Duke Physics

Deciphering the properties of hot and dense matter with hadron-hadron correlations

A. Majumder

In collaboration with

X. N. Wang, V. Koch @LBNL & Enke Wang @IPP

Why high pT correlations?

1) Very noticeable modifications at RHIC

2) A lot of handles available: angle, rapidity, flavor, energy, spin?!

3) At large enough Q^2, should be computable from first principles

4) More differential observables better test of calculations and models of QGP!

5) Direct measurement of fundamental properties of the QGP, density profile, c_s, n !!

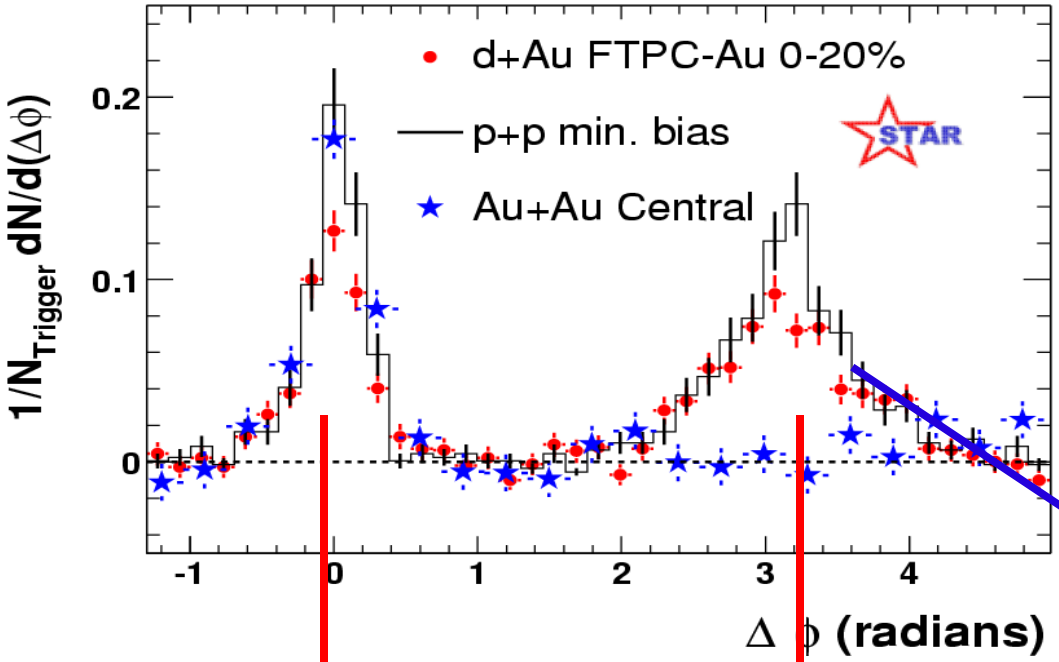
Which jet correlations and why?

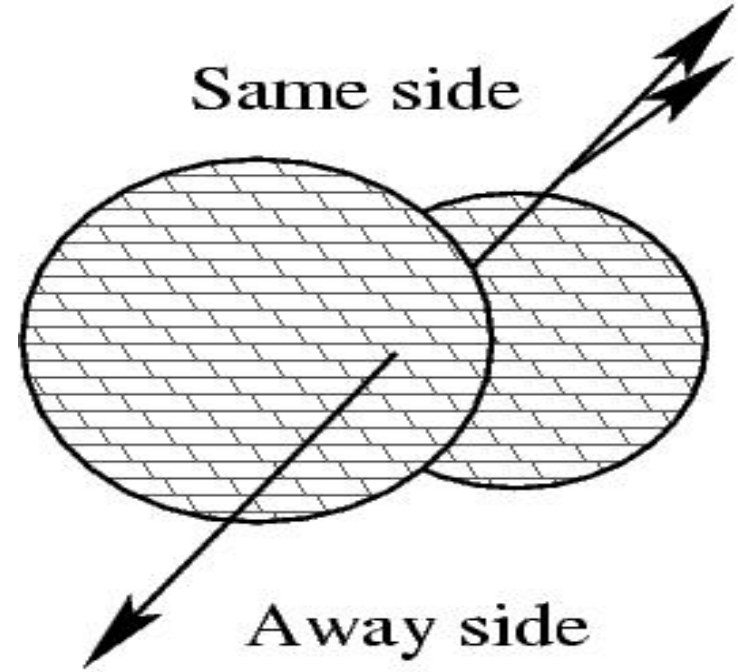
1) Near-side Jet correlations at very high-pT:

Constraint over-all gluon density
Check on consistency of calculations,
Gluon density profile!!

2) Away side Jet correlations at low pT:

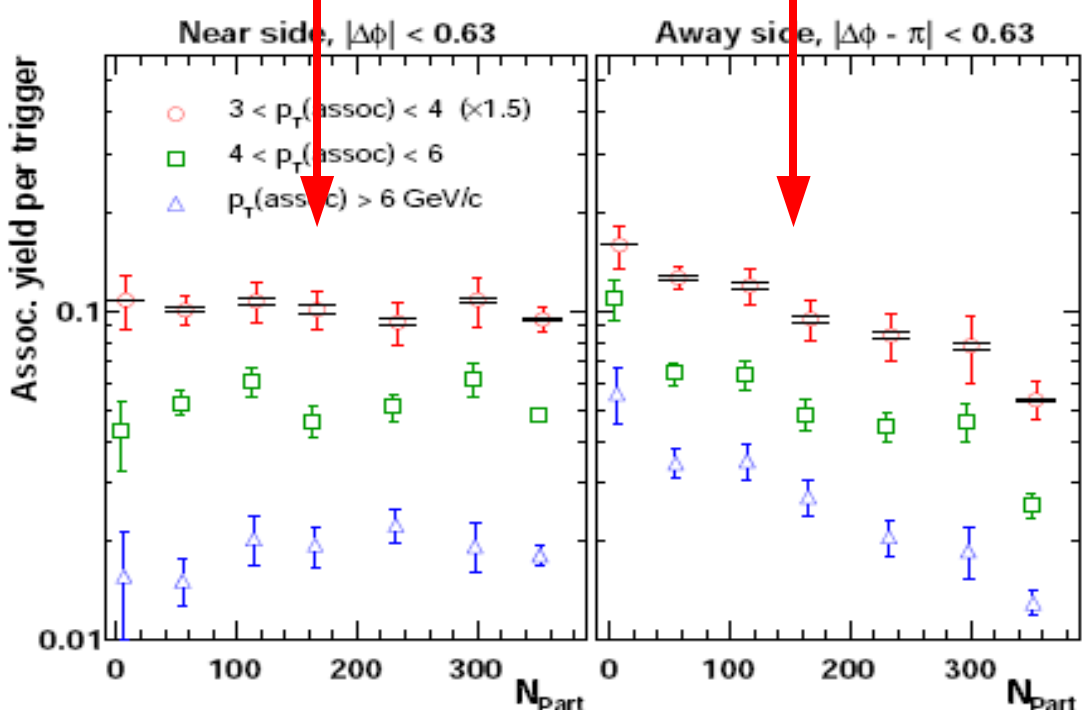
Complete jet extinction
Hadronization from collective modes in matter:

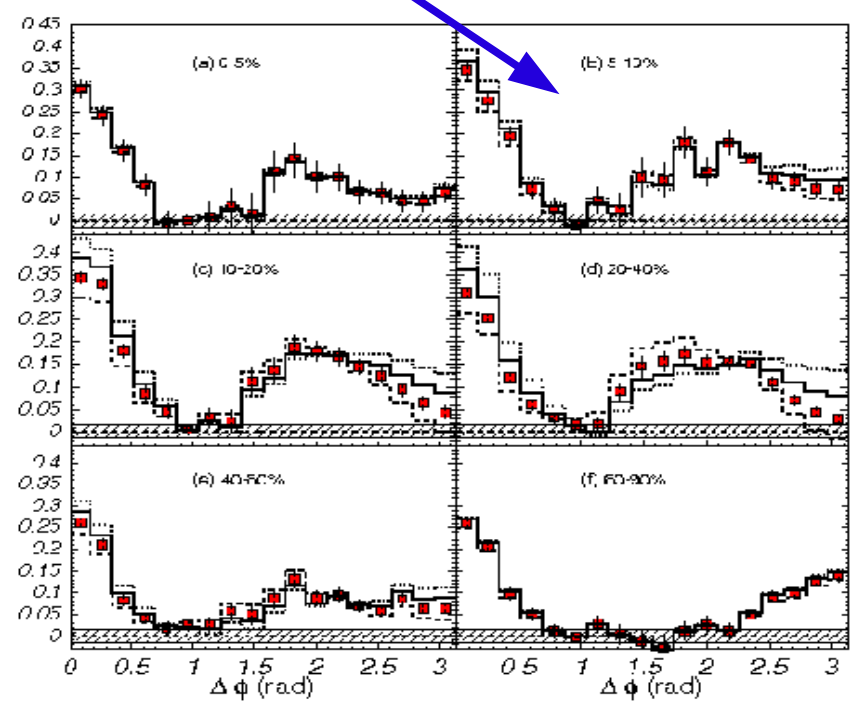




Area under peaks

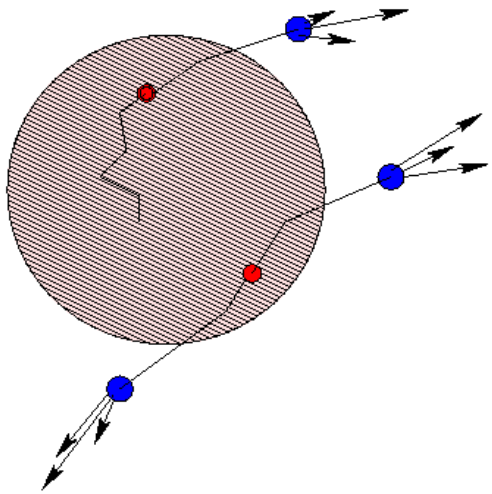
lower Pt of Assoc

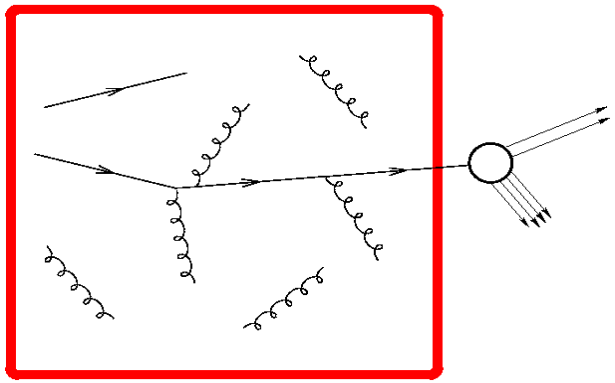




High Q^2, high p_T / fragmenting outside the medium!

For a given Q^2, higher p_T means more boost, longer lifetime/ shorter medium





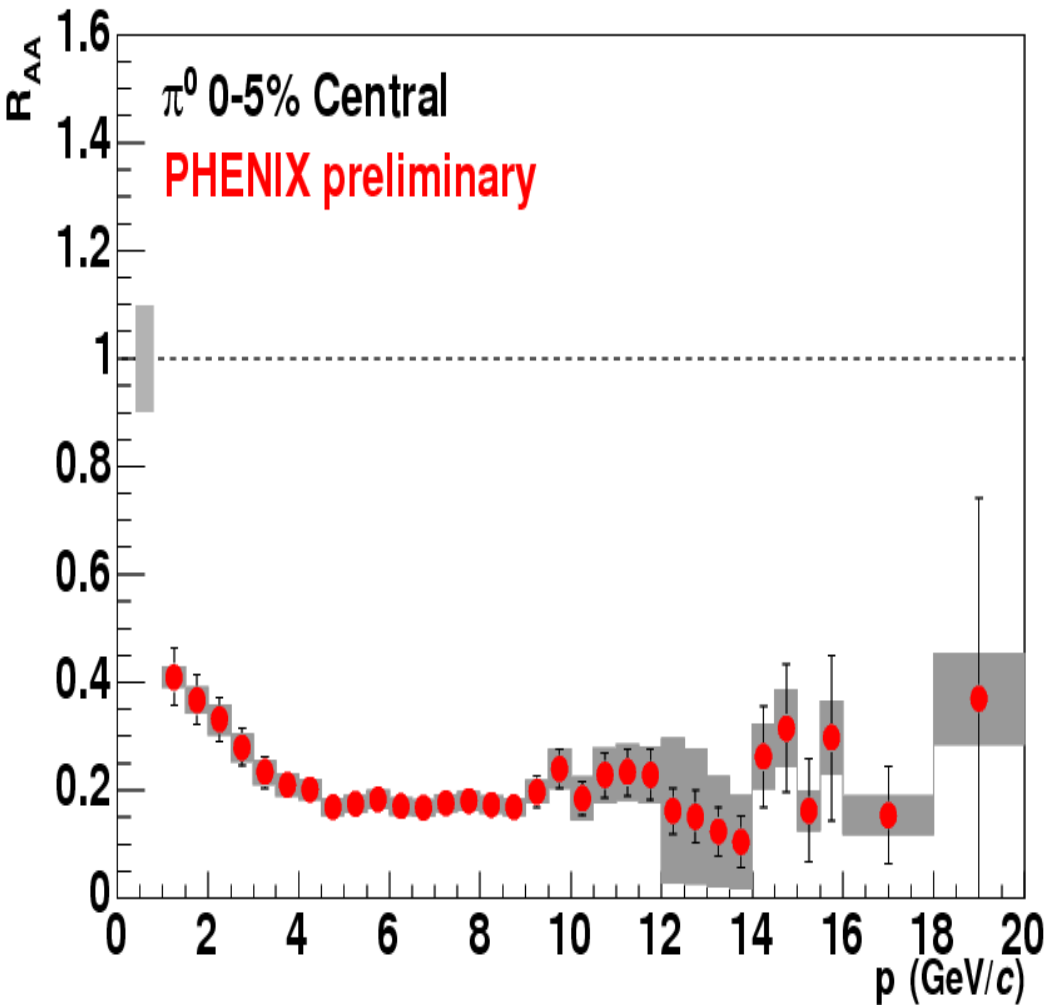
- ***Lose energy by partonic interaction, medium may be hadronic or partonic***
- ***Emerge as partons and then fragment***
- ***Require knowledge of single and double fragmentation functions***

