Cronin effect and hadron formation times in dA and eA collisions at RHIC and HERMES

Alberto Accardi
Columbia U.

Gießen, 1 September 2003

Overview

Intro - pA, AA and the QGP

Part I - Cronin effect in pA/dA collisions: Glauber-Eikonal models

- pQCD + Glauber rescatterings of partons
- Comparison to Fermilab and RHIC data
- Centrality dependence

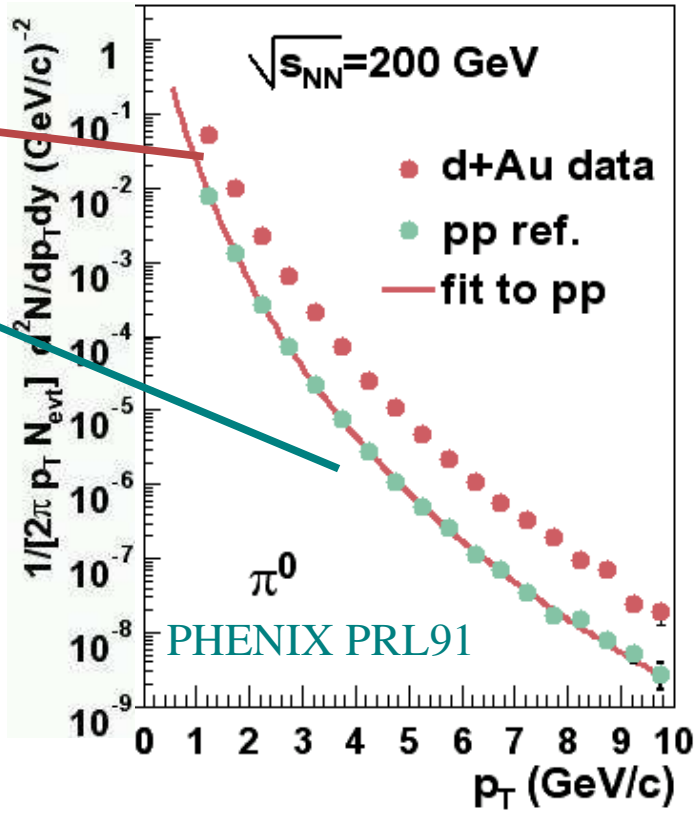
Part II - Hadron formation times and eA collisions

- Nuclear absorption of hadrons and rescaling of FF's
- Comparison with HERMES data
- Other models: absorption vs. energy-loss

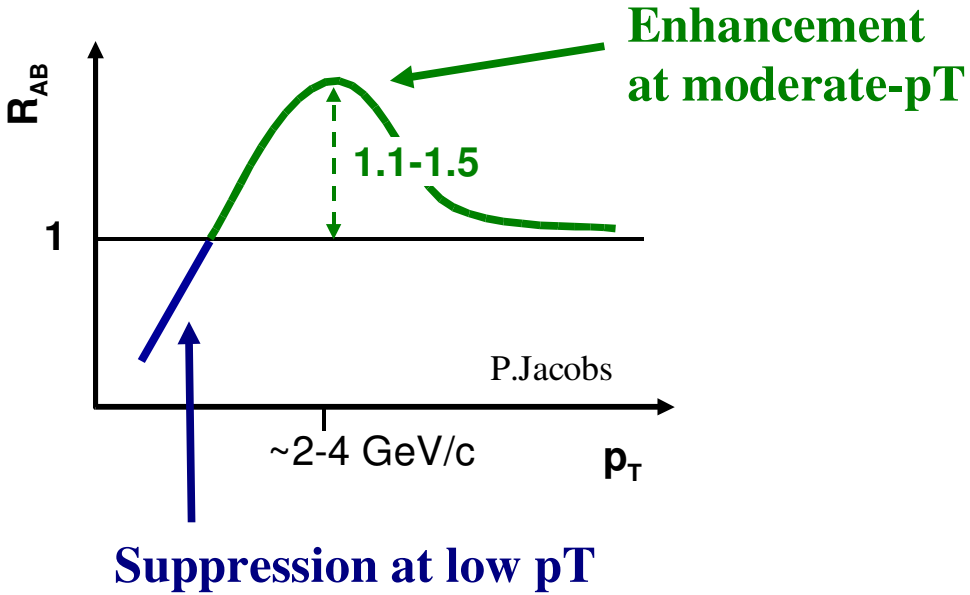
Cronin ratio of inclusive spectra

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

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

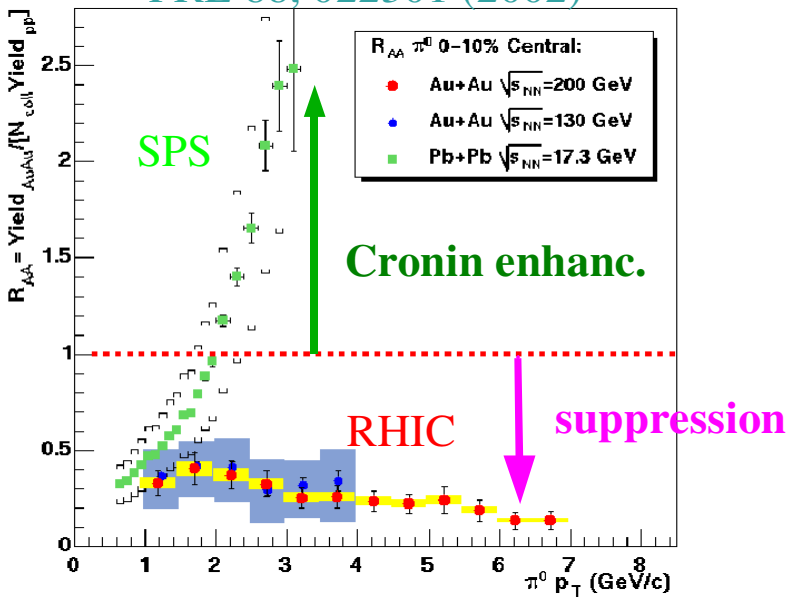


In low-energy pA and AA collisions:

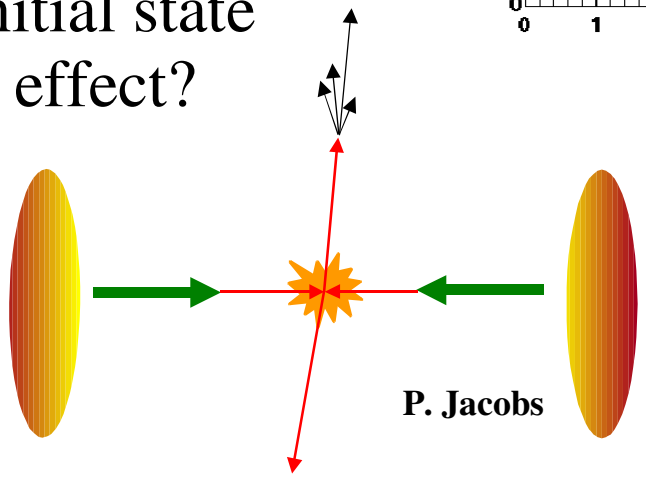


AA collisions: SPS vs. RHIC

PRL 88, 022301 (2002)

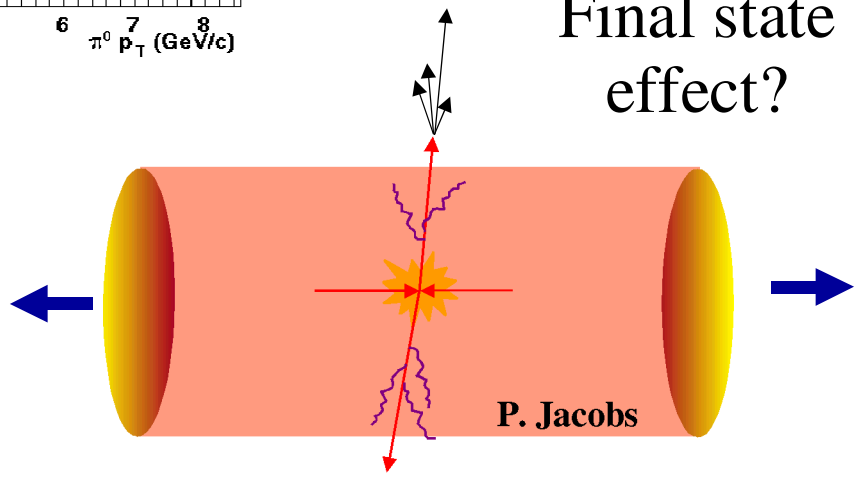


Initial state effect?



or

Final state effect?



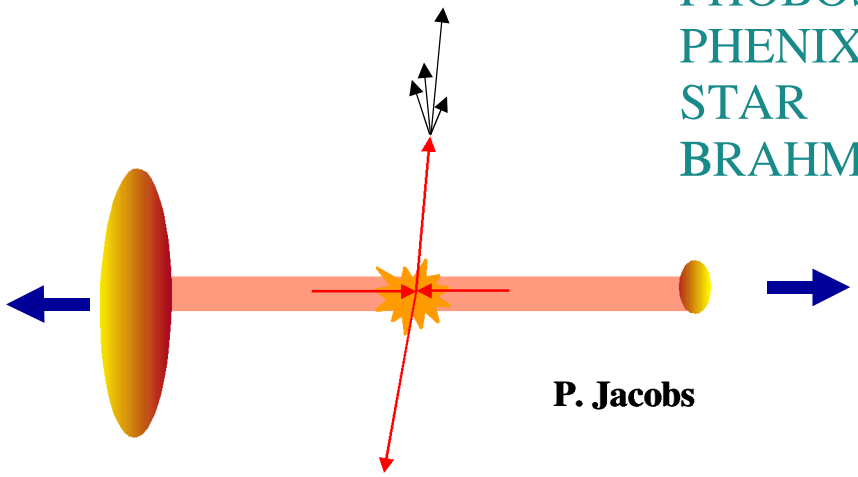
strong modification of Au wavefunction (gluon "saturation")

partonic energy loss in dense medium (or hadron absorption?)

How to discriminate?

