High P_T hadron-hadron correlations in Vacuum and in Matter

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Based on,

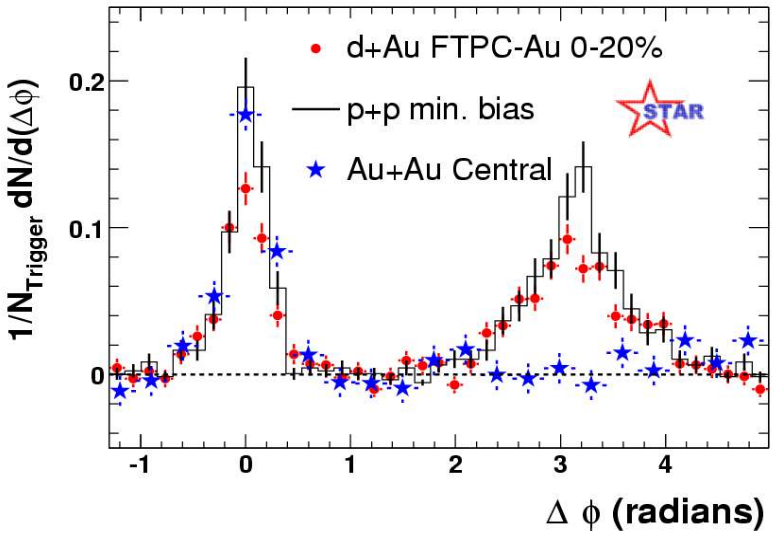
A. Majumder and Xin-Nian Wang, PRD D. 70, 014007 (2004).

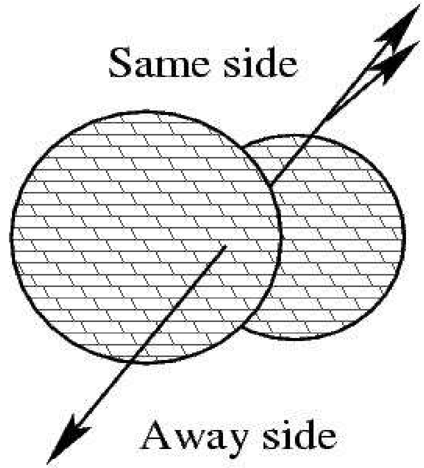
A. Majumder, J. Phys. G. 30, S1305 (2004). *Proc. QM2004.*

A. Majumder and Xin-Nian Wang, LBNL-56199, *to be published*,

A. Majumder, and Xin-Nian Wang J. Phys. G., *Proc. Hot Quarks 2004, hep-ph/0410...*

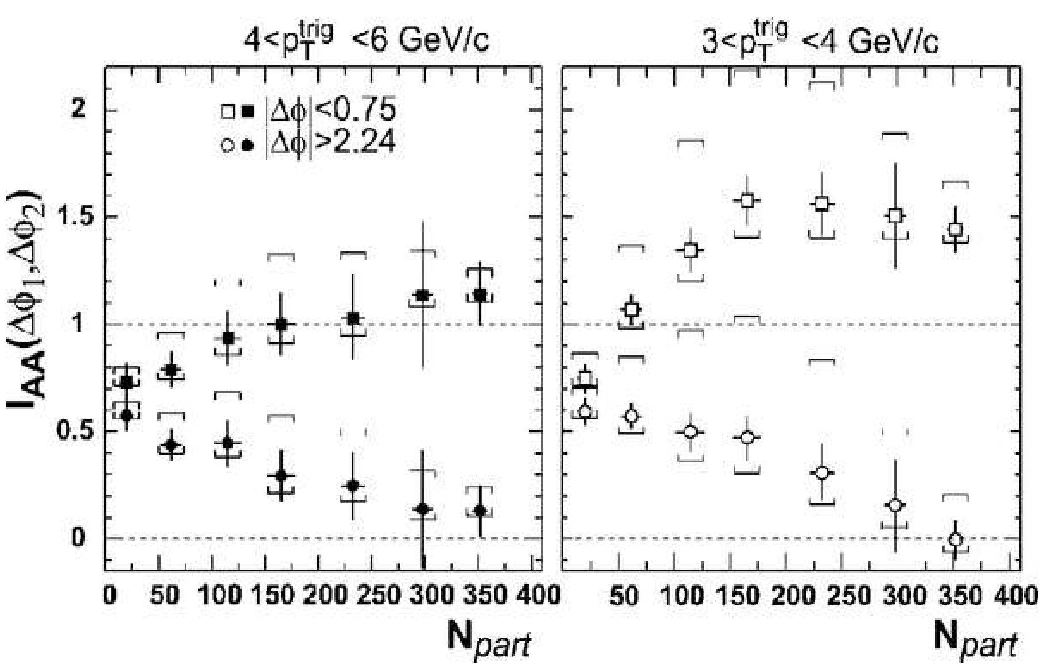
Dihadron measurements in heavy-ion coll.





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

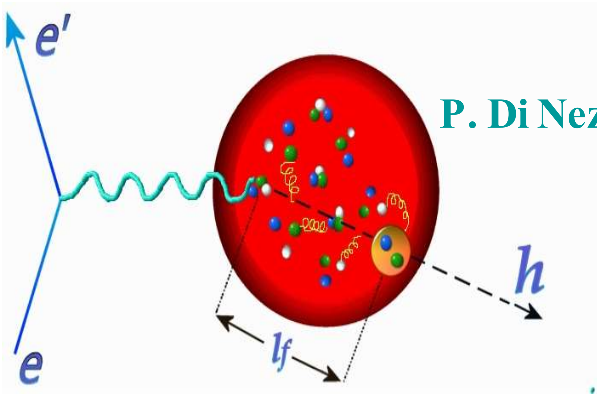
- *Away side, central Au+Au suppressed*



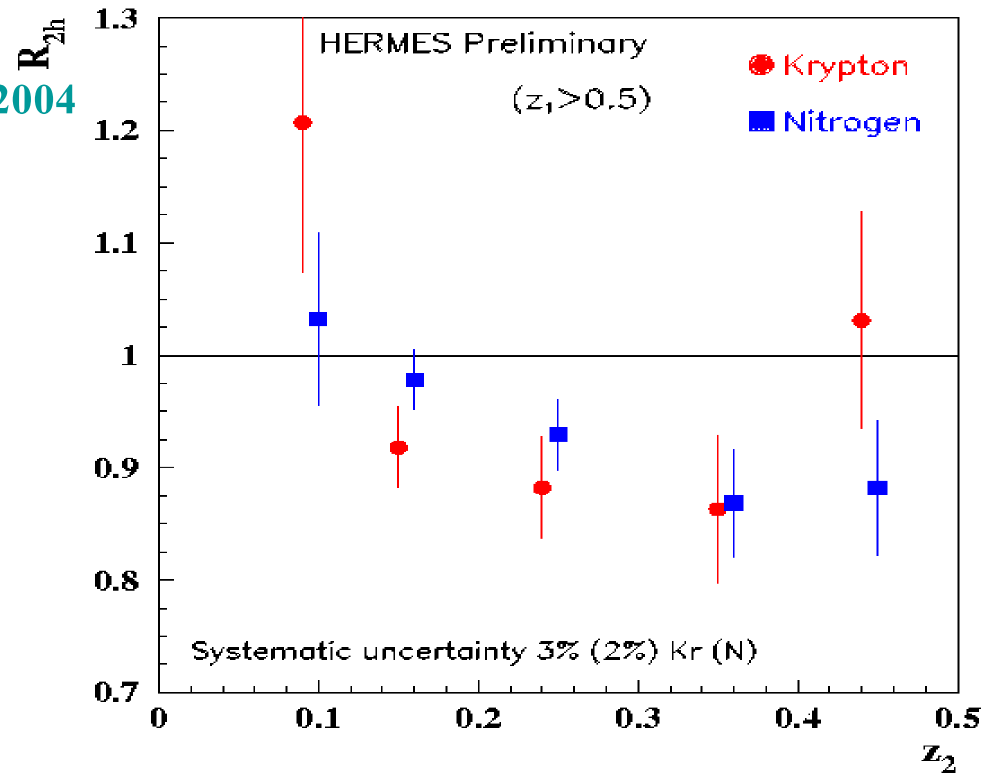
- *Near side, central Au+Au unchanged*

Some variation with centrality and flavour of trigger

RESULTS FROM HERMES, DIS on cold nuclei



P. Di Nezza @ QM2004



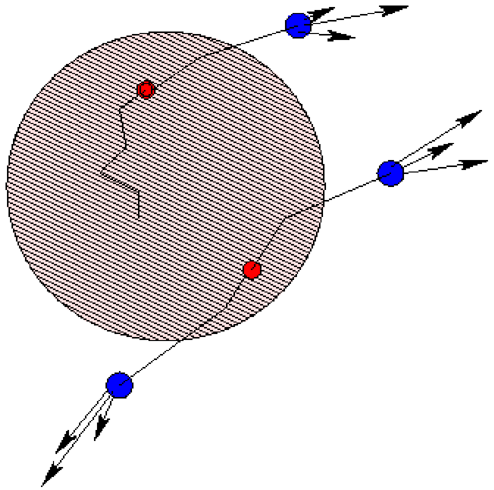
- *Always measure a ratio of double to single production*
- *Divide by same ratio in deuterium to remove detector systematics*

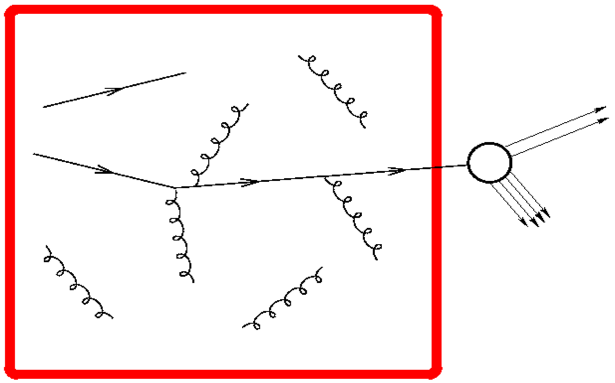
$$R_{2h} = \frac{\frac{No.\ of\ events\ with\ at\ least\ 2\ hadrons\ with\ z_1 > 0.5}{No.\ of\ events\ with\ at\ least\ one\ hadron\ with\ z > 0.5}}{same\ ratio\ on\ deuterium}$$

TWO POSSIBILITIES !

PARTONIC ENERGY LOSS :

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





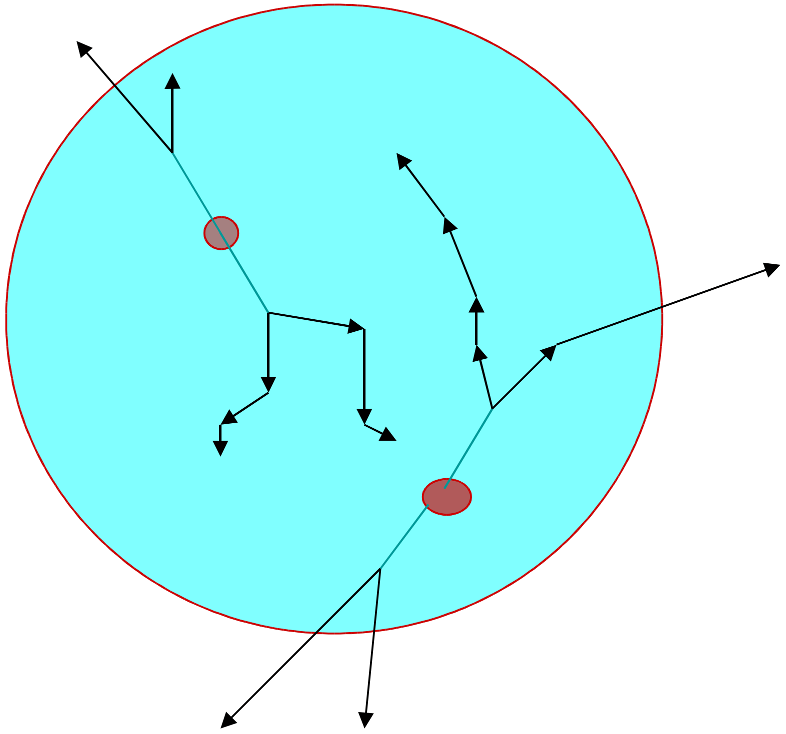
- *Lose energy by partonic interaction, medium may be hadronic or partonic*
- *Emerge as partons and then fragment*
- *Require knowledge of single and double fragmentation functions*

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

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

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!)

- ***NOTE! IN THIS CASE DONT NEED A $D(z_1, z_2)$***
- ***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***

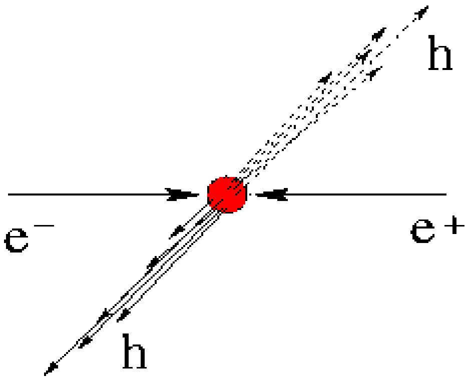
$$\frac{P(1,2)}{P(1)} = \frac{P(1)P(2)}{P(1)} = P(2) = sp(2) = s\,\frac{p(1)p(2)}{p(1)}$$

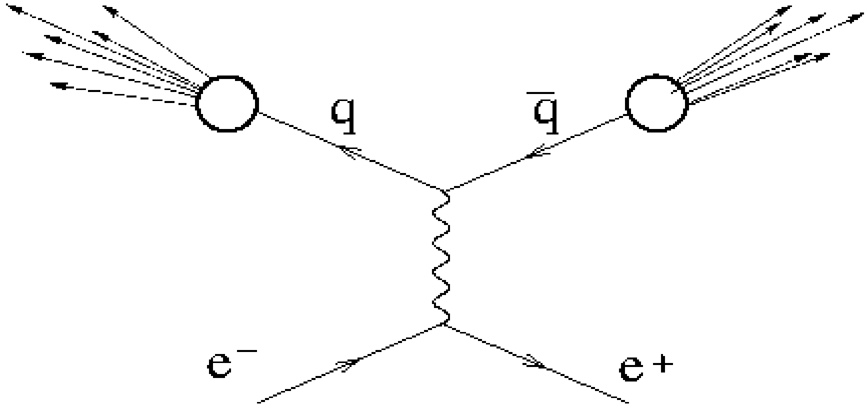
P(h) is for A+A;   p(h) is for p+p

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

Defining the Dihadron fragmentation function!

