Dihadron fragmentation

in vacuum and in matter

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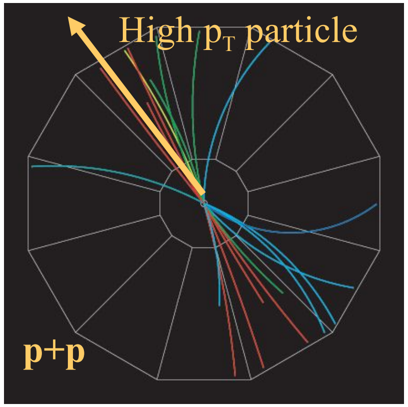
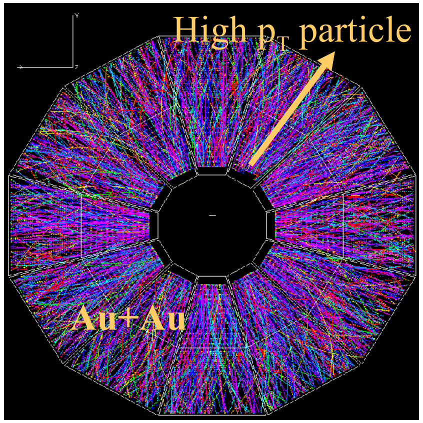
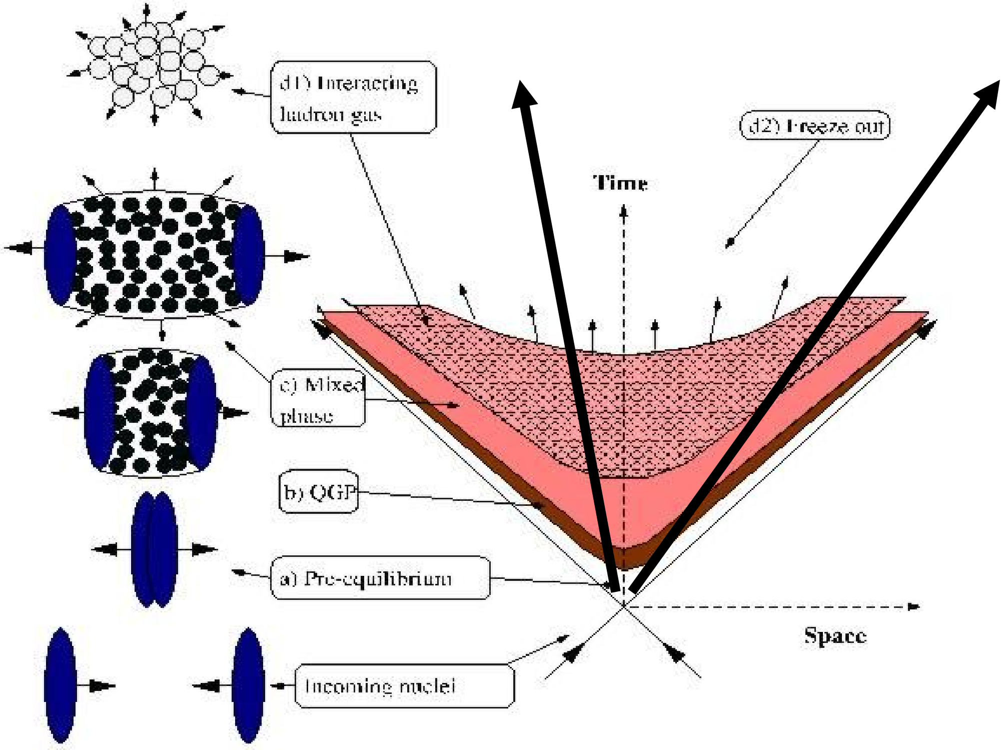
Hard Probes 2004
Ericeira, Portugal
Nov. 4 - 10

HEAVY-ION COLLISIONS AND JETS



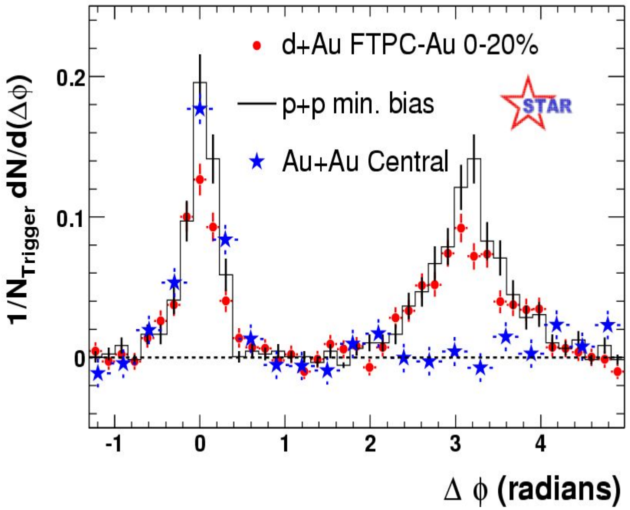


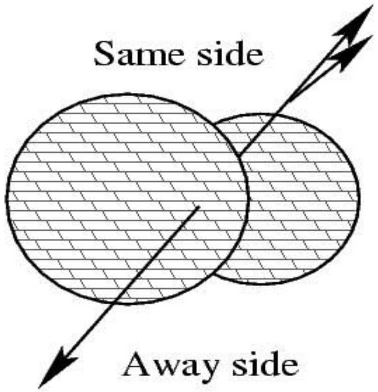


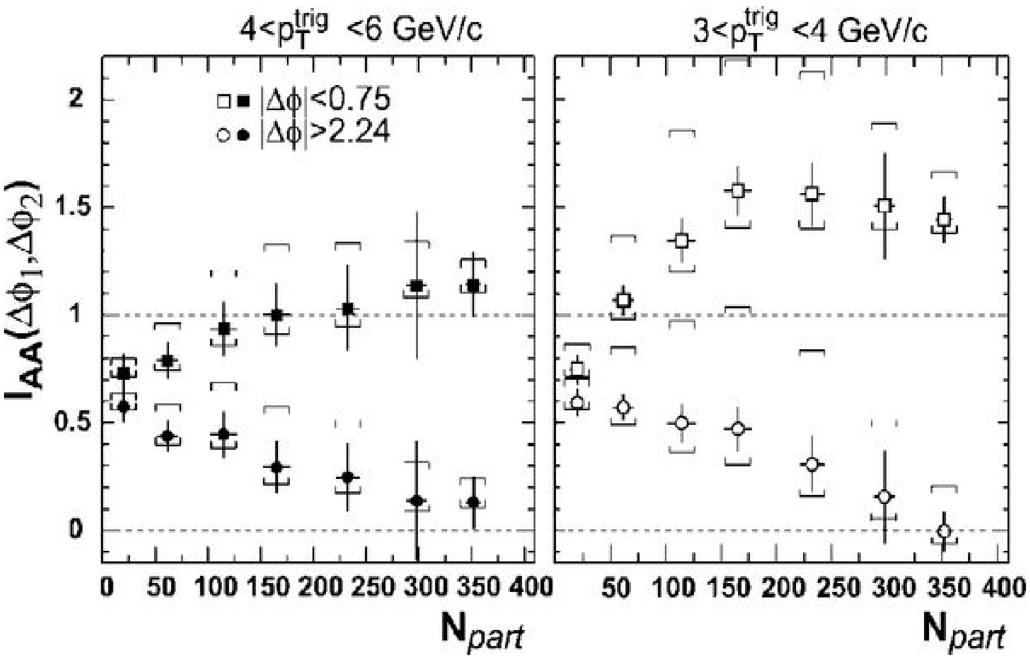
Select a leading particle $4<p_t<6$ GeV/c, $|\eta|<0.75$

Associate all other particles ($0.15<p_t<4$ GeV/c, $|\eta|<1.1$) with the leading particle.

