Naked Cronin effect in Au+Au collisions

Alberto Accardi (Iowa State U.)

Hard Probes 2004 - Ericeira, Nov 3-10, 2004

- **Intro:** overview of theory models
- **Glauber-Eikonal model** (pQCD multiple parton scatterings)
  - calibrated in p+p collisions
  - d+Au @ $\eta = 0 \quad \Rightarrow \quad$ OK!
- **Naked Cronin effect =** Au+Au without medium effects
  - onset and magnitude of hadron quenching
  - from RHIC to SPS
- **Remarks** on baryon anomaly and HERMES data

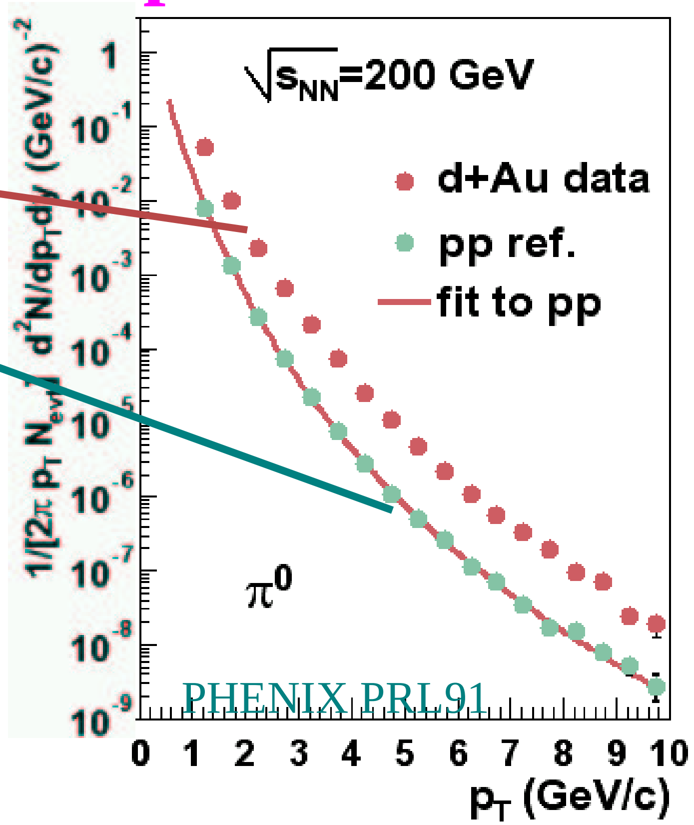
Based on: A.A., M.Gyulassy, PLB 586 (04) 244 & J.Phys.G 30 (04) s969
A.A., nucl-th/0405046

Cronin ratio of inclusive spectra

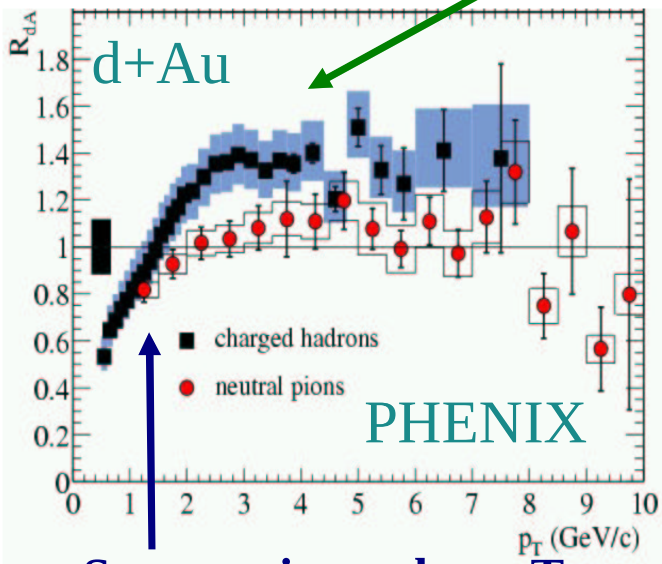
$$R_{AB}(p_T) = \frac{d^2 N^h_{AB} / dp_T\, d\eta}{T_{AB}\, d^2\sigma^h_{NN} / dp_T\, d\eta}$$

Binary collision scaling

p+p reference



Enhancement at moderate-pT



Suppression at low pT

(same pattern in Fermilab p+A data)

Note: baryon/meson anomaly

Theoretical models for hA

- **Parton rescatterings**
  - **Glauber-Eikonal models** (pQCD)

    "Exact" Kuhn '76; Kryzwicky '79; Lev-Petersson '83; A.A.,Gyulassy; Cattaruzza, Treleani;

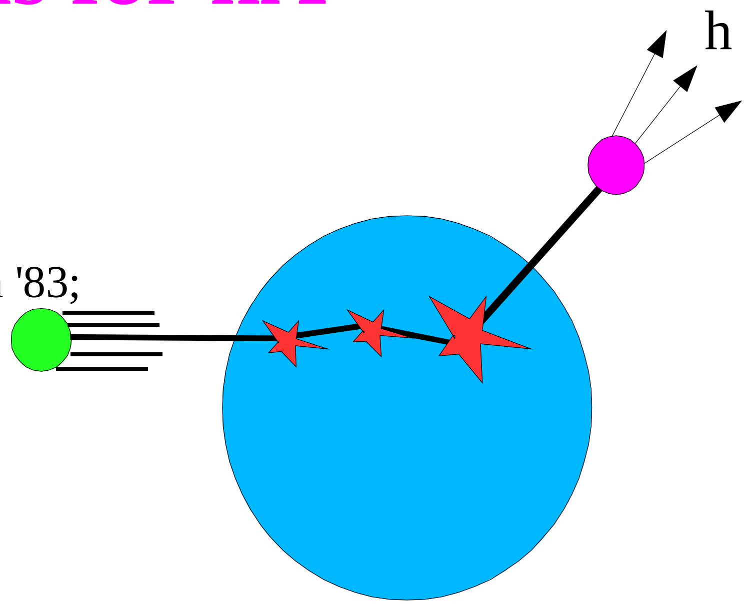
    Approx. X.N.Wang et al.; Barnafoldi et al.; Vitev,Gyulassy; Fai,Zhang;
  - **Colour dipole models**

    Vintage Kopeliovich et al.

    → Golec Biernat-Wuesthoff σ_{dip}

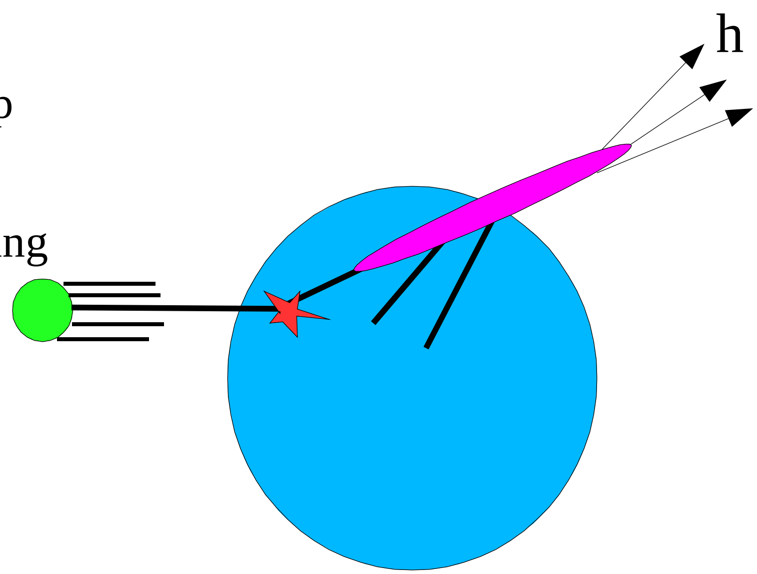
    CGC inspired Jalilian-Marian Kharzeev,Kovchegov,Tuchin

    → CGC inspired parametrization of σ_{dip}



- **Final state parton recombination** Hwa,Yang

  (parton shower and pickup from medium)



First act: p+p collisions

Single scattering
= LO in pQCD

renormalization scale — fragmentation scale

$$\frac{d\sigma^{pp}}{d^2p_t} = \int dx \sum_i f_{i/h}(x, Q_p^2)\, K \int dx' \sum_j f_{j/A}(x', Q_p^2) \frac{d\sigma^{ij}_{pQCD}}{d^2p_T} \int dz D_{i\to h}(z, Q_h^2)$$

$$\underbrace{\qquad}_{= d\sigma^{iN}/d^2p_T}$$

K-factor (simulates NLO) — IR regulator

where
$$\frac{d\sigma^{iN}}{d^2p_T} \approx K \int_{\frac{4p_T^2}{x\sqrt{s}}}^1 dx'\, f_{j/A}(x', Q^2) \frac{C^{ij}}{(p_T^2+p_0^2)^2} \propto \frac{1}{(p_T^2+p_0^2)^{2+n}}$$
= parton-nucleon cross section

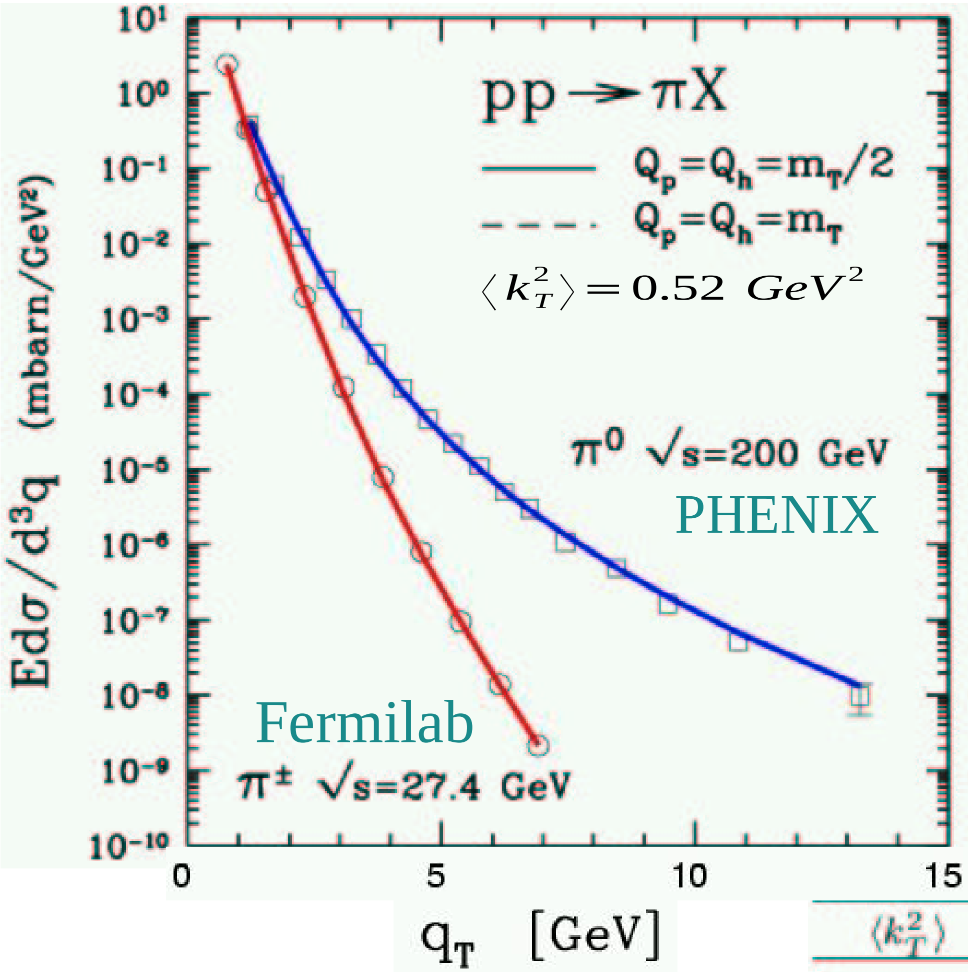
a) CHOOSE the scales: $Q_p = Q_h = \sqrt{p_T^2+p_0^2}\,/\,2$
(or $Q_p = Q_h = \sqrt{p_T^2+p_0^2}$)

