The Medium Modification of Two Hadron Correlations

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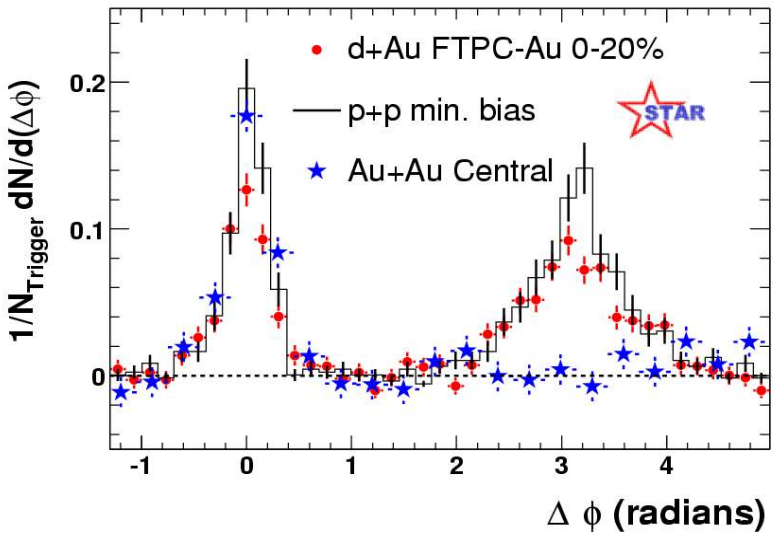
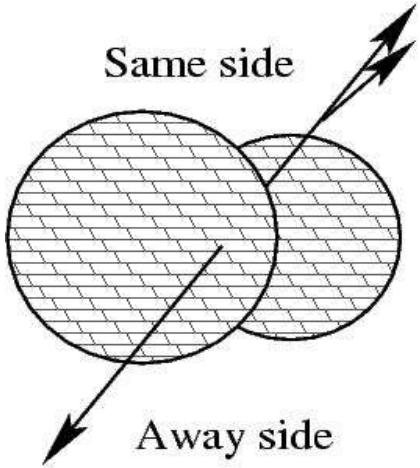
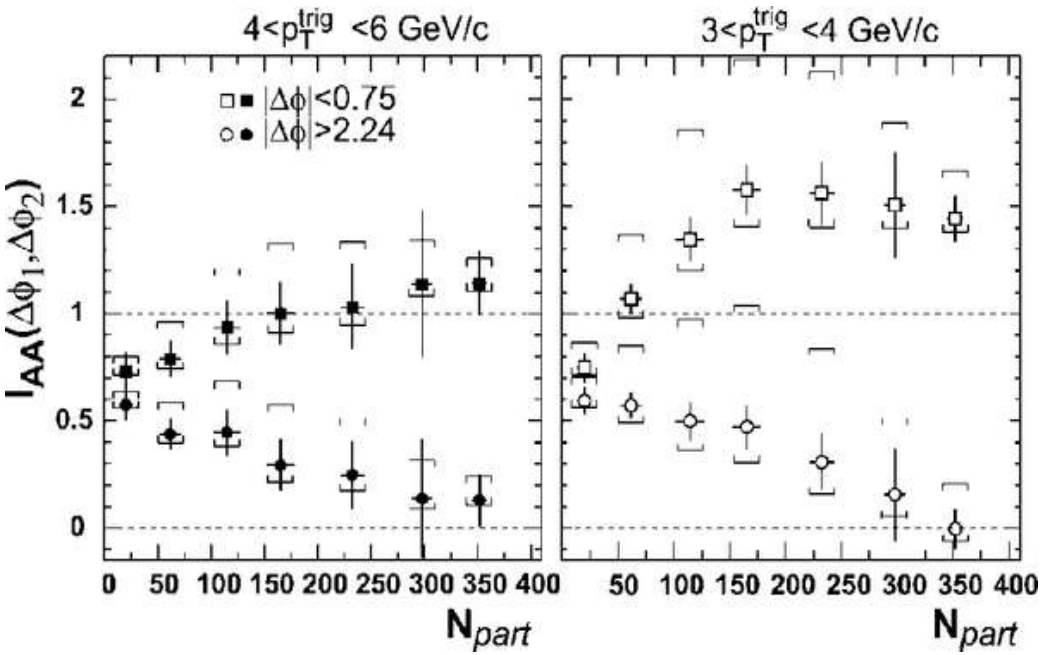
RIKEN BNL Research Center Workshop - Jet Correlations at RHIC

Dihadron measurements in heavy-ion coll.



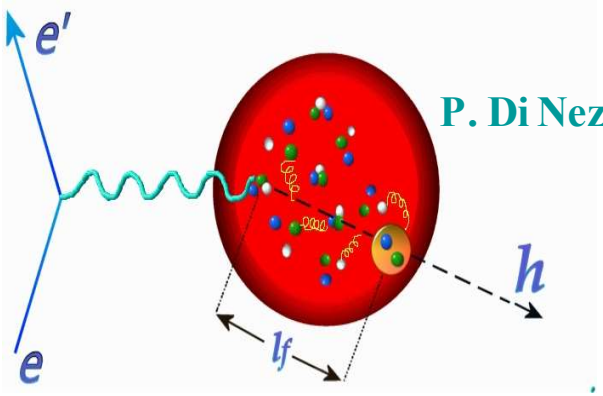


- *d+Au central very similar to p+p*
- *Away side, central Au+Au suppressed*
- *Near side, central Au+Au unchanged*

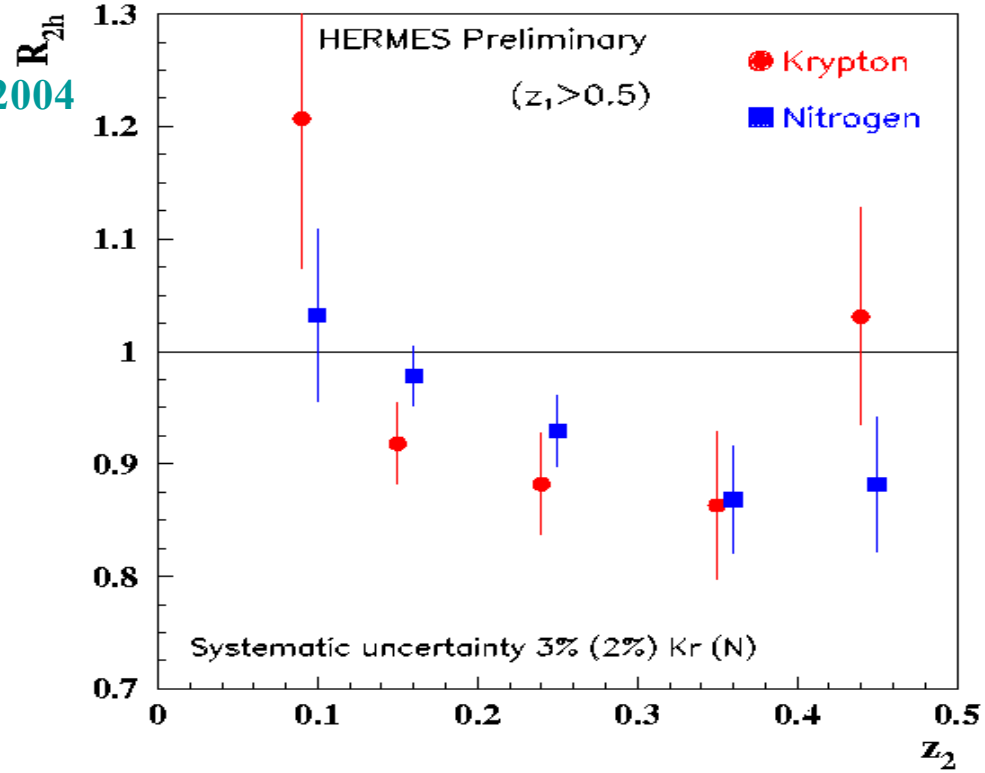


Some variation with centrality and flavour of trigger

RESULTS FROM HERMES, DIS on cold nuclei



P. Di Nezza @ QM2004



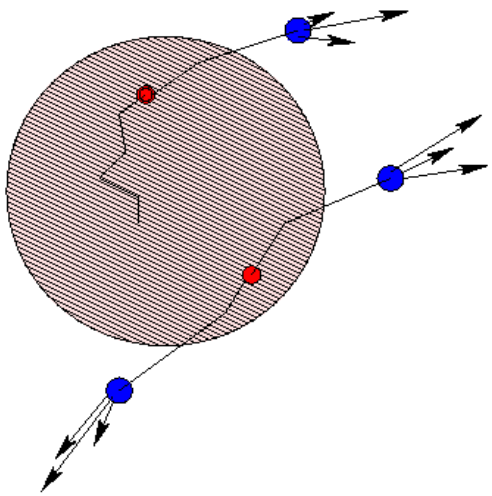
- ***Always measure a ratio of double to single production***
- ***Divide by same ratio in deuterium to remove detector systematics***

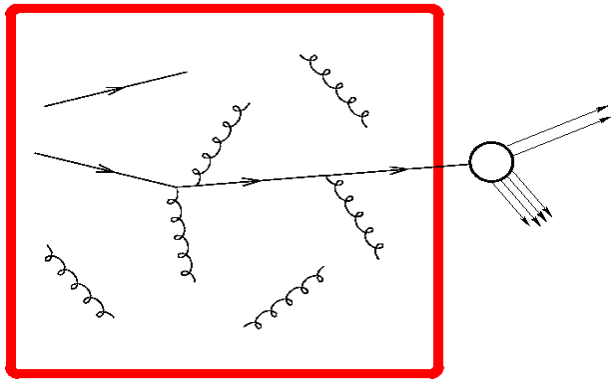
$$R_{2h} = \frac{\text{No. of events with at least 2 hadrons with } z_1 > 0.5}{\text{No. of events with at least one hadron with } z > 0.5}$$

$$\text{same ratio on deuterium}$$

THE PICTURE OF PARTON ENERGY LOSS :

- ***High energy partons are created over the entire collision zone***





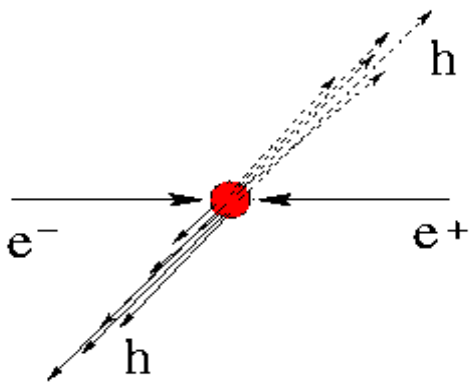
- ***Lose energy by partonic interaction, medium may be hadronic or partonic***
- ***Emerge as partons and then fragment***
- ***Require knowledge of single and double fragmentation functions***

