Duke Physics

Jet Quenching: status and open questions

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Produced matter at RHIC strongly coupled

Success of ideal hydro ⇨ d.o.f. have a very short mean free path

Short mean free paths ⇨ Strong coupling, Strong interaction

Not a weakly interacting plasma of quarks and gluons,

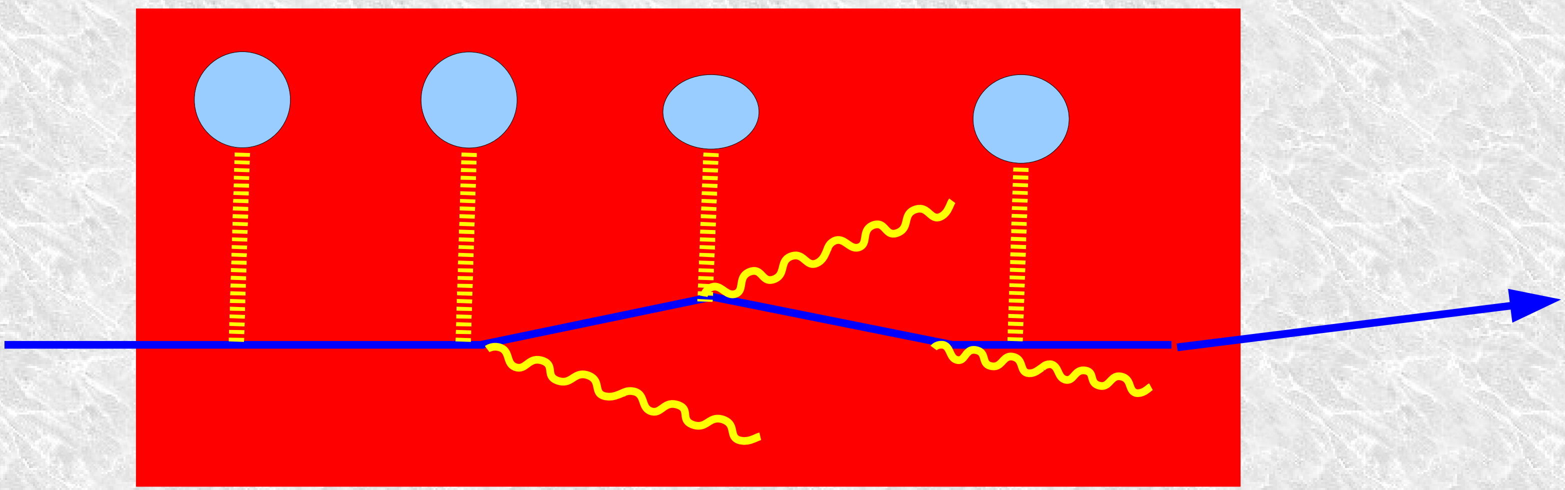
This is good! QCD matter is not boring, even at T=300 MeV!

Bulk analysis from first principles QCD not feasible

Can still study systematically using a microscopic probe

The canonical picture, from QED

High energy electron (all most on-shell) travels long distances in vacuum [PROBE]



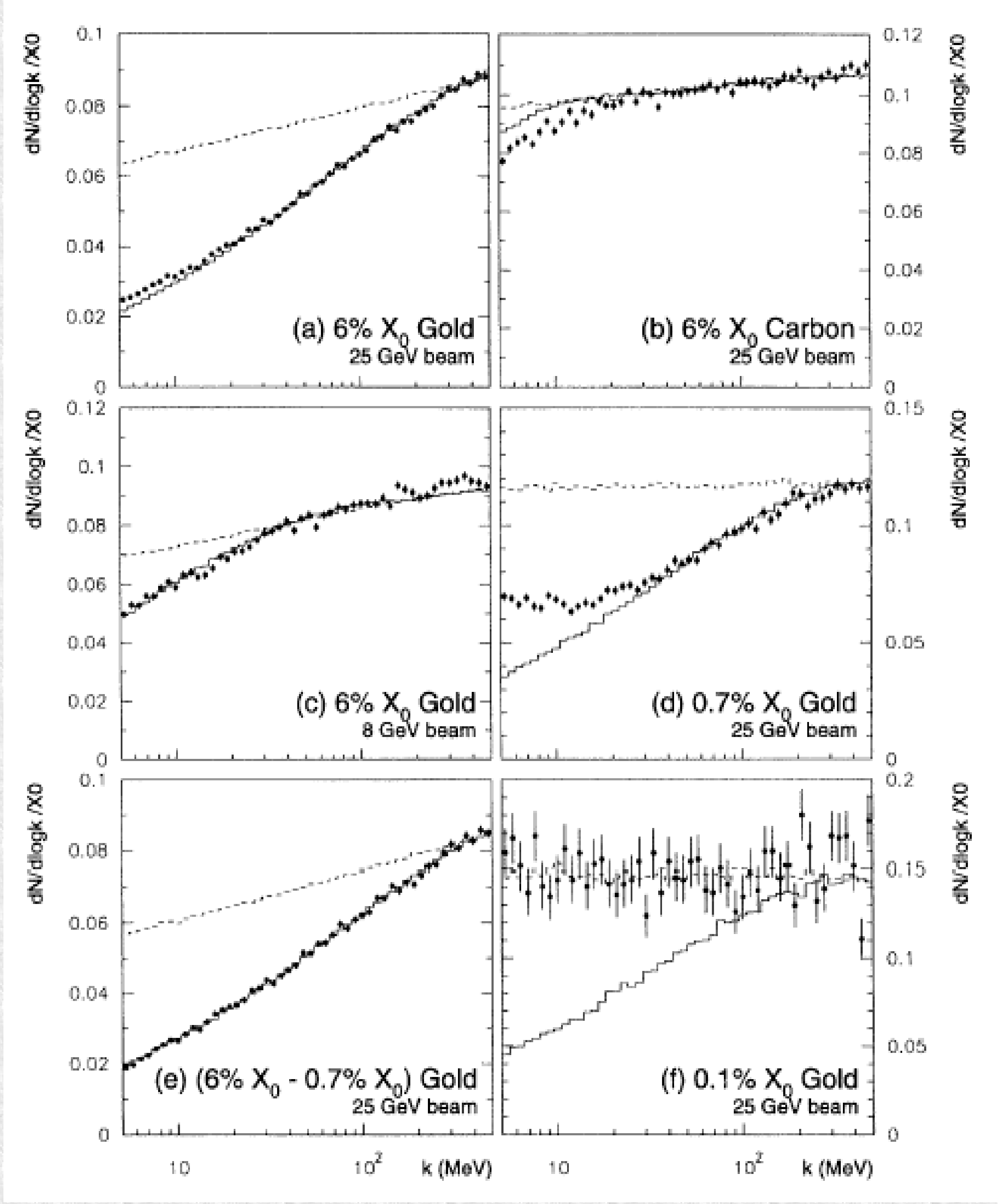
Large chunks of matter, reasonable understanding of internal structure (e.g. well separated atoms) [MEDIUM]

L. Landau, I. Pomeranchuck, Dokl.Akad.Nauk Ser.Fiz.92:535,1953; Dokl.Akad.Nauk Ser.Fiz.92:735-738,1953.
A. B. Migdal, Phys.Rev.103:1811-1820,1956. **P.L. Anthony, et. al.,Phys.Rev.Lett.75:1949, (1995).**
R. Blankenbecler, S. Drell, Phys.Rev.D53:6265,1996.

QED energy loss circa. 1995!

Good agreement between theory and experiment

Question: what is being tested!



QED energy loss circa. 1995!

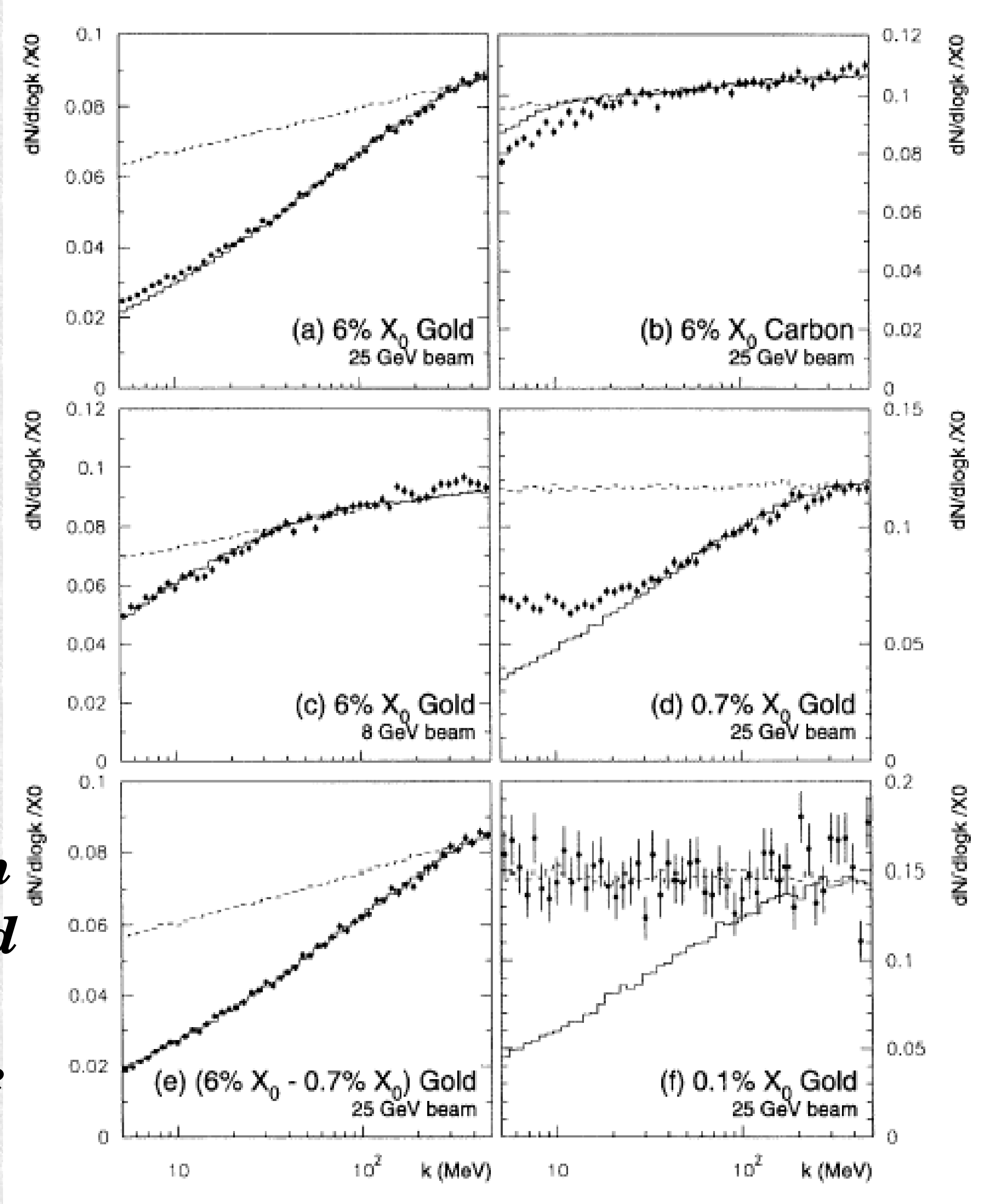
Good agreement between theory and experiment

Question: what is being tested!

Answer:
The LPM effect in QED!!

Probe: stable, well understood
no issues with production
Target: stable, well understood

Theory: pQED, very applicable



Moving to QCD!!

1) Understanding of probe/ probe production and control ??

2) Stability of probe/ propagation in vacuum ??

3) Modeling of medium ????

