Many Body QCD Effects in Proton-Nucleus Collisions at RHIC

Ivan Vitev

In part in collaboration with T. Goldman, M.B. Johnson and J.W. Qiu

Los Alamos
NATIONAL LABORATORY

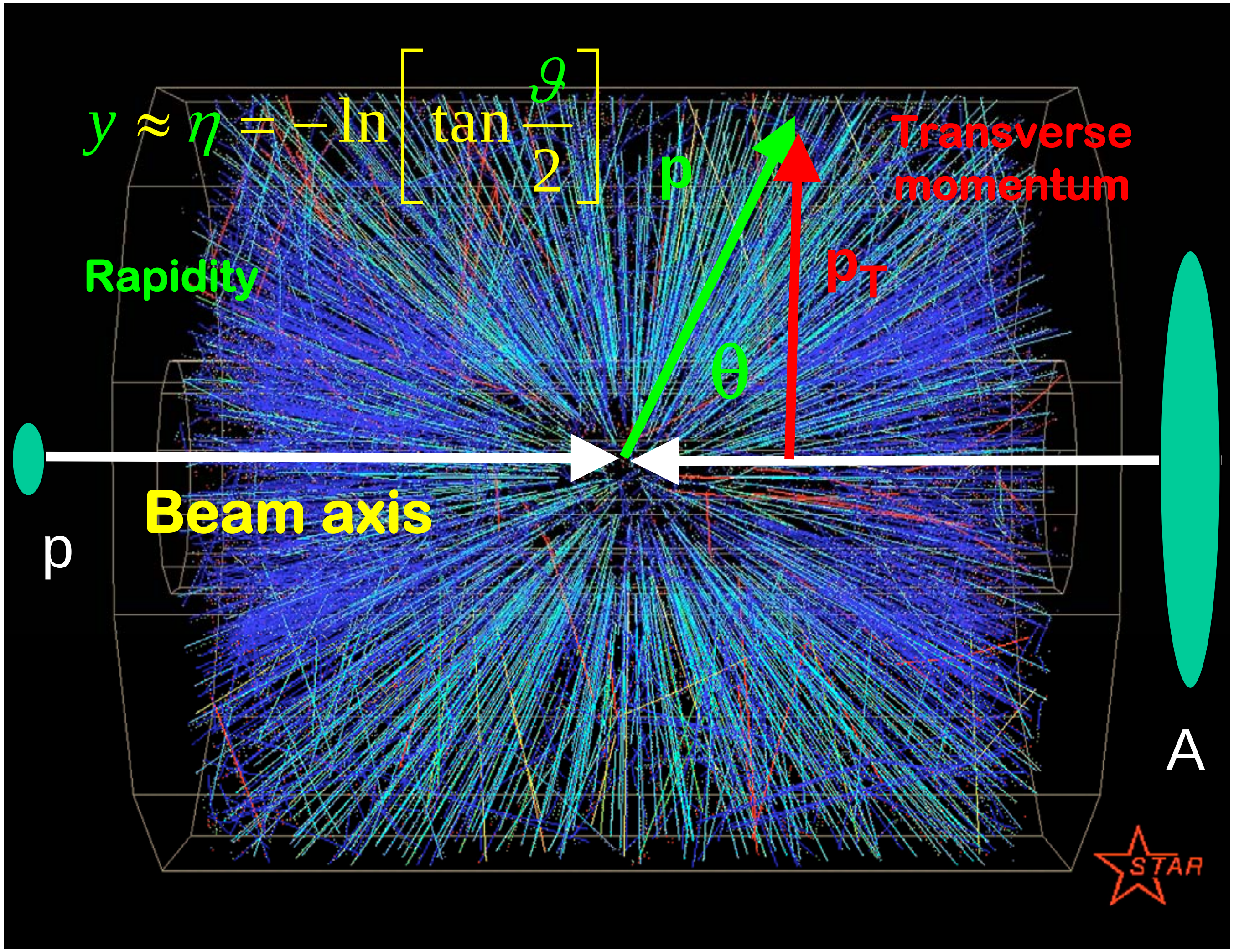
Nuclear Theory Seminar
T-16, LANL, Los Alamos, NM

Outline of the Talk

- **Overview of p+A data:**
  - Review of key RHIC results in p+A (nuclear modification vs Y)
  - Proposed explanations (QCD Monte Carlos, coalescence, CGC)
- **Strong interaction dynamics in nuclei:**
  - Transverse momentum diffusion (Cronin effect)
  - Coherent final state scattering (high twist shadowing)
  - Initial state energy loss
- **Application in the pQCD formalism:**
  - Light hadron production and modification
  - Open heavy flavor production and modification
- **Conclusions:**

Basic Definitions: Kinematics

Central Au+Au event in the STAR TPC



$$E = p_T \cosh y$$

$$p_{\|} = p_T \sinh y$$

Important at forward rapidity

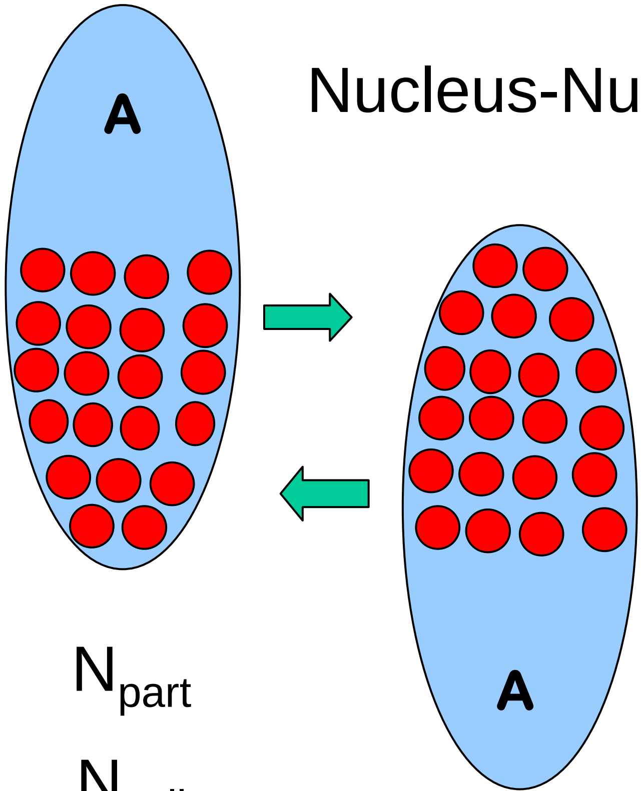
Take a guess for the hadron rapidity density

$$dN^h / dy$$

p+A

Basic Definitions: Geometry

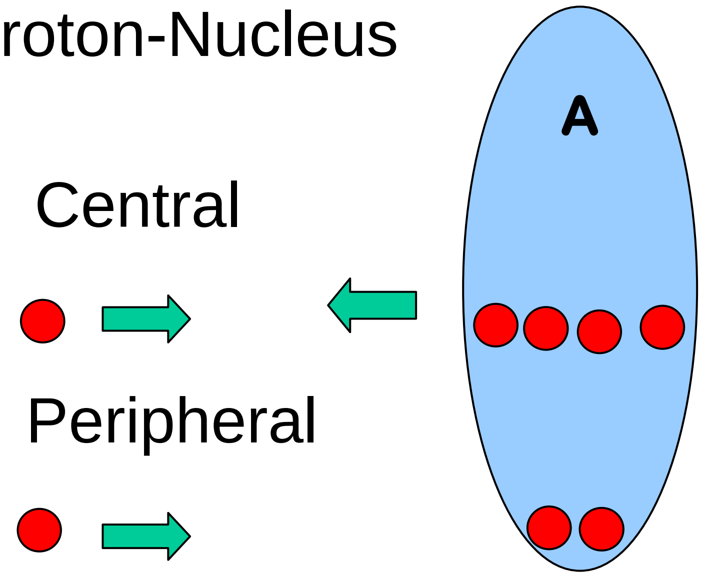
Nucleus-Nucleus



N_{part}

N_{coll}

Proton-Nucleus



$N_{part} = N_{coll} + 1$

Inelastic cross section: $\sigma_{in} \ (42 \ mb \ at \ RHIC)$

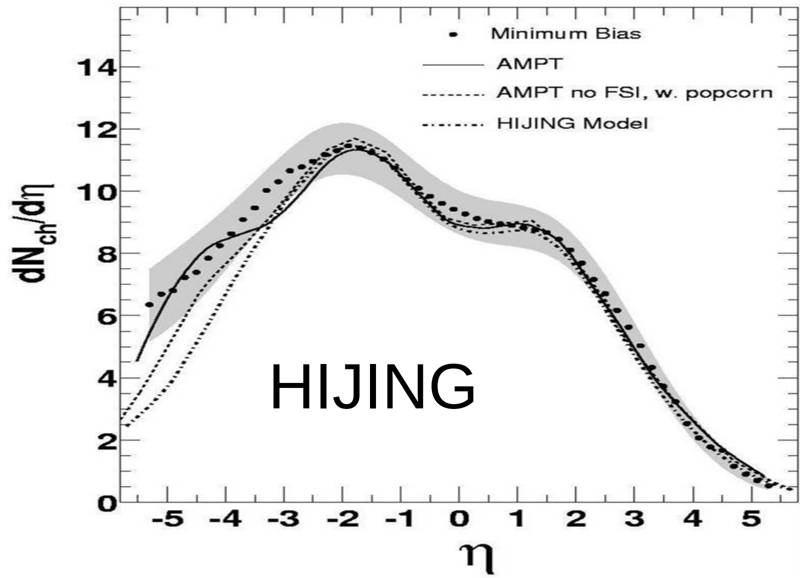
$$\rho_{nucl}(r) \rightarrow \int \rho_{nucl}(r) \ d^3 r = A$$

Nuclear thickness: $T_A(b) = \int \rho_{nucl}(b,z) \ dz$

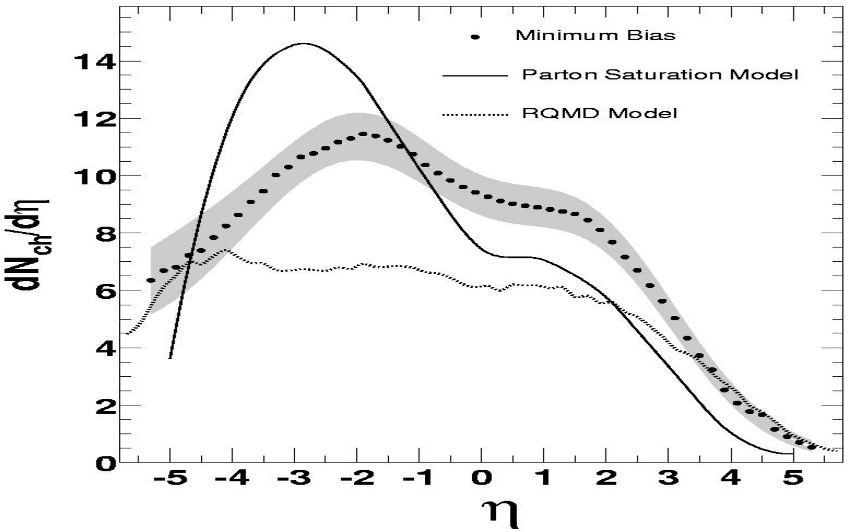
$$N_{coll} = \sigma_{in} T_A(b)$$

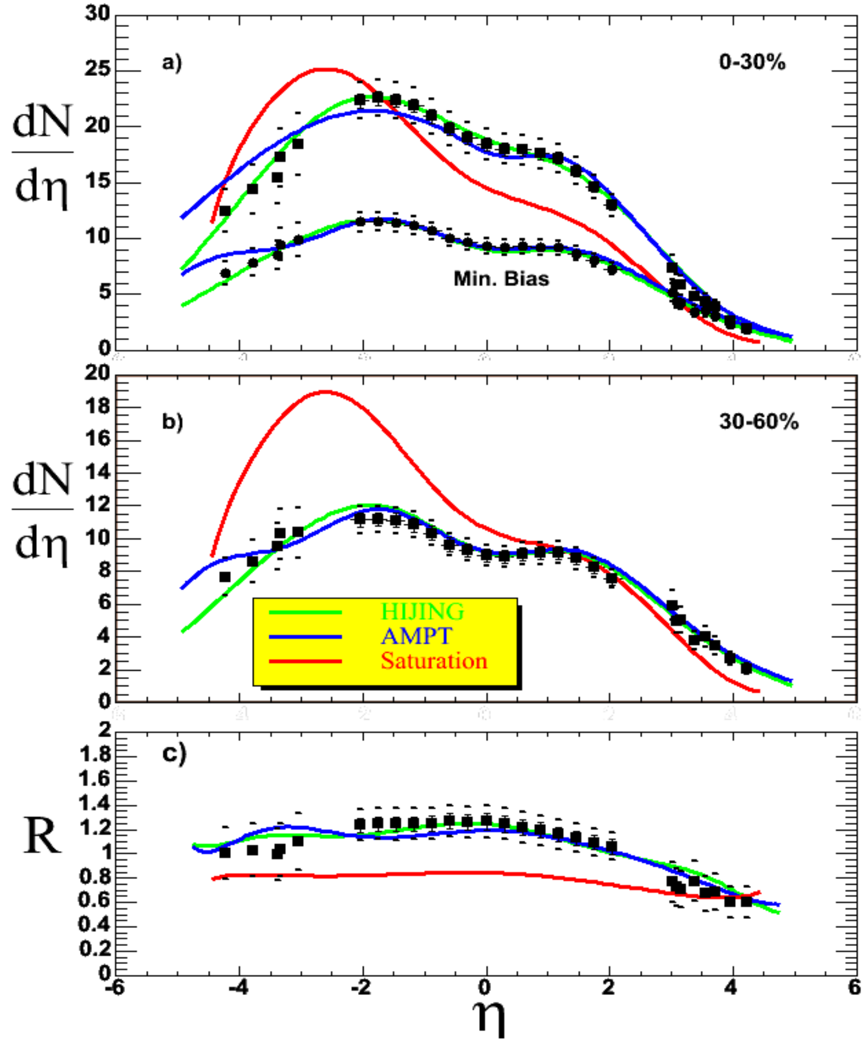
- **Optical Glauber model**
- **That Glauber (2005 Nobel Prize)**

Hadron Rapidity Density



PHOBOS collab., Phys.Rev.Lett.

