Energy loss and fragmentation of hard jets in dense matter

Abhijit Majumder

The Ohio State University

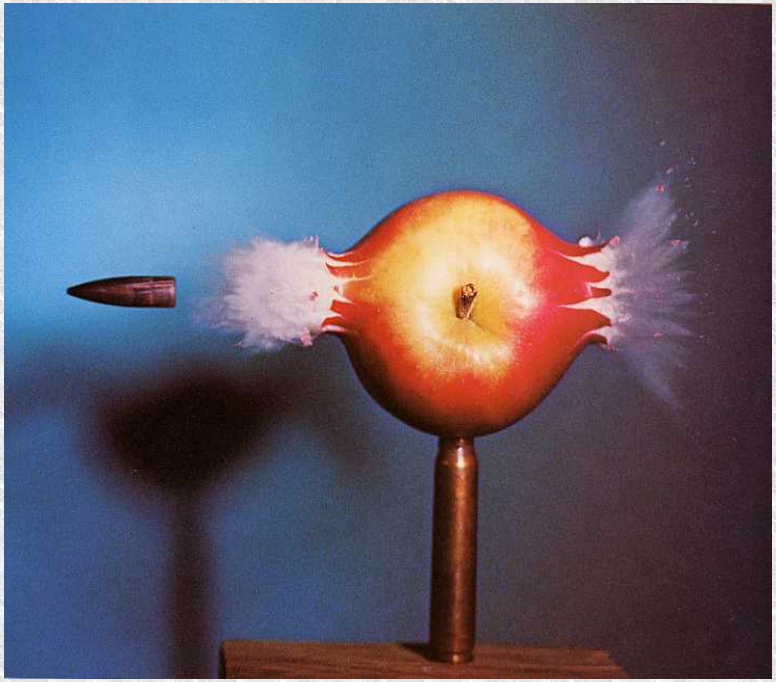
Electron-Ion Collider Collaboration Meeting, LBNL Dec 11-13 2008

Outline

- *Parton propagation in dense matter*
- *Energy loss, hadron attenuation and transport coeffs.*
- *Hadronization and hadronic correlations*
- *Multiple scattering and multiple emissions*
- *Photon production and Generalized parton distribution*
- *Relation to jets in HIC*
- *Conclusions*

Two basic, related questions

1) How is jet structure modified by the presence of a dense medium



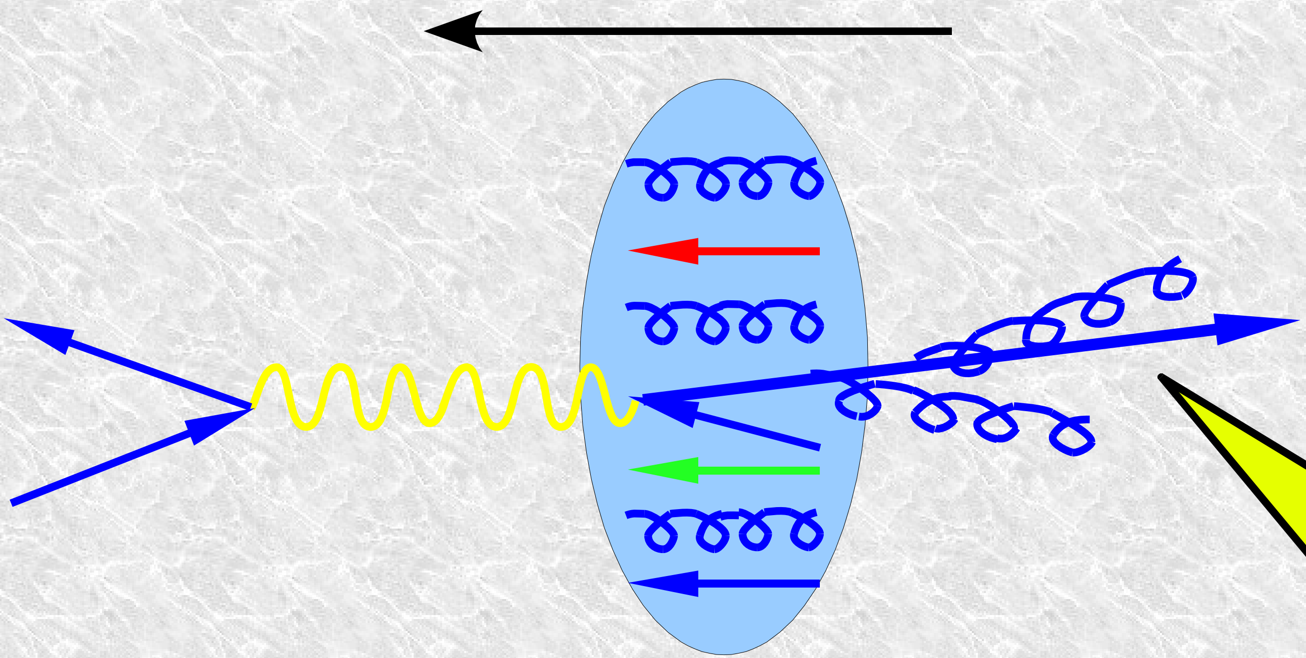
2) What can be learnt about the structure of the medium from studying jet modification

What is the experiment?

Semi-Inclusive Deep Inelastic Scattering on a large nucleus,

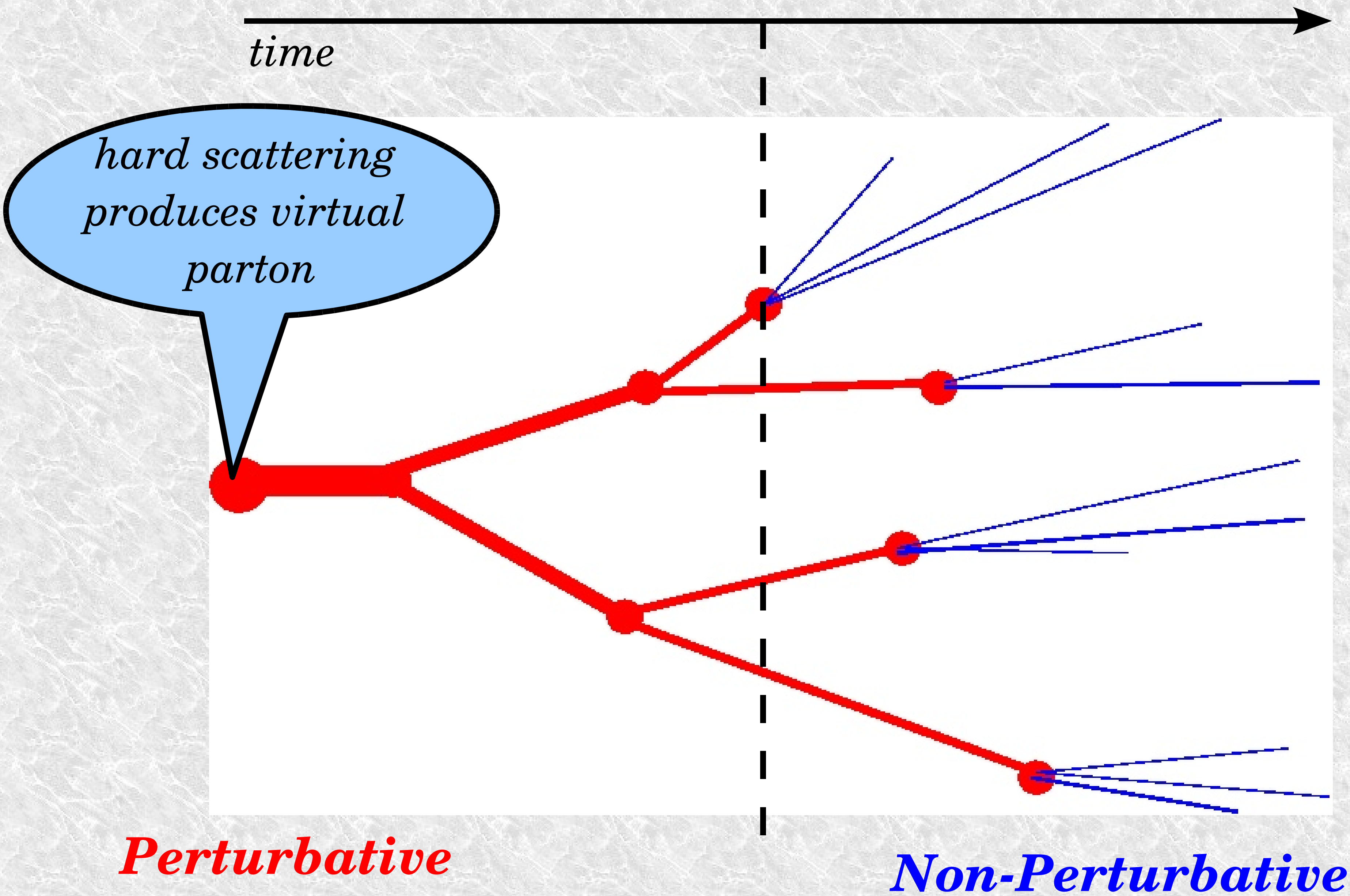
At short enough distance, high momentum transfer, strongly interacting matter has a quark gluon substructure.