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

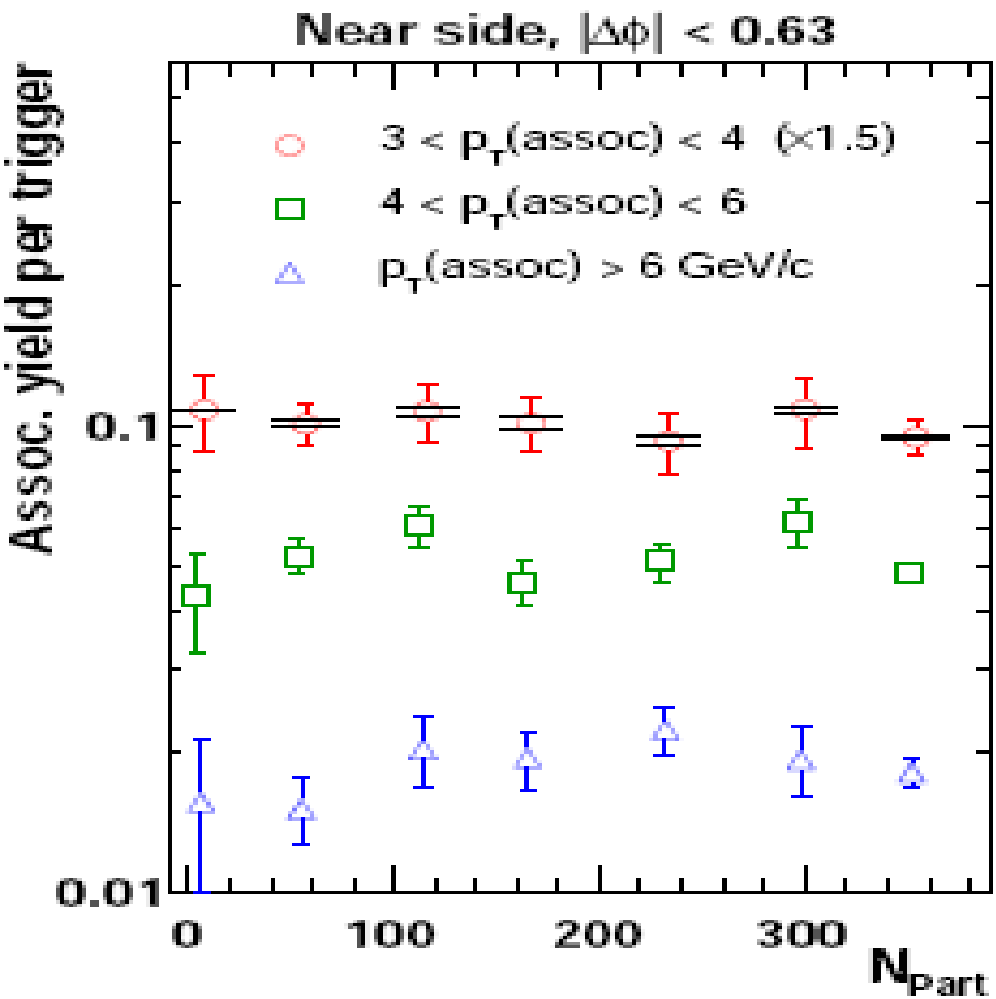
$$D_{q}^{h_1 h_2}(z_1, z_2)$$

The primary qualitative observations

Flat-ish R_{AA}



Flat-ish Assoc. Yield



A too naïve picture

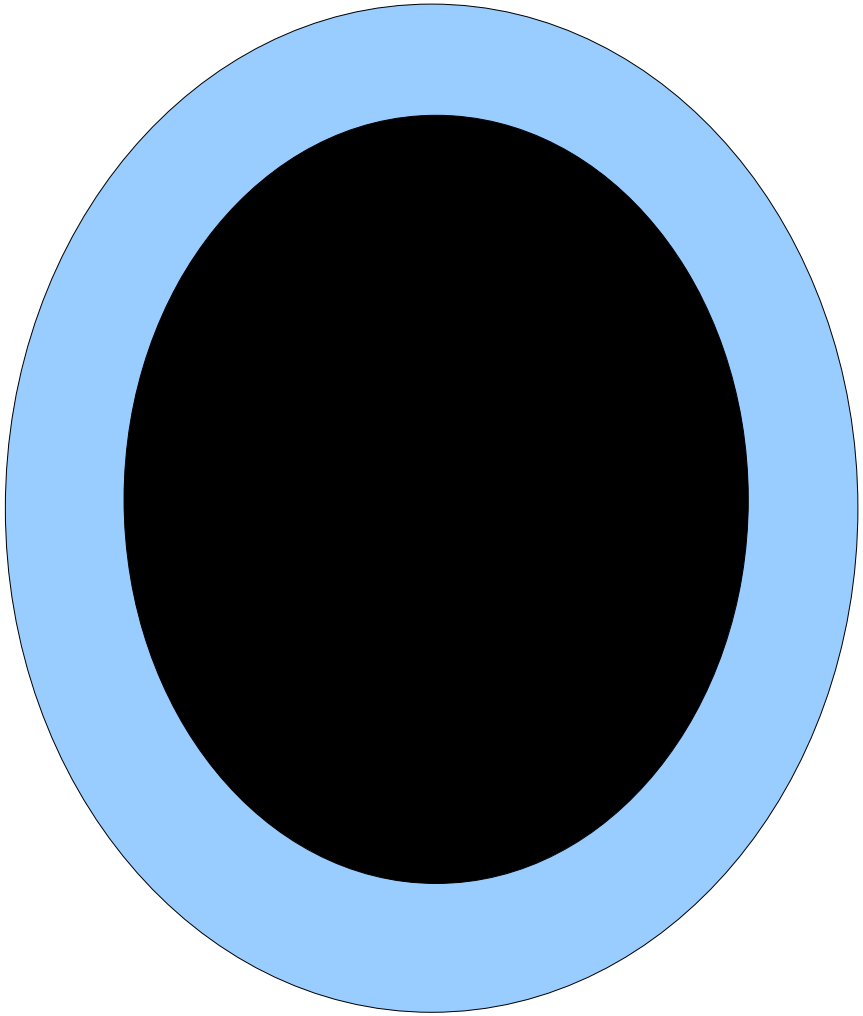
The black core scenario

Identify an annulus with $R_{AA} * T_{AB}$

All jets come from here unmodified any direction

All jets, in the black region are trapped, any energy

Dihadrons may resolve this structure.



What one calculates essentially are the two cross-sections

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

$$\int dp_{T_2} \frac{d\sigma^{h_1, h_2}}{dy\,dp_{T_1} dp_{T_2}} \sim \int d z_2 dx_a dx_b G(x_a) G(x_b) \frac{d\hat{\sigma}}{d\hat{t}} D_q^{h_1 h_2}(z_1, z_2)$$

in pp and in AA collisions

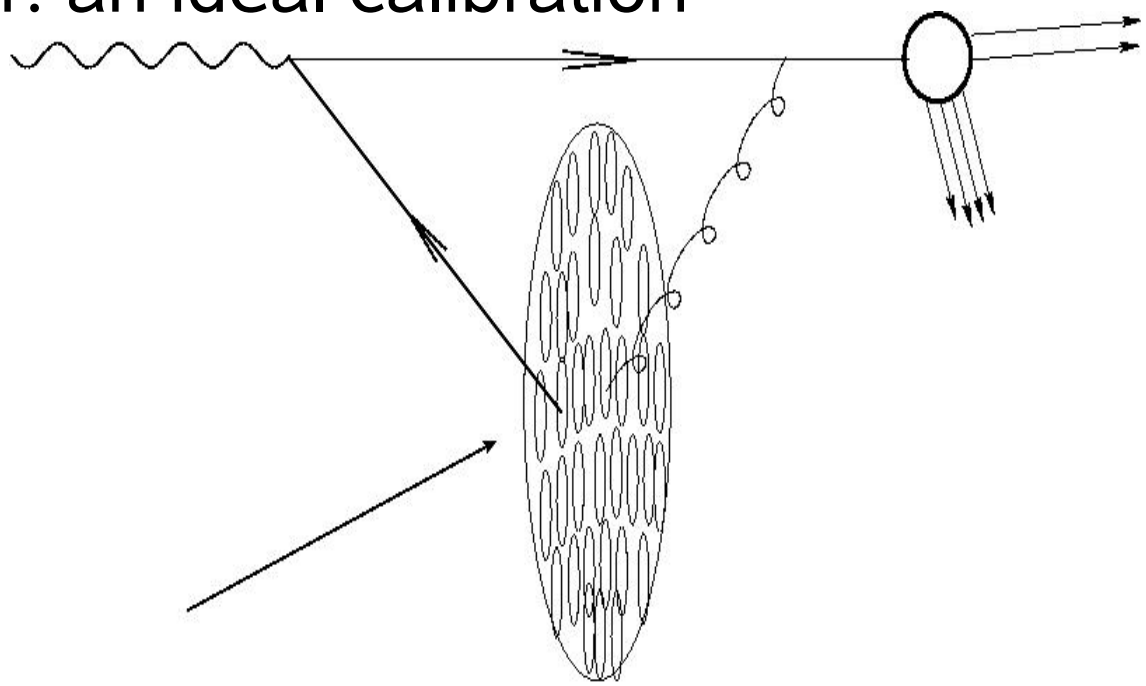
The main difference is in the fragmentation functions

$$D^{AA} = D + \Delta D(medium)$$

$$\Delta D \sim -\int d l_T^2 d z\, f(l_T, R_{origin}, R_{length}, x_B) P(z)$$
$$\times \int d y_1^- d y_2^- \langle Matter | G^{+\mu}(y_1^-) G_{+\mu}(y_2^-) | Matter \rangle$$

X.-N. Wang and X. Guo, NPA 696, 788 (2001);
A. Majumder, E. Wang, X.-N. Wang nucl-th/0412061; A. Majumder EPJC 43, 259 (2005).

DIS in cold nuclear matter: an ideal calibration



Simple expressions for a Gaussian density distribution for nucleons in a medium sized nucleus

$$\rho(r) = \rho_0 e^{\frac{-r^2}{2R_A^2}}$$

$$Mod \sim C\, A^{1/3} \left(F(x_B)\, x\, G^N(x) \right) \left(1 - e^{-x_L^2/x_A^2}\right)$$

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

τ_f ***= Formation time***

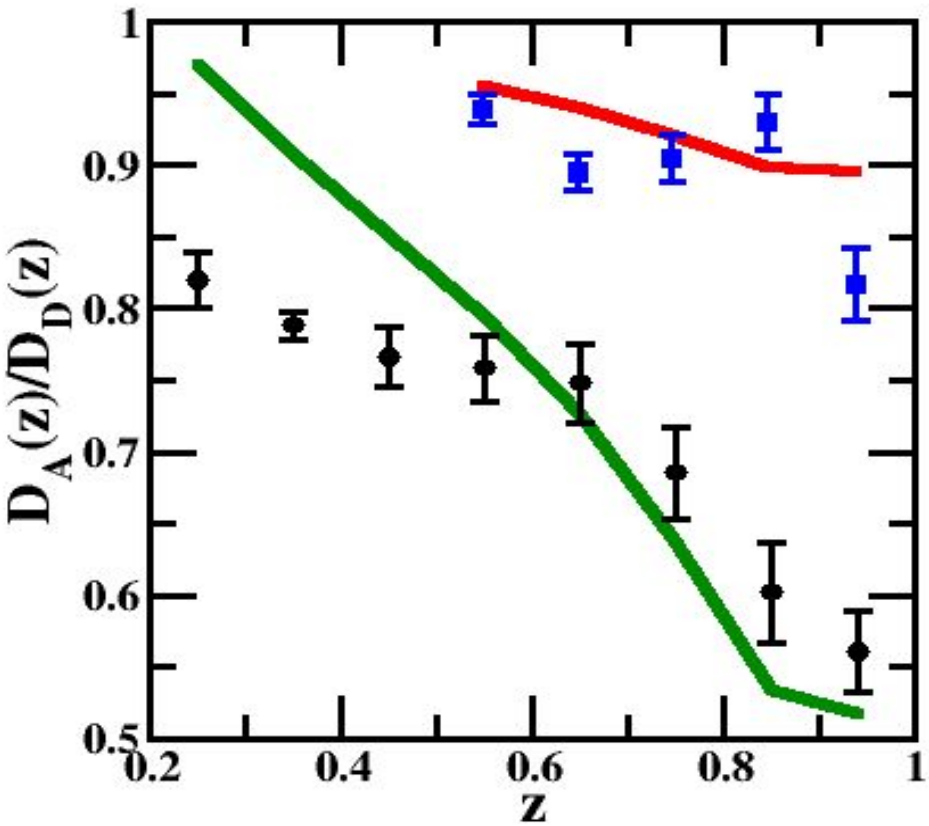
R_A ***= Nuclear size***

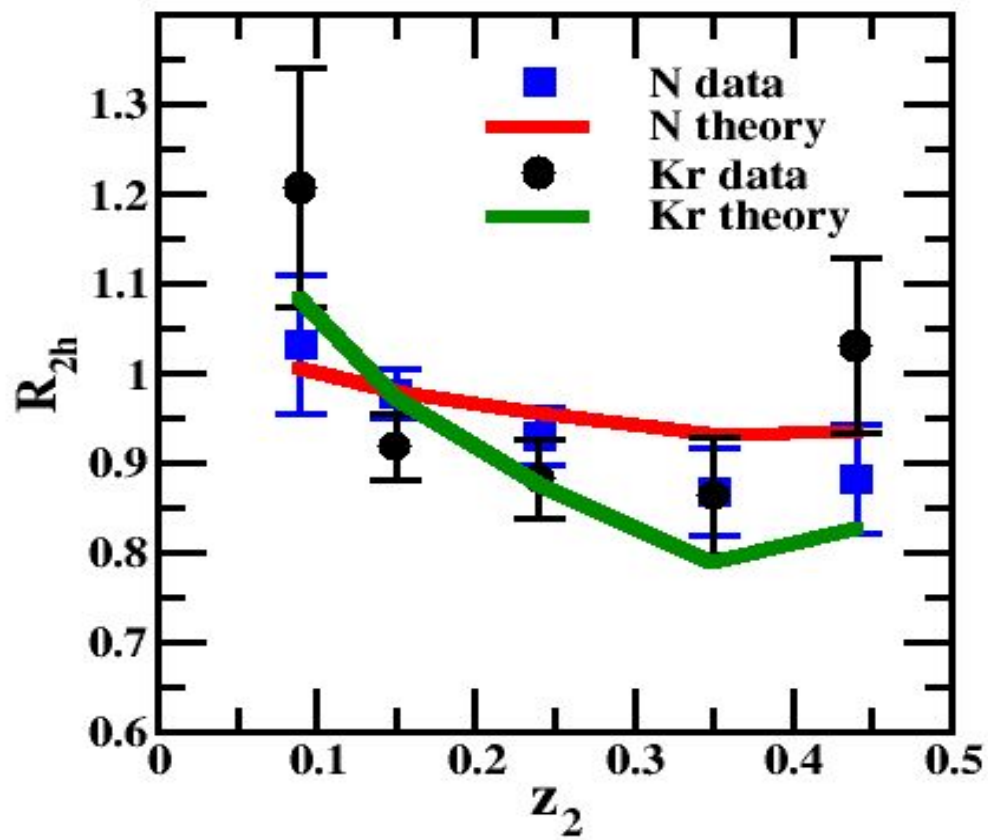
γ ***= boost***

What you actually measure is $\int dy_1^- \, dy_2^- \langle A | F(y_1) F(y_2) | A \rangle$

which simplified to G(x) in a nucleus

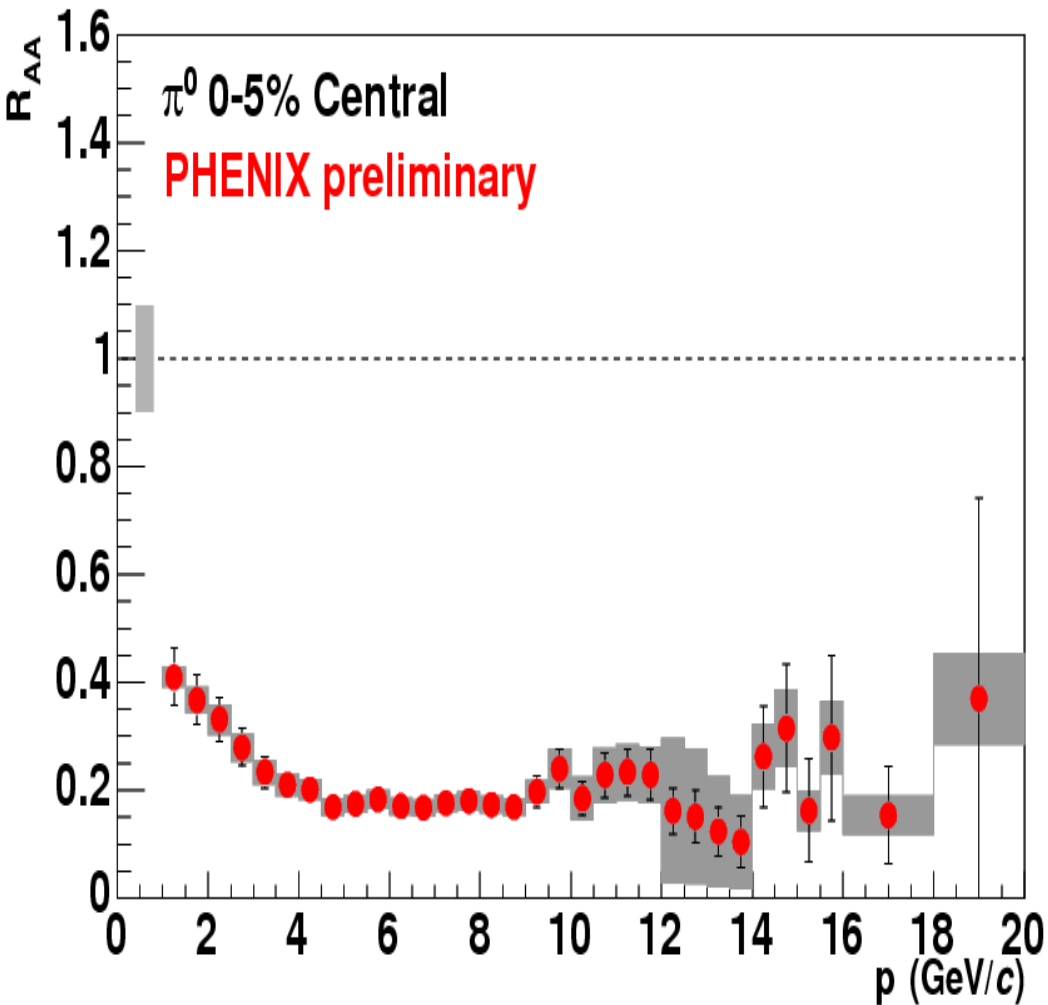
- *Fit C to the Nitrogen data, rest is prediction*
- *ν, Q is measured, direct measure of modified fragmentation*
- *Drop with A in D(z)*
- *Suppression and enhancement in $D(z_1,z_2)$*

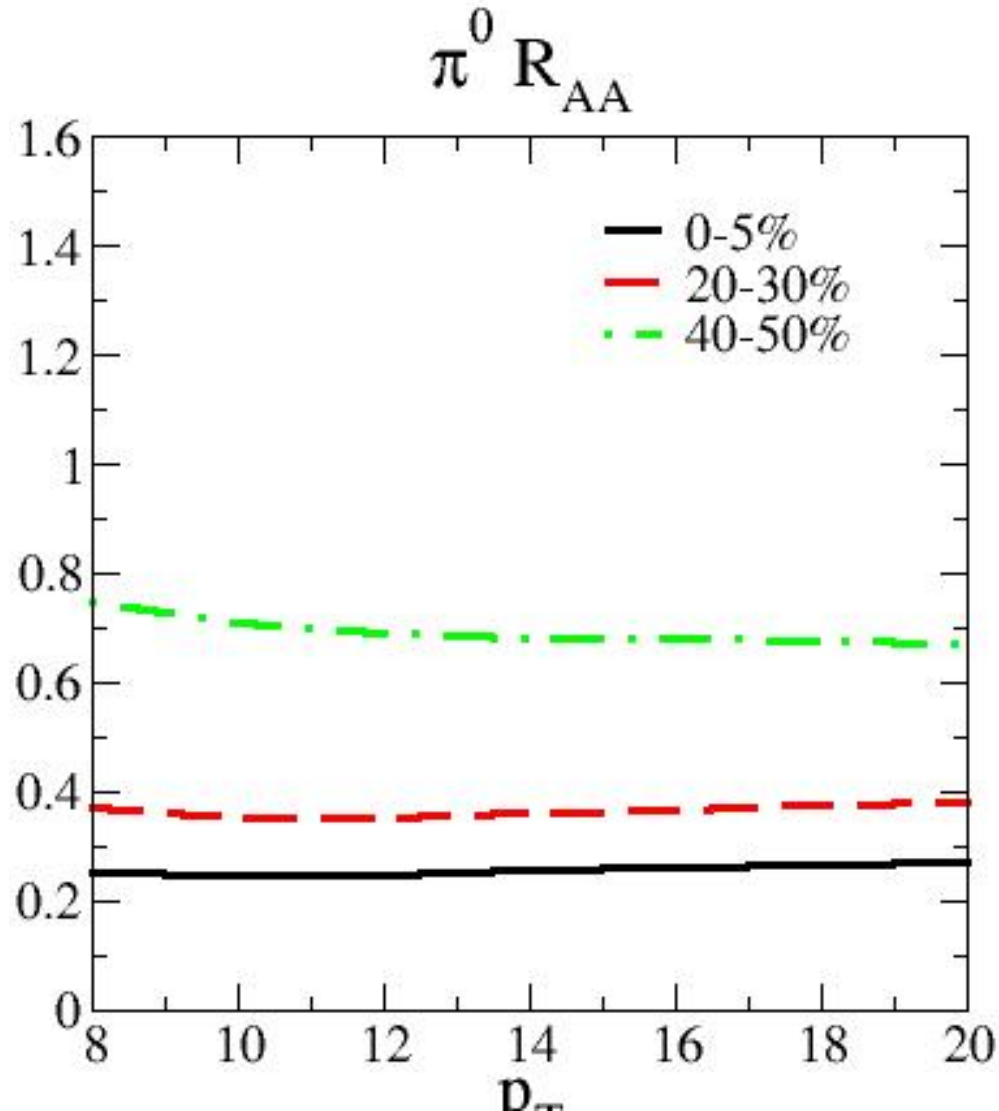




Moving on to Heavy-ion collisions, the Raa…

Keeping it simple,
calculations will not include Cronin effect
No recombination, no detailed balance
Remain above 8 GeV!