RESULTS FROM STAR, heavy-ion collisions







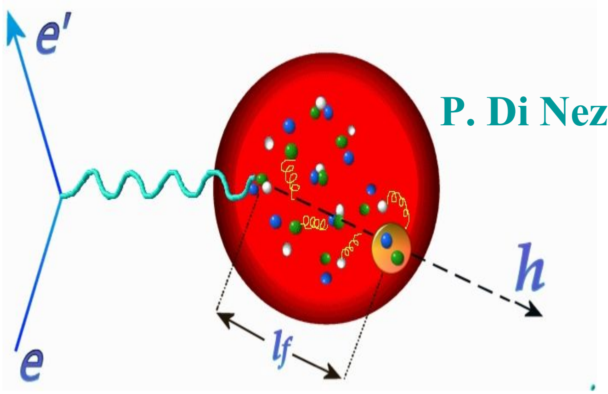
- ***d+Au central very similar to p+p***

- ***Away side, central Au+Au suppressed***

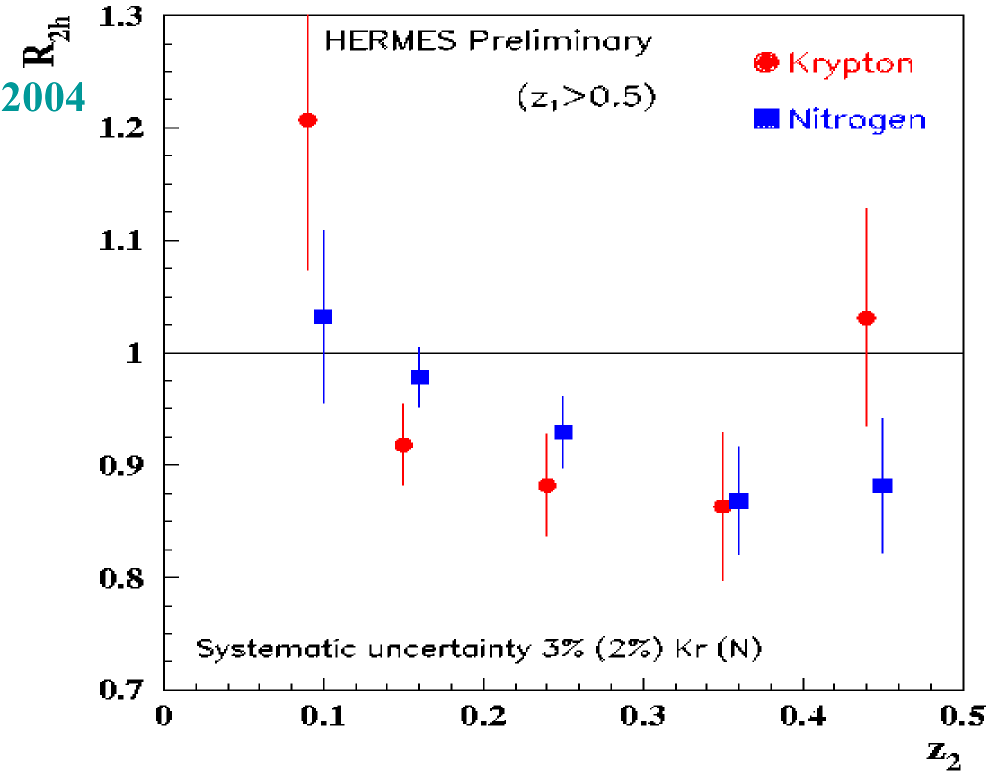
- ***Near side, central Au+Au unchanged***

- ***Can explain the integral of the near side vs Npart.***

RESULTS FROM HERMES, DIS on cold nuclei



P. Di Nezza @ QM2004



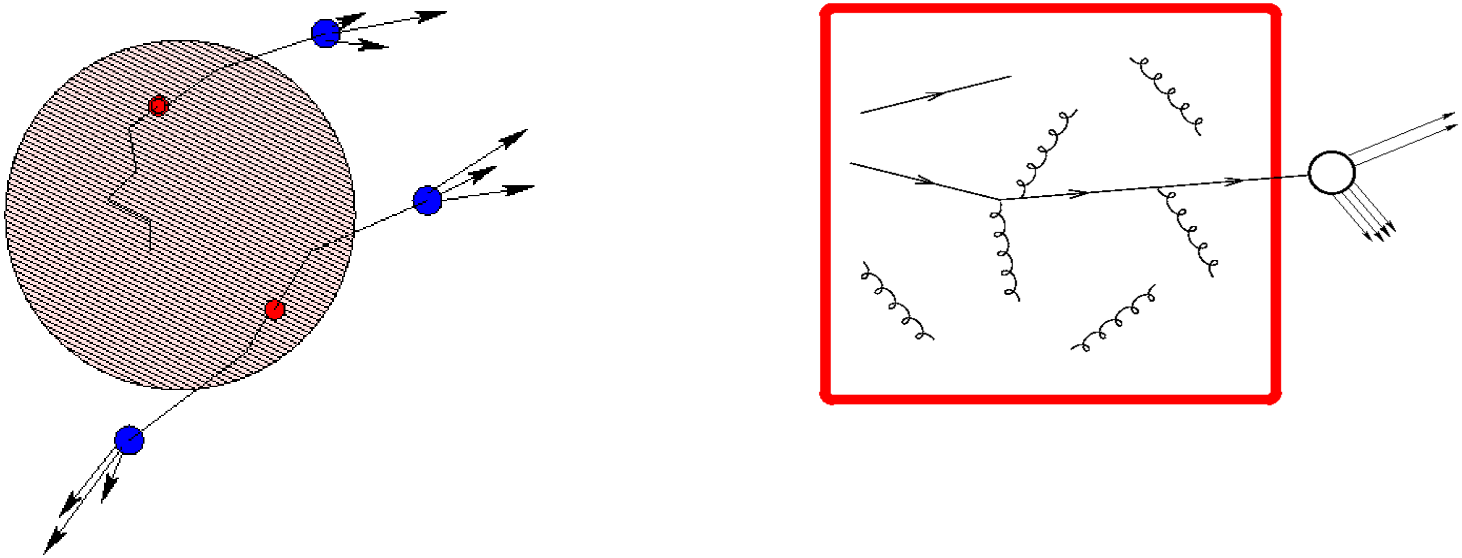
- *Always measure a ratio of double to single production*
- *Divide by same ratio in deuterium to remove detector systematics*

$$R_{2h} = \frac{\dfrac{No.\ of\ \ events\ \ with\ \ at\ \ \ least\ \ \ 2\ hadrons\ with\ \ z}{No.\ of\ \ events\ \ with\ \ at\ \ \ least\ \ \ one\ hadron\ \ with}}{same\ ratio\ \ on\ \ \ deuterium}$$

TWO POSSIBILITIES !

