Duke Physics

The Study of Dense Matter through Perturbative Jet Modification

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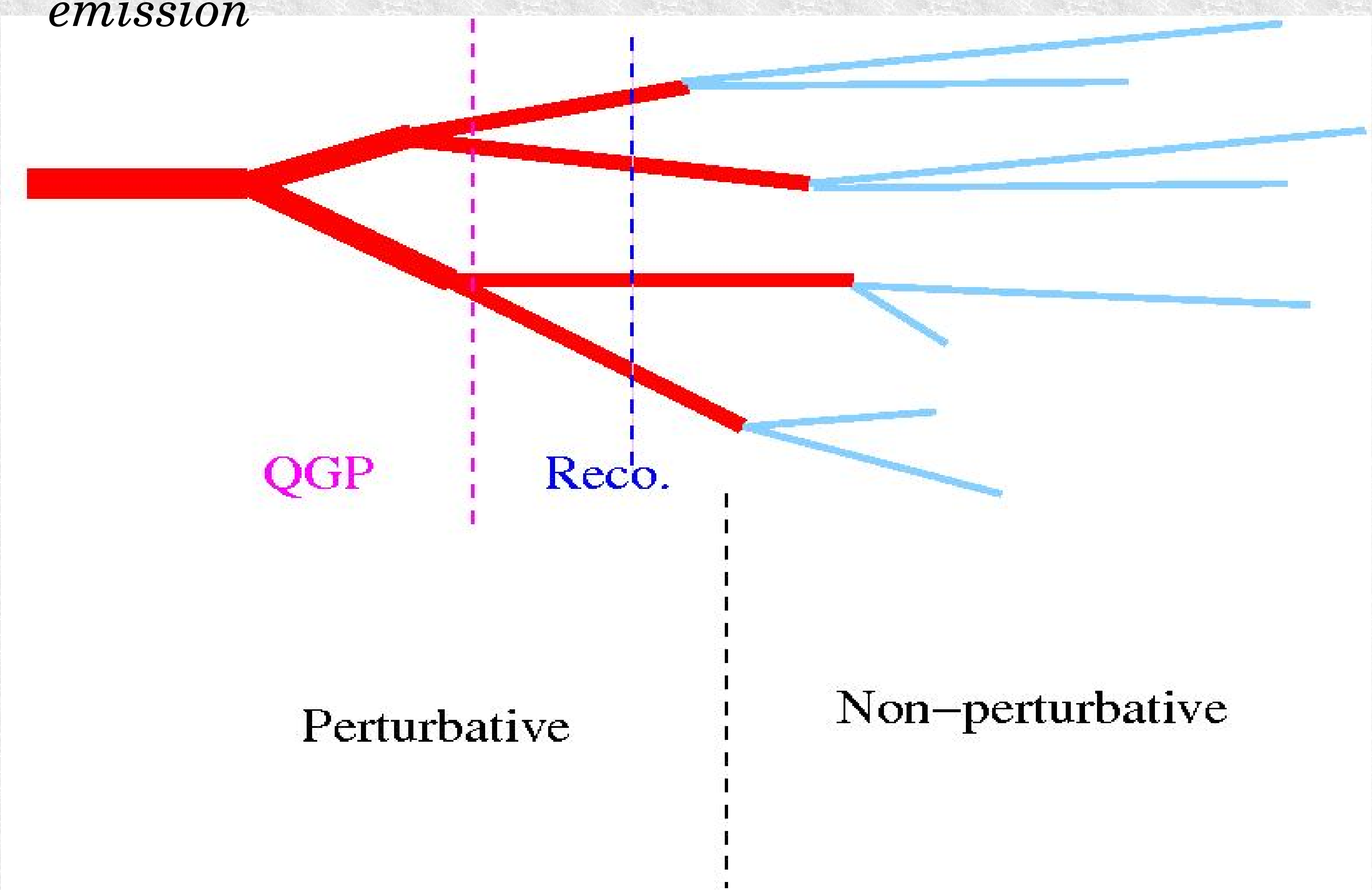
Outline

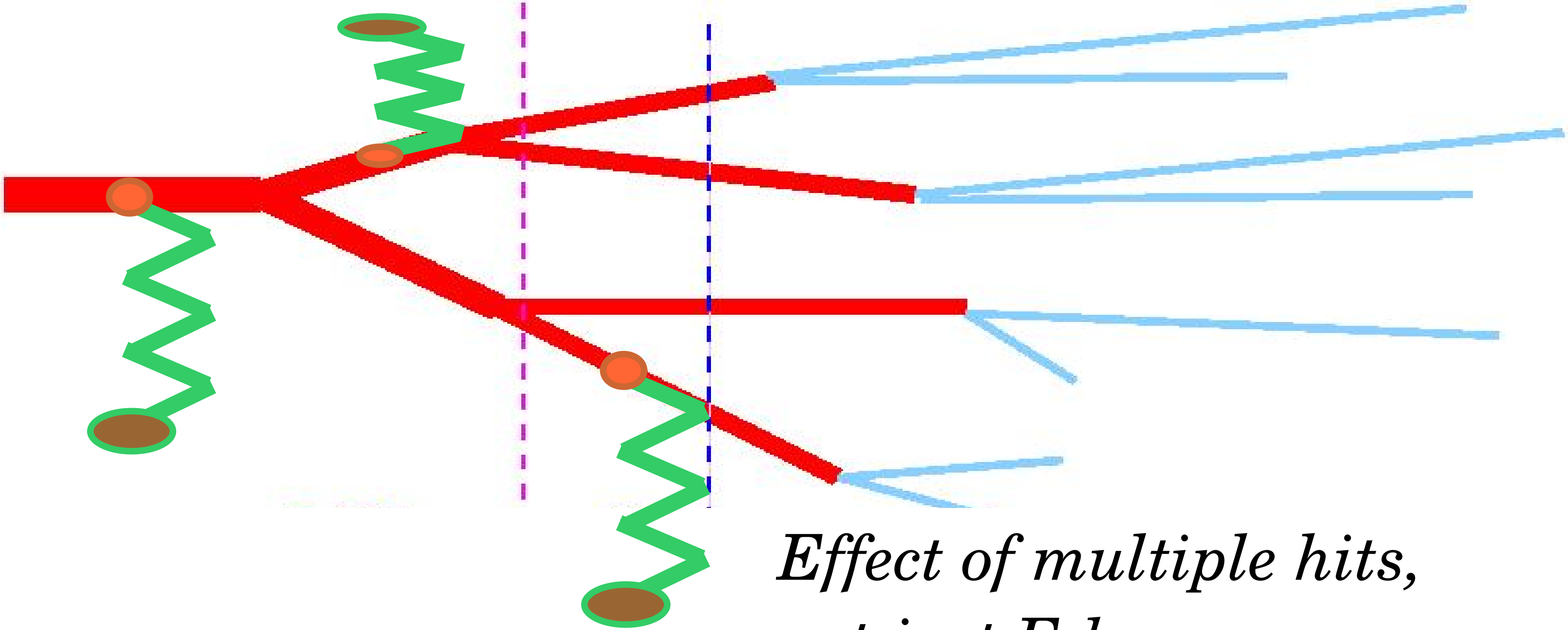
- *Jet quenching $\rightarrow$ jet modification*
- *Theory of hard jets as probes,*
- *The space-time picture,*
- *Jet correlations and medium response*
- *The momentum space picture, (Ridge)*
- *LHC expectations*

How to think about this!

A hard virtual jet loses virtuality by sequential emission



Multiple scattering in the medium changes the whole jet structure

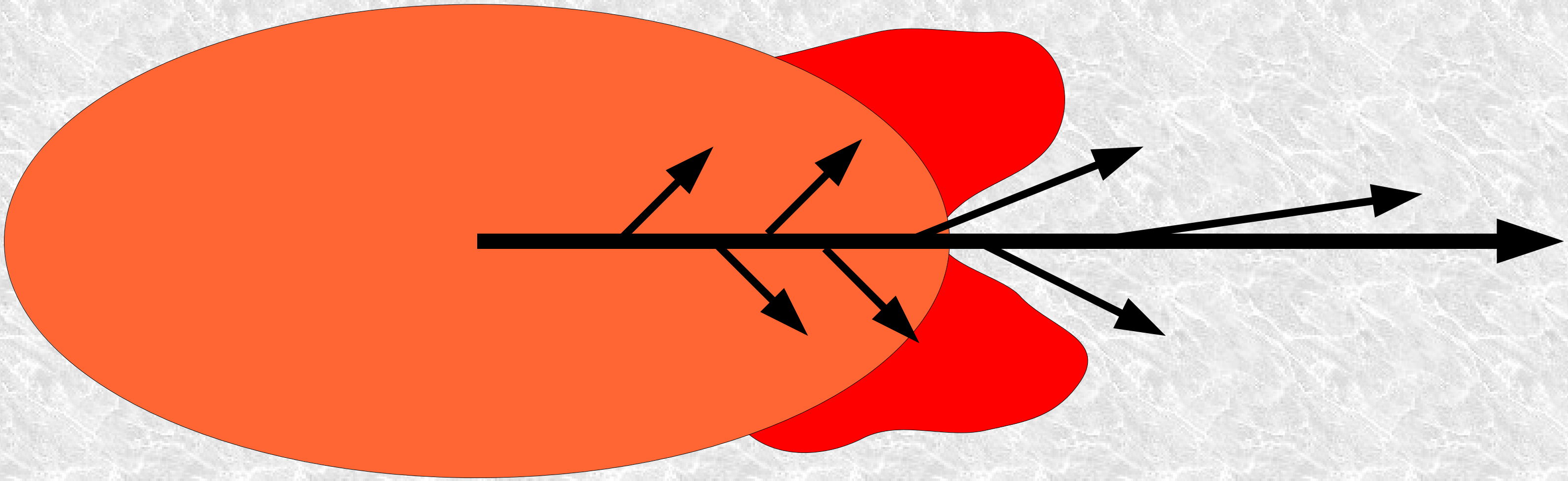


Type of hit depends on type of medium

Effect of multiple hits, not just E-loss, Changes final jet structure

Modification of jet means modification of assoc. particles
For a believeable calculation, keep assoc. p_T above reco.

