# Cronin effect and colour dipoles in dA collisions: pQCD vs. CGC

**Alberto Accardi**
**Columbia U.**

Stony Brook, October 21st, 2003

# Overview

**Intro - pA, AA and the QGP**

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

- pQCD + Glauber rescatterings of partons
- dipole representation of parton-nucleus scattering

**Part II - Cronin effect on $\pi$ in pA / dA collisions**

- From pp to pA collisions
- Comparison to Fermilab and RHIC data
- pQCD vs. CGC
- Centrality dependence

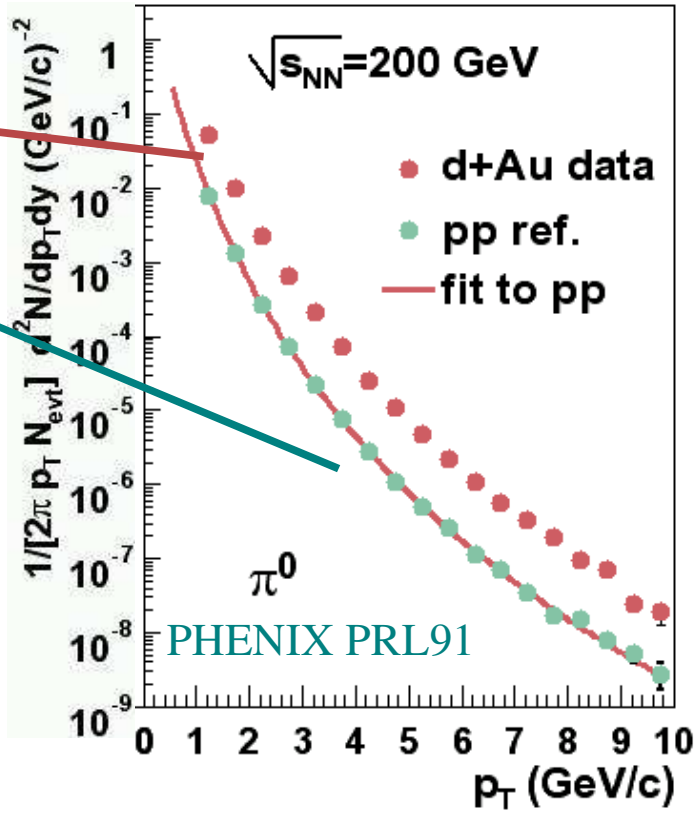
**Part III - The elusive baryons & the fair kaons**

- Cronin effect: mesons vs. baryons

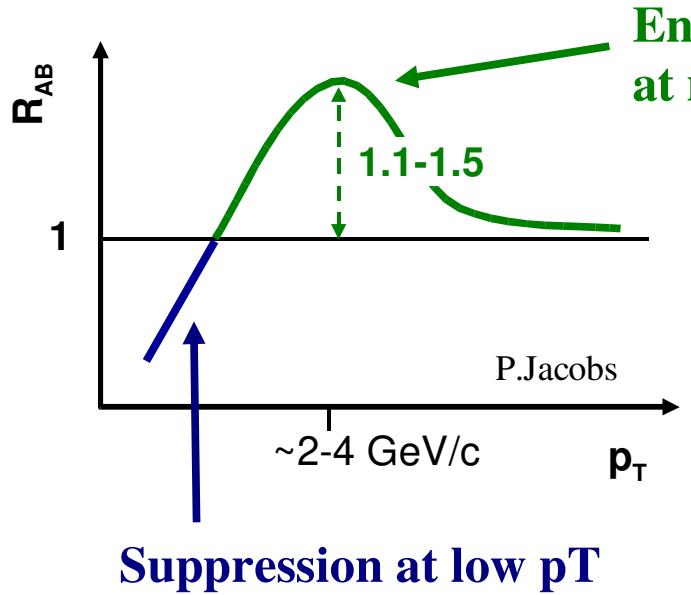
# Cronin ratio of inclusive spectra

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

**Binary collision scaling** — **p+p reference**

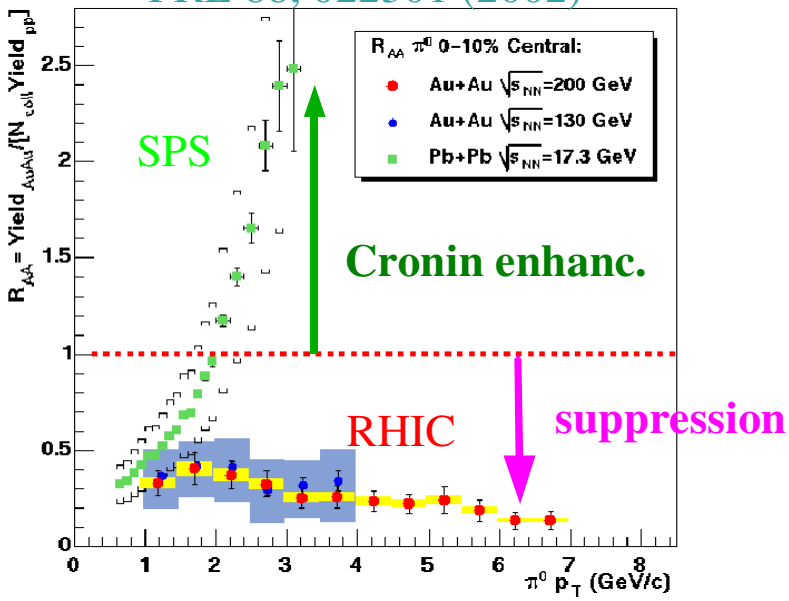



At low-energy pA and AA:

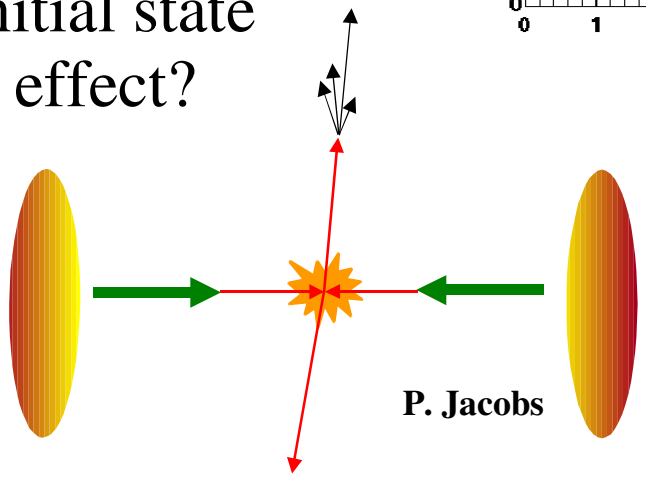


# AA collisions: SPS vs. RHIC

PRL 88, 022301 (2002)



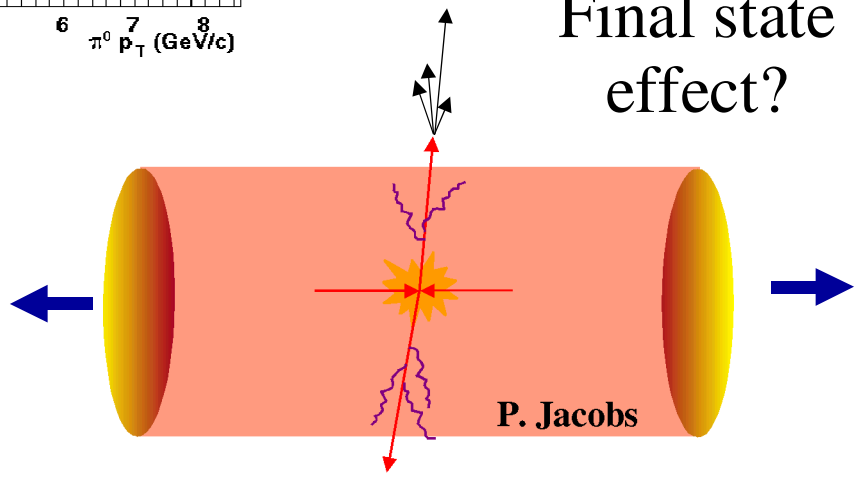

Initial state effect?




strong modification of Au wavefunction (gluon saturation)

or

Final state effect?

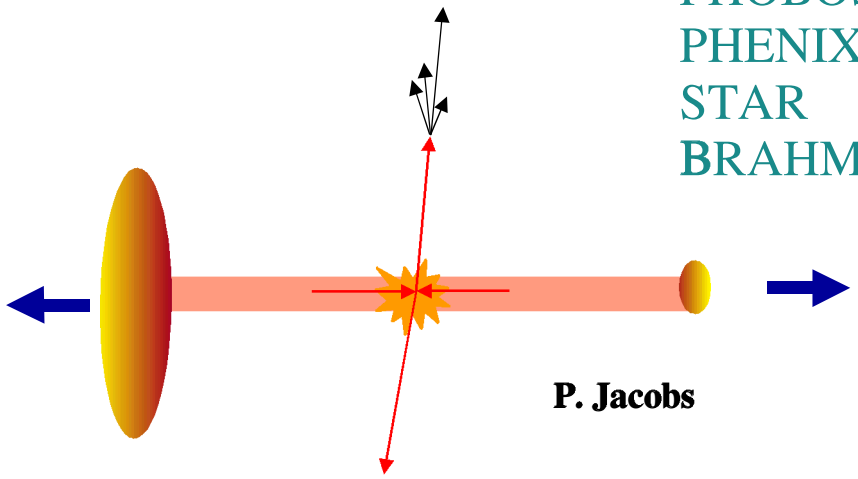



partonic energy loss in dense medium generated in collision

# How to discriminate?

Turn off final state
⇒ h+Au collisions

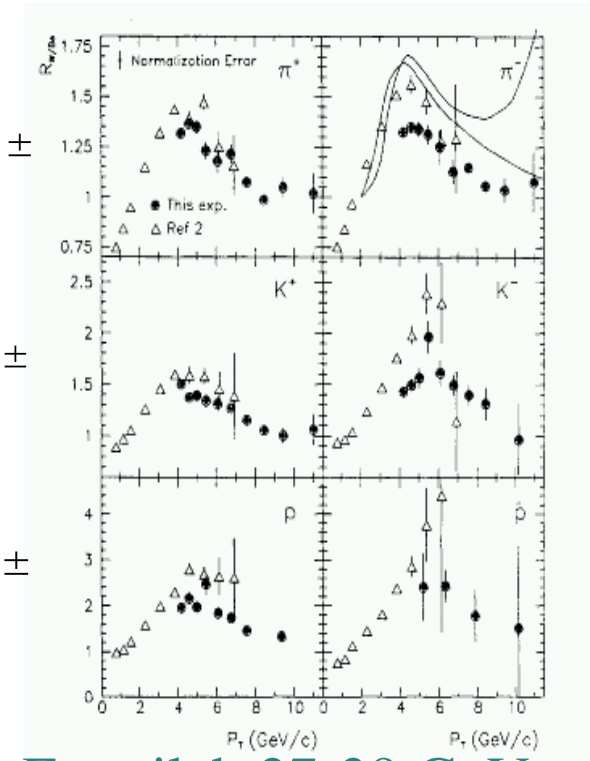
PHOBOS PRL91(03)072302
PHENIX " 03
STAR " 04
BRAHMS " 05



