Theory Overview

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ISMD 2013, Illinois Institute of Technology, Chicago, Sept 19 2013

Jet Modification in heavy-ion collisions:
Theory Overview

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Outline

- A bit of history
- The pQCD paradigm, lost and found
- The underlying physics
- Outstanding challenges
- Future calculations

From my last ISMD 2007

From my last ISMD 2007

Duke Physics

The Study of Dense Matter through Perturbative Jet Modification

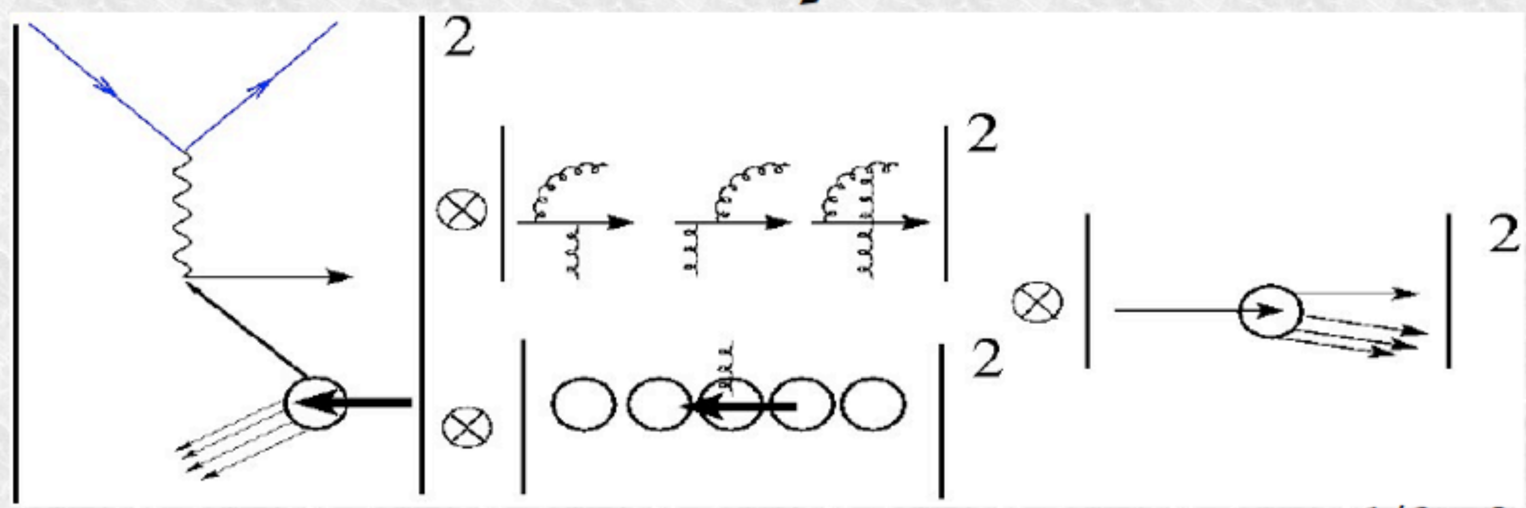
A. Majumder
Duke University

International Symposium on Multi-particle Dynamics 2007, LBNL, Aug 3-9

From my last ISMD 2007

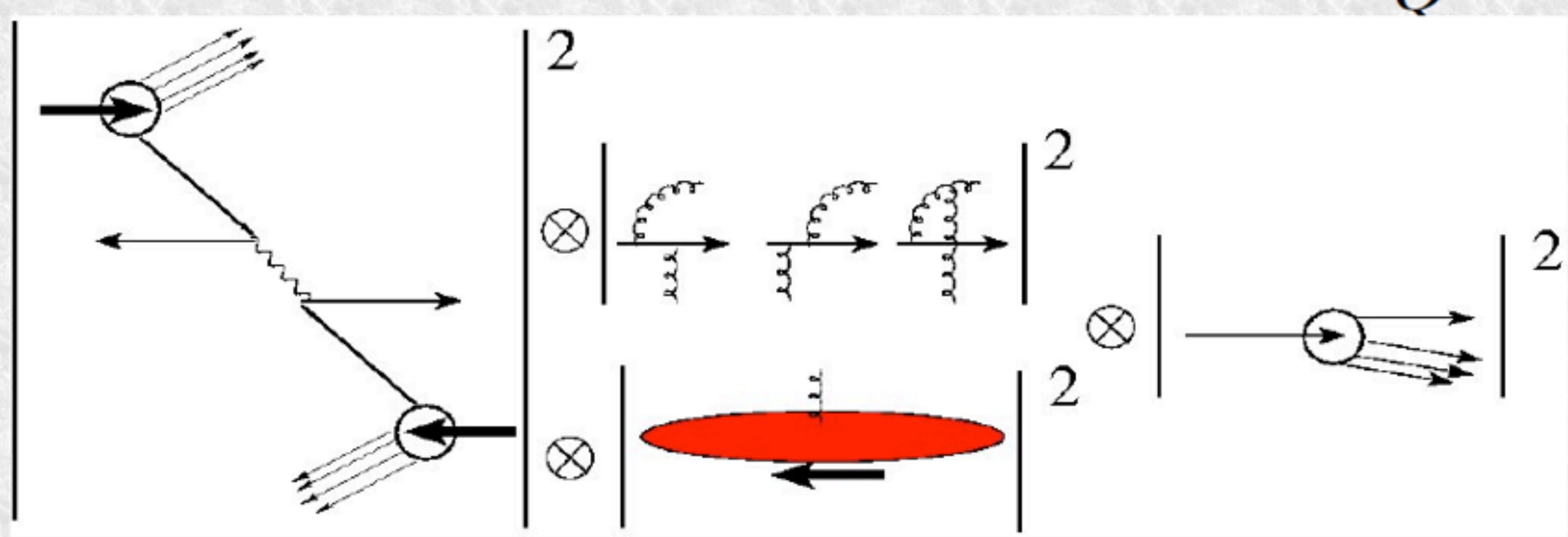
E-loss kernel same: factorization

A-DIS



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

Au-Au



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

From my last ISMD 2007

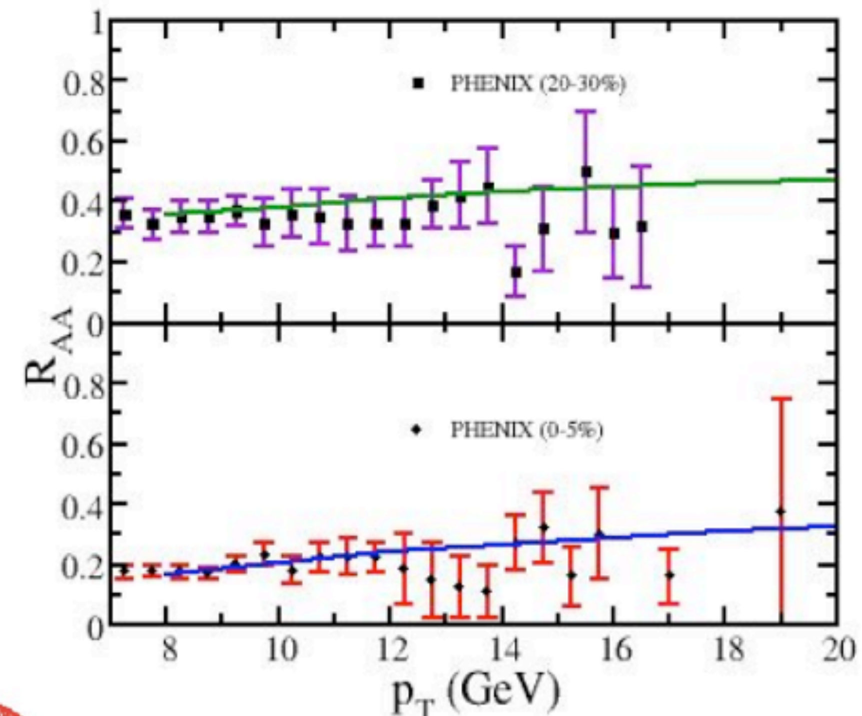
An example: the space-time profile

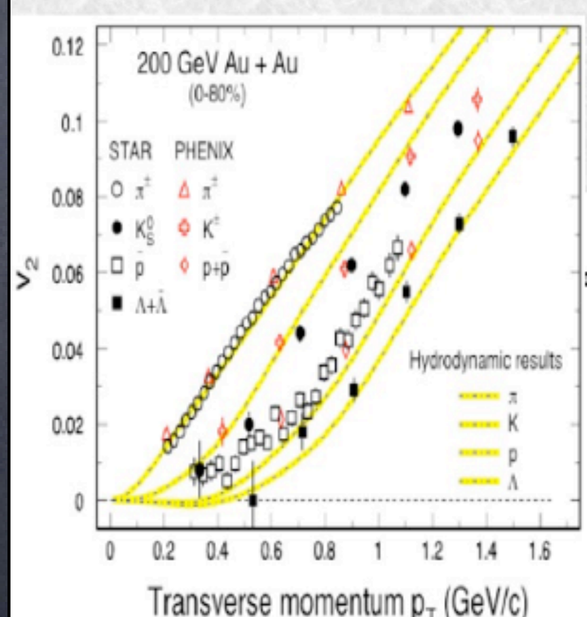
$$\hat{q}^{\mu\nu} = \hat{q}_0(f)\,\delta^{\mu\nu}\,\frac{\gamma_\perp(x,y,z,t)\,T^3(x,y,z,t)}{T_0^3(x,y,z,t)}$$

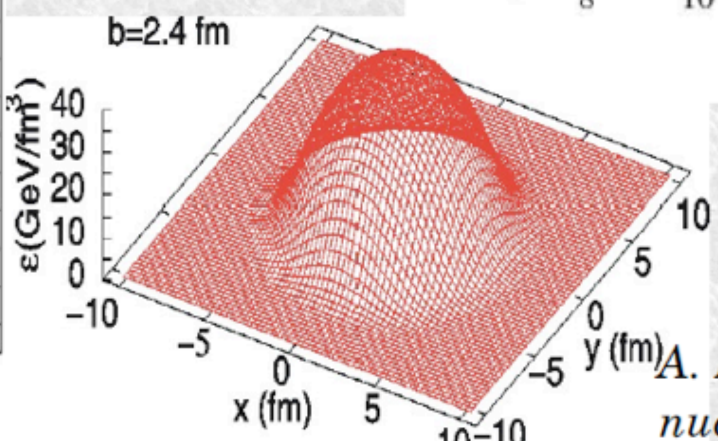
$$\hat{q}_0(quarks) = 1.3\,GeV^2/fm$$

Test of the hydro model!

Use the same hydrodynamic model that predicted the soft spectra

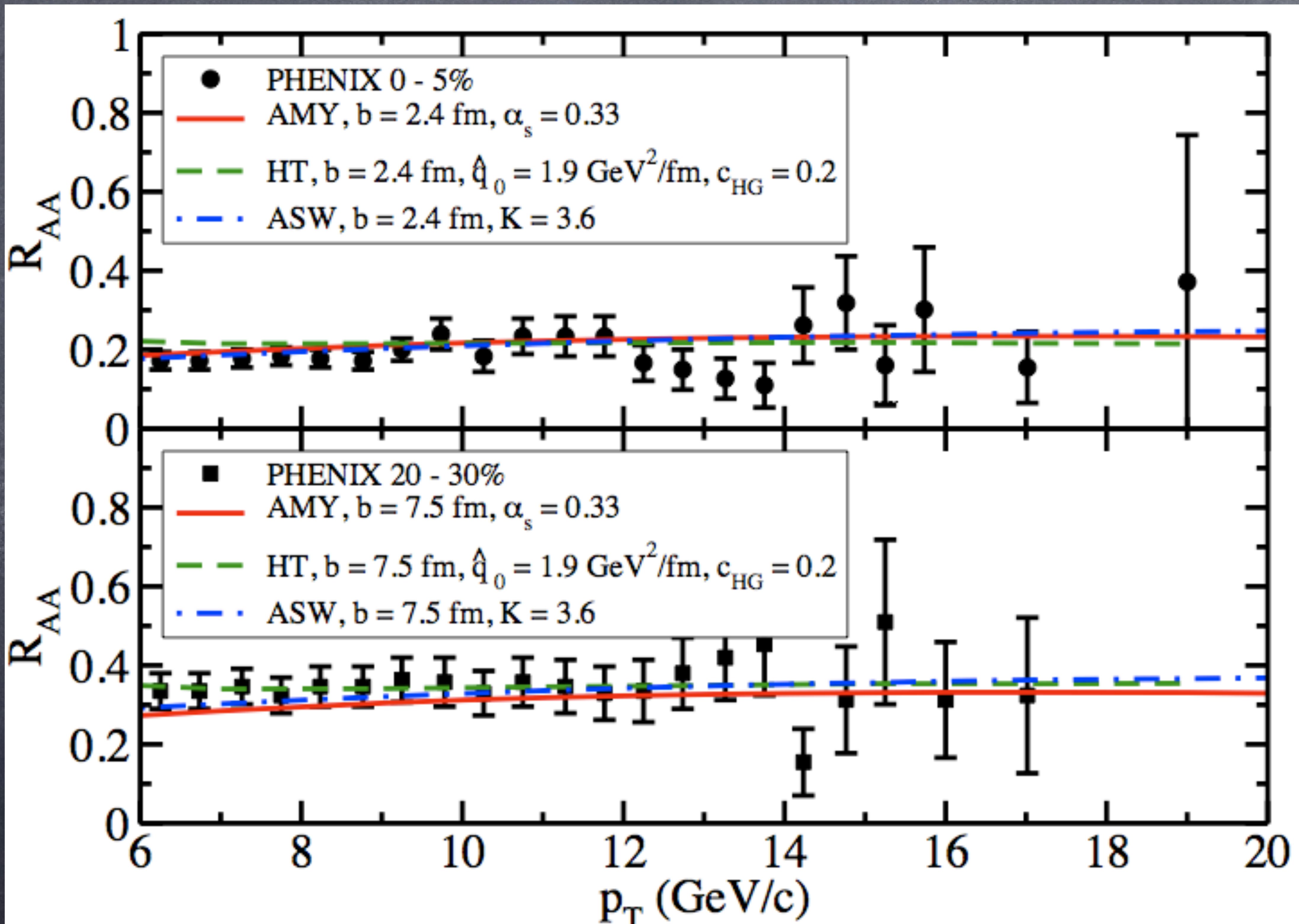






A. Majumder, C. Nonaka, S. Bass, nucl-th/0703019

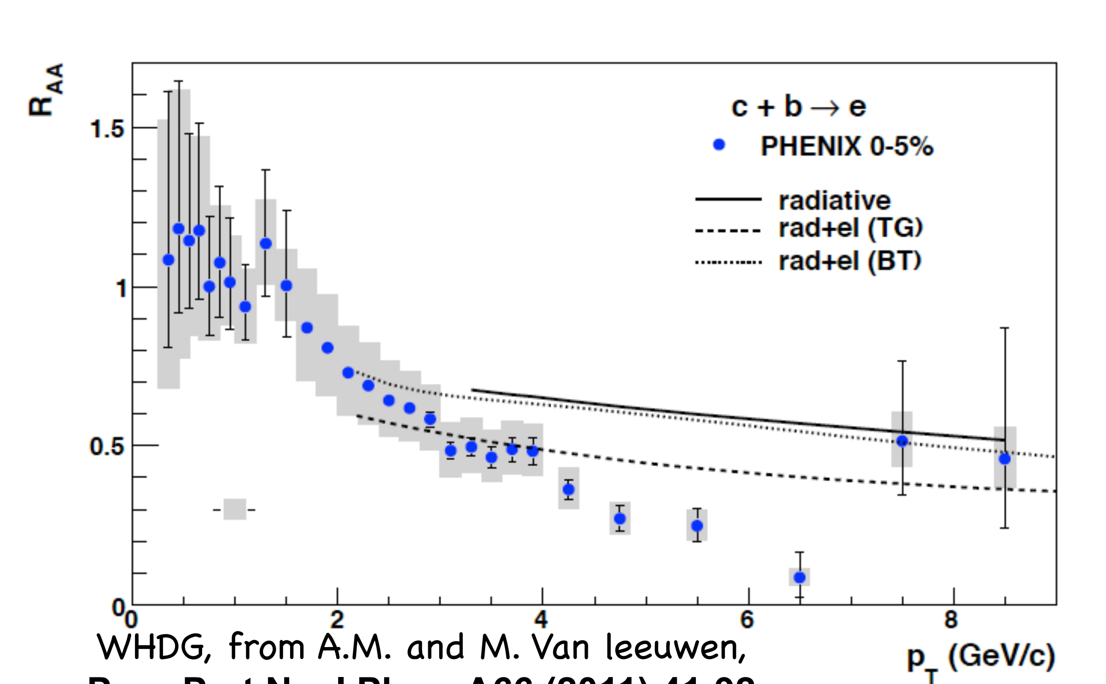
But there were multiple formalisms that were indistinguishable!



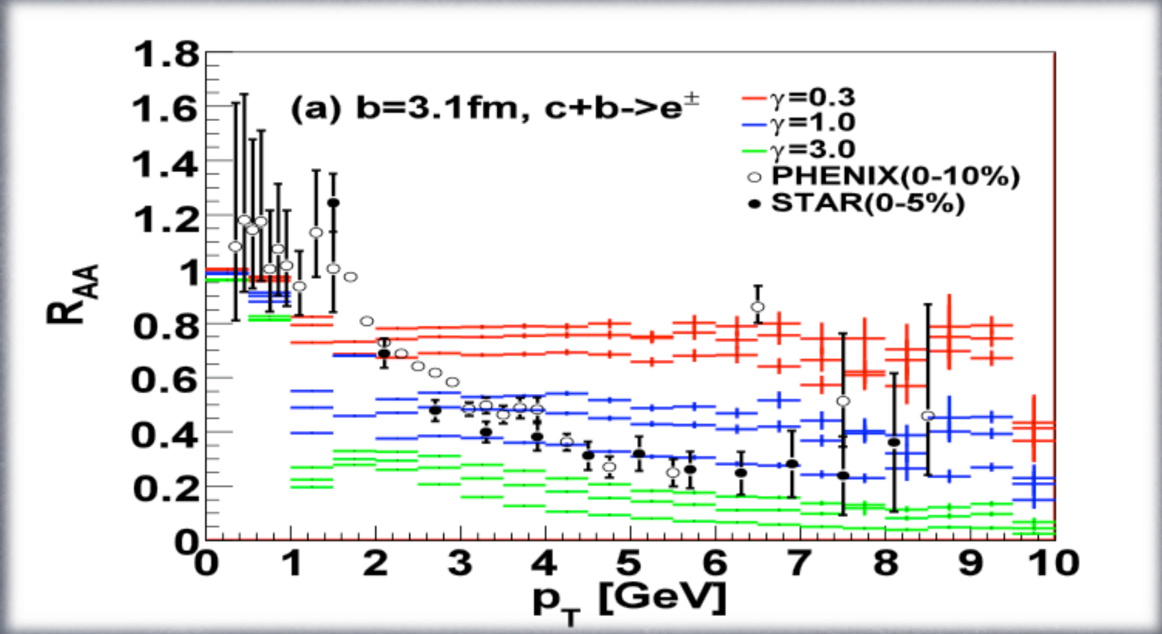
But there were multiple formalisms that were indistinguishable!

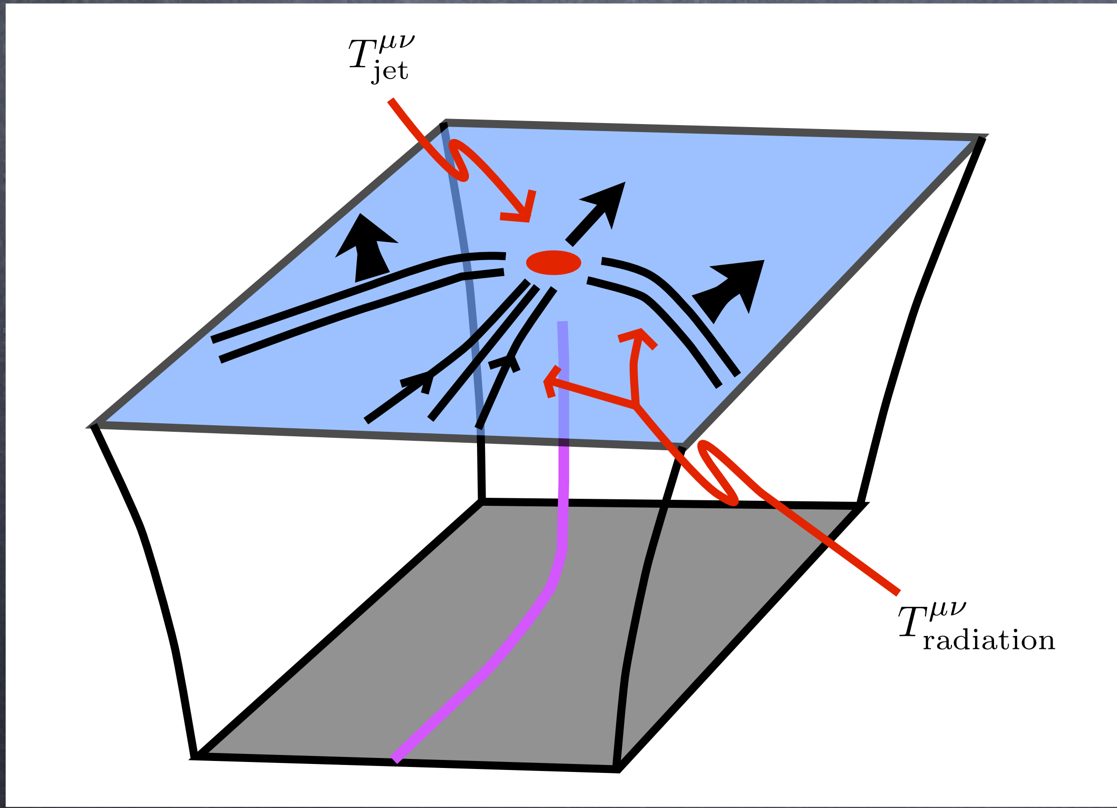
$\hat{q}(\vec{r},\tau)$ scales as	ASW $\hat{q}_0$	HT $\hat{q}_0$	AMY $\hat{q}_0$
$T(\vec{r},\tau)$	10 GeV^2/fm	2.3 GeV^2/fm	4.1 GeV^2/fm
$\epsilon^{3/4}(\vec{r},\tau)$	18.5 GeV^2/fm	4.5 GeV^2/fm	
$s(\vec{r},\tau)$		4.3 GeV^2/fm	

pQCD lost!