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



This is soft physics 1 – 3 GeV

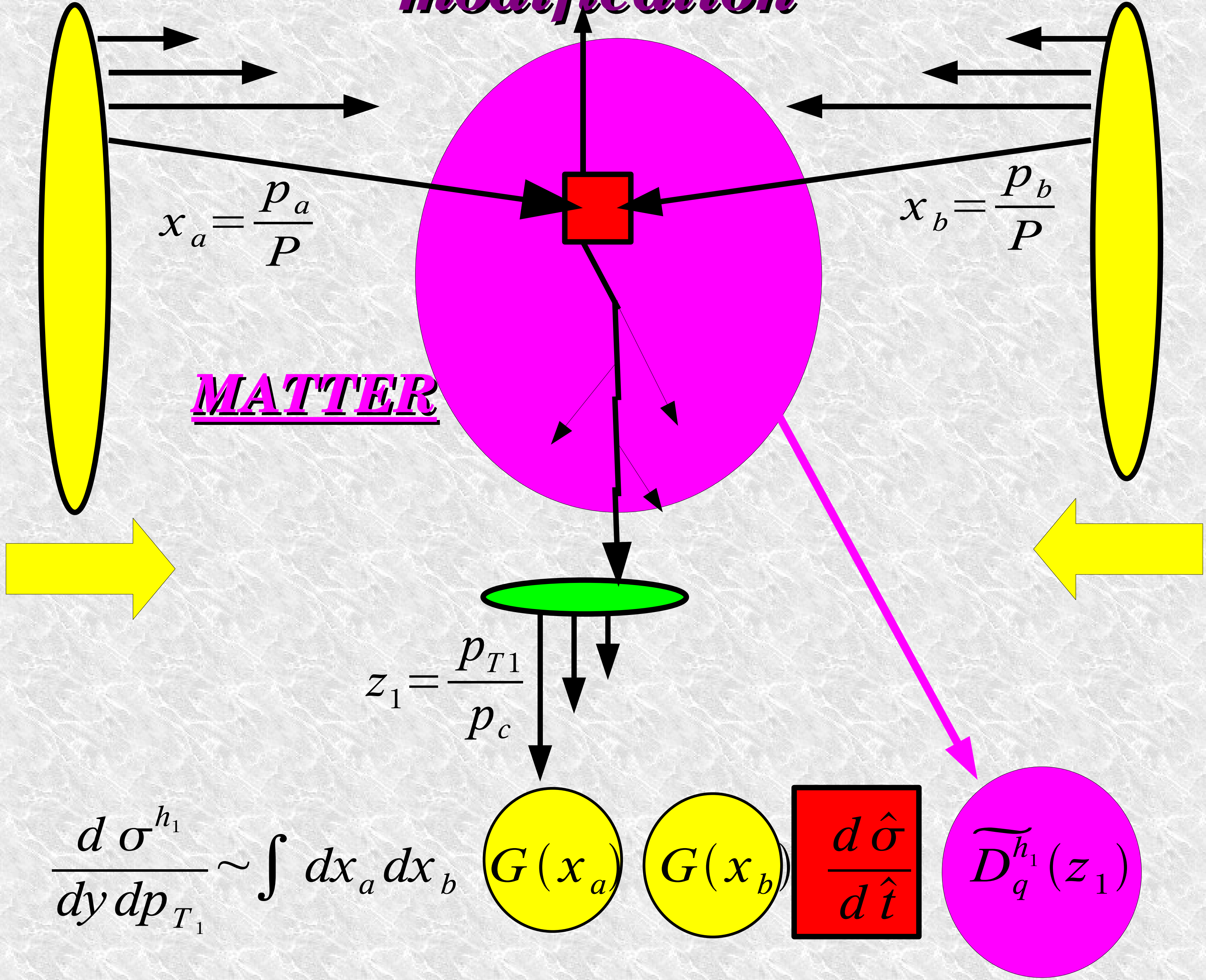
Cannot get this from pQCD

Need some model!

Intermediate region from 3-7 GeV, interaction between Jet frag. and Reco.

See talks by J. Ruppert, C. Salgado and I. Dremin

Factorized approach for hard jet modification



Four schemes of jet quenching

1) Gyulassy, Levai, Vitev,(GLV)

- *Medium of heavy (static) scattering centers with Yukawa like potentials*
- *Parton picks up transverse kicks* **~ μ^2**
- *Operator formalism that sums order by order in opacity* $\bar{n} = \frac{L}{\lambda_g}$

2) Armesto, Salgado, Wiedemann, (ASW)

- *Medium of heavy (static) scattering centers with Yukawa like potentials*
- *Parton picks up transverse kicks* **~ μ^2**
- *Path integral over multiple scatterings in the medium*

3) Arnold, Moore, Yaffe (AMY)

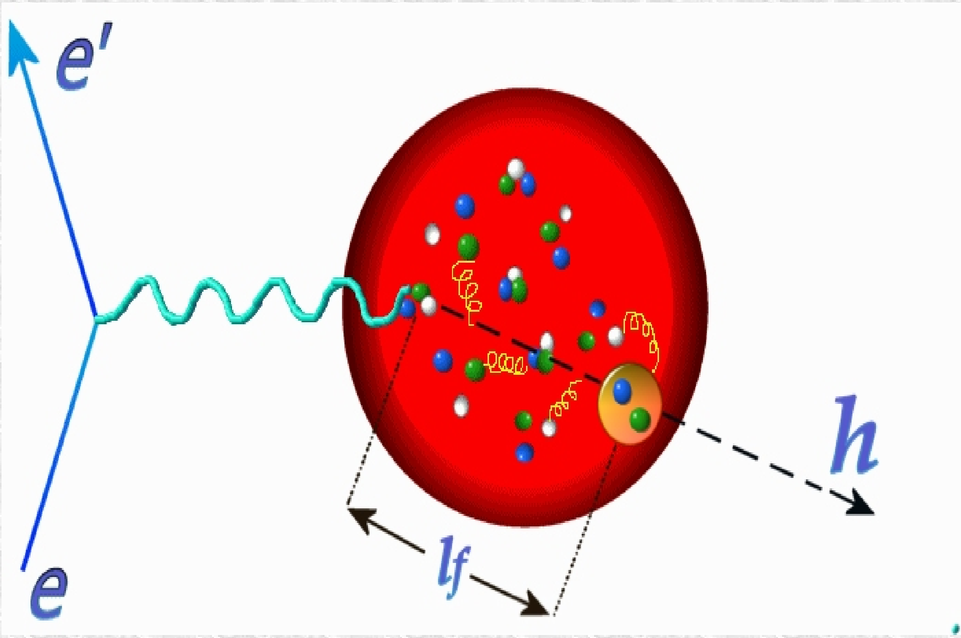
- *Thermalized partonic medium at $T \to \infty$,$g \to 0$ HTL medium*
- *Hard parton comes on shell receives, hits of $\mu \sim gT$*
- *Resummation over multiple scatterings*

4) Higher Twist Scheme

- *Devised to study the modification of hard jets in A-DIS*
- ***Look at single inclusive-DIS in large nuclei***
- ***Same formalism for cold matter and hot matter***

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

$$\frac{d\sigma}{dz_1} \sim f_q^A(x) H^{\mu\nu} \tilde{D}^{h_1}(z_1)$$



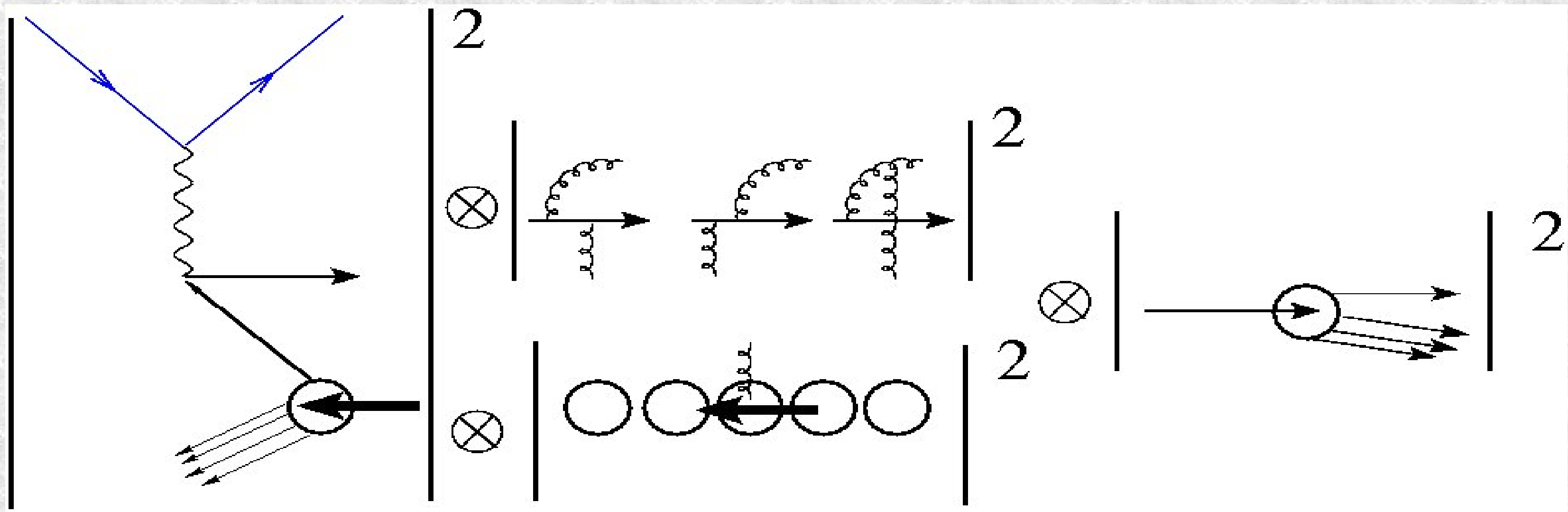
in DIS look at $\frac{\tilde{D}=D+M}{D}$

In A-A, look at $\frac{\sigma_{AA}}{N_{AA}\sigma_{pp}}$

Guo Wang, NPA 696:78, 2001

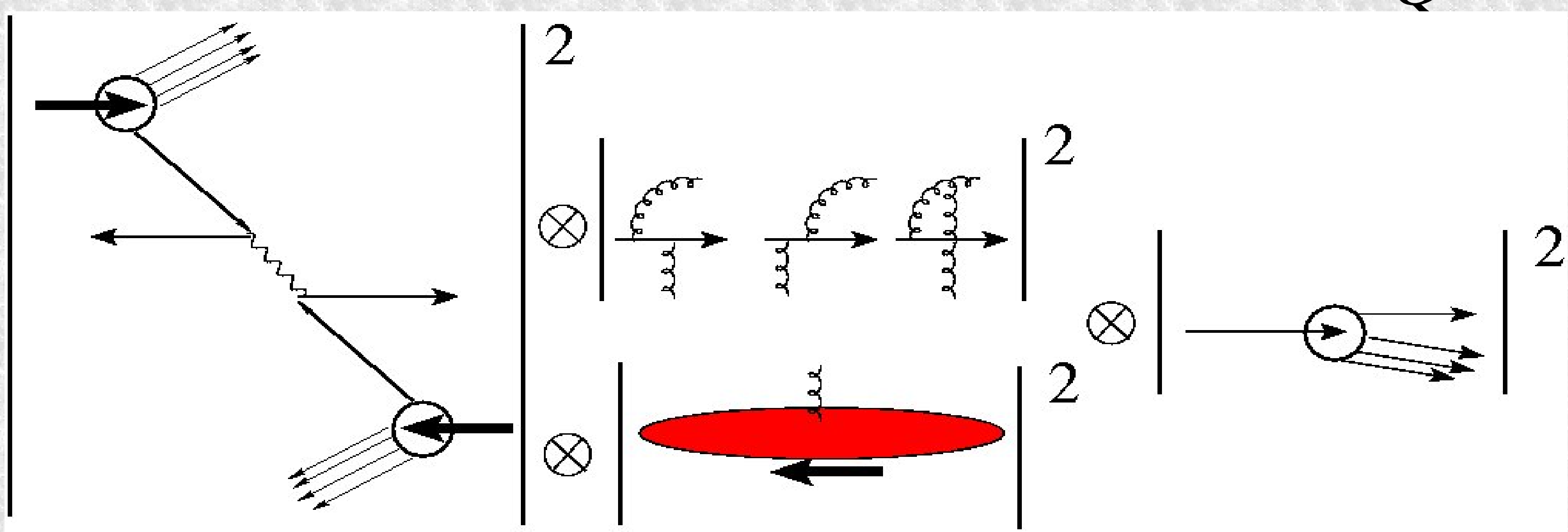
E-loss kernel same: factorization

A-DIS



$$A\,F(p/p_h)\,d\sigma_{e^-+q\to q+e^-} \qquad L\int dt\left\langle F^{\mu\alpha}(t)\,v_\alpha\,F^{\beta}_{\mu}(0)\,v_\beta\right\rangle \qquad \sigma_T \propto \frac{A^{1/3}\mu_H^2}{Q^2}$$

Au-Au



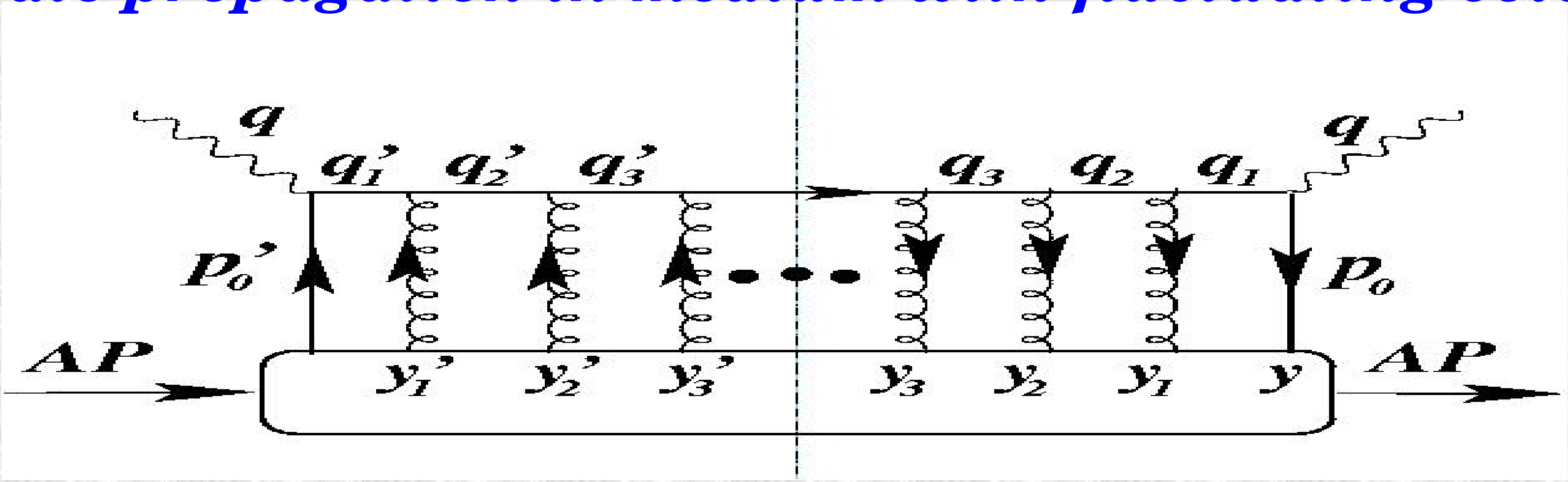
Guo, Wang, NPA 696:78, 2001. Majumder, EPJC 43, 259, 2005.