Double inclusive,

Double inclusive is the number of pairs!

If N flavors detected, there are N*N pairs

Big difference between charged pion associated yield and Charged hadrons associated yield.

In R_{AA} the same number goes in both numerator and denominator

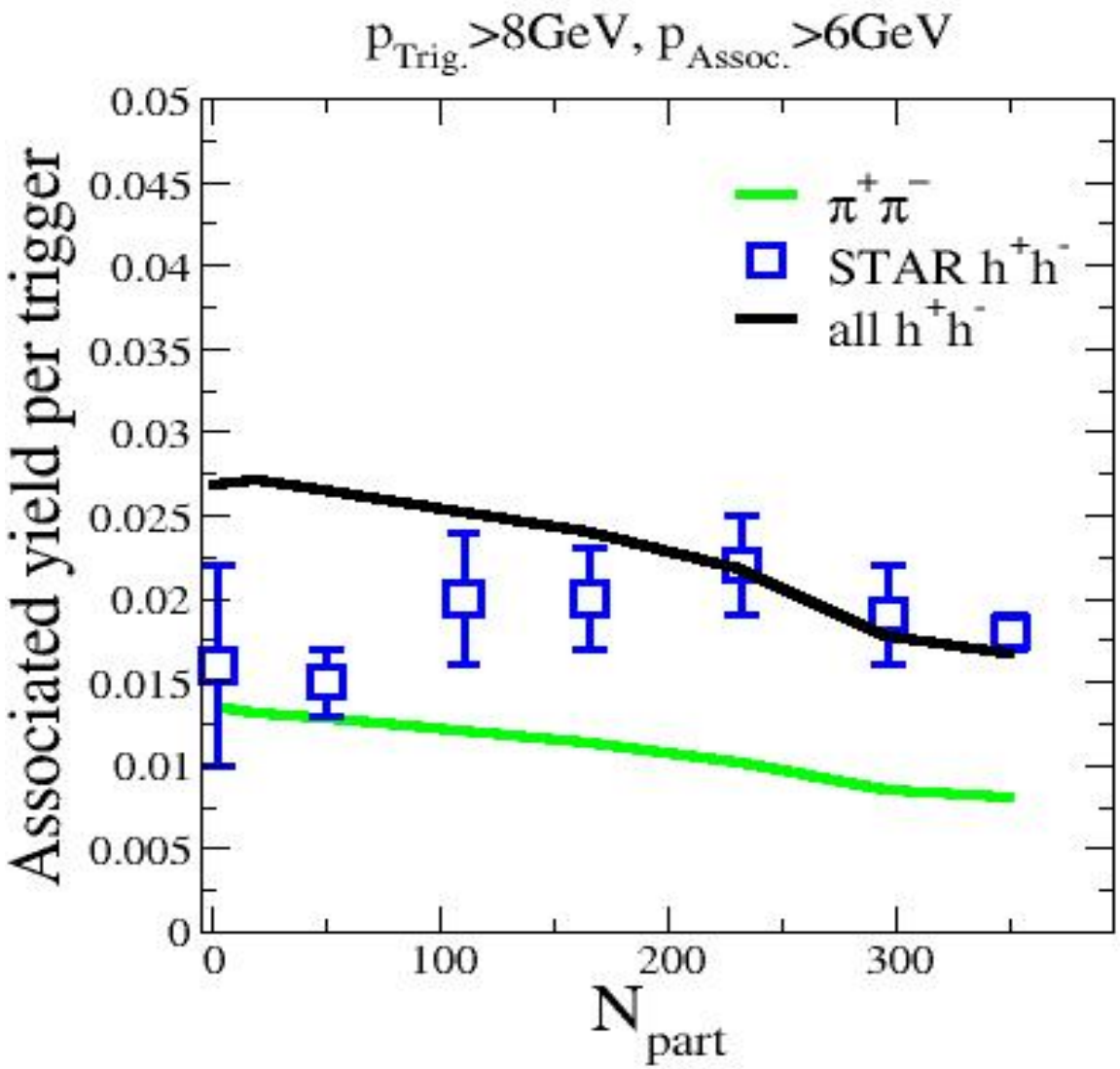
Going from pions to charged hadrons will cause upward shift in associated yield.

A flavor number dependence in the assoc. yield

Calculation includes all hadrons,

no correction for decays included.

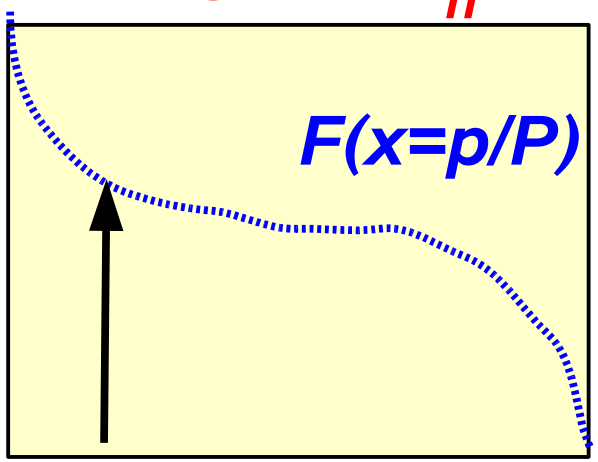
Assumes, gluon density goes as Npart



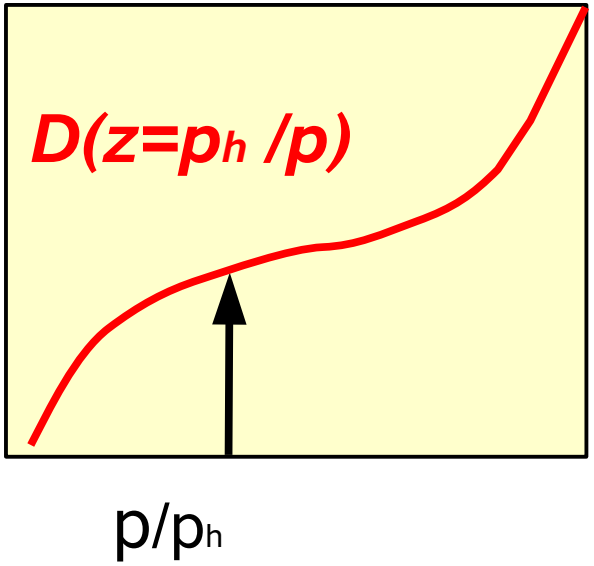
Very preliminary!

Asking questions about the medium

For a given p_h, there is a distribution of p

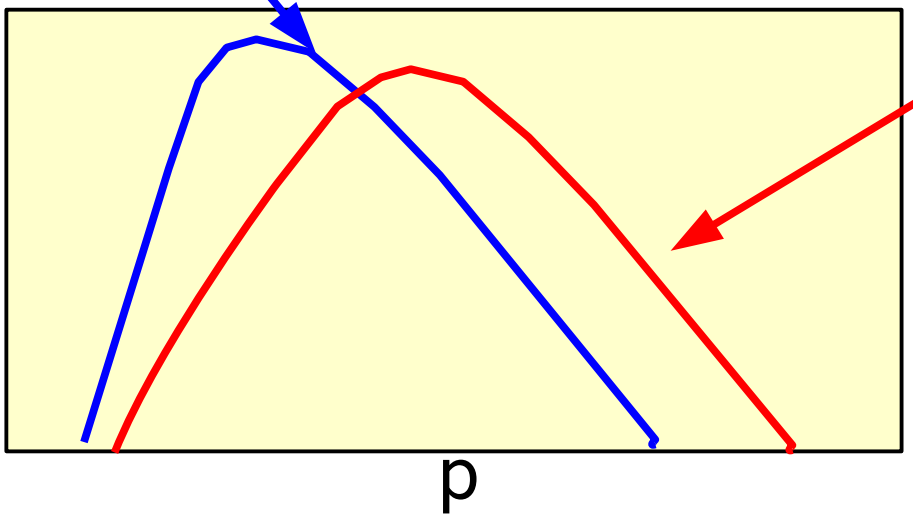


$* \ \sigma(p+q) \ *$



Distribution of p without E-Loss

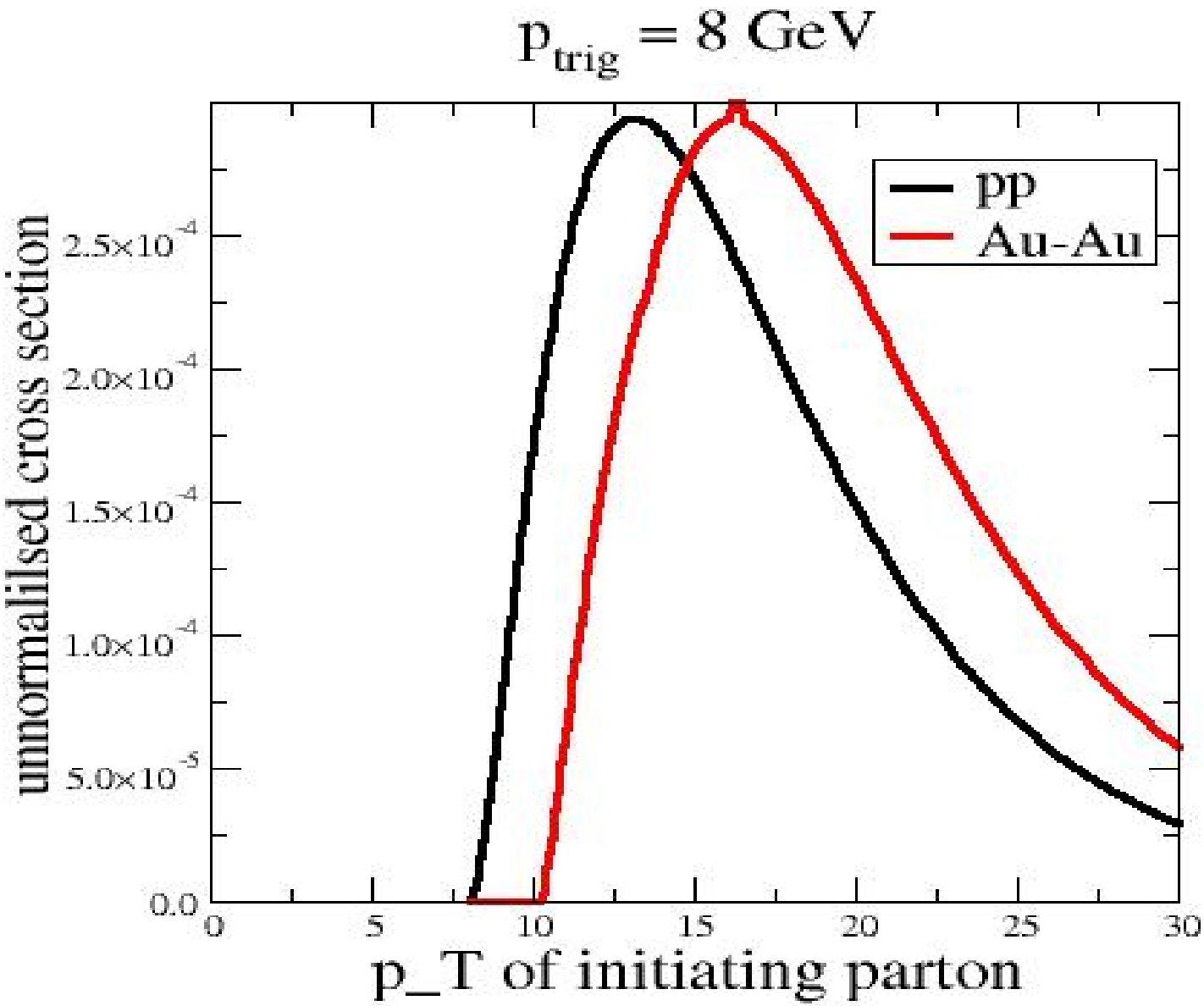
Distribution of p with E-Loss



Energy loss selects events with a higher initial parton energy when you trigger on hadron pT

Trigger bias in pp versus central Au-Au

Calculation shows, noticeable trigger bias

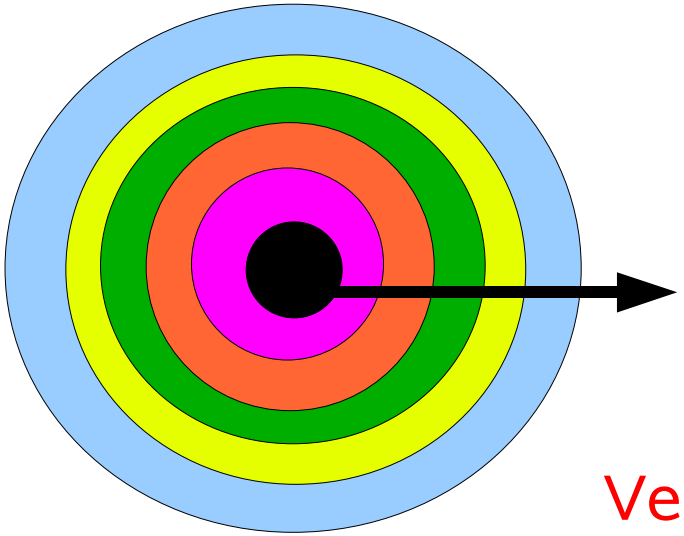


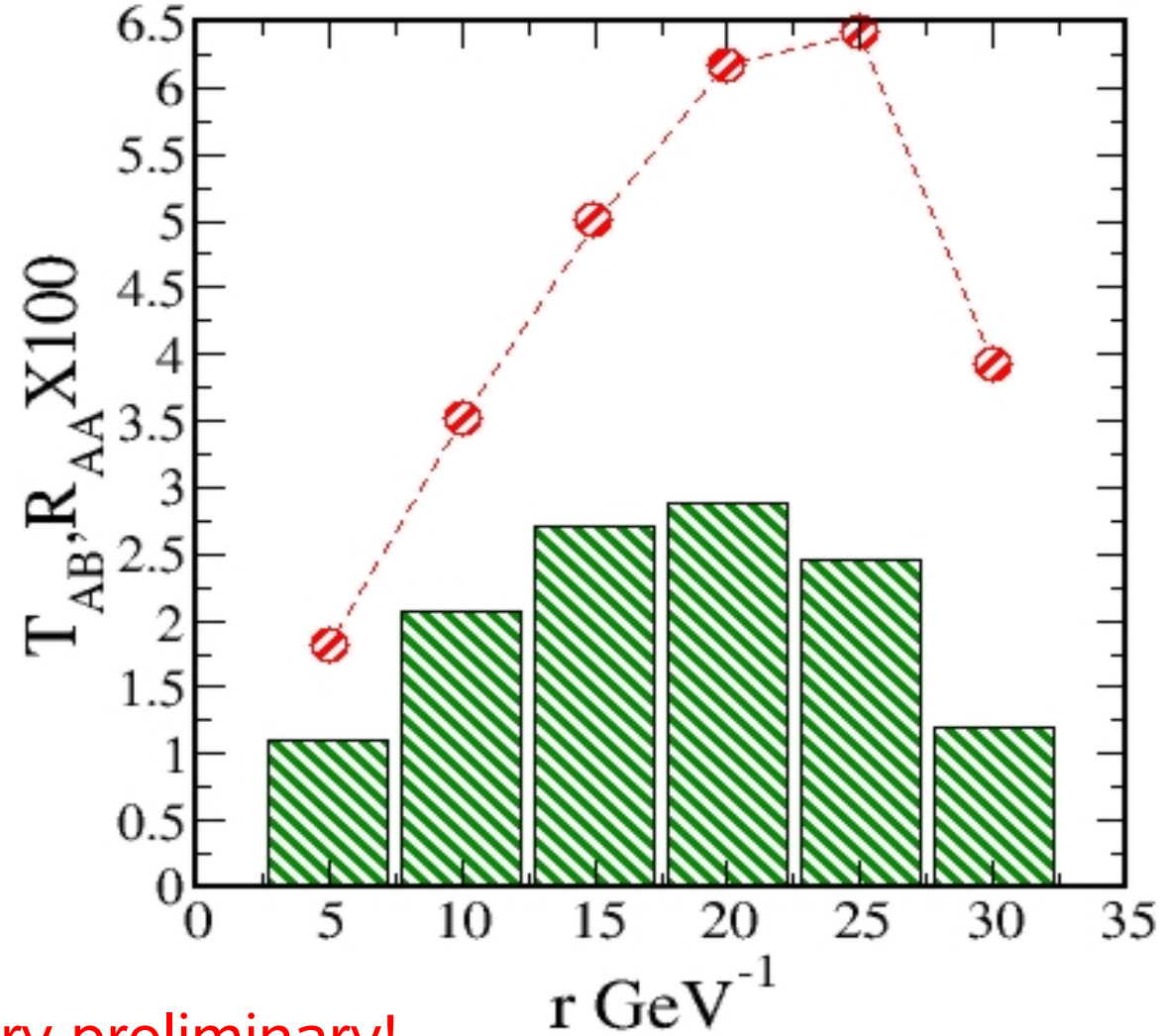
Very preliminary!