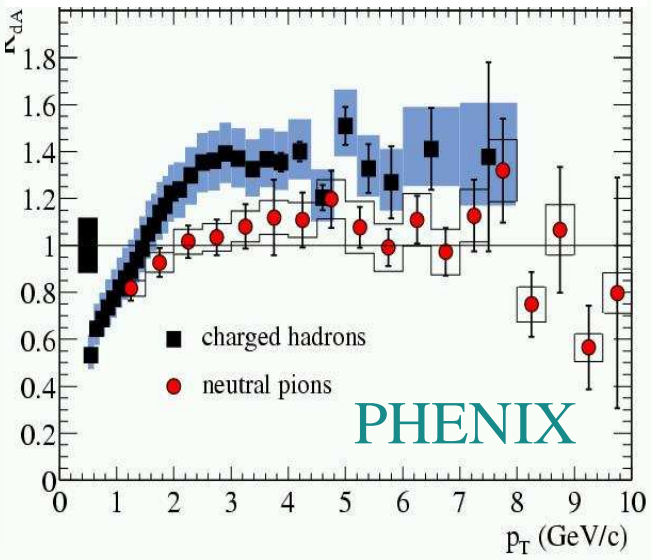

$\pi^{\pm}$

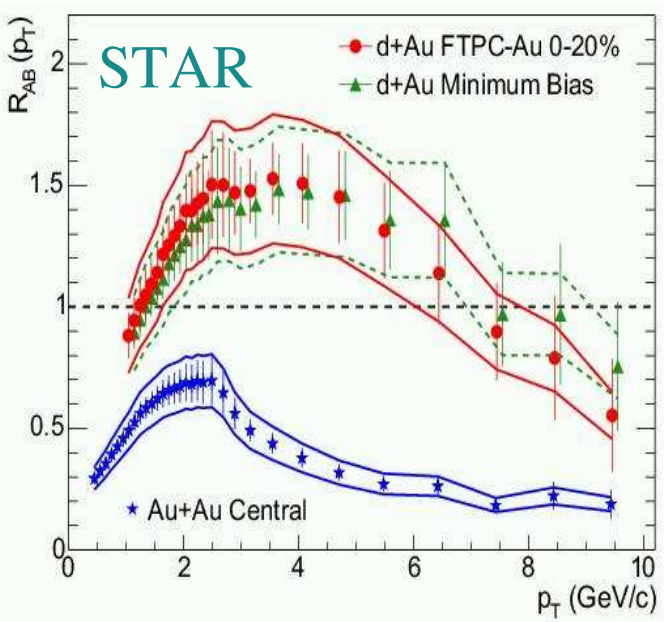
$K^{\pm}$

$p^{\pm}$




Fermilab 27-39 GeV



# Theoretical models for hA

**Glauber-Eikonal models**

**- hard partonic -**

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

A.A., M.Gyulassy

**Colour dipole model**

**- soft partonic -**

B. Kopeliovich et al.

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

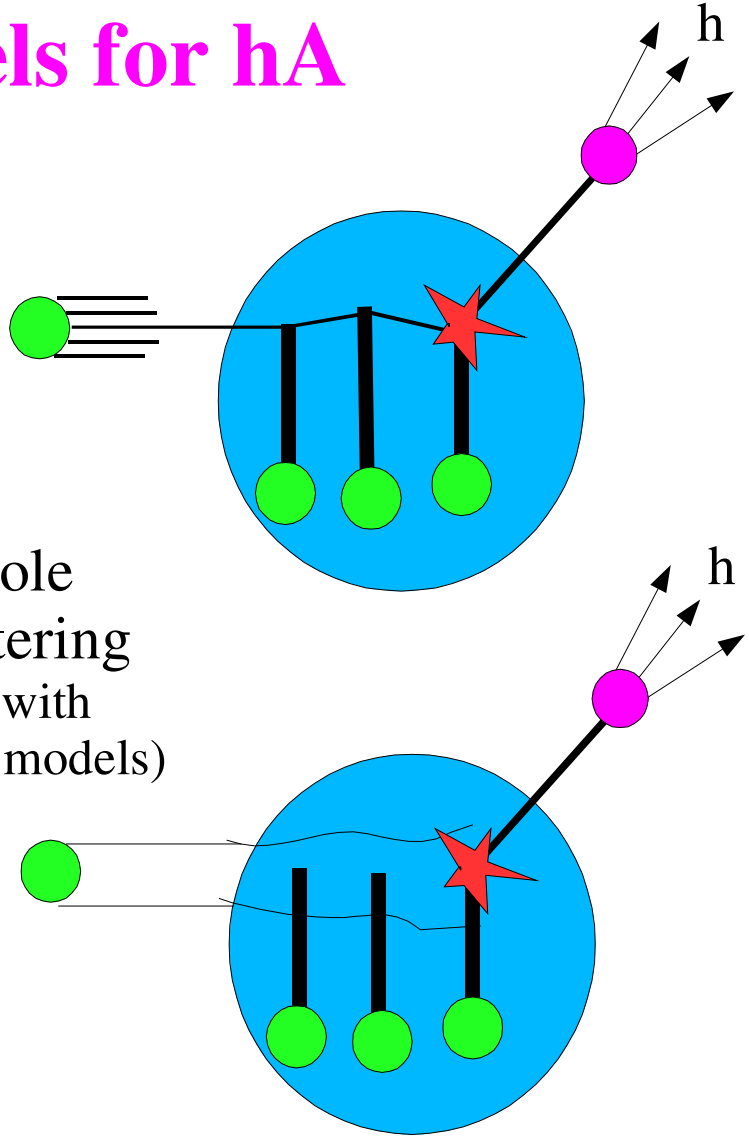
**Glauber-Eikonal Approximated**

**- soft 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**

# Saturation models - a broad category

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

Kovchegov

Dumitru, Gelis, Jalilian-Marian

Jalilian-Marian, Nara, Venugopalan

**MV model plus BK evolution**

Kovchegov, Tuchin

Albacete et al.

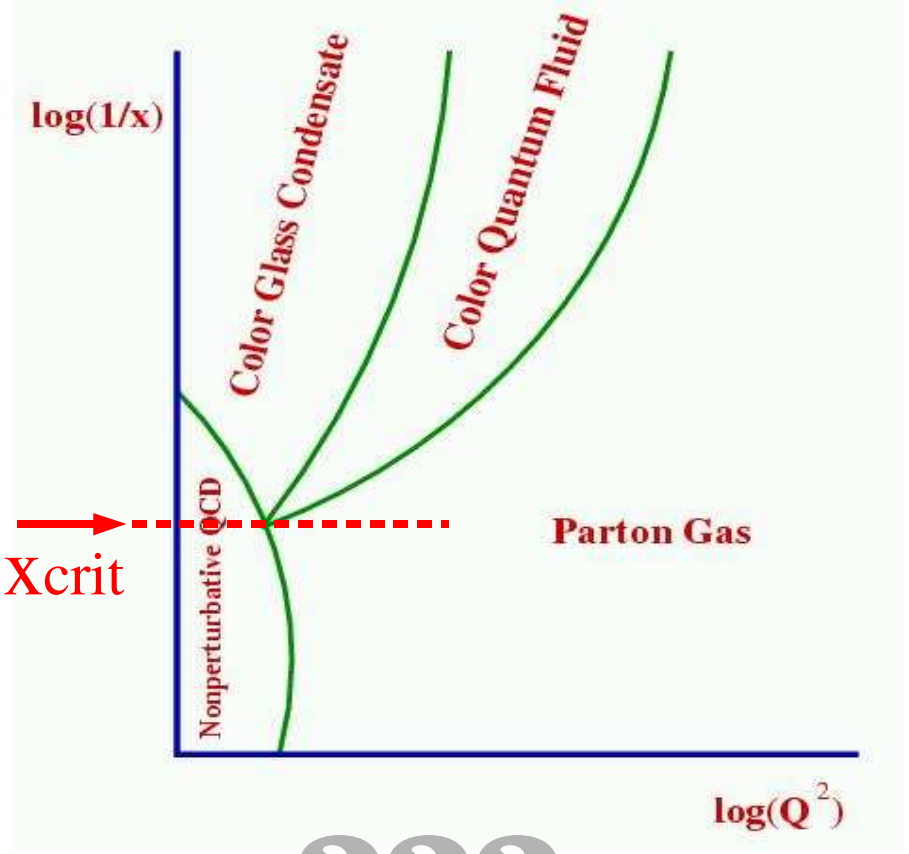
**CGC = MV + quantum evolution**

Iancu, Itakura, McLerran + ...

**CGC inspired models**

Kharzeev, Levin, McLerran

Kharzeev, Kovchegov, Tuchin




**??? QUESTIONS...**

**How small is xcrit?**

**Where does RHIC stand?**

# Part I

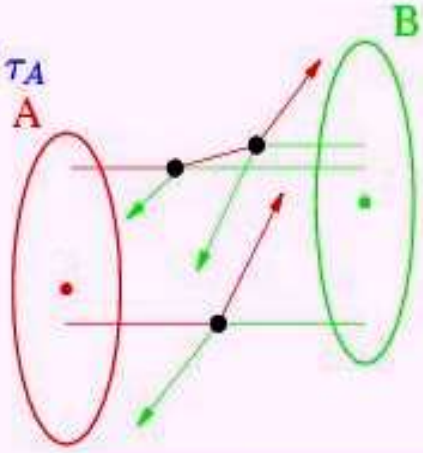
# Glauber-Eikonal models:
# pQCD + partonic rescatterings

# Semihard interactions: rescatterings

Calucci, Treleani, PRD41(90)3367, PRD44(91)2746

**Assumptions:**

- QCD generalized factorization: $D_A^n = \frac{1}{n!} \overbrace{G\tau_A \dots G\tau_A}^{n \text{ times}} e^{-\int G\tau_A}$
- Factorization of the $n$-body x-sec.: $S^{(n,m)} = \prod_{\substack{i=1,n \\ j=1,m}} S_{ij}$
- Only partonic elastic scatterings




**Average number of minijets** $\sigma_{mj} = \sum_{n,m=1}^{\infty} \int D_A^n \, P_{nm} \, D_B^m$

Def. minijet = parton with at at least 1 semi-hard scattering

semi-hard scattering = $p_{exch} > p_0$

$N_{jet} \leq 2 N_{collisions}$

$$\frac{dN_{jet}^A}{dx}(b) = \int d^2r \; \overbrace{G(x,Q^2)\tau_A(b-r)}^{\text{density of projectiles}} \; \underbrace{\left(1 - e^{-\overbrace{\sigma_{hard}^{gN}(x;p_0)\tau_B(r)}^{\langle n_B^{scat} \rangle \text{ or "target opacity"} \omega_B}}\right)}_{\text{prob. of at least 1 scatt.}}$$

where $\sigma_{hard}^{gN}(x;p_0) = \int d^2k \int dx' G(x') \frac{9/2\,\alpha_S^2(Q^2)}{(k^2+p_0^2)^2} \propto \frac{1}{p_0^2}$ = gluon-nucleon cross section cross section

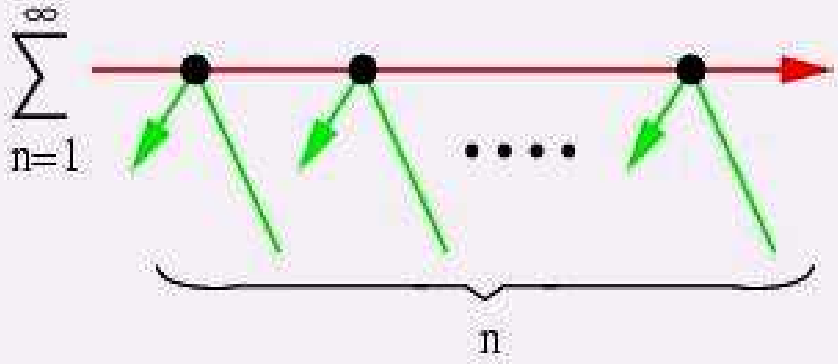
$\rightsquigarrow$ Glauber multiple scattering formula at parton level