Energy loss and transverse broadening

Energy loss depends on expectation in Nucleus or QGP

$$\int dt \left\langle F^{\mu\alpha}(t) v_\alpha F_\mu^\beta(0) v_\beta \right\rangle$$

Calculate propagation in medium with fluctuating color fields



This yields transverse momentum diffusion equation!

$$\frac{\partial f(p_\perp, t)}{\partial t} = \nabla_{p_\perp} \cdot D \cdot \nabla_{p_\perp} f(p_\perp, t)$$

$$p_\perp^2 = 4Dt$$

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

A. Majumder, B. Muller, arXiv:0705.1147

$\hat{q}$ *a multidimensional object*

A full study of the medium requires a comprehensive probe

$$\hat{q}^{\mu\nu} = \hat{q}_0 f^{\mu\nu}(x, y, z, t, \gamma_{flow}; \mu^2, p_{jet})$$

Medium parameters

Jet parameters

$$\begin{pmatrix} \bullet & \bullet \\ \bullet & \bullet \end{pmatrix}$$

Macroscopic models test the space time dependence

Microscopic models can give $\hat{q}$ directly!

The hard-sphere model for a nucleus

$$\hat{q}^{\mu\nu} = \hat{q}_0 \delta^{\mu\nu} \theta\left(R_A^2 - x^2 - y^2 - z^2\right)$$

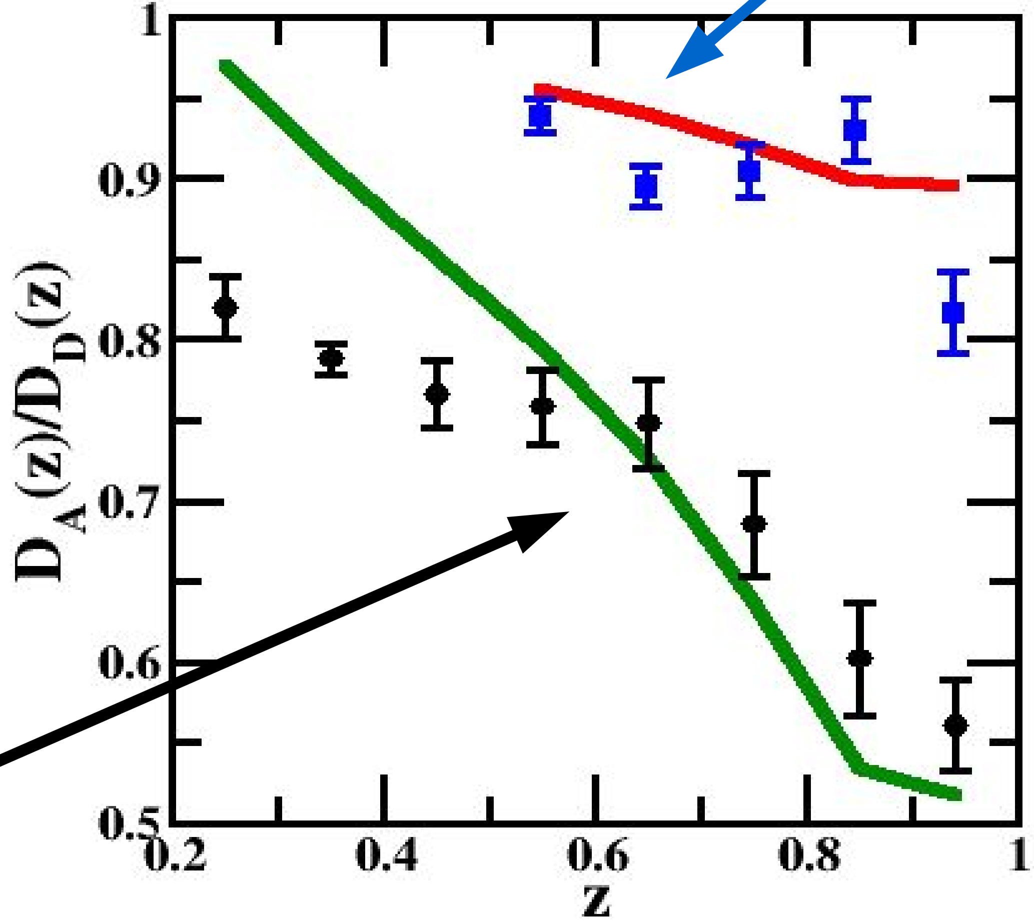
Fit one point in Nitrogen

$$\hat{q}_0 = 0.015\, GeV^2 / fm$$

Data from the HERMES detector at DESY

Directly measure the ratio of fragmentation functions

Assuming a Hard sphere density distribution for nucleons,



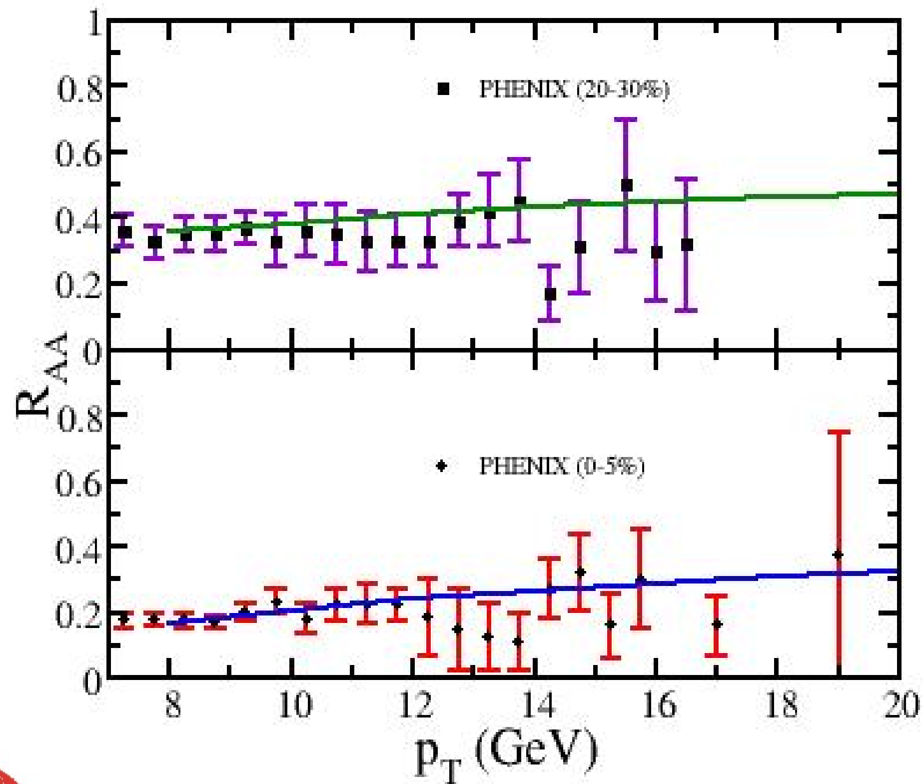
Kr is a prediction

A. Majumder, X.N, Wang, to appear

An example: the space-time profile

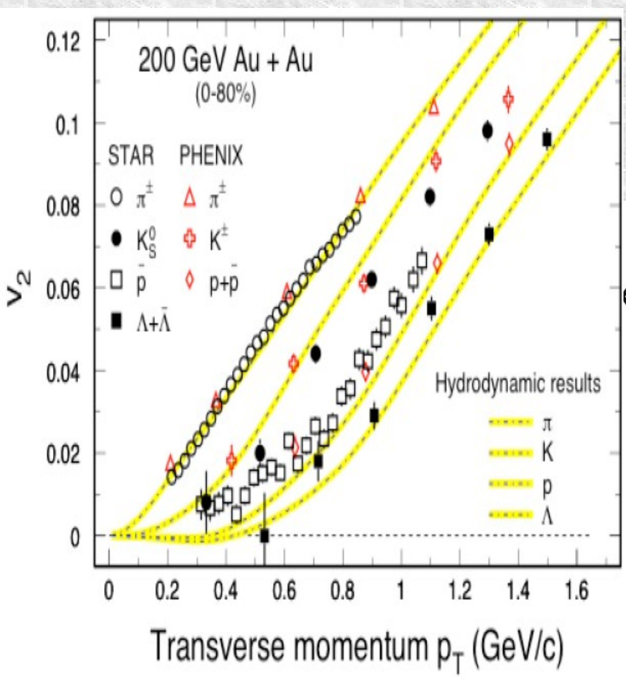
$$\hat{q}^{\mu\nu} = \hat{q}_0(f)\,\delta^{\mu\nu}\,\frac{\gamma_\perp(x,y,z,t)\,T^3(x,y,z,t)}{T_0^3(x,y,z,t)}$$

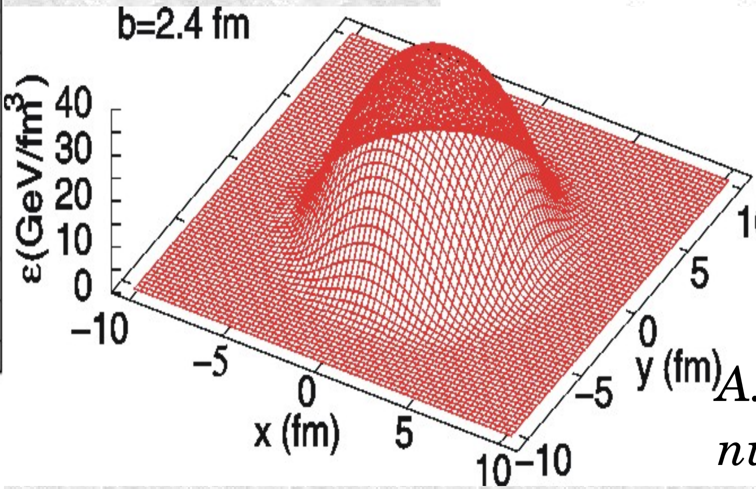
$$\hat{q}_0(quarks) = 1.3\,GeV^2/fm$$



Test of the hydro model!