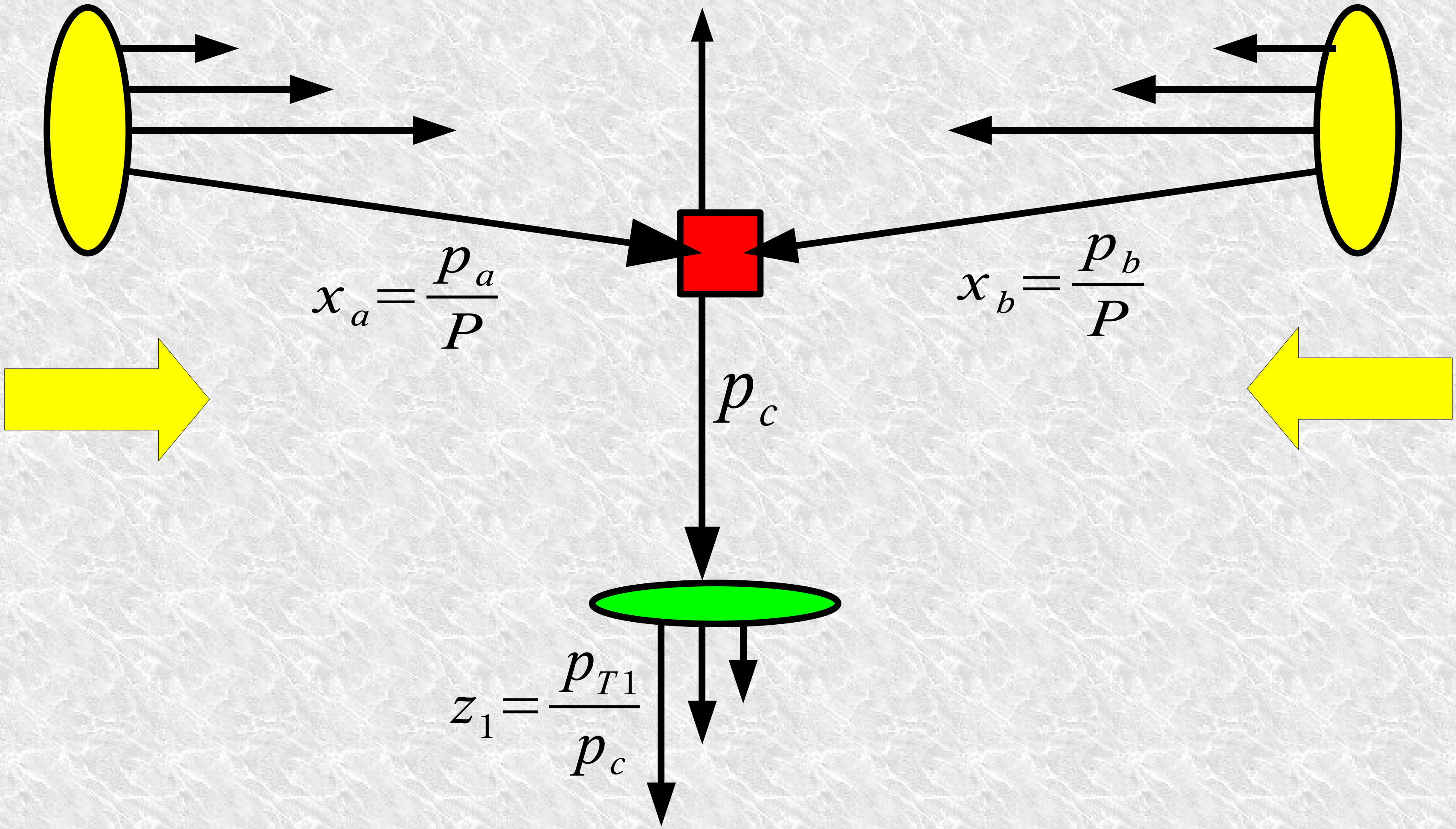
4) Probe medium interaction ?????

5) What can we learn/ generalized properties of medium ?????

6) Control experiment !!!

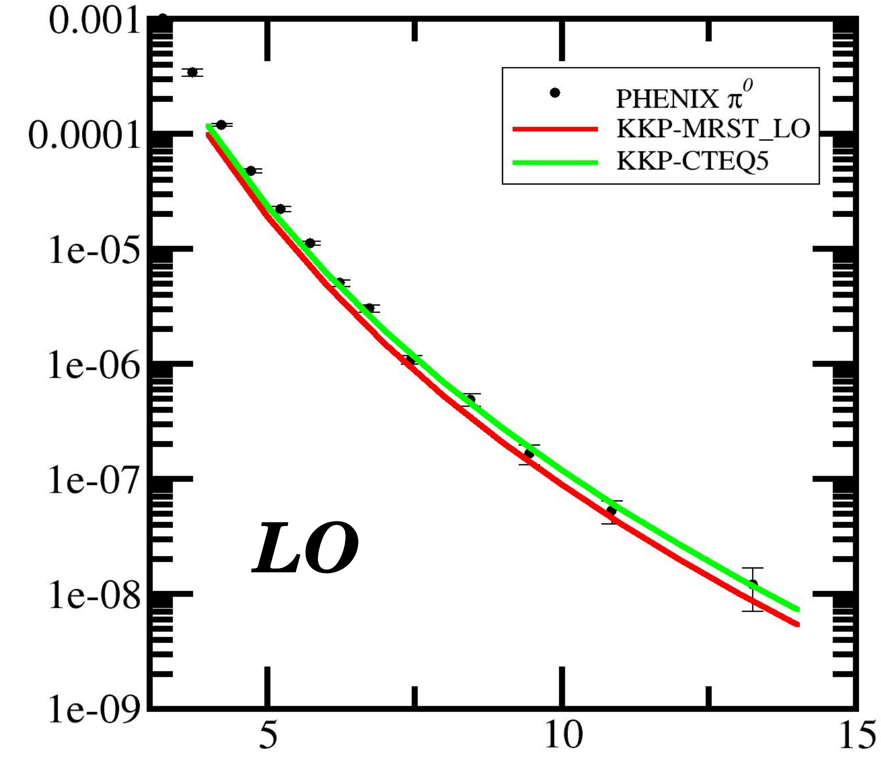
7) Range of applicability of theory !!

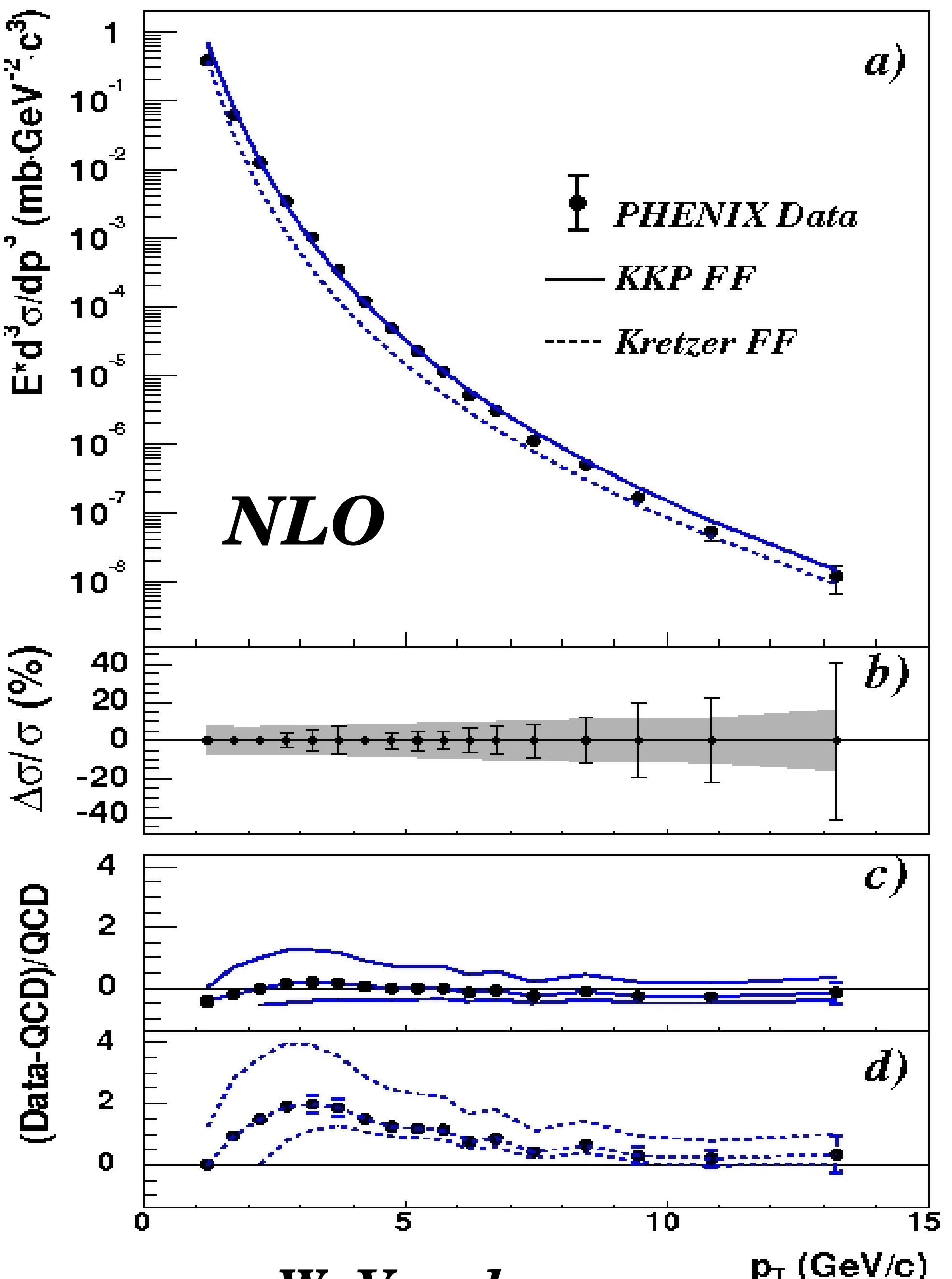
Probe in vacuum, factorization!



$$\frac{d\sigma^{h_1}}{dy\, dp_{T_1}} \sim \int dx_a\, dx_b\; G(x_a)\; G(x_b)\; \frac{d\hat{\sigma}}{d\hat{t}}\; D_q^{h_1}(z_1)$$

Comparing with experiment



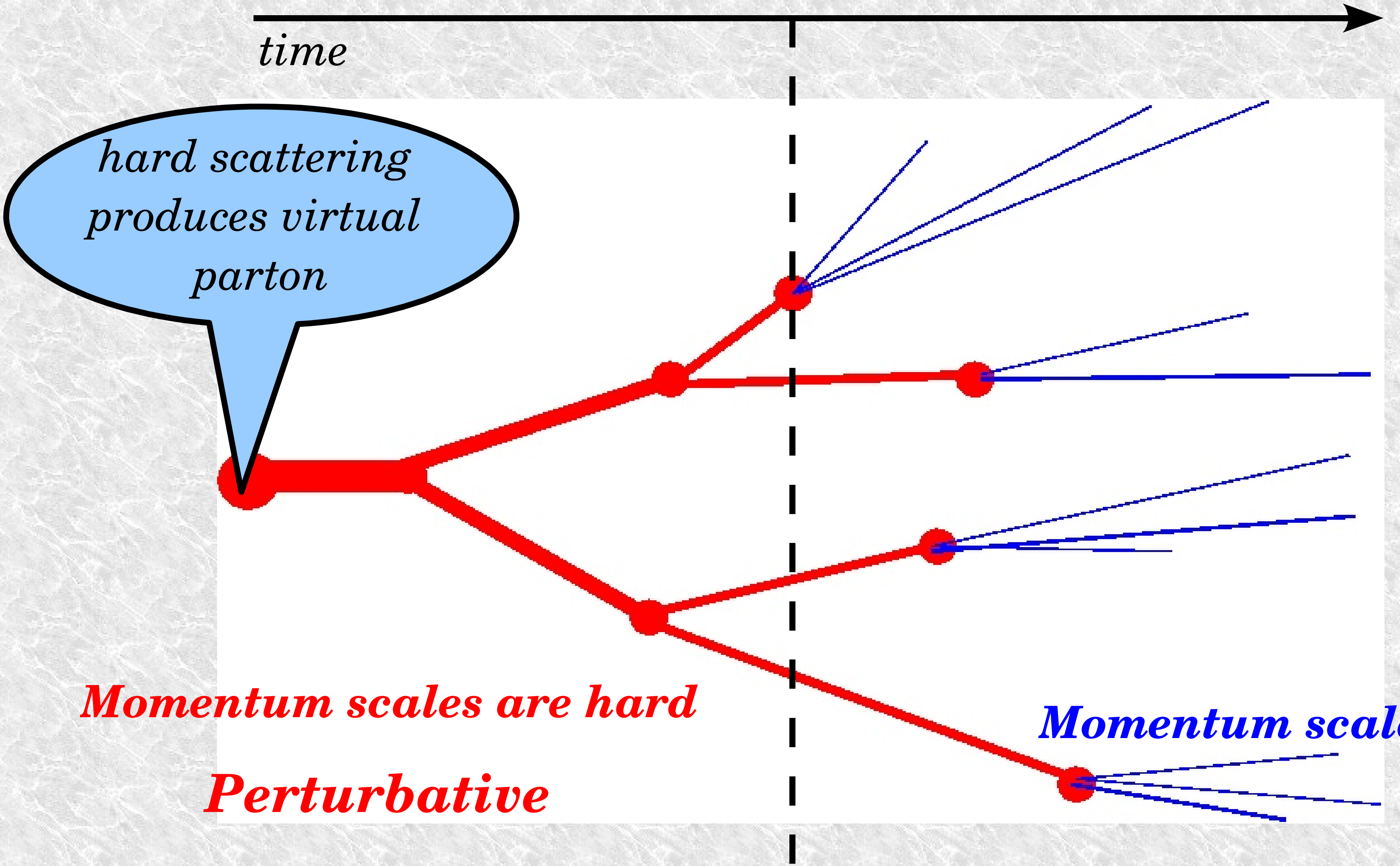


pion cross-section in p-p

Agreement with pQCD over nine orders of magnitude

W. Vogelsang

Understanding propagation in vacuum!