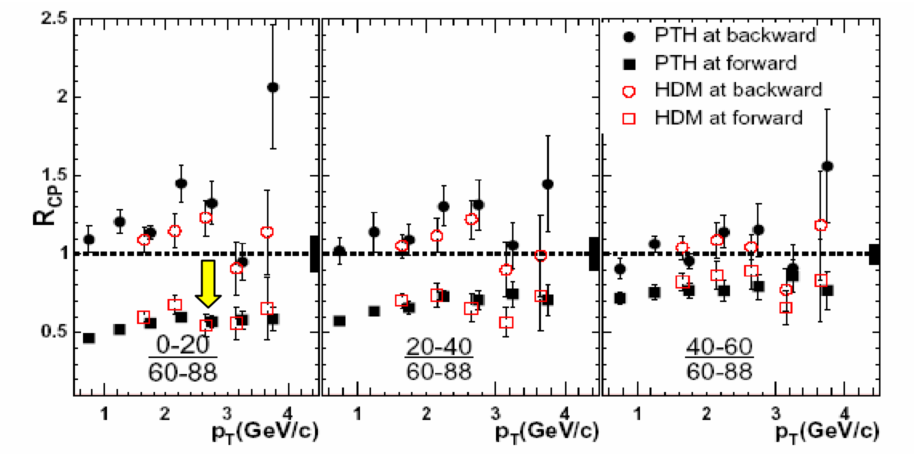


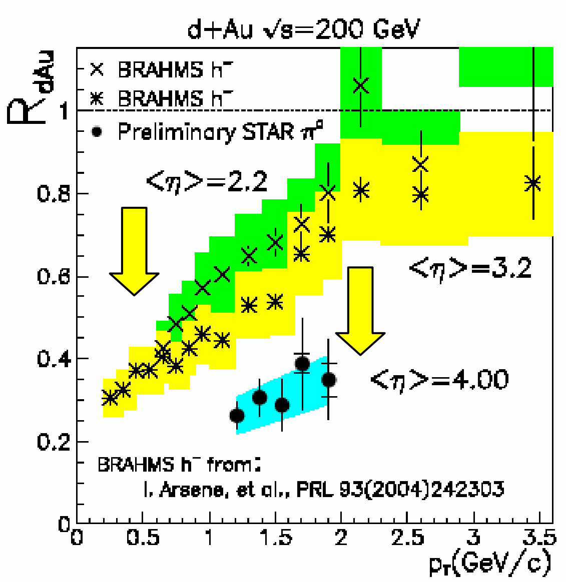


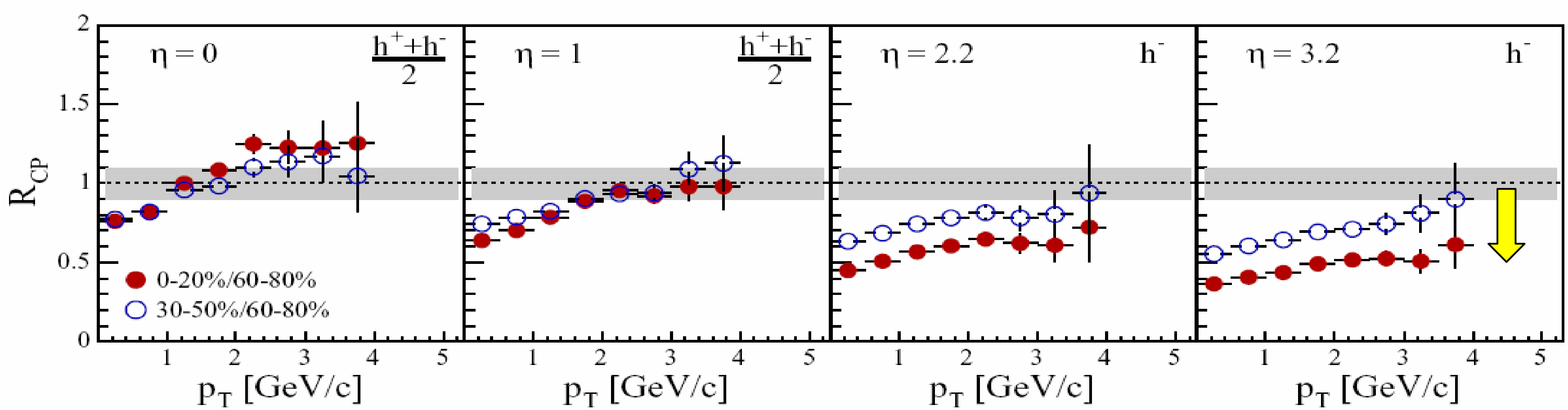
M.Murray, BRAHMS collaboration, QM 2004

Forward Rapidity Suppression

$$R_{pA}(p_T) = \frac{d^2N^{pA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta} = \frac{d^2\sigma^{pA}/dp_T d\eta}{N_{coll} d^2\sigma^{NN}/dp_T d\eta}$$

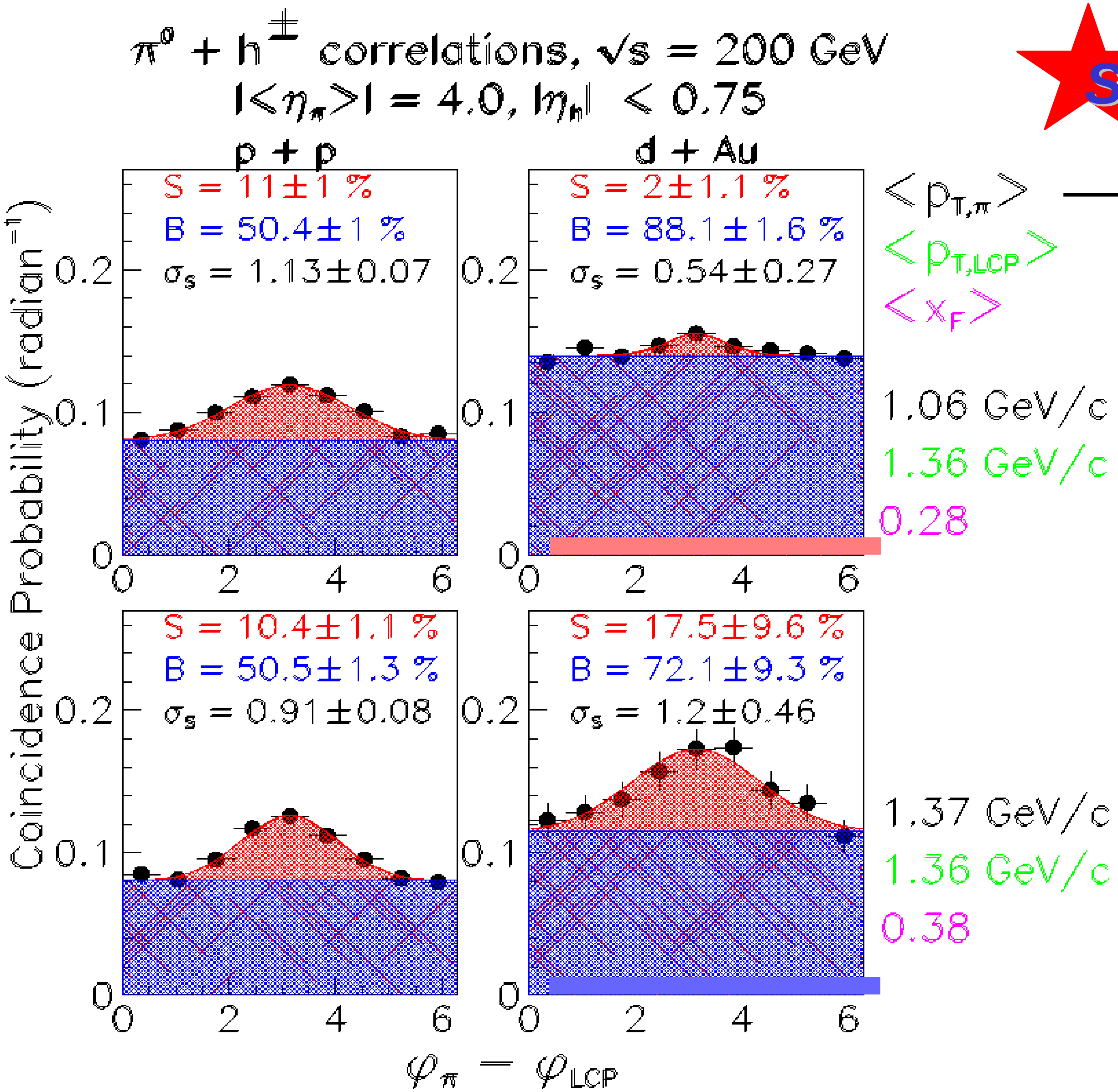




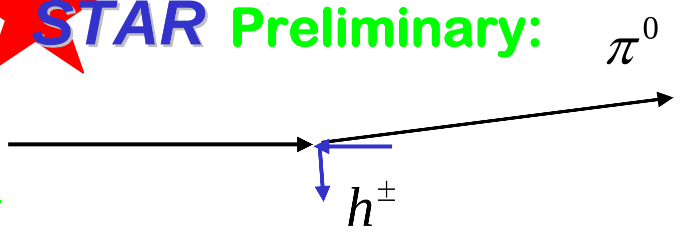


C/P = central to peripheral

Forward Correlations



STAR Preliminary:



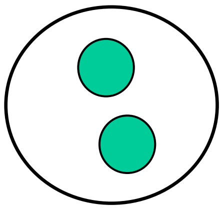
- At p_T = 1.25 GeV hard scattering is similar in p+p and p+A
- There isn't mono jettiness or g-fusion
- I think that the p+A analysis has under and over estimated the away-side area

Statistical errors only

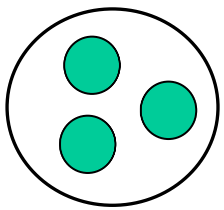
Alternative Explanations: I

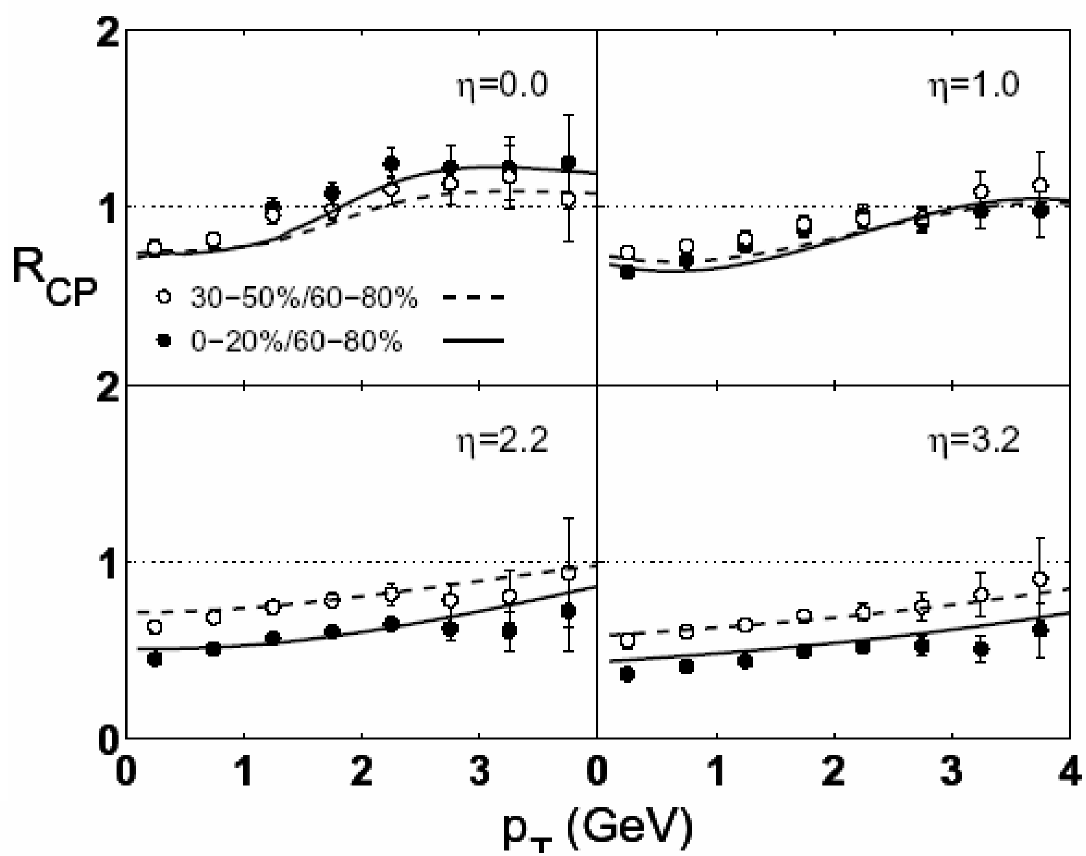
Parton recombination:
model of hadroization

Meson



Baryon





$$E\frac{dN_M}{d^3P} = C_M \int \frac{d^3R\, P\cdot u(R)}{(2\pi)^3} \int \frac{dx P^+ d^2k_\perp}{\sqrt{2}(2\pi)^3}$$

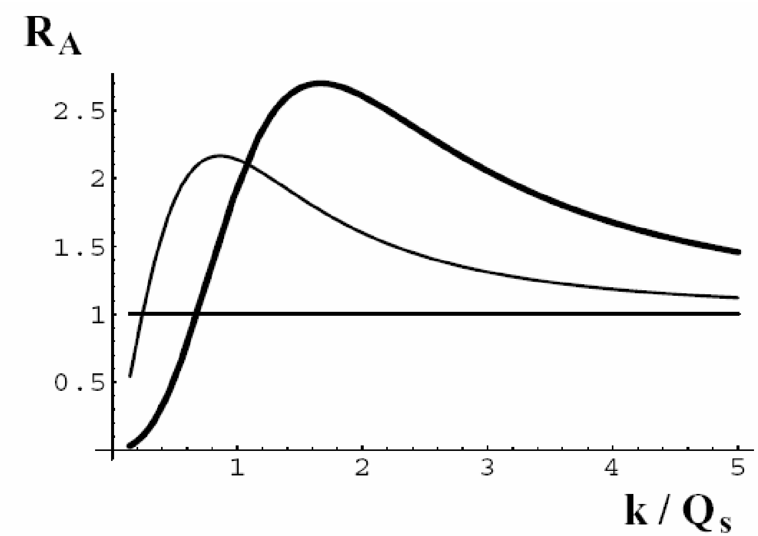
$$w_a(R; xP^+, \mathbf{k}_\perp)\, \Phi_M(x, \mathbf{k}_\perp)\, w_b(R; (1-x)P^+, -\mathbf{k}_\perp)$$

Hwa and Fries

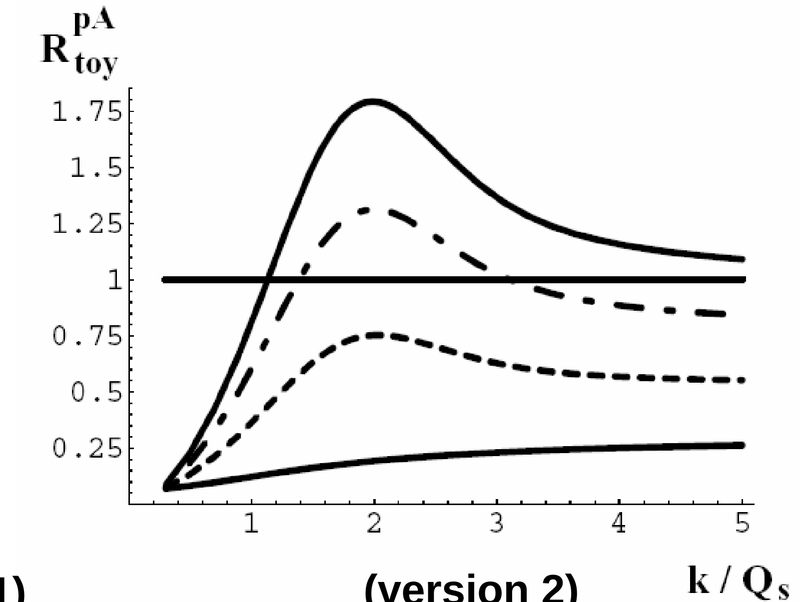
The consequence of reduced parton production. What is the cause?