At high enough energy a hard virtual parton is produced

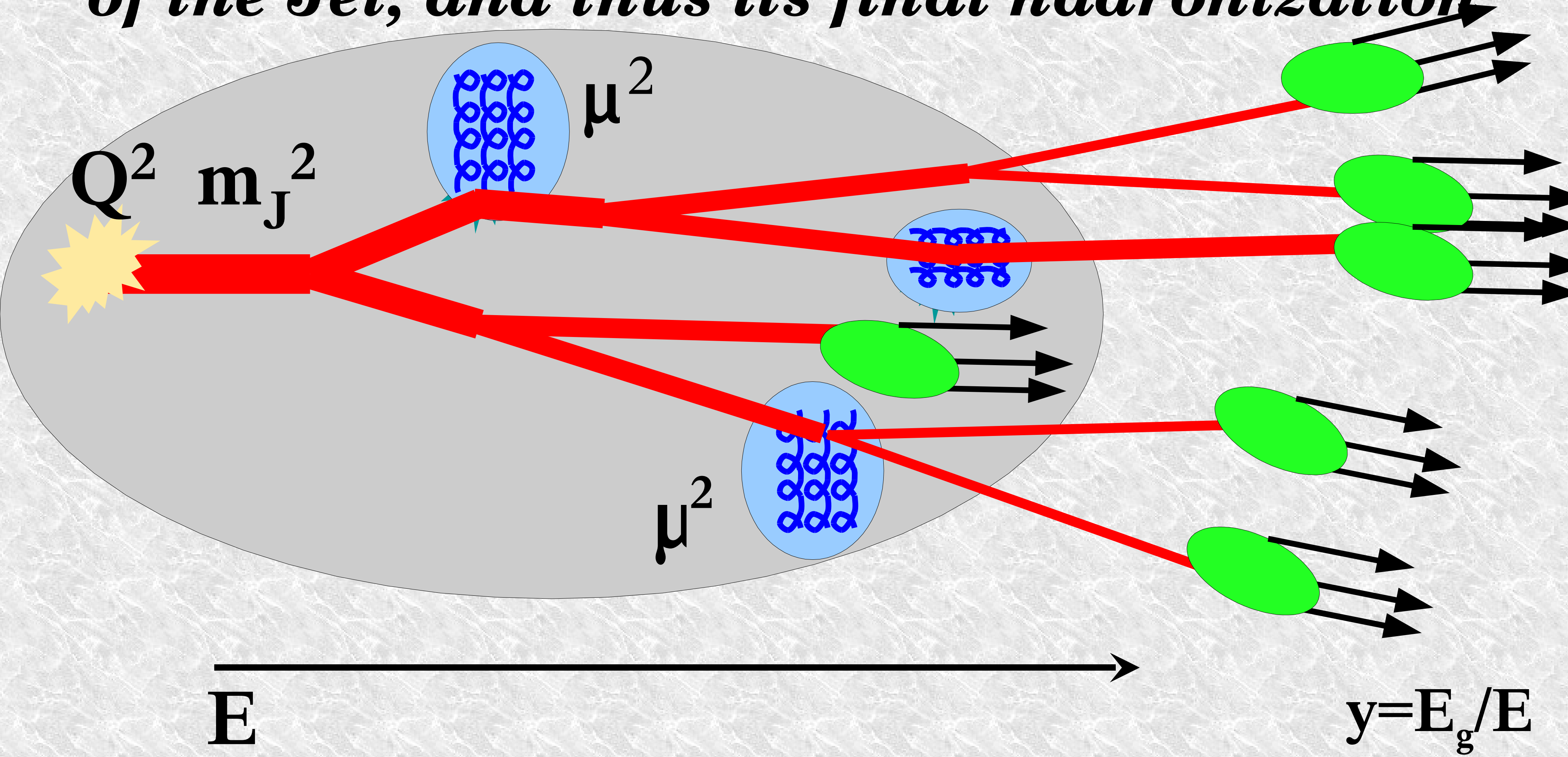


The struck quark has a short perturbative life!
How is it modified?

What exactly is being modified ?
Jet space-time structure in vacuum



Medium modifies the space time evolution of the Jet, and thus its final hadronization



In the limit $E \sim Q >> m_J >> \mu$.

If medium within perturbative domain,

Can calculate the modification using pQCD.

Our Methodology: A pheno-approach

1) Assume factorization !

2) Do the simplest calculation first

3) Check with data !

4) Do the next simplest thing

5) Check with data, are we getting closer !!

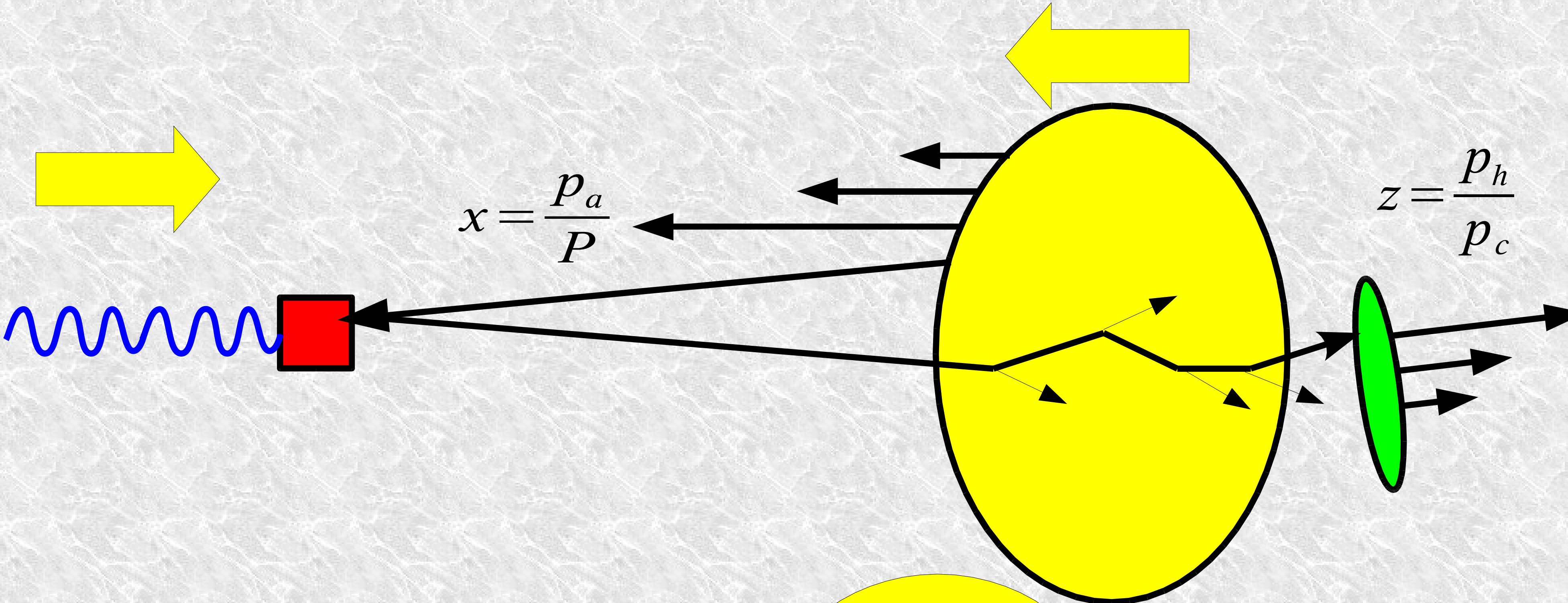
6) Worry about extra new matrix elements

7) Do the resummation

8) Check with data, are we still getting closer !!!

9) Write effective theory i.e., prove factorization

A factorized approach at high energy

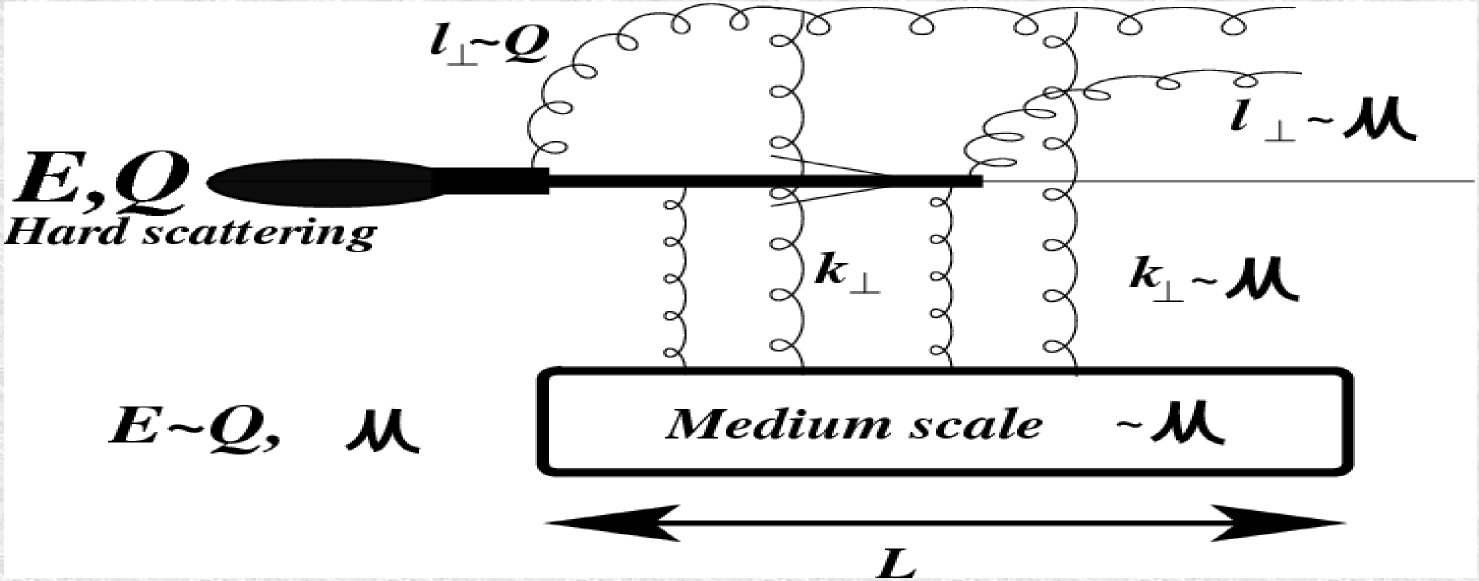


$$d\sigma^{h_1} \sim \int dx \; G(x) \; d\hat{\sigma}(x, q, Q^2) \; \widetilde{D}_q^{h_1}(z_1)$$

$$\widetilde{D}(z, Q^2) = D(z, \mu^2) + \int_{\mu^2}^{Q^2} d\, l^2 \int_z^1 dy \; M(y, l^2)$$