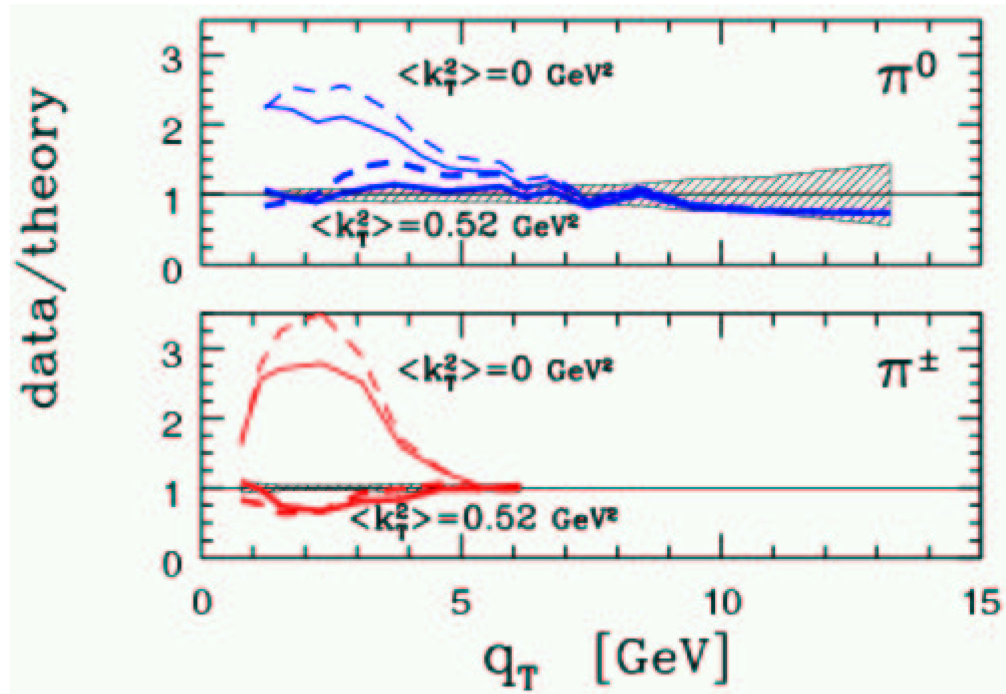
b) FIT **K=K(s)** to the **high-p_T** tail of the hadron spectrum
(χ^2 fit, sensitive to the choice of scales)

c) FIT intrinsic $\langle k_T^2 \rangle = 0.52$ GeV^2 to the **moderate-p_T**

d) FIT $p_0 = p_0(s)$ to the **low-p_T** hadron spectrum

Results of the fit





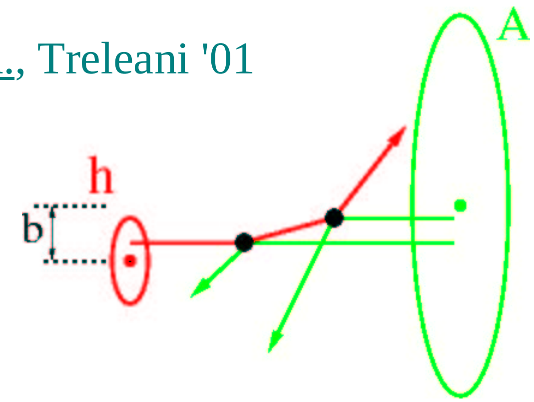
Fit procedure: Eskola, Honkanen '02

$\langle k_T^2 \rangle$	$Q_p = Q_h$	$\sqrt{s} = 27.4$ 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$)$ $K = 2.04 \pm 0.12$

other energies ⇒ log fit:

$p_0 = 0.151 + 0.200 \log \sqrt{s}$

Second act: h+A 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

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

n-fold parton rescattering

unitarity factor (probability conserv.)

and: $$\frac{d\sigma^h_{pA}}{d^2p_t} = \sum_i f_{i/p}\otimes\frac{d\sigma^{iA}}{d^2p_t}\otimes D_{i\to h} + A\sum_j f_{j/A}\otimes\frac{d\sigma^{jp}}{d^2p_t}\otimes D_{j\to h}$$

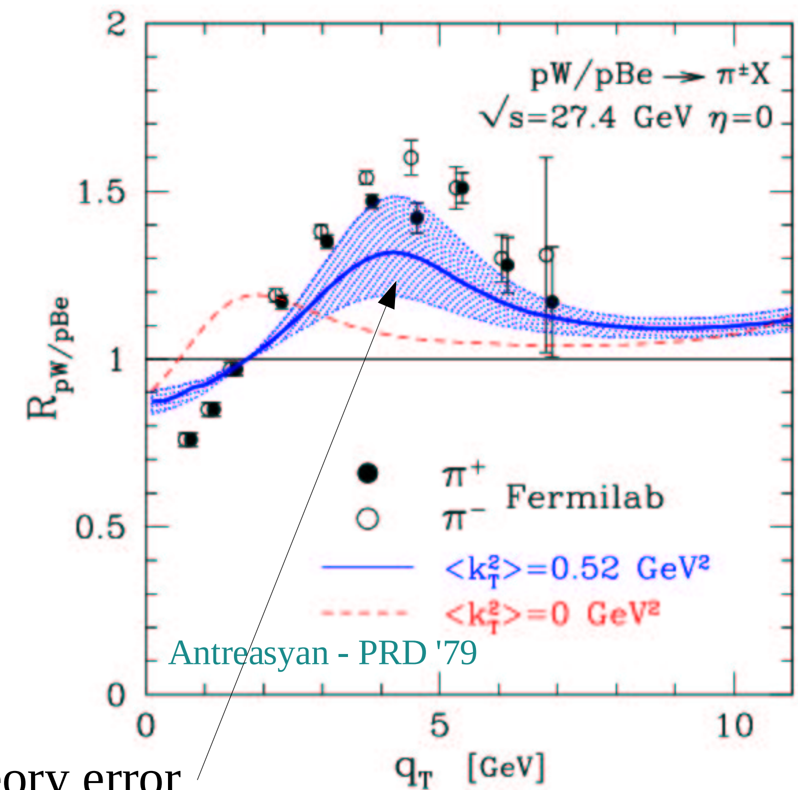
- **pA = unitarized multiple parton scatterings on free nucleons**
- **Spectra in pp coll. as limiting case (high-pT or A->1)**
- **No extra free parameters**

$$\frac{d\sigma^h_{pA}}{d^2p^h_T} \underset{p_T\to\infty}{\longrightarrow} A\frac{d\sigma^h_{pp}}{d^2p^h_T}$$