Alternative Explanations: II

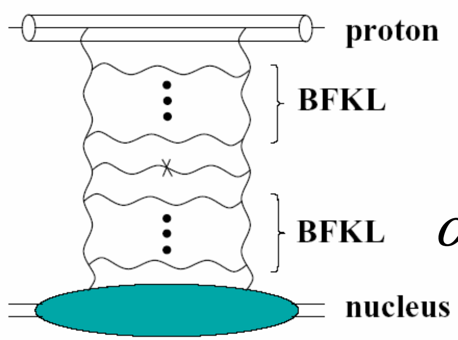
Gluon saturation



Kharzeev, Kovchegov Tuchin (version 1)



(version 2)



DGLAP $\alpha_s \ln Q^2 / \mu^2$

$\alpha_s \ln x_0 / x$

No evidence of BFKL to x = 10^{-5} HERA

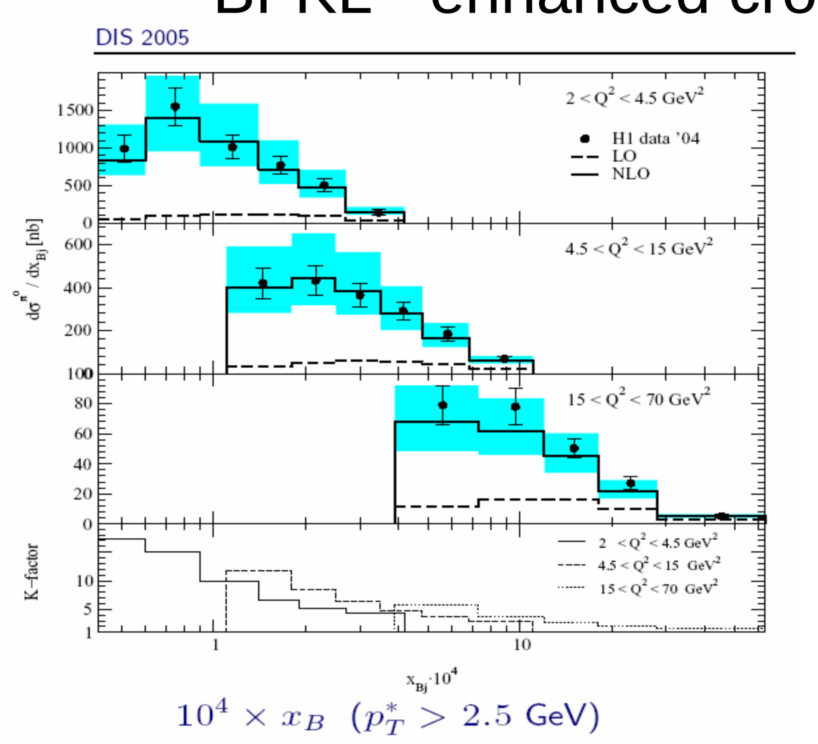
Start at y = 1 → **y = 4, 1 gluon**

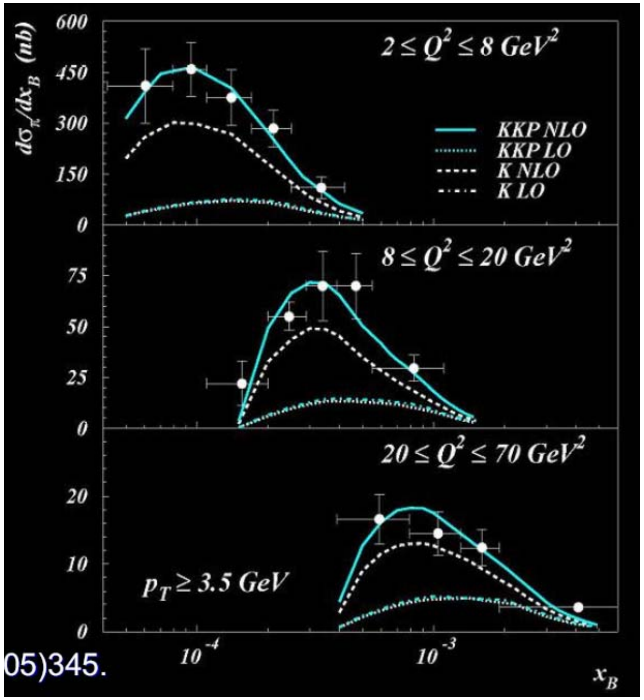
$$\Delta n^g{}_{BFKL} = \alpha_s \Delta y$$

No phase space for this effect. Inconsistency with low energy data.

HERA Forward Jet Production

BFKL - enhanced cross sections, not suppressed





B.Khiehl

- DGLAP in good health (within present uncertainties)

– $\theta \to 0$ (or $\eta \to \infty$ or $x_F \to -1$): hadron h close to proton remnant $\rightsquigarrow$ fracture functions.

– $x_B \to 0$: BFKL dynamics. But no convincing case yet, see also forward-jet electroproduction (E. Gallo's talk).

R.Sassot

pQCD Jets and Hadrons

Instead of making models

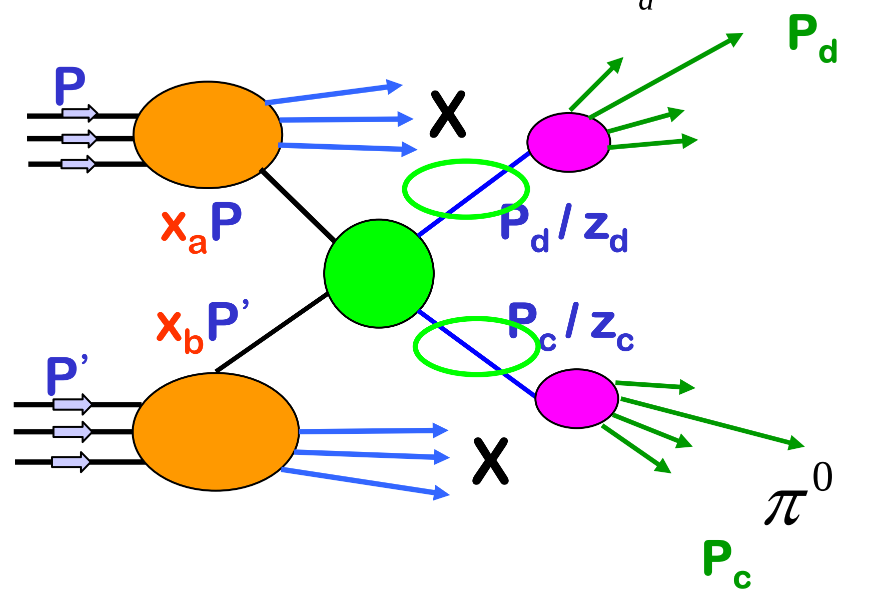
Factorization approach

Collins, Soper, Sterman

- **To LO (2 to 2 scattering) - single and double inclusive hadron production**

$$p + p \to h(l) + X$$

$$p + p \to h_1(l_1) + h_2(l_2) + X \quad \int d\,\frac{p_d}{z_d} \left\{ \pi^0 \right.$$



Can also incorporate Cronin effect: $\int d^2k_T\, f_{med}(k_T)$

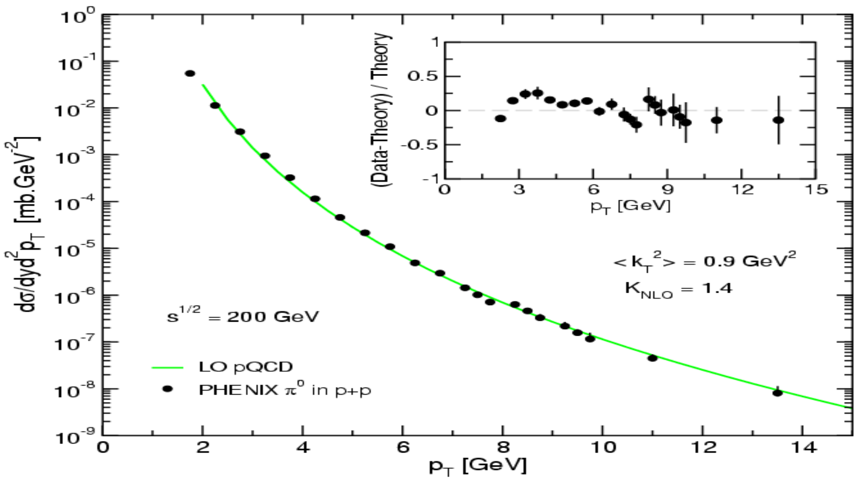
$$\frac{d\sigma^{h_1}_{NN}}{dy_1\, d^2p_{T1}} = \sum_{abcd} \int_{x_a\,\min}^{1} dx_a \int_{x_b\,\min}^{1} dx_b\, \phi(x_a)\phi(x_b)\, \frac{\alpha_s^2}{(x_a x_b S)^2} \left|\overline{M}\right|^2_{ab\to cd} \frac{D_{h_1/c}(z_1)}{z_1}$$

$$\frac{d\sigma^{h_1h_2}_{NN}}{dy_1\, dy_2\, d^2p_{T1}\, d^2p_{T2}} = \frac{\delta(\Delta\varphi - \pi)}{p_{T1}\, p_{T2}} \sum_{abcd} \int_{z_1\,\min}^{1} dz_1\, \frac{D_{h_1/c}(z_1)}{z_1} D_{h_2/d}(z_2)\, \frac{\phi(\bar{x}_a)\phi(\bar{x}_b)}{\bar{x}_a \bar{x}_b} \frac{\alpha_s^2}{S^2} \left|\overline{M}\right|^2_{ab\to cd}$$

Examples of PQCD Cross Sections

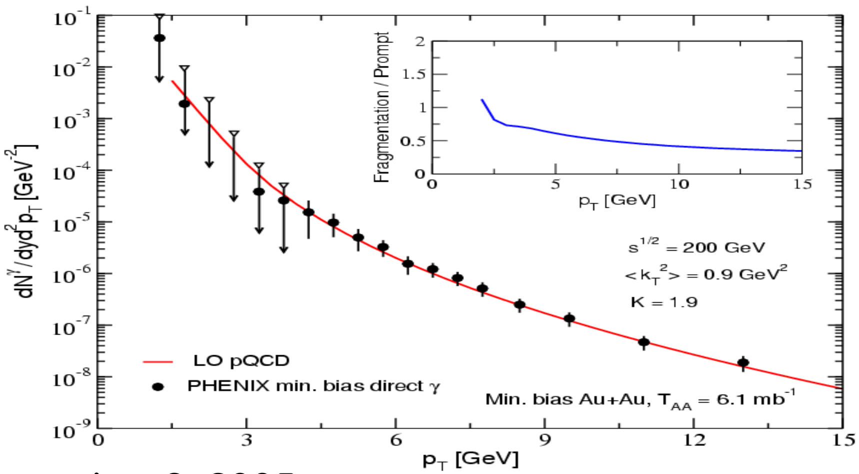
$$p + p \rightarrow \pi^0 + X$$

Inclusive neutral pions **PHENIX**



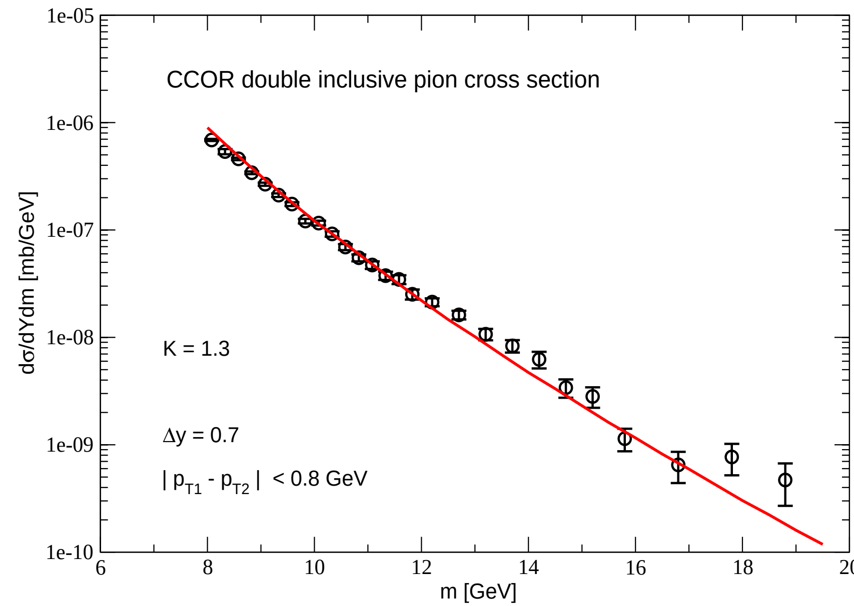
$$p + p \rightarrow \gamma + X$$

Direct photons **PHENIX**



$$p + p \rightarrow h_1 + h_2 + X$$

ISR dihadrons **CCOR**



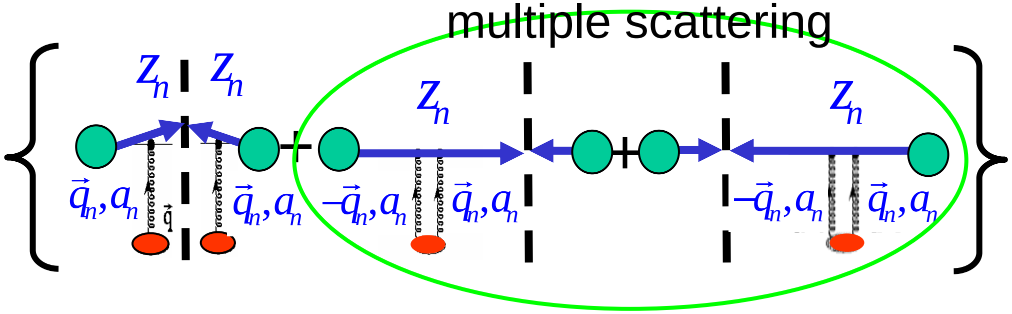
Parton distribution functions

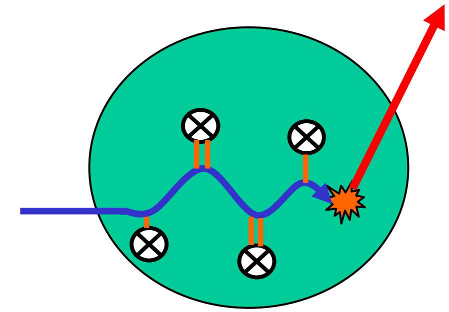
X Perturbative cross sections

X Fragmentation functions

I. Multiple Elastic Scatterings

Eikonalization of the multiple scattering





$$\frac{d\sigma_{el}(R,T)}{d^2\mathbf{q}} = \frac{C_R C_2(T)}{d_A}\frac{|v(\mathbf{q})|^2}{(2\pi)^2}$$