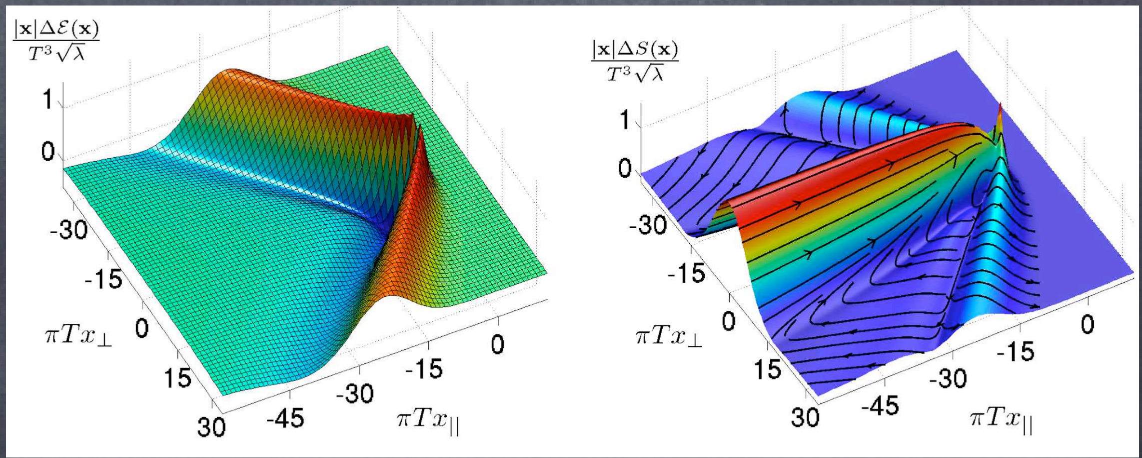
WHDG, from A.M. and M. Van leeuwen,
Prog.Part.Nucl.Phys. A66 (2011) 41-92





Akamatsu, Hatsuda Hirano 2008

$$\Delta\vec{p} = -\gamma\frac{T^2}{M}\vec{p}\Delta t + \vec{\xi}(t)$$



Chesler and Yaffe

The LHC and the return of pQCD

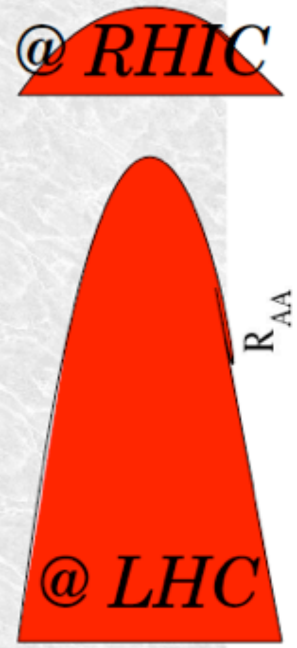
Jets @ LHC

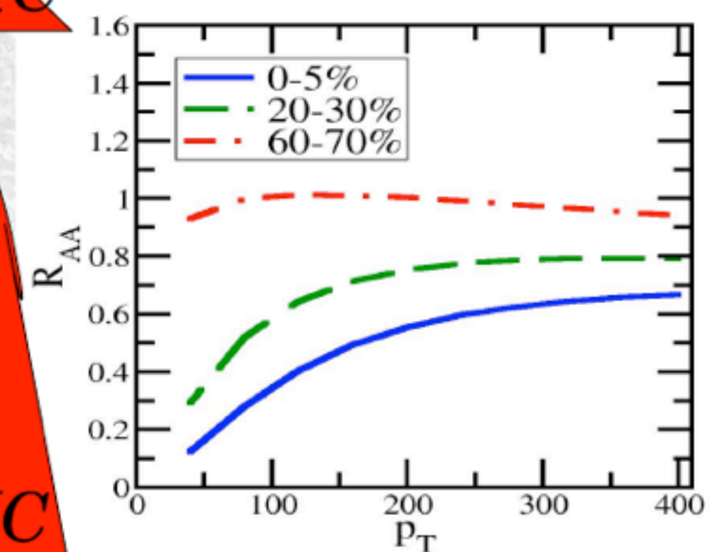
How to deal with denser medium,

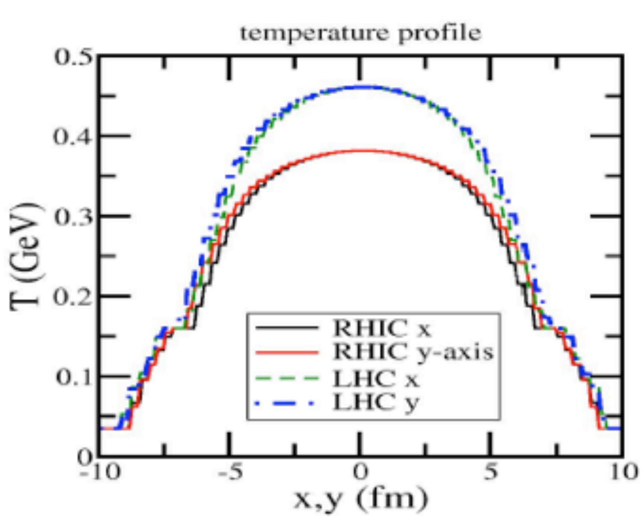
Medium may be denser overall

Space time dist. may be different

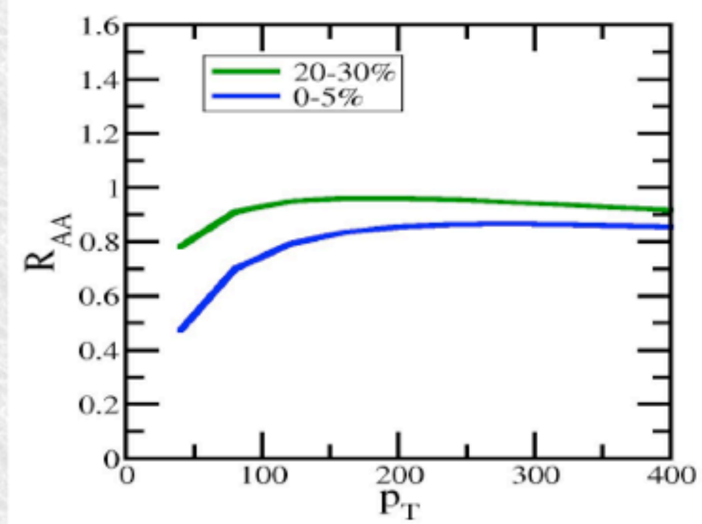
Jet correlations will tell the difference

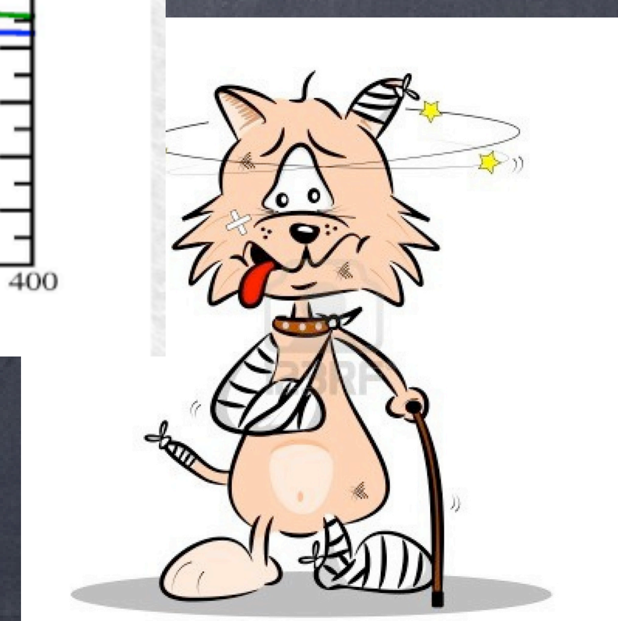




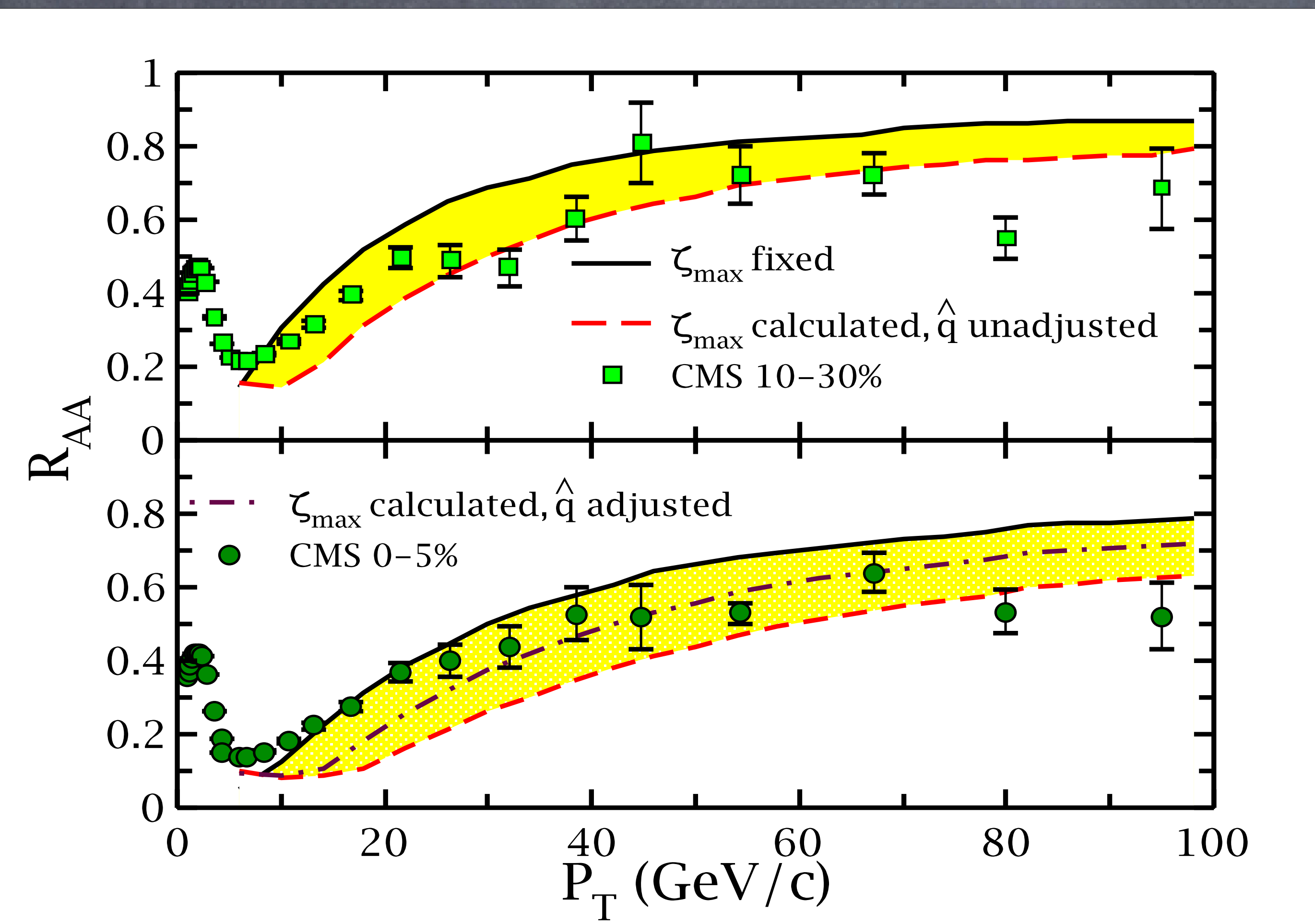


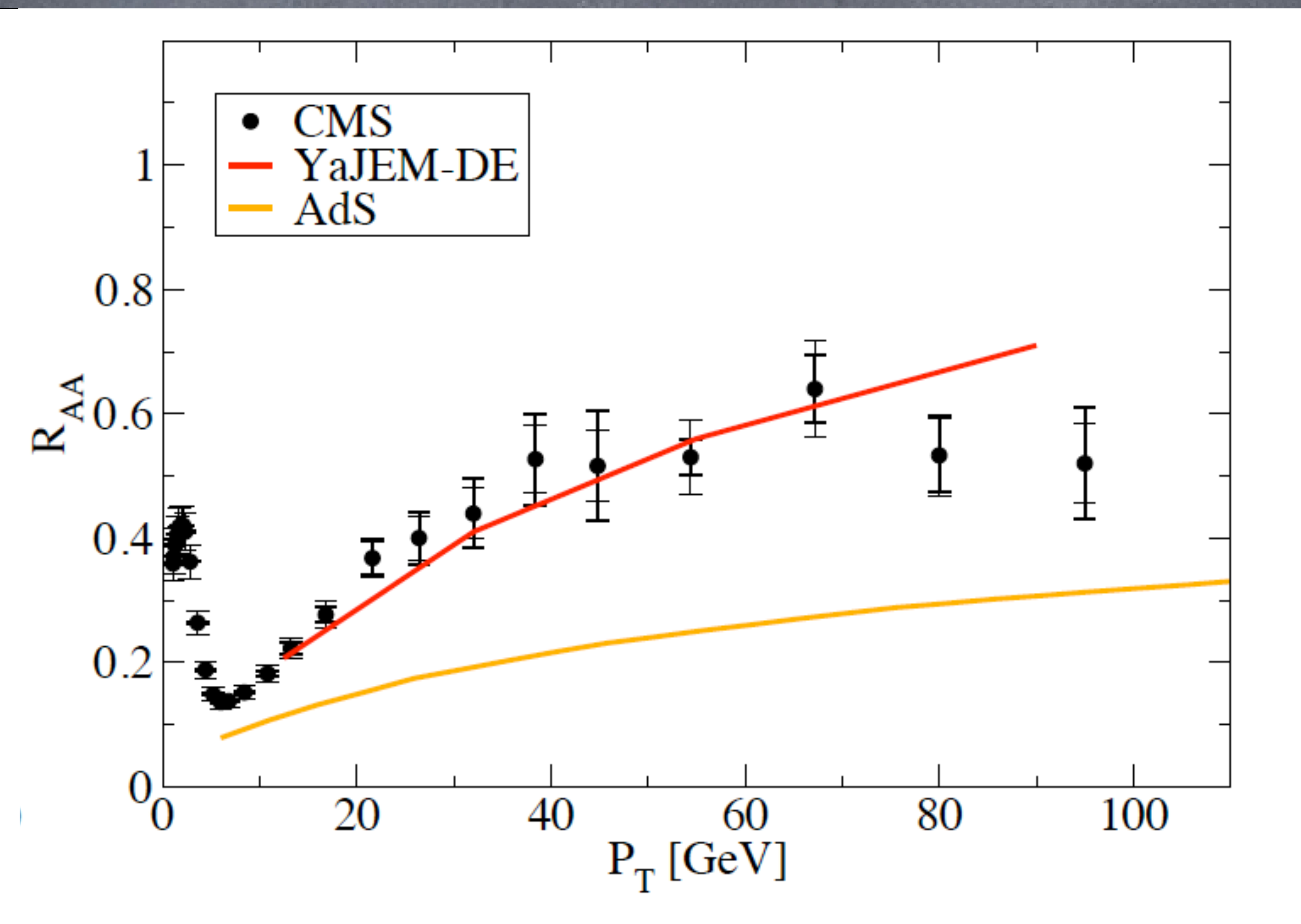
Density bunched up in the middle





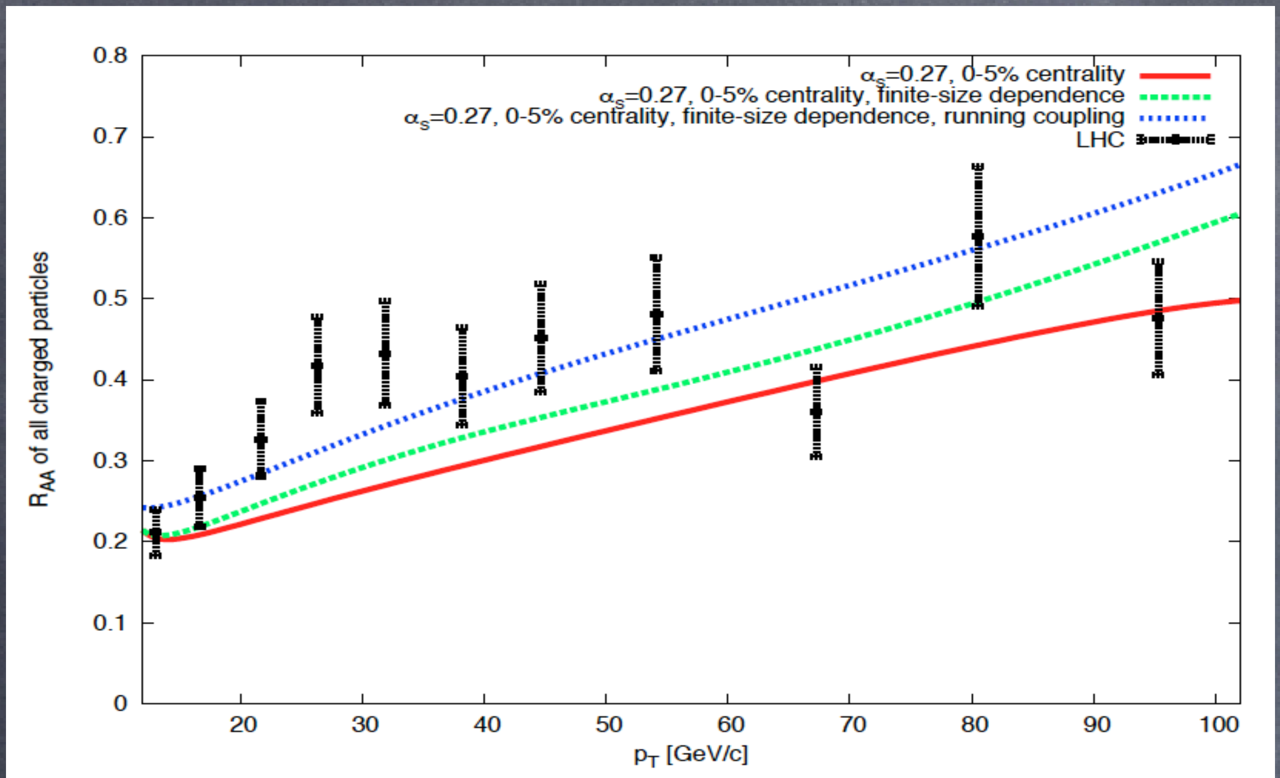
The LHC and the return of pQCD

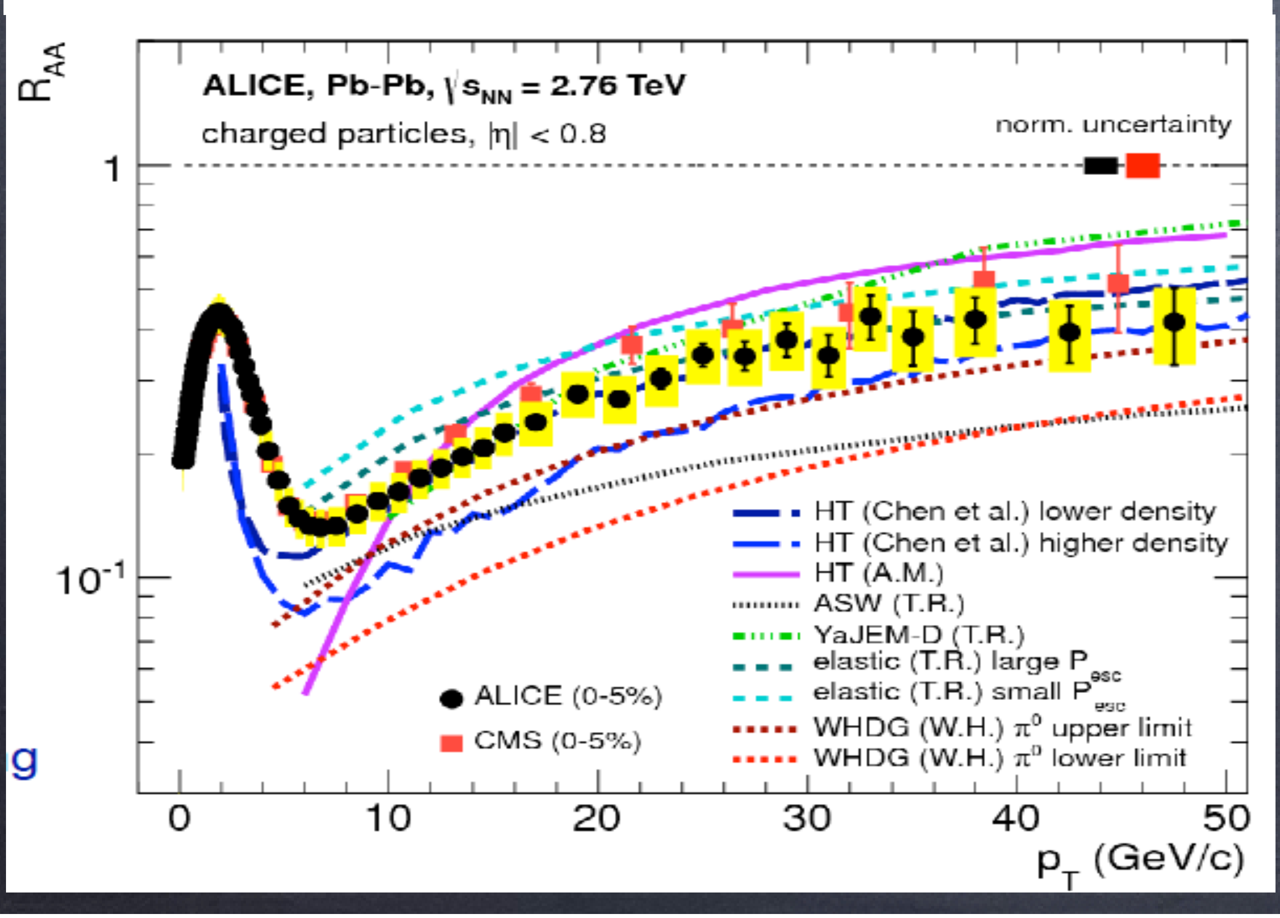




strong coupling energy loss ruled out

LHC also makes it hard for other unfactorized pQCD approaches





AMY: ignores α_s running, ignores initial virtuality

ASW: Strictly Eikonal ruled out

GLV: ignores α_s running

What about that $\hat{q}$?