From e⁺e⁻, ep, pp Expt.

Non-Perturbative

Pert. length limited by uncertainty!

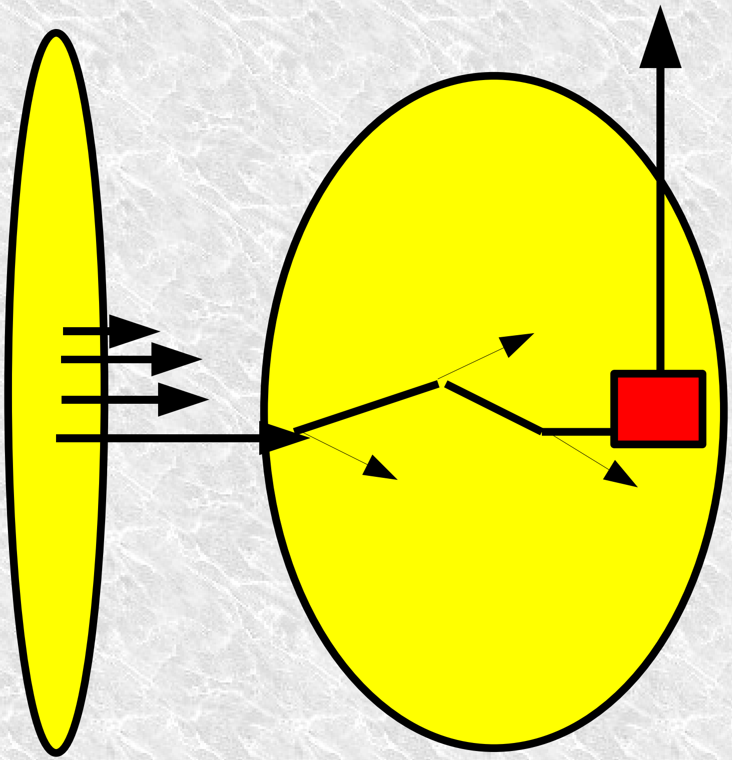
Problem (1) details of initial state

1) Shadowing of quark distribution

2) Initial multiple scattering/ Cronin

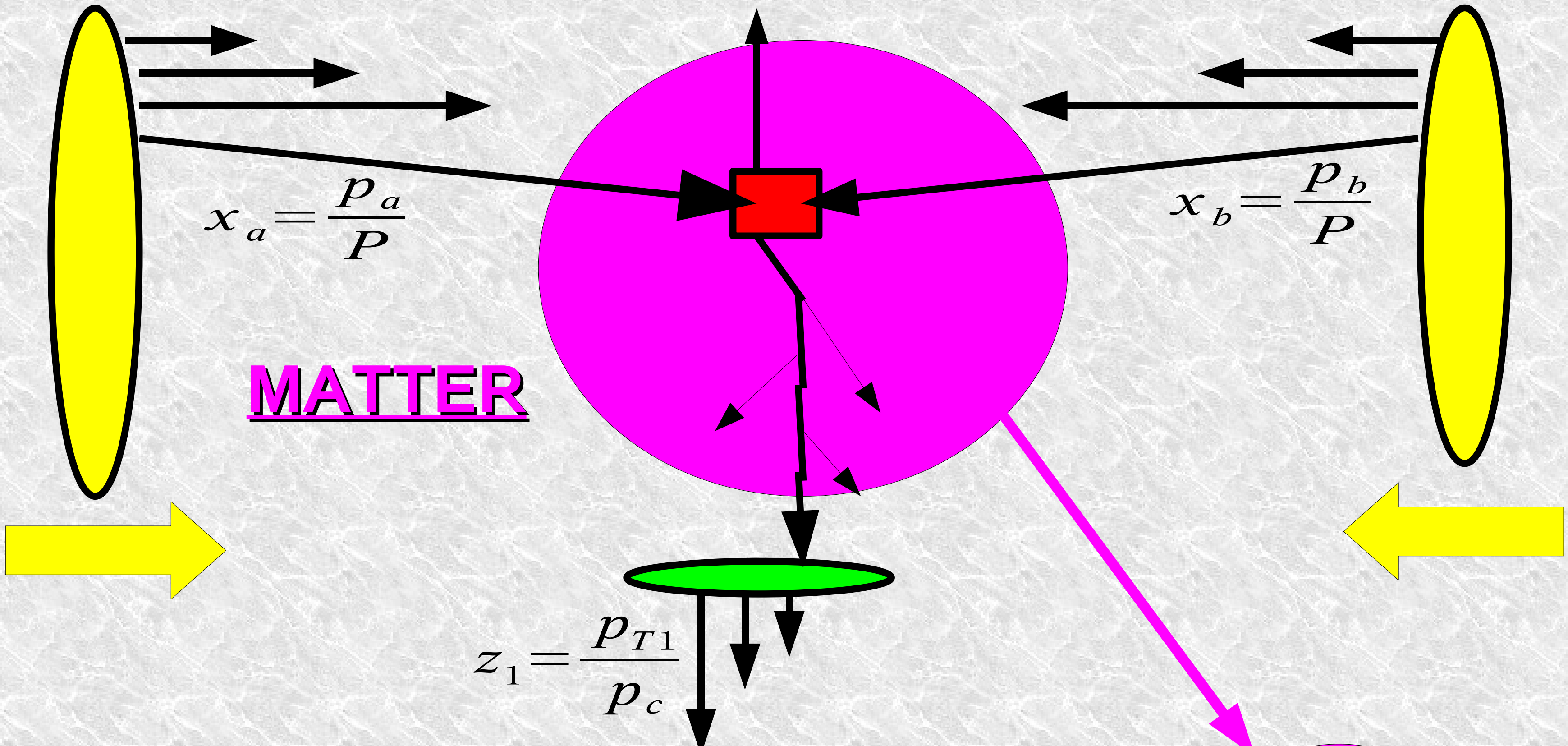
3) Initial state energy loss

4) Good if can be done in the same formalism as final state jet modification



Already being done in GLV,
In the works, in HT,
Can also be done in ASW,
Cannot be done in AMY

Enter the QGP



$$\frac{d\sigma^{h_1}}{dy\, dp_{T_1}} \sim \int dx_a dx_b \; G(x_a)\, G(x_b)\, \frac{d\hat{\sigma}}{d\hat{t}}\, \widetilde{D_q^{h_1}}(z_1)$$

Problem 2) Can we demonstrate factorization as above

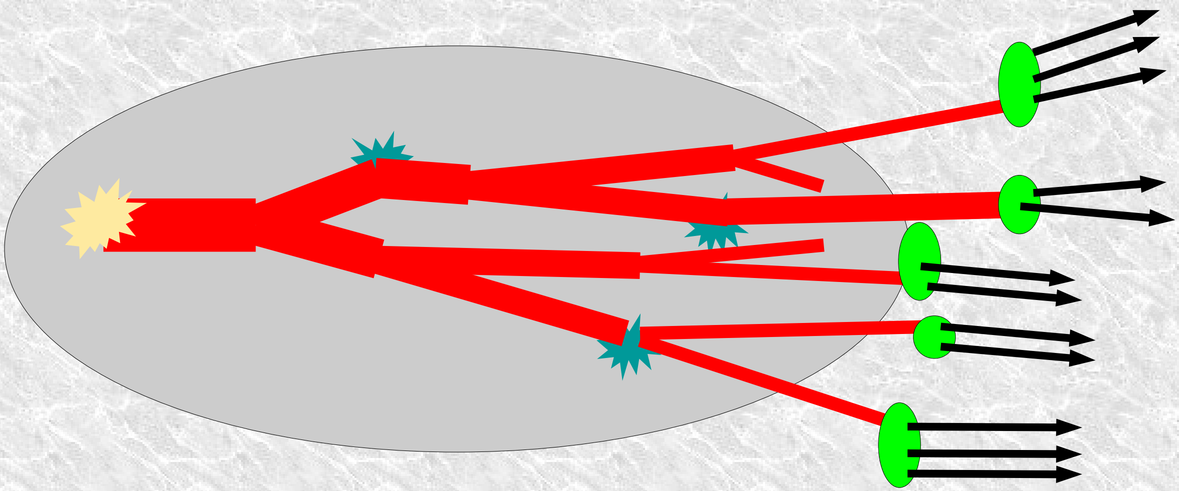
Too hard, difficult factorization proofs, almost nobody really cares !!

New elegant methods from Effective theories, e.g., SCET

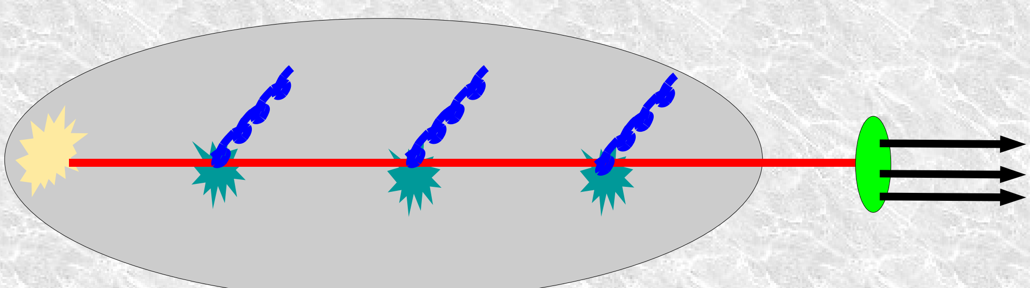
Problem 3) At least 4 ways to calculate

Can be divided into 2 basic types of schemes

1) Those which calculate the change in distribution of partons or hadrons: HT, AMY,



2) Those which calculate the energy lost by parent parton: (D)GLV, ASW



In either case, fragmentation always happens in vacuum. Medium modification always refers to the parton

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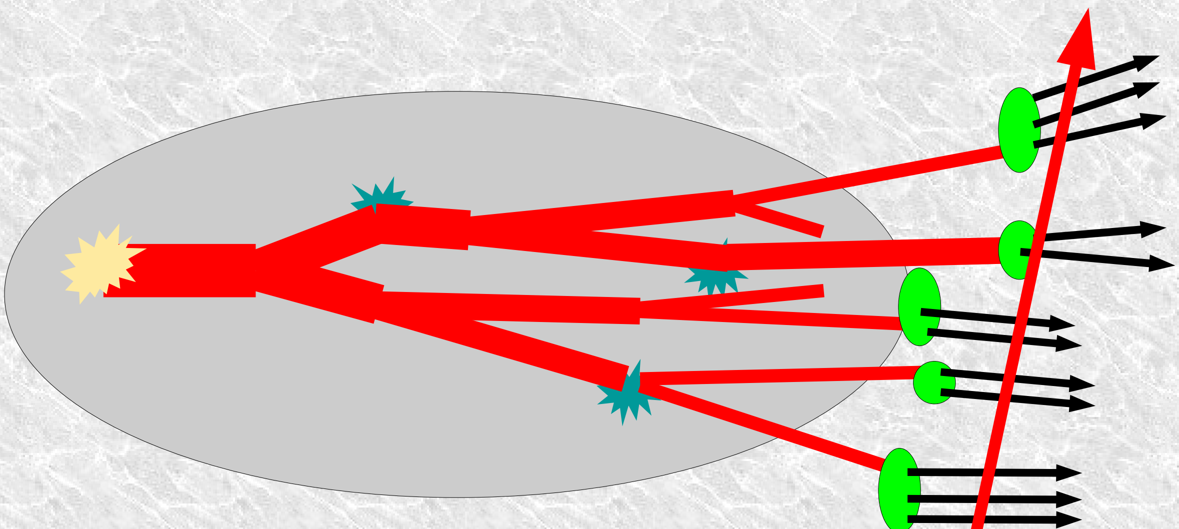

