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

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CERN, 2 September 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 in pA / dA collisions

- From pp to pA collisions
- Comparison to Fermilab and RHIC data
- Centrality dependence

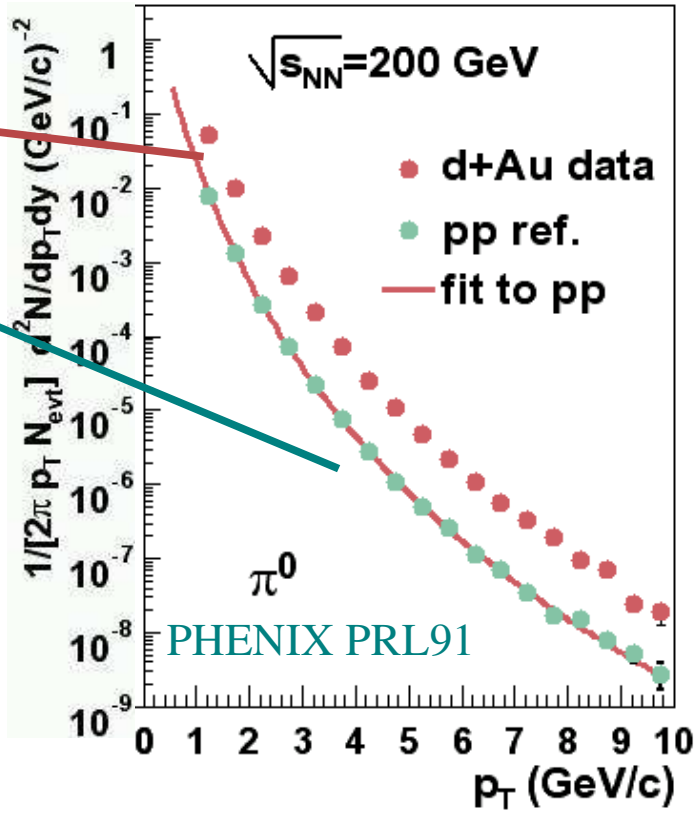
Part III - The elusive baryons

- Cronin effect: mesons vs. baryons

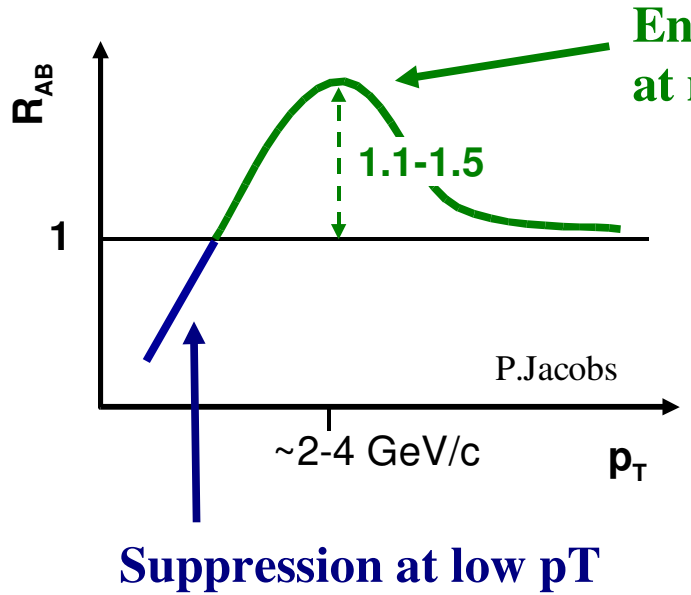
Cronin ratio of inclusive spectra

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

Binary collision scaling **p+p reference**

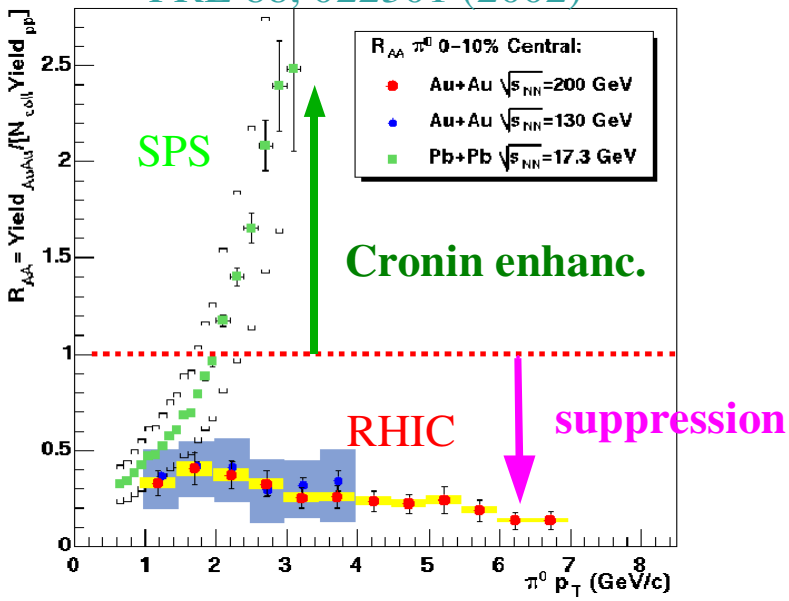


At low-energy pA and AA:

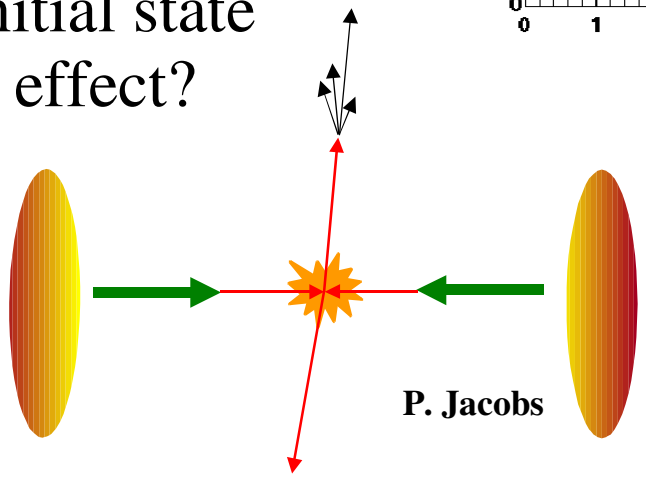


AA collisions: SPS vs. RHIC

PRL 88, 022301 (2002)



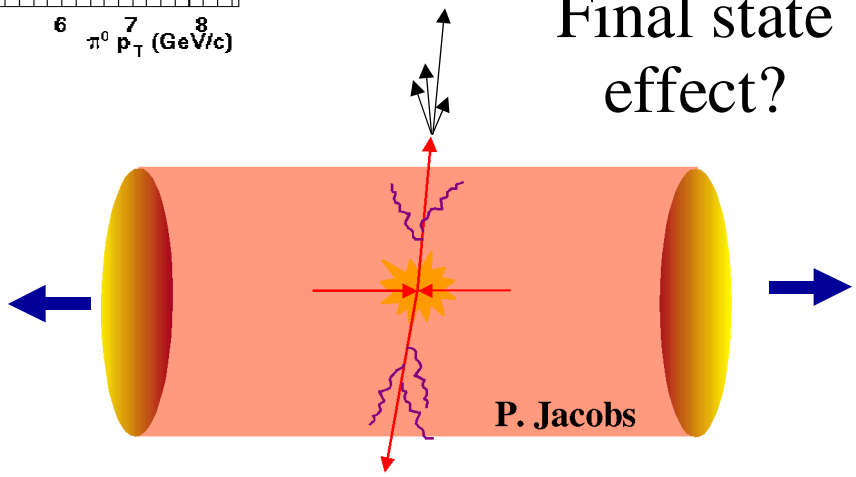
Initial state effect?



strong modification of Au wavefunction (gluon saturation)

or

Final state effect?

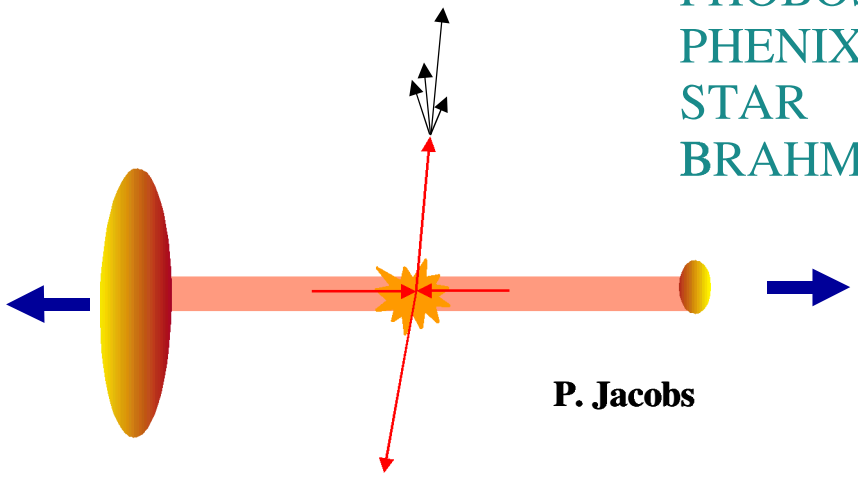


partonic energy loss in dense medium generated in collision

How to discriminate?