Use the same hydrodynamic model that predicted the soft spectra

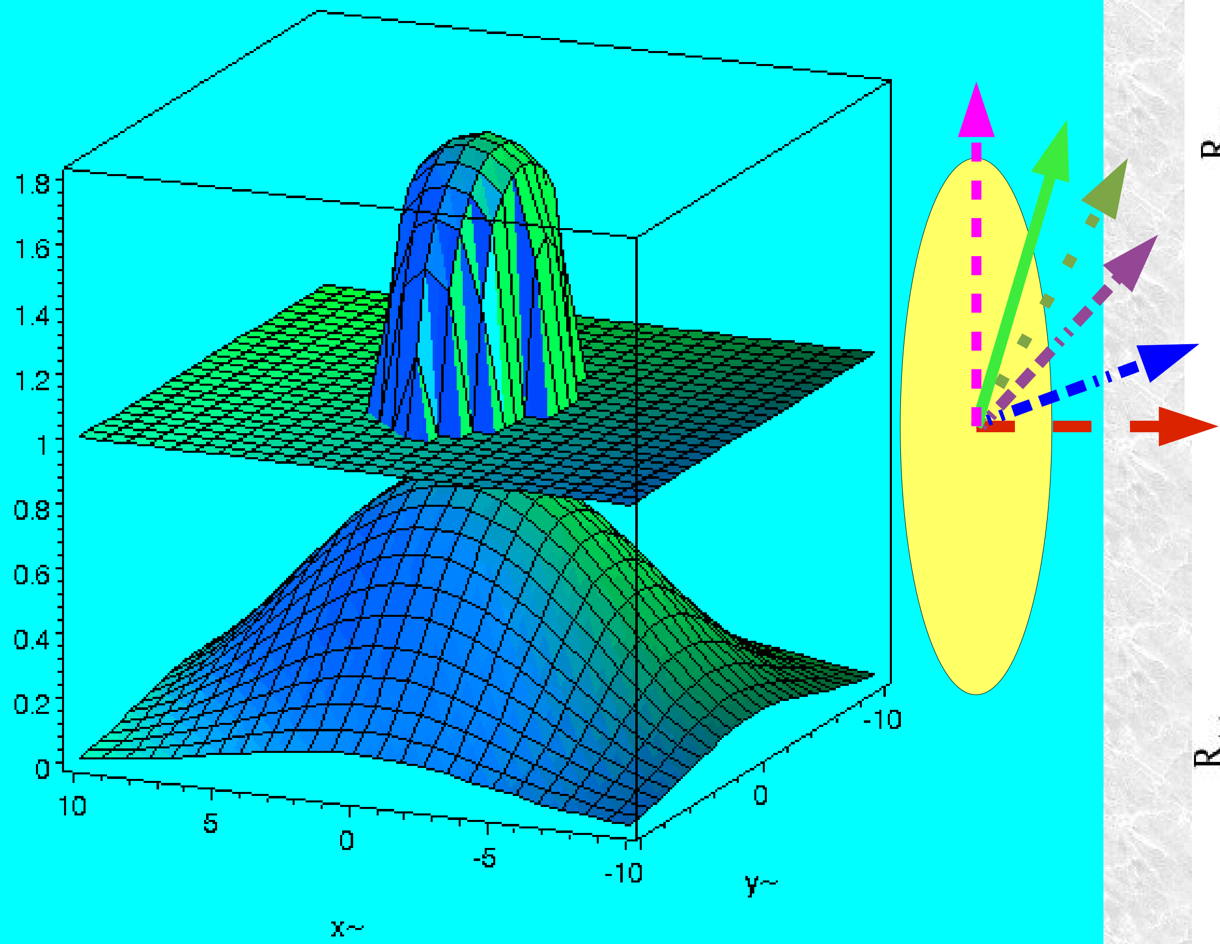


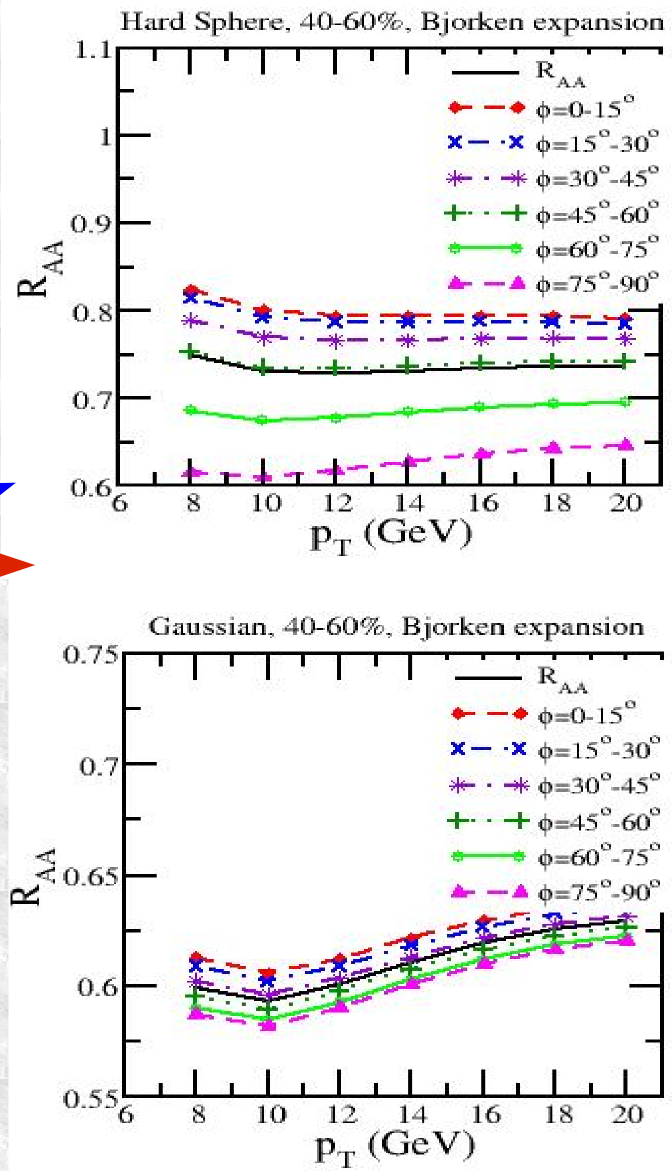


A. Majumder, C. Nonaka, S. Bass, nucl-th/0703019

Need (x,y,z,t) dependent $\hat{q}$ for differential spectra

- ***Azimuthally dependent R_{AA} can distinguish***
- ***Look at two extreme cases, with Bjorken exp.***



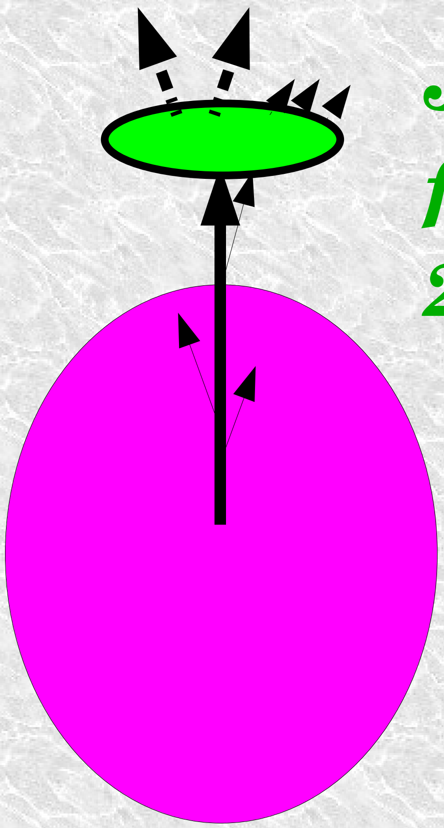


A. Majumder, PRC 75:021901, 2007.

Probing microscopic structure

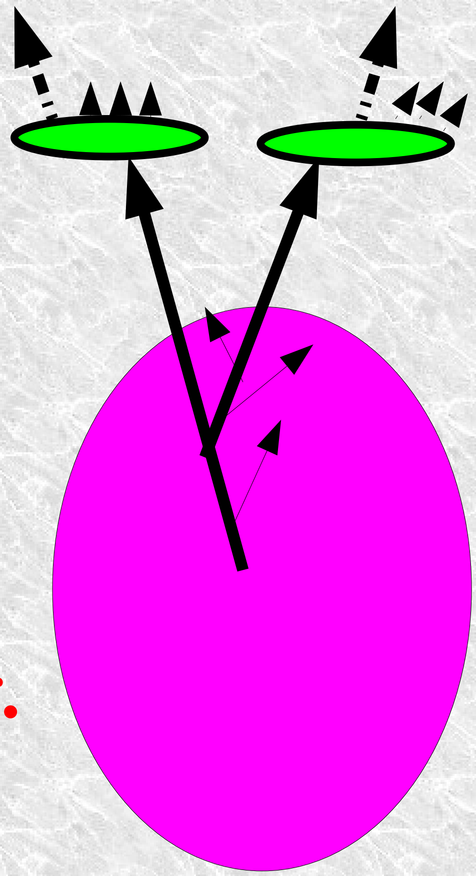
Need very differential probes: modification of jet structure,
Modification of near side correlation!

Can be decomposed into two components



Jet loses energy,
fragments outside,
2 h from vac. frag.

Jet radiates gluon,
Gluon escapes,
Assoc. h from glue frag.



gluon may thermalize, may hadronize by ReCo.