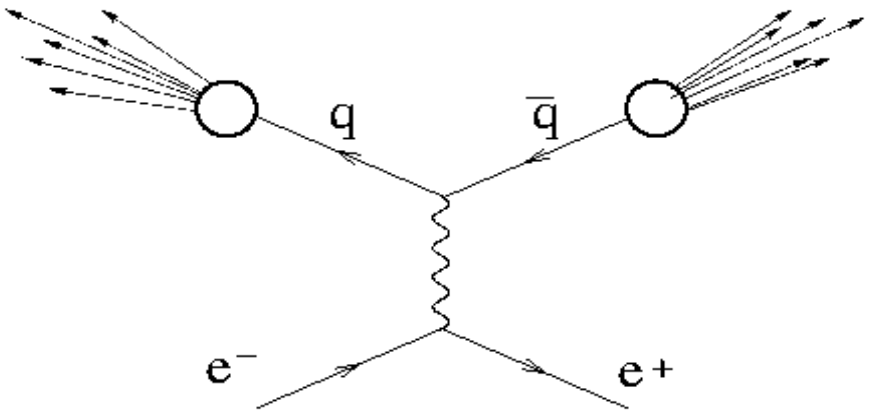
$$D^{h}_{q,g}(z)$$

$$D^{h_1 h_2}_{q,g}(z_1, z_2)$$

Defining the Dihadron fragmentation function!

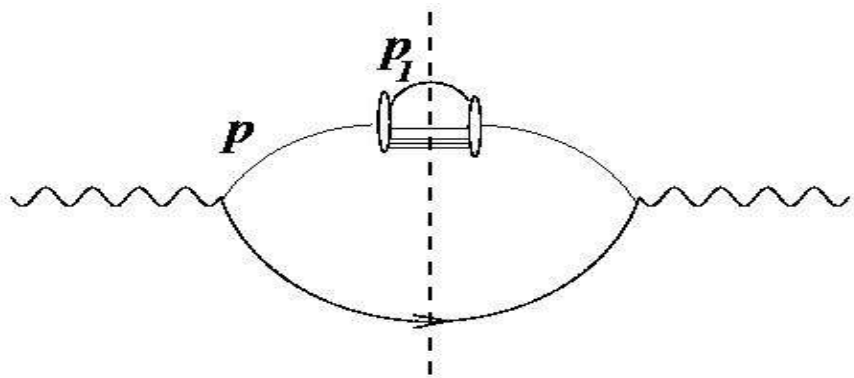
- *Vacuum fragmentation functions must be universal*
- *We need a definition in terms of operators*
- *Start with simple system :* $e^+ e^-$*, show factorization*
- *Derive evolution (vacuum splitting functions)*
- *Measure at* μ *and predict its evolution to scale Q*

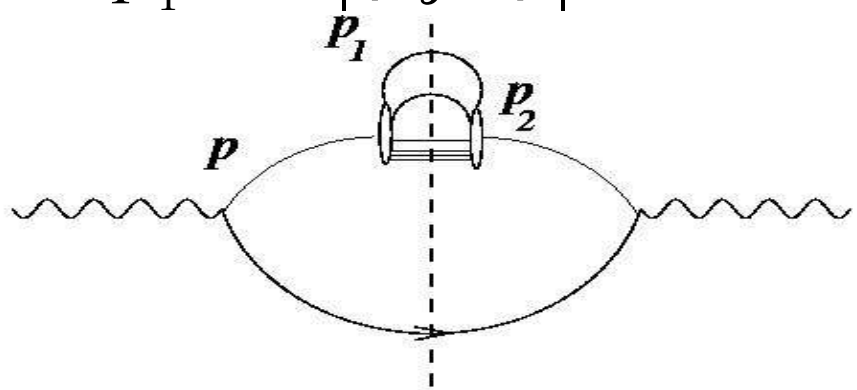




$$W^{\mu\nu} = \sum_{S-1} e_q^2 \int \frac{d^3 p_1 d^3 k}{4 E_1 E_k (2\pi)6} (2\pi)^4 \delta(q - p_1 - k - \sum_{s-1} p_f)$$

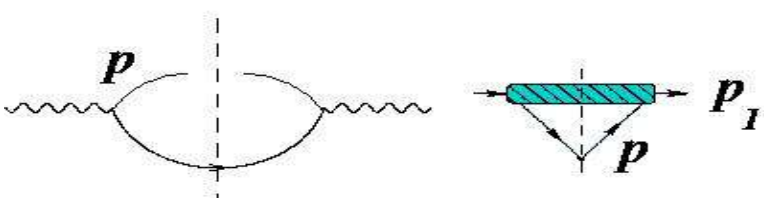
$$<0|\bar{\psi}\gamma^\mu \psi| k\, p_1 S-1> <k\, p_1 S-1|\bar{\psi}\gamma^\nu \psi|0>$$

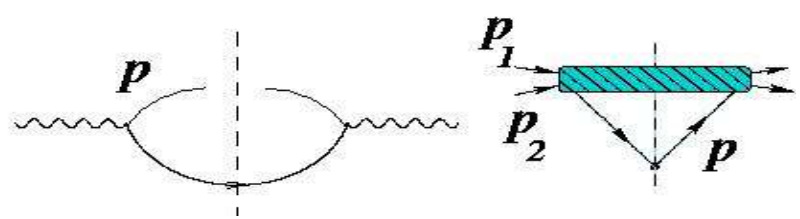




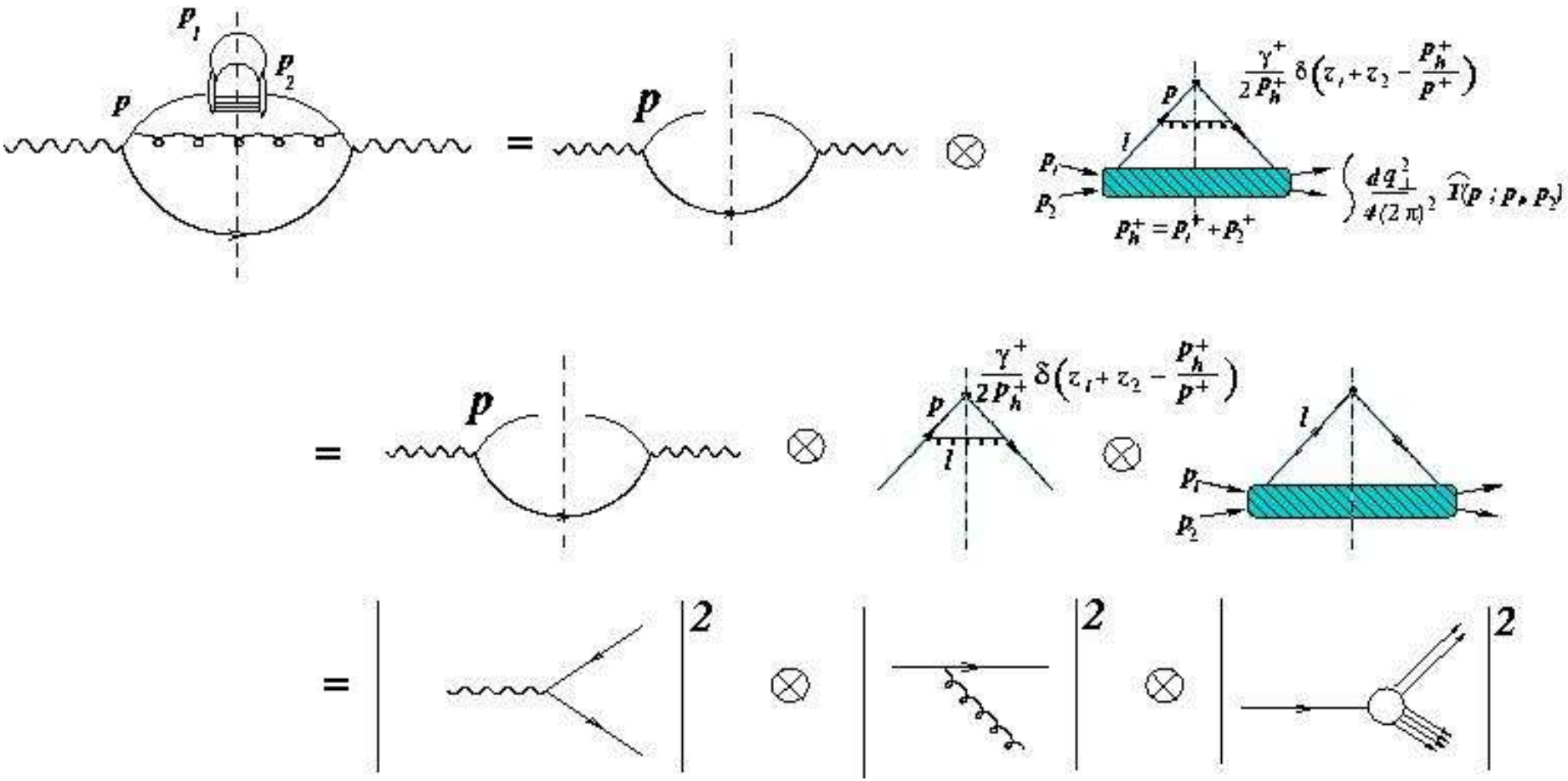
Collinear approximation: $p_h^+, p^+, p_1^+, p_2^+ >> p_h^-, p^-, p_1^-, p_2^-, p_\perp$

Can factorize matrix elements from hard part: $Tr[\gamma^\alpha p_\alpha \gamma^\mu \gamma^\beta k_\beta \gamma^\nu] Tr[\frac{\gamma^+}{2p^+}\hat{T}]$



