Back-to-Back Correlations in p+p, p+A and A+A Reactions

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Outline of the Talk

- **Open charm production and correlations:**
  - Partonic subprocesses and cross sections
  - D meson triggered correlations and hadrochemistry
- **p+A reactions at RHIC:**
  - Understanding initial and final state multiple scattering
  - Dynamical gluon "shadowing" - yields and correlations, including open charm
  - E-loss in cold nuclear matter
- **A+A jet triggered correlations:**
  - Phase space distribution of non-Abelian energy loss
  - Redistribution of the lost energy in jet triggered correlations
  - Broadening of the away-side correlation function

Theoretical Approach

Collinear factorization approach: can be systematically expanded to include nuclear corrections

Other phenomenologies: data = model

NLO correction at LT

$$
\begin{aligned}
\sigma_{\mathrm{hadron}} = \\
& \sigma_0^{(2)} \left(1 + C_1^{(2)}\alpha_s + C_2^{(2)}\alpha_s^2 + C_3^{(2)}\alpha_s^3 + \cdots\right) T^{(2)} \\
& + \frac{\sigma_0^{(4)}}{Q^2} \left(1 + C_1^{(4)}\alpha_s + C_2^{(4)}\alpha_s^2 + C_3^{(4)}\alpha_s^3 + \cdots\right) T^{(4)} \\
& + \frac{\sigma_0^{(6)}}{Q^4} \left(1 + C_1^{(6)}\alpha_s + C_2^{(6)}\alpha_s^2 + C_3^{(6)}\alpha_s^3 + \cdots\right) T^{(6)} \\
& + \cdots
\end{aligned}
$$

Non-perturbative matrix elements: Twist 2, 4, 6, ...

Twist: from Opertaor Product Expansion (OPE)

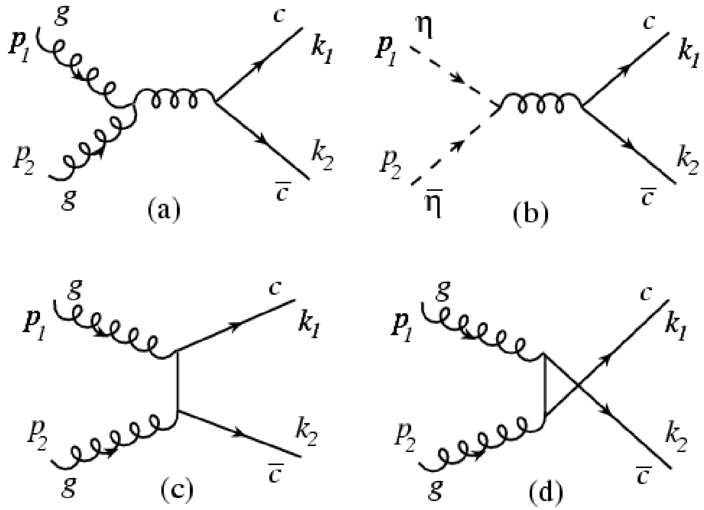
T = Dimension - Spin

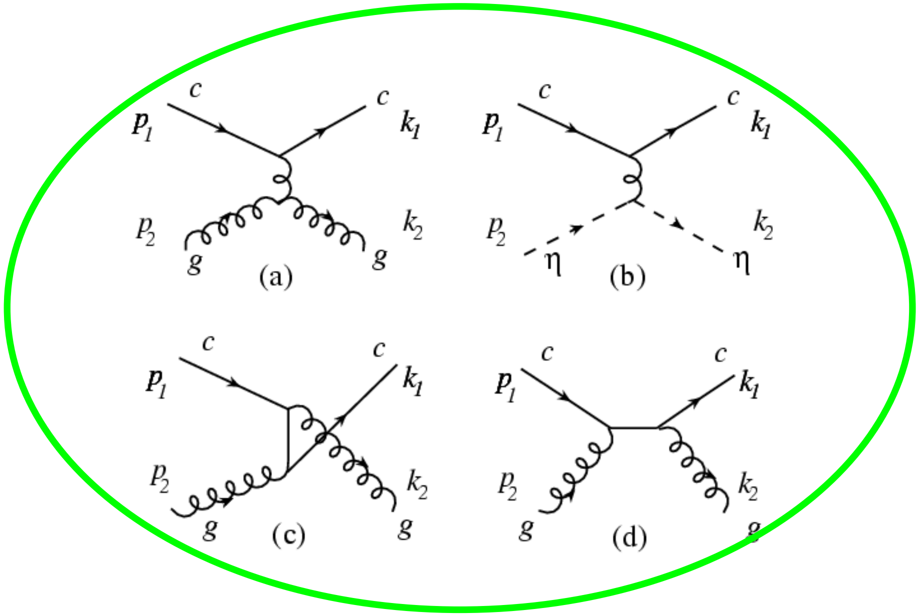
Energy loss - enhanced by the nuclear size

Higher twist (elastic) corrections: dynamical shadowing

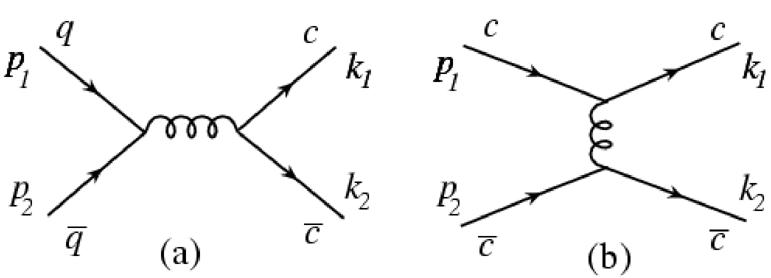
I. Open Charm Production

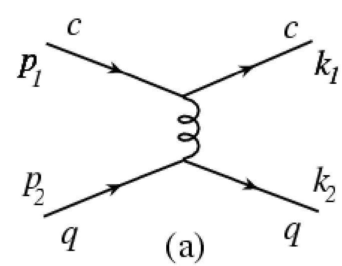
Time direction





Popular belief **In practice to LO (NLO)** **from PDFs**





Many of the interesting features that follow are related to the $cg \to cg$
$cq(\bar{q}) \to cq(\bar{q})$ **scattering**

D^0 and D^+ at the Tevatron

$$\frac{d\sigma_{NN}^{D_1}}{dy_1 d^2p_{T_1}} = K_{NLO} \sum_{abcd} \int_{x_{1,2}\leq 1} dy_2 \int_{x_{1,2}\leq 1} dz_1 \times \frac{1}{z_1^2} D_{D_1/c}(z_1) \frac{\phi_{a/N}(x_a)\phi_{b/N}(x_b)}{x_a x_b} \frac{\alpha_s^2}{S^2} |\overline{M}_{ab\to cd}|^2$$

- **Fragmentation functions: From heavy quark effective field theory (Vector and Pseudoscalar)**

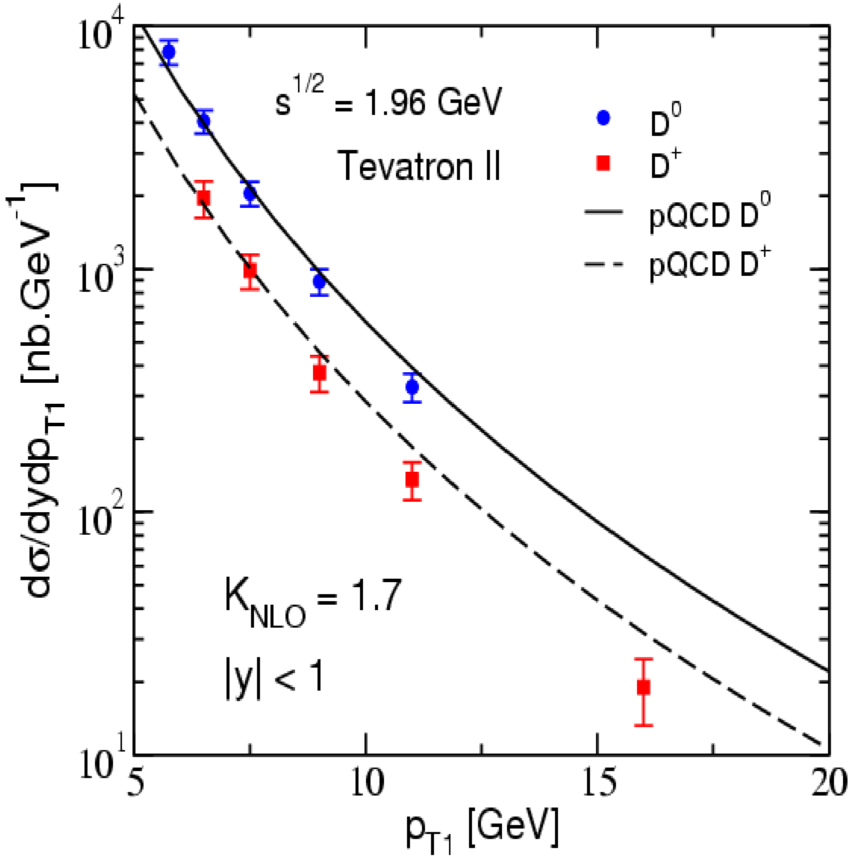
E.Braaten *et al.*, Phys.Rev.D 51 (1995)

- **Branching ratios taken into account**

$D^{0*} \to D^0 \ (BR\ 100\%)$ …

Very reasonable K-factor: K_{NLO} = 1.7

Slightly stiffer power law



Data from:

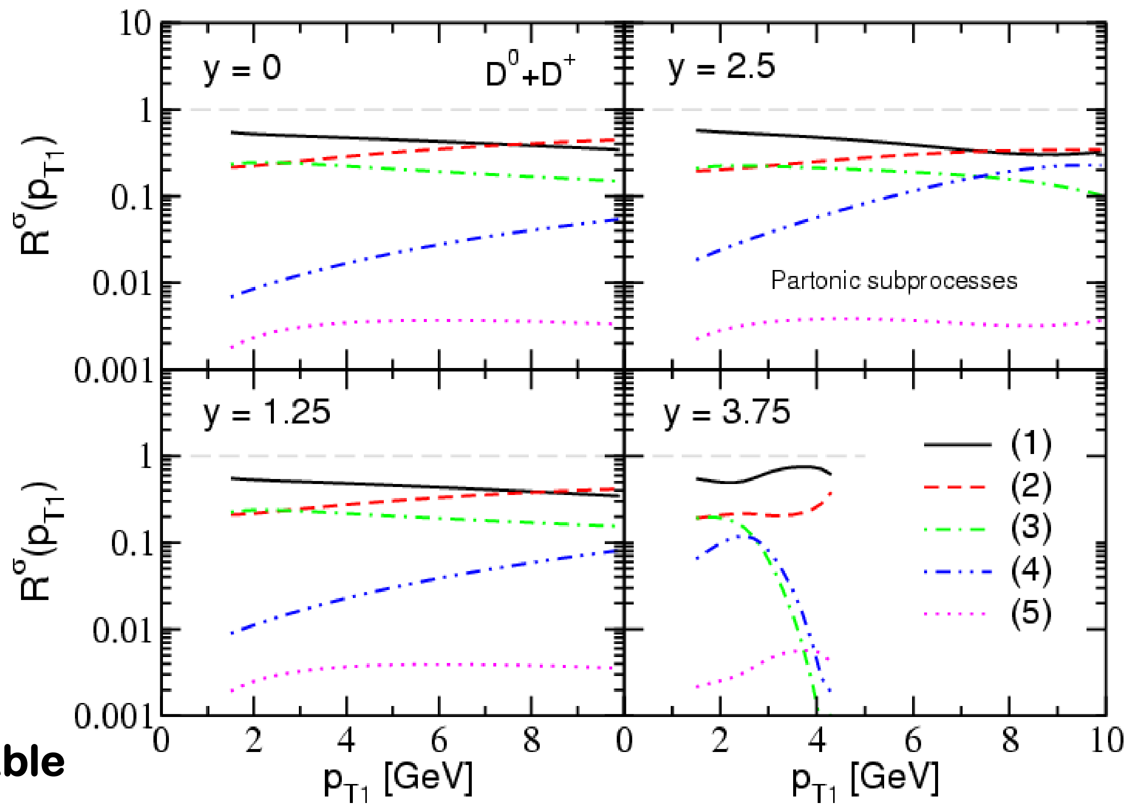
D.Acosta *et al.*, Phys.Rev.Lett. 91 (2003)

