Probing hot and dense matter through high pT particle production and correlations

A. Majumder

Why jets and jet correlations?

1) Production well calibrated in vacuum

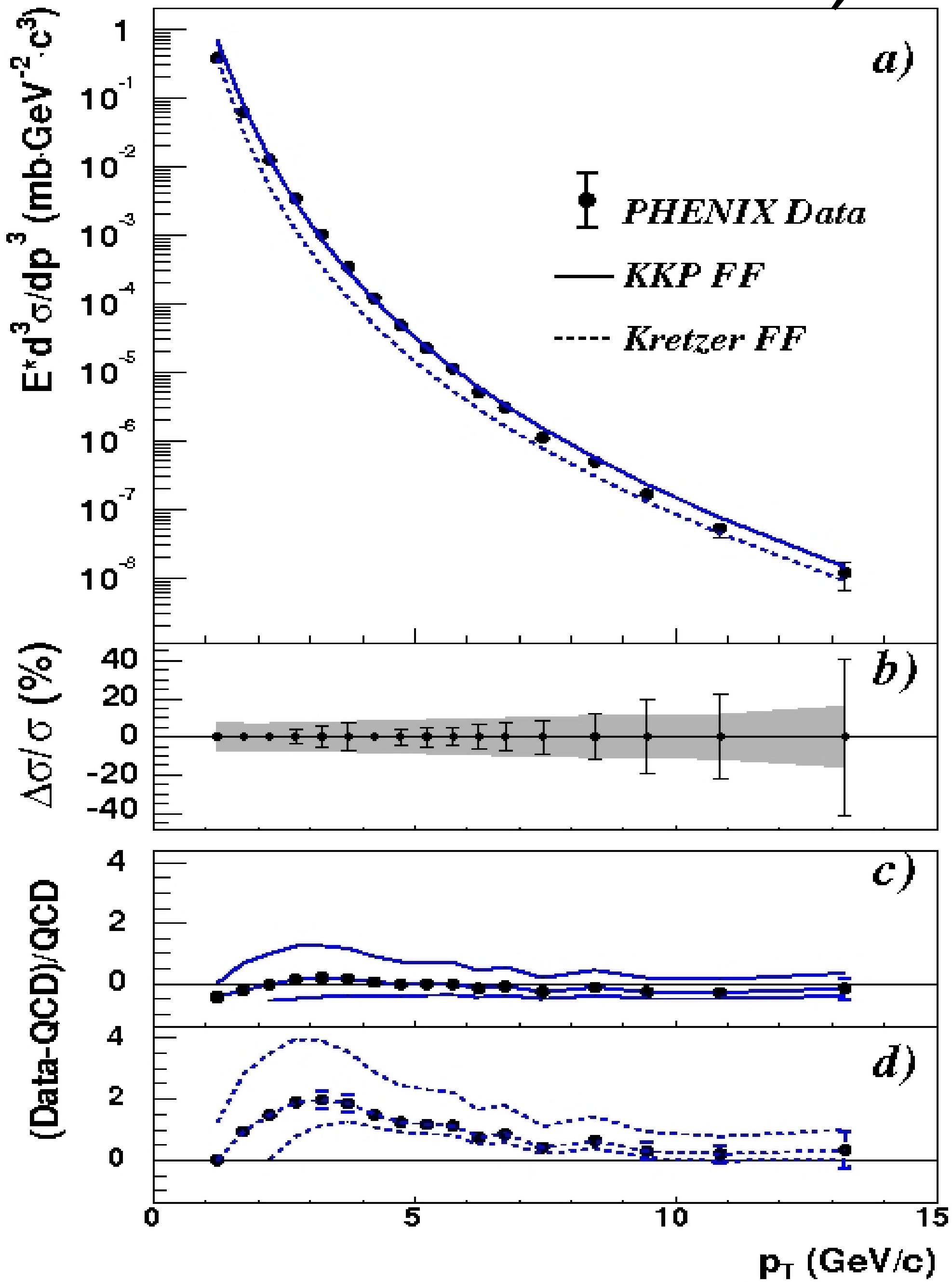
2) Very noticeable modifications at RHIC

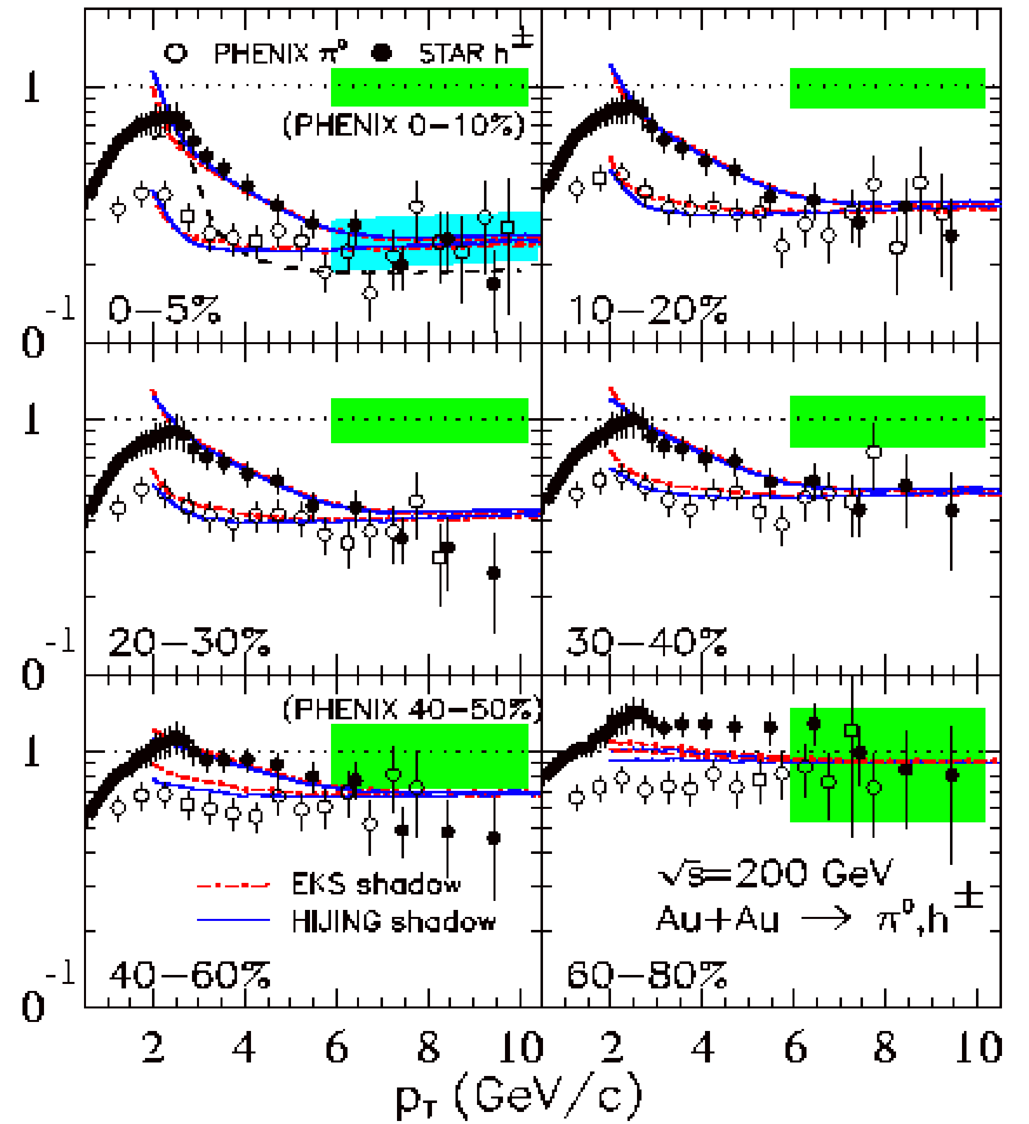
3) A lot of handles available: angle, rapidity, flavor, energy, spin?!

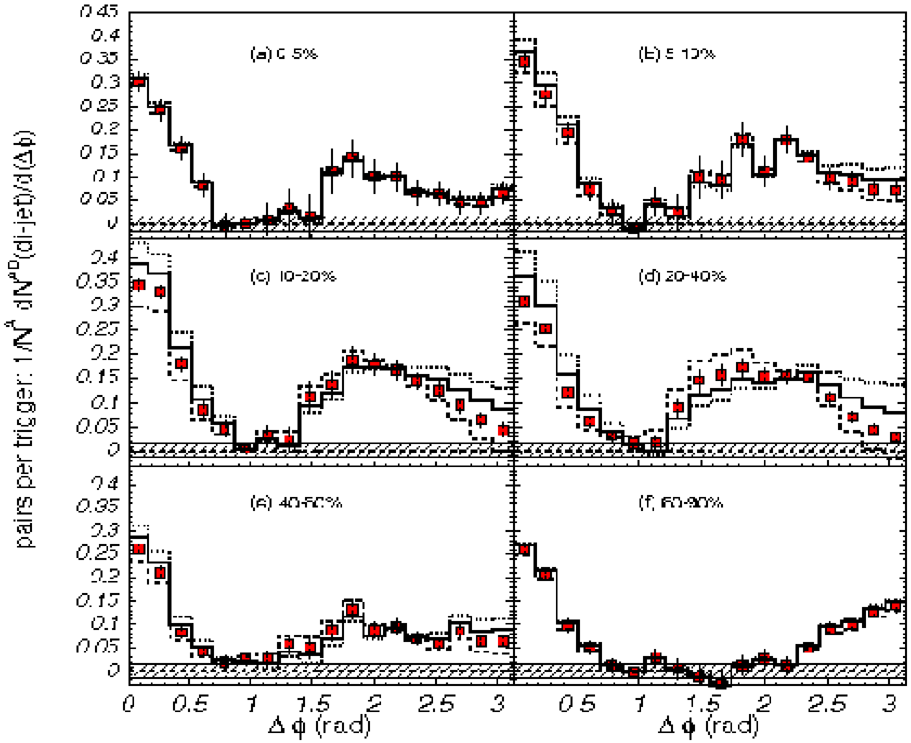
4) At large enough Q^2, should be computable from first principles

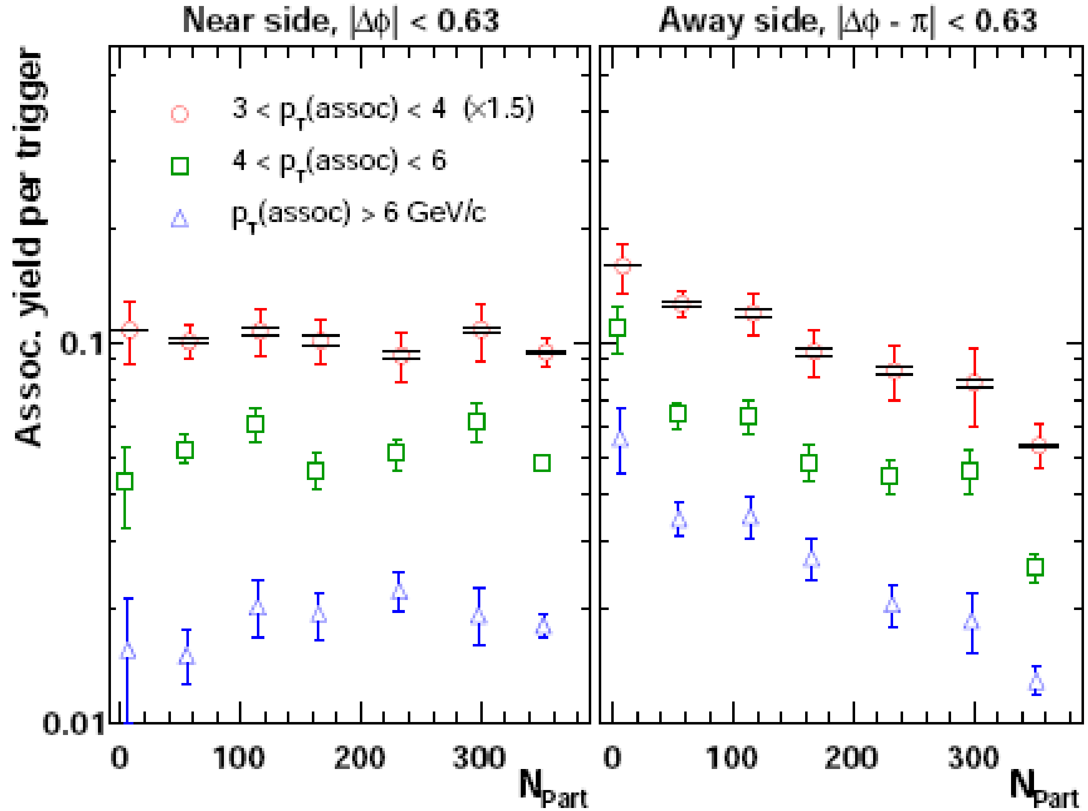
5) More differential observables better test of assumptions in calculations