Turn off final state
⇒ h+Au collisions

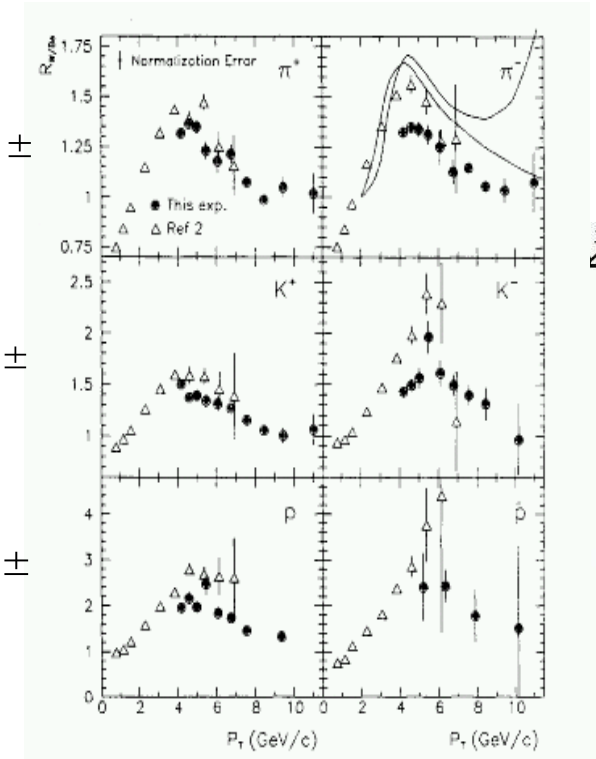
PHOBOS PRL91(03)072302
PHENIX " 03
STAR " 04
BRAHMS " 05



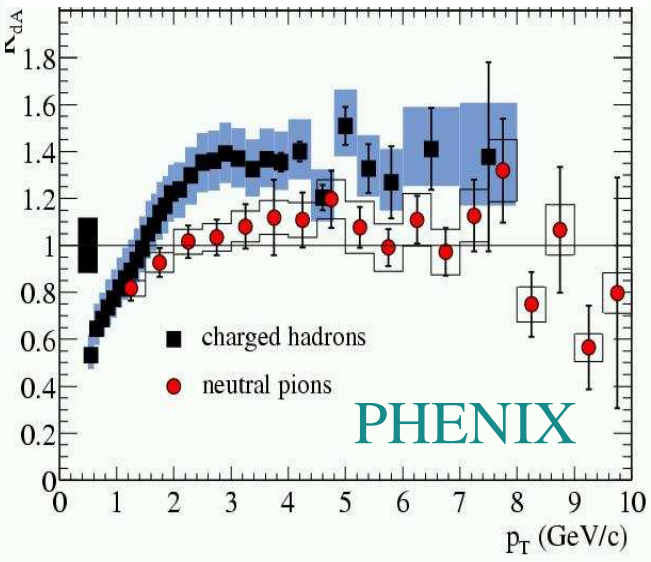
$\pi^{\pm}$

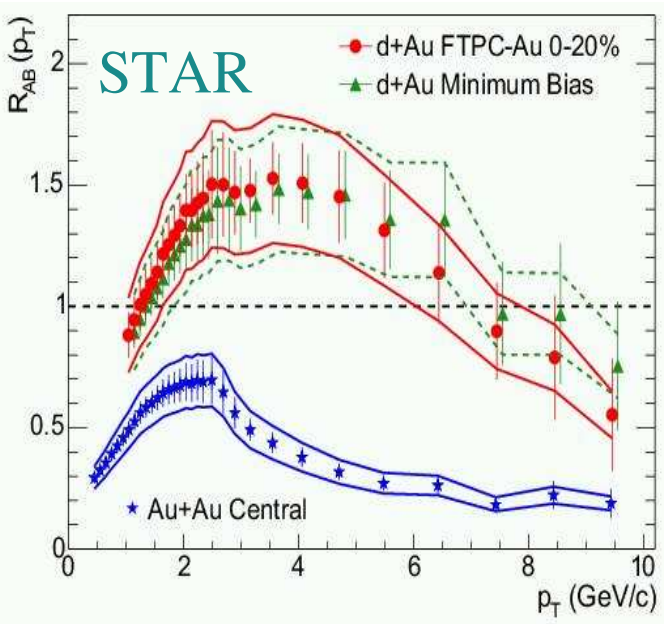
$K^{\pm}$

$p^{\pm}$



Fermilab 27-39 GeV





Theoretical models for hA

Glauber-Eikonal models

- hard partonic -

Kuhn '76; Kryzwicky '79; Lev-Petersson '83;
A.A, Treleani '01; Vitev, Gyulassy '02

A.A., M.Gyulassy

Soft partonic rescatterings

- soft partonic -

B. Kopeliovich et al.

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

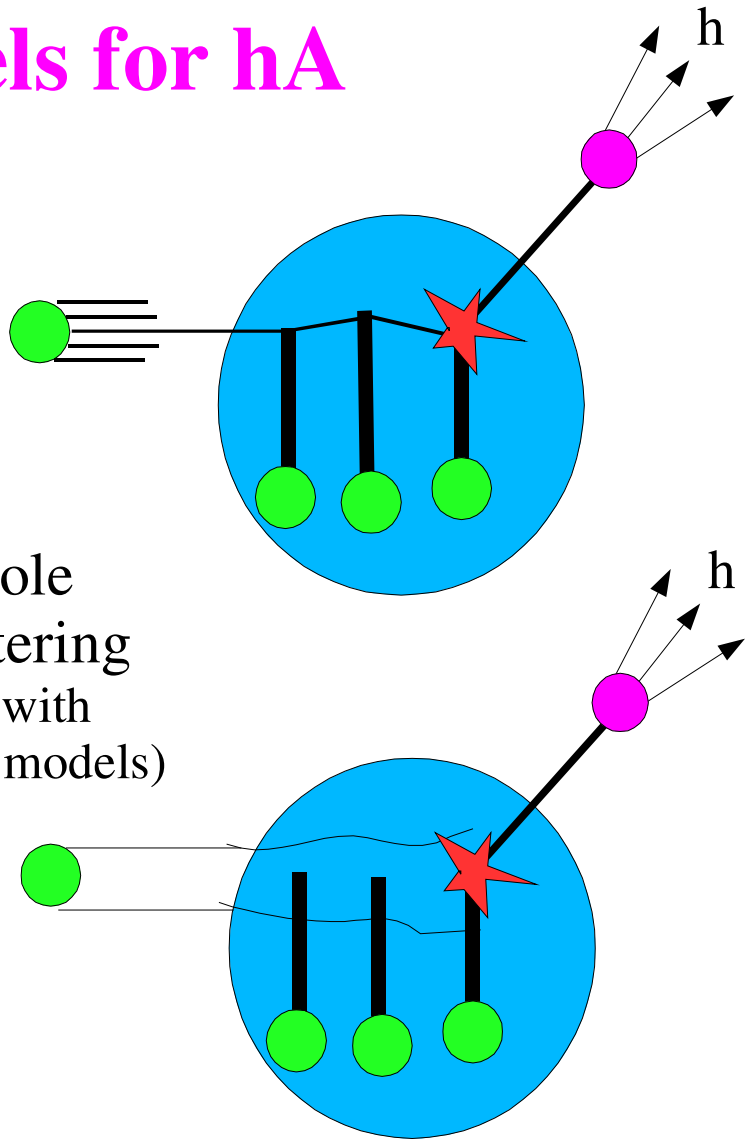
Glauber-Eikonal Approximated

- 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 nonlinear evolution

Kovchegov, Tuchin

Albacete et al.

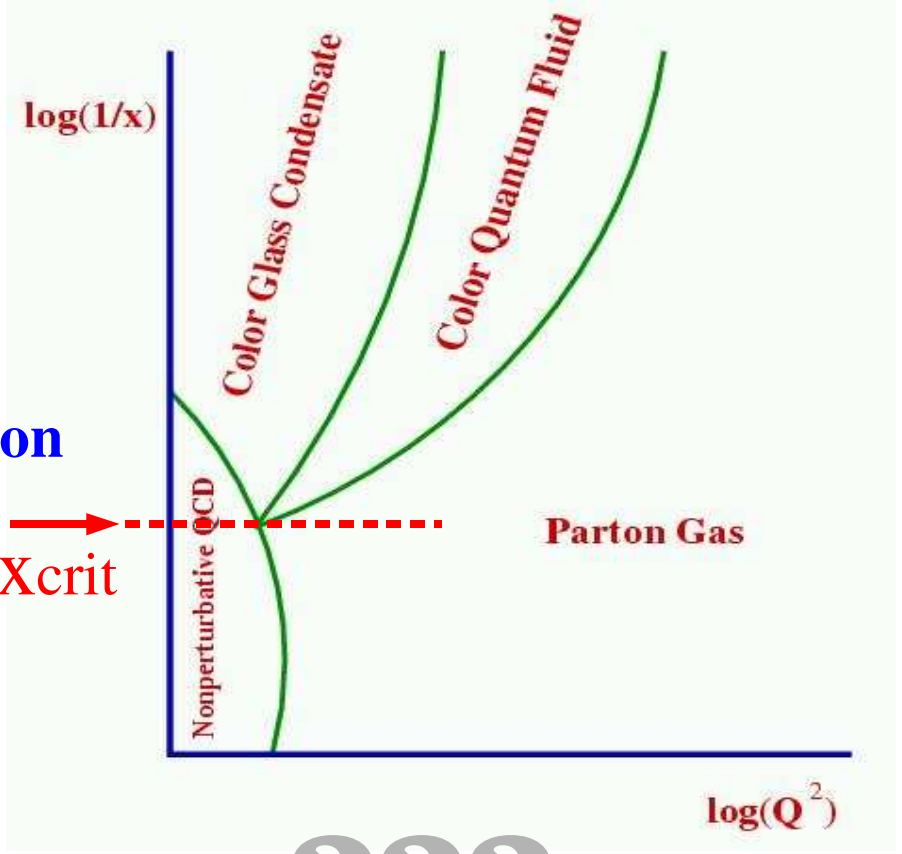
CGC = MV + quantum evolution

Iancu, Itakura, McLerran + ...

CGC inspired models

Kharzeev, Levin, McLerran

Kharzeev, Kovchegov, Tuchin



???

QUESTIONS...

How small is xcrit?

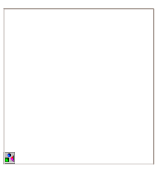
Where does RHIC stand?