Contribution of Partonic Subprocesses

Define **partial cross sections**

$$R^{\sigma}(p_{T_1}) = \frac{d\sigma^{D_1}_{ab\to cd}}{dy_1 d^2 p_{T_1}} \Bigg/ \frac{d\sigma^{D_1}_{tot}}{dy_1 d^2 p_{T_1}}$$

Gluon fussion is not the dominant mechanism for open charm production



Clearly one expects 2 things:

- **Dynamical shadowing comparable to light pions**
- **Trigger dependent hadrochemistry**

$$(1)\ cg \to cg,\ (2)\ cq(\bar{q}) \to cq(\bar{q})$$

$$(3)\ gg \to c\bar{c},\ (4)\ q\bar{q} \to c\bar{c}$$

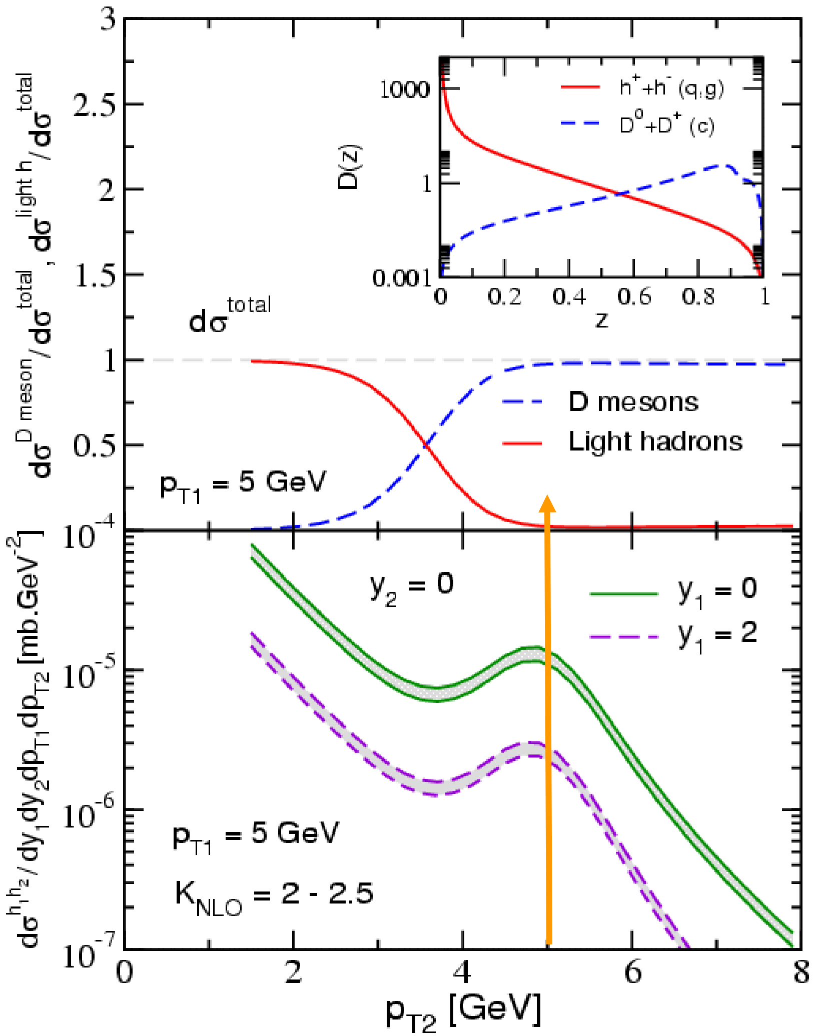
$$(5)\ c\bar{c} \to c\bar{c}$$

How to test this? - di-hadron correlations

D Triggered Correlations

$$\frac{d\sigma_{NN}^{D_1 h_2}}{dy_1 dy_2 dp_{T_1} dp_{T_2}} = K_{NLO} \sum_{abcd} 2\pi \int_{x_1 \le 1, x_2 \le 1, z_2 \le 1} dz_1 \times \frac{1}{z_1} D_{D_1/c}(z_1) D_{h_2/d}(z_2) \frac{\phi_{a/N}(x_a)\phi_{b/N}(x_b)}{x_a x_b} \times \frac{\alpha_s^2}{S^2} |\overline{M}_{ab\to cd}|^2 \,.$$

- **Very strong dependence of particle species in the away side jet on p_{T2}**
- **Non-monotonic behavior on the away side yields: anti D at $p_{T2} = p_{T1}$**



T.Goldman *et al.*, in preparation

Never measured before:

Real possibility for RHIC experiments to discover D meson triggered correlations

Constrain D meson production, c quark fragmentation

II. Shadowing in DIS and p+A

- **Lightcone gauge:** $A\cdot n = A^{+} = 0$
- **Breit frame:** $\bar{n} = [1,0,0_{\perp}],\ \ n = [0,1,0_{\perp}]$

$$q = -xp^{+}\bar{n} + \frac{Q^2}{2xp^{+}}n,\ \ p = \bar{n}p^{+},\ \ xp + q = \frac{Q^2}{2xp^{+}}n$$

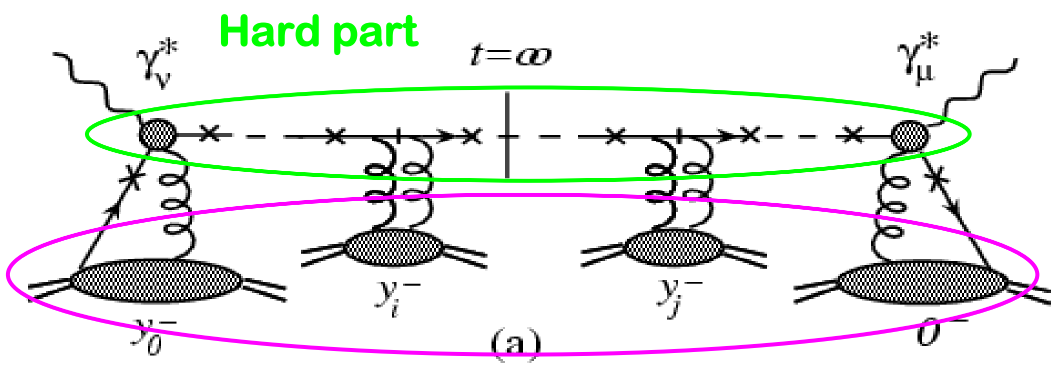
$$Cut = (2\pi)\frac{\gamma^{+}}{2p^{+}}\delta(x_i - x_B)$$

$$\Delta(x_i p + q) = \pm i\frac{\gamma^{+}}{2p^{+}}\frac{1}{x_i - x \pm i\varepsilon} \pm i\frac{xp^{+}\gamma^{-}}{Q^2}$$

Long distance **Short distance**

Perturbative

Non-perturbative



Matrix element

$$\langle P|\hat{O}^{T=2+2n}|P\rangle = A\langle P/A|\hat{O}_q^{T=2}|P/A\rangle$$

Decompose $\prod_{i=1}^{n}\langle P/A|\hat{O}_g^{T=2}|P/A\rangle$

Contribution of single scatter: $\sim \xi^2/Q^2$

$$\xi^2 = \left(\frac{3\pi\alpha_s(Q^2)}{8r_{0\perp}^2}\right)\langle p|\hat{F}^2(\lambda_i)|p\rangle$$

$$\hat{F}^2(\lambda_i) = \int\frac{d\tilde{\lambda}_i}{2\pi}\frac{F^{+\alpha}(\lambda_i)F_{\alpha}^{\ +}(\tilde{\lambda}_i)}{(p^{+})^2}\theta(\lambda_i - \tilde{\lambda}_i) \Rightarrow \lim_{x\to 0}\frac{1}{2}xG(x,Q^2)$$

Numerical A- and x_B-Dependence

Purely quantum effect

$$\exp\left[+ \frac{\xi^2 (A^{1/3}-1)}{Q^2} x \frac{d}{dx} \right] F_2(x)$$

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

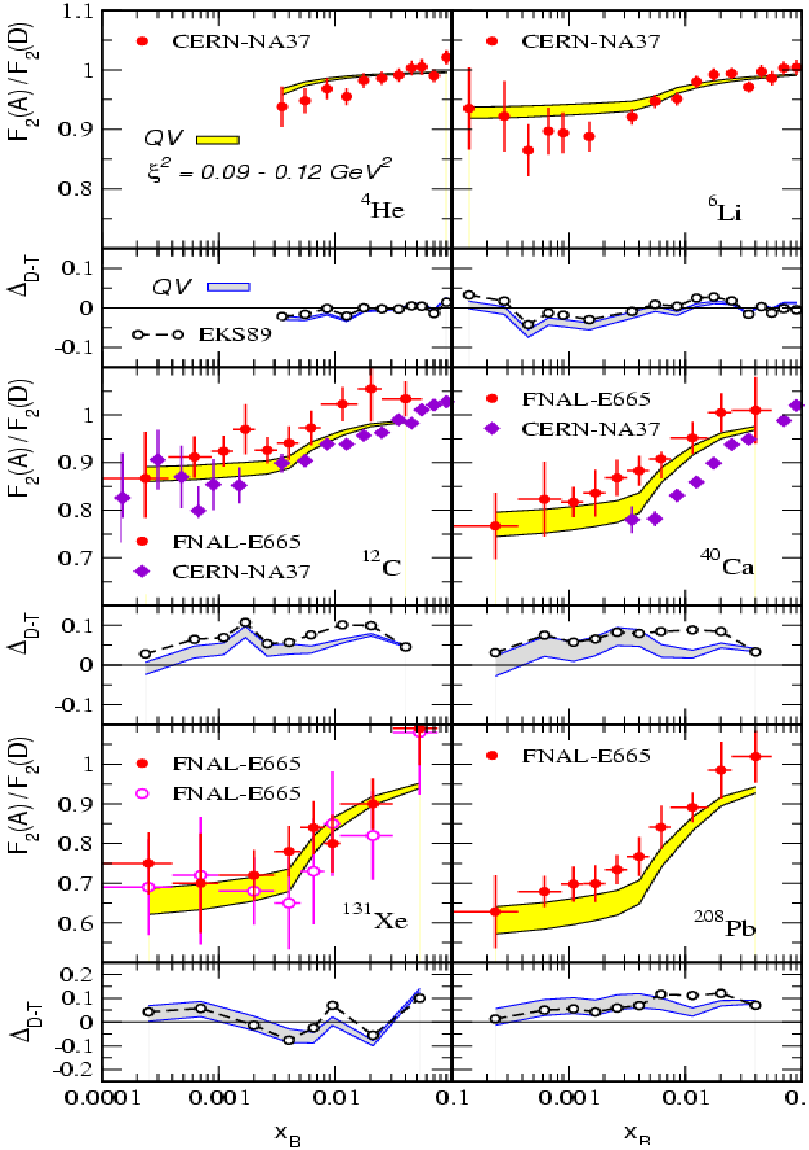
The scale of higher twist per nucleon is small $\xi^2 \simeq 0.1\ GeV^2$

- Favorable comparison for the x- and A-dependence NA37 (NMC) and E665 data

- For $Q^2 \to 0$ we impose $Q^2 = m_N^2$.