Turn off final state
⇒ h+Au collisions

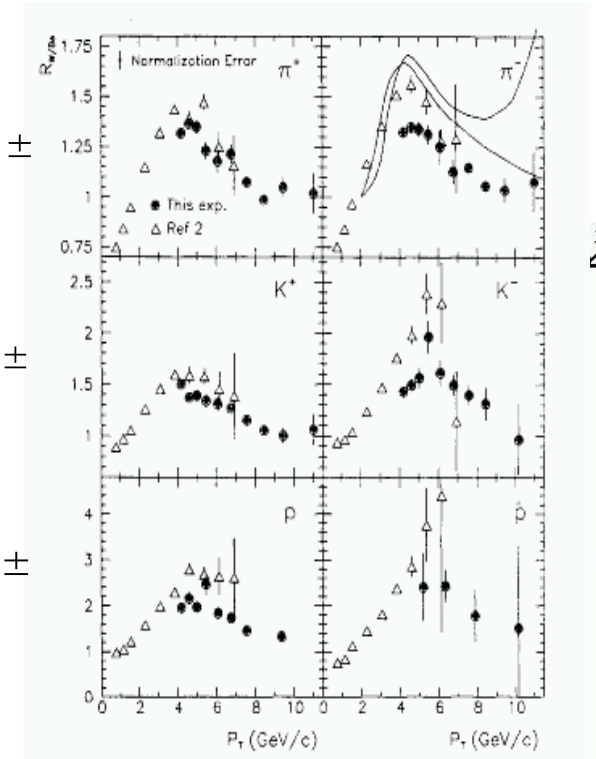
PHOBOS PRL91(03)072302
PHENIX " 03
STAR " 04
BRAHMS " 05



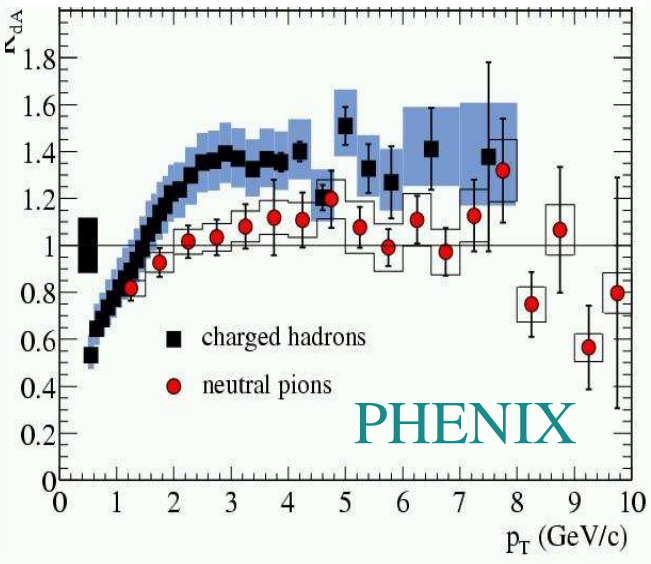
$\pi^{\pm}$

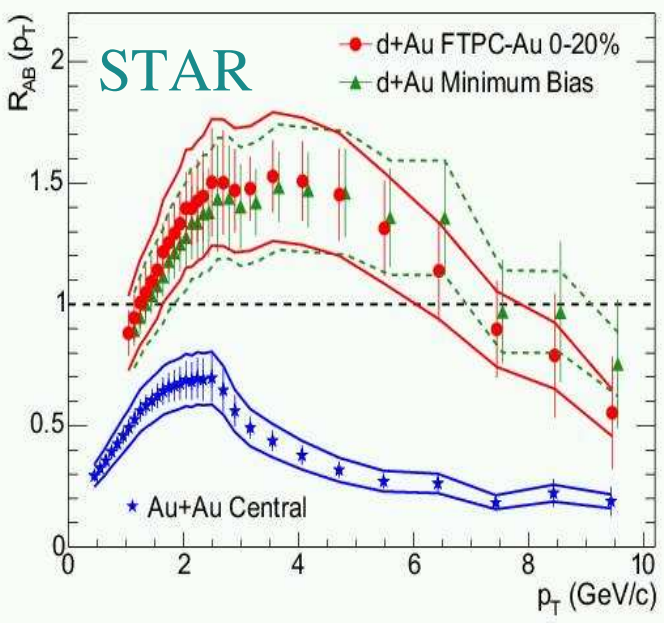
$K^{\pm}$

$p^{\pm}$



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

Soft partonic rescatterings

- soft partonic -

B. Kopeliovich et al.

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

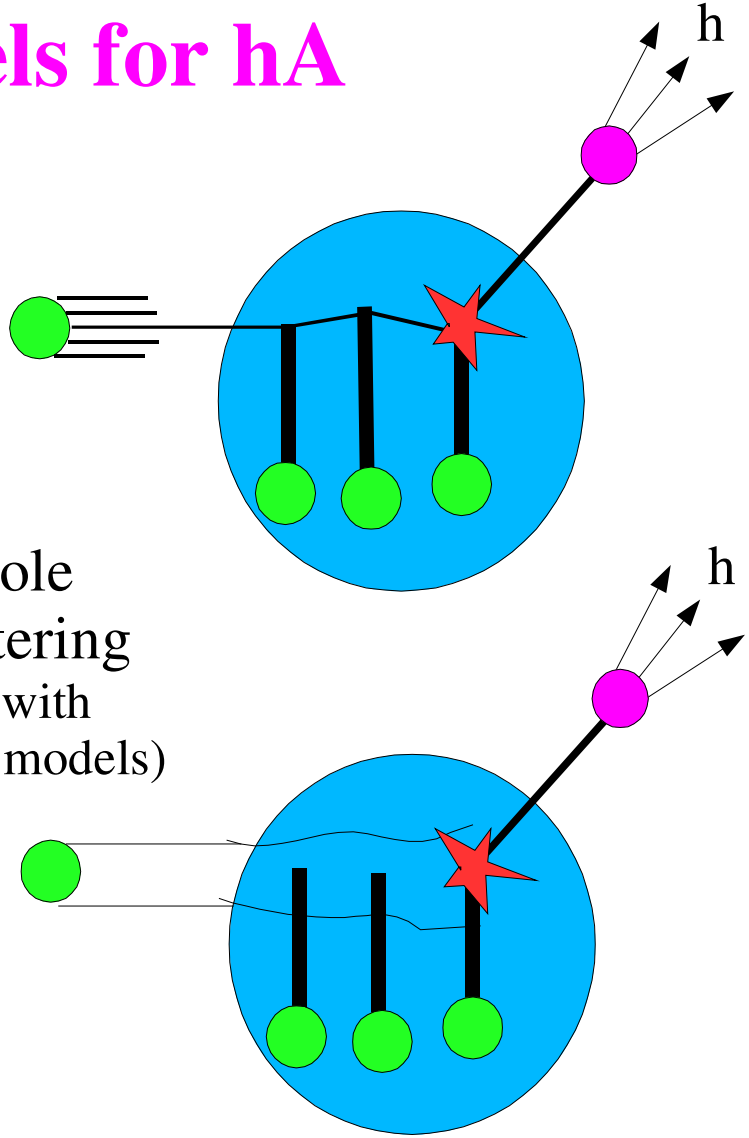
Glauber-Eikonal Approximated

- 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**

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.

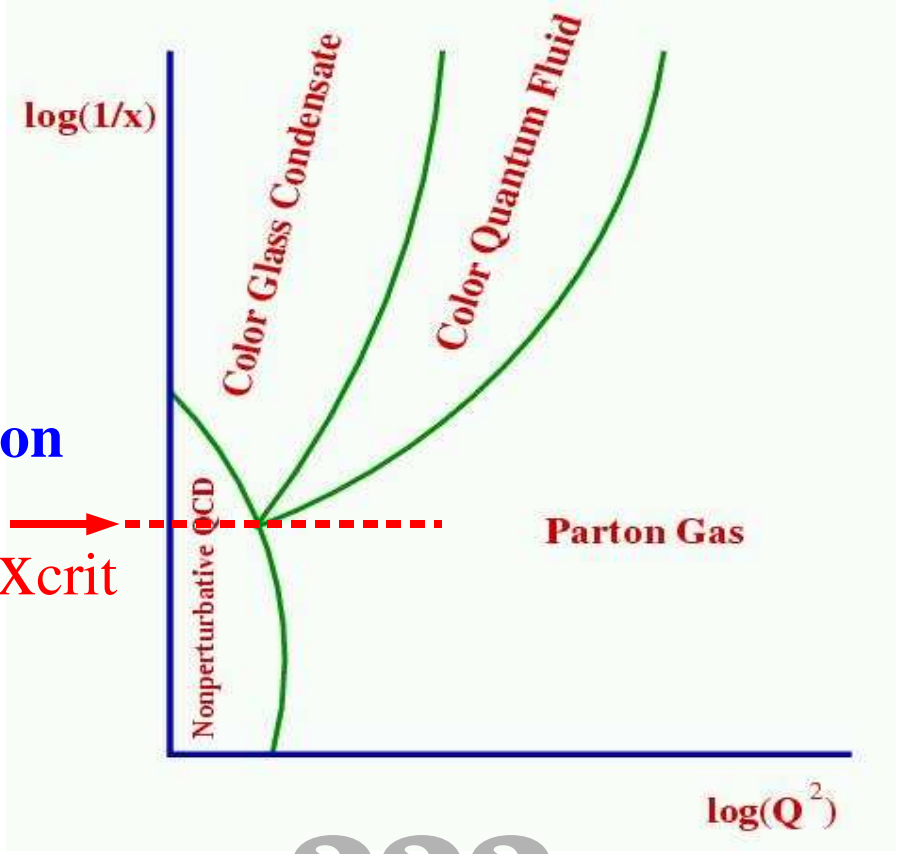
CGC = MV + quantum evolution

Iancu, Itakura, McLerran + ...