Proof for total CS (Qiu & Sterman), Assumption in SIDIS

Scales in the problem



Jet forward energy: $E, q^- \sim Q \gg m_J \gg M$ ***mass of proton,***

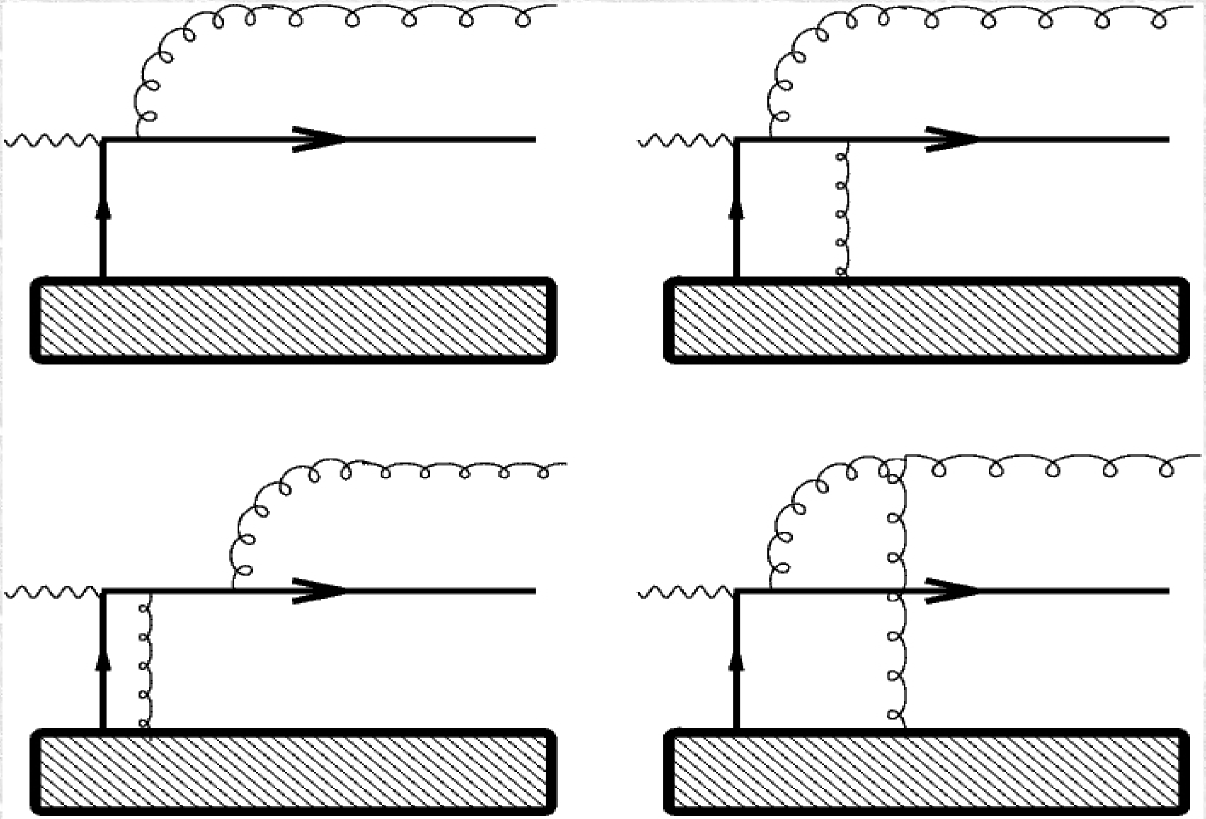
Virtuality of photon: $Q \gg l_\perp \leqslant m_J$ ***Virtuality of jet,***

Radiated gluon momentum: $\left[\frac{l_\perp^2}{2q^- y}, yq^-, l_\perp \right]$

Soft medium gluons $\lambda_{QCD} \leqslant k_\perp \ll l_\perp$ ***However!*** $A^{\frac{1}{3}} k_\perp \leqslant l_\perp$

$L \sim A^{\frac{1}{3}}$ ***A, atomic number of the nucleus,***

Simplest example: single scattering & radiation



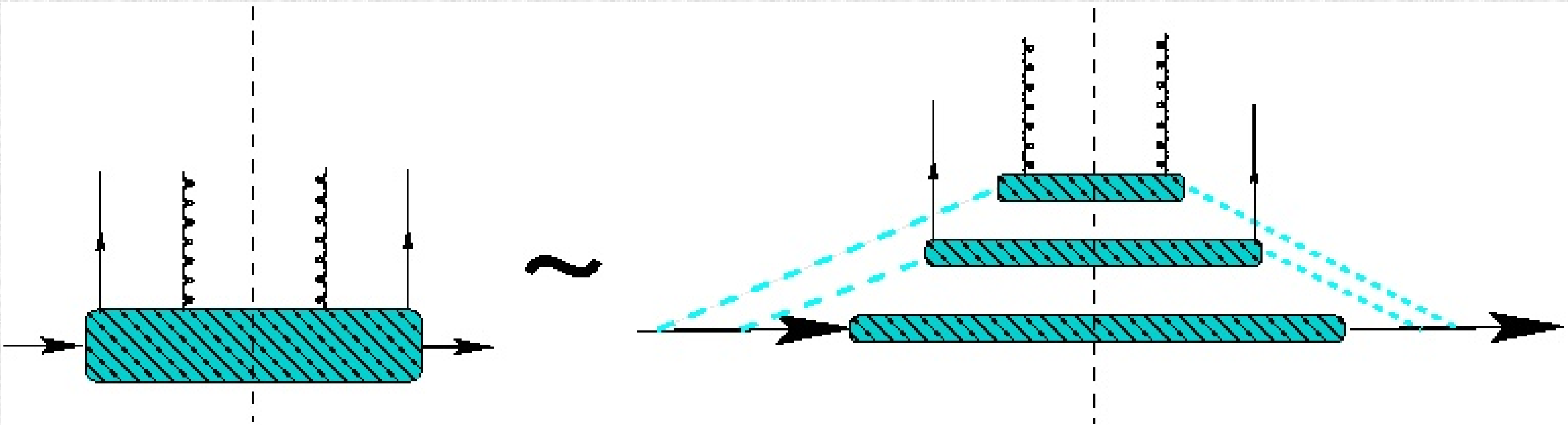
+ interference terms + virtual corrections …

About 23 different contributions

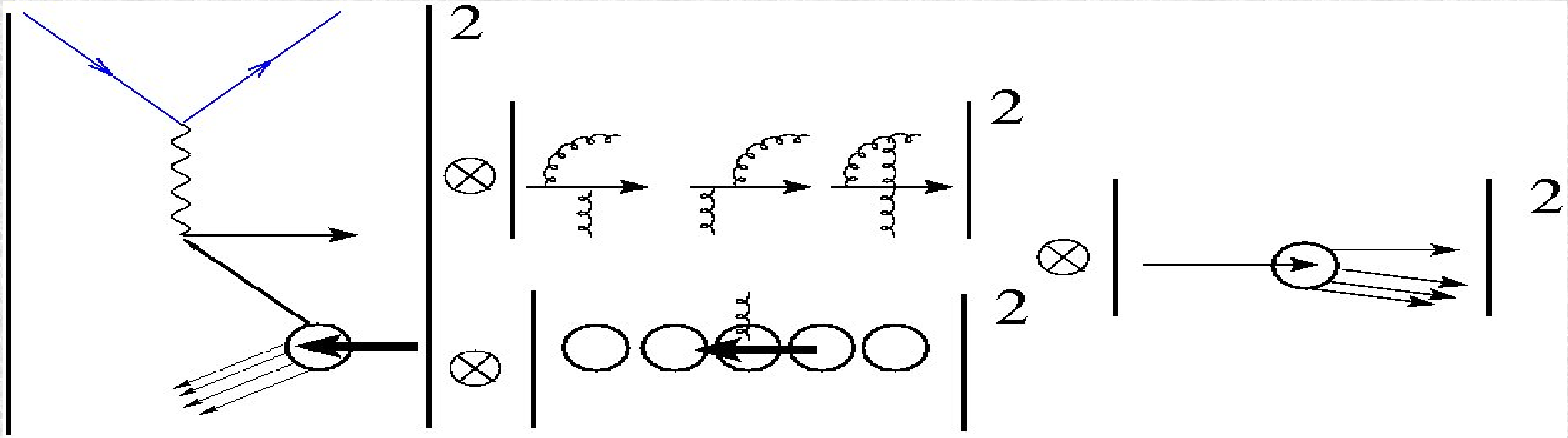
The convolution model for the nucleus

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

- *As Nucleons are color singlets, have to act with color singlet operators*
- *Can have all 4 operators on 1 nucleon, length factor = 1*
- *Can have quarks in one nucleon and gluons in one nucleon, length enhancement ~ $A^{1/3}$*



Apply factorization of matrix elements



$$A\,F(p/p_h)\,d\sigma_{e^- + q \to q + e^-}$$

$$\int dY^- dt \langle A | F^{\mu +}(Y^- + t) F^{+}_{\mu}(Y^-) | A \rangle$$

$$L \int d\,t \left\langle N \left| F^{\mu\alpha}(t)\, v_\alpha\, F^{\beta}_{\mu}(0)\, v_\beta \right| N \right\rangle$$

note $F^{\mu +} = F^{\alpha\mu} v_\alpha$

$$then \;\; M \sim C\,F(x_B)\,A^{\frac{1}{3}} \int dt \left\langle N \left| F^{\mu\alpha}(t)\, v_\alpha\, F^{\beta}_{\mu}\, v_\beta \right| N \right\rangle$$

The cross section to produce a hadron in a nucleus is $\sigma_T \propto \dfrac{A^{1/3}\mu_H^2}{Q^2}$

How well does this work

Set the one over all constant!

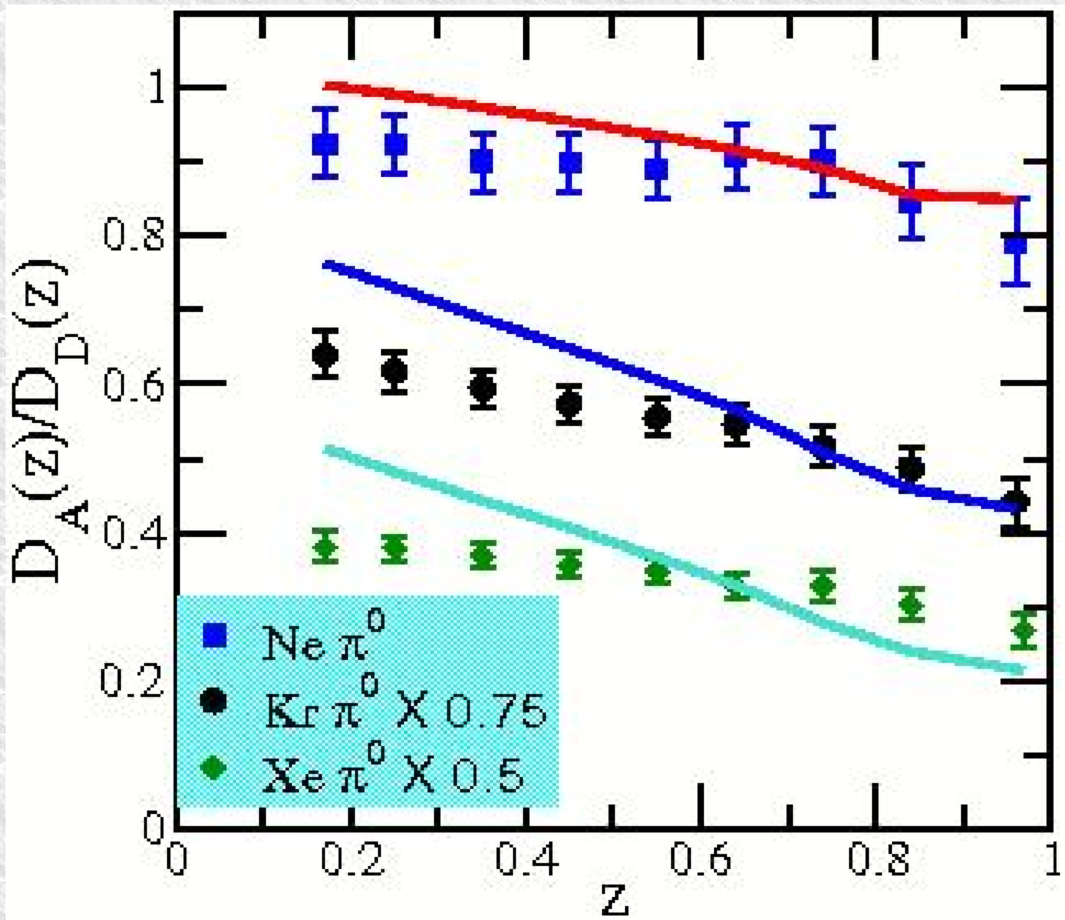
$$\hat{q} = \frac{8\pi^2 \alpha_s C_R}{N_c^2 - 1} \int \frac{dy^-}{2\pi} e^{-ixp^+ y^-} \left\langle F^{\mu +}(y^-) F_\mu^+(0) \right\rangle$$

$$= \frac{4\pi^2 \alpha_s}{N_c} \rho\, x G(x)_{R=q} \sim \frac{4\pi^2 \alpha_s}{N_c} \rho \left\langle x G(x) \right\rangle \qquad \hat{q}_0 = 0.015\, GeV^2 / fm$$

Data from HERMES
Nitrogen (blue), Krypton (black)
Xenon(green).

