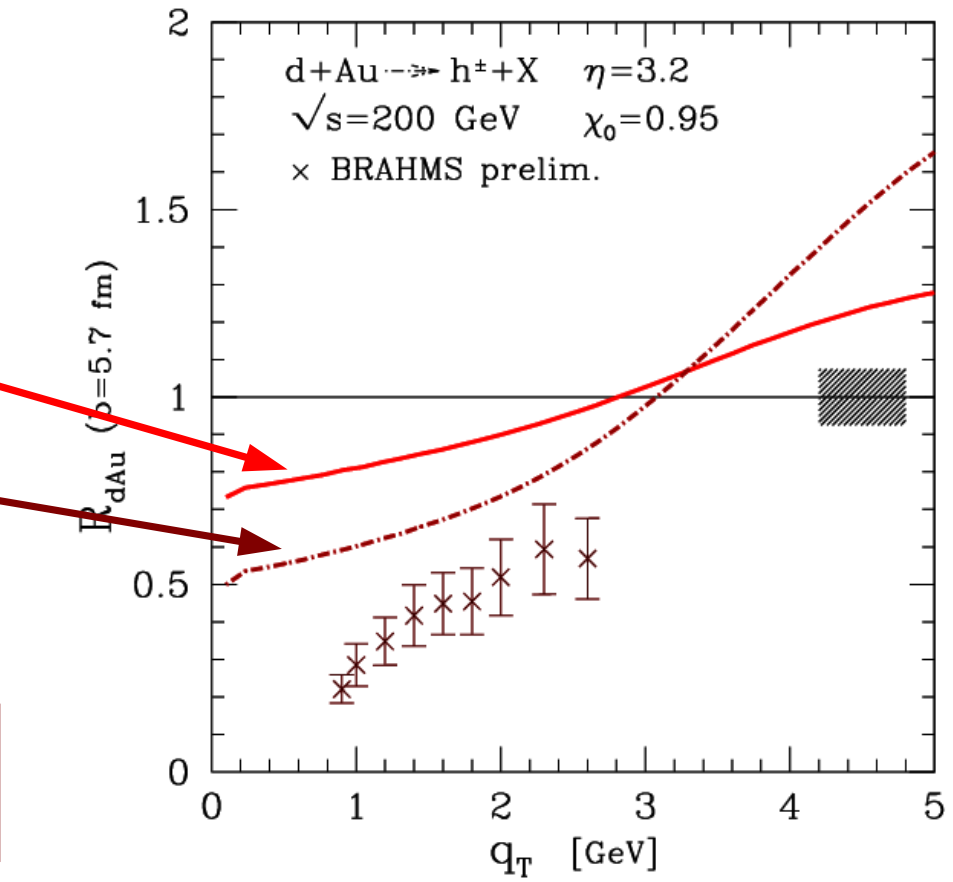
Using $p_0$ and K fitted in pp at $\eta$=0, we have $\chi_0$=0.95 at $\eta$=3.2.
This may be underestimated, though, and must be checked in $p_T$-spectrum in pp collisions at $\eta$=3.2

But even with $\chi=3\chi_0$, data lie below the computation:

There seems to be some dynamical shadowing!

...or non perturbative effects?

data at higher pT are needed to assess and measure dynamical shadowing



# 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**

# Part IV

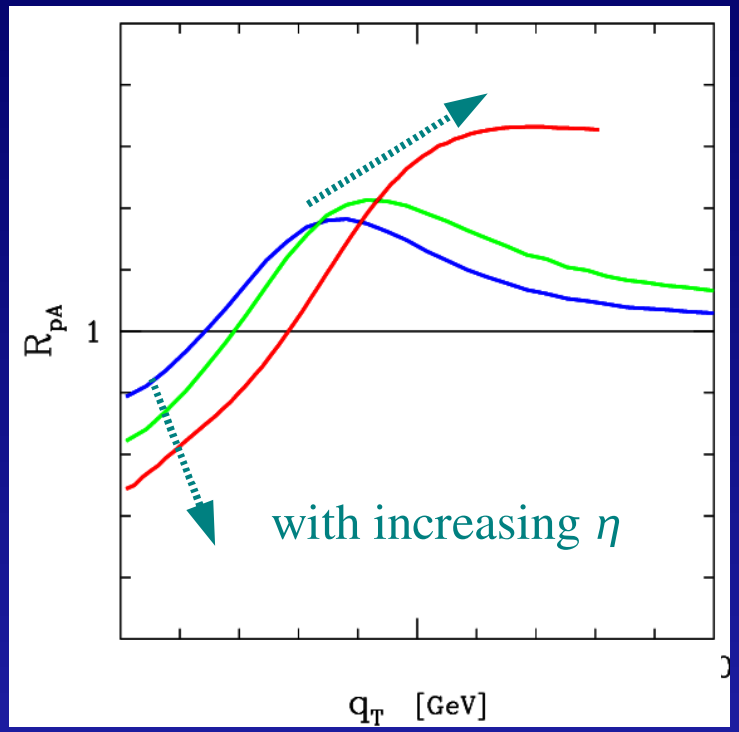
# Many new data from QM2004!
## - some quick remarks -

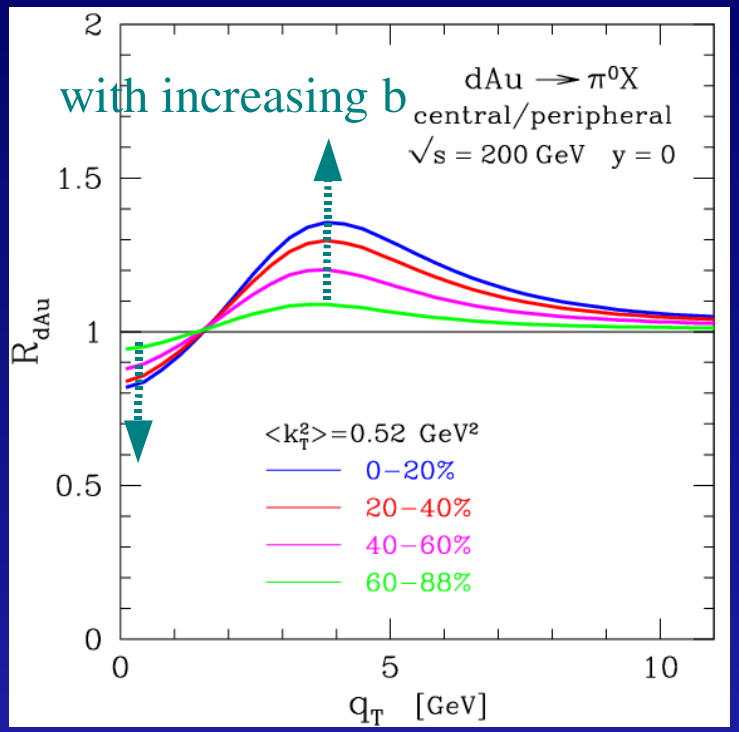
- **How to quantify the strength of Cronin effect?**
  - The "Cronin peak"
  - Attention: $\pi$'s are not $h^{\pm}$

- **Centrality and rapidity dependence**

- **Flavour dependence**

# How to quantify the strength of Cronin effect?



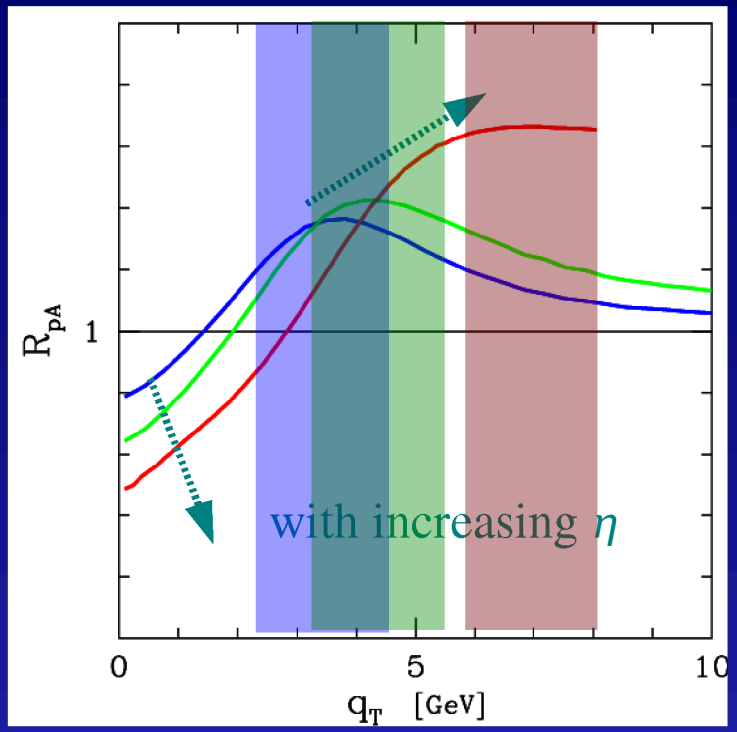

Two regions in pT in GE models:

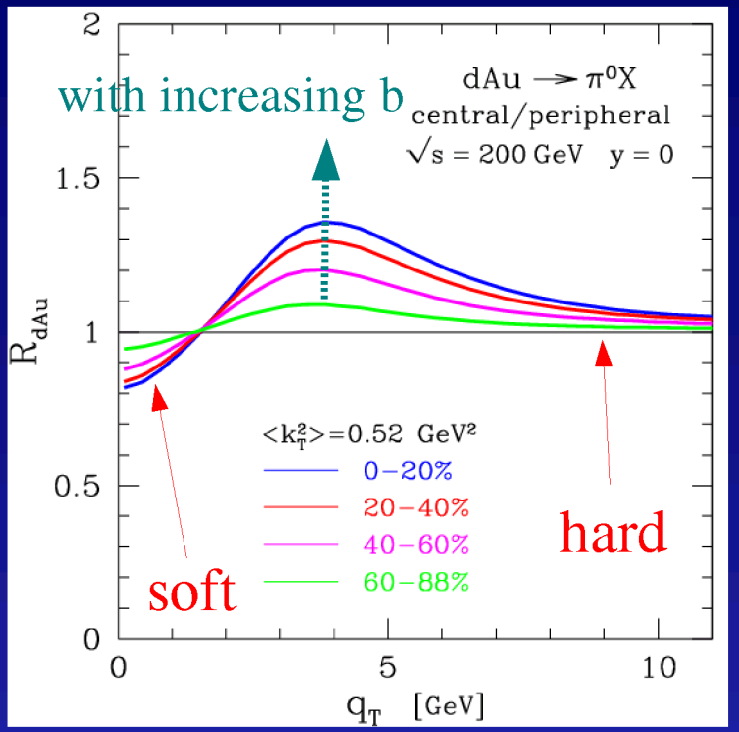
a) Low-pT $\Rightarrow R_{dAu}$ <u>decreases</u> with η and b

b) High-pT $\Rightarrow R_{dAu}$ <u>increases</u> with η and b

To use conventional wisdom, we need to consider pT values to the right of the "crossing point" from below to above 1

# How to quantify the strength of Cronin effect?




Two ways:

1) Fix pT and plot $R_{dAu}$ vs. the interesting variable

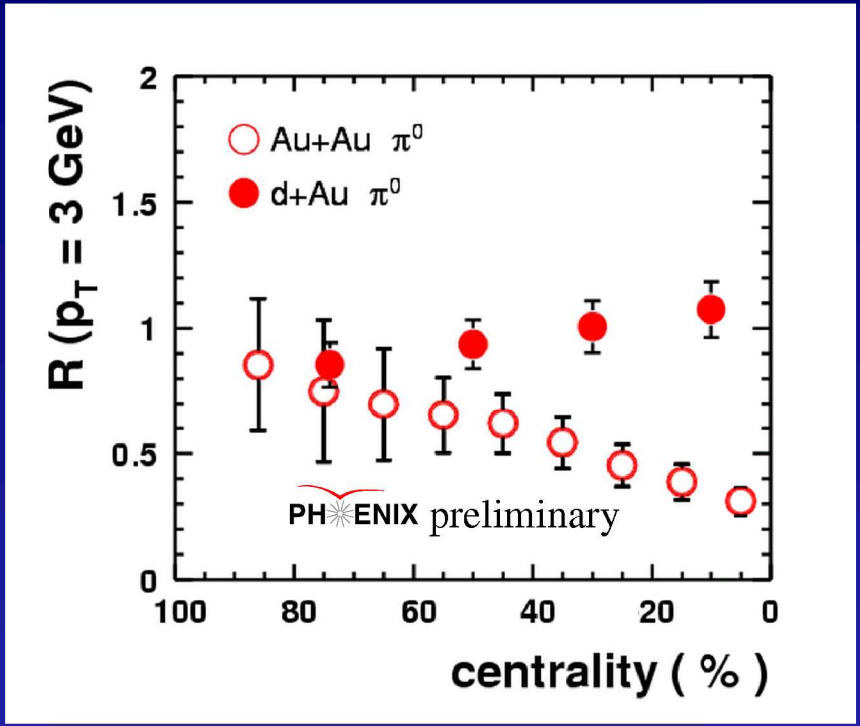
   ⇒ Good only for b-dependence - needs $p_T$ large enough

   (Cronin peak and crossing point are fixed in pT)

2) Integrate "<u>below the Cronin peak</u>" at each η

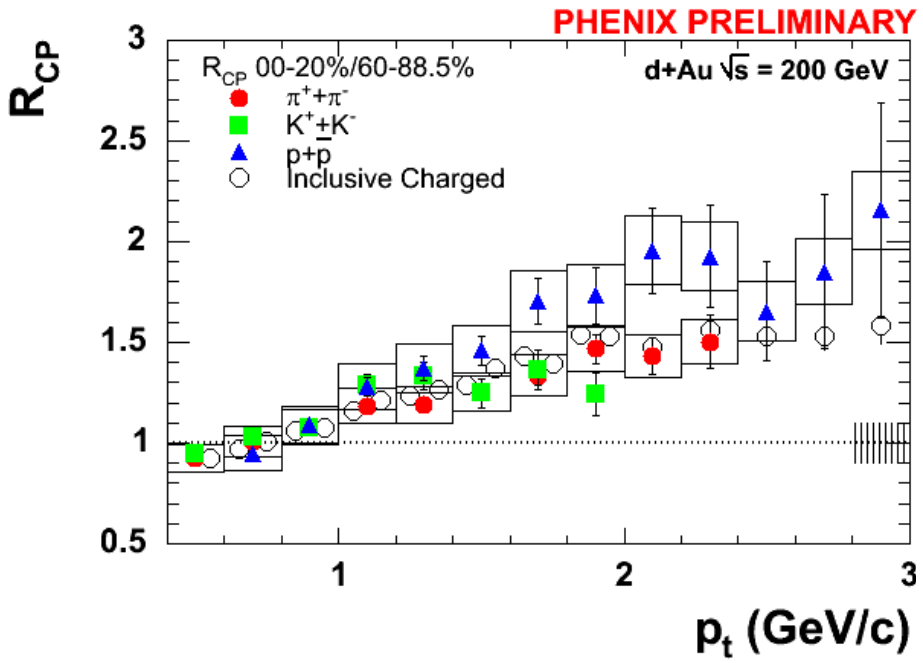
   Plot the integrated $R_{dAu}$ vs. η

# Example: centrality dependence at η=0



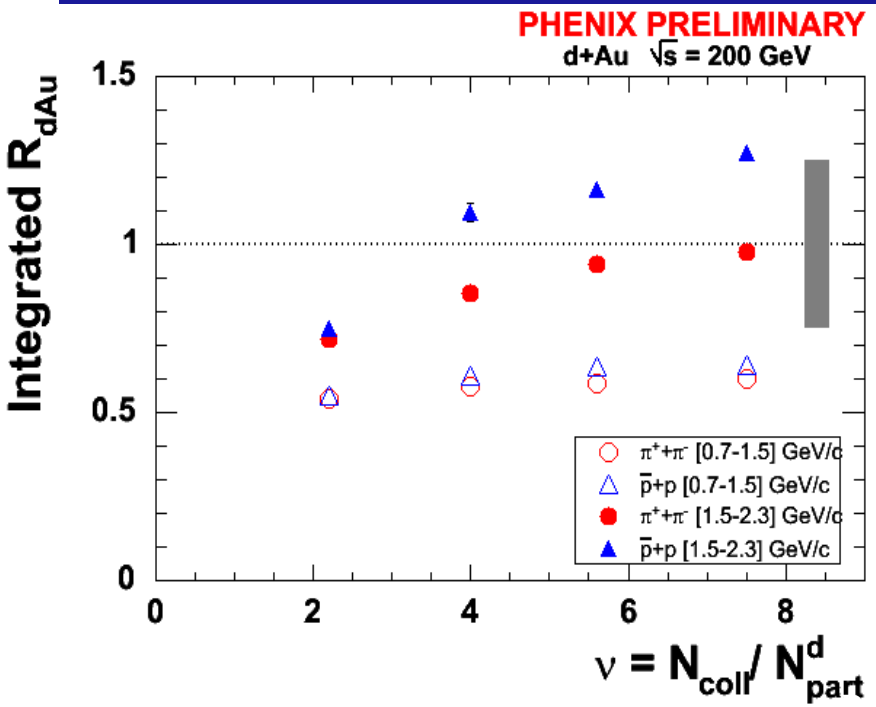

- The choice of fixed pT=3 GeV is correct: it is to the right of the crossing point, and the Cronin peak doesn't change position with b.
- Maybe pT=4 GeV is better as it is closer to the peak position

# Example 2, remaining at η=0




Cronin effect at η=0 increases with b...

