# Hard jets as probes of dense matter:

## SCET, Glauber gluons, factorization

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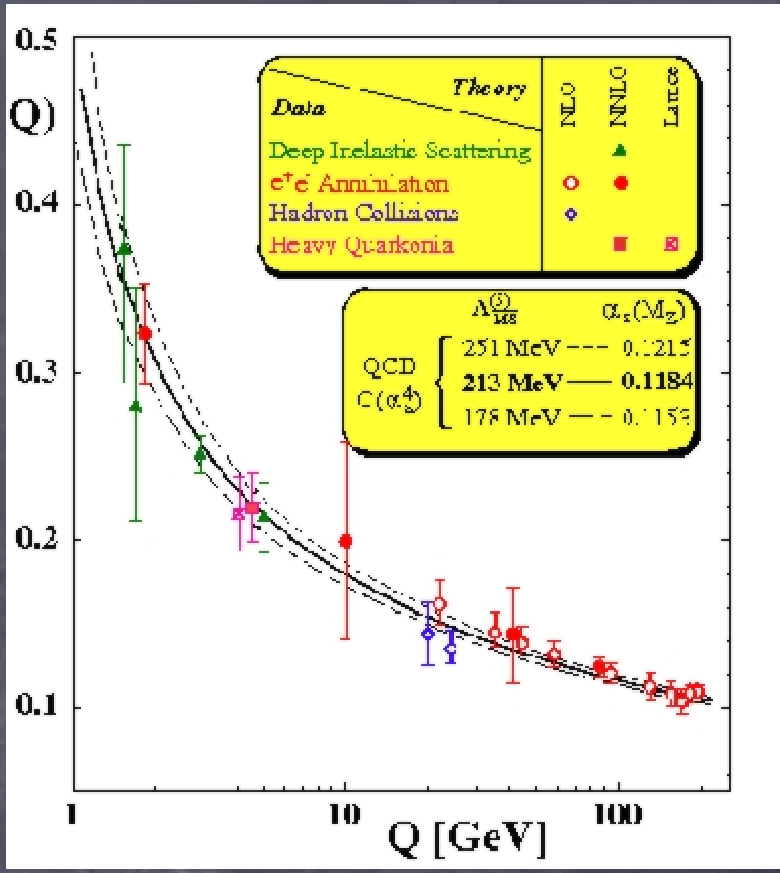
SCET workshop, MIT March 25th 2009

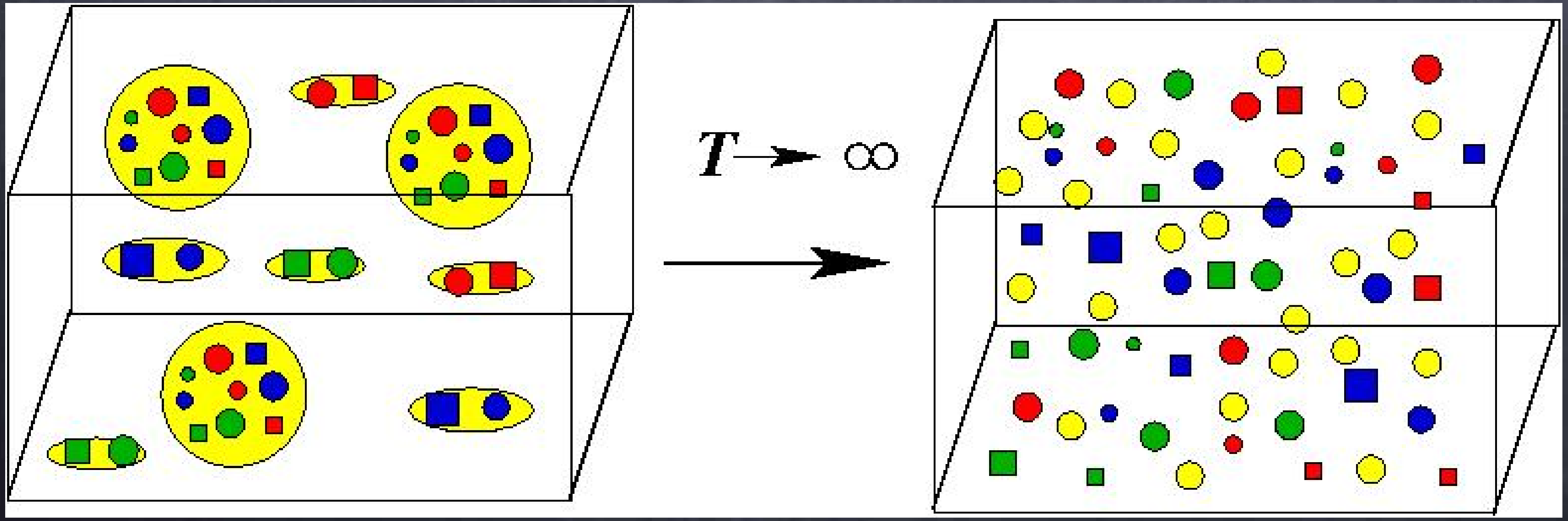
# Heating QCD matter

Heating matter increases momentum transfers




This should reduce the coupling

Heat hadronic matter and make a quark gluon plasma (QGP)



# Heavy-ion Collisions and the QGP

Collide two heavy ions at very high energy

200 GeV per n n pair

*Animation by Jeffery Mitchell (Brookhaven National Laboratory).*
*Simulation by the UrQMD Collaboration*

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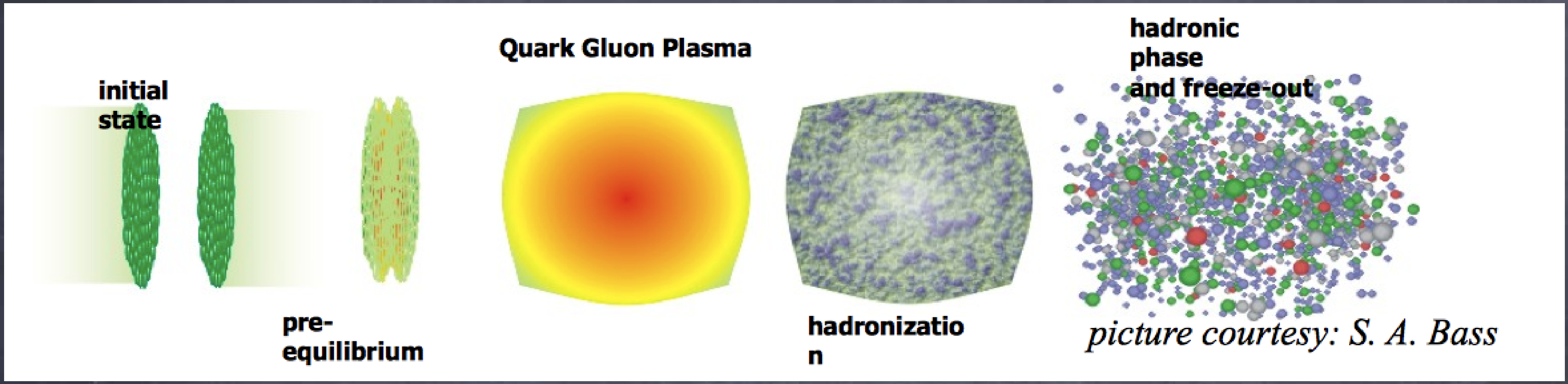

# Heavy-ion Collisions and the QGP

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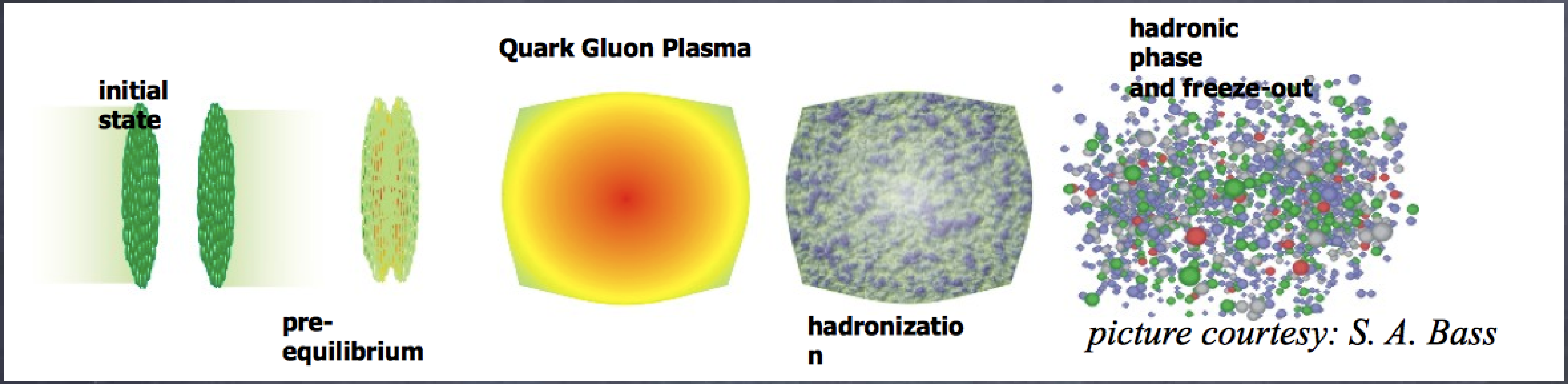
## 200 GeV per n n pair



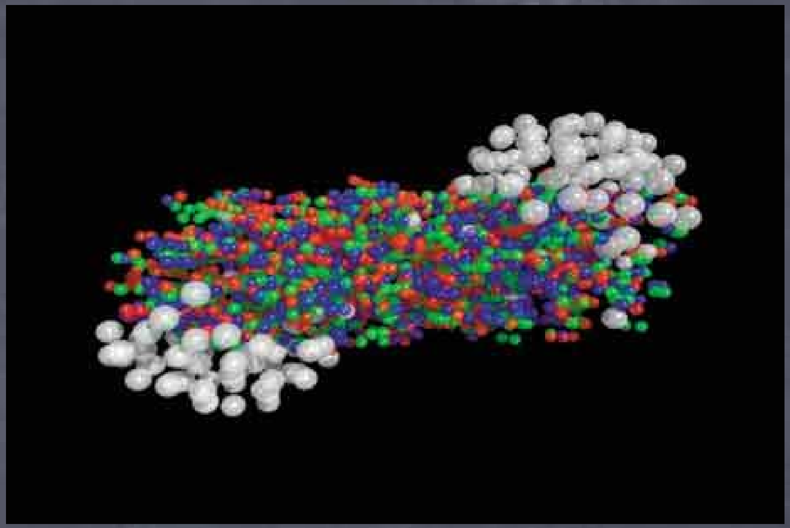

De-confined phase lives for a very short time ~ 10 fm/c = 3.3 x $10^{-23}$ secs

Simple estimates put highest T ~ 400 MeV

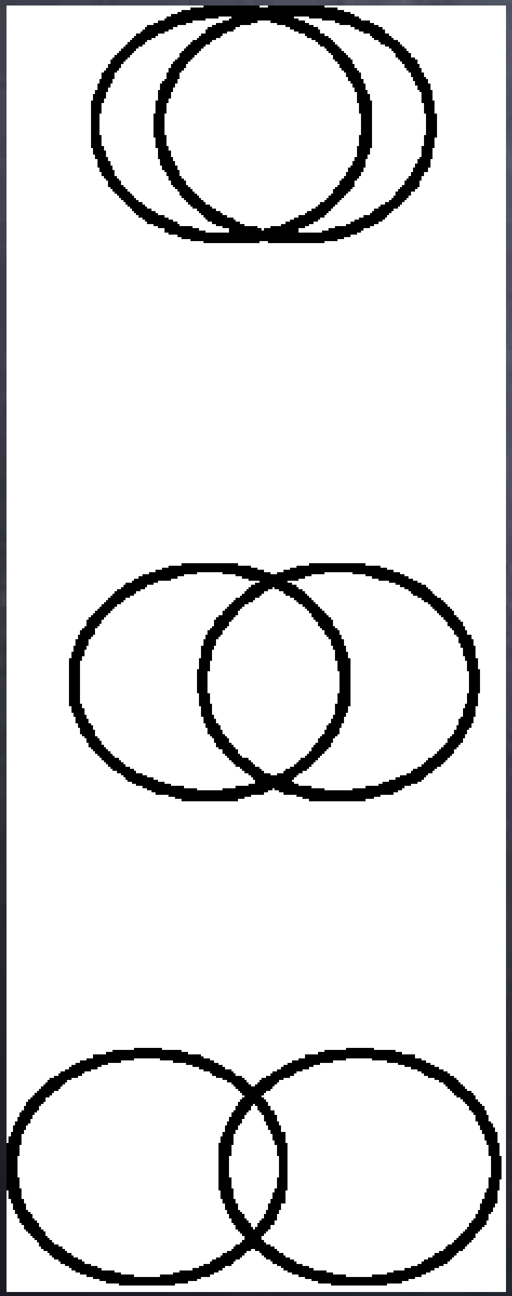
Everything turns into an expanding hot hadron gas