Experiment measures the modified fragmentation func.

Set q from one point in N.
Everything else is prediction



Understanding hadronization, after modification of gluon cloud!

A parton in a hard scattering forms a gluon cloud around it

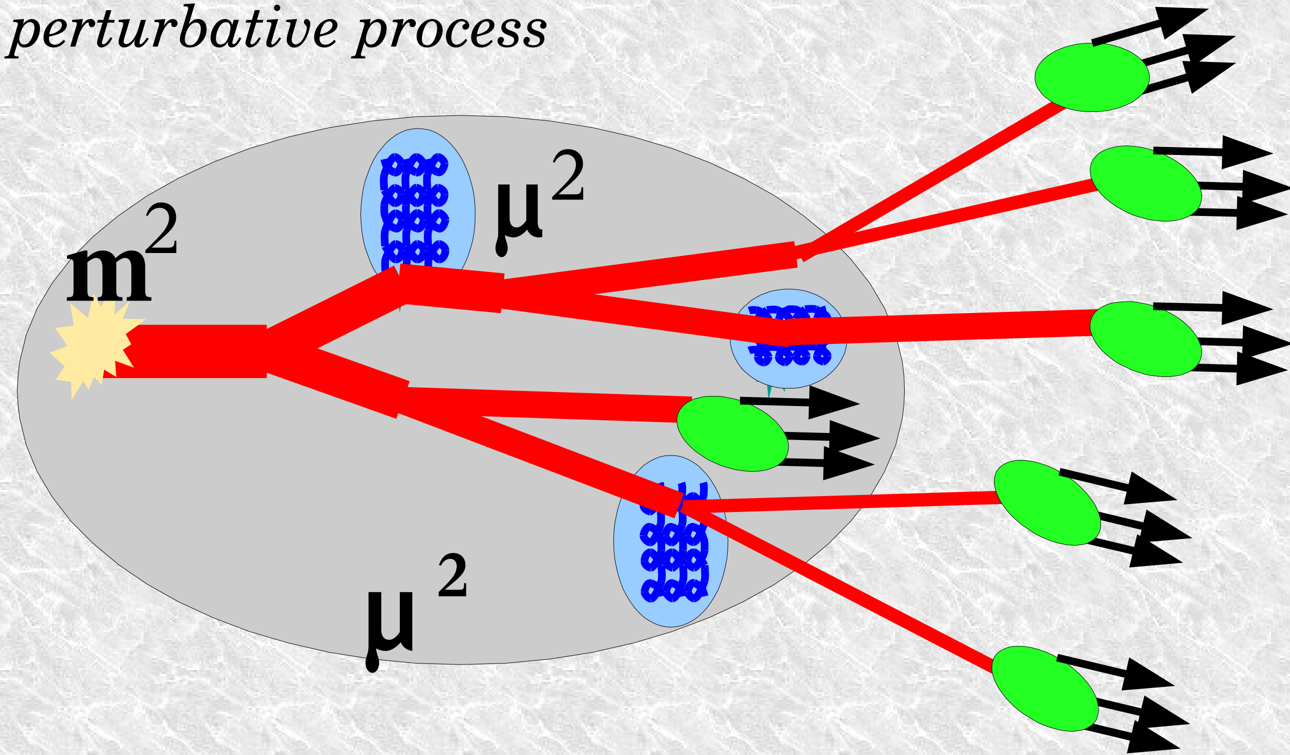
Part of this is perturbative, then the cloud turns into hadrons

The radiated gluon cloud is affected by the medium,

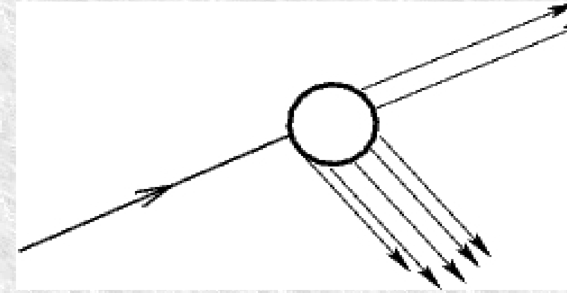
At high energy this is also a perturbative process

Can this be calculated

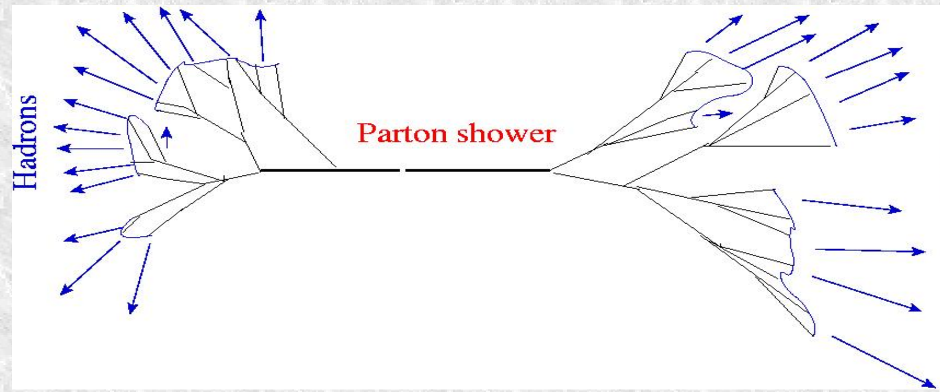
Take the simplest step: hadron correlations



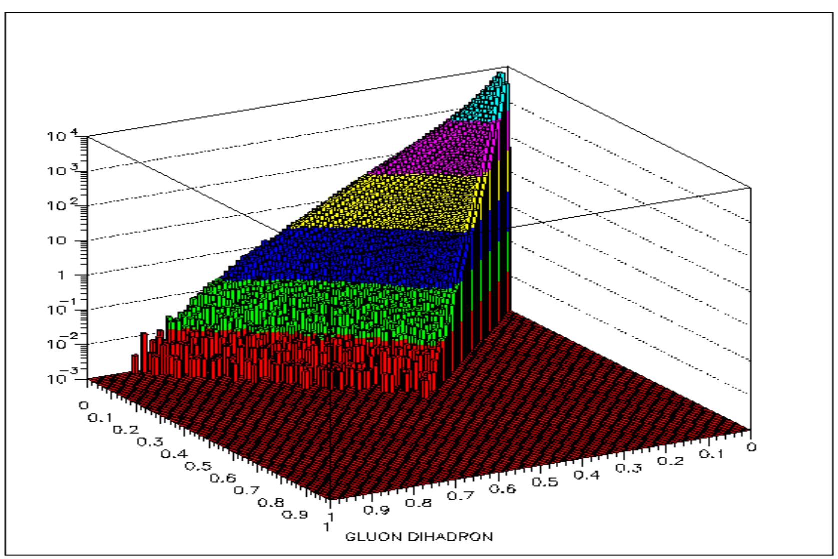
Understanding modified hadronization

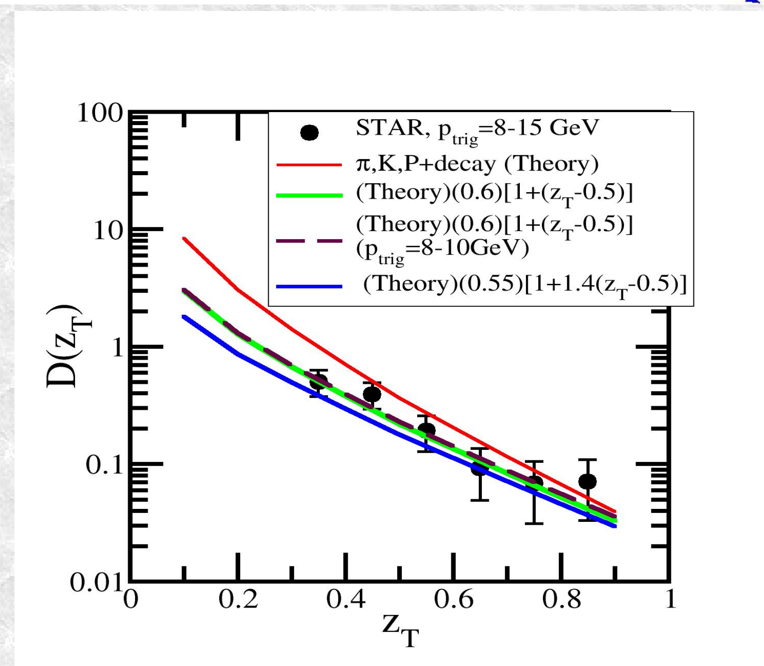


Simplest extension: hadron-hadron correlations
Need new non-perturbative object: Dihadron frag. func.