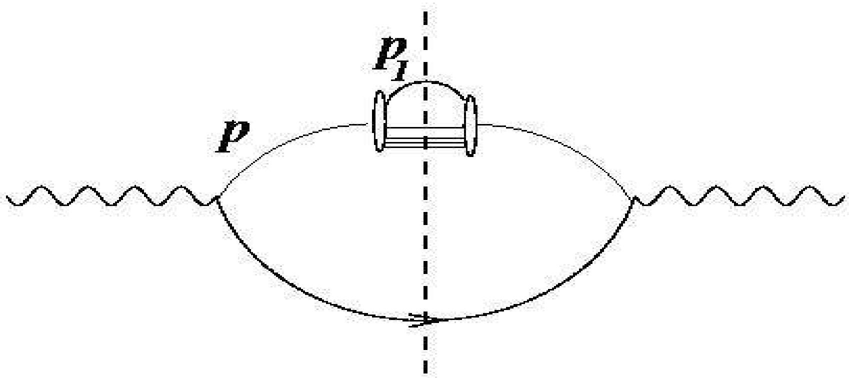
- *Fragmentation functions have to be universal*
- *We need a definition in terms of operators*
- *Start with simple system :* e^+e^-*, is factorization valid*
- *Derive evolution (vacuum splitting functions)*
- *Measure at* μ *and predict its evolution to scale Q*

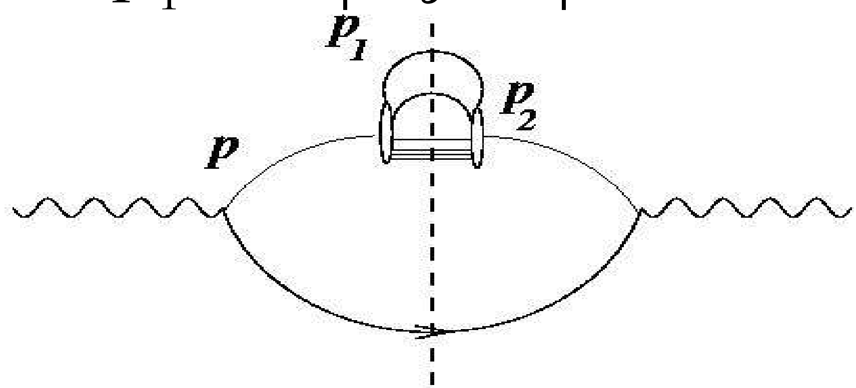




$$W^{\mu\nu} = \sum_{S-1} e_q^2 \int \frac{d^3 p_1 d^3 k}{4 E_1 E_k (2\pi) 6} (2\pi)^4 \delta(q - p_1 - k - \sum_{s-1} p_f)$$

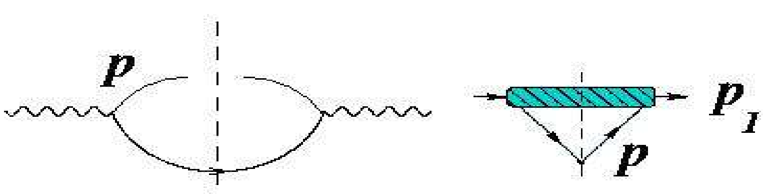
$$< 0 \left| \bar{\psi} \gamma^\mu \psi \right| k\, p_1\, S-1 > < k\, p_1\, S-1 \left| \bar{\psi} \gamma^\nu \psi \right| 0 >$$

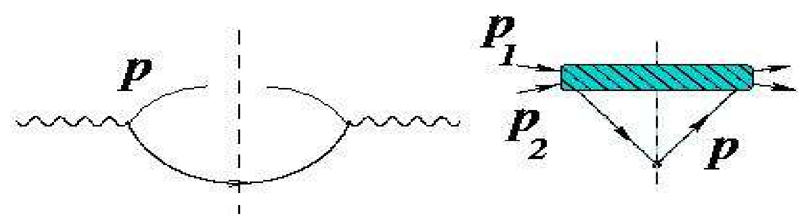




Collinear approximation: $p_h^+, p^+, p_1^+, p_2^+ >> p_h^-, p^-, p_1^-, p_2^-, p_{perp}$

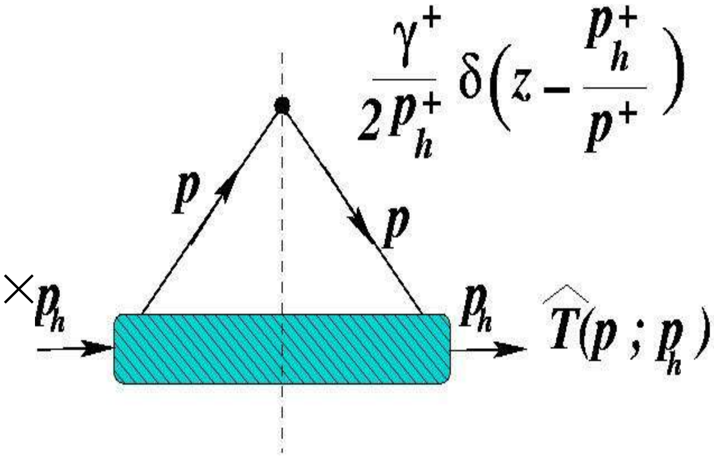
Can factorize matrix elements from hard part: $Tr[\gamma^\alpha p_\alpha \gamma^\mu \gamma^\beta k_\beta \gamma^\nu] Tr[\frac{\gamma^+}{2p^+} \hat{T}]$





Use of universal single and double fragmentation functions defined in e^+e^-

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

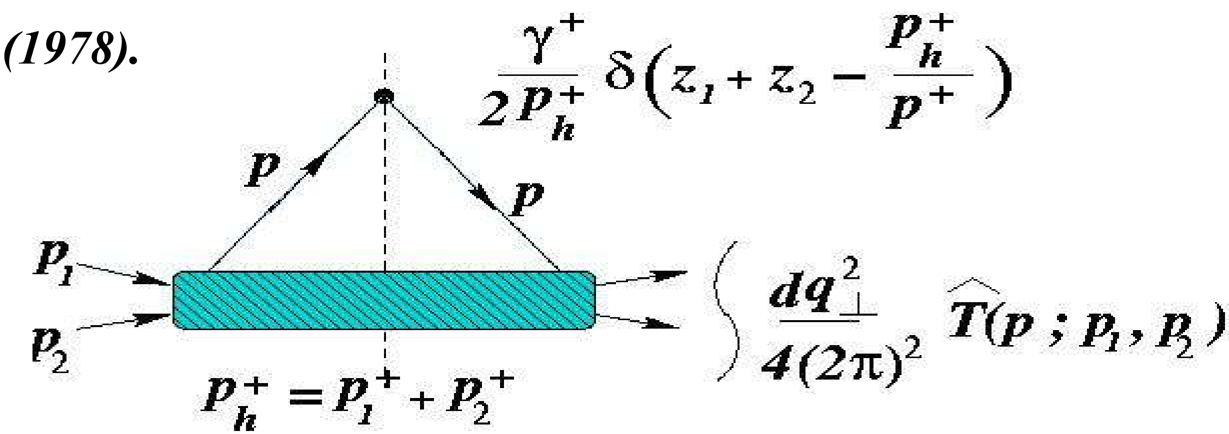


where $$\hat{T}_q(p,p_h)=\int d^4x\, e^{-ip\cdot x}\sum_{S-1}\langle 0|\psi(0)|p_h,S-1\rangle\langle p_h,S-1|\bar{\psi}(x)|0\rangle$$

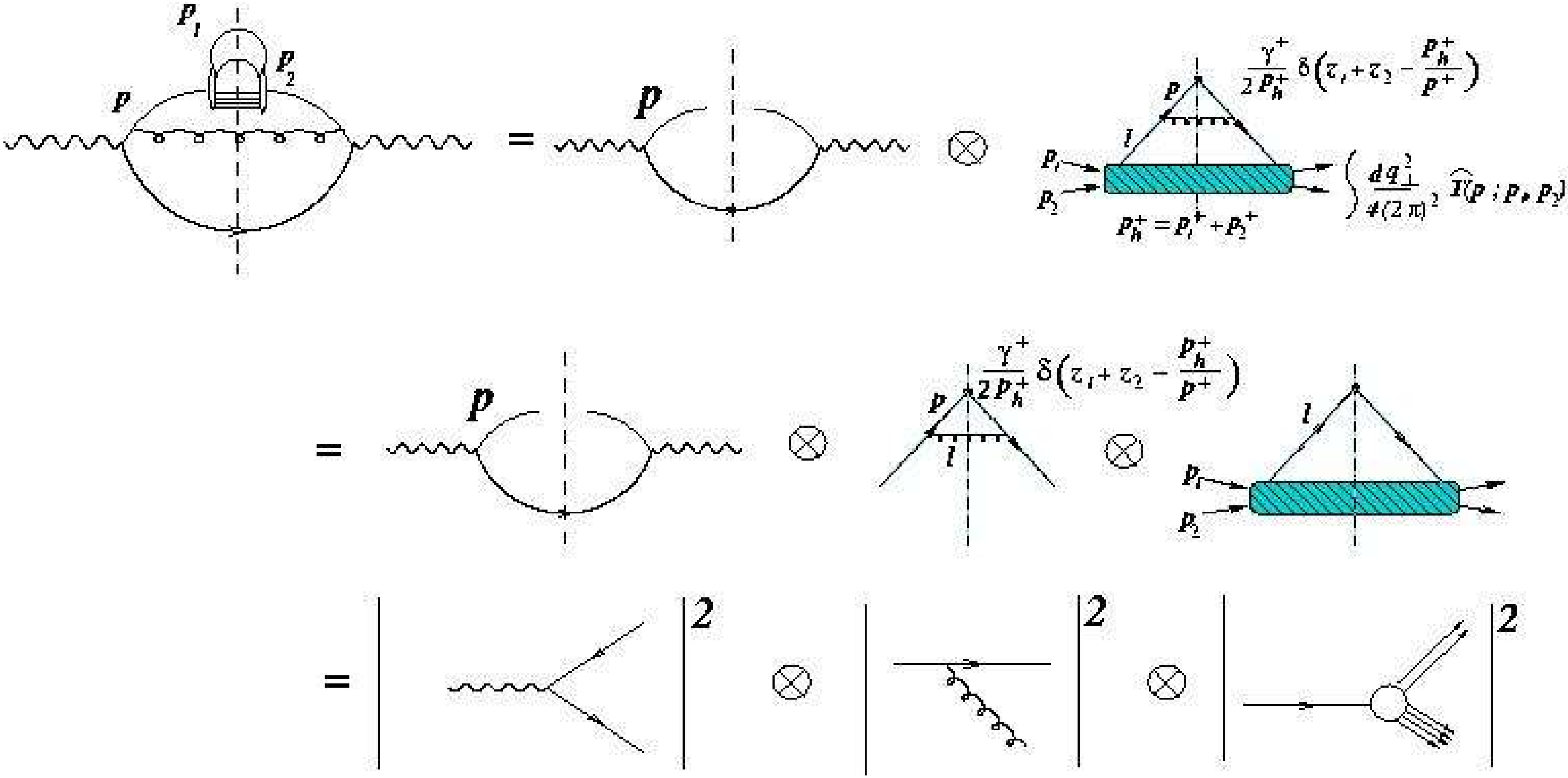
$$D_q(z_1,z_2)=\int\frac{dq_\perp^2}{8(2\pi)^2}\frac{z^4}{4z_1z_2}\int\frac{d^4p}{(2\pi)^4}Tr\left[\frac{\gamma^+}{2p_h^+}\delta\left(z_1+z_2-\frac{p_h^+}{p^+}\right)\hat{T}_q(p,p_1p_2)\right]$$

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

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

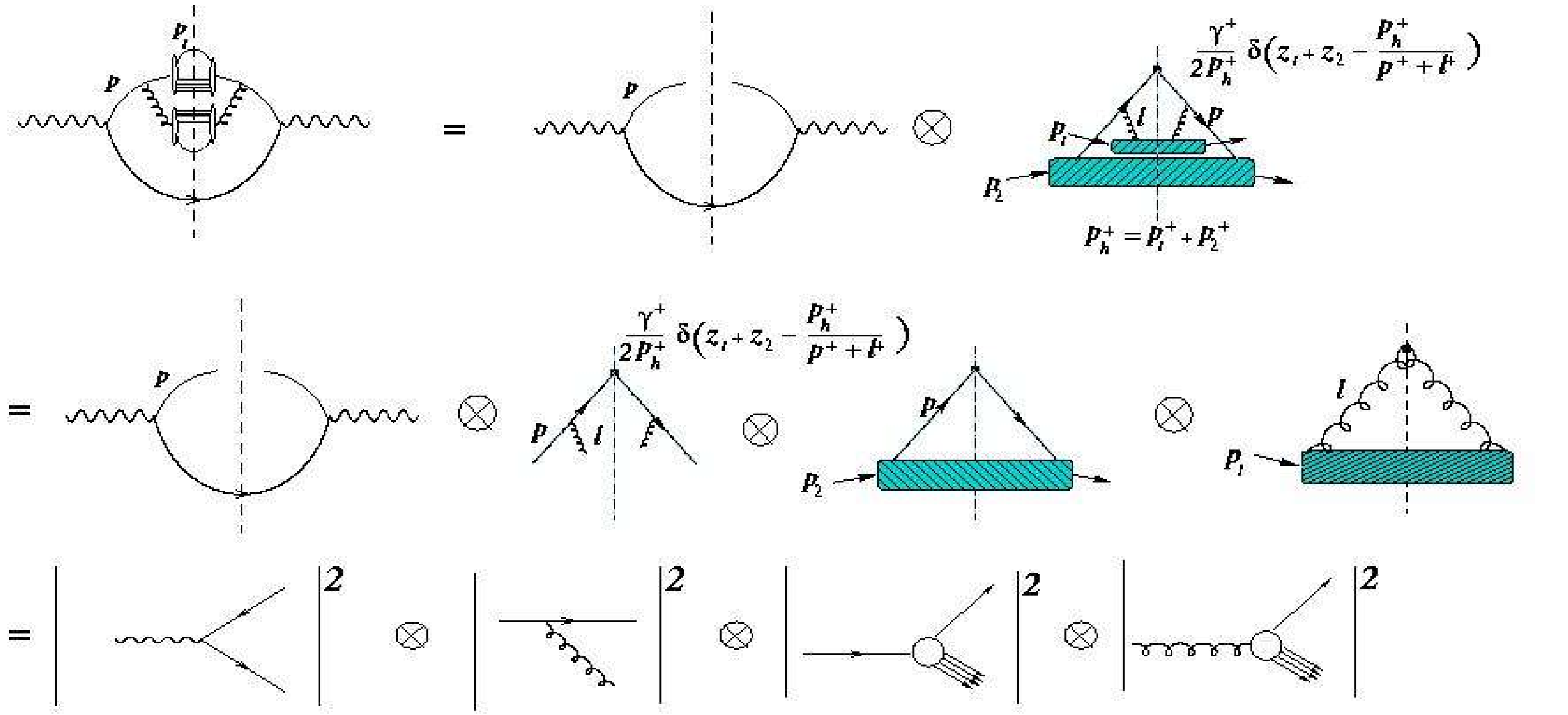


NLO contribution from quark dihadron fragmentation function



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

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 $\lambda^2_{QCD} \ll \mu^2 \ll Q^2$