Finite resolution: same for all models (r_{max})

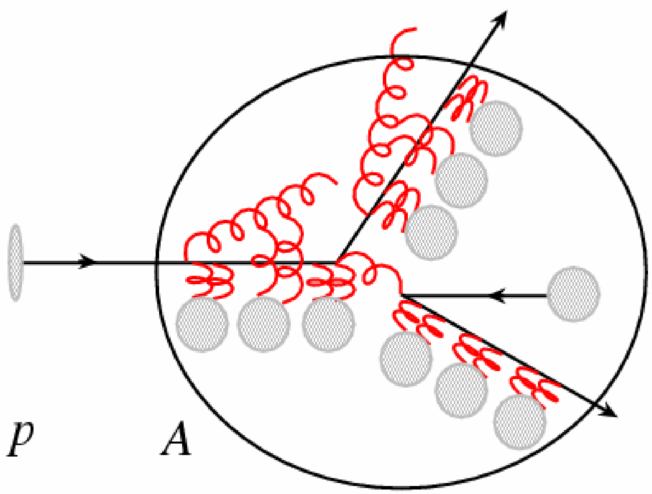
J.W.Qiu, I.V., Phys.Rev.Lett. 93 (2004)



p+A Collisions are not DIS

Type of scattering	Transverse momentum dependence of the nuclear effect
Elastic (incoherent)	Cronin effect: small suppression at low p_T, enhancement at moderate p_T, disappears at high p_T. Dijet acoplanarity: p_T diffusions, broadening of away-side corelations
Inelastic (radiative)	Single inclusives: suppression at all p_T, weak p_T dependence, persists at high p_T (amplified near kinematic bounds). Double inclusive: suppression of high p_T correlations, reapearance of the energy at low p_T
Coherent (elastic $t-$channel)	Both single and double inclusive: suppression at low p_T, disappears at high p_T, pronounced p_T dependence

TABLE I: Effect of elastic, inelastic and coherent multiple scattering on the transverse momentum dependence of single and double inclusive hadron production in the perturbative regime.



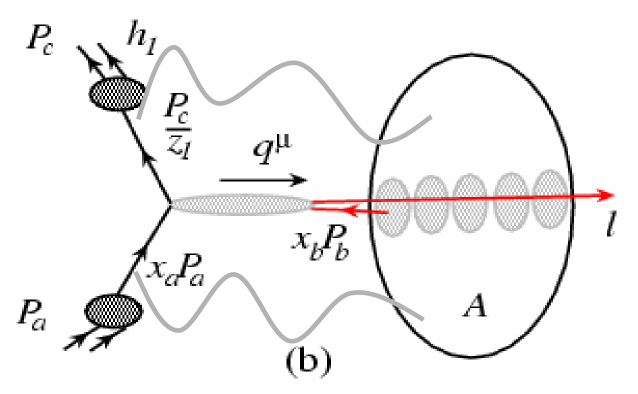
- **p+A collisions do not carry direct information about PDFs (unfortunately all effects)**
- **Forward (backward) physics not equal small x (large x)**

1) Initial state energy loss and broadening - DY

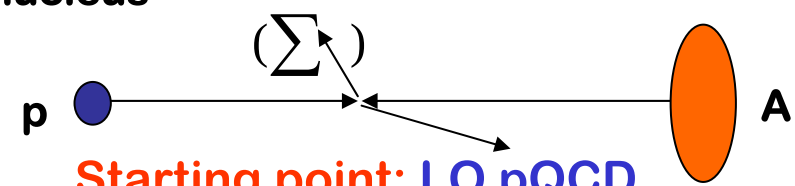
2) Shadowing - DIS

3) Final state e-loss is added in p+A

p+A Collisions



Resum the **multiple final state scattering of the parton "d"** with the remnants of the nucleus



Starting point: LO pQCD

- Other interactions are less coherent (elastic) and sppressed at forward rapidity by a large scale 1/u, 1/s

$$\frac{d\sigma_{NN}^{h_1}}{dy_1 d^2 p_{T1}} = K \sum_{abcd} \int_{z_1 \min}^{1} dz_1 \frac{D_{h_1/c}(z_1)}{z_1^2} \int_{x_a \min}^{1} x_a \frac{\phi(x_a)}{x_a} \frac{1}{x_a S + U/z_1} \frac{\alpha_s^2}{S} \int_0^1 x_b \delta(x_b - \bar{x}_b)\, F(x_b)$$

$$\frac{d\sigma_{NN}^{h_1 h_2}}{dy_1 dy_2 d^2 p_{T1} d^2 p_{T2}} = \frac{\delta(\Delta\varphi - \pi)}{p_{T1} p_{T2}} \sum_{abcd} \int_{z_1 \min}^{1} dz_1 \frac{D_{h_1/c}(z_1)}{z_1} D_{h_2/d}(z_2) \frac{\phi(\bar{x}_a)}{\bar{x}_a} \frac{\alpha_s^2}{S^2} \int_0^1 x_b \delta(x_b - \bar{x}_b)\, F(x_b)$$

$\phi(x_b)$ - standard parton distribution functions

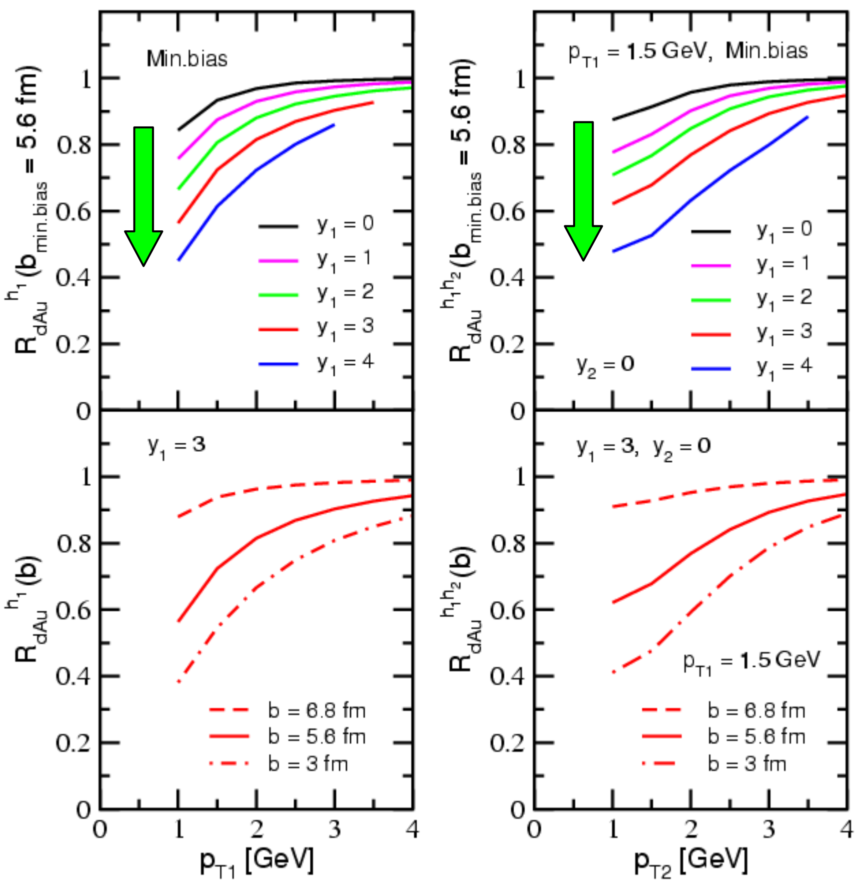
$D_{h_1/c}(z_1)$ - standard parton distribution functions

Isolate all the x_b dependence of the integrand: $F(x_b) = \frac{\phi(x_b)}{x_b} \left| \bar{M}^{\,2}_{ab \to cd} \right|$

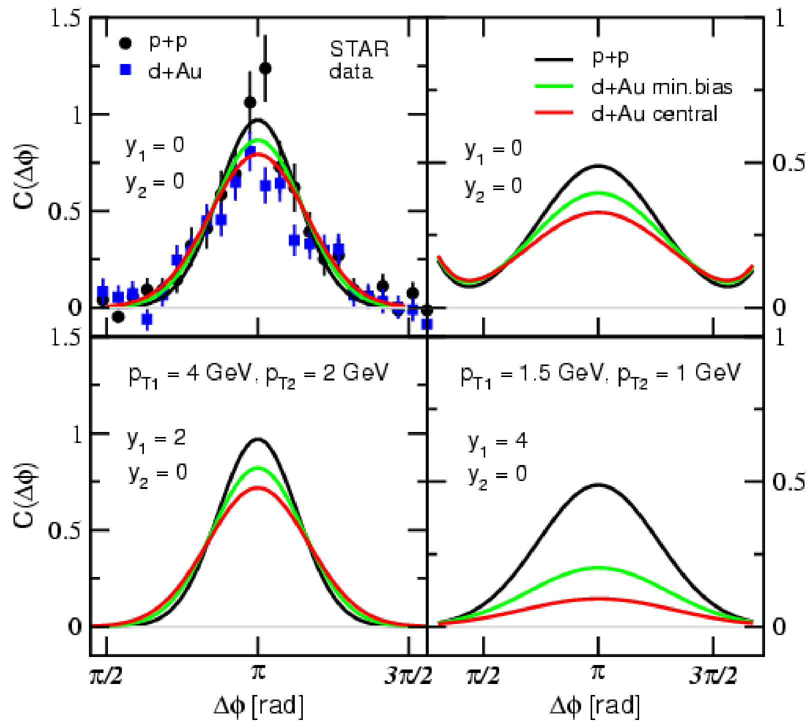
Numerical Results

$$\sum_{N=0,\infty} \int dx_b \delta(x_b - \bar{x}_b) F(x_b) \;\rightarrow$$

$$\int dx_b \delta(x_b - \bar{x}_b) F\left(x_b + x_b C_d \frac{\xi^2}{-t} (A^{1/3} - 1) \right)$$



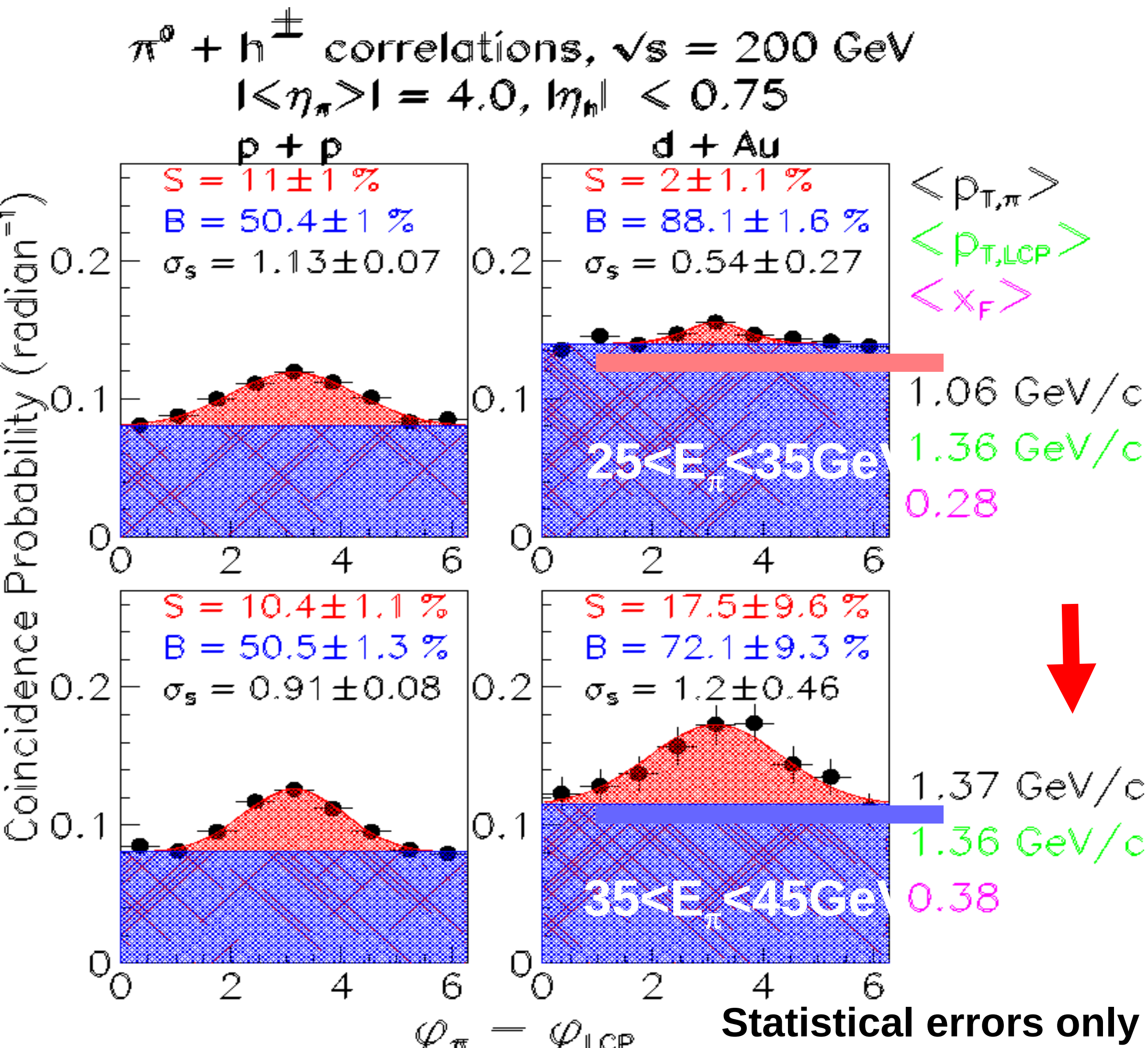
- **Similar** power corrections modification to **single and double inclusive hadron production**
  - **increases** with **rapidity and centrality**