$\hat{q}(\vec{r},\tau)$ scales as	ASW $\hat{q}_0$	HT $\hat{q}_0$	AMY $\hat{q}_0$
$T(\vec{r},\tau)$	10 $\mathrm{GeV}^2/\mathrm{fm}$	2.3 $\mathrm{GeV}^2/\mathrm{fm}$	4.1 $\mathrm{GeV}^2/\mathrm{fm}$
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Ruled out by LHC

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Ruled out by LHC

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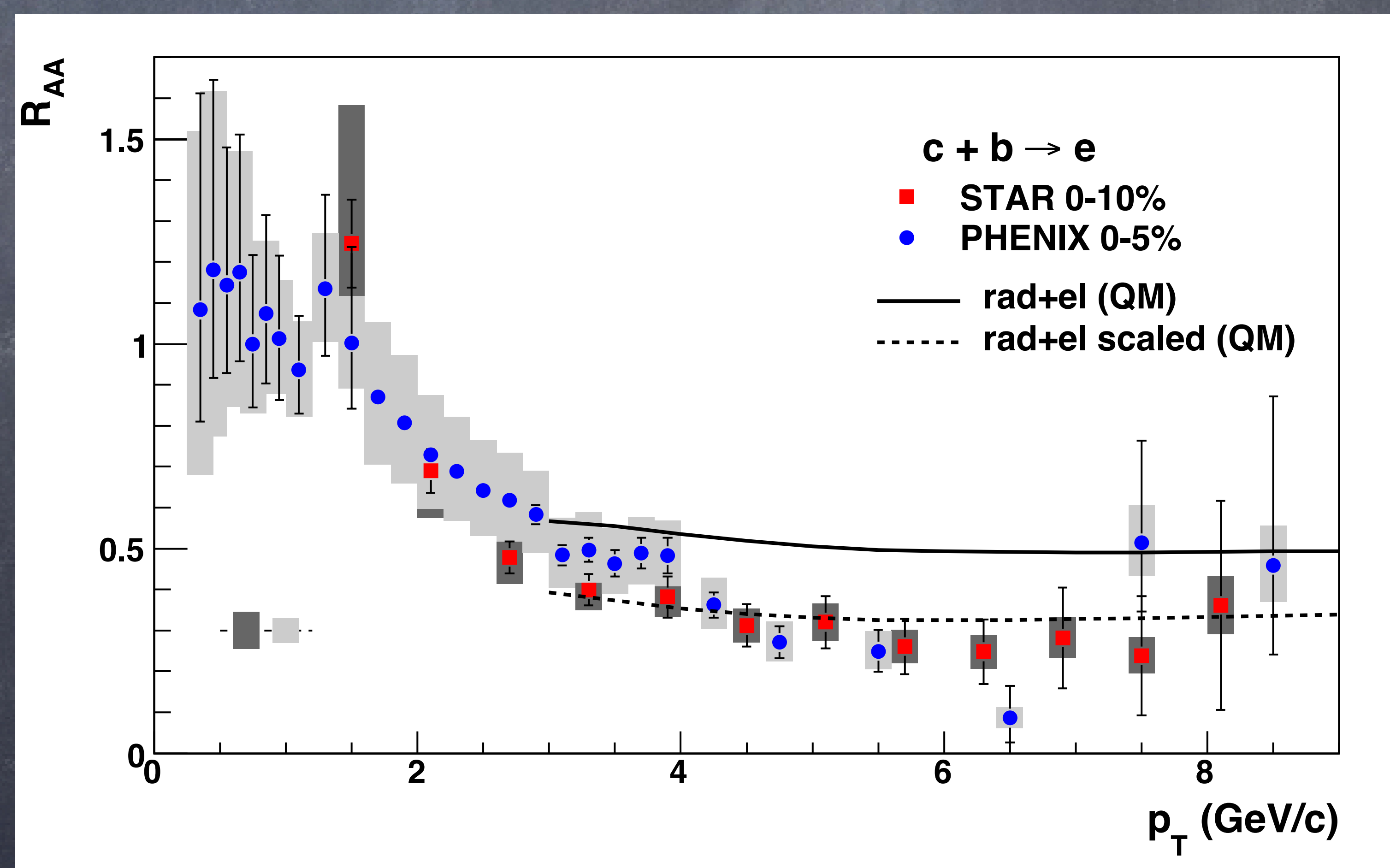
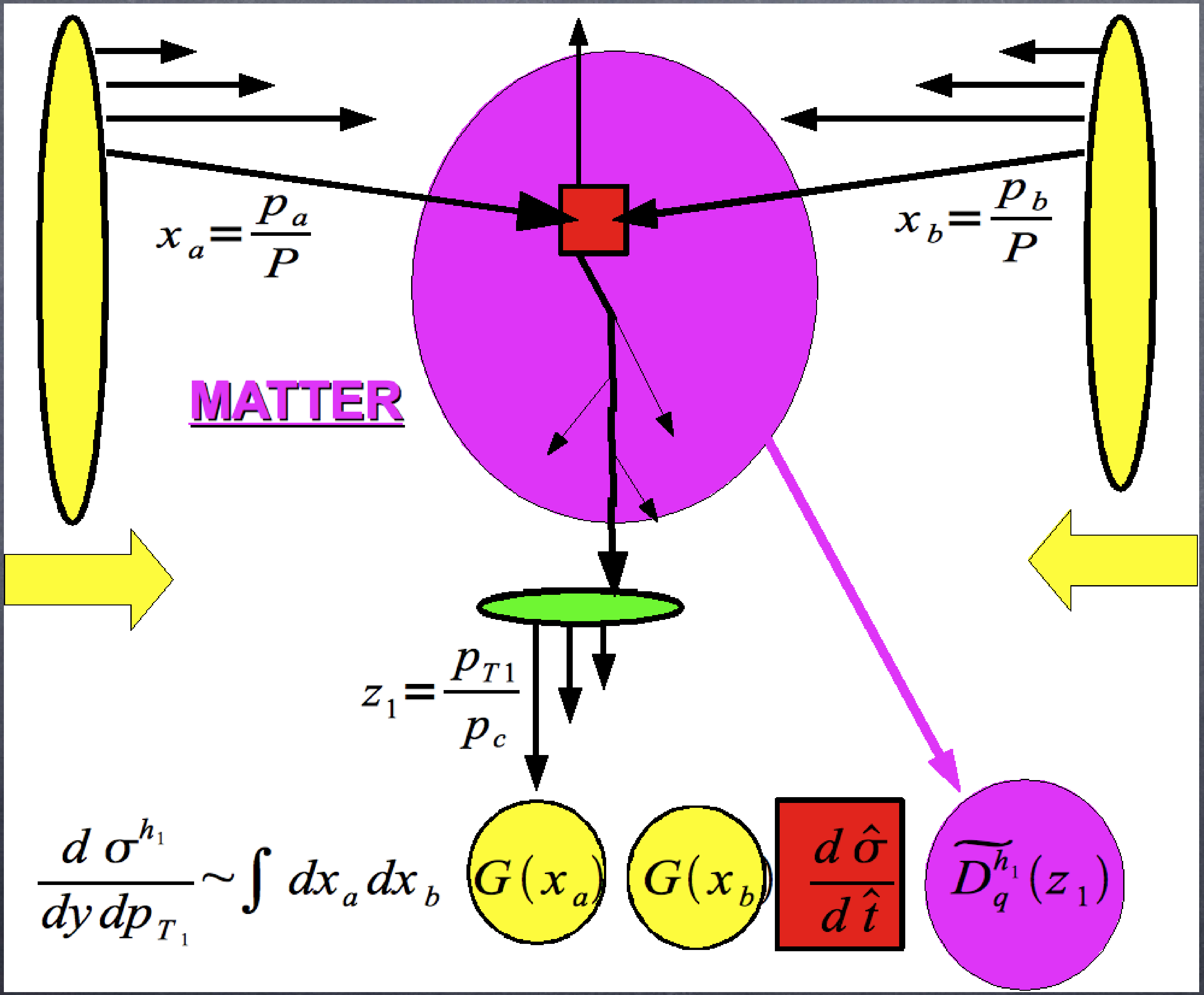
$s(\vec{r},\tau)$	[illegible]	$4.3\ \mathrm{GeV}^2/\mathrm{fm}$	

Drop the requirement that the medium can be described by LO pQCD



The requirements for a successful pQCD formalism



What goes into this calculation

Jet scale assumed much harder than medium scale (factorization of jet from soft matrix element)

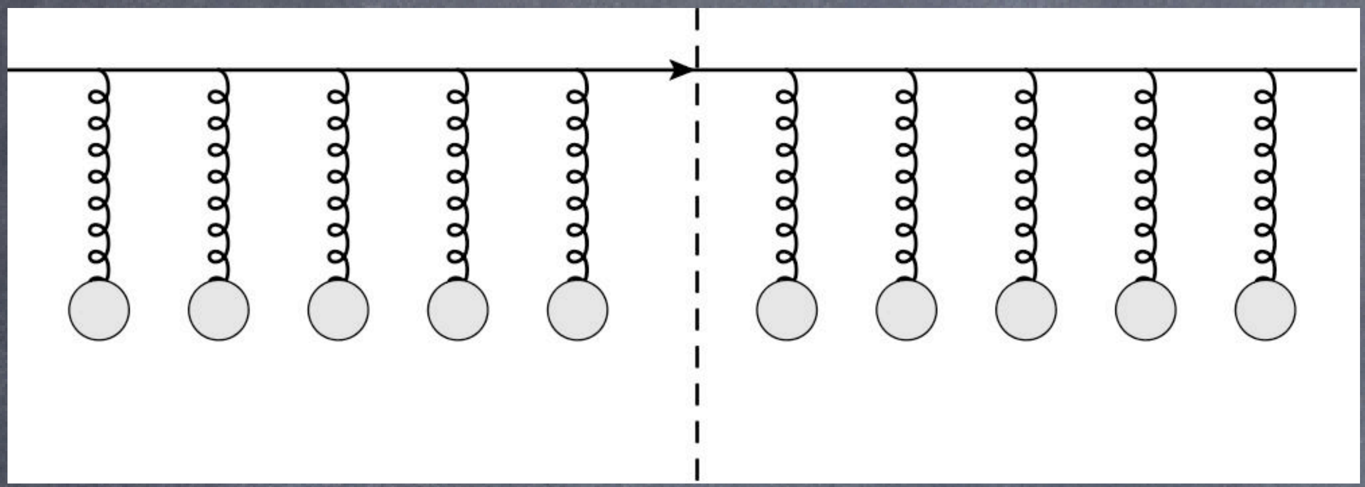
Multiple scatterings resummed in single gluon emission

Expansion in powers of Λ^2/Q^2

DGLAP k_T^2 systematics assumed for multiple emissions

Fluid dynamical simulation of medium and trans. coeffs.

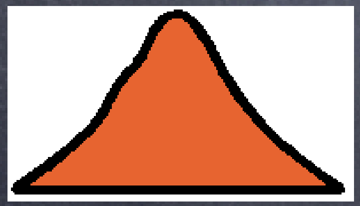
Multiple scattering induced transverse broadening



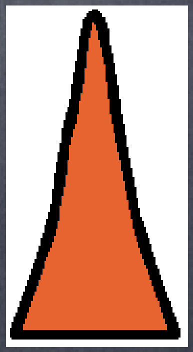
$$q^- \to \infty$$

Assuming independent scattering of nucleons gives a diff. equation

These cannot be soft, they must have transverse momentum, Glauber gluons.



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



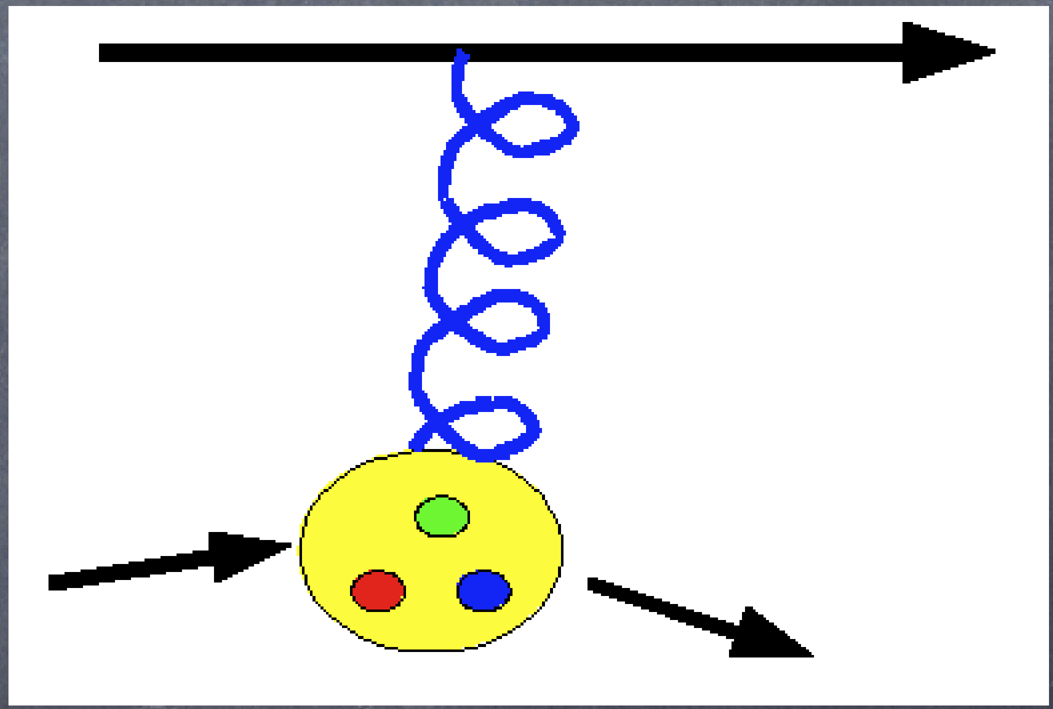
$$\langle p_\perp^2 \rangle = 4Dt$$

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

Longitudinal drag and diffusion

A close to on shell parton has a 3-D distribution

$$p^+ = \frac{p_\perp^2}{2p^-}$$



$$f(\vec{p}) \equiv \delta^2(p_\perp^2)\delta(p^- - q^- + k^-)$$

Using the same analysis, we get a drag. and diff. term

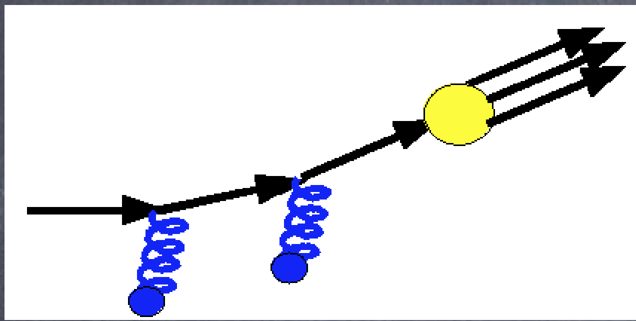
$$\frac{\partial f(p^-, L^-)}{\partial L^-} = c_1 \frac{\partial f}{\partial p^-} + c_2 \frac{\partial^2 f}{\partial^2 l^-}$$

c_1 is dE/dL, calculate in a deconfined quasi-particle medium.

Majumder 2009

There are a bunch of medium properties which modify the parton and frag. func.

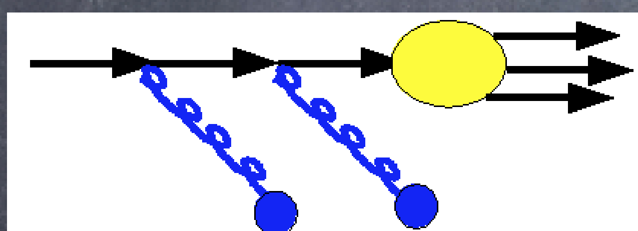
q̂, ê = dE/dL and f̂ = dN/dL



$$D\left(\frac{\vec{p}_h}{|\vec{p}+\vec{k}_\perp|}, m_J^2\right)$$

$$\hat{q} = \frac{\langle p_T^2 \rangle_L}{L}$$

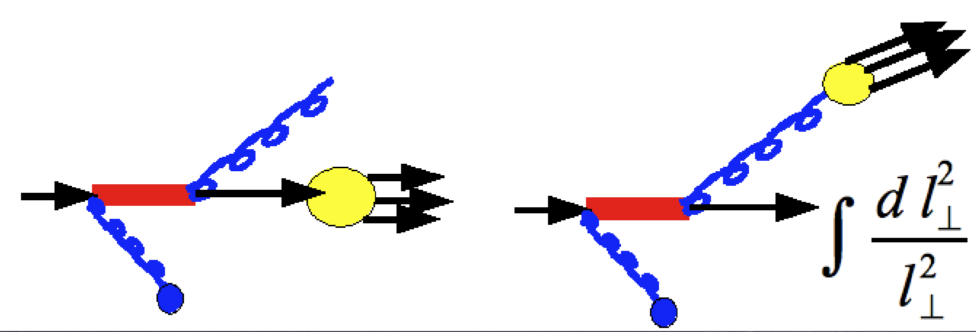
Transverse momemtum diffusion rate



$$D\left(\frac{p_h}{p-k}, m_J^2\right)$$

$$\hat{e} = \frac{\langle \Delta E \rangle_L}{L}$$

Elastic energy loss rate also diffusion rate e_2

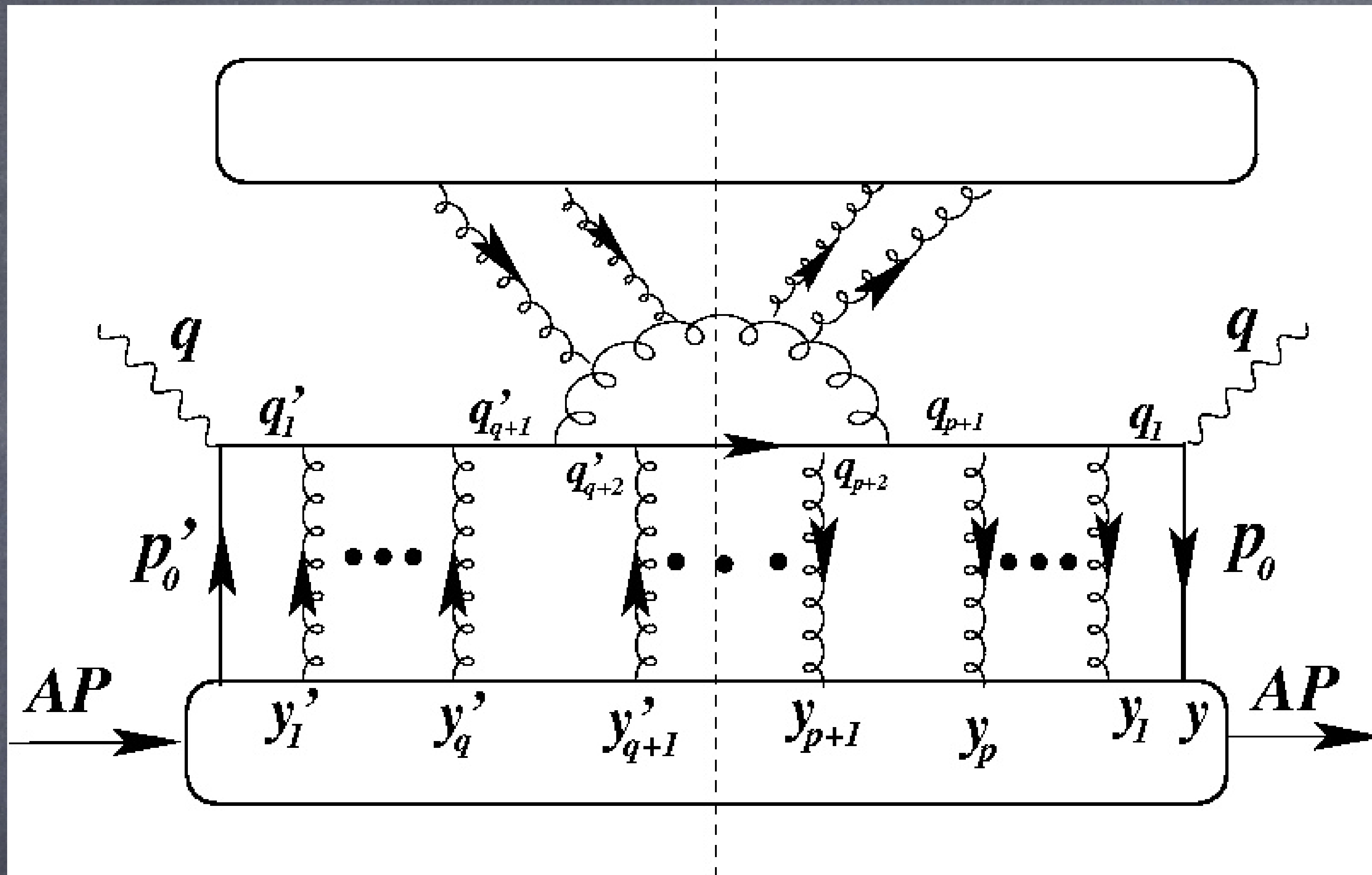


$$\int \frac{d\,l_\perp^2}{l_\perp^2} \int_{\frac{p_h}{p}}^{1} \frac{d\,y}{y} P(y)\, M(\vec{r}, y, l_\perp)\, D\left(\frac{p_h}{p\,y}\right)$$