CGC inspired models

Kharzeev, Levin, McLerran

Kharzeev, Kovchegov, Tuchin



???

QUESTIONS...

How small is xcrit?

Where does RHIC stand?

Part I

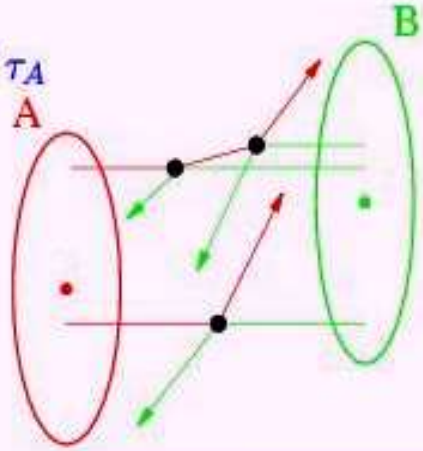
Glauber-Eikonal models:
pQCD + partonic rescatterings

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

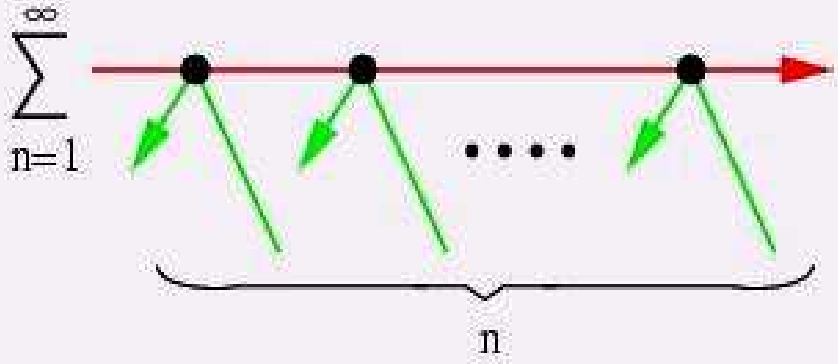
$\rightsquigarrow$ Glauber multiple scattering formula at parton level

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:

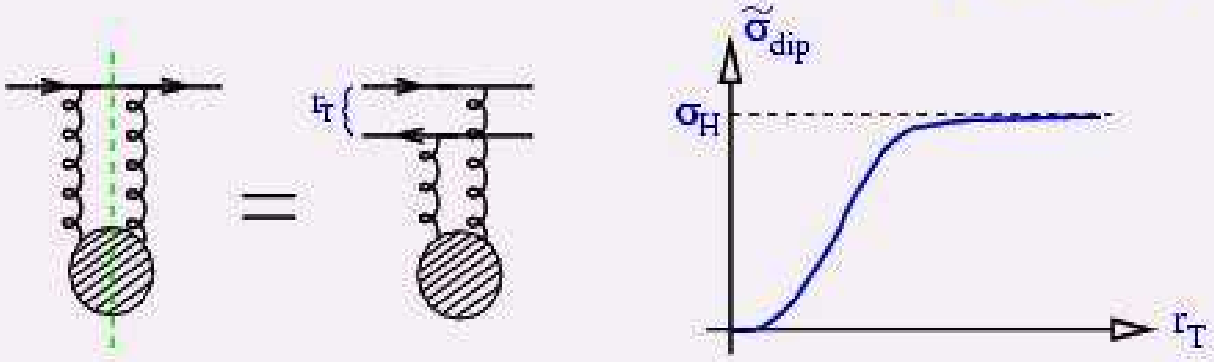
$$\frac{d\sigma^{qA}_{hard}}{d^2p_T} = \int \frac{d^2r_T}{4\pi^2} e^{-i\vec{k}_T\cdot\vec{r}_T} \left[e^{-\tilde{\sigma}^{qN}_{hard}(r_T, p_0) T_A(b)} - e^{-\sigma^{qN}_{hard}(p_0) T_A(b)} \right]$$

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

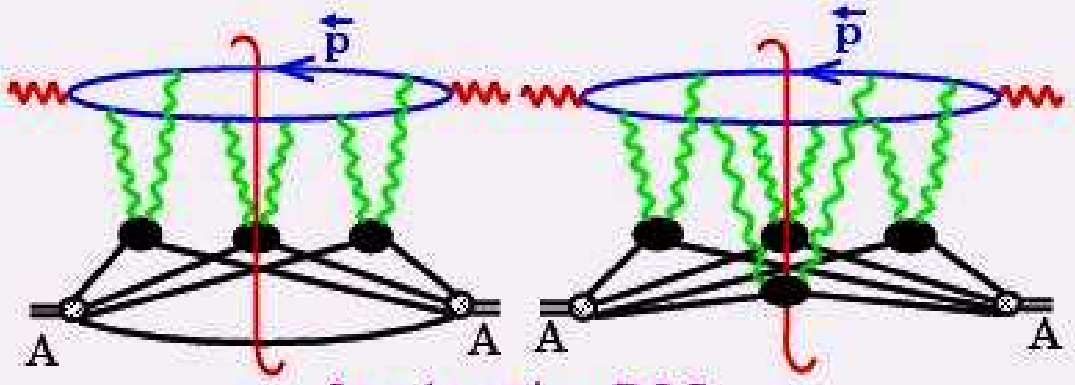
and $\sigma^{qN}_{hard}(p_0) = \int d^2k \frac{d\sigma^{qN}_{hard}}{d^2k} s$ is the integrated quark-nucleon cross section.

- $\tilde{\sigma}_{dip}(r_T)$ 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



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 pA = 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: $p_T^2 \to p_T^2 + p_0^2 = m_T^2$

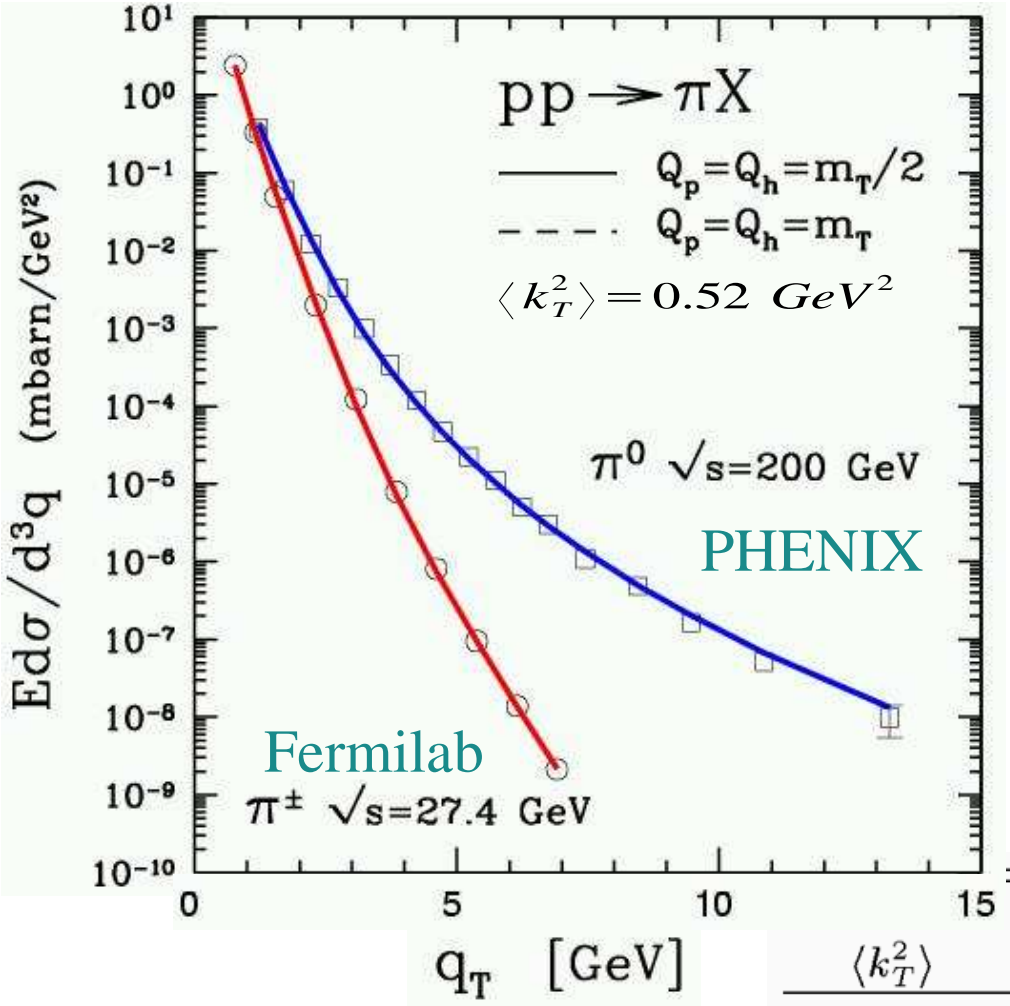
a) CHOOSE the scales: **$Q_R = Q_F = m_T/2$** (or **$Q_R = Q_F = m_T$**)