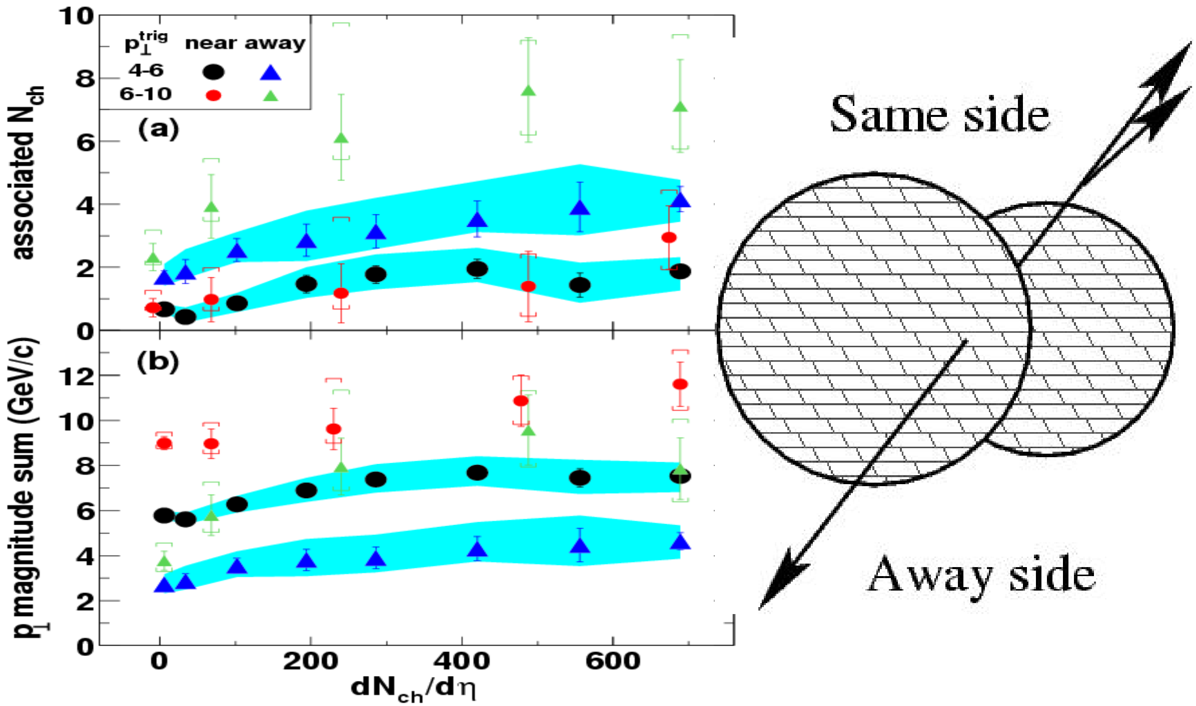
1) and 2)

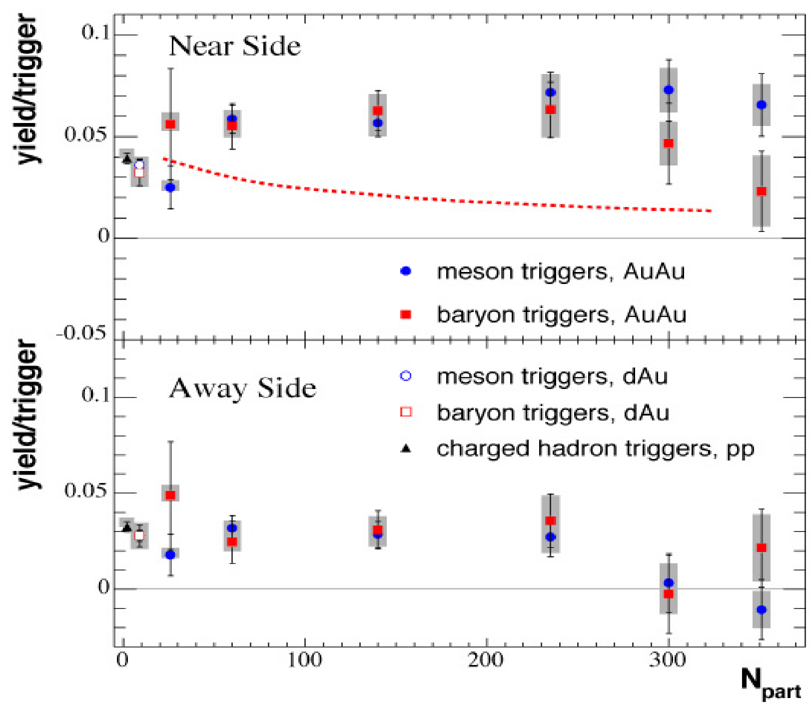

a)
b)
c)
d)
PHENIX Data
KKP FF
Kretzer FF
E*d³σ/dp³ (mb·GeV⁻²·c³)
Δσ/σ (%)
(Data-QCD)/QCD
p_T (GeV/c)


PHENIX π⁰
STAR h±
(PHENIX 0-10%)
(PHENIX 40-50%)
0-5%
10-20%
20-30%
30-40%
40-60%
60-80%
EKS shadow
HIJING shadow
√s=200 GeV
Au+Au → π⁰,h±
p_T (GeV/c)


(a) 0-5%
(b) 5-10%
(c) 10-20%
(d) 20-40%
(e) 40-60%
(f) 60-90%
pairs per trigger: 1/N^A dN^AB(di-jet)/d(Δφ)
Δφ (rad)

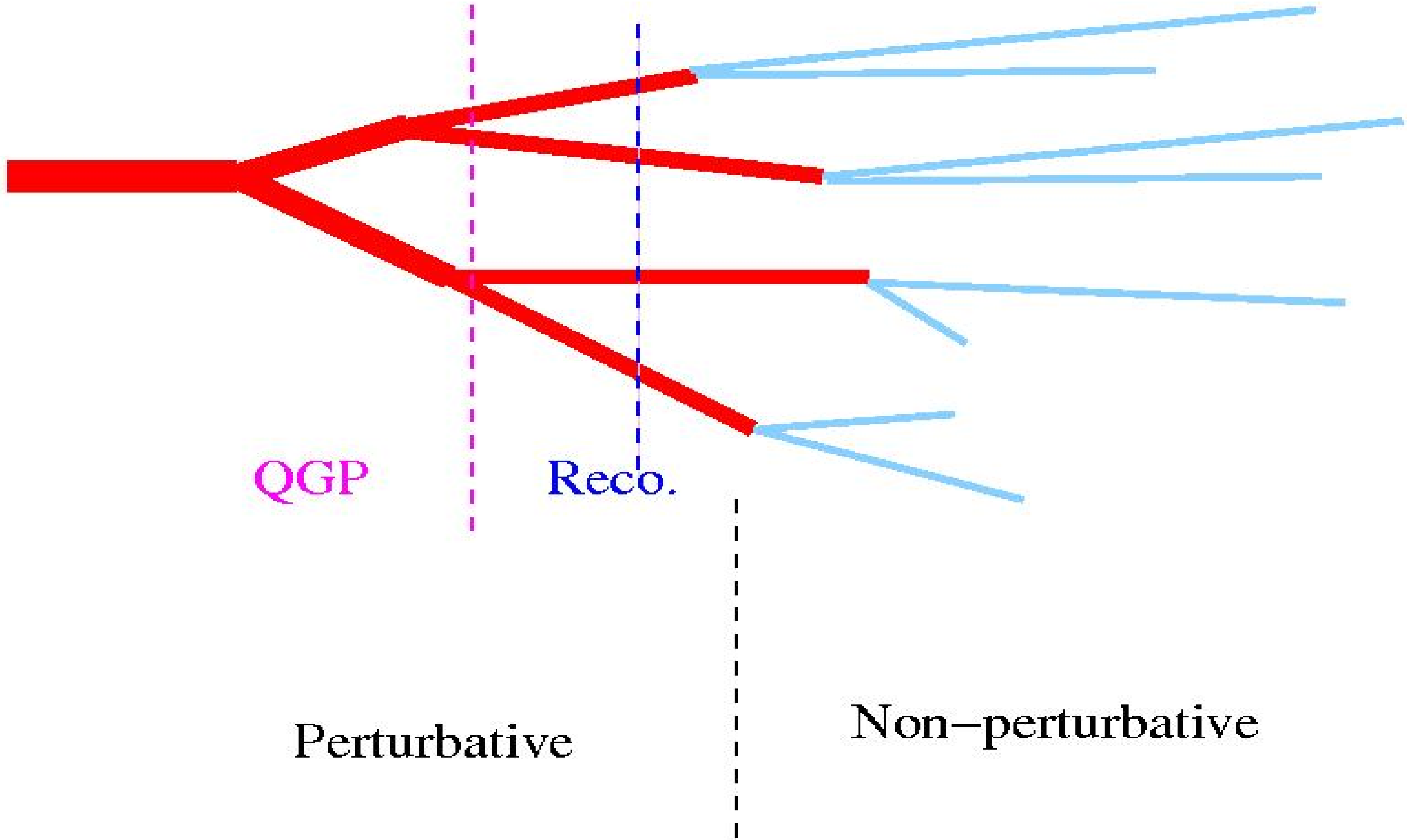

Near side, |Δφ| < 0.63
Away side, |Δφ - π| < 0.63
Assoc. yield per trigger
3 < p_T(assoc) < 4 (×1.5)
4 < p_T(assoc) < 6
p_T(assoc) > 6 GeV/c
N_Part


p_⊥^trig near away
4-6
6-10
(a)
(b)
associated N_ch
p_⊥ magnitude sum (GeV/c)
dN_ch/dη
Same side
Away side


Near Side
Away Side
yield/trigger
meson triggers, AuAu
baryon triggers, AuAu
meson triggers, dAu
baryon triggers, dAu
charged hadron triggers, pp
N_part

The basic picture behind the formalism

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



Which jet correlations and why?

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

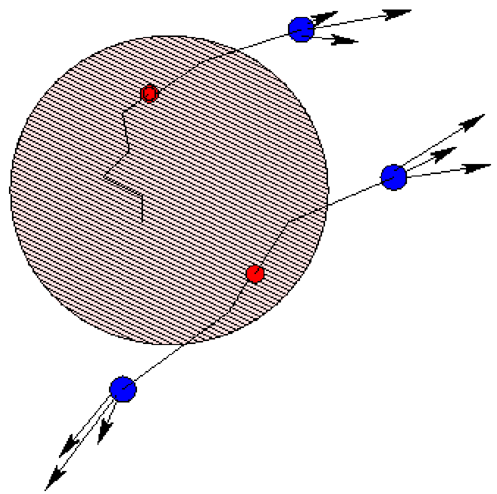
provides constraints on the over-all gluon density which also determines R_{AA}.
Check on consistency of calculations

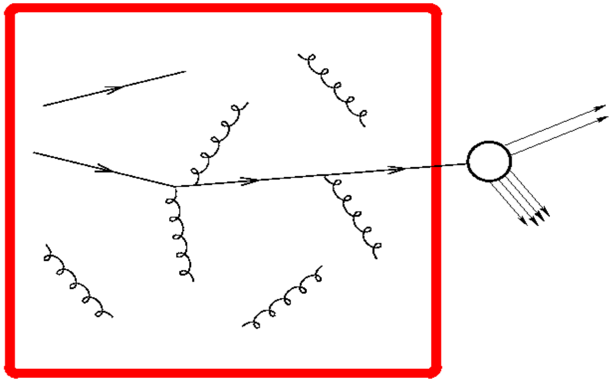
2) Away side Jet correlations at low pT:

select events which lead to complete extinction of the away side jet. Radiation may excite resonances in matter.

