Cronin effect in d+Au collisions: where does pQCD meet CGC?

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Based on

A.A., M.Gyulassy, nucl-th/0308029 v2 (PLB in press)

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

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Outline

Part I - Glauber-Eikonal models

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

Part II - Saturation models

Part III - Where does pQCD meets the CGC?

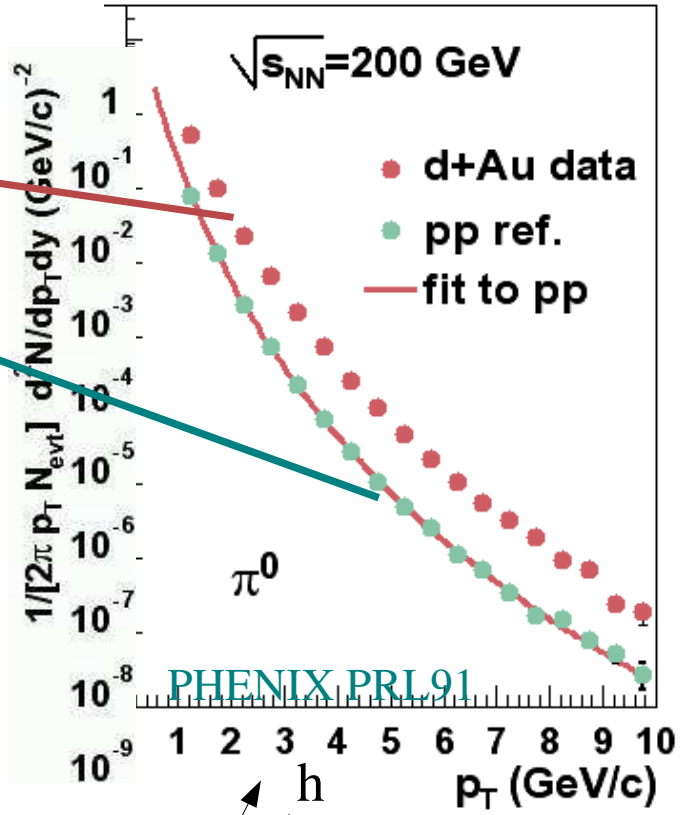
- Need to better understanding of p+p collisions

Cronin ratio of inclusive spectra

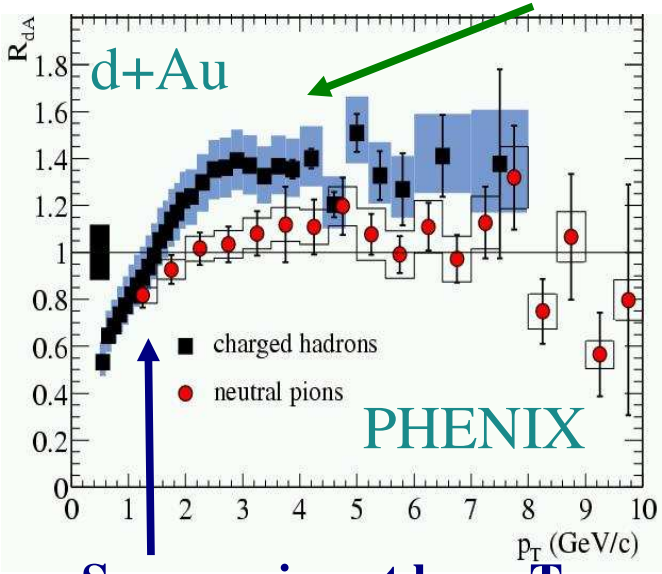
$$R_{AB}(p_T) = \frac{d^2 N^h_{AB} / dp_T d\eta}{T_{AB}\, d^2 \sigma^h_{NN} / dp_T d\eta}$$

Binary collision scaling

p+p reference

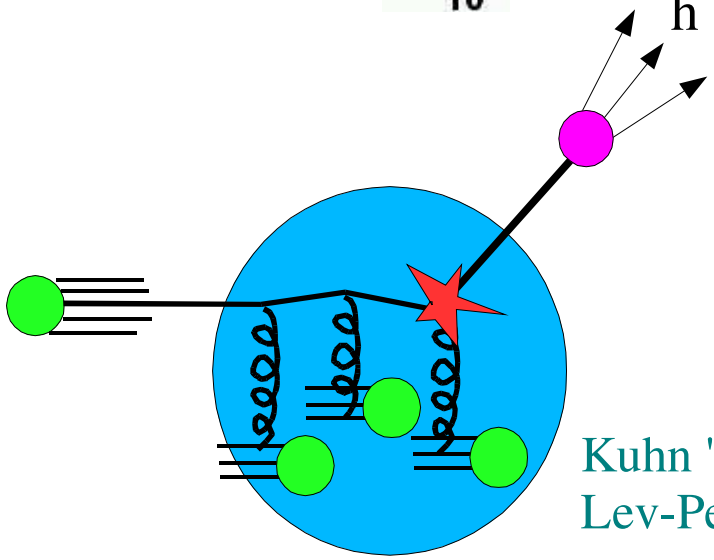


Enhancement at moderate-pT



Suppression at low pT

(same pattern at Fermilab)



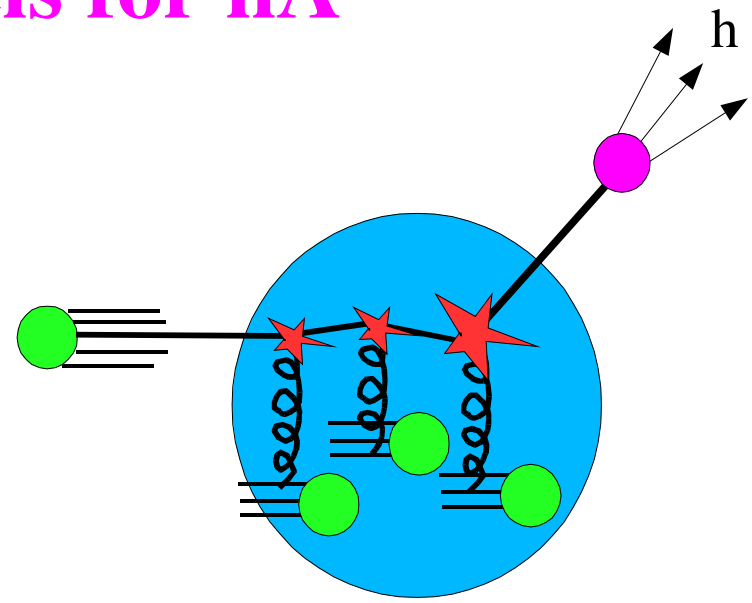
Kuhn '76; Kryzwicky '79;
Lev-Petersson '83;

Theoretical models for hA

Glauber-Eikonal models

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

A.A., M.Gyulassy



Glauber-Eikonal Approximated

- hard partonic/hadronic -

X.N. Wang et al.; Barnafoldi et al.;
Vitev & Gyulassy

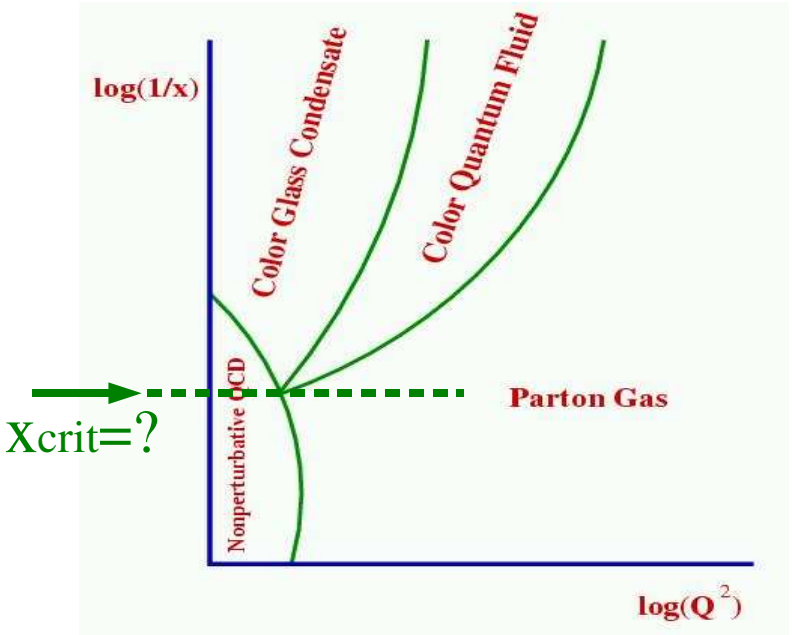
see talk

"Saturation" models

MV model — Kovchegov;
Dumitru, Gelis, Jalilian-Marian;
Jalilian-Marian, Nara, Venugopalan
etc...