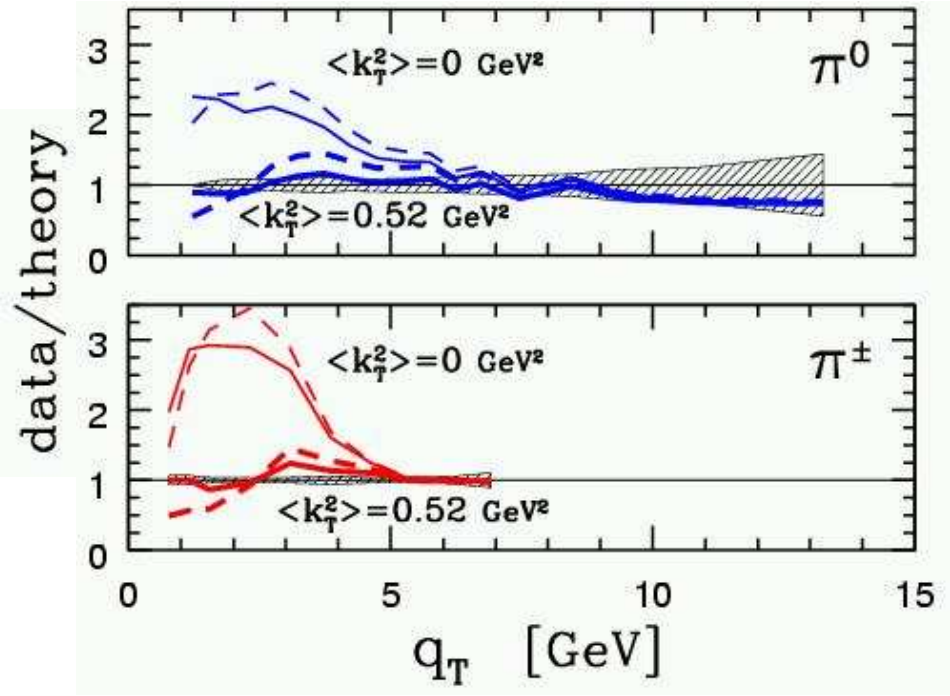
b) FIT **K=K(s)** to the **high-p_T** tail of the hadron spectrum (χ^2 fit - sensitive to the choice of scales)

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

pp collisions: π_0 at Fermilab and RHIC





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

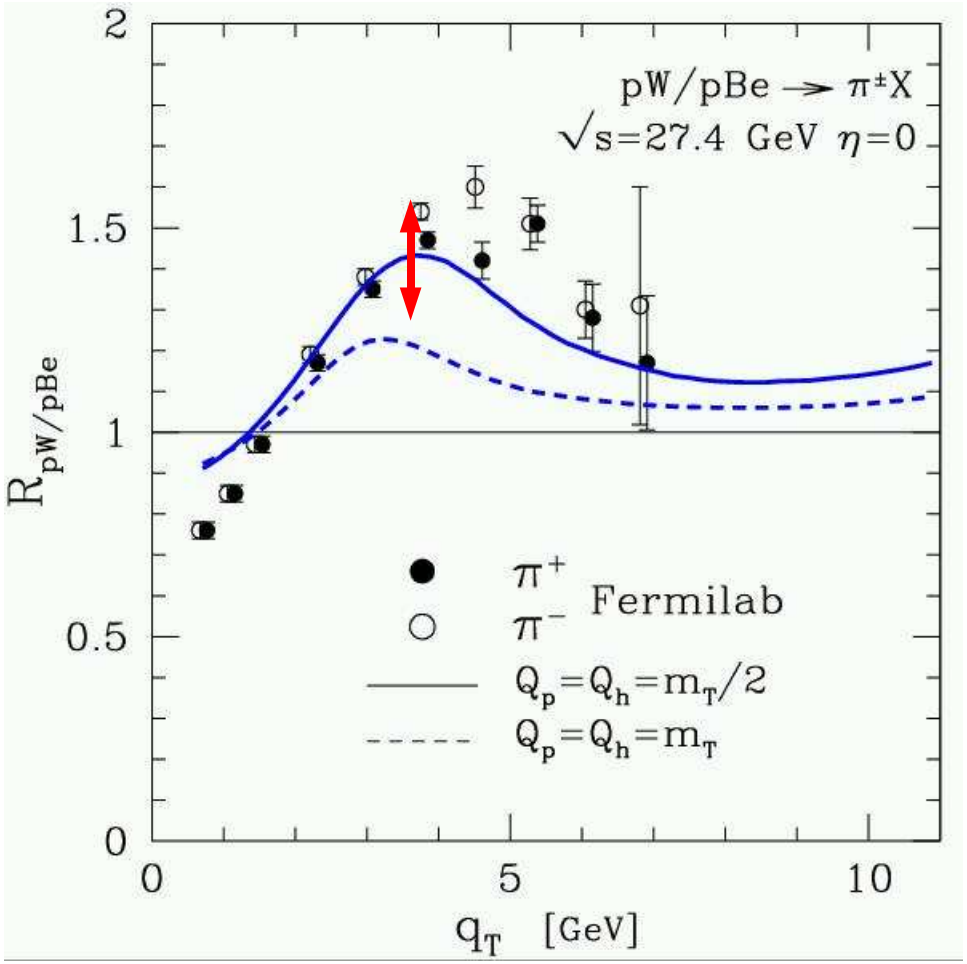
parton-nucleon cross section

- **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



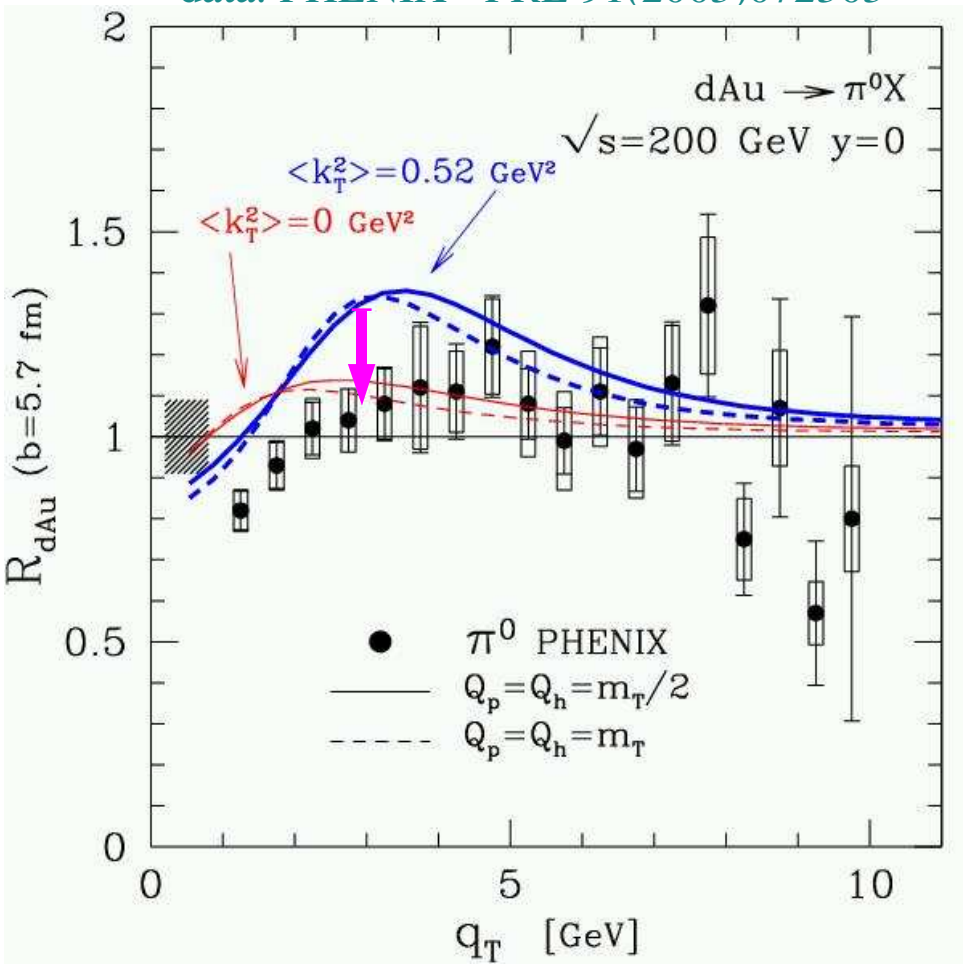
↕ = theoretical error due to fit of $p_0 = 0.8 \pm 0.1$ GeV (it's max. at the peak, dies away far from it)

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 suppress the spectrum at low p_T, barring shadowing.