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





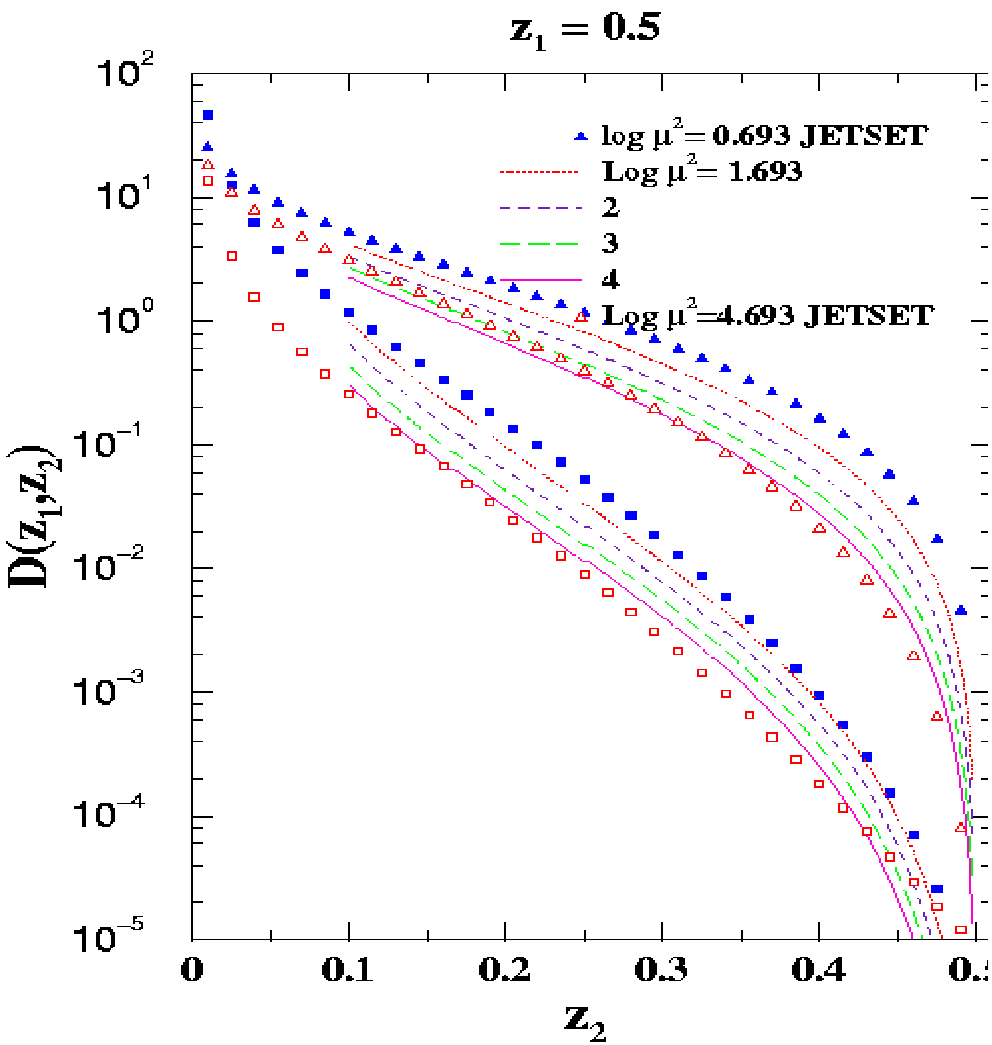
- ***Lose energy by partonic interaction, medium may be hadronic or partonic***
- ***Emerge as partons and then fragment***
- ***Require knowledge of single and double fragmentation functions***

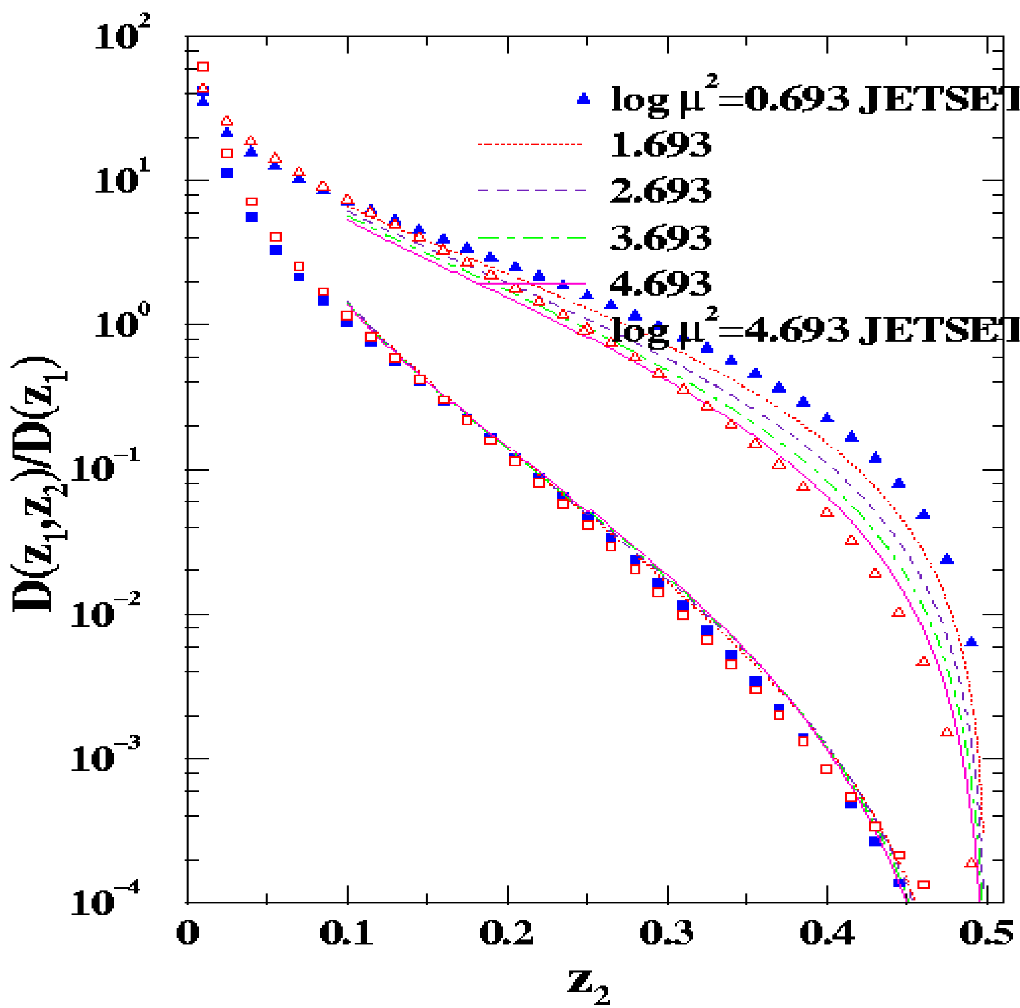
$$D^{h}_{q,g}(z)$$

$$D_q^{h_1 h_2}(z_1, z_2)$$

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

Convolutes differently with the initial parton cross section





What one calculates essentially are the two cross-sections

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

$$\int dp_{T_2} \frac{d\sigma^{h_1,h_2}}{dy\,dp_{T_1} dp_{T_2}} \sim \int dz_2 dx_a dx_b G(x_a) G(x_b) \frac{d\hat{\sigma}}{d\hat{t}} D_q^{h_1 h_2}(z_1, z_2)$$

in pp and in AA collisions

The main difference is in the fragmentation functions

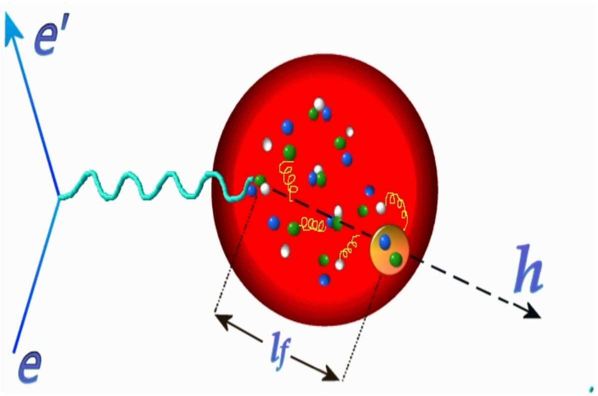
$$D^{AA} = D + \Delta D(medium)$$

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

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).

- ***The calculation of the double is now in lock-step with the calculation of the single… hard part is the same***

- ***Multiple higher twist diagrams need to be evaluated***



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***

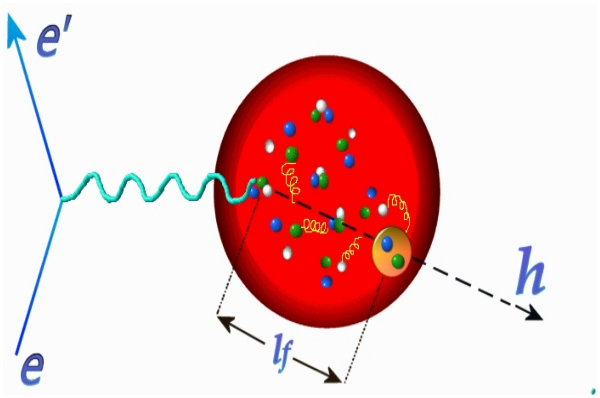
R_A ***= Nuclear size***

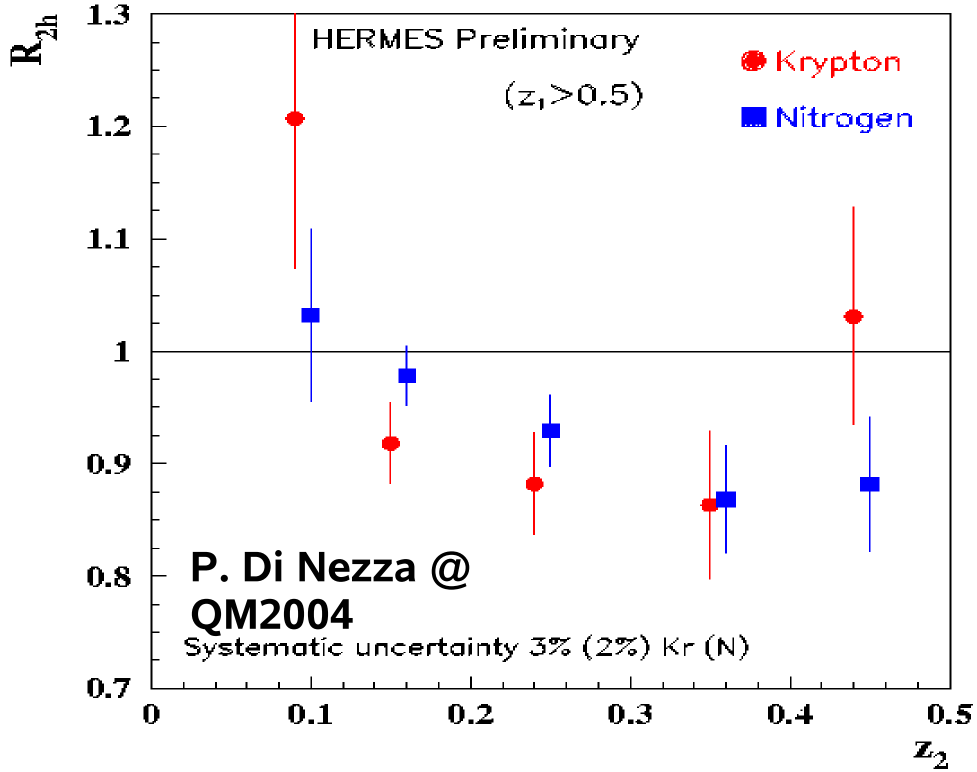
γ ***= boost***

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

Analogue of near side in cold matter: DIS on nuclei

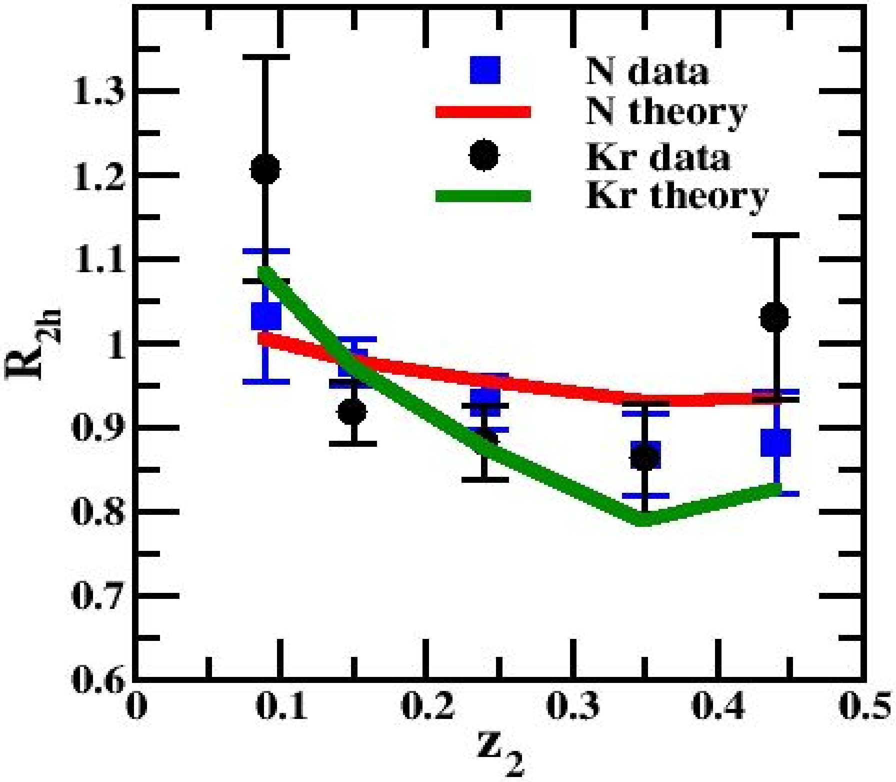


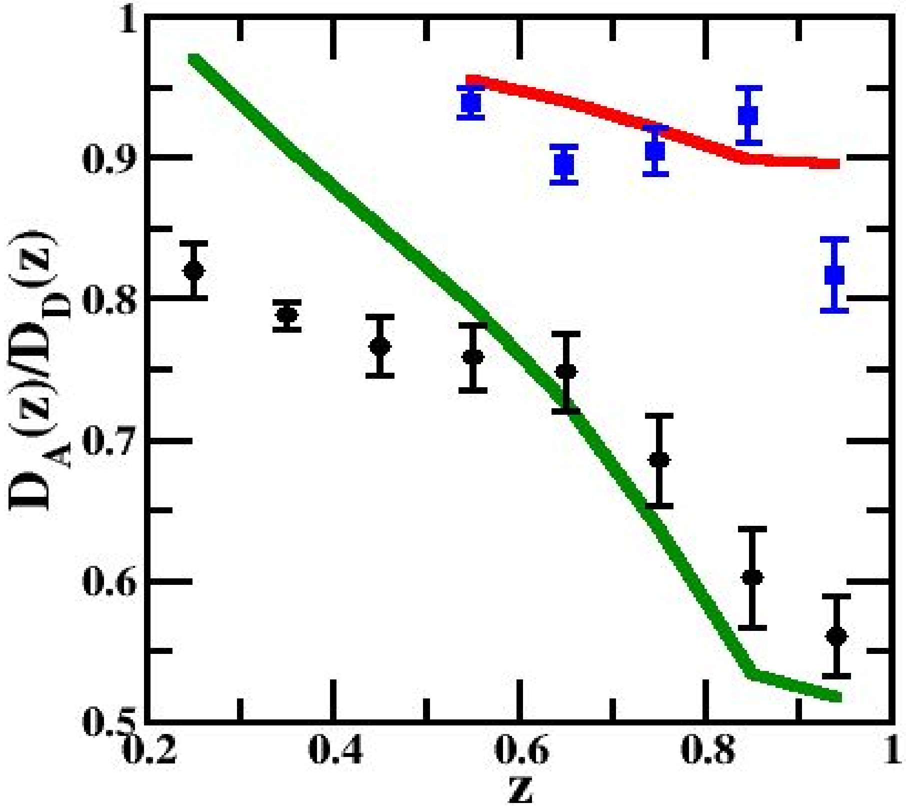


- ***R_{2h} is like I_{AA} :***
- ***replace p with D***
- ***replace p_T with $z\nu$***