Where are the jets coming from ? Surface bias

Look at a very central event and make annular rings around the center at 0.

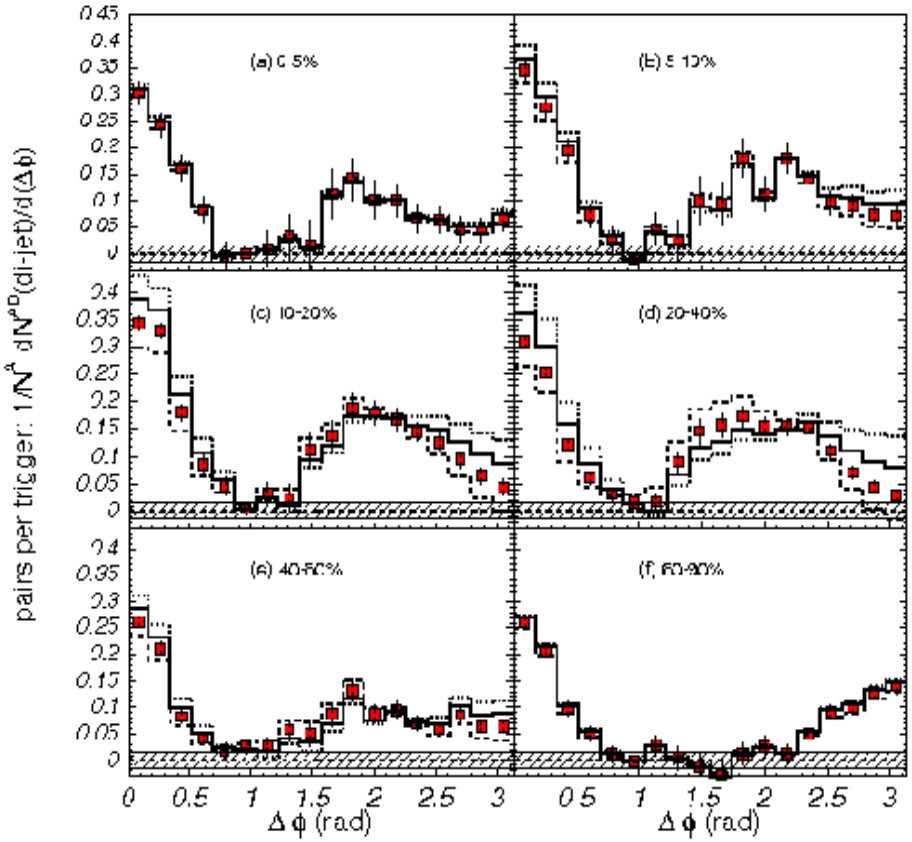
System cylindrically symmetric

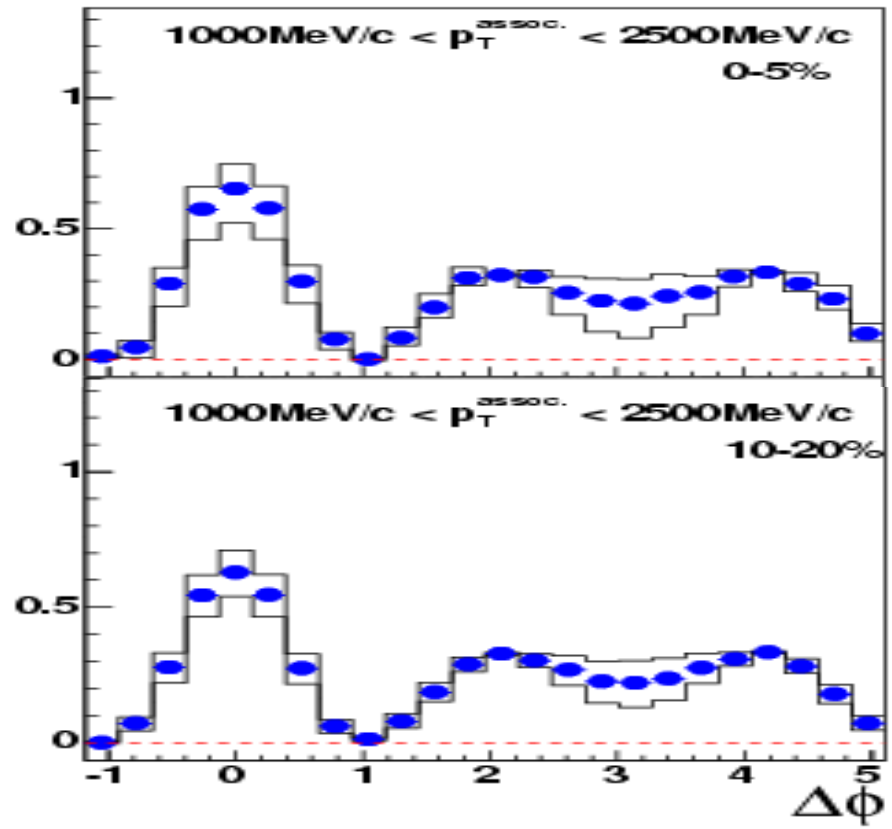


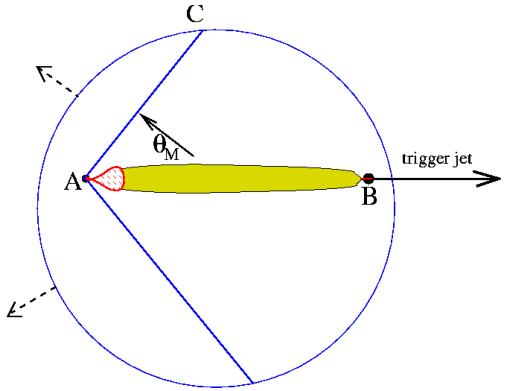


Very preliminary!

Low Pt on away side





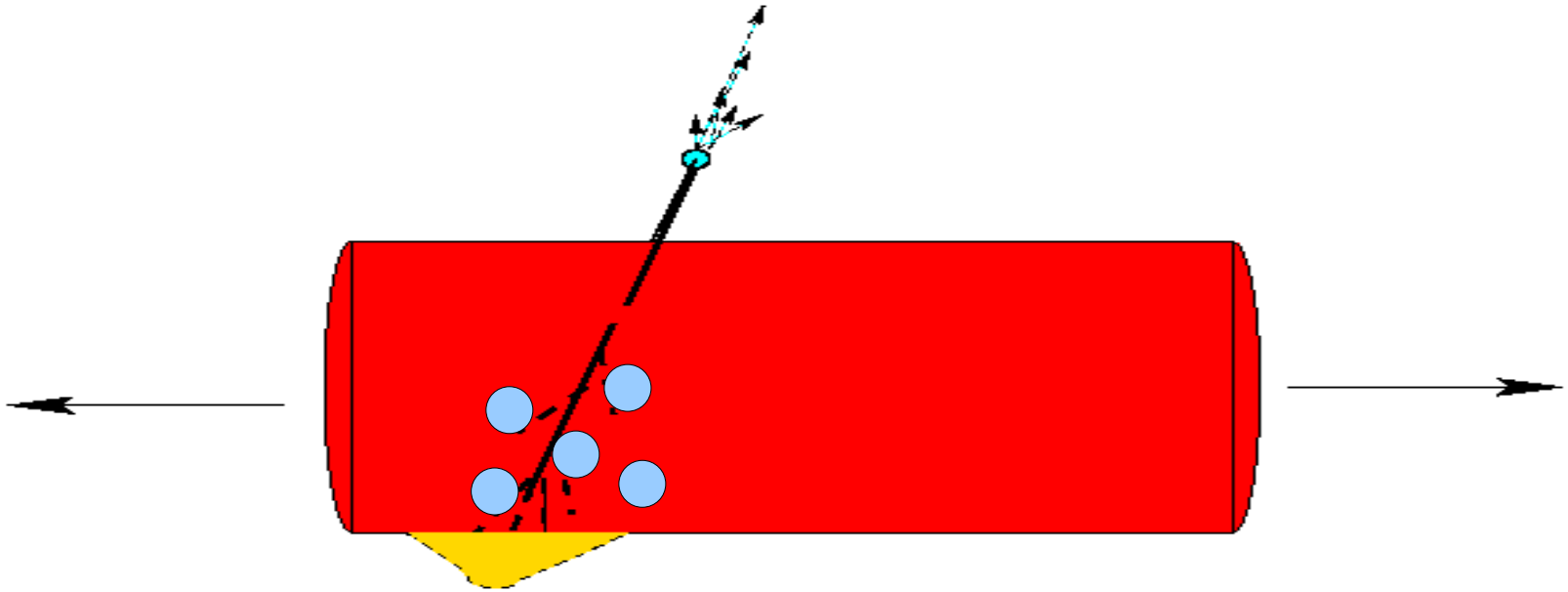


One explanation: Mach Cones

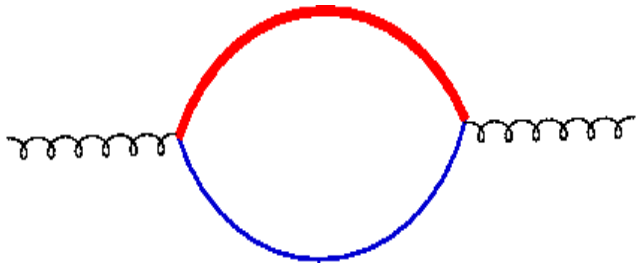
Alternate possibility: Cherenkov radiation

Matter from 1-2Tc may have heavy colored bound states

E. Shuryak and I. Zahed, **PRC70:021901,2004; PRD70:054507,2004.**



- ***Away side partons travel through a lot more matter***
- ***Jet can excite collective modes of dense matter!***
- ***If the s-QGP has heavy colored (bound) states***
- ***Soft gluons effect transitions between these states***



Any medium has a permitivity ε

Gluon phase velocity, $$v = \frac{c}{n} = \frac{c}{\sqrt{\epsilon}}$$

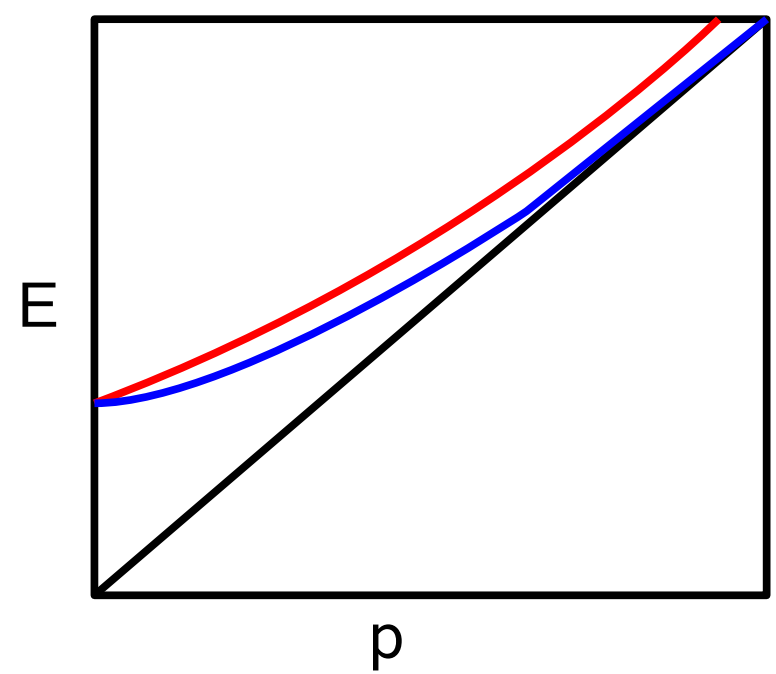
$$A(x,t) \sim \exp\left(ip\left(x - \frac{p^0(p)}{p}t\right)\right)$$

$$v = \frac{p^0(p)}{p}$$

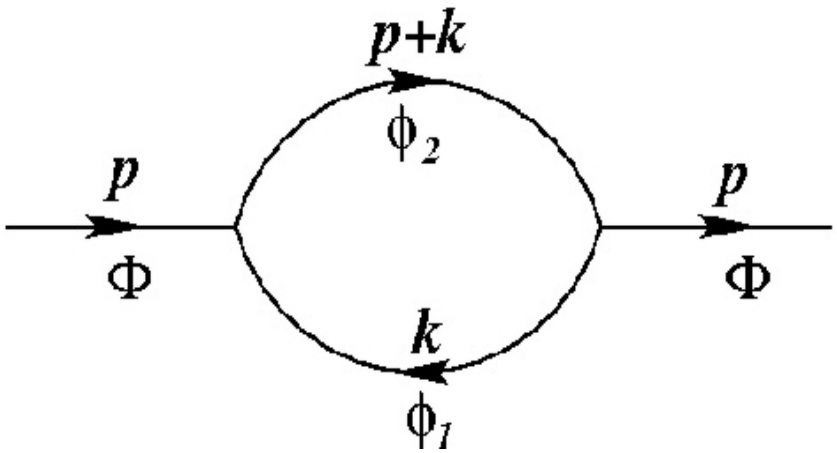
In Regular HTL finite temperature calulations E<p,

Gluon scatters off massless quarks and gluons

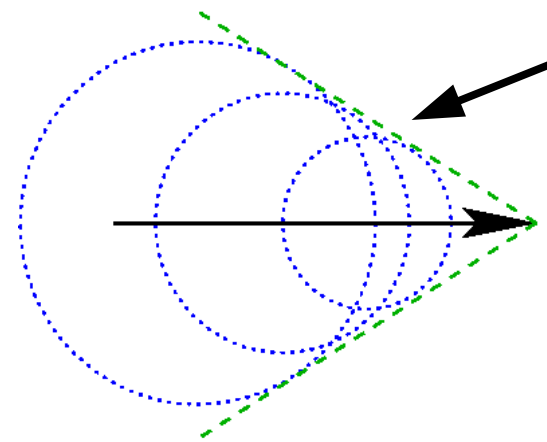
Will also happen in a scalar theory with massless scalars