J.W.Qiu, I.V., hep-ph/0405068

Forward Correlations

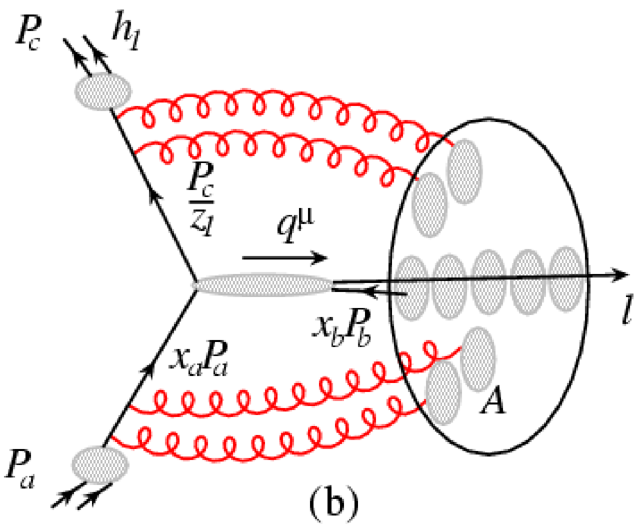
STAR **Preliminary:** L.Bland, [STAR Colaboration]



Statistical errors only

- There isn't mono jettiness
- There is room for suppression due to power corrections
- There is room for suppression due to energy loss

Dynamical Shadowing to Inclusive D^0+D^+



Increases with centrality:

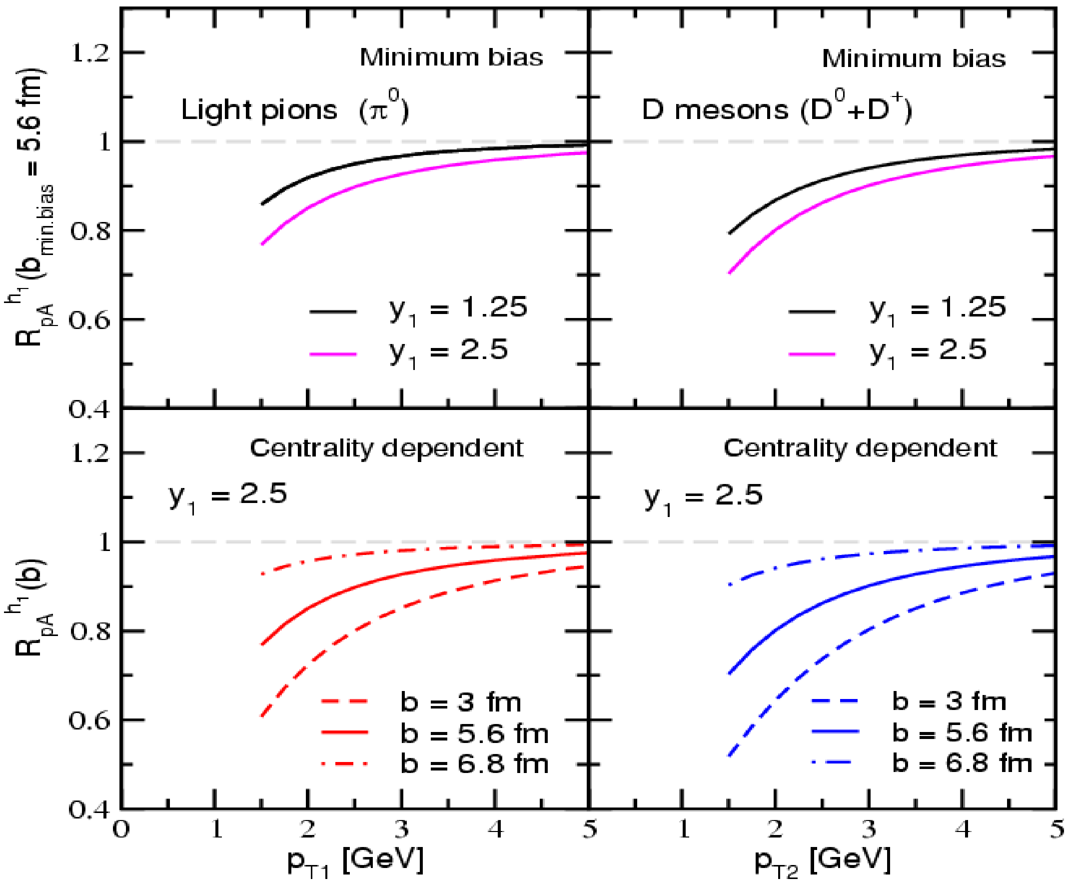
(dynamical shadowing has little to do with A but with the local path length through nuclear matter)

Increases with rapidity:

(slightly)

Disappears at high p_T:

(power correction type, coherent elastic)



Quite similar to light pions (even slightly larger)

$(D^0+D^+) - (\bar{D}^0+D^-)$ Triggered Correlations

Similar results for the D meson triggered correlations

$$\hat{t} = (x_a P_a - p_c / z_1)^2$$

- **We know for a fact that the c quark rescatters (as in DIS)**

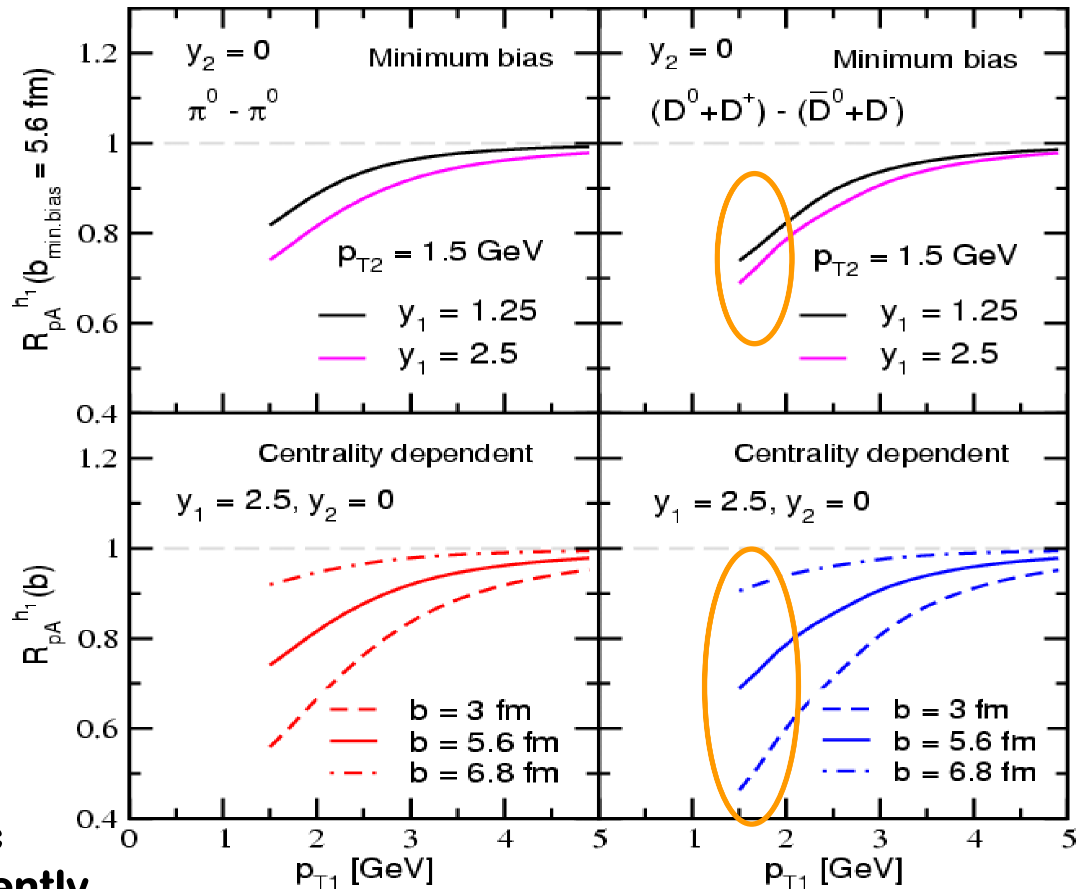
$$\xi^2 (A^{1/3} - 1) / (-\hat{t})$$

- **In light hadrons**

$$C_A / C_F \xi^2 (A^{1/3} - 1) / (-\hat{t})$$

Naively expected that the partonic composition will matter but apparently what dominates is:

$$z_{light\ hadons} < z_{charm\ mesons}$$



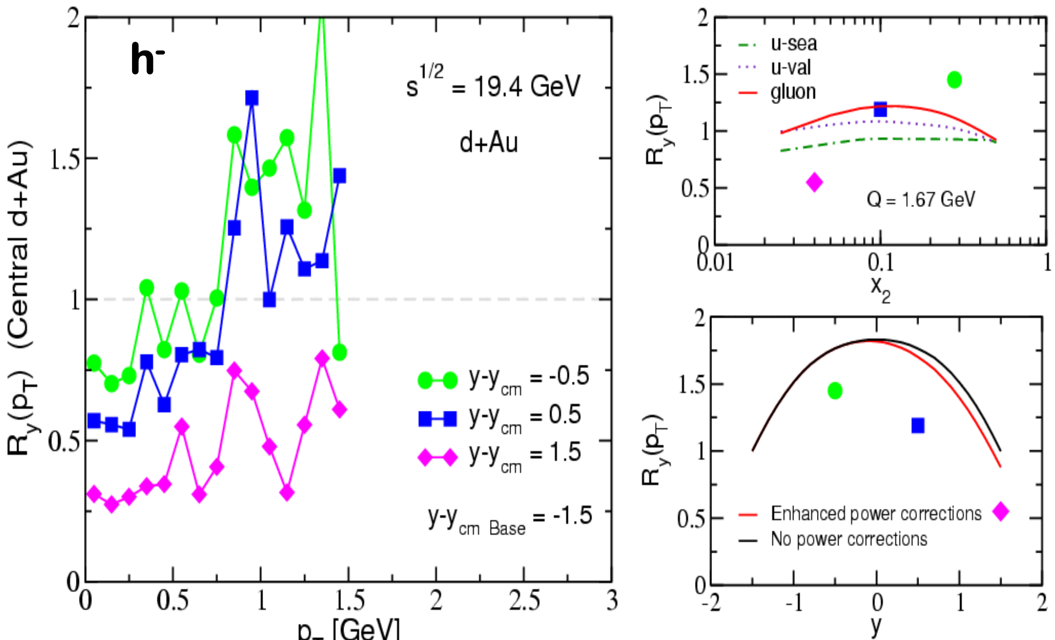
Experimentally probably biased to $p_{T1} = p_{T2}$

Energy Loss in Cold Nuclear Matter

- **Before jumping to conclusions investigate existing data**

NA35 collaboration: d+Au (interestingly enough) data - $\sqrt{s_{NN}} = 19.4\ GeV$

Same rapidity asymmetry as at $\sqrt{s_{NN}} = 200\ GeV$



T.Goldman *et al.*, in preparation

- **Leading twist shadowing: (phenomenology) clearly insufficient (in fact antishadowing)**
- **Power corrections (theory) : clearly insufficient (~13%)**

Leaves additional effects: enegy loss

One Implementation of Energy Loss

Bertsch-Gunion bremsstrahlung:

$$\frac{dn_G}{dy} = \frac{3\alpha_s}{\pi} \ln\left(\frac{m_\rho^2}{\Lambda_{QCD}^2}\right)$$