Gluon radiation is sensitive to all these transport coefficients

And a bunch of off diagonal and higher order transport coefficients

The single gluon emission kernel

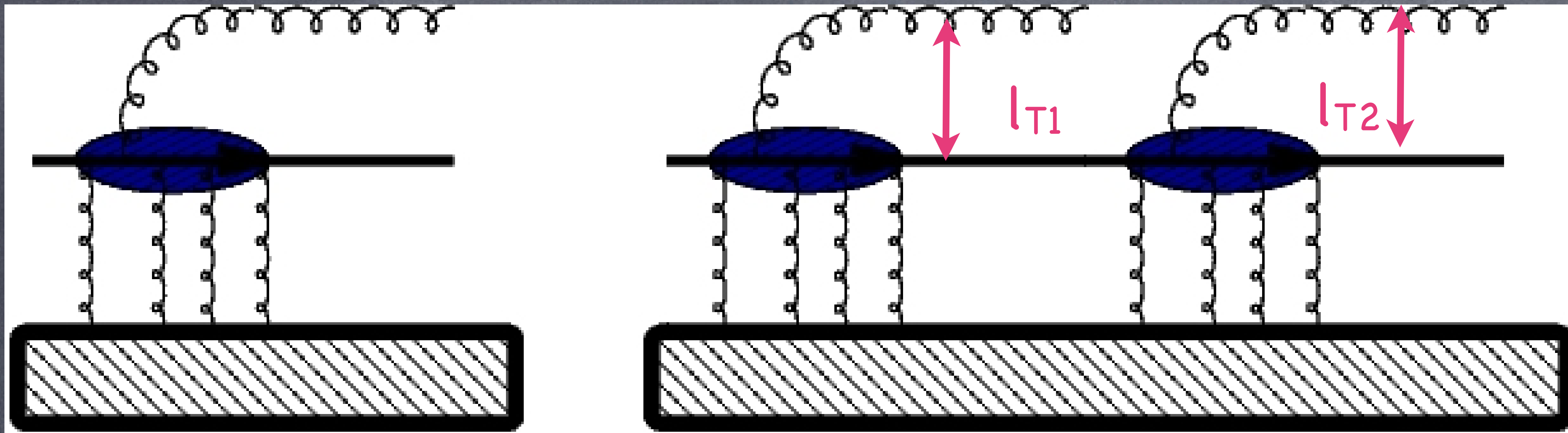


Calculate 1 gluon emission with quark & gluon N-scattering with transverse broadening and elastic loss built in

Finally solved analytically, in large Q^2 limit.

A. Majumder: arXiv:0912.2987 [nucl-th]

Need to repeat the kernel



What is the relation between subsequent radiations ?

In the large Q^2 we can argue that there should be ordering of l_T. $\quad if \;\; \hat{q}L \;\; < \;\; Q^2$

$$\text{then} \qquad \frac{dQ^2}{Q^2}\left[1 + c_1 \frac{\hat{q}L}{Q^2}\right] \leq \frac{dQ^2}{Q^2}[1 + c_1]$$

However, at lower Q^2, possible anti-ordering

Coherence effects and broadening in medium-induced QCD radiation off a massive q q antenna

Néstor Armesto, Hao Ma, Yacine Mehtar-Tani, Carlos A. Salgado, Konrad Tywoniuk

JHEP 1201 (2012) 109

Analytical calculations always have approximations

$$\frac{\partial D_q^h(z,\mu^2)}{\partial \log(\mu^2)} = \frac{\alpha_s}{2\pi}\int_z^1 \frac{dy}{y} P_{q\to i}(y) D_i^h\left(\frac{z}{y},\mu^2\right)$$

Thus you need a grid in z, q⁻ , and ζ

+

$$\frac{\partial D_q^{h^2}(z,M^2,q^-)|_{\zeta_i}^{\zeta_f}}{\partial \log(M^2)} = \frac{\alpha_s}{2\pi}\int_z^1 \frac{dy}{y}\frac{\tilde{P}_{q\to i}(y)}{M^2}\int_{\zeta_i}^{\zeta_f} d\zeta \frac{2\pi\alpha_s}{N_c} \times \rho_g(\zeta)\left[2-2\cos\left\{\frac{M^2(\zeta-\zeta_i)}{2q^- y(1-y)}\right\}\right] \times D_q^{h^1}\left(\frac{z}{y},M^2,q^- y\right)\Big|_{\zeta}^{\zeta_f}$$

Really hard numerically, so far grid in z, q⁻, and in z,ζ

To go beyond this would require a MC Evt. Gen.

Majumder 2009

A DGLAP formalism requires an upper scale and a lower scale

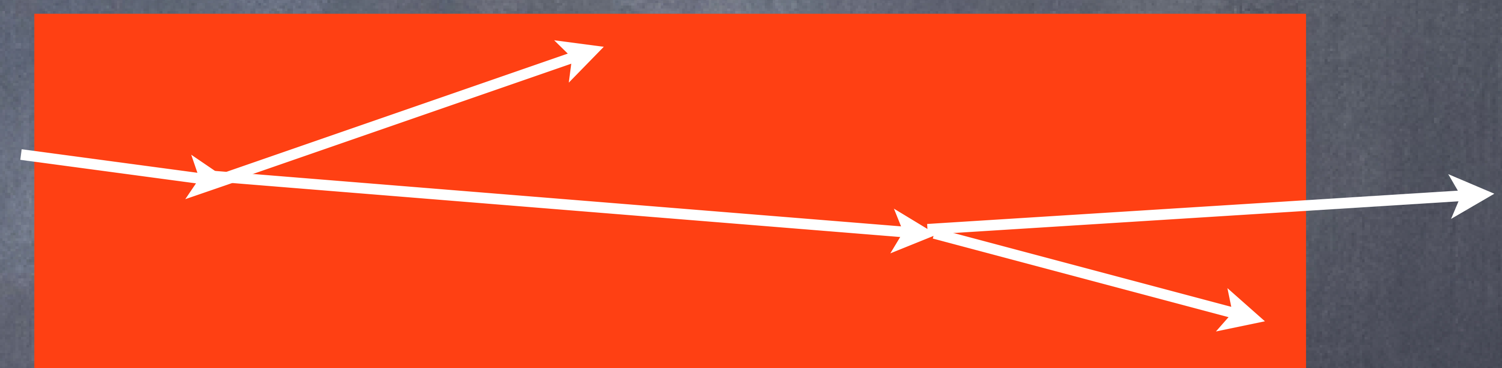
Upper scale is p_T^2 , same as in vacuum

What is the lower scale?

what is the virtuality of a parton on exit ?

Natural choice

$Q^2_{min} = E/L$



Realistically, this should be done for each path

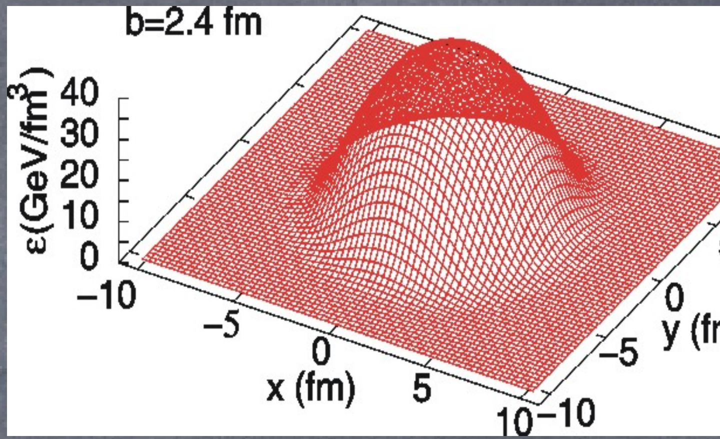
In reality we average kernel over many paths

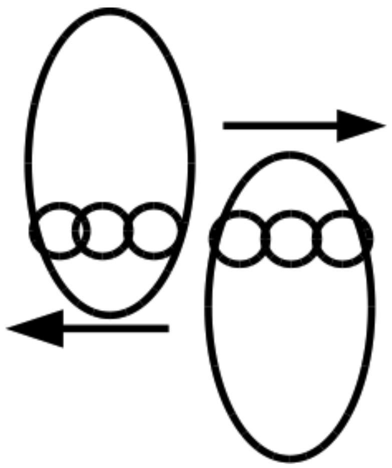
and calculate a mean distance based on the maximum length that the jet can travel in the representative brick

Bulk medium described by viscous fluid dynamics

Medium evolves hydro-dynamically as the jet moves through it

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

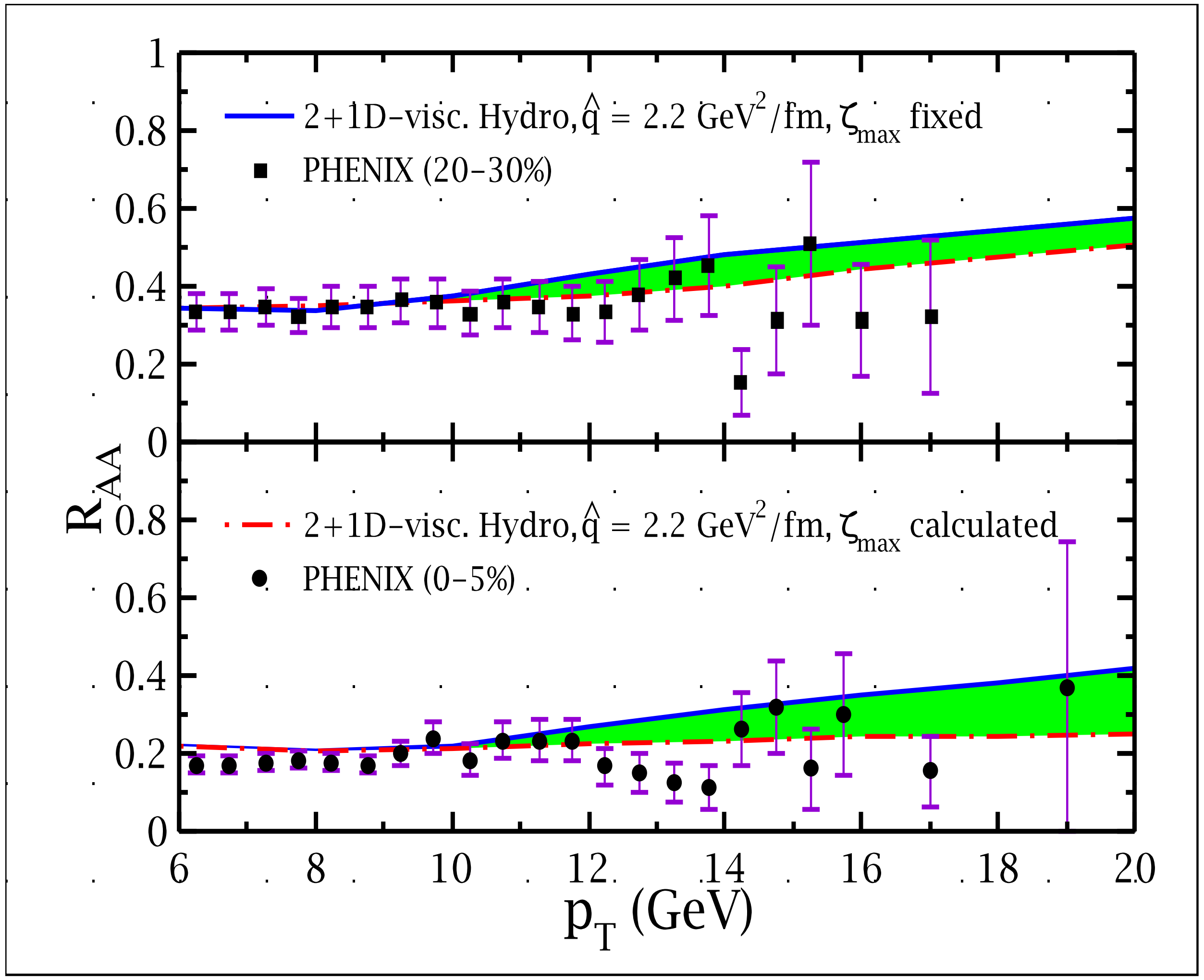




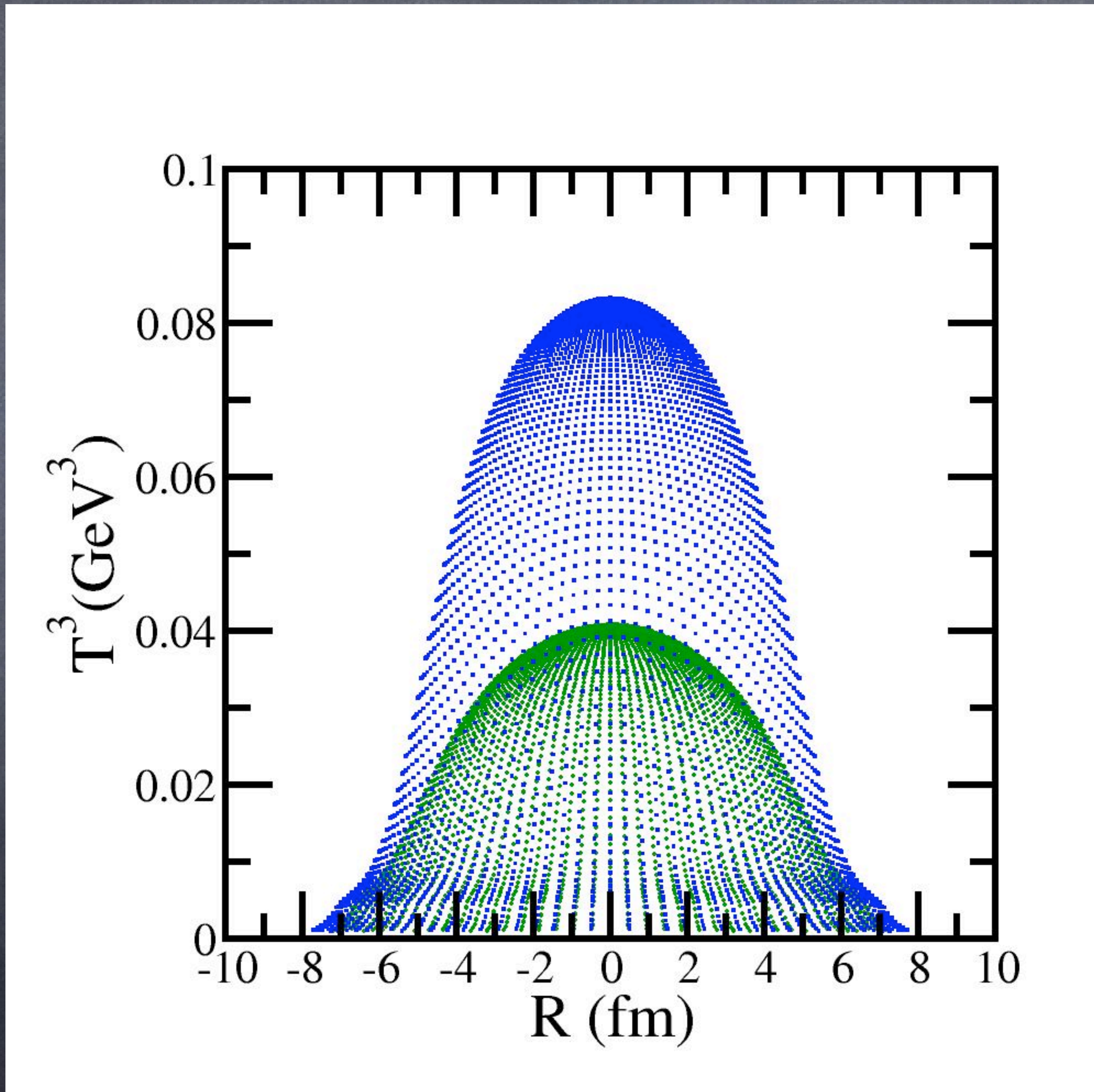
$$\hat{q}(\vec{r},t) = \hat{q}_0 \frac{s(\vec{r},t)}{s_0}$$

$$s_0 = s(T_0)$$

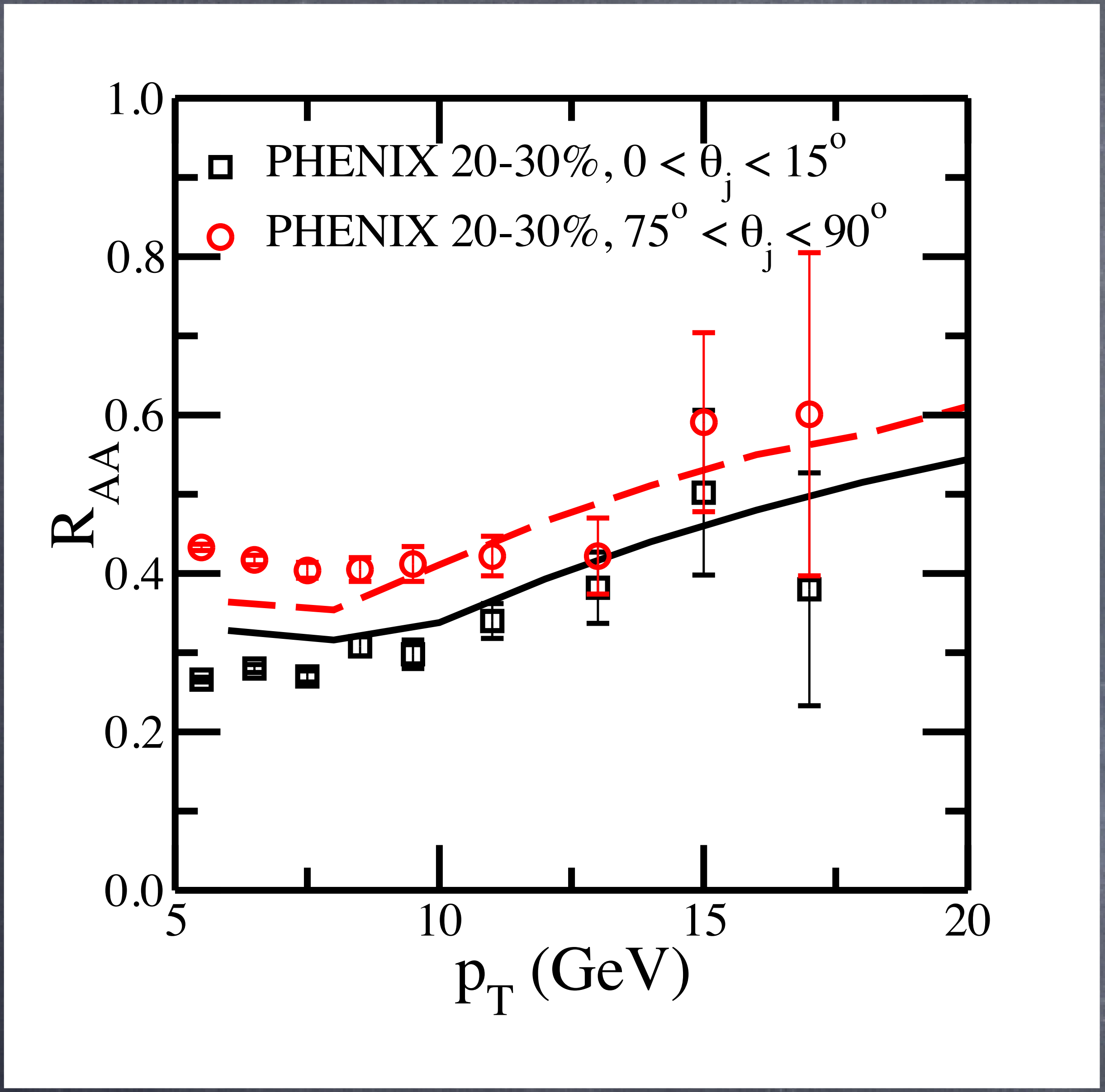
$$R_{AA} \sim \frac{\frac{dN_{AA}}{dp_T dy}}{N_{bin} \frac{dN_{pp}}{dp_T dy}}$$

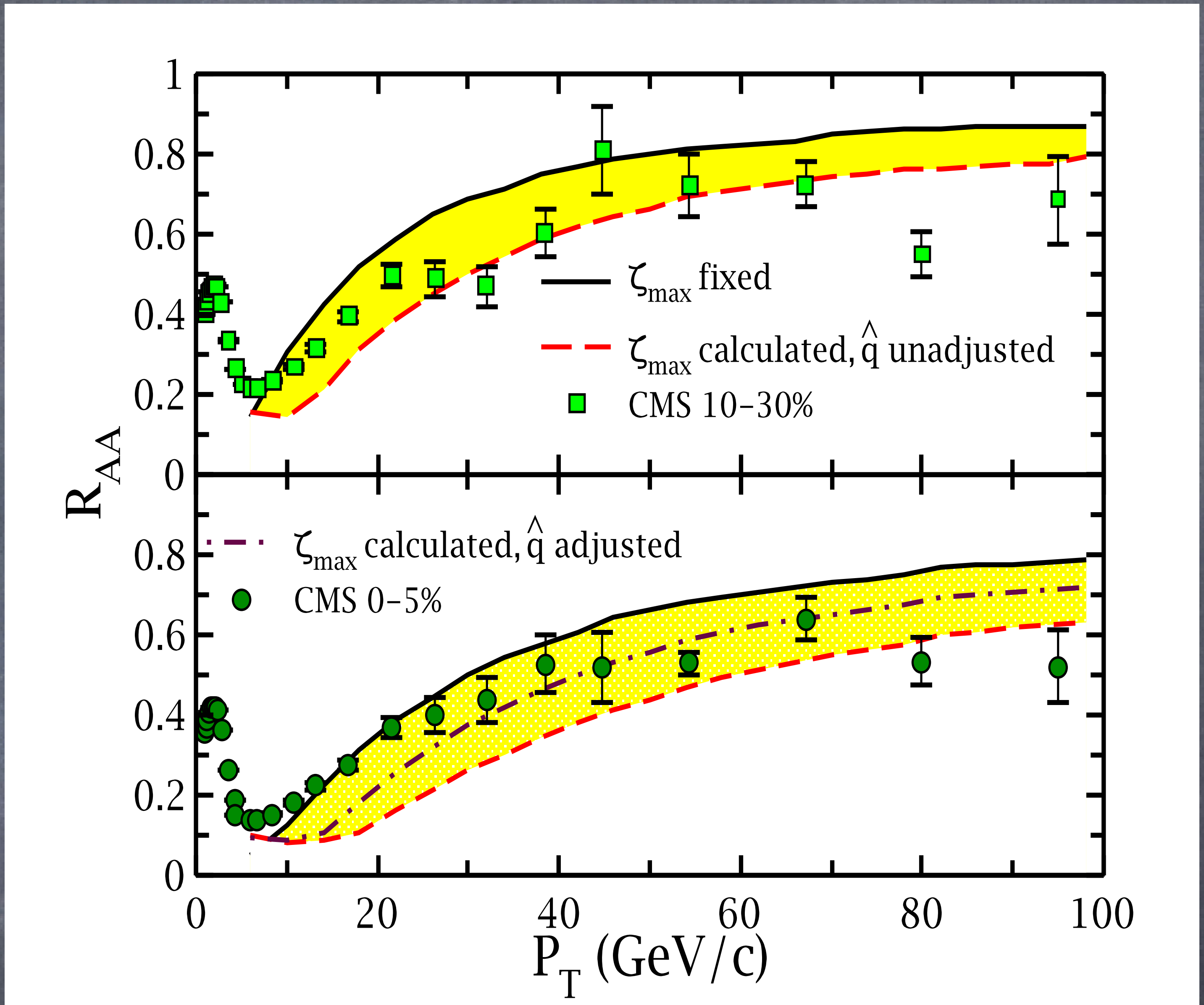


Note: no refitting between RHIC and LHC.