CGC = MV + evolution

Blaizot, Gelis, Jalilian-Marian;
Kovchegov et al.; Albacete et al.;
Iancu, Itakura, McLerran;
etc...



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

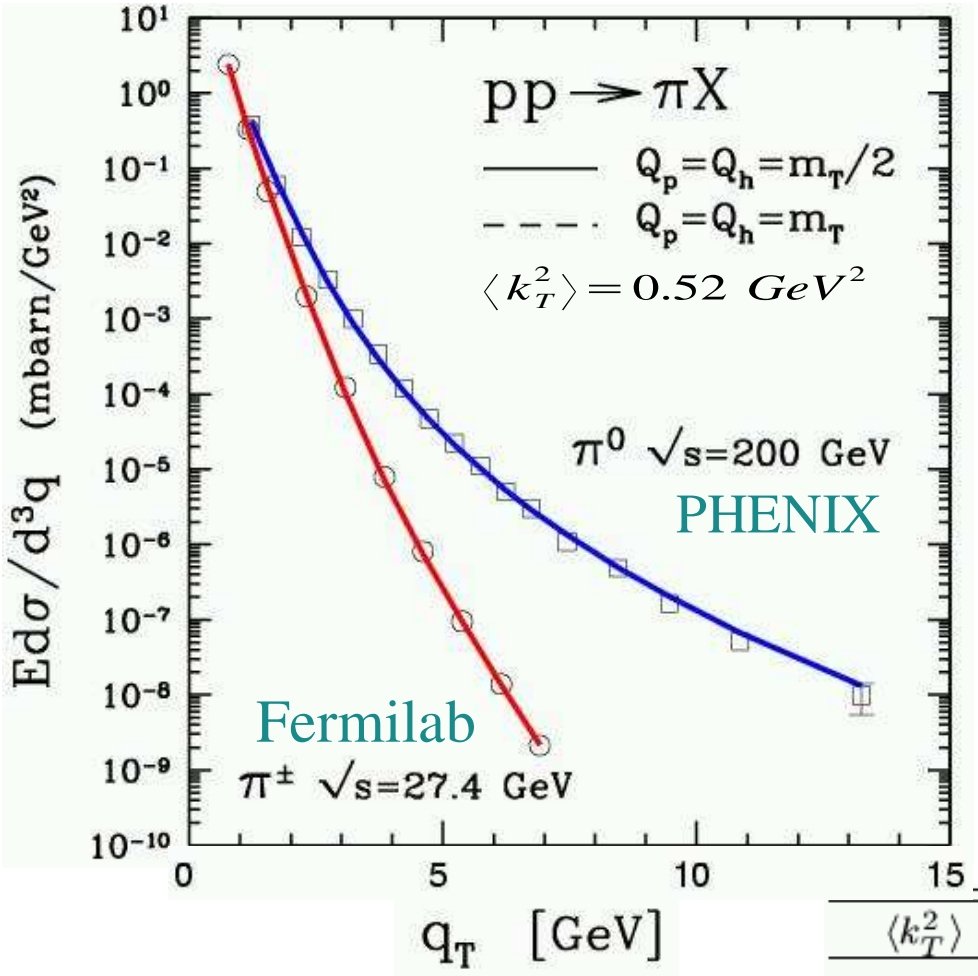
a) <u>CHOOSE</u> the scales: $\mathbf{Q_p = Q_h = m_T/2}$ (or $\mathbf{Q_p = Q_h = m_T}$)

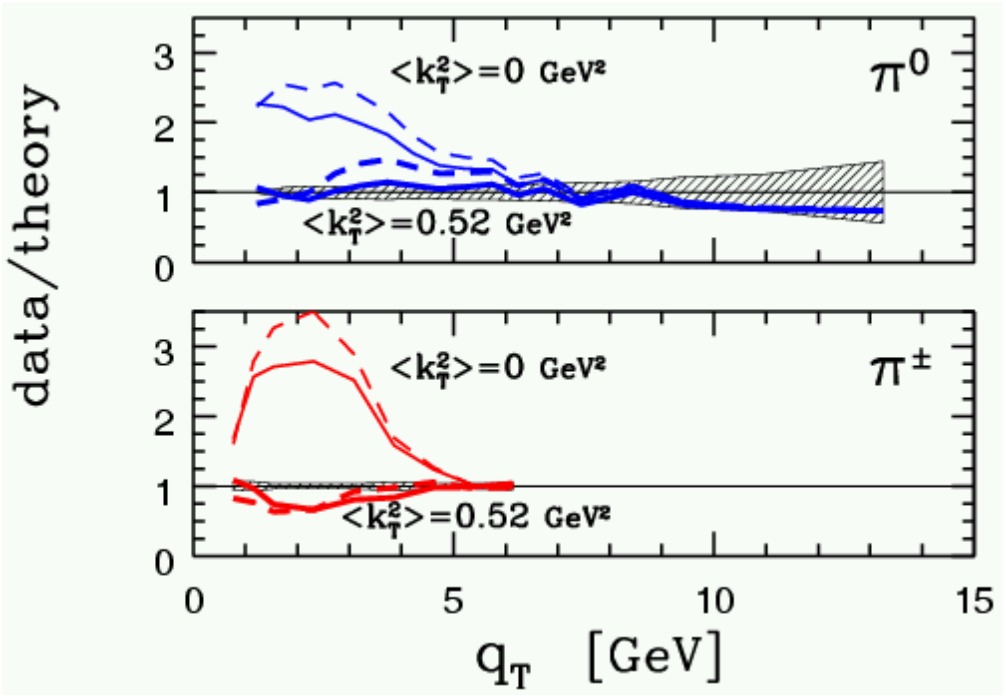
b) Intrinsic $\langle k_T^2 \rangle = 0.52$ GeV^2

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

d) <u>FIT</u> **p0 = p0(s)** to the **low-pT** hadron spectrum

Results of the fit





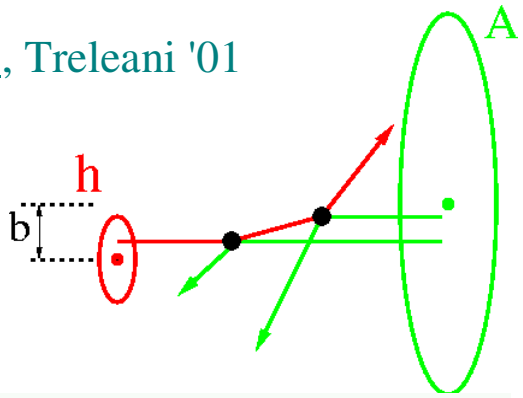
Fit procedure: Eskola, Honkanen '02

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

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



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

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:

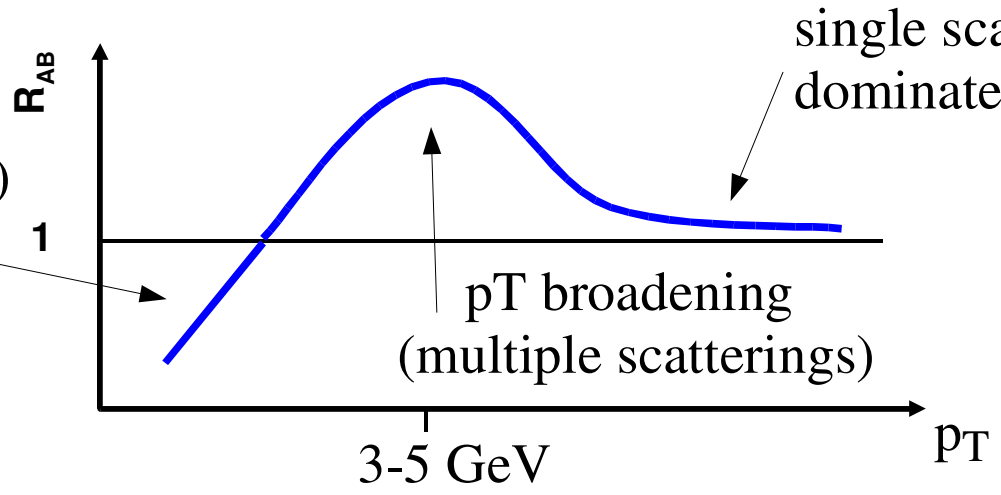
1) low-opacity $\chi \langle\langle 1 \Longrightarrow \frac{d\sigma^{iA}}{d^2b d\eta} \approx T_A\,\sigma^{iN}$ collision scaling (single semihard scattering)

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 CGC, no geom. scaling, no EKS98, ...)

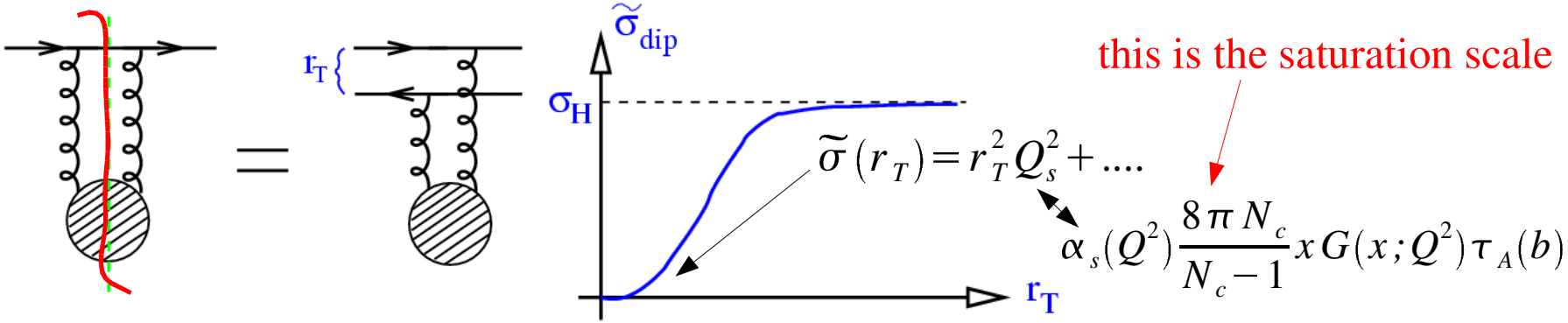
pA as multi-scattering of a dipole

Resummation of pt-spectrum possible in coordinate-space:

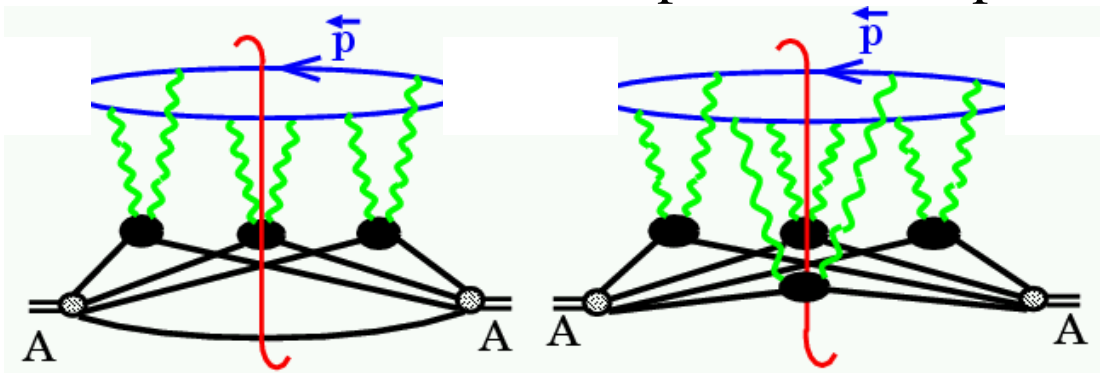
$$\frac{d\sigma^{iA}}{d^2p_T} = \int \frac{d^2r_T}{4\pi^2} e^{-i\vec{k}_T\cdot\vec{r}_T} \left[e^{-\tilde{\sigma}^{iN}(r_T)\,T_A(b)} - e^{-\sigma^{iN}T_A(b)} \right]$$

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

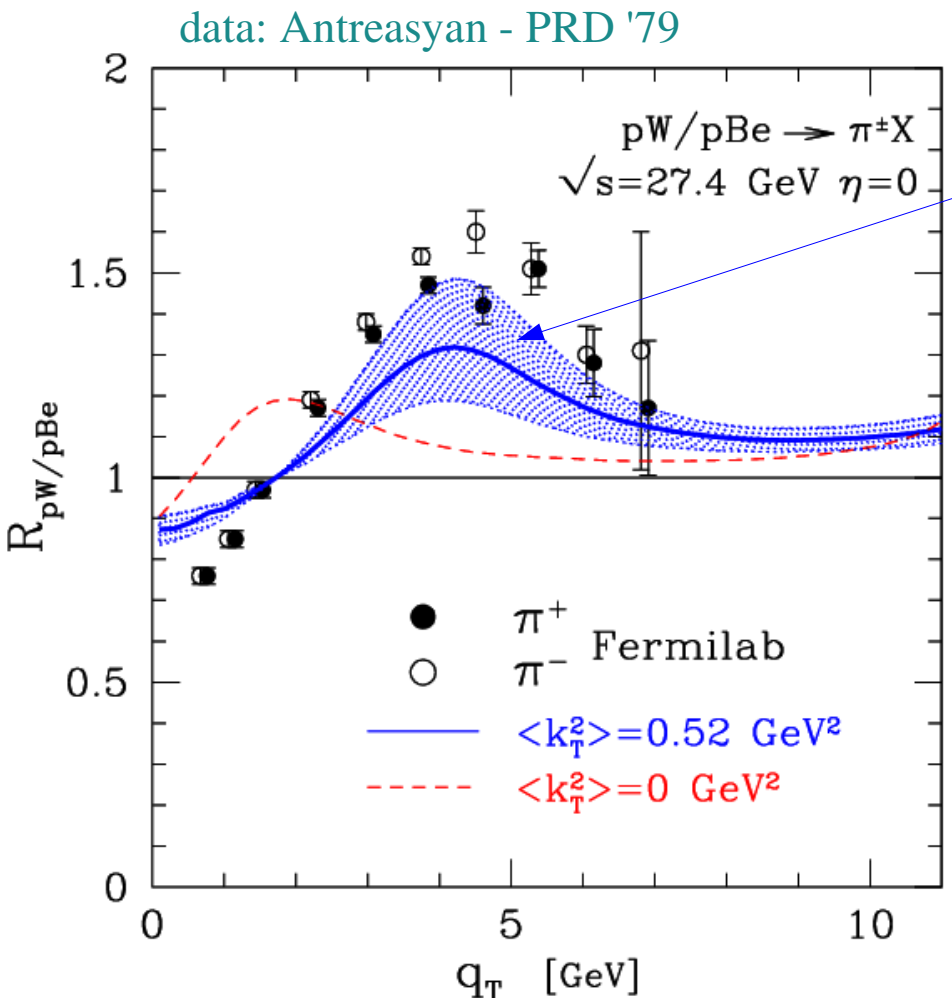
where $\tilde{\sigma}^{iN}(r_T) = \int d^2k \left[1 - e^{-i\vec{k}\cdot\vec{r}_T}\right] \frac{d\sigma^{iN}}{d^2k}$ is a dipole cross-section