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

- *Note the drop with N_part*
- *ν is measured, initial parton energy known (No triggering!)*



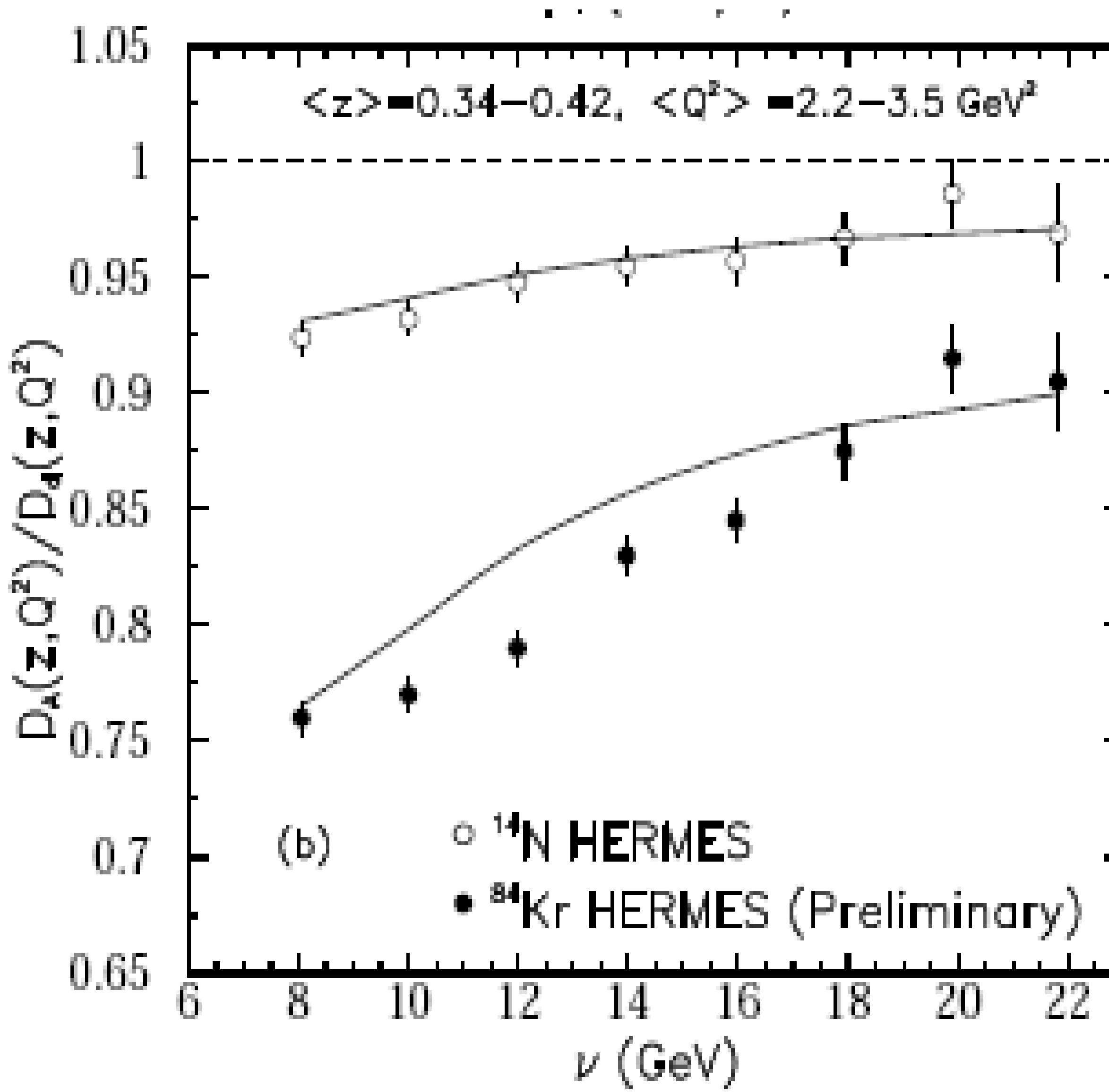


Dividing by the single inclusive takes out a lot of the suppression

Energy dependence of energy loss

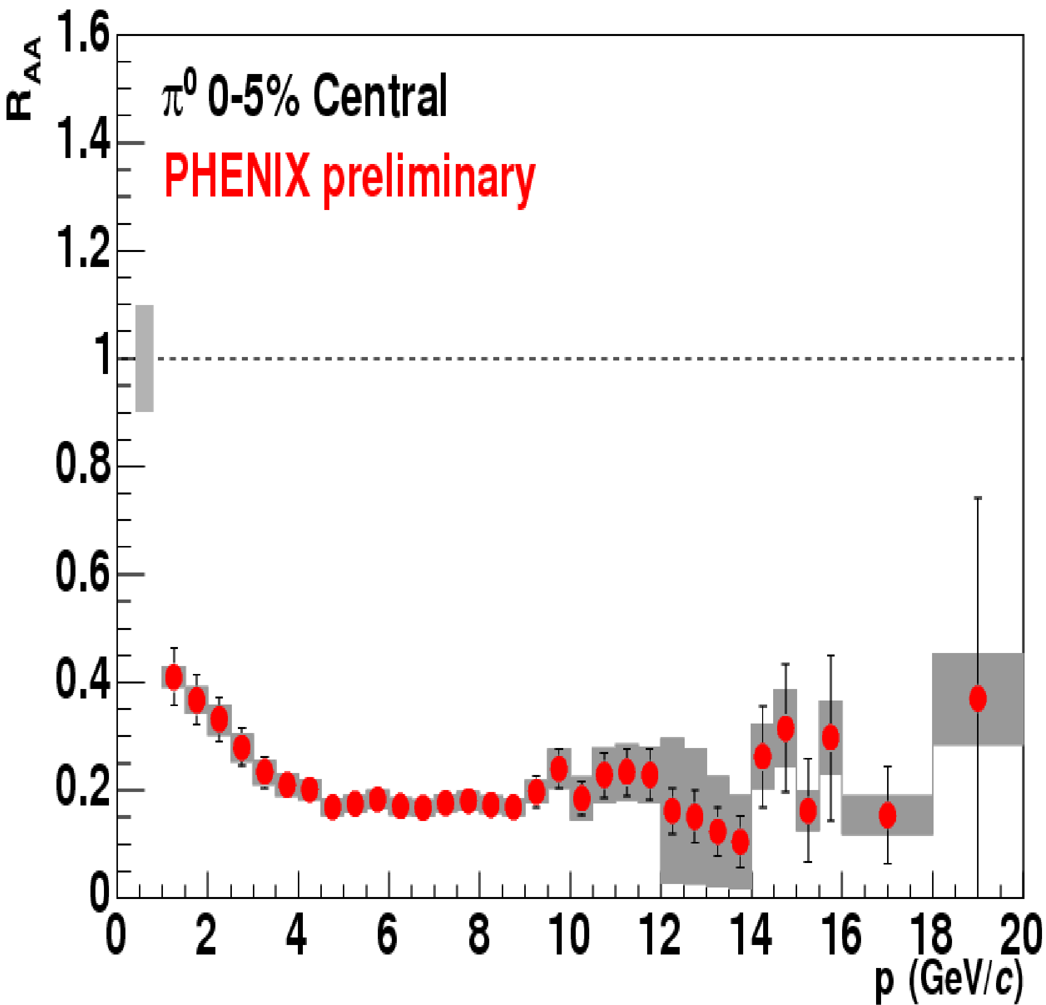
$$p \cdot q = M\,\nu$$

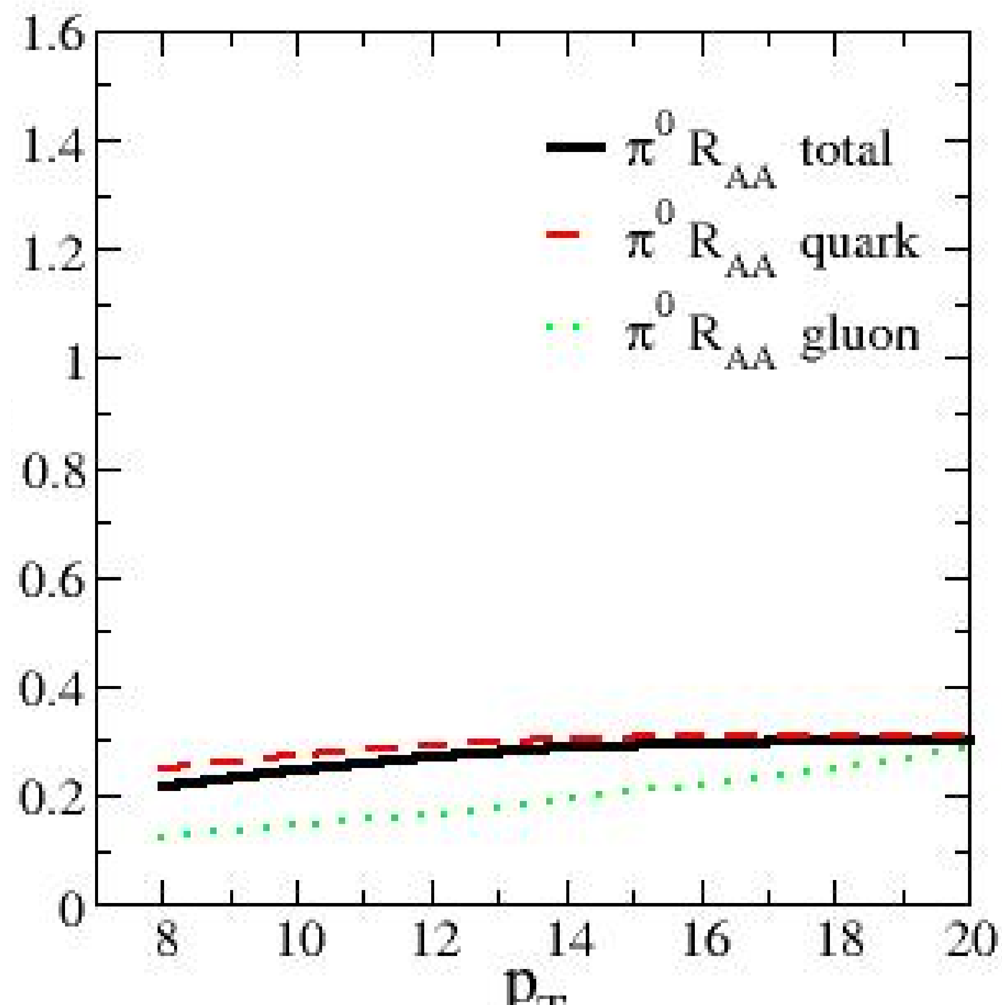
Increasing forward energy of the jet reduces the modification



Getting the single inclusive RAA...

To keep it simple, calculations will not include Cronin effect
also no recombination, so cant go below 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.