PARTONIC ENERGY LOSS :

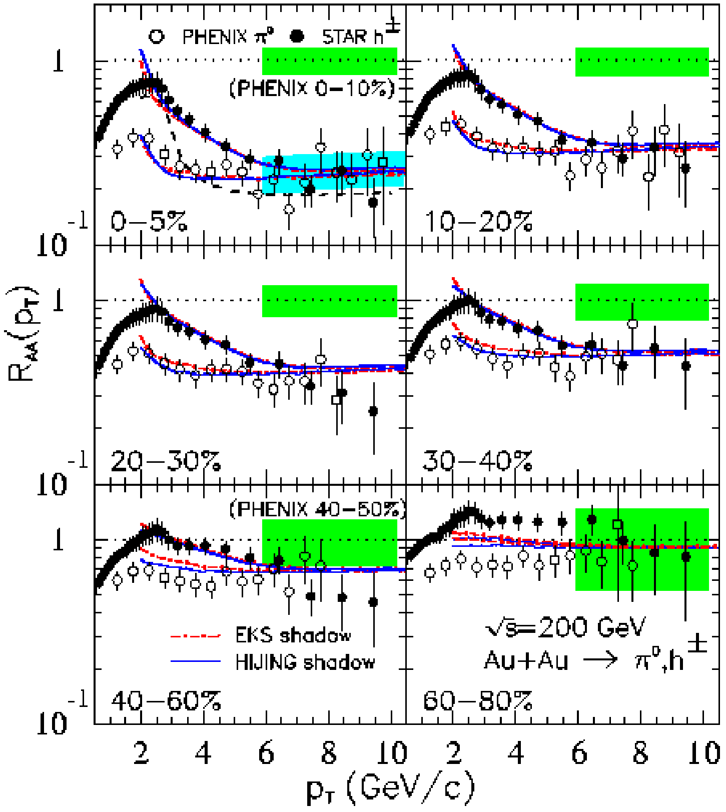
- *High energy partons are created over the entire collision zone*

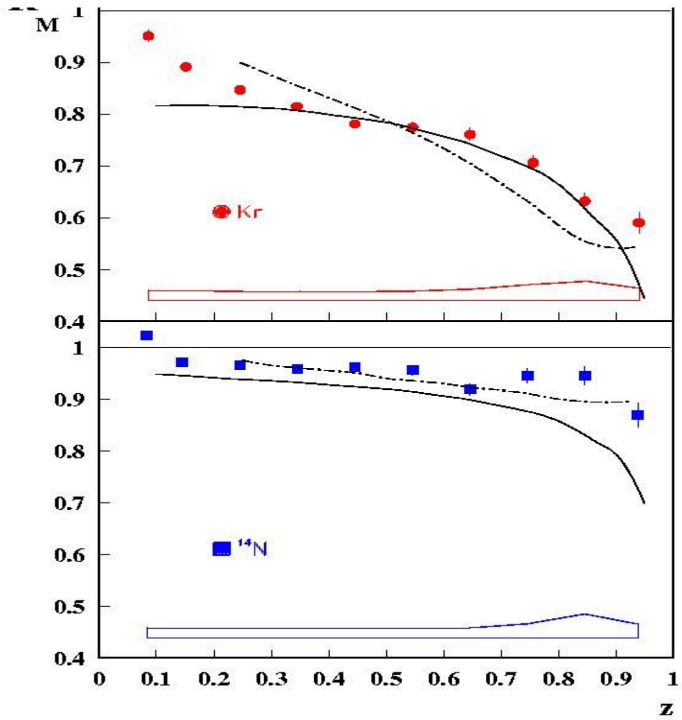


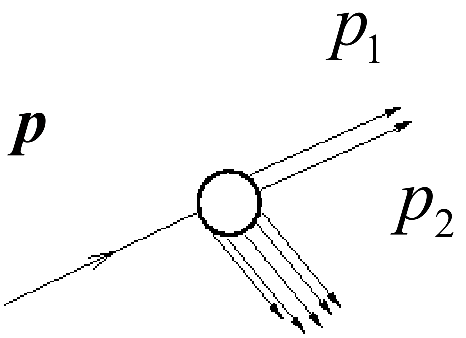
- *Lose energy by partonic interaction, medium may be hadronic or partonic*
- *Emerge as partons and then fragment*

- ***Partonic energy loss models explain single inclusive suppression pretty well !***
  (GLV, BDMPS, WGZ, SW)

To explain double inclusive spectra requires a new phenomenological object: Dihadron fragmentation function! $D_{q,g}^{h_1 h_2}(z_1, z_2)$





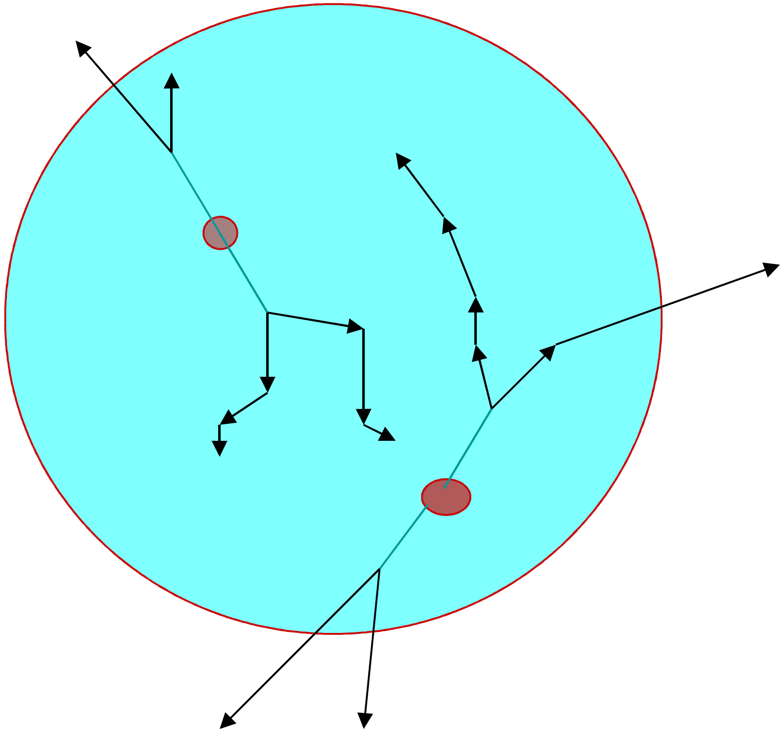


$$z_1 = \frac{p_1^+}{p^+}$$

$$z_2 = \frac{p_2^+}{p^+}$$

HADRONIC ENERGY LOSS:

- *Fragmentation occurs inside the hot medium*
- *Hadrons become independent due to scattering*
- *Each hadron suffers the same Energy Loss on average*



Hadronic scattering models can explain mean single supp. !
C. Greiner et. al. @QM2004, V. Koch (unpublished!)