$$= \begin{Bmatrix} 2/9 \\ 1/2 \\ 9/8 \end{Bmatrix} \frac{4\alpha_s^2}{\left(q_\perp{}^2 + \mu^2\right)^2}$$

$$\boxed{\hat{R}_n = \hat{D}_n{}^\dagger \hat{D}_n + \hat{V}_n + \hat{V}_n{}^\dagger}$$

Opacity $\bar{n} = \chi = L/\lambda$ ~ few

$$\mu^2 \sim \Lambda_{QCD}{}^2 \sim 0.05 - 0.1\ GeV^2$$

Reaction Operator = all possible on-shell $t = \infty$ cuts through a new Double Born interaction with the propagating system

(Neglect $p_{||}$ and $O(\langle(\nabla_k \bullet k_\perp)^3\rangle)$)

The approximate solution is that of a 2D diffusion

2D Diffusion

- **Moliere multiple scattering (see Jackson's E&M)**

$$dN^f(p) = \sum_{n=0}^{\infty} dN^n(p) = \sum_{n=0}^{\infty} \frac{\chi^n}{n!} \int \prod_{i=1}^{n} d^2q_i \, \frac{1}{\sigma_{el}} \frac{d\sigma_{el}}{d^2q_i} \left(e^{-q_{i\perp}\cdot\nabla_{p\perp}} \otimes e^{-q_{i\parallel}\partial_{p\parallel}} - 1 \right) dN^i(p)$$

$$dN^f(p) = \sum_{n=0}^{\infty} e^{-\chi} \frac{\chi^n}{n!} \int \prod_{i=1}^{n} d^2q_i \, \frac{1}{\sigma_{el}} \frac{d\sigma_{el}}{d^2q_i} \, dN^i(p - q_1 - \dots - q_n)$$

Approximate solution to 2D diffusion equation

Opacity $\chi = L/\lambda$

Specific case: broadening of a collinear beam of energetic partons

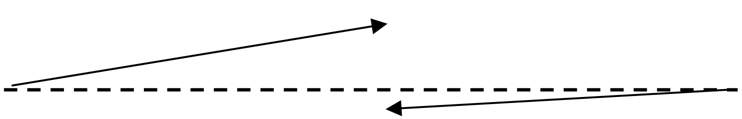
$$dN^i(k_\perp) = \delta^2(k_\perp) \Rightarrow \frac{d\sigma_{el}(b)}{d^2q} = \frac{\mu b}{4\pi^2} K_1(\mu b) \approx \frac{1}{4\pi^2}\left(1 - \frac{\mu^2 b^2}{2}\xi + O(b^3)\right) \Rightarrow dN^f(k_\perp) = \frac{1}{2\pi} \frac{e^{-\frac{k_\perp^2}{\chi\mu^2\xi}}}{\chi\mu^2\xi},$$

$$\boxed{\text{For } \langle \Delta k_\perp^2 \rangle = 2\chi\mu^2\xi, \quad -\Delta k_\parallel = 2\chi\mu^2\xi \frac{1}{2k_\parallel}}$$

$$\xi = \log 2 / (1.08\, \mu b)$$

Implementation in pQCD

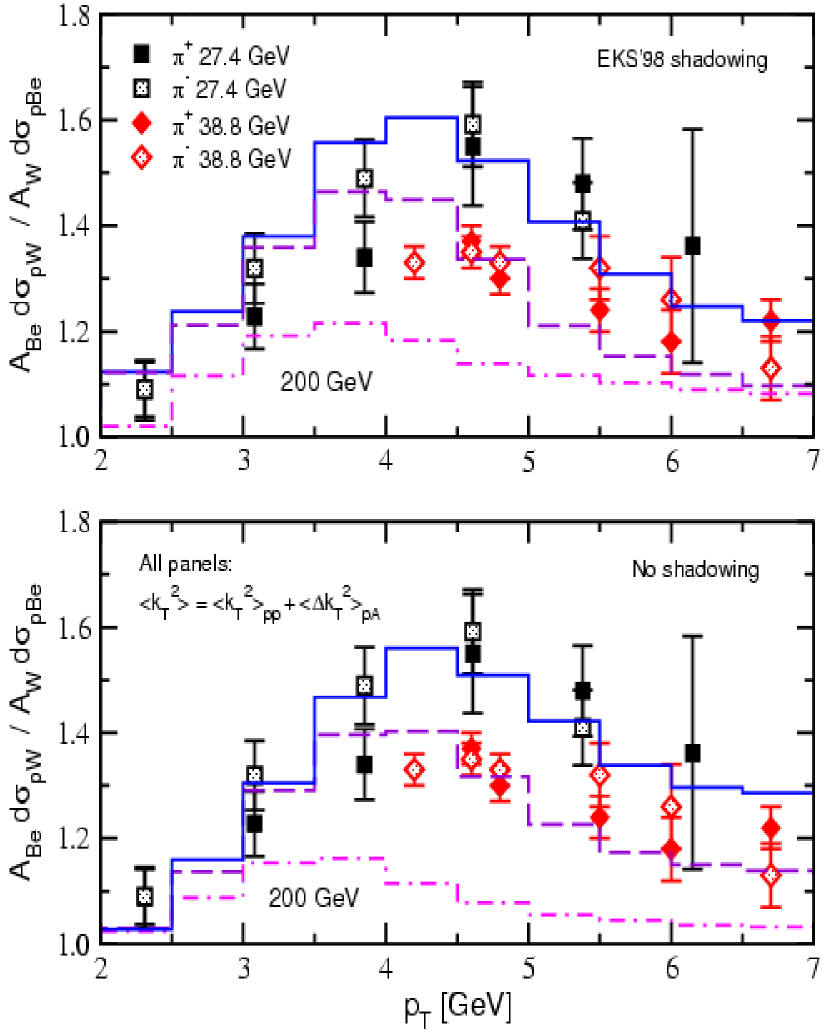
$$g(k_T) \simeq Exp\left(-k_T^2 / \langle k_T^2 \rangle\right) / \pi \langle k_T^2 \rangle$$



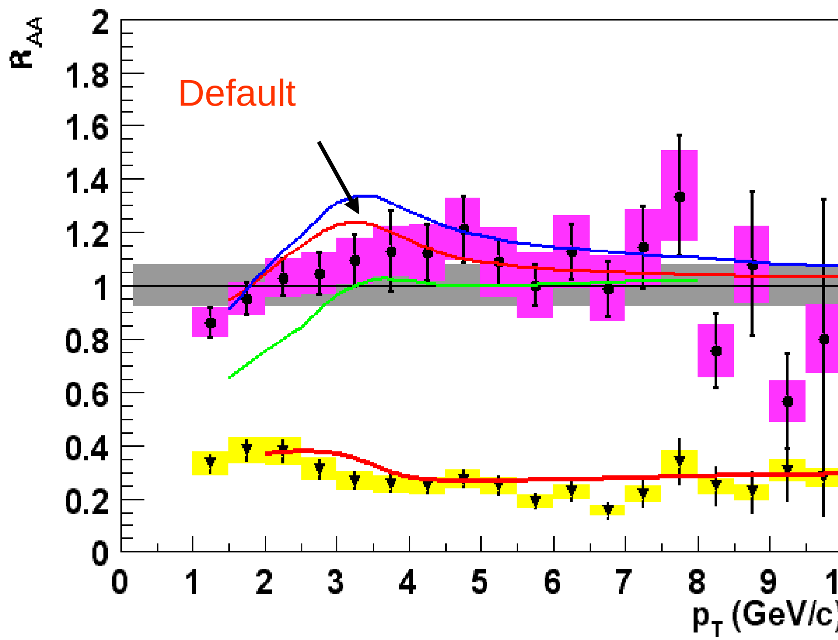
M. Gyulassy, P. Levai, I.V., J.W. Qiu, I.V.

Success at Mid rapidity

$$\frac{p+W \rightarrow \pi^{\pm}+X}{p+Be \rightarrow \pi^{\pm}+X}$$



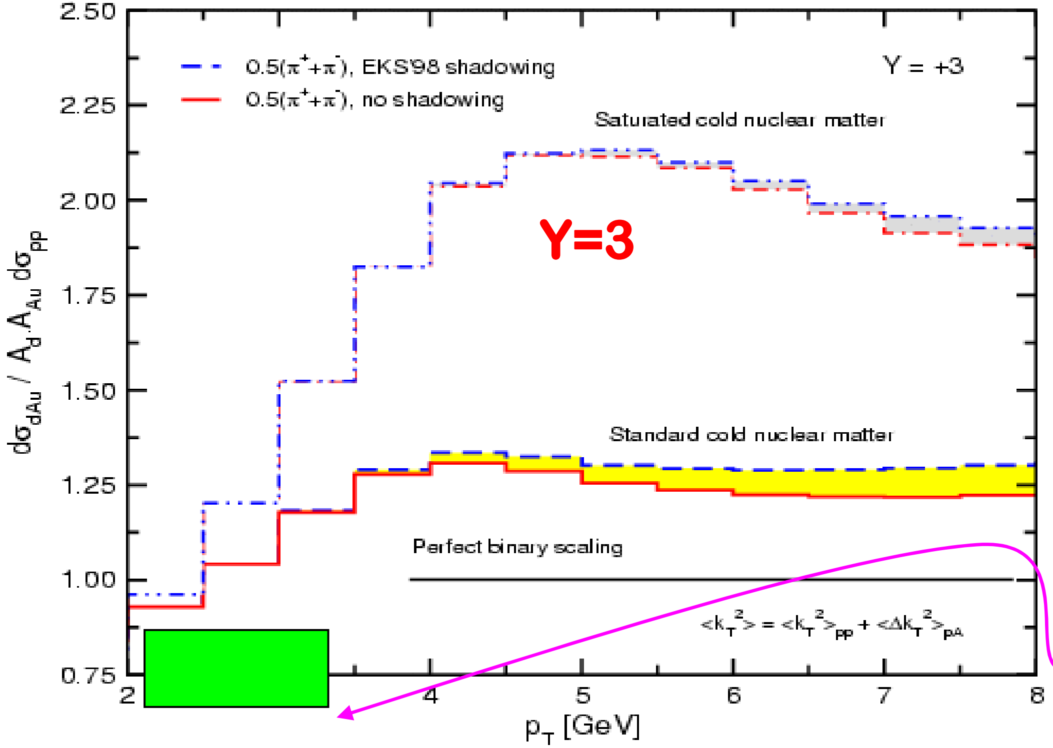
$$d+Au \rightarrow \pi^{0}+X$$

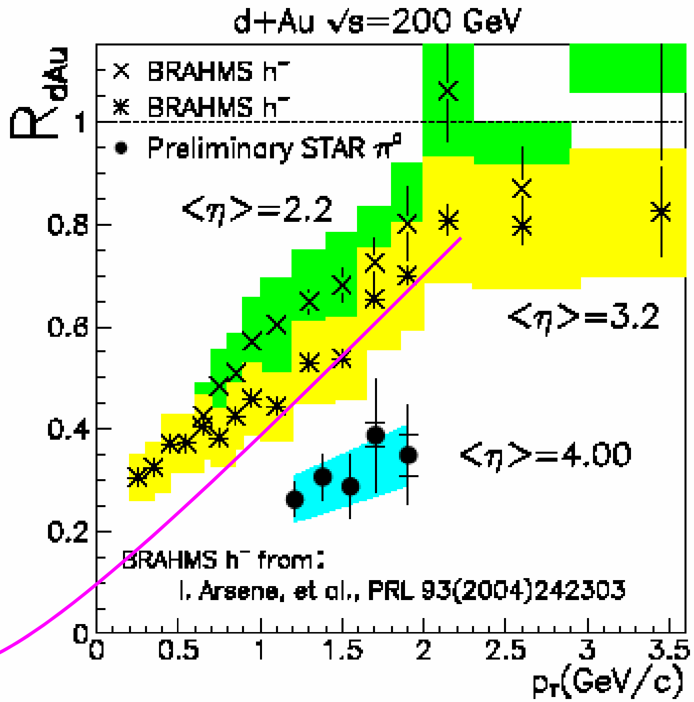


- **Consistent with small Cronin enhancement**
- **Very different from Au+Au**
- **Additional effects may be present (especially baryons)**

Failure at Forward Rapidity

Extrapolating to the regions where it was not tested does not work

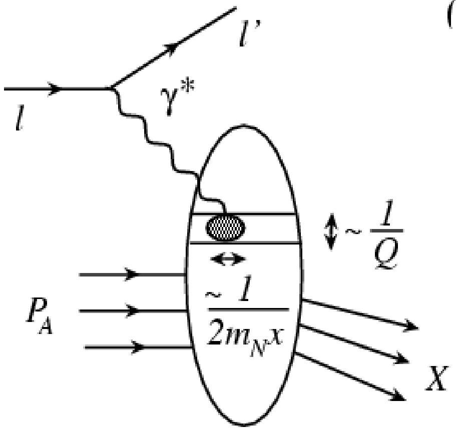


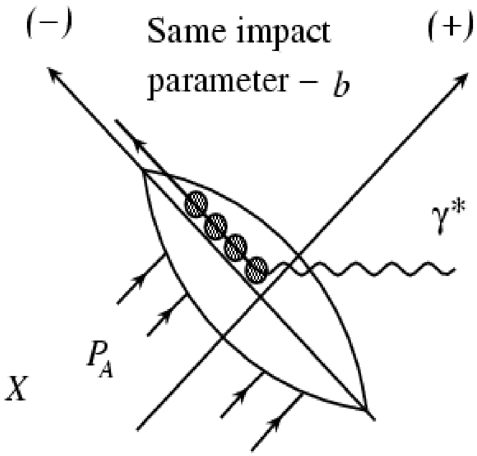


I.V.