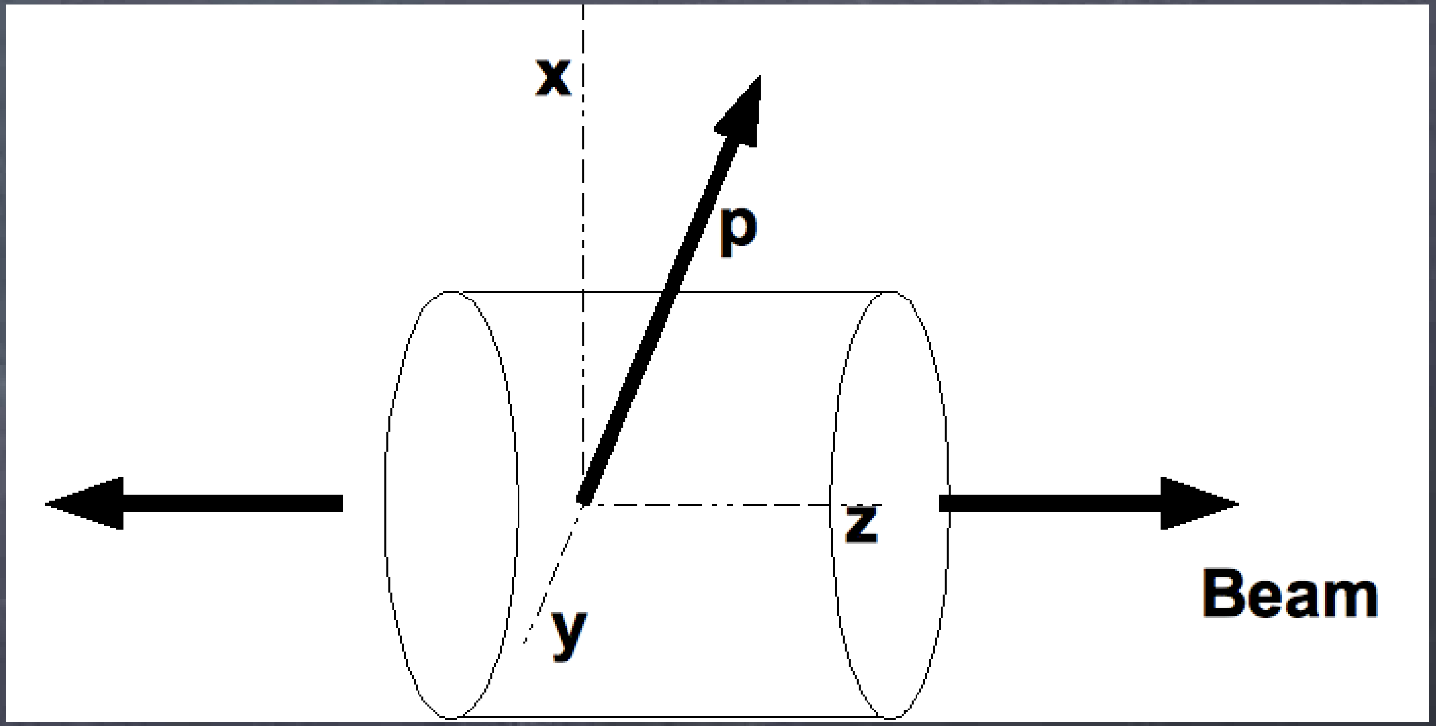
Have to study to final state to figure out if a QGP is formed

# The variables that we use



Centrality or impact parameter

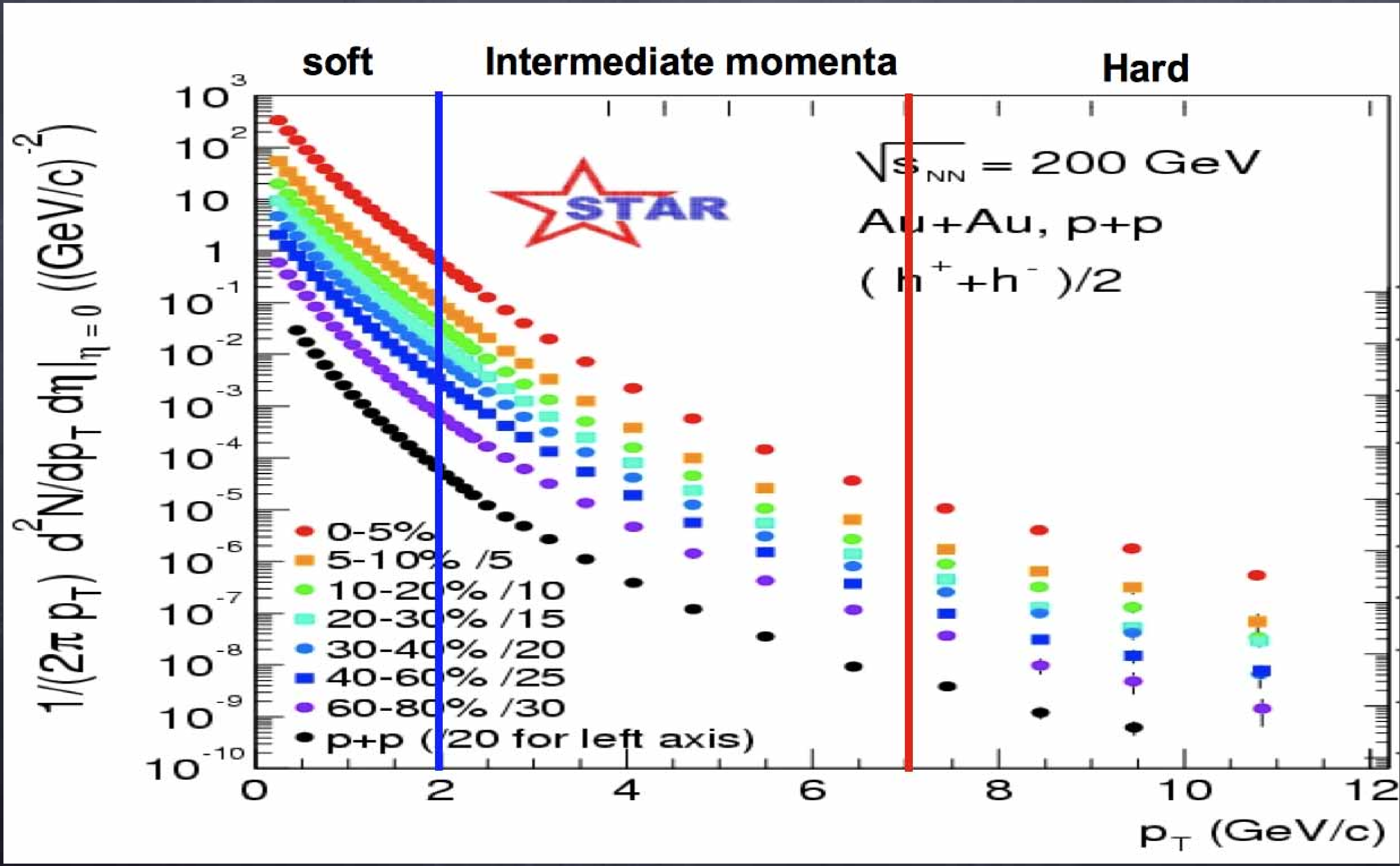





$$p_T^2 = p_x^2 + p_y^2$$

$$y = \frac{1}{2}\log\left|\frac{E+p_z}{E-p_z}\right| \qquad \eta = \frac{1}{2}\log\left|\frac{p+p_z}{p-p_z}\right|$$

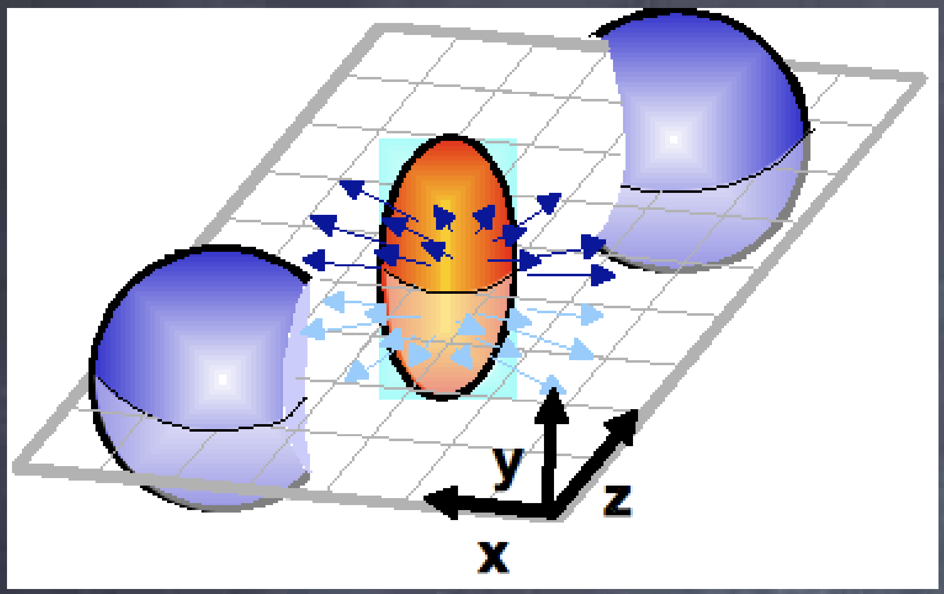
# The spectra !

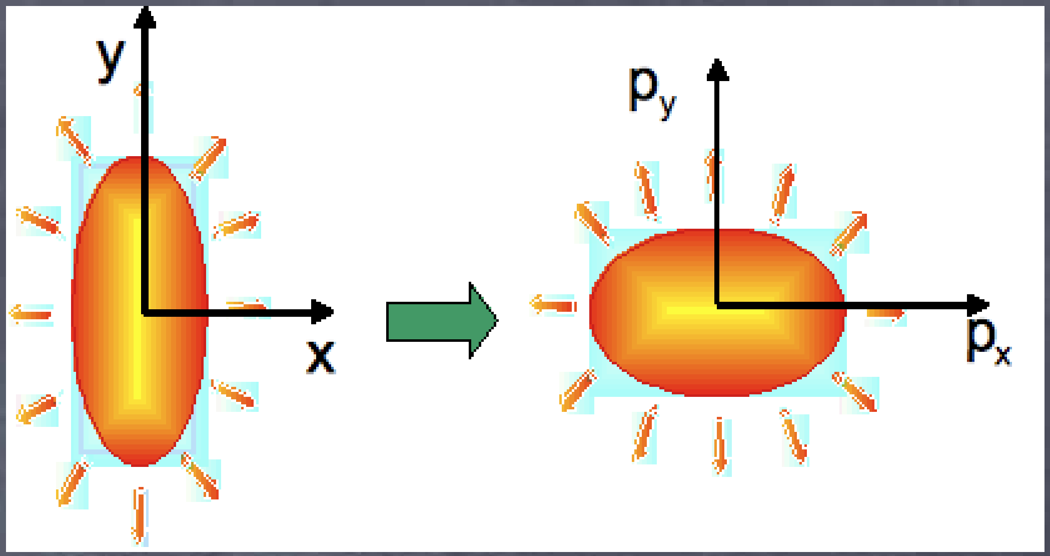


soft
Intermediate momenta
Hard
$\sqrt{s_{NN}} = 200$ GeV
Au+Au, p+p
$(h^+ + h^-)/2$
STAR
0-5%
5-10% /5
10-20% /10
20-30% /15
30-40% /20
40-60% /25
60-80% /30
p+p (/20 for left axis)
$1/(2\pi p_T)\ d^2N/dp_T d\eta|_{\eta=0}$ ((GeV/c)$^{-2}$)
$p_T$ (GeV/c)

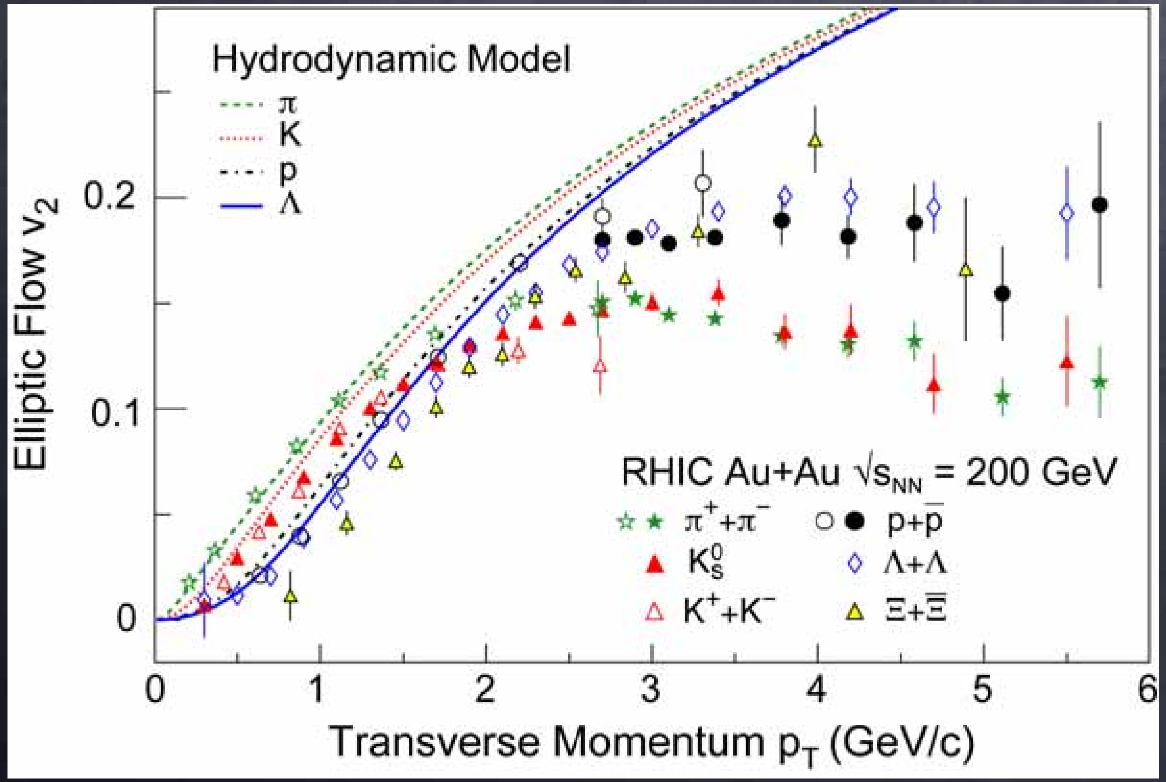
# Evidence for a new state of matter

## Look at semicentral collisions




$$\frac{dN}{dyp_T dp_T d\phi} = \frac{1}{2\pi}\frac{dN}{dyp_T dp_T}(1 + 2v_2\cos(2\phi) + \ldots)$$