h+A : midrapidity pions

Fermilab $\sqrt{s}$ = 27.4 GeV

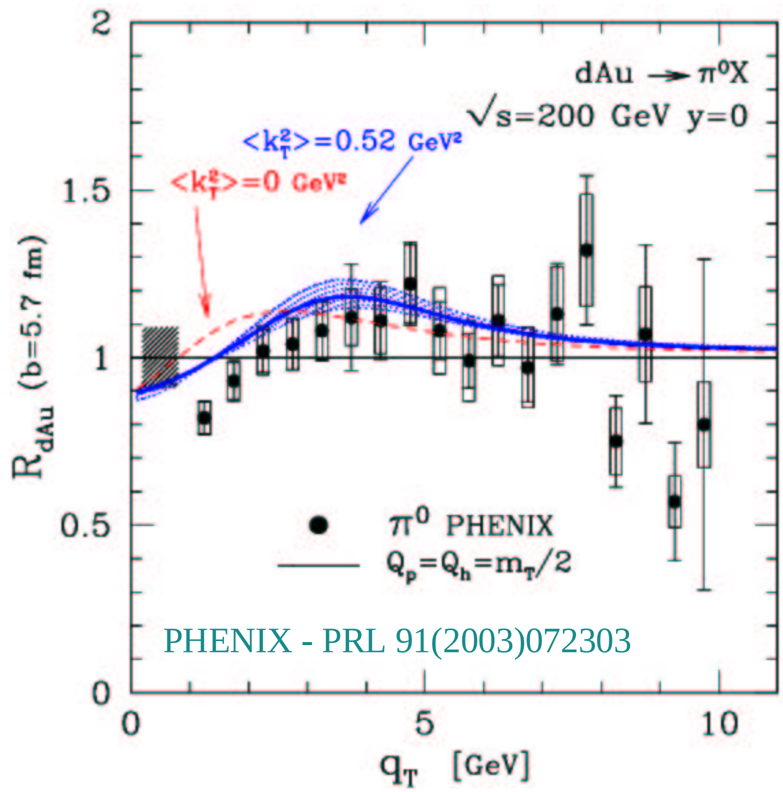
p_0 = 0.7 GeV ± 10%



theory error
due to fit of p_0

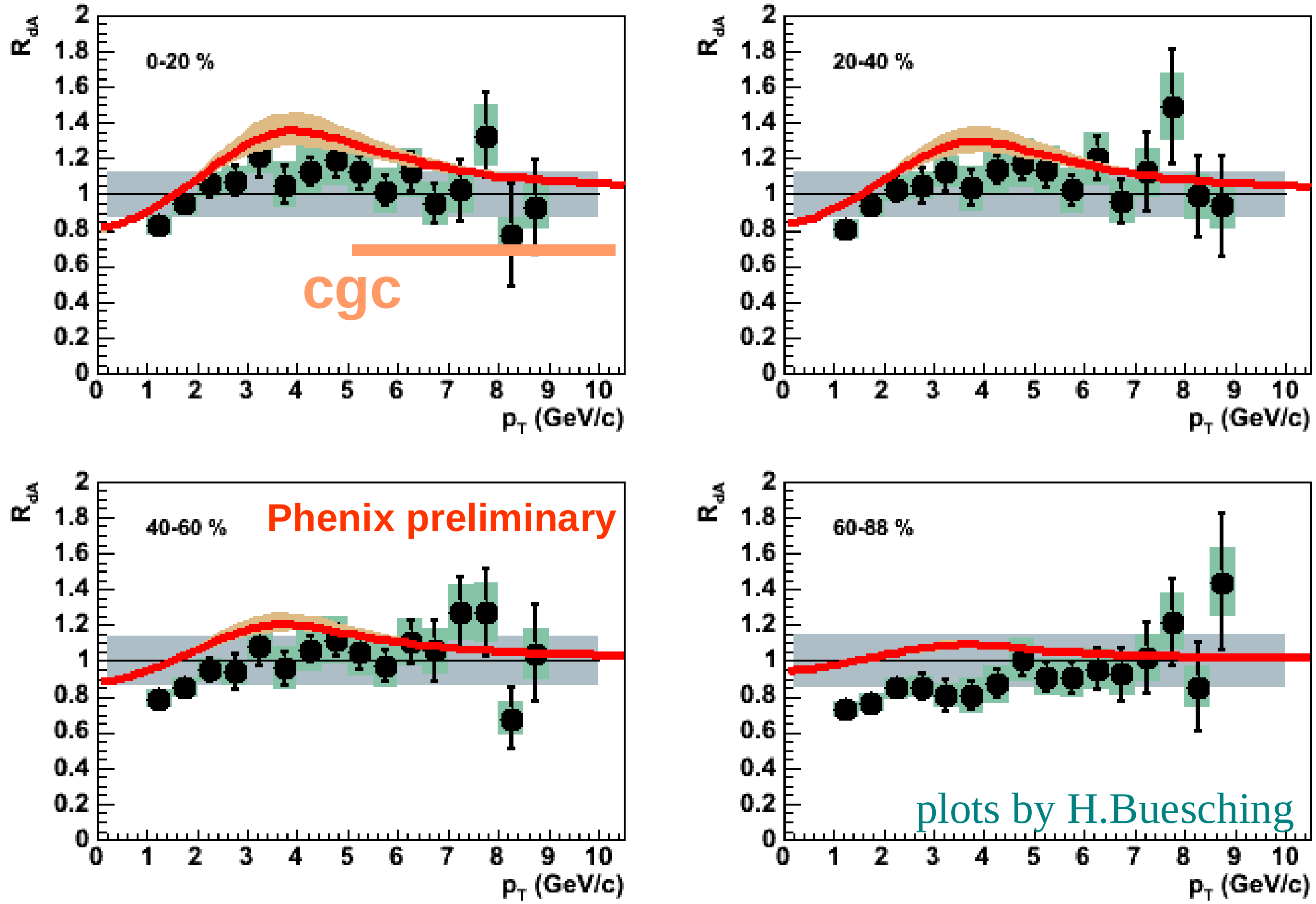
Phenix $\sqrt{s}$ = 200 GeV

p_0 = 1.0 GeV ± 10%



Glauber-Eikonal model is OK at η=0

Check: centrality dependence at 200 GeV



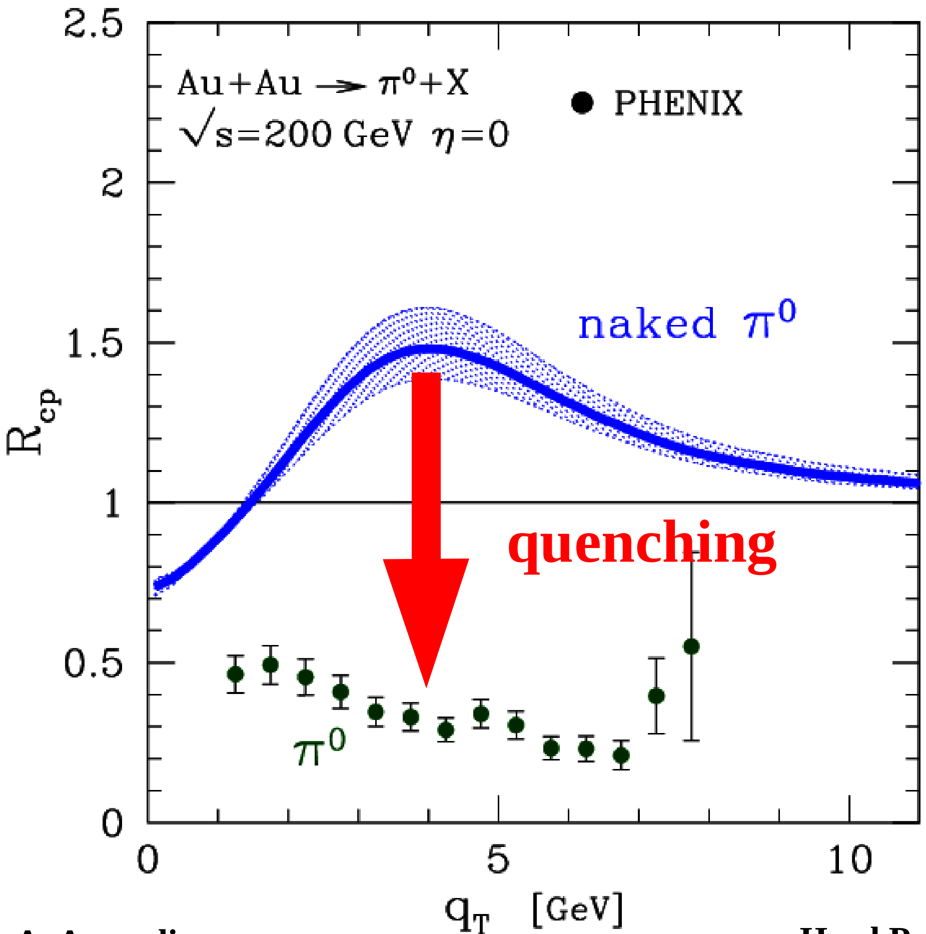
Glauber-Eikonal model is OK at η=0

Third act: A+A collision

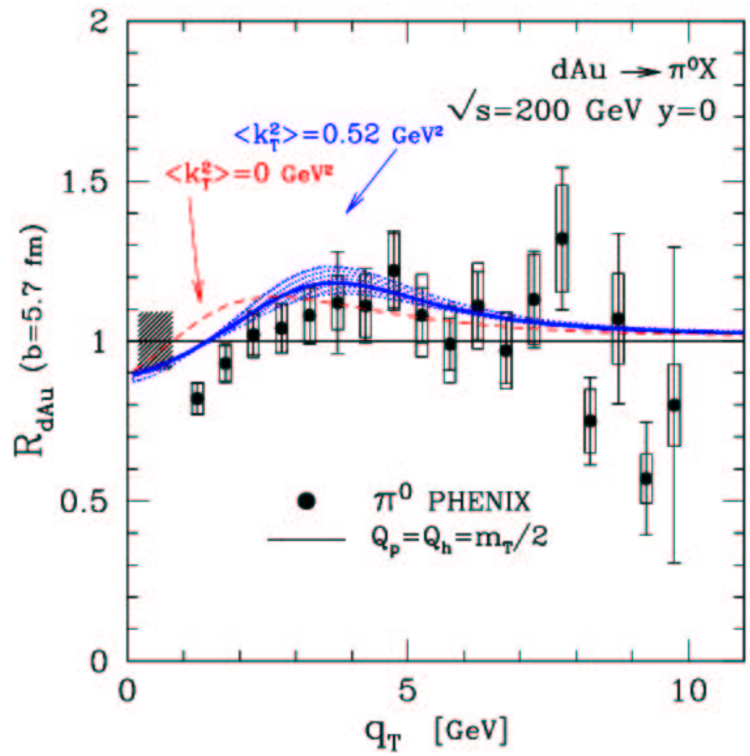
minimal extension of GE model:

$$\frac{d\sigma^h_{AB}}{d^2b d^2p_t} = \sum_i f_{i/A} \otimes \frac{d\sigma^{iB}}{d^2b d^2p_t} \otimes D_{i\to h} + \sum_j f_{j/B} \otimes \frac{d\sigma^{jA}}{d^2b d^2p_t} \otimes D_{j\to h}$$

1) Phenix π^0 - $\sqrt{s}$=200 GeV (p_0 = 1.0 GeV ± 10%)

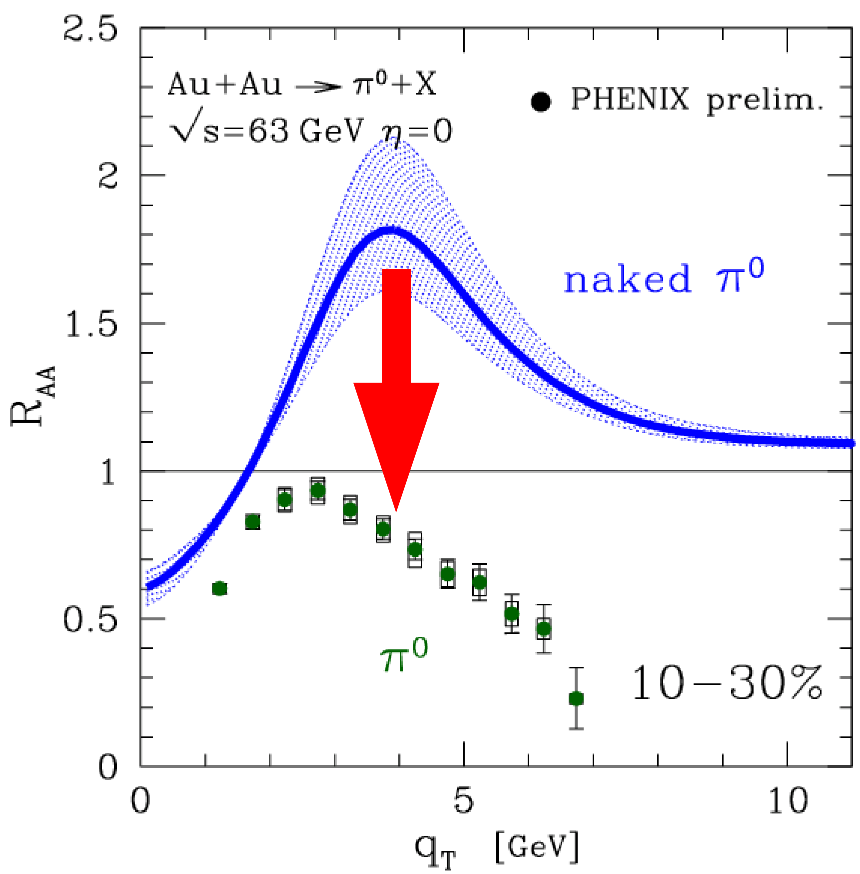


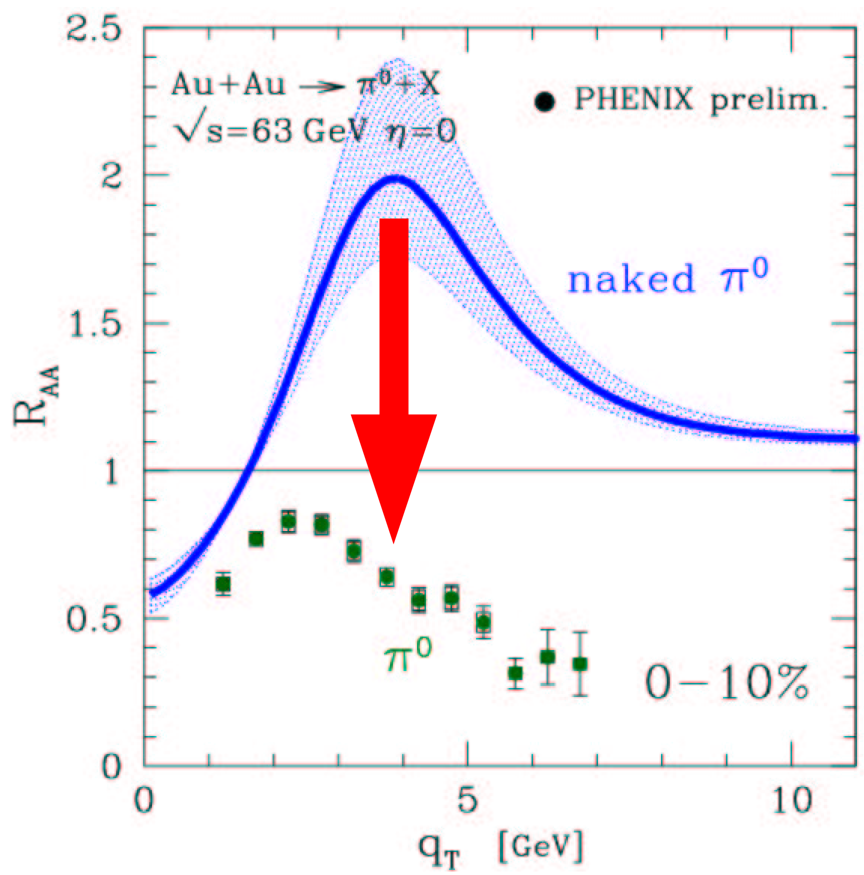
Note: existence of quenching from d+Au data alone - for magnitude we need theory computation



2) Phenix π^0 - $\sqrt{s}$=62.4 GeV (p_0 = 0.82 GeV ± 10%)