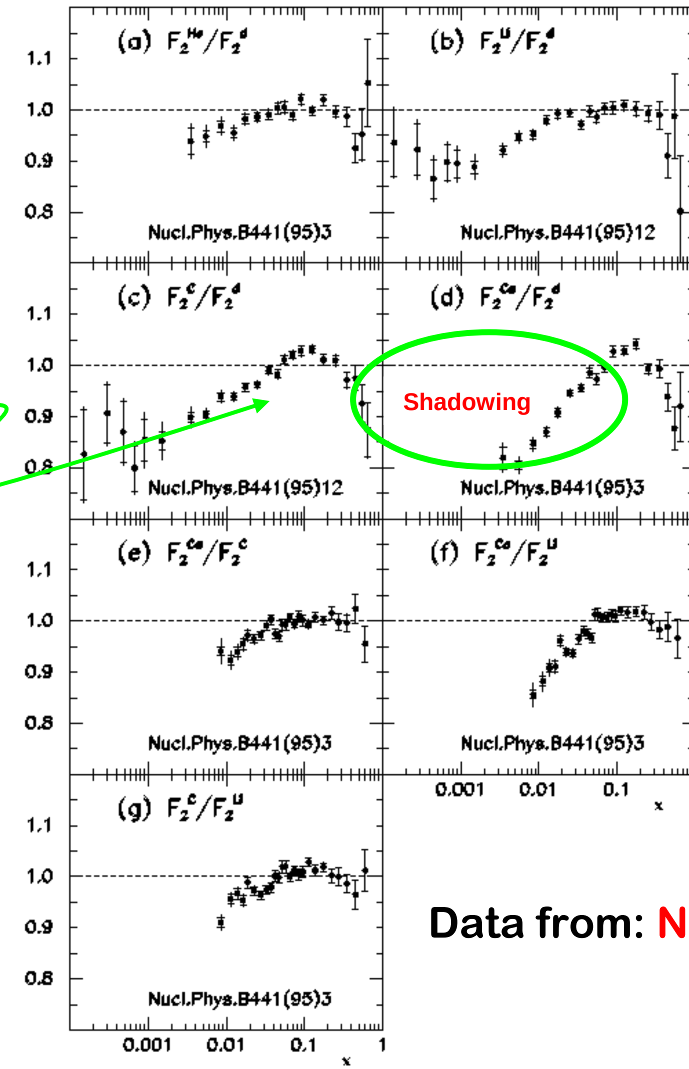
Very nice disagreement between the data and the random walk in p_T space. ⇨ New effects.

II. Coherent Power Corrections





Deviation from A-scaling: $\sigma_A \neq A \times \sigma$



Longitudinal size: $\sim 1/2m_N x$

If $x < 0.1$ **then** $\Delta z > r_0$

Transverse size: $\sim 1/Q$

If $Q < m_N$ **then exceed the parton size**

What remains for theory: power corrections in DIS - suppression

Data from: NMC

FSI are always present:

S.Brodsky et al.

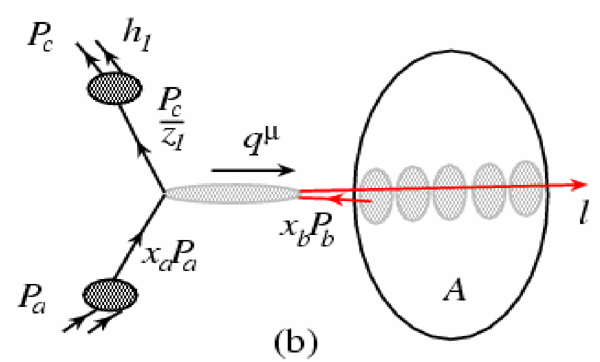
Comparison to Shadowing

$$F_T^A(x,Q^2) \approx A\, F_T^{(LT)}\left(x+\frac{x\xi^2(A^{1/3}-1)}{Q^2},Q^2\right)$$

$$= A\, F_T^{(LT)}\left(x\left(1++\frac{m_{dyn}^2}{Q^2}\right),Q^2\right)$$

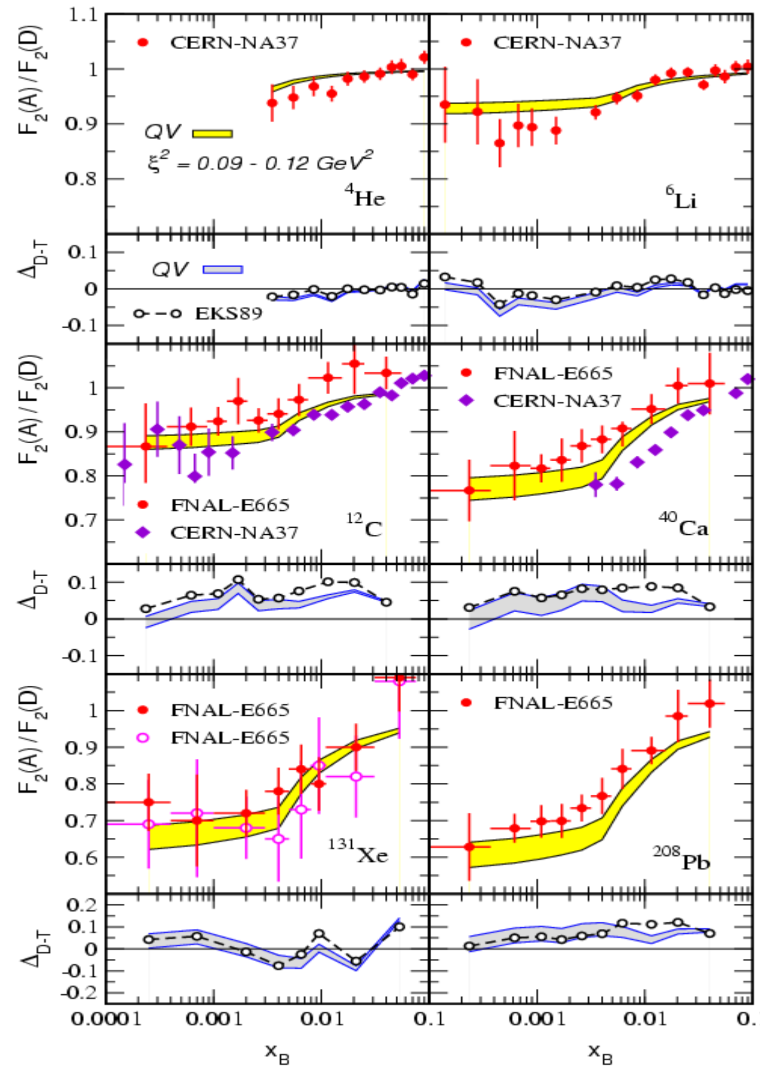
The scale of higher twist per nucleon is <u>small</u> $\xi^2 \simeq 0.1 \;-\; 0.12 GeV^2$

First calculation in p+A reactions



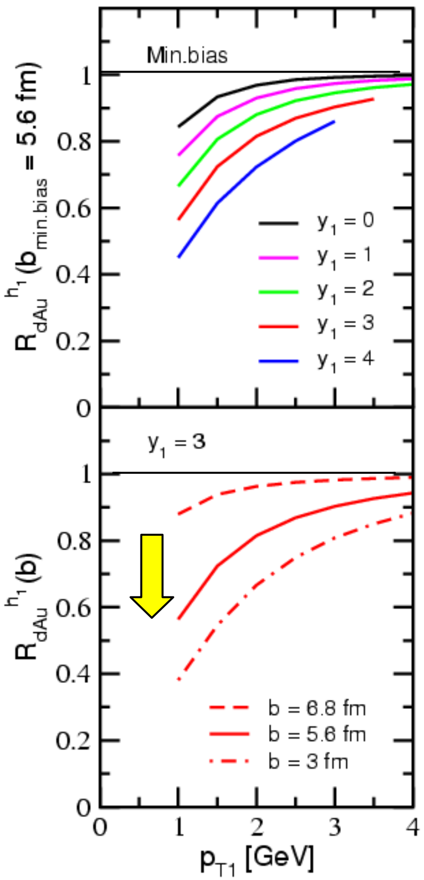
$$F(x_b) = \frac{\phi(x_b)}{x_b}\left|\overline{M}\;^2_{ab\to cd}\right|$$

$$F(x_b) \;\to\; F\left(x_b + x_b C_d \frac{\xi^2}{-t}(A^{1/3}-1)\right)$$

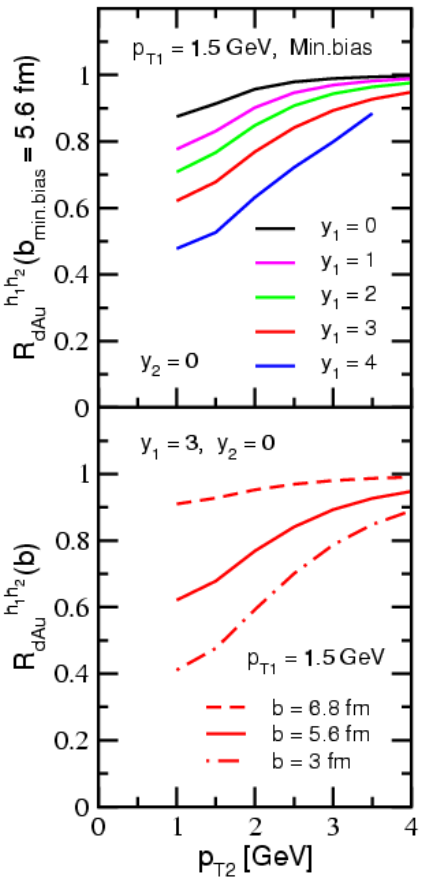


J.W.Qiu, I.V.

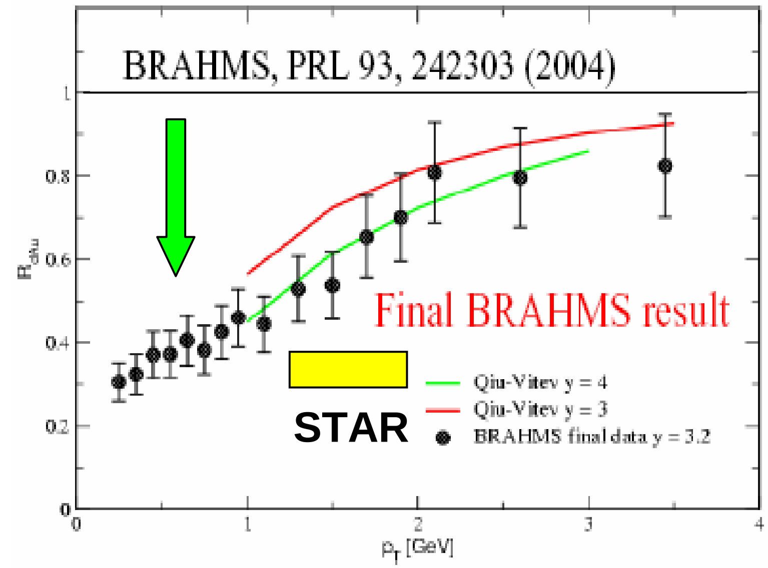
p+A Yields and Correlations



Single inclusive h



Double inclusive h



J.W.Qiu, I.V.,

Suppression disappears at high p_T

Suppression increases with rapidity and centrality

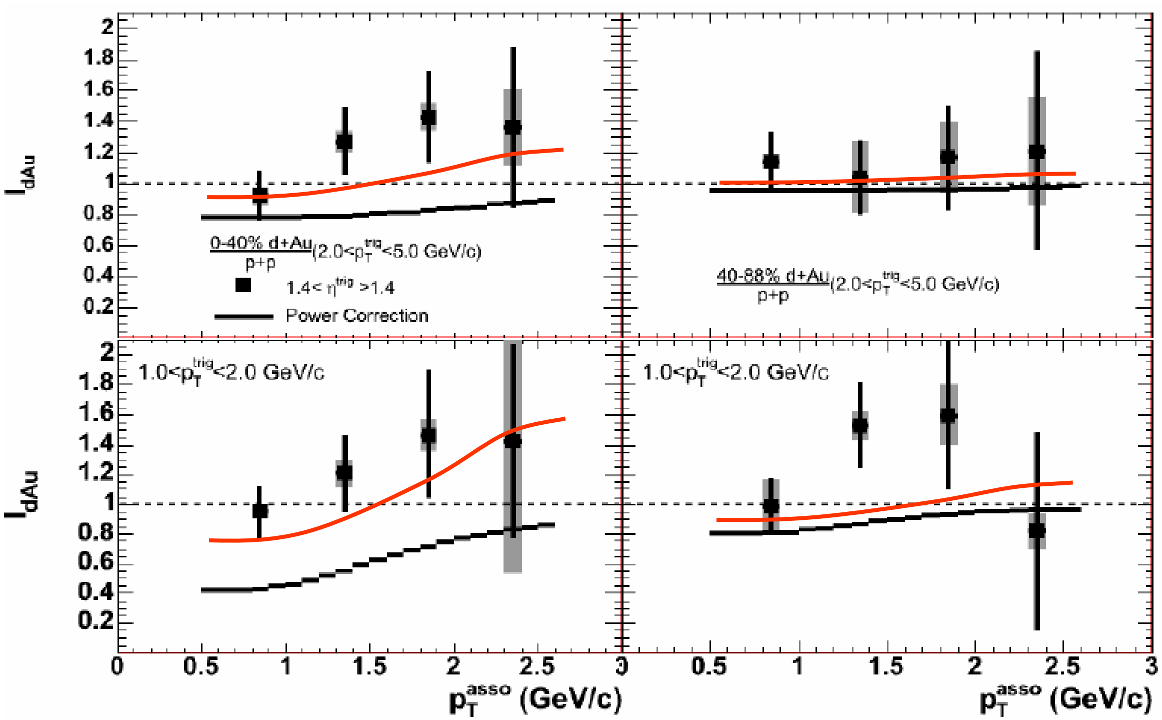
Additional effects possible (E-loss)