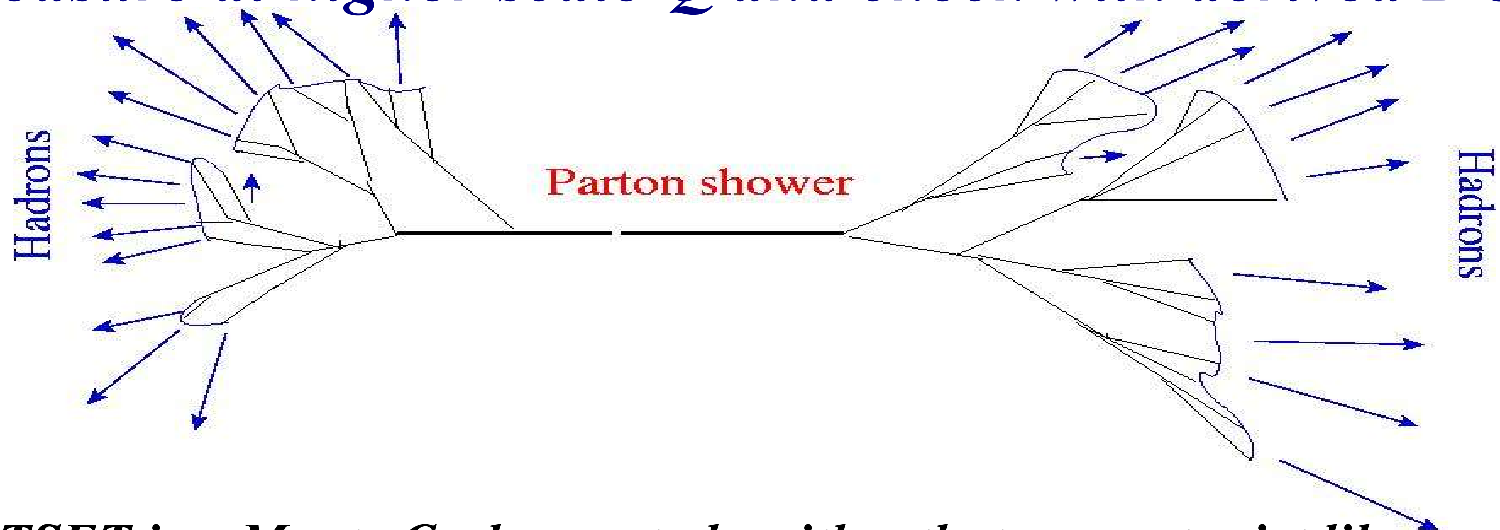
Measure the function at the scale μ, can be done in 2 ways

$$Factorized\ Distribution: D(z_1, z_2, \mu) = D(z_1, \mu) D(z_2, \mu)$$

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

Evolution of full quarks and gluons

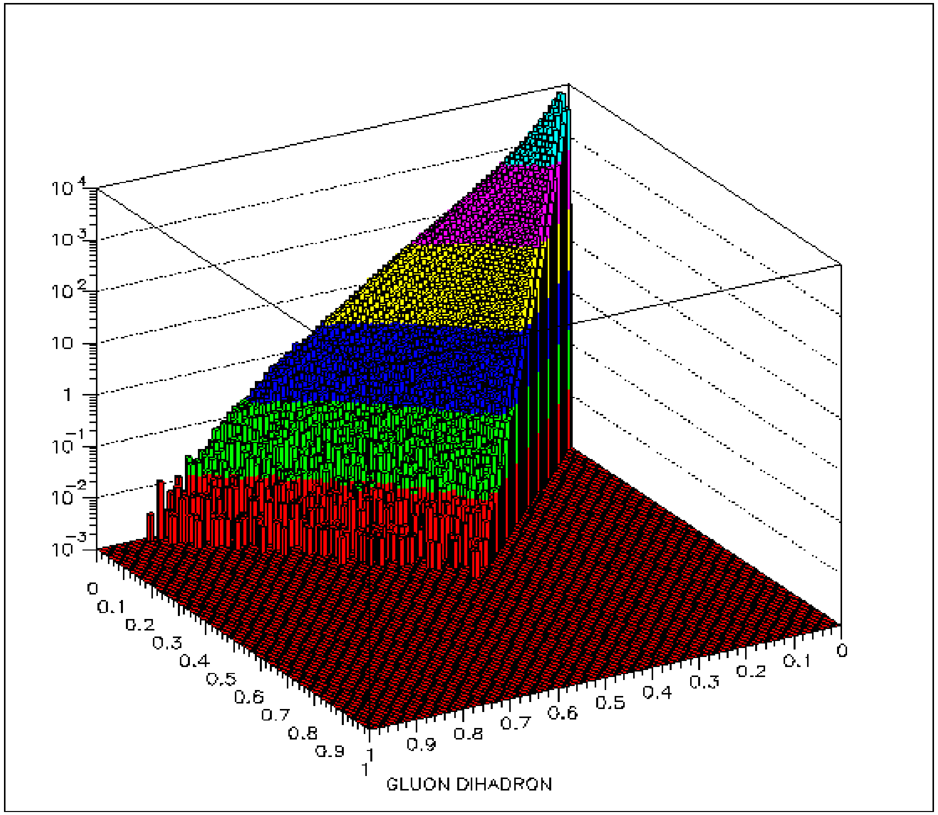
- ***No experimental data to date on dihadron frag. In*** e^+e^-
- ***Phenomenological event generators can explain most data!***
- ***Most successful of these is JETSET***
- ***Use a tuned JETSET to measure dihadrons at scale*** μ
- ***Measure at higher scale Q and check with derived DGLAP***

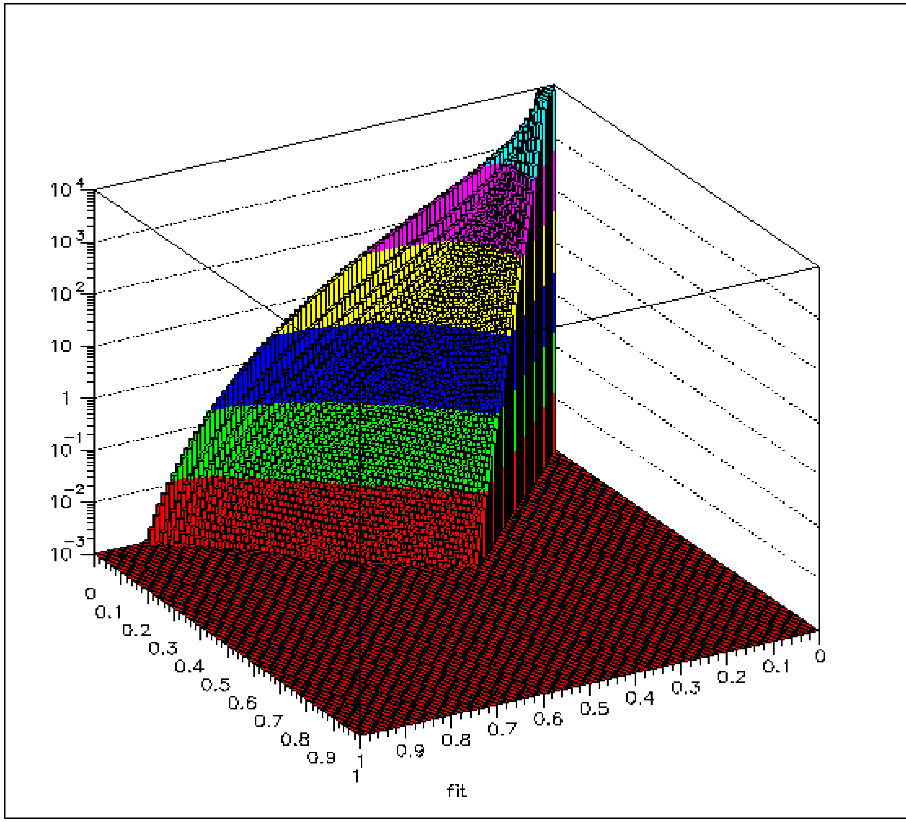


JETSET is a Monte Carlo event algorithm that generates jet like events with a parton shower followed by a string fragmentation routine to get hadrons. It has many parameters tuned to fit almost all experimental data.

Results from Event generators:

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





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

Modification in vacuum = DGLAP evolution

Non-singlet quarks $D_{NS} = D_q - D_{\bar{q}}$

Simpler: contribution from gluon fragmentation cancels out

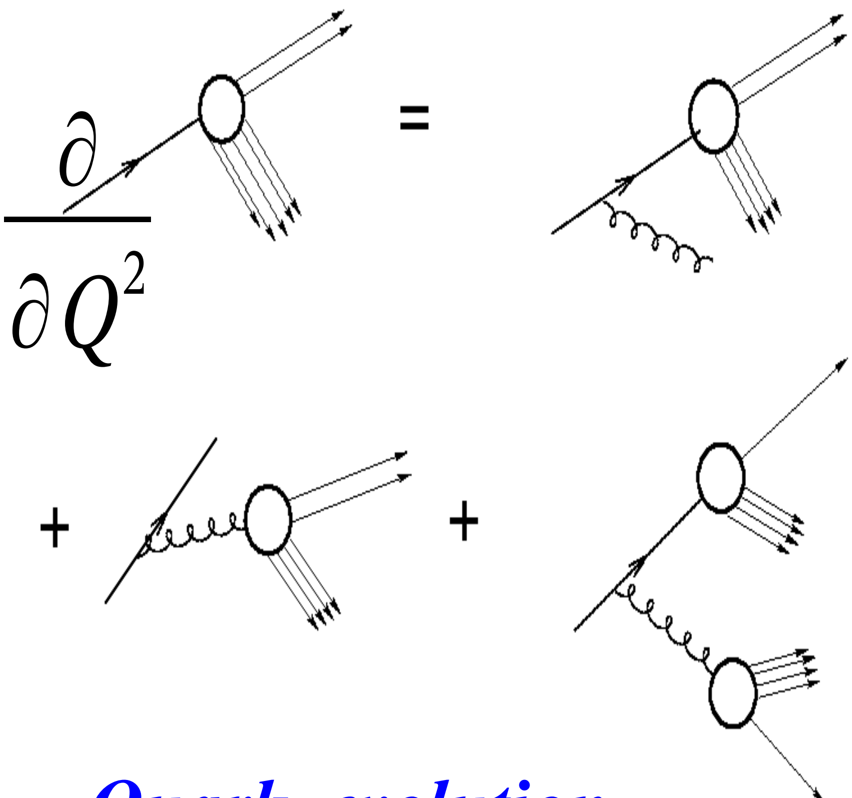
$$\text{Single evolution}: \frac{\partial D_{NS}(z, Q^2)}{\partial \log Q^2} = \int_z^1 \frac{dy}{y} P_{q\to qg}(y) D_{NS}(z/y, Q^2)$$

$$\text{Double evolution}: \frac{\partial D_{NS}(z_1, z_2, Q^2)}{\partial \log Q^2} = \int_{z_1, z_2}^1 \frac{dy}{y^2} P_{q\to qg}(y) D_{NS}(z_1/y, z_2/y, Q^2)$$

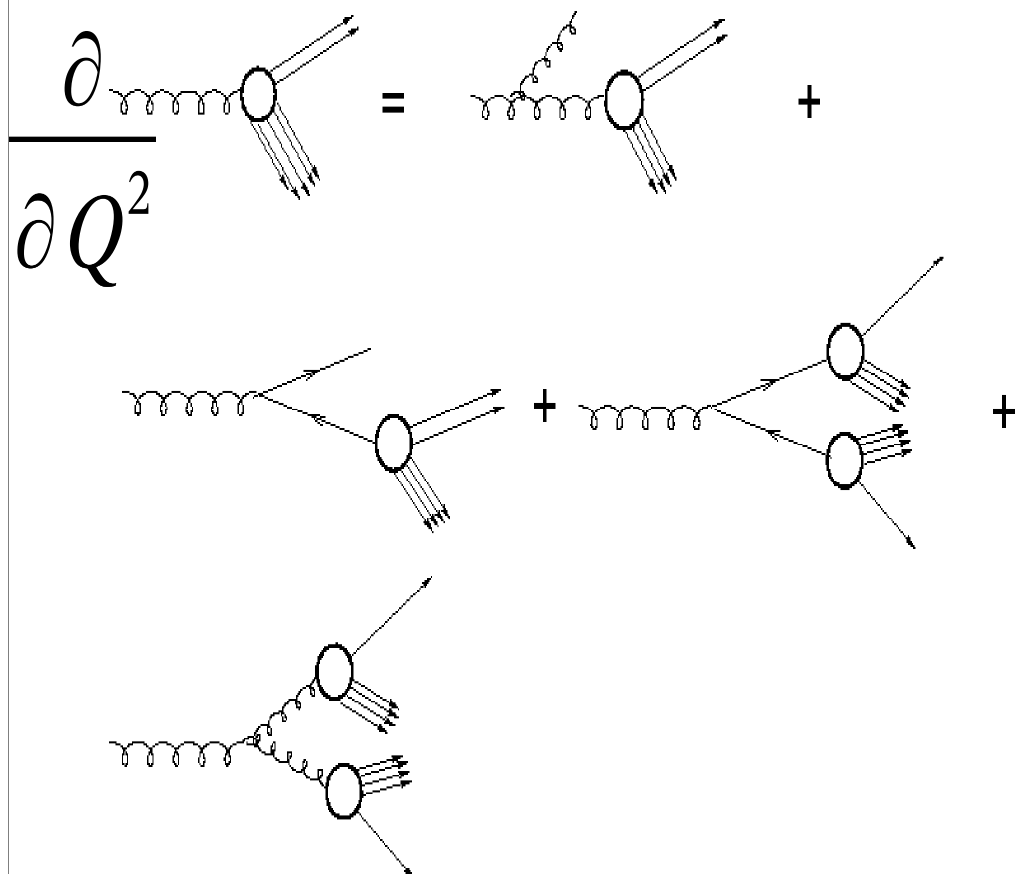
$$+ \int_{z_1}^{1-z_2} \frac{dy}{y(1-y)} \hat{P}_{q\to qg}(y) D_q(z_1/y, Q^2) D_g(z_2/(1-y), Q^2)$$

$$\hat{P} = P - \text{virtual corrections}$$

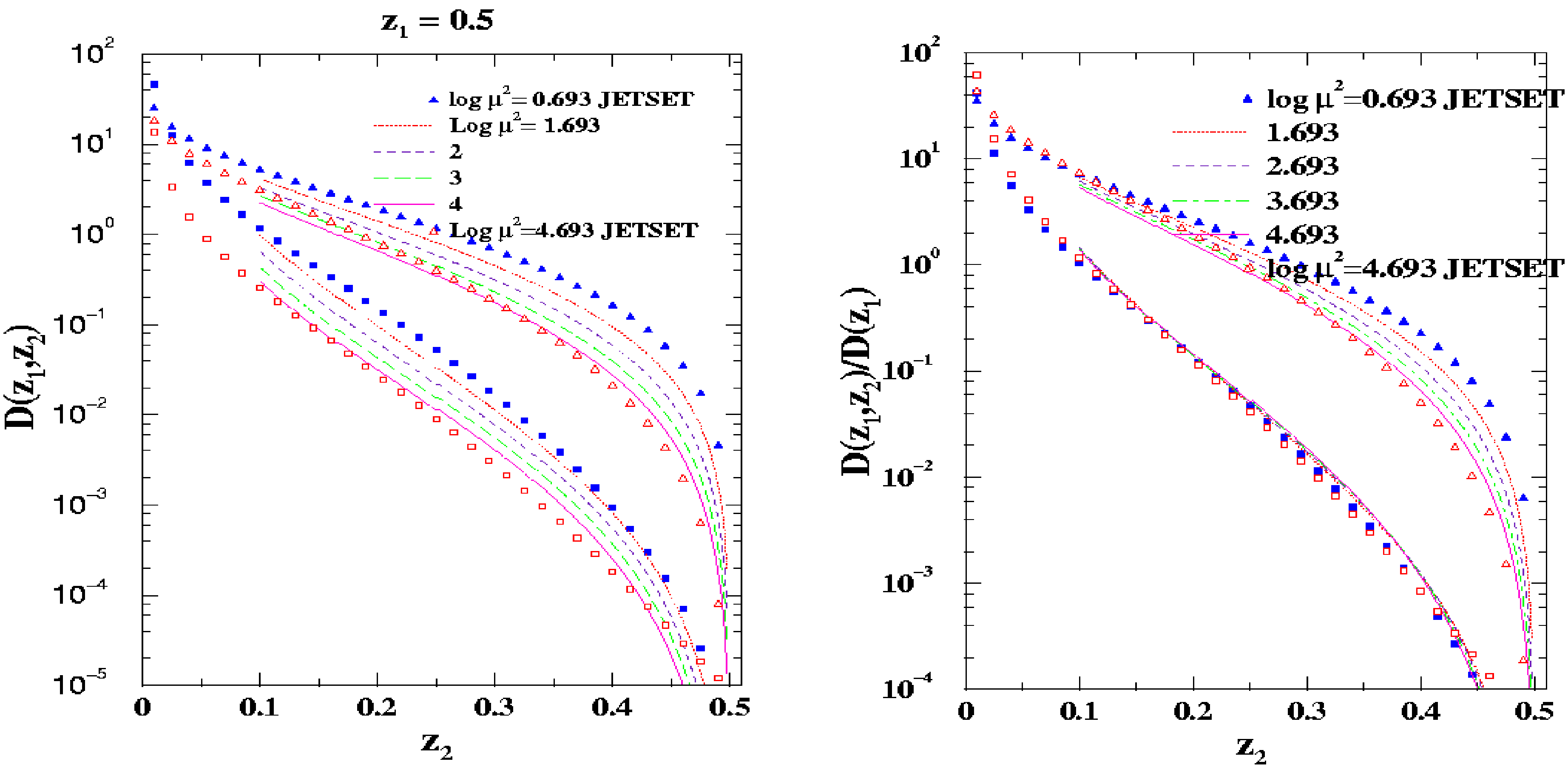
- *Evolving to a higher scale Q ☞ solving DGLAP equations*
- *Set of coupled differential equations containing the following processes: for quarks and gluons..*



Quark evolution



Gluon evolution



Quark and Gluon evolution fits event generator data very well!