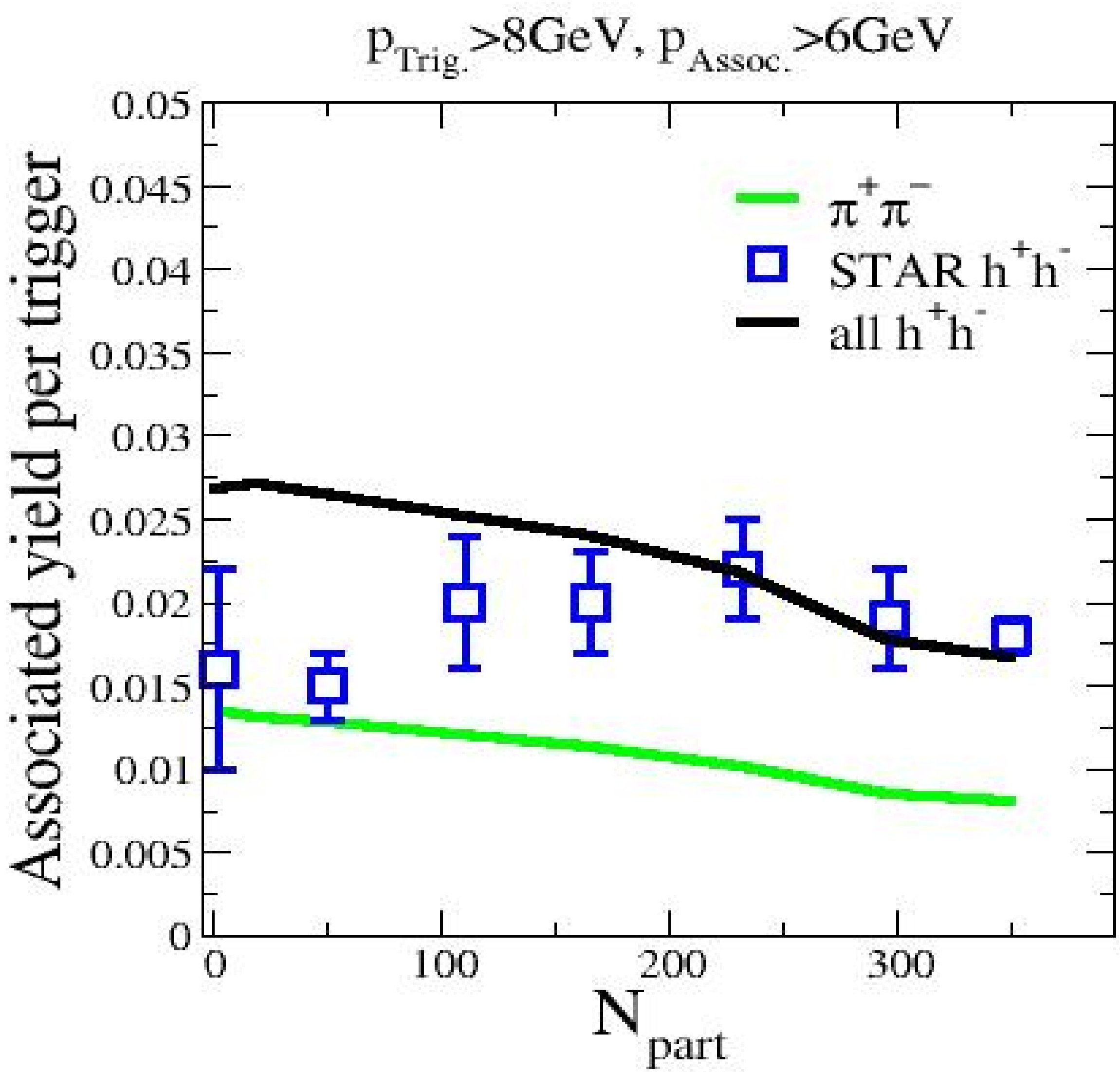
In R_{AA} the same number goes in both numerator and denominator

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

Trigger is at 8-15 GeV and Associated is 6GeV to trigger

Calculation includes all hadrons,

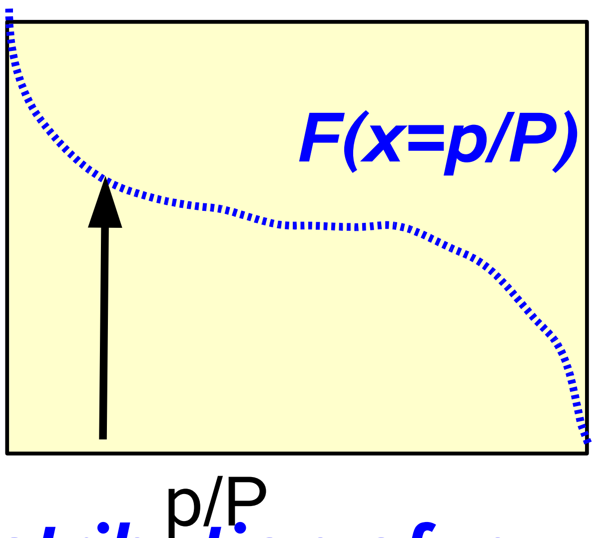
no correction for decays included.



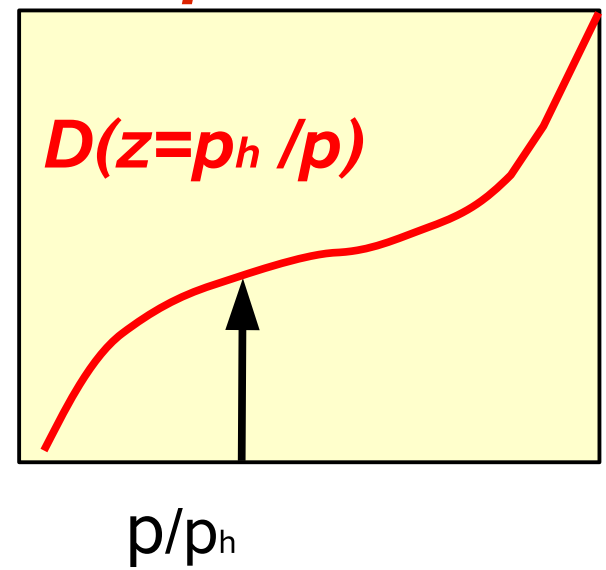
Very preliminary!