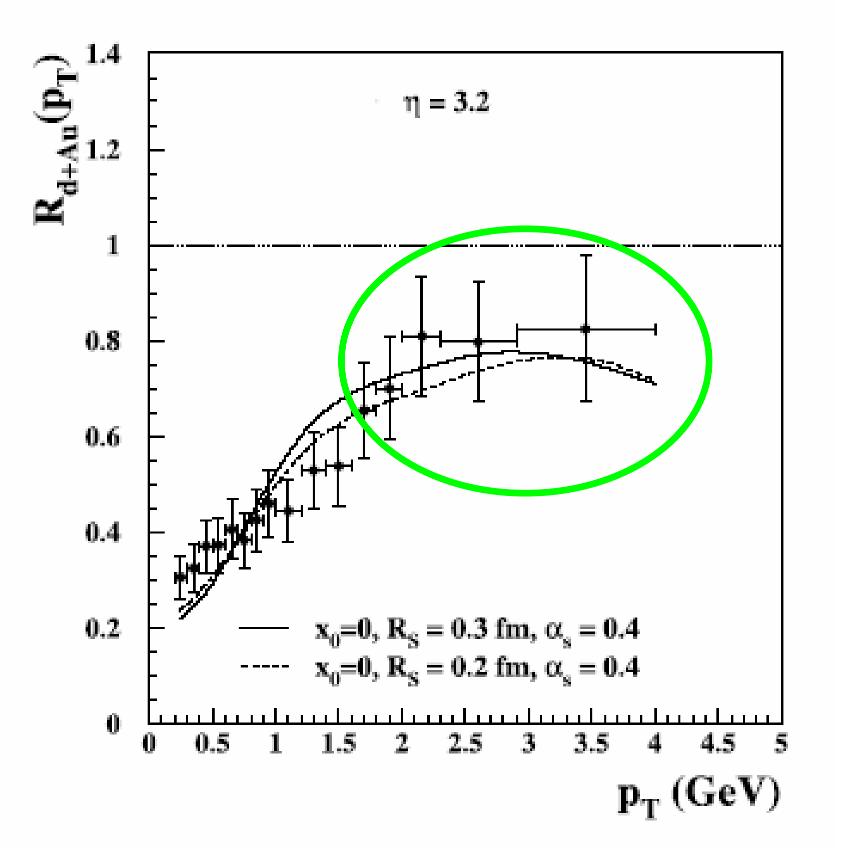
Implemented as "Sudakov Form Factors":

$$S(x_F) = (1 - x_F)^{dn_G/dy}$$

This is one way of implementing energy loss (large rapidity gap events, amplification near kinematic bounds)

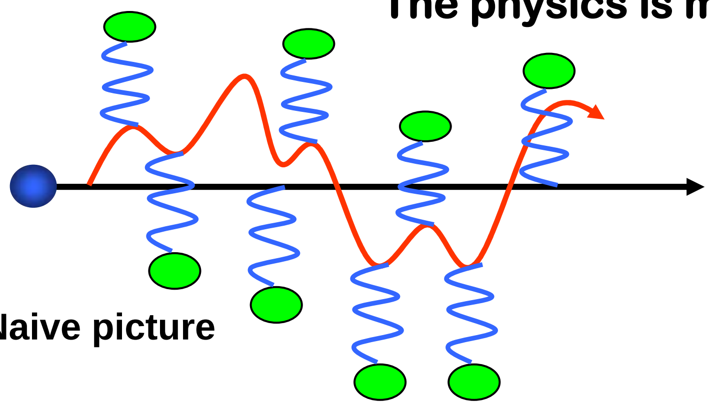
B. Kopeliovich *et al.*, hep-ph/0501260

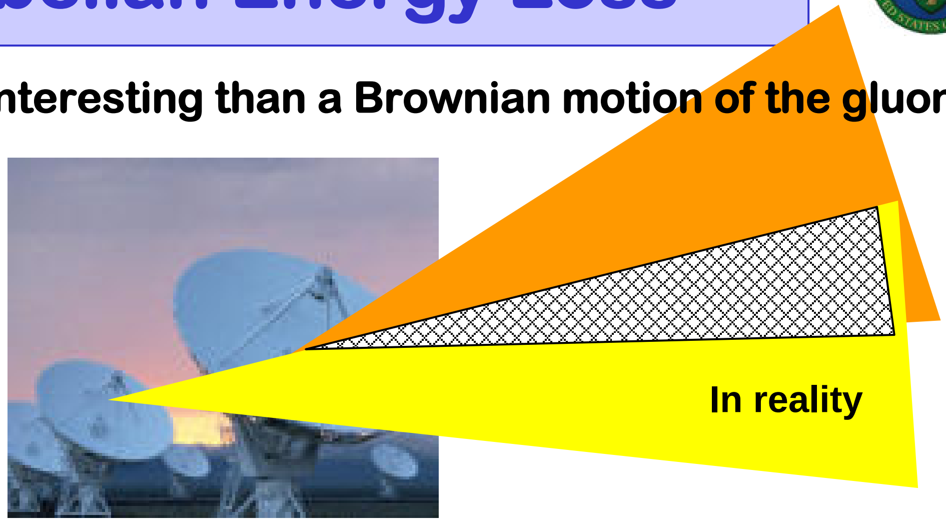
Where energy loss arguably plays a role



III. Non-Abelian Energy Loss

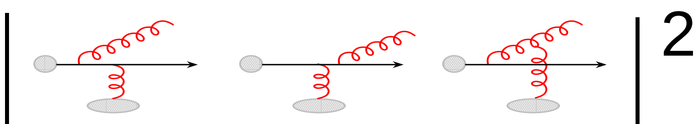
The physics is more interesting than a Brownian motion of the gluon





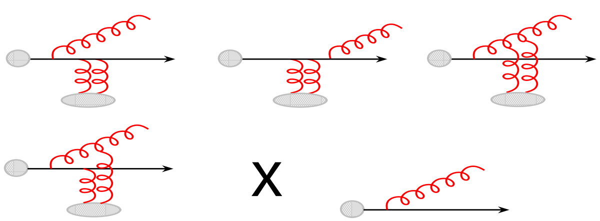
$$i(-i) = 1 \qquad i\,(i) = -1 = \cos(\pi)$$

$$\frac{dN^{g}{}_{med}}{d\omega d\sin\theta^* d\delta} \propto \left(\left| M_a \right|^2 + 2\,\mathrm{Re}\, M_b^{\,*} M_c \right) + \ldots$$



(a)

+2Re



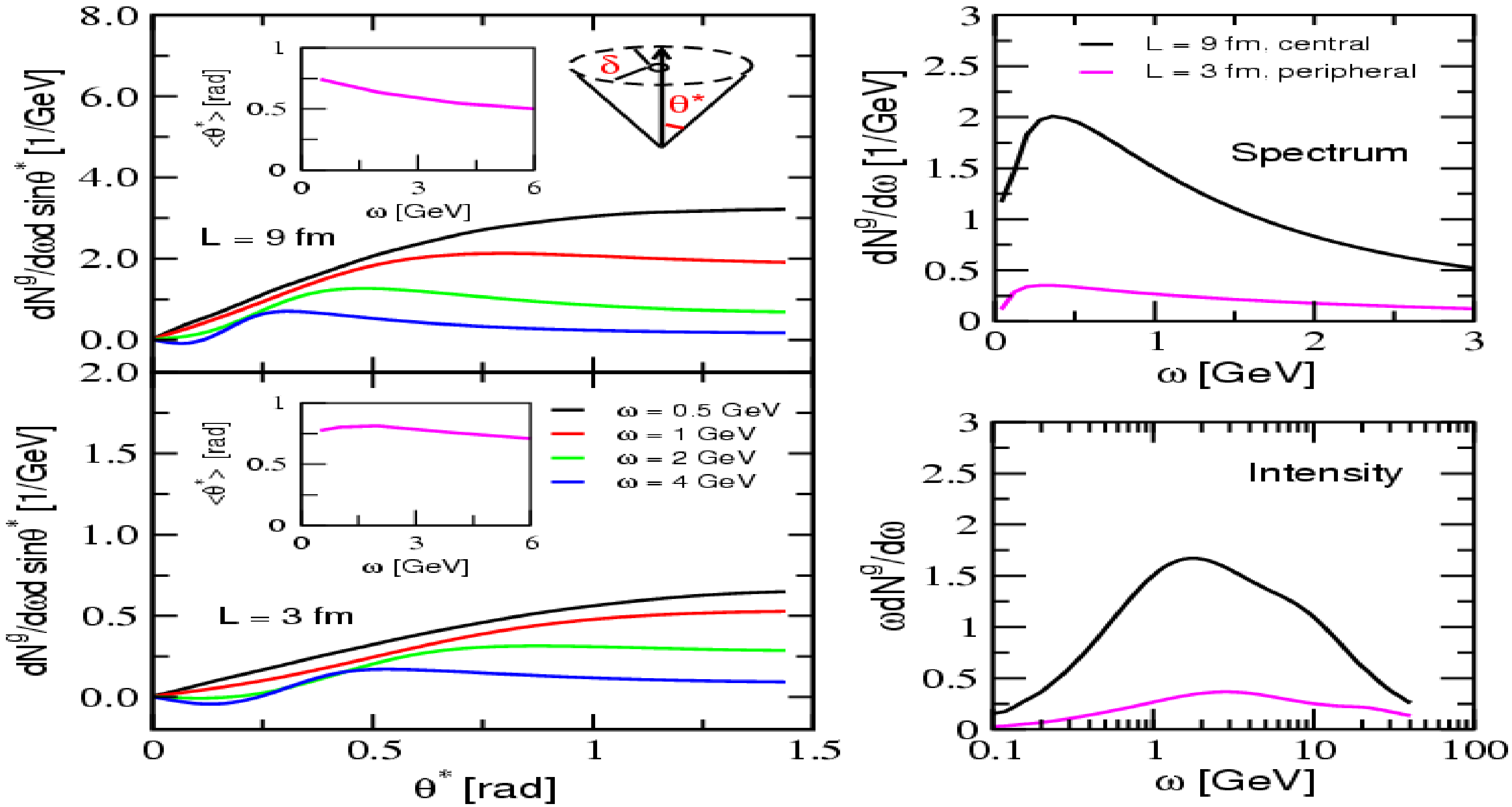
(b) (c)

Solution to first order in the mean # of scatterings

$$\frac{dN^{g}{}_{med}}{d\omega d\sin\theta^* d\delta} \approx \frac{2C_R\alpha_s}{\pi^2} \int_{z_0}^{L} \frac{d\Delta z}{\lambda_g(z)} \int_0^{\infty} dq_\perp q_\perp{}^2 \frac{1}{\sigma_{el}} \frac{d\sigma_{el}}{d^2 q_\perp}$$
$$\times \int_0^{2\pi} d\alpha \frac{\cos\alpha}{(\omega^2 \sin^2\theta^* - 2q_\perp \omega \sin\theta^* \cos\alpha + q_\perp^2)}$$
$$\times \left[1 - \cos\frac{(\omega^2 \sin^2\theta^* - 2q_\perp \omega \sin\theta^* \cos\alpha + q_\perp^2)\Delta z}{2\omega} \right]$$