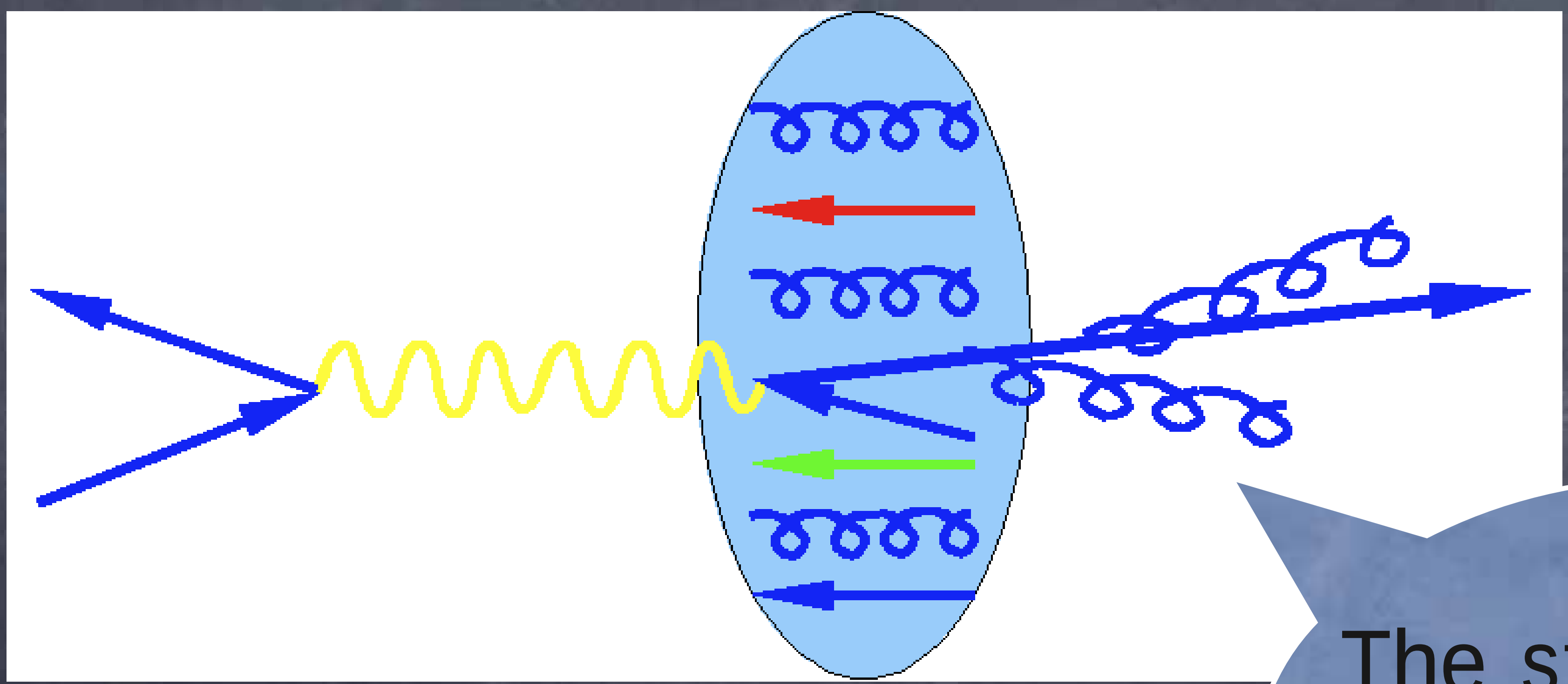



*Ideal Hydro calculabilityations by P. Houvinen, also Nonaka, Bass, Teaney, Lauret, Shuryak and Kolb, Heinz*

Produced matter behaves like an inviscid fluid
Not like a weakly interacting quark, gluon gas
Matter is strongly interacting, even at T = 300 MeV
How to systematically study matter using pQCD ?

# Hard probes of strongly interacting matter

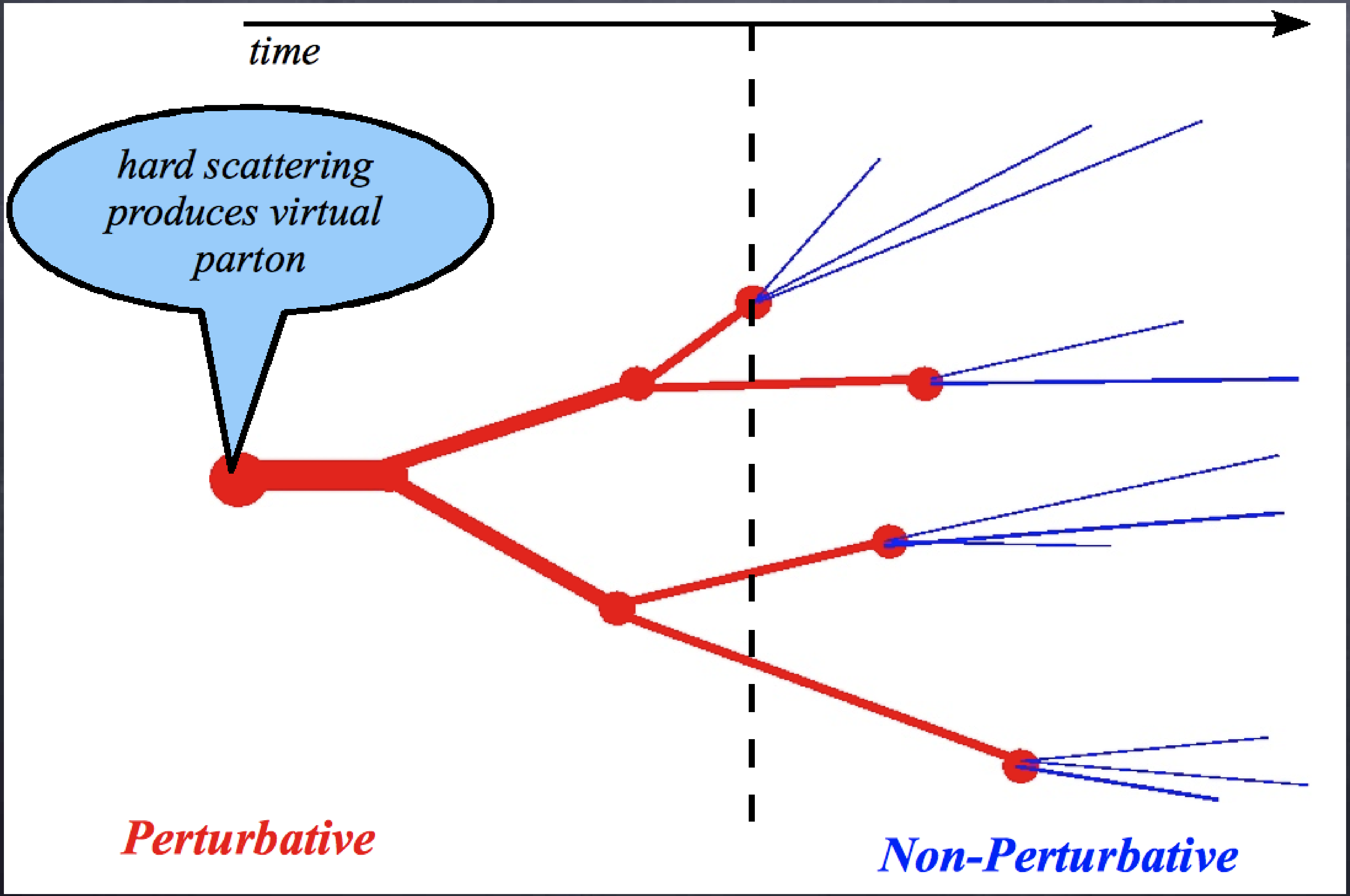
A proton is a strongly interacting system of partons,
but we can still study its short distance structure
in Deep-Inelastic Scattering



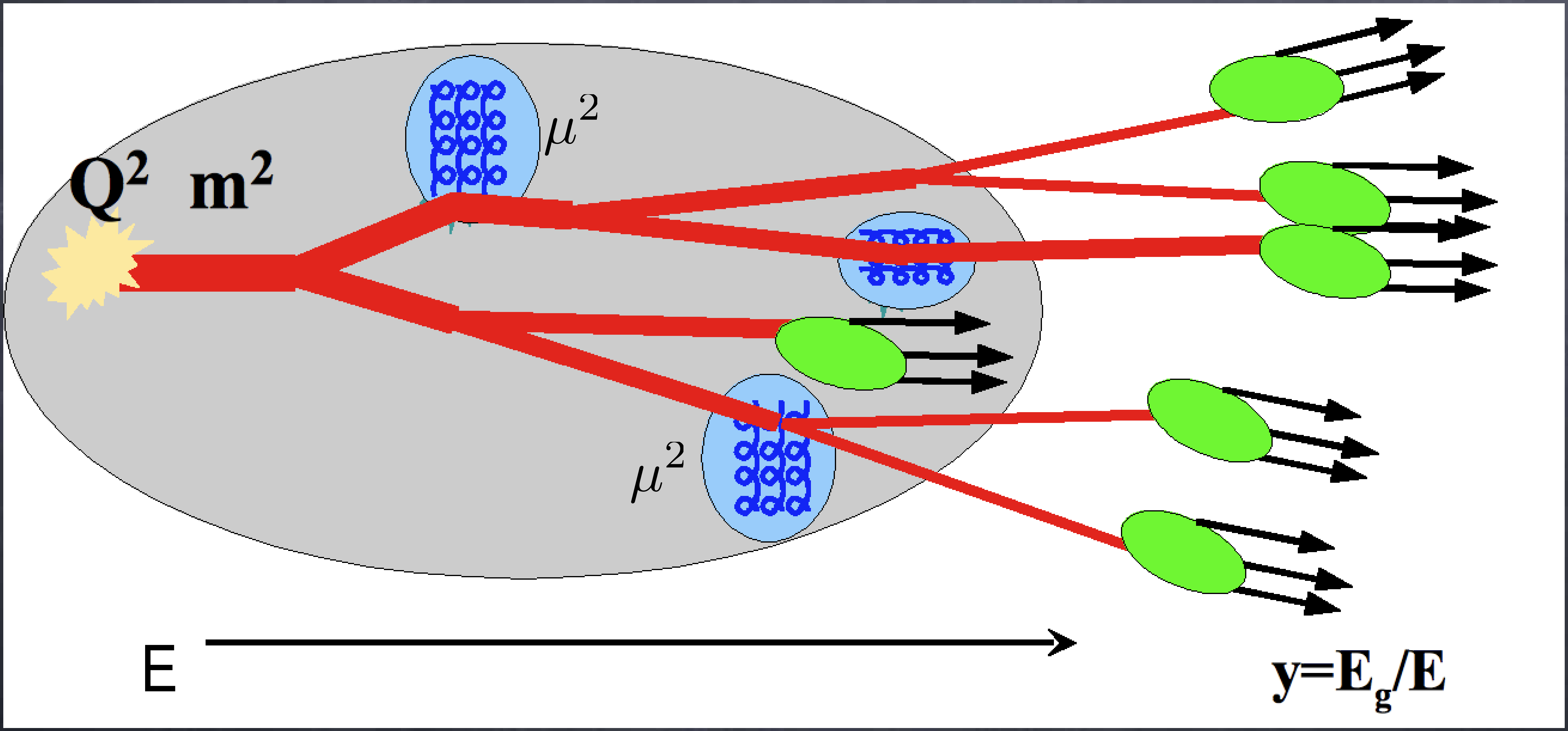
The struck quark is a hard jet, use this to probe the medium

Cannot do DIS on a QGP
Use a derivative approach !