Measure in event generator JETSET
Compare with Experimental data





A. Majumder, X.N.Wang, PRD 70,014007, 2004

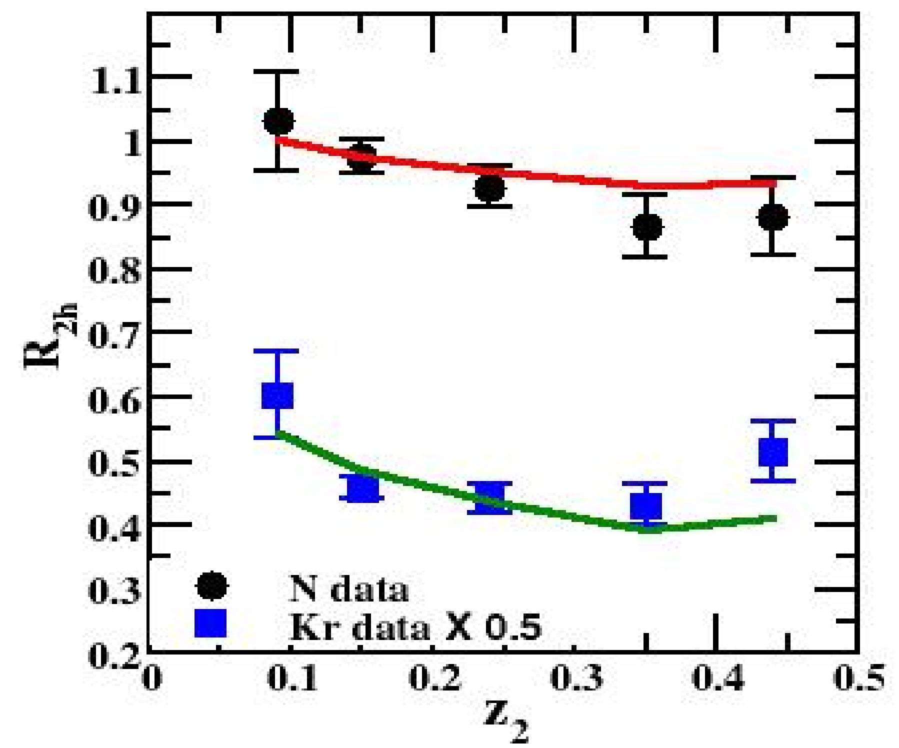
Comparison with Data from HERMES !

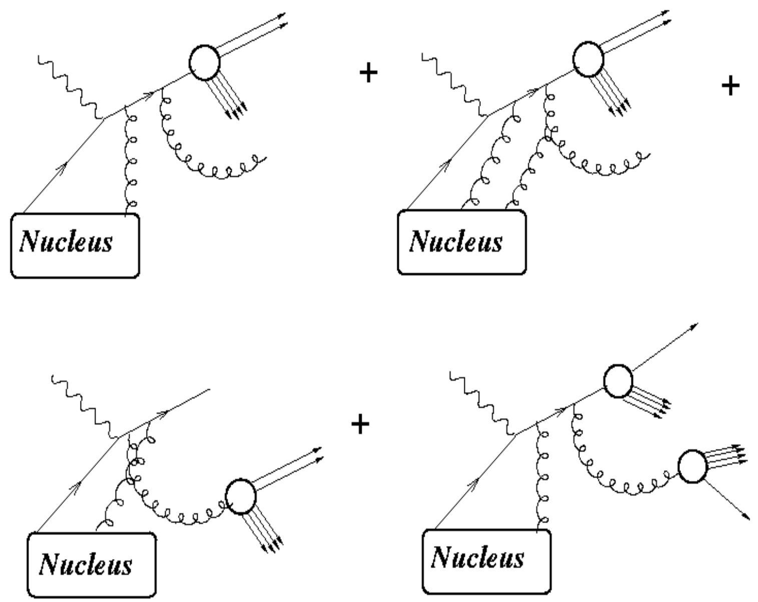
The partonic part is the same.

Calculation in lock-step with single

Extra hadronization requires

extra diagrams





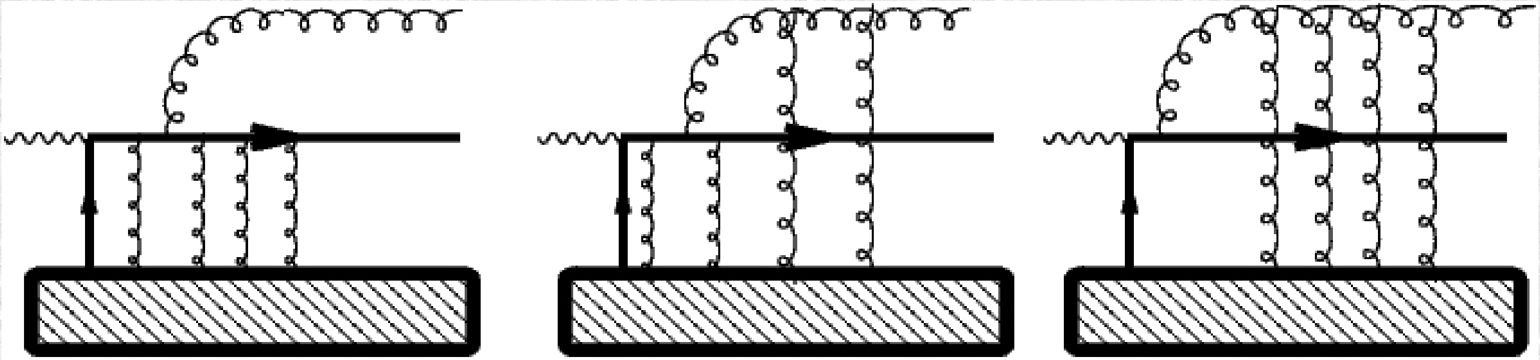
$$R_{2h} = \frac{\dfrac{No.\ of\ events\ with\ at\ least\ 2\ hadrons\ with\ z_1 > 0.5}{No.\ of\ events\ with\ at\ least\ one\ hadron\ with\ z > 0.5}}{same\ ratio\ on\ deuterium}$$

A. Majumder, E. Wang, X. N. Wang, PRL99, 152301 2007

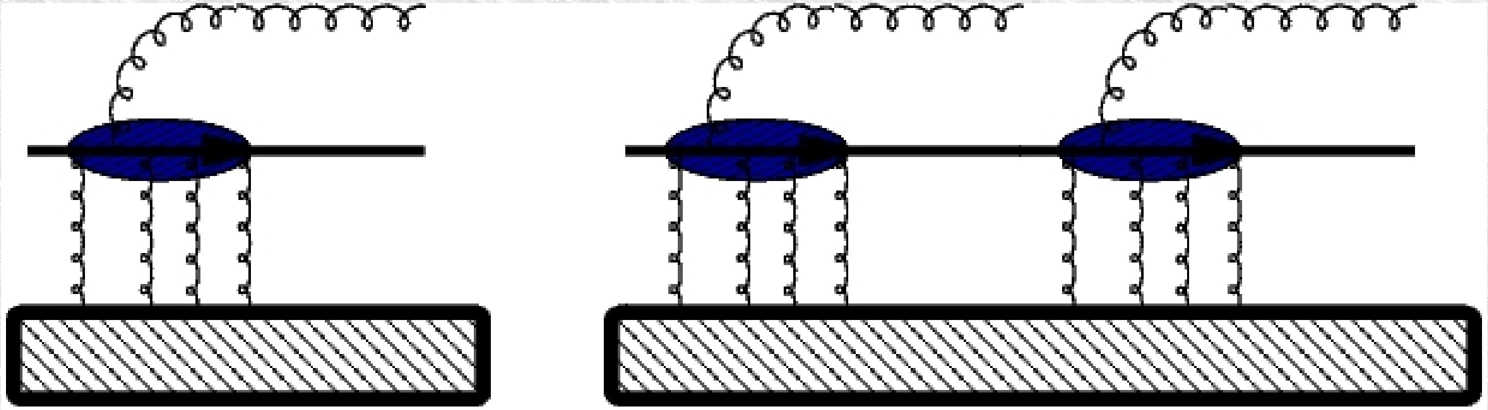
Multiple scattering, multiple radiation

We need to incorporate:

1) Multiple scattering for each radiation



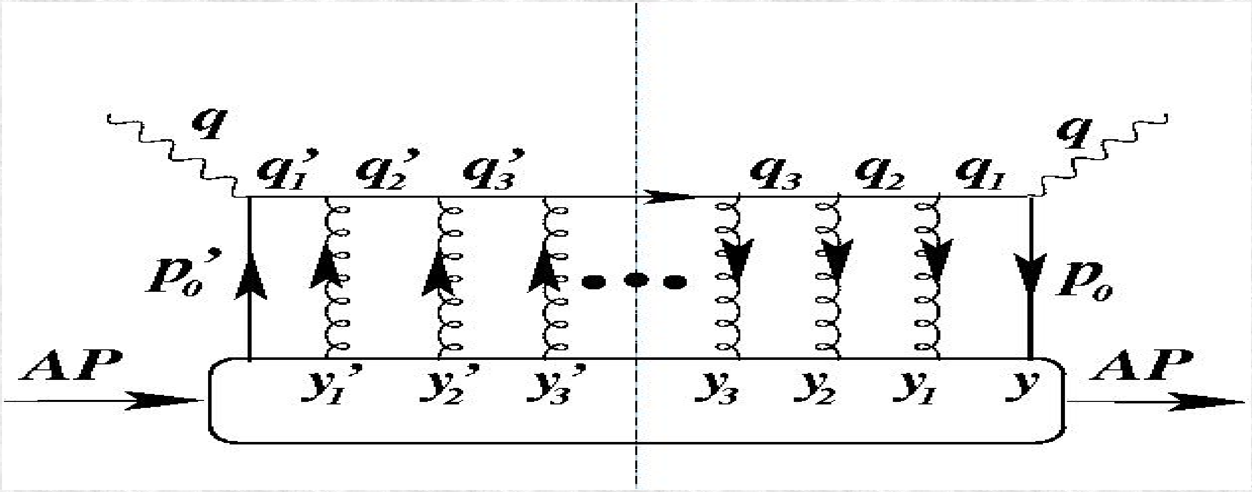
2) Multiple radiation / evolution in medium



3) Possibility of non-trivial nuclear matrix elements

Multiple scattering

Imagine multiple scattering without radiation



No Scattering $\delta^2(l_\perp)$

1 Scattering $\nabla_{l_\perp \mu}\delta^2(l_\perp)F^{+\mu}$

n Scattering $(\nabla_{l_\perp \mu})^n\delta^2(l_\perp)(F^{+\mu})^n$

Recall: $q^- \gg l_\perp \gg p_\perp^i \sim \dfrac{l_\perp}{A^{\frac{1}{3}}}$

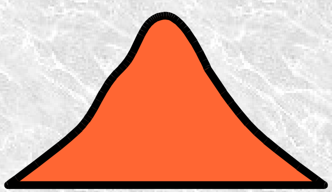
A. Majumder, B. Muller, PRC May 2008 issue

The diffusion equation!