Versus reaction plane, versus energy

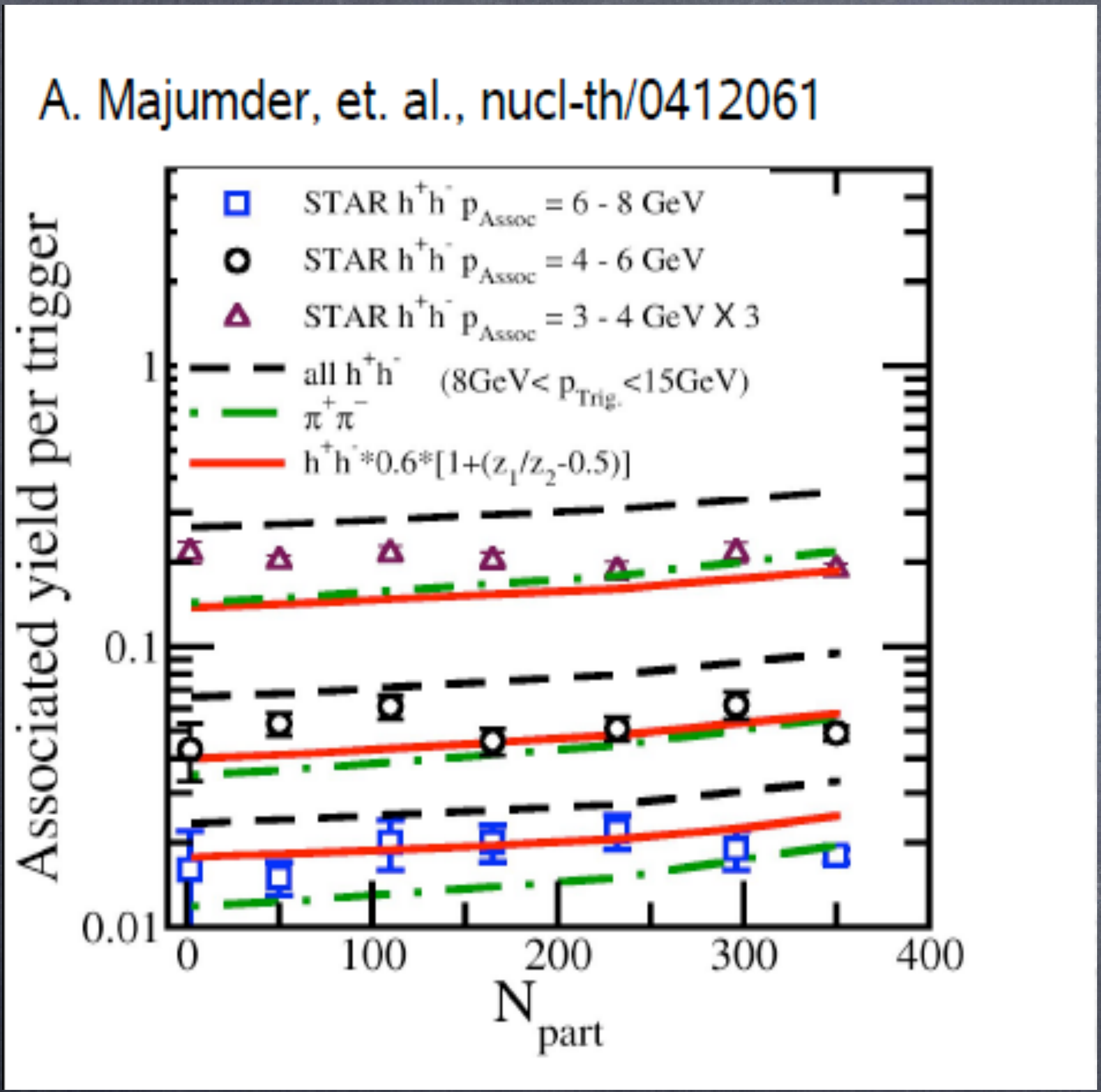


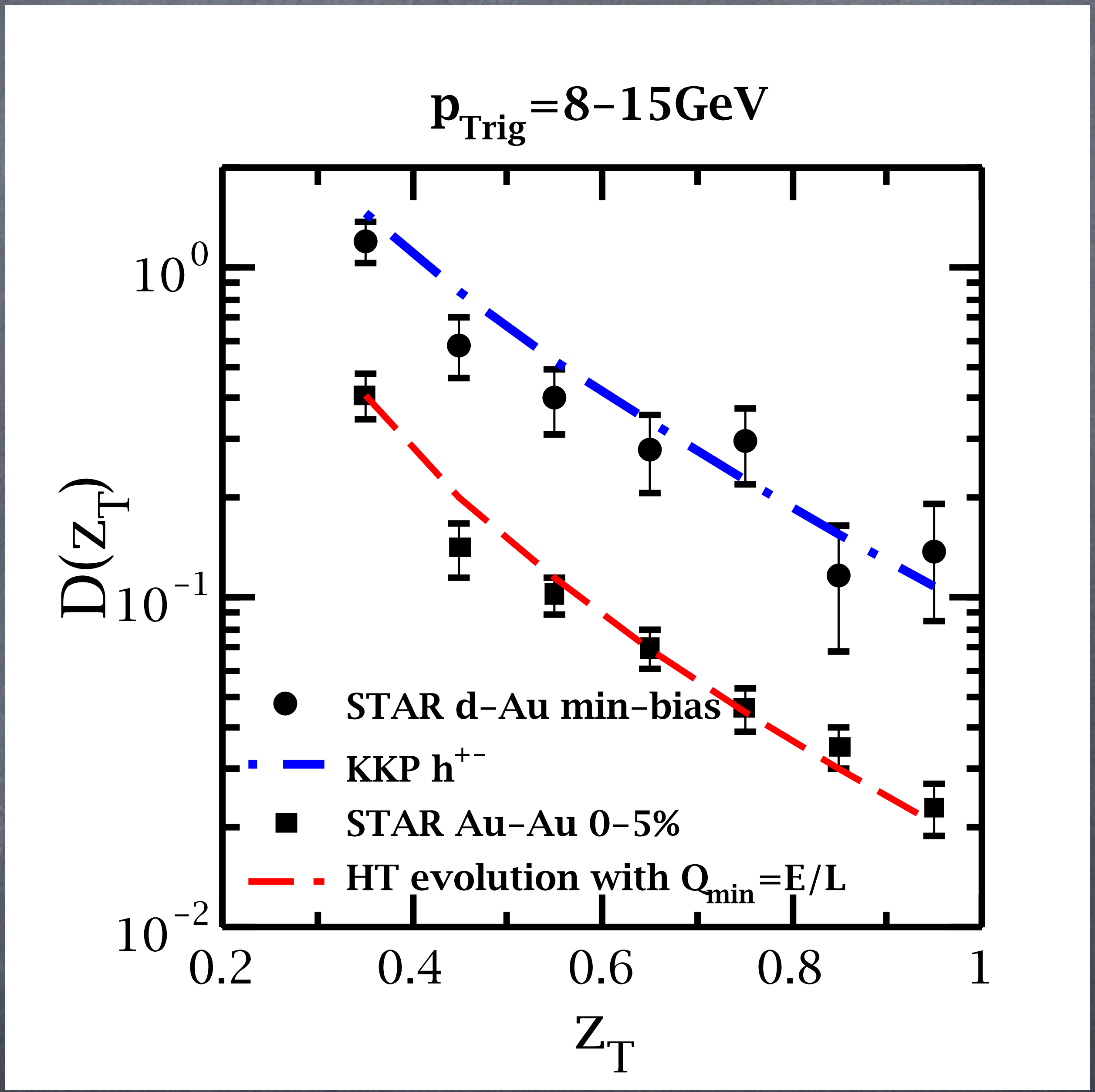


Reasonable agreement with data

Several improvements can be made from this point

Completely consistent predictions for Dihadrons





These are parameter free calculations

The near side involves a new non-perturbative object the dihadron fragmentation function

From factorized analytical approaches to event generators

From factorized analytical approaches to event generators

Looks at full jet, so less sensitive to fragmentation

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In reality, have to include a detailed model of fragmentation

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Usual background subtraction, includes jet medium interaction as part of jet

From factorized analytical approaches to event generators

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In reality, have to include a detailed model of fragmentation so not as well defined as few particle observables

Always an issue with separating the jet from the medium

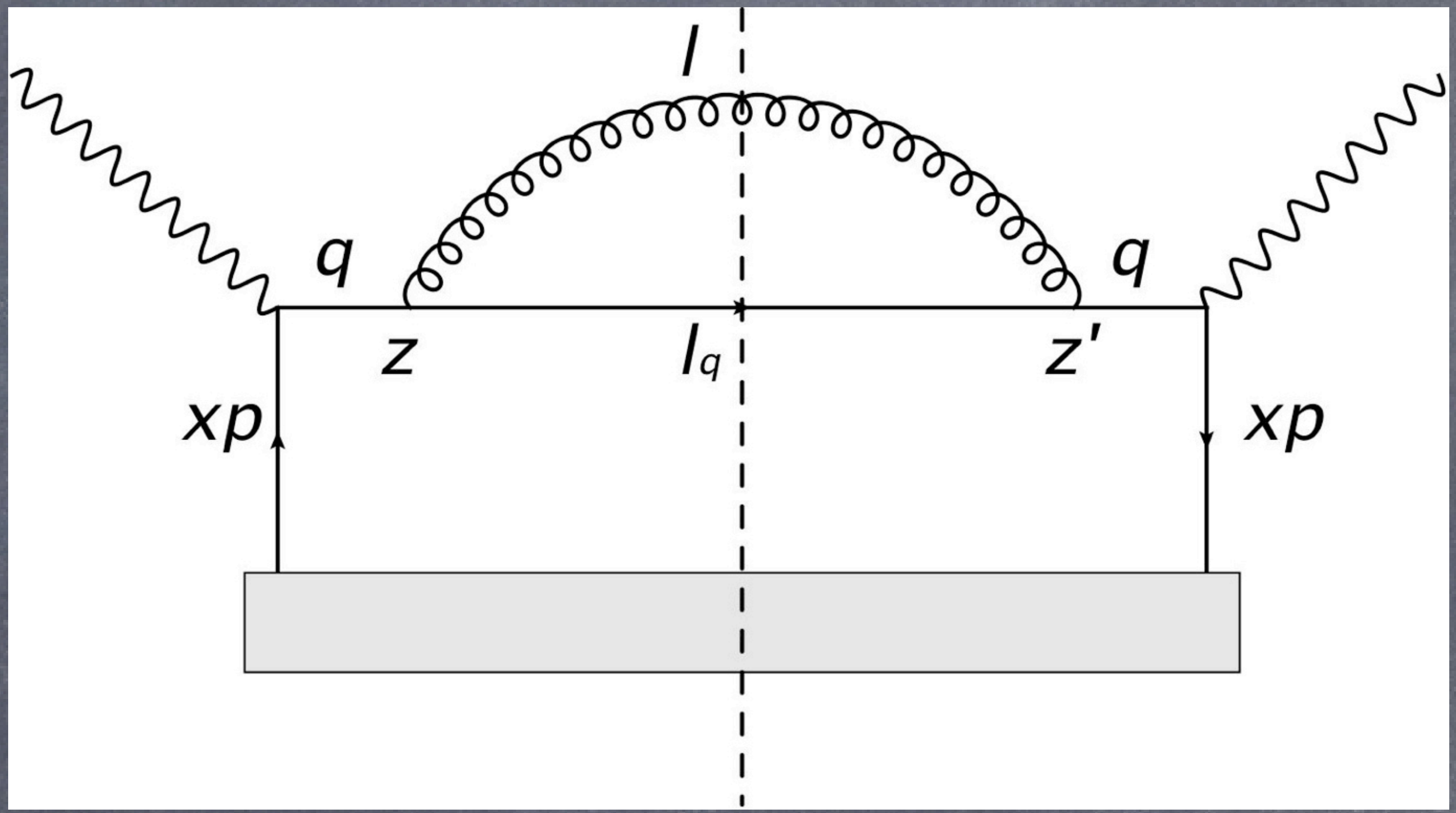
Usual background subtraction, includes jet medium interaction as part of jet

Rigorously calculating this requires more non-perturbative transport coefficients

Main problem: Introducing distance into a DGLAP shower

No space-time in the usual Monte-Carlo showers

$$\bar{z} = \frac{z + z'}{2}$$



$$\delta z = z - z'$$

what is the role of z and z' ?

$$\int_0^\infty d^4 \bar{z} \exp\left[i(\delta q)\bar{z}\right]$$

$$\int d^4 \delta z \exp\left[i\delta z(l + l_q - q)\right]$$

δq is the uncertainty in q,

How much uncertainty can there be ?

To be sensible: $\delta q \ll q$

we assume a Gaussian distribution around q^+

And try different functional forms of the width

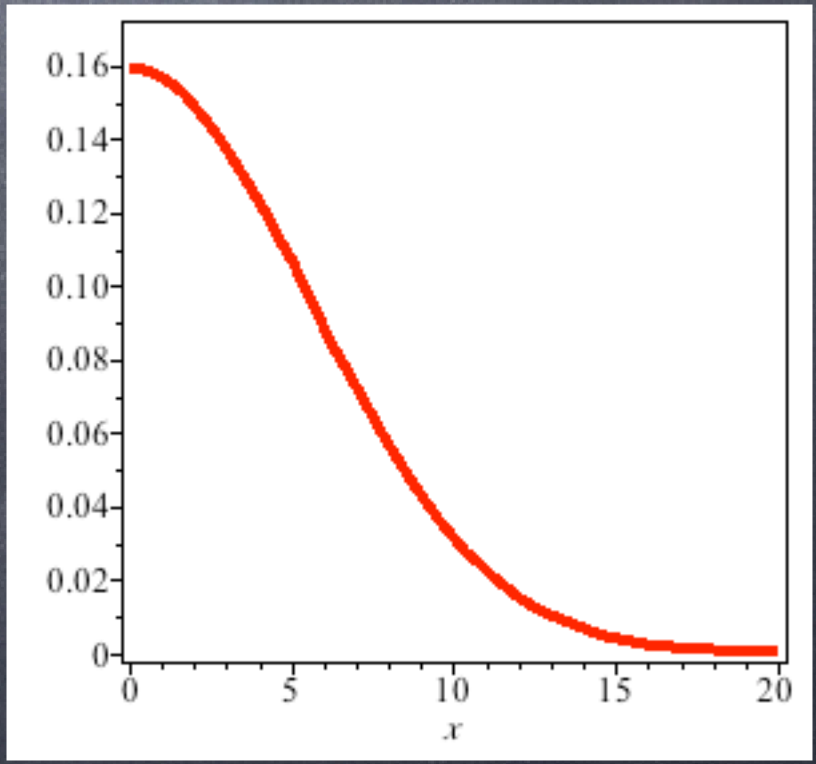
We set the form by insisting $\langle \tau \rangle = 2q^- / (Q^2)$

to obtain the z^- distribution only need to assume a δq^+ distribution

$$\rho(\delta q^+) = \frac{e^{-\frac{(\delta q^+)^2}{2[2(q^+)^2/\pi]}}}{\sqrt{2\pi[2(q^+)^2/\pi]}}$$

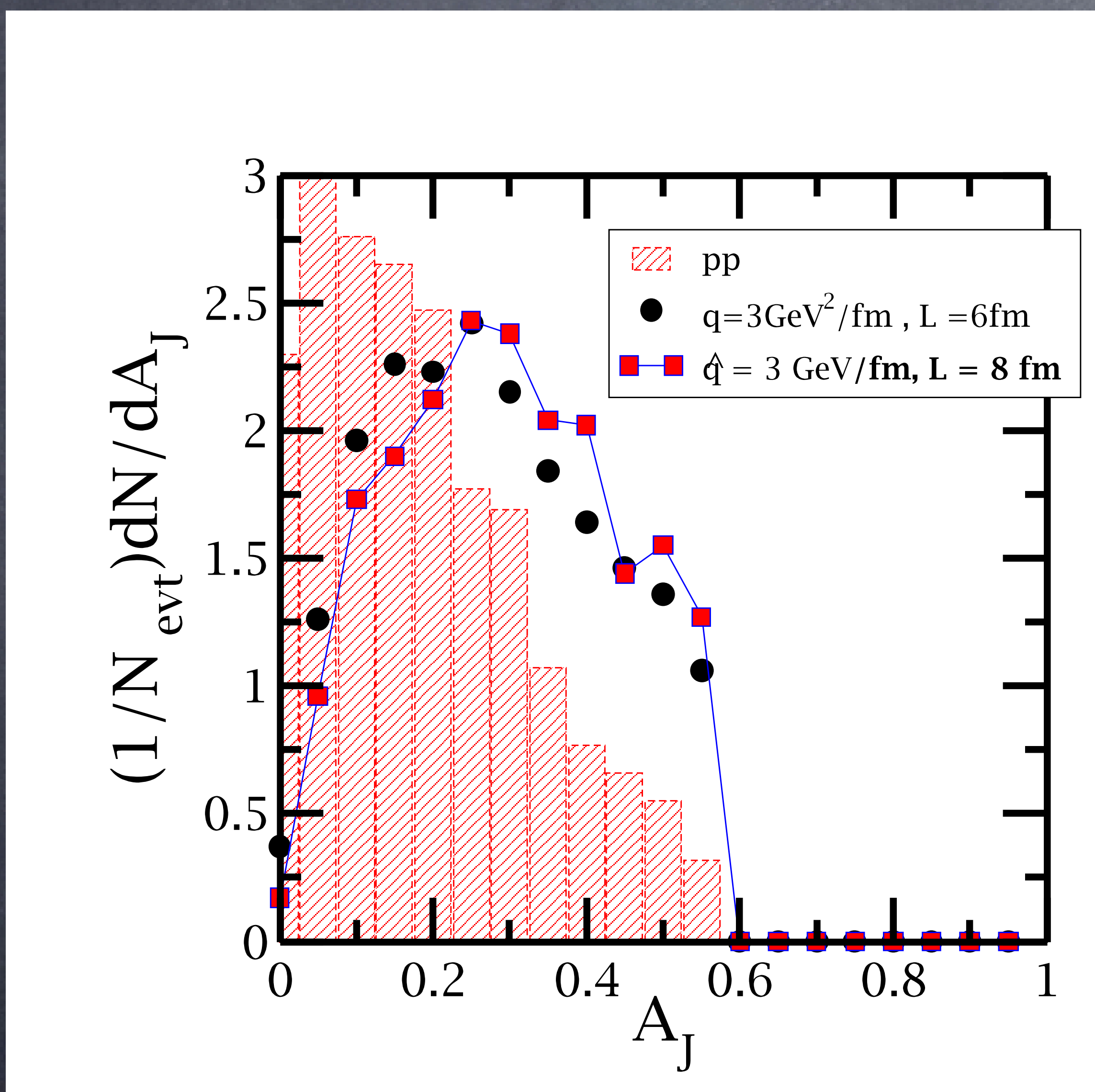
A normalized Gaussian with a variance $2q^+/\pi$