The integrated Cronin "peak" has slightly higher rate for p than for p than for π



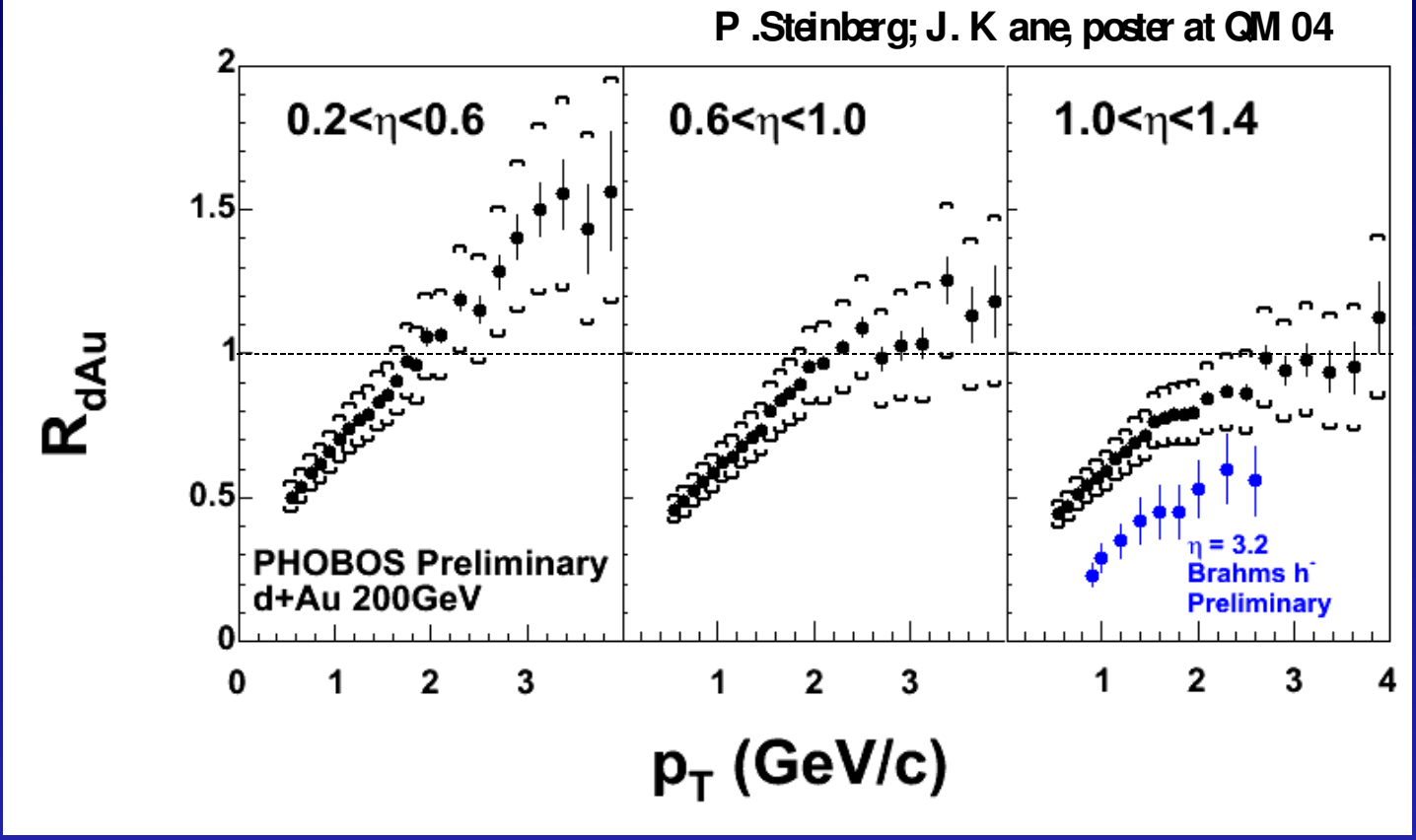

but it's better to integrate "below the peak":

$1.5 < pT < 4.5$ GeV

(maximal sensitivity to multiscattering)

**Let's have a closer look at $\eta>0$...**

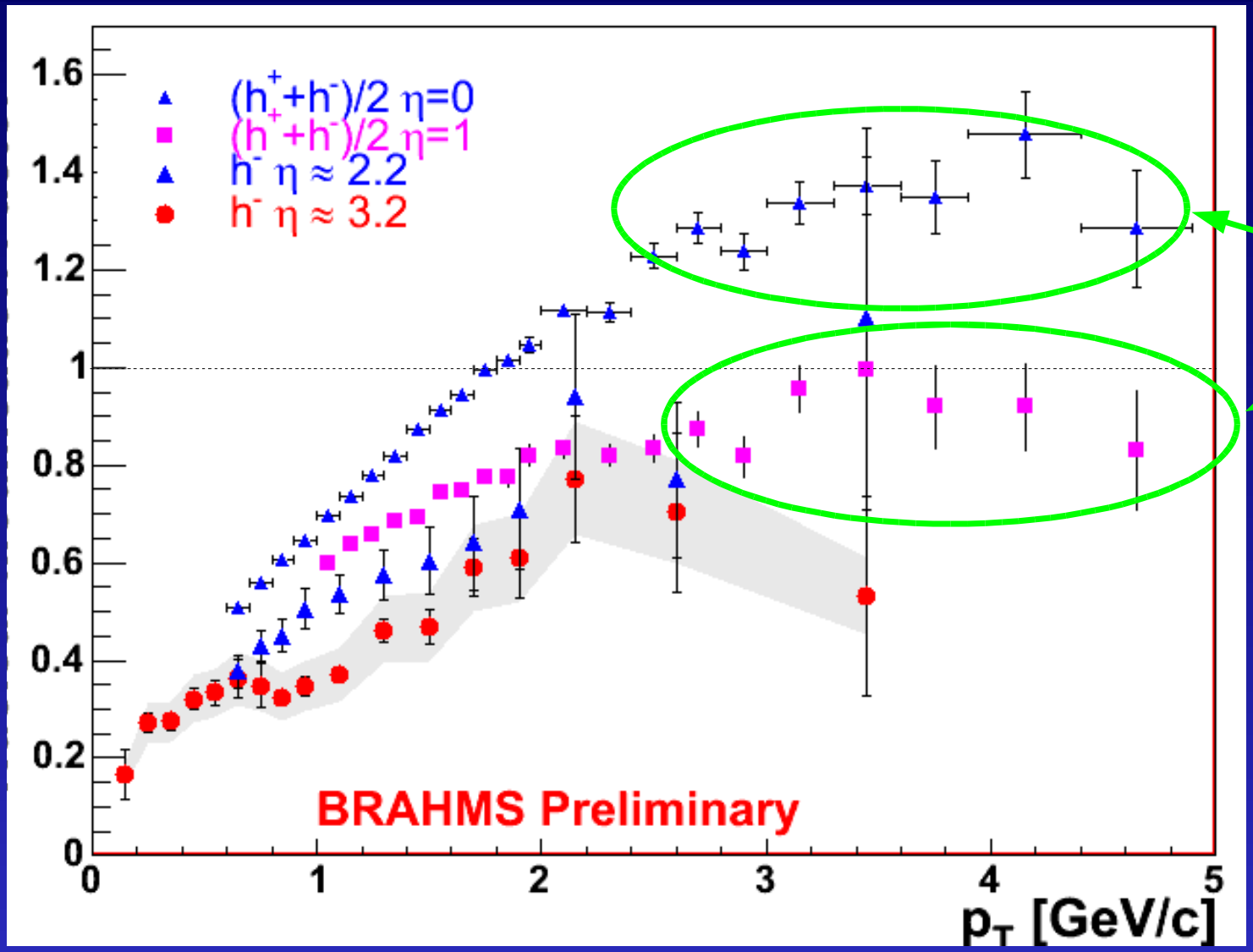
# Phobos d+Au for η>0



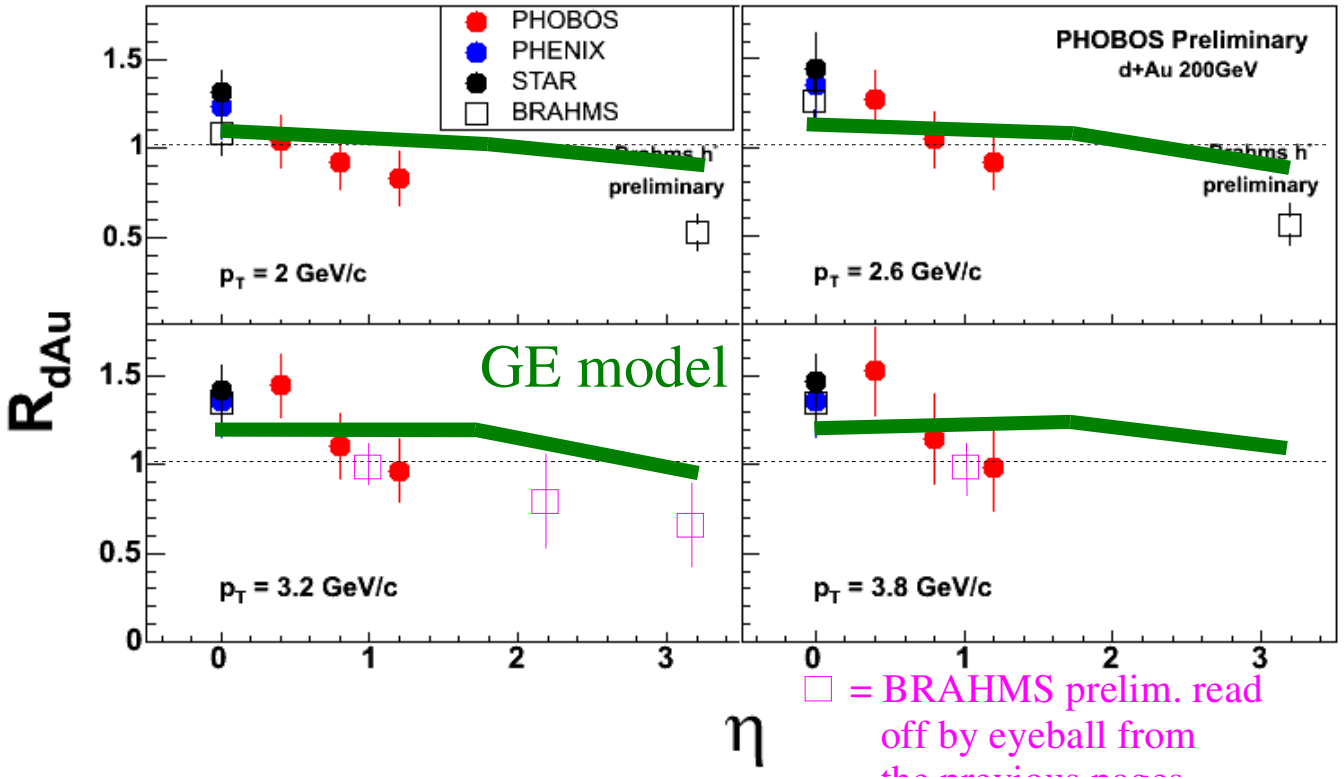

- Systematic decrease in $R_{d+Au}$ with increasing η
- pT may not be high enough to see the Cronin peak