## Expansion in the no. of scatterings

$$\left(1 - e^{-\int dx' \sigma_H(xx') G(x') \tau_B(r)}\right)$$

absorption factor (prob. conservation)

$$\frac{dN^A_{jet}}{dx}(b) = \int d^2r \; G(x,Q^2)\tau_A(b-r) \sum_{n=1}^{\infty} \underbrace{\frac{1}{n!}\left[\sigma^{gN}_{hard}(x;p_0)\tau_B(r)\right]^n e^{-\sigma^{gN}_{hard}(x;p_0)\tau_B(r)}}_{\text{PROBABILITY of } n \text{ scatterings}}$$




## Two remarkable limits

$$\frac{dN_{jet}}{dx}(b) \longrightarrow \begin{cases} 2\int G\tau_A \sigma_H G\tau_B = \dfrac{dN^{(1)}_{jet}}{dx}(b) & \dfrac{p_0}{\sqrt{s}} \to 1 \quad \text{single scatt. at low opacity} \\ \int G\tau_A + \int G\tau_B \overset{def.}{=} \dfrac{dN_{lim}}{dx}(b) & \dfrac{p_0}{\sqrt{s}} \to 0 \quad \text{high opacity : all scatter} \end{cases}$$

"black-disc limit"

# Dipole representation

AA, Trelani PRD64(2001); Gyulassy, Vitev PRD66(2002), AA hep-ph/0212148

- Consider a quark scattering on A at impact parameter $b$

$$\frac{d\sigma^{qA}_{hard}}{d^2p_t} = \sum_{n=1}^{\infty} \frac{1}{n!} \frac{d\sigma^{qN}_{hard}}{d^2k_1} T_A(b) \times \cdots \times \frac{d\sigma^{qN}_{hard}}{d^2k_n} T_A(b)\, e^{-\sigma^{qN}_{hard}(p_0) T_A(b)} \times \delta^{(2)}\Big(\sum \mathbf{k}_i - \mathbf{p_t}\Big)$$

where $\frac{d\sigma^{p}_{hard}}{d^2p_T} = \int_{x'_{min}}^{1} dx'\; G(x', p_T^2) \frac{d\hat{\sigma}}{d^2p_T}$ is the pQCD quark-nucleon cross-section

- Resummations are possible in coordinate space:

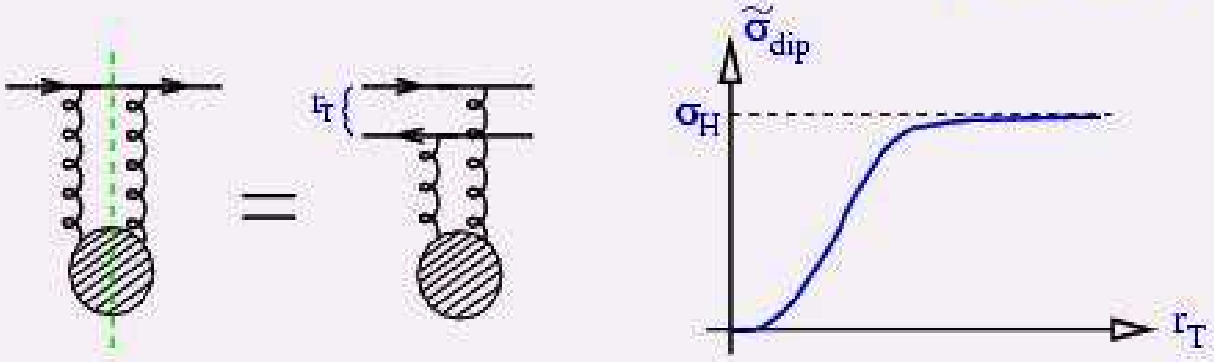
$$\frac{d\sigma^{qA}_{hard}}{d^2p_T} = \int \frac{d^2r_T}{4\pi^2} e^{-i\vec{k}_T\cdot\vec{r}_T} \left[ e^{-\tilde{\sigma}^{qN}_{hard}(r_T, p_0) T_A(b)} - e^{-\sigma^{qN}_{hard}(p_0) T_A(b)} \right]$$

where $\tilde{\sigma}^{p}_{hard}(r_T; p_0) = \int d^2k \left[1 - e^{-i\vec{k}\cdot\vec{r}_T}\right] \frac{d\sigma^{p}_{hard}}{d^2k}$,

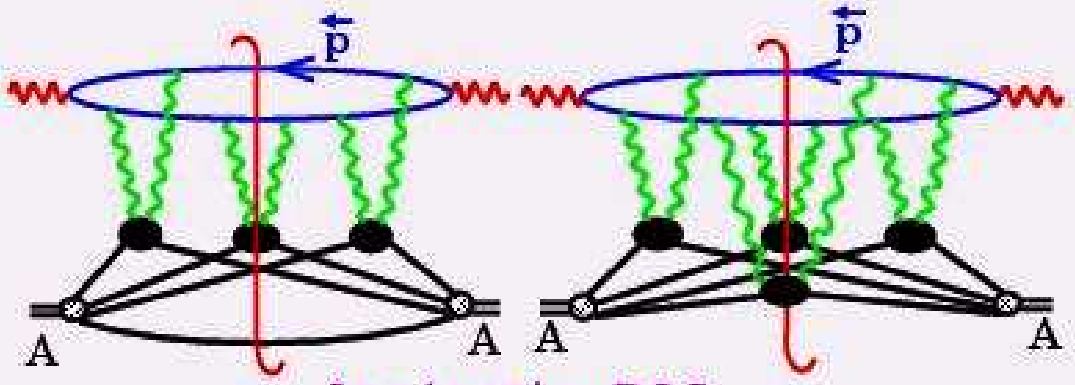
and $\sigma^{qN}_{hard}(p_0) = \int d^2k \frac{d\sigma^{qN}_{hard}}{d^2k} s$ is the integrated quark-nucleon cross section.

- $\tilde{\sigma}_{dip}(r_T)$ interpreted as semihard dipole-nucleon cross section.

$$\tilde{\sigma}^p_{hard}(r_T; p_0) = \int d^2k \left[1 - e^{-i\vec{k}\cdot\vec{r}_T}\right] \frac{d\sigma^p_{hard}}{d^2k} \longrightarrow \begin{cases} Cr_T^2 & r_T \sim 0 \\ \sigma_p^{hard}(p_0) & r_T \to \infty \end{cases}$$




$\Longrightarrow$ $qA$ is rewritten as a multiscattering of a $q\bar{q}$ dipole on $A$




Inelastic DIS:

Single color excitation  Multiple color excitation

N.N.Nikolaev, lectures at Columbia U. and hep-ph/0212161

# Part II

# Cronin effect in pA/dA collisions

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

# First act: pp collisions

**Single scatt. in pp = LO pQCD:**

renormaliztion scale

fragmentation scale

$$E_\pi \frac{d\sigma^{pp}}{d^2 p_T^h dy} = K \sum_{abcd} \int^1 dx_a dx_b dz_c f_a(x_a, Q_R^2) \frac{d\sigma^{ab\to cd}}{d\hat{t}\, dy} f_b(x_b, Q_R^2) \frac{D_c^h(z_c, Q_F^2)}{\pi z_c^2}$$

K-factor (simulates NLO)

IR regulator: $p_T^2 \to p_T^2 + p_0^2 = m_T^2$

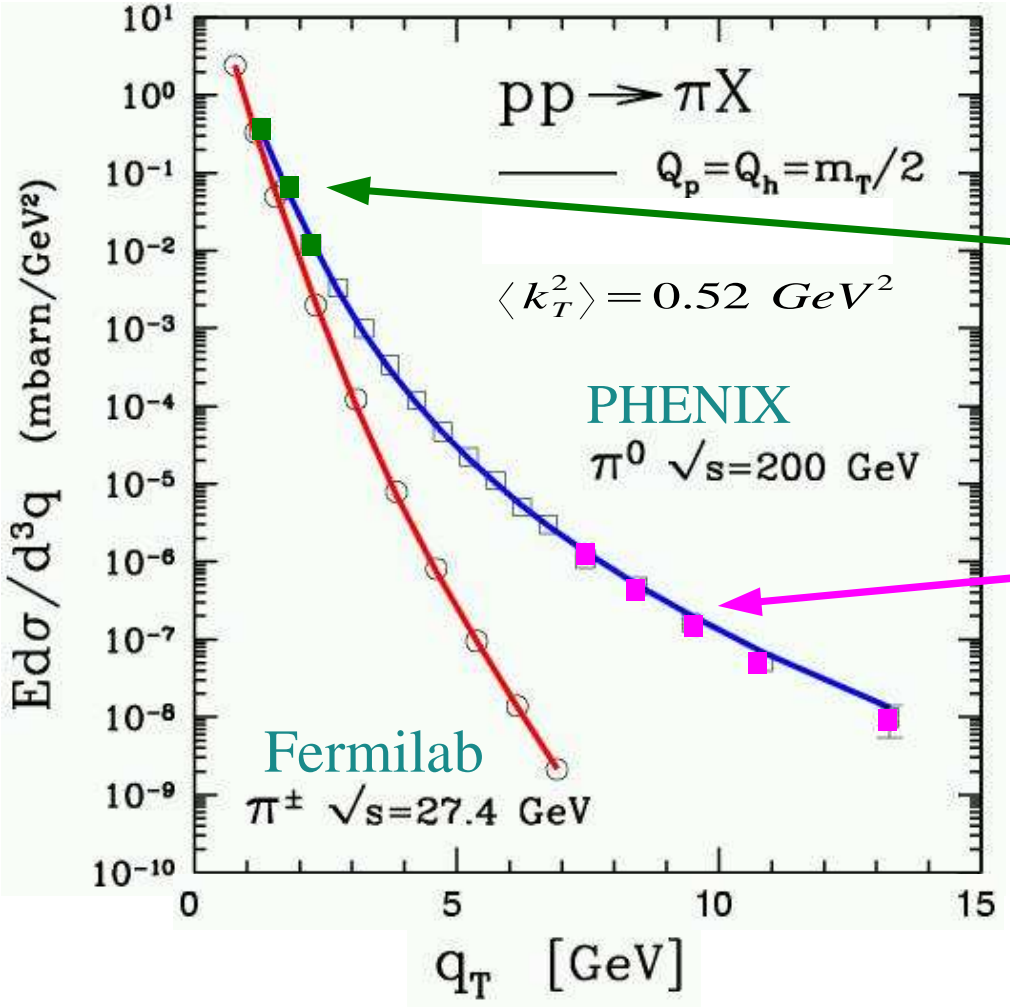
a) CHOOSE the scales: **$Q_R = Q_F = m_T/2$** (or **$Q_R = Q_F = m_T$**)

b) FIT **K=K(s)** to the **high-$p_T$** tail of the hadron spectrum ($\chi^2$ fit - sensitive to the choice of scales)

c) FIT **$p_0 = p_0(s)$** to the **low-$p_T$** hadron spectrum (rather stable against the choice of scales)

Note: • $p_0$ constant for gluons and quarks

# π at Fermilab and RHIC




## Fit procedure

(Eskola, Honkanen '02)

2) Low-$q_T$ ⇒ $p_0$

"eyeball" fit to low $q_T$ ~ $\langle q_T \rangle$ s.t. theory doesn't overestimate data