FT gives the following distribution in distance

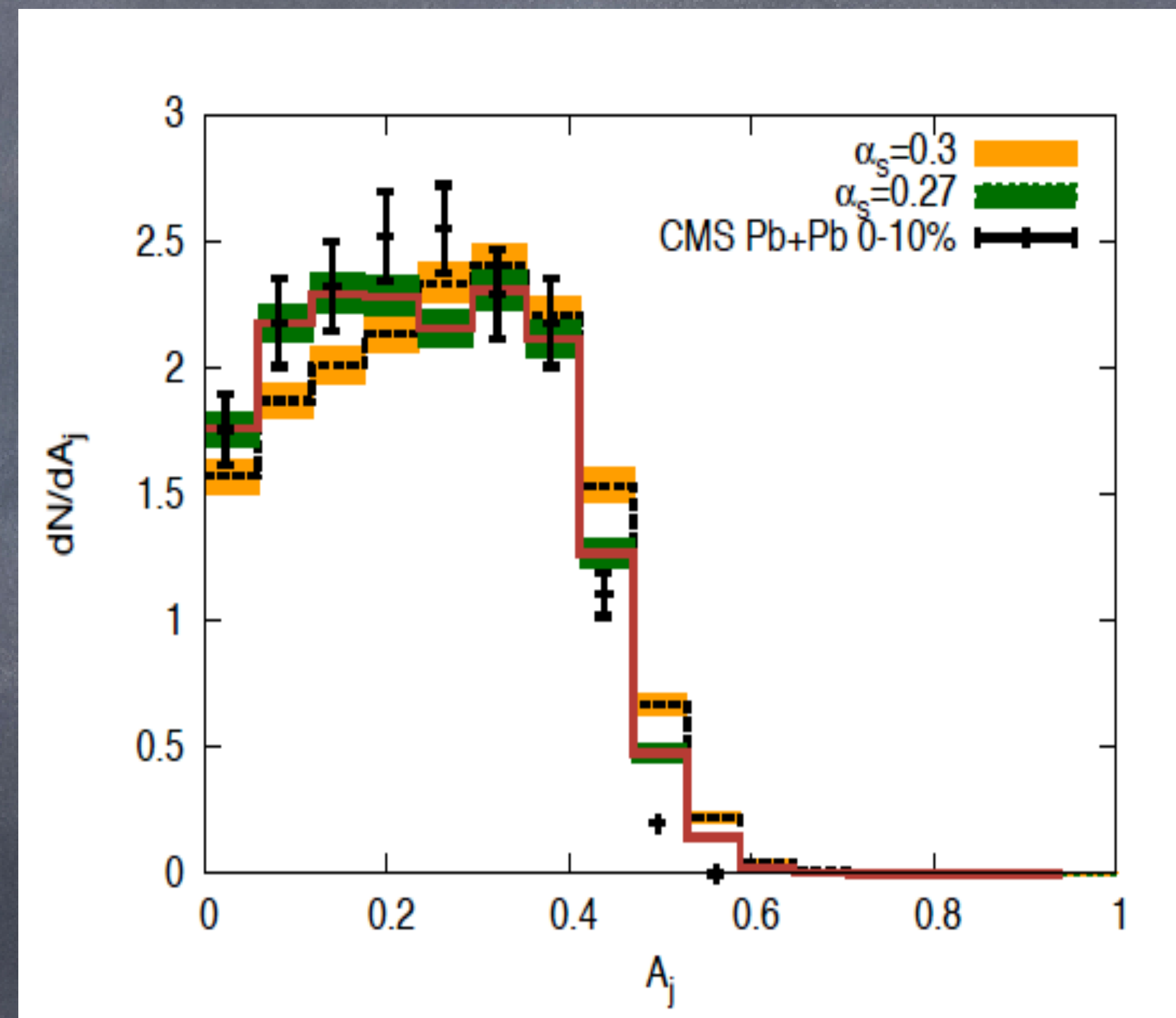


Observables 1. A_J

If you ignore R_{AA} this is not hard



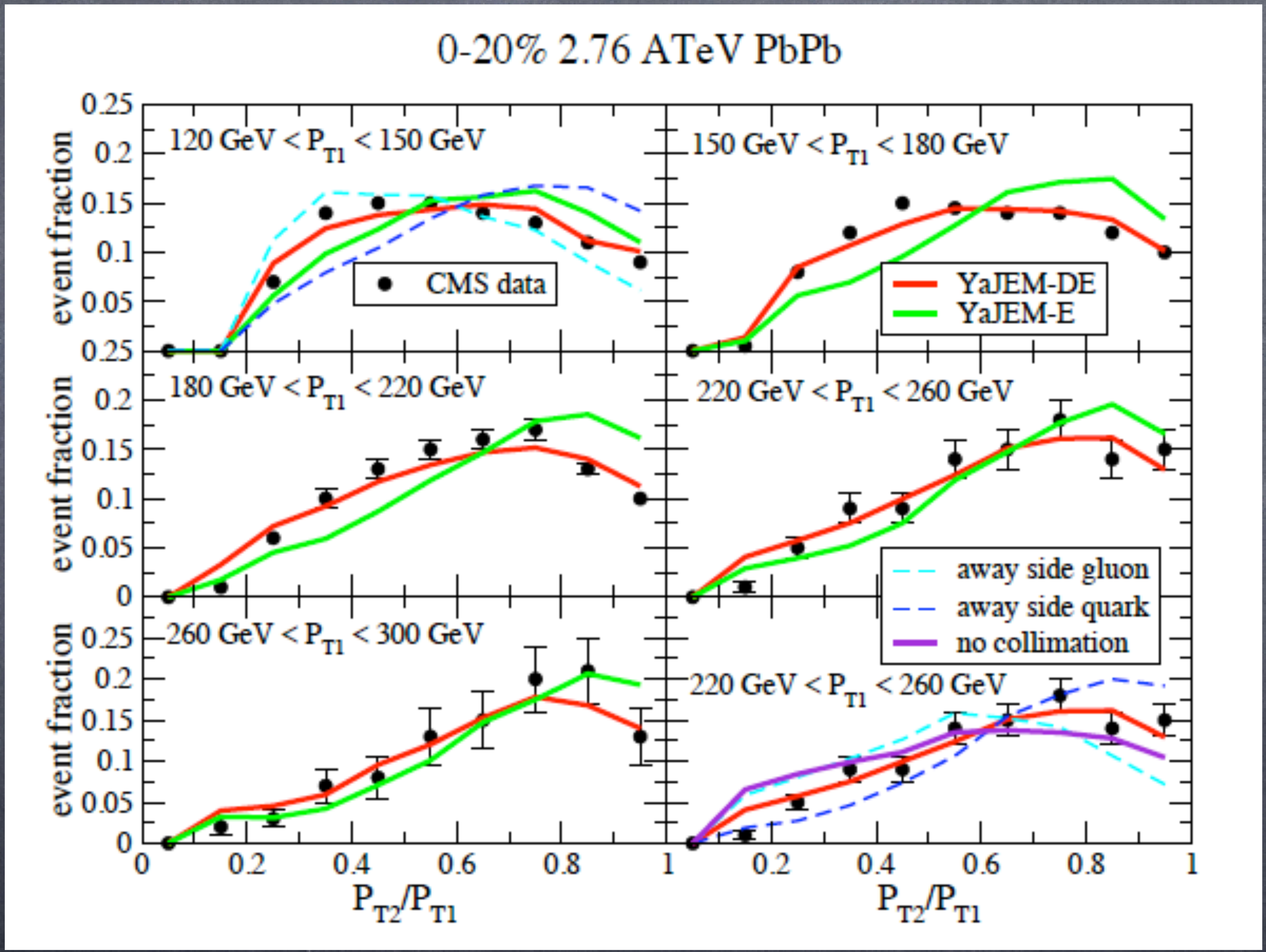
Higher Twist in box



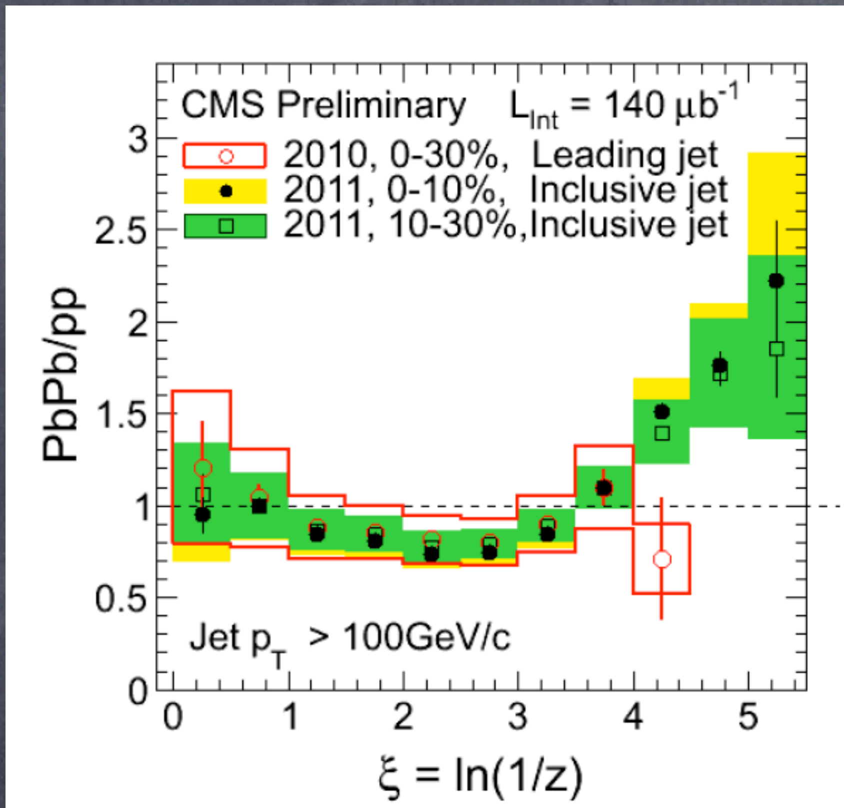
MARTINI without R_{AA}

Observables 1. A_J

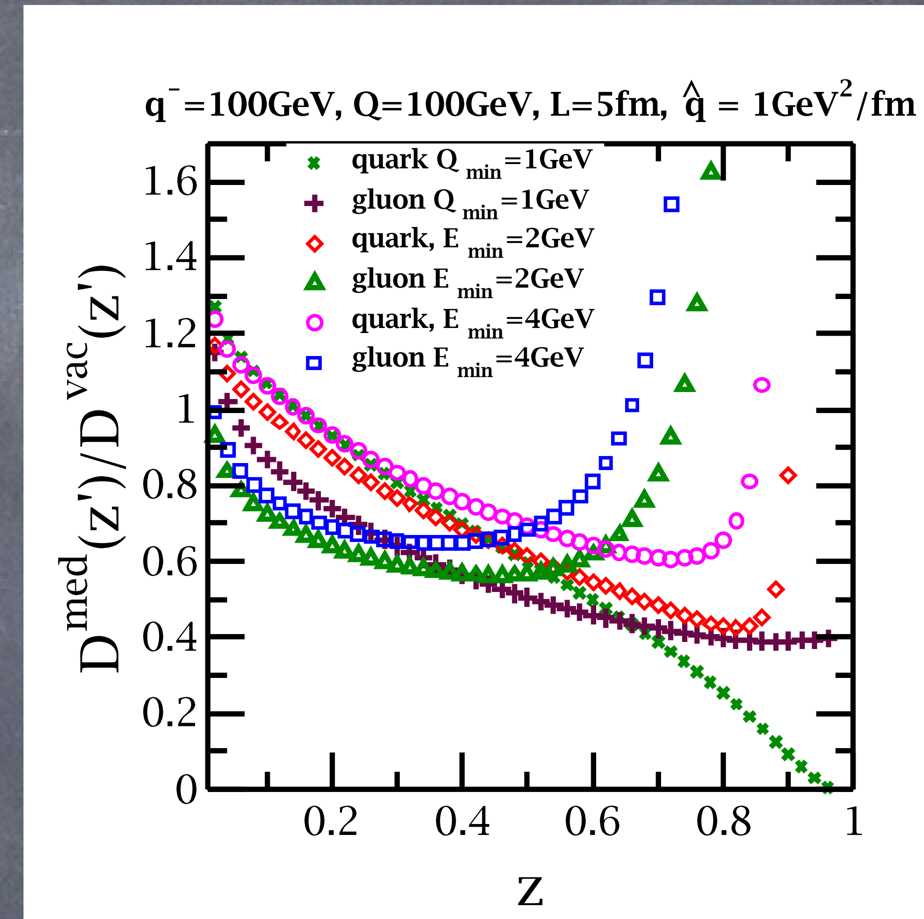
If you ignore R_{AA} this is not hard



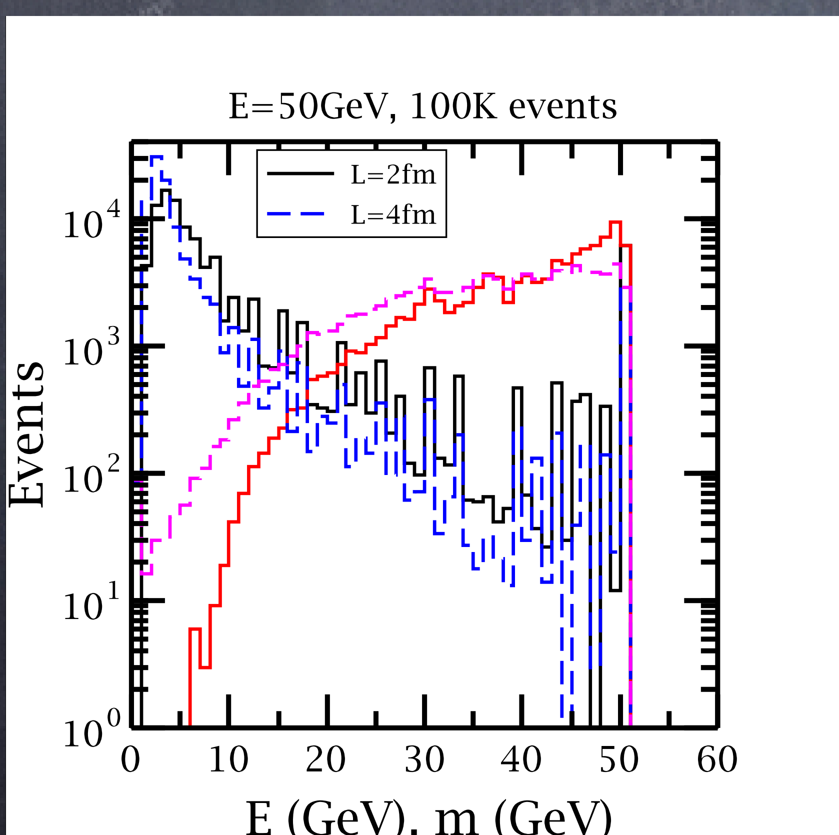
Observable 2: Fragmentation function!