Part I

Cronin effect in pA/dA collisions: Glauber-Eikonal models

(pQCD + partonic rescatterings)

A.A. and M.Gyulassy, **nucl-th/0308029**
A.A. and D.Treleani, '01



- Minijet cross-section is unitarized: $\sigma_{mj} \underset{p_0 \to 0}{\longrightarrow} \pi(R_A + R_B)^2$
- BUT energy conservation is violated: E_T diverges as $p_0 \to 0$

$$N_{jet}^{eik}(b) = 2\sigma_J T_{AB}(b) \propto 1/p_0^2$$

$$E_T{}_{jet}^{eik}(b) \approx p_0 N_{jet}^{eik} \propto 1/p_0$$

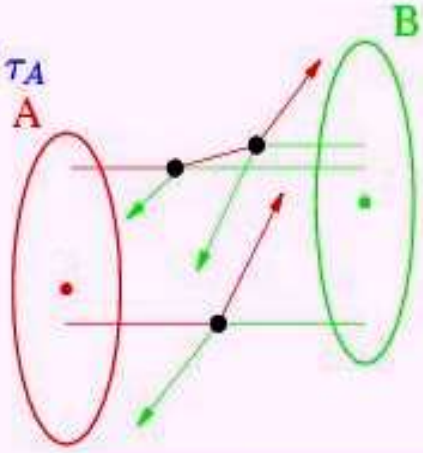
$\Longrightarrow$ some dynamics is missing

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

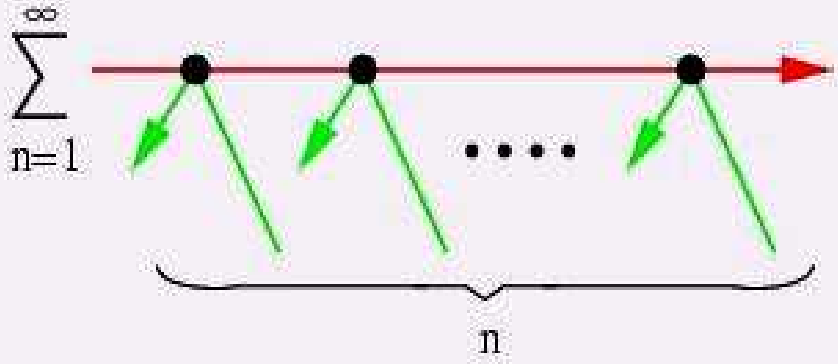
$\rightsquigarrow$ Glauber multiple scattering formula at parton level

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:

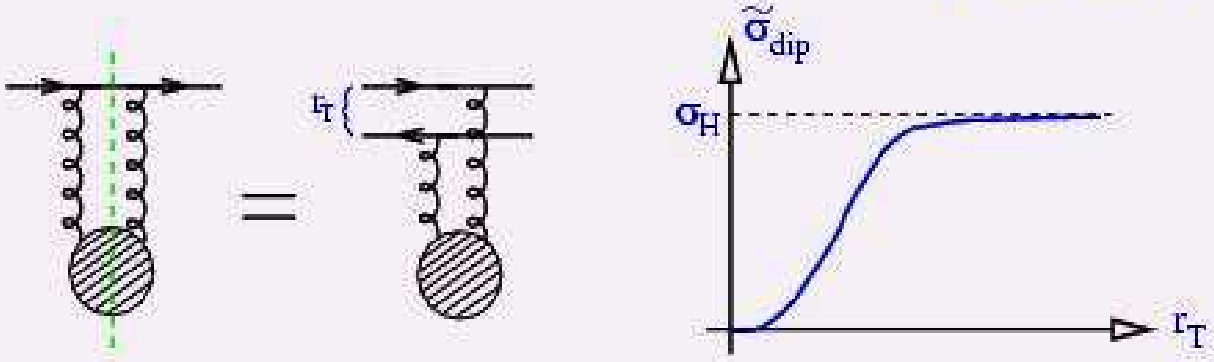
$$\frac{d\sigma^{qA}_{hard}}{d^2p_T} = \int \frac{d^2r_T}{4\pi^2} e^{-i\vec{k}_T\cdot\vec{r}_T} \left[e^{-\tilde{\sigma}^{qN}_{hard}(r_T, p_0) T_A(b)} - e^{-\sigma^{qN}_{hard}(p_0) T_A(b)} \right]$$

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

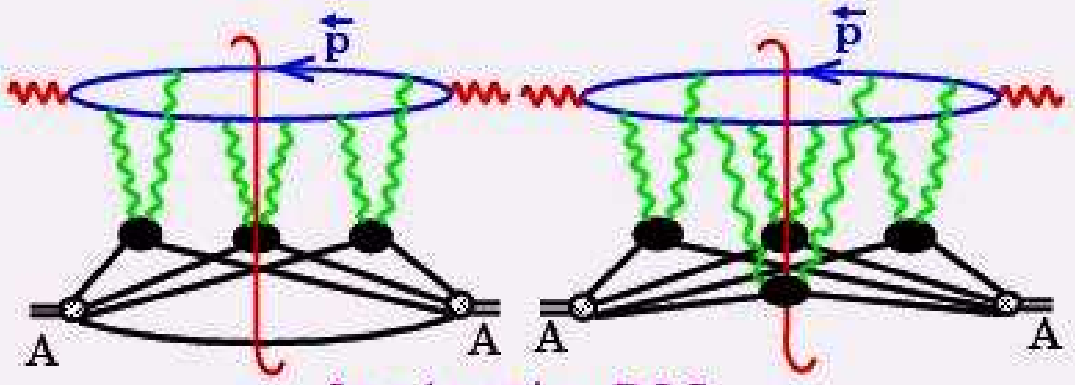
and $\sigma^{qN}_{hard}(p_0) = \int d^2k \frac{d\sigma^{qN}_{hard}}{d^2k} s$ is the integrated quark-nucleon cross section.

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

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

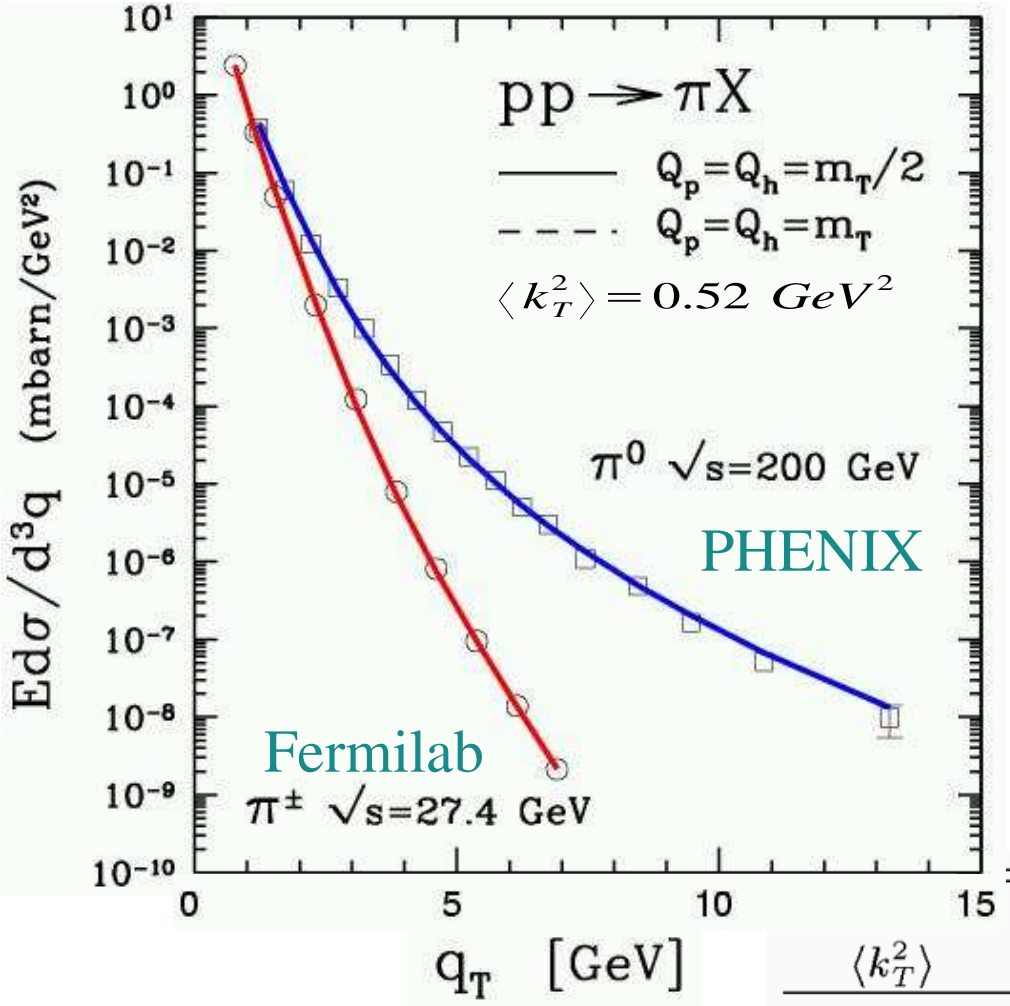
a) CHOOSE the scales: $Q_R = Q_F = m_T/2$ (or $Q_R = Q_F = m_T$)