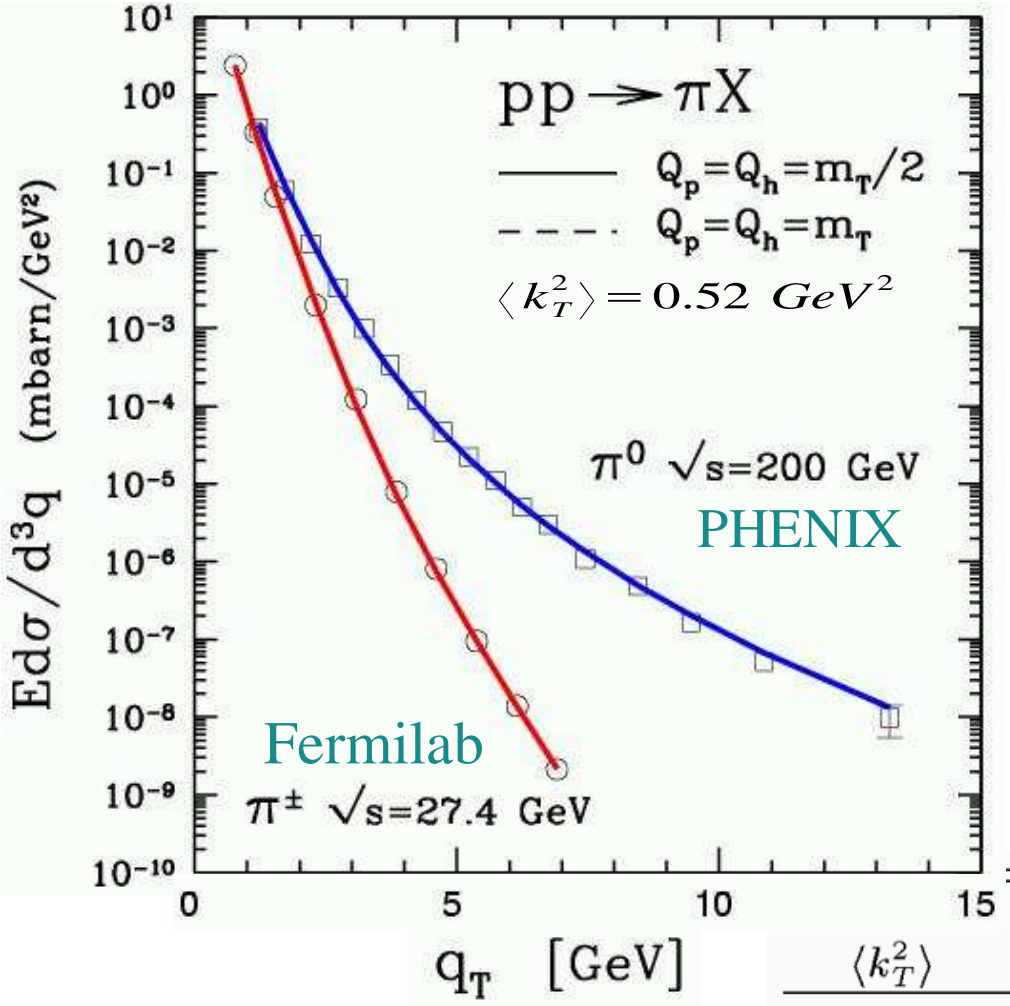
⇒ $p_0 = 1.0 \pm 0.1$

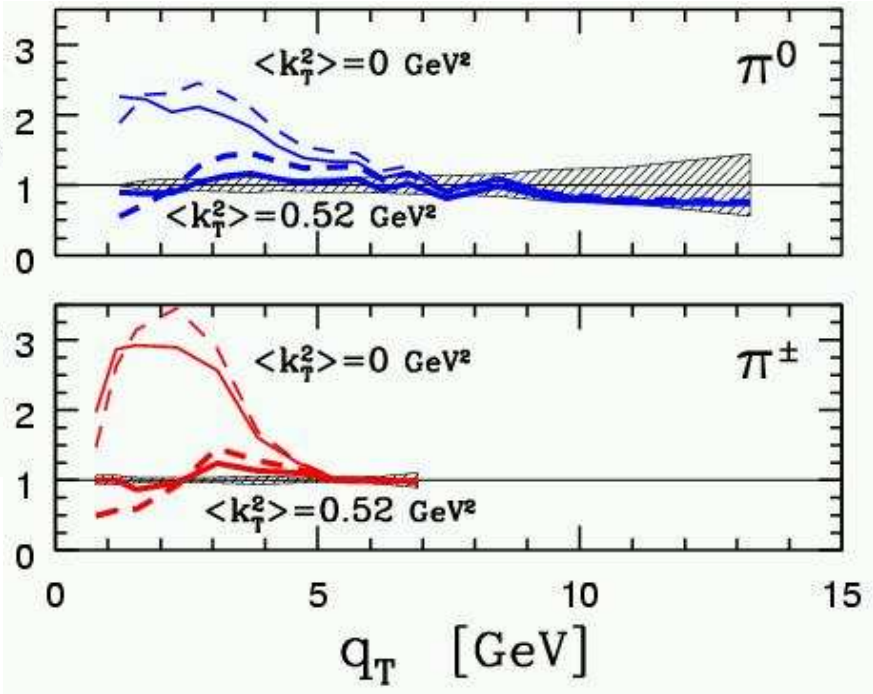
1) High-$q_T$ ⇒ $K$-factor

$\chi^2$-fit to N rightmost points s.t. $\chi^2 \leq 1$

⇒ $K = 0.88 \pm 0.03$

# 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 |
|---|---|---|---|
| | | $p_0 = 0.8 \pm 0.1$ GeV | $p_0 = 1.0 \pm 0.1$ GeV |
| 0.52 GeV$^2$ | $m_T/2$ | $K = 1.27 \pm 0.03$ | $K = 0.88 \pm 0.03$ |
| | $m_T$ | $K = 4.26 \pm 0.17$ | $K = 1.78 \pm 0.11$ |
| 0 GeV$^2$ | $m_T/2$ | $K = 4.04 \pm 0.11$ | $K = 1.04 \pm 0.06$ |
| | $m_T$ | $K = 13.2 \pm 0.4$ | $K = 2.20 \pm 0.16$ |

**from PHENIX prelim. (nucl-ex/0306031)**

# Second act: pA collision and Cronin effect

$$R^h_{pA}(p_T;b) = \frac{d\sigma^h_{pA}/d^2p^h_T}{d\sigma^h_{pp}/d^2p^h_T} = \frac{\cancel{K}\, f^i_p \otimes \sum_{n=1}^{\infty} \frac{1}{n!}\left(\frac{d\hat{\sigma}^{iN}}{d\hat{t}}\tau_A(b)\right)^{\otimes n} e^{-\hat{\sigma}^{iN}\tau_A(b)}}{\cancel{K}\,\tau_A(b)\; f^a_p \otimes \frac{d\hat{\sigma}^{ip}}{d\hat{t}}}$$

n-fold parton rescattering

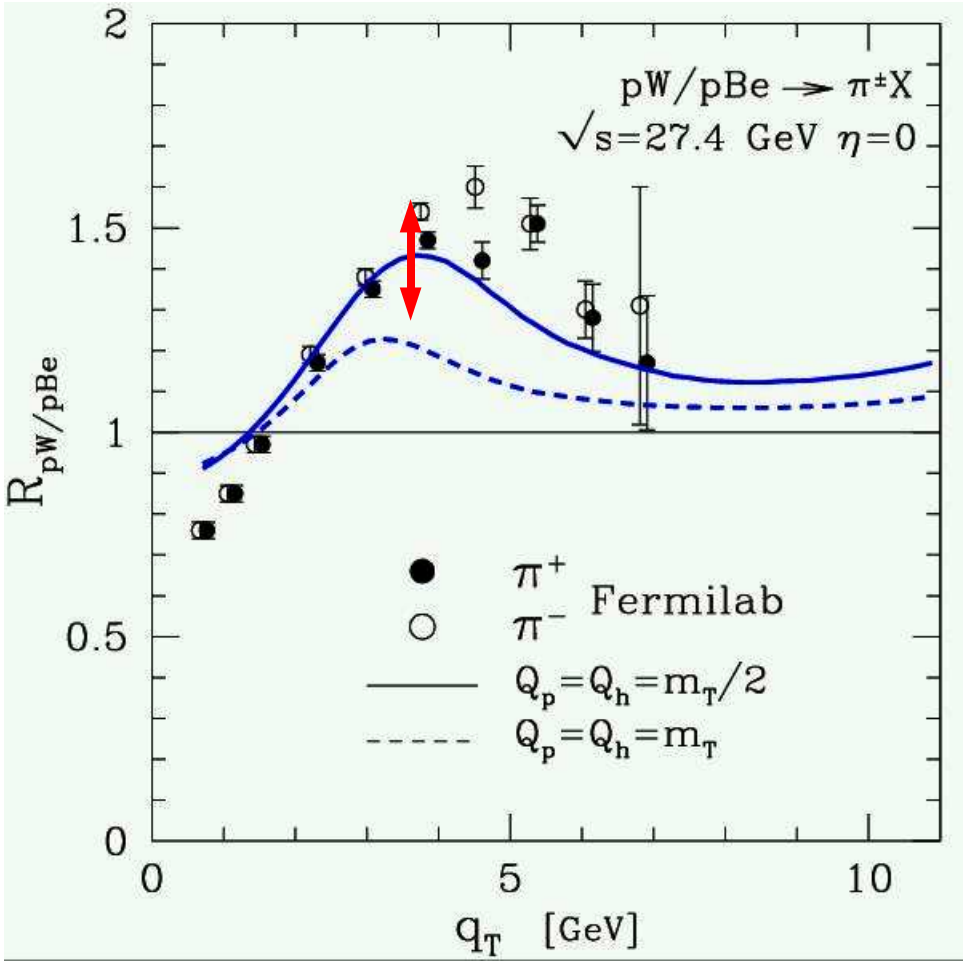
parton-nucleon cross section

- **pA as unitarized multiple parton scatterings on free nucleons**
- **Spectra in pp coll. as limiting case (high-pT or A->1)**
- **No extra free parameters**

- **"Geometric" shadowing included by Glauber rescatterings**
- **"Dynamical" shadowing NOT included (no non-linear QCD evolution)**

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

# Cronin effect on pions at Fermilab



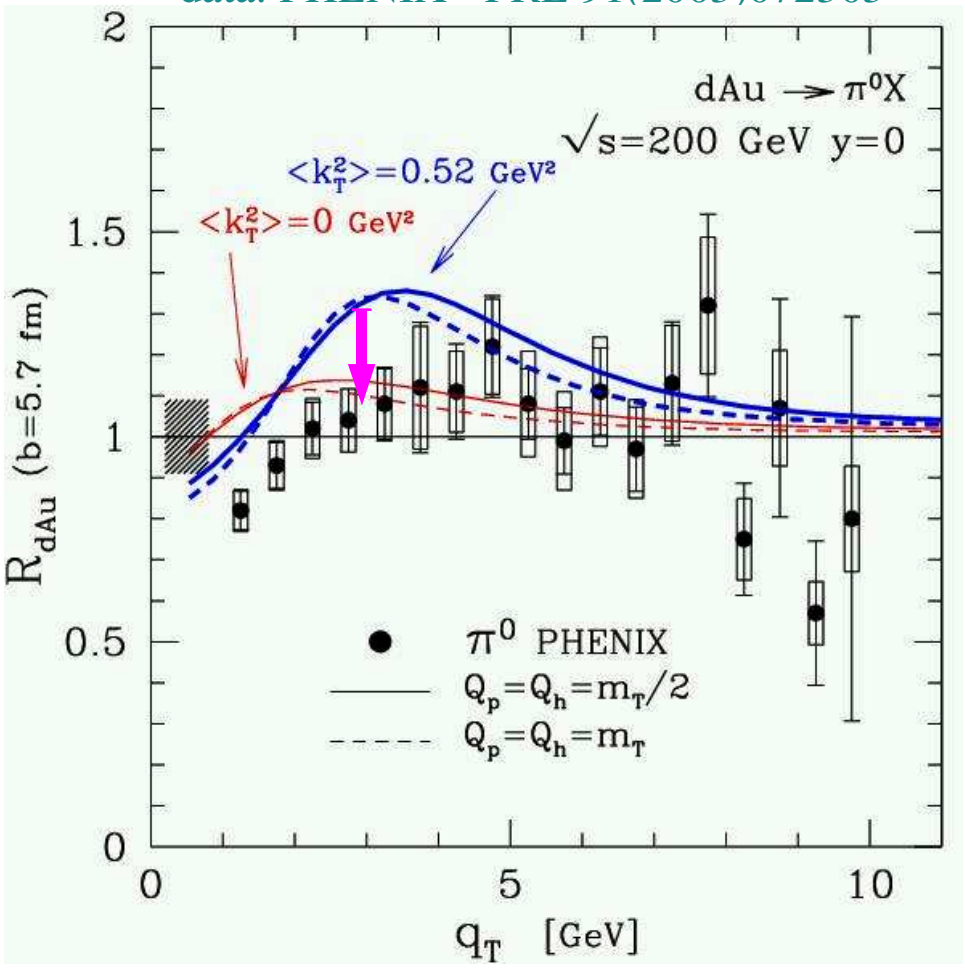

↕ = theoretical error due to fit of $p_0 = 0.8 \pm 0.1$ GeV
(it's max. at the peak, dies away far from it)