# Brahms' d+Au for η>0

R.Debbe QM04



# η-Dependence of $R_{dAu}$ - summary




soft

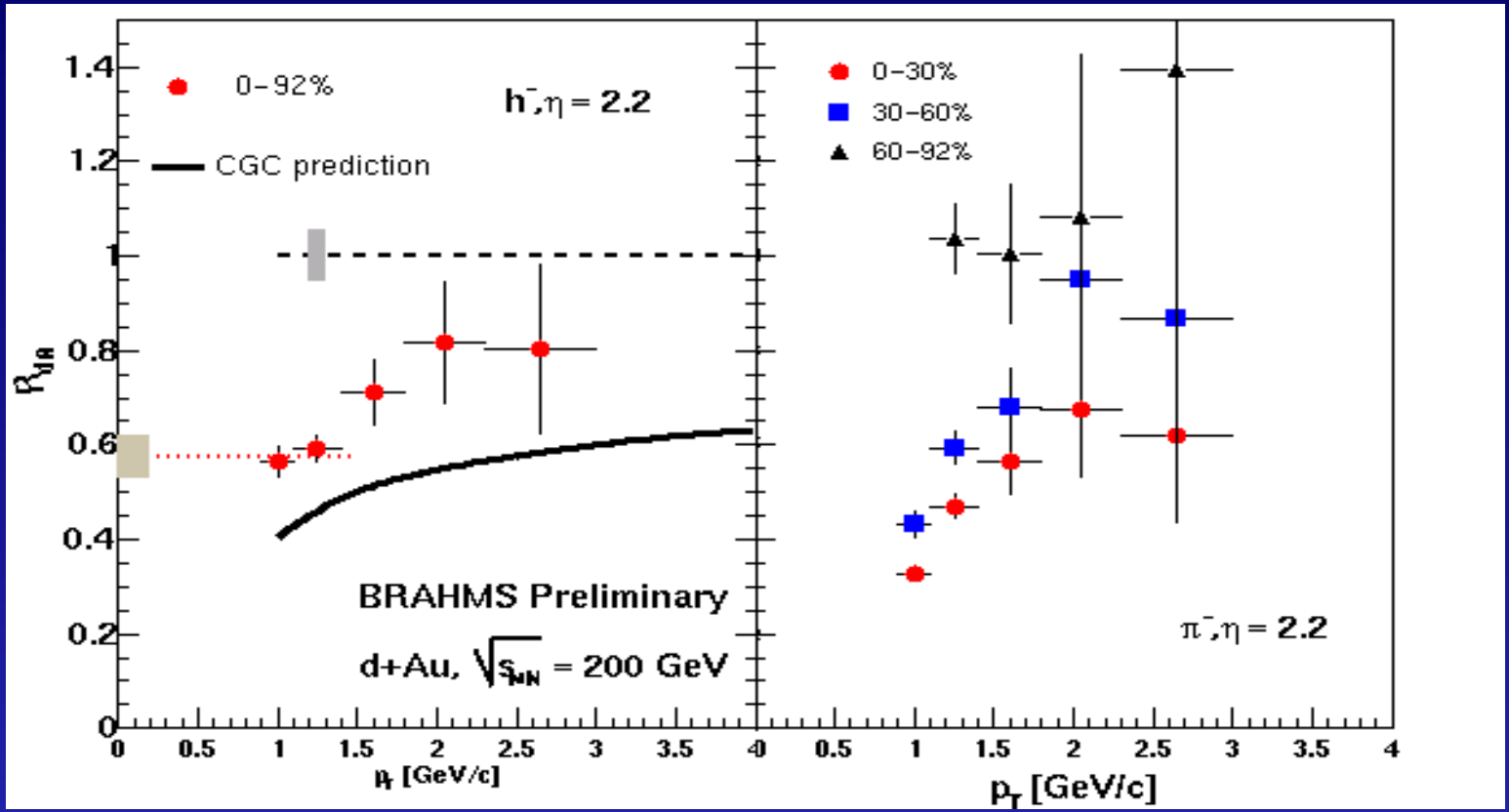
hardish

**Monotonic evolution from mid-rapidity to forward rapidities.**
**BRAHMS data is a continuation of trends starting at η=0**

**But it uses a fixed pT:**
**might be misleading for the interpretation of exp. results**

**e.g., also GE model tends to decrease at fixed pT<4 GeV**

# Let's change centrality at fixed η=2.2

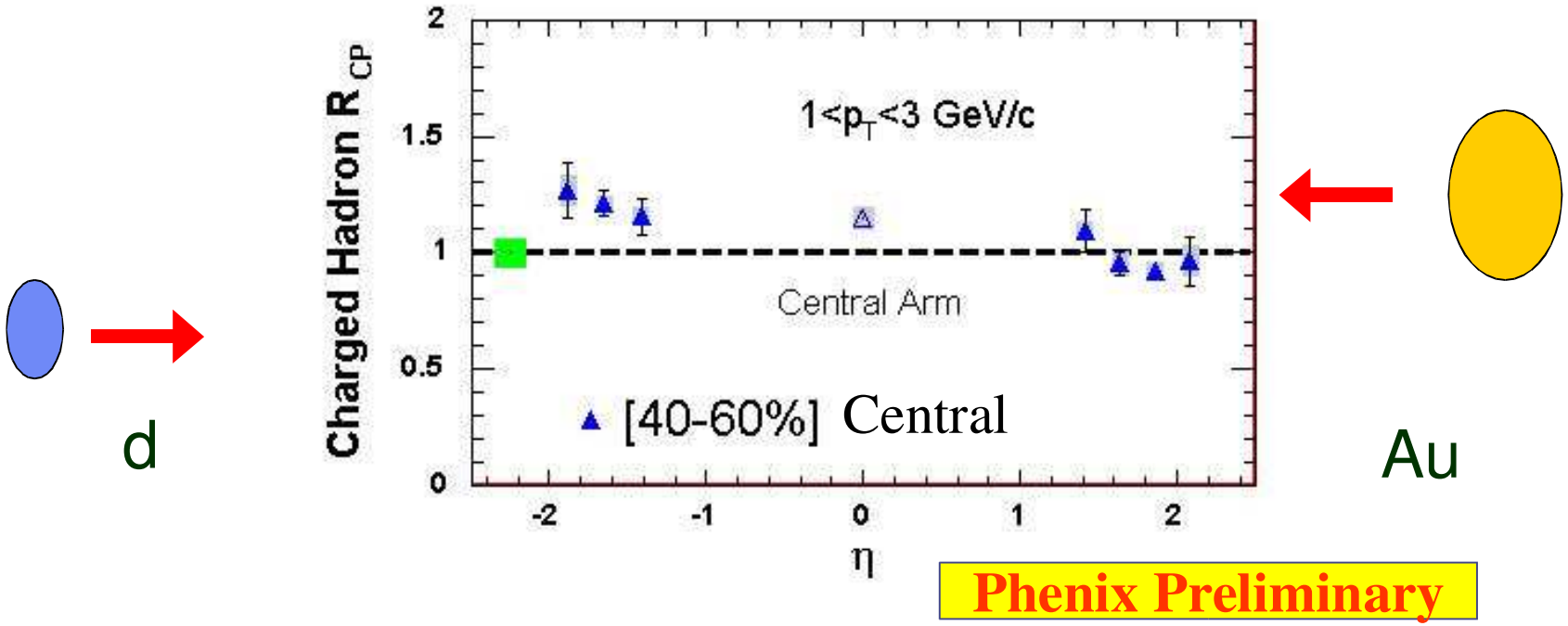



Cronin ratio decreases with centrality,
but at low pT this is true also in GE models!

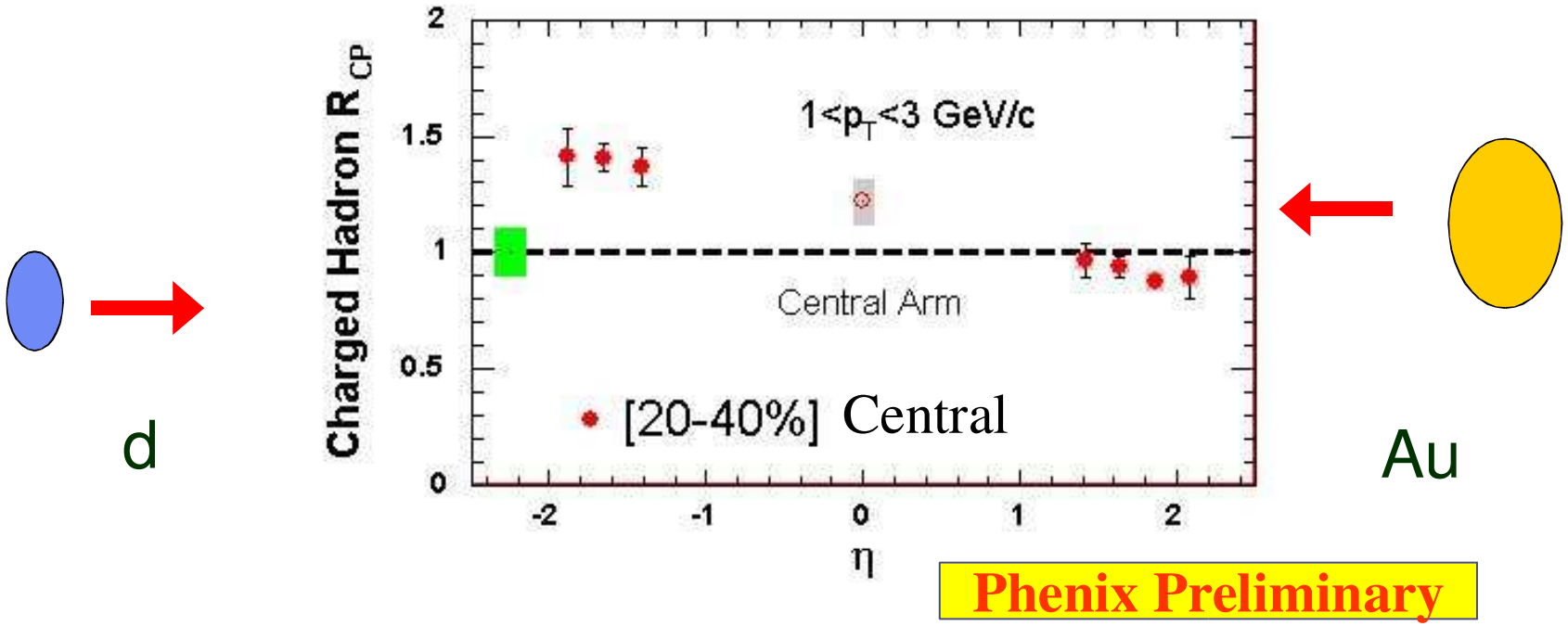
**We need higher pT,possibly "below the Cronin peak".**