Solve a simple scalar theory with two massive scalars

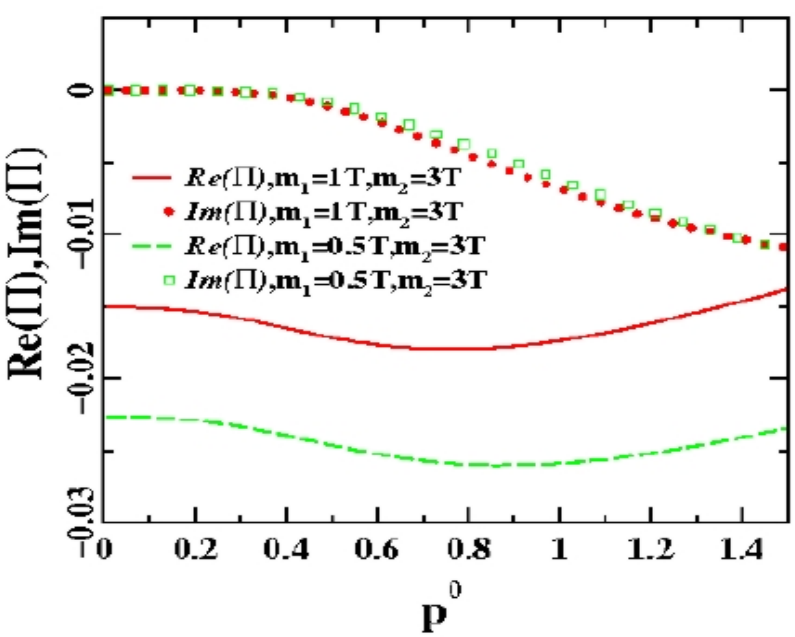


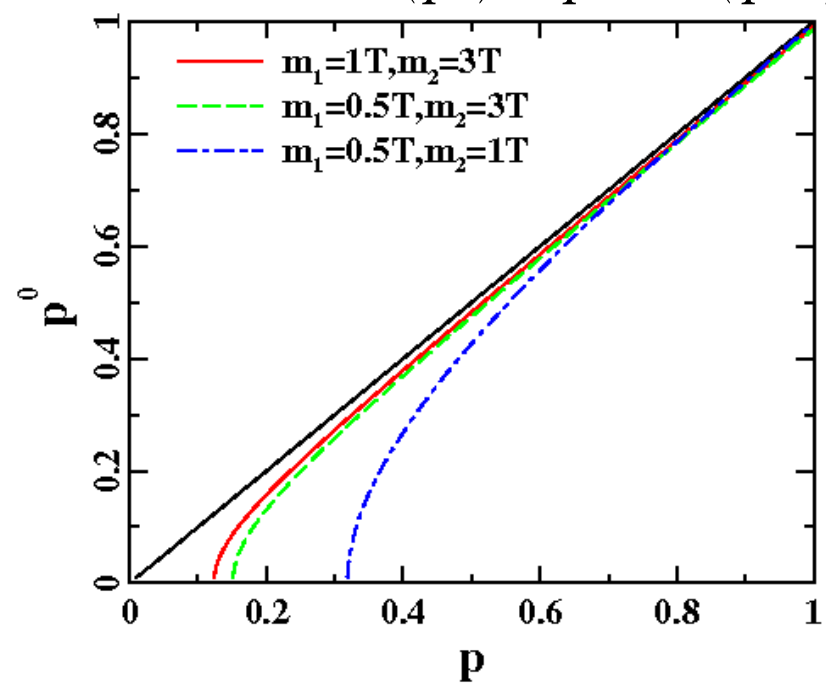
$$v=\frac{1}{\sqrt{\epsilon}}=\frac{p^0}{p}<1$$



In the medium, solve dispersion relation

$$(p^0)^2-p^2=\Pi(p^0,p,T)$$



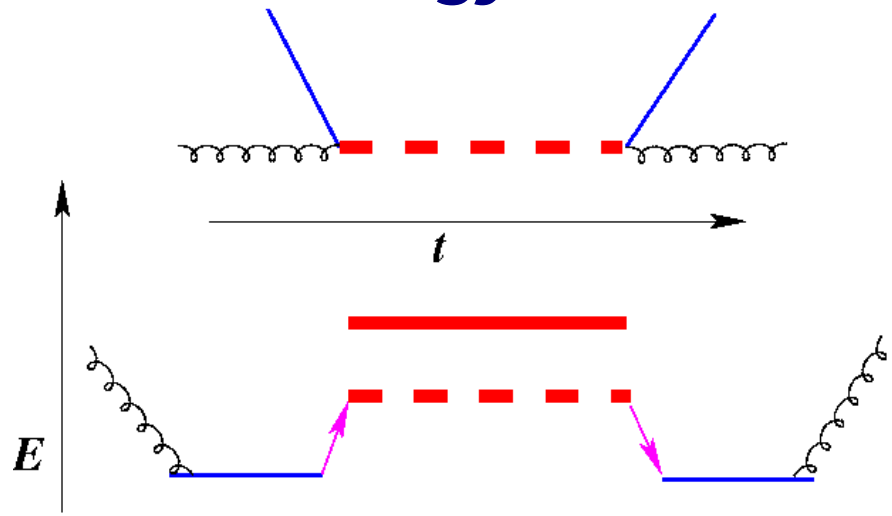


What causes the large negative self energy?

Open the thermal loop!

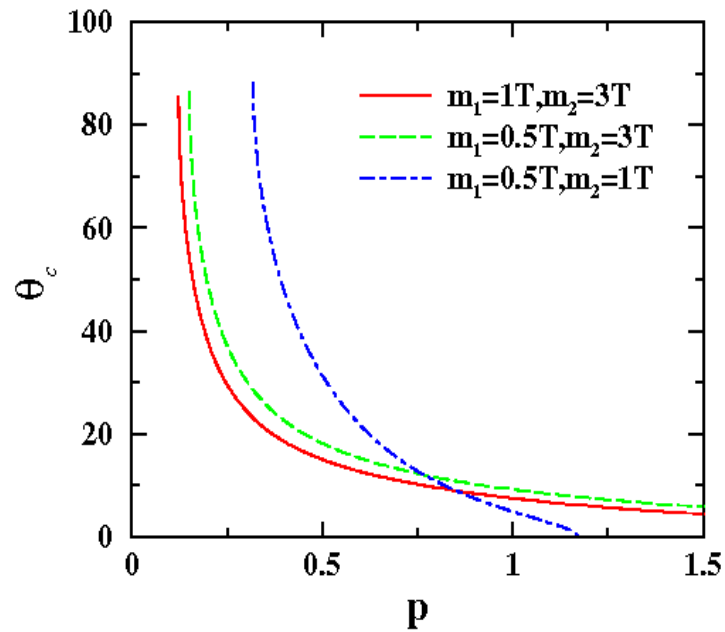
- ***Space like virtual intermediate state***

- ***Due to large mass gap, cannot excite the intermediate state to its on-shell energy***



Regular Cherenkov, gives small E-loss

Scattering induced Cherenkov Brem. gives large E-loss,



V. Koch, A. Majumder, X.N. Wang, PRL 96, 172302 (2006);

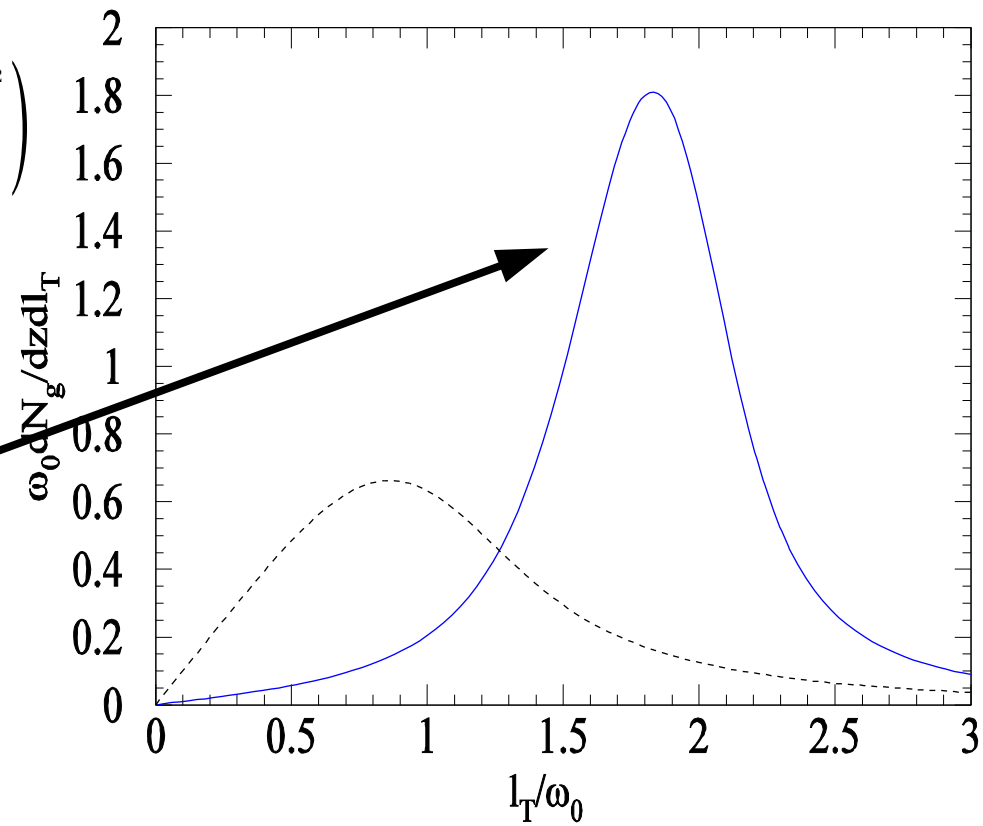
Induced radiation with out Cherenkov dispersion relation

$$\frac{dN_g}{dz\,dl_\perp^2} \propto \frac{1}{l_\perp^4}\left(1-e^{-\left(\frac{R}{\tau_f}\right)^2}\right) \qquad \tau_f = \frac{2Ez(1-z)}{l_\perp^2+(1-z)\Pi}$$

Including the Cherenkov dispersion relation, modifies the radiated gluon splitting function

$$\frac{dN_g}{dz\,dl_\perp^2} \propto \frac{1}{(l_\perp^2+(1-z)\Pi)^2}\left(1-e^{-\left(\frac{R}{\tau_f}\right)^2}\right)$$

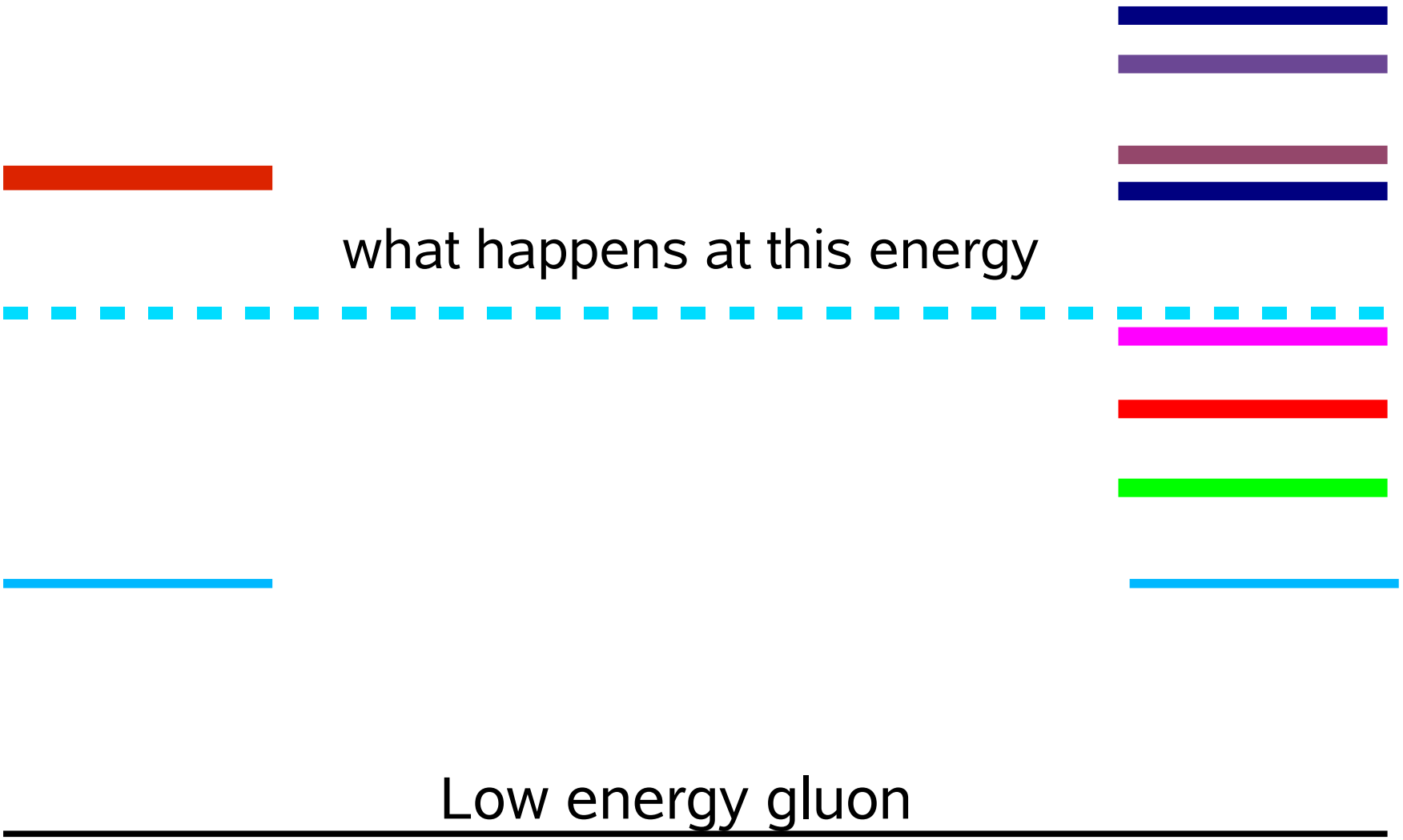
Shifts the peak and increases the E-Loss



A. Majumder, X. N. Wang, PRC (to appear)

We did this case

What about this



We are talking about this kind of Cherenkov

But, it could also happen at a particular higher freq. as it does in water.

Then Cherenkov radiation will happen at a particular energy only!

Also requires that the imaginary part takes a dip at this energy

If Ch. gluons have a finite energy, only a few of them, will not give a clear 3-particle corr.

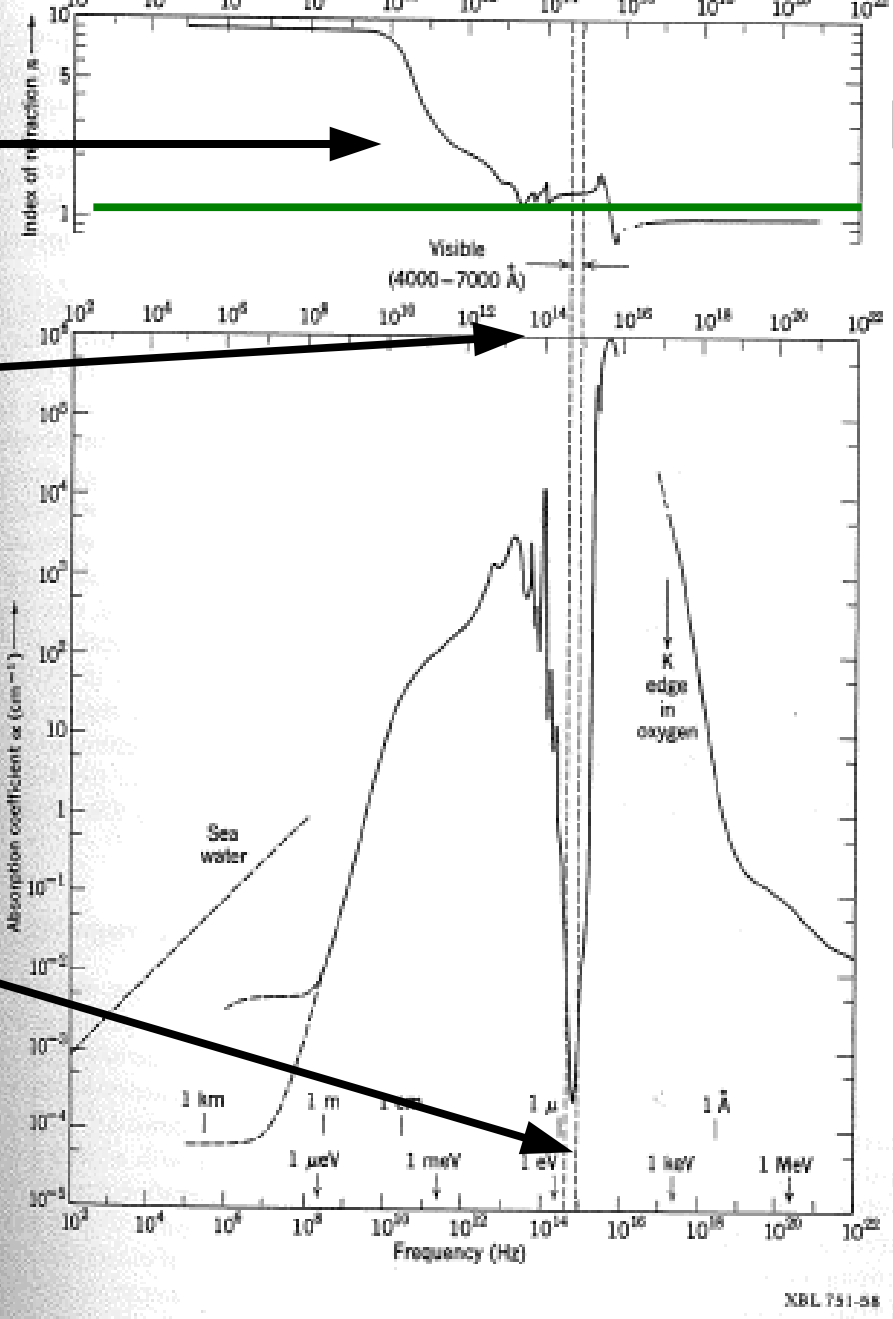


Fig. 7.9 The index of refraction (top) and absorption coefficient (bottom) for liquid water as a function of linear frequency. Also shown as abscissas are an energy scale (arrows) and a wavelength scale (vertical lines). The visible region of the frequency spectrum is indicated by the vertical dashed lines. The absorption coefficient for sea water is indicated by the dashed diagonal line at the left. Note that the scales are logarithmic in both directions.

Summary!

1) Jets provide ideal, caliberated probes of the dense medium.