**With $Q=m_T/2$ we reproduce the data quite well.**

NOTE: $Q=m_T/2$ was the optimal choice also in pp coll's

# 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.

# Saturation vs. Glauber-Eikonal

Saturation models: control y-dependence of $Q_{sat}$, not absolute value

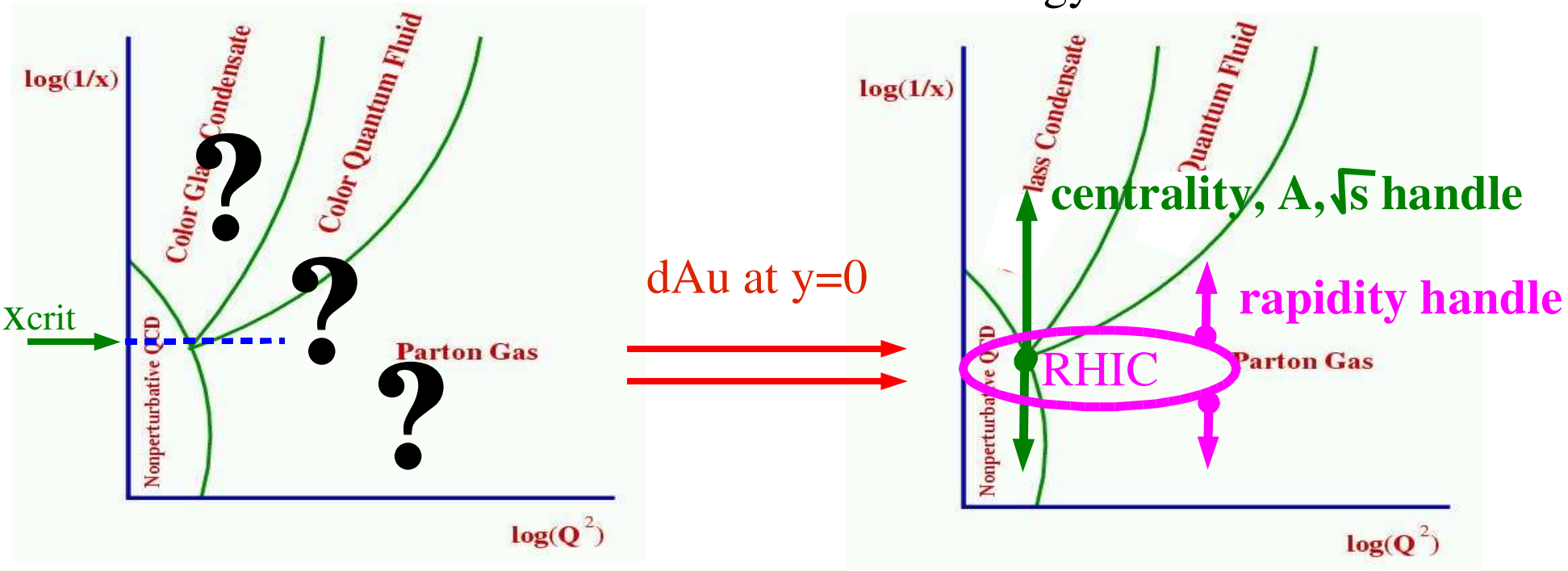
: $d\sigma^{gN}/d^2p_T \sim 1/p_T^4$ + asymptotic kinematics

$\Longrightarrow$ cannot reproduce hadron spectrum in pp collisions

Glauber-Eikonal model: linear evolution (DGLAP) included in PDF's

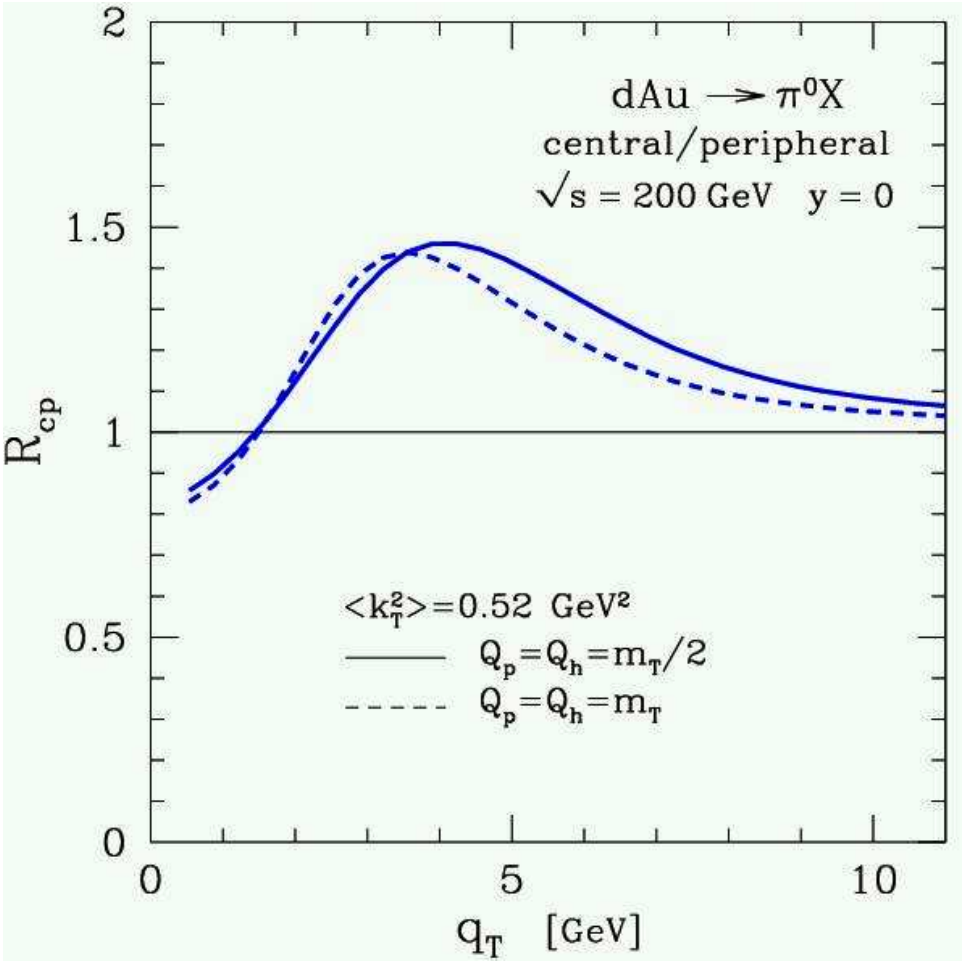
spectra in pp-collisions OK

Cronin effect at low energy OK




**can find $x_{crit}$ by comparing Glauber-Eikonal and exp. data**

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




In exp. data, most systematic errors drop out: shape and height of peak will be better measured.

If dynamical shadowing is at work,
$\Longrightarrow$stronger in central than in peripheral collisions
we would expect a larger suppression compared to our baseline computation