# And what about the Au side $\eta<0$?

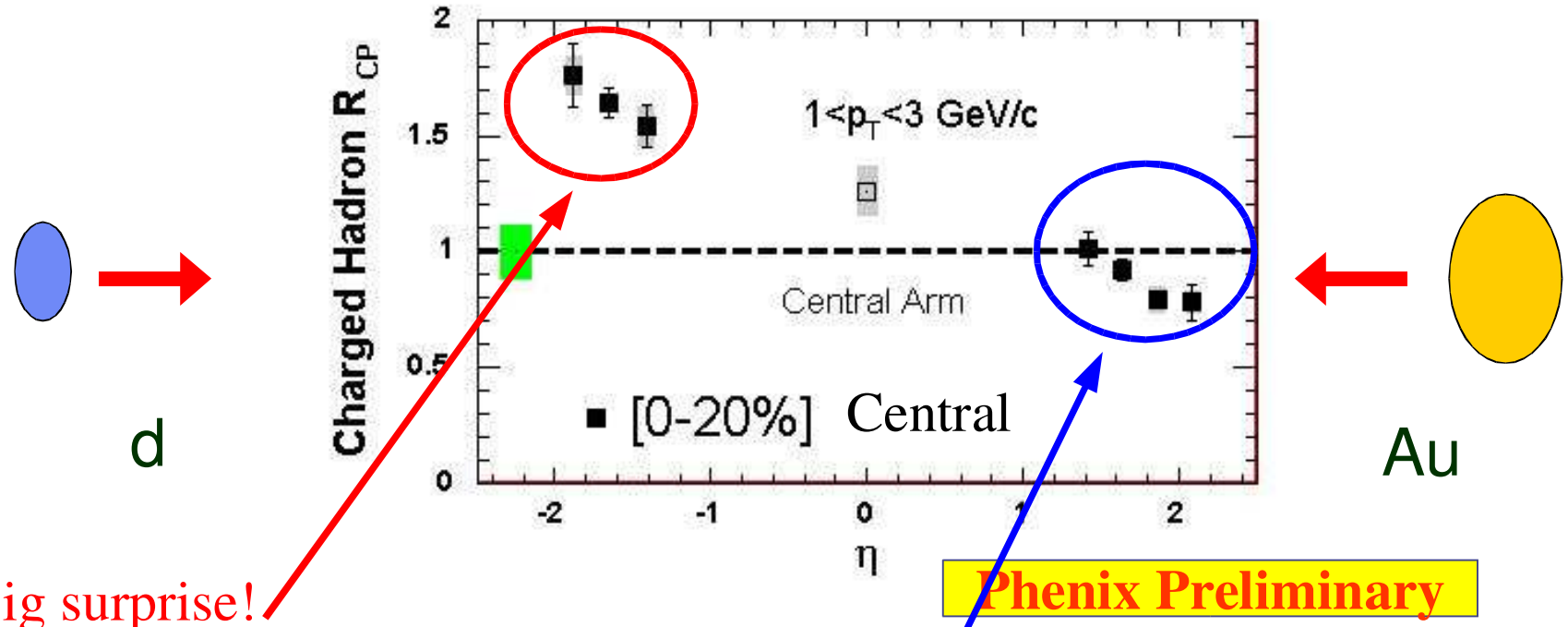
# 200 Gev d+Au unidentified hadron Rcp



# 200 Gev d+Au unidentified hadron Rcp



# 200 Gev d+Au unidentified hadron Rcp

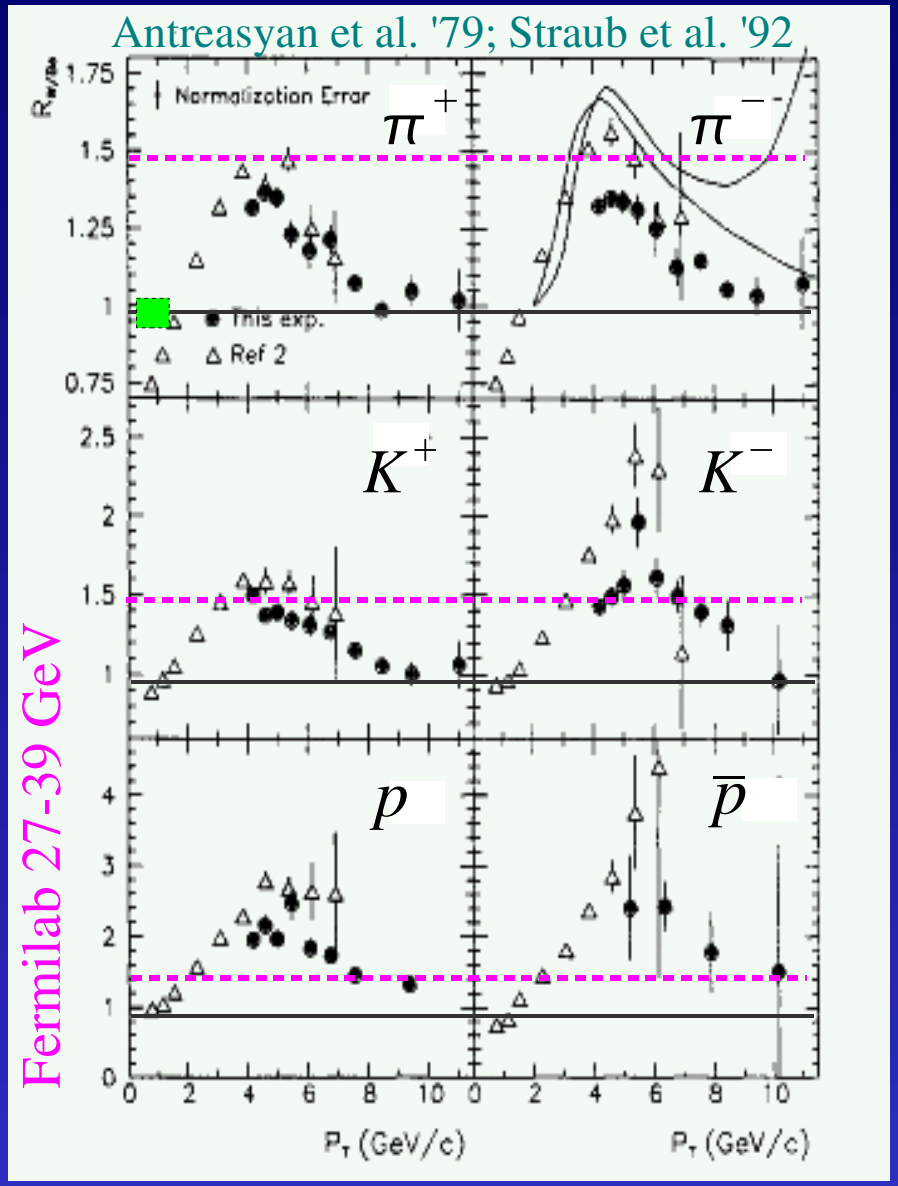



Big surprise!
The deuterium is a smallish object,
it should cause only a small Cronin!
Soft physics? Particle mix?
Anti-shadowing of Au partons?