Asking questions about the medium

For a given p , there is a distribution of p

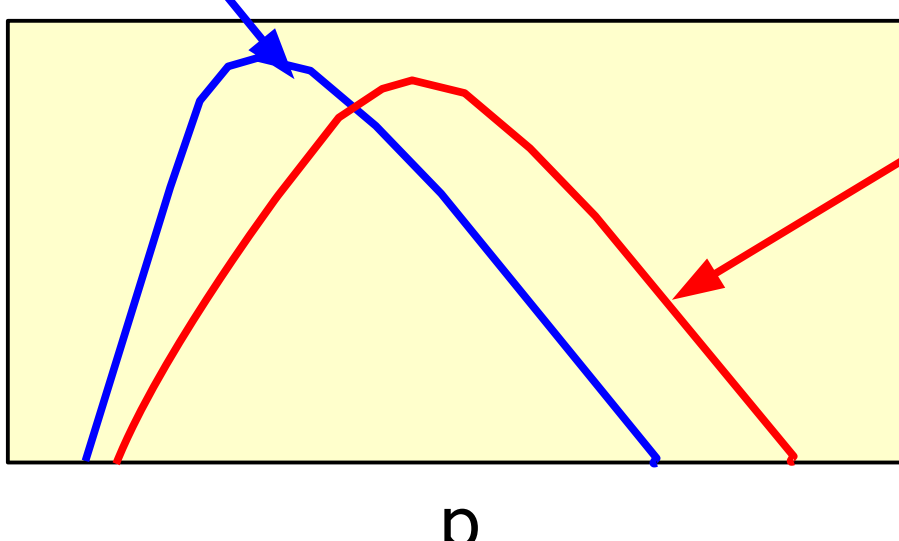


$* \quad \sigma(p+q) \quad *$



Distribution of p without E-Loss

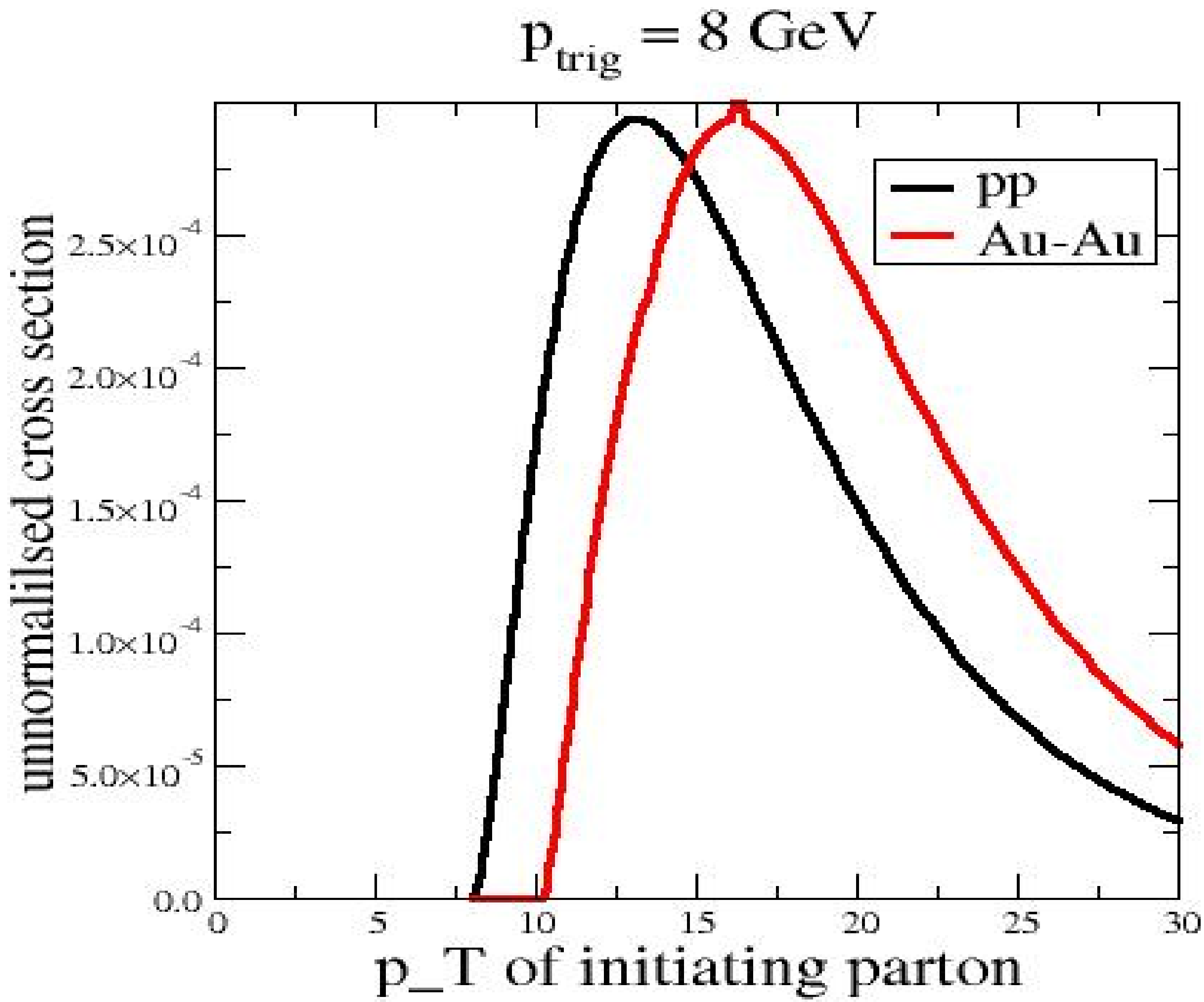
Distribution of p with E-Loss



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

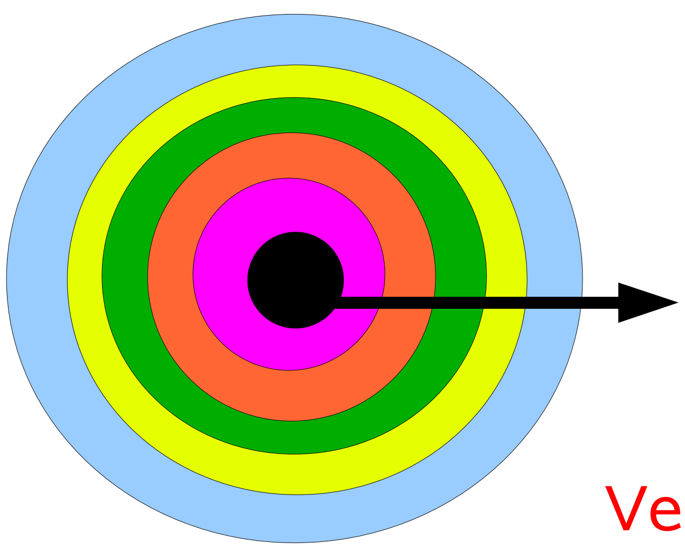


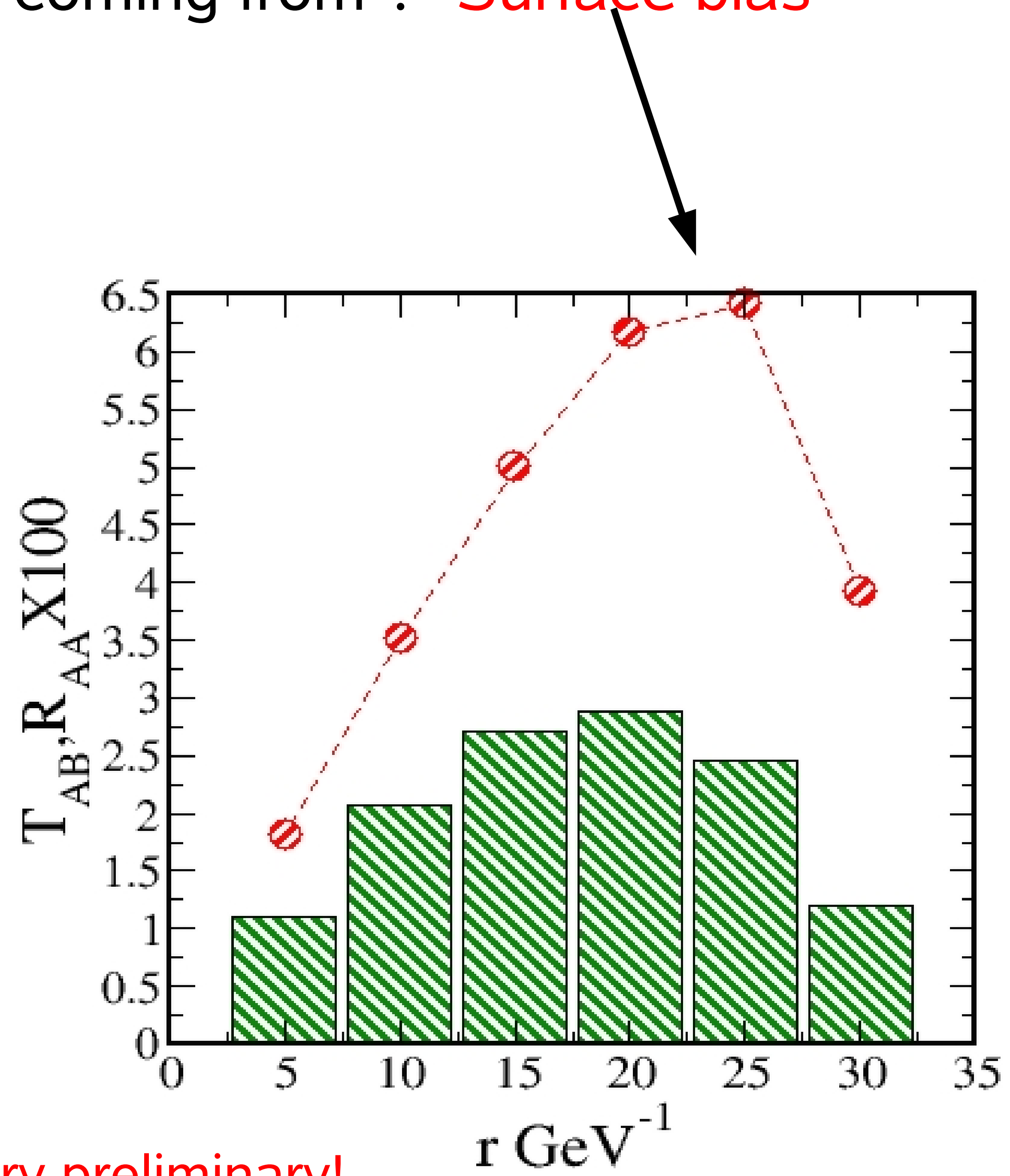
Very preliminary!

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!

Ramping up to flat distributions

How to compare apples with apples ?

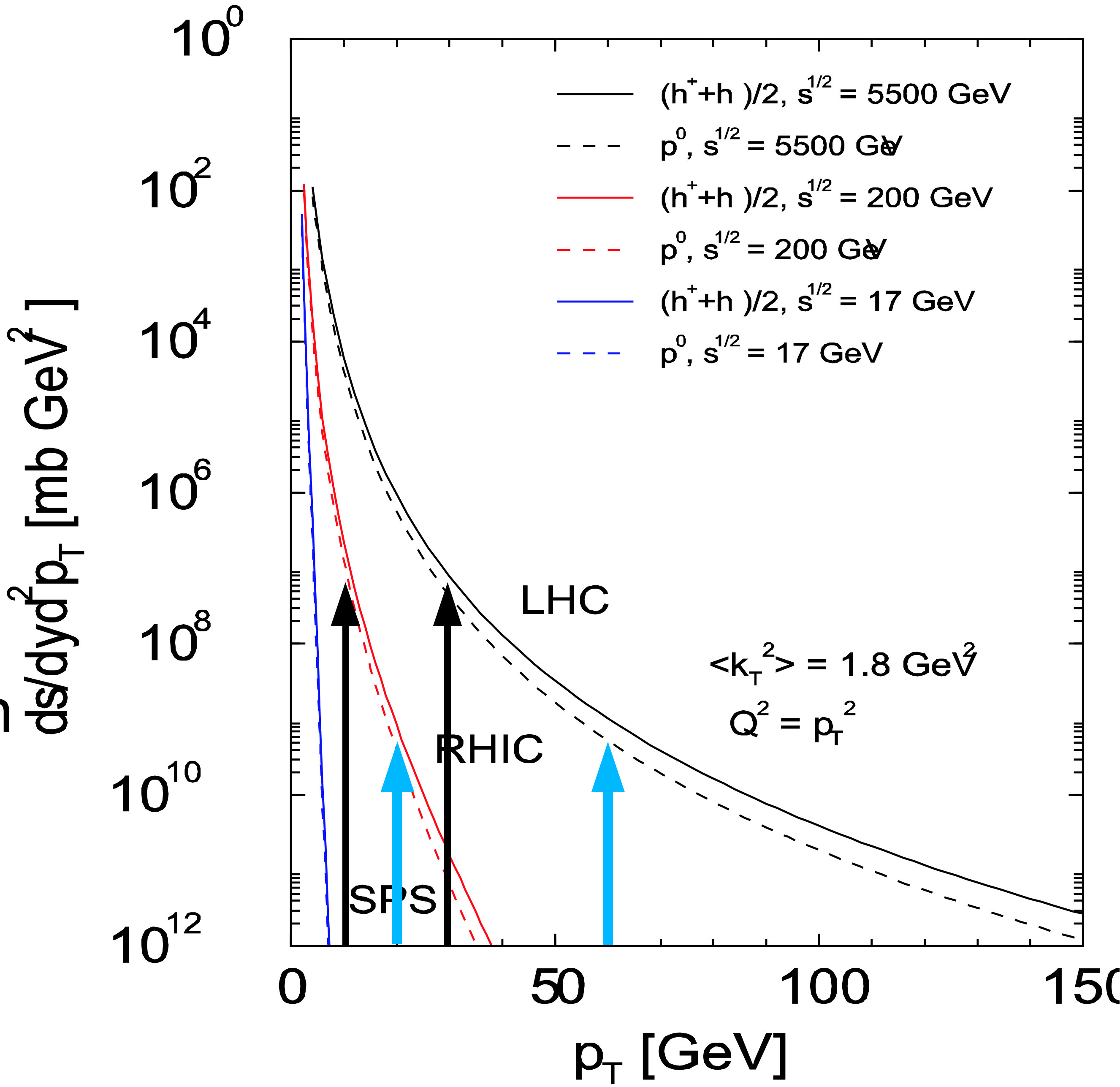
1) Same p_T !

2) Same x_T,
is that possible ??

3) Same cross section range

10 – 20 GeV RHIC

20 – 60 GeV LHC



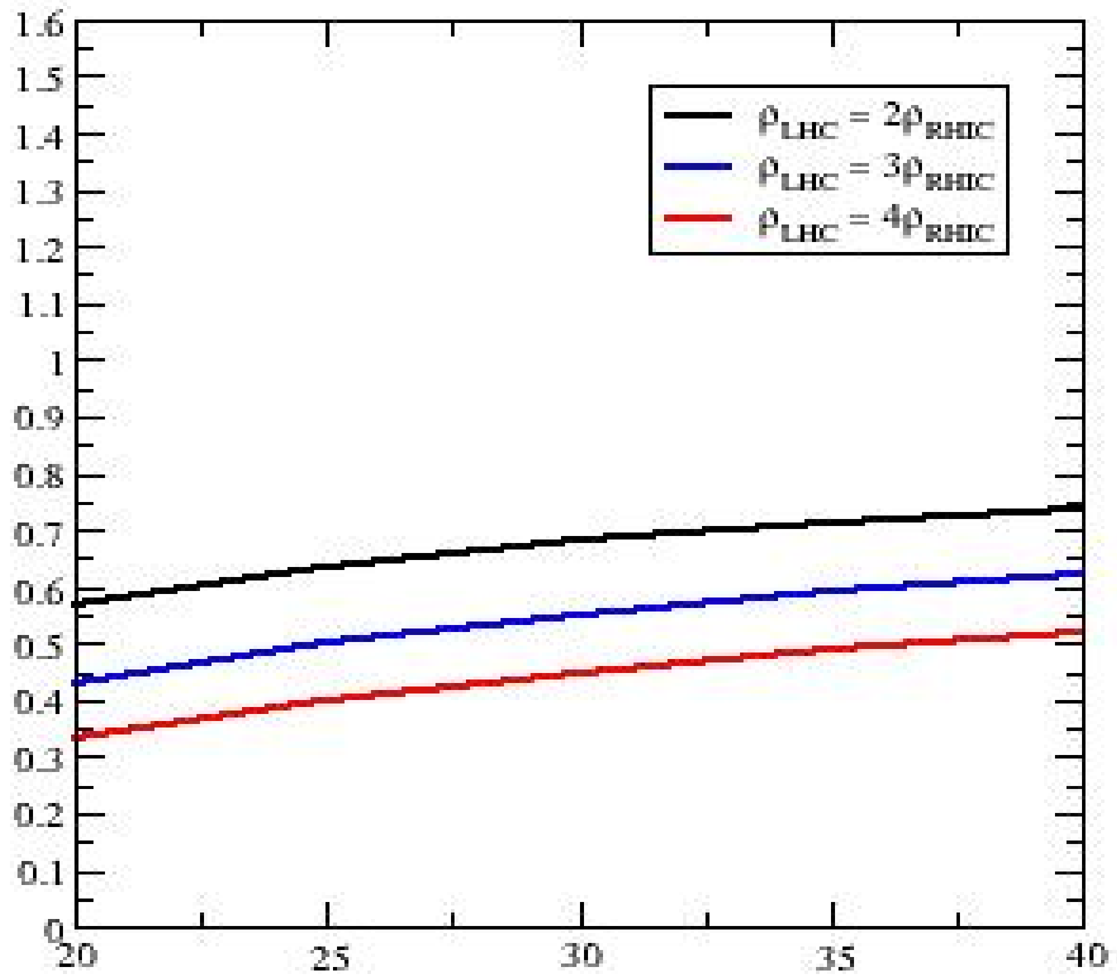
Ramping up to the LHC

At root s = 2TeV

R_AA flat-ish!

No shadowing included

Lower estimate of the density of matter created



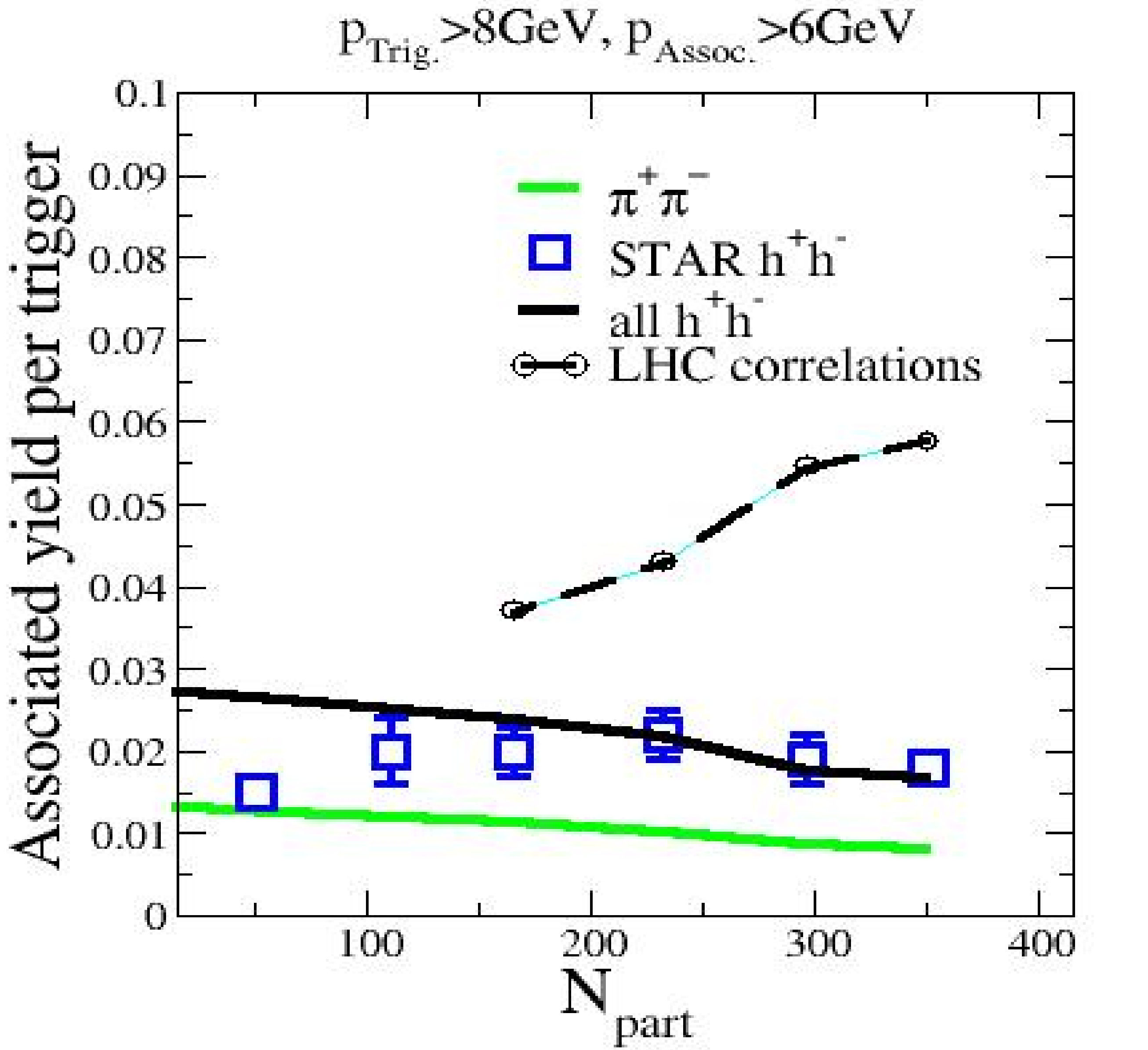
Really really preliminary!