At 62 GeV we do not have data on d+Au ⇒ theory is needed





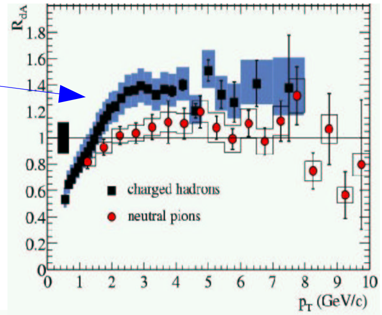
- As expected, less suppression in peripheral collisions.
- Where does quenching begin? theory vs. data is needed

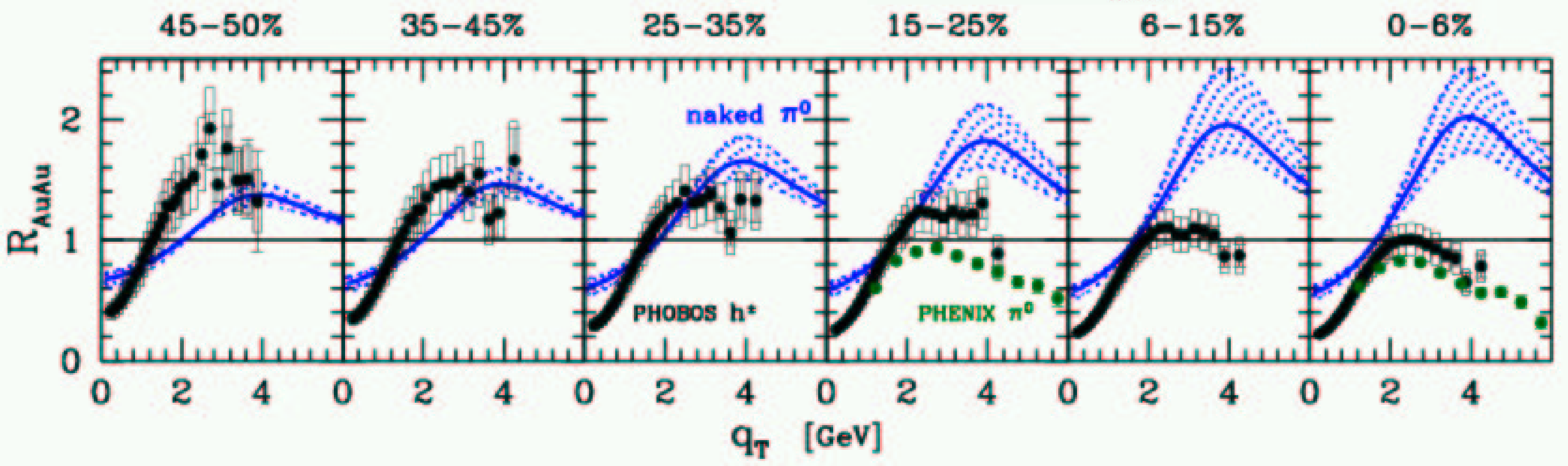
⇒ let's look at PHOBOS **$h^{\pm}$ data**

3) Phobos $h^{\pm}$ - $\sqrt{s}$=62.4 GeV

(p_0 = 0.82 GeV ± 10%)

Attention: baryon-meson anomaly
computations are for π^0's





no quenching

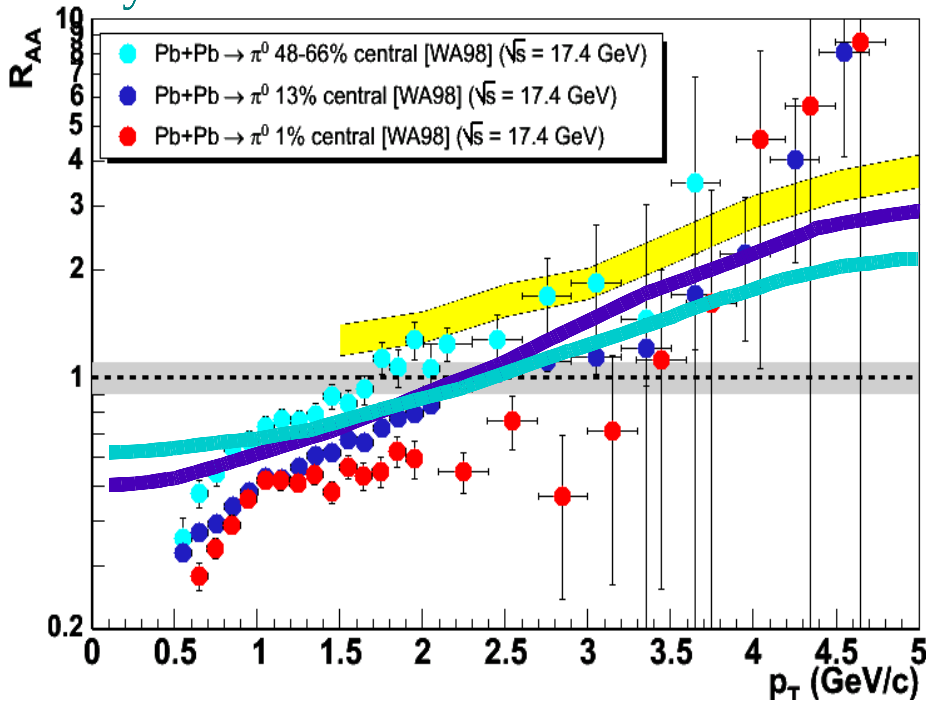
quenching begins

more and more quenched

Quenching begins at around 40-45% centrality

4) WA98 π^0 - $\sqrt{s}$=17.4 GeV (p_0 = 0.59 GeV ± 10%) work in progress

reanalysis of p+p reference for WA98 data
by D.D'Enterria - PLB'04



indications of:

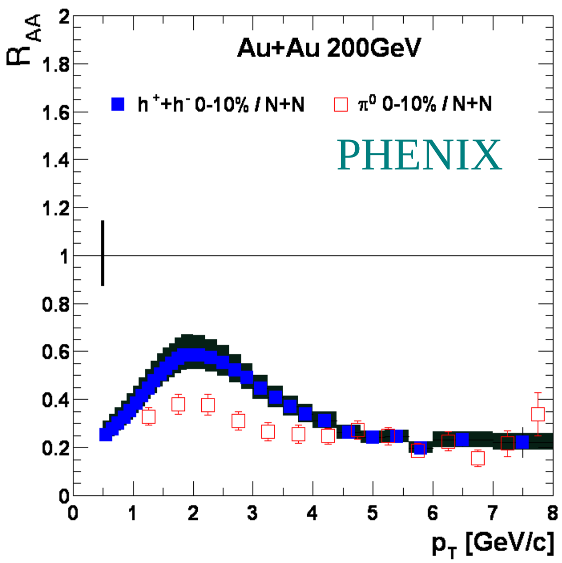
very small or no quenching in peripheral collisions

Moderate quenching in central collisions

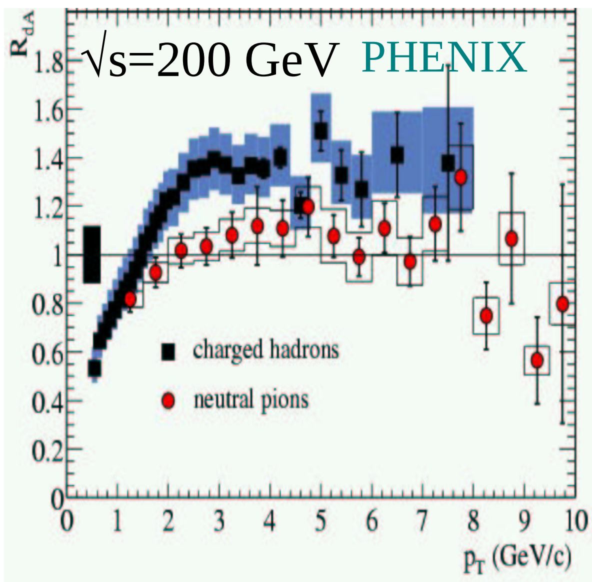
- large experimental uncertainty due to p+p normalization
  - 25% systematic error on p+p baseline not shown
  - chosen p+p arametrization underestimates data at $p_T \gtrsim 3$ GeV
- large theory uncertainty due to K=1.1 log-extrapolation
  - theory curves to be taken as approximate lower limits
  - also, scales are quite low for perturbative computations...

Baryon anomaly, a pervasive theme

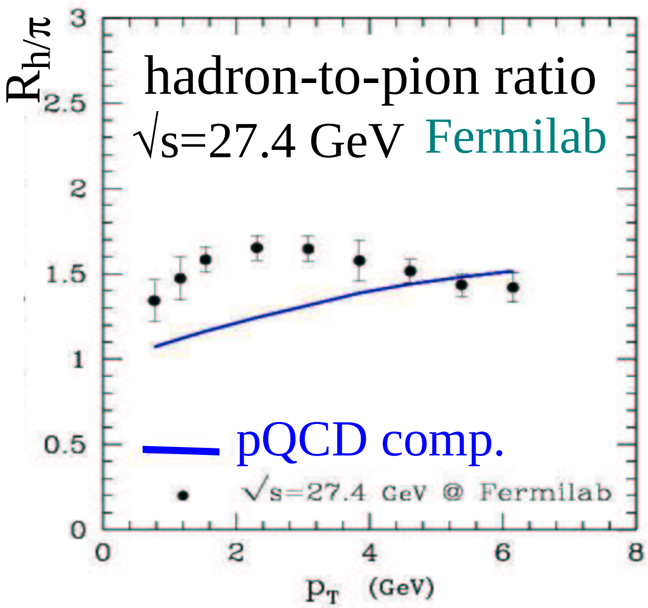
in A+A



in h+A



in p+p



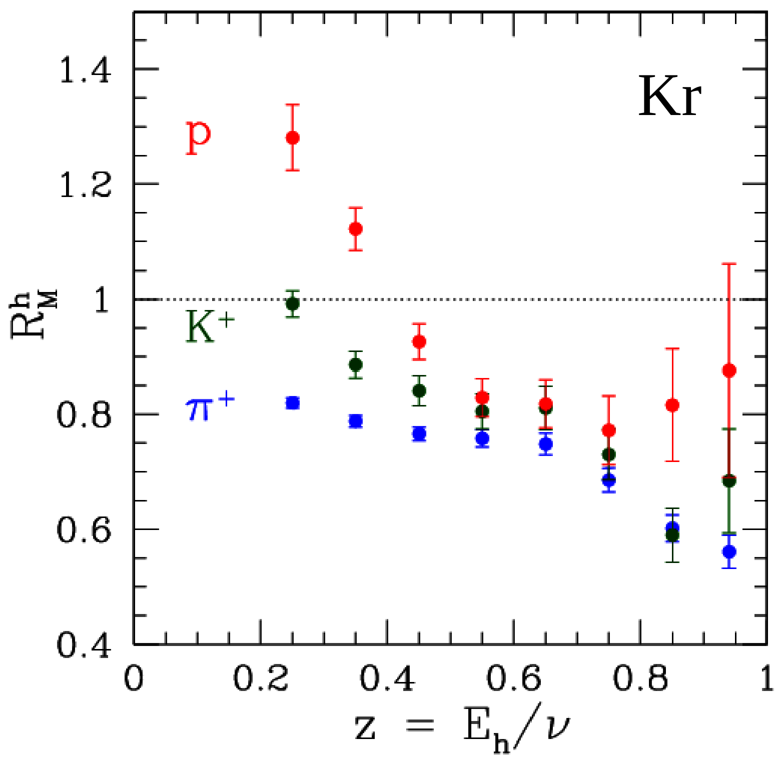
Baryon anomaly is hard to understand in pQCD

$\Rightarrow$ Cronin computations only for π^0

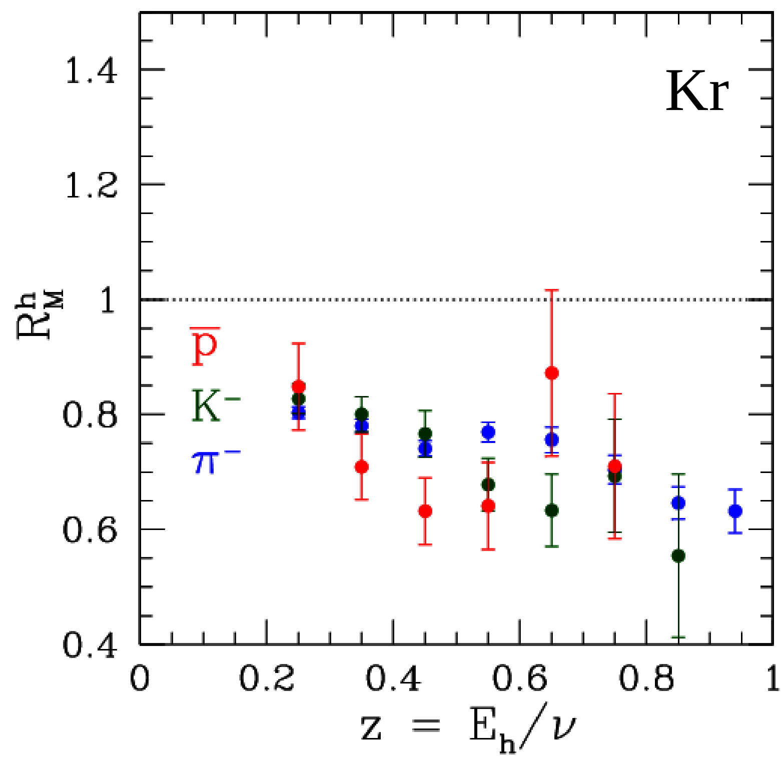
Baryon anomaly also in DIS on nuclei!