Decreasing with η, but they integrate over too low values of pT: at $|\eta| > 0$ range, points lie to the left of the crossing point

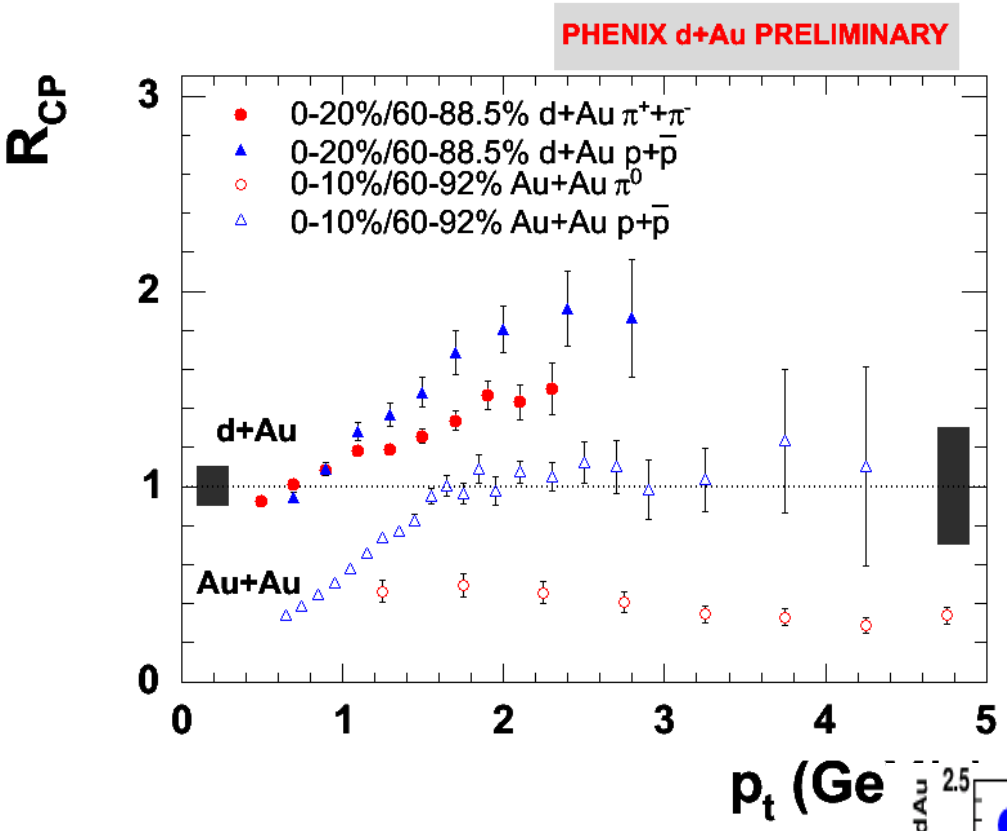
# Flavour dependence at $\eta=0$

# Fermilab @ 27-39 GeV



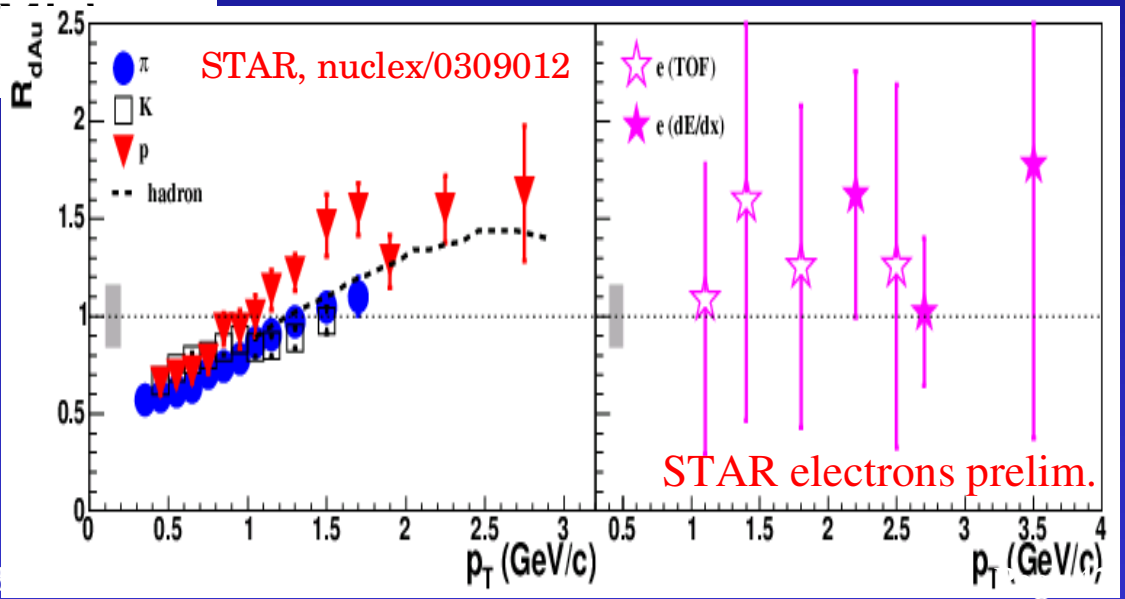

- protons have much larger Cronin than p and K
- K slightly larger than π
- Effect not explained in GE models

# RHIC @ 200 GeV




- protons have larger Cronin effect than pions already in d+Au...
- ...but this does not explain their difference in Au+Au

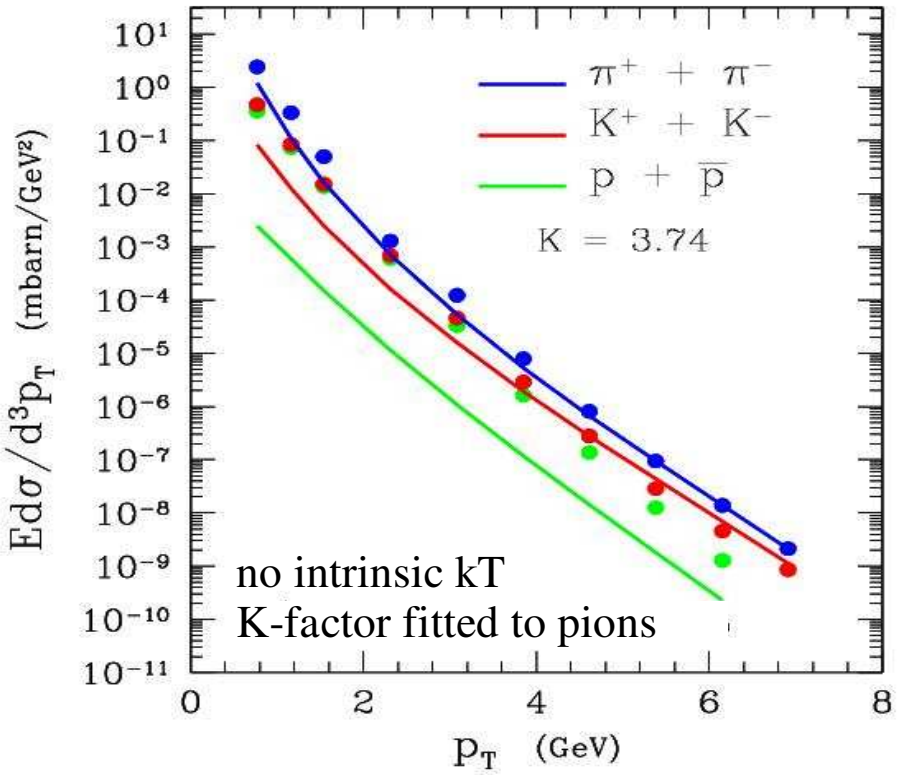
- STAR systematically lower than PHENIX
- K seem similar to π

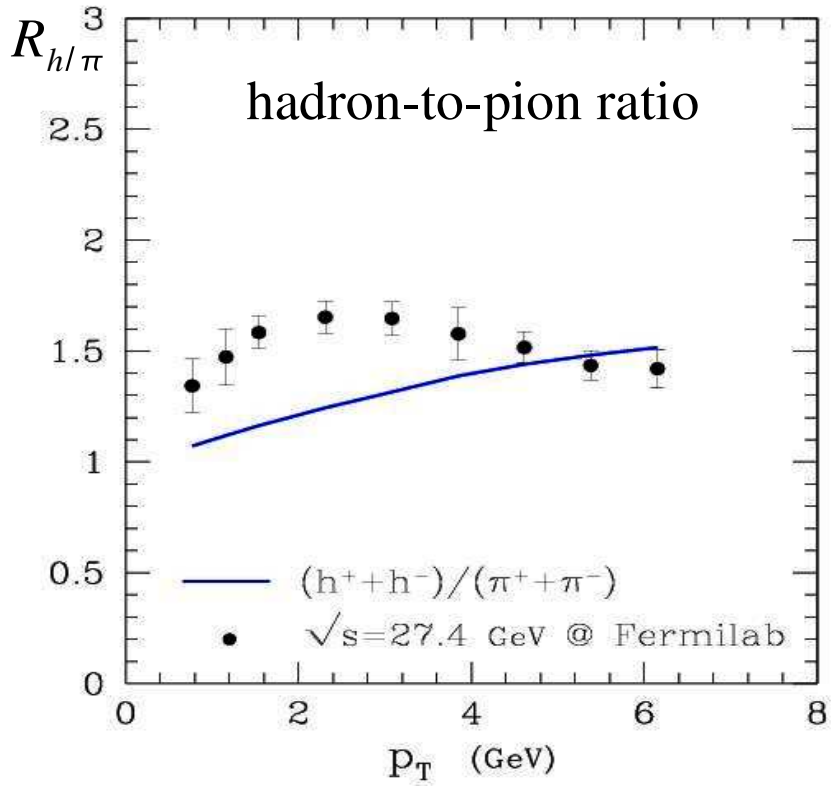



Difference between p and π is smaller than at Fermilab: due to softening of underlying pp spectrum?