Comparing to the vacuum

Differential predictions from JETSET, compare with d-Au
Set Base-line

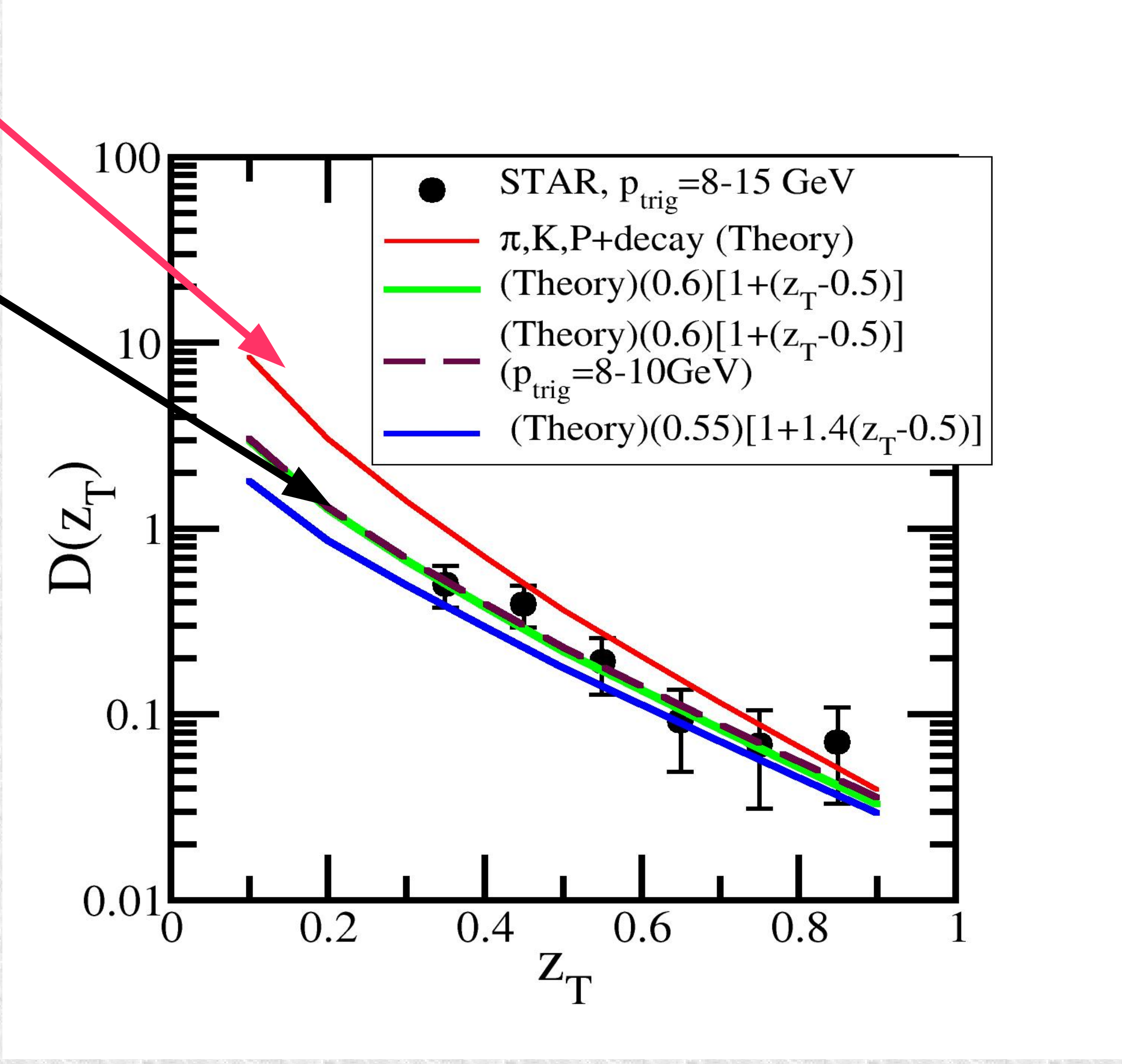
Bare JETSET prediction

Optimal decay correction

d-Au is not vacuum

Vacuum profile should be steeper

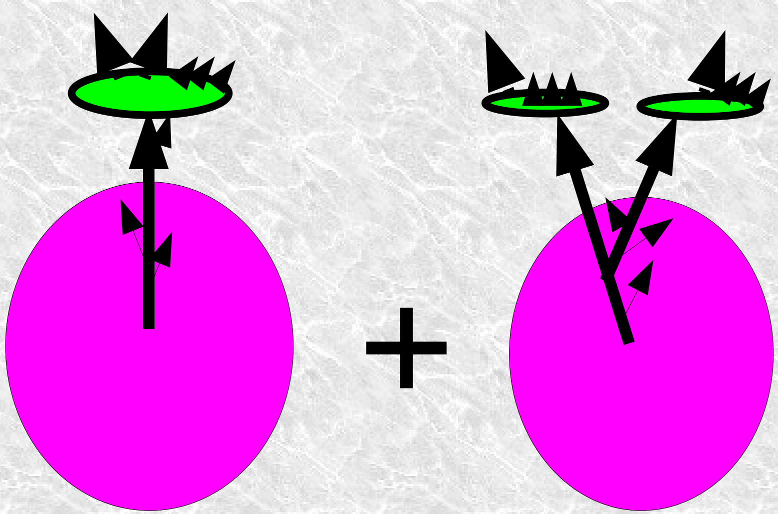
$$z_T = \frac{p_{T,\,Assoc.}}{p_{T,\,Trig.}}$$



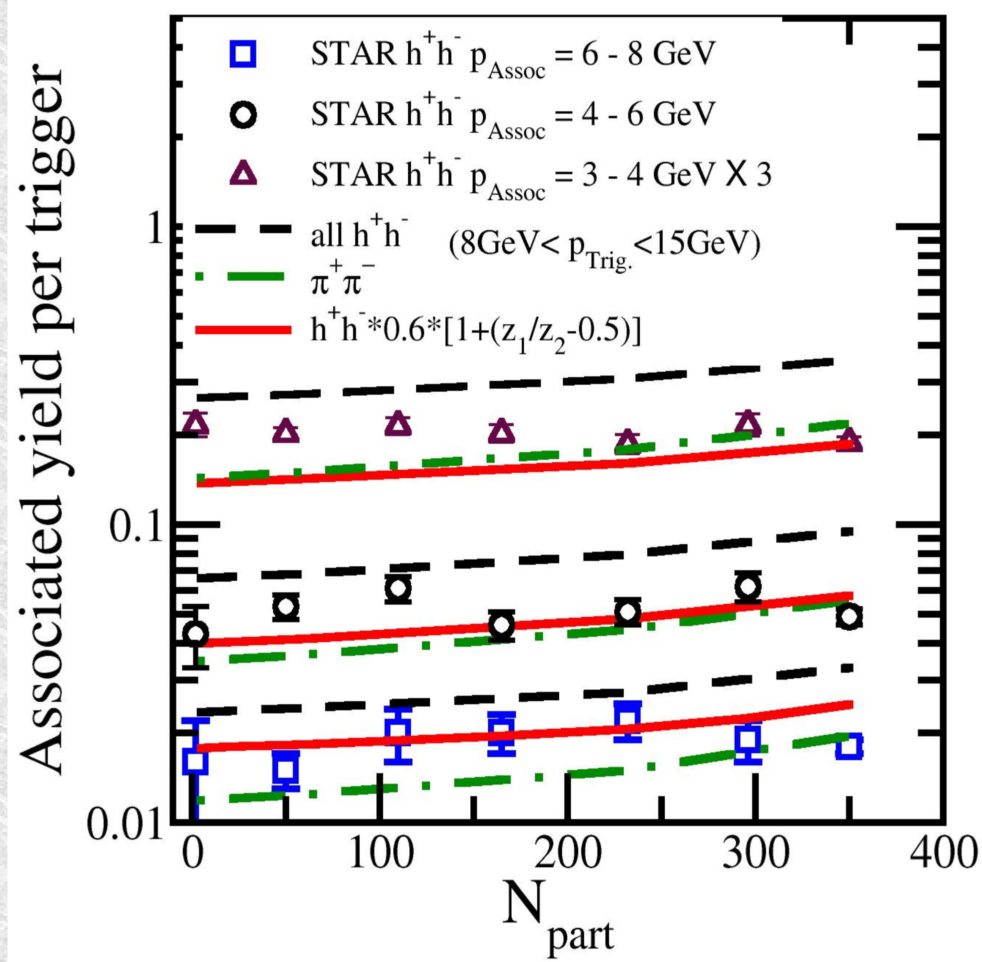
Does the whole thing add up?

Can we account for the near side associated yield in this 2-part formalism ?

At high trigger p_T, Yes!
low trigger p_T, Sort of!