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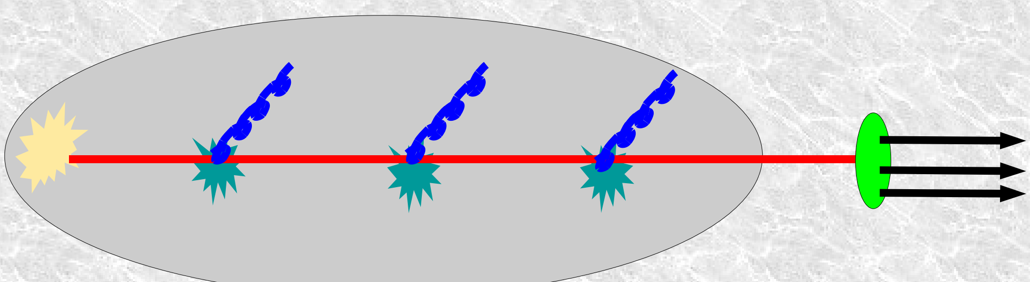
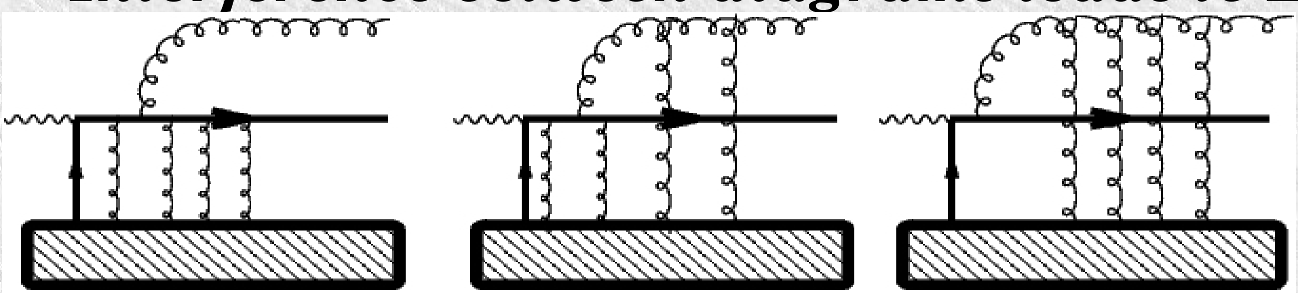


In either case, fragmentation always happens in vacuum. Medium modification always refers to the parton

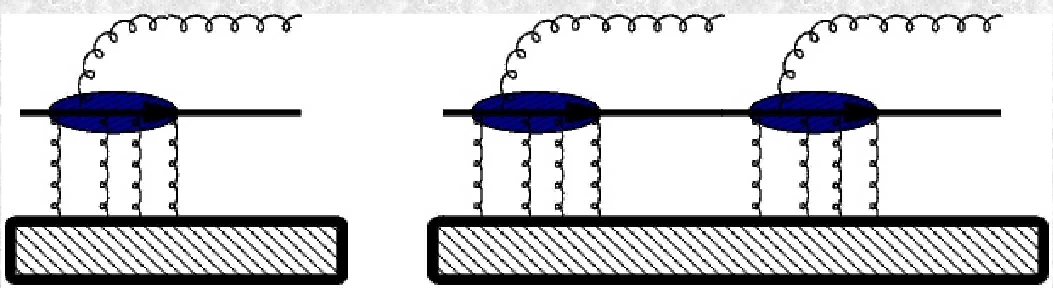
Higher twist method

- ***A medium with a color correlation length λ << L***
- ***Highly VIRTUAL parton produced in hard collision***
- ***Parton picks up extra SMALL transverse kicks ~ μ***
- ***Expand diagrams in μ/Q,***
- ***Interference between diagrams leads to LPM suppression***



$$\int dy\, P(y)\, M(r_i, r_f)$$

Multiple scattering for each radiation



$$e^{\int dy\, P(y)\, M(r_i, r_f)}$$

Multiple radiation / evolution in medium

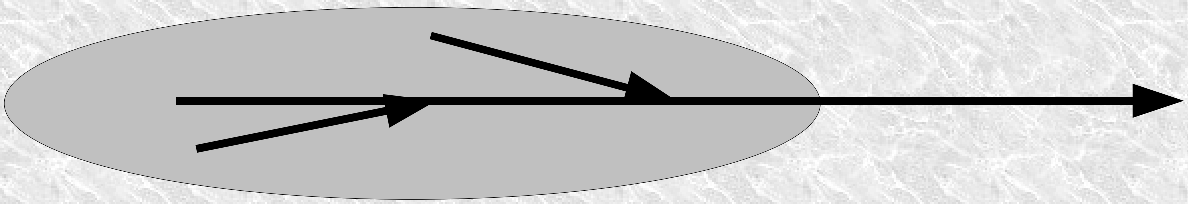
$$\hat{q}_0 = 2 - 3\, GeV^2 / fm$$

Issues: Higher twist

- *A systematic extension of hard pQCD processes in vacuum*
- *Contains vacuum and medium induced rad. and interference*
- *Directly computes the final distribution of hadrons*
- *Straightforward generalization to multi-hadron observables*
- *Can apply to any medium: need short distance correlation*

$$\hat{q} = \frac{p_\perp^2}{t} = \frac{2\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dt \left\langle F^{\mu\alpha}(t) v_\alpha F_\mu^\beta(0) v_\beta \right\rangle \propto \; T^3, \;\; \mu^3, \;\; \epsilon^{\frac{3}{4}}, \;\; s$$

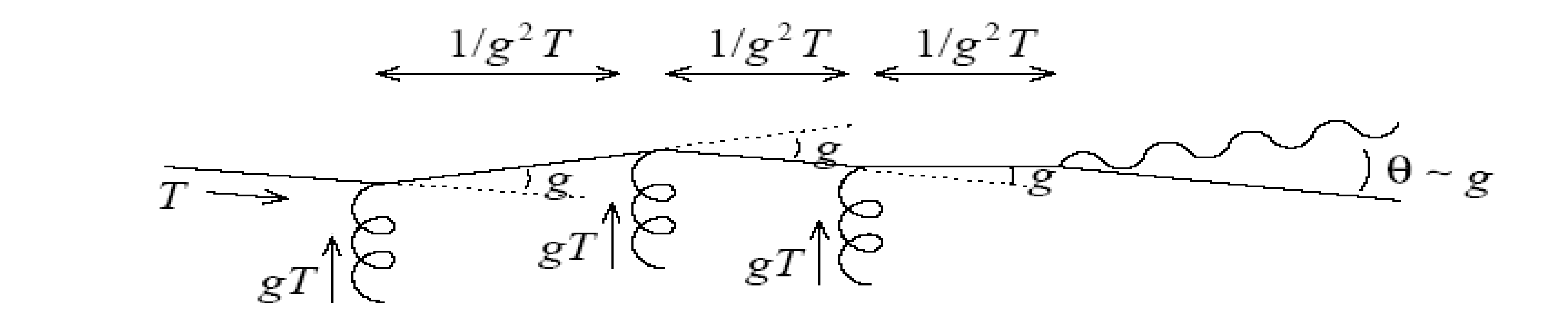
- *Does not contain flavor changing scatterings, yet!*
- *So far, worked out to few scatterings per radiation,*
- *Has not included elastic energy loss/ionization loss!*



- *Not clear how to include thermal push from medium*
- *Can say very little beyond the transport coefficients*
- *Cannot describe energy flow within the plasma from the jet*
- *Not applicable when jet scale comparable to medium scale*

AMY- Finite temperature field theory formalism

- *Hot thermal medium of quarks and gluons at $T \rightarrow \infty$*
- *$T \rightarrow \infty$ implies $g \rightarrow 0$*
- *Hard parton comes in on shell $E \sim T$*
- *Picks up multiple soft hits, $\mu \sim gT$ from hard particles of $\sim T$*
- *The hard lines never go off-shell by more than g^2T*
- *Long formation time leads to multiple scattering*

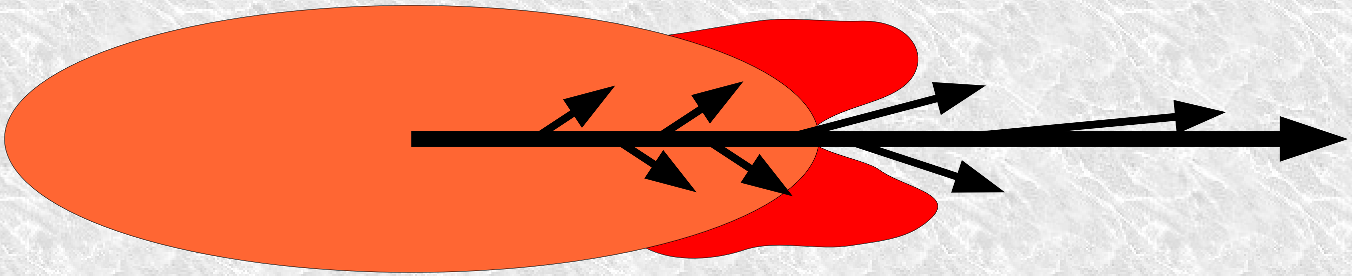


Calculate conversion rates: q ⇔ g , g ⇔ q
Use rates to evolve distributions with time with a Fokker Plank eqn.

$$\hat{q}_0 = 2 - 3\, GeV^2 / fm$$

Issues: AMY

- By far the most systematic approach applied to jet modification
- Both medium and Jet described within the same theory
- Includes flavor changing interactions and thermal push!
- Includes elastic energy loss, almost naturally!
- A universal coupling α_S for both jet and medium

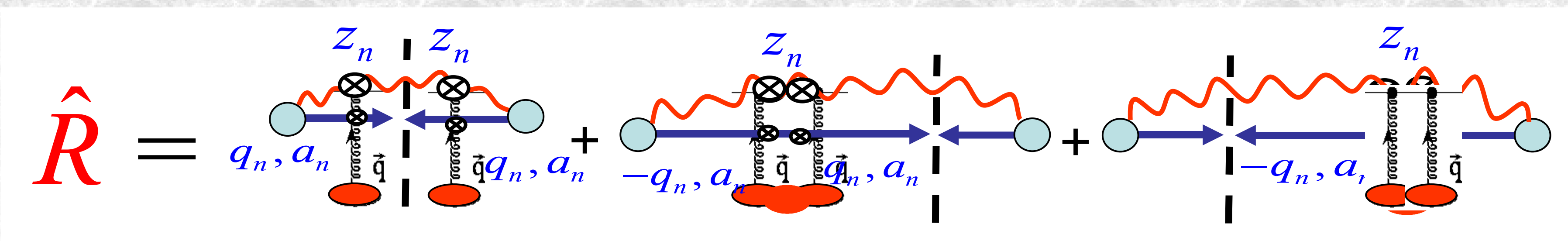


- Can easily describe flow of energy from jet into medium
- Can be extended to include multi-hadron observables

- Cannot describe hadronic phase or energy loss in hadronic phase
- No initial state/cold nuclear matter effects
- No vacuum radiation or interference with vacuum radiation
- Unclear applicability/interpretation in strongly coupled media

GLV- Recursive operator in opacity

- ***Medium of heavy (static) scattering centers(Yukawa potentials)***
- ***Parton picks up transverse kicks ~ μ^2***
- ***Operator formalism that sums order by order in opacity***
- ***Approximate gluon x ➔ 0 (soft gluons), ignore spins !***
- ***Interference between different diagrams leads to the LPM effect and the L^2 length dependence of E-loss.***



- ***Central quantity calculated is radiated gluon intensity***
- ***Gives direct measure of E-loss***
- ***Measurable (Opacity) gives no. of scattering centers in medium***

$$\hat{q}_0 = 1 - 2.5\, GeV^2 / fm$$

Issues: GLV

- Formulation in terms of scattering centers, allows to measure 2 properties: no. of scattering centers, screening length
- Can be applied to both confined and de-confined media
- Mobile scattering centers allows for elastic energy loss
- Includes vacuum and medium induced rad. and interference

- Does not contain flavor changing scatterings, yet!
- So far, worked out to few scatterings per radiation,
- Requires a difficult extension to elastic energy loss
- Probably an even more difficult extension to thermal push

- Unclear identification of scattering centers: degrees of freedom or (problems with entropy), fluctuation gluons (scale relations?)
- Problem with describing multi-hadron observables
- Poisson process not amenable to virtuality evolution
- Cannot describe energy flow into medium