- *Probability of observing two hadrons factorizes $P(1,2) = P(1)P(2)$*
- *Each probability is suppressed compared to p+p: $P(h) = s\, p(h)$*

- *Thus the conditional probability is also suppressed compared to p+p collisions*

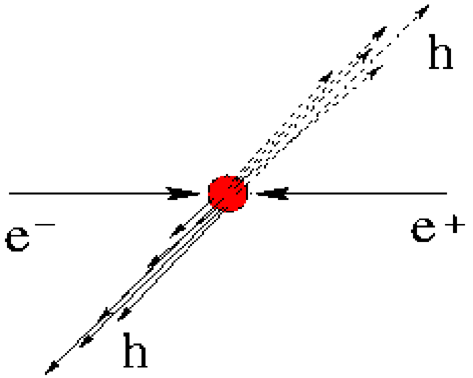
$$\frac{P(1,2)}{P(1)} = \frac{P(1)P(2)}{P(1)} = P(2) = sp(2) = s\,\frac{p(1)p(2)}{p(1)}$$

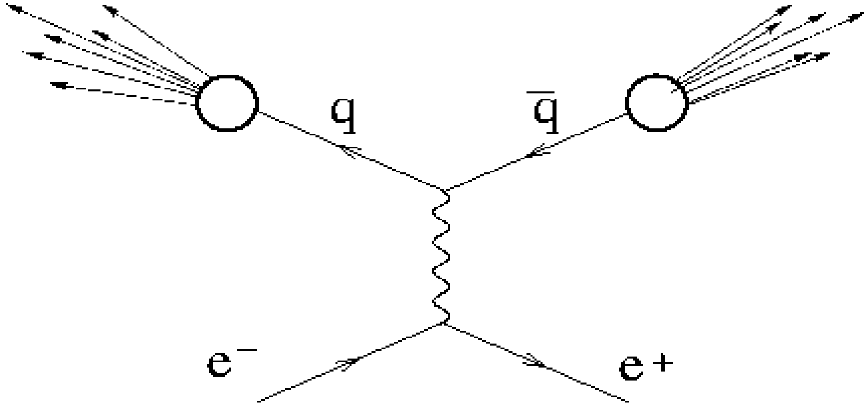
P(h) is for A+A;   p(h) is for p+p

- *Hadronic absorption models cannot explain the double inclusive spectrum*

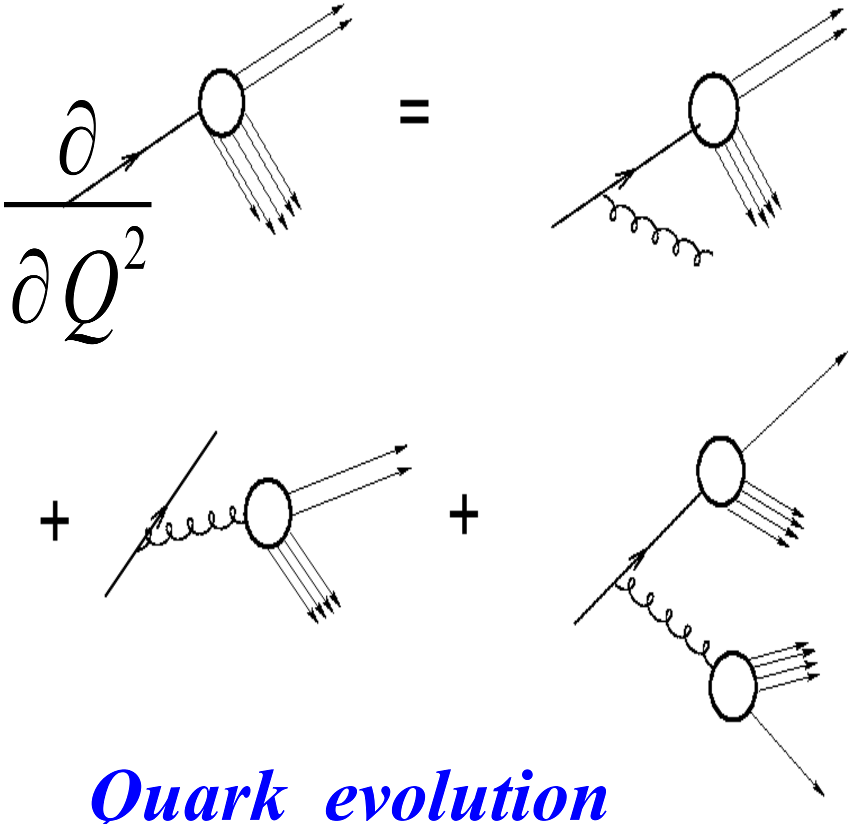
Modification of Dihadron fragmentation function!

- *Fragmentation functions are universal*
- *We have a definition in terms of operators*
- *Start with simple system :* $e^{+}e^{-}$*, can factorize* $\lambda^2 \ll \mu^2 \ll Q^2$
- *Derive evolution (vacuum splitting functions same)*
- *Check with data and repeat in medium (similar to single)*

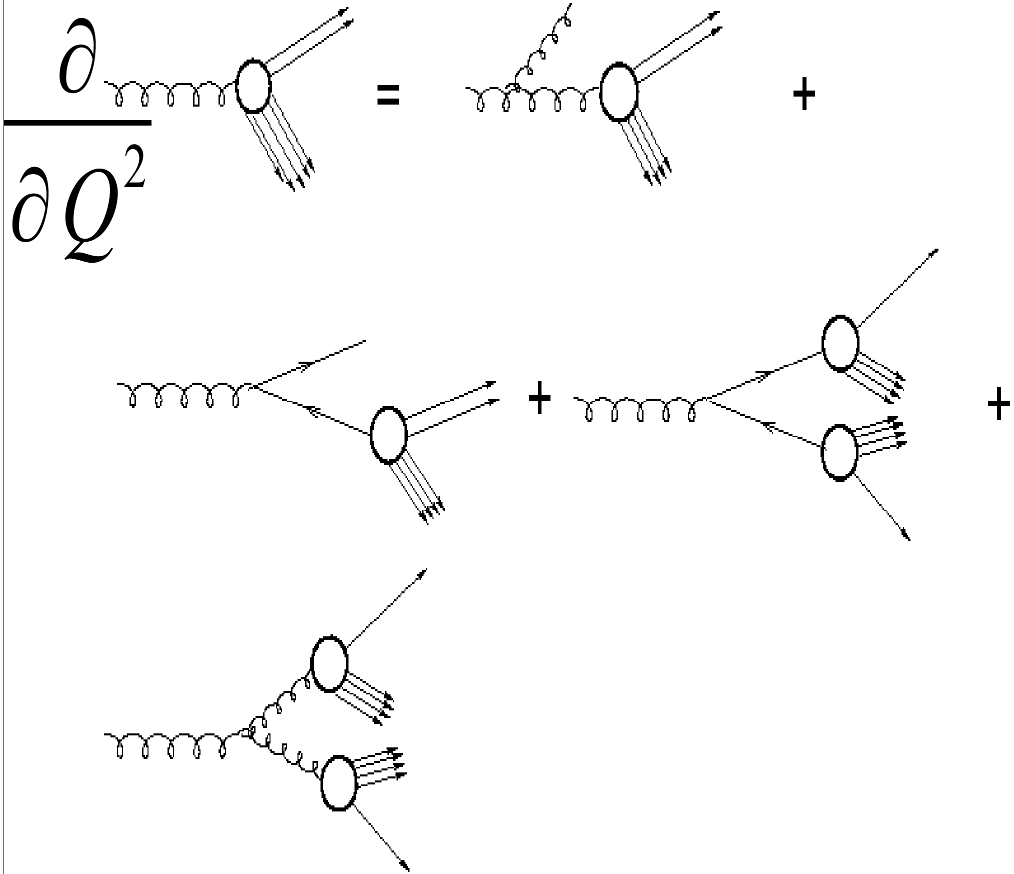




- Evolving to a higher scale Q   solving DGLAP equations
- Set of coupled differential equations containing the following processes:



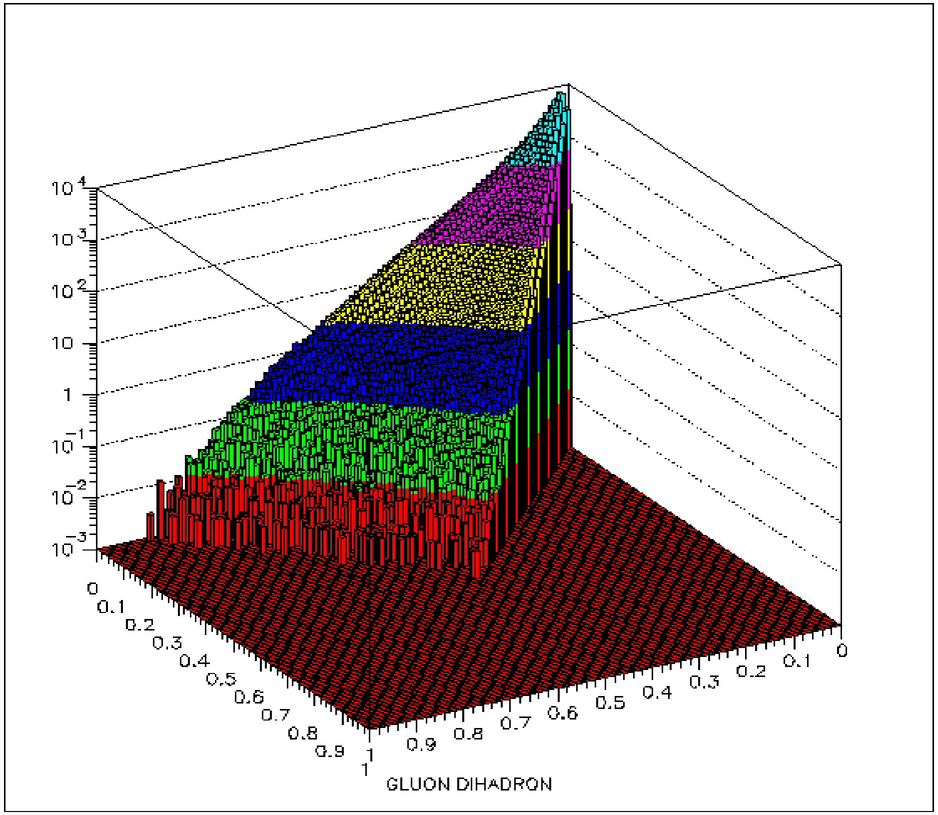
Quark evolution

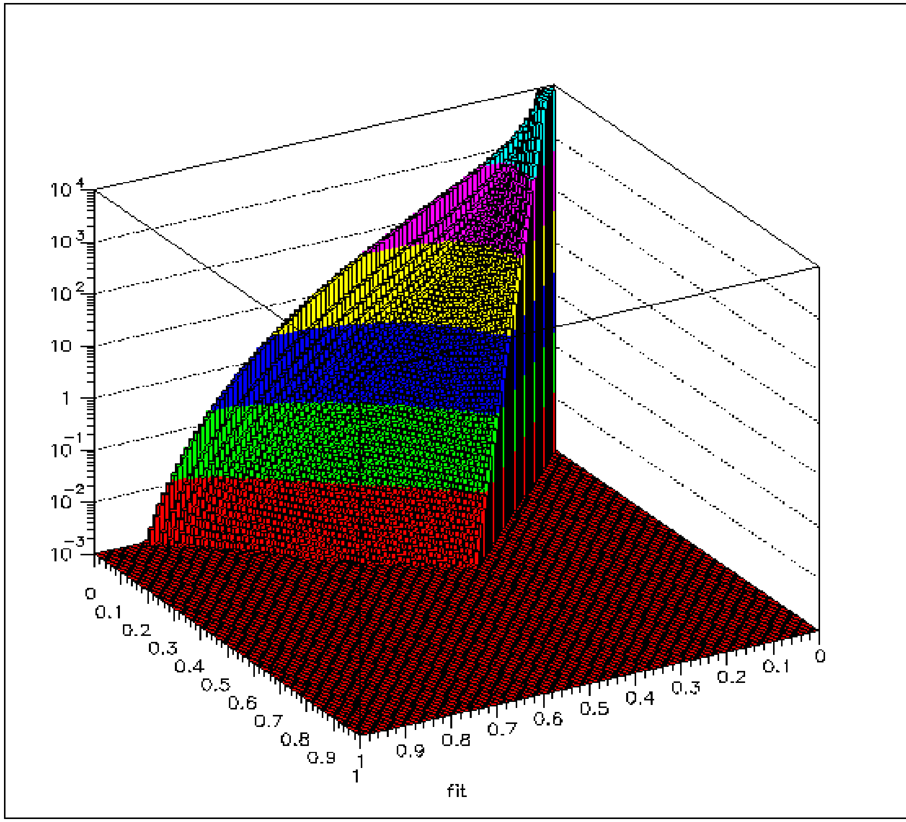


Gluon evolution

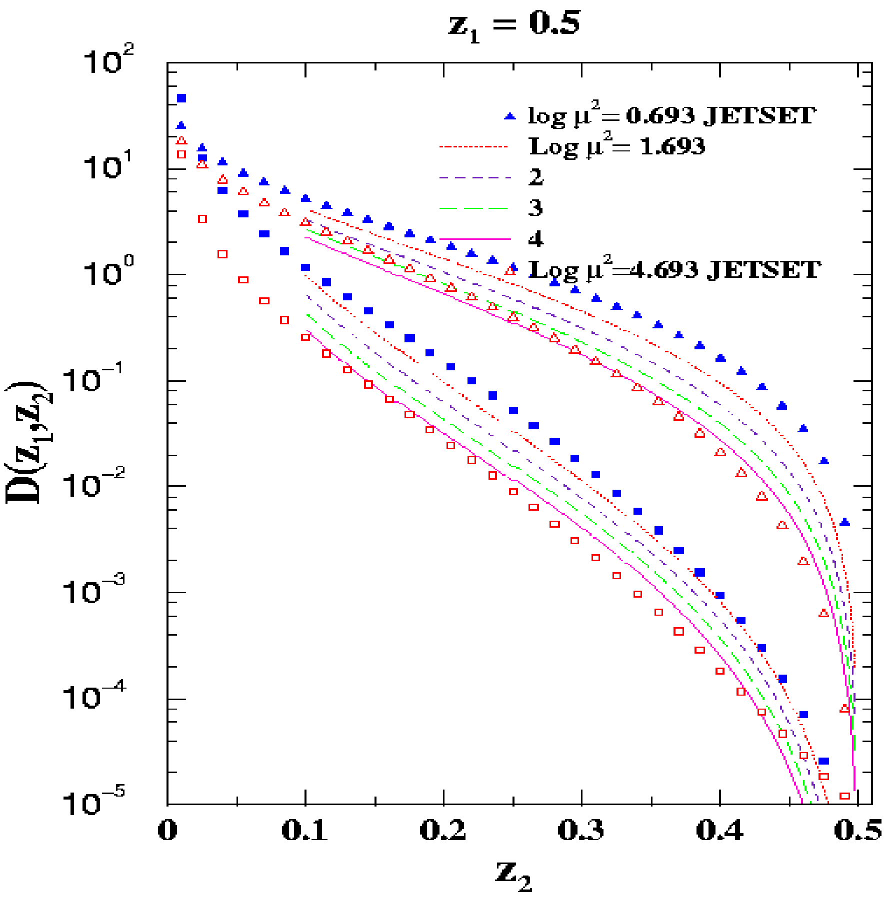
Results from Event generators: JETSET

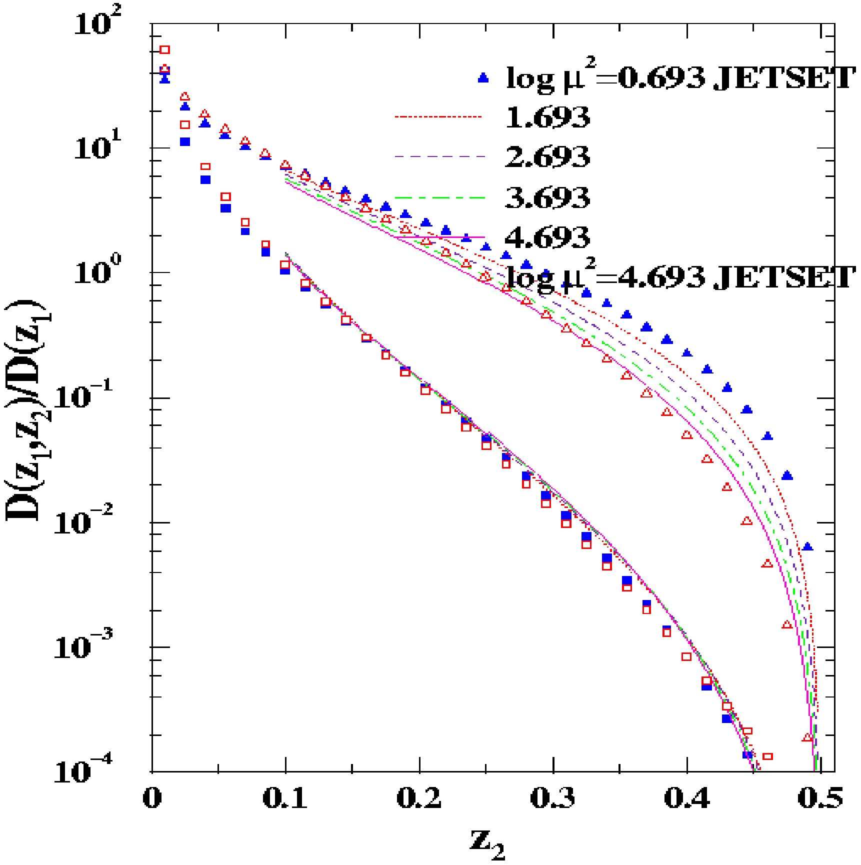