# Back to pp at Fermilab: mesons vs. baryons

Fermilab 27 GeV - Antreasyan et al. '79



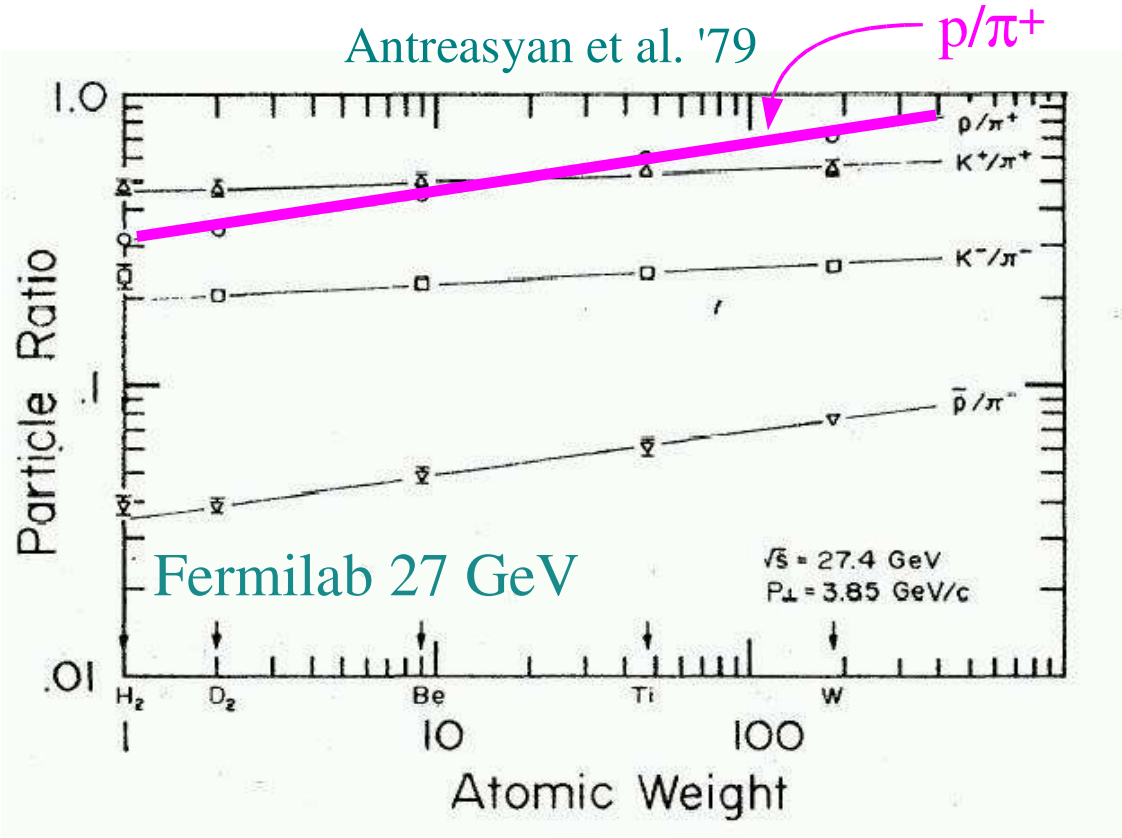




* π fairly well described
* *K* slightly underestimated at low-$p_T$

BUT...

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

# From pp to pA at Fermilab



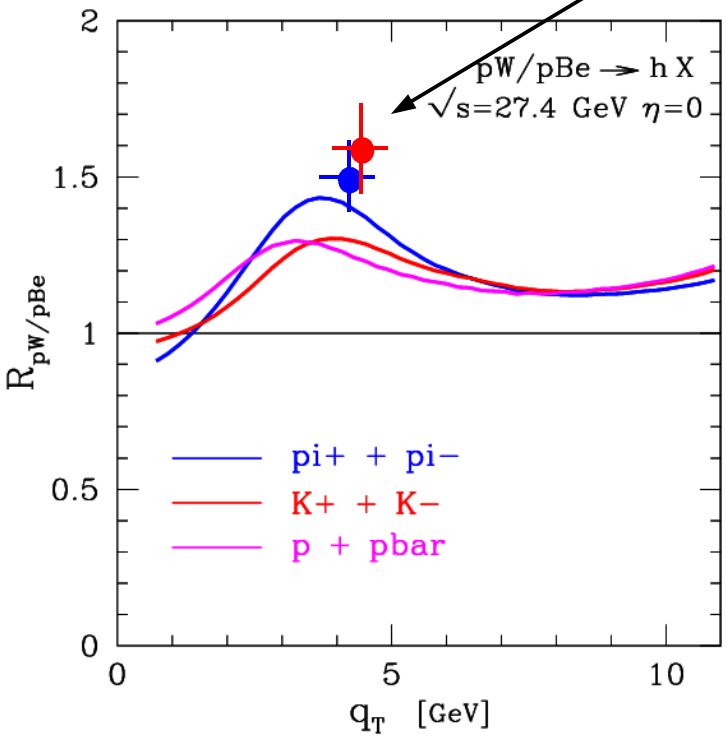

Baryons are even worse in pA collisions....

Baryon excess - possible solutions:

- different $k_T$-broadening for baryons and mesons Fai,Zhang '03
- new mechanism: hadronization by parton recombination at small pT?
  Greco et al. '03 - Bass et al. '03
  (already in pp coll's? what about 2 part's corr's?)
  baryon junctions?

# Flavour dependence of Cronin effect at Fermilab

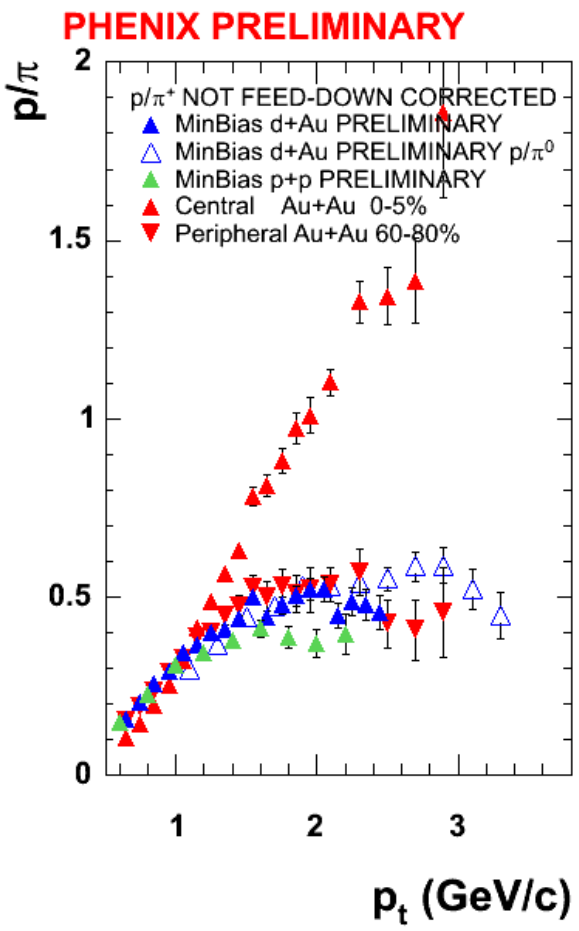
position of the Cronin peak
(eyeball estimate from data)

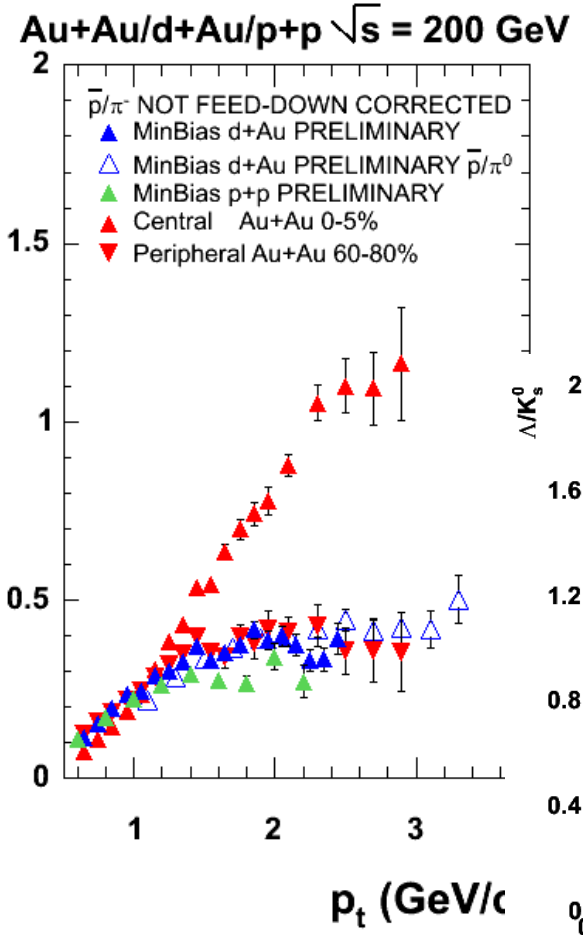



As expected,
pions: fairly described
kaons: slightly too low
protons: completely missed

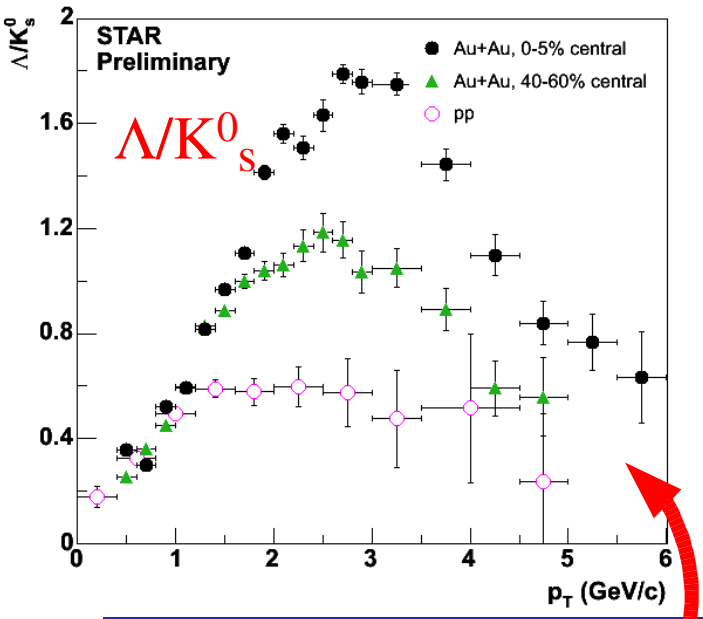
**different hadronization mechanism for baryons and mesons**

# Flavour at RHIC - p/π ratio




- d+Au follows peripheral Au+Au.
- p+p slightly lower.
- Central Au+Au much higher




- If flow (recombination) is causing the "baryon anomaly"
  ⇒ mid-peripheral p/π even larger
- Is it a baryon/meson effect? ⇒ look at Λ/π, Λ/K or p/ϕ or ...