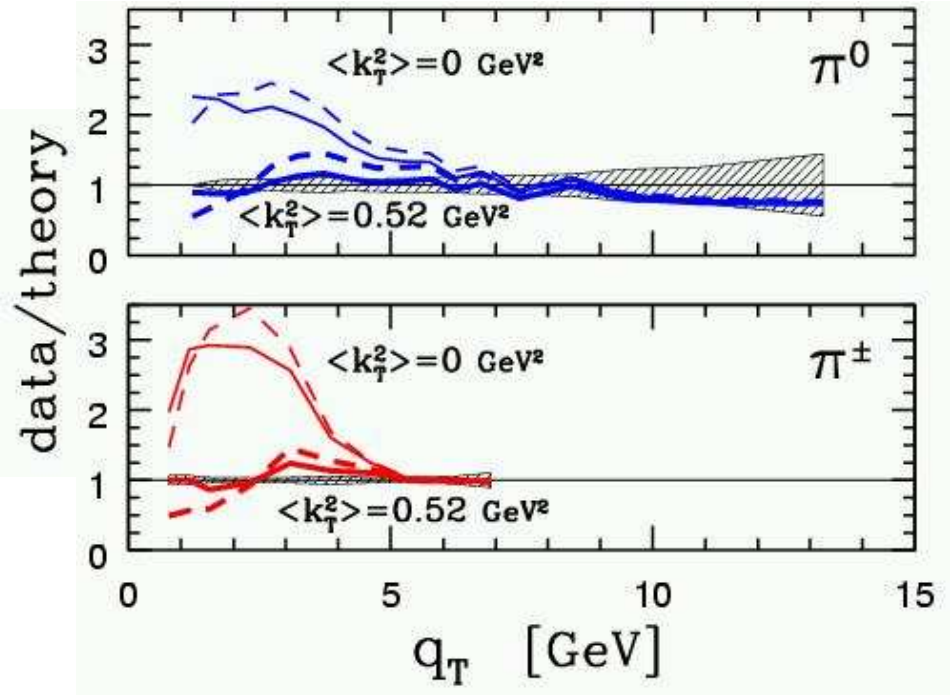
b) FIT **K=K(s)** to the **high-p_T** tail of the hadron spectrum (χ^2 fit - sensitive to the choice of scales)

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

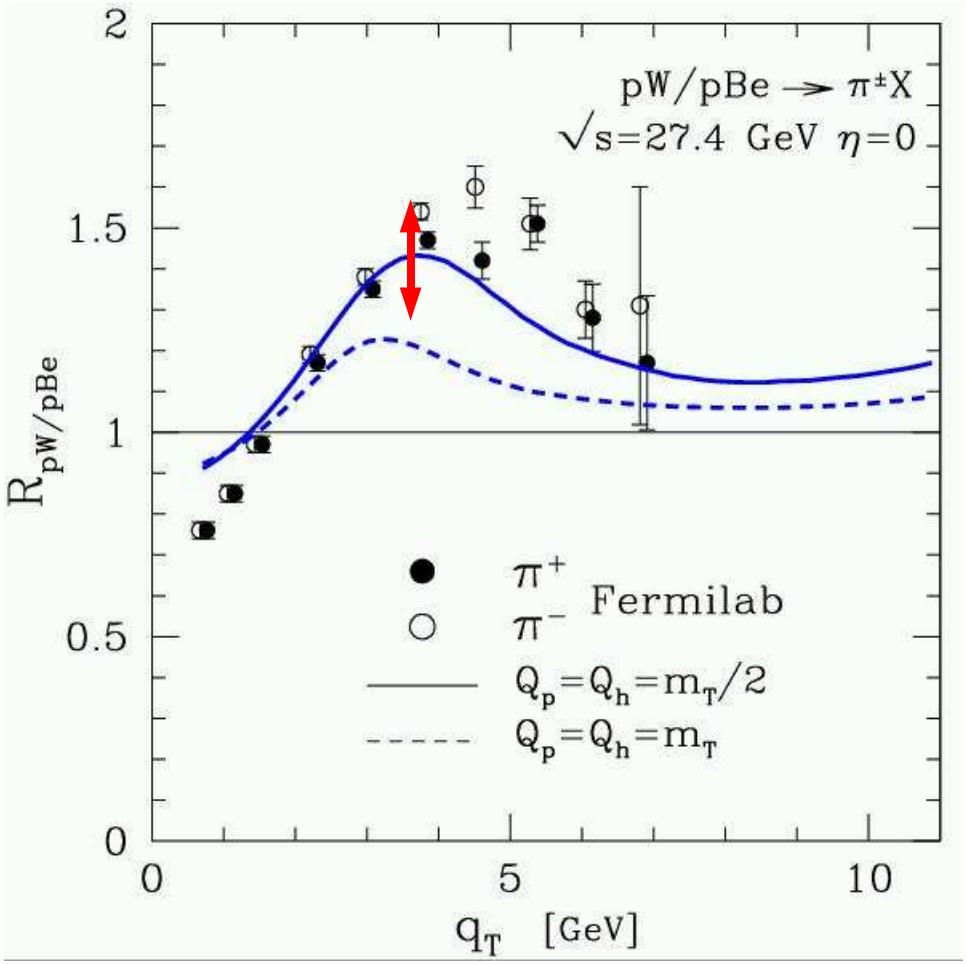
parton-nucleon cross section (depends on p_0)

- **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



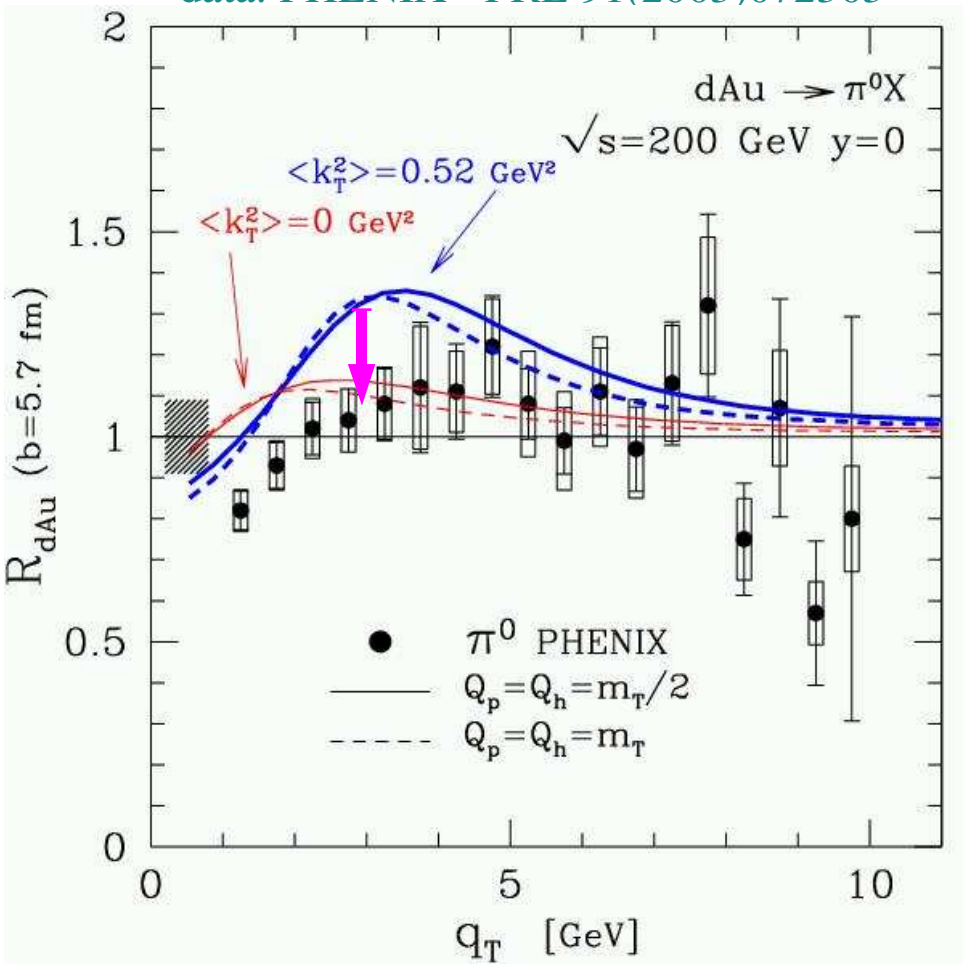
↕ = theoretical error due to fit of $p_0 = 0.8 \pm 0.1$ GeV (it's max. at the peak, dies away far from it)

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:
<u>radiative and collisional en. loss.</u>
(here neglected) may suppress the spectrum at low p_T, barring shadowing.

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

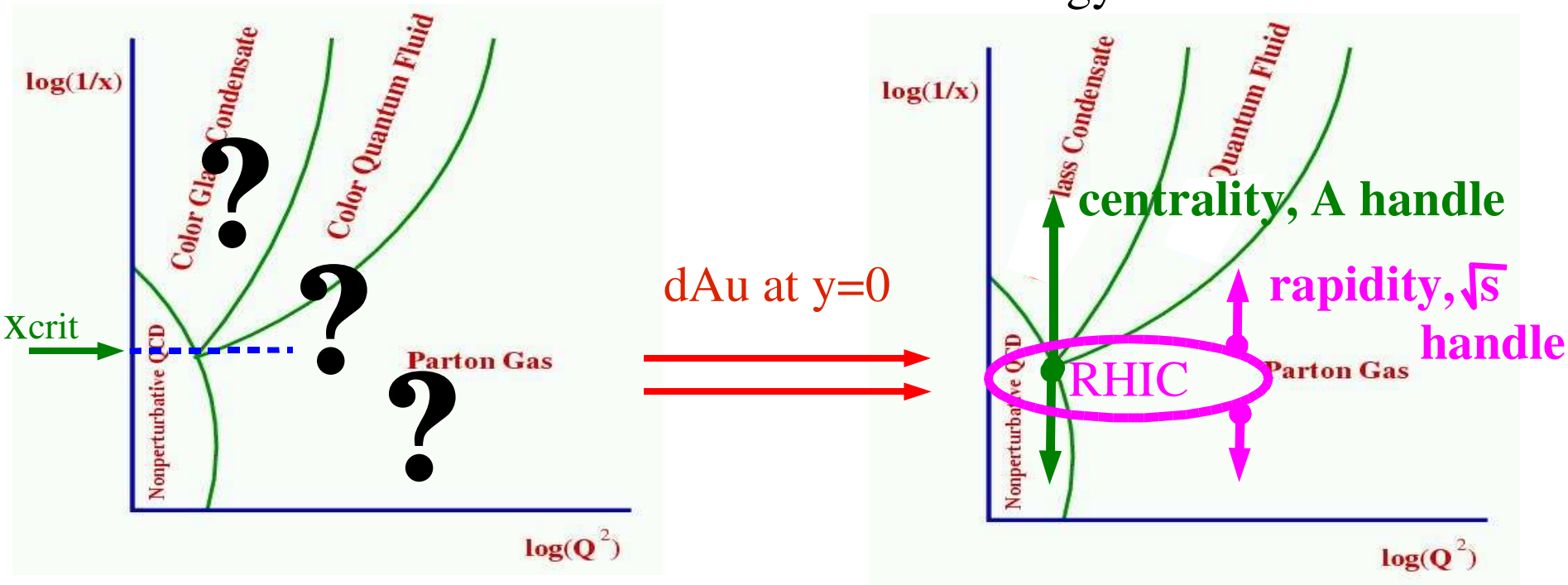
: $d\sigma^{gN}/d^2p_T \sim 1/p_T^4$ + asymptotic kinematics