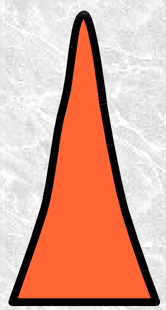
Resum infinite scatterings, involves hierarchy of medium correlators

$$\left\langle A \middle| F(t_1)F(t_2) \middle| A \right\rangle, \quad \left\langle A \middle| F(t_1)F(t_2)F(t_3)F(t_4) \middle| A \right\rangle \quad \ldots$$

Use convolution model, decompose nucleus to nucleons
Fields correlated within nucleon length, domination of 2-point correlators



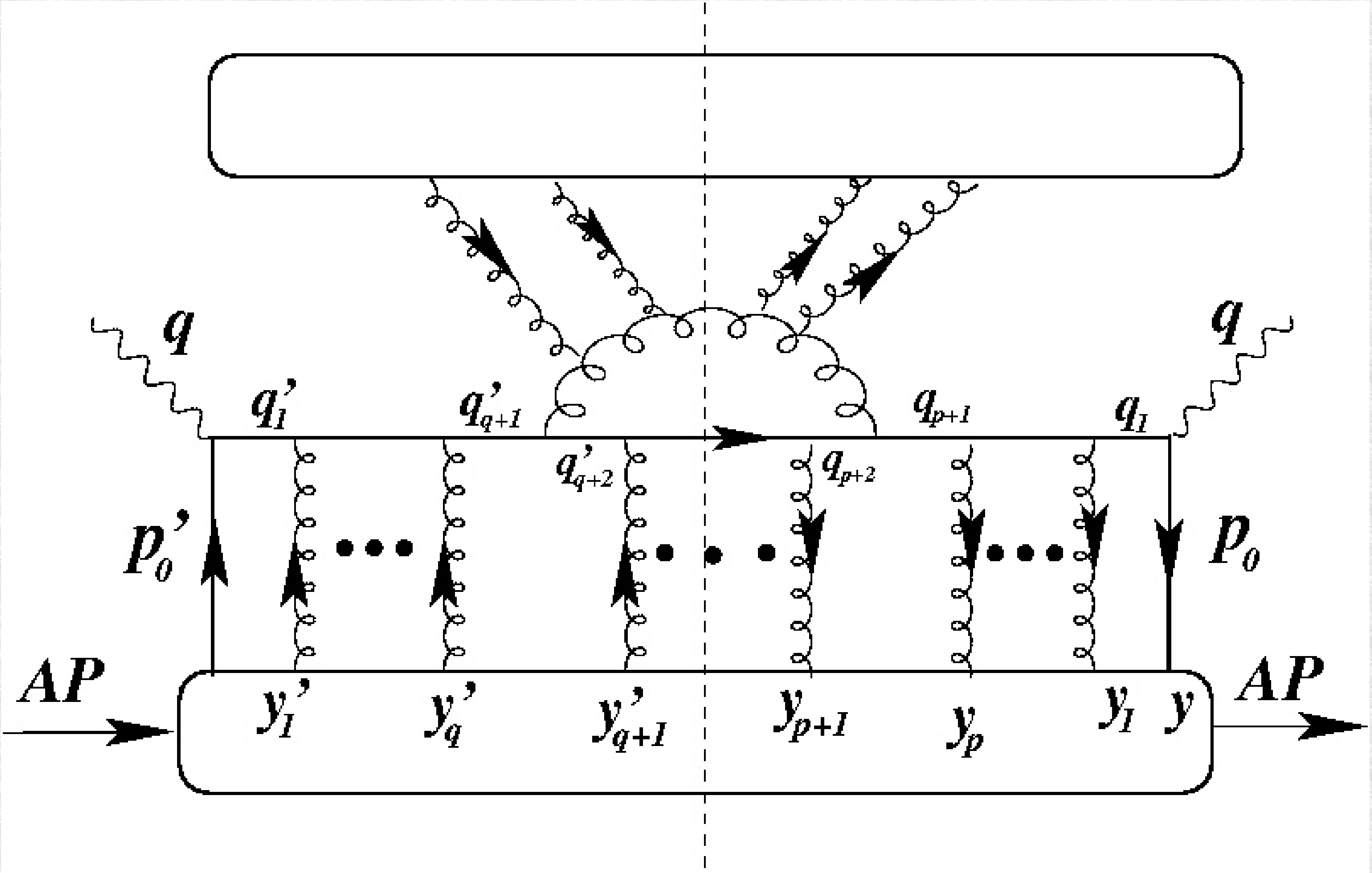
$$\frac{\partial f(l_\perp, L^-)}{\partial L^-} = \nabla_{l_\perp} \cdot D \cdot \nabla_{l_\perp} f(l_\perp, L^-)$$



$$f(l_\perp, L^-) = \frac{1}{4\pi D L^-} e^{\frac{l_\perp^2}{4\mathrm{DL}^-}} \qquad l_\perp^2 = 4 D L^- = 4\sqrt{2}\, Dt$$

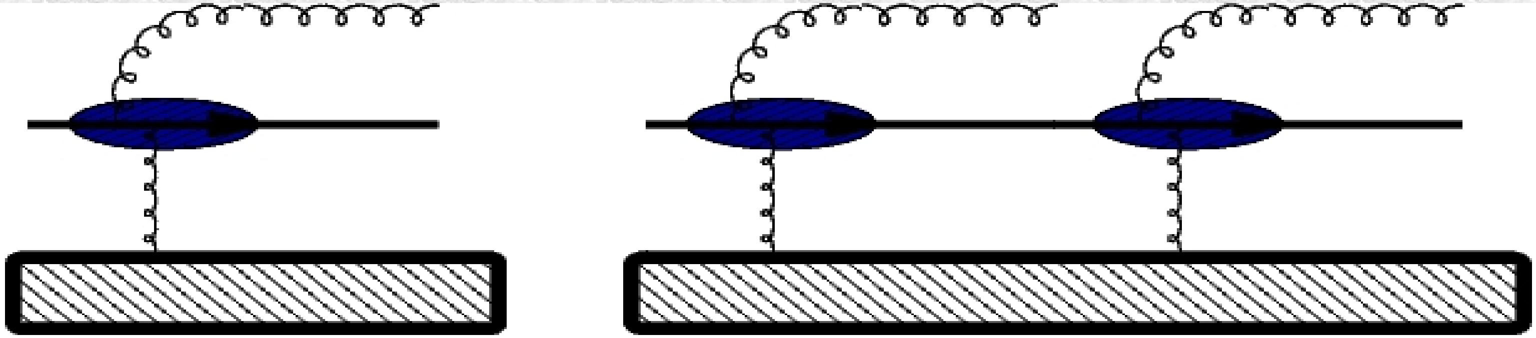
$$\boxed{\hat{q} = \frac{l_\perp^2}{t} = \frac{8\pi^2 \alpha_s C_R}{N_c^2 - 1} \frac{\int dy^-}{2\pi} \left\langle N \middle| F^{\mu\alpha}(t)\, v_\alpha F_\mu^{\beta}(0)\, v_\beta \middle| N \right\rangle}$$

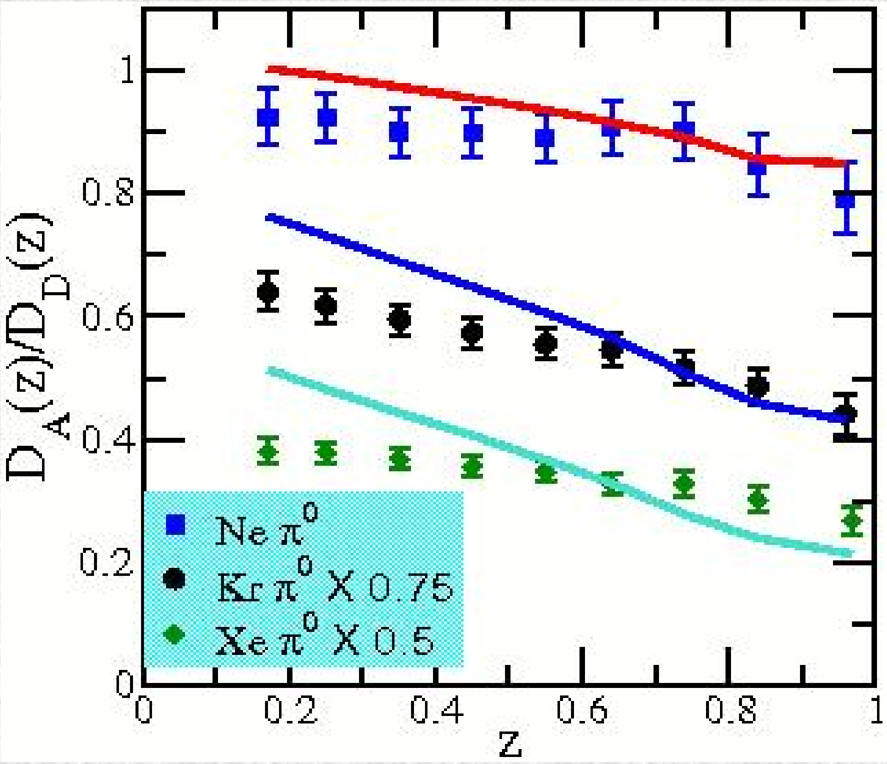
multiple scattering per radiation

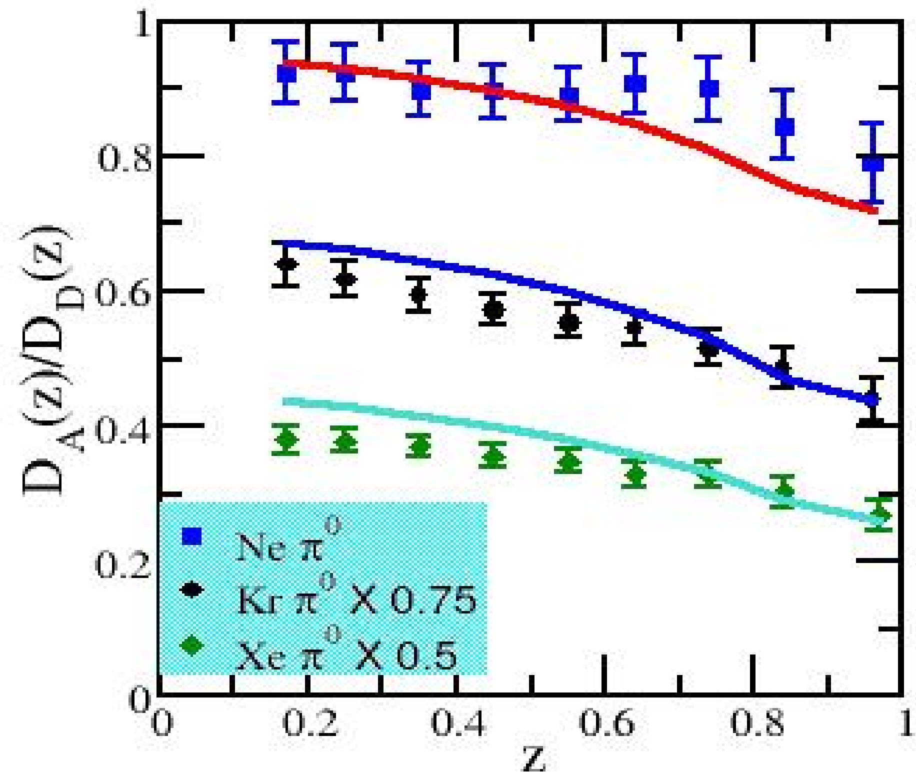


A realistic calculation requires realistic non-trivial nuclear matrix elements
No result in closed form, requires an expansion in 1/Nc .