I.V., hep-ph/0501255

Angular and Frequency Behavior



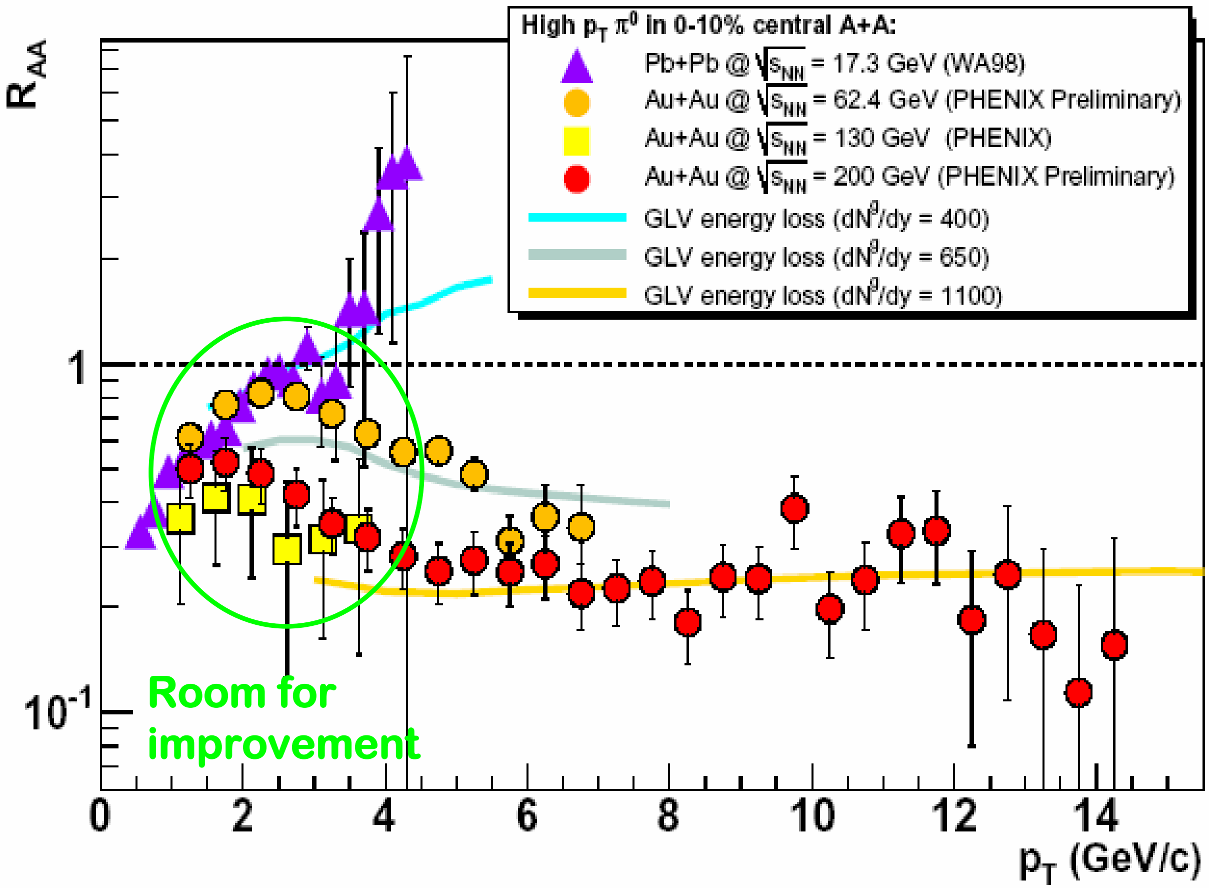
I.V., hep-ph/0501255

- Radiation is moderately large angle. Finite gluon number
- The small angle $\theta^* \to 0$ and small frequency $\omega \to 0$ behavior of the radiative spectrum is under perturbative control

Jet Tomography

Depletion of high-p_T hadron multiplicities in Au+Au relative to the binary collision scaled p+p result

$$R_{AA} = \frac{d\sigma^{AA}}{dyd^2p_T} / \frac{N^{bin}d\sigma^{pp}}{dyd^2p_T}$$



D.d'Enterria, nucl-ex/0504001 (EJP)

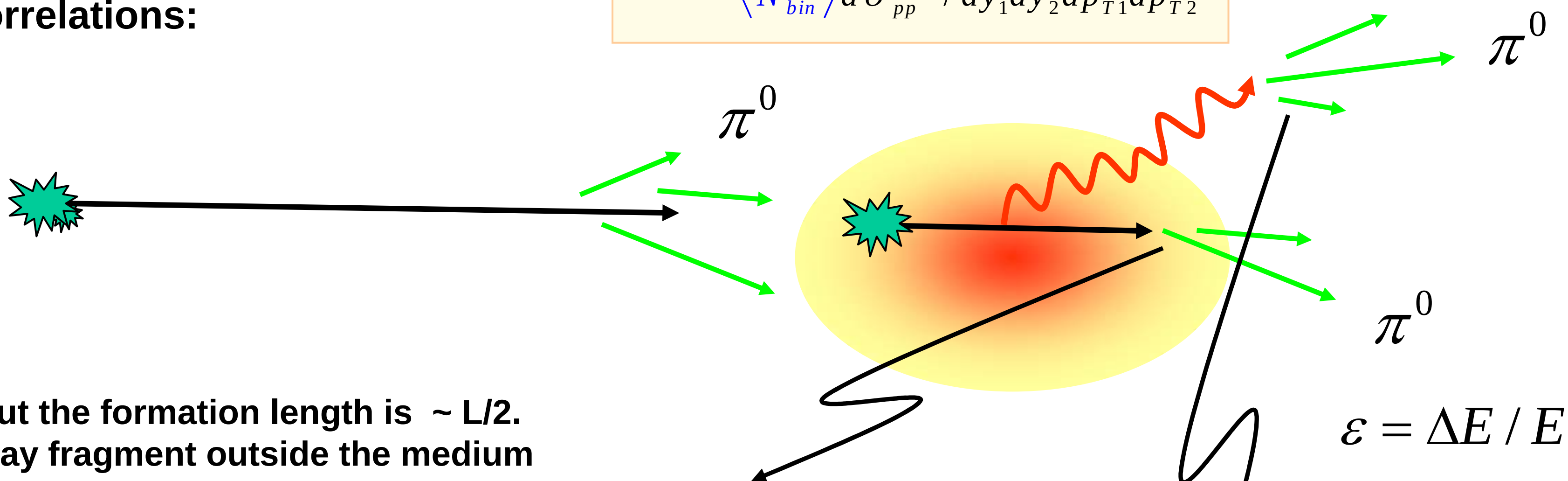
- **Predicted nuclear modification**
  Non-Abelian energy loss

  (GLV formalism)

Deriving the Fragmentation Contributions

Define a measure for nuclear modifications to di-hadron correlations:

$$R_{AA}^{(2)} = \frac{d\sigma_{AA}^{h_1h_2} / dy_1 dy_2 dp_{T1} dp_{T2}}{\langle N_{bin} \rangle d\sigma_{pp}^{h_1h_2} / dy_1 dy_2 dp_{T1} dp_{T2}}$$



But the formation length is ~ L/2.
May fragment outside the medium

$$D_{h_1/d}(z_2)\delta(\Delta\varphi - \pi) \rightarrow \frac{1}{1-\varepsilon} D_{h_1/d}\left(\frac{z_2}{1-\varepsilon}\right) f_{med}(\Delta\varphi)$$

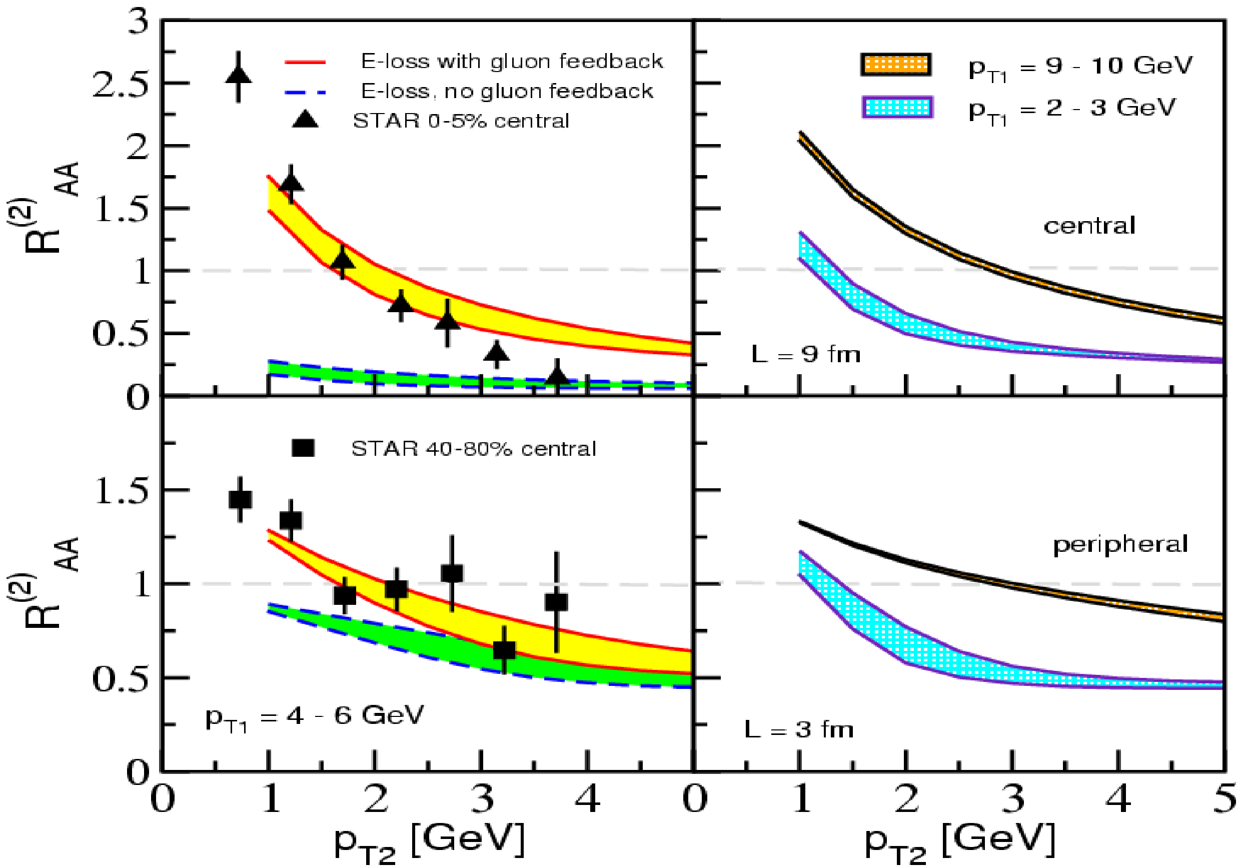
Quenched parent parton

Feedback gluons
(not DGLAP)

$$+ \frac{p_{T_1}}{z_1} \int_0^1 \frac{dz_g}{z_g} D_{h_1/g}(z_g) \int_{-\pi/2}^{\pi/2} d\phi \, \frac{dN^g(\phi)}{d\omega d\phi} f_{vac}(\Delta\varphi - \phi)$$

- Use energy conservation to verify the fragmentation sum rule

Numerical Results



I.V., hep-ph/0501255

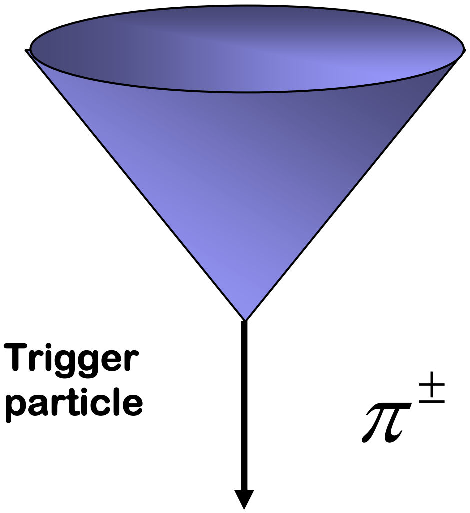
Data is from:

J.Adams *et al.*, nucl-ex/0501016

Very interesting as a function of trigger

- **The redistribution of the energy is a parameter free prediction**
- **For large energy loss - the radiative gluons dominate to unexpectedly high** $p_{T2} \sim 10\ GeV$
- **The amount of energy depends on the trigger p_T**