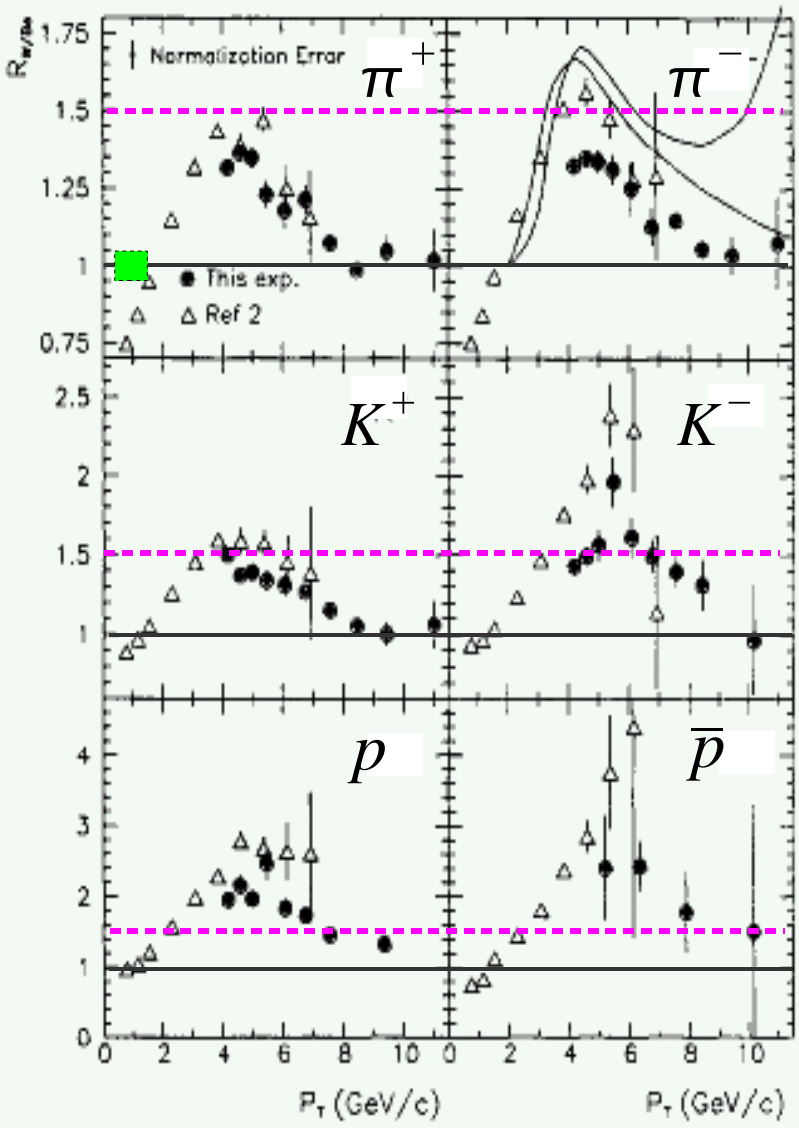
# Part III

# Why we compute only pions?
# (the elusive baryons & the fair kaons)

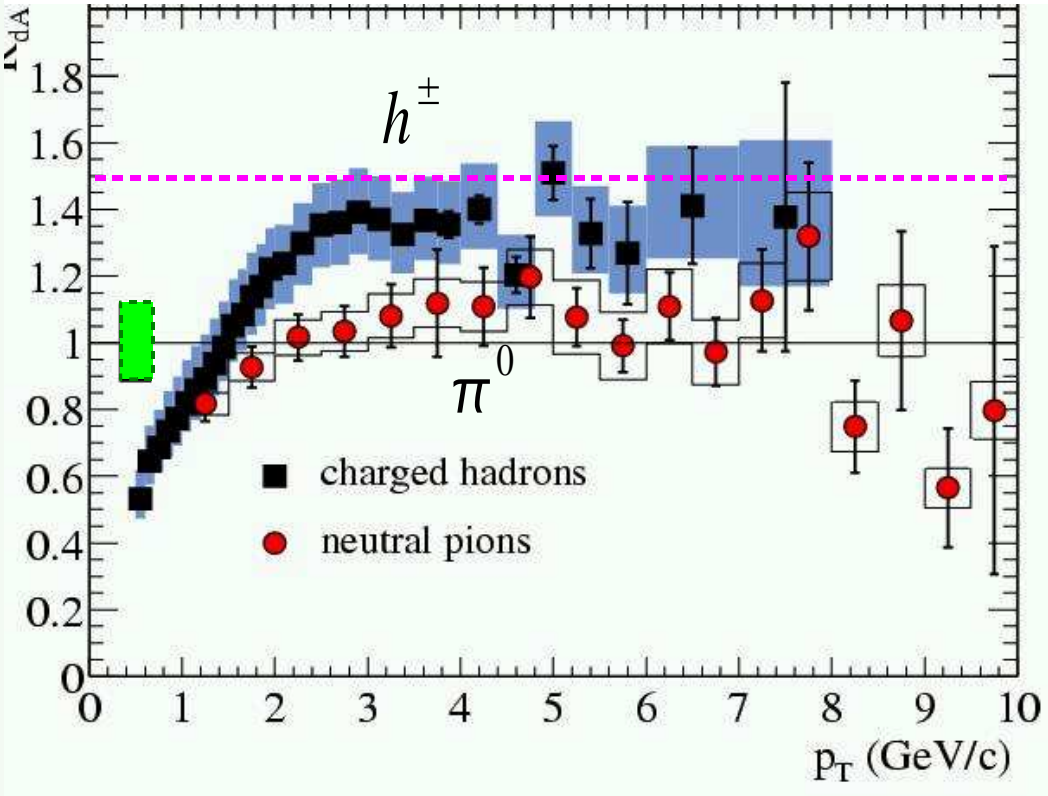
# Cronin effect: pions vs. charged

## Fermilab 27-39 GeV

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

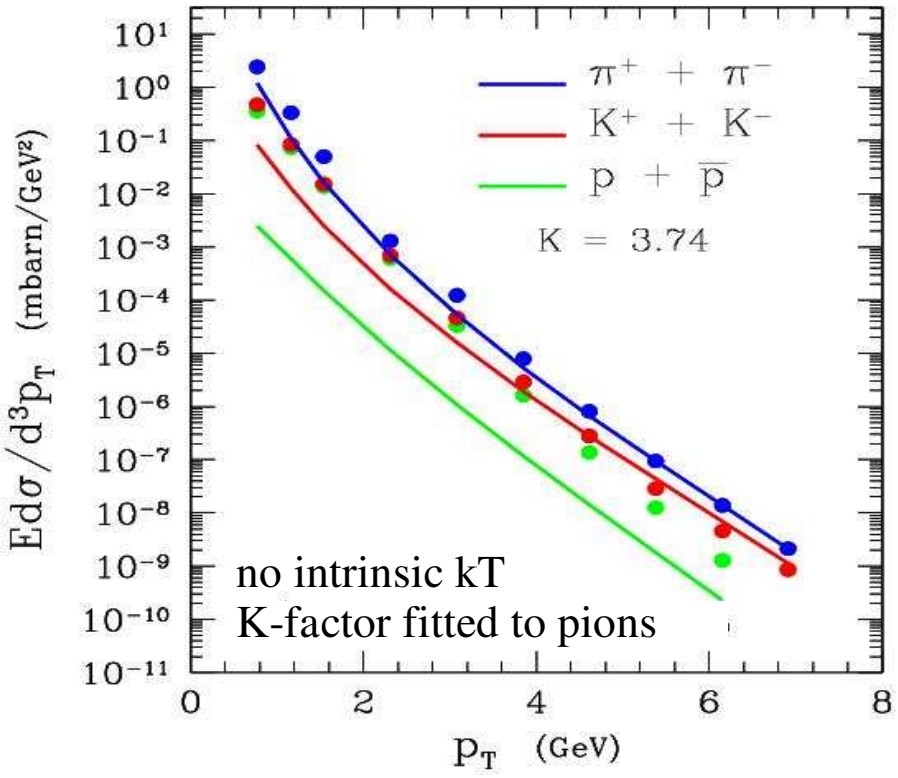


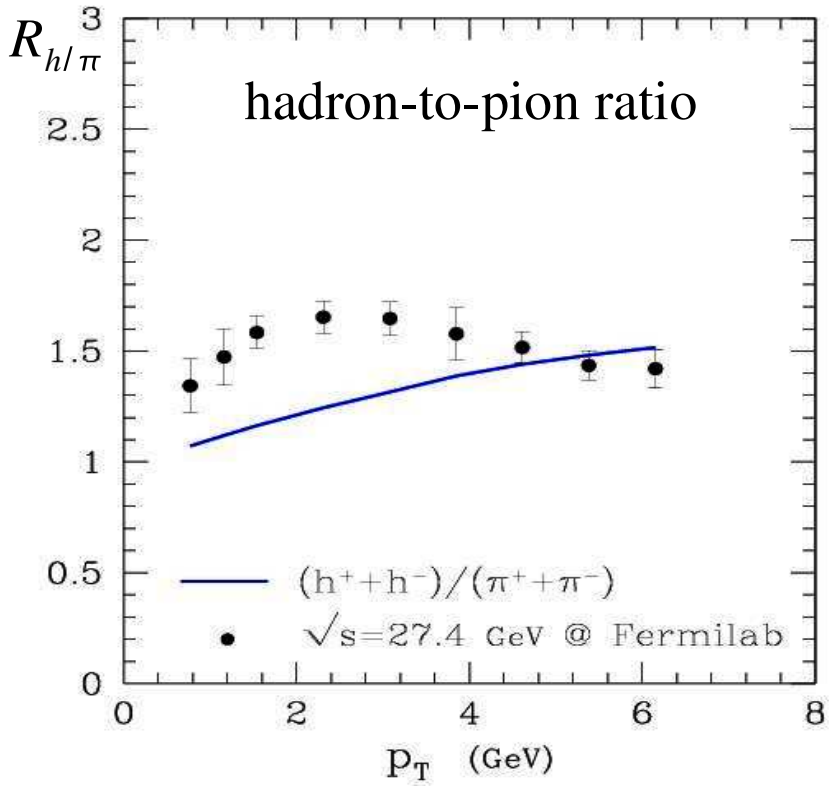

## PHENIX 200 GeV



# Back to pp at Fermilab: mesons vs. baryons

Fermilab 27 GeV - Antreasyan et al. '79



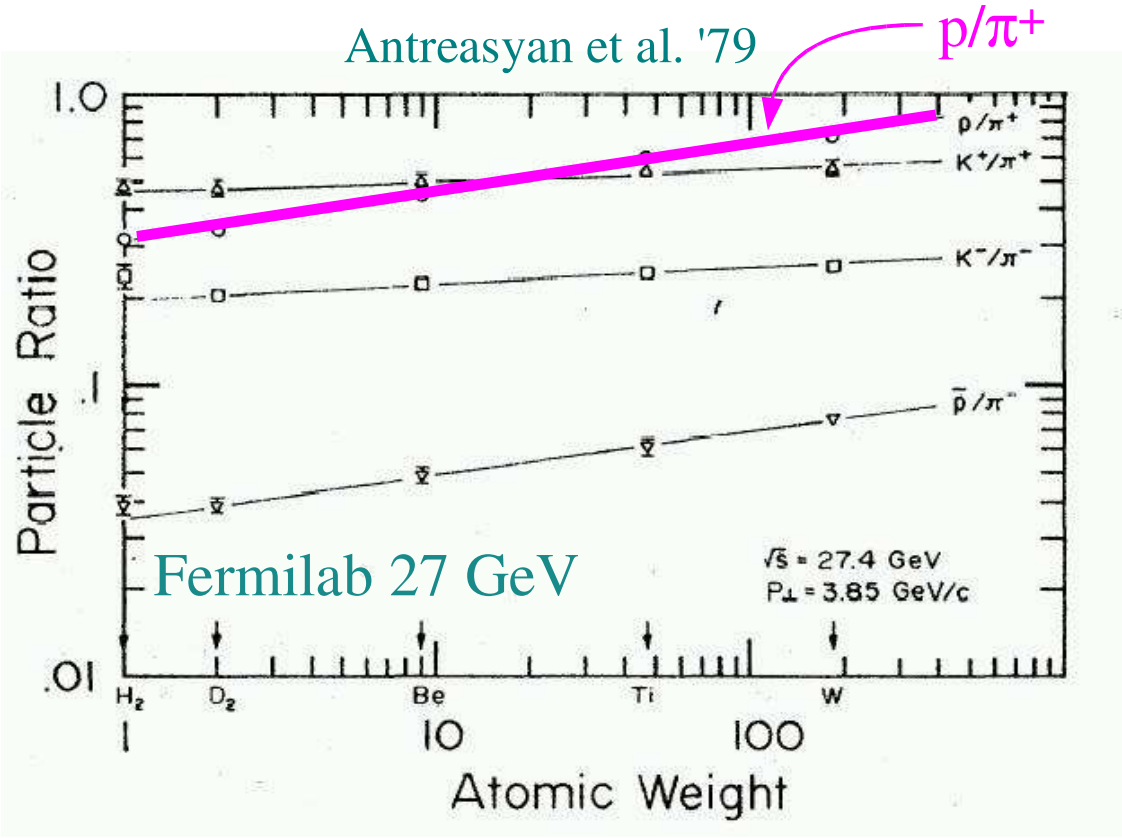




* π fairly well described
* *K* slightly underestimated at low-$p_T$

BUT...

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

# From pp to pA at Fermilab

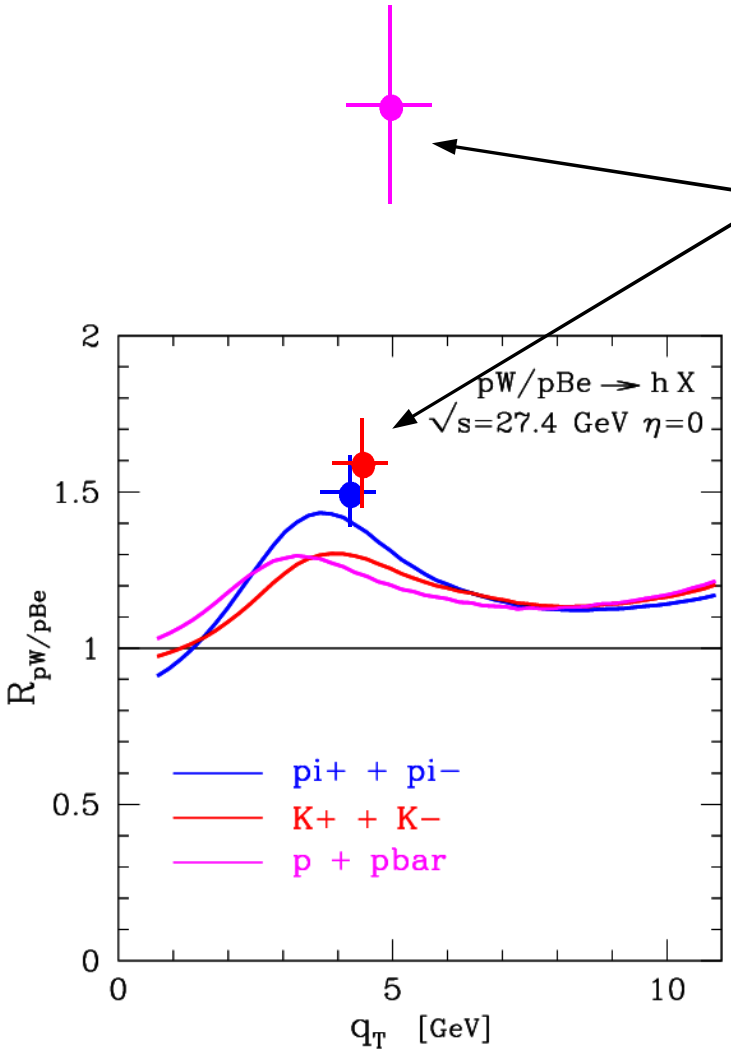



Baryons are even worse in pA collisions....