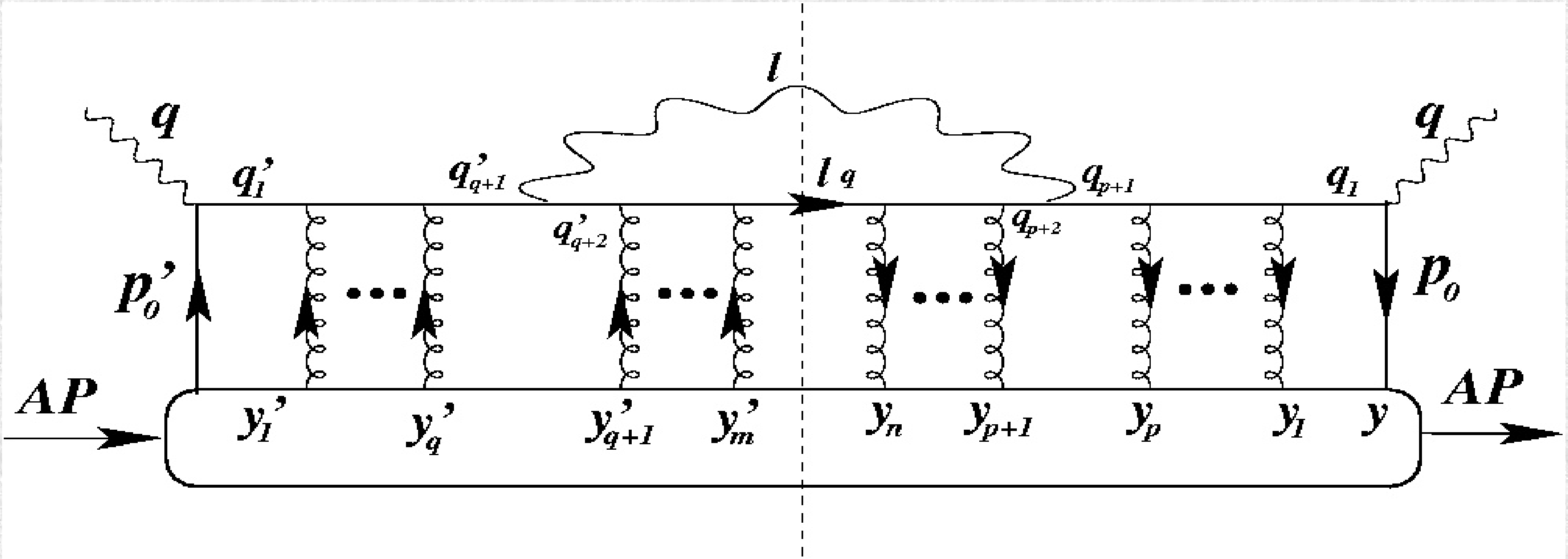
Multiple radiations through evolution







Non-trivial matrix elements: Photon production



Very similar to E-loss, except photon does not scatter
Sum over photon radiation points separately on either side
Sum over infinite number of scatterings.

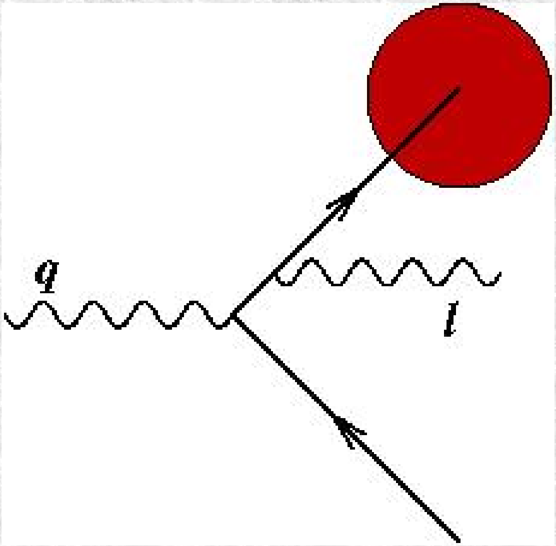
A. Majumder, R. J. Fries, B. Muller, PRC June 2008 issue

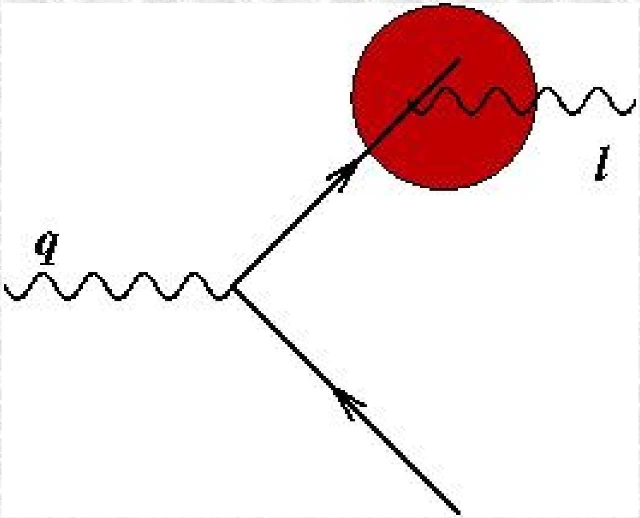
Small y approximation, Landau-Pomeranchuck-Migdal Interference

Go through the same set of approx. and take leading and NLO behavior at small y

$$d\sigma \sim P_\gamma(y)$$

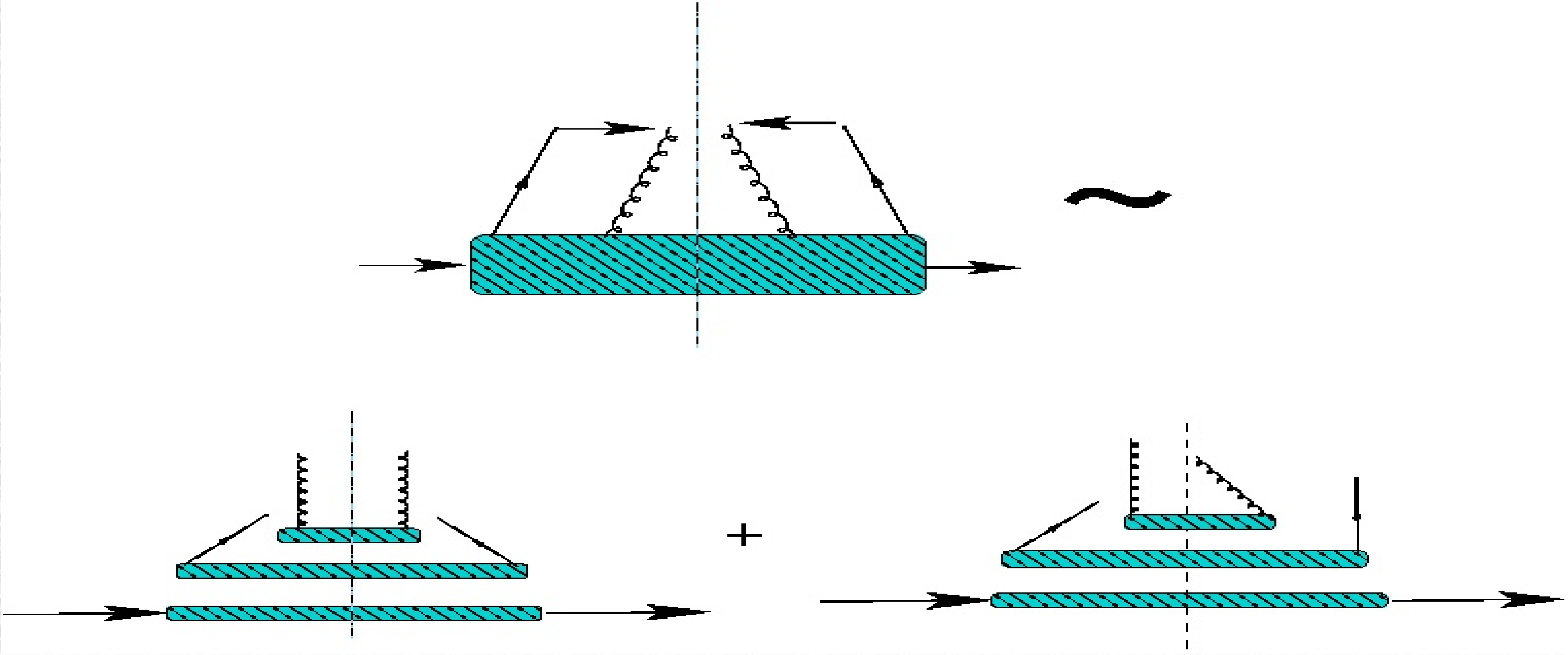
$$\times \left\langle e^{-i(x_B+x_L)P^+ y_0^-} C\left[\frac{(D\nabla^2_{l_{q\perp}})^n}{n!} - y\left(e^{-ix_L P^+(y_p-y_0)}+e^{ix_L P^+ y'_p}\right)\frac{l_\perp \nabla_{l_{q\perp}}}{l_\perp^2}\frac{(D\nabla^2_{l_{q\perp}})^{n-1}}{(n-1)!}\right]\delta^2(l_\perp+l_{q\perp})\right\rangle$$





$$X_L = \frac{l_\perp^2}{2P^+ q^- y}$$

Generalized Parton Distribution



These two states have to share the momentum $x_L P^+$

Thus, these are off forward parton distributions!

We usually approximate them as regular C X PDFs!!

C also includes momentum correlation between nucleons,
A 2nd transport coefficient

Without a knowledge of the GPD's, E-loss calculations incomplete!

Lots of work yet to be done!