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

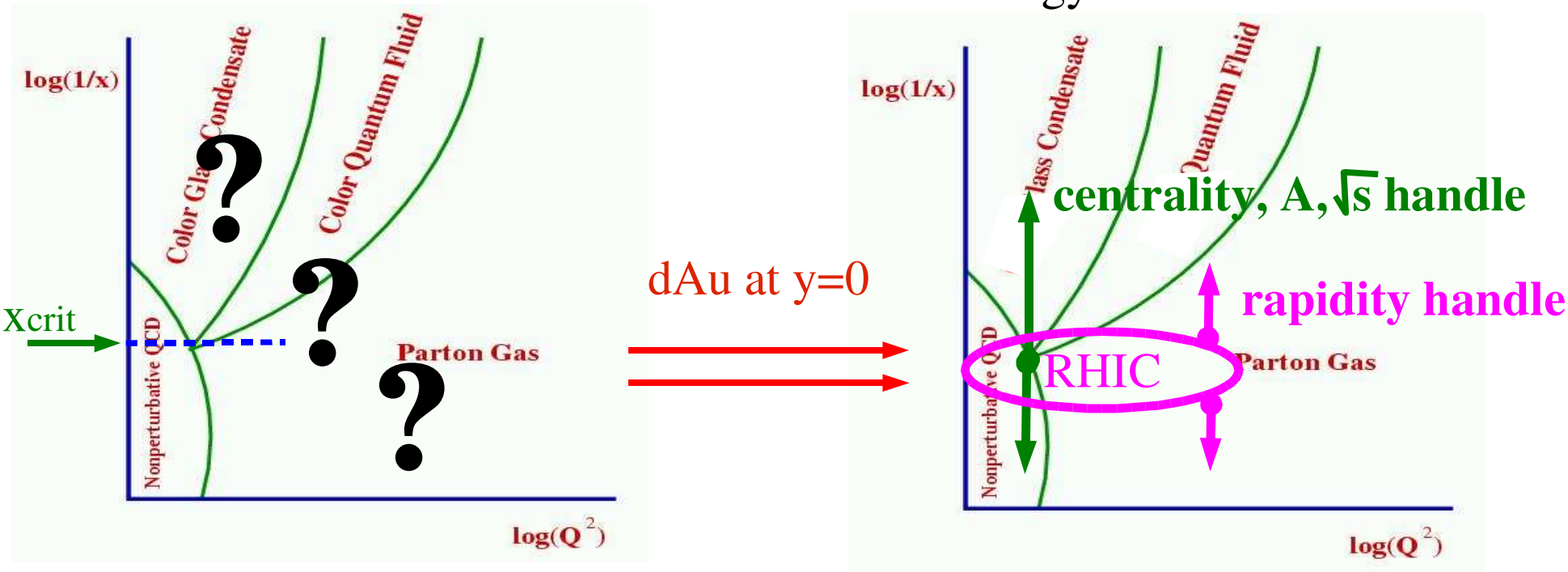
: $d\sigma^{gN}/d^2p_T \sim 1/p_T^4$ + asymptotic kinematics