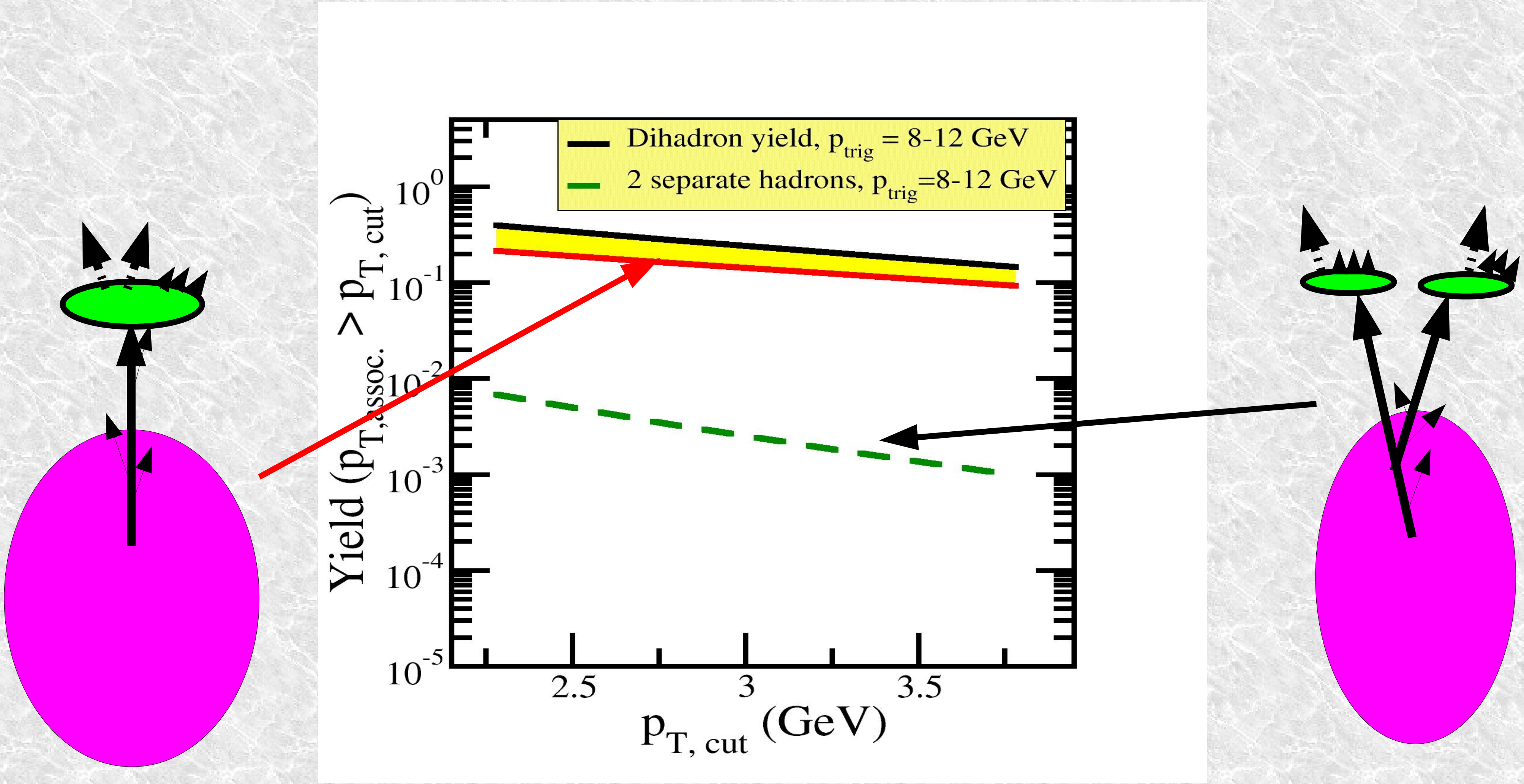


A. Majumder, E. Wang and X. N. Wang, nucl-th/0412061

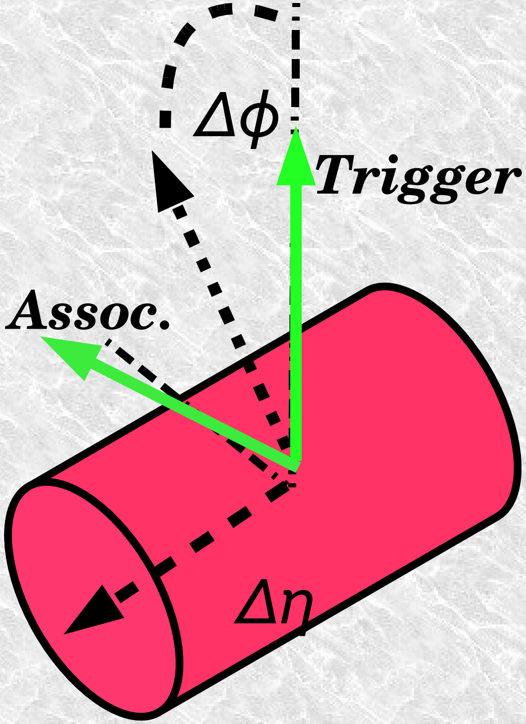


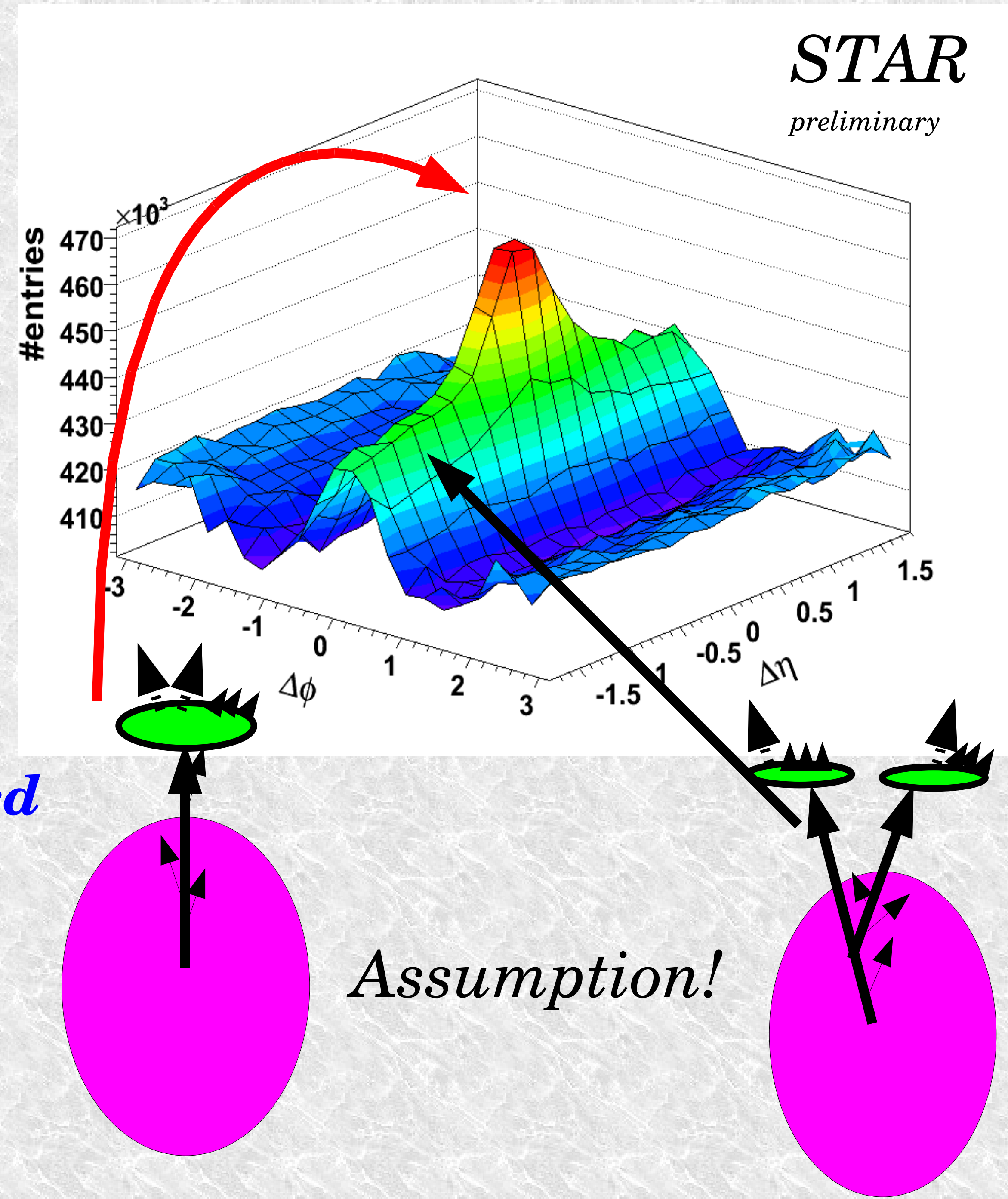
How much is each ?

- *Energy loss on the near side is small,*
- *Leads to small multiplicity*
- *How can experiment pick up this little bit ??*



They live in a different phase space



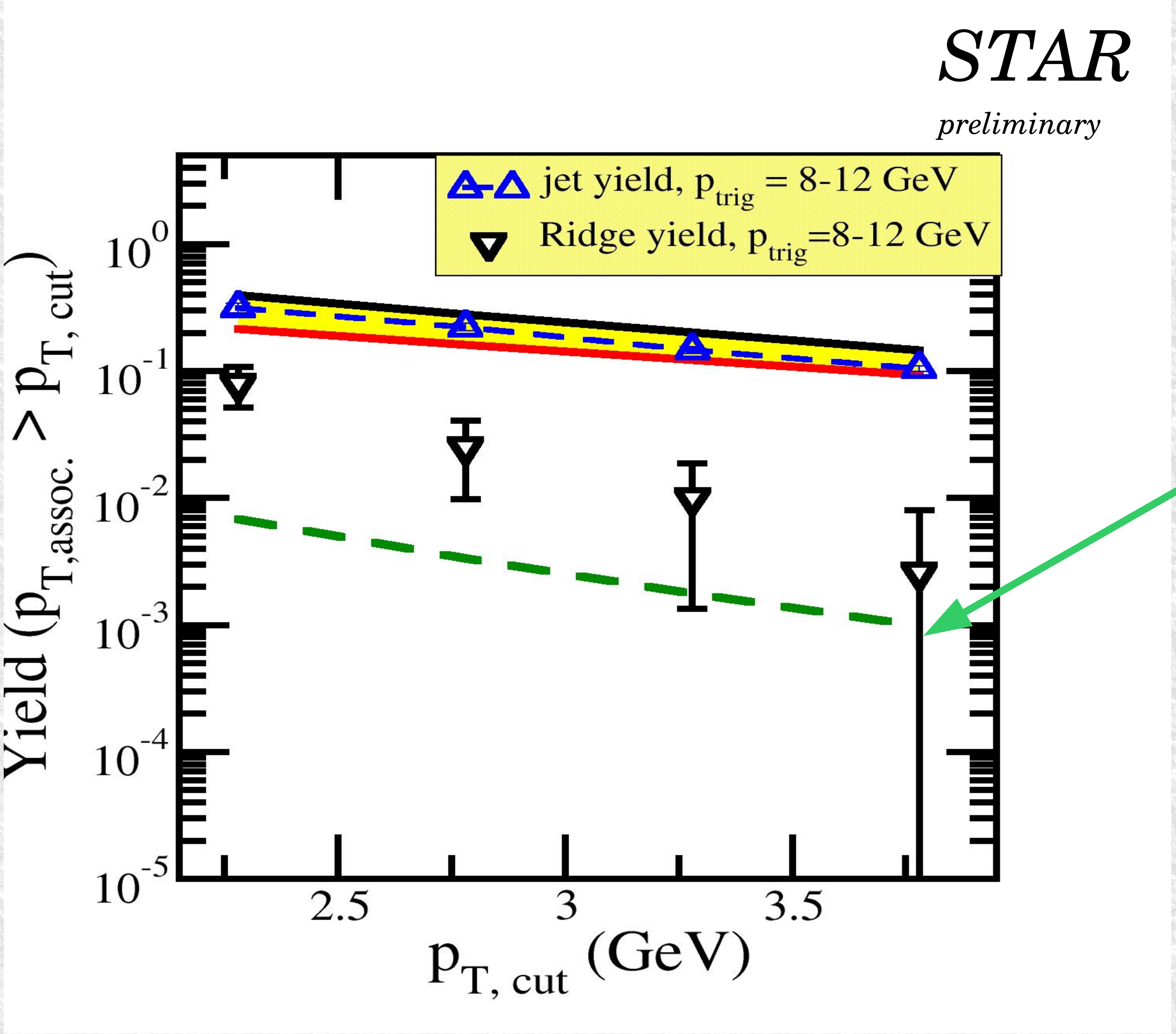


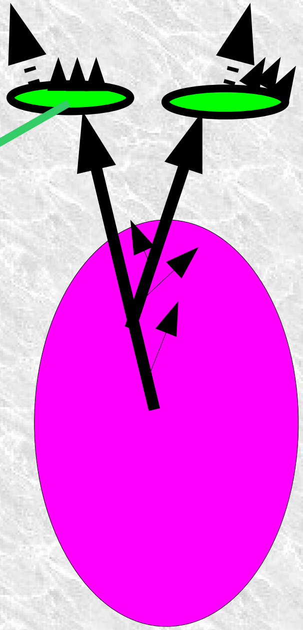
- *Radiated gluon broadened in η, tensor q*
- *Why broadened? Microscopic theory !*

Comparing theory to experiment

Vacuum fragmentation explains high assoc. p_T

Excess at lower p_T, must be due to medium effects: thermalization, recombination!





Both vacuum frag. piece and medium frag. piece are broadened in rapidity, why? *Microscopic theory!*

Why are the radiated gluons spreading in rapidity ?

1) Armesto, Salgado, Wiedemann; Phys.Rev.Lett.93:242301,2004

The longitudinal flow changes the quenching in different directions

2) Chiu, Hwa: Phys.Rev.C72:034903,2005

Recombination of shower quark and quark with large longitudinal flow at the surface of the medium

3) Majumder, Müller, Bass: Phys.Rev.Lett.99:042301,2007

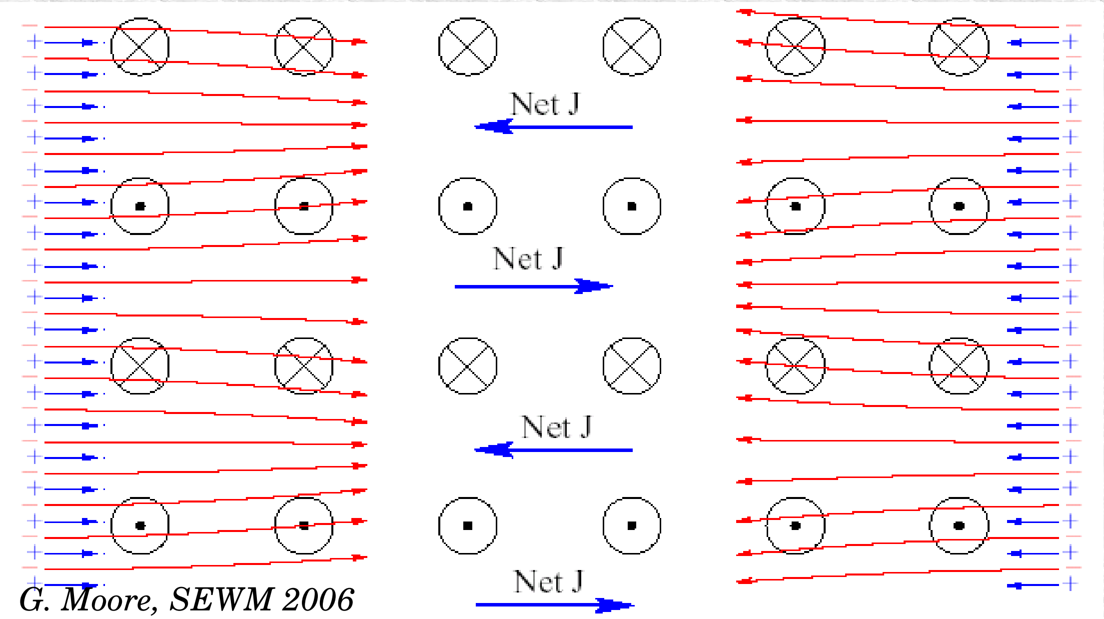
Large transverse (to beam) magnetic instabilities caused by anisotropic momentum distributions bend radiated gluons in rapidity.

Same mechanism provides qualitative explanation for fast thermalization, small viscosity and large jet quenching.

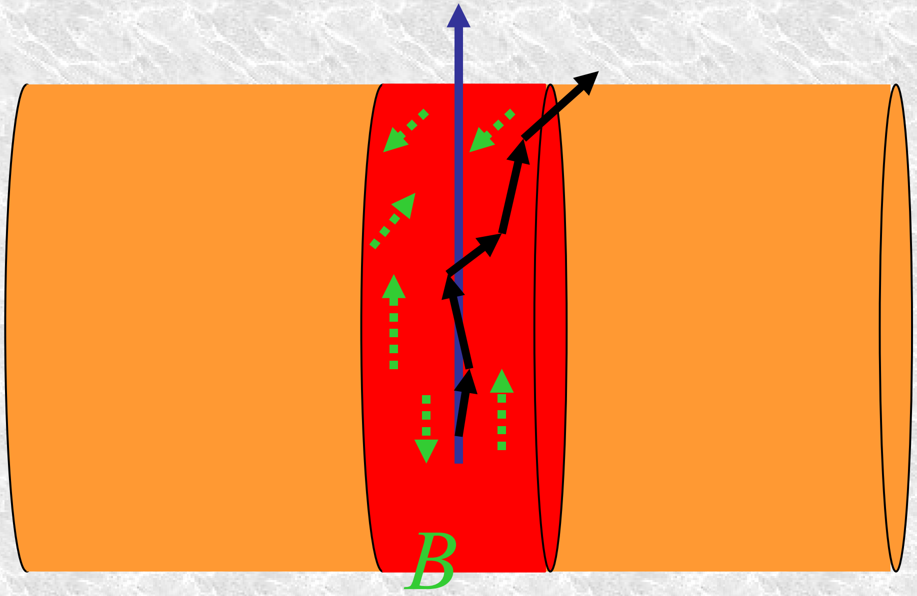
The quasi-particle model with large fields ! (pre-equilibrium QGP)

$$\hat{q}^{\mu\nu} = \frac{p_\perp^\mu p_\perp^\nu}{t} = \frac{2\pi^2 \alpha C_R}{N_c^2 - 1} \int dt \left\langle F^{\mu\alpha}(t) v_\alpha F^{\nu\beta}(0) v_\beta \right\rangle$$