ASW- path integral in opacity

Almost on-shell parton produced in hard collision

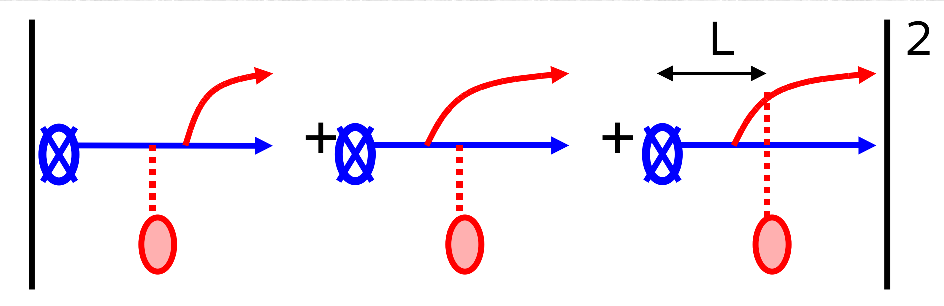
Parton picks up virtuality from kicks in medium

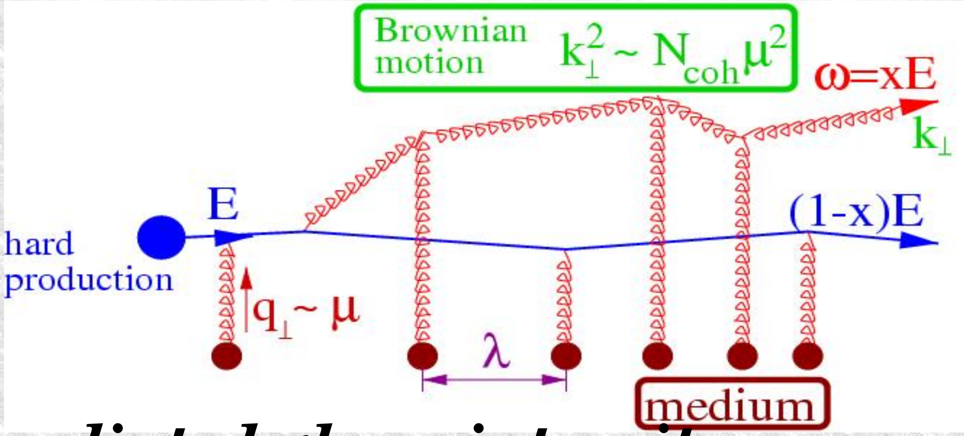
Two simple limits of calculation

a) Few hard scatterings (GLV)

b) Many soft scatterings (BDMPS)

Medium also made up of heavy (static) scattering centers with Yukawa like potentials



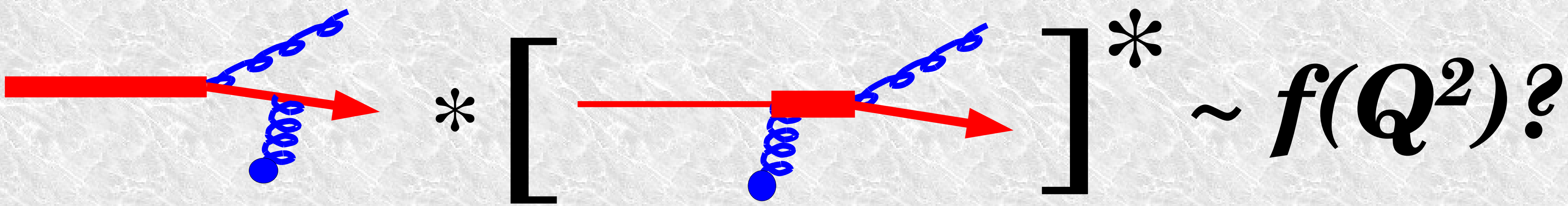


- *Central quantity calculated is radiated gluon intensity*
- *Gives direct measure of E-loss*
- *Measurable (qhat) encodes the number of scattering centers and the screening length*

$$\hat{q}_0 = 18 - 22\, GeV^2 / fm$$

ASW: Issues

- Formulation in terms of scattering centers ⇔ qhat
- Can be applied to both confined and de-confined media
- Most versatile in applicability to thick and thin media
- Includes vacuum and medium induced rad. and interference



- Does not contain flavor changing scatterings, yet!
- Rather difficult extension to elastic energy loss

- Extension of formalism to include multi-hadron observables
- Extension of formalism to include virtuality evolution
- Probably no way to describe thermal push from medium
- Cannot describe energy flow into a medium
- Disagreement with all other formalisms on value of qhat

Problem 4) What are we measuring?

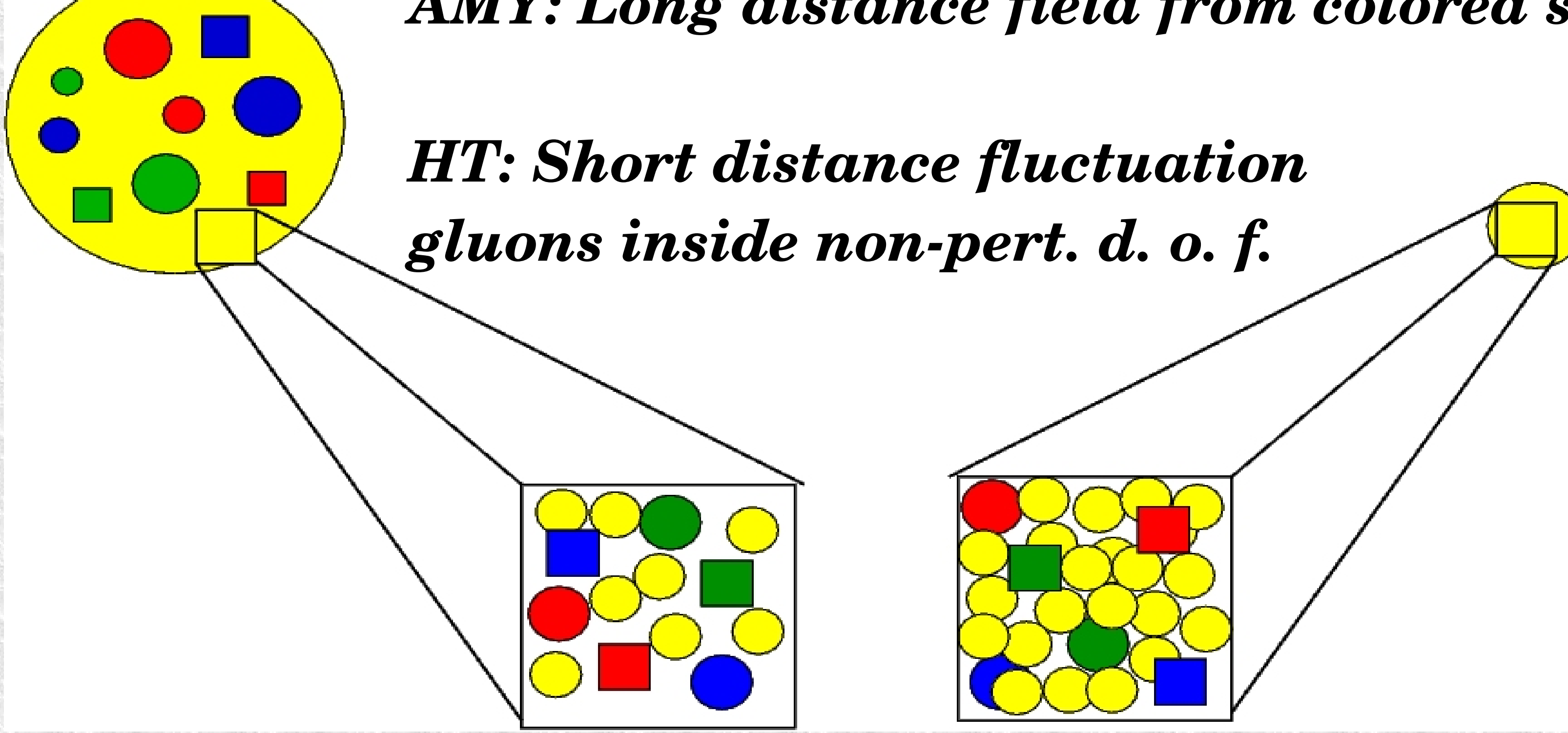
$$\hat{q} = \frac{\langle p_\perp^2 \rangle}{L}$$

Interaction with medium constituents leads to transverse broadening

What is the jet ``mostly'' colliding off ?

AMY: Long distance field from colored sources !

HT: Short distance fluctuation gluons inside non-pert. d. o. f.



DGLV & ASW: somewhere in between, depends on interpretation of scattering centers !!

Does it really matter?

Compare HT, ASW and AMY with identical systematics

All models constrained

1) Same nuclear profile

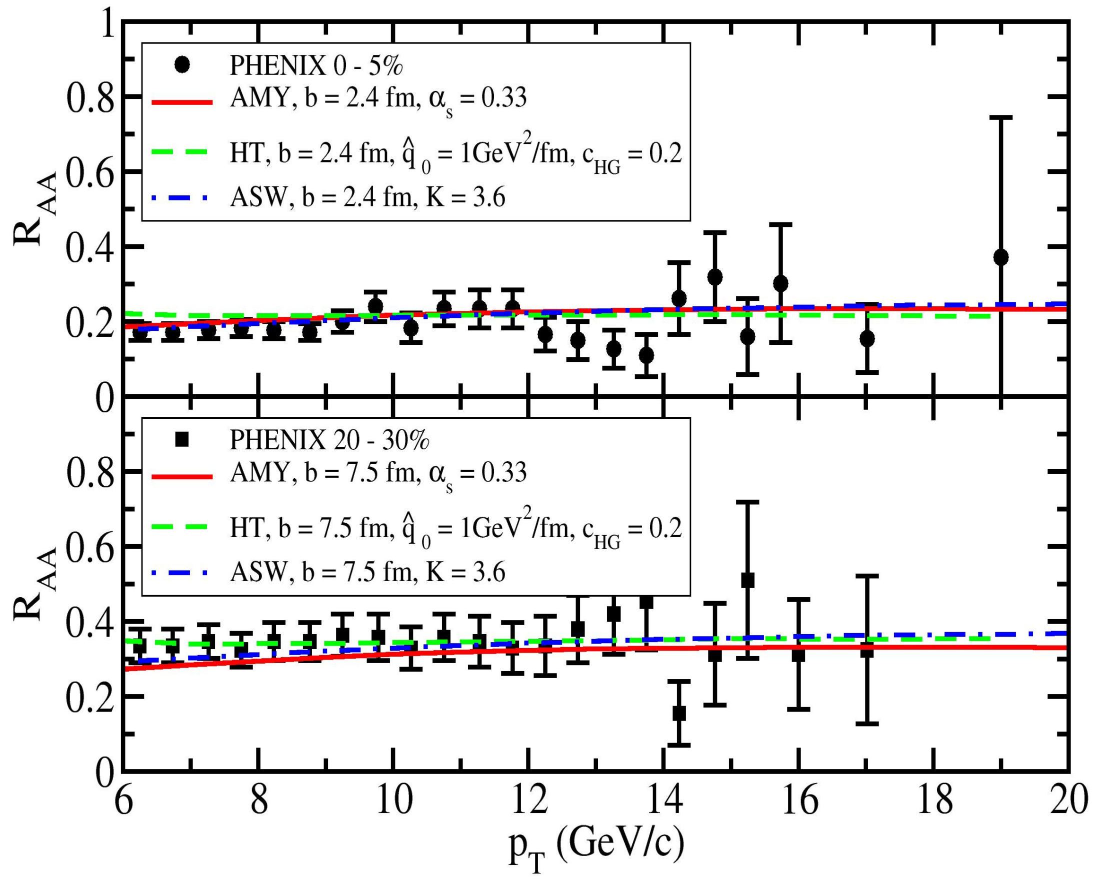
2) Same structure func.

3) Same fragmentation func.

4) Same 3-D hydro medium

Results look very similar!!