$\Longrightarrow$ cannot reproduce hadron spectrum in pp collisions

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

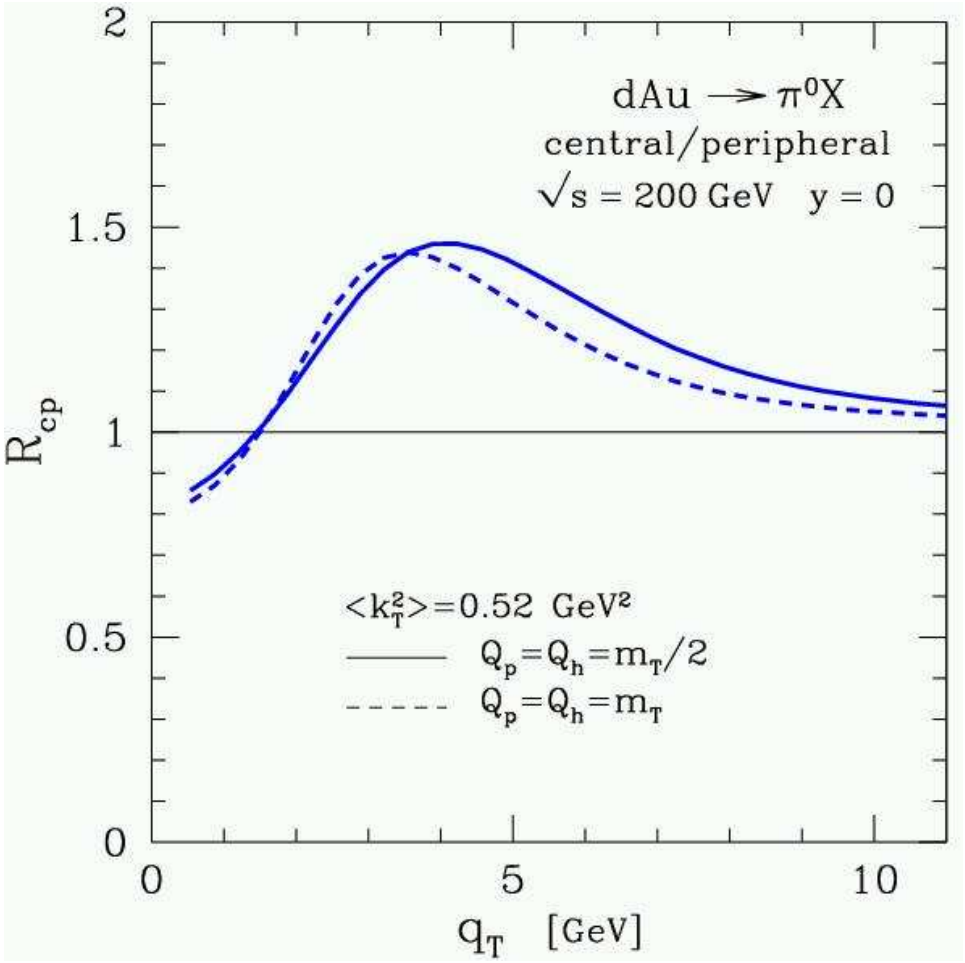
spectra in pp-collisions OK

Cronin effect at low energy OK



can find x_{crit} by comparing comp's and exp. data

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

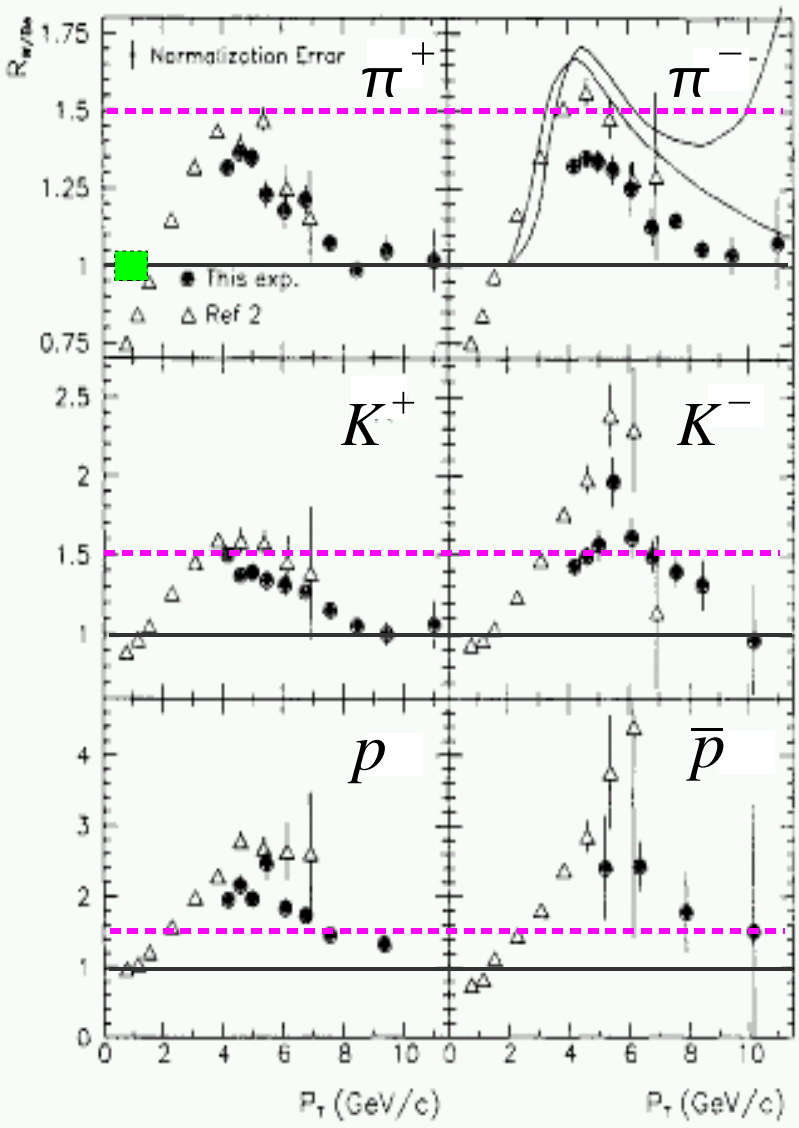
Part III

Why we compute only pions?
- the elusive baryons -

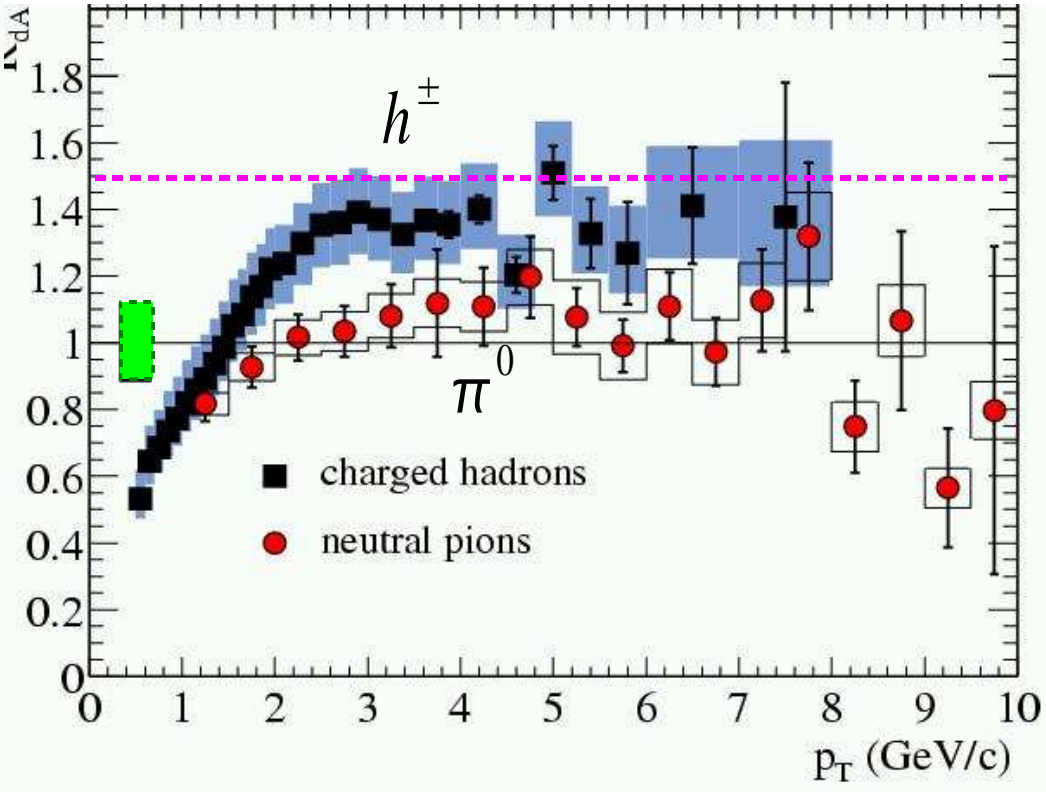
Cronin effect: pions vs. charged

Fermilab 27-39 GeV

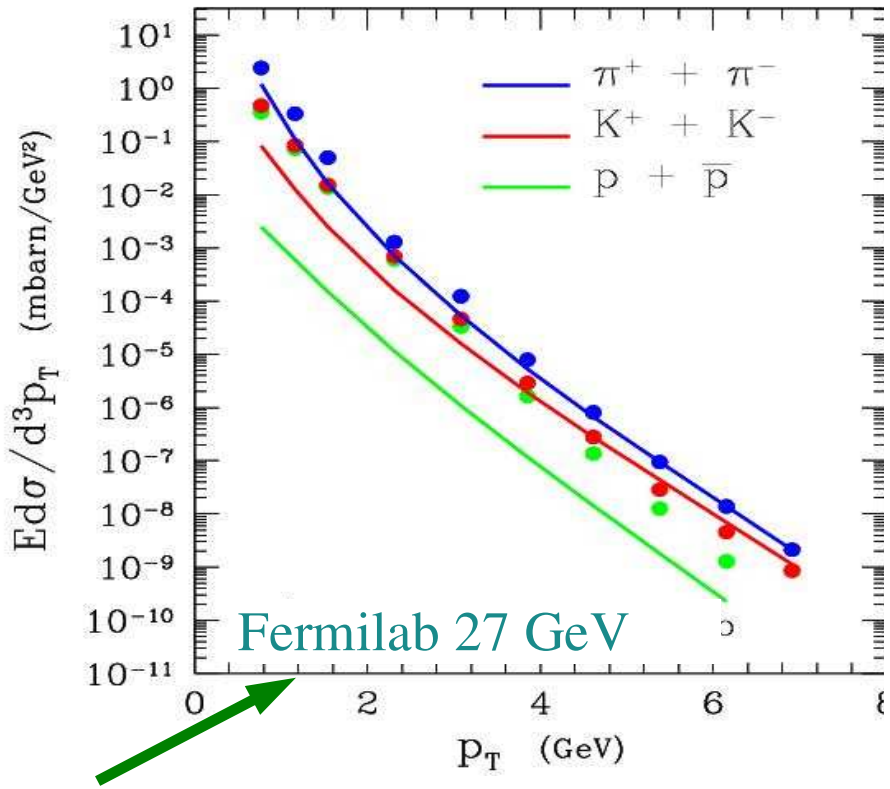
Antreasyan et al. '79; Straub et al. '92