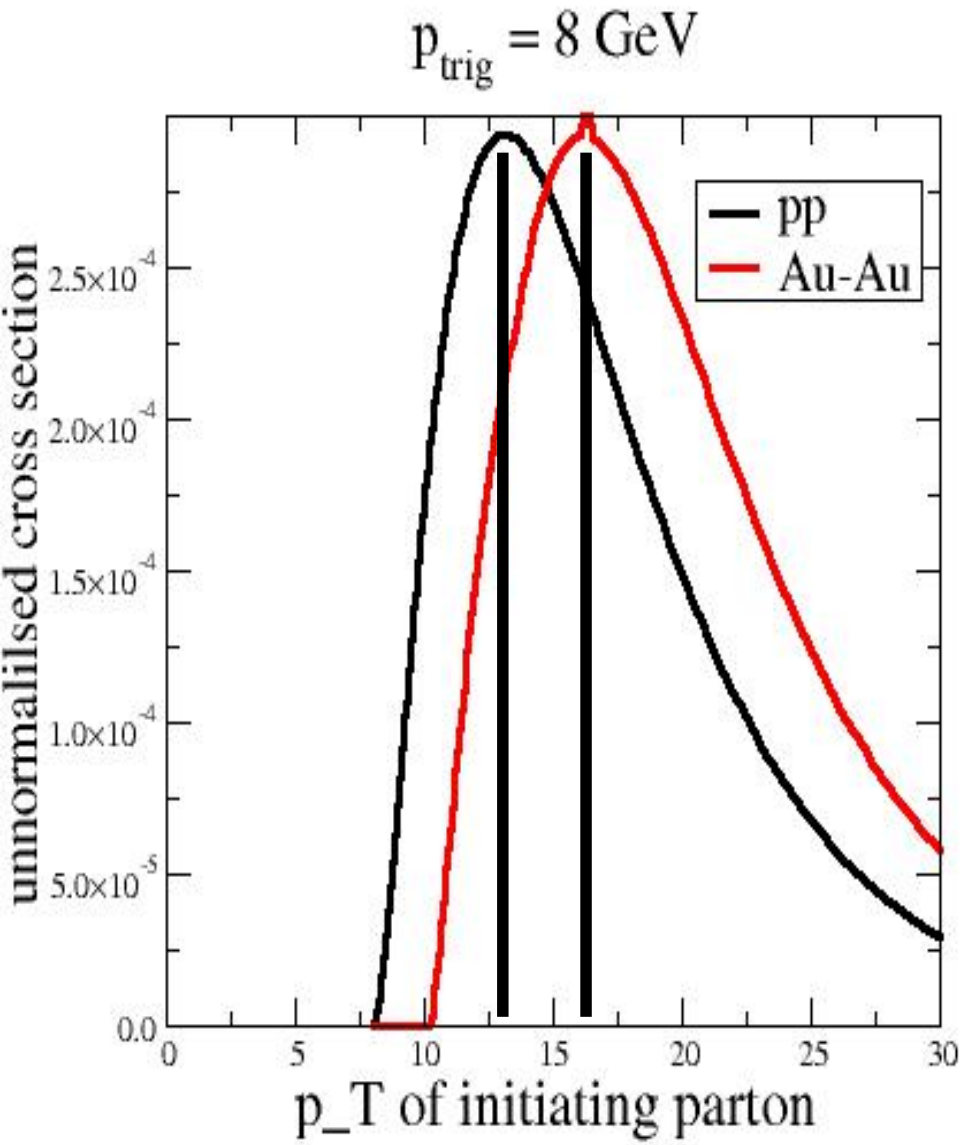
2) Jet correlations provide both tests and new insight into the properties of the medium

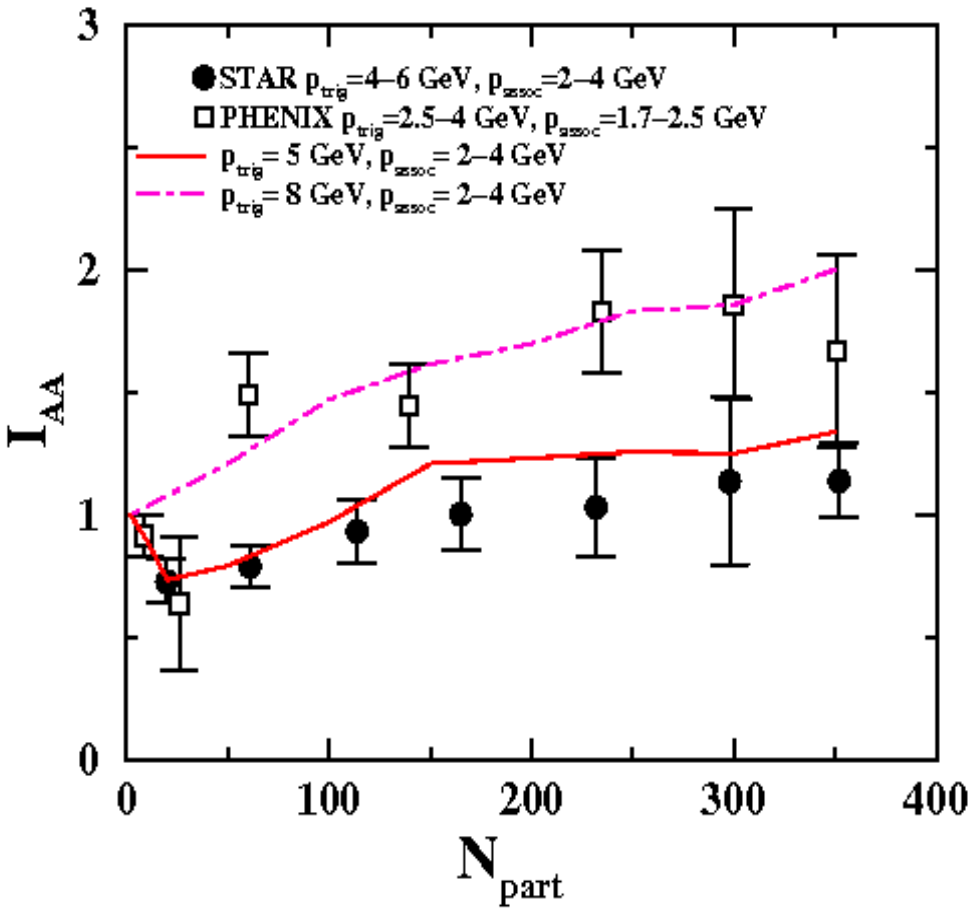
3) A complete calibrated setup of jet correlation observables will define the medium in terms of its unknown parameters!

4) These parameters will constrain models of QGP

Back up!!

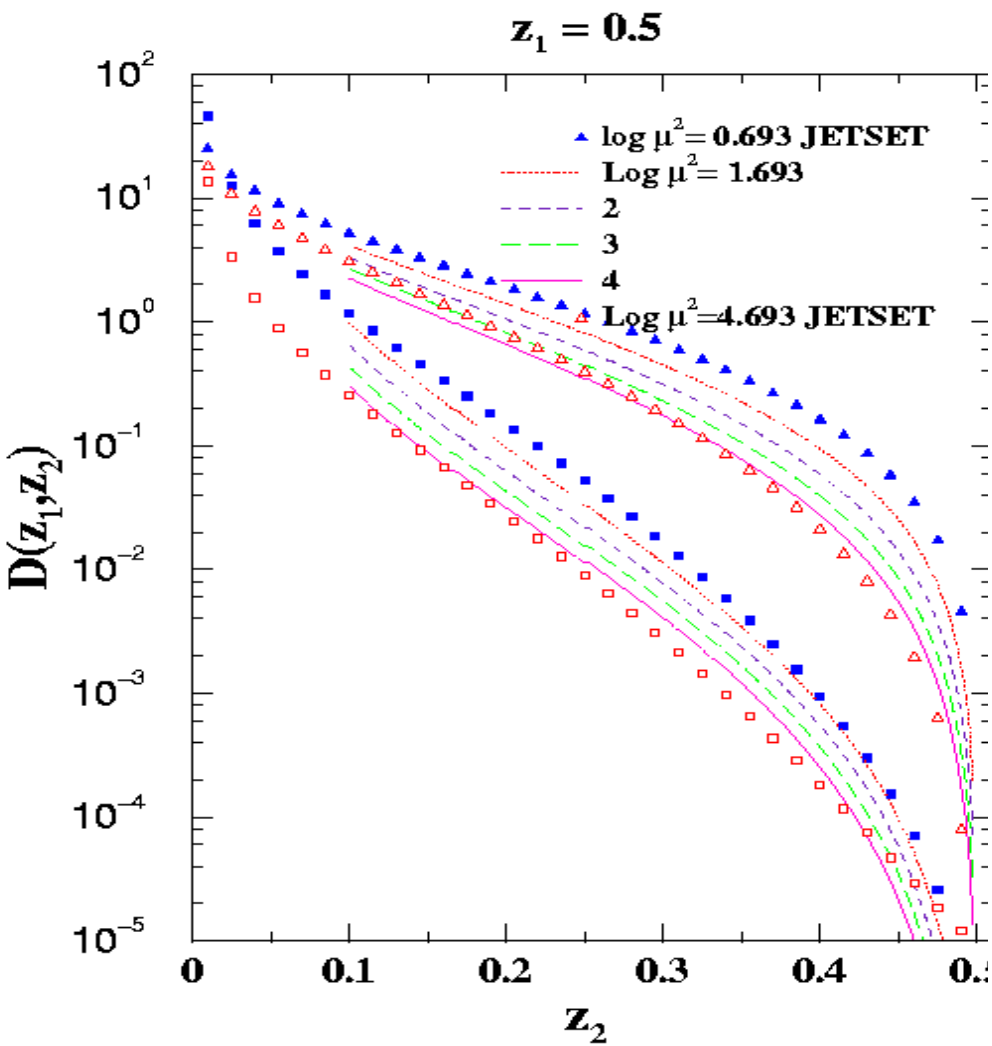
differences with schematic calc.

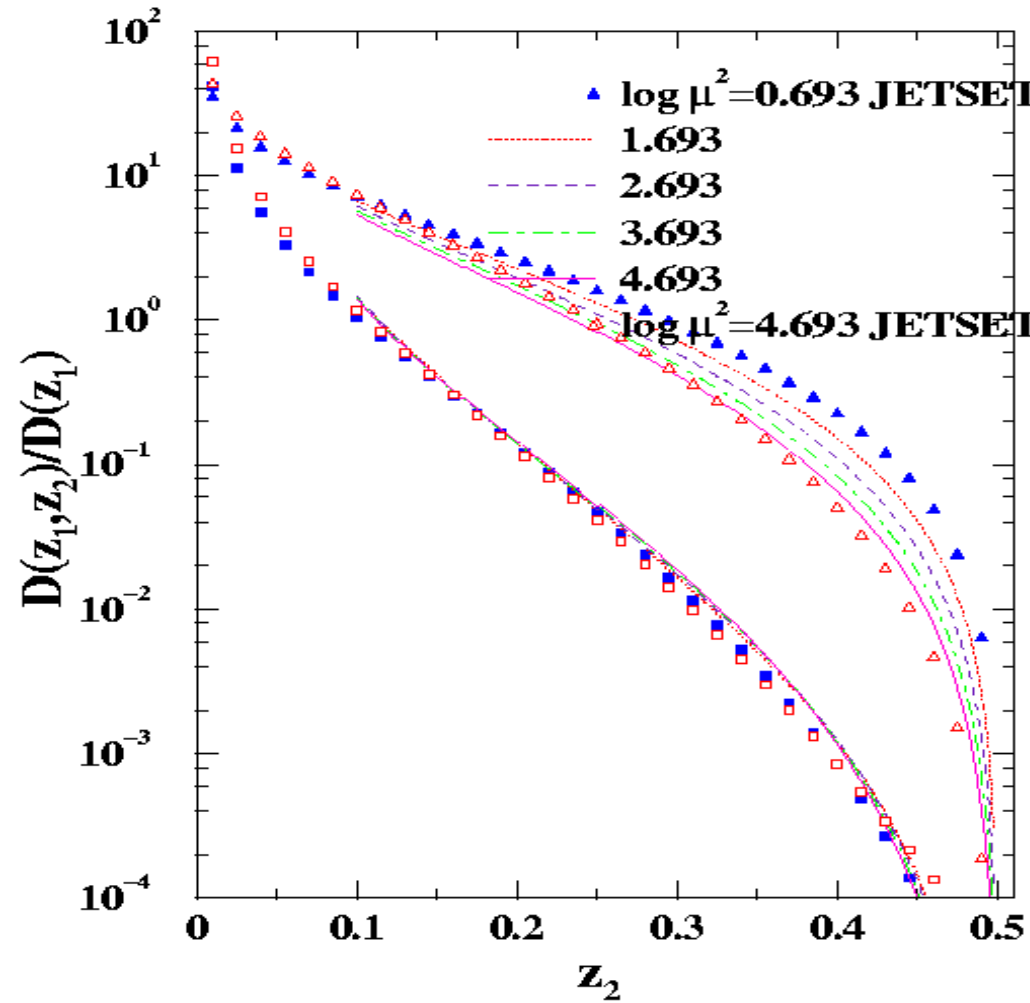




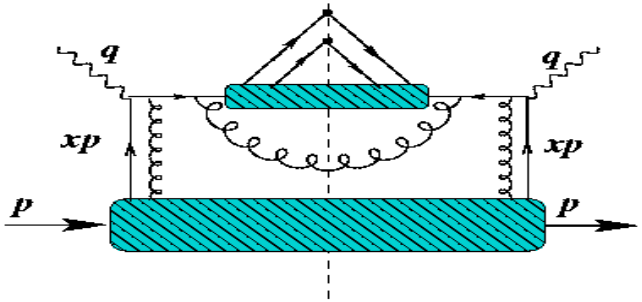
The dihadron frag. func. has a different shape than the single hadron frag. func.

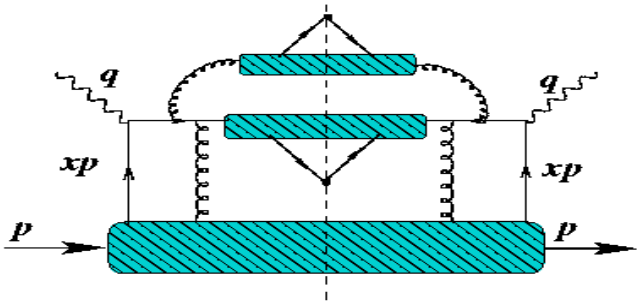
Convolutes differently with the initial parton cross section





The kinds of diagrams that need to be evaluated !

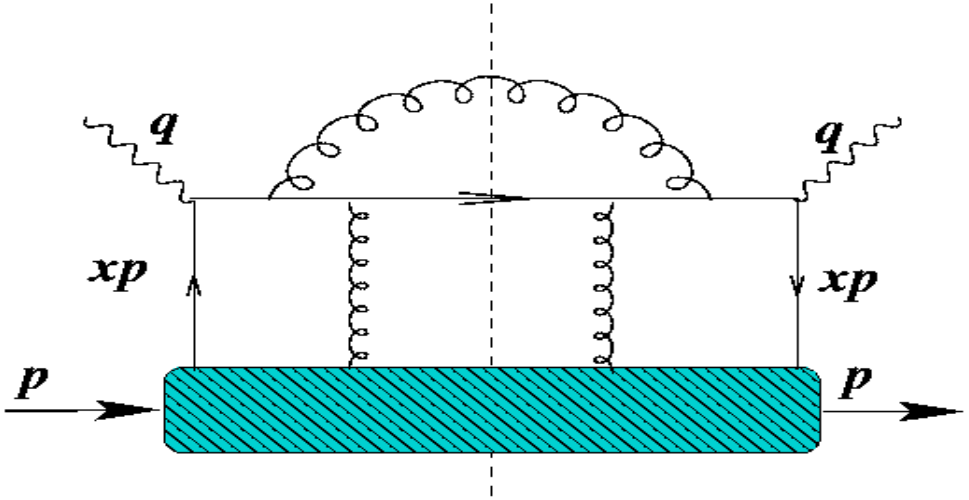




The second diagram has two independent fragmentations can be factorized in the collinear limit as...

$$\frac{dW^{\mu\nu}}{dz_1 dz_2} = \int \frac{dz}{z^2} D_q(z_1/z, z_2/z) H^{\mu\nu} + \int \frac{dz}{z(1-z)} D_q(z_1/z) D_g(z_2/(1-z)) H^{\mu\nu}$$

$$H^{\mu\nu} =$$



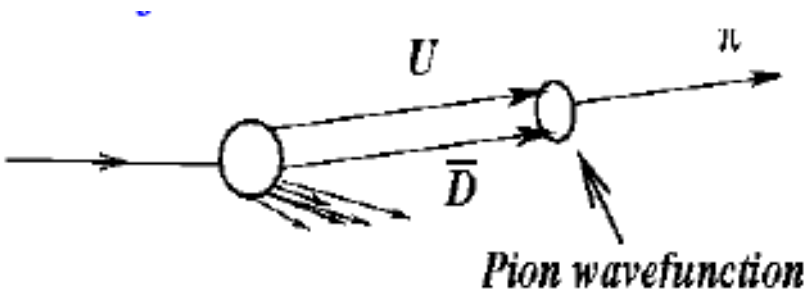
Lowering the pT of the associated particle
Make the jet fragment at the Reco. stage...