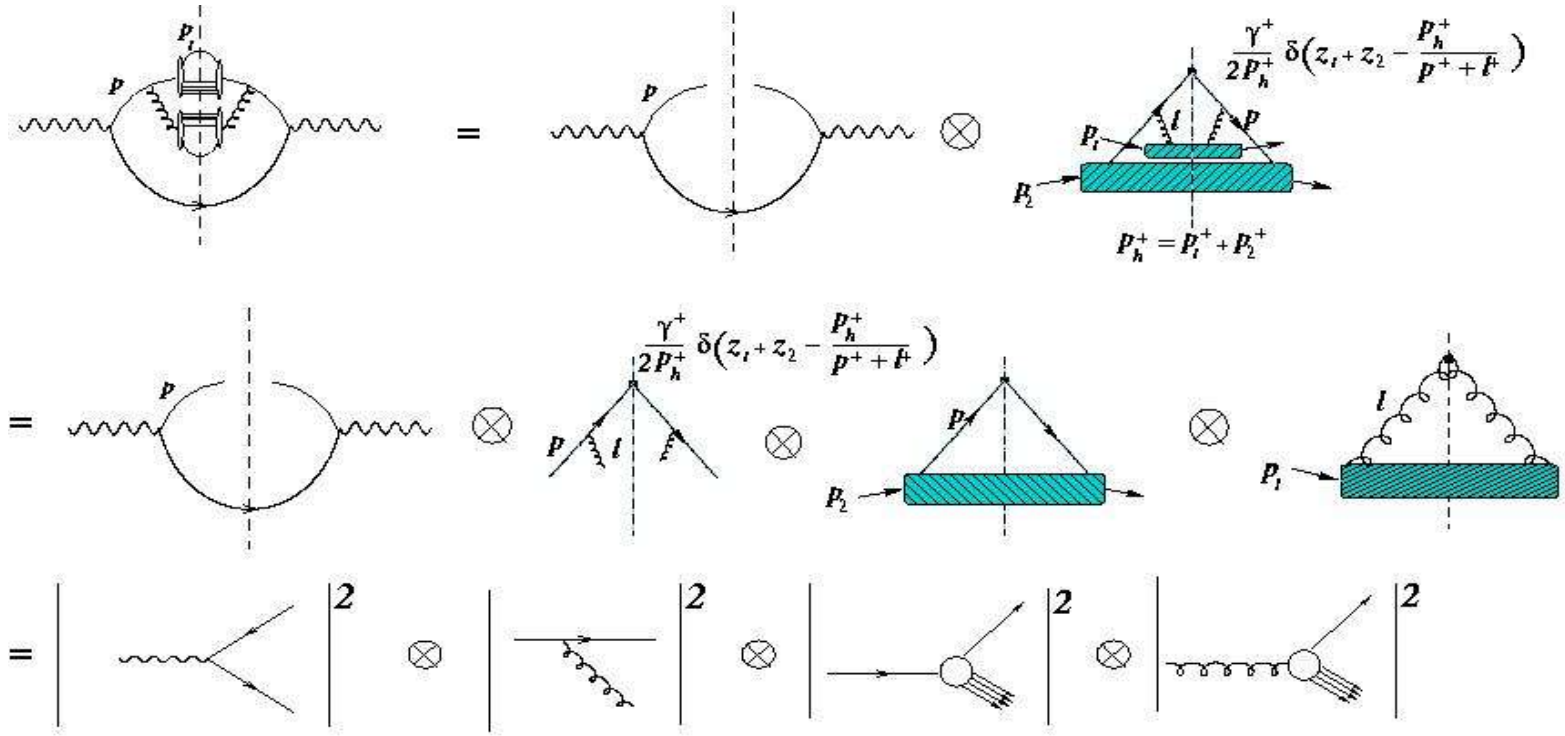


NLO contribution from quark dihadron fragmentation function



$$=\sigma_0 \otimes P_{q\to qg}(y) \otimes D_q\left(\frac{z_1}{y},\frac{z_2}{y}\right)$$

NLO contribution from independent quark and gluon fragmentation



$$= \sigma_0 \otimes \hat{P}_{q\to qg}(y) \otimes D_q\left(\frac{z_1}{y}\right) \otimes D_g\left(\frac{z_2}{1-y}\right)$$

The hat indicates there is no virtual correction.

Also no infra-red divergence as hadrons from both partons detected

However, perturbative corrections under control only if $\mu_\perp^2 \gg \lambda_{QCD}^2$

Konishi, Ukawa and Veneziano, NPB157, 45 (1979).

Dihadron fragmentation in e^+e^- Collisions

The basic process may be factorized as:

$$\frac{d^2\sigma}{dz_1 dz_2} = \sigma_0 [D_q(z_1, z_2, \mu) + D_{\bar{q}}(z_1, z_2, \mu)]$$

$$\sigma_0 = Hard\ Cross\ section$$

$$D_q(z_1, z_2, \mu) = Dihadron\ fragmentation\ function$$

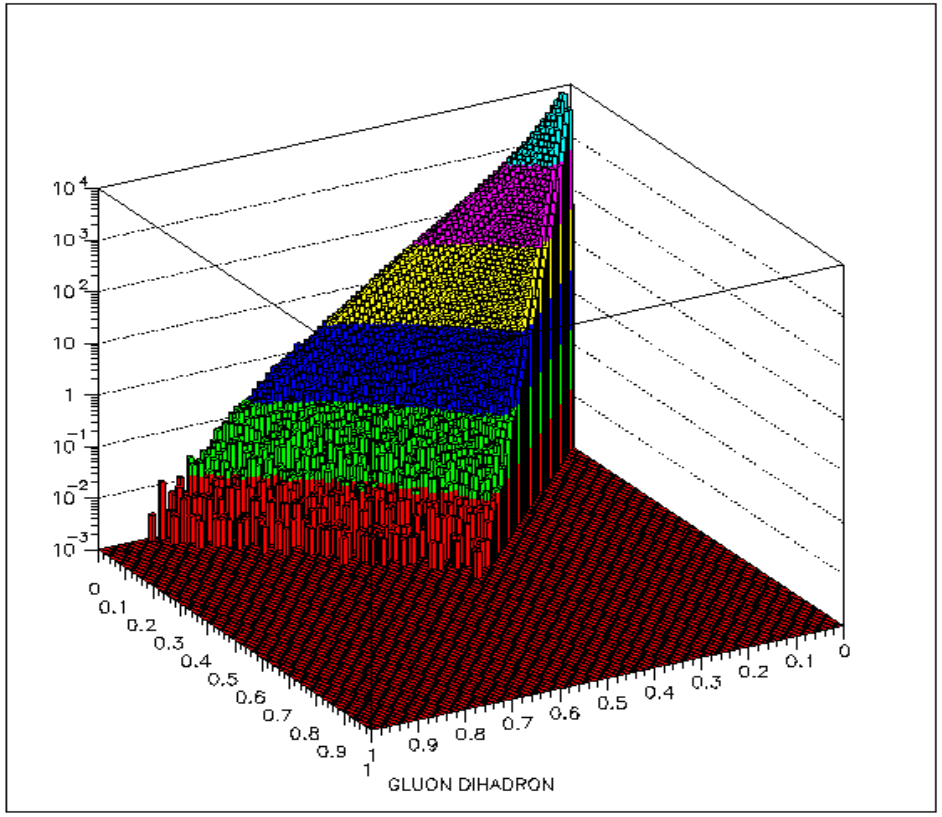
Can be factorized from hard process if $\lambda_{QCD}^2 \ll \mu^2 \ll Q^2$

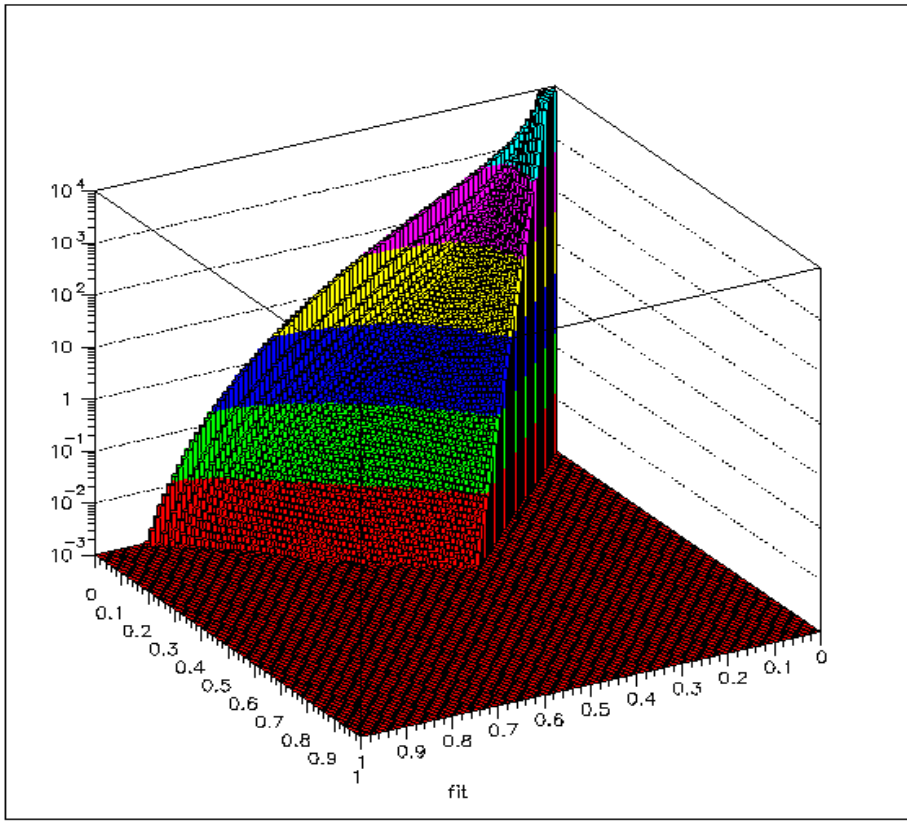
Measure the function at the scale μ, can be done in 2 ways

$$Event\ generator\ distribution: D(z_1, z_2, \mu) = \frac{1}{N_{events}} \frac{dN}{dz_1 dz_2}$$

Results from JETSET:

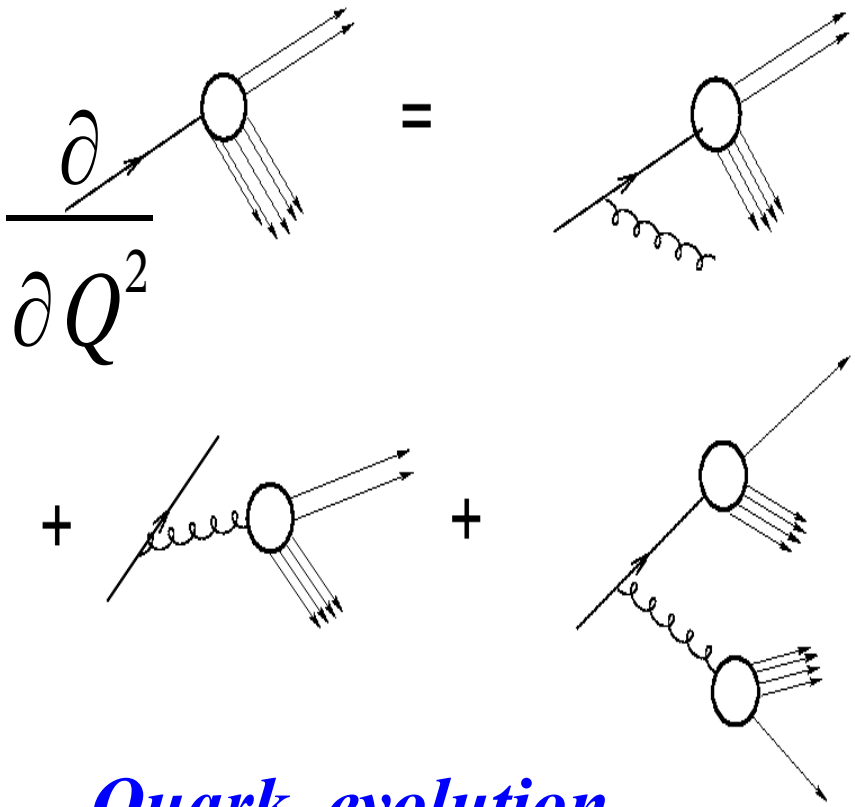
a bit ragged (Monte Carlo), fit a function to it !



