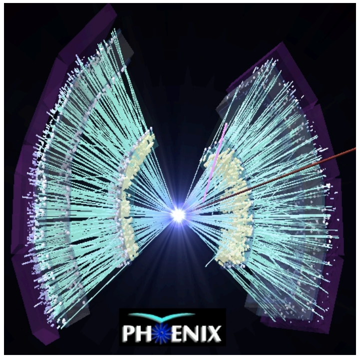
Measurements and calculations of q-hatL via azimuthal broadening (acoplanarity) in RHI collisions using-dihadron correlations

M. J. Tannenbaum
Brookhaven National Laboratory
Upton, NY 11973 USA

How hadron collider experiments contributed to the development of QCD arXiv:1801.08969



Also see MJT: PLB771(2017) 553; arXiv:1808.07357v2

Nuclear Physics Seminar
January 29, 2019
BNL, Upton NY

From Miklos Gyulassy talk QM2018

Jet-hadron acoplanarity azimuthal distribution from Chen,Qin,Xiao,Zhang PLB773, 2017
A+A Vacuum Sudakov+ BDMS(Qs) model compared