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



Cronin effect on pions at Fermilab η=0



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

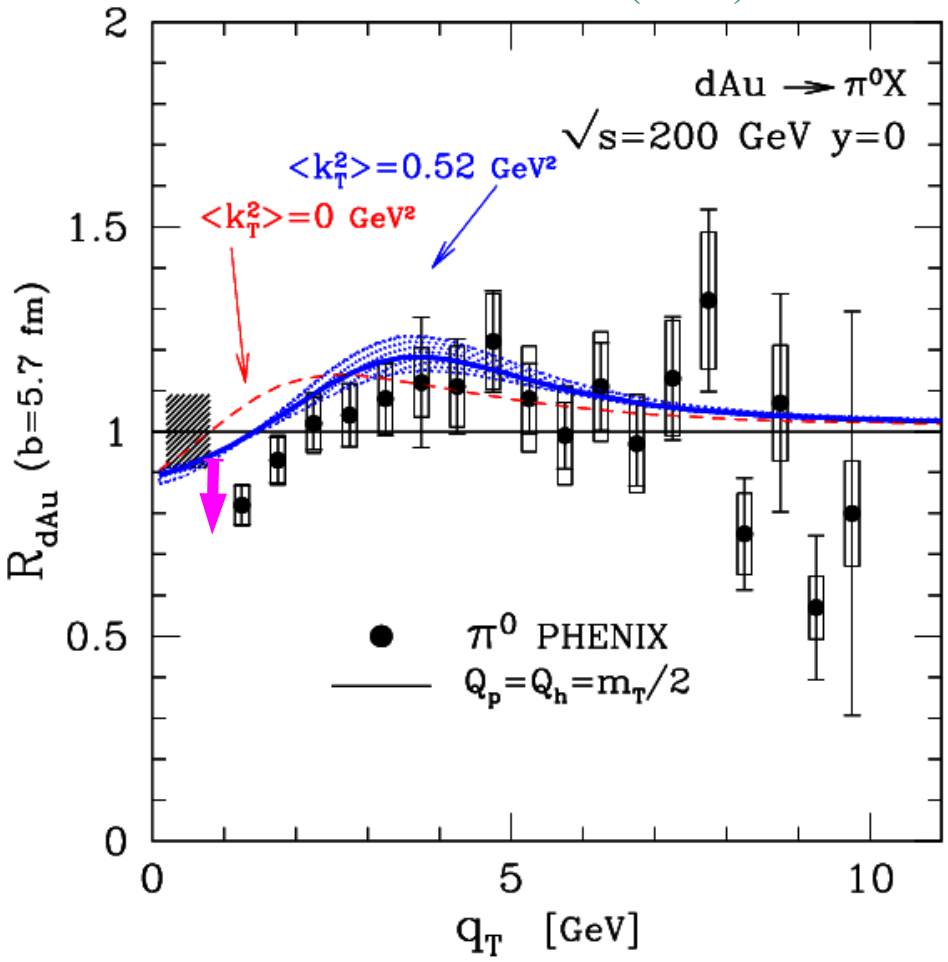
Q=mT/2 or Q=mT give similar results

We reproduce the data well.

At low-p_T, theory overestimates data

Cronin effect on pions at PHENIX η=0

data: PHENIX - PRL 91(2003)072303



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

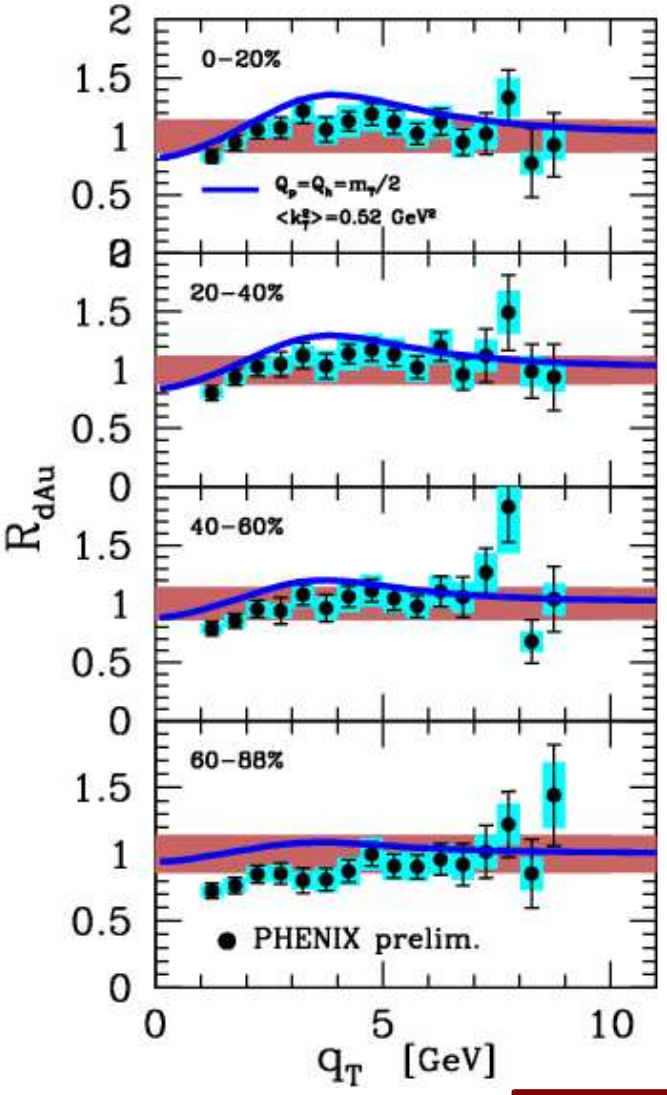
Computation compatible with data inside exper. and theor. errors

Tends to overestimate data at low pT

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

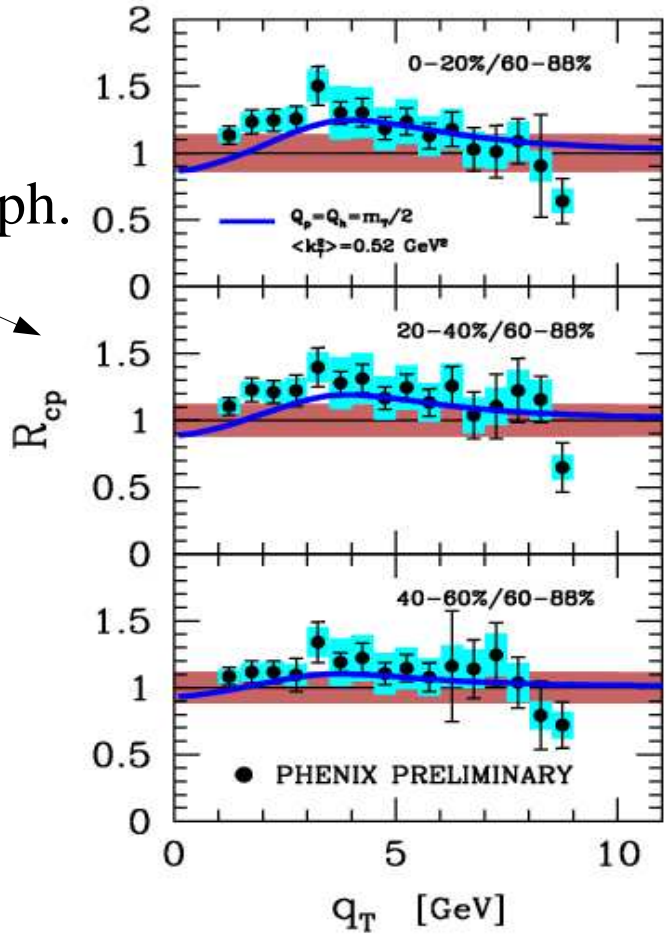
Centrality dependence at η=0

If dynamical shadowing at work, ⟹ stronger suppression in central



d+Au/p+p

central/periph.