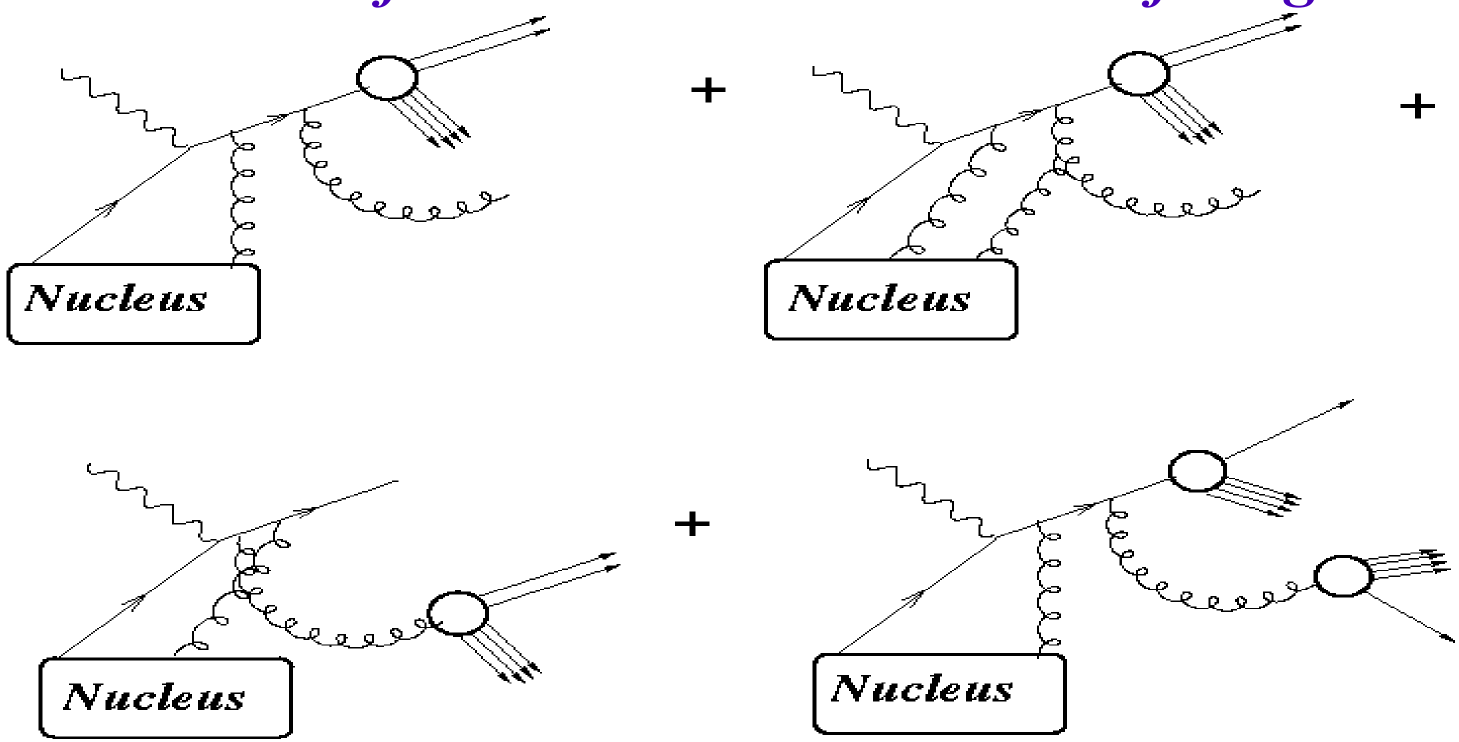
Thus we can understand evolution of DFF from QCD.

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!

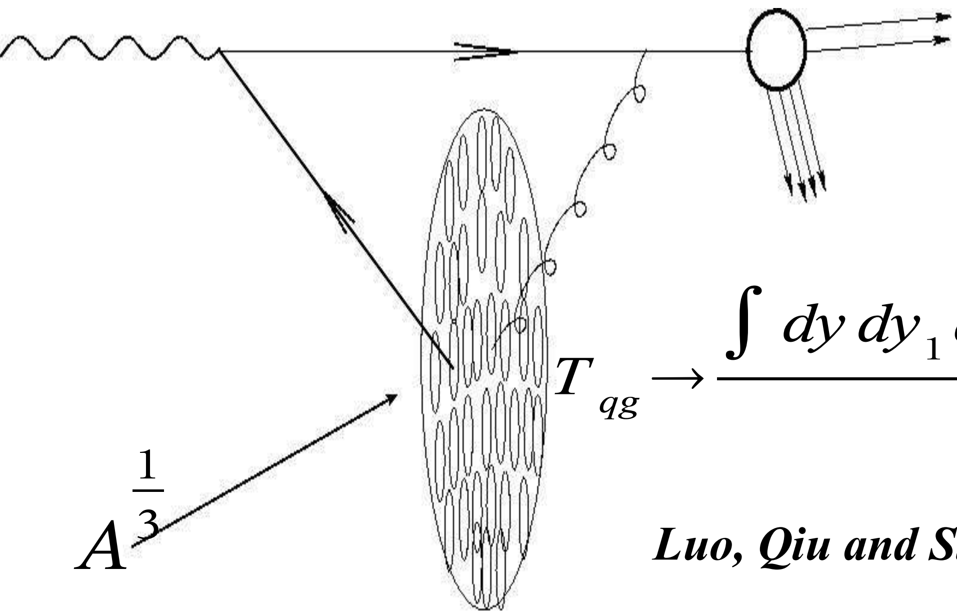


DIS followed by di hadron fragmentation from a large nuclei may be generally expressed as

$$\frac{d^2 W^{\mu\nu}}{dz_1 dz_2} = \int dx\, f_q^A(x)\, H^{\mu\nu}\, \tilde{D}^{h_1 h_2}(z_{1,}\, z_2)$$

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

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



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

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

Results for DIS on Nuclei: energy loss in cold matter

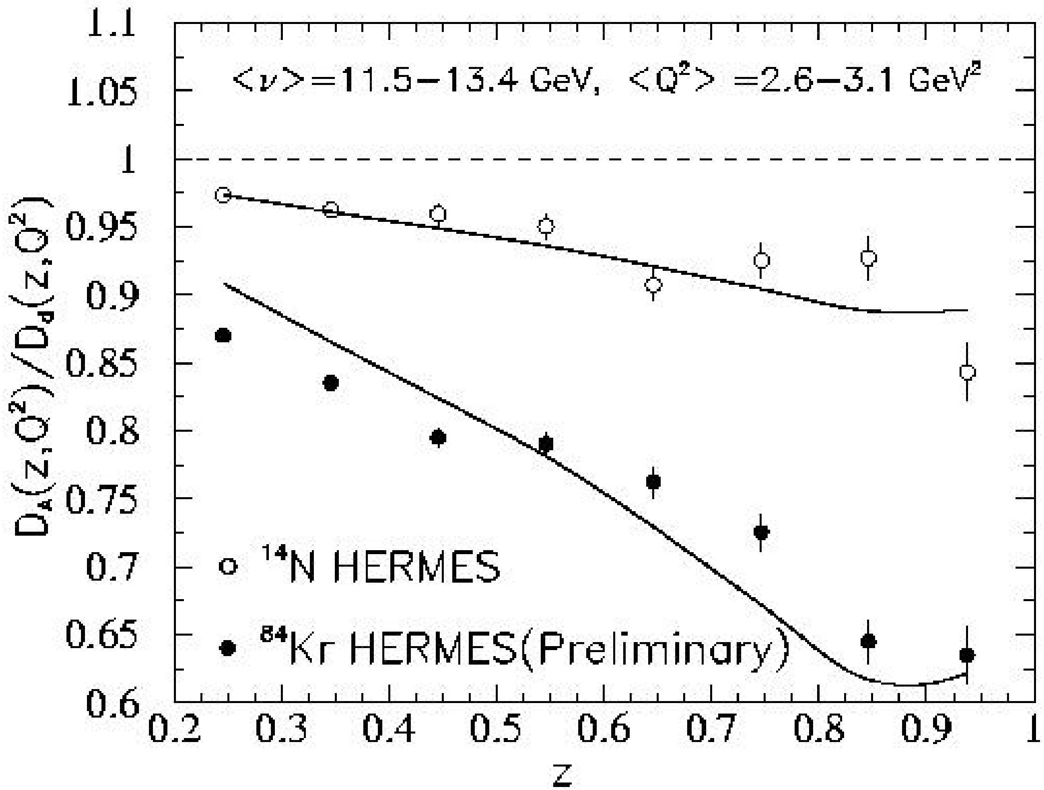
Single inclusive suppression

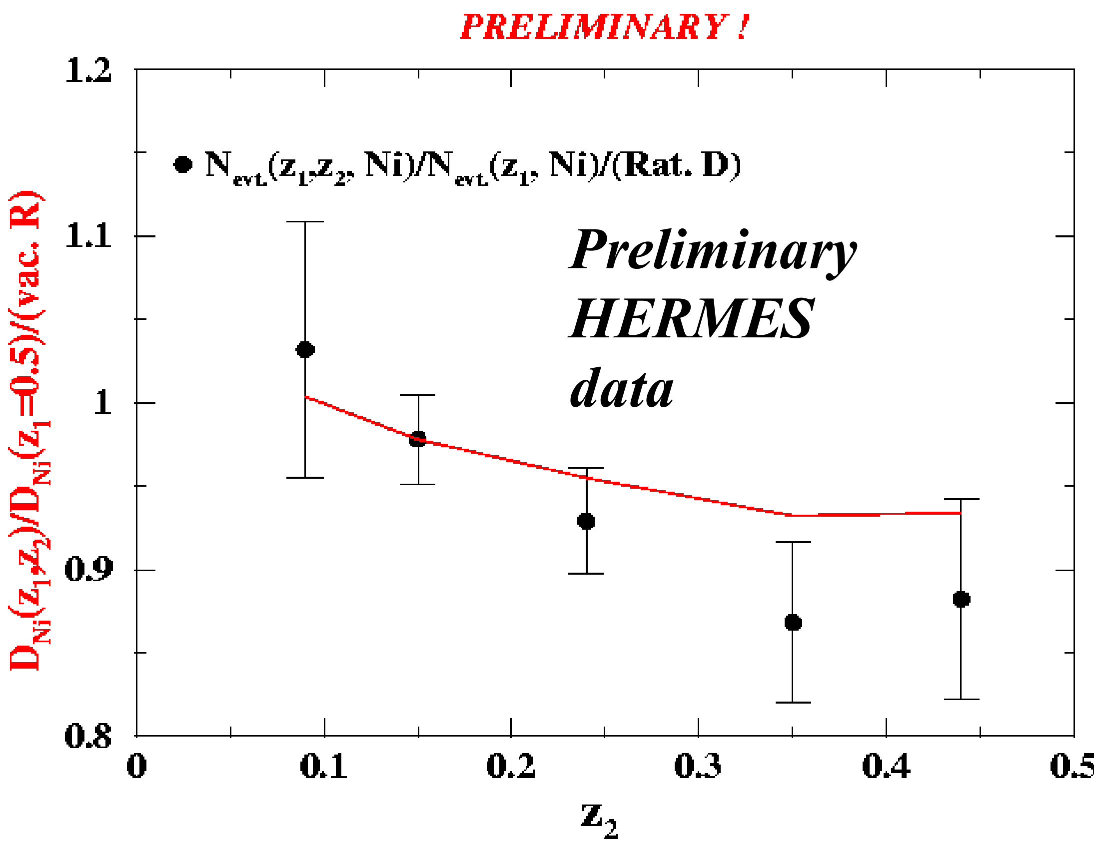
Gaussian distribution of nucleons used

Very good agreement with data

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 $z_1 > 0.5$.

Gaussian approx. for nuclear density used!

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

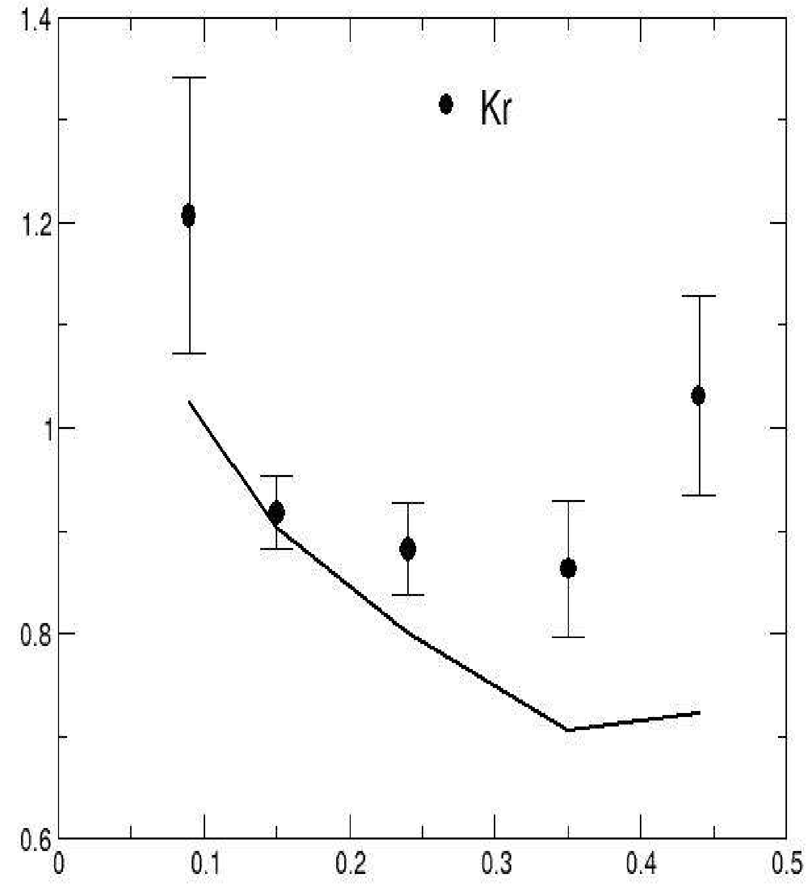
$$\textit{Expt ratio} = \frac{\dfrac{\text{No. of events with at least 2 hadrons with } z_1 > 0.5}{\text{No. of events with at least one hadron with } z > 0.5}}{\text{same ratio on deuterium}}$$

Gaussian approximation not so good for large Nuclei like Kr.