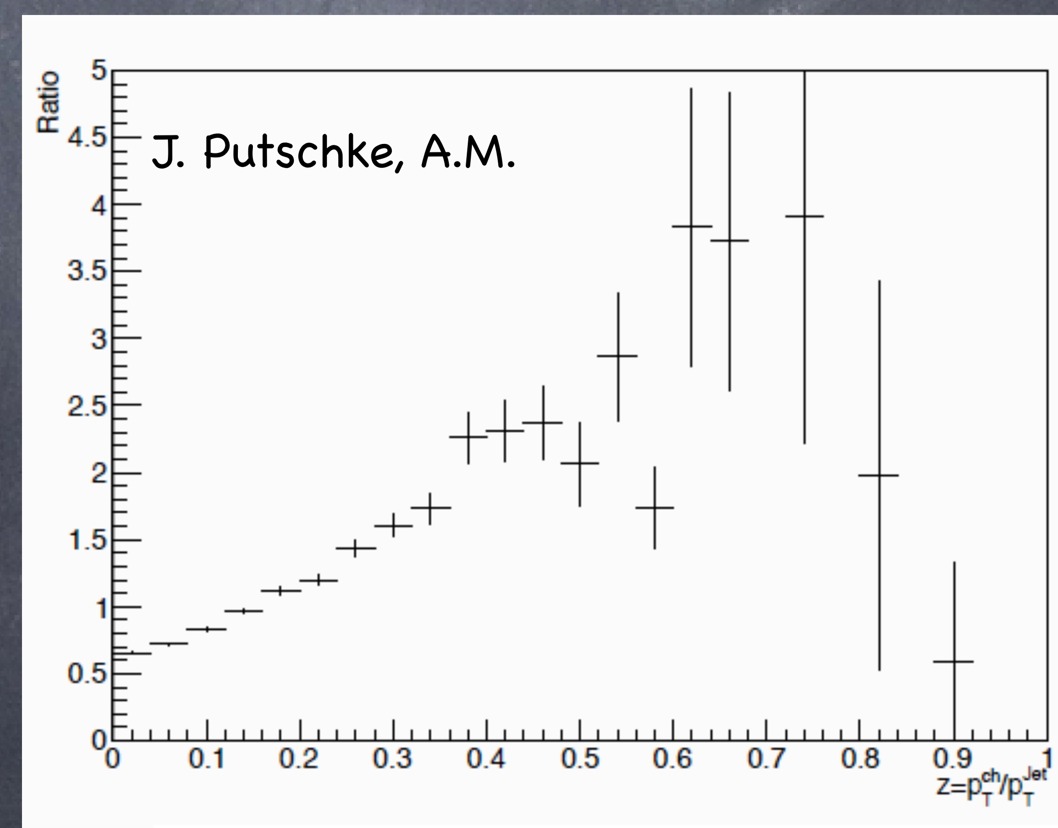
lost energy ->



loss of virtuality



ratio of fragmentation functions with different virtuality



Observable 3. Appearance of lost Energy

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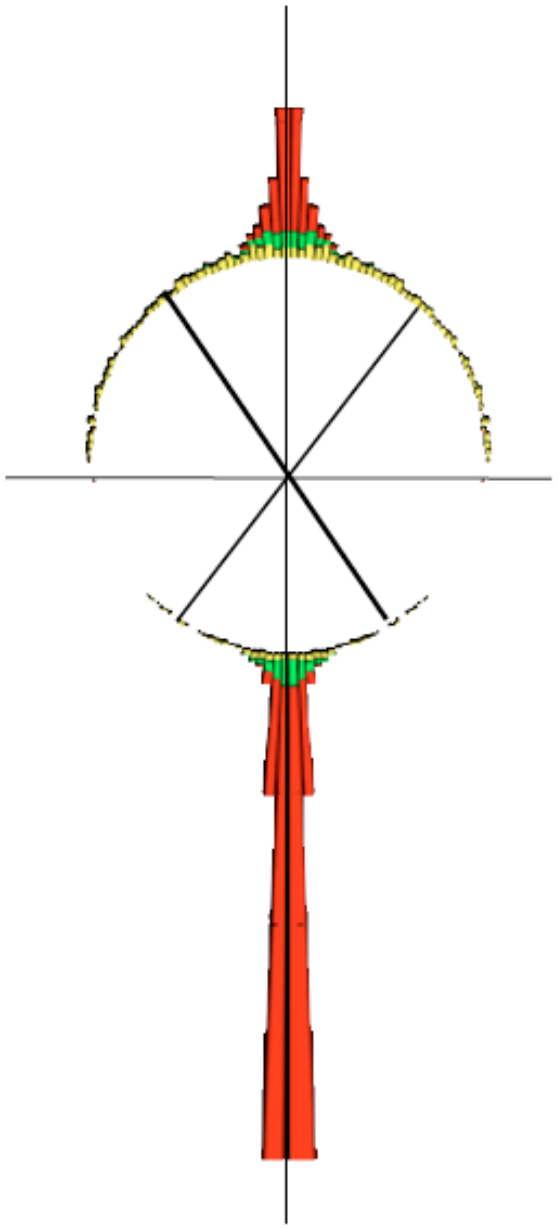
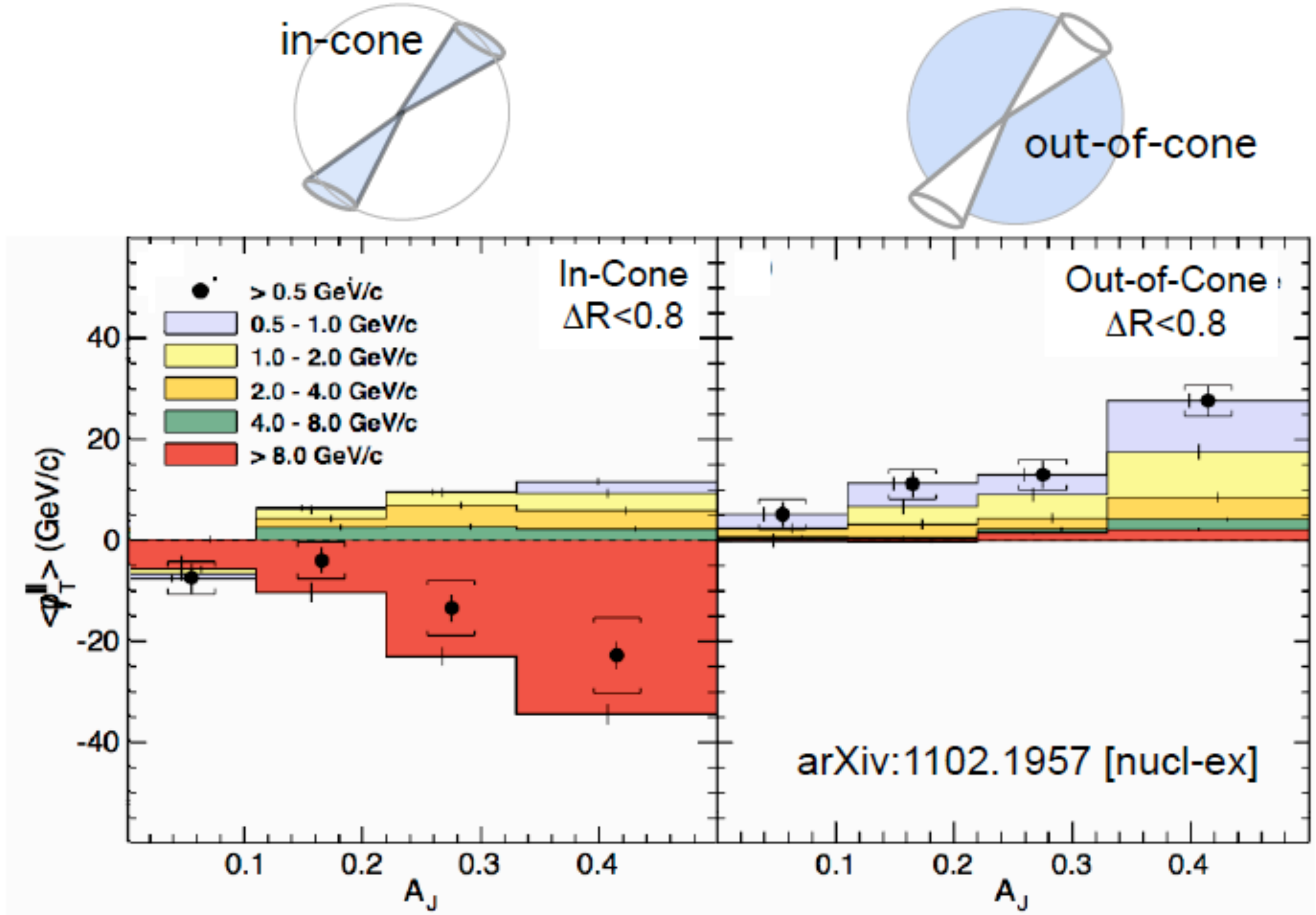
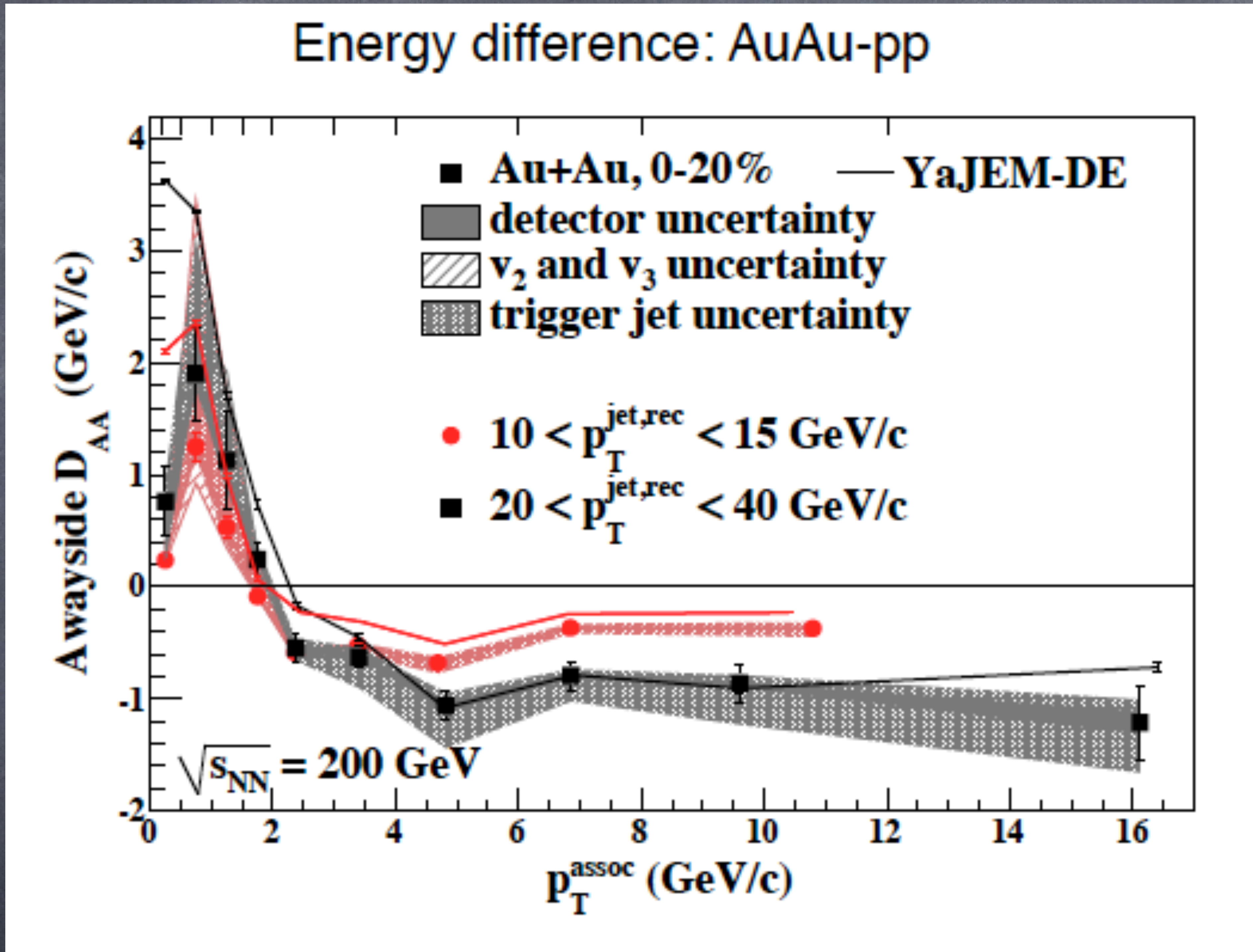




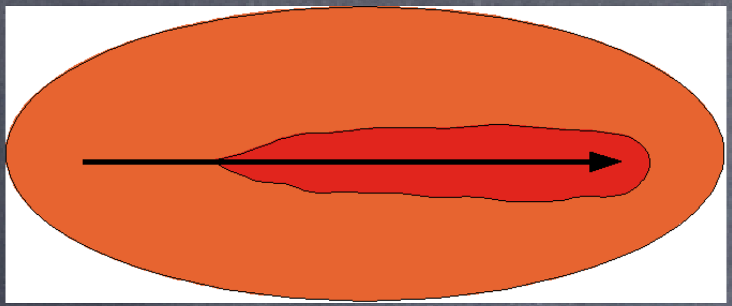
Momentum balance in the event is carried by low momentum particles at large angles to jets

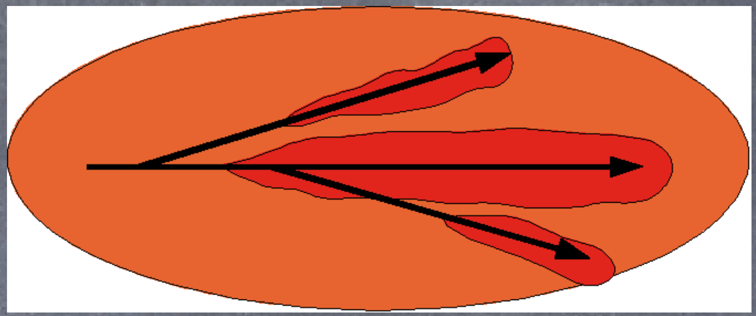
$$\not{p}_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$

Observable 3. Appearance of lost Energy



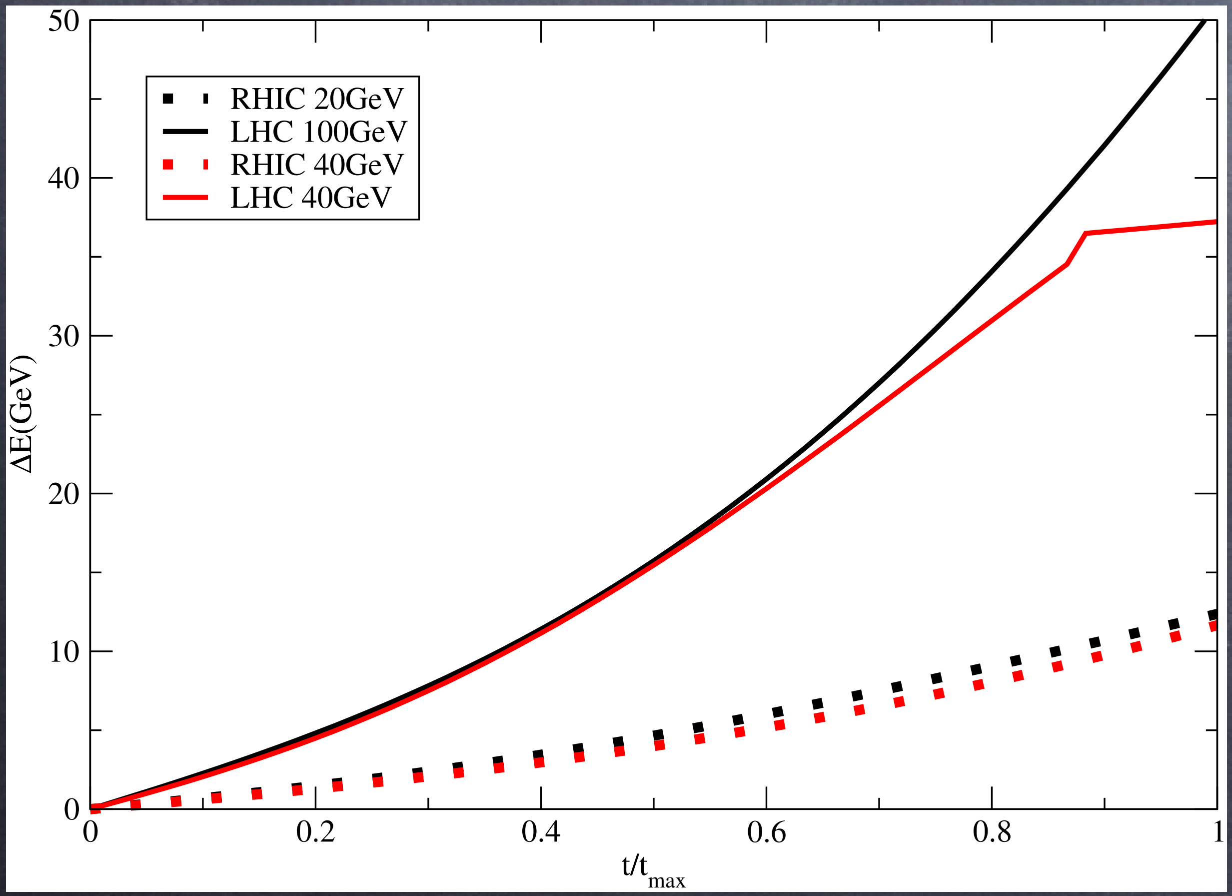
To understand this need to know how jets deposit energy into a medium

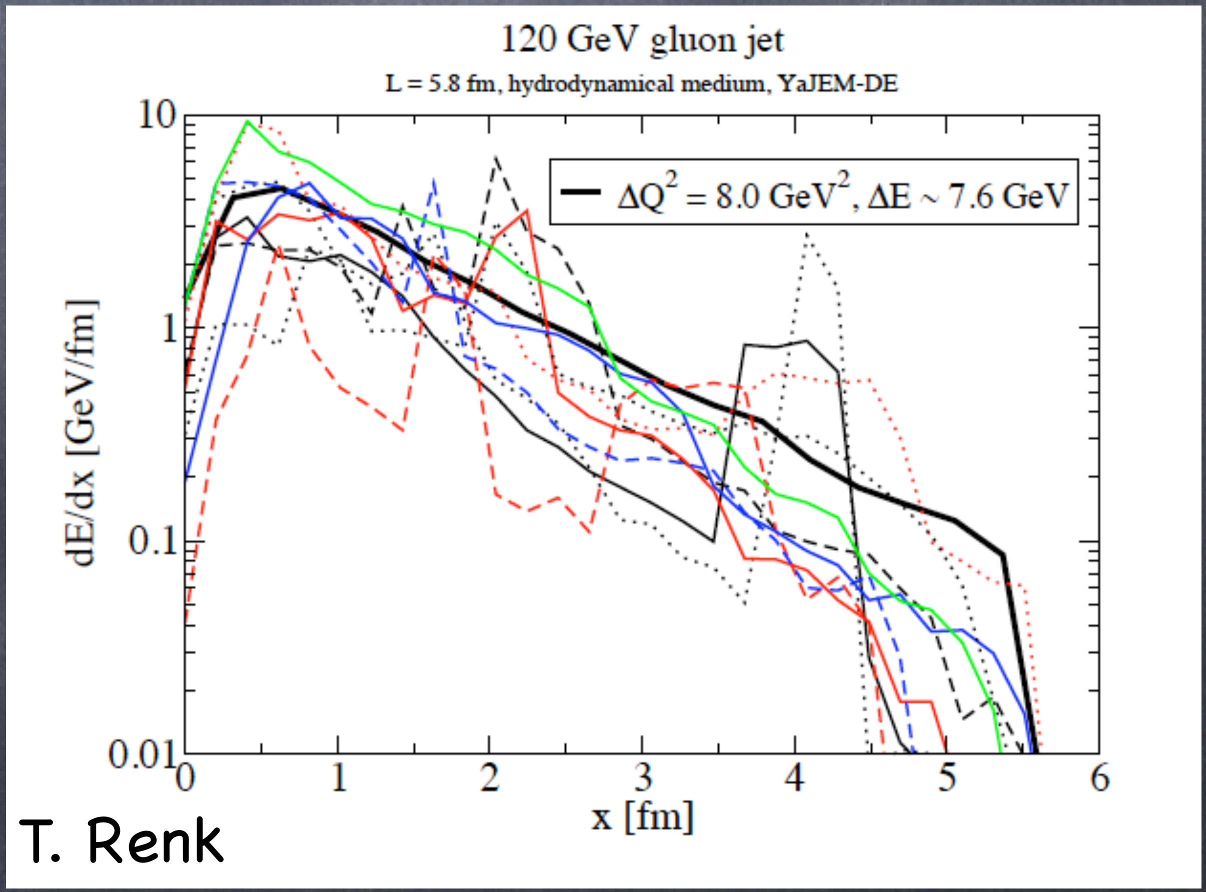




Rate of energy deposition greater at LHC large part of the jet escapes the medium

Medium dissipates in time, so early energy loss is important





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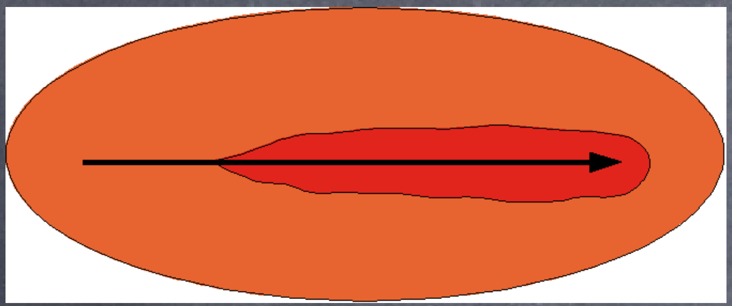

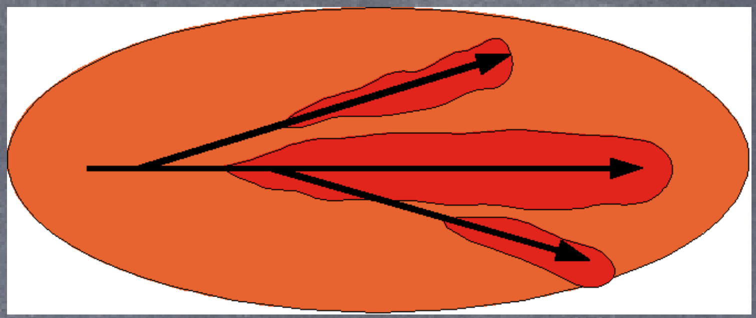

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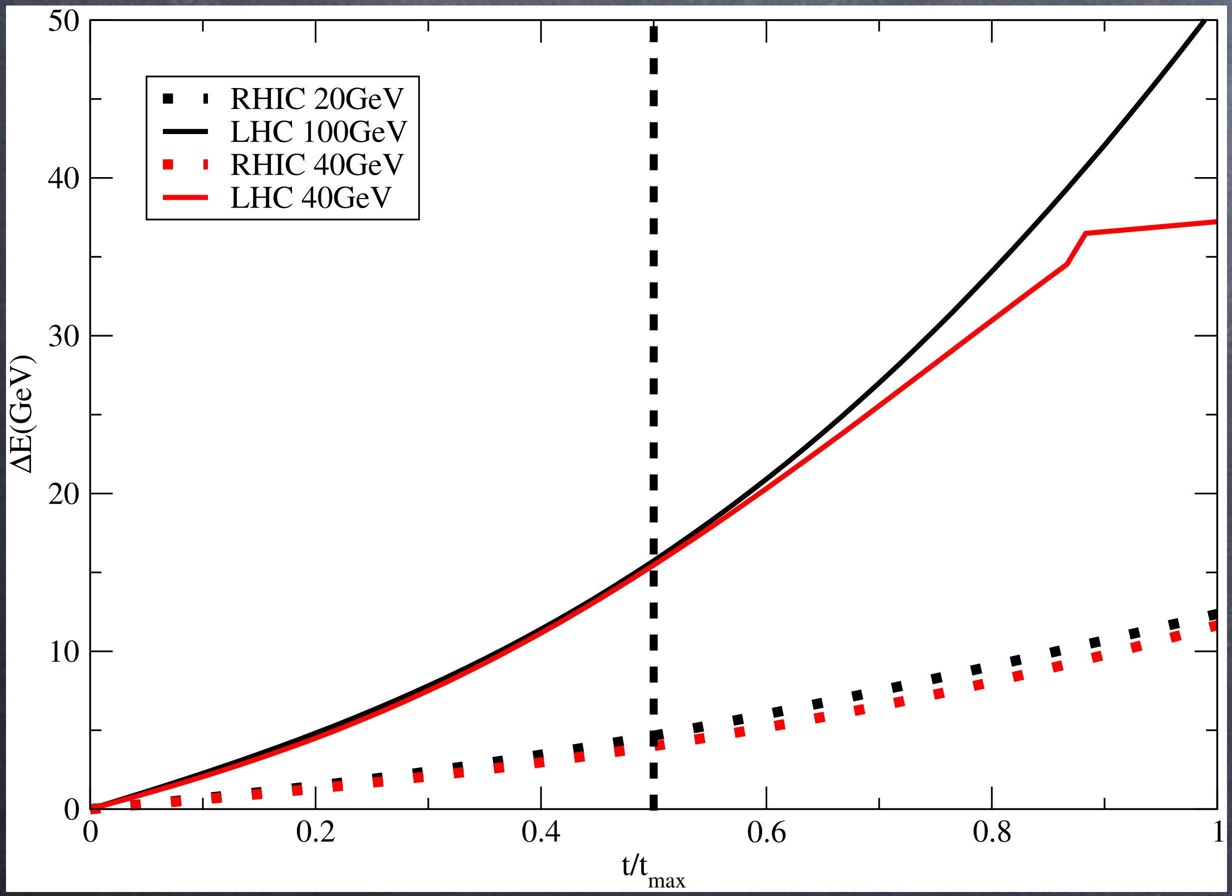
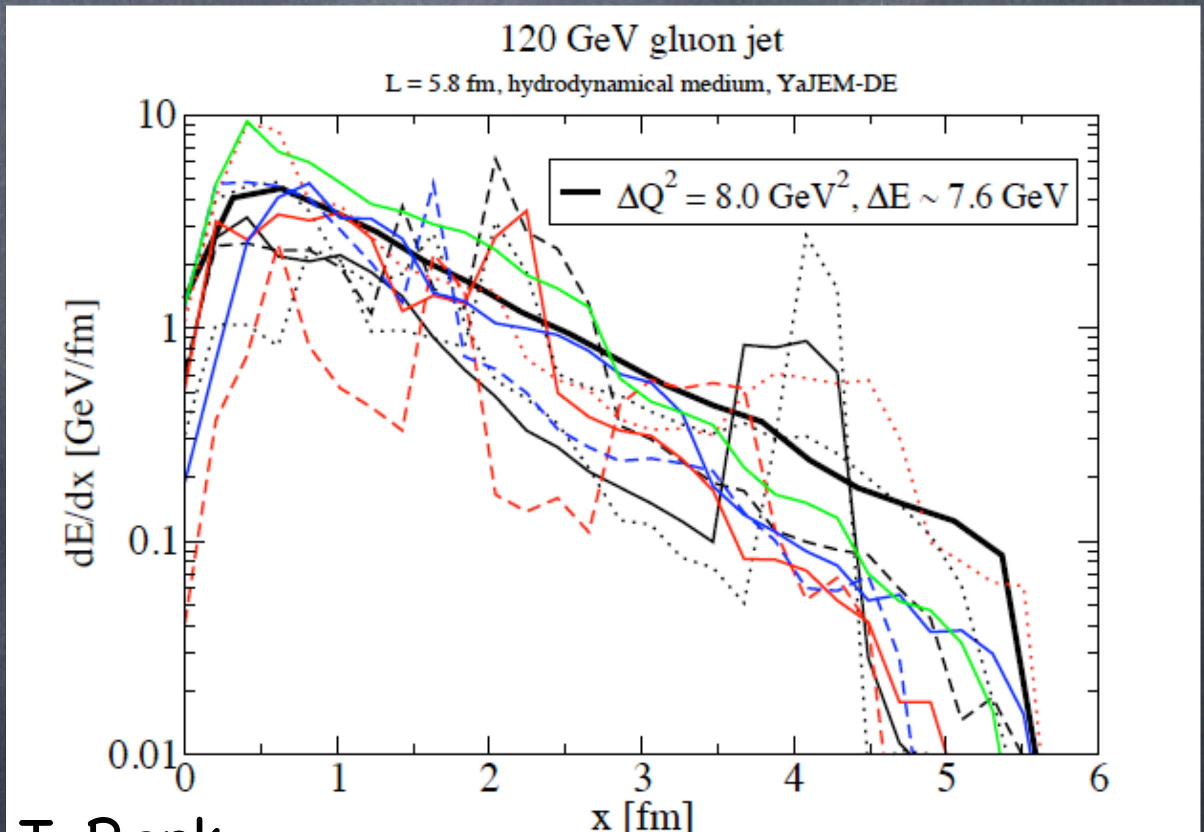
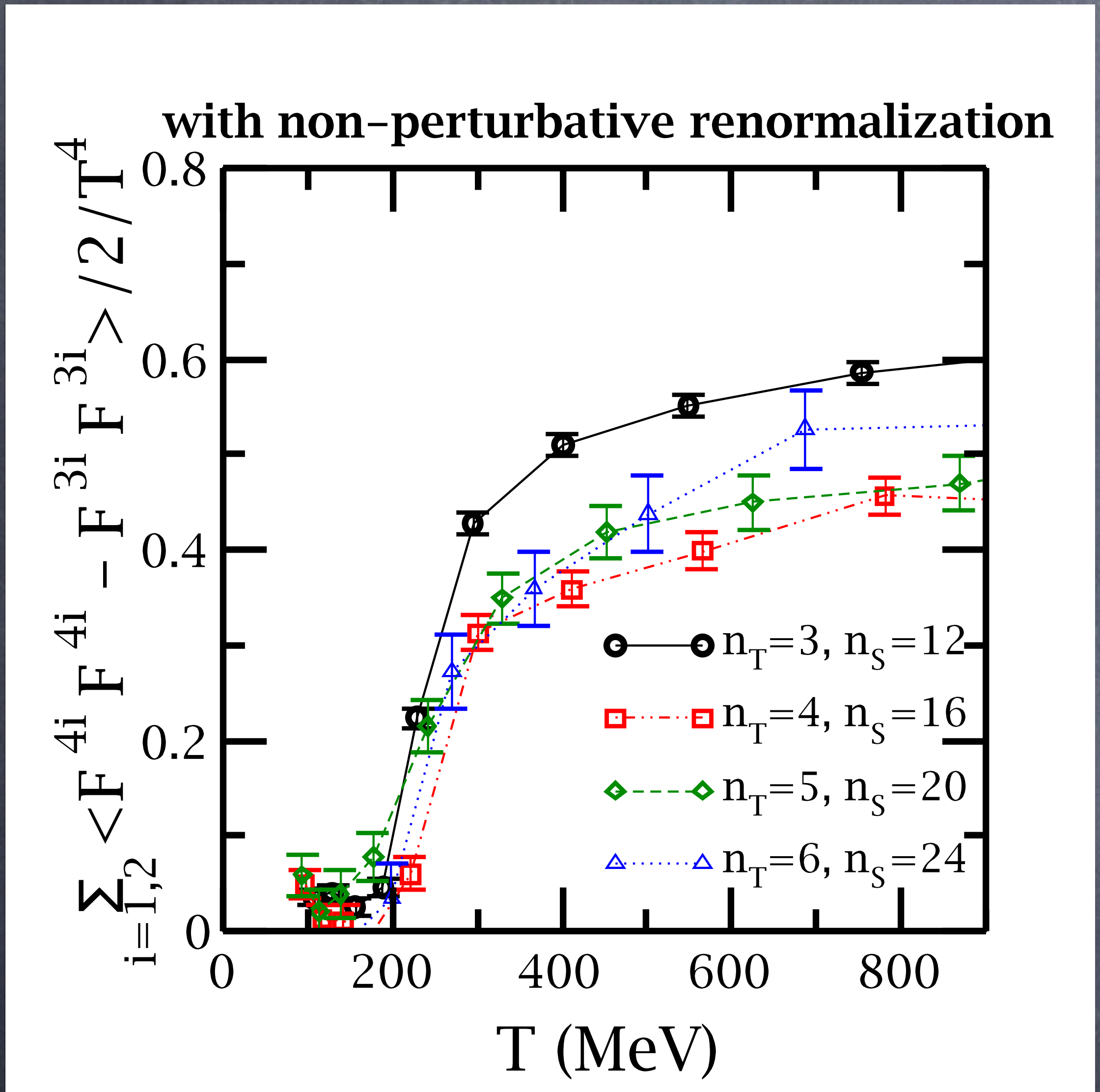