## 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?)

# Flavour dependence of Cronin effect at Fermilab

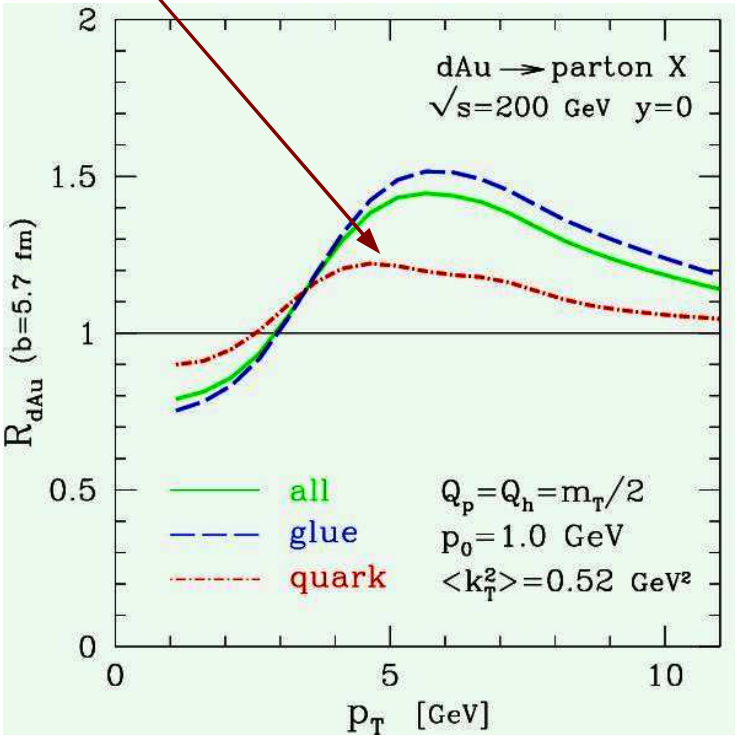


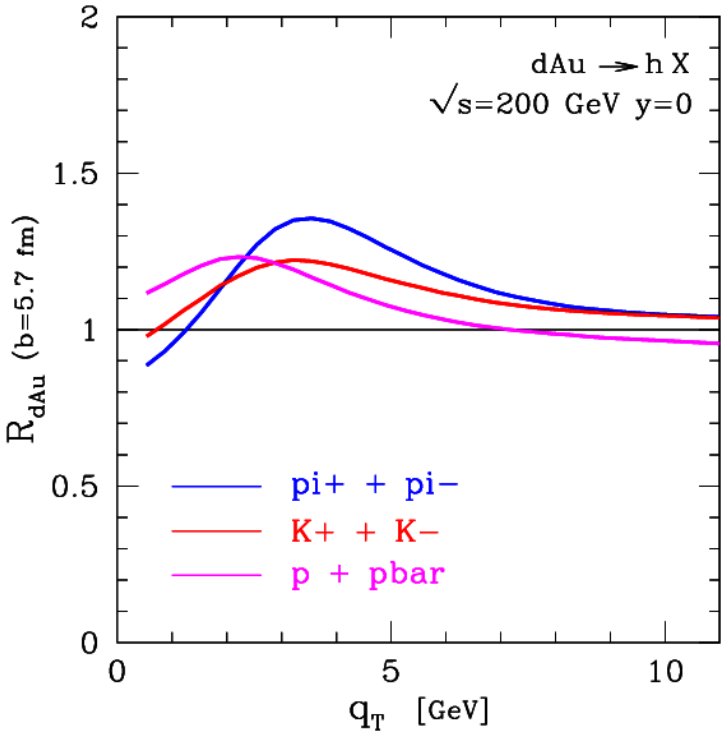

As expected,
pions: fairly described
kaons: slightly too low
protons: completely missed

# Partons vs. hadrons at RHIC

quarks: smaller peak, shifted left

π comes mostly from gluons
K feels also quarks




BUT: is it justified to take $p_{0/\,quarks} = p_{0/\,gluons}$ ?

**IF** $p_0 \Leftrightarrow$ unitarity in pp coll. $\Rightarrow$ $p_{0/\,quarks} \sim \frac{4}{9} p_{0/\,gluons}$

$\Rightarrow$ Need data on $\pi$ and $K$ in pp collision at least $0.7\,GeV \leqslant p_T \leqslant 8\,GeV$

# Conclusions

**Glauber-Eikonal model (= pQCD + rescatterings):**

- pA collisions as multiparton scatterings
- "almost free" nucleons + unitarization
- Correct hadron spectrum in the "pp" limit
- Correct magnitude of Cronin effect for pions, no extra phenomenological parameters
- Flavour dependence still to be understood

**Good baseline** {
- **to search where "saturation" begins (dA)**
- **to measure final state effects (AA)**
- **to compare pA/AA when pA is missing (e.g. at SPS)**

# Part IV

# Building a dictionary: pQCD vs. CGC and saturation

**The dipole representation allows to connect pQCD to other formalisms for multiple scatterings:**

- Kovchegov, Mueller
- Jalilian-Marian, Gelis, Dumitru
- Kopeliovich et al.

**1)** expanding $\sigma_{hard}(r_T)$ to first order in $r_T$ and using DGLAP equation:

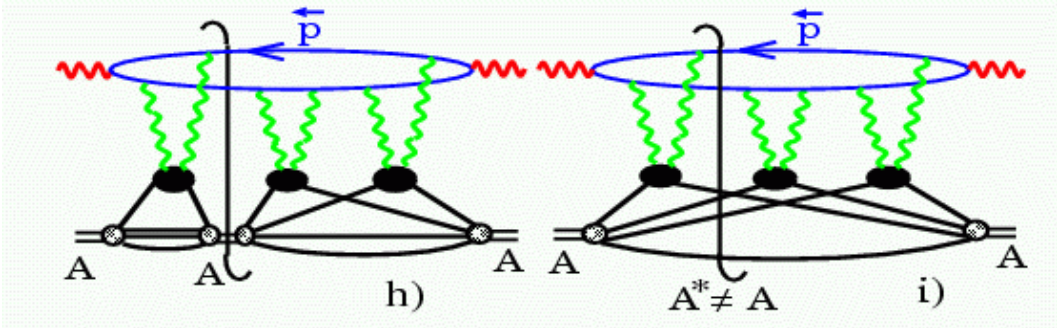
$$\sigma_{hard}(r_T) = r_T^2 Q_s^2 / 4 + O(r_T^4)$$

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

**saturation momentum**

Mueller et al.

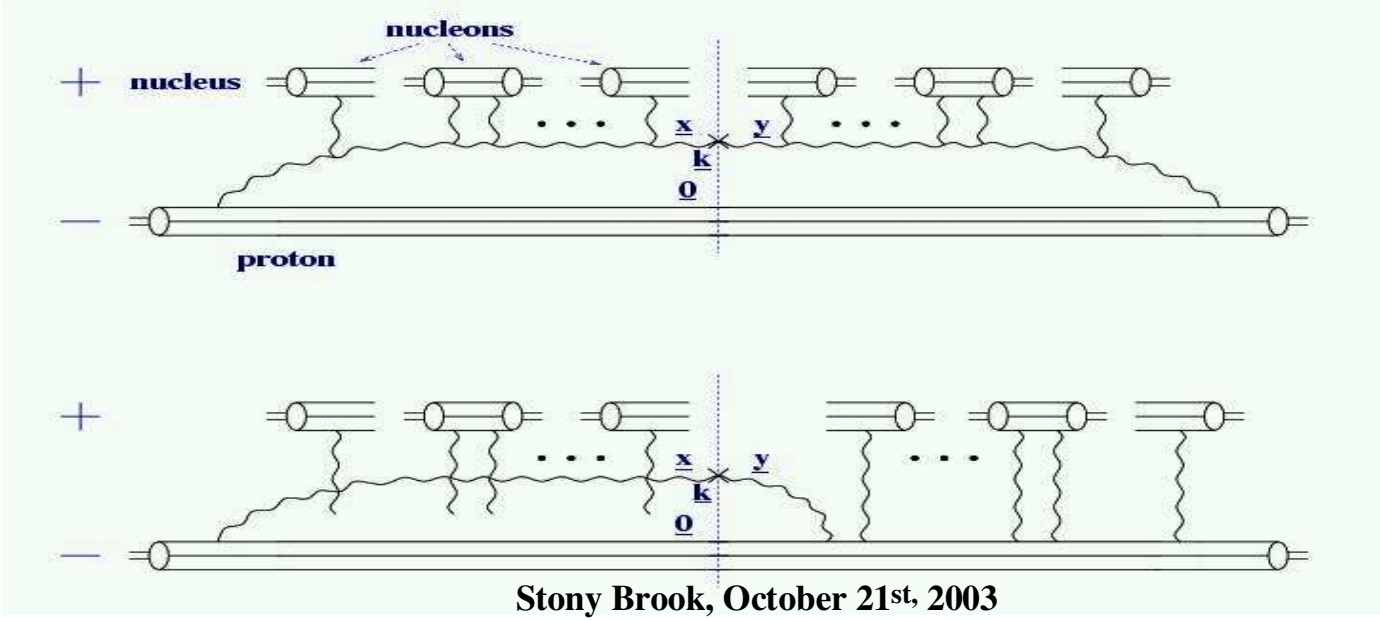
**2)** Though unitarity has been implemented in the previous formula, we still miss the diffractive contribution (important at low-pT):




When including this, one* recovers Y. Kovchegov's formula for dipole-nucleus scattering:

* N.N.Nikolaev, lectures at Columbia U.

$$\frac{d\sigma^{pA}}{d^2k\,dy} = \int d^2b\,d^2x\,d^2y\,\frac{\alpha_s C_F}{\pi^2\,(2\pi)^2}\,\frac{\underline{x}\cdot\underline{y}}{\underline{x}^2\underline{y}^2}\,e^{i\underline{k}\cdot(\underline{x}-\underline{y})}\left(1-e^{-\underline{x}^2\,Q_s^2/4}-e^{-\underline{y}^2\,Q_s^2/4}+e^{-(\underline{x}-\underline{y})^2\,Q_s^2/4}\right).$$



## 3) qA scattering and the dipole: Dumitru, Gelis, Jalilian-Marian '02

Related to the $q\bar{q}$-nucleus cross-section:

$$\frac{d\sigma_{qA}^{A}}{d^2b\,dx\,d^2p_T} = \int \frac{d^2r}{(2\pi)^2}\, e^{i\vec{p}_T\cdot\vec{r}_T}\, S(r_T;b)$$

- If straight popagation & no gluon bremsstrahlung $\Rightarrow$ in the Gaussian Approximation:

Iancu, Itakura, McLerran '03

$$S_{GA}(r_T;b) = \exp\left\{ -\underbrace{4\pi\alpha_s N_c \int d^2k_T \frac{\mu_y(k_T)}{k_T^4}\left[1-e^{-\vec{k}_T\cdot\vec{r}_T}\right]}_{\tilde{\sigma}_{CGC}(r_T)}\, \tau_A(b)\right\}$$

where $\mu_y$ is interpreted as unintegrated gluon PDF, and has two limits

$$\mu_y(k_T,b) = \begin{cases} k_T^2\phi_y(k_T,b) \propto k_t^2\alpha_s \int_{-\infty}^{y} dy' \frac{\partial x' G(x',k_T^2)}{\partial k_T^2}\tau_A(b) & k_T^2 \rangle\rangle Q_s^2 \\ \delta_y k_T^2 \gamma_A(b) & k_T^2 \langle\langle Q_s^2 \end{cases}$$

with $Q_s^2 = Q_0^2\, e^{c\alpha_s(y-y_0)}$ the saturation momentum.