Hard sphere works better!

Remember, no free parameters used in plot

dE/dx = 0.5Gev/fm



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

Medium modification in a deconfined medium

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

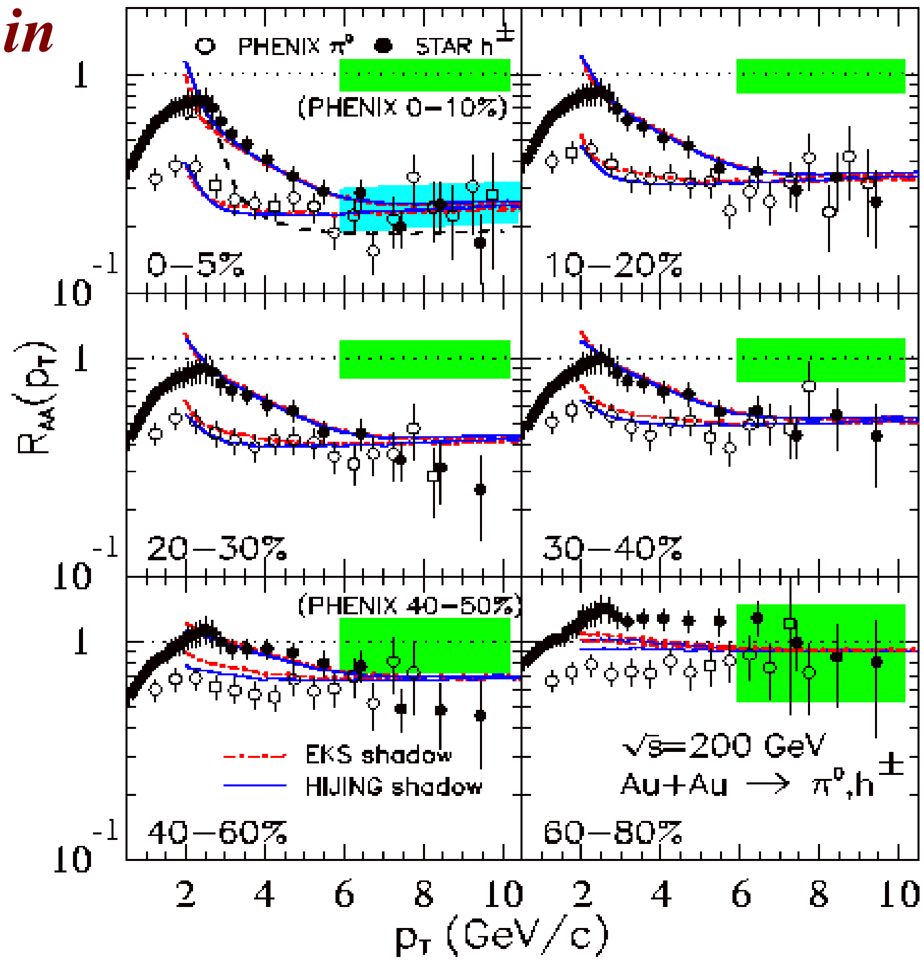
X.N.Wang, \nucl-th 0305010

Calculate medium modification in a 1-D expanding medium,

Dial up gluon density to get suppression.

Gluon density proportional to number of participants

dE/dx ~ 14 GeV/fm

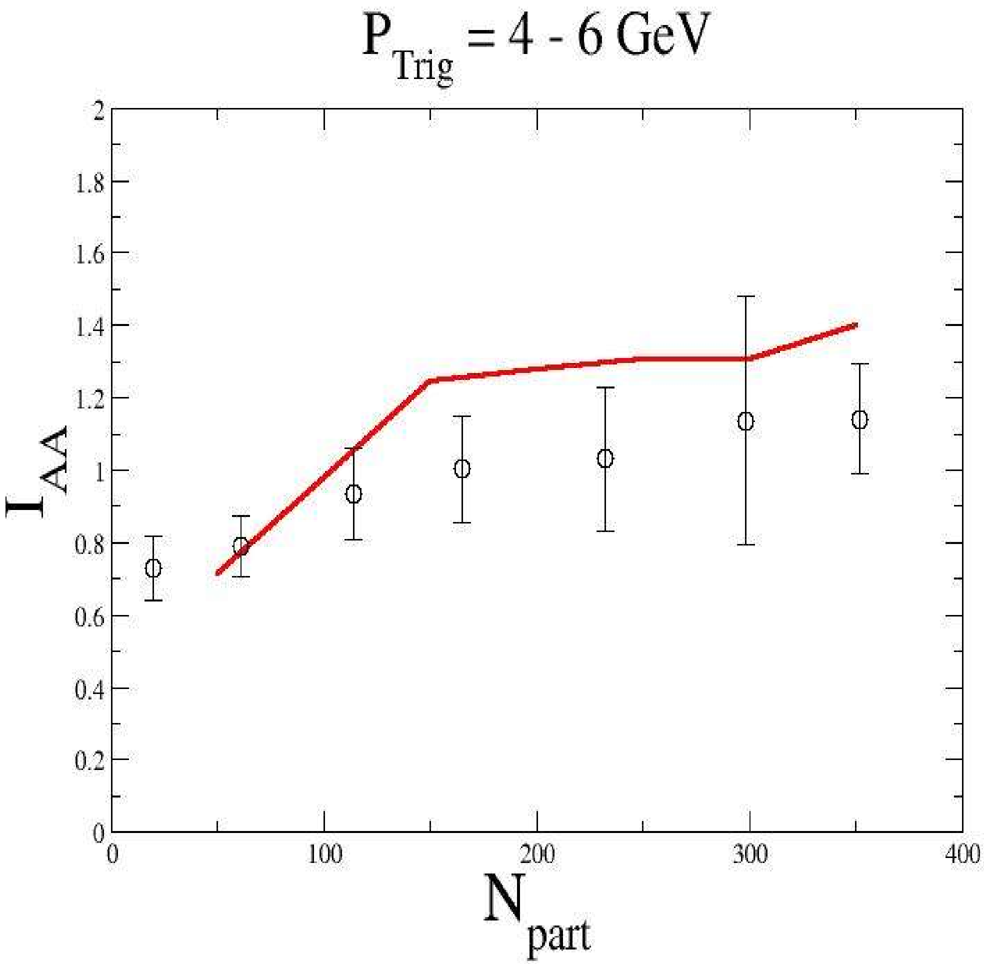


Dihadron results for hot medium

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!

- *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.*
- *Defined a new object: Dihadron fragmentation function*
- *Medium modification from A enhanced power corrections in DIS*
- *Extended formalism to modification in hot matter*

Back Up ..

Medium modification

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

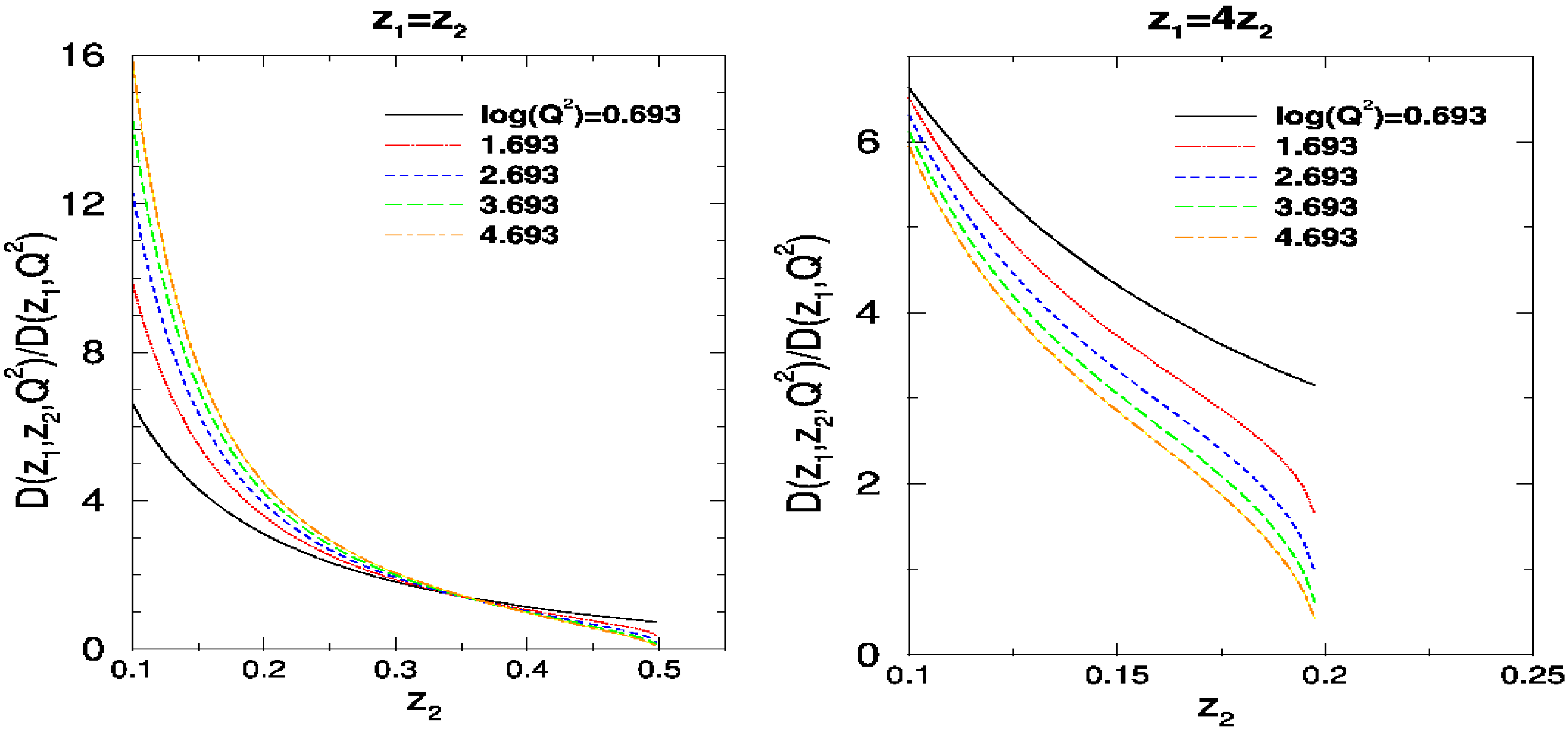
The medium modification equation looks very similar to the vacuum evolution equation...

$$\tilde{D}_q(z_{1,}z_{2,}\mu^2)=D_q(z_{1,}z_{2,}\mu^2)+\int dl_T\int_{z_1+z_2}^{1}\frac{dy}{y^2}\tilde{P}_{q\to qg}(y)D(z_1/y,z_2/y,\mu^2)$$

$$+\int dl_T\int_{z_1}^{1-z_2}\frac{dy}{y(1-y)}\hat{\tilde{P}}_{q\to qg}(y)D(z_1/y,\mu^2)D(z_2/(1-y),\mu^2)$$

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

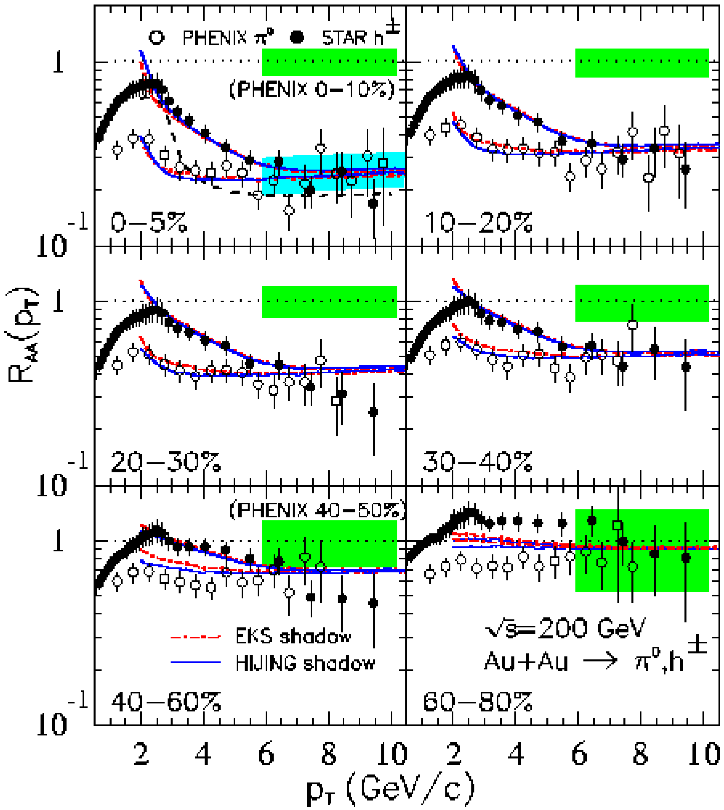
$$\tilde{P}=medium\,modified\ splitting\ function$$



Measure the function at the scale μ, from JETSET

JETSET is a Monte Carlo event algorithm that generates jet like events with a parton shower followed by a string fragmentation routine to get hadrons. It has many parameters tuned to fit almost all experimental data.

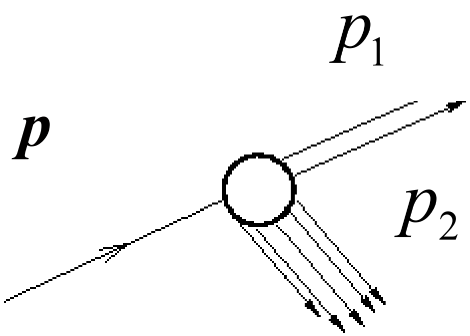
- ***Partonic energy loss models explain single inclusive suppression pretty well !***
(GLV, BDMPS, WGZ, SW)



All models require a high density of scattering centers
High density seen as evidence of QGP.

To explain double inclusive spectra requires a new phenomenological object: Dihadron fragmentation function!

$$D_{q,g}^{h1h2}(z1, z2)$$

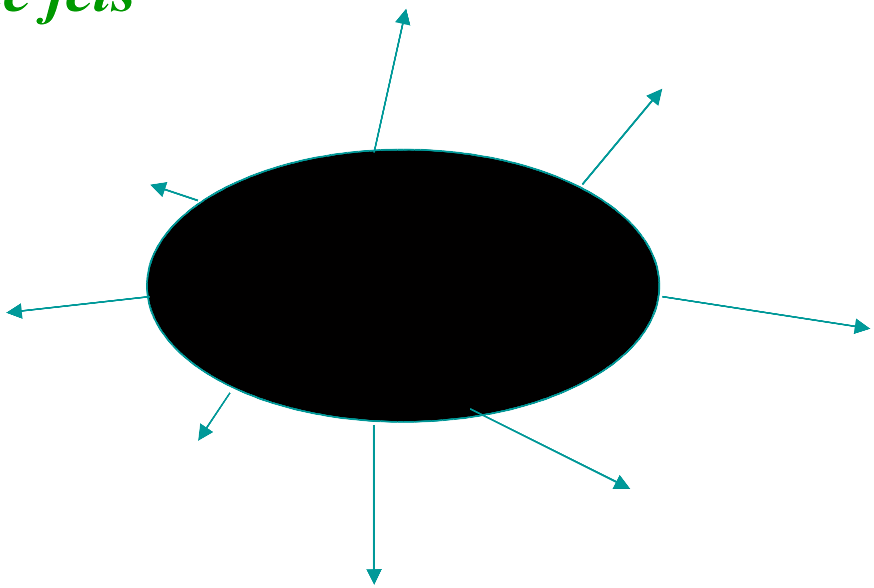


$$z_1 = \frac{p_1^+}{p^+}$$

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

SURFACE EMISSION PICTURE

- ***Suppose the matter produced is very opaque***
- ***Hence only hard collisions on the surface will produce observable jets***



- ***Inconsistent with an R_{AA} near participant scaling***
- ***Inconsistent with all energy loss models which require bulk emission and fit single inclusive data!***

How does partonic interaction effect dihadrons?