Per Trigger Yields

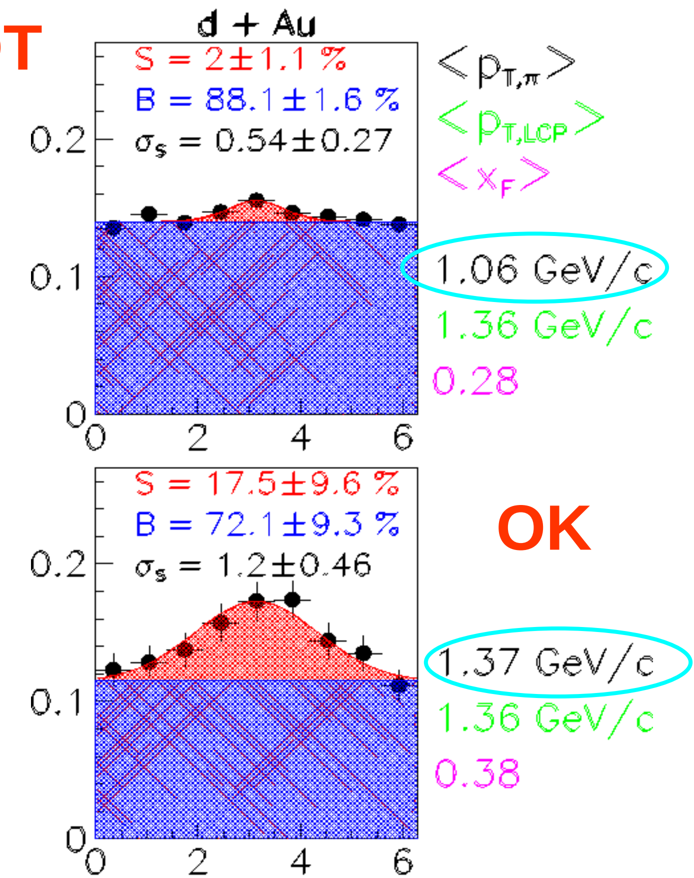
Good example that improved communication will be helpful

$$I^{c}_{d+Au} = \frac{\dfrac{N^{d+Au}_{asso}}{N^{d+Au}_{trig}}}{\dfrac{N^{p+p}_{asso}}{N^{p+p}_{trig}}}$$

Consistent, the yield per trigger does not change



NOT



OK

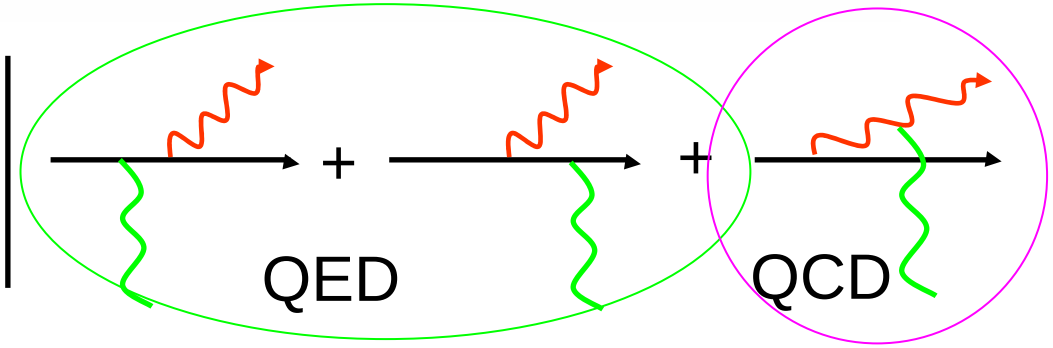
STAR has stopped showing the bottom plot ... (withholding evidence)

III. E-loss Limits

G.Bertsch and F.Gunion

On shell weakly interacting quark

$$\mathcal{M}_1 \to -2ig_s\vec{\epsilon}_\perp \cdot \vec{B}_1 e^{it_1\omega_0}\,[c,a_1] = \mathcal{M}_{GB}\;,$$



$$\sim |B|^2$$

$$\mathcal{M}_1 = -2ig_s e^{it_0\omega_0}\vec{\epsilon}_\perp \cdot \left\{ \vec{H} a_1 c + \vec{B}_1 e^{it_{10}\omega_0}\,[c,a_1] + \vec{C}_1 e^{-it_{10}(\omega_1-\omega_0))}\,[c,a_1] \right\}.$$

Take the $t_0 \to -\infty$ **limit before squaring the amplitudes**

$$\frac{dN^g(BG)}{dy} \sim \frac{C_A\alpha_s}{\pi}\ln\frac{\mu^2}{\Lambda^2_{QCD}}$$

$$\frac{dN_g^{(GB)}}{dy\,d^2\vec{k}_\perp} = C_A\frac{\alpha_s}{\pi^2}\frac{q_1^2}{k_\perp^2(k-q_1)_\perp^2}$$

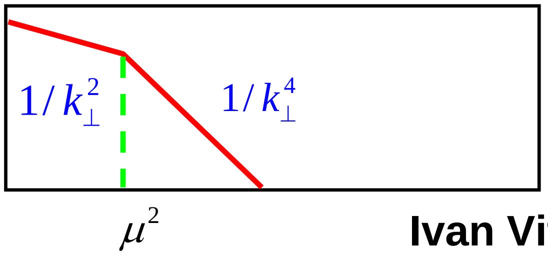
Where $y = \ln 1/x$ **is interpreted as rapidity**

$$\frac{dN^g(QED)}{dy} \sim \frac{C_F\alpha_s}{\pi}\ln\frac{s}{\Lambda^2_{QCD}}$$

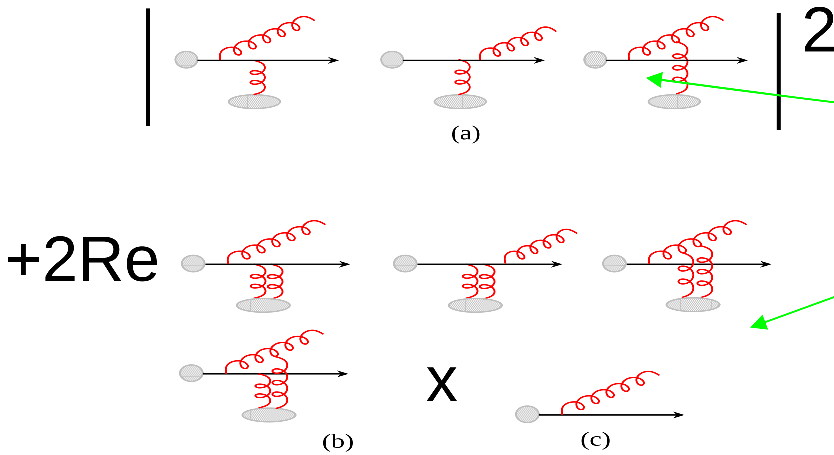
Argue the regulator (originally m_ρ**)**

$$\Delta E \sim E\frac{L}{\lambda}\frac{C_A\alpha_s}{\pi}\ln\frac{\mu^2}{\Lambda^2_{QCD}}$$

Can be large



Cold Nuclear Matter Effects



Final state radiation with interference

$$\Delta E^{(1)} \approx \frac{C_R \alpha_s}{4} \frac{\mu^2 L^2}{\lambda_g} \mathrm{Log} \frac{2E}{\mu^2(L) L} + \ldots ,$$

– Static medium

$$\Delta E^{(1)} \approx \frac{9\pi C_R \alpha_s^3}{4} L \frac{1}{A_\perp} \frac{dN^g}{dy} \mathrm{Log} \frac{2E}{\mu^2(L) L} + \ldots ,$$

– 1+1D Bjorken

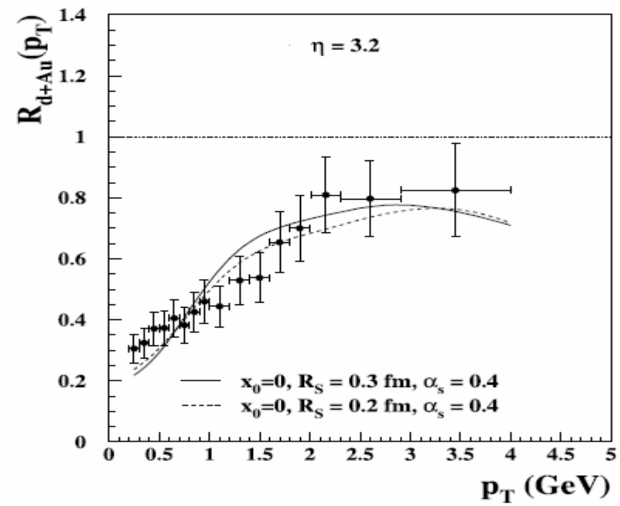
1. The relevant case for pA collisions (interference of the initial state shower with the Bertsch-Gunion) has not been computed

in progress I.V.

2. No detailed study of the implementation of the E-loss (unlike in the final state)

Fluctuations and ΔE redistribution

Scheme was proposed by Kopeliovich and Johnson

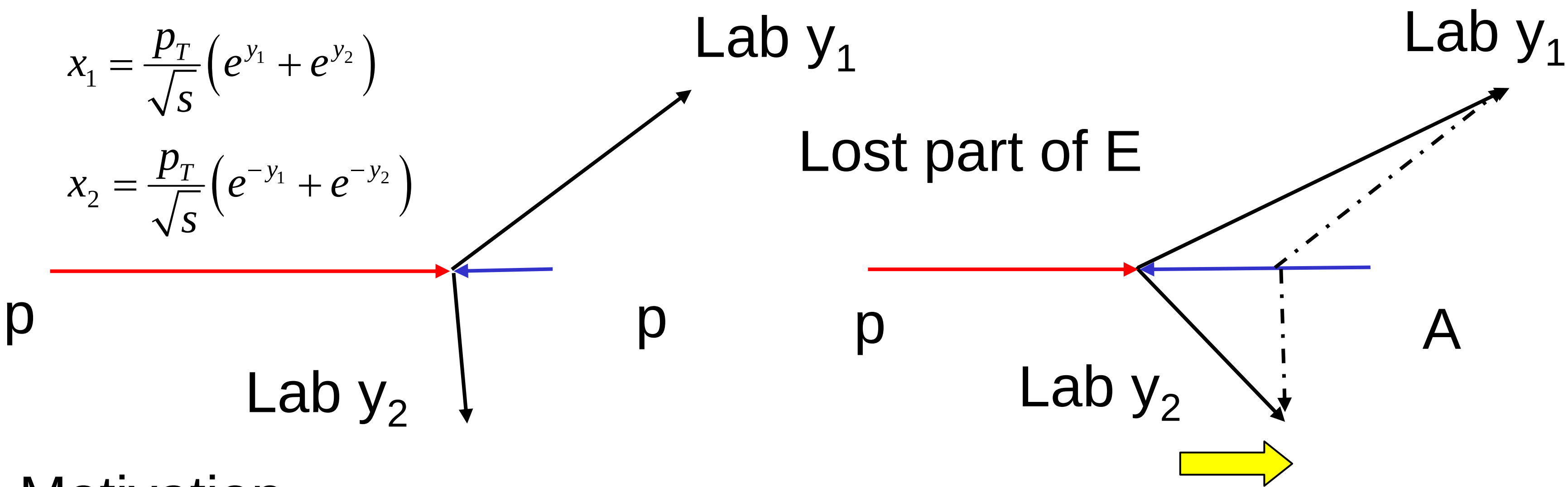


Based on 1. and 2. at this point it is useful to carry out phenomenological investigation. The full theory and implementation can be substantially different

Approx. Implementation of E-loss

$$x_1 = \frac{p_T}{\sqrt{s}}\left(e^{y_1} + e^{y_2}\right)$$

$$x_2 = \frac{p_T}{\sqrt{s}}\left(e^{-y_1} + e^{-y_2}\right)$$



Motivation

Rapidity is shifted relative to CM.

$$y_{cm} = y_1 + y_2 \;, \quad \Delta y = y_1 - y_2$$

$$y_{cm} = \frac{1}{2}\ln\frac{x_1}{x_2}$$

If $\quad x_1 \to x_1(1-\varepsilon)\quad$ then $\quad y_{cm} \to y_{cm} - \Delta y$, $\quad y_i - y_{cm} \to y_i - y_{cm} + \Delta y$

Clearly approximate, but can serve as a guidance on the p_T and y dependence of the QCD energy loss