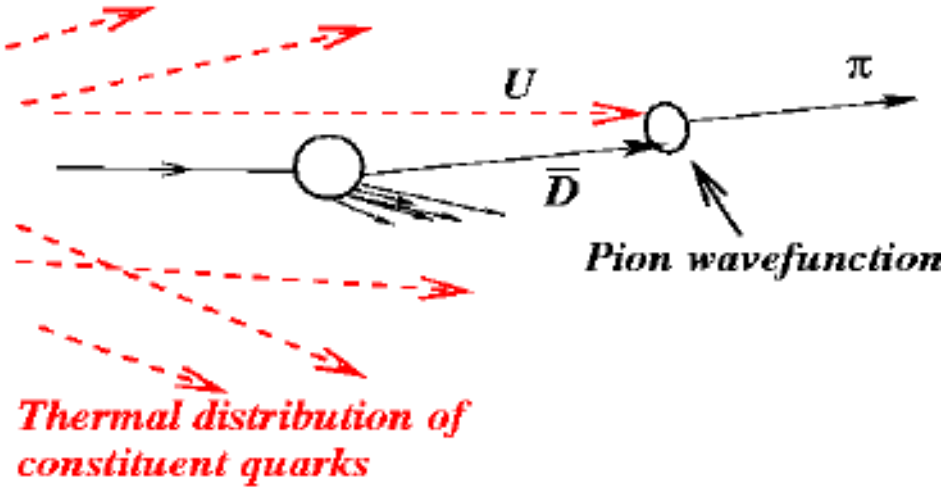
Start by recasting fragmentation in Vacuum in terms of recombination of constituent quarks:

Need a parton to constituent quark fragmentation function,

Combine the constituent quarks into a meson by means of the meson wave-function

Immersing in a thermal medium automatically gives TS, TT

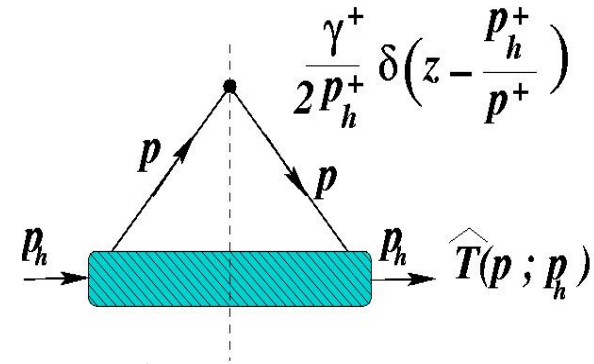




Can recombination be included in jet formalism?

What is a fragmentation function ?

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



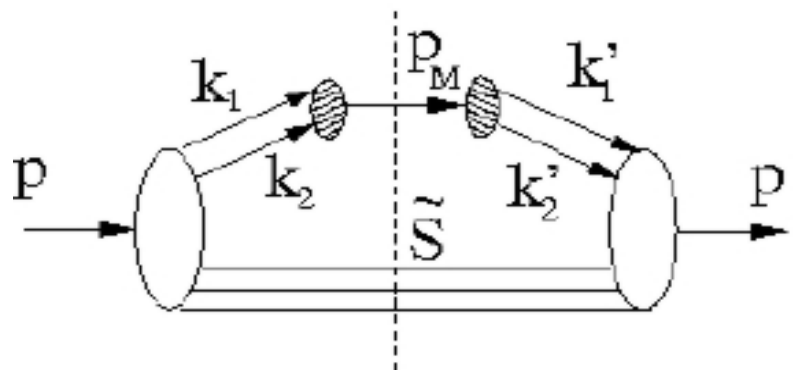
$$\hat{T}_q(p,p_h)=\int d^4x\, e^{-ip\cdot x}\sum_{S-1}\langle 0|\psi(0)|p_h,S-1\rangle\langle p_h,S-1|\bar{\psi}(x)|0\rangle$$

Expressing the meson in terms of constituent quarks

$$|p_h\rangle=\int dx\, dk_\perp\phi(x,k_\perp)|x,k_\perp,1-x,-k_\perp\rangle$$

$$D_q^M(z)=C\int_0^z dz_1 R_M(z_1/z)F_q^{(q\bar{q})}(z_1,z-z_1)$$

$$R_M(x)=|\phi(x)|^2$$



Only works if the wave function is sharply peaked at x = 0.5, k_T=0

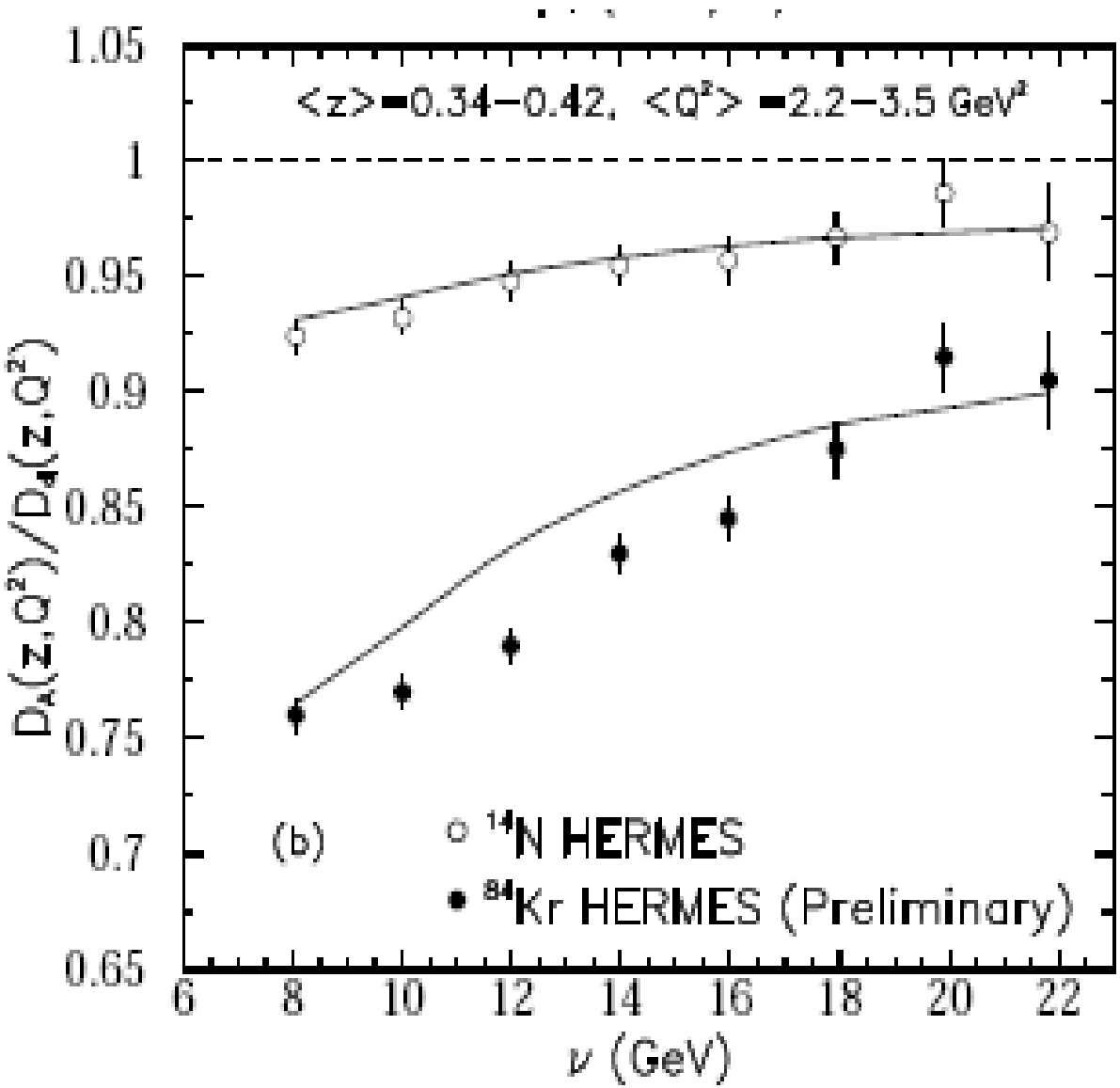
Only then are interference contributions zero!

Can this be checked??

Energy dependence of energy loss

$$p \cdot q = M\,\nu$$

Increasing forward energy of the jet reduces the modification



Ramping up to flat distributions

How to compare
apples with apples ?

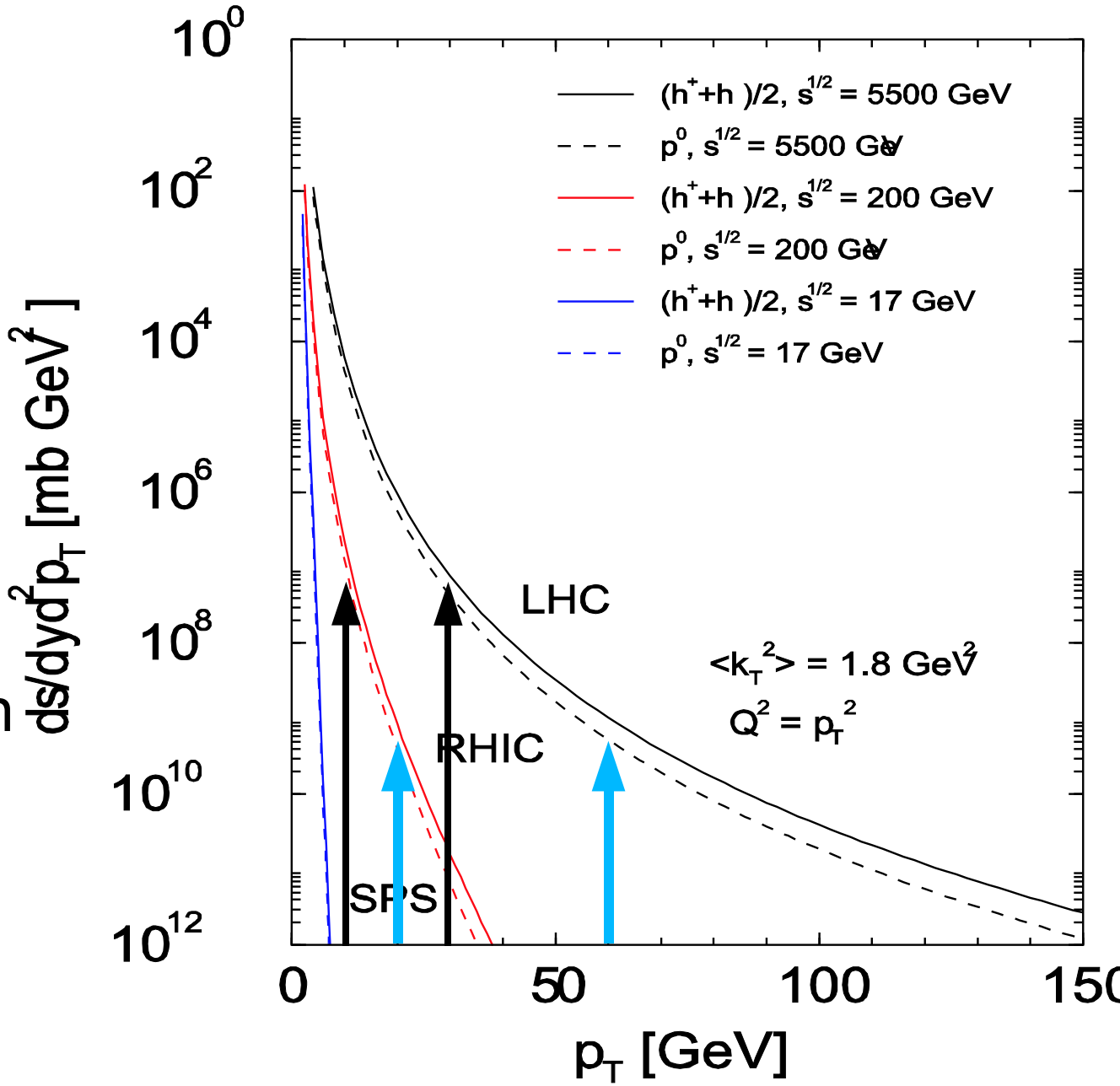
1) Same p_T !

2) Same x_T,
is that possible ??

3) Same cross section
range

10 – 20 GeV RHIC

20 – 60 GeV LHC



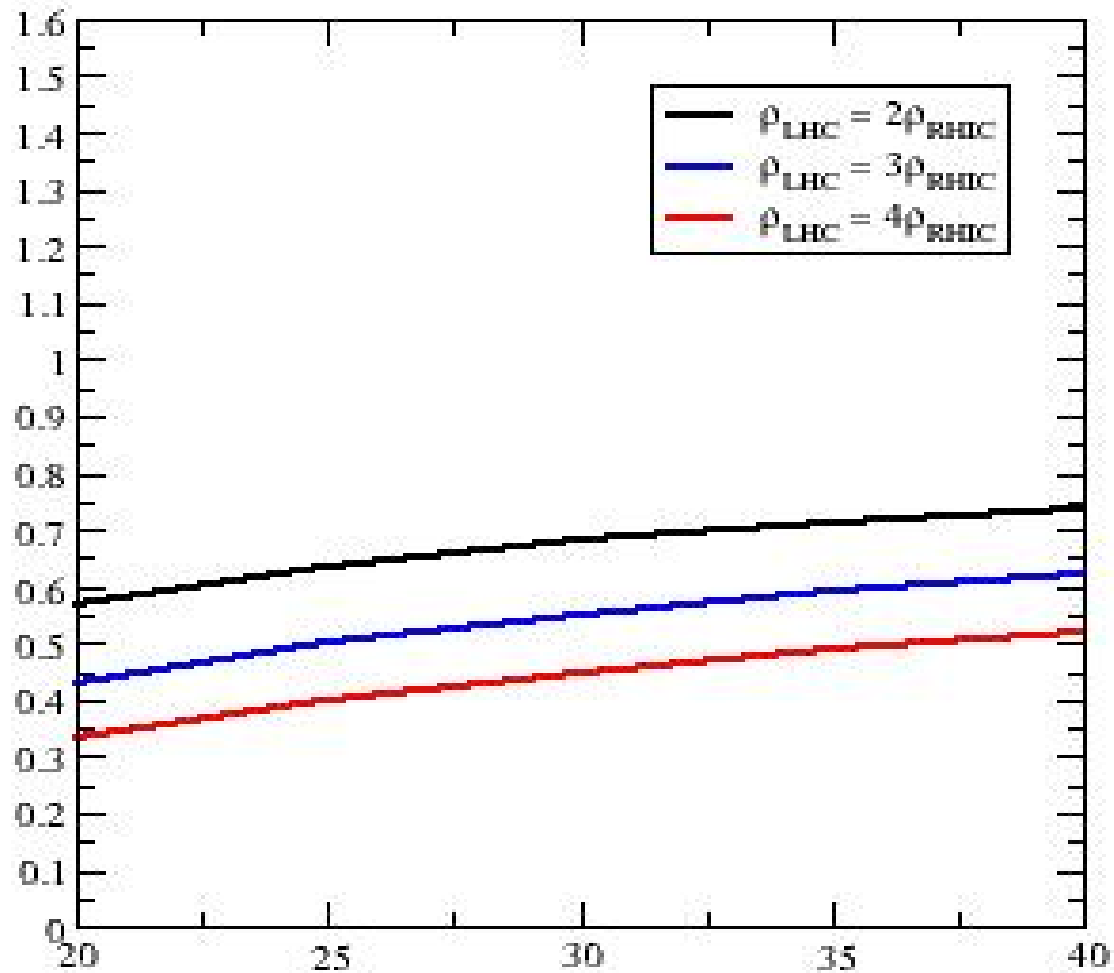
Ramping up to the LHC

At root s = 2TeV

R_AA flat-ish!

No shadowing included

Lower estimate of the density of matter created



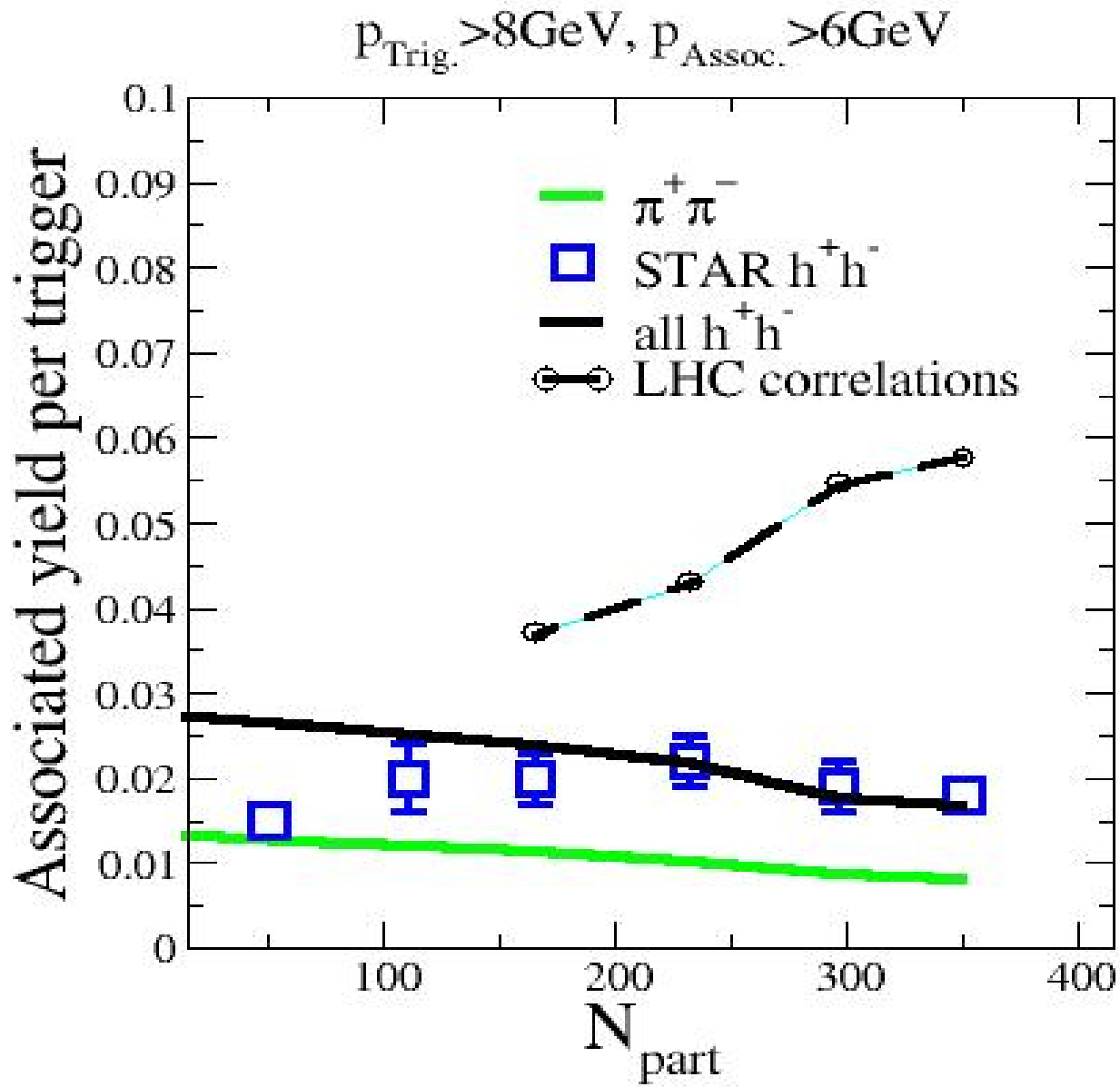
Really really preliminary!