HERMES E_{lab}=27 GeV - Phys.Lett.B577(03)37

hadron "quenching" in e+A: $R_M^h(z,\nu,p_t^2,Q^2) = \dfrac{\left.\dfrac{N_h(z,\nu,p_t^2,Q^2)}{N_e(\nu,Q^2)}\right|_A}{\left.\dfrac{N_h(z,\nu,p_t^2,Q^2)}{N_e(\nu,Q^2)}\right|_D}$



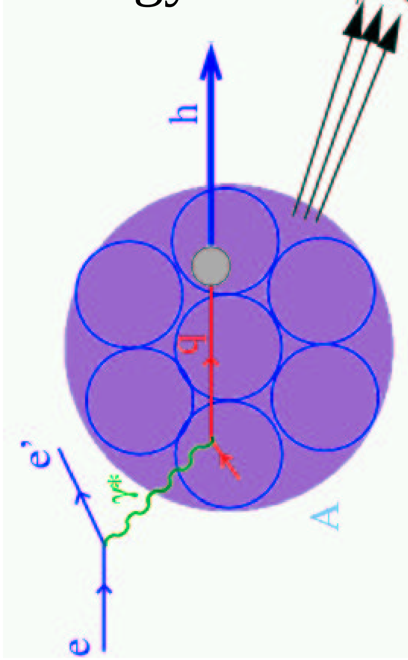
baryons are anomalous...

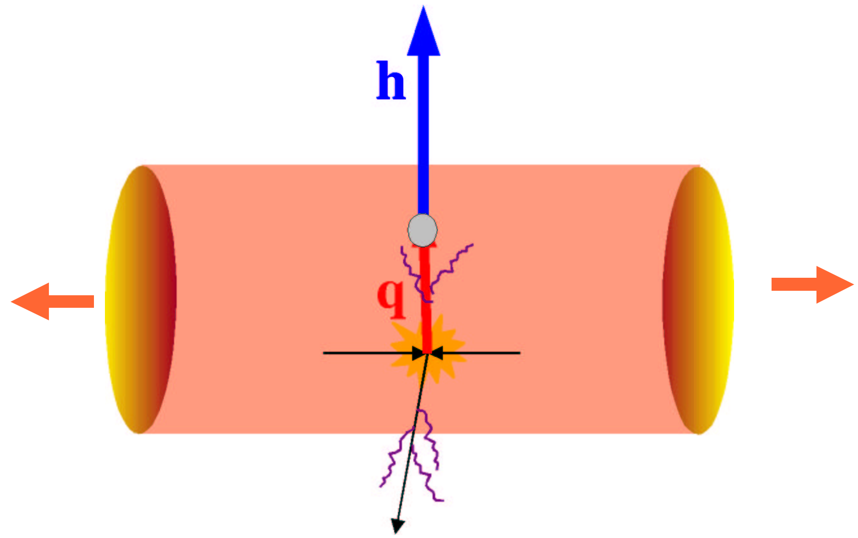


... but antibaryons are not!

Lessons from HERMES data

- **cold nuclear matter effect in clean environment**
  - hadron formation time
  - energy loss





$E_q = \nu = E_e - E_{e'} \approx 13$ GeV on average

$E_h = z\,\nu \approx$ **2 - 12 GeV**

$E_q = p_T / z$

$E_h = p_T \approx$ **2 - 12 GeV**

HERMES kinematics is relevant to RHIC mid-rapidity

Conclusions

- **Glauber-Eikonal model** describes fairly well Cronin effect in mid-rapidity d+Au on a broad energy range $\sqrt{s}$=20-200 GeV
  $\Rightarrow$ **baseline computation for Au+Au collisions**
  ("Naked Cronin effect")

- **d+Au data vs. theory**
  - no initial-state effect at mid-rapidity

- **Au+Au data vs. theory**
  - quenching at $\sqrt{s}$=62.4 GeV starts at around 40% centrality
  - indications moderate quenching in SPS central collisions?

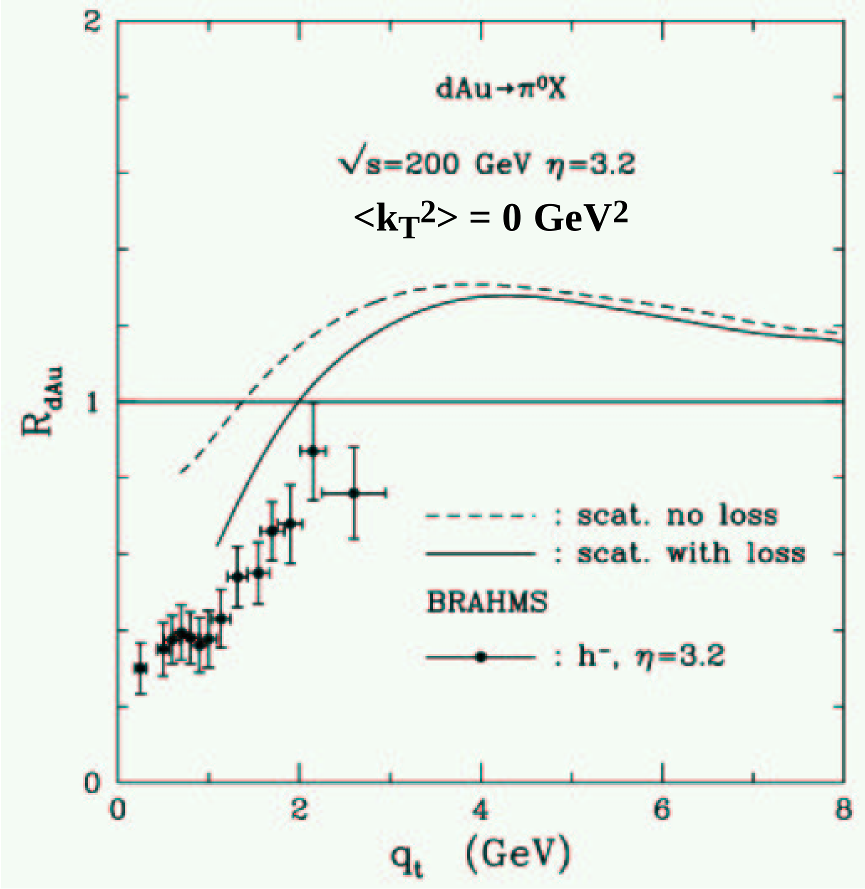
- **read HERMES papers:** nDIS is relevant to RHIC!

- <u>Future</u>:
  - careful check of assumptions
  - inclusion of elastic energy loss & coherent multi-scatterings

The End

Glauber-Eikonal with elastic energy loss

Cattaruzza, Treleani, PRD...(04)...



Elastic energy loss:
parton energy is conserved,
but x is not!

- $x \to x + \Delta x$
- negligible at high-p_T
- **potentially large correction at low-p_T**

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:

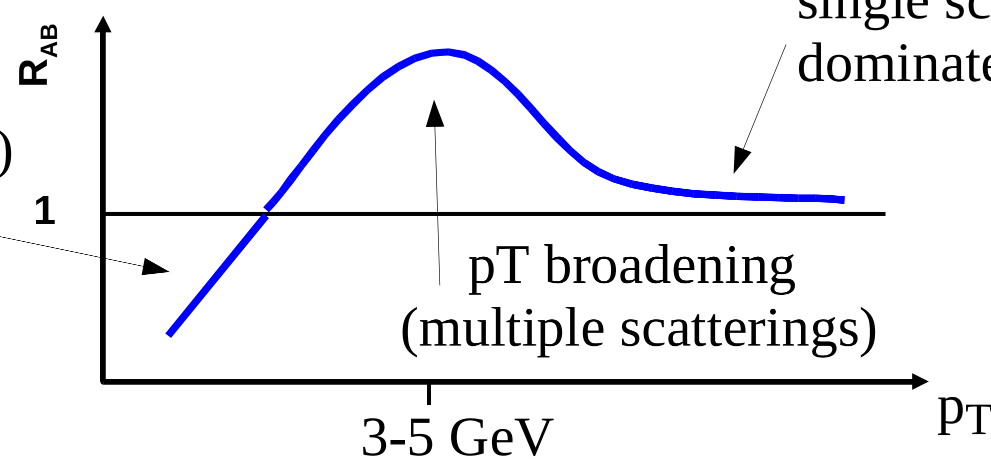
1) low-opacity $\chi \langle\langle 1 \Longrightarrow \frac{d\sigma^{iA}}{d^2b d\eta} \approx T_A \sigma^{iN}$ collision scaling (single semihard scattering)