$\Longrightarrow$ cannot reproduce hadron spectrum in pp collisions

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

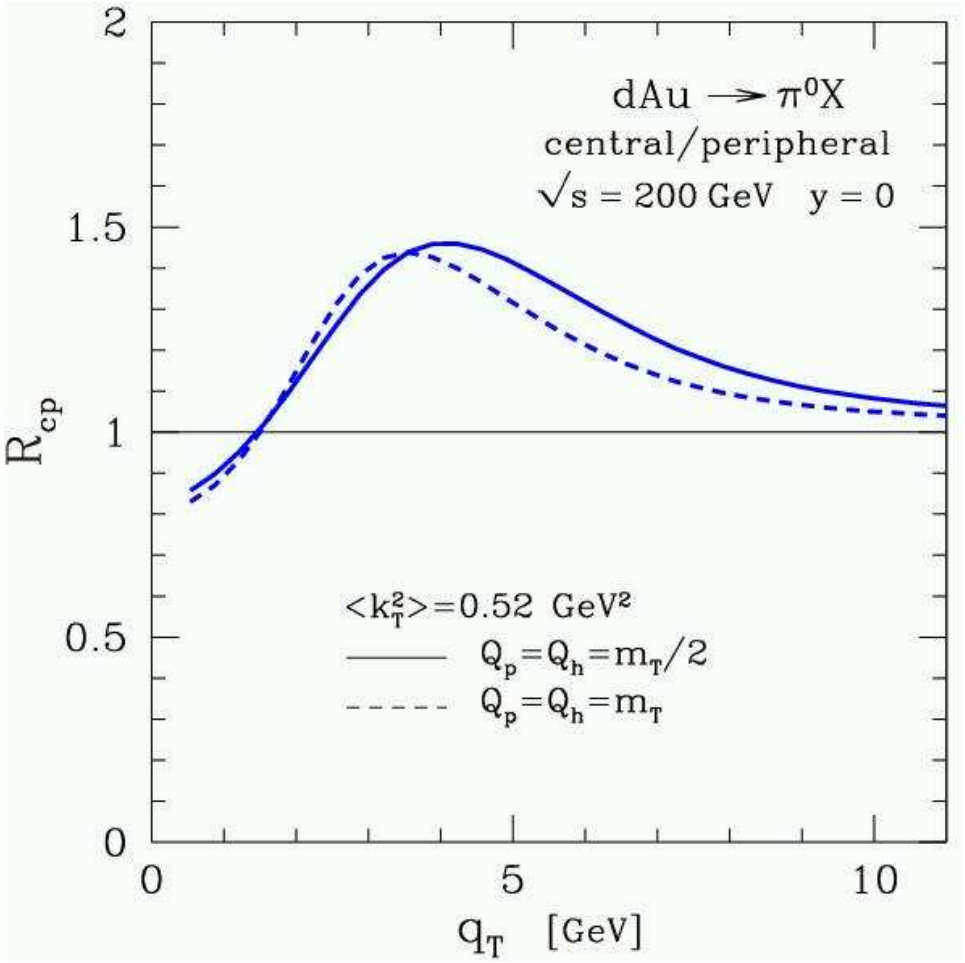
spectra in pp-collisions OK

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

Conclusions - I

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)**

Indication for onset of dynamical shadowing at RHIC

- **centrality dependence**
- **forward rapidity**

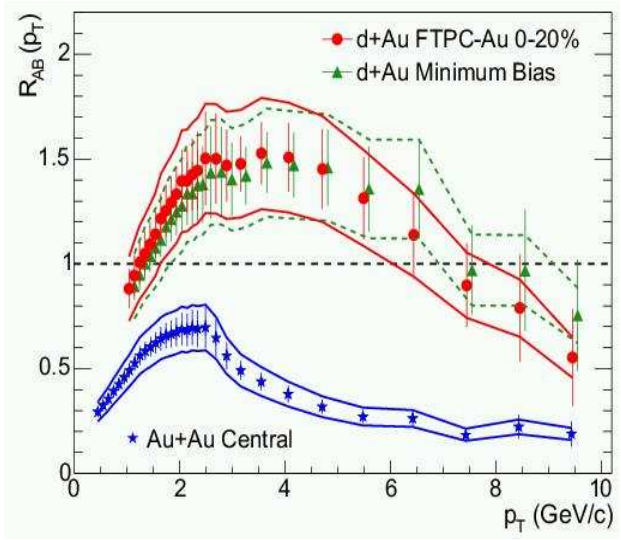
Part II

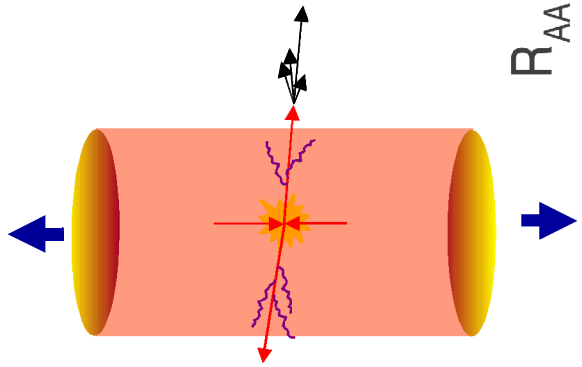
Hadron formation times: eA scattering at HERMES

A.A, Muccifora, Pirner '03

Parton energy loss or final state interactions (FSI)?