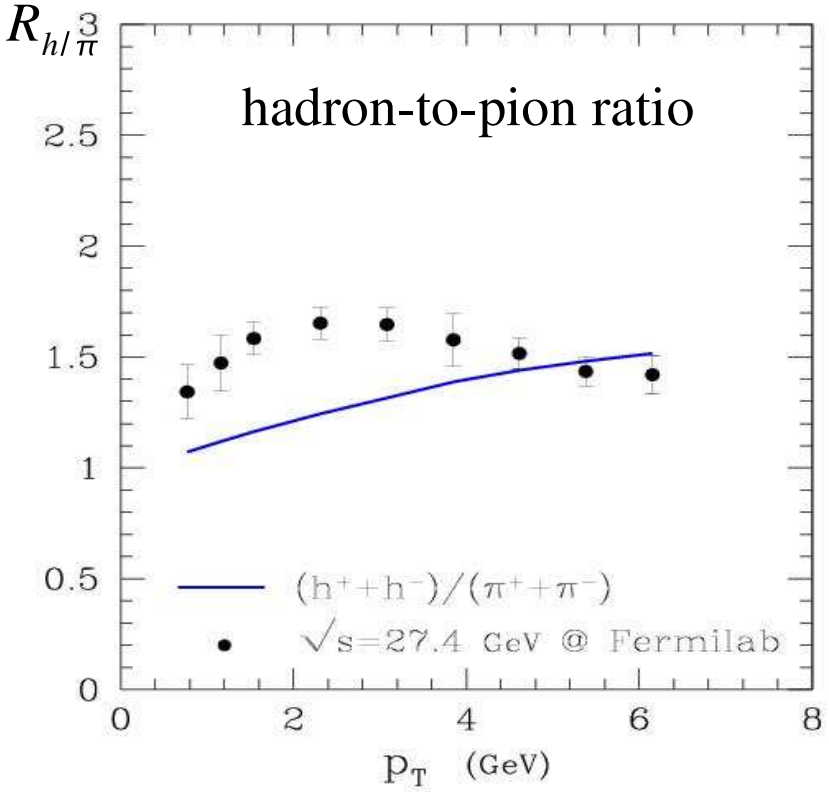


PHENIX 200 GeV



Back to pp at Fermilab: mesons vs. baryons





- K-factor fitted to pions
- no intr. kT

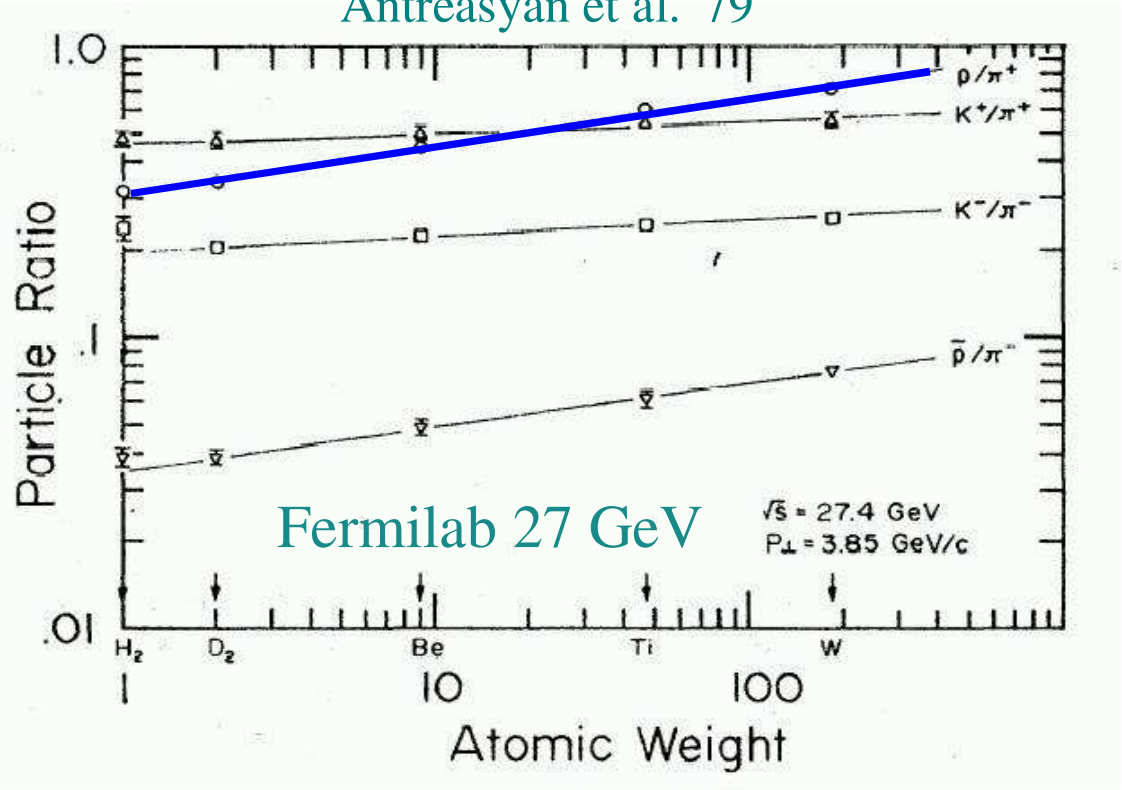
π and K ~ OK

baryons underestimated in pQCD + indep. fragmentation already in pp collisions

Data: Antreasyan et al. '79

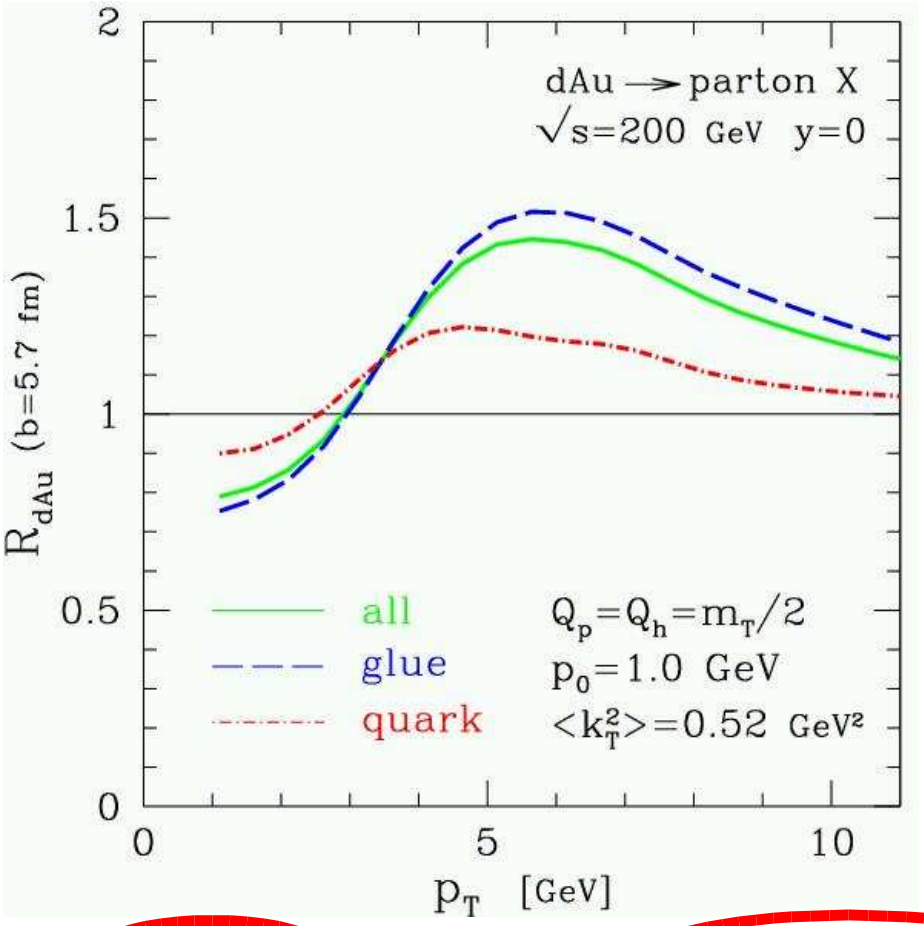
pp→pA at Fermilab

Antreasyan et al. '79



Baryons are even worse in pA collisions....

Cronin effect on parton production (RHIC)



quarks:
- smaller peak
- peak shifted to the left

BUT: is it justified to take

$$p_{0/\,quarks} = p_{0/\,gluons} \ ?$$

if $p_0 \Leftrightarrow$ unitarity in pp coll.

$$\Rightarrow p_{0/\,quarks} \sim \frac{4}{9} p_{0/\,gluons}$$

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

- π come mostly from gluons
- K mostly from quarks

Baryon excess - possible solutions

- Glauber-Eikonal model:
  unitarity corrections in pp -> different p0 for gluons and quarks

- Glauber-Eikonal Approximated:
  different $\langle k_T \rangle$-broadening for baryons and mesons Fai,Zhang '03
  (may be attacked experimentally)

- new mechanism: hadronization by parton recombination at small p_T
  Greco,Ko,Levai '03 - Bass,Fries,Mueller,Nonaka '03
  (already in pp coll's? what about 2 part's corr's?)

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, with no extra phenomenological parameters

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:

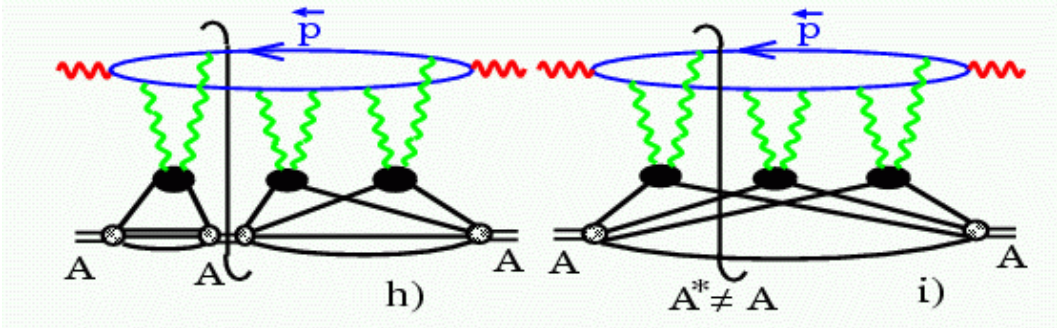
$$\sigma_{hard}(r_T) = r_T^2 Q_s^2 / 4 + O(r_T^4)$$

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.

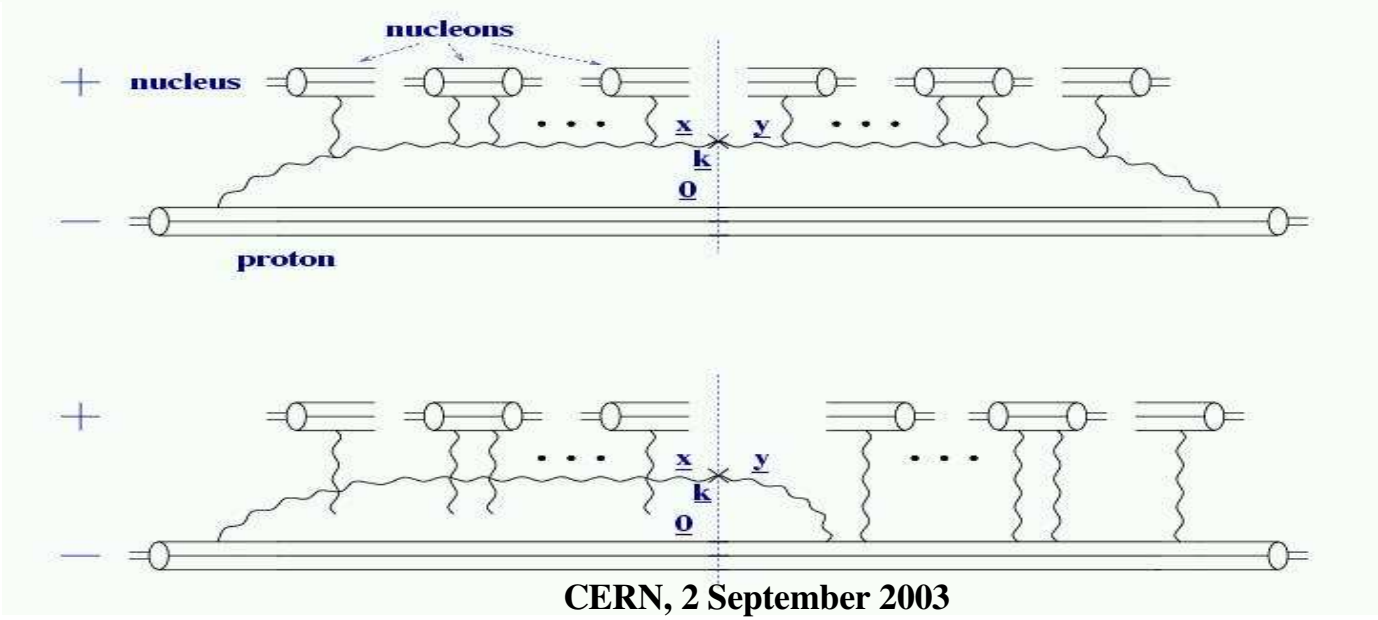
2) Though unitarity has been implemented in the previous formula, we still miss the diffractive contribution (important at low-pT):