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

<u>Sum of 2 effects:</u>

a) momentum conservation (spectrum shifted to higher p_T)

b) geometric shadowing



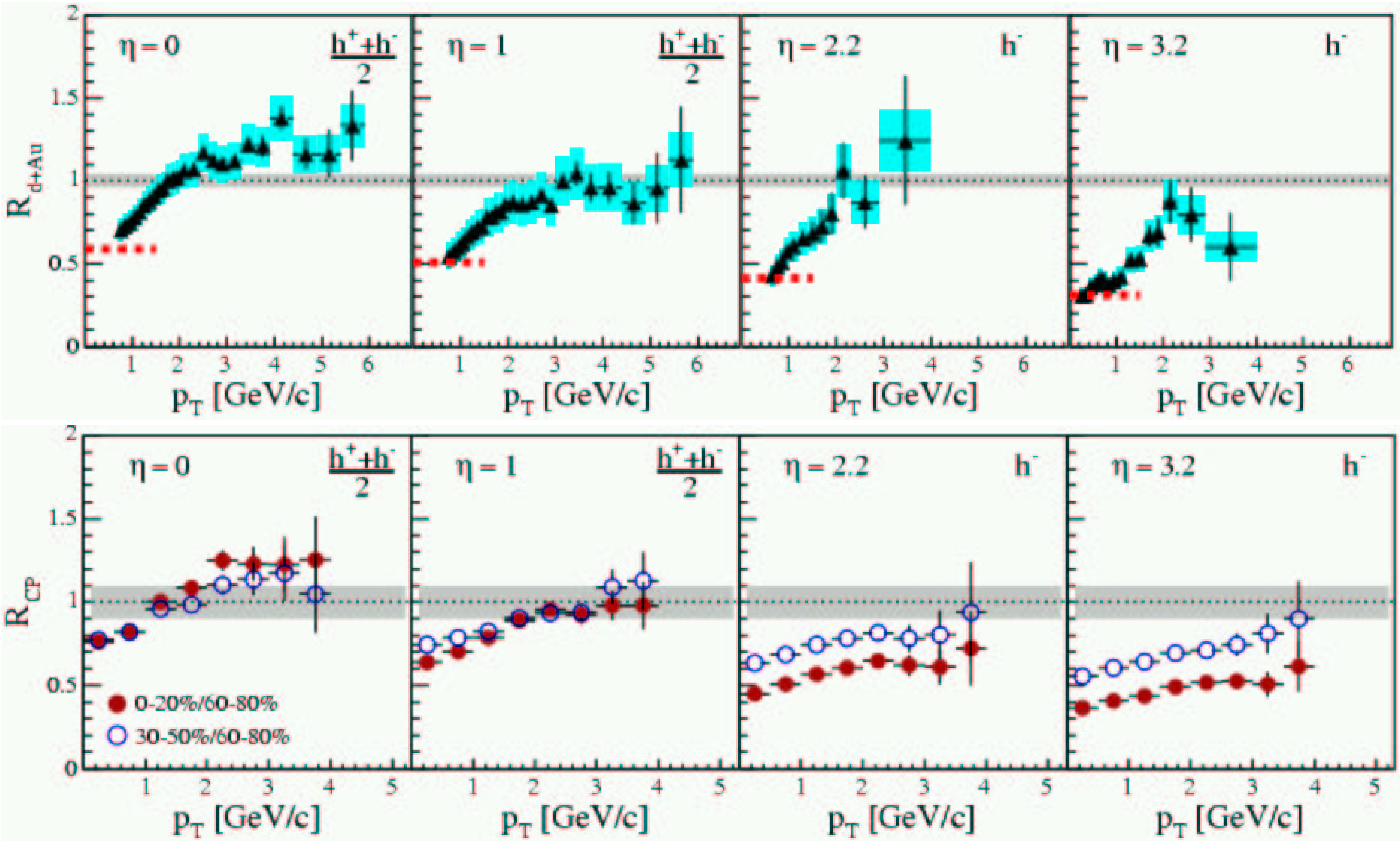
NOTE: "Dynamical" shadowing NOT included (no CGC, no geom. scaling, no EKS98, ...)

Hermes kinematics

		EMC		HERMES	
		h		h	π, K
E_{beam}	GeV	100	200	27.5	27.5
Q^2_{min}	GeV^2	2	2	1	1
W^2_{min}	GeV^2	4	4	4	4
y_{max}		0.85	0.85	0.85	0.85
x_{min}		0.02	0.02	0.06	0.02
x_{max}		1	1	1	1
z_{min}		0.2	0.2	0.2	0.2
z_{max}		1	1	1	1
ν_{min}	GeV	10	30	7	7
ν_{max}	GeV	85	170	23.4	23.4
$E_{h\text{min}}$	GeV	3	3	1.4	2.5
$E_{h\text{max}}$	GeV	85	170	23.4	15.0

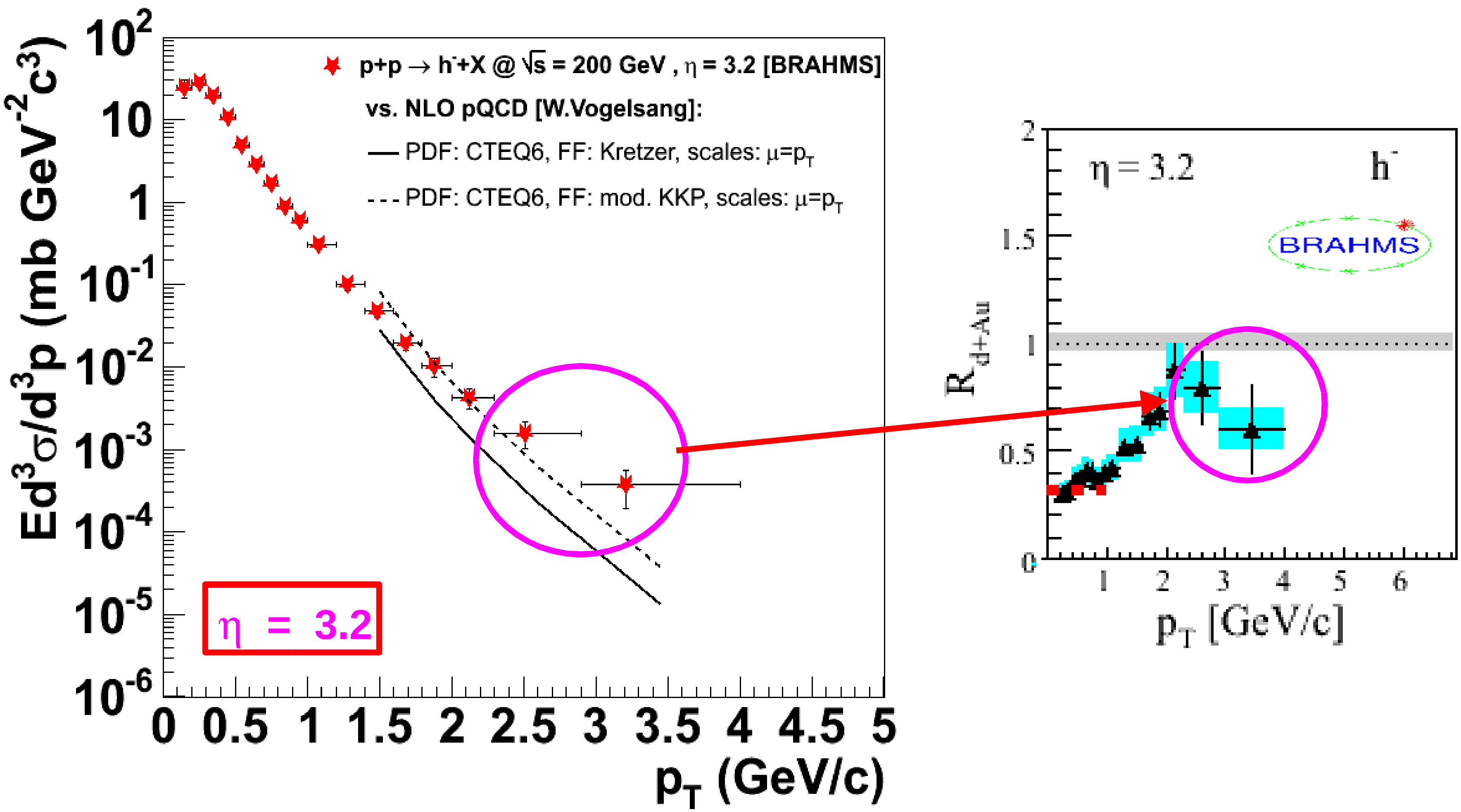
Table 3: Kinematic cuts of the EMC and HERMES experiments.

Mistery no. 1



- **Discrepancy between R_{dAu} and R_{cp}**
- Hard to understand theoretically

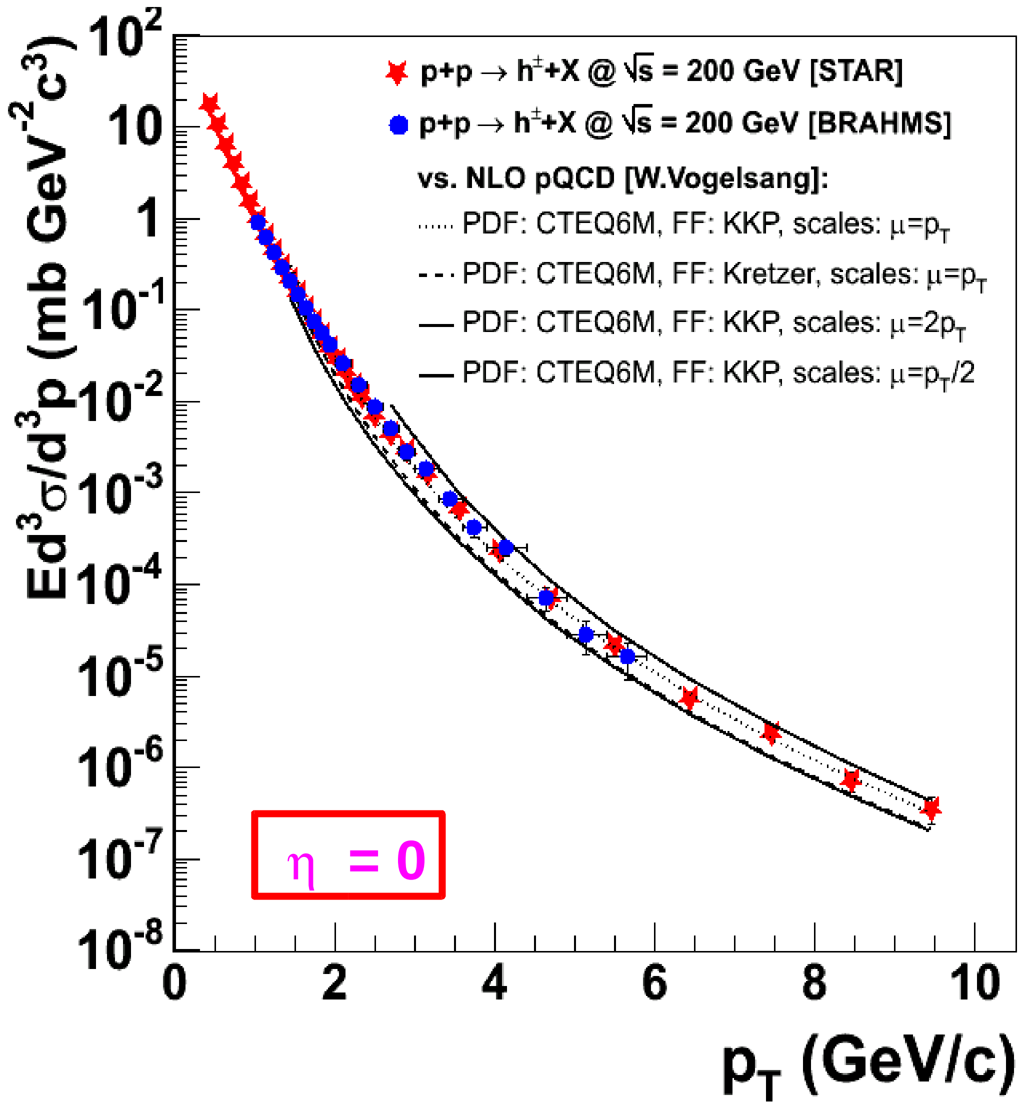
High p_T p+p reference spectrum vs pQCD (=3.2)