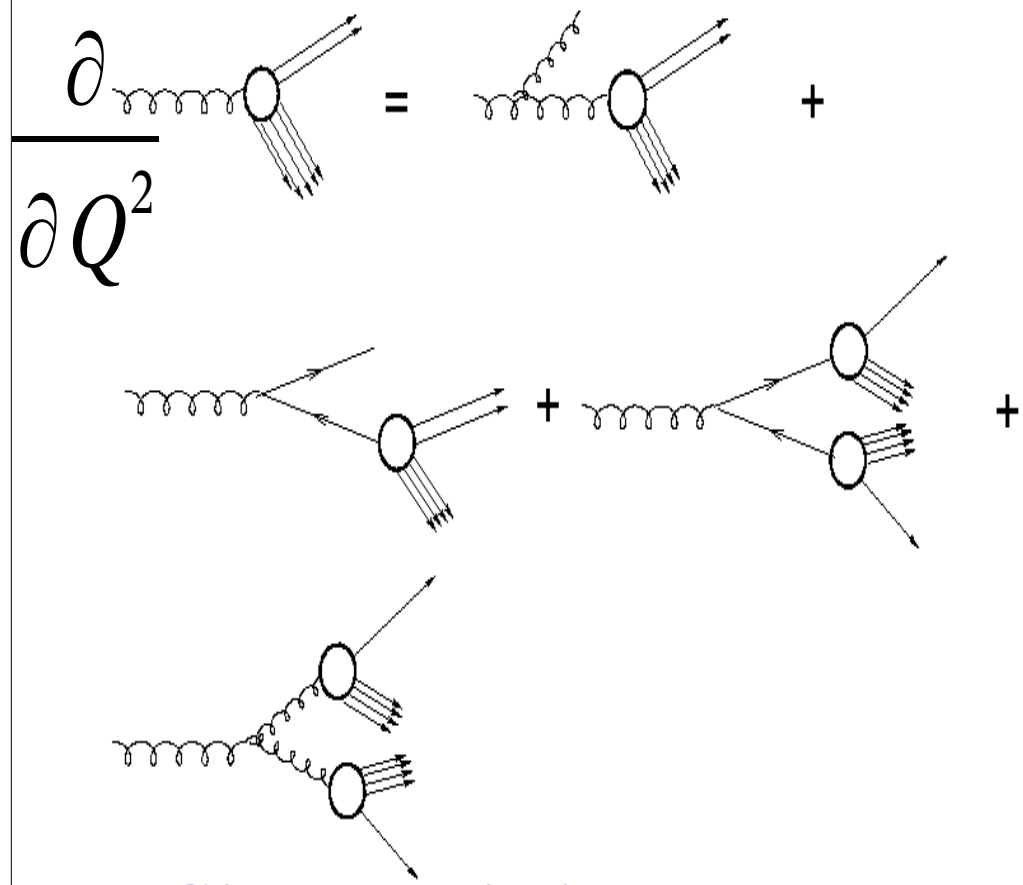


$$D(z_1, z_2) = N z_1^{\alpha_1} z_2^{\alpha_2} (z_1 + z_2)^{\alpha_3} (1 - z_1)^{\beta_1} (1 - z_2)^{\beta_2} (1 - z_1 - z_2)^{\beta_3}$$

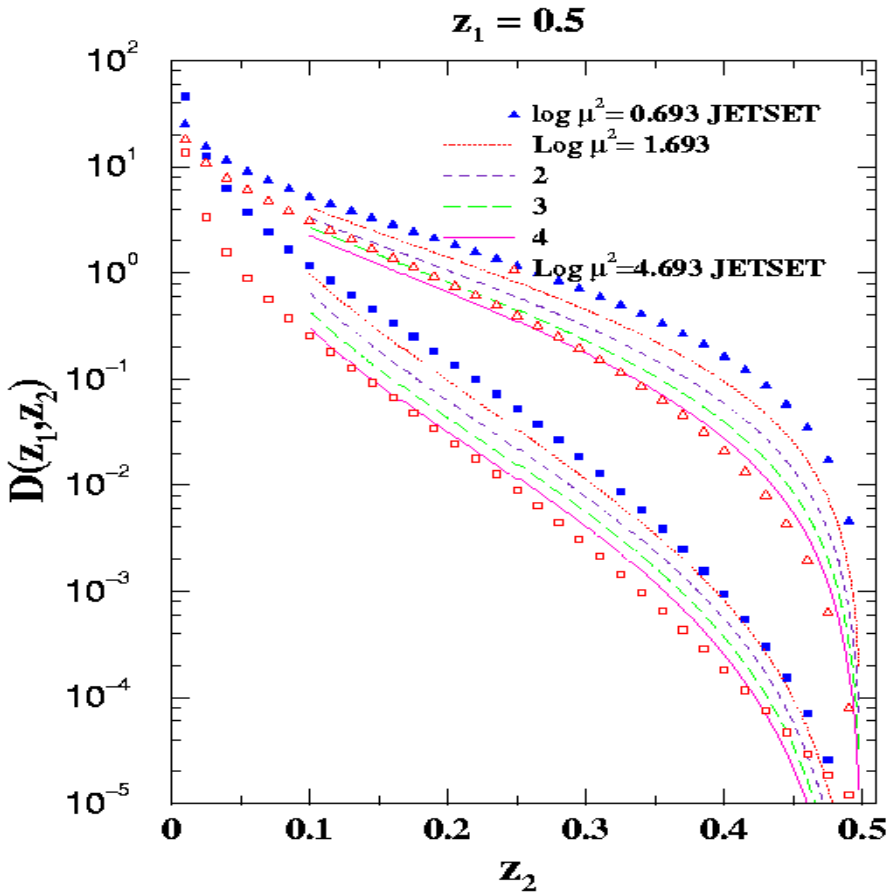
- *Evolving to a higher scale Q ☞ solving DGLAP equations*
- *Set of coupled differential equations containing the following processes: for quarks and gluons..*

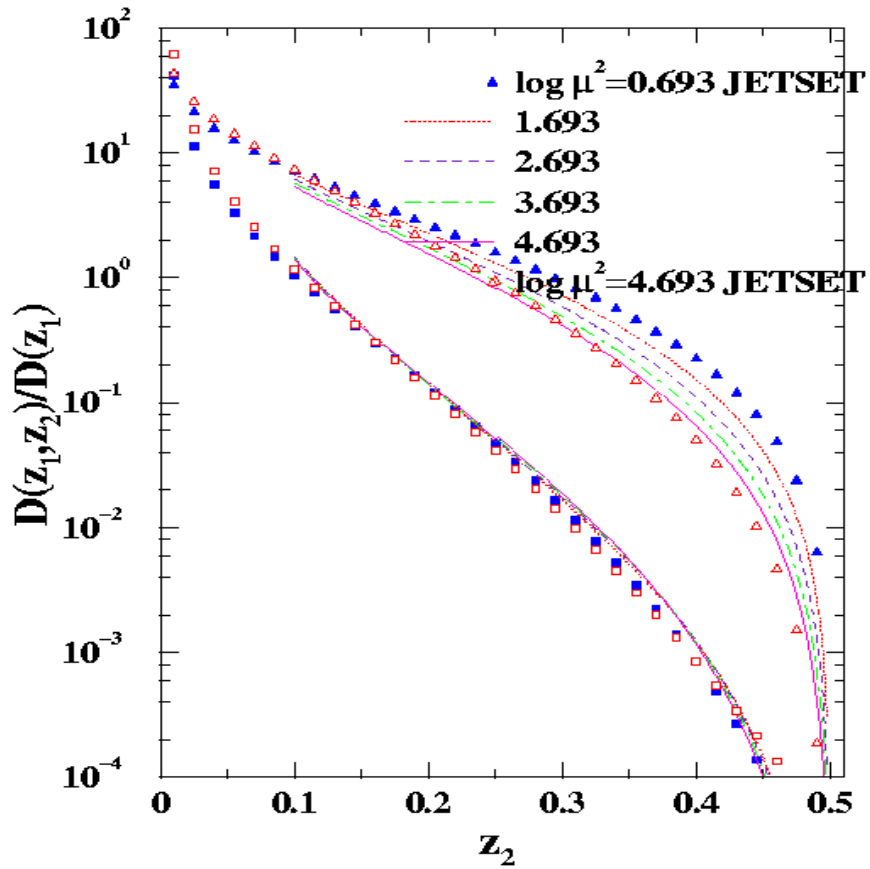


Quark evolution



Gluon evolution





Quark and Gluon evolution fits event generator data very well!