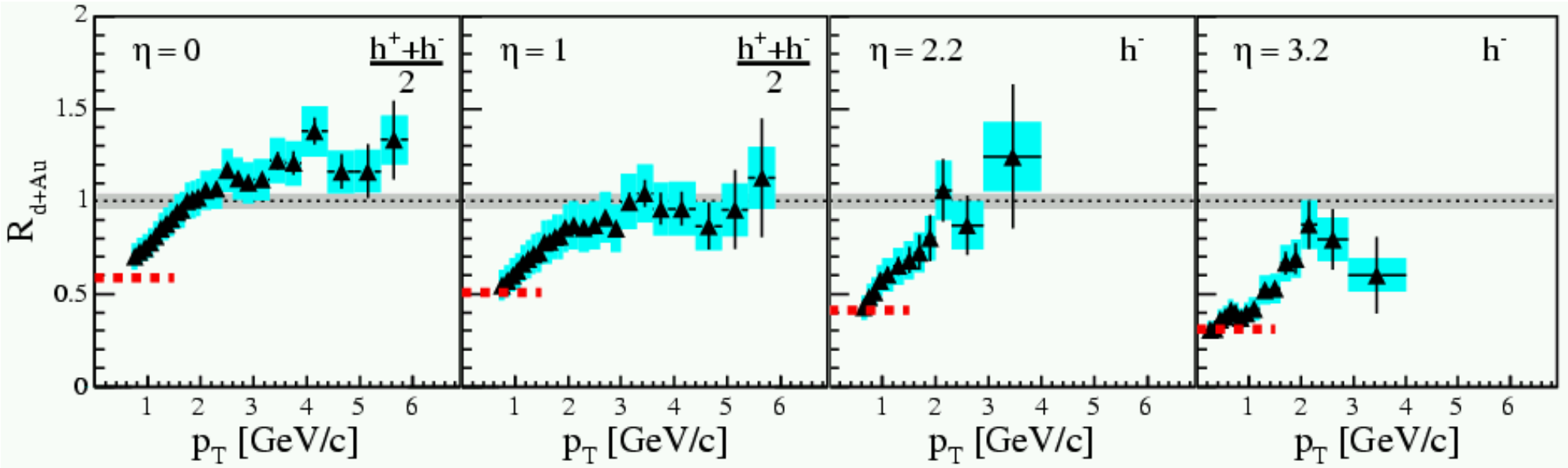


prelim. data: T.Awes, DNP Tucson Nov'03

no dynamical shadowing at η=0

Let's move forward: η=3

BRAHMS nucl-ex/.... (see talk by Z.Yin)



PHOBOS data at y=0.2, 0.6, 1.0, see talk by G.Veres

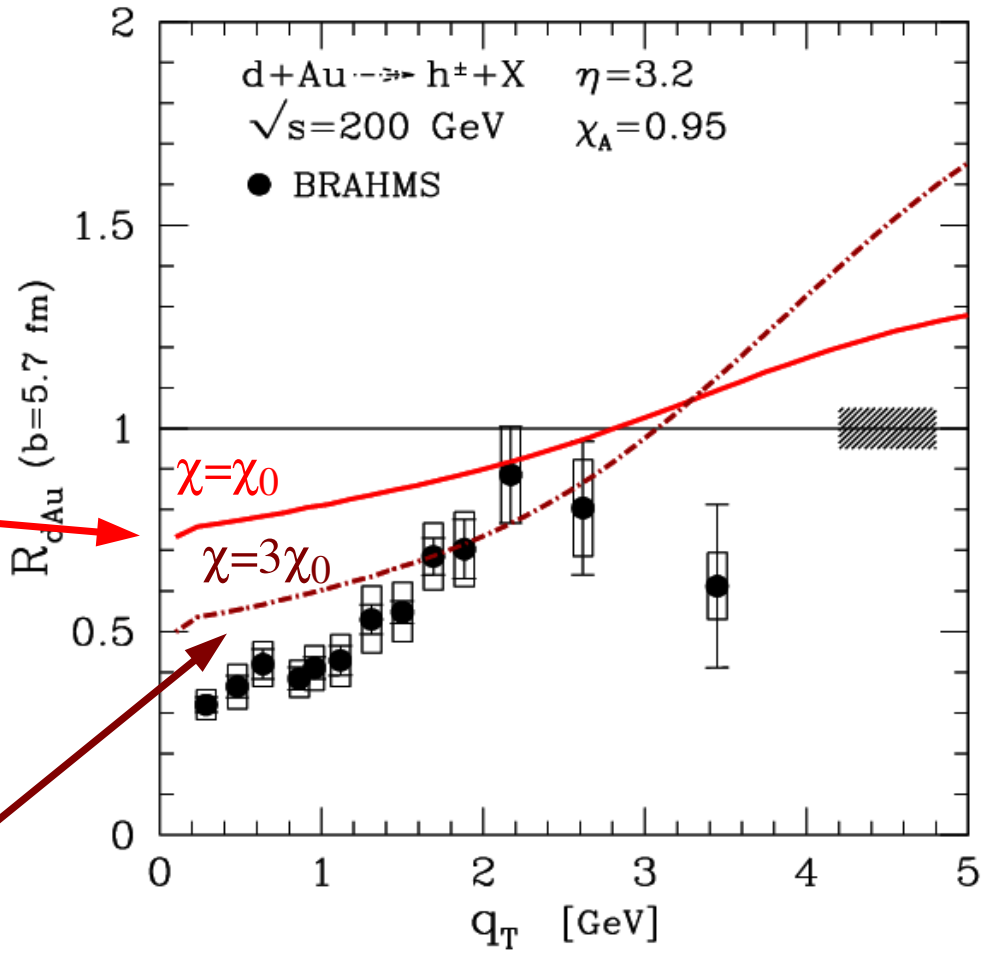
Some trend is visible:

- Progressive suppression of Cronin peak (η=0-1)
- More suppression at η=2-3, but precision insufficient at large p_T

GE model computation

- No available data for pp coll's at forward rapidity ⇒ we take **same parmeters as for η=0:**
  - $p_0(\eta>0) = p_0(\eta=0) = 1.0$ GeV
  - $K(\eta>0) = K(\eta=0) = 1$

η	0	1.8	3.2
χ	0.74	0.85	0.95



Are we underestimating opacity?
χ_0=0.95 obtained with **p_0 and K** fitted in pp at η=0: **may change with η**:

With $\chi=3\chi_0$, we are not so bad

if point at p_T=3.5 GeV confirmed - evidence of dynamical shadowing!