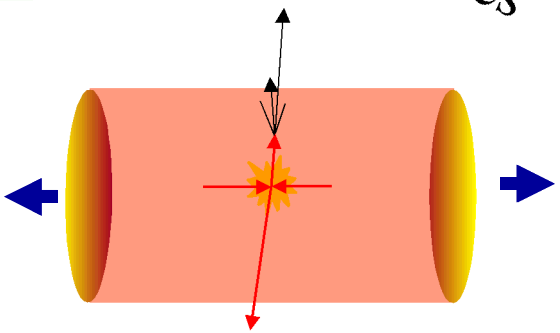
STAR

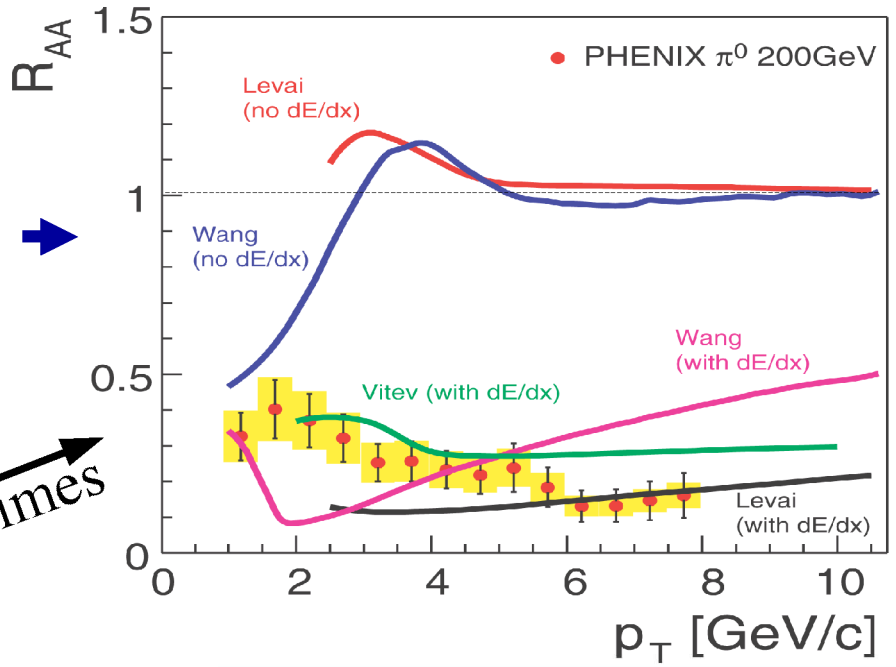


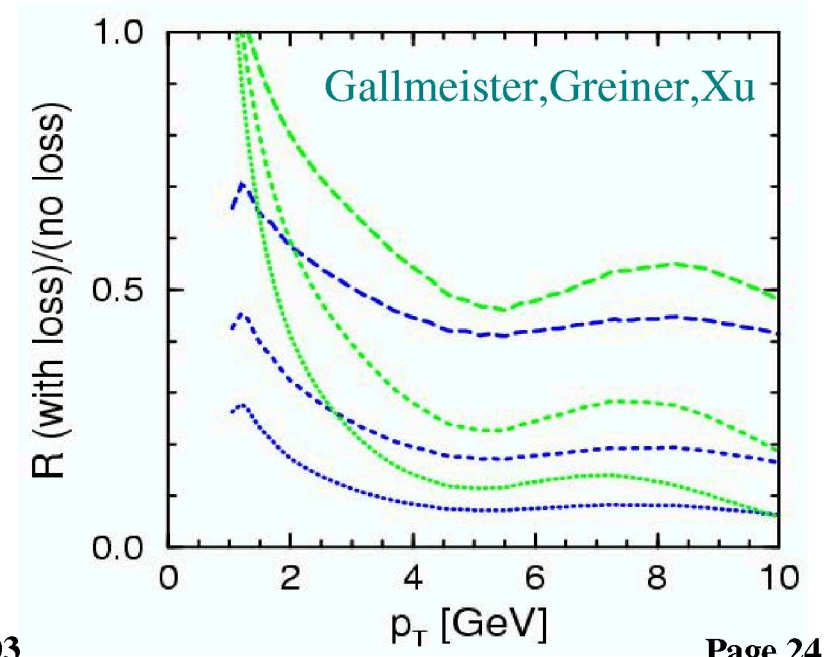


energy loss
long formation times

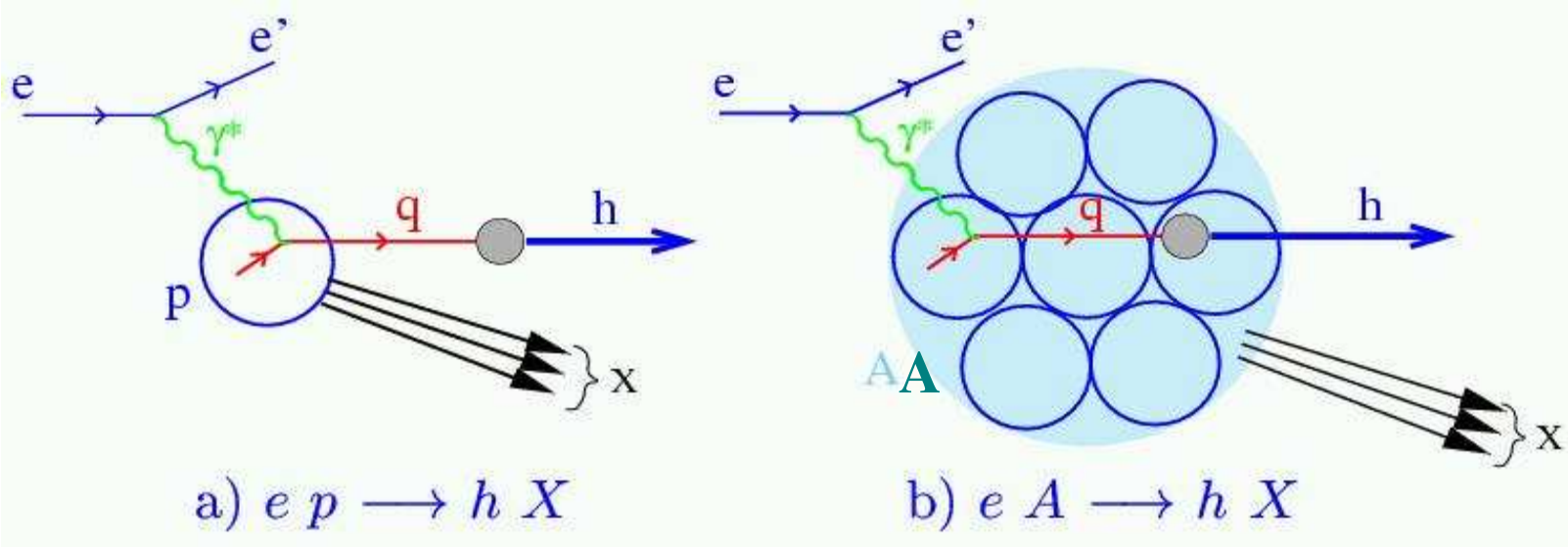
FSI
short formation times



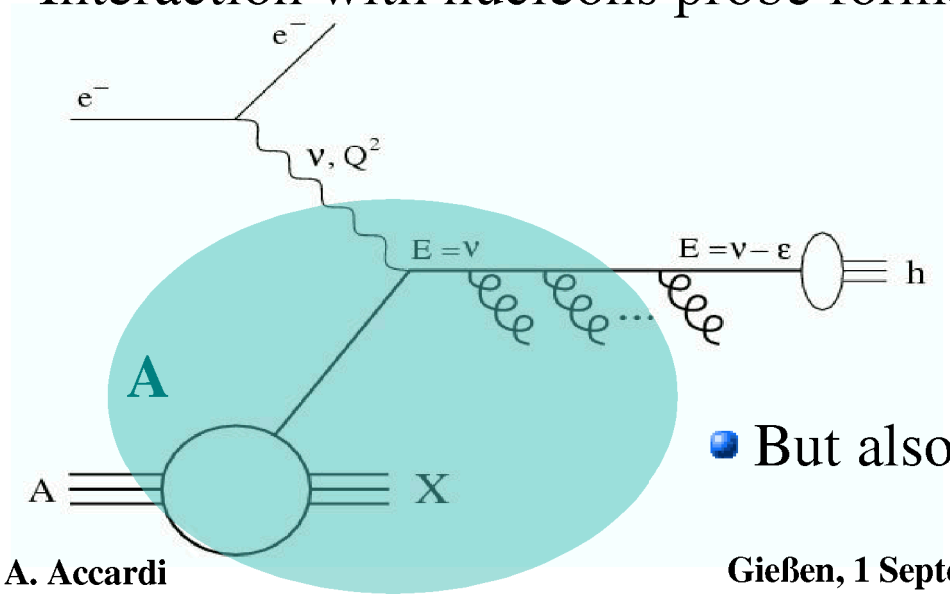




Nuclei as fermi-scale detectors



- DIS: a "clean" process (no created medium - simple projectile)
- Internucleon distance ~1 fm:
  Interaction with nucleons probe formation times ~1-10 fm

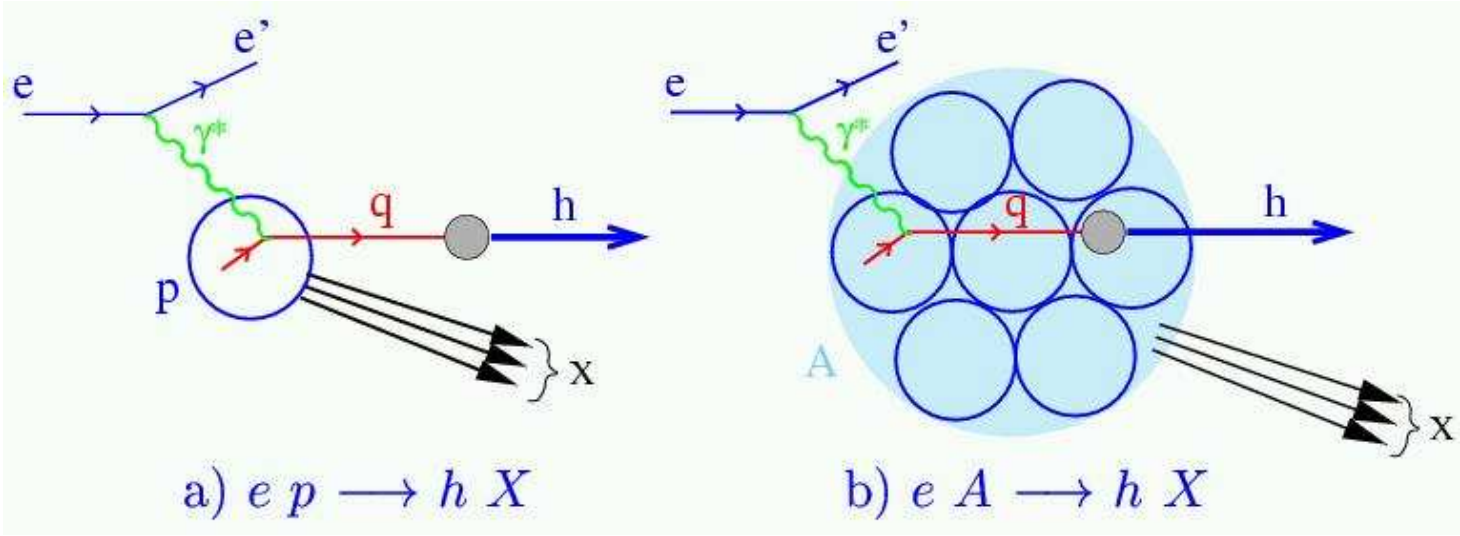


Bialas & Gyulassy; Kopeliovich et al.;
Accardi et al. '03; Falter et al. '03

- But also energy loss in cold nuclear matter...

X.N.Wang et al; F.Arleo

pQCD description of DIS



$$\frac{1}{N_A^{DIS}}\frac{dN_A^h}{dz} = \frac{1}{\sigma^{\gamma^* A}}\int_{\text{exp. cuts}} dx\, d\nu \sum_f e_f^2\, q_f(x, \quad Q^2)\, \frac{d\sigma^{\gamma^* q}}{dx\, d\nu}\, D_f^h(z, \quad Q^2)$$

PDF pQCD x-sec FF

No nuclear effects, then:

$$\frac{1}{N_A^\ell}\frac{dN_A^h}{dz} = \frac{1}{N_D^\ell}\frac{dN_D^h}{dz} \times \boxed{R_M^h(z)}$$

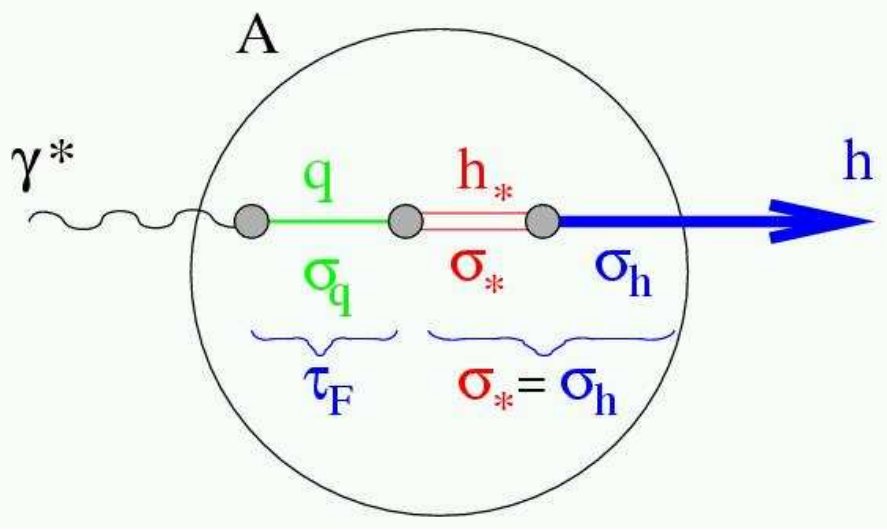
with $\boxed{R_M^h(z) = 1}$.