- In the high-$k_T$ limit $S_{GA}$ very similar to $S_{pQCD}$, but self-regulates the IR divergences.

# CGC vs. pQCD+rescatterings

A.A. and M.Gyulassy, nucl-th/0304083

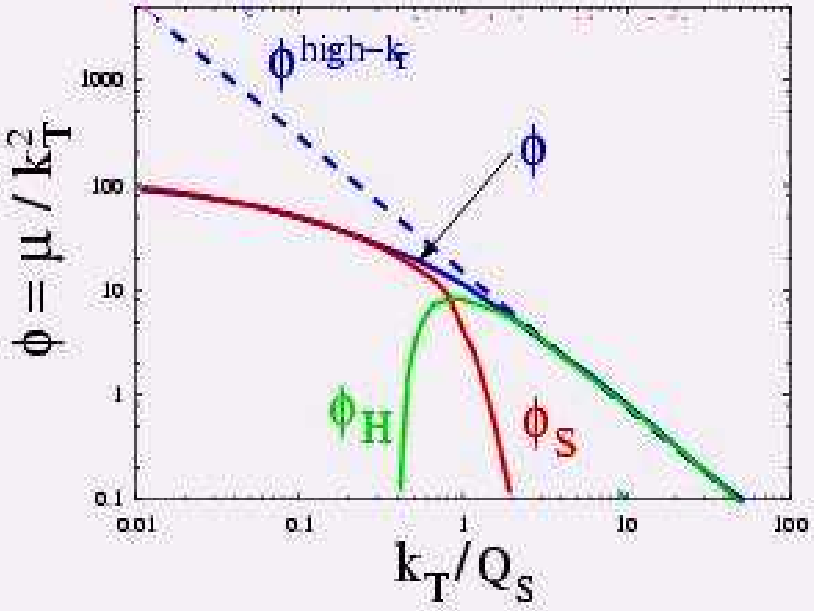
**Step 1** In CGC separate "hard" and "soft" interactions:

Def. $\mu_y = \mu_y^S + \mu_y^H$ with with $\begin{cases} \mu_y^H = \dfrac{4\pi^2}{N_c^2-1} \dfrac{dxG(x,k_T^2)}{d\ln(k_T^2)} \times \dfrac{k_T^4}{(k_T^2+Q_s^2)^2} \\ \mu_y^S = \mu_y - \mu_y^H \end{cases}$

Accordingly: $\tilde{\sigma}_{CGC}(r_T) = \tilde{\sigma}_S(r_T) + \tilde{\sigma}_H(r_T)$

- The "hard" dipole-nucleon cross-section is then

$$\tilde{\sigma}_H \propto \int d^2k_T \frac{\mu_y^{\text{high}-k_T}(k_T,b)}{(k_T^2+Q_s^2)^2}\left[1-e^{-\vec{k}_T\cdot\vec{r}_T}\right]$$



**Step 2** Use DGLAP to approximate unintegrated PDF with integrated ones:

$$\frac{d\,xG(x,k_T^2)}{d\,\ln k_T^2} \approx \frac{\alpha_s N_c}{\pi}\int_x^1 dx'\; G(x',k_T^2)$$

and take $G(x,Q^2)$ from, e.g., the CTEQ5 parametrization.

$\Longrightarrow$ We obtain the same as in pQCD but with $p_0 = Q_s$:

$$\tilde{\sigma}_H\, y_A \propto \int d^2k_T \frac{\int_{-\infty}^{y} dy' x' G(x',k_T^2) \tau_A(b)}{(k_T^2+Q_s^2)^2}\left[1-e^{-\vec{k}_T\cdot\vec{r}_T}\right]$$

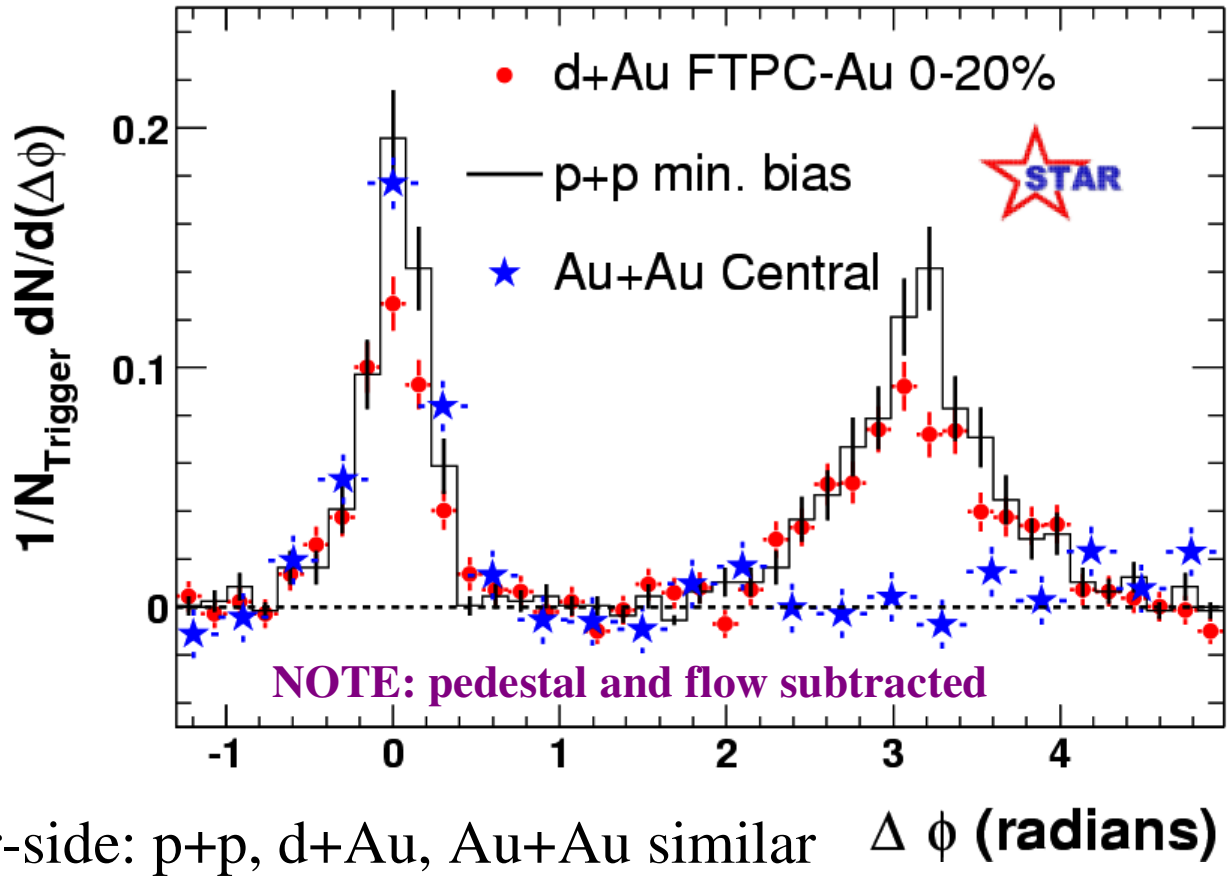
**Step 3** Assume dominance of hard scatterings, e.g.,

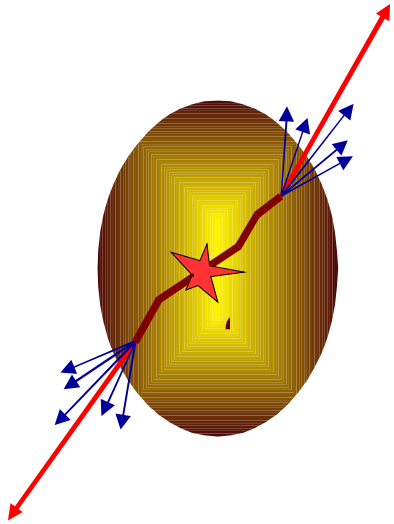
- semihard hadron spectra ($p_T \gtrsim 1-2GeV$)
- Integrated multiplicities: $\frac{d\sigma_q}{dx\,d^2b} = \underbrace{e^{-\sigma_H \tau_A}\left[1-e^{-\sigma_S \tau_A}\right]}_{\text{soft part}} + \underbrace{\left[1-e^{-\sigma_H \tau_A}\right]}_{\text{hard part}} \approx \left[1-e^{-\sigma_H \tau_A}\right]$

$\Longrightarrow$ In the region where all the above is valid (high $p_T$, $Q^2 \langle\langle Q_s^2$, not too small $x$)

**CGC is nothing more than pQCD+rescatterings**

# Azimuthal distributions: pp vs. d-Au vs. Au-Au



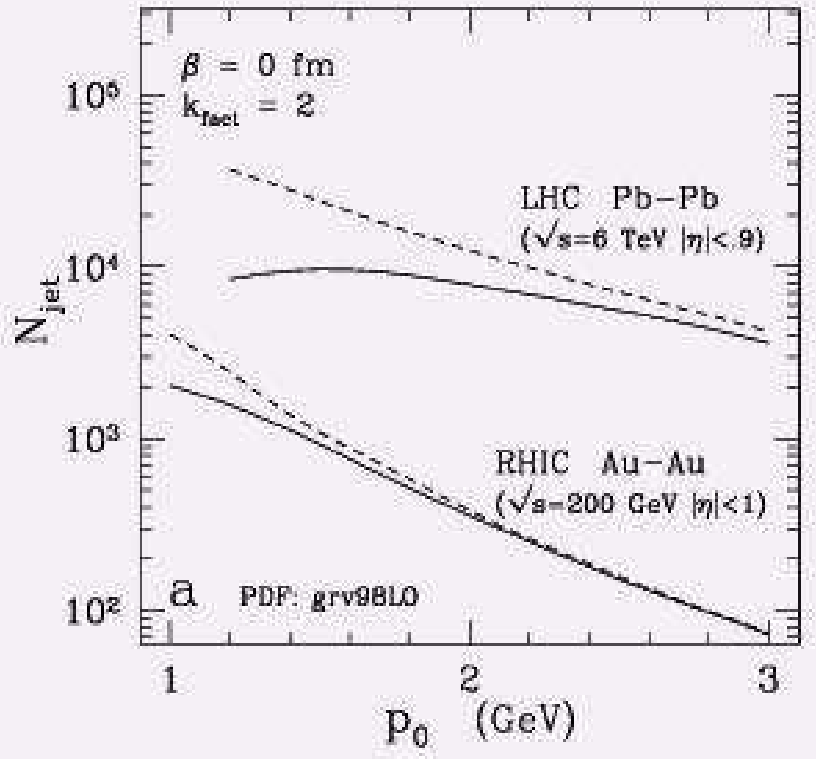



Near-side: p+p, d+Au, Au+Au similar

Back-to-back: Au+Au strongly suppressed relative to p+p and d+Au

Suppression of the back-to-back correlation in central Au+Au is a final-state effect

## Initial conditions A.A., D.Treleani, Phys.Rev.D 63(2001)116002




Rescatterings vs. single-scattering:

- Less sensitive to $p_0$
- Minijet multiplicity saturates at low $p_0$:
  the black-disc regime is setting in

Choosing $p_0 = 1\text{GeV}$ at RHIC, $p_0 = 2\text{GeV}$ at LHC

$$\left.\frac{dN}{dy}\right|_{y=0} \approx \begin{array}{l} 1000 \text{ (RHIC)}, \\ 5000 \text{ (LHC)} \end{array}$$