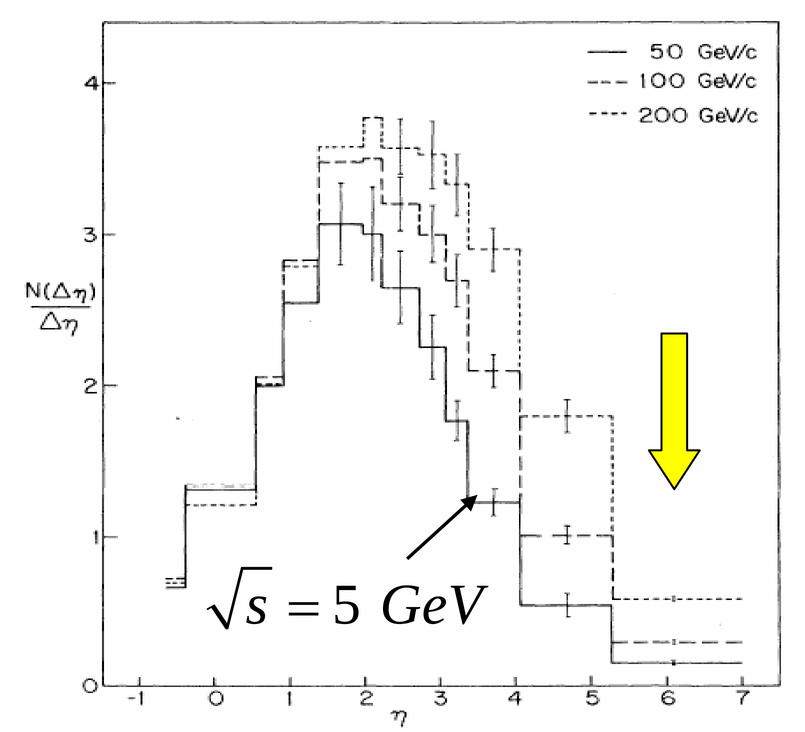
Assume $A^{1/3}$, no p_T, y dependence

Phenomenological but could give guidance to (A, y, p_T) dependence

Low Energy p+A data

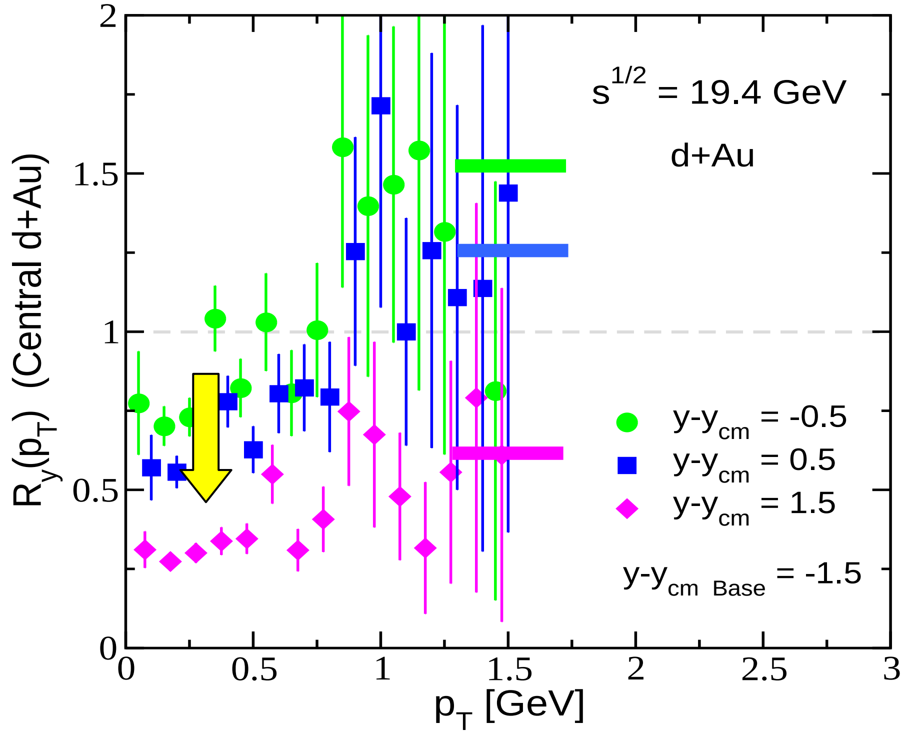
Best evidence

W. Busza et al.



NA35 at SPS

$$R_y(y_1, y_2) = \frac{d^2\sigma^{pA}(y_2)/dp_T dy_2}{d^2\sigma^{pA}(y_1)/dp_T dy_1}$$



Same rapidity asymmetry is seen down to $s^{1/2}$ = 5 - 20 GeV

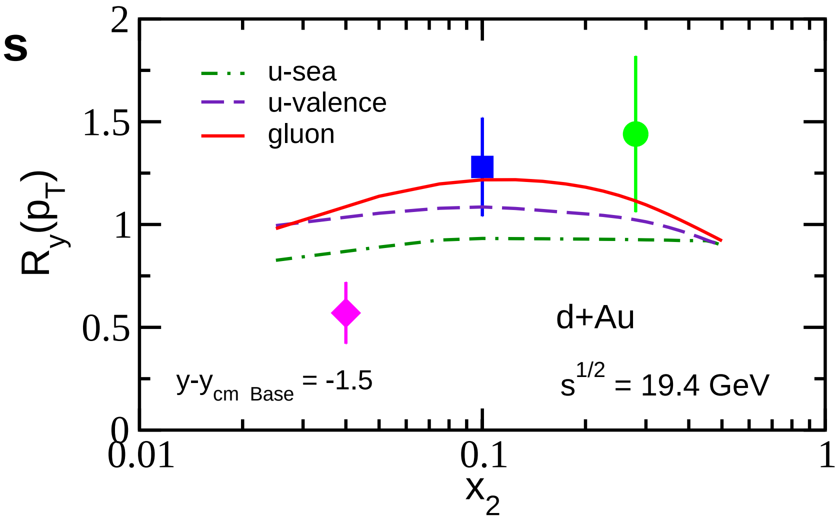
No coherence, eliminates gluon saturation explanations (hardly many gluons) and power corrections explanation in this regime

Comparison to Theory

Leading twist shadowing parameterizations cannot account for the asymmetry

$$S(x,Q^2) = \phi^A(x,Q^2)/\phi^p(x,Q^2)$$

$$h^- = \pi^- + K^- + \overline{p}$$



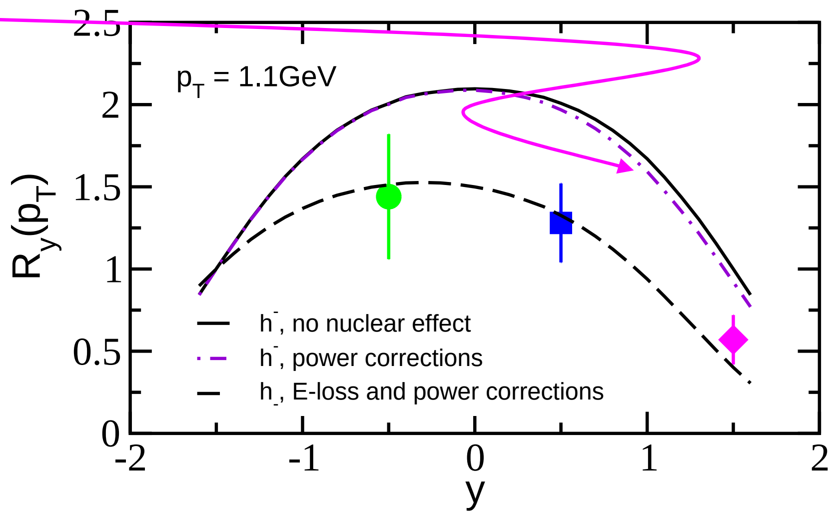
High twist shadowing calculations (fully implemented) cannot account for the asymmetry

$$x_{Bj} \sim 0.1$$

Initial state energy loss can describe the data

$$\Delta y(y, p_T, A) = 0.25$$

No Cronin effect



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200 GeV d+Au Revisited

Incorporate: power corrections, p_T diffusion, rapidity shift

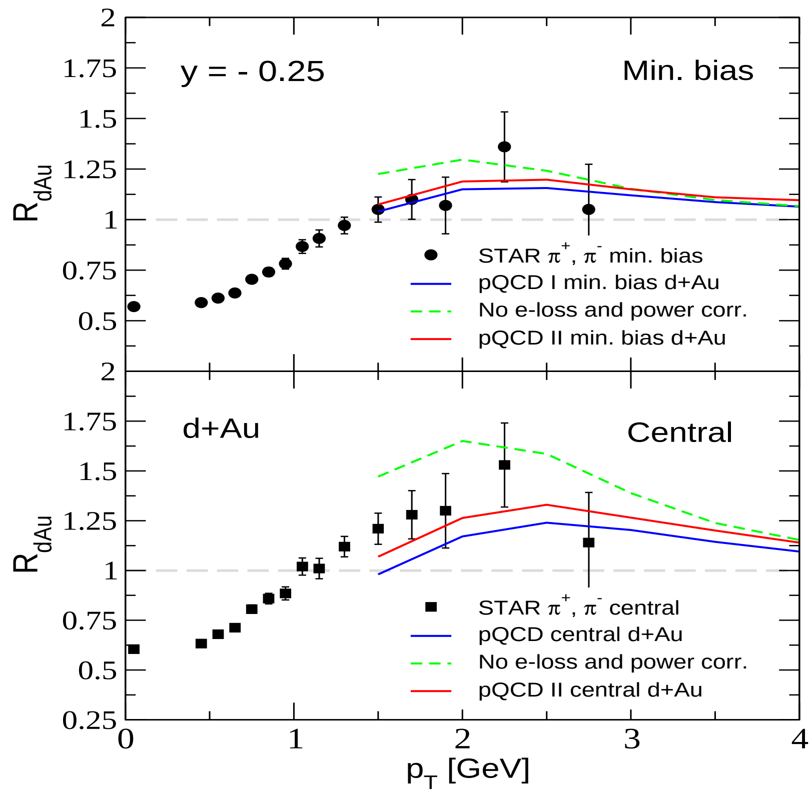
pQCD I:

$$\Delta y(\min.bias) = 0.35,\ \ \Delta k_T^2 = \left(\frac{3}{4} 1.2 A^{1/3}\, fm\right)\begin{pmatrix} q\ \ 0.08\ \ GeV^2 / fm \\ g\ \ 0.17\ \ GeV^2 / fm \end{pmatrix}$$

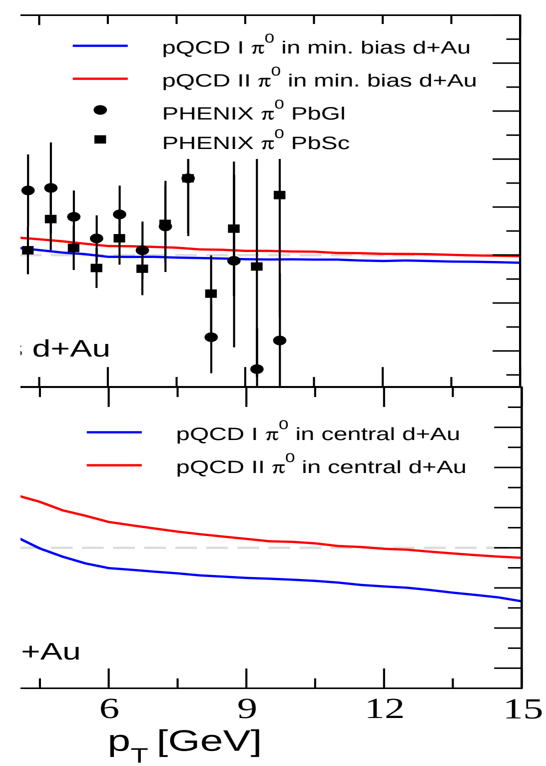
pQCD II:

$$\Delta y(\min.bias) = 0.25,\ \ \Delta k_T^2 = \left(\frac{3}{4} 1.2 A^{1/3}\, fm\right)\begin{pmatrix} q\ \ 0.08\ \ GeV^2 / fm \\ g\ \ 0.17\ \ GeV^2 / fm \end{pmatrix} \max(1, \ln(1 + 0.15 p_T^2))$$

- **Reduces the centrality dependence of the Cronin peak**
- **May induce high p_T suppression at y=0 (15%), not EMC**



I.V.



Forward Rapidities

Interplay of QCD many body effects
- work differently at different Y

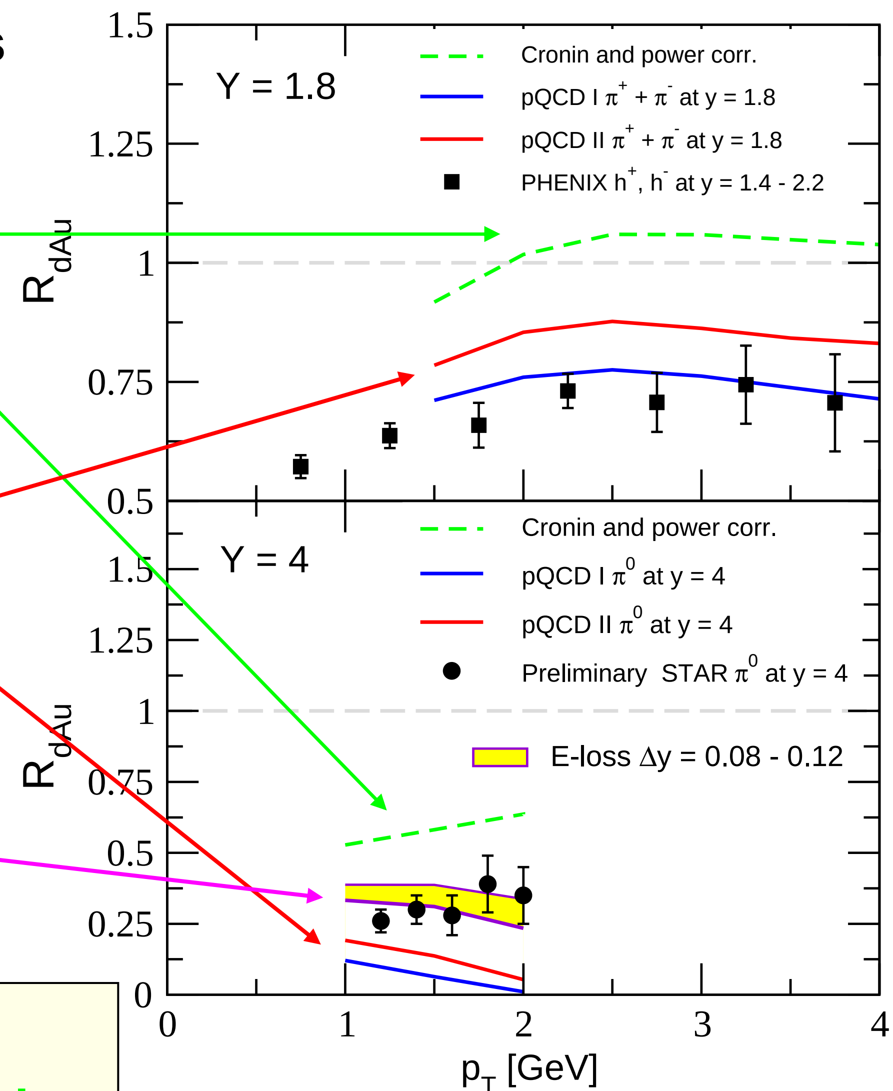
High twist shadowing
+ Cronin effect

Effective energy loss

Very forward rapidities

$\Delta y = 0.08 - 0.12 \;\; versus \;\; \Delta y = 0.25 - 0.35$

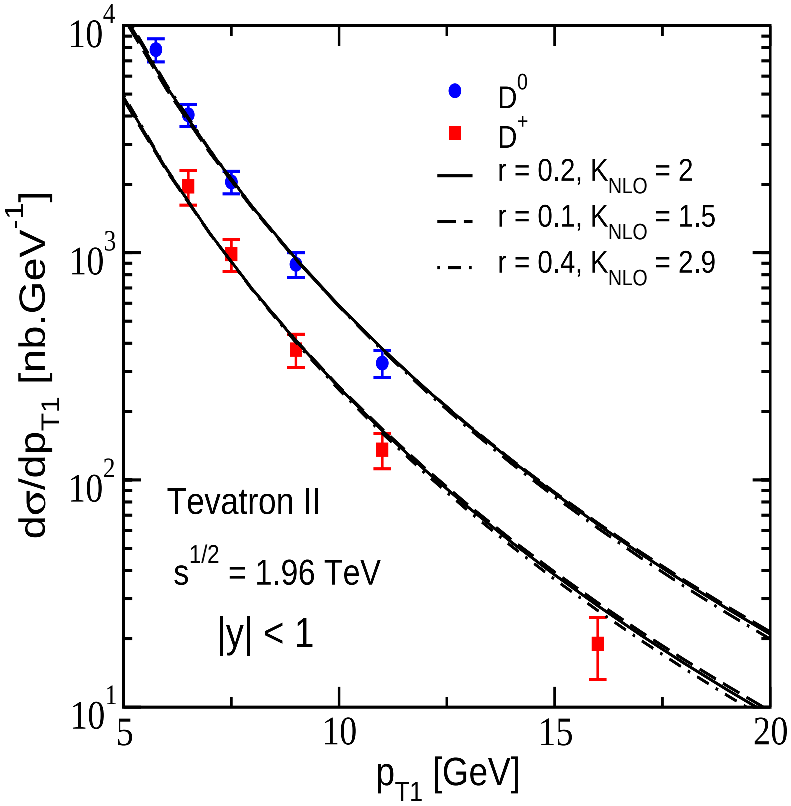
Also look in p_T



The most important step will be to derive the e-loss and its implementation

I.V.