Part II

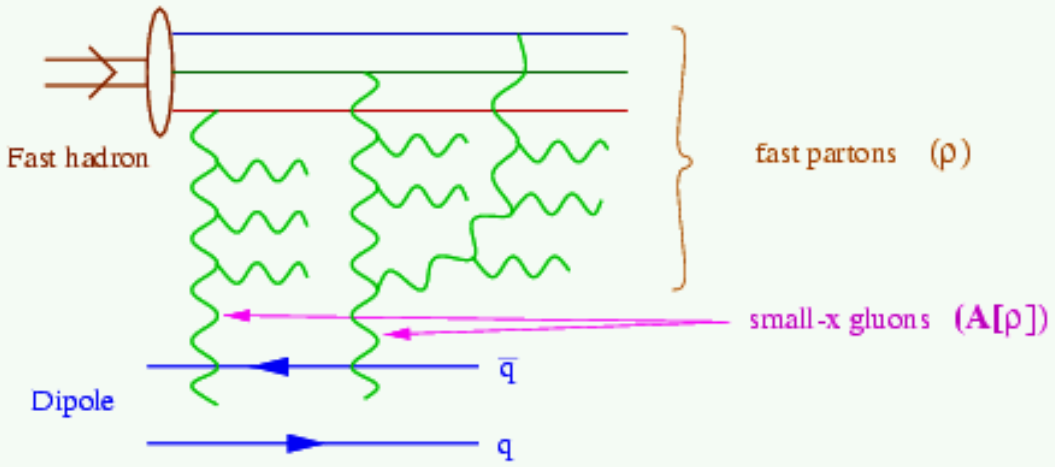
Saturation models

The Colour Glass Condensate

review: Iancu, Leonidov, McLerran, hep-ph/0202270

- An effective theory for the nucleus gluon field at small-x
- Observables $\mathcal{O}[A[\rho]]$ are averaged over ρ with weight function $W_y[\rho]$, where $y = \log(1/x)$:

$$\langle \mathcal{O} \rangle_y = \int D\rho W_y[\rho] \mathcal{O}[A[\rho]]$$



- Gluons at x' are colour sources for gluons at $x < x' \Longrightarrow$ RGE for W_y:

$$\frac{\partial W_y}{\partial y} = \frac{1}{2} \int \delta_\rho \chi[\rho] \delta_\rho W_y[\rho]$$

- **Gaussian approximation (GA)** Iancu,Itakura,McLerran '02

A self consistent approximation for W_y:

$$W_y[\rho] = \mathcal{N}_y \exp\left[-\frac{1}{2} \int_\infty^y dy \int dx_\perp dy_\perp \frac{\rho^a(x_\perp)\rho^a(y_\perp)}{\lambda_y(x_\perp, y_\perp)} \right]$$

CGC and p+A collisions

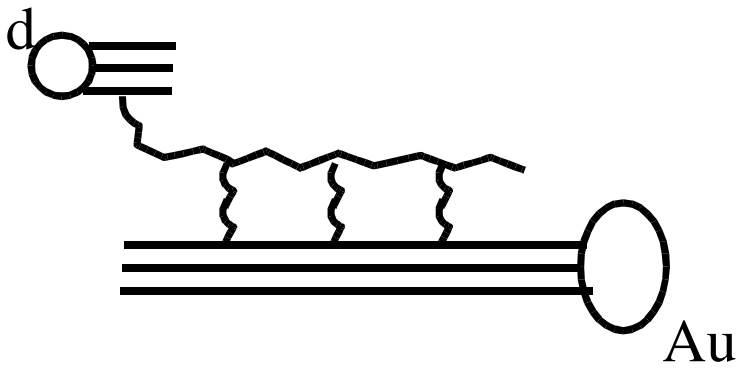
For gluon and valence quark production (Dumitru,Gelis,JalilianMarian; Blaizot et al.)

$$\frac{d\sigma^{d+A\to g(q_V)+X}}{d^2p_T dy} \propto \frac{1}{p_T^2}\int \frac{d^2k_T}{(2\pi)^2} f^p_{g(q_V)}(x_1,\vec{p}_T-\vec{k}_T)k_T^2 C(x_2;\vec{k}_T)$$

where $C(x_2;k_T)=\int d^2r_T\, e^{i\vec{r}_T\cdot\vec{k}_T}\langle U^\dagger(0)U(\vec{r}_T)\rangle_{x_2}$ (fundam. or adjoint Wilson line).

If W is Gaussian, then Glauber multiscattering interpratation:

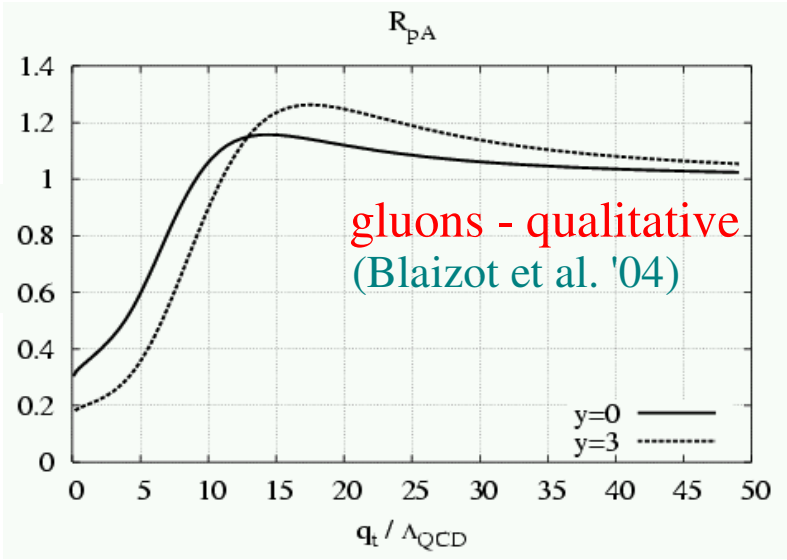
$$C(x_2;k_T)=\int d^2r_T\, e^{i\vec{r}_T\cdot\vec{k}_T}\; e^{\tilde{\sigma}(r_T;b)}$$



MV model: local gaussian correlations

$$\lambda_y(y_T - x_T) = \lambda_y = Q_s^2(x_2) = \alpha_s^2 \frac{8\pi N_c}{N_c - 1} x_2 G(x_2; Q^2)$$

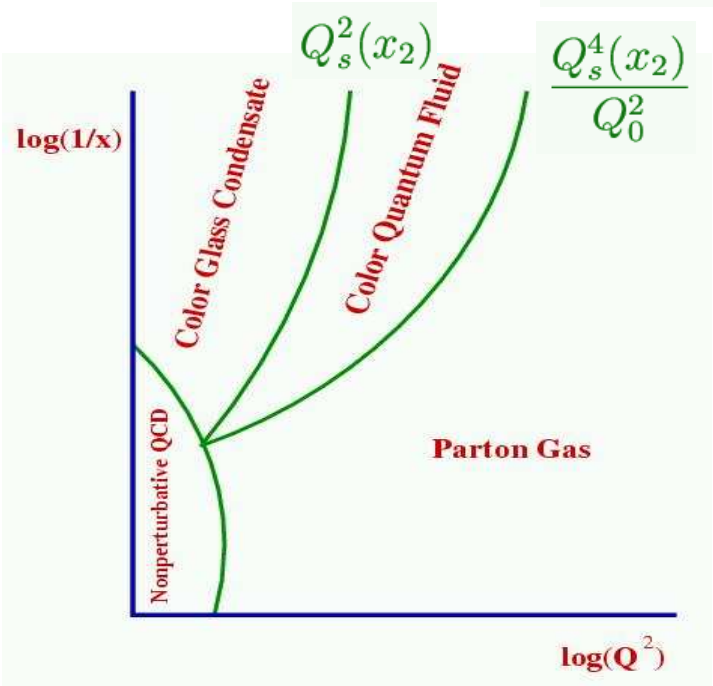
$$\tilde{\sigma}(r_T) = r_T^2 \, Q_s^2(x_2) + O(r_T^4) \approx \tilde{\sigma}_{pQCD} \;!! \implies$$

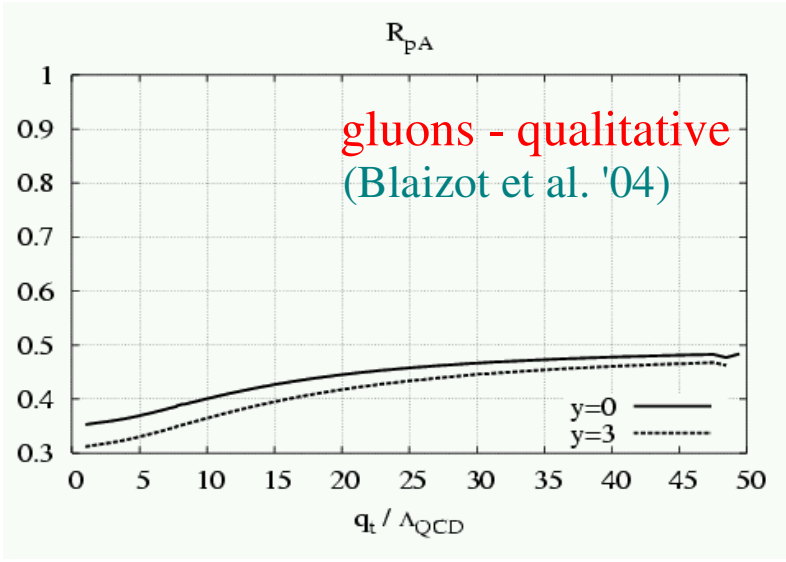


CGC = MV + quantum evolution:

non-local gaussian correlations ⇒ approx. solution of RG equation: (Iancu, Itakura,McL)