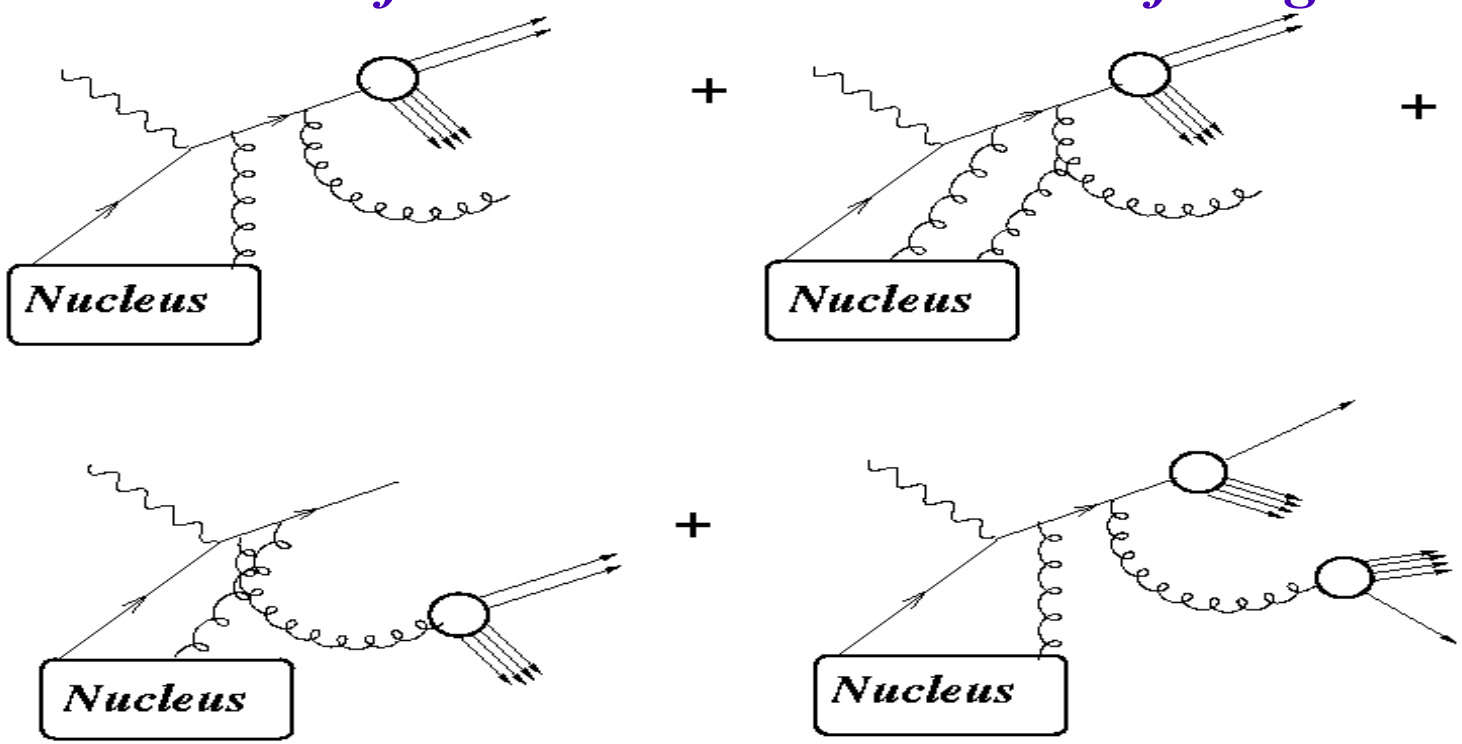
Thus we can understand evolution of DFF from QCD.

Note: the double to single ratio shows little change

Medium modification

- *Apply to DIS of Nuclei (HERMES expt. at DESY)*
- *A parton in a nucleon is struck by EM probe*
- *Parton scatters in medium and then exits & fragments*
- *Fragmentation function is medium modified.*

The medium modification also has new set of diagrams!

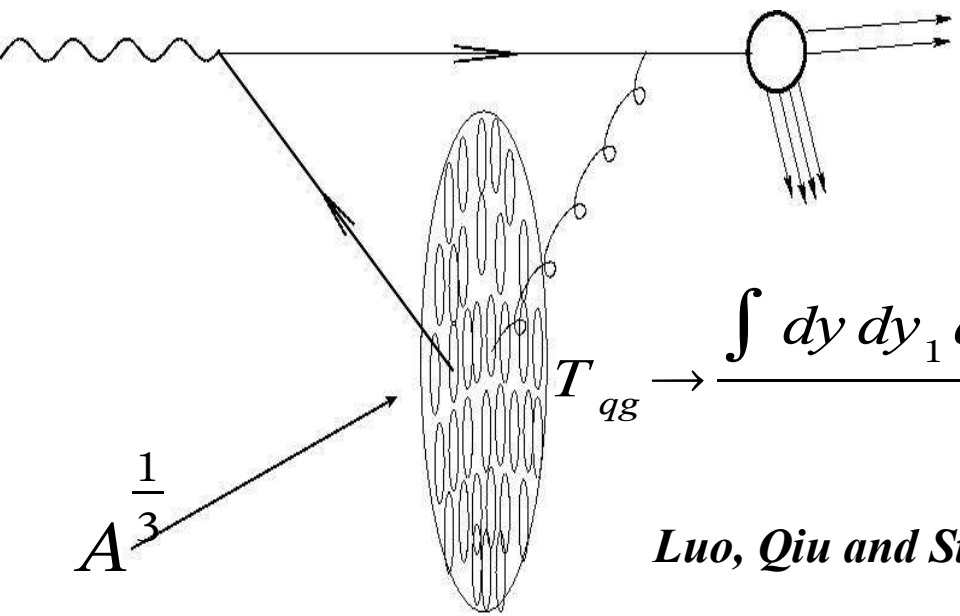


DIS followed by di hadron fragmentation from a large nuclei may be generally expressed as

$$\frac{d^2 W^{\mu\nu}}{dz_1 dz_2} = \int dx\, f_q^A(x)\, H^{\mu\nu}\, \tilde{D}^{h_1 h_2}(z_1, z_2)$$

$$\tilde{D} = medium\ modified\ fragmentation\ function$$

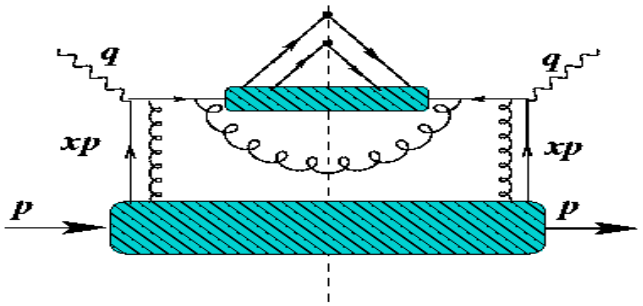
$$\tilde{D}(z_1, z_2, \mu^2) = D(z_1, z_2, \mu^2) + \frac{\alpha_s}{2\pi}\int_0^{\mu^2} \frac{dl_\perp^2}{l_\perp^2}\int \frac{dy}{y^2}\left(\frac{1+y^2}{1-y} T_{qg}(x, y, Q^2, l_\perp) + V.C.\right) D(z_1/y, z_2/y, \mu^2)$$

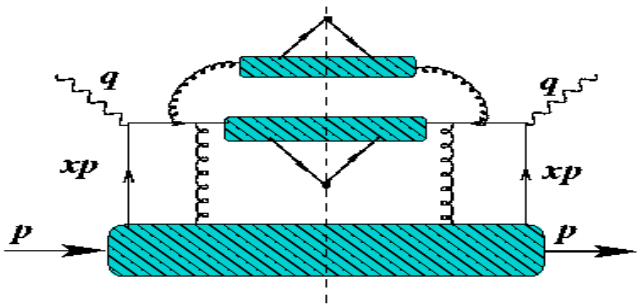


$$T_{qg} \rightarrow \frac{\int dy\, dy_1\, dy_2 \left\langle A \middle| \bar{\Psi}(y) F(y_1) F(y_2) \psi(0) \middle| A \right\rangle}{f^A(x)}$$

Luo, Qiu and Sterman PRD 50, 1951 (1994).

New kinds of diagrams that need to be evaluated !

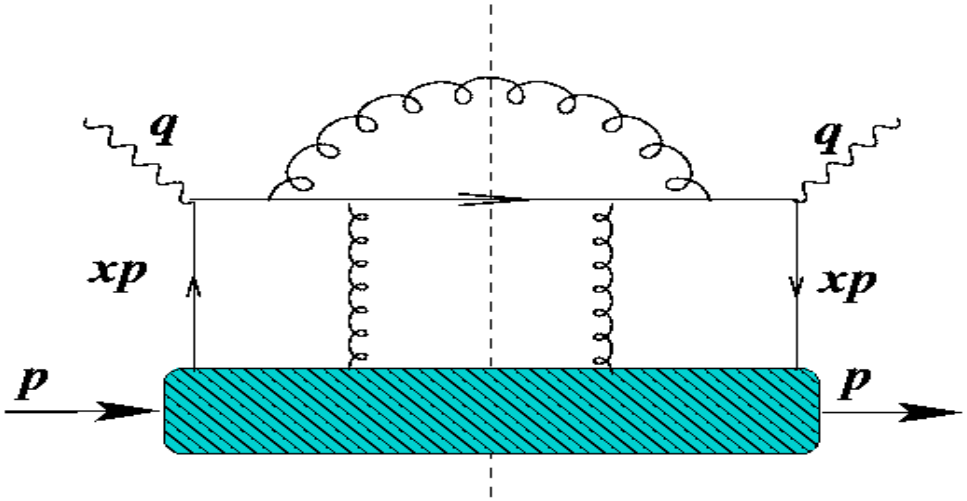




The second diagram has two independent fragmentations can be factorized in the collinear limit as...