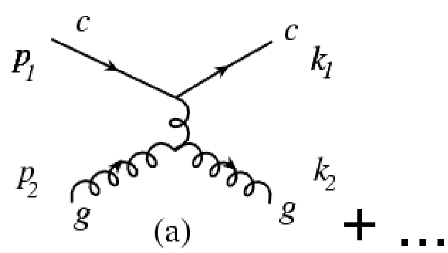
harm Production

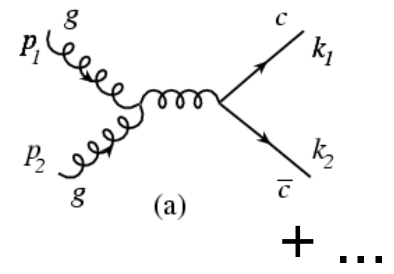


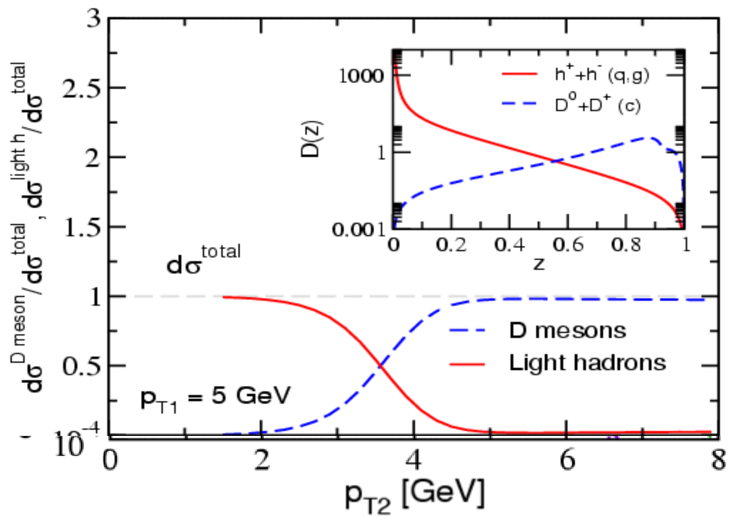
CTEQ6 LO PDFs

E.Braaten et al. FFs

Can study D-meson triggeerd correlations







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Gluon fusion is not the dominant process in inclusive open charm production.

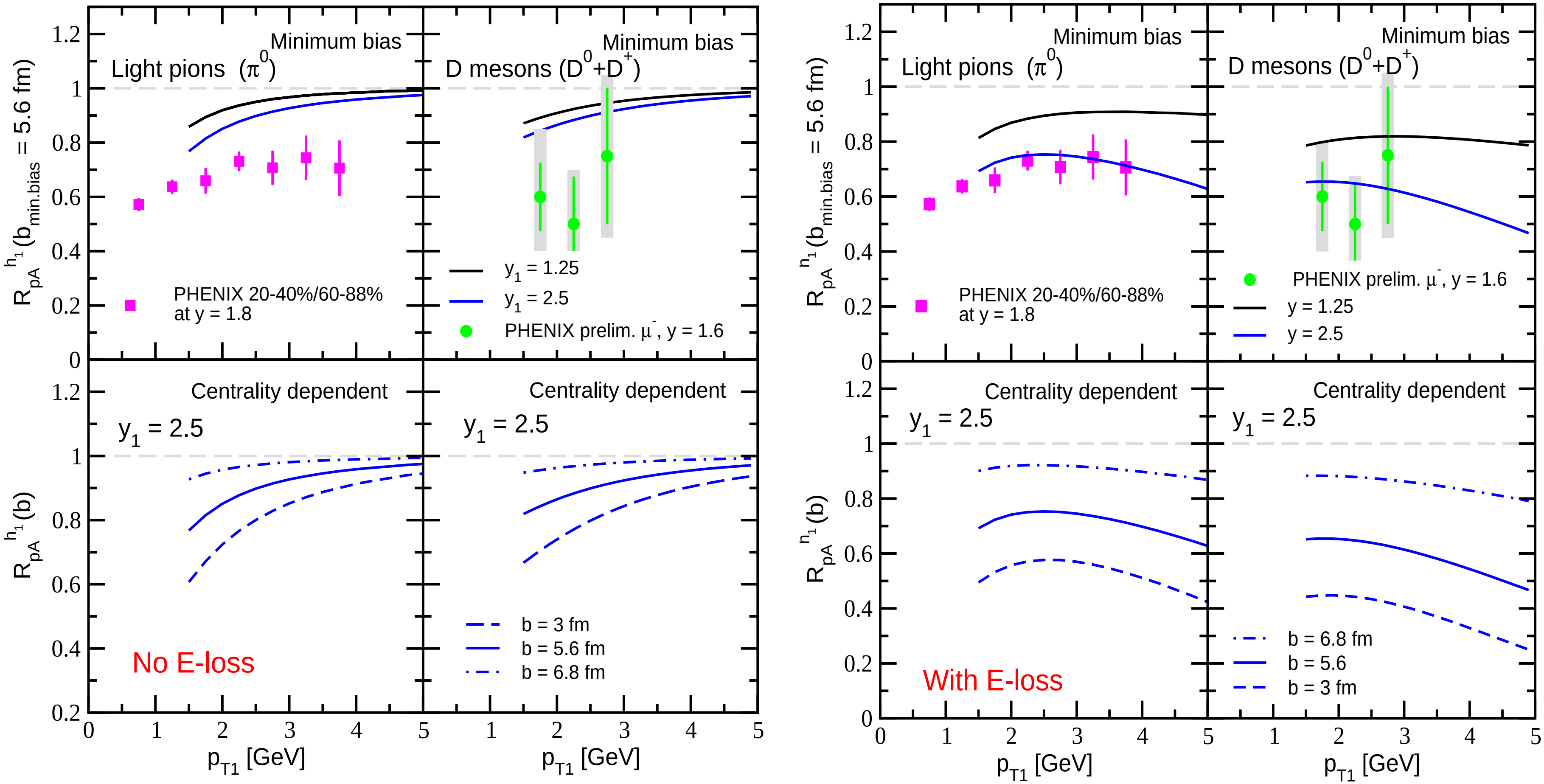
what dominates is $c+g \rightarrow c+g \quad c+q(\bar{q}) \rightarrow c+q(\bar{q})$

Cold Nuclear Matter Effects

$$\Delta y(\min.bias) = 0.25, \;\; No\ Cronin$$

E-loss seems to play a similarly important role

Very similar behavior of charm quarks (D-mesons) to light hadrons



PHENIX data

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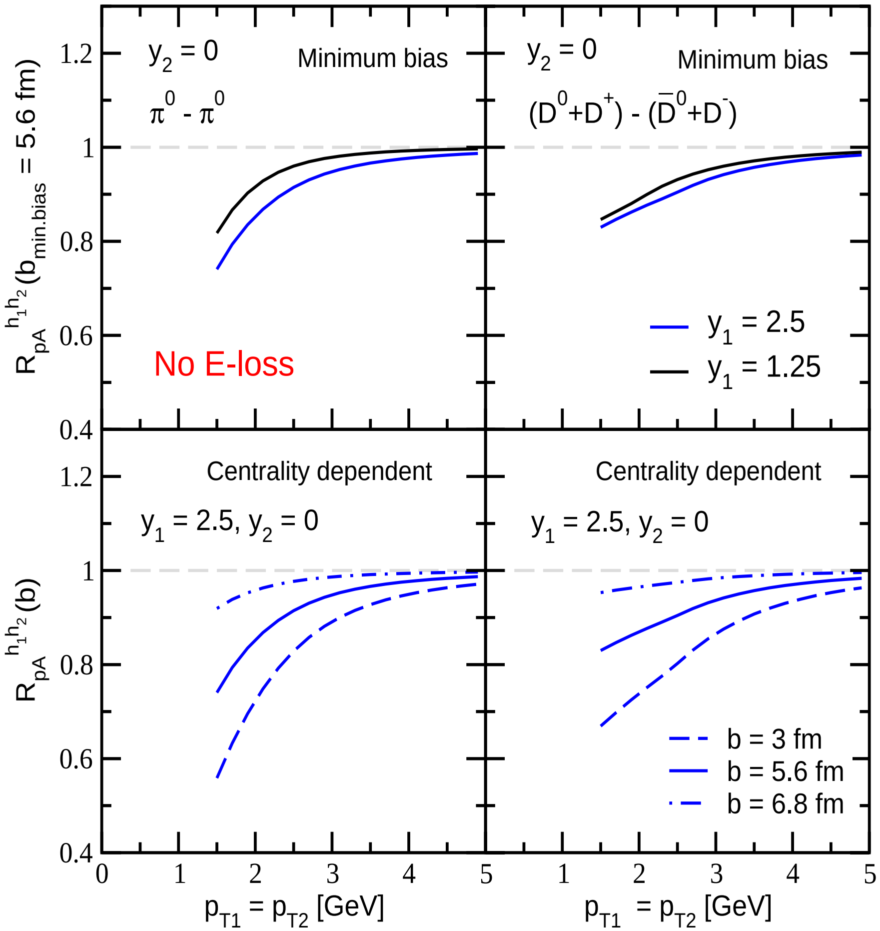
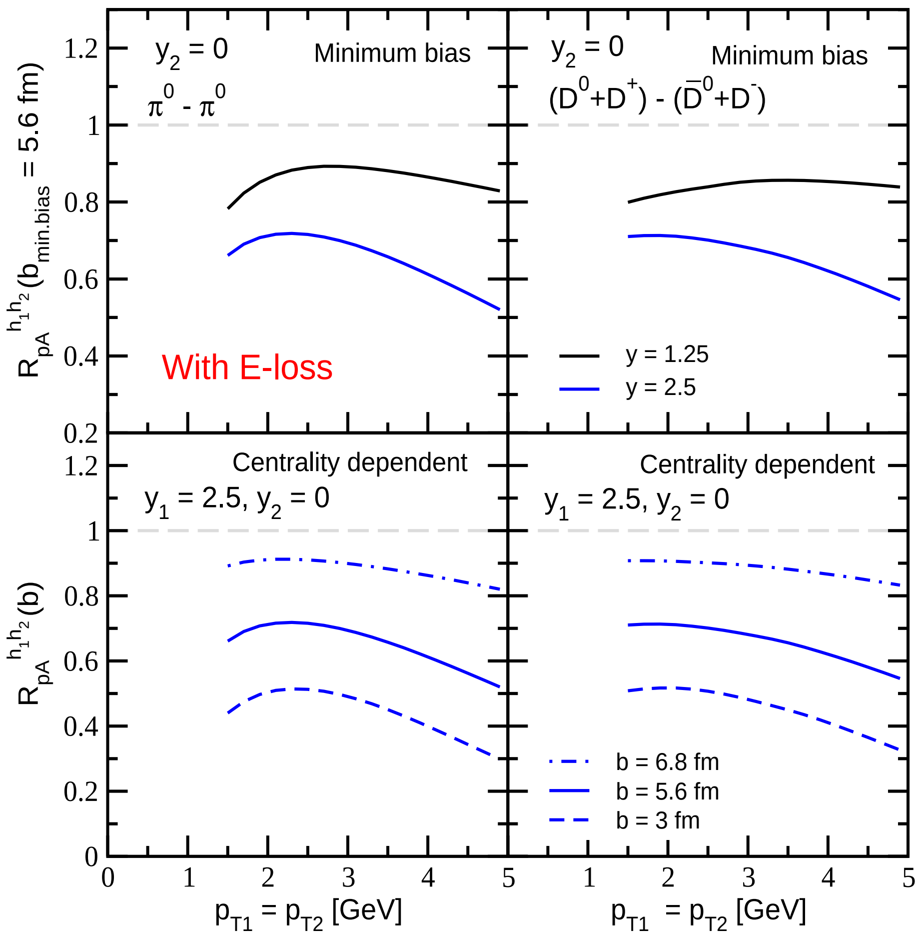
Conclusions

- **Rapidity asymmetry - forward rapidity attenuation in p+A relative to N_{bin}:**
  - Is a universal feature of p+A reactions
  - Is related to the interplay of the power corrections and energy loss. Cronin effect is more effective at mid and backward rapidities
- **More work is necessary to understand E-loss in the initial state and its implementation in pQCD**
- **Charm quarks provide a new probe of the QCD dynamics**
  - Should rethink the dominant production pocesses. New charm trigger measurements
  - The modification of open charm production is very similar to light hadrons

Charm Triggered Correlations

Similar difference in the p_T behavior between single inclusive D-mesons and D-meson triggered correlations





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