# The space-time structure of the produced jet

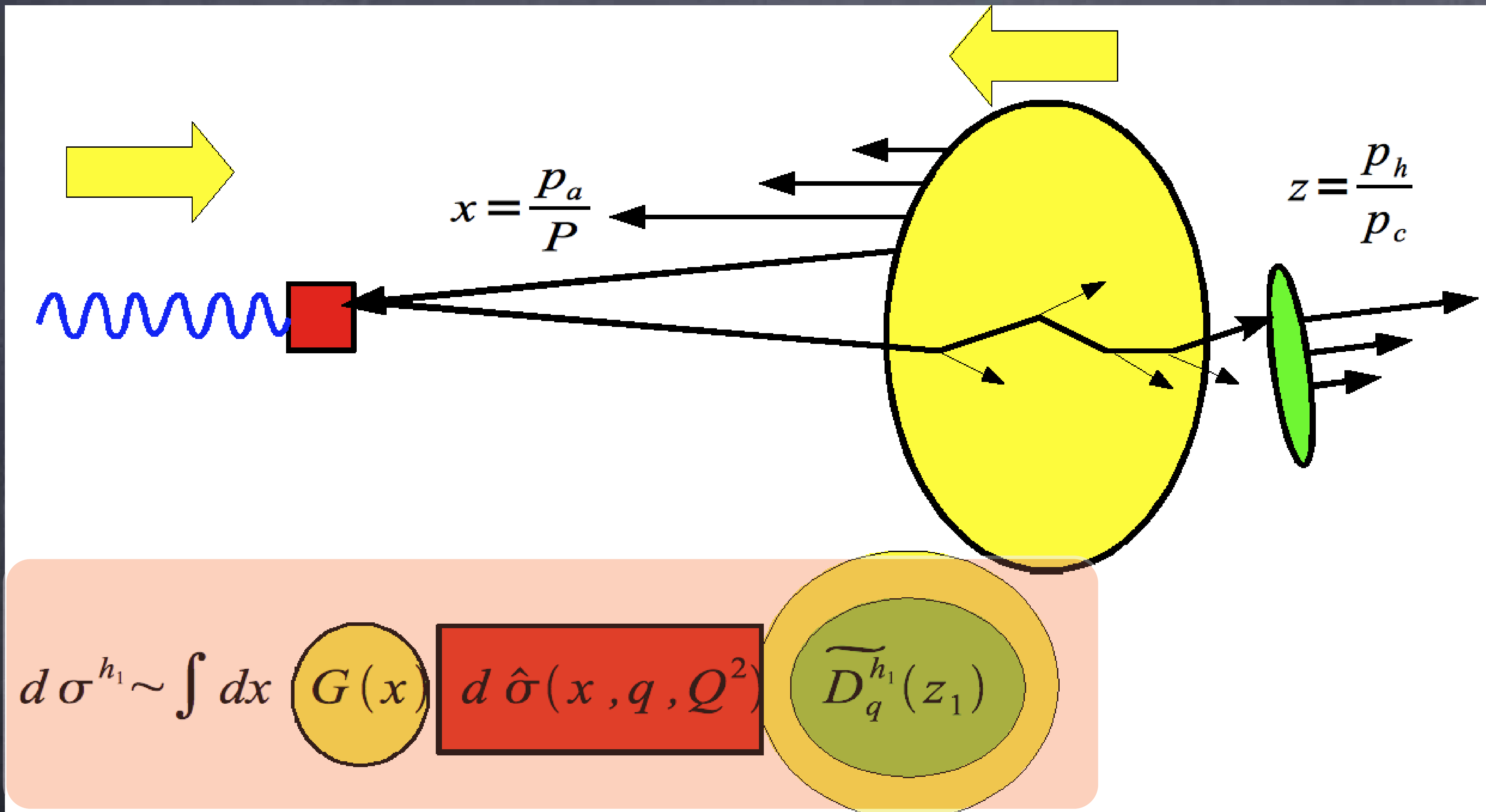


# If we can place a medium in the way we can study the change in jet structure



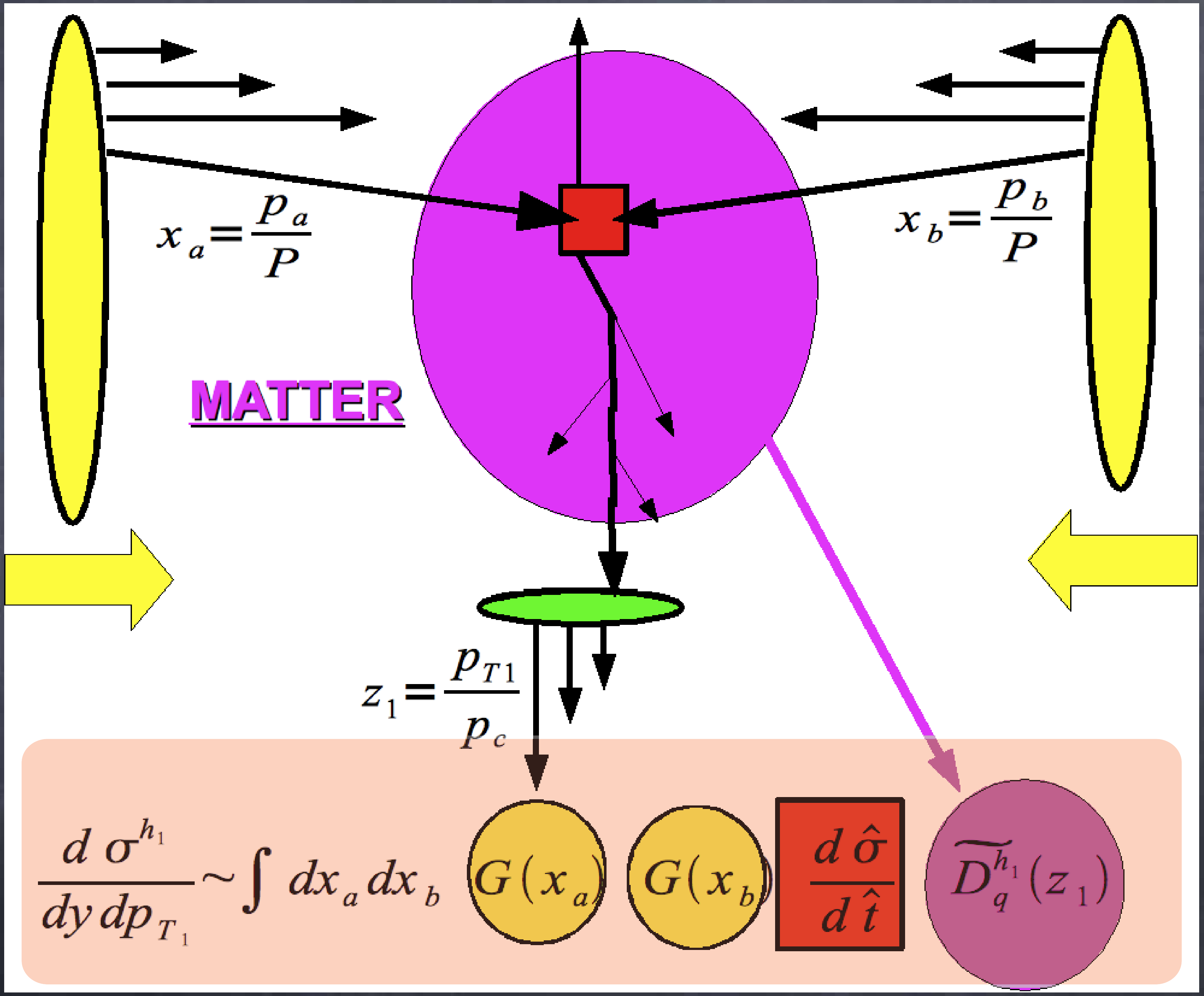

The multiple scattering of the jet will change the radiation pattern and final hadronic shower

# Canonical (baseline) QCD experiment: Single-Incl. DIS on a large nucleus



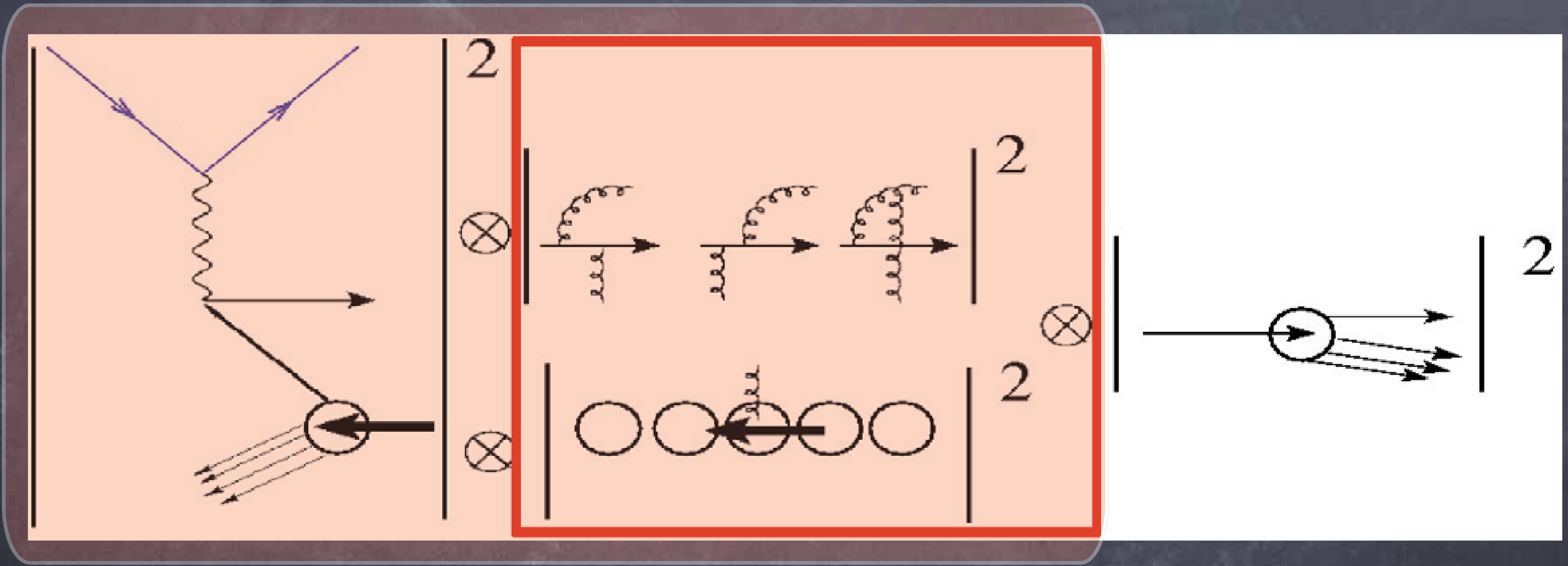

Entire effect of multiple scattering is in frag. func. called a Medium modified fragmentation function

# Extend this concept to jets in heavy-ion collisions



# Doing a calculation requires more approx. !

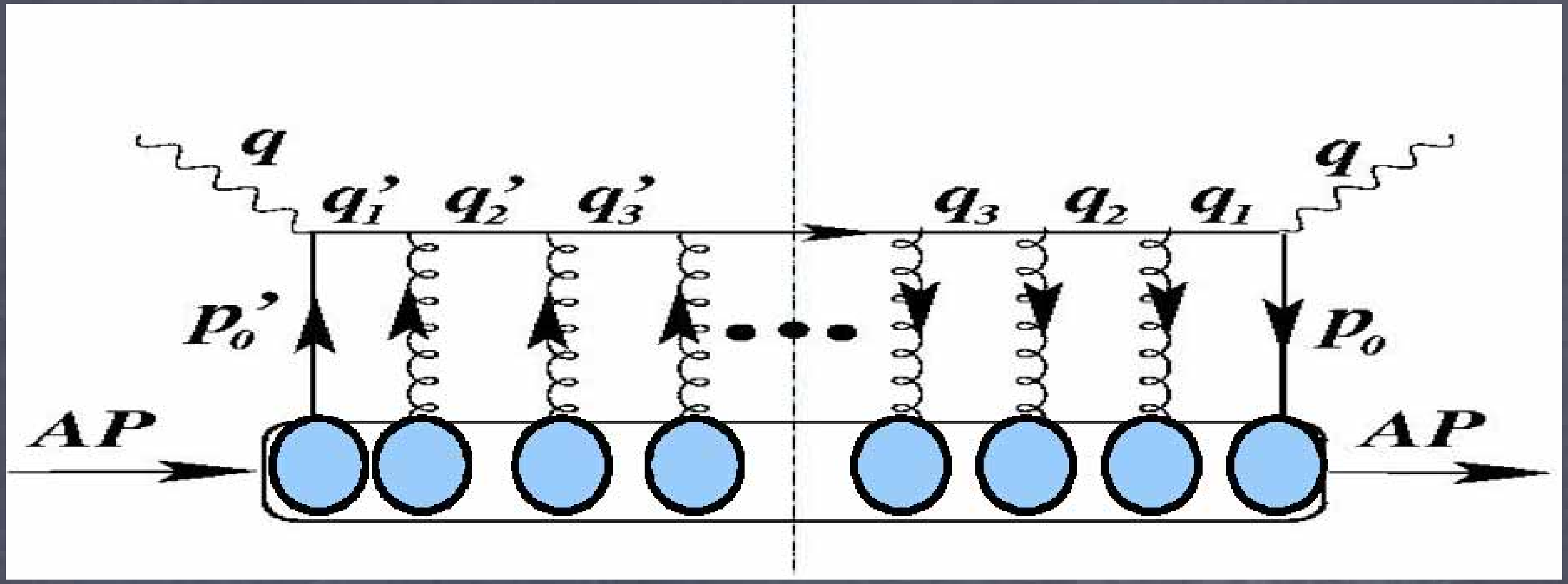
For the case of DIS factorize the initial hard scattering from the later scattering of the quark




The scattering of the quark in the soft glue field induces further radiation which interferes with the initial hard radiation

THIS IS S.C. rad. AND GLAUBER INDUCED S.C. rad.