insist $z_1 > z_2$, fit a function to it !





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





Quark and Gluon evolution fits event generator data very well!

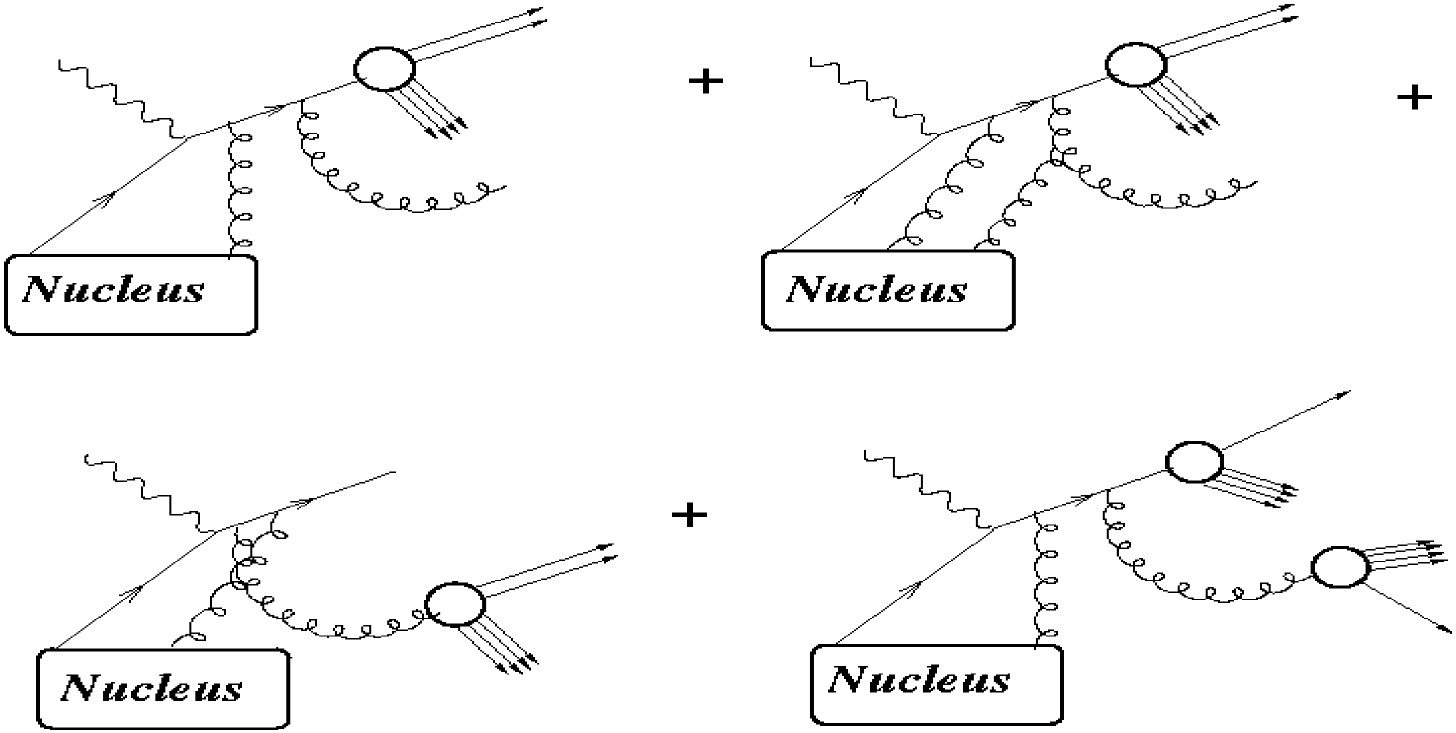
Thus we can understand evolution of FF from QCD.