Bass et. al., to appear

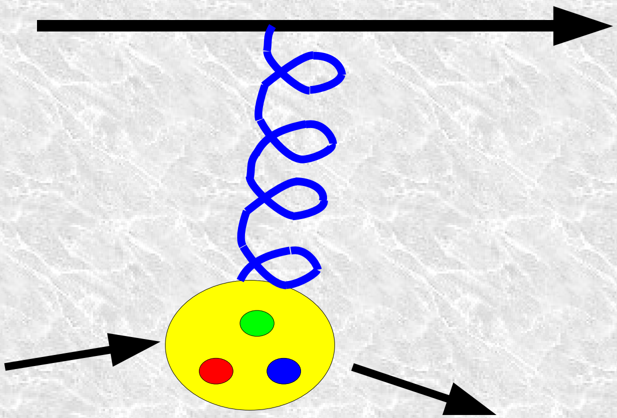


To really probe the degrees of freedom:

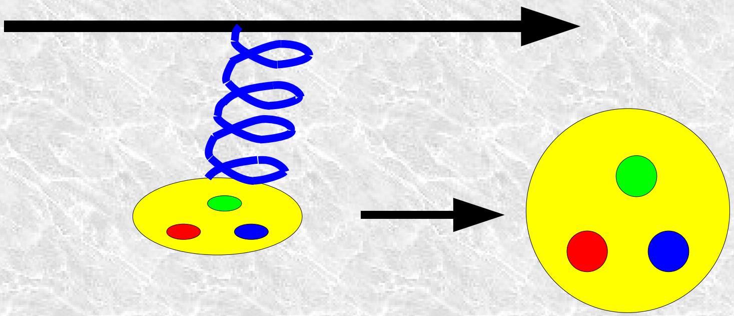
Pheno: go to more differential probes,   Theory: Include elastic E-loss

Problem 5) Elastic/Ionization energy loss

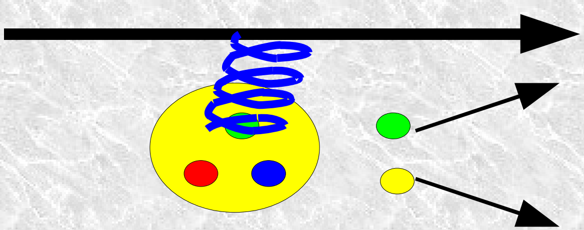
Seems to depend on what the parton bounces off and what happens to the struck constituent of the medium



long distance/elastic E-loss at L.O.
only if object is colored,
Included in AMY, DGLV



Short distance Excitation loss
Not included in any formalism!



Deep-Inelastic E-loss, already in HT
Ionization E-loss, in HT shortly!

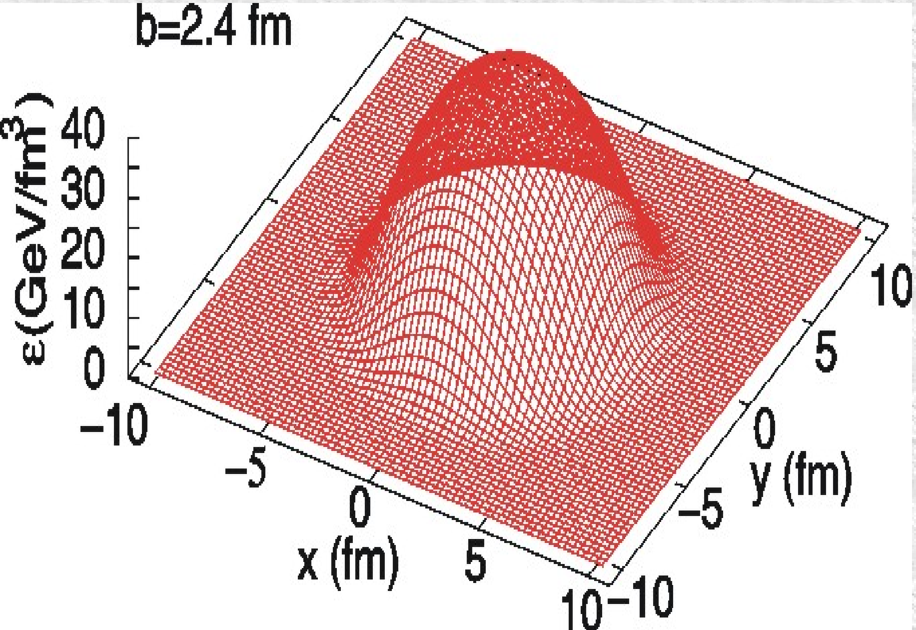
Problem 6) A realistic medium profile

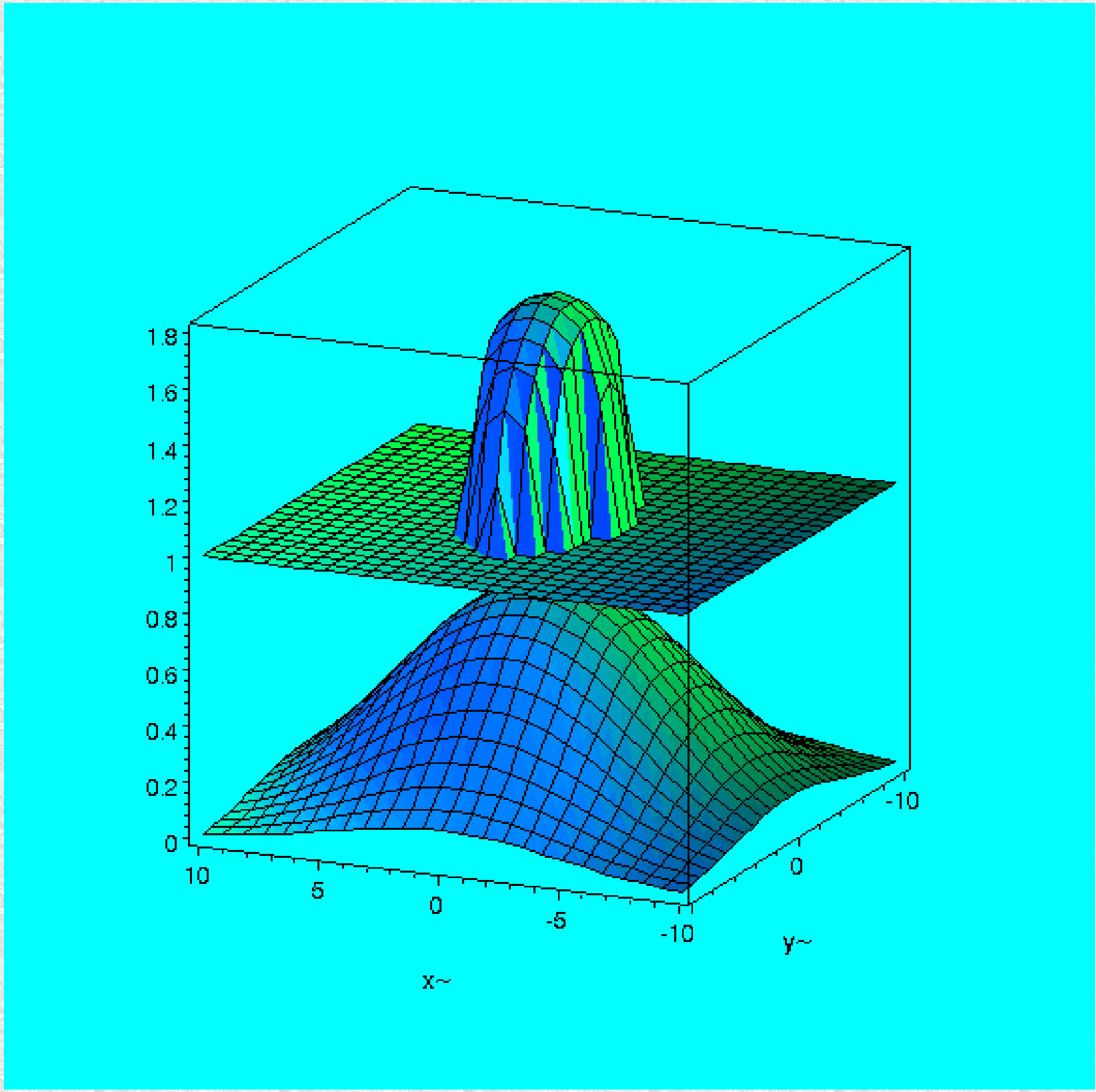
To test any new idea need realistic medium profile:
3-D viscous hydro, correct initial states

Not a question of, is the 3-D hydro better than the Brick

3-D hydro represents reality
hence a constraint
Serious constraint for R_{AA} vs. θ,