# Looking at just the multiple scattering gives us a parameter to describe the medium




Assuming independent scattering of nucleons gives a diff. equation

$$\frac{\partial f(p_\perp, t)}{\partial t} = \nabla_{p_\perp} \cdot D \cdot \nabla_{p_\perp} f(p_\perp, t) \qquad \langle p_\perp^2 \rangle = 4Dt$$

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

# Comparing to data!

Assuming that the nuclear pdf = A * nucleon pdf

we can just take the ration of the frag. funcs.

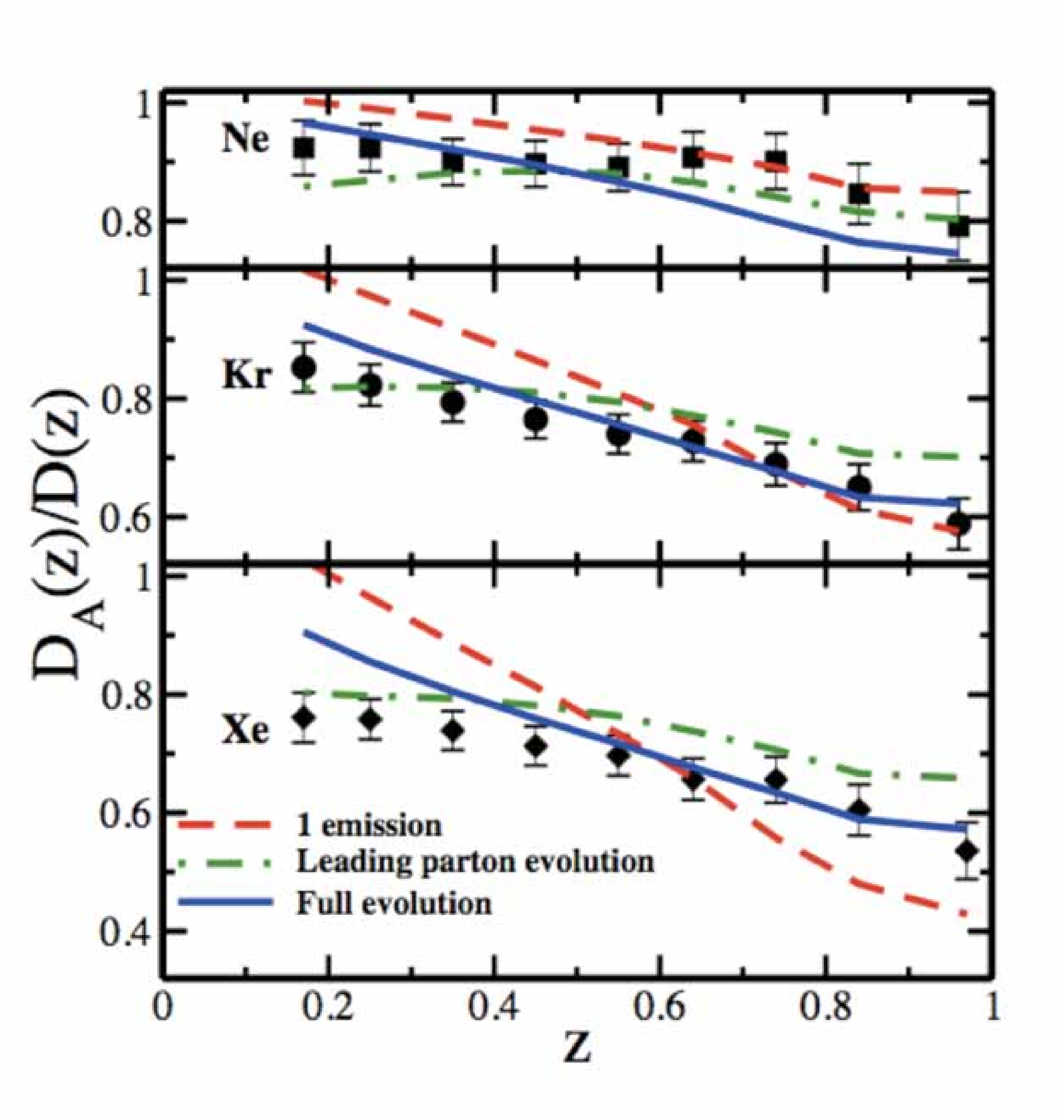
Data from HERMES at DESY

Three different nuclei

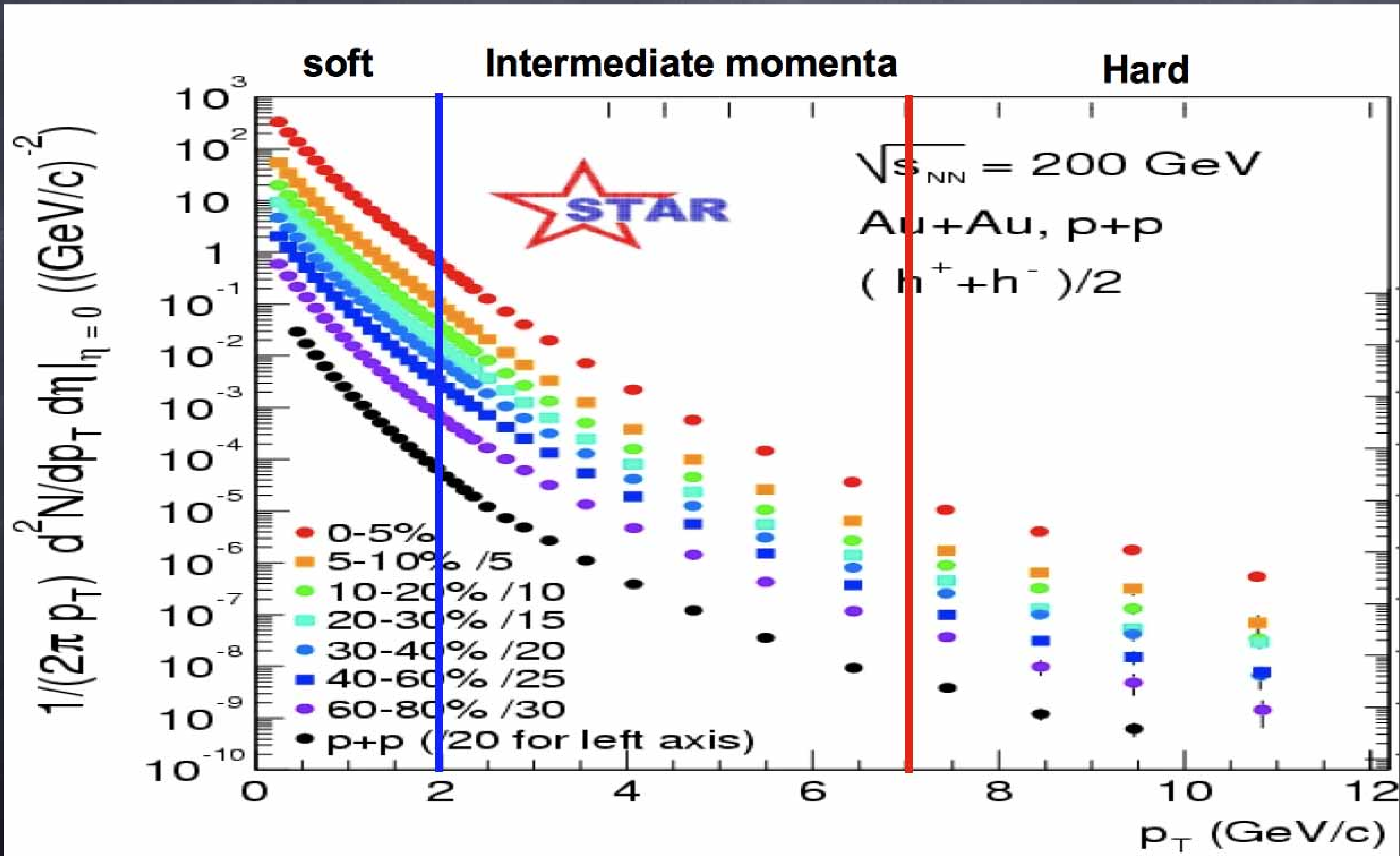
one qhat = $0.08 GeV^2/fm$

Fit one data point in Ne
everything else is prediction

$Q^2 = 3 GeV^2$ ,nu = 16-20 GeV



# In HIC look at ratio of cross sections

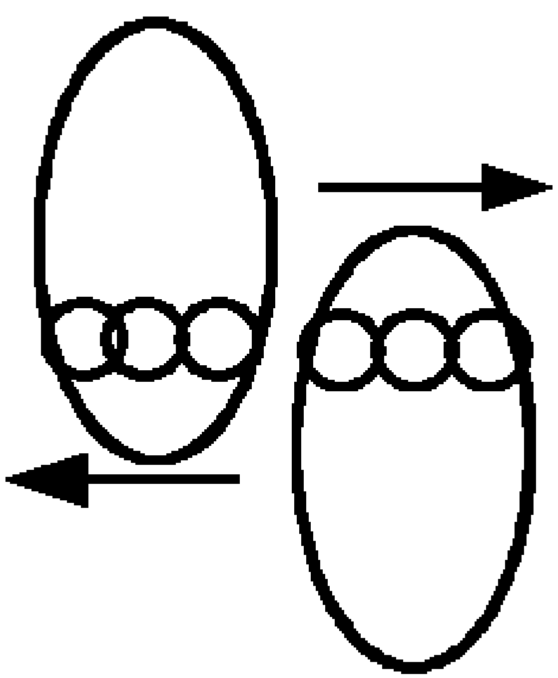


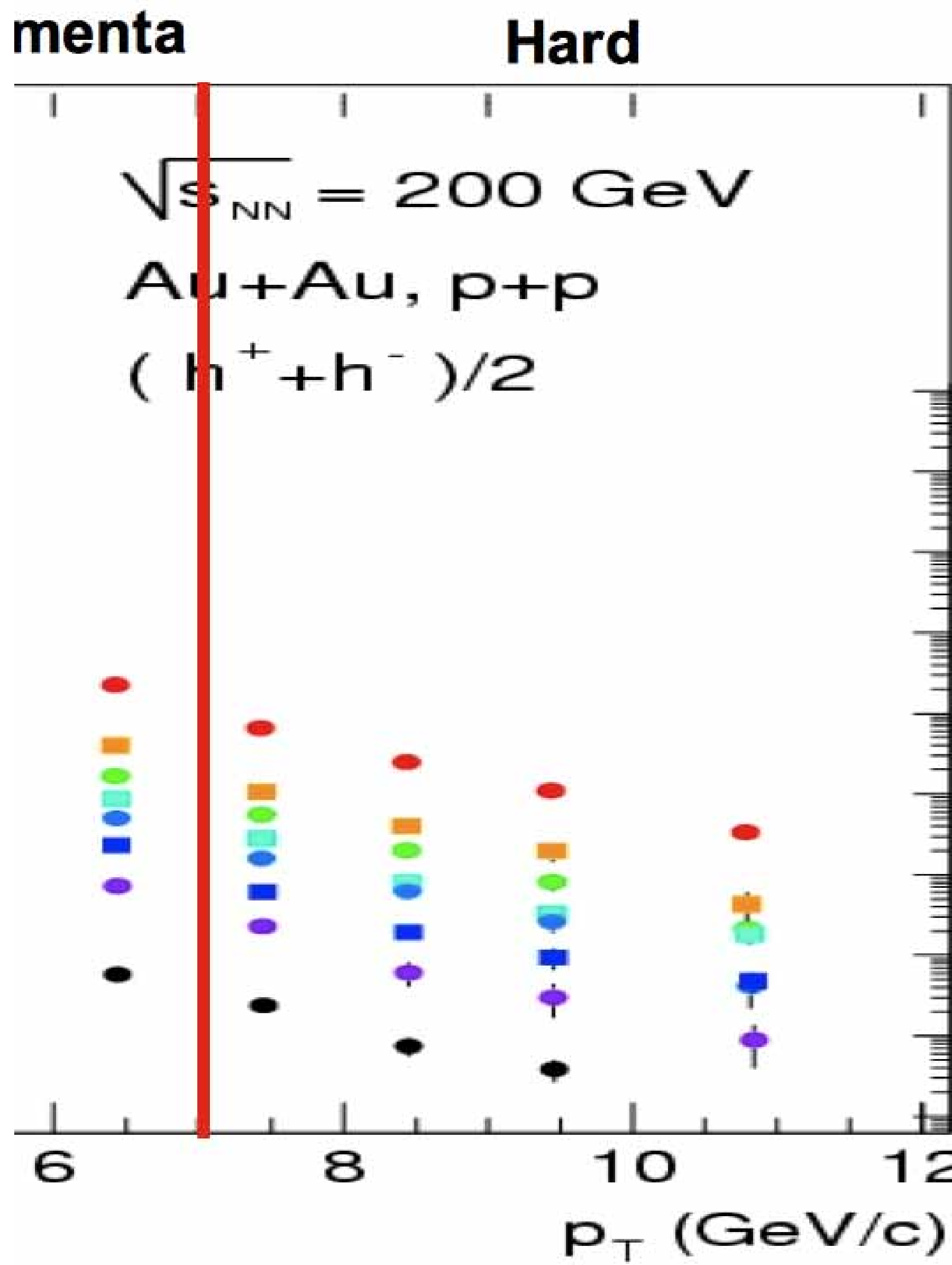
# In HIC look at ratio of cross sections