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:

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

- 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 μ_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

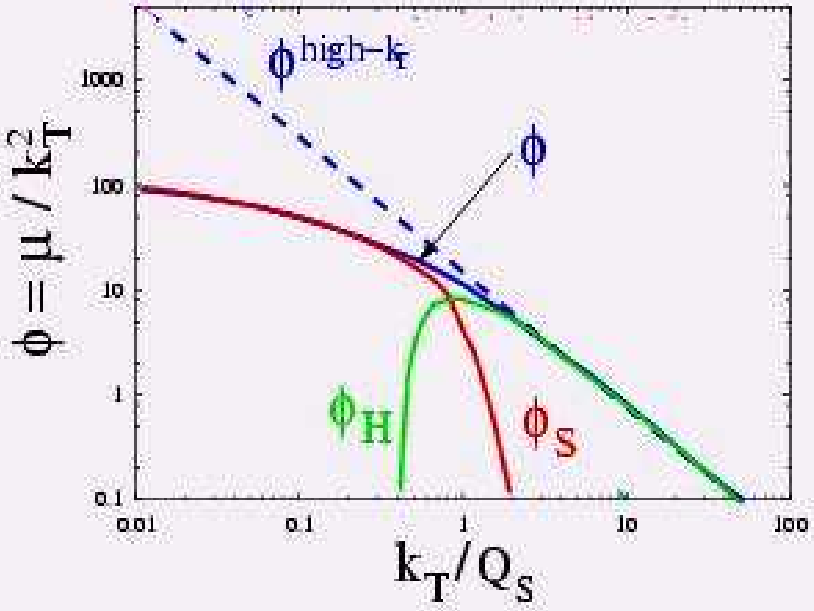
Step 1 In CGC separate "hard" and "soft" interactions:

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 $p_0 = Q_s$:

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

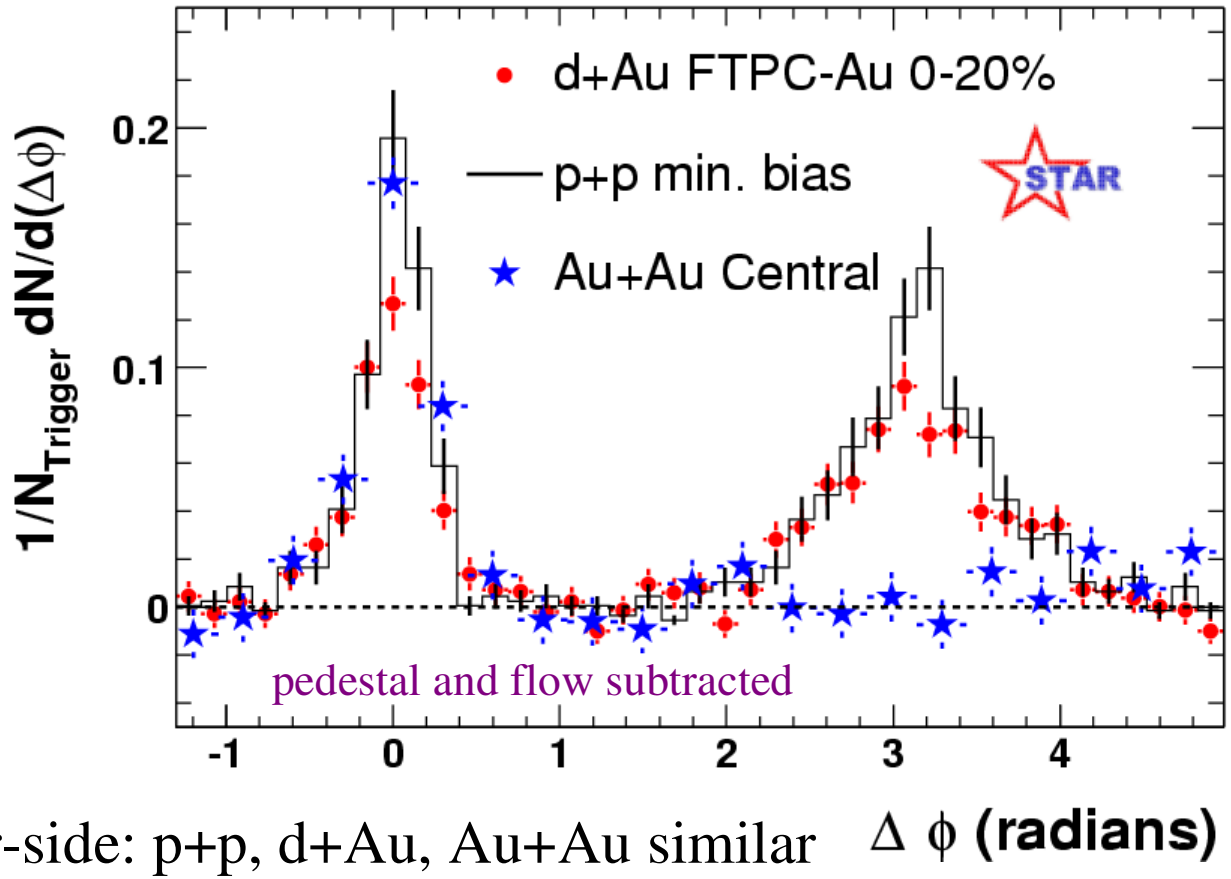
Step 3 Assume dominance of hard scatterings, e.g.,

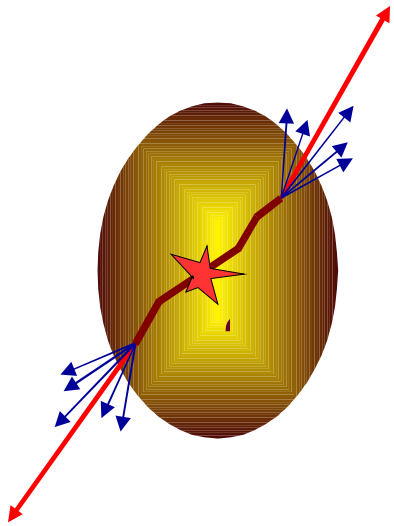
- semihard hadron spectra ($p_T \gtrsim 1-2GeV$)
- Integrated multiplicities: $\frac{d\sigma_q}{dx\,d^2b} = \underbrace{e^{-\sigma_H \tau_A}\left[1-e^{-\sigma_S \tau_A}\right]}_{\text{soft part}} + \underbrace{\left[1-e^{-\sigma_H \tau_A}\right]}_{\text{hard part}} \approx \left[1-e^{-\sigma_H \tau_A}\right]$

$\Longrightarrow$ 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



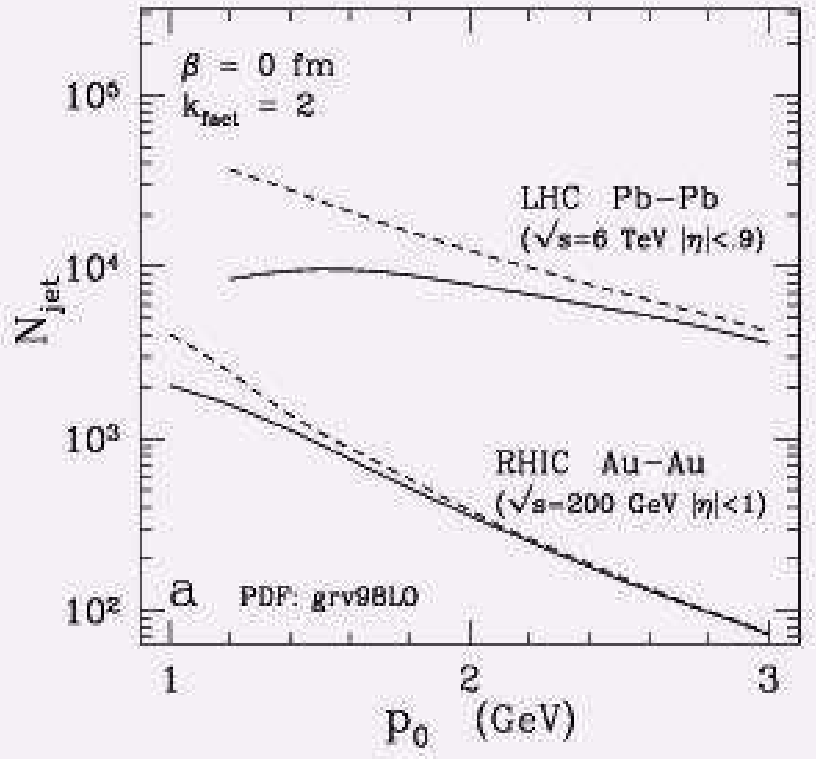


Near-side: p+p, d+Au, Au+Au similar

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

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