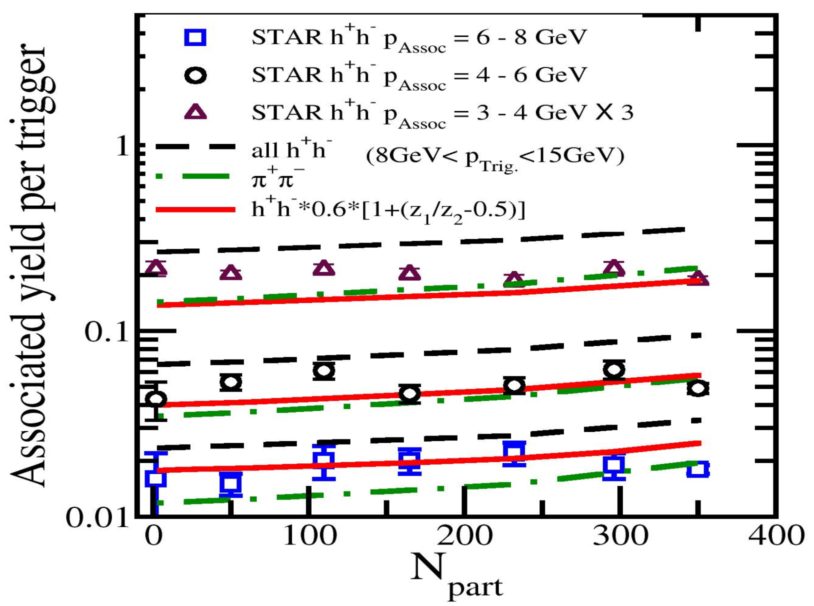
Bass et. al. to appear





Problem 7) Comprehensive phenomenology

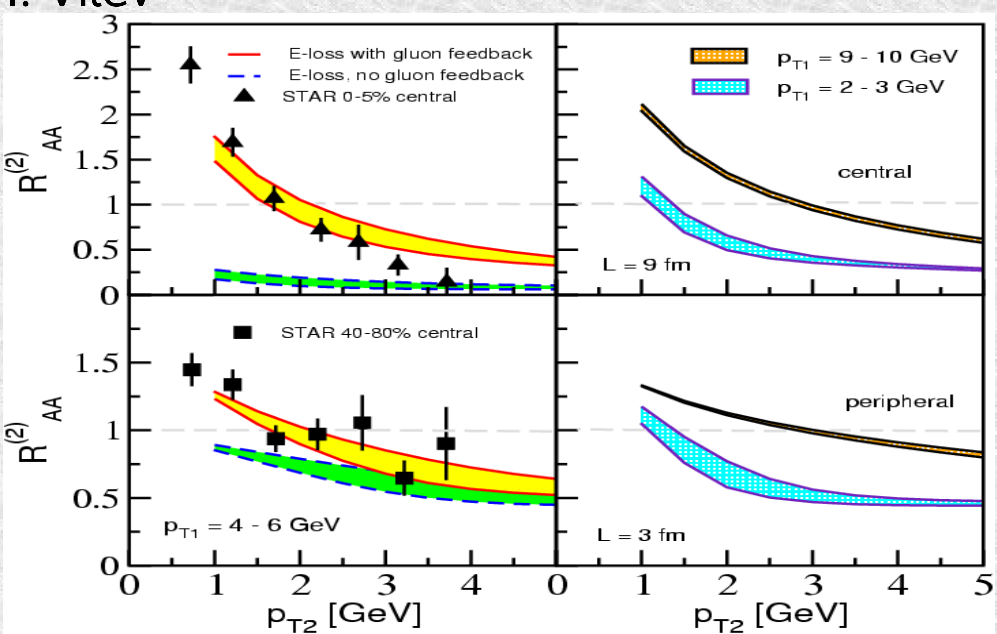
A. Majumder, et. al., nucl-th/0412061



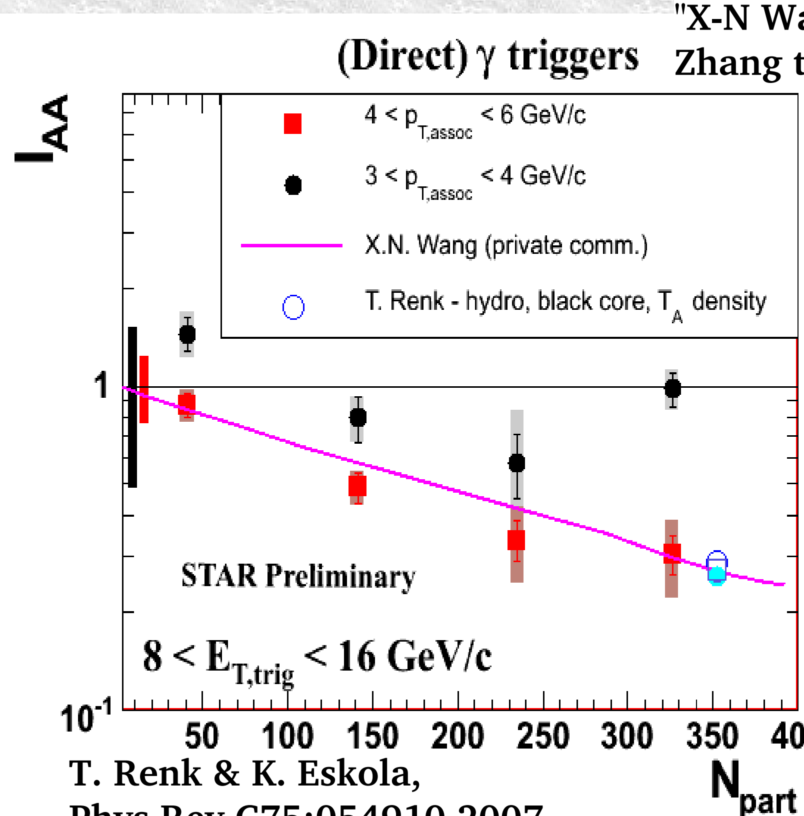
Near side, Away side, photons

Any formalism has to address all pheno within range of applicability

I. Vitev



"X-N Wang & H. Zhang to appear

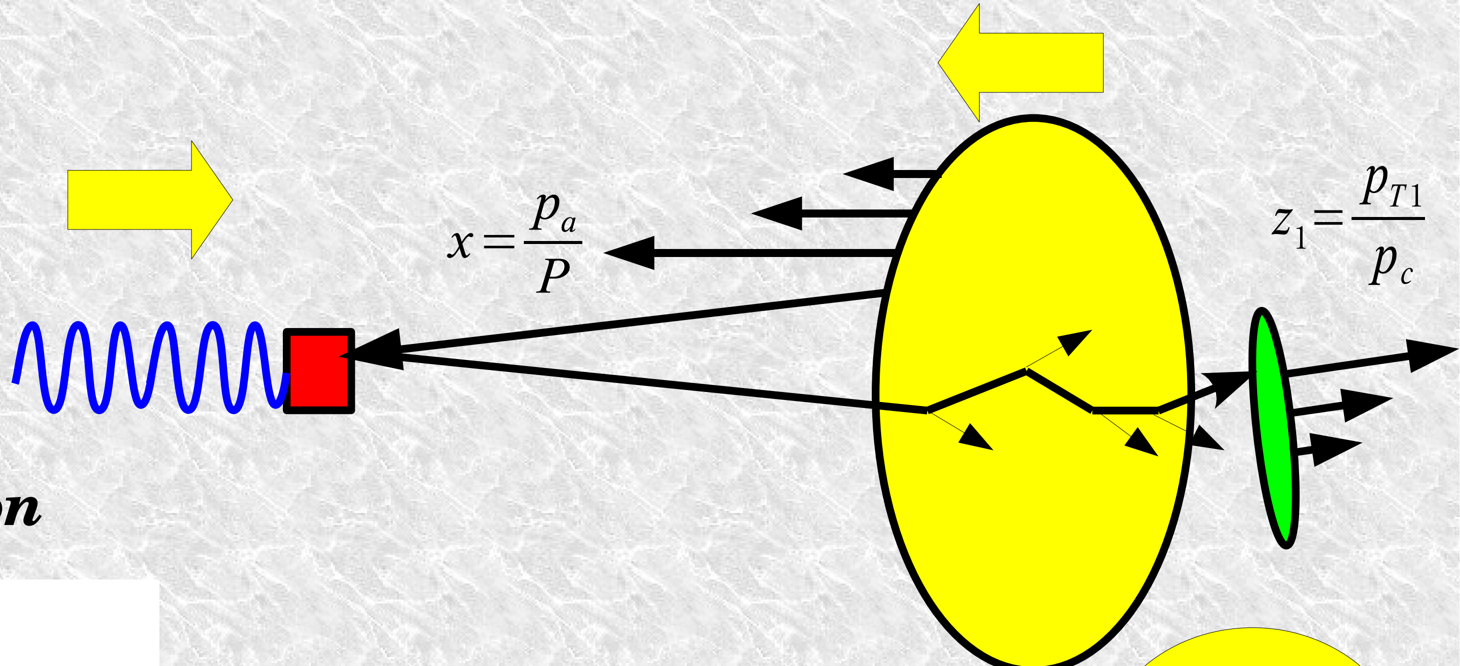


T. Renk & K. Eskola, Phys.Rev.C75:054910,2007

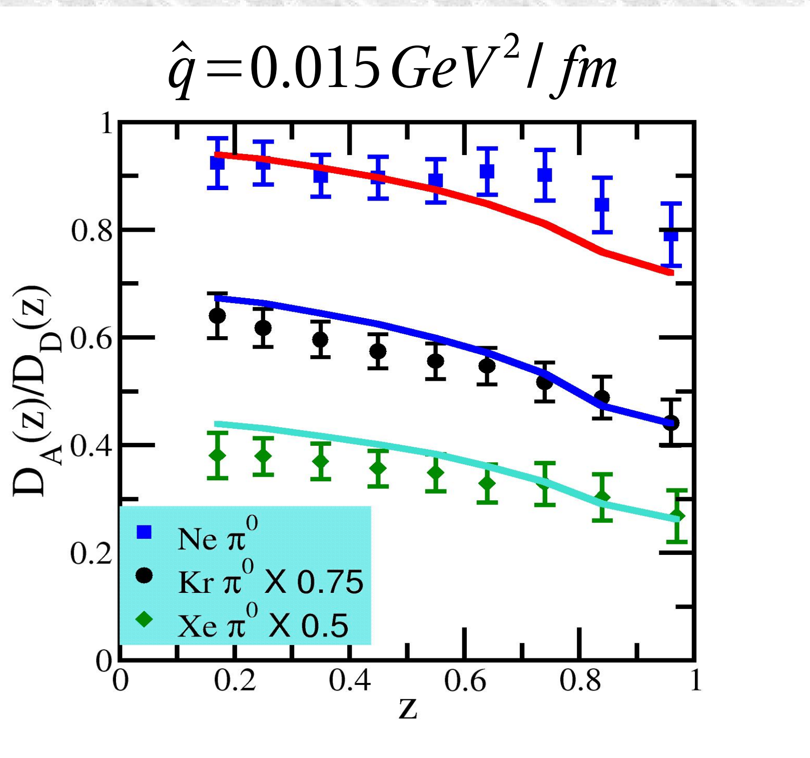
Problem 8) Control experiment

DIS on nuclei, crucial test of formalism

e.g. at HERMES with 27.6 GeV electron



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



Jlab @ 12 GeV will provide some help

Real test at E-RHIC, benchmark for both RHIC and LHC,

Jet mod. a complementary program at E-RHIC, initial state measurements

Summary: problems, problems, problems

1) Initial state, good if done in the same formalism

2) Factorization/effective theory issues

3) Four different looking formalisms: look for common ground

4) Probe resolution, what is being measured

5) Elastic/Ionization energy loss

6) Realistic Medium models from 3-D hydro

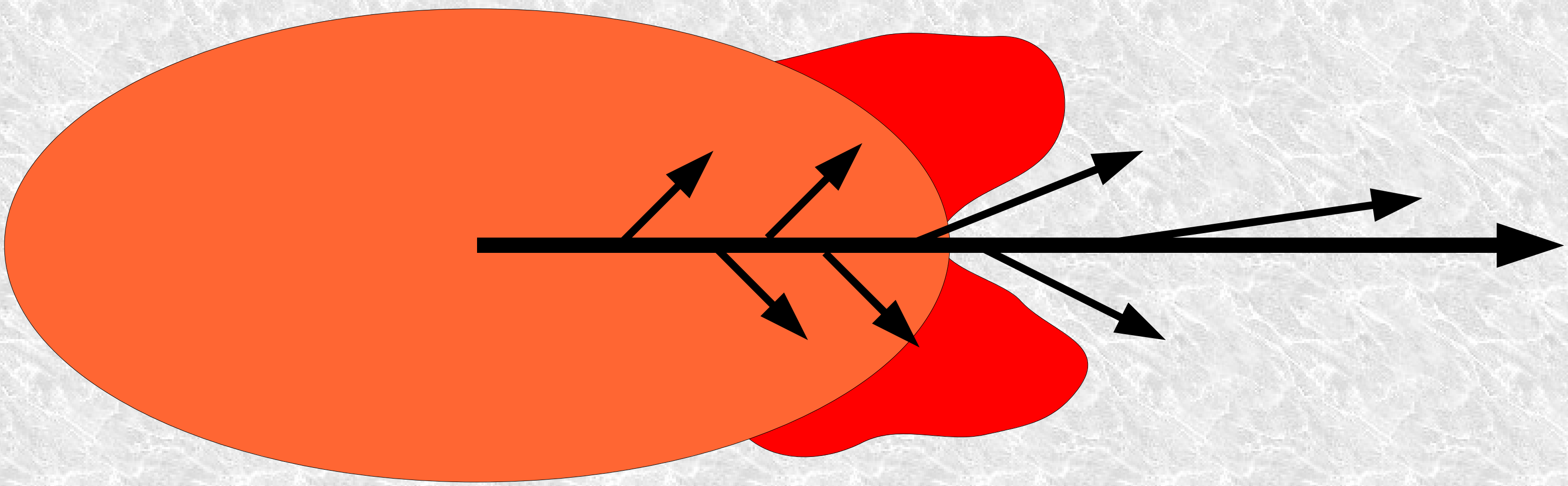
7) Comprehensive phenomenology

8) Control experiment

9) Range of applicability of theory!!

Back Up!

Some part of the radiated energy interacts strongly with the medium: Medium Response



This is soft physics 1 – 2 GeV

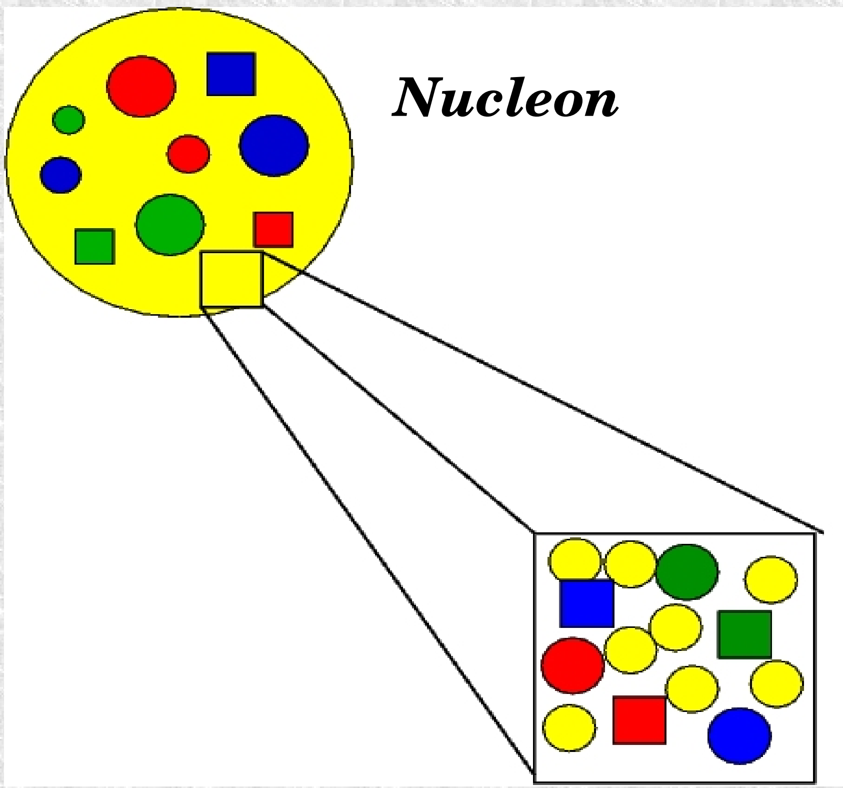
Cannot get this from pQCD

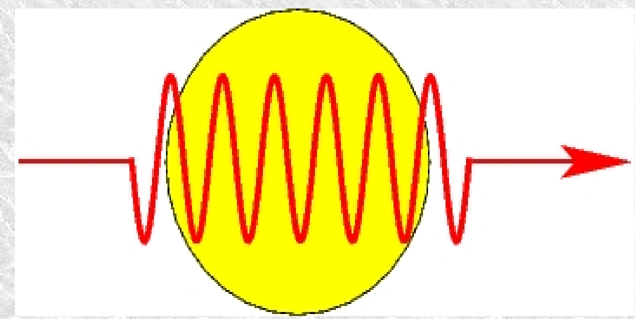
Need some model!