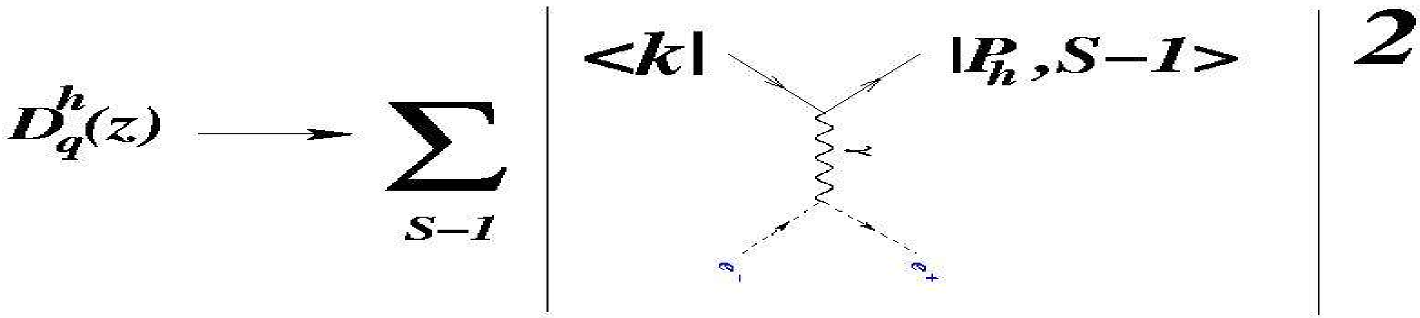
- *Important to A+A, d+A, DIS and* $e^+ e^-$ *experiments.*
- *To date observations in A+A d+Au and DIS*

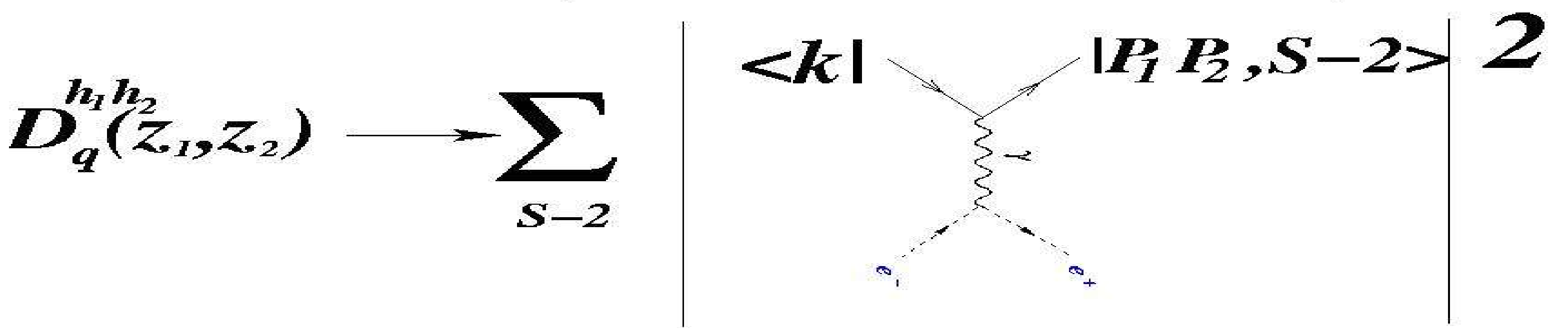
Wish List!

- *Definition and factorization of fragmentation functions*
- *Calculate the effect of medium modification*
- *Requires the evaluation of twist 4 diagrams,*
- *But medium modification similar to vacuum evolution*
- *Calculate and check vacuum evolution first (simpler!)...*

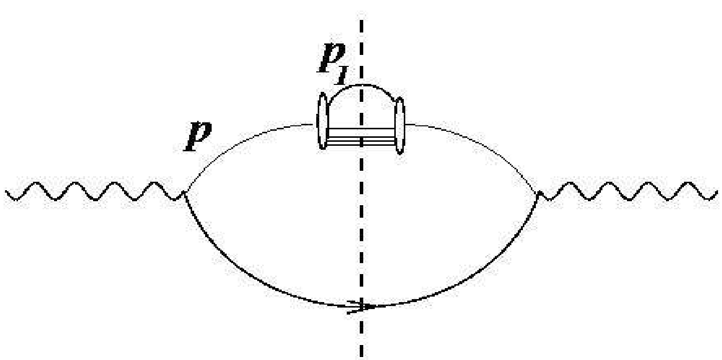
Basic Methodology at L. O. in α_s :

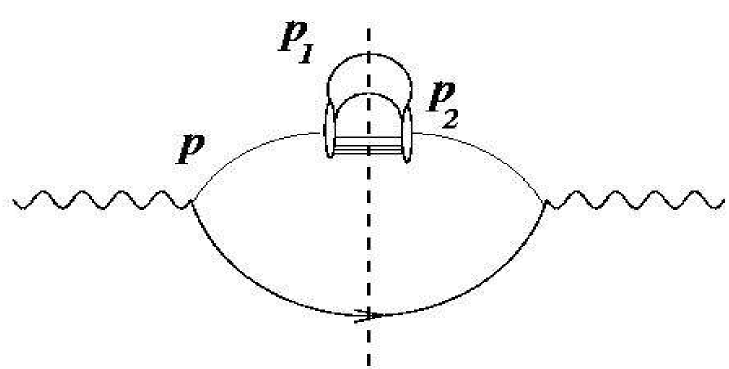
Replace partonic basis with hadronic basis



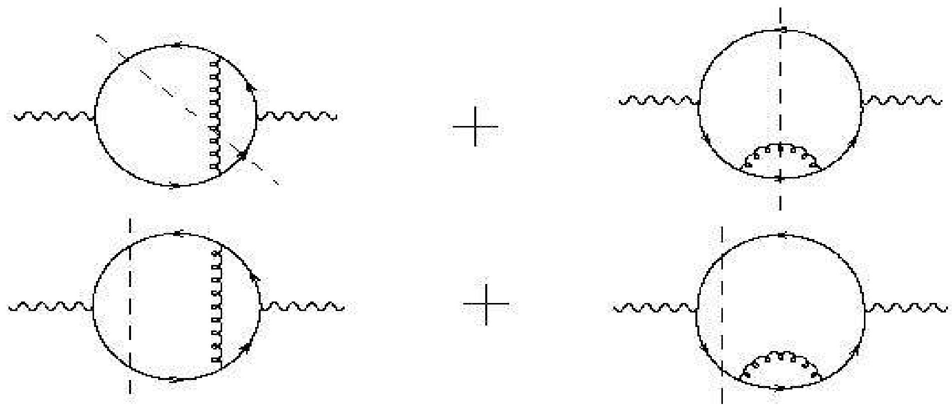


In self-energy diagrams

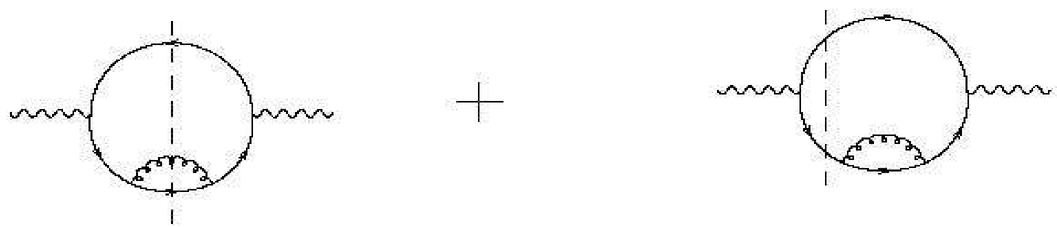




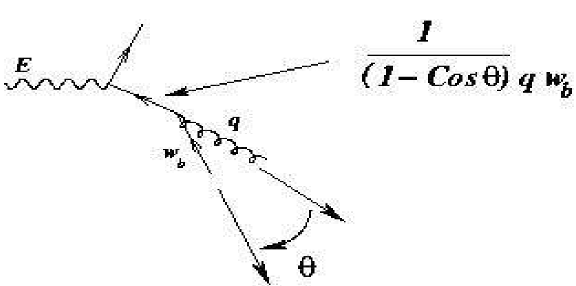
- ***Isolation of matrix element is the first step of factorization***
- ***Calculate higher order corrections and isolate leading log and power contributions. Isolate the hard part.***
- ***Leading log contributions have divergences, absorb into fragmentation functions***



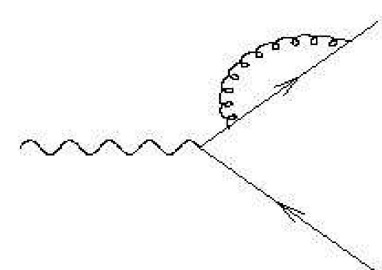
In Light cone gauge, leading log contributions only come form



Infrared and collinear divergences from soft and collinear gluons



Infrared divergences cancelled by self energy diagrams

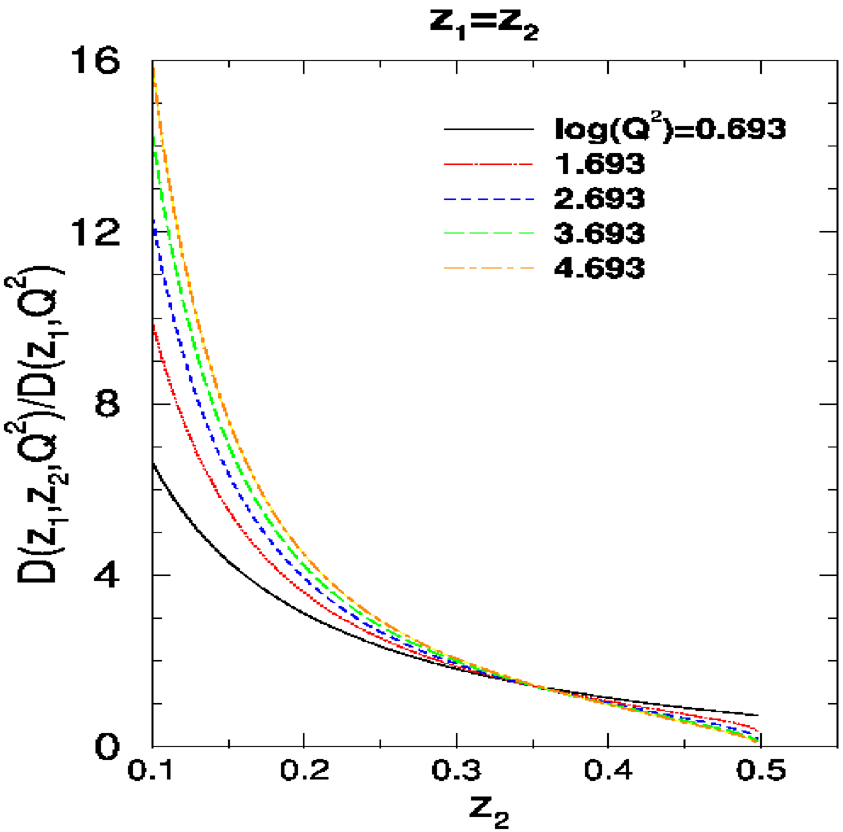


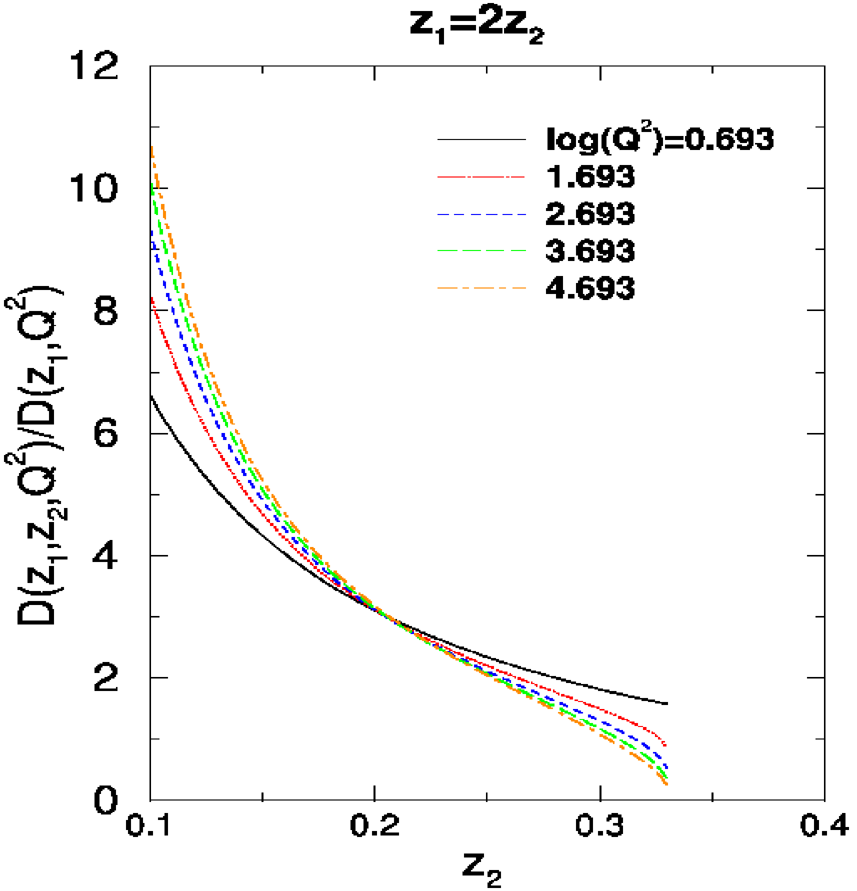
Use factorized distribution for Non-singlet fragmentation function

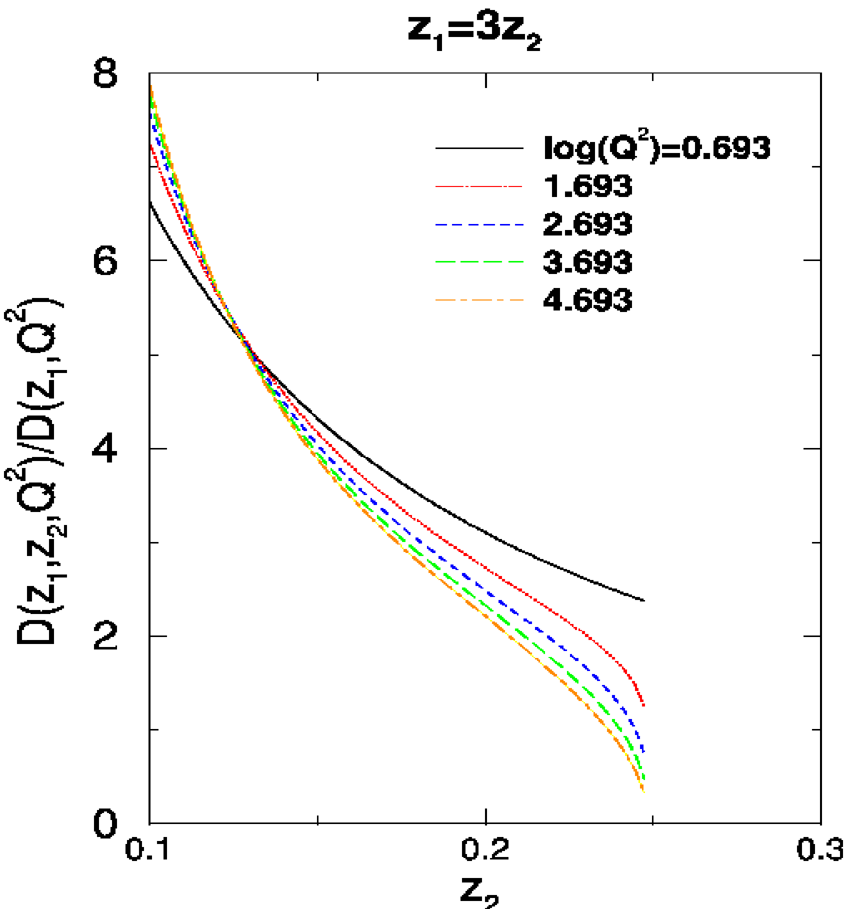
$$Factorized\ Distribution: D(z_{1,} z_{2,} \mu) = D(z_{1,} \mu) D(z_{2,} \mu)$$