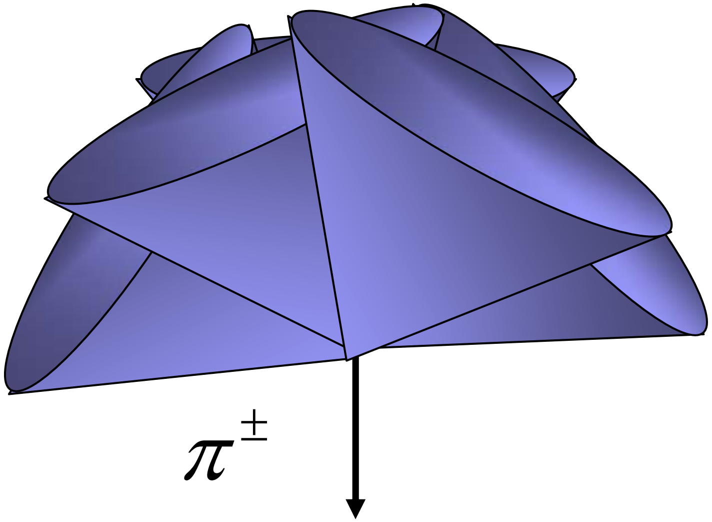
Superposition of Jet Cones

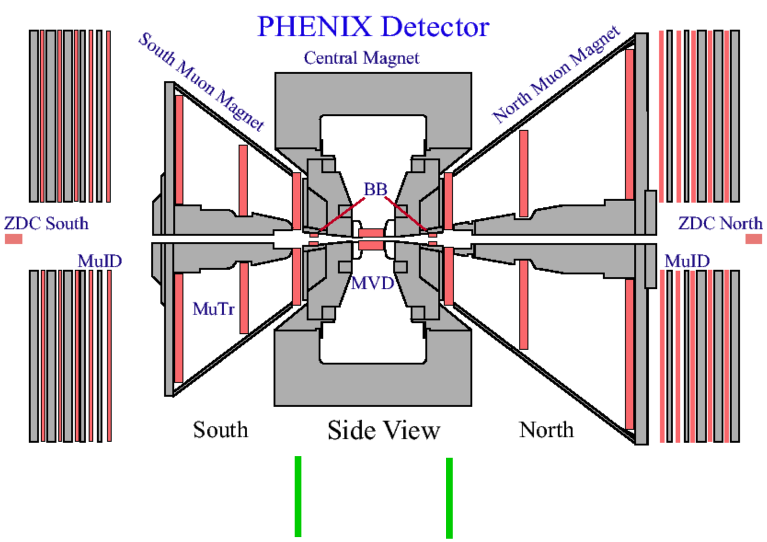


Trigger particle

$\pi^{\pm}$

<u>Some</u> mechanism of jet cone production





$\Delta\eta = \pm 0.35$

Experiments measure in the plane ϕ
(to make the life of theorists difficult)

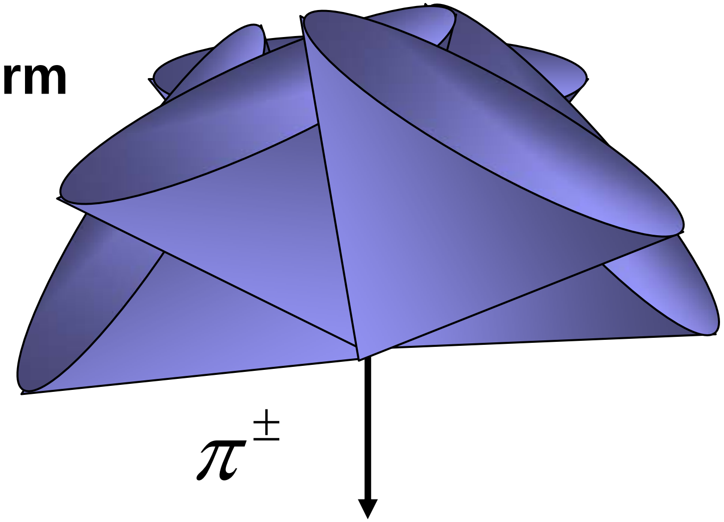
- Surprisingly flat dijets in a wide rapidity range $\Delta y \simeq 2-3$
- One has to filter through the di-jet rapidity distribution

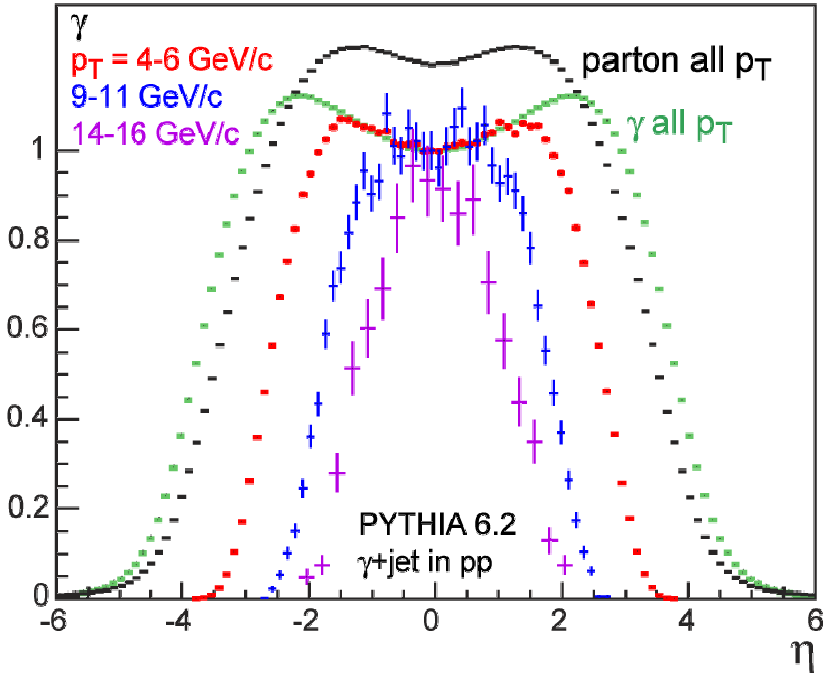
Independent Verification

- The distribution of away-side jets comes form

$$\frac{d\sigma_{NN}^{h_1}}{dy_1 d^2 p_{T1}} = \sum_{abcd} \int_{x_a \min}^{1} dx_a \int_{x_b \min}^{1} dx_b \cdots$$

- It is there in p+p
- Has nothing to do with random walk





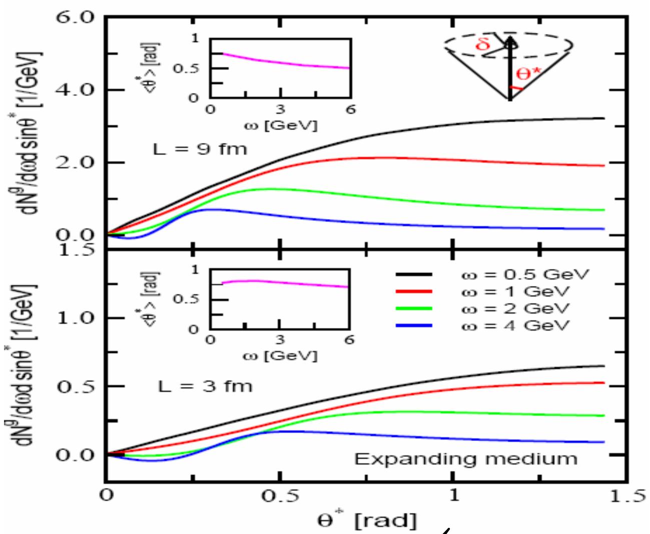
How broad is broad?

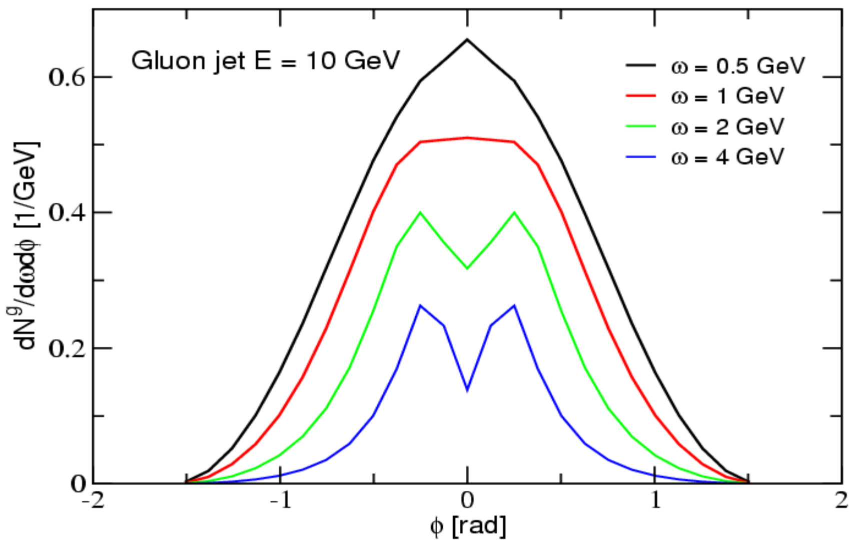
- Practically flat at all angles except very close to the beam pipes

R.Bellwied, RHIC II presentation, April 2005

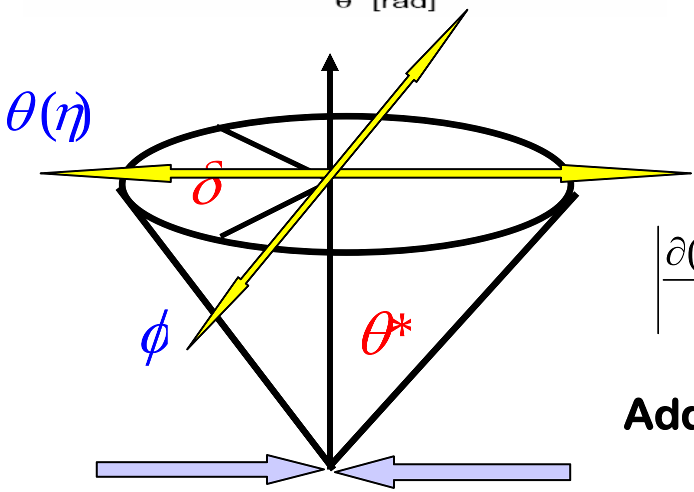
Projected Medium-Induced Radiation

From this **to that** **Approximation**





The double hump structure is partly gone



$$y \approx \eta = -\ln tg(\theta/2)$$

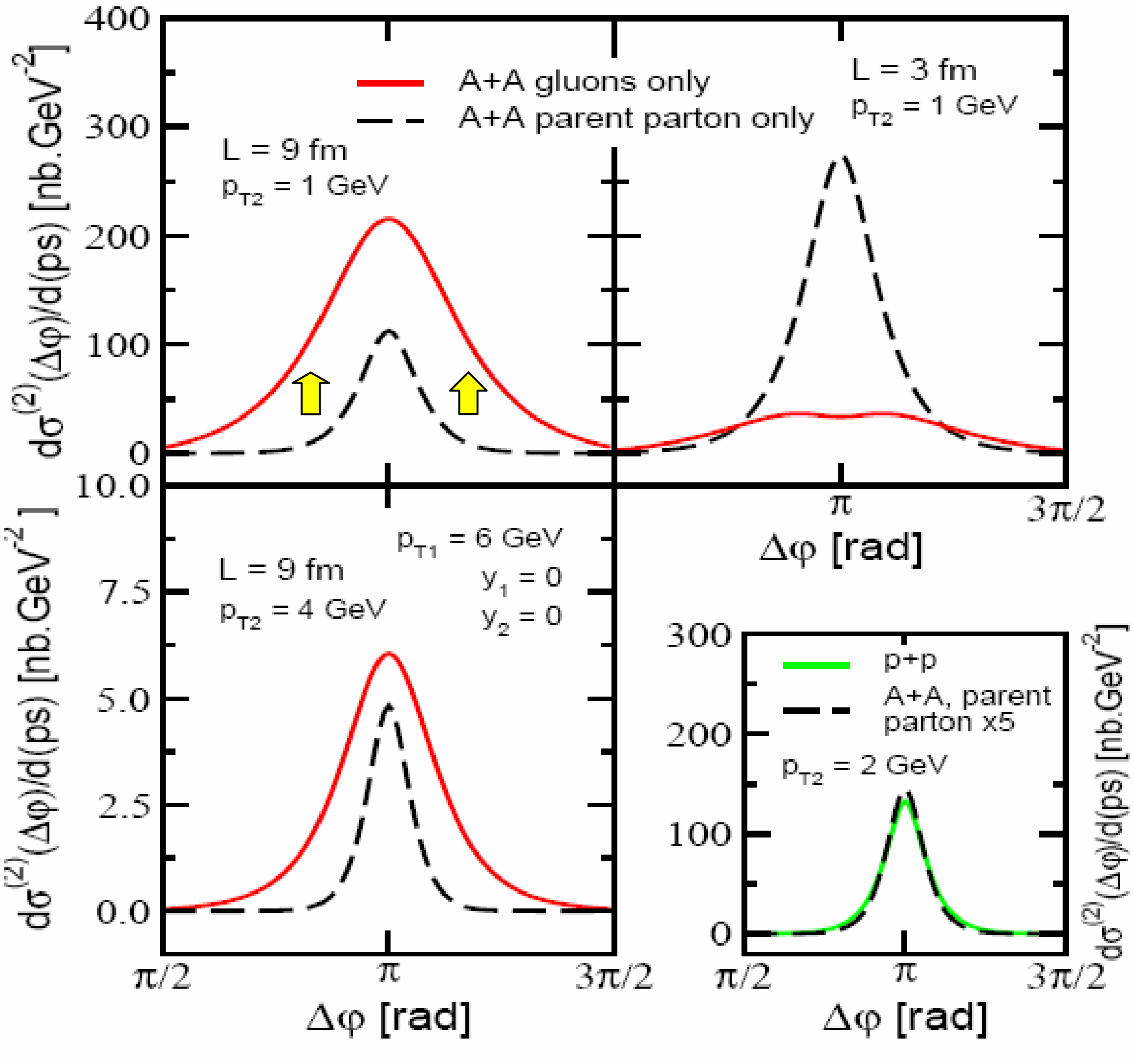
$$\left|\frac{\partial(\sin\theta^*,\delta)}{\partial(\theta,\phi)}\right| = \frac{1}{\sin^2\theta\cos^2\phi}\,\frac{(ctg^2\theta + tg^2\phi)^{-1/2}}{(1+ctg^2\theta+tg^2\phi)^{3/2}}$$