- ***If original particle density distributions anisotropic***
- ***Can lead to the production of a Weibel instability***
- ***This leads to large transverse color magnetic fields***

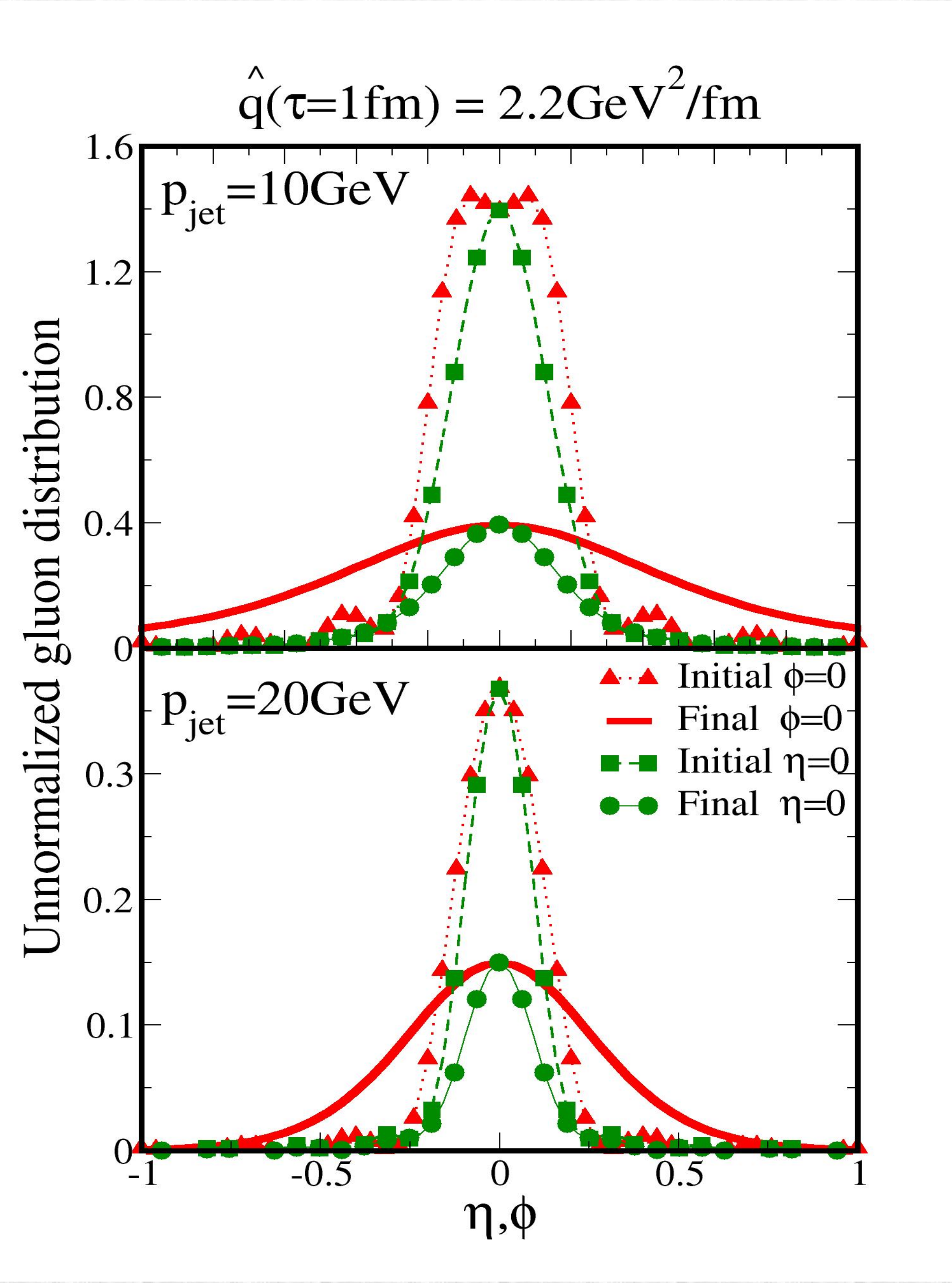


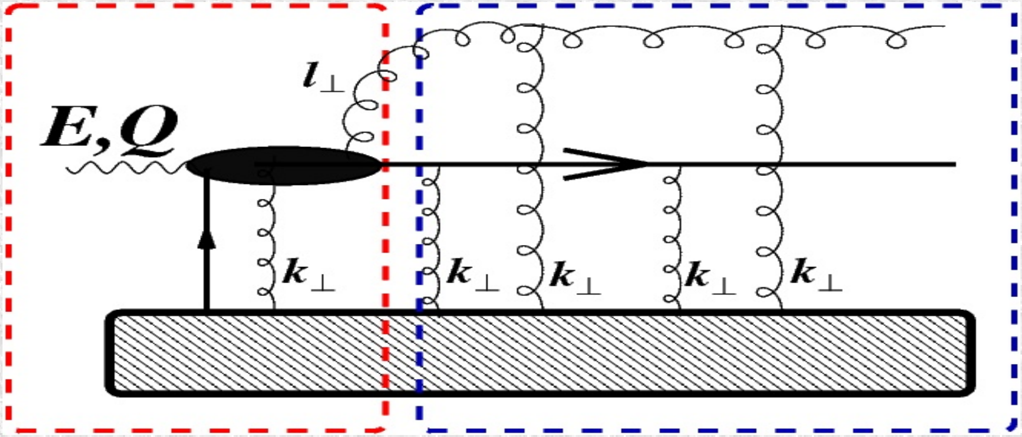
G. Moore, SEWM 2006



Romatschke, Strickland, Phys.Rev.D68:036004,2003; Romatschke, Rebhan, Phys.Rev.Lett.97:252301,2006
Arnold et. al. Phys.Rev.Lett.94:072302,2005;Phys.Rev.D73:025006,2006,
Dumitru, Nara, Phys.Lett.B621:89-95,2005;

The diffusion of soft gluons





We use a factorized form:

1) Radiation formed in Mult. scat.

2) Soft gluon separates and multiply scatters.

3) Use the diffusion equation.

$$\frac{\partial f(p_\perp, t)}{\partial t} = \nabla_{p_\perp} \cdot D \cdot \nabla_{p_\perp} f(p_\perp, t)$$

Procedure completely partonic

How to hadronize the soft mode?

A.Majumder, B. Mueller, S. A. Bass, hep-ph/0611135

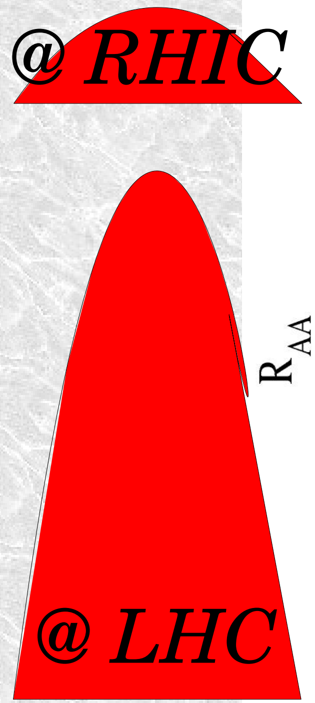
Jets @ LHC

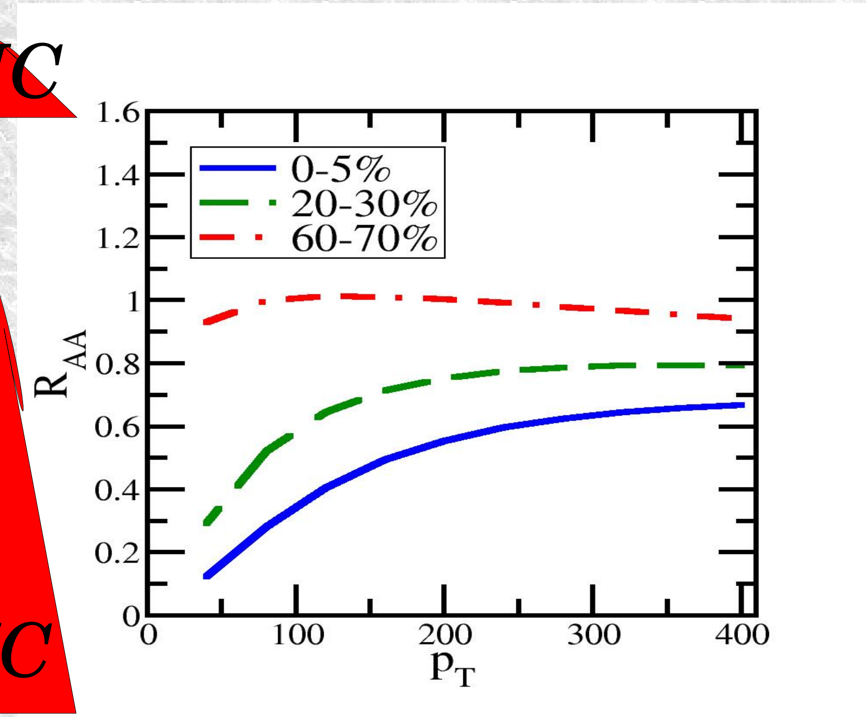
How to deal with denser medium,

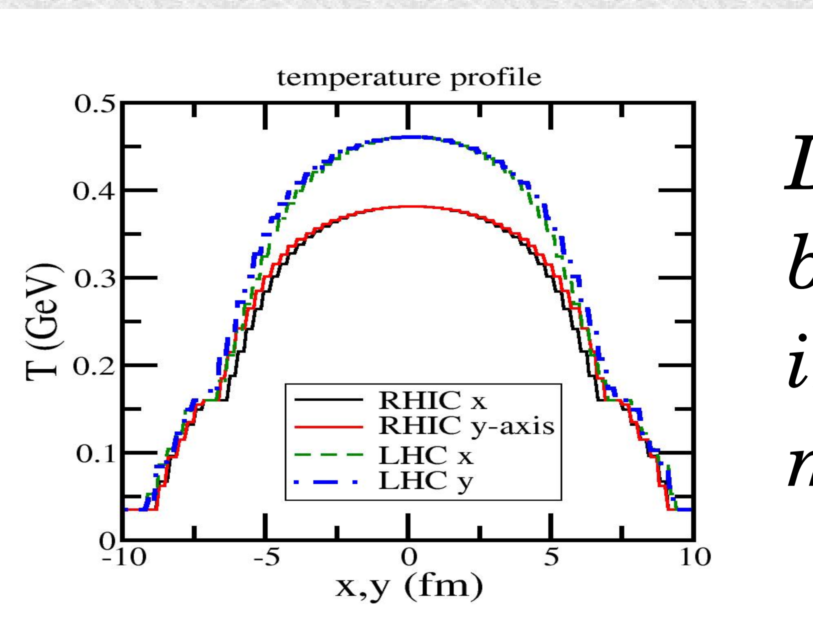
Medium may be denser overall

Space time dist. may be different

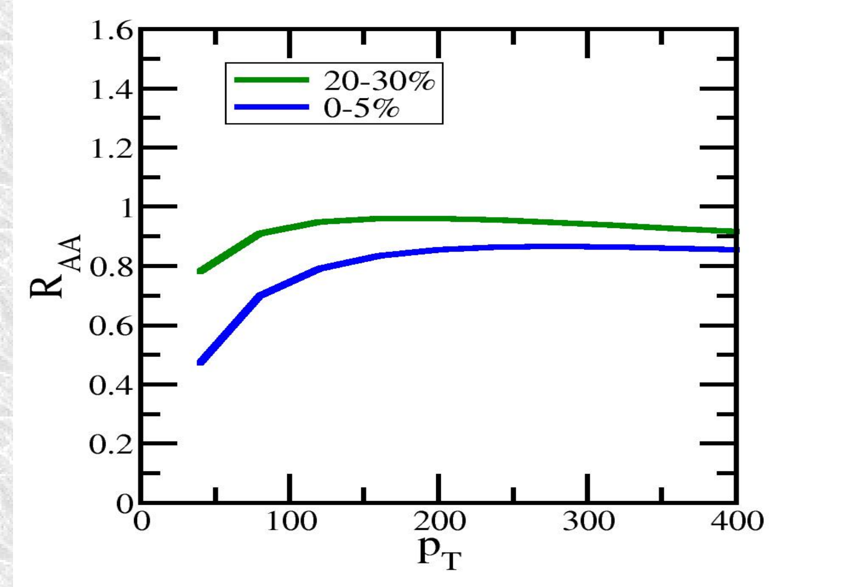
Jet correlations will tell the difference