T. Renk

Getting ahead of the experiment

Calculating $\hat{q}$ on the lattice



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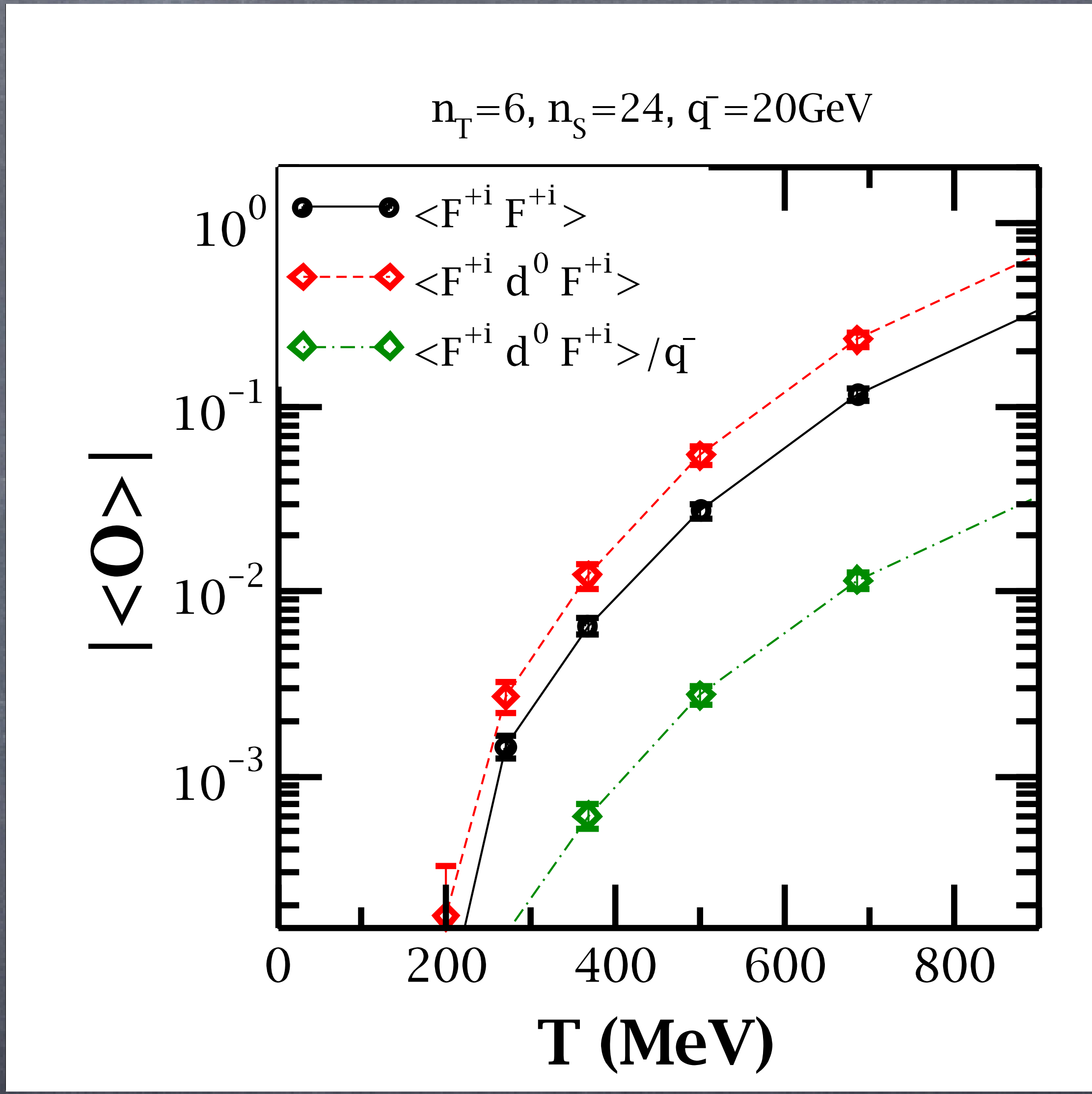
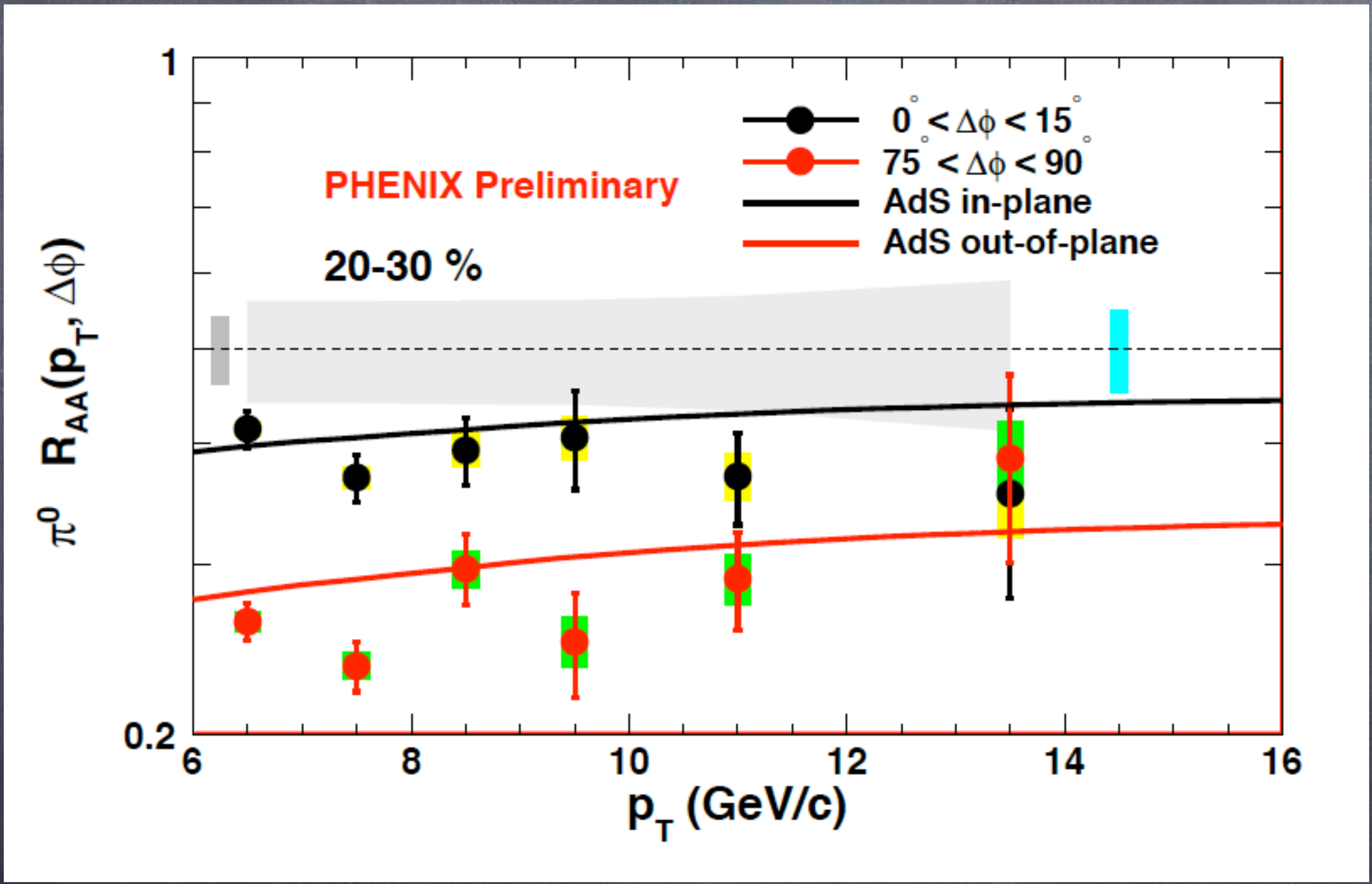


Future calculations will have T dependent $\hat{q}$ input from lattice

Conclusions

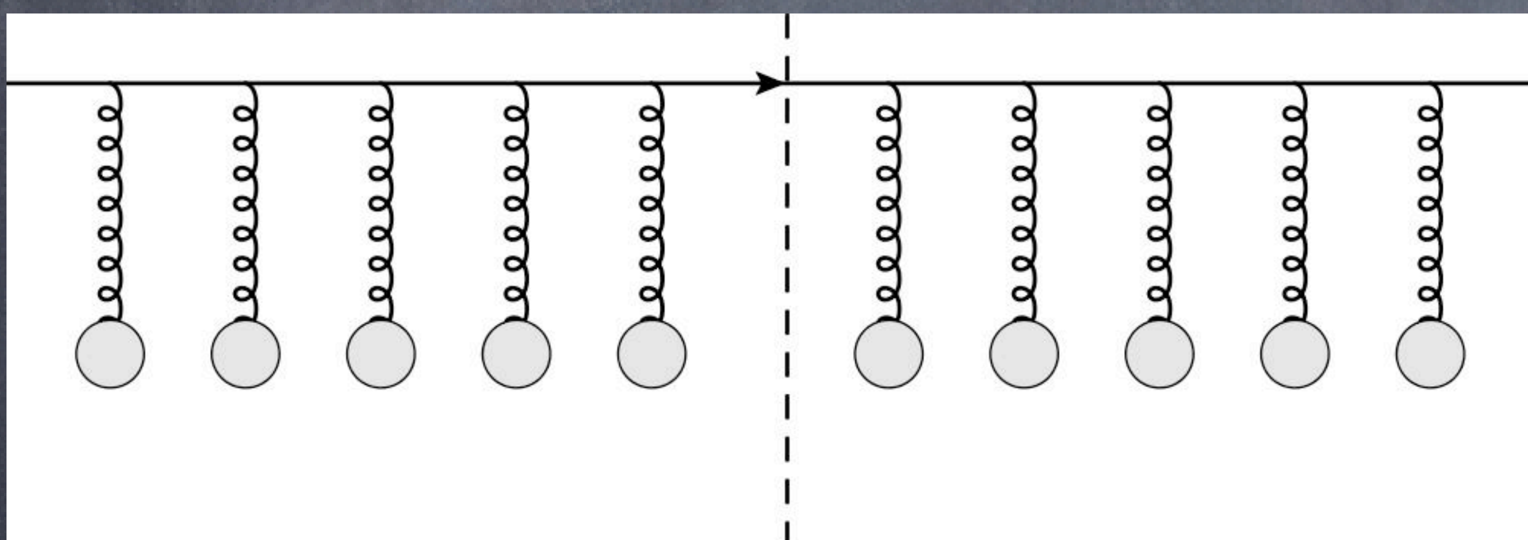
- I have ignored γ-h and γ-jet, lack of space
- There is now a clear theory of pQCD based jet modification (Jet coupled weakly to a strongly coupled medium)
- Have a series of transport coefficients from few h data
- Sensitivity to new transport coefficient from new jet data
- Lots of work to be done in resolving the intricate details of comparing and tuning event generators to data.


1
0.2
π^0 $R_{AA}(p_T, \Delta\phi)$
$0^\circ < \Delta\phi < 15^\circ$
$75^\circ < \Delta\phi < 90^\circ$
AdS in-plane
AdS out-of-plane
PHENIX Preliminary
20-30 %
6
8
10
12
14
16
p_T (GeV/c)

How the medium affects the parton.

A parton in a jet shower, has momentum components

$q = (q^-, q^+, q_T) = (1, \lambda^2, \lambda)Q$, Q: Hard scale, $\lambda \ll 1$, $\lambda Q \gg \Lambda_{QCD}$



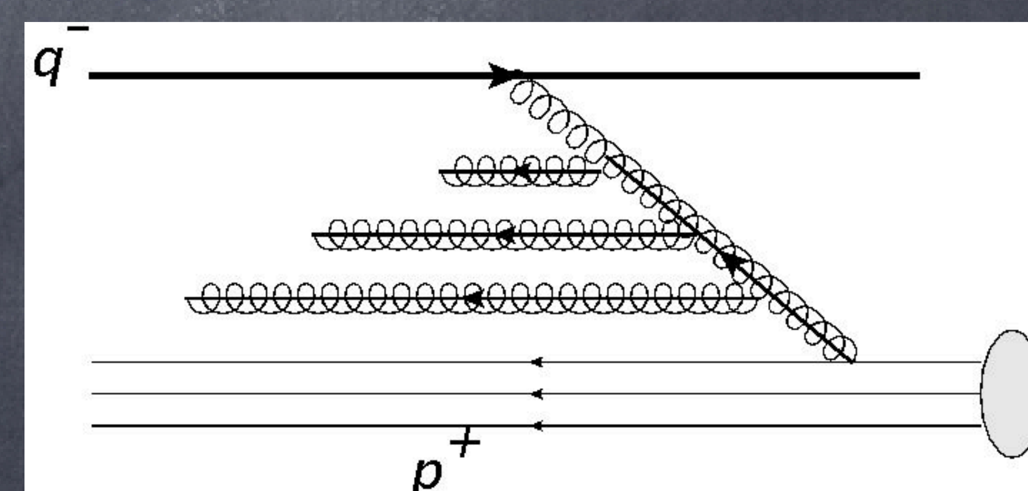
$$p^+ = \frac{p^0 + p_z}{\sqrt{2}}$$

$$p^- = \frac{p^0 - p_z}{\sqrt{2}}$$

hence, gluons have

$$k_\perp \sim \lambda Q, \qquad k^+ \sim \lambda^2 Q$$

could also have $k^- \sim \lambda Q$



Idlilbi, Majumder 2008

The Basic steps:

1) Write down the general structure in position space.

2) Fourier transpose all propagators to momentum space

3) Assume all k^- are << q^-, integrate. out the k^- .

4) Do as many k^+ integrals, this time-orders the locations

5) There will always be one propagator not on shell

6) Expand in k_T^2/l_T^2 and keep the leading term.

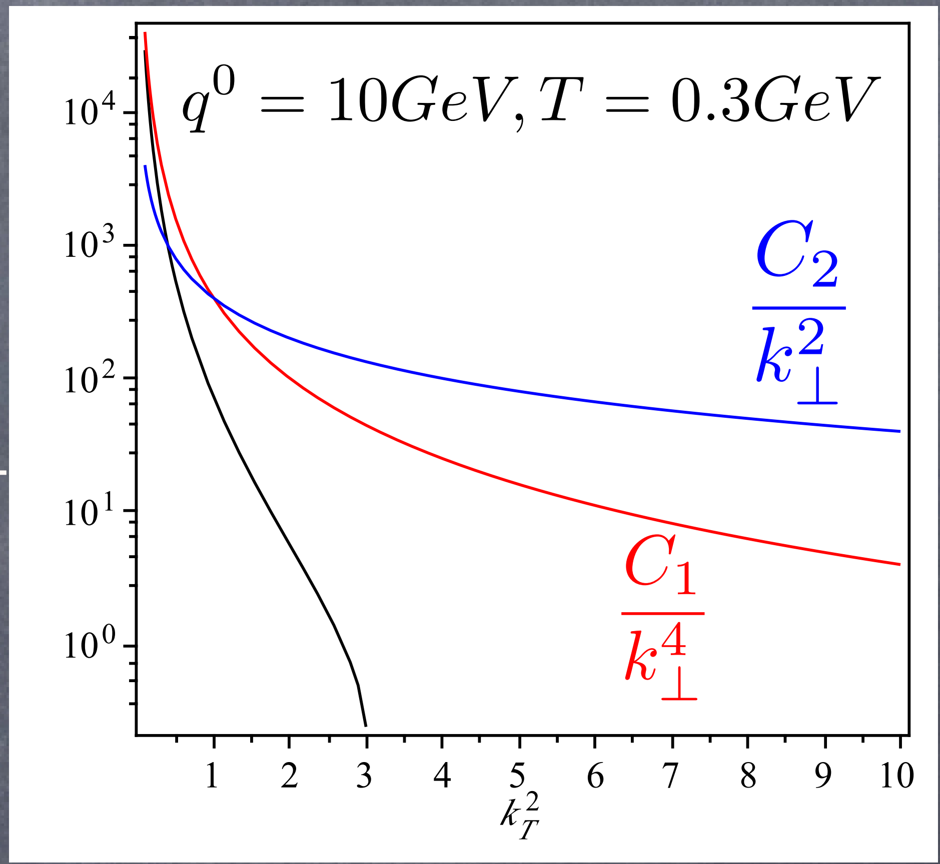
Gaussian distribution/temperature dependence/fit parameter !!!

Multiple scattering off any distribution samples a Gaussian

$$\hat{q} \sim T^3, s, \epsilon^{3/4}$$

is basically a model

$$\frac{d\sigma}{dk_\perp^2}$$



Ultimately you have to fit the normalization to 1 data point at one centrality, one value of p_T , one HIC energy

``So, its not really first principles!", S.S. Gubser