$$\frac{dW^{\mu\nu}}{dz_1 dz_2} = \int \frac{dz}{z^2} D_q(z_1/z, z_2/z) H^{\mu\nu} + \int \frac{dz}{z(1-z)} D_q(z_1/z) D_g(z_2/(1-z)) H^{\mu\nu}$$

$$H^{\mu\nu} =$$

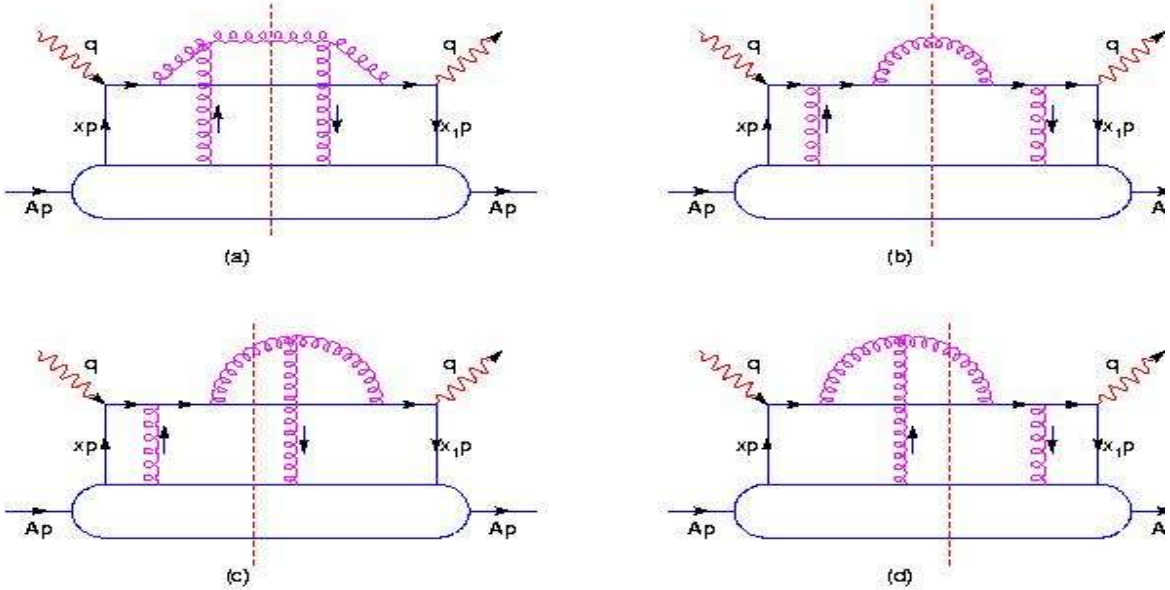


- *The calculation of the double is now in lock-step with the calculation of the single... hard part is the same*
- *Multiple higher twist diagrams need to be evaluated*

Squares of double scattering amplitudes

Interferences between single and triple scattering amplitudes

Imaginary parts where the radiated gluon line is uncut



Multiple scattering from soft gluons lead to LPM interference

Final results are quite simple...

$$x = \frac{-Q^2}{2p^+q^-}$$

$$\tilde{D}(z_1, z_2, \mu^2) = D(z_1, z_2, \mu^2) + \frac{\alpha_s}{2\pi}\int_0^{\mu^2}\frac{dl_\perp^2}{l_\perp^2}\int\frac{dy}{y^2}\left(\frac{1+y^2}{1-y}T_{qg}(x,y,Q^2,l_\perp) + V.C.\right)D(z_1/y, z_2/y, \mu^2)$$

$$+\frac{\alpha_s}{2\pi}\int_0^{\mu^2}\frac{dl_\perp^2}{l_\perp^2}\int\frac{dy}{y(1-y)}\left(\frac{1+y^2}{1-y}T_{qg}(x,y,Q^2,l_\perp)\right)D(z_1/y,\mu^2)D(z_2/(1-y),\mu^2)$$

$$T_{qg} = \int dy\, dy_1\, dy_2 \left\langle A \middle| \bar{\Psi}(y) F(y_1) F(y_2) \psi(0) \middle| A \right\rangle e^{i(\text{phase factors})}$$

The nuclear state can be expressed in terms of nucleons

$$|A\rangle = \int \Pi_i \frac{d^3 p_i}{(2\pi)^3 2p_i}\Theta(p_i)\Phi([p_1,\ldots,p_i,\ldots])\left|p_1,\ldots p_i,\ldots\right\rangle (2\pi)^3 \frac{2P_A}{A}\delta^3\left(\sum_i p_i - P_A\right)$$

Counting powers of A, much more likely for quark and gluon to come from separate nucleons...

Fourier transform from momentum to position space

Assume a Gaussian density distribution for nucleons in a medium sized nucleus

$$\rho(r) = \rho_0 e^{\frac{-r^2}{2R_A^2}}$$

$$T_{qg}^A = C A^{1/3} (x G^N(x)) (1 - e^{-x_L^2/x_A^2})$$

$$\frac{x_L^2}{x_A^2} = \frac{R_A^2}{\gamma^2 \tau_f^2}$$

τ_f = ***Formation time***

R_A = ***Nuclear size***

γ = ***boost***

Results for DIS on Nuclei: energy loss in cold matter

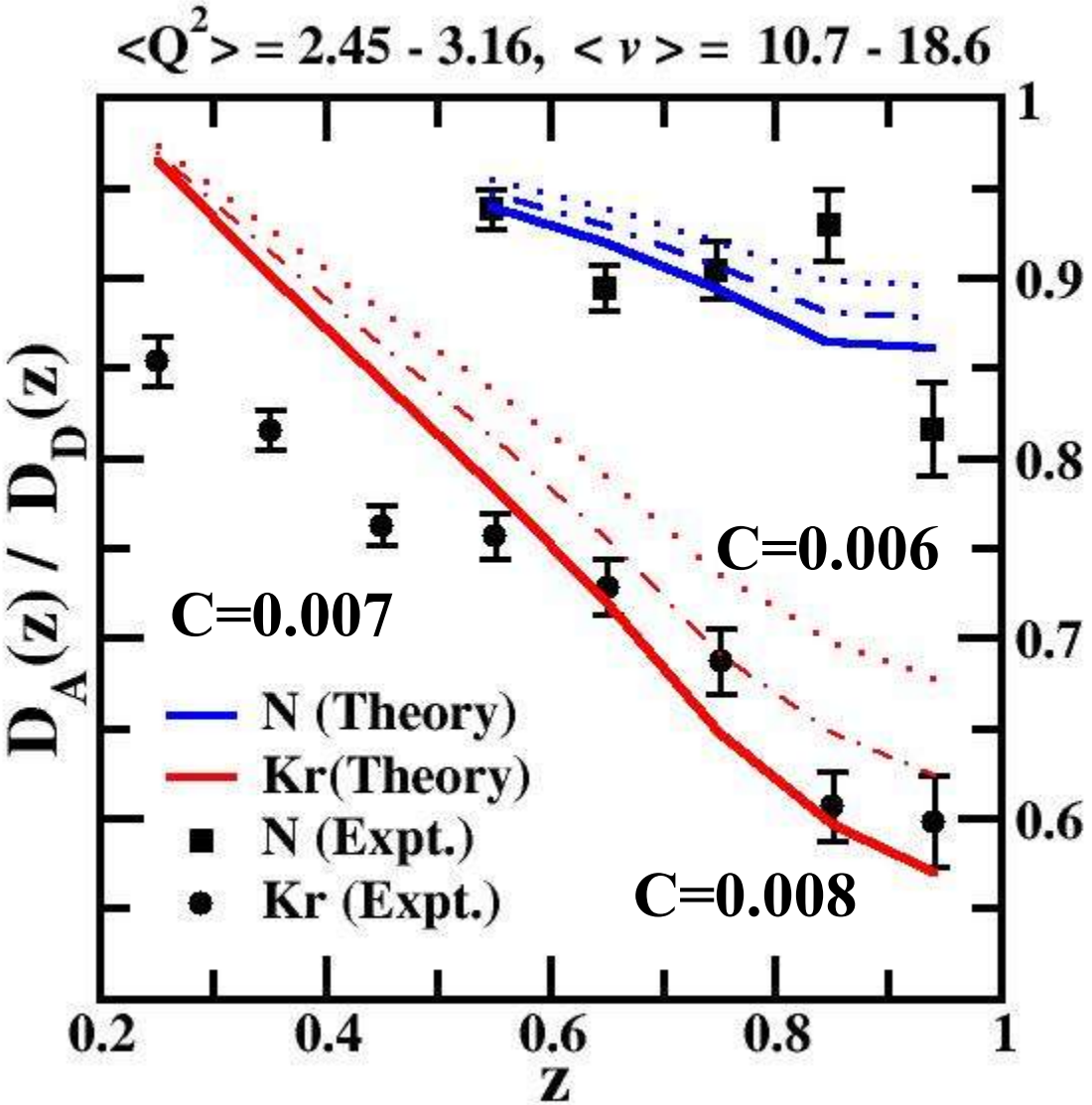
Single inclusive suppression for pions

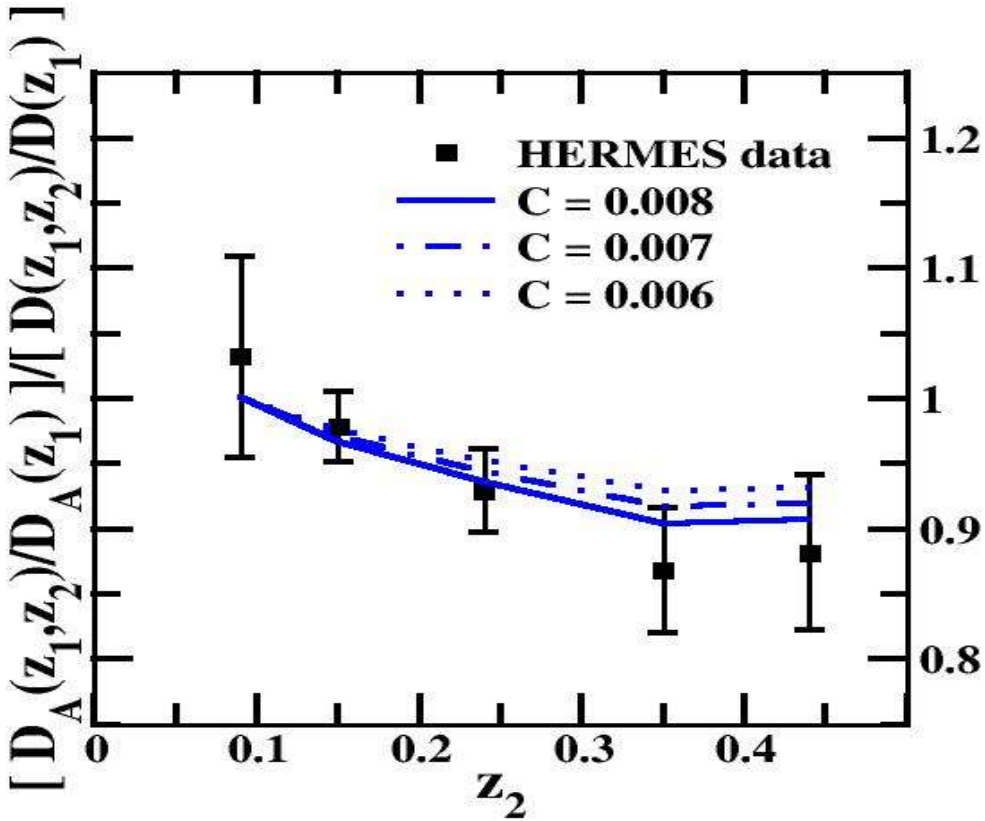
Gaussian distribution of nucleons used

Good agreement with data, 3 different normalizations

Over all normalization is now fixed:

No free parameters for double calculation





The theory curve is the number of pairs with one hadron at $z_1 = 0.5$ and one at z_2.