1) *Incorporation of a parametrization of the GPD.*

2) *Testing it through triggered photon production.*

3) *Setting the momentum sharing coefficient C.*

4) *Re-summing of n scatterings with GPD's into energy loss.*

5) *Compare with 1,2,n-hadron observables!*

6) *A baseline for jet-modification in HIC.*

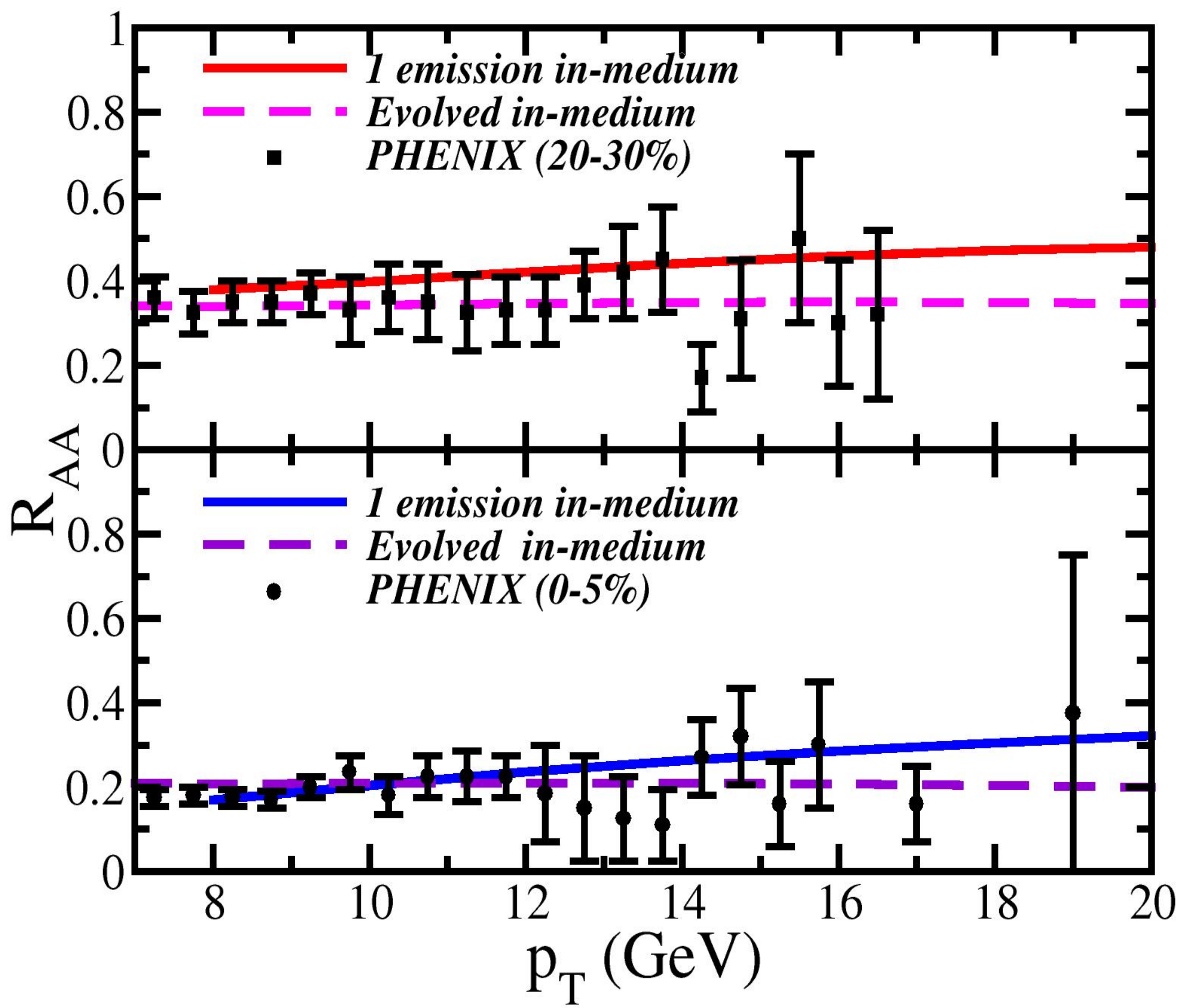
Hard jets in heavy-ion collisions

$$\hat{q} = \hat{q}_0(f)\frac{\gamma_{\perp}(x,y,z,t)\,T^3(x,y,z,t)}{T_0^3(x,y,z,t)}$$

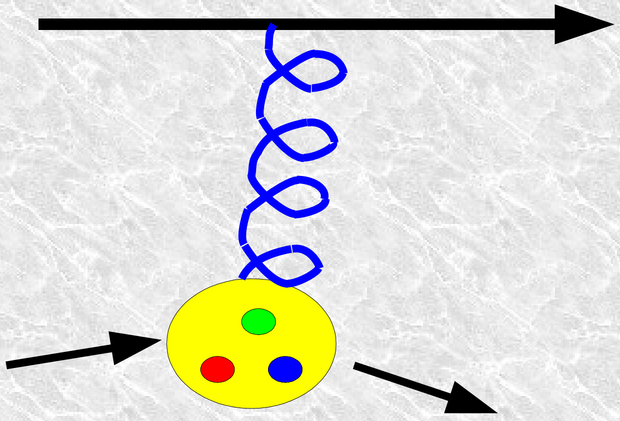
Only diff from DIS is initial distribution and time dependent density

Same medium model as for single gluon emission and evolution

Error bars in data still too large for a clear discrimination between approaches`



More transport coeffs: Elastic energy loss



Every interaction induces not only transverse but also longitudinal momentum

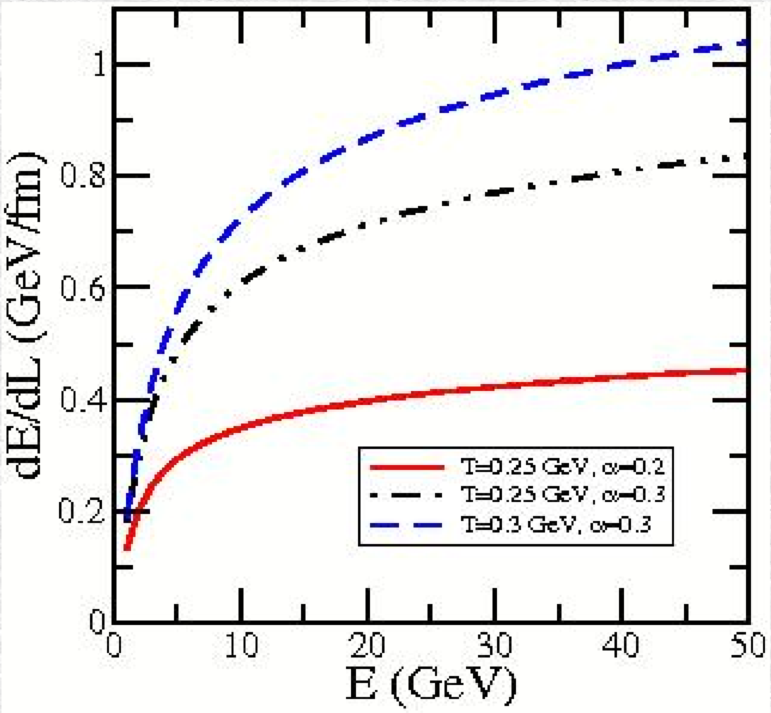
$$f(\vec{l}) \equiv \delta^2(\vec{l}_{perp}) \Rightarrow \delta^2(\vec{l}_{perp})\,\delta(l^- - q^- + k^-)$$

This k^- is tiny and usually ignored

$$\frac{\partial f(l^-, L^-)}{\partial L^-} = c_1 \frac{\partial f}{\partial l^-} + c_2 \frac{\partial^2 f}{\partial^2 l^-}$$

Keeping these contributions and resumming leads to drag and diff

Evaluating c_1 in a thermal medium



A.M. arXiv:0810.4967 [nucl-th]

Summary

The first steps towards a detailed and complete theory of hard probes

A study of the partonic sub-structure of nucleons and nuclei

A series of transport coefficients, in terms of non-trivial matrix elements

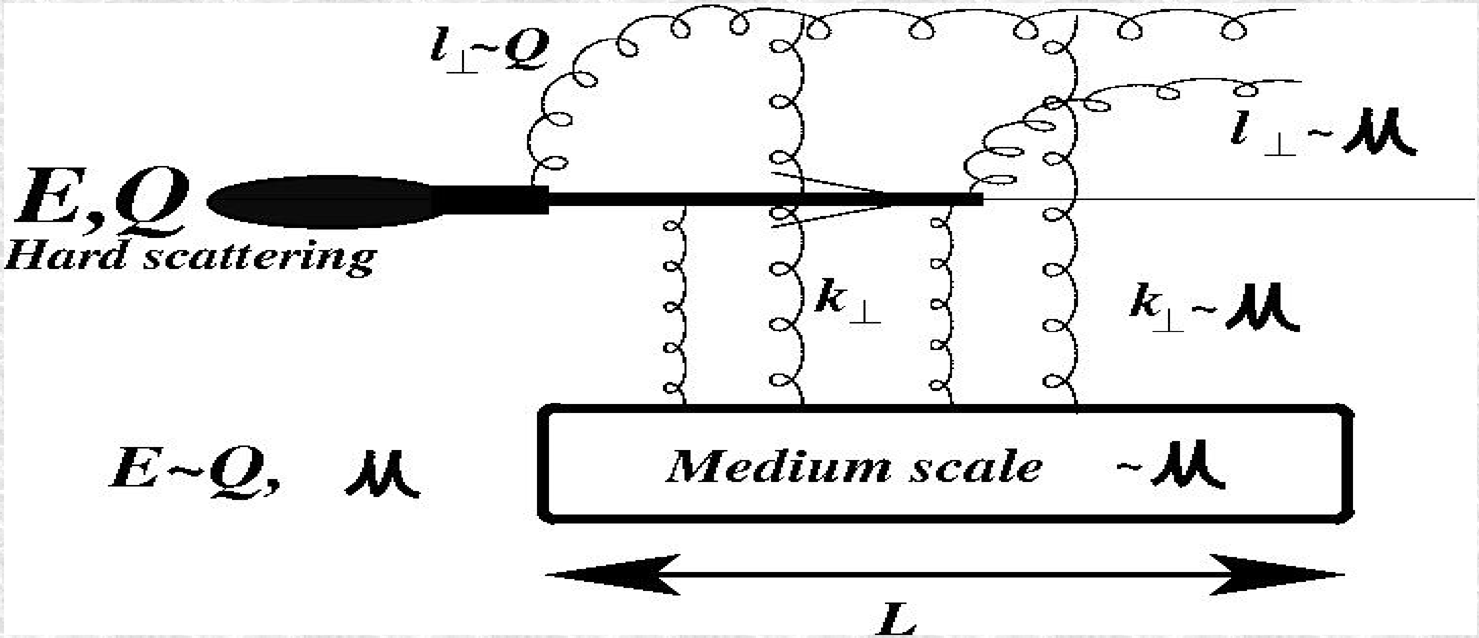
Incorporate/understand elastic energy loss

Reveals how partons live inside nucleons inside nuclei

Need high statistics experimental data to constrain theory

Need high energy and large Q^2. ----> EIC

Specific momenta in DIS



Jet forward energy: $E\,,q^{-}\sim Q\gg M$ **mass of proton,**

Virtuality of photon: $Q\gg l_{\perp}\sim m_{J}\,,$ **Virtuality of jet,**

Radiated gluon momentum:

Soft medium gluons $E\,,q^{-}\sim Q\gg M$ **However!** $Q\gg l_{\perp}\sim m_{J}\,,$

A, atomic number of the nucleus,