In saturation region: $\lambda_y(y_T - x_T) \propto \int d^2k_T \, e^{i(\vec{y}_T - \vec{x}_T)\cdot\vec{k}_T} \, k_T^2 \, \ln\left(1 + \left(\frac{Q_s^2(x_2)}{k_T^2}\right)^{\gamma}\right)$

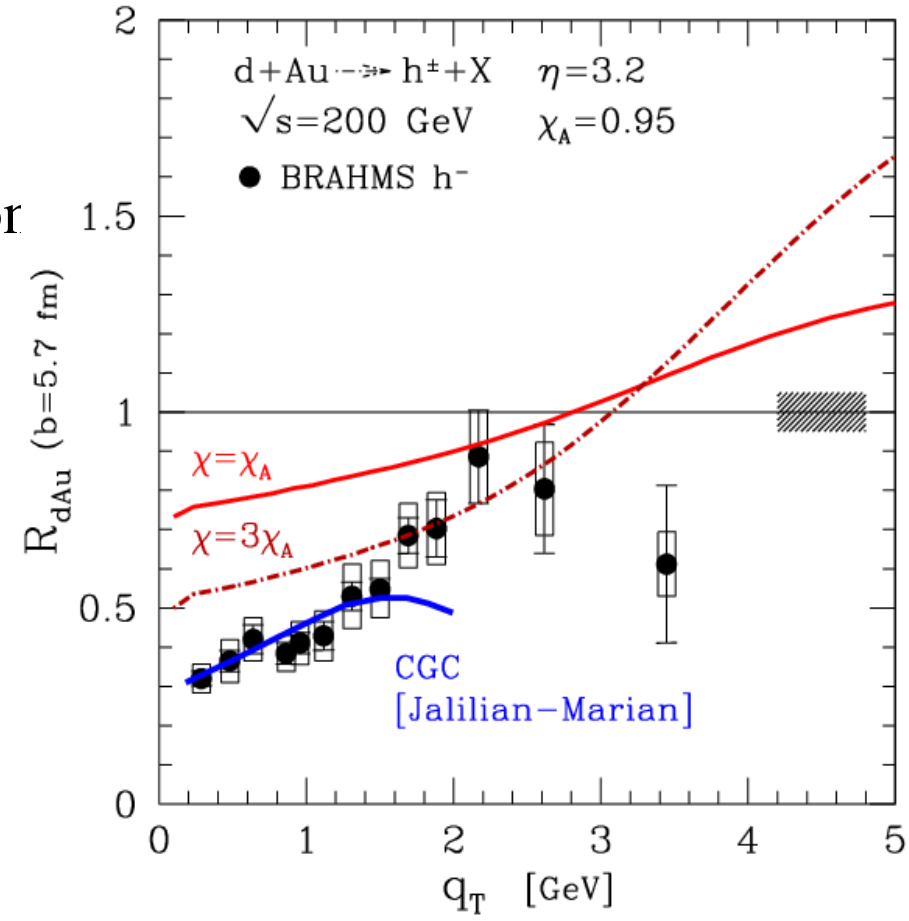




Quantitative computation in CGC: d+Au at η=3.2 (Jalilian-Marian '04)

Assumptions:

- at large η only valence quark in deuteron
- deuteron PDF's are collinear factorized
- Au treated in CGC
- only single scattering
- dipole cross-section from saturation
- and scaling regions only



Underestimates BRAHMS data at p_T>1.5 GeV!

Data seem to interpolate between CGC and Glauber-Eikonal pQCD

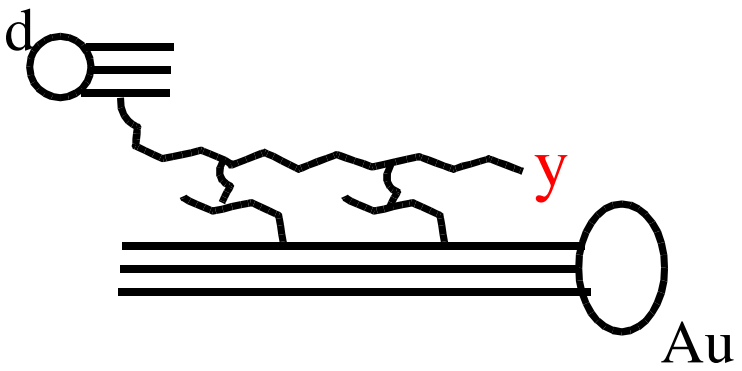
Part III

Where does pQCD meet CGC?

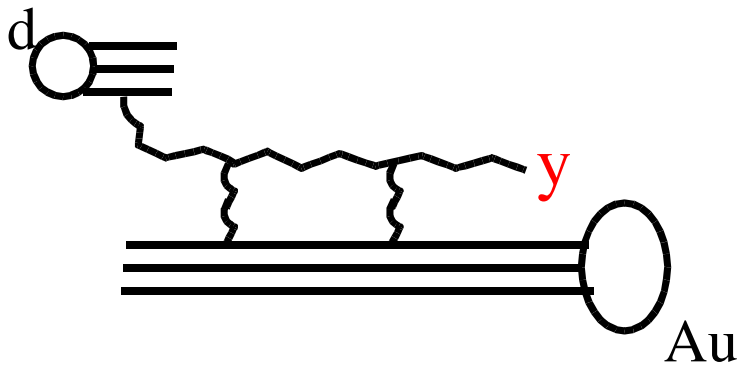
- let's go back to p+p -

2→2 vs. 2→1 processes

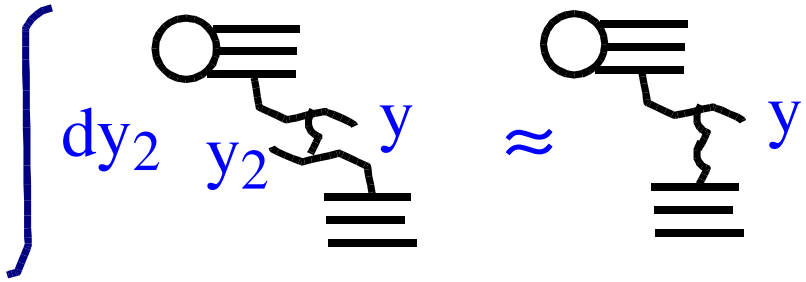
pQCD: multiple 2→2



CGC & k_T-fact: multiple 2→1



p+p collisions at $p_T > Q_s$:
(Gyulassy,McLerran '97)



Common lore:

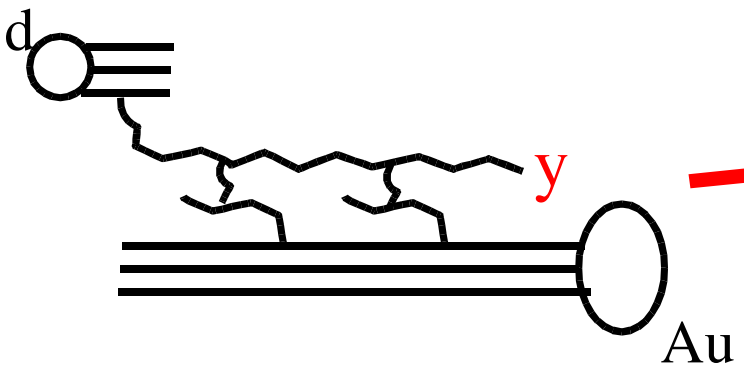
⇒ 1) MV model ≈ GE pQCD

2) CGC → pQCD at high pT

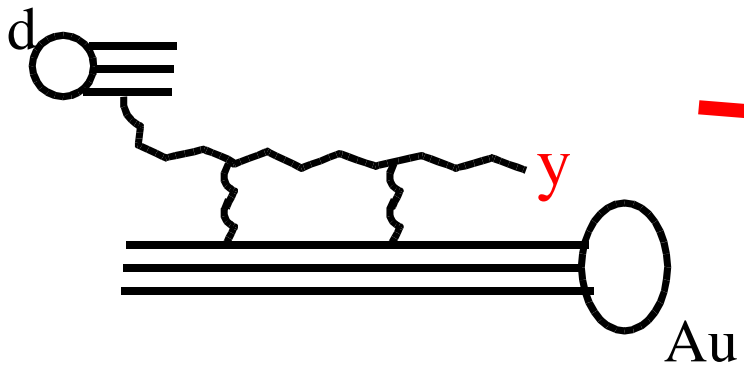
Equality is approx. true,
but conclusions 1 and 2 wrong!

2→2 vs. 2→1 processes

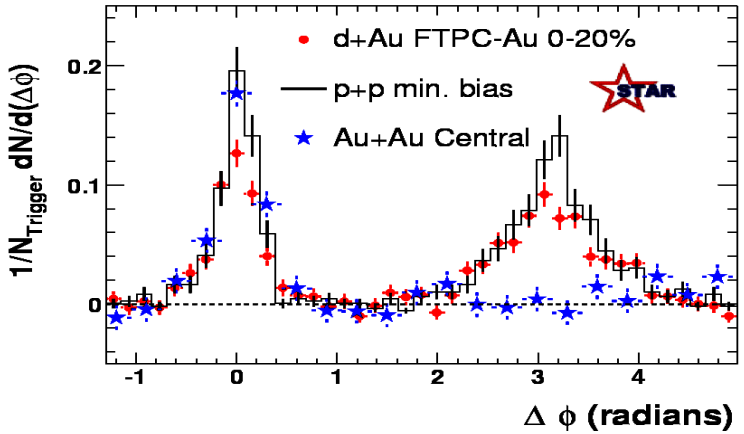
pQCD: multiple 2→2



CGC & k_T-fact: multiple 2→1



Indeed,

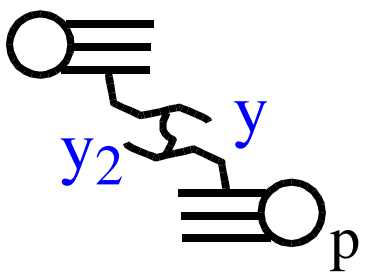


back-to-back jets observed in p+p and d+Au

No back-to-back jets predicted

Another important difference (pp collisions)

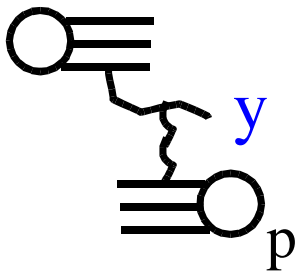
2→2



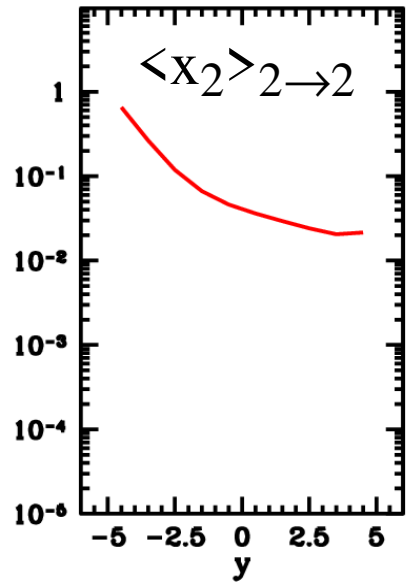
$$x_2 = \frac{p_T}{\sqrt{s}}\left(e^{-y} + e^{-y_2}\right)$$

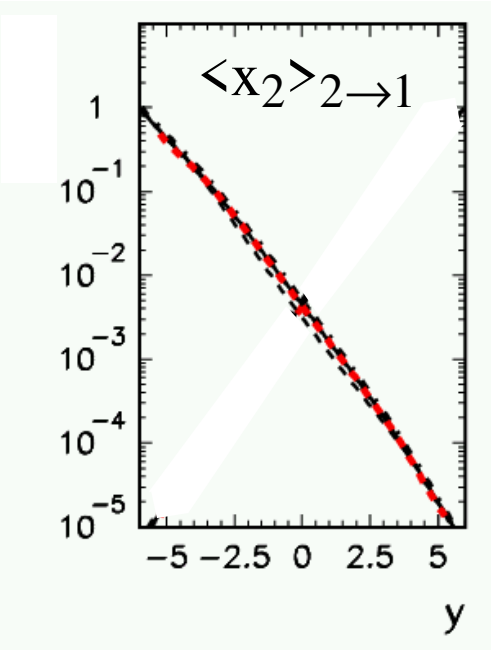
when averaging x_2 we integrate over unobserved y_2

2→1



$$x_2 = \frac{p_T}{\sqrt{s}} e^{-y}$$

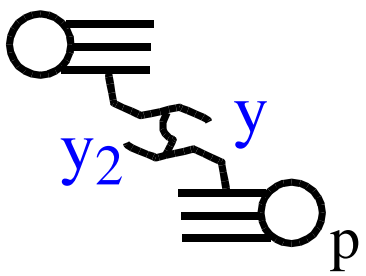




2→2 and 2→1 processes probe the target at quite different Bjorken's x!

Which process is dominant and where?

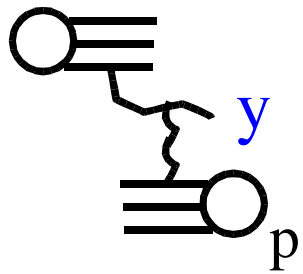
2→2



$$\frac{d\sigma^{p+p\to g+X}}{d^2p_T dy} \approx \int dy_2\, xG(x_1)\, xG(x_2)\, \frac{d\hat{\sigma}}{d\hat{t}}$$

$$\approx \Delta y_2 \times xG\left(\langle x_1\rangle_{2\to 2}\right) xG\left(\langle x_2\rangle_{2\to 2}\right) \frac{d\hat{\sigma}}{d\hat{t}}$$

2→1



$$\frac{d\sigma^{p+p\to g+X}}{d^2p_T dy} \approx xG\left(\langle x_1\rangle_{2\to 1}\right) xG\left(\langle x_2\rangle_{2\to 1}\right) \frac{d\hat{\sigma}}{d\hat{t}}$$

From kinematics,

At low rapidity, $\langle x2\rangle_{2\to1} \sim \langle x2\rangle_{2\to2}$ then **2→2 dominant** ($\Delta y_2 \sim 10$)

At forward rapidity, $\langle x2\rangle_{2\to1} \ll \langle x2\rangle_{2\to2}$ then **2→1 dominant**

(rise of gluon density at small x_2)

Need dynamical detailed computation: k_T-factorization formalism?

see A.Szczurek's talk

Conclusions

- **pQCD GE model:**
  - 2→2 multiple scatterings
  - OK at η=0
  - overestimate at η=3
- **CGC:**
  - 2→1 multiple scatterings
  - underestimates at η=3
- They describe differente elementary processes
- The question is not "Which one is right?", but

**"Where is one dominant over the other?
Where does the transition occur?"**

- We don't yet know the answer even in p+p (i.e., 1 scattering)!

Need detailed study of 2→2 to 2→1 transition in p+p (k_T-factorization formalism seems the most adequate)

The End