***Scale cross section by***

***No. of expected binary collisions***

$$R_{AA} \sim \frac{\dfrac{d\sigma_{AA}}{dp_T\,dy}}{N_{bin}\dfrac{d\sigma_{pp}}{dy\,dp_T}}$$





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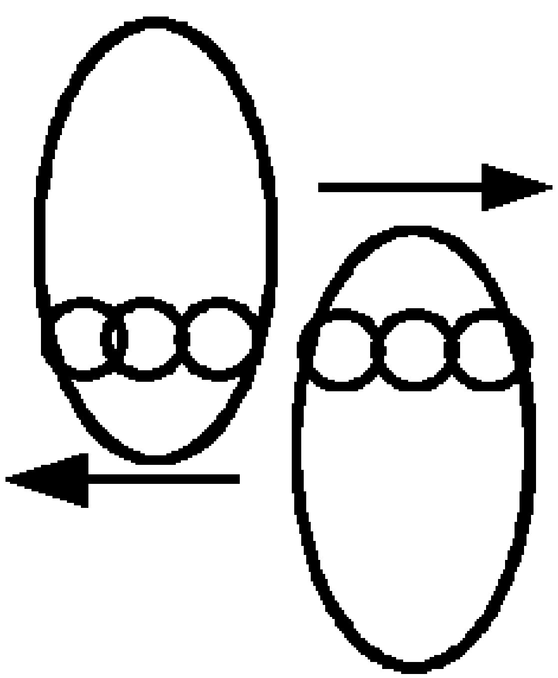

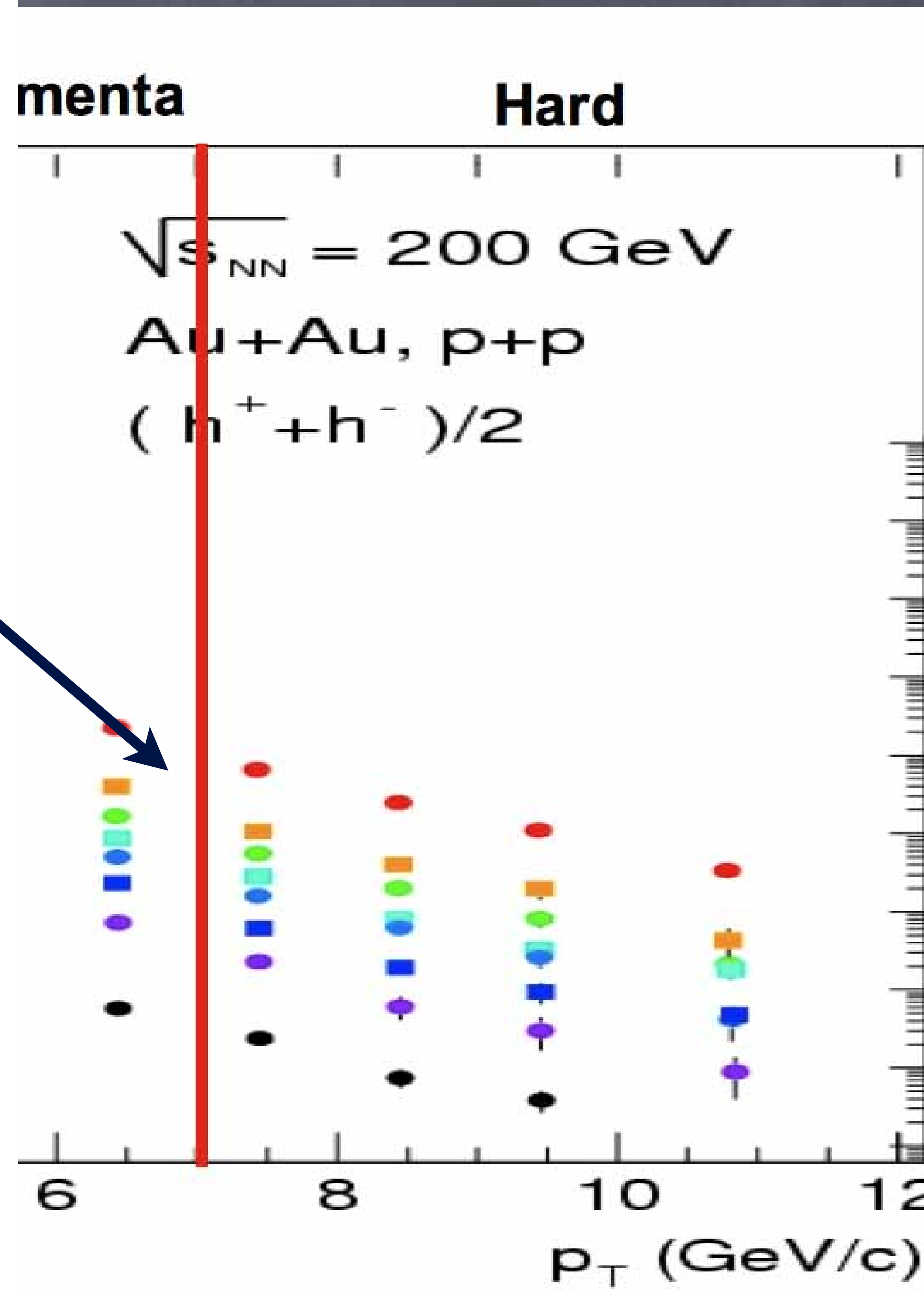

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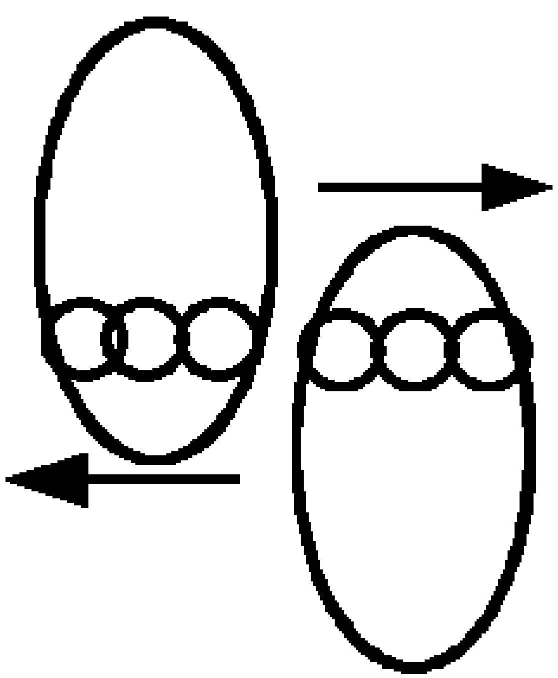
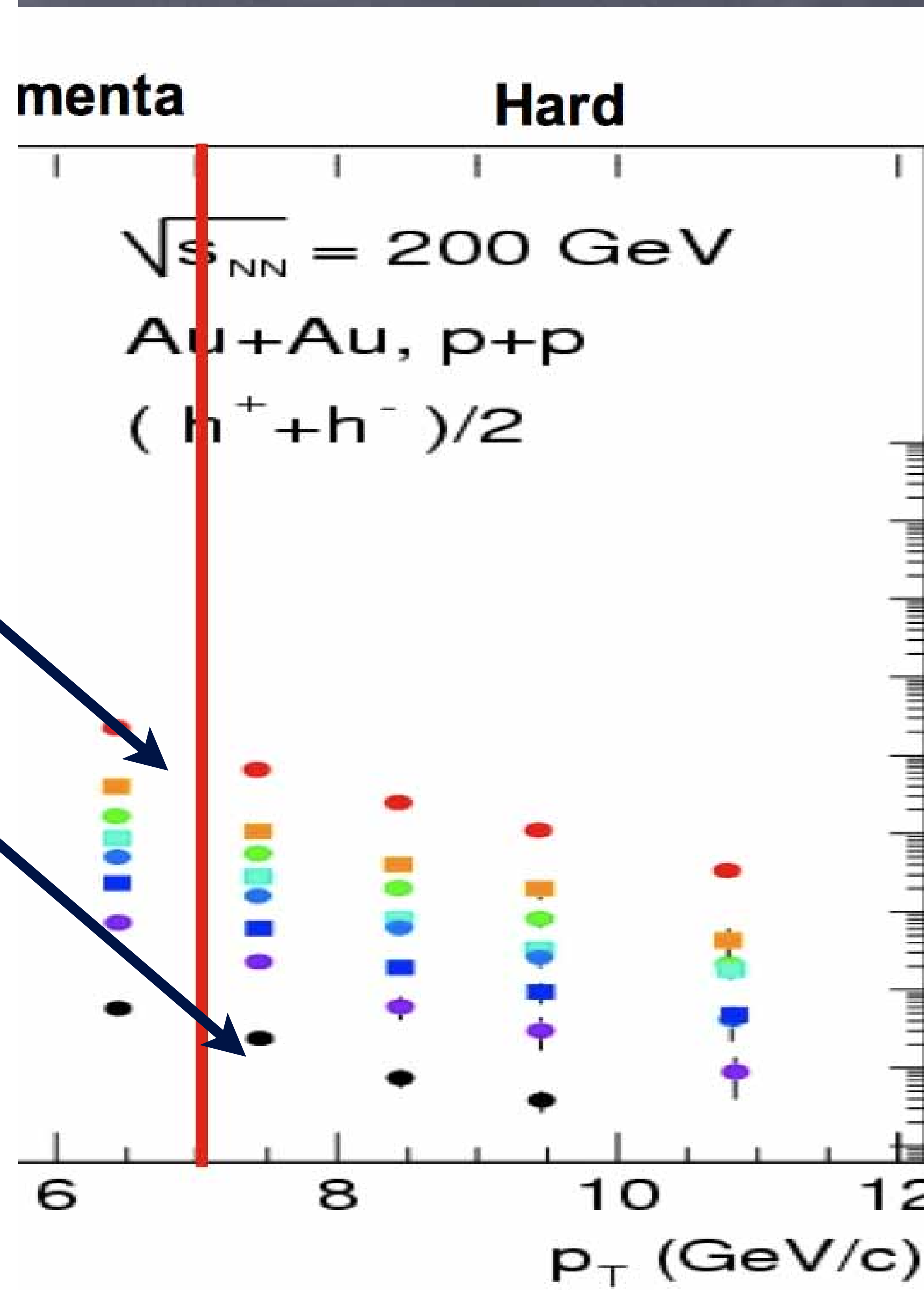
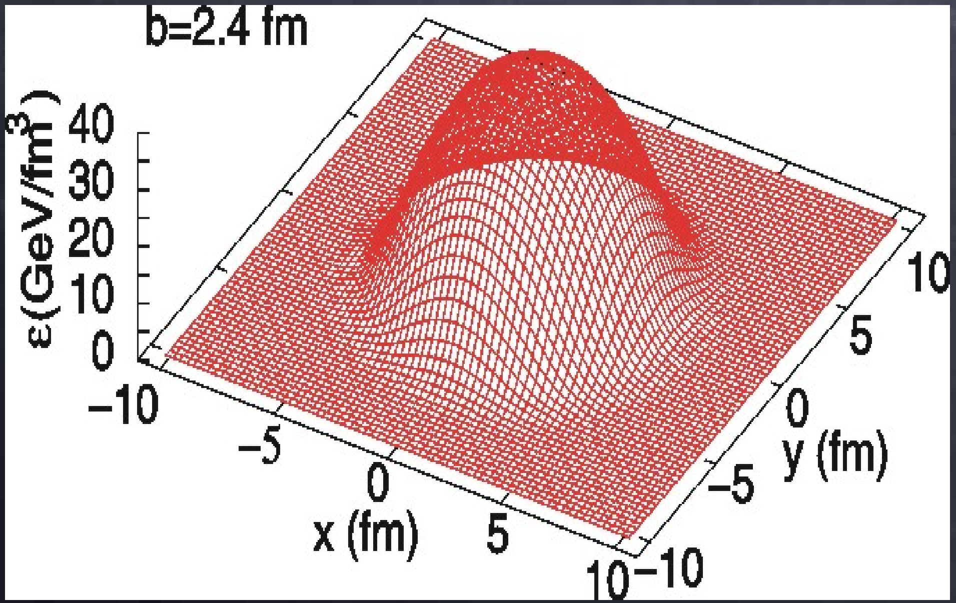