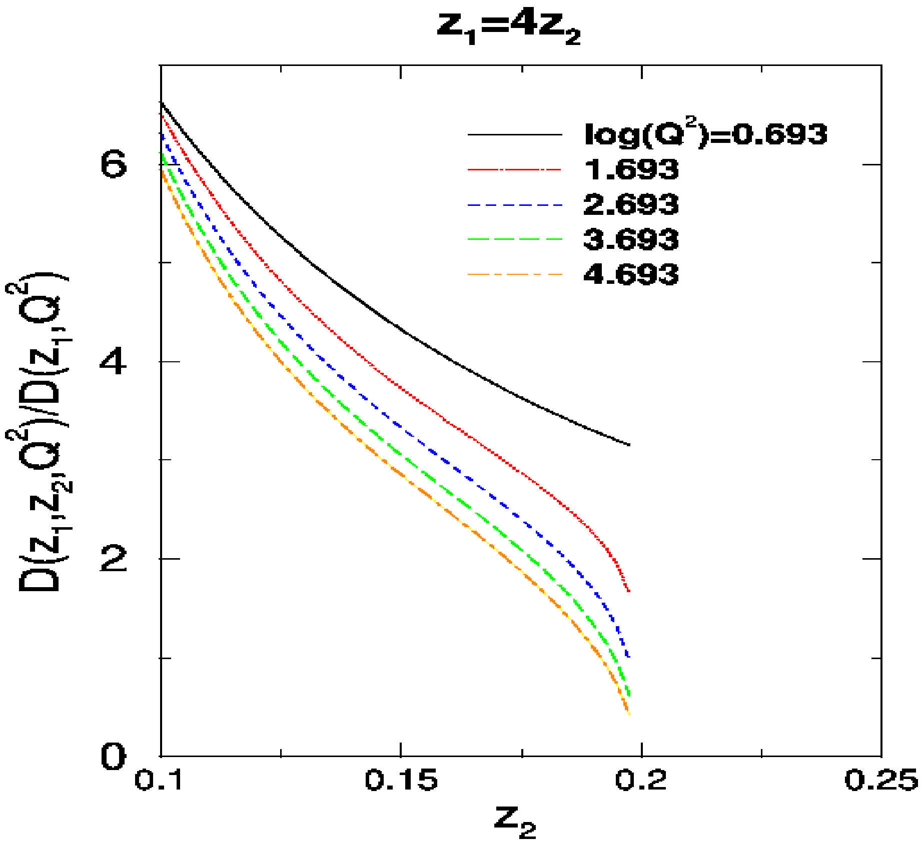
Single fragmentation functions taken from KKB

Plots for z_1/z_2 = 1,2,3,4 $\log(Q^2 = 2 \ldots 110\, GeV^2) = 0.693 \ldots 4.693$









Note: ratio double/single shows little change at intermediate z. Why ?

Ratio is the number of associated particles for given trigger !

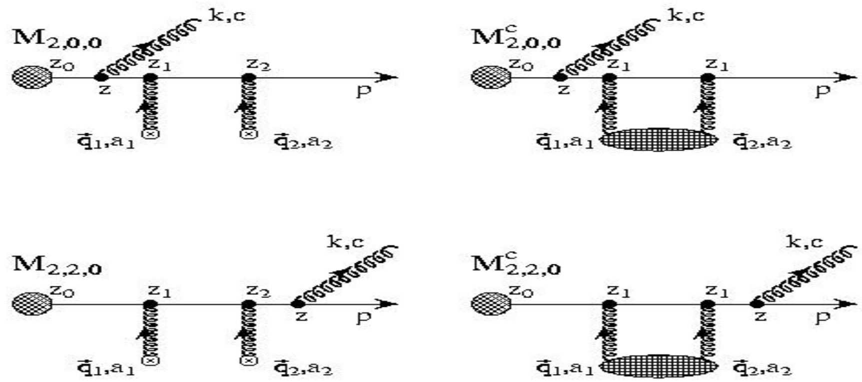
Regular evolution softens the spectrum: as for single hadrons

Single gluon fragmentation increases multiplicity!

CALCULATION OF THE MODIFICATION

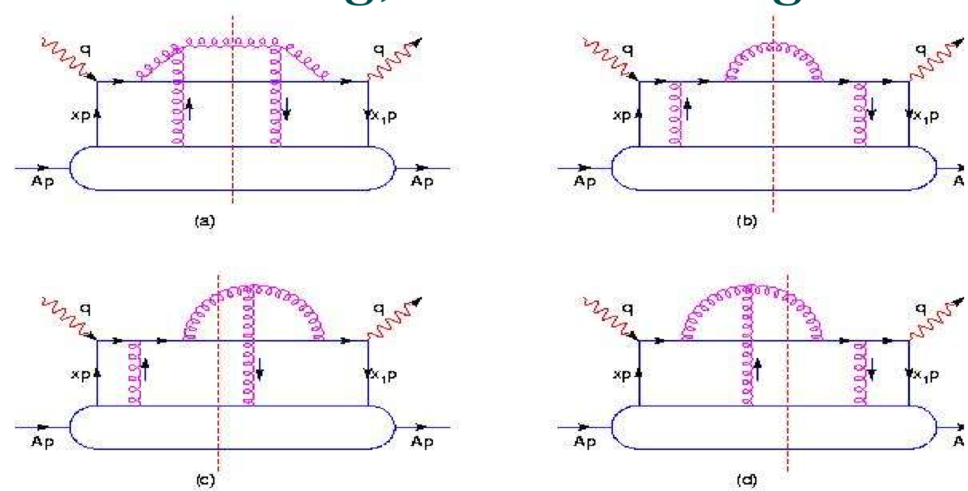
1) Potential scattering model : Gyulassy Wang; Gyulassy Levai Vitev; Weidemann Salgado..

Scattering of static color sources, e-loss by gluon radiation, followed by radiation reinteraction..



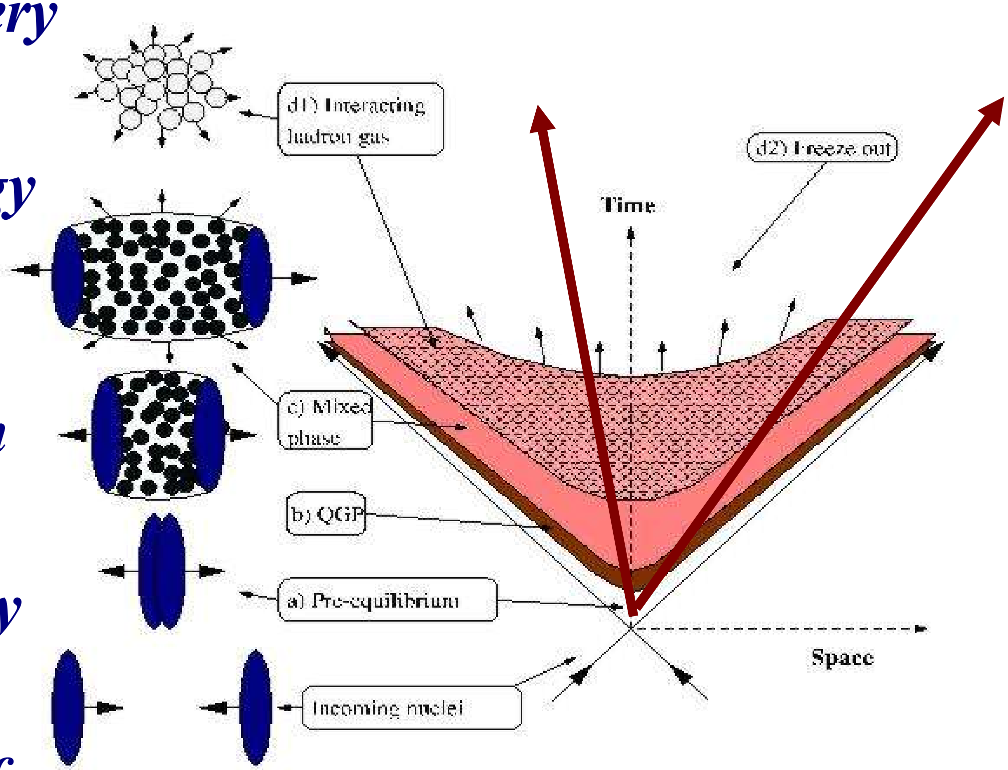
2) Modification of fragmentation function by higher power corrections from the medium: Guo Wang; Osborne Wang..

Based directly on DIS formalism,
Power corrections from structure functions enhanced by size!



HEAVY-ION COLLISIONS AND JETS

- *Collide 2 heavy ions at very high energy.*
- *Given high enough energy density a QGP may be created.*
- *But QGP turns to hadron gas and freezes out.*
- *Occasionally, high energy jets produced.*
- *Jets sample the history of the collision.*
- *Study of jet properties may produce insight into matter produced*



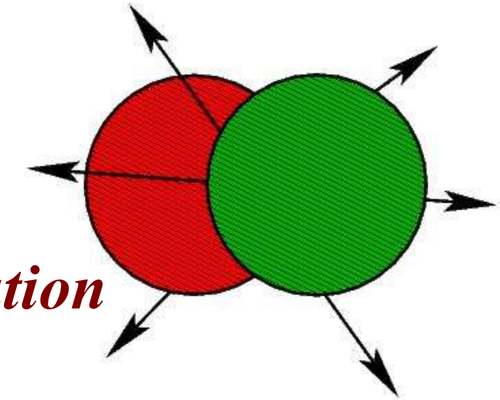
Compare with jet properties in p-p or electron positron annihilation

And with modification in cold nuclear matter

SINGLE PARTICLE MEASUREMENTS in heavy-ion coll.

High P_T particle production at midrapidity

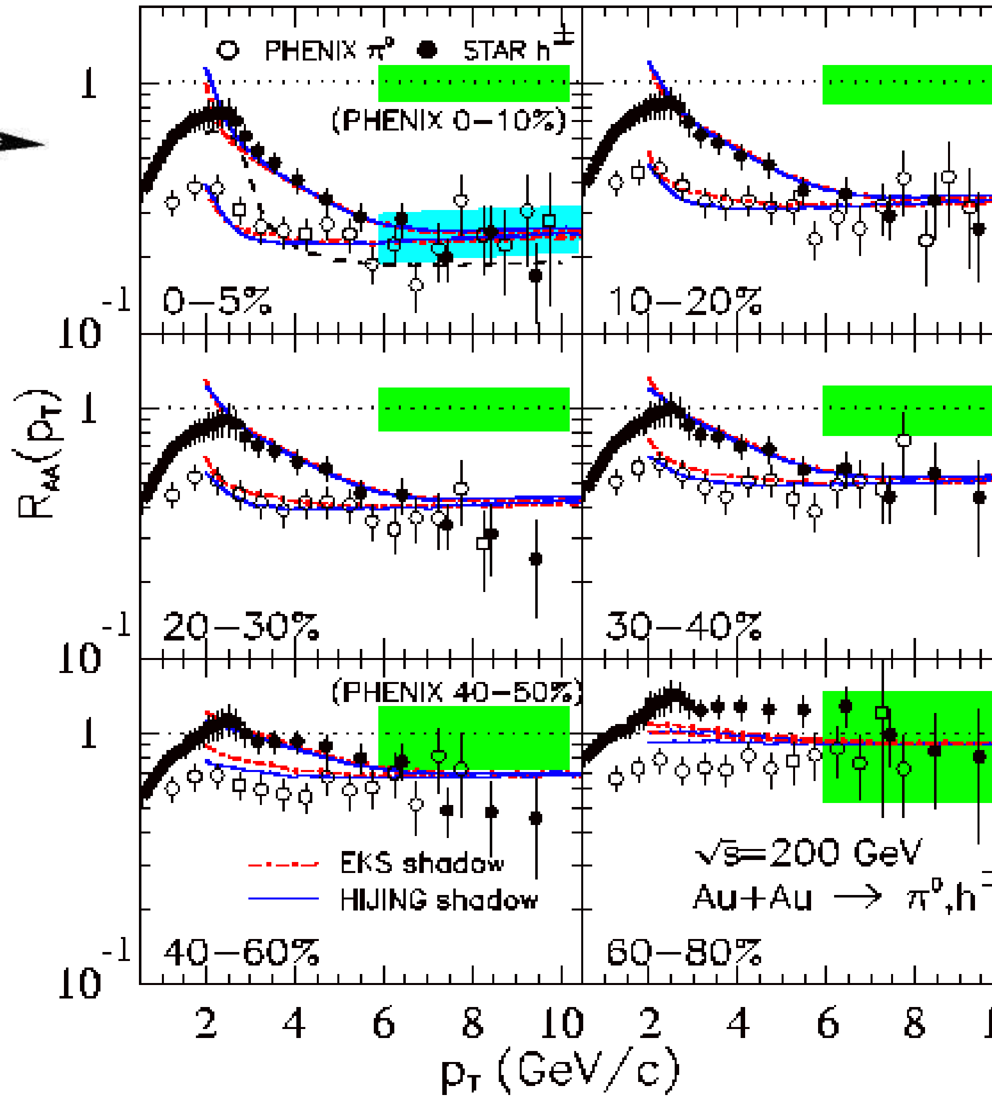
Nuclear modification factor R_{AA}



$$R_{AA} = \frac{d^2 N_{AA} / d\eta \, dp_\perp}{(N_{coll} / \sigma_{pp}^{inelastic}) \, d^2\sigma / d\eta \, d p_\perp}$$

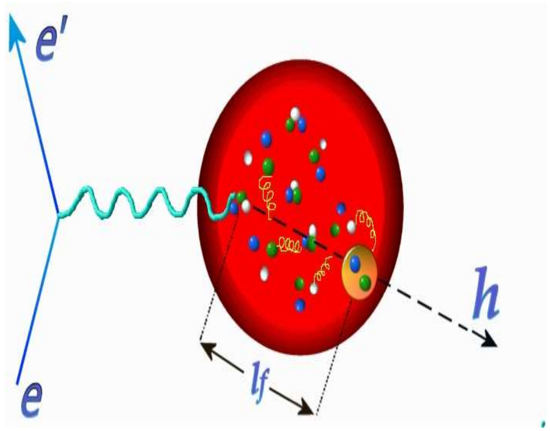
1 = particle production scales with number of expected p-p collisions