Correlations at LHC !!

for LHC points

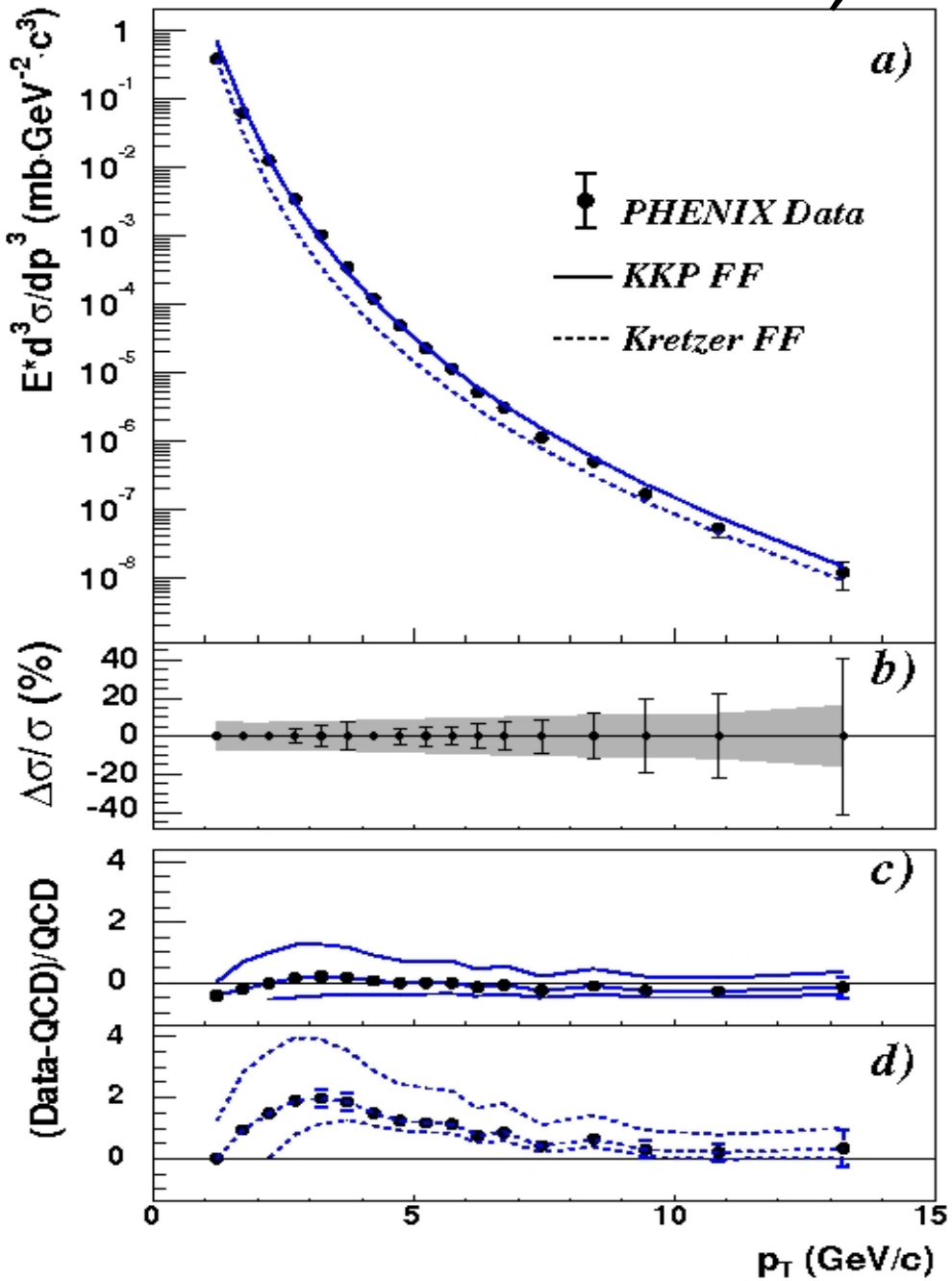
p_tr = 30 – 40 GeV

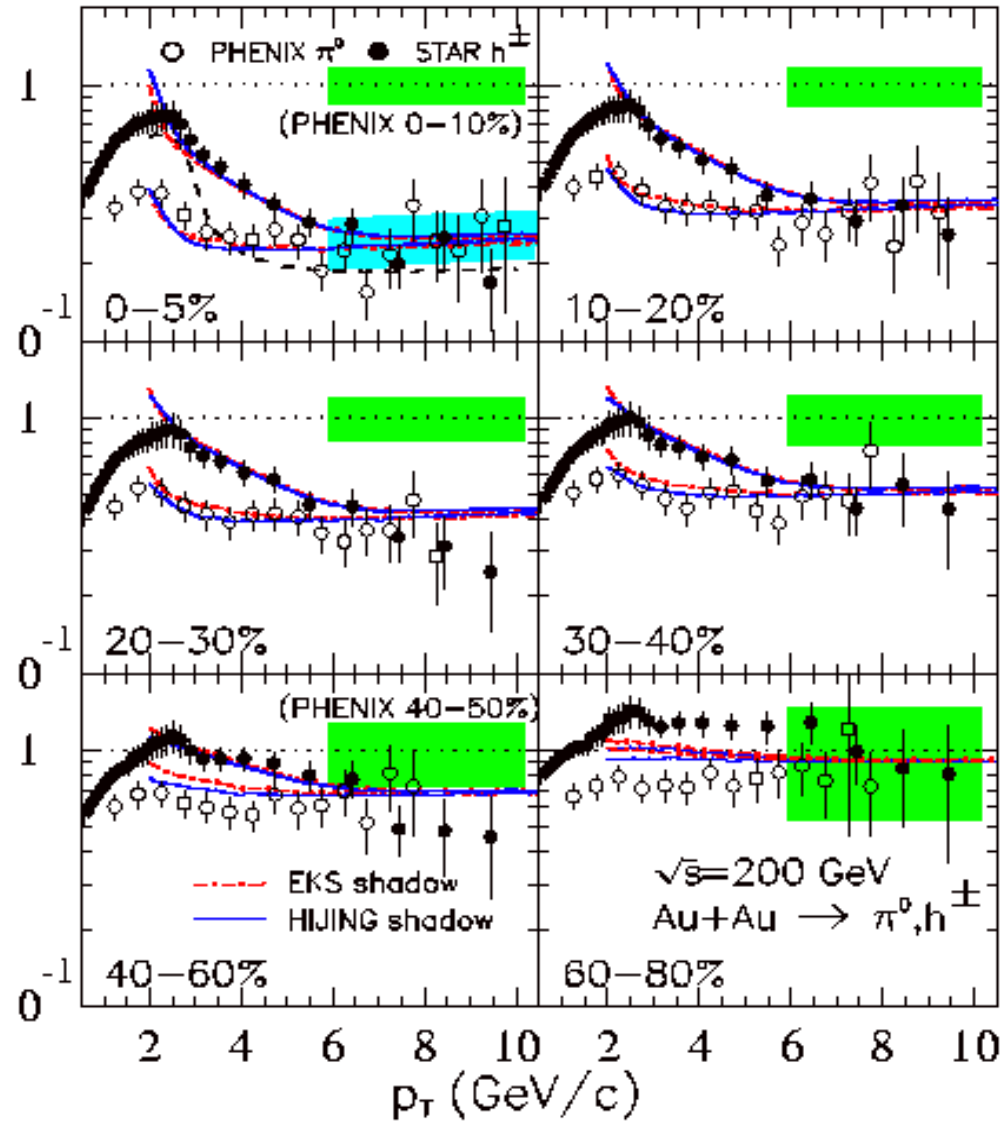
p_as > 20 GeV



Really really preliminary!

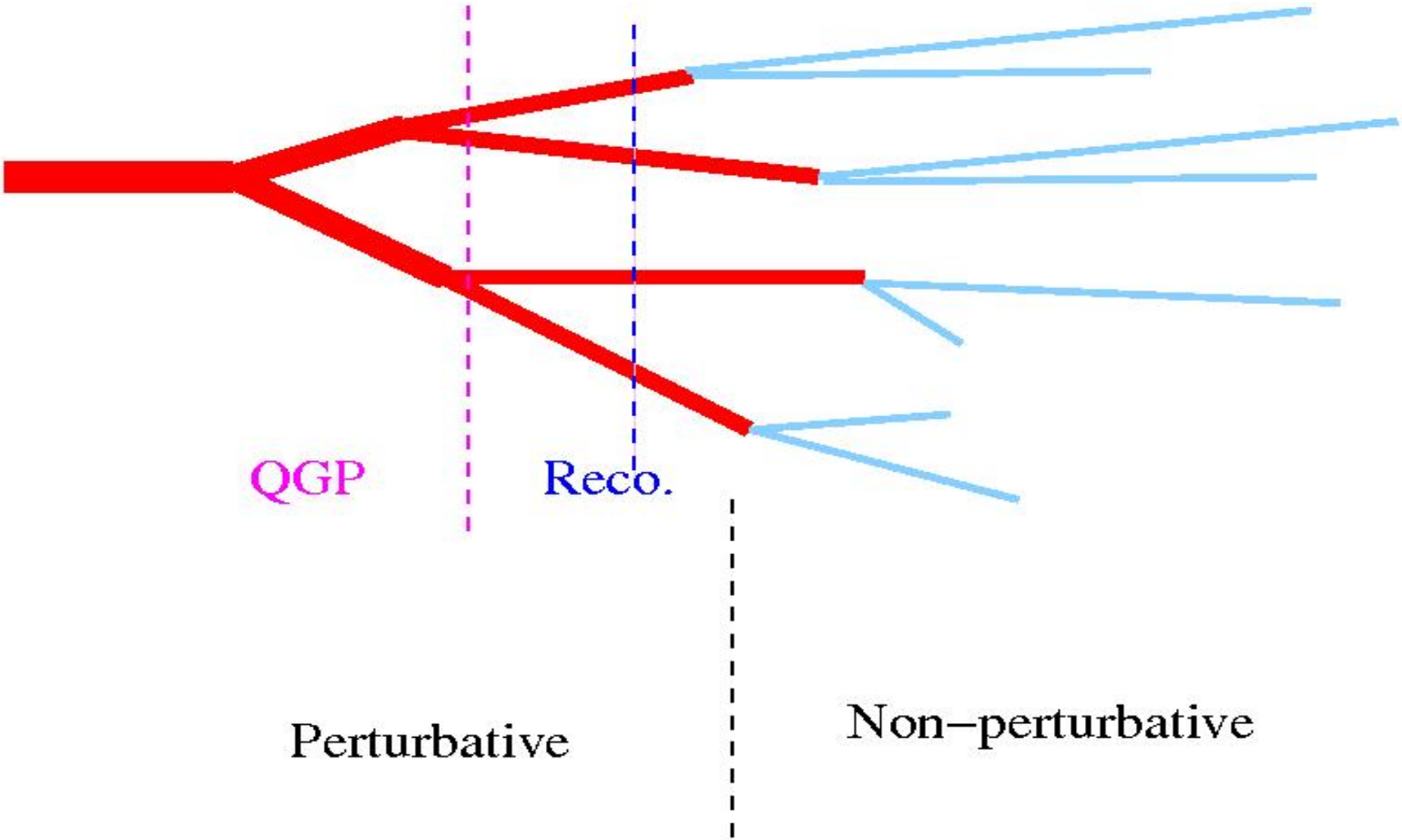
1) and 2)


a)
PHENIX Data
KKP FF
Kretzer FF
$E^*d^3\sigma/dp^3$ (mb·GeV^{-2}·c^3)
b)
$\Delta\sigma/\sigma$ (%)
c)
d)
(Data-QCD)/QCD
p_T (GeV/c)


PHENIX π^0
STAR $h^\pm$
(PHENIX 0−10%)
0−5%
10−20%
20−30%
30−40%
(PHENIX 40−50%)
40−60%
60−80%
EKS shadow
HIJING shadow
$\sqrt{s}$=200 GeV
Au+Au → π^0,$h^\pm$
p_T (GeV/c)

The basic picture behind the formalism

Where the jet fragments relative to the medium influences its outcome!



Why high pT correlations?

1) Very noticeable modifications at RHIC

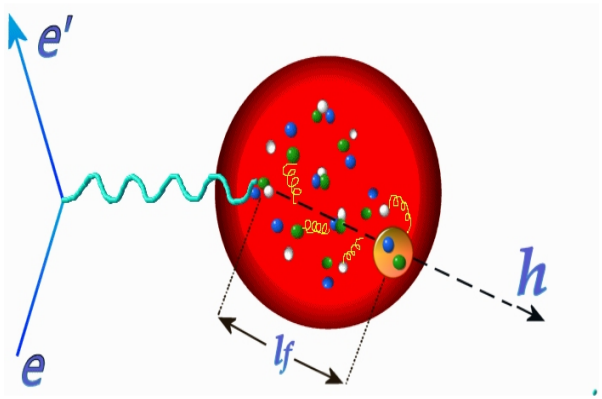
2) A lot of handles available: angle, rapidity, flavor, energy, spin?!

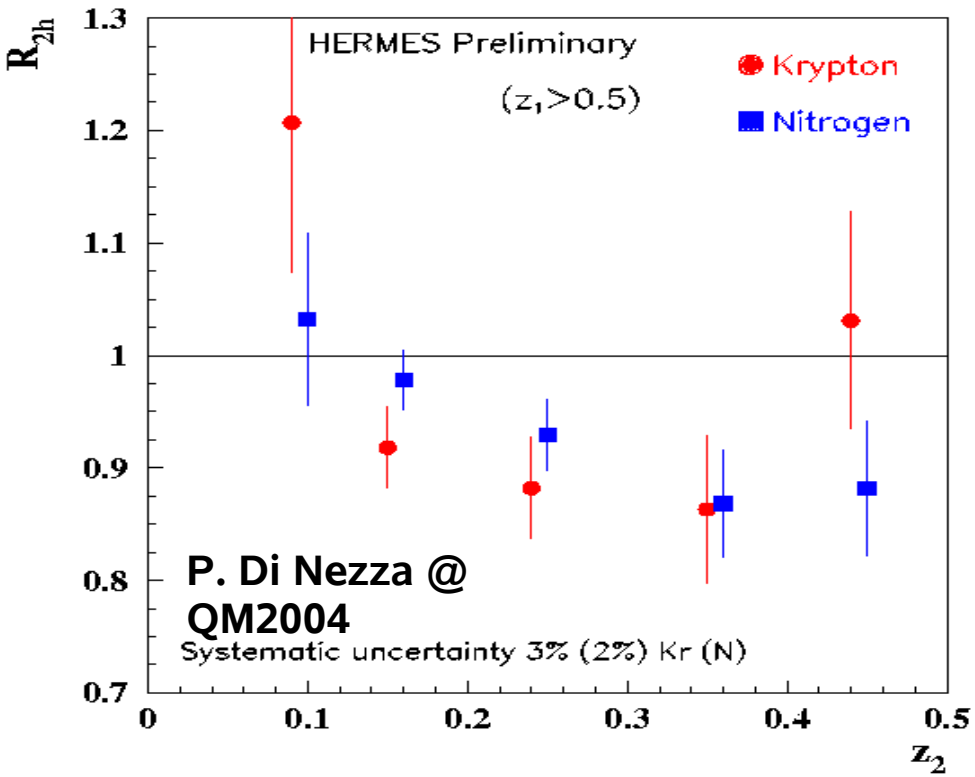
3) At large enough Q^2, should be computable from first principles

4) More differential observables better test of assumptions in calculations and models of QGP!

5) May allow for direct measurement of fundamental properties of the QGP, c_s, n !!

Analogue of near side in cold matter: DIS on nuclei





- R_{2h} is like I_{AA} :
- replace p with D
- replace p_T with z_ν

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

$$\text{same ratio on deuterium}$$