$$tg^2\theta^* = ctg^2\theta + tg^2\phi$$

$$tg\delta = -\frac{ctg\theta}{tg\phi}$$

Additionally: acoplanarity and incomplete jet energy loss

Angular Di-Hadron Distribution



I.V., hep-ph/0501255

$$\sigma_{Far}(AA) > \sigma_{Far}(pp)$$

- The width $|\Delta\varphi - \pi|$ of the large-angle correlations is dominated by medium induced gluon radiation

- Reassessment of the origin of small and moderate p_T away triggered hadrons

The quenched parton is not wider

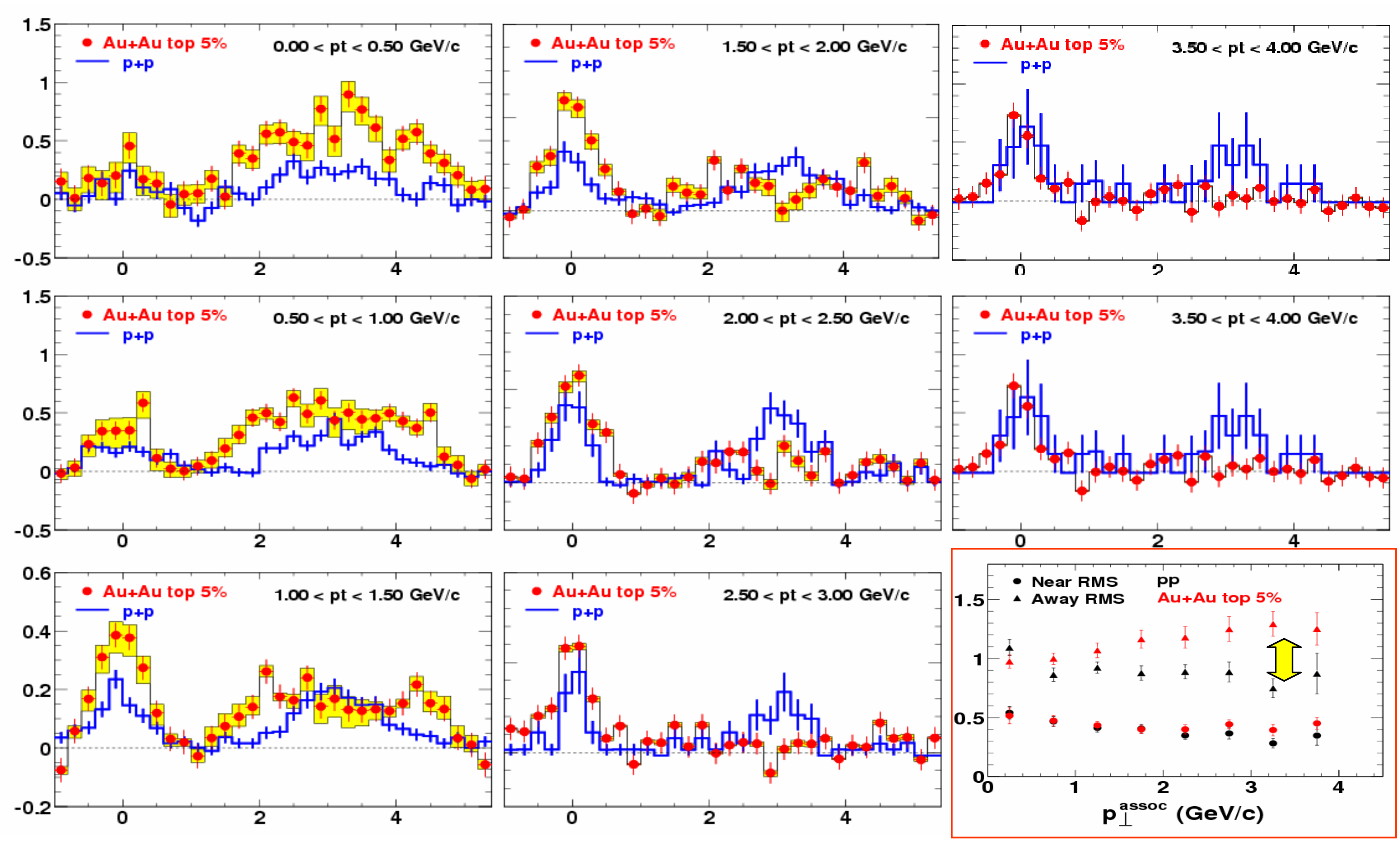
Because:

$$\sigma_{Far} \approx \frac{\sqrt{\langle k_T^2 \rangle_{vac}}}{p_{Tc}} \rightarrow \frac{\sqrt{\langle k_T^2 \rangle_{tot}}}{[p_{Tc}/(1-\varepsilon)]}$$

Results in Au+Au: STAR

STAR preliminary:

Talk by F.Wang, March 2005

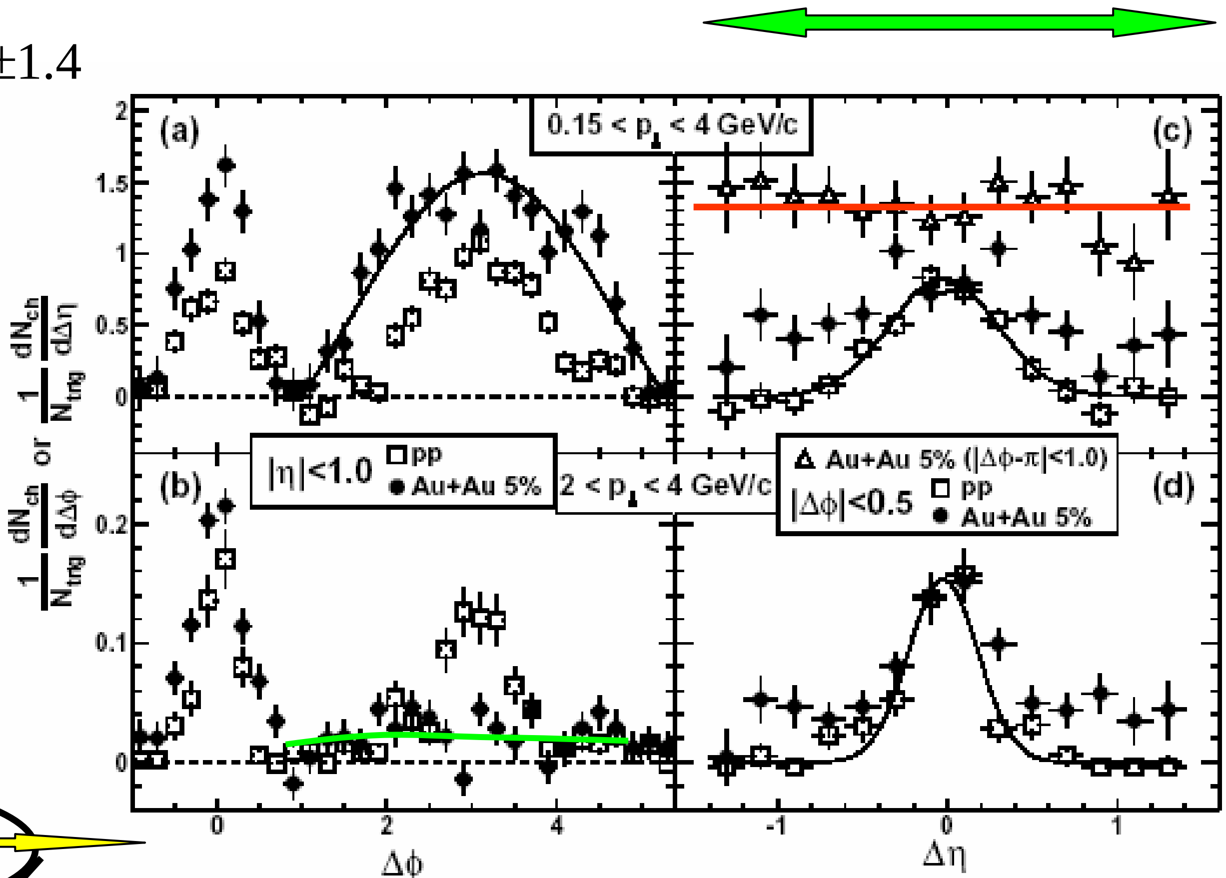


The Rapidity Story is Known

Rapidity coverage $\eta = \pm 1.4$

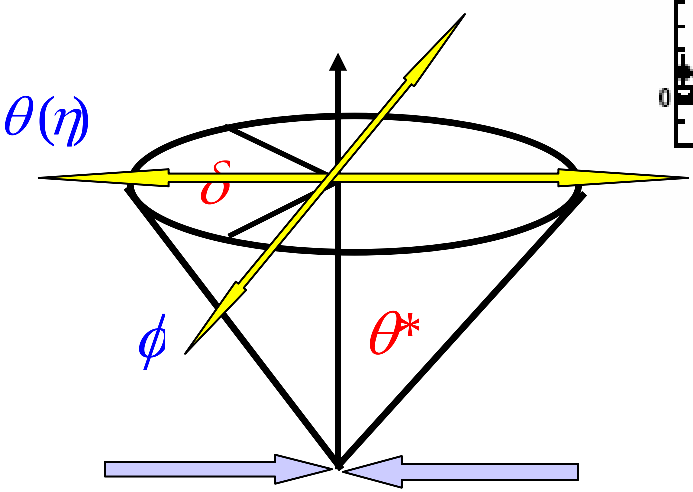
$$y \approx \eta = -\ln tg(\theta / 2)$$

$$\theta \in (28^{\circ}, 152^{\circ})$$



J.Adams *et al.*, nucl-ex/0501016, submitted to Phys.Rev.Lett.

No (curious) structure in rapidity or azimuth



• Slicing in ϕ and slicing in $\theta(\eta)$ is the same

Conclusions

- Charm triggered correlations are new - p_T dependent hadron composition (light hadrons and charm mesons). It will be interesting to test experimentally.
- Dynamical power corrections lead to shadowing and suppression of yields and correlations. Has very well defined p_T dependence. Additional effects are related to energy loss. Low energy.
- Medium induced radiation converts the high p_T suppression enhancement produces large angle correlations. However there are a number of effects that tend to dilute these signatures.
- If one looks for topological structures one has to do event by event analysis in more detail