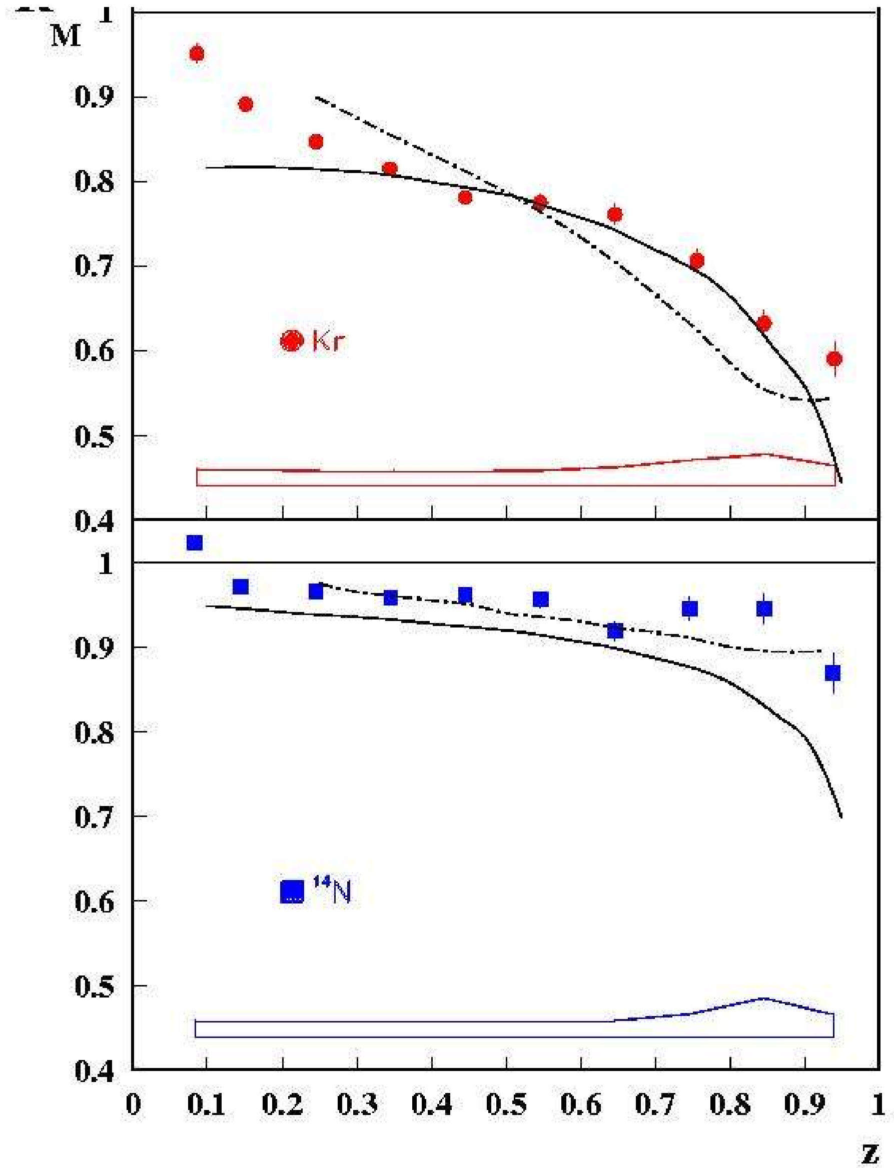
includes initial state modification of structure functions



$\eta = 0$

Single hadron attenuation in Deep-Inelastic Scattering





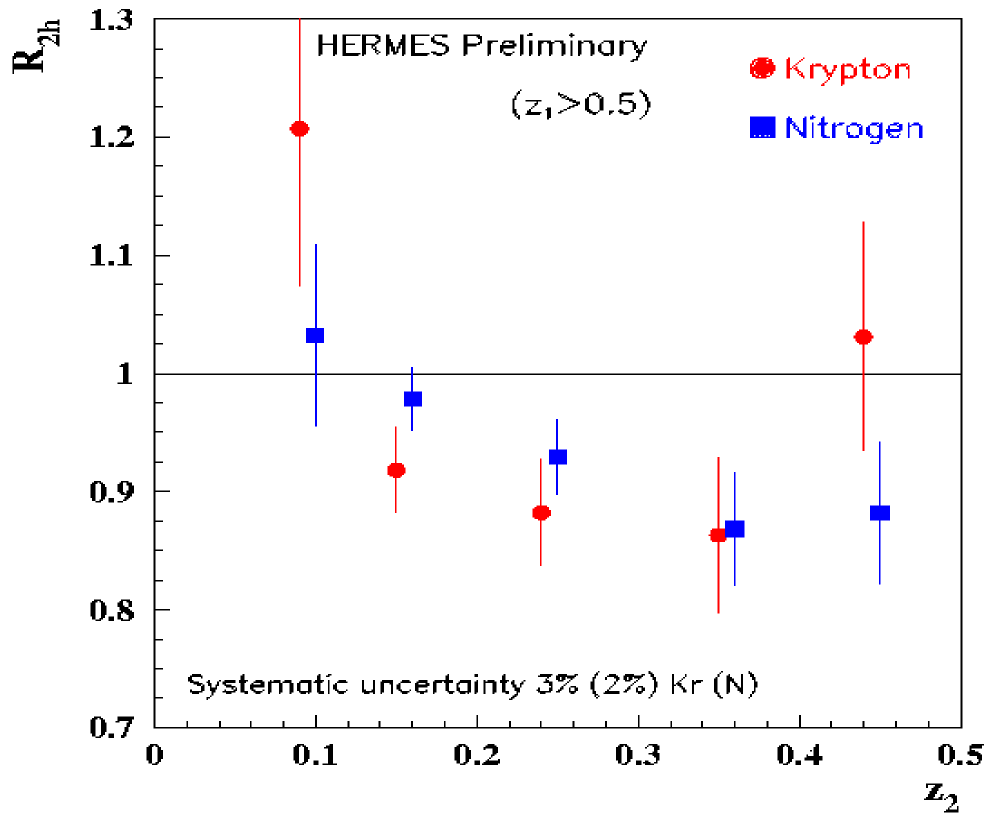
Perform DIS of nuclei

Look at particle production in the forward region

compare with DIS off light nuclei: Deuterium

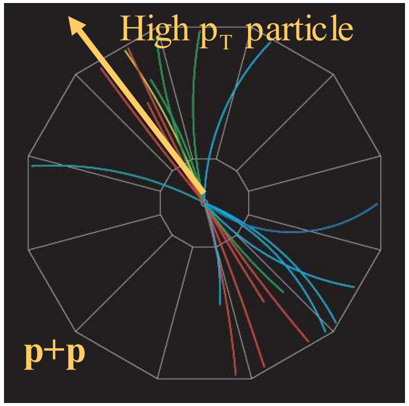
Double hadron measurements in DIS

- *Always measure a ratio of double to single production*
- *Divide by same ratio in deuterium to remove detector systematics*
- *As in Heavy-ion collisions very little change of double/single ratio.*

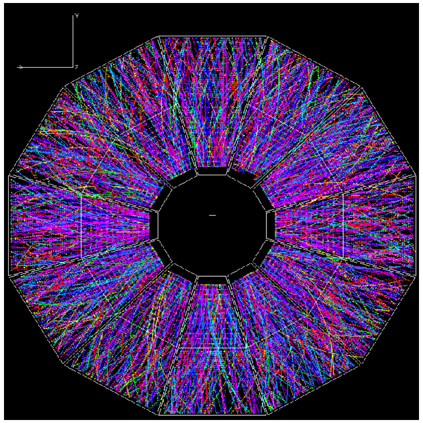


$$R_{2h} = \frac{\dfrac{No.\ of\ events\ with\ at\ least\ 2\ hadrons\ with\ z_1 > 0.5}{No.\ of\ events\ with\ at\ least\ one\ hadron\ with\ z > 0.5}}{same\ ratio\ on\ deuterium}$$

SINGLE HADRONS AND DI-HADRONS



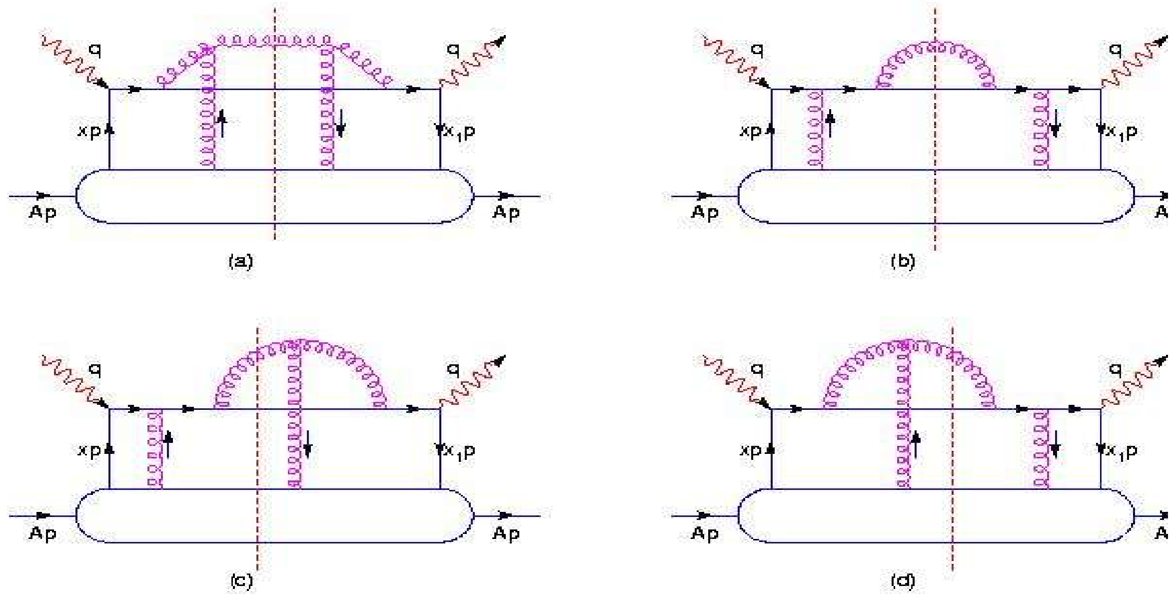
- *1 particle inclusive production, factorize from hard cross section ☞ D(z) fragmentation function*
- *Measure 2 particle distribution ☞ $D(z_1, z_2)$*



- *Can do single inclusive measurements*
- *Can still do 2-particle measurements*
- *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.*

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

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

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

τ_f = *Formation time*

γ = *boost*

R_A = *Nuclear size*

OUTLINE

- *MOTIVATIONS: HEAVY-ION COLLISIONS AND QGP, DIS*

- *VARIOUS APPROACHES: MEDIUM MODIFICATION OF FRAGMENTATION FUNCTIONS VIA PARTONIC INTR.*

- *DEFINITION OF DIHADRON FRAGMENTATION* ☞ e^+e^-

- *DGLAP EVOLUTION: MODIFICATION IN VACUUM*

- *MEDIUM MODIFICATION IN COLD MEDIUM (DIS)*

- *MEDIUM MODIFICATION IN HOT MEDIUM (QGP)*

Simpler case of Non-singlet quarks

$$D_{NS} = D_q - D_{\bar{q}}$$

Simpler: contribution from gluon fragmentation cancels out

$$D_{NS}(z_{1,} z_{2,} \mu^2) = D_{NS}(z_{1,} z_2) + \int_0^{\mu^2} \frac{dl_\perp^2}{l_\perp^2} \int_z^1 \frac{dy}{y^2} \left[\frac{1+y^2}{1-y} \right]_+ D_{NS}(z_1/y, z_2/y)$$

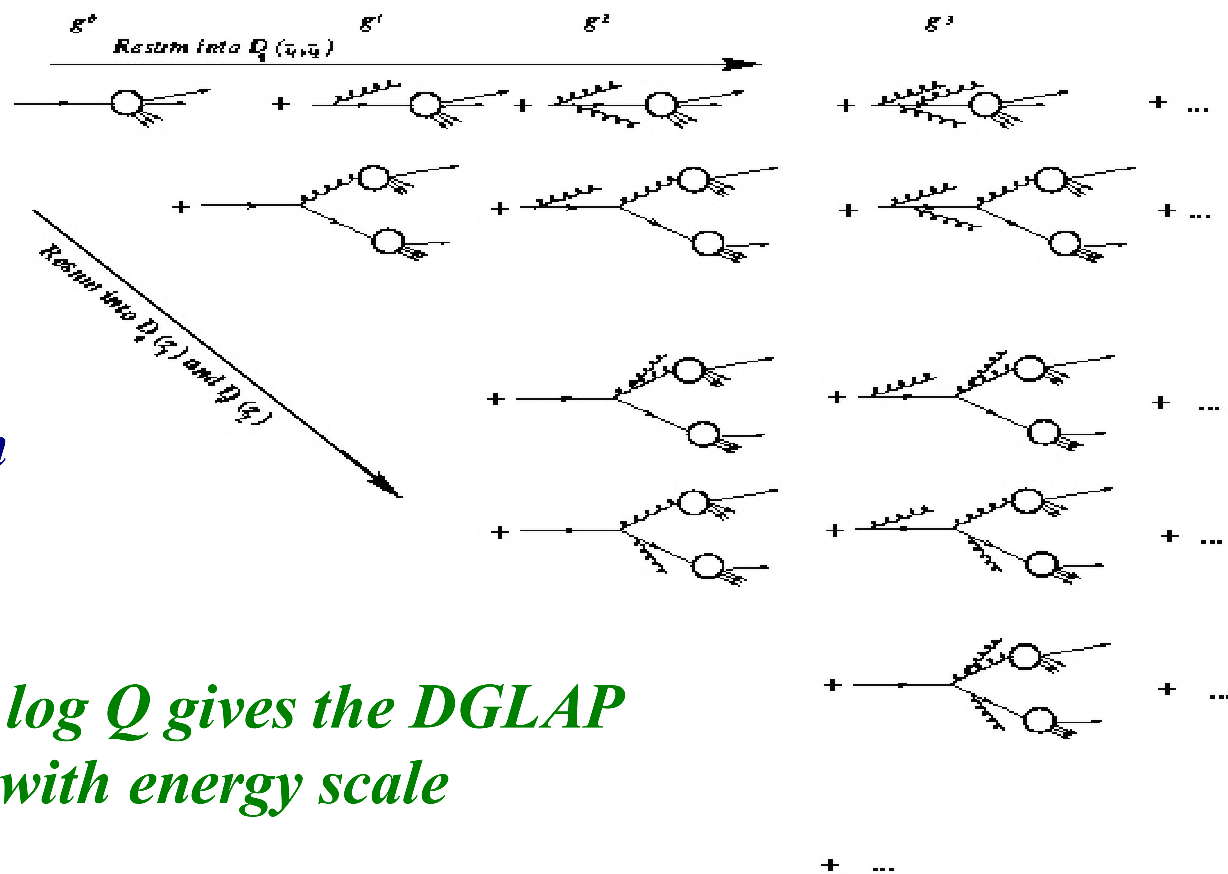
$$+ \int_0^{\mu^2} \frac{dl_\perp^2}{l_\perp^2} \int_{z_1}^{1-z_2} \frac{dy}{y(1-y)} \frac{1+y^2}{1-y} D_q(z_1/y) D_g(z_2/(1-y))$$

- *Absorb collinear divergences up to a scale* μ
- *Defines fragmentation function at scale* μ
- *Note: only retained leading log and leading power corrections*
- *To go to a higher scale this has to be repeated to all orders*
- *Leading log corrections absorbed at each order*

To obtain the dihadron fragmentation function at a higher scale Q need to resum the LL contributions from all orders as shown...

LL contributions can be resummed

part of the LL contributions resummed into the single fragmentation functions...



Differentiating with log Q gives the DGLAP evolution equations with energy scale

Each differentiation extracts a splitting function, and reduces the number of gluons