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!

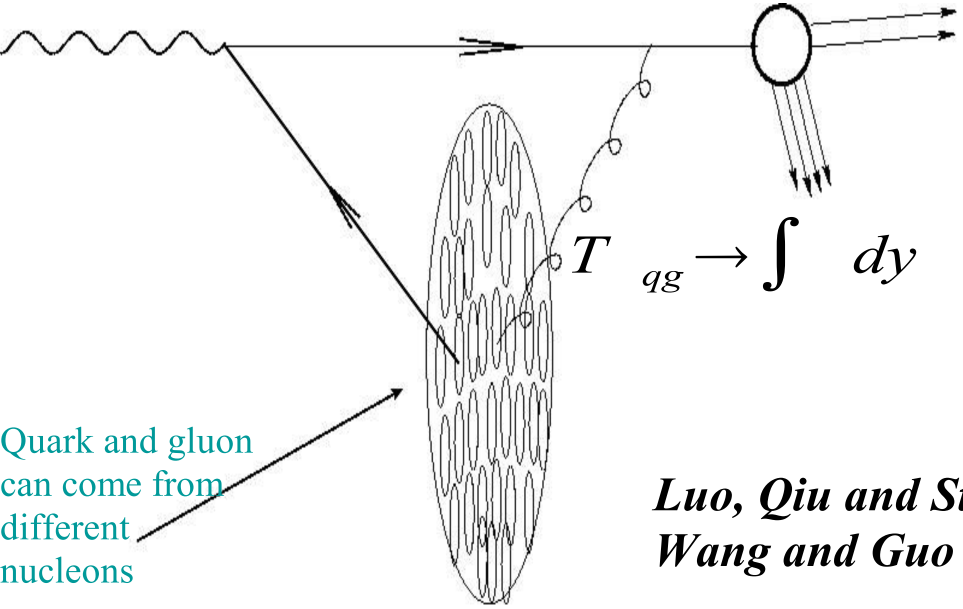


DIS followed by di-hadron fragmentation from a large nuclei may be generally expressed as

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

$$\tilde{D} = medium \;\; modified \quad fragmentation \quad fun$$

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

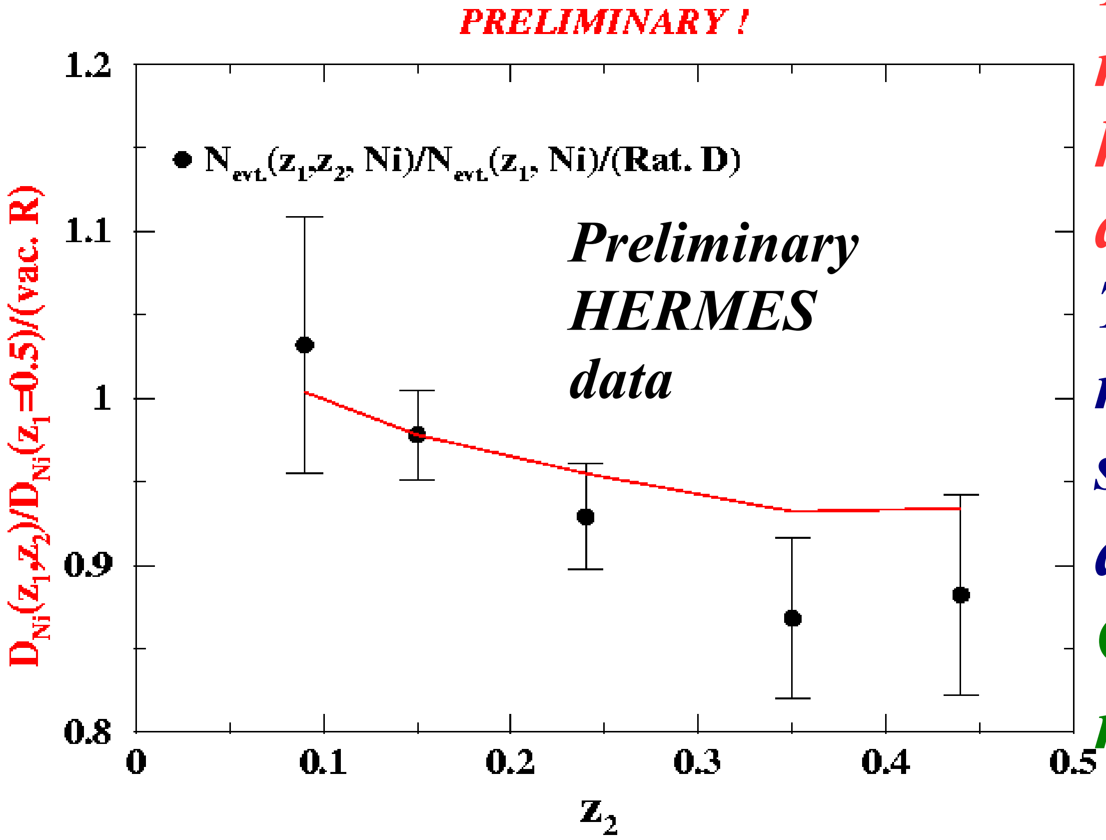


Quark and gluon can come from different nucleons

$$T_{qg} \rightarrow \int dy \quad dy_1 \; dy_2 \langle A | \bar{\Psi}(y) F \;(y_1) F \;(y_2)$$

$$this \sim A^{\frac{1}{3}}$$

Luo, Qiu and Sterman PRD 50, 1951 (1994).
Wang and Guo NP A696, 788 (2001).



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 $z_1 > 0.5$.

Gaussian approx. for nuclear density used!