Intermediate region from 2-6 GeV, interaction between Jet frag. and Reco.

Looking at QCD matter at high resolution!

Use a high momentum ↔ short distance probe

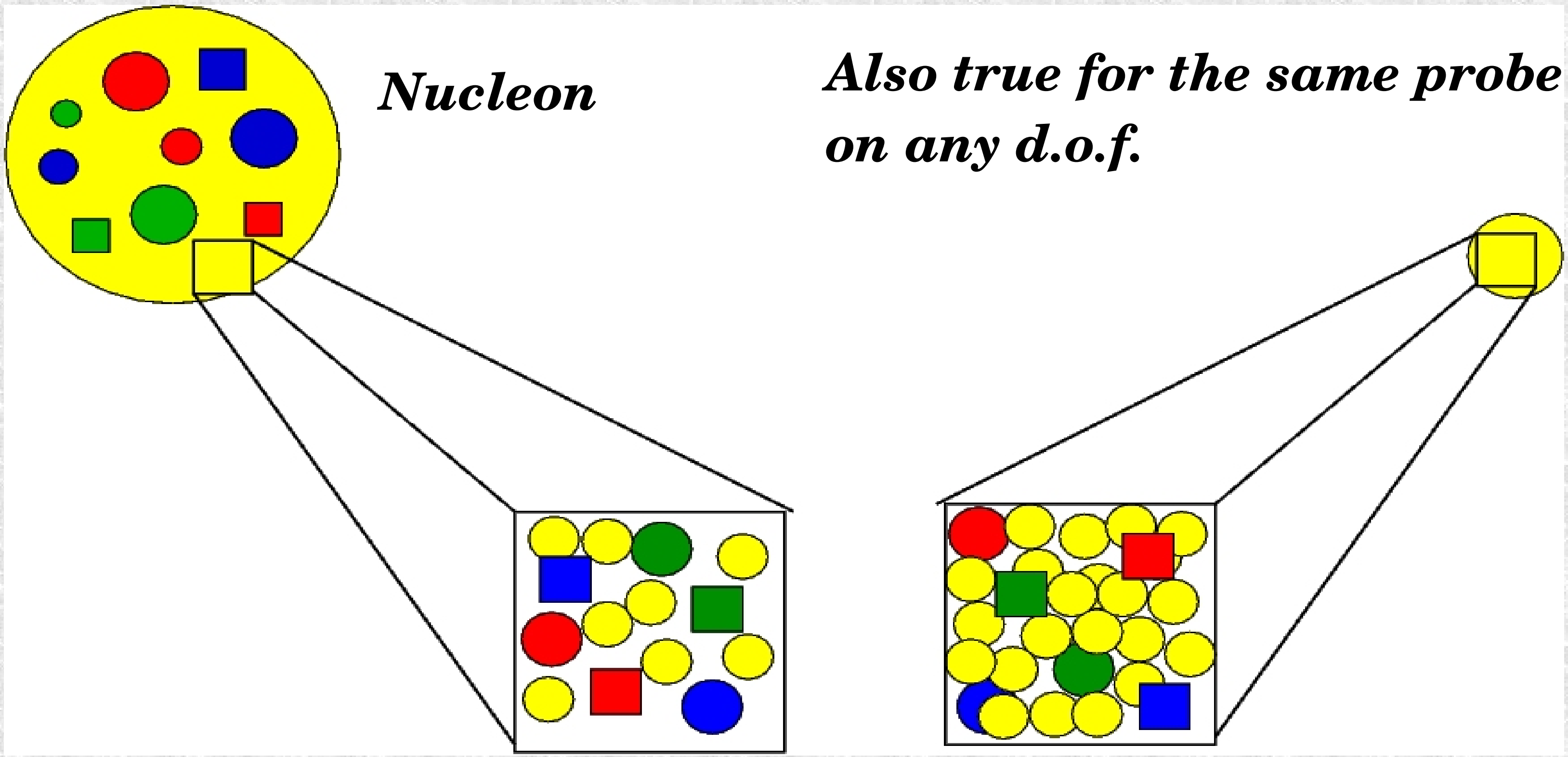




At short enough distance, all QCD degrees of freedom have a partonic sub-structure

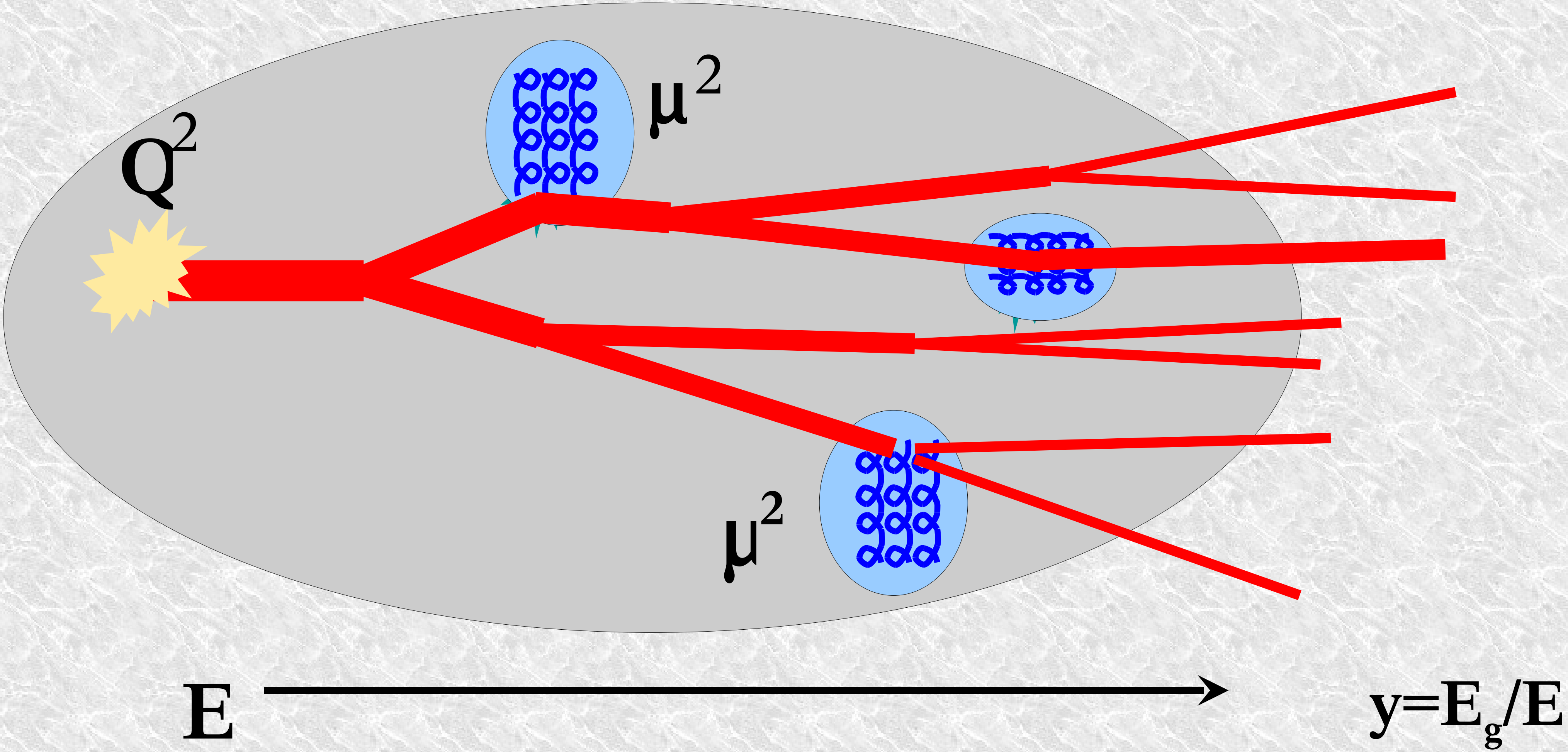
Looking at QCD matter at high resolution!

Use a high momentum ↔ short distance probe



At short enough distance, all QCD degrees of freedom have a partonic sub-structure

Medium modifies the space time evolution of the Jet!!



In the limit $E >> Q, \mu$.

The medium may be within perturbative domain,

Can calculate the modification using pQCD.

Higher twist Calculational details

$$\frac{d\sigma^{h_1}}{dy\,dp_{T_1}} \sim \int dx_a dx_b \;\; G(x_a) \;\; G(x_b) \;\; \frac{d\hat{\sigma}}{d\hat{t}} \;\;\; \widetilde{D_q^{h_1}}(z_1)$$

Calculate in-medium evolution of fragmentation function

$$\frac{\partial D}{\partial \log Q^2} \propto \int_0^L d\zeta\, \hat{q}(\zeta) \int \frac{dy}{y} P(y) M\left(\frac{Q^2 \zeta}{2E\, y(1-y)} \right) D\left(\frac{z}{y}, Q^2 \right) + vacuum\, evolution$$

The space-time dependence of qhat is a model of the medium

Universal formalism: can be applied to almost any medium

Current implementations only involve one scattering per radiation

Elastic energy loss being incorporated

AMY Calculational details

Use the rates to compute the time change in parton distributions

$$\frac{dP_{q\bar{q}}(p)}{dt} = \int_k P_{q\bar{q}}(p+k)\frac{d\Gamma^q_{qg}(p+k,k)}{dkdt} - P_{q\bar{q}}(p)\frac{d\Gamma^q_{qg}(p,k)}{dkdt} + 2P_g(p+k)\frac{d\Gamma^g_{q\bar{q}}(p+k,k)}{dkdt},$$

$$\frac{dP_g(p)}{dt} = \int_k P_{q\bar{q}}(p+k)\frac{d\Gamma^q_{qg}(p+k,p)}{dkdt} + P_g(p+k)\frac{d\Gamma^g_{gg}(p+k,k)}{dkdt} - P_g(p)\left(\frac{d\Gamma^g_{q\bar{q}}(p,k)}{dkdt} + \frac{d\Gamma^g_{gg}(p,k)}{dkdt}\Theta(2k-p)\right),$$

Fold final distribution of partons with frag. func. to get hadrons

$$D_{\pi,c}(z,Q;r,n) = \int dp_f \frac{z'}{z}\left(P_{q\bar{q}/c}(p_f;p_i)D_{\pi/q}(z',Q) + P_{g/c}(p_f;p_i)D_{\pi/q}(z',Q)\right)$$

Temperature profile and $\alpha(T)$ are the model of the medium

- ***Multiple scattering per radiation included***
- ***Elastic energy loss incorporated***
- ***Strongly dependent on presence of a thermlized plasma,***
- ***Cannot be applied to hadronic gas or cold matter***
- ***No means to incorporate the effect of initial state virtuality***

GLV Calculational details

Using the energy loss spectrum per radiation construct a Poisson distribution for hard jet to lose energy E

$$P_E(\epsilon) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int d\omega_i \frac{dI(\omega_i)}{d\omega} \right] \delta\left(\epsilon - \sum_{i=1}^{n} \frac{\omega_i}{E} \right) \exp\left[- \int d\omega \frac{dI}{d\omega} \right]$$

Fold the probability of E-loss with vacuum fragmentation to get final hadrons

$$D_{h/q}^{(\mathrm{med})}(z, Q^2) = \int_0^1 d\epsilon \, P_E(\epsilon) \frac{1}{1-\epsilon} D_{h/q}\left(\frac{z}{1-\epsilon}, Q^2\right).$$

Can be applied to any media,
radiation intensity can be calculated to desired level of accuracy

Fate of radiated gluon not clear,
Elastic energy loss zero by definition,

ASW Calculational details

Using the energy loss spectrum per radiation construct a Poisson distribution for hard jet to lose energy E

$$P_E(\epsilon) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int d\omega_i \frac{dI(\omega_i)}{d\omega} \right] \delta\left(\epsilon - \sum_{i=1}^{n} \frac{\omega_i}{E} \right) \exp\left[- \int d\omega \frac{dI}{d\omega} \right]$$

Fold the probability of E-loss with vacuum fragmentation to get final hadrons

$$D_{h/q}^{(\mathrm{med})}(z, Q^2) = \int_0^1 d\epsilon \, P_E(\epsilon) \, \frac{1}{1-\epsilon} \, D_{h/q}\left(\frac{z}{1-\epsilon}, Q^2\right) .$$

Can be applied to any media,
radiation intensity can be calculated to desired level of accuracy

Fate of radiated gluon not clear,
Elastic energy loss zero by definition,