Density bunched up in the middle



A required extension to the formalism for LHC comparisons

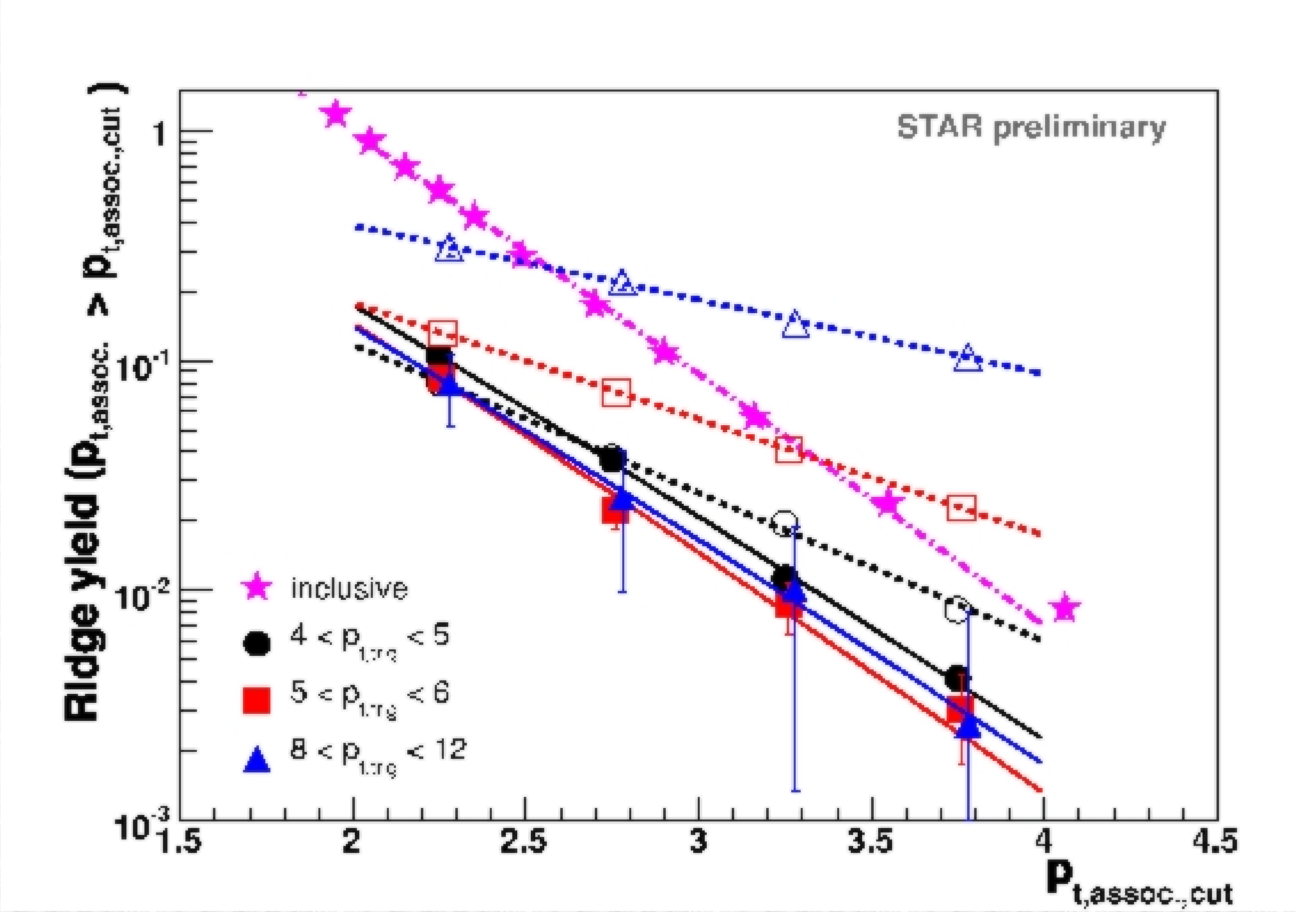
$$\hat{q}^{\mu\nu} = \hat{q}_0 f^{\mu\nu}(x, y, z, t, \gamma_{flow}; \mu^2, p_{jet})$$

- *Has not been rigorously calculated !!!!*
- *Probably log dependence*
- *Jet energies @RHIC 10-20 GeV ~ factor 2*
- *Jet energies @LHC 10-100 GeV ~ factor 10*
- *A required extension of the formalism*

Conclusions and open issues

- *Jet modification a short distance, descriptive probe*
- *Need to extend qhat to full tensor structure*
- *Jets can also provide a space-time picture of the medium*
- *Jet correlations give evidence for momentum structure*
- *Along with Medium response can reveal structure of QGP*
- *Multiple phenomenological evidence for quasi-particle picture of QGP.*
- *At LHC, qhat will evolve, but true study of modified jet structure!*

back up!



STAR preliminary
Ridge yield ($p_{t,assoc.} > p_{t,assoc.,cut}$)
$p_{t,assoc.,cut}$
inclusive
$4 < p_{t,trg} < 5$
$5 < p_{t,trg} < 6$
$8 < p_{t,trg} < 12$

The models!
1 macroscopic, 3 microscopic

Viscous Hydrodynamics:
finite no. of parameters from micro-theories

1) Bound states:

2) QCD Quasi-Particle (HTL, Mean-field theories)

3) ADS/CFT !!

Jets (short distance processes)
direct probe of microscopic dynamics

The quasi-particle model

+

instabilities

How does it stack up ?

- Instabilities ➔ fast thermalization

- Large fields ➔ small viscosity
- Large fields ➔ more``perturbative'' jet quenching

- Large transverse fields ➔ Ridge on near side
- Supported by lattice susceptibilities (BS corr.)

- Microscopic explanation of cone on away side !

- Can a theory be setup without $T \to \infty$

Bound state picture?

- Large resonance scattering ➔ fast thermalization
- Small viscosities
- More jet quenching !! not pertubatively

- No Ridge
- Not supported by lattice susceptibilities(flavor sec.)
- No derivation from first principles QCD.

- Microscopic explanation of away side cone: Cherenkov radiation

Energy loss and transverse broadening

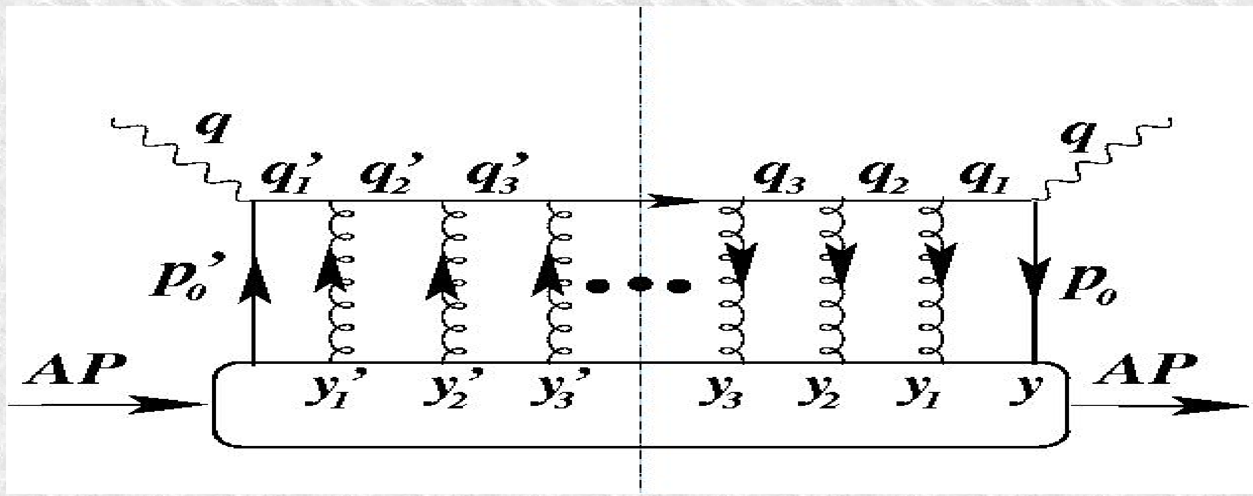
Energy loss depends on expectation in Nucleus or QGP

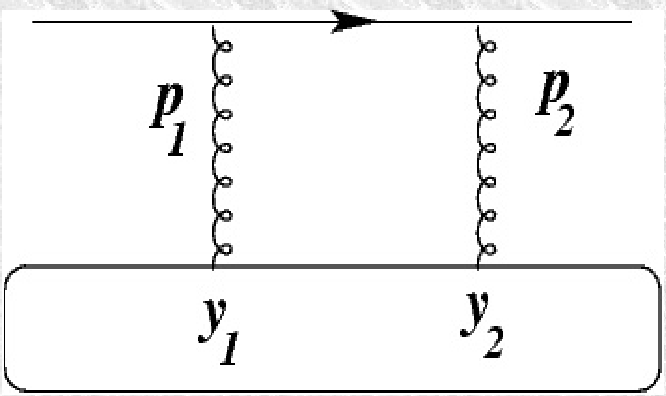
$$\int d\,t \left\langle F^{\mu\alpha}(t)\, v_\alpha\, F^{\beta}_{\mu}(0)\, v_\beta \right\rangle$$

Calculate propagation in medium with fluctuating color fields

Assume hard jet scales

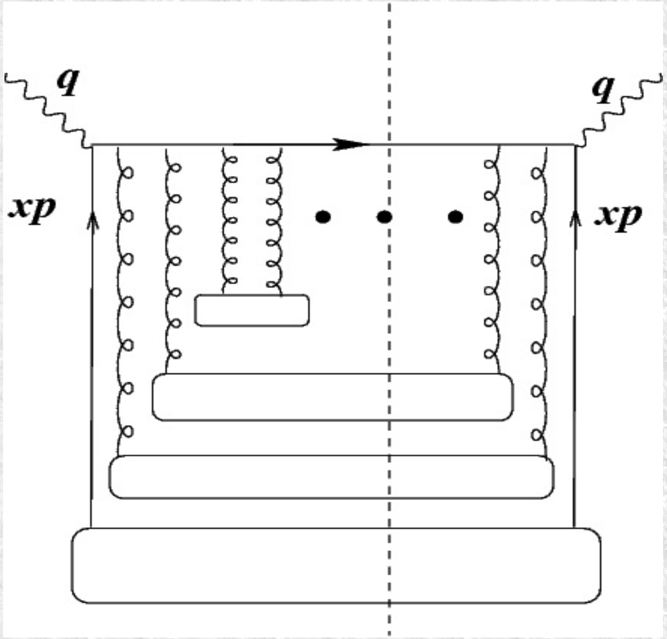
$$E \gg Q \gg \mu$$





- *Near on-shell propagation gives L enhancement*
- *Sets* $y_2 > y_1$
- *Assume* $k_\perp$ is << Q *Taylor expand in k*

Near Collinear Physics



Assume short distance correlation between gluon fields at subsequent locations

Similar to independent scatterings

Different from assuming a model of the medium

This yields transverse momentum diffusion equation!

$$\frac{\partial f(p_\perp, t)}{\partial t} = \nabla_{p_\perp} \cdot D \cdot \nabla_{p_\perp} f(p_\perp, t)$$

$$p_\perp^2 = 4Dt$$

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

A. Majumder, B. Muller, to appear

The matter formed @ RHIC

Shows Large elliptic flow, near ideal-Hydro!

Matter thermalizes rapidly ~ 0.6 fm/c

Very low viscosity, $\eta/s \geq 0.08$

Probe microscopic dynamics with,

1) Modification of hard jets,

Produced matter very dense, >1GeV^2/fm

Quenching @ early times, < 5 fm/c

2) In-Medium Jet correlations,

Cone structure on away side

Ridge structure on near side