The expt. curve is the number of events with a subleading hadron at z_2, and $z_1 > 0.5$.

Theory curve: (FF(2h)/FF(1h) in A) / (FF(2h)/FF(1h) in vac.)

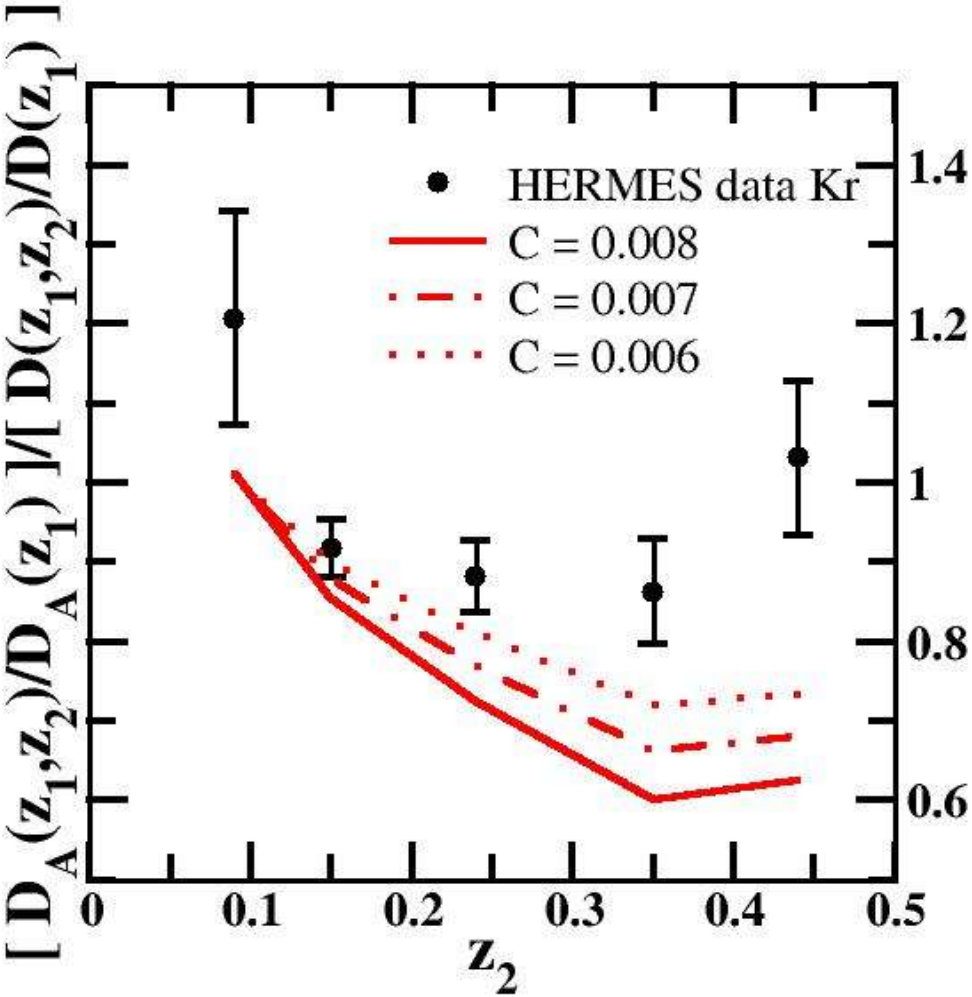
$$\textbf{Expt ratio} = \frac{\dfrac{\text{No. of events with at least 2 hadrons with } z_1 > 0.5}{\text{No. of events with at least one hadron with } z > 0.5}}{\text{same ratio on deuterium}}$$

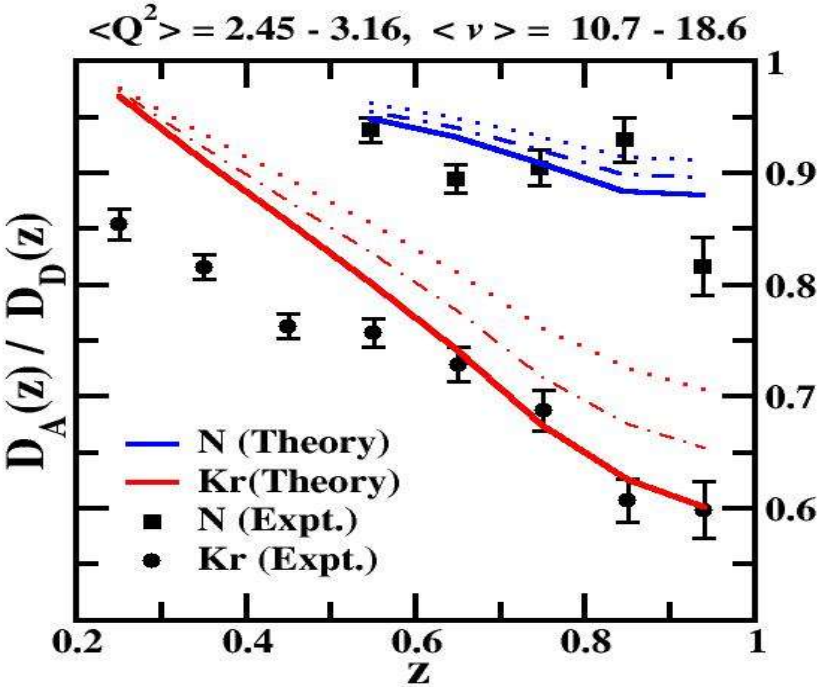
Gaussian approximation not so good for large Nuclei like Kr.

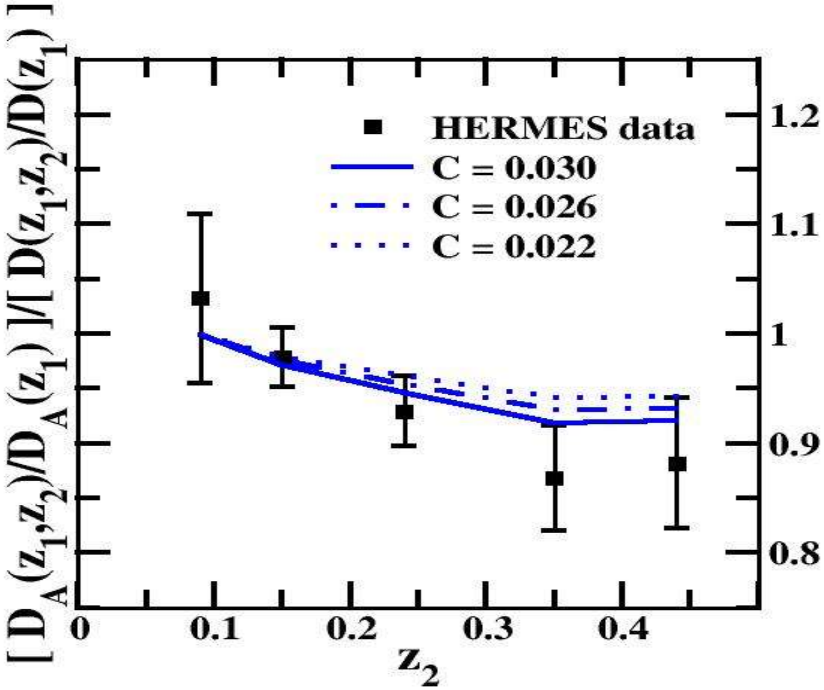
Hard sphere improves comparison with Kr,

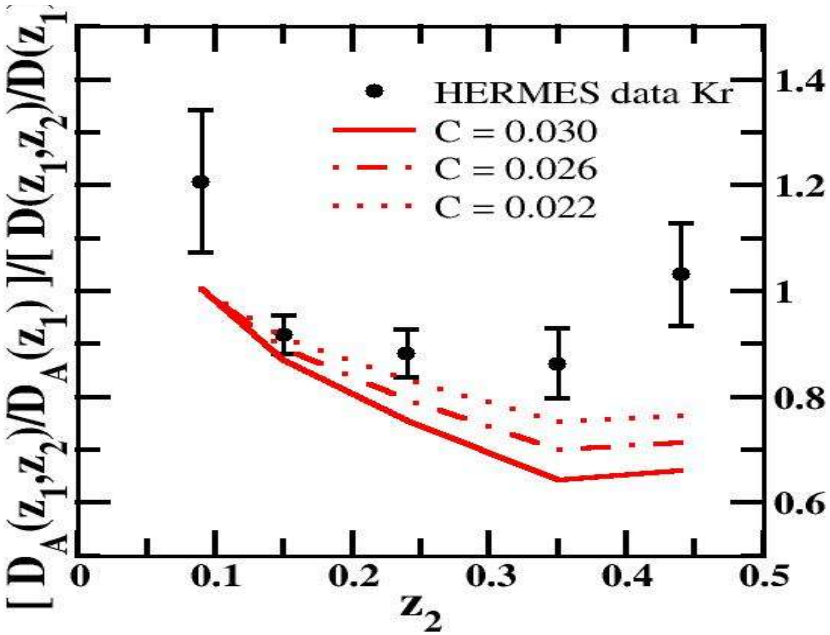
But looks worse for N,

Over all very slight difference !









dE/dx = 0.5 GeV/fm

Perhaps at Larger A one needs to go to higher order power corrections.