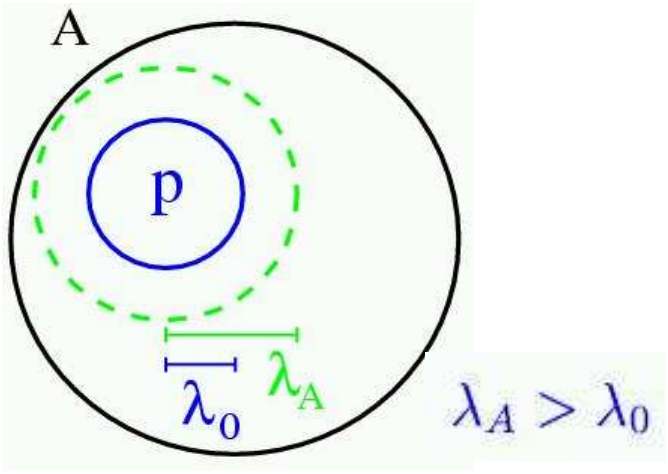
But experimentally:

$$R_M^h(z) \neq 1 \Longrightarrow \text{NUCLEAR EFFECTS}$$

- Hadron FSI (absorption, decay, ...)
- partial deconfinement in A
- struck quark energy loss

Nuclear absorption & rescaling of FF's





nucl. abs. factor = probability of exiting from the nucleus:

$$\mathcal{N}_A = \int d^2b \int_{-\infty}^{\infty} dy\, \rho_A(b,y) \left[S_A(b,y)\right]^{A-1}$$

$$S_A(b,y) = 1 - \sigma_h \int_y^{\infty} dy'\, P_h(y'-y)\rho_A(b,y')$$

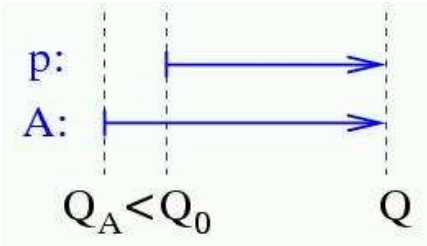
prob. that *h* is formed at y'-y from interaction point:

$$P_h(y'-y) = \left(1 - e^{-(y'-y)/\langle l_F\rangle}\right)$$

Change of confinement scale in A:

$$\lambda_0 Q_0 = \lambda_A Q_A$$

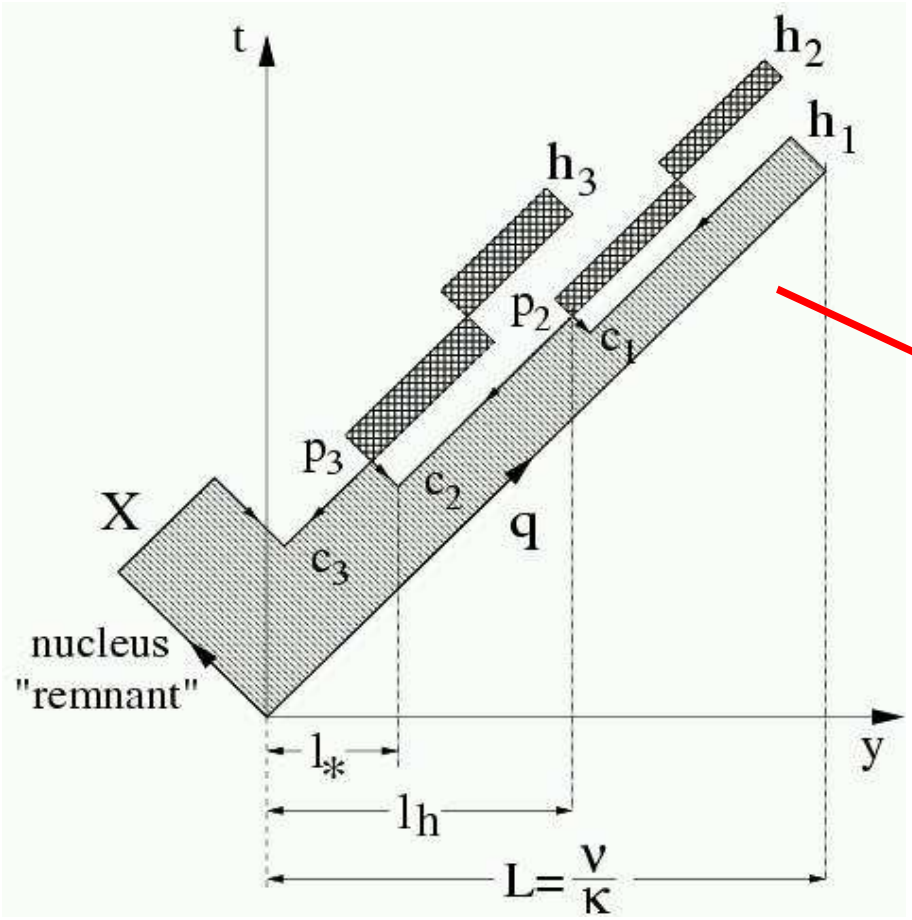
Q_0 = start of DGLAP evolution



$$q_f^A(x,Q) = q_f(x, \xi_A(Q)Q)$$

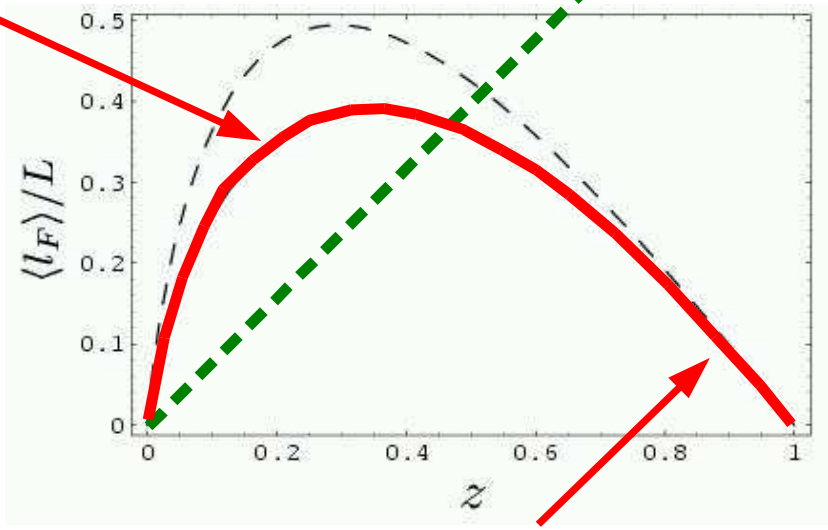
$$D_f^{h|A}(z,Q) = D_f^h(x, \xi_A(Q)Q)$$

LUND string model & formation times



Lorentz dilatation of rest-frame form. time:

$$\tau_F = \frac{z_h \nu}{\underbrace{m_h}_{\gamma}} \tau_0 \propto z_h \nu$$

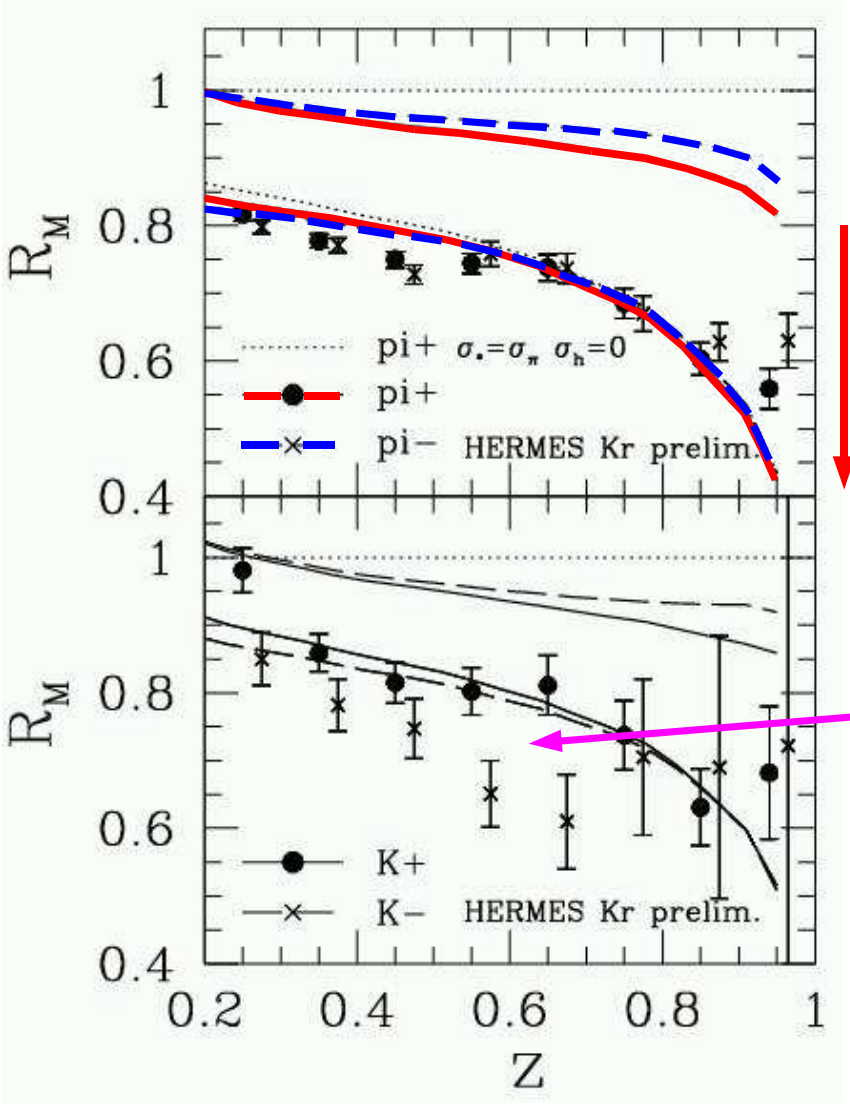


$$\propto (1 - z_h)\nu$$

see also Kopeliovich et al. '96 + recent talks
Airapetian et al. (HERMES) '01

Model vs. HERMES data

A.A, Muccifora, Pirner '03



rescaling

absorption

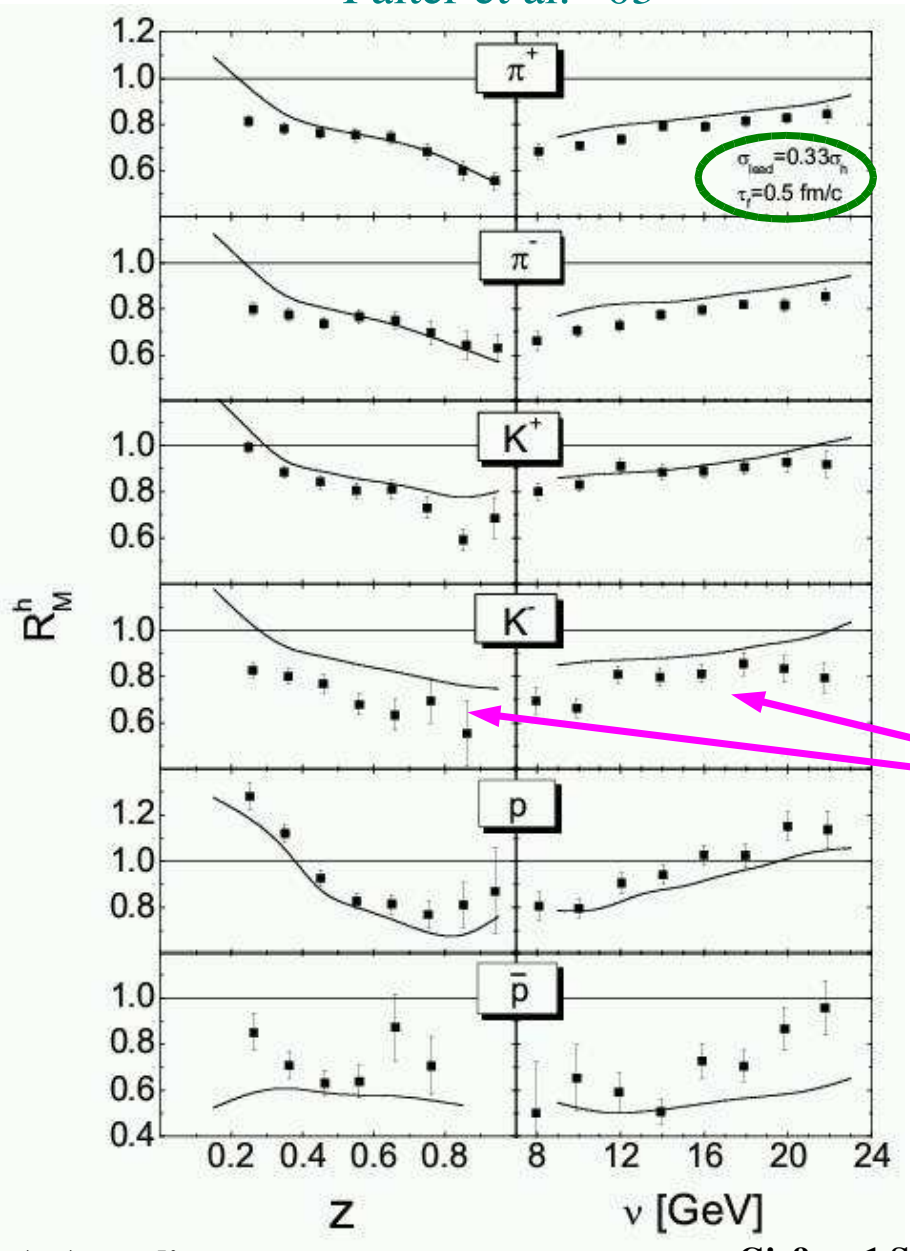
- two-step hadronization
- $\sigma_q = 0 \qquad \sigma_* = \sigma_h$
- $\tau_F \propto (1 - z_h)\nu$

free parameter:
string tension k

K- overestimated:
shorter form. time
(or σ_* - less natural)

Other models I - formation times + FSI

Falter et al. '03



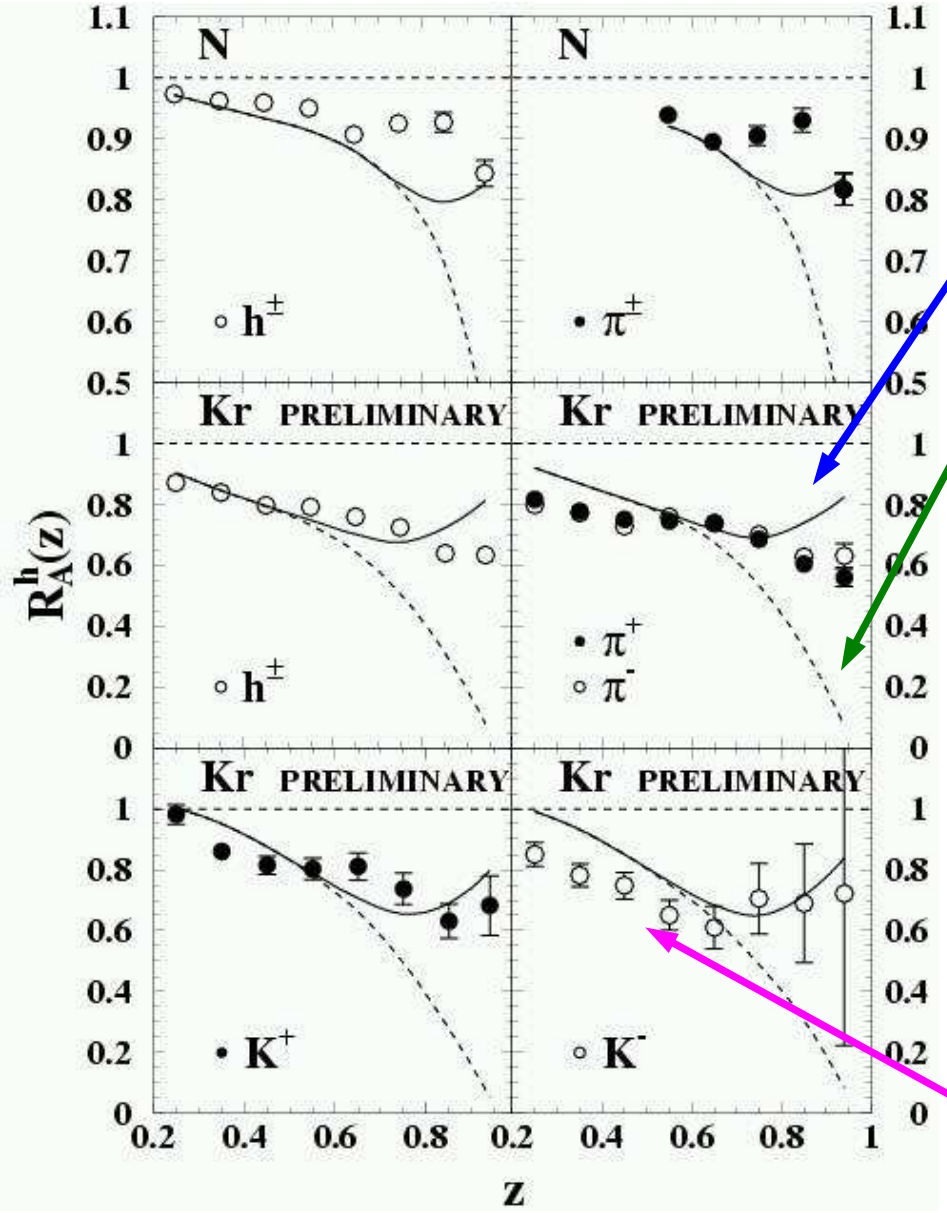
- one-step hadronization + feed-back (reson. decay, elastic scatterings, ...)
- $\sigma_* < \sigma_h$
- $\tau_F \propto \tau_0 z_h \nu$

free parameters

K- overestimated

Other models II: energy loss

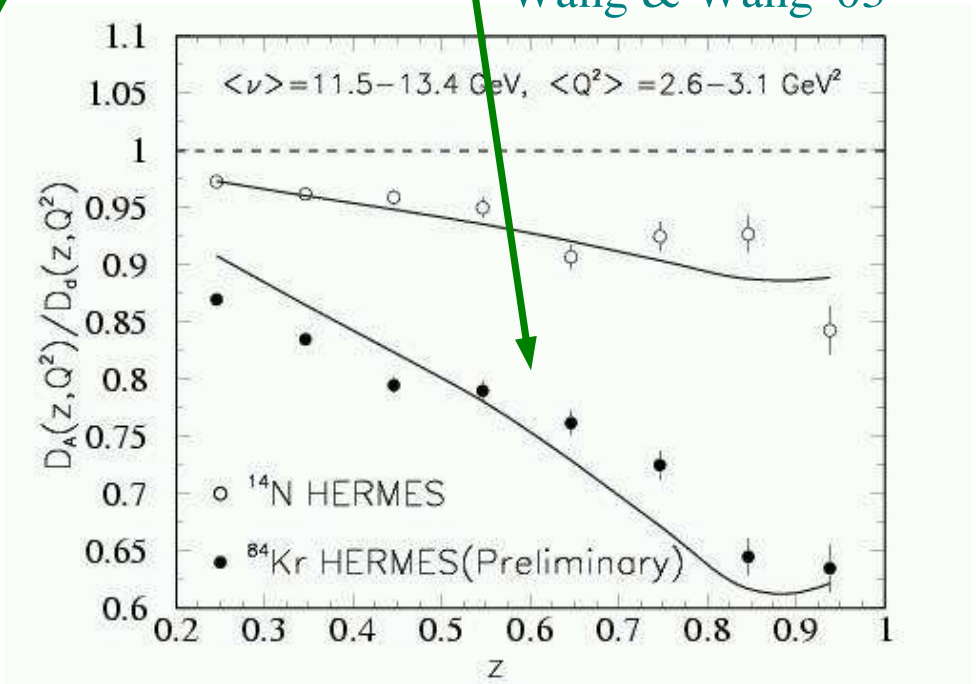
Arleo '03



en. loss + LUND form. time

energy loss only

Wang & Wang '03



K- overestimated

(see also nu-dependence)

Conclusions - II

- HERMES data have good precision for detailed study
- Formation times and assumptions vary strongly from model to model
- Both absorption and energy-loss models account for data

How to decide?

- K- production
- A systematics
  (D, N, Ne, Kr data available - Xe planned at HERMES: A=2-131)
- Study observables different for absorption and en. loss
  Lessons from heavy-ions: Cronin effect?
  Two-particle azimuthal correlations?

Epilogue

Glauber-Gribov models:

Compare pA and AA & pin down
- pA: cold nuclear matter effects -- shadowing, absorption
- AA: medium effects -- energy loss, absorption (modified??)

Hadronization in nuclear DIS:

Study cold nuclear matter effect in clean environment
- formation times
- energy loss

Together:

help in deciding if the hot and dense medium
created in AA coll's is indeed a QGP or not