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

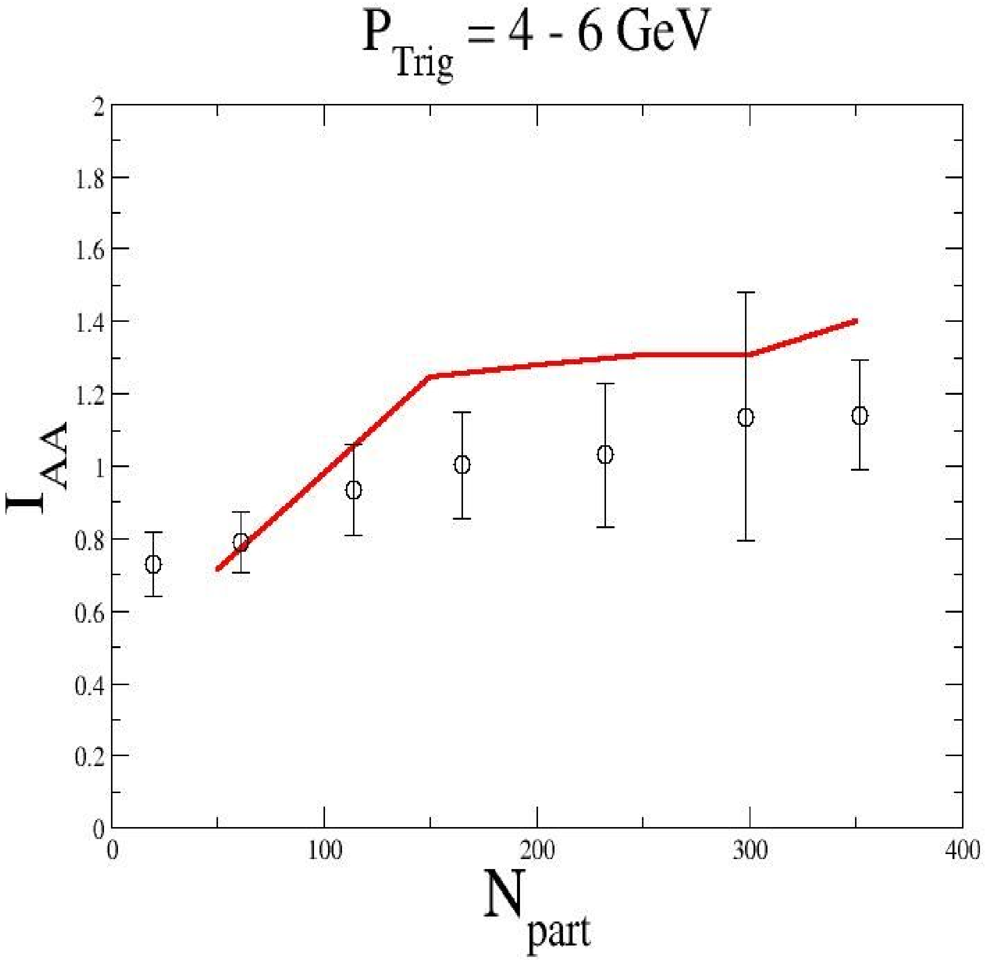
$$\textbf{\textit{Expt ratio}} = \frac{\dfrac{No.\ of\ \ events\ \ with\ \ at\ \ least\ \ 2\, hadrons\ with\ \ z}{No.\ of\ \ events\ \ with\ \ at\ \ least\ \ one\ hadron\ \ with}}{same\ ratio\ \ on\ \ \ deuterium}$$

Dihadron results for hot medium

Very preliminary estimate for the same side two body correlation

Results include the effect of trigger bias.

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



Summary & Conclusions!

- ***We have defined a new phenomenological object in QCD:***

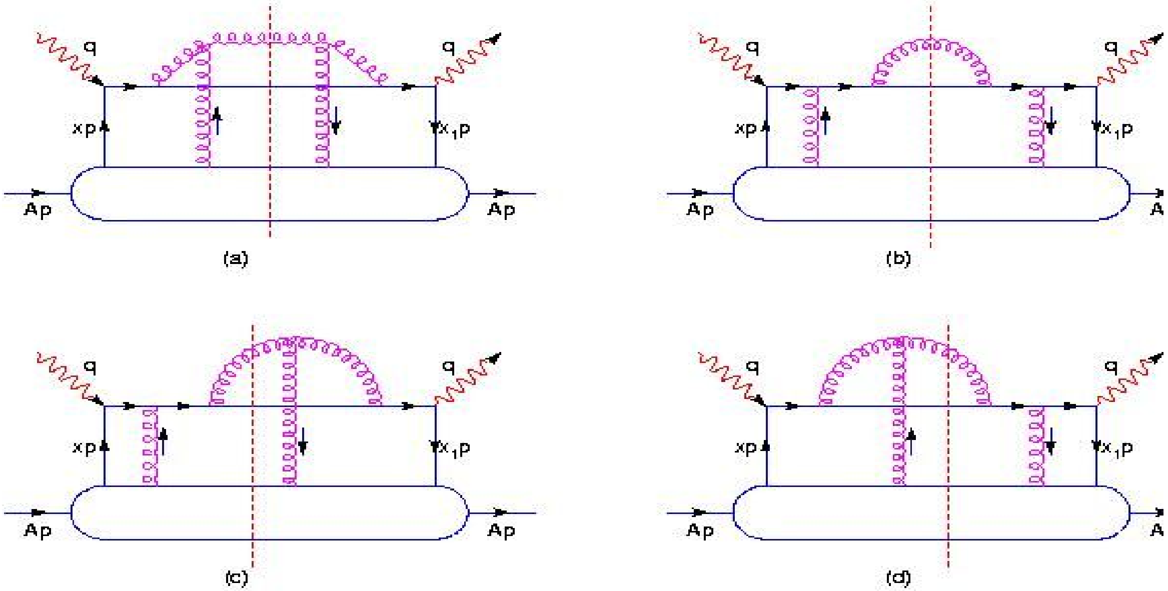
  `` The Dihadron Fragmentation function ''
- ***Demonstrated its factorization at LO in*** $e^+ e^-$
- ***Derived it evolution equation (has extra components)***
- ***Matched results with JETSET!!***
- ***Allowed a physical understanding of change with scale***
- ***Extended formalism to medium modification in DIS***
- ***Extended formalism to medium modification in heavy-ion collision***

Back up slides …

Multiple higher twist diagrams need to be evaluated

Multiple scattering from soft gluons lead to LPM interference

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



$$T^{A}_{qg} = C\,A^{1/3}\left(x\,G^{N}(x)\right)\left(1 - e^{-x_L^2/x_A^2}\right)$$

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

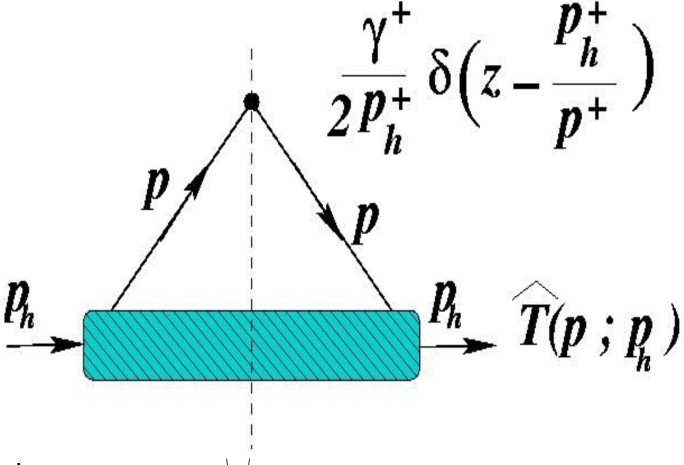
τ_f ***= Formation time***

γ ***= boost***

R_A ***= Nuclear size***

Fragmentation functions come from the soft matrix elements

$$D_q(z)=\frac{z^3}{2}\int\frac{d^4p}{(2\pi)^4}Tr\left[\frac{\gamma^+}{2p_h^+}\delta\left(z-\frac{p_h^+}{p^+}\right)\hat{T}_q(p\ ,$$



where $$\hat{T}_q(p\ ,p_h)=\int d^4x\,e^{-ip\cdot x}\sum_{S-1}\langle 0|\psi(0)|p_h,S-1\rangle\langle p_h,S-1$$

$$D_q(z_1,z_2)=\int\frac{dq^2}{8(2\pi)^2}\frac{z^4}{4z_1z_2}\int\frac{d^4p}{(2\pi)^4}Tr\left[\frac{\gamma^+}{2p_h^+}\delta\left(z_1+z_2-\frac{p_h^+}{p^+}\right)\hat{T}_q(p$$

A. Mueller, PRD 18, 3705 (1978).

$$=\frac{z^4}{z_1z_2}$$