# What remains to do?

Good indications of emergence of dynamical shadowing at forward η

To assess dynamical shadowing / CGC we need

- **More statistics:**
  - **PID**: π vs. p, or at least mesons vs. baryons
    direct comparison to GE models, extraction of $x_{crit}$ & $Q_{sat}$
  - **Centrality dependence** at fixed η
  - **$p_T \leq$ 5-6 GeV at least:** evolution of "Cronin peak" with b and η:
    (for η dependence, need to "find" experimentally the peak)
- **Back-to-back jets in d+Au:**
  - CGC predicts "monojets"
  - Suppression of b-t-b jet correlated with emergence of dynamical shadowing would be good proof for saturation dynamics
- **Quantitative predictions in saturation models**
- **Understand baryon production already in pp!**

# The End

# CGC toy model

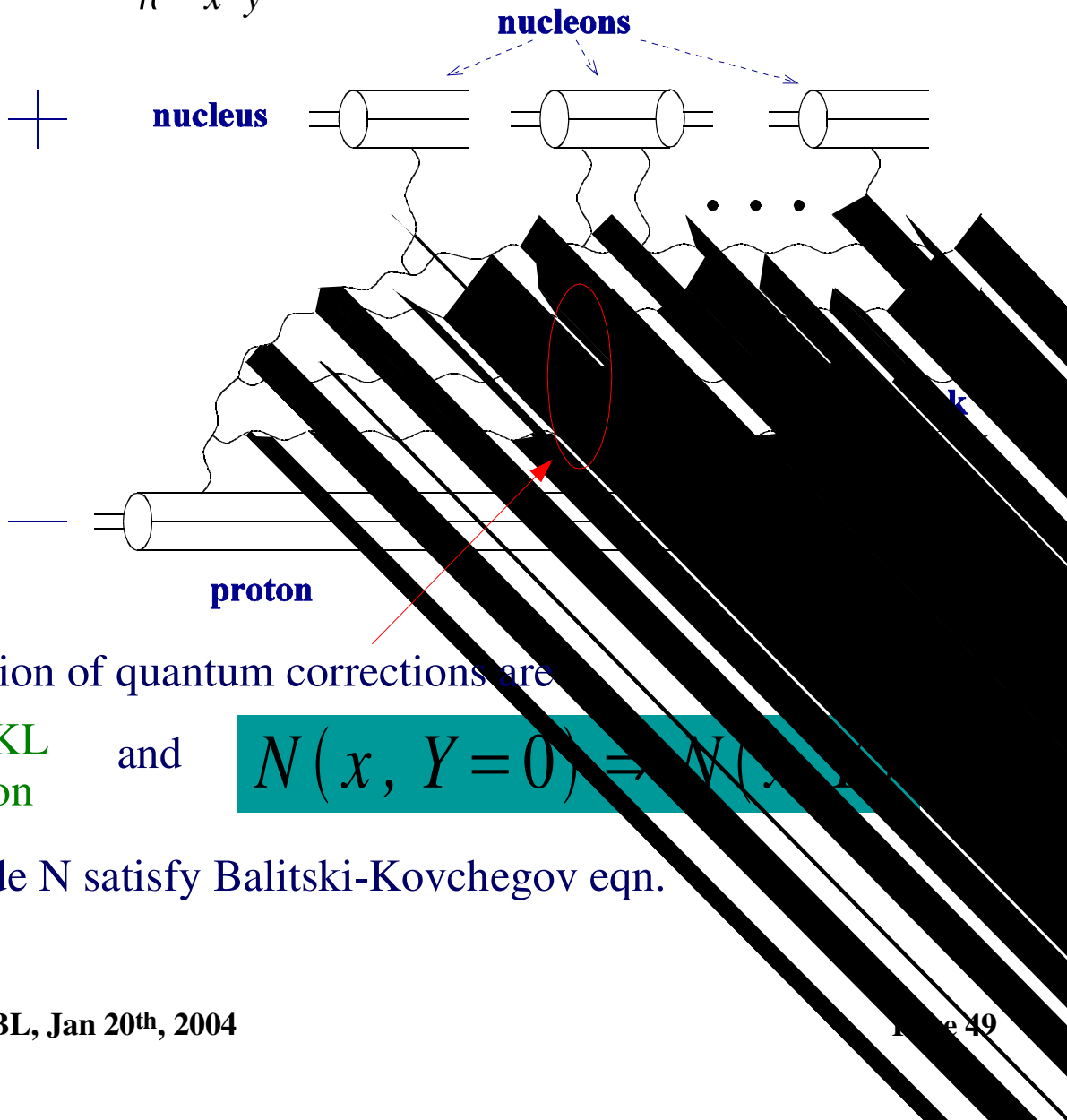
Classical YM gluon production cross section is given by

(Kovchegov, Mueller, hep-ph/9802440)

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

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 $\Rightarrow$ 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

$$N_G^{toy}(z_T, y) = 1 - e^{-z_T\, Q_s(y)}, \qquad (118)$$

$$Q_s(y) \approx Q_{s0}\, e^{2.44\,\overline{\alpha}_s\, y}$$

(Mueller-Triantafyllopoulos)

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

$$\frac{d\sigma^{pA}_{toy}}{d^2k\; dy} = \frac{\alpha_s C_F}{\pi^2}\,\frac{S_A}{k_T^2}\,\frac{Q_s}{k_T^2+Q_s^2}\left[-Q_s(k_T^2+Q_s^2) + \sqrt{k_T^2+Q_s^2}\left(2Q_s^2 + \gamma\, k_T^2 + k_T^2\,\ln\frac{2(k_T^2+Q_s^2)}{k_T\,\Lambda}\right.\right.$$
$$\left.\left. + \frac{k_T^2}{2}\,\ln\frac{\sqrt{k_T^2+Q_s^2}-Q_s}{\sqrt{k_T^2+Q_s^2}+Q_s}\right)\right], \qquad (119)$$

where $\gamma$ 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 $\Lambda$ instead of $Q_s$ and $S_p$ instead of $S_A$:

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

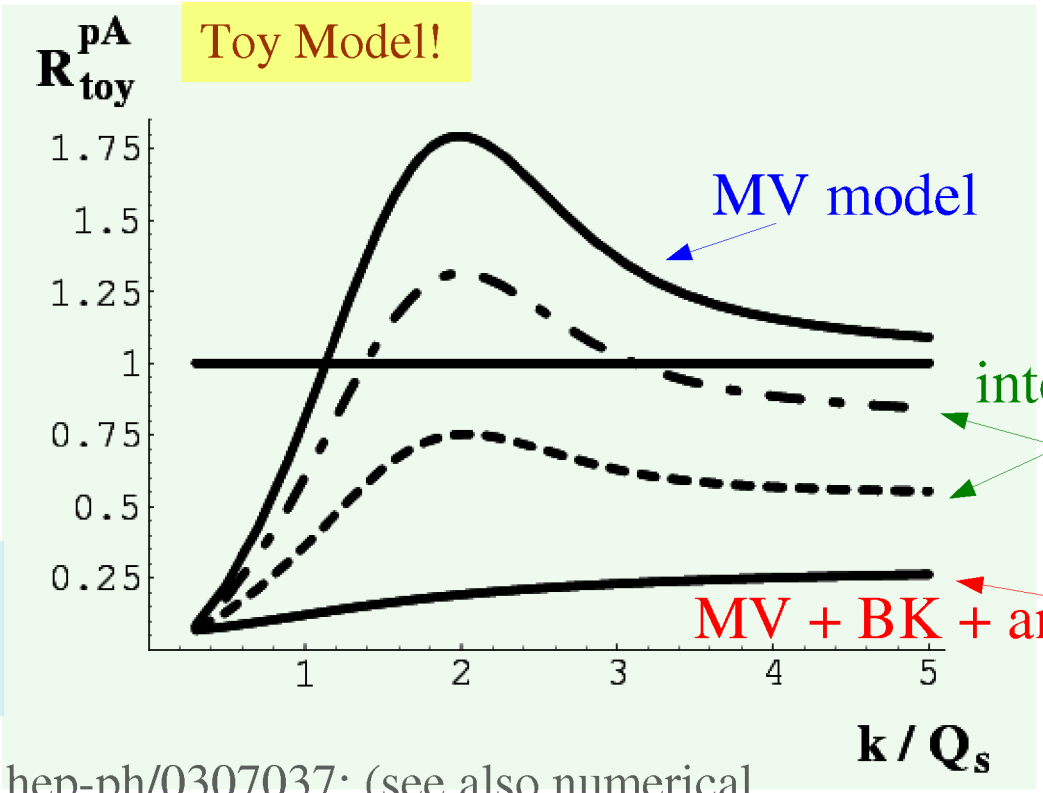
# Toy-model prediction

**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???