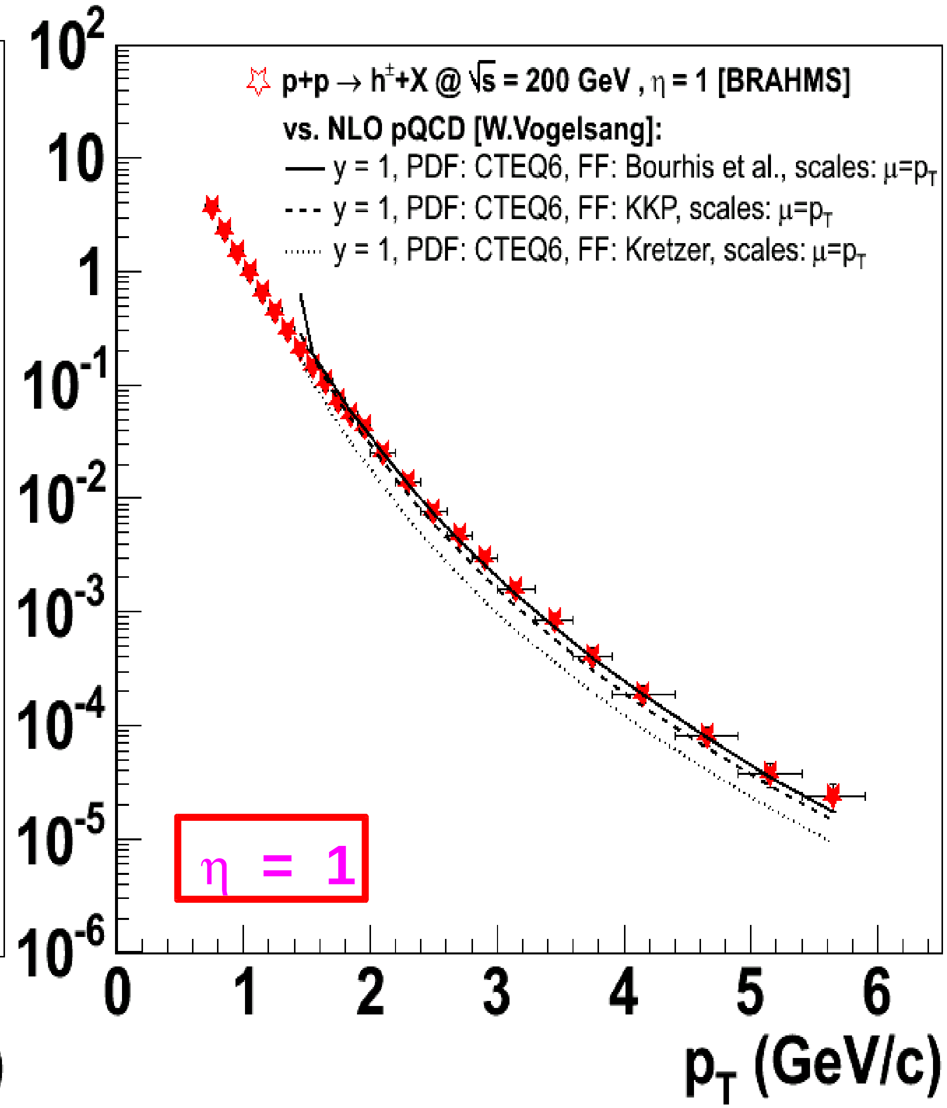


- Two highest p_T points (there where the R_{dAu} "suppression" appears) are enhanced w.r.t. NLO (which describes all other rapidities, even y = 3.8 !).
- Let's be provocative ... Is there d+Au suppression or (genuine" ?) p+p enhancement

Slide by D.D'Enterria, HotQuarks 2004, Taos, NM

High p_T p+p reference spectra vs pQCD (mid-rapidity)



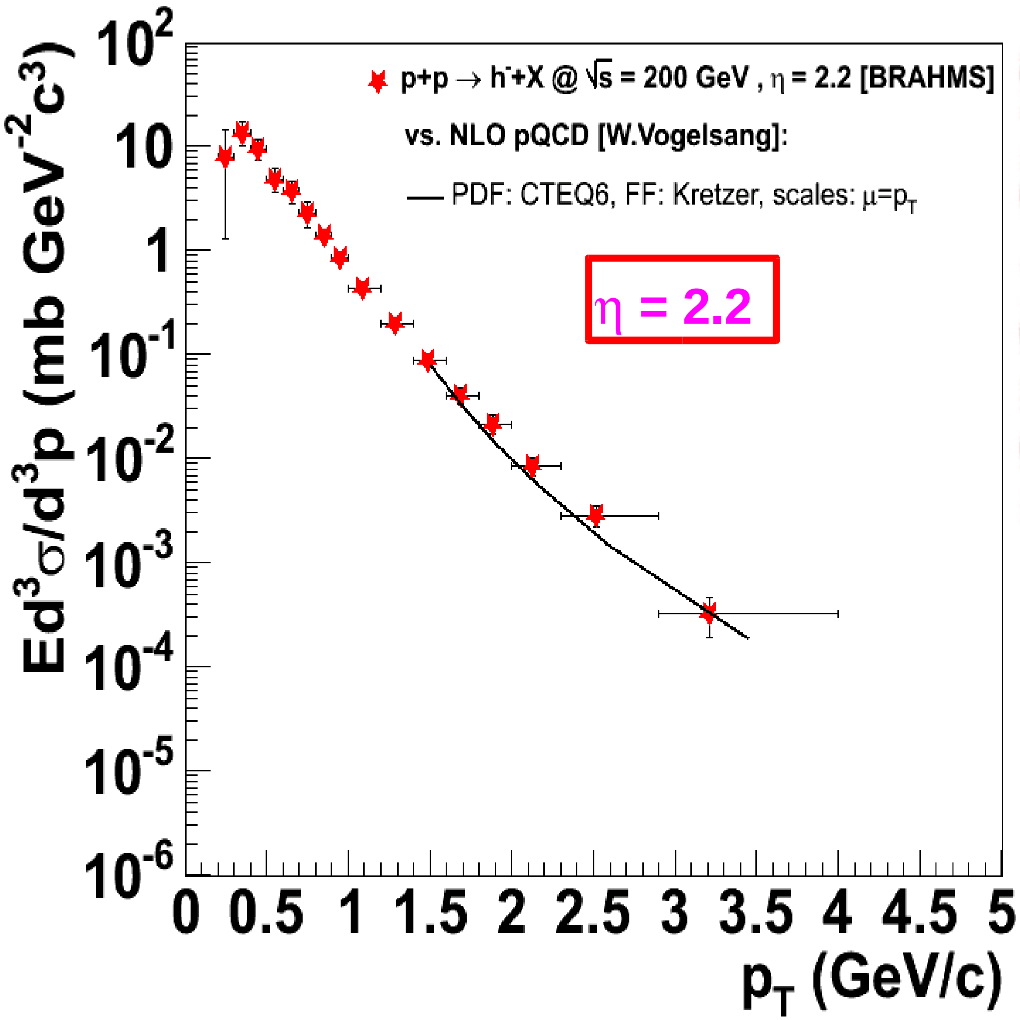


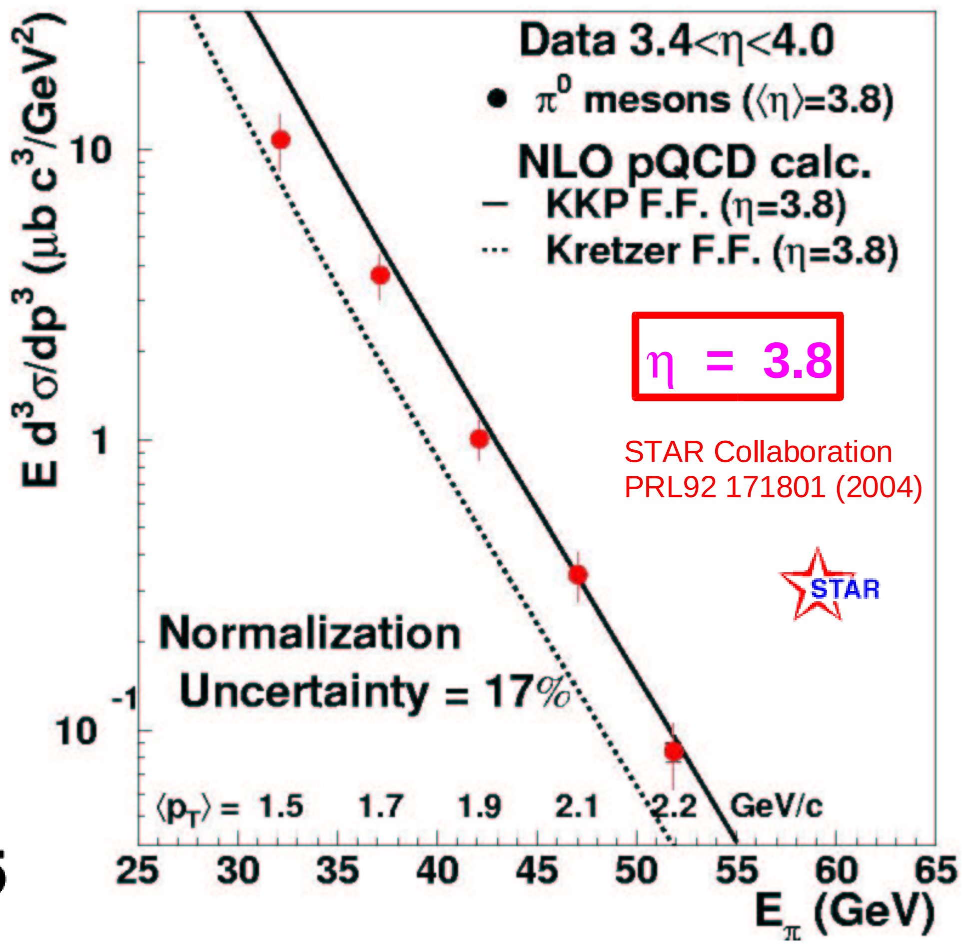
[calculations by W. Vogelsang]

- Good agreement with NLO pQCD

Slide by D.D'Enterria, HotQuarks 2004, Taos, NM

High p_T p+p reference spectra vs pQCD (forward)

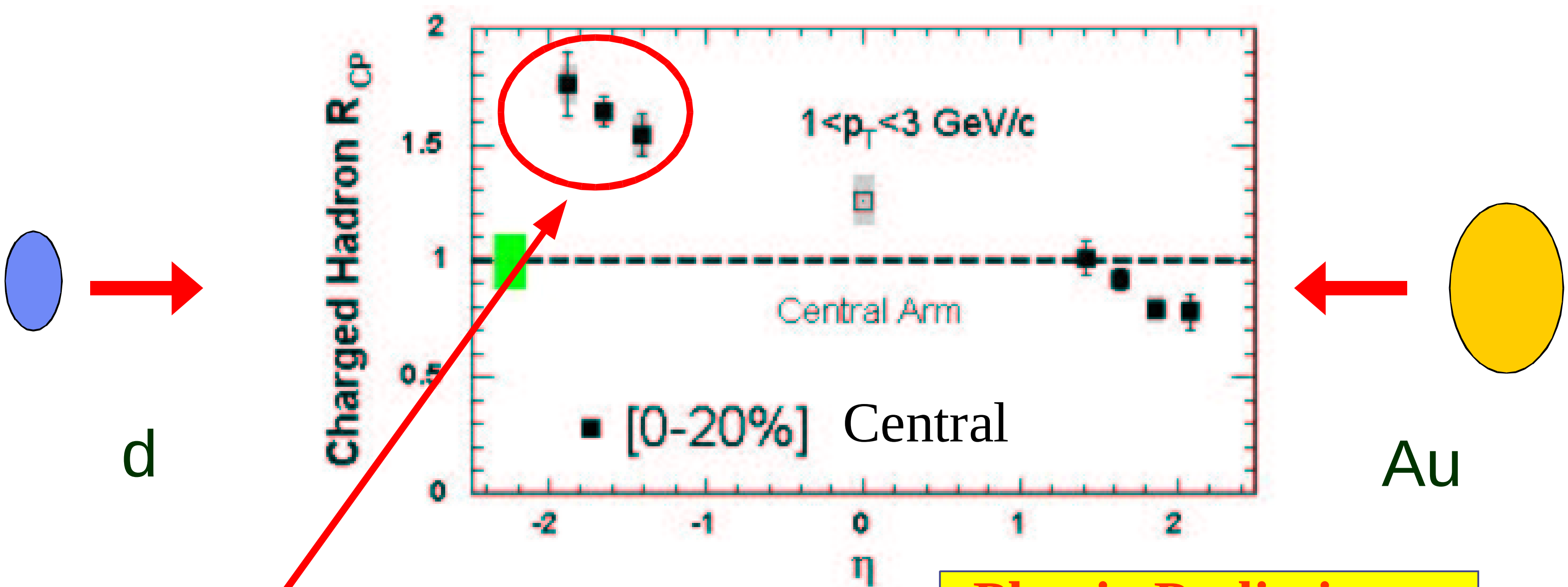




- Good agreement with NLO pQCD [calculations by W. Vogelsang]

Slide by D.D'Enterria, HotQuarks 2004, Taos, NM

Mistery no. 2: increasing Cronin at $\eta<0$



Phenix Preliminary

Big surprise!