Medium modification in a deconfined medium

$$d\sigma = \int dx_1 f_q^A(x_1) f_q^A(x_2) d\sigma_{hard} \tilde{D}^h(z)$$

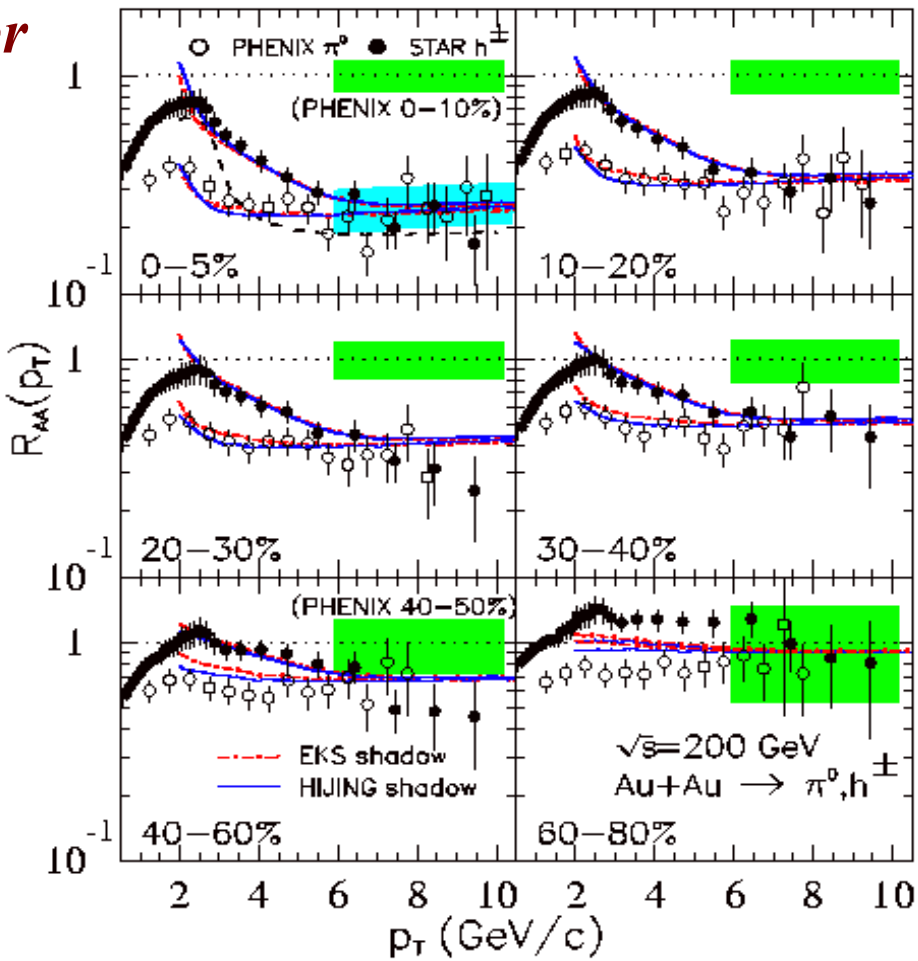
X.N.Wang, \nucl-th 0305010

Calculate D(z) as in DIS, but for a 1-D expanding medium, i.e, density drops with time..

Dial up the constant = gluon density to get suppression, in central Au-Au

Assume gluon density prop. to number of participants

dE/dx ~ 14 GeV/fm



Dihadron results for hot medium

Use the same overall constant C as for singles

Results include the effect of trigger bias.

Initiating parton in a heavy-ion collision has higher energy than that in p-p collision,

Use the single inclusive results to get mean E_{parton} for a given E_{hadron}.

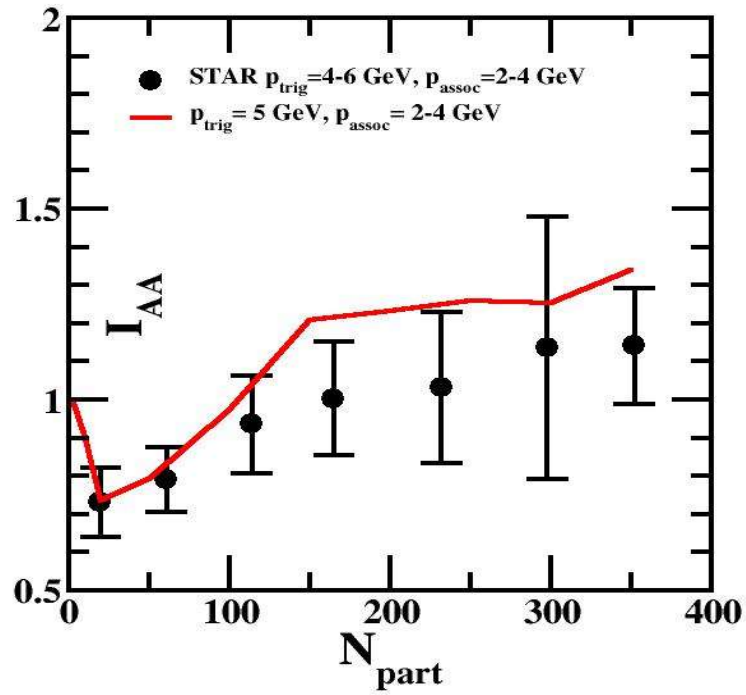
$$z = \frac{E_{hadron}}{E_{parton}}$$

If E_loss dominates

$z_{AA} < z_{pp}$, $D(z_{AA}) > D(z_{pp})$

If Cronin effect dominates,

$z_{AA} > z_{pp}$, $D(z_{AA}) < D(z_{pp})$



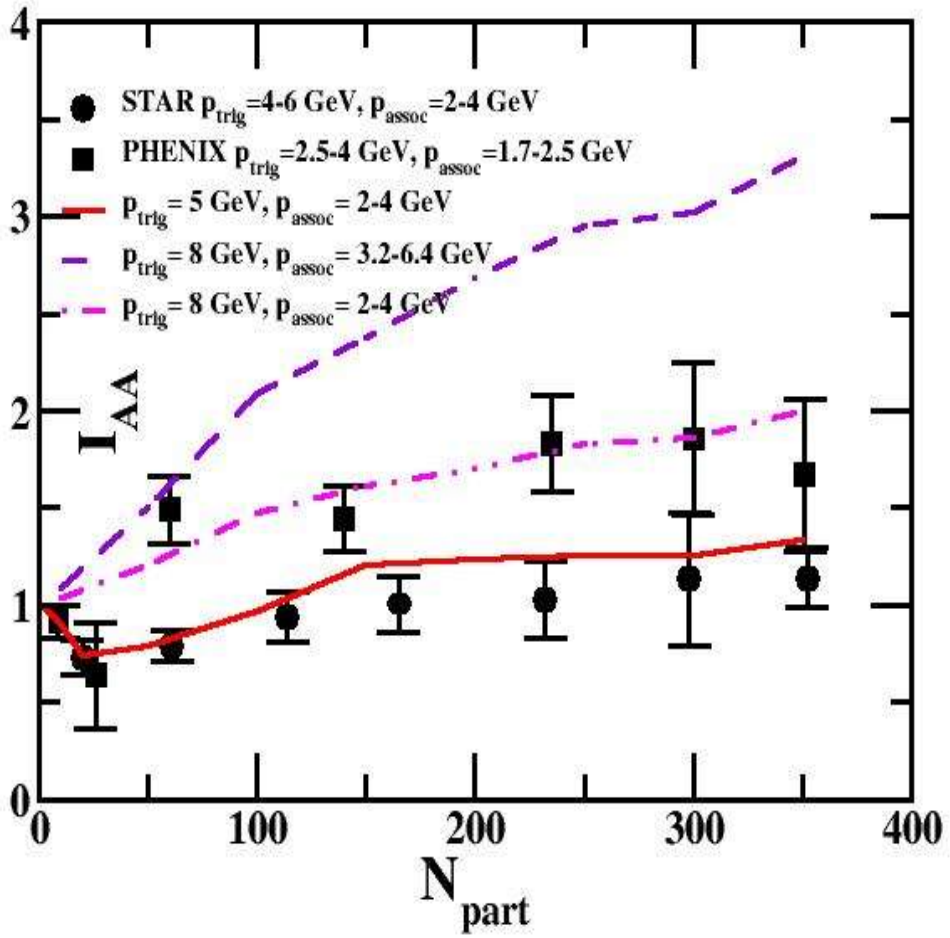
Increase the energy of the hadron, Cronin effect goes away!

Increasing P_{trig}
go to higher z

Increase P_{trig} = 8 GeV
Increase P_{assoc}
in proportion..

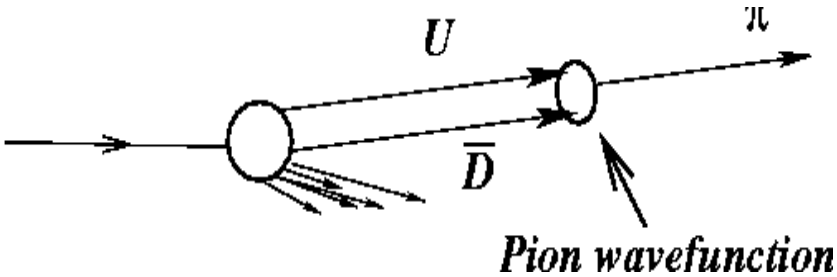
Increase P_{trig} ,
keep P_{assoc} the same

Low P_T data show
different trend.
PHENIX/STAR



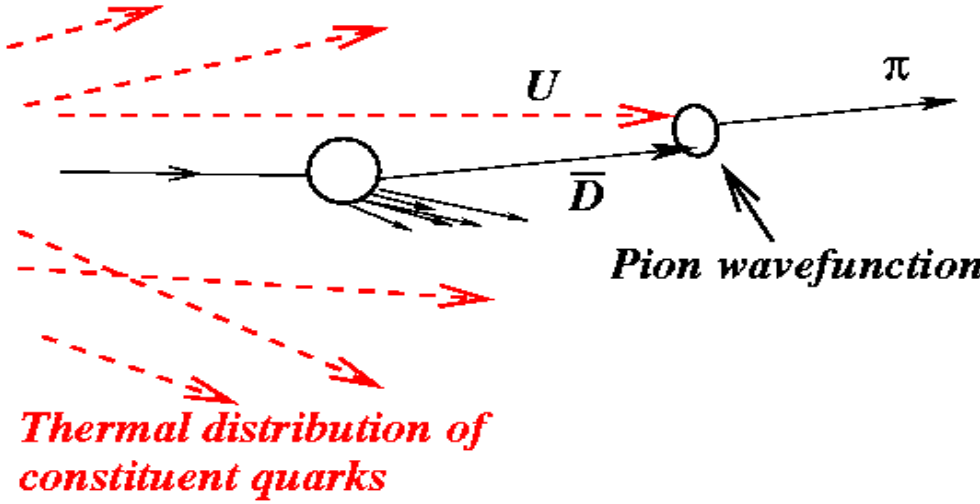
Application to recombination, work in progress!

- Replace basis of hadrons with basis of constituent quarks...
- Construct parton–constituent quark fragmentation function
- Recombine cons. quarks into hadrons with hadron wavefunction



In Vacuum, Need tri-hadron frag. function for baryons

Use a thermal ensemble of constituent quarks in a medium.



Summary & Conclusions!

- ***A unified picture of jet quenching in cold and hot matter***
- ***Modification of fragmentation functions***
- ***Single inclusive and double inclusive measurements***
- ***Modification is a partonic effect.***
- ***Need a new object: Dihadron fragmentation function***
- ***Modification from A enhanced power corrections in DIS***
- ***Extended formalism to modification in hot matter***
- ***Incorporation of low P_T effects...*** (preliminary !)