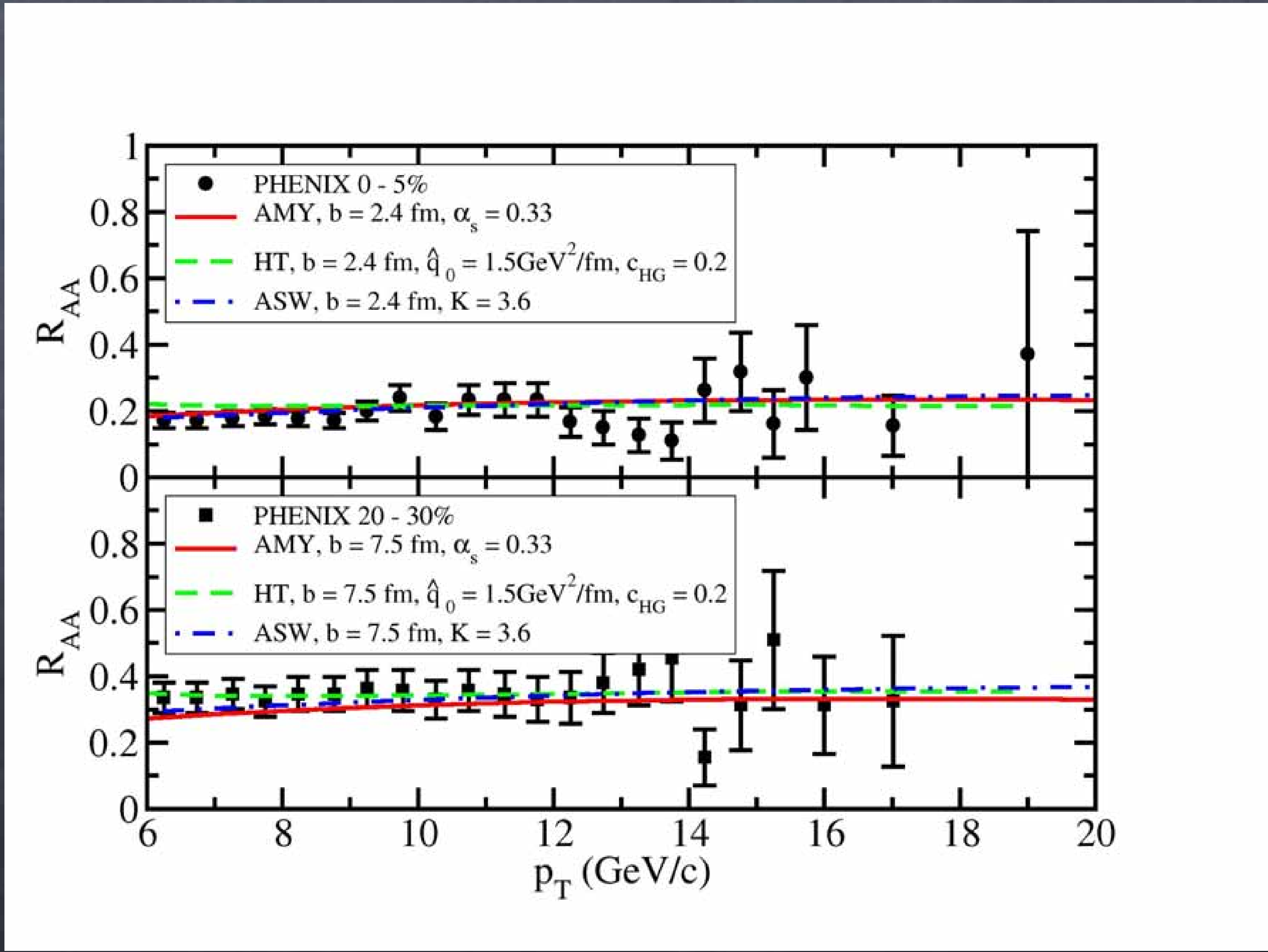


# The medium is a bit more complicated in HIC

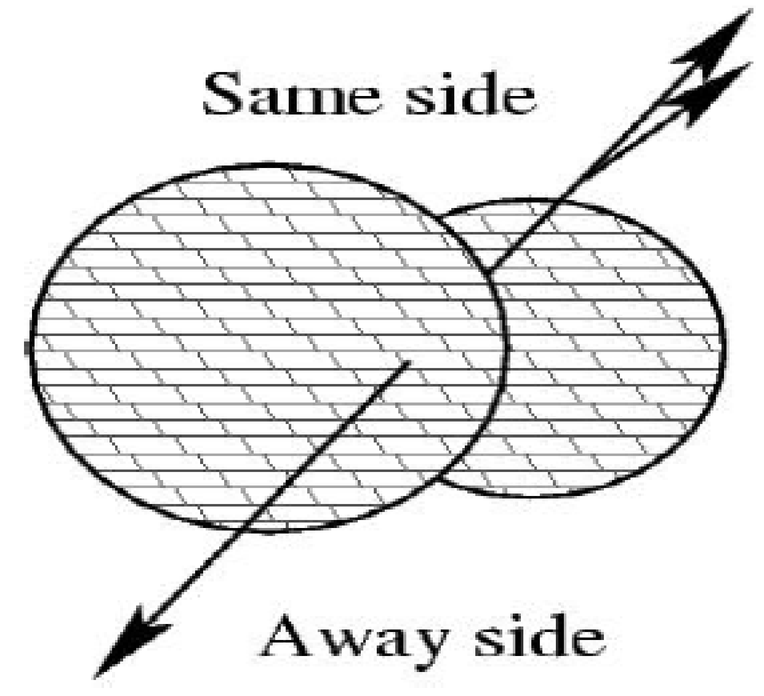
Evolves hydro-dynamically as the jet moves through it

Fit the qhat for the initial T in the hydro in central coll.



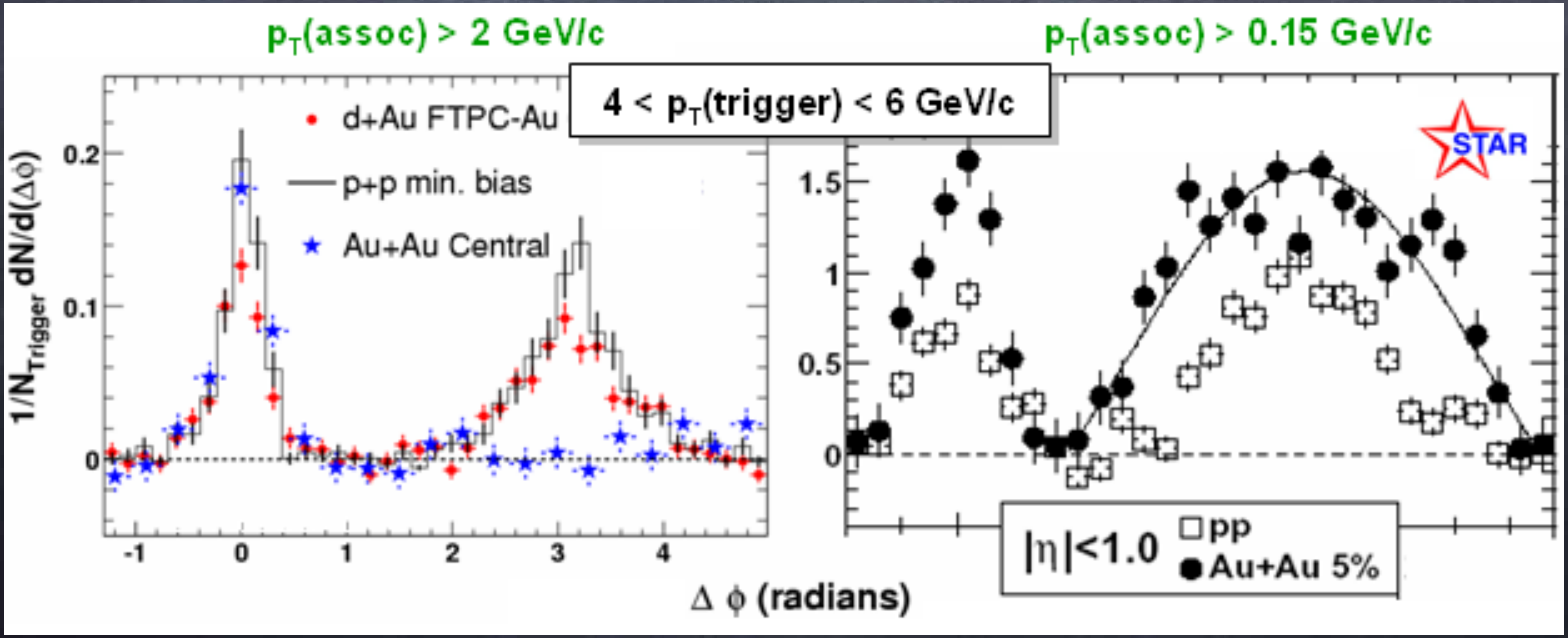



# Tons of DATA from RHIC of all sorts!



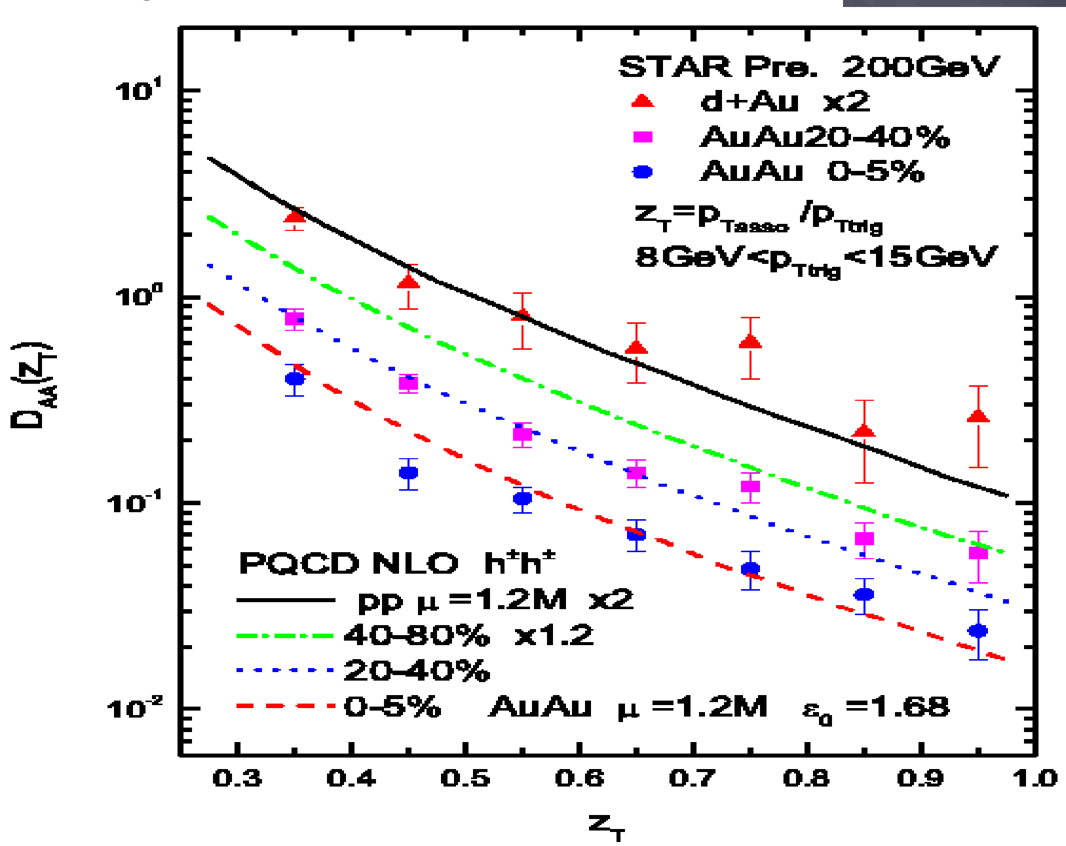

Jet dies on away side

actually reappears at lower $p_T$



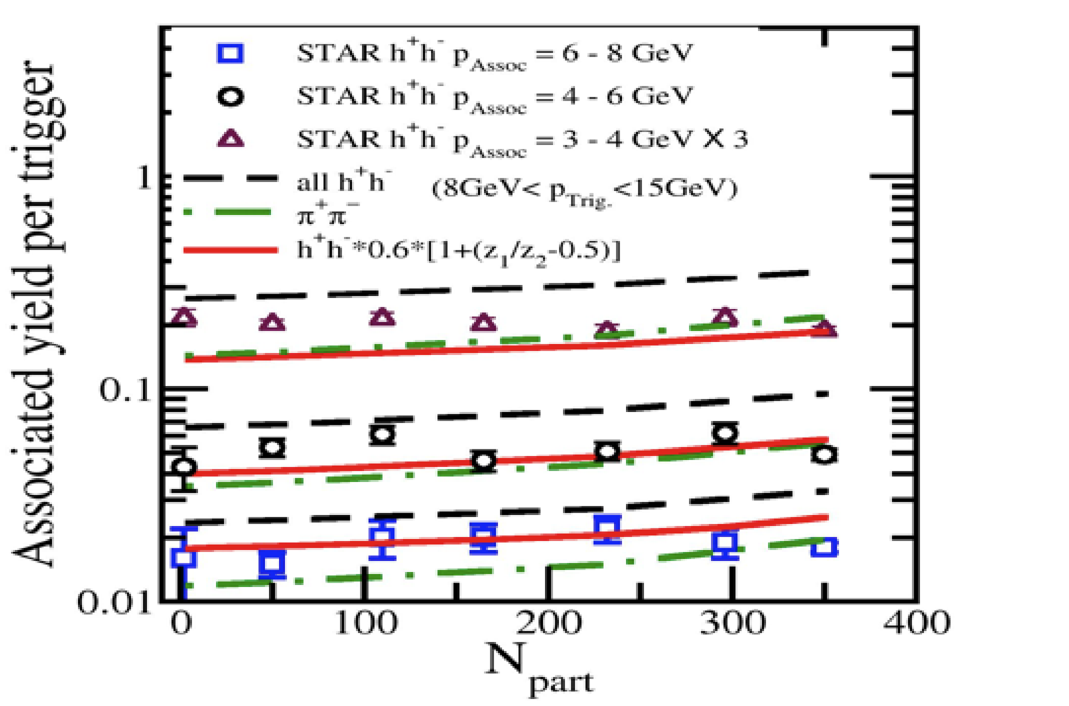
# This one parameter approximate formalism does a very very good job!