The deuterium is a smallish object,
it should cause only a small Cronin!

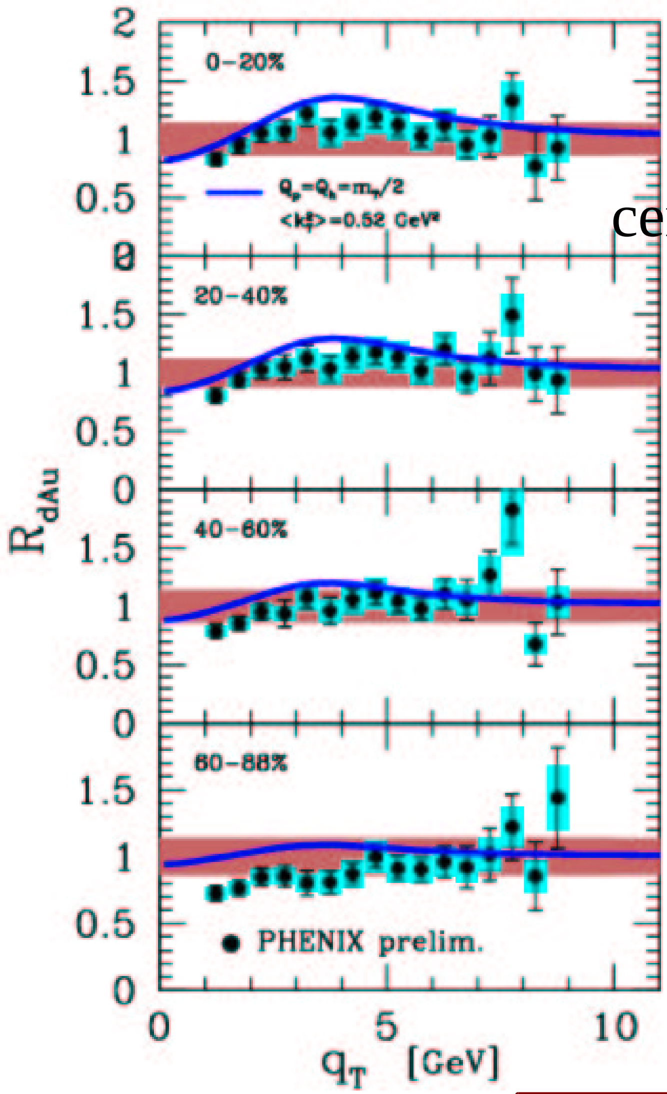
Soft physics? Particle mix?

Anti-shadowing of Au partons?

no model to my knowledge can explain this

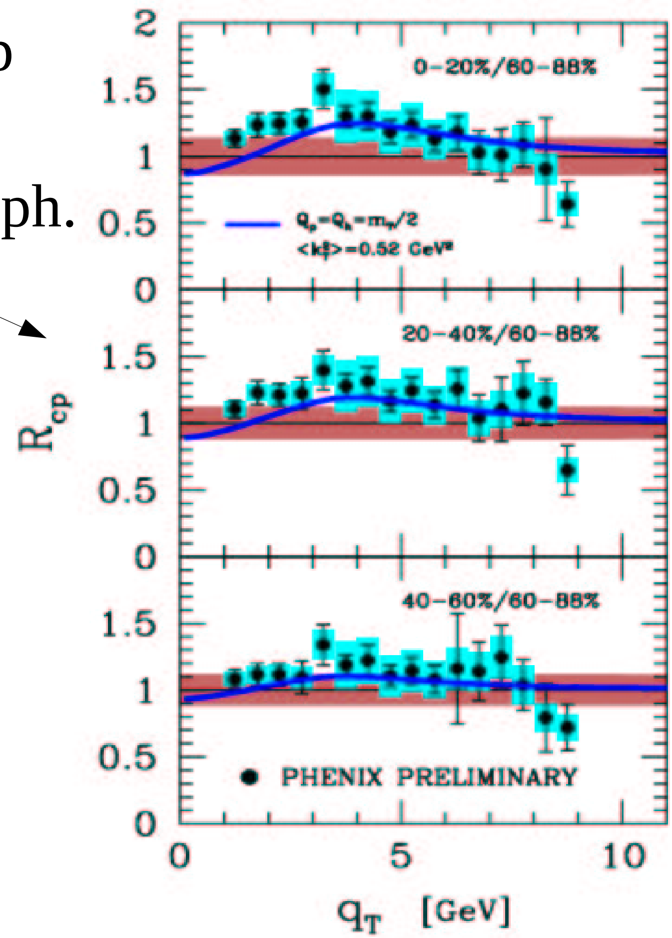
Centrality dependence at η=0

<u>If</u> dynamical shadowing at work, ⟹ stronger suppression in central



d+Au/p

central/periph.



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

no dynamical shadowing at η=0

GE model computation

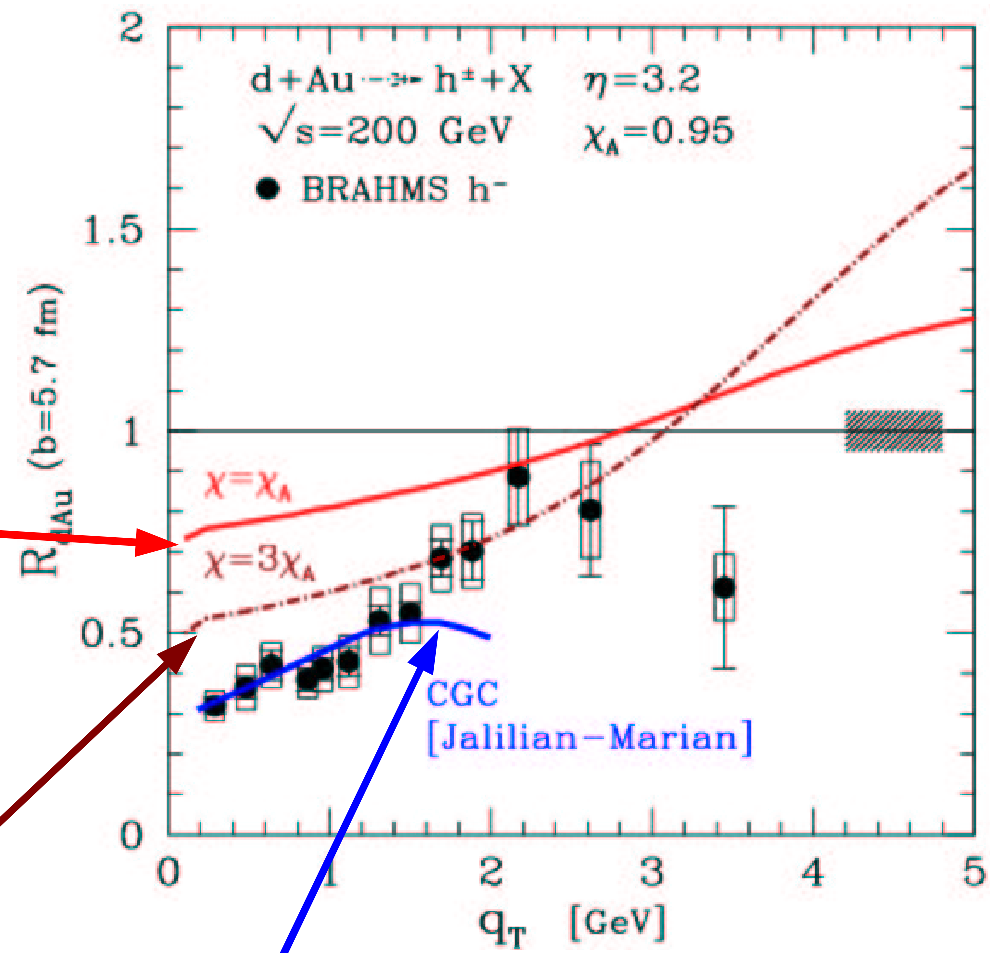
- No available data for pp coll's at forward rapidity ⇒ we take **same parmeters as for η=0:**
  - $p_0(\eta>0) = p_0(\eta=0) = 1.0$ GeV
  - $K(\eta>0) = K(\eta=0) = 1$

η	0	1.8	3.2
χ	0.74	0.85	0.95

Are we underestimating opacity?

χ_A=0.95 obtained with **p_0 and K** fitted in pp at η=0: **may change with** η:

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



CGC à la Jalilian-Marian underestimates data at p_T>1.5 GeV

CGC and p+A collisions

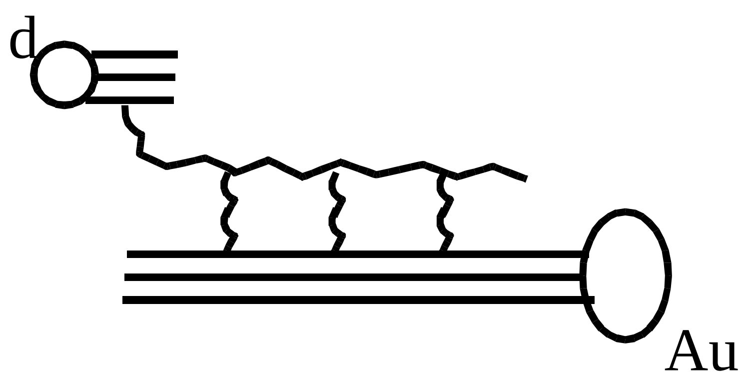
For gluon and valence quark production (Dumitru,Gelis,JalilianMarian; Blaizot et al.)

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

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:

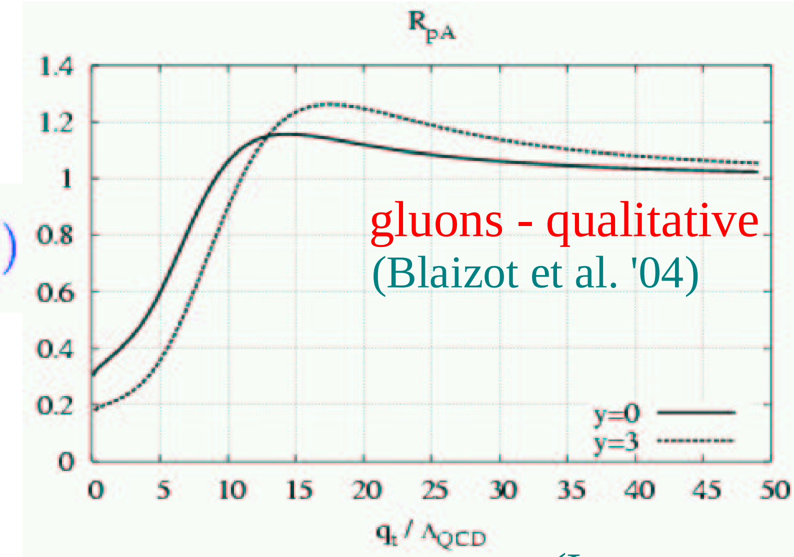
$$C(x_2;k_T) = \int d^2r_T\, e^{i\vec{r}_T\cdot\vec{k}_T}\; e^{\tilde{\sigma}(r_T;b)}$$



MV model: local gaussian correlations

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

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



CGC = MV + quantum evolution:

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

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