Correlations at LHC !!

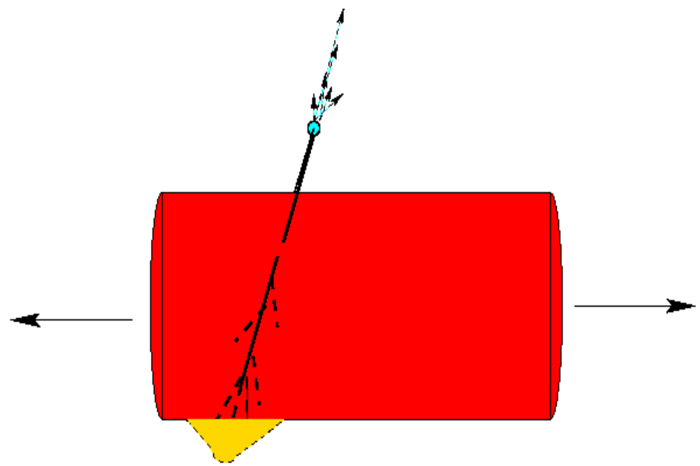
for LHC points

p_tr = 30 – 40 GeV

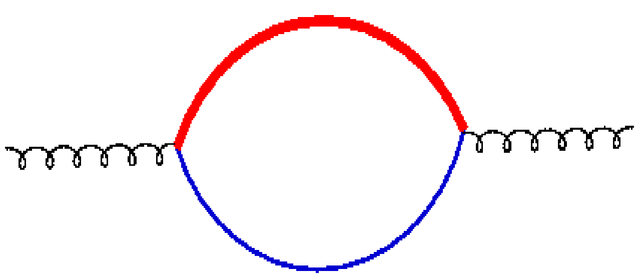
p_as > 20 GeV



Going to very low pT on the away side,
complete jet extinction!



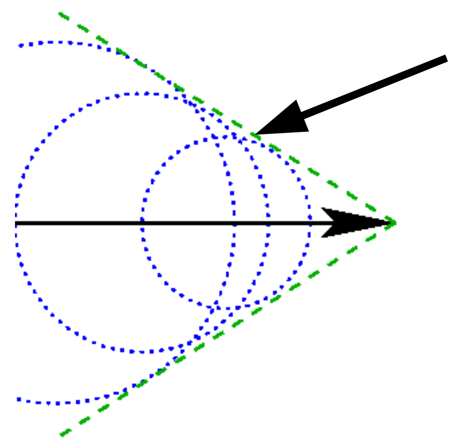
- ***Away side partons travel through a lot more matter***
- ***Jet can excite collective modes of dense matter!***
- ***If the s-QGP has heavy colored (bound) states***
- ***Soft gluons effect transitions between these states***



- *Gluon dispersion relation will be modified*
- *Large mass diff.* → *space-like dispersion*
- *Space-like dispersion* → *large ε* → *Cherenkov radiation*

To get Cherenkov radiation:

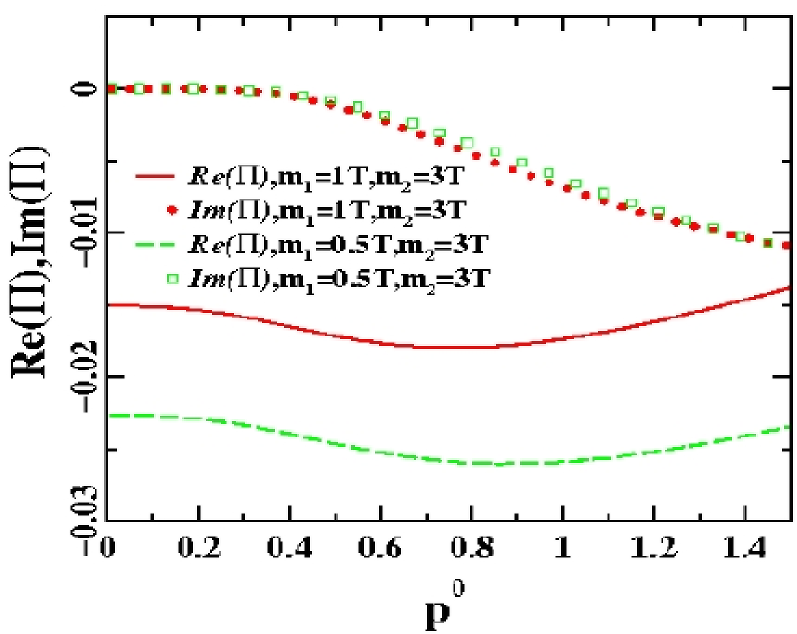
$$A(x,t) \sim \exp\left(ip\left(x - \frac{p^0(p)}{p}t\right)\right)$$

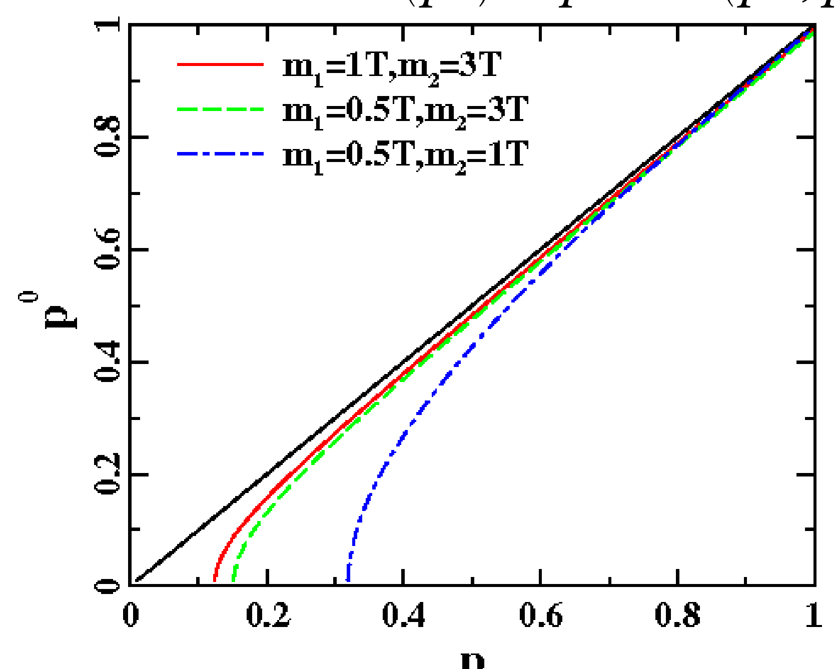


$$v = \frac{1}{\sqrt{\epsilon}} = \frac{p^0}{p} < 1$$

In the medium, solve dispersion relation

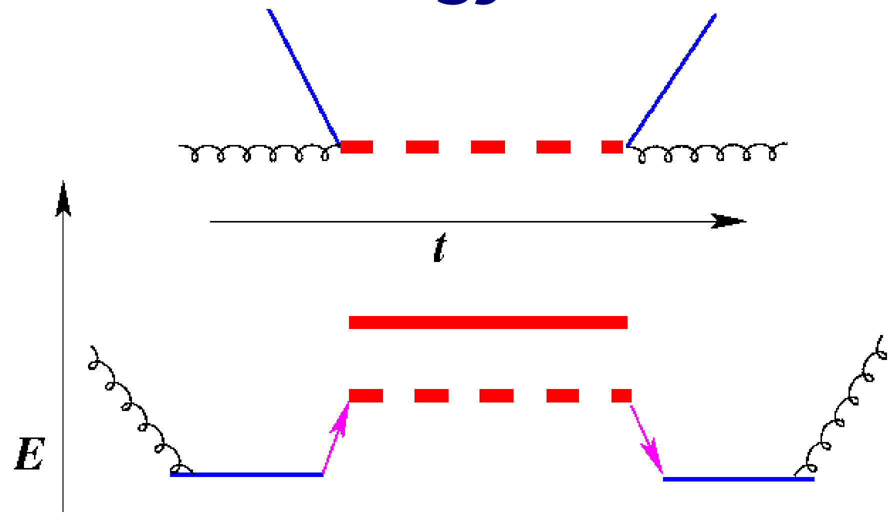
$$(p^0)^2 - p^2 = \Pi(p^0, p, T)$$





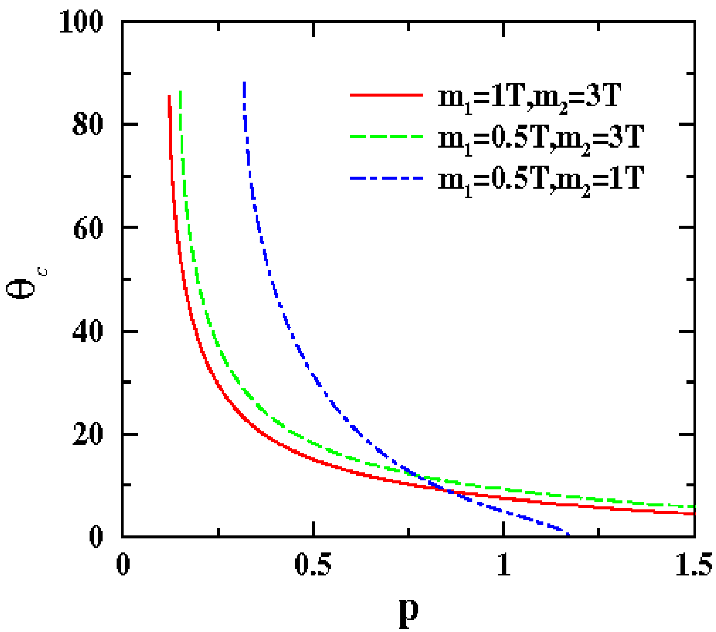
What causes the large negative self energy?

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

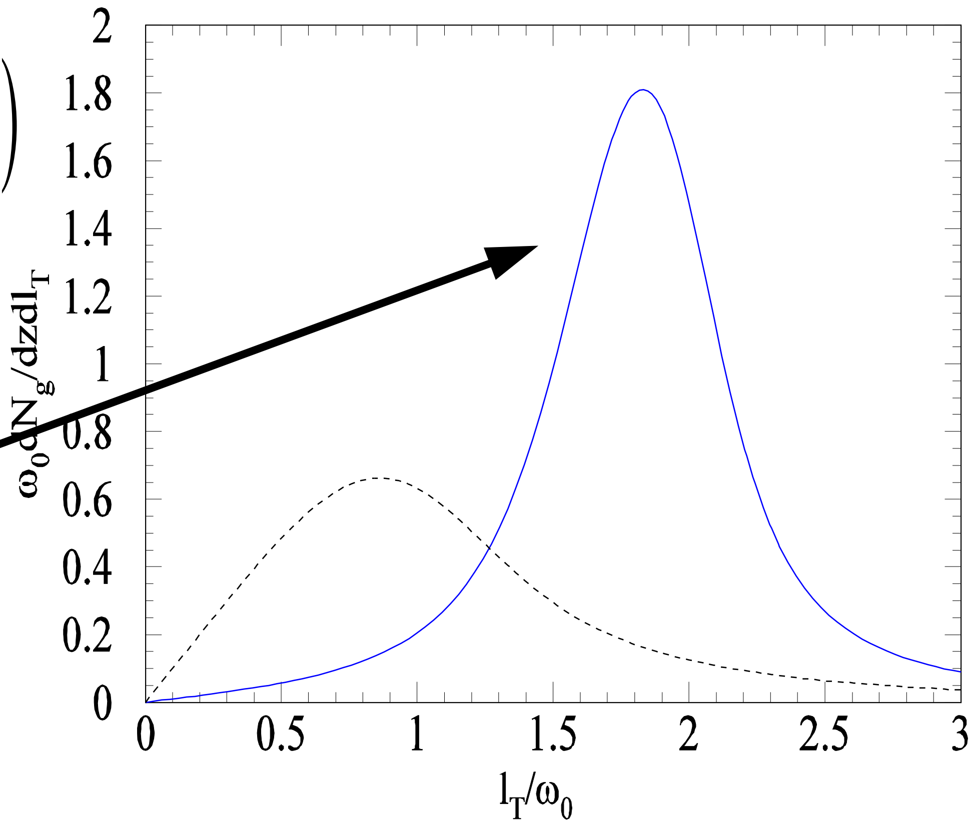
$$\frac{dN_g}{dz\,dl_\perp^2} \propto \frac{1}{l_\perp^4}\left(1 - e^{-\left(\frac{R}{\tau_f}\right)^2}\right)$$

$$\tau_f = \frac{2Ez(1-z)}{l_\perp^2 + (1-z)\Pi}$$

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 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.