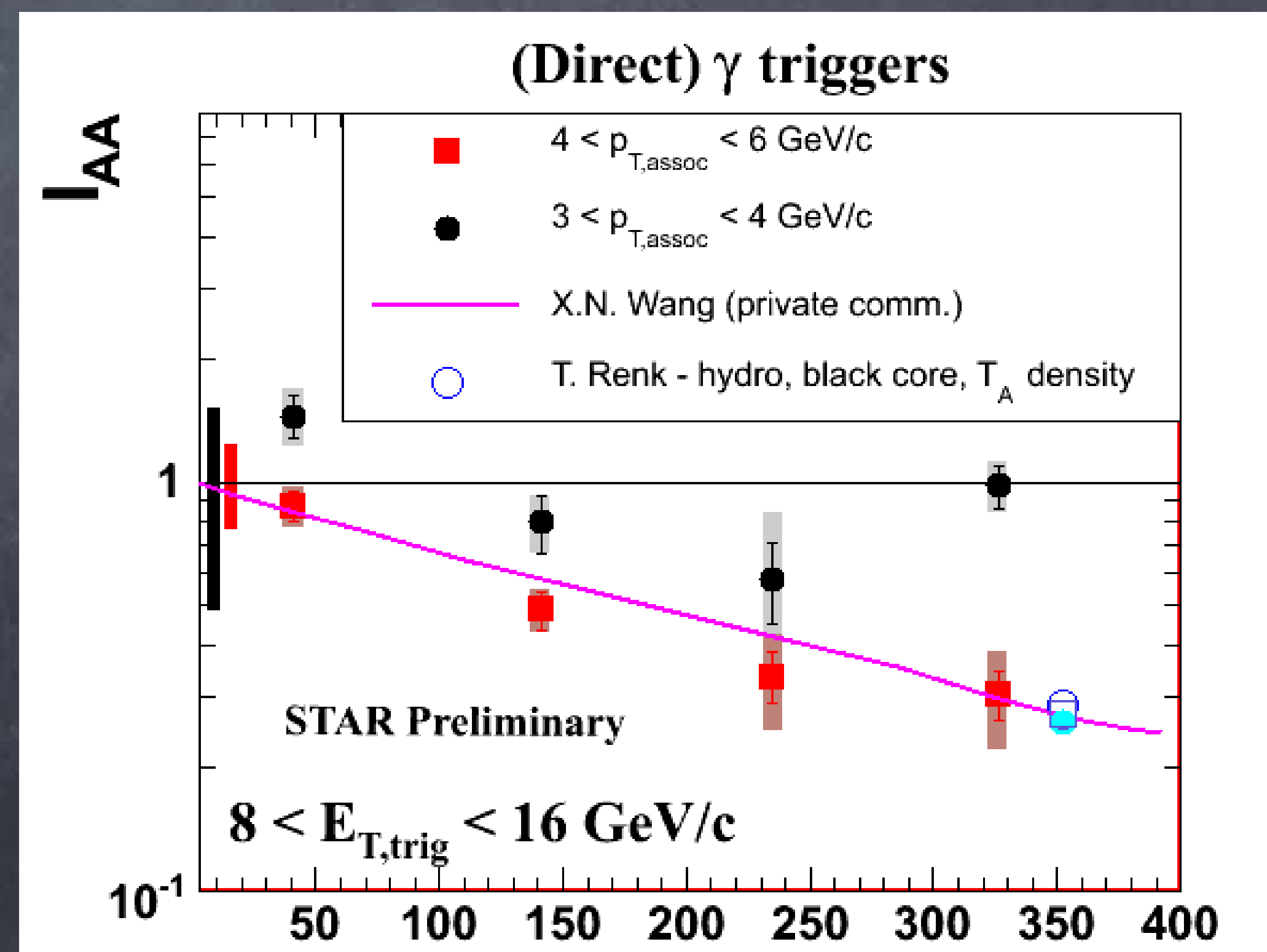
H. Zhang, et. al. PRL 98, 212301, 2007




Away side , Near side , photon triggered, all with one qhat

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

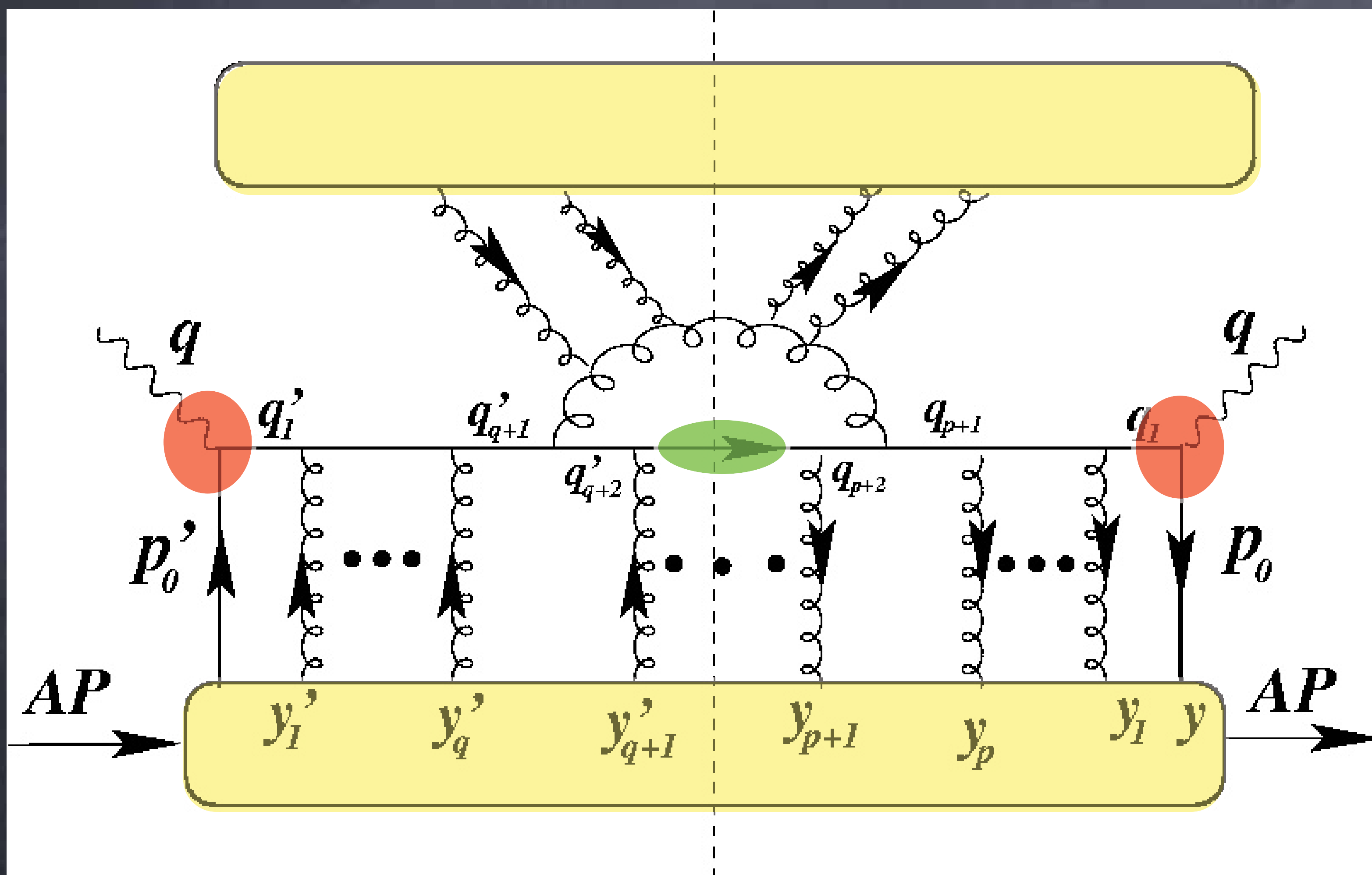



T. Renk & K. Eskola, Phys.Rev.C75:054910,2007

# The big caveat: Factorization(s) involved!

including the effect of gluon scattering off the medium
is including the effect of higher twist operators




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

Can an arbitrary order diagram be always reduced to the simple factorized form

Semi-rigorous proof up to twist-4 Qiu & Sterman

# Problem, slightly more complicated in HIC

Also, somewhat less complicated !
The medium for initial state scattering is different from that in final state scattering

Usual argument: final medium is too dense, ignore scattering in the initial state and only consider scattering in the final state!

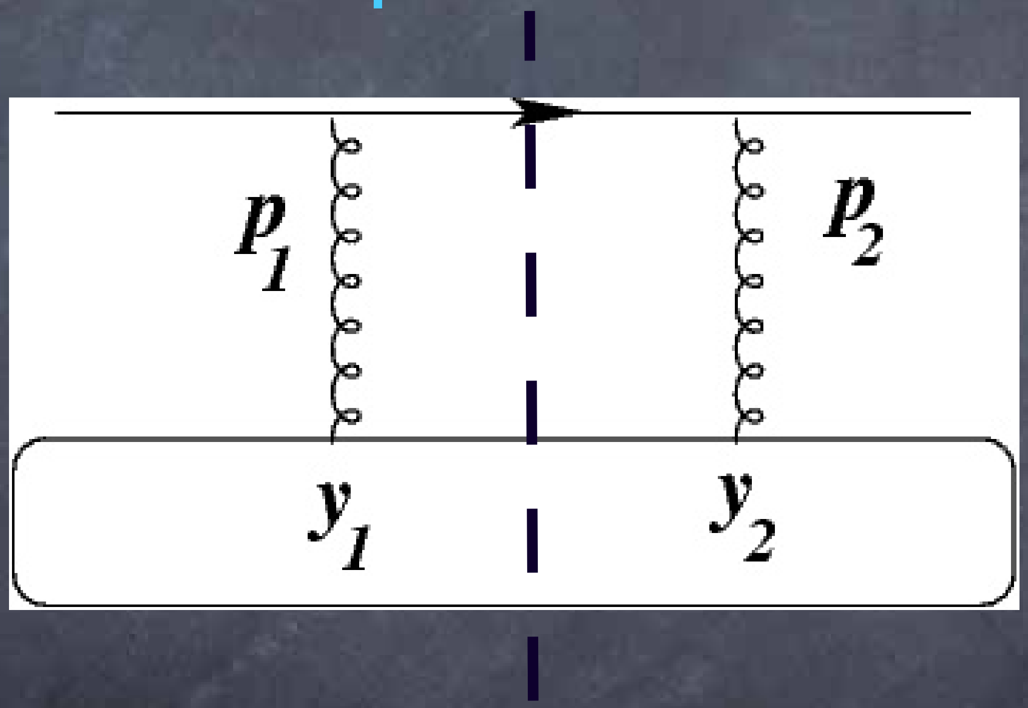
$$\frac{d\sigma^{h_1}}{dy\,dp_{T_1}} \sim \int dx_a\,dx_b\; G(x_a)\; G(x_b)\; \frac{d\hat{\sigma}}{d\hat{t}}\; \widetilde{D}_q^{h_1}(z_1)$$

None of this has been demonstrated!

# The factorization in the definition of qhat

In these calculations, the gluons originate from some soft non-perturbative source

Can this be decoupled from the collinear quark




Can all these questions be answered with SCET

1) SCET does not have gluons with $p_T >> p^+, p^-$
2) SCET does not include gluons with intermediate lines becoming virtual

# Conclusions

1) Need to introduce a Glauber lagrangian as an additional piece to the SCET lagrangian.

2) This may be it, all questions may be addressable using this two part lagrangian.

3) May need to incorporate interactions which make intermediate lines go more off-shell than in SCET.

4) Need to set up or outline the limits of a factorized formalism so as to make rigorous statements about matter formed at RHIC and LHC - HI experiments