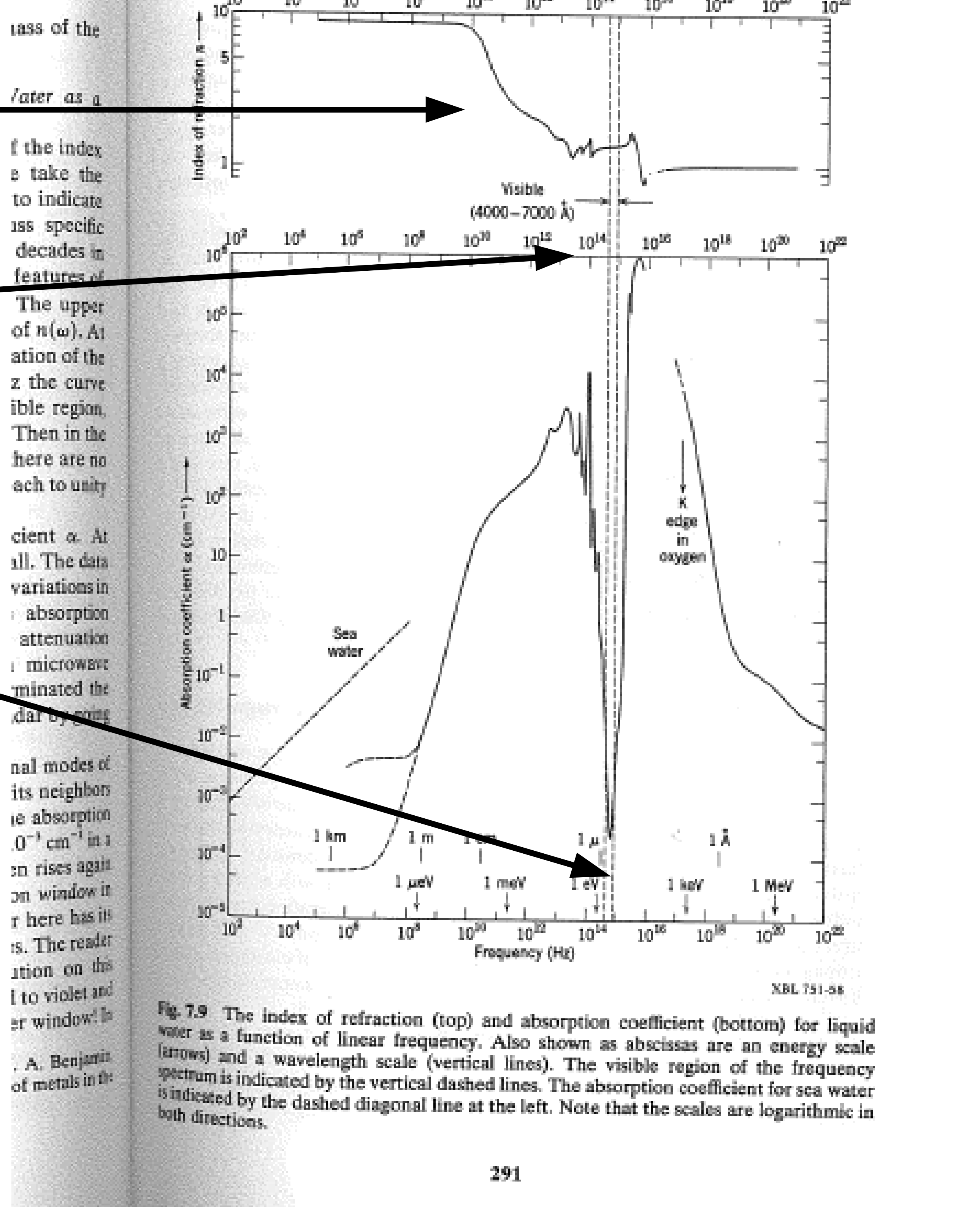


Fig. 7.9 The index of refraction (top) and absorption coefficient (bottom) for liquid water as a function of linear frequency. Also shown as abscissas are an energy scale (arrows) and a wavelength scale (vertical lines). The visible region of the frequency spectrum is indicated by the vertical dashed 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.

291

Summary!

1) There is hope in trying to understand the global set of jet correlation observables within one formalism

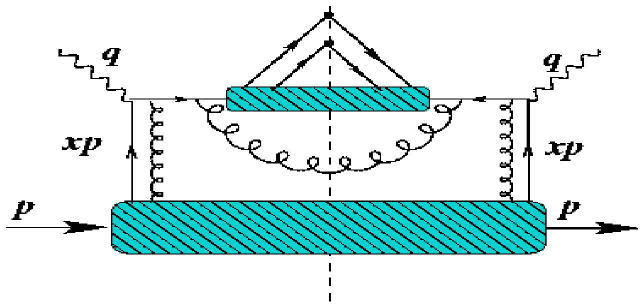
2) Requires lots of work in theory and some more in experiment

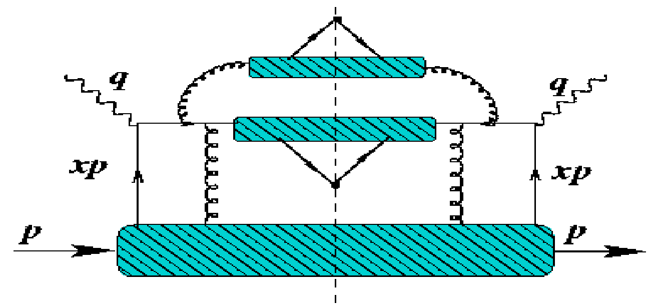
3) A complete calibrated setup of jet correlation observables will define the medium in terms of its unknown parameters!

4) These parameters will constrain models of QGP

Back up!!

The kinds of diagrams that need to be evaluated !

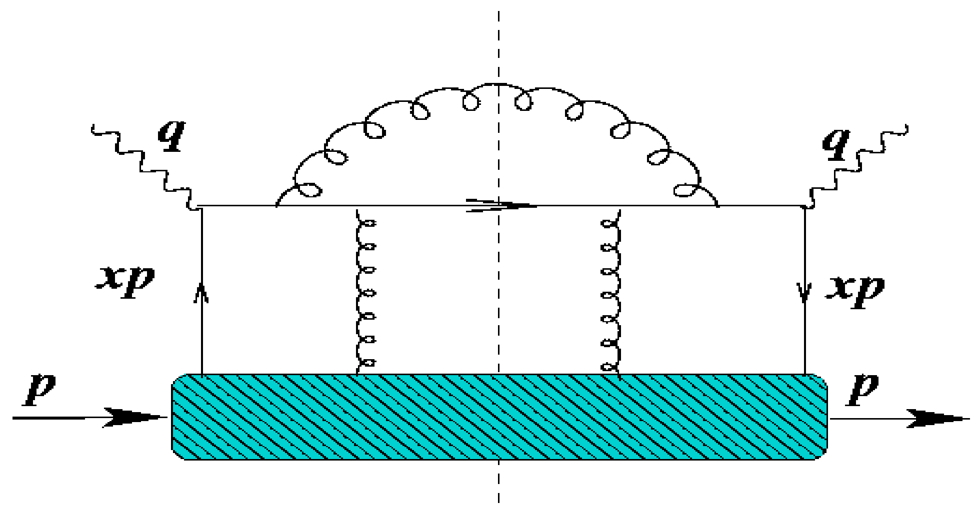




The second diagram has two independent fragmentations
can be factorized in the collinear limit as…

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

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



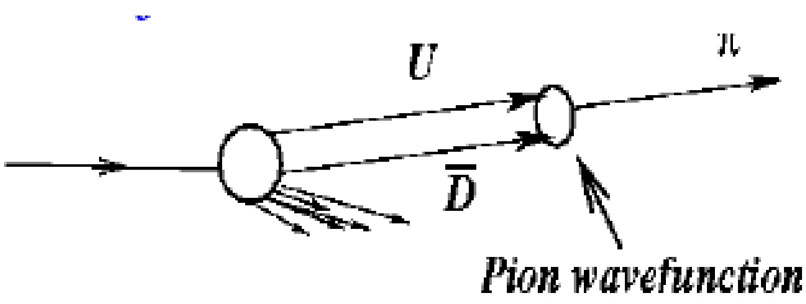
Lowering the pT of the associated particle
Make the jet fragment at the Reco. stage...

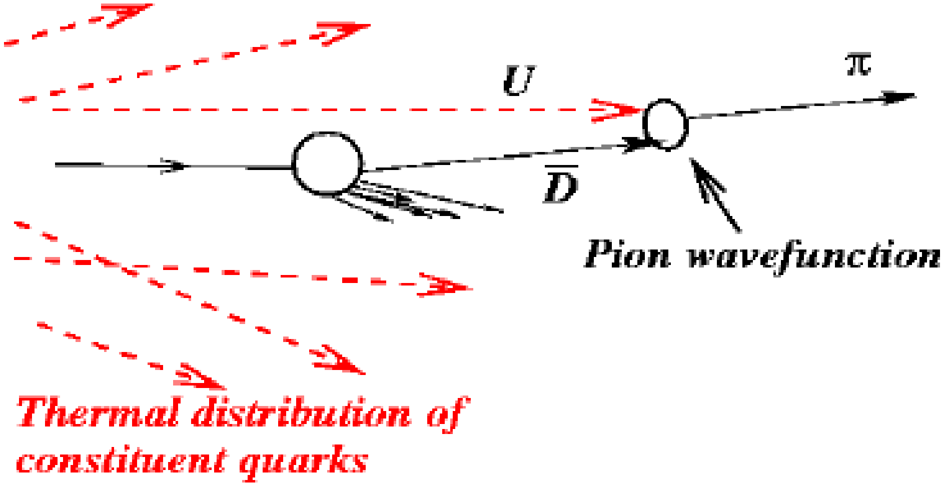
Start by recasting fragmentation in Vacuum in terms of recombination of constituent quarks:

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

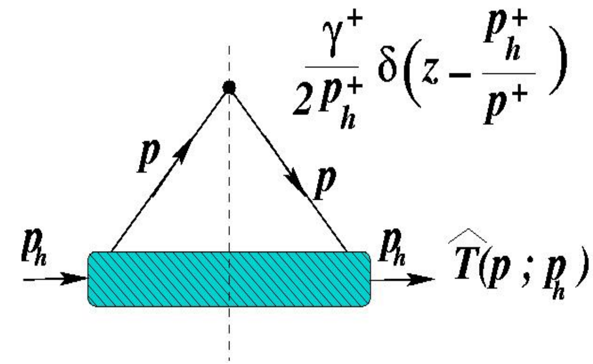




Can recombination be included in jet formalism?

What is a fragmentation function ?

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



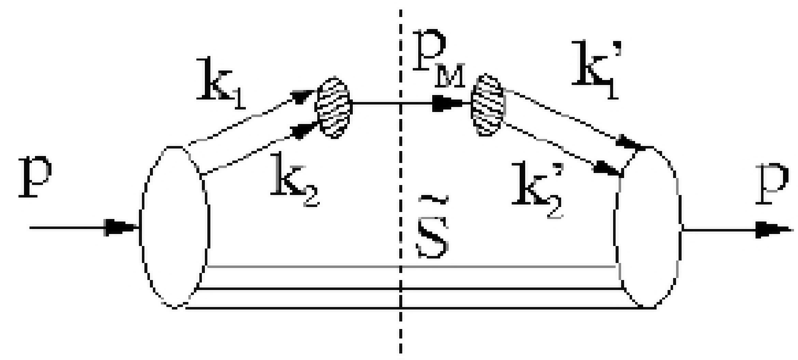
$$\hat{T}_q(p,p_h)=\int d^4x\, e^{-ip\cdot x}\sum_{S-1}\langle 0|\psi(0)|p_h,S-1\rangle\langle p_h,S-1|\bar{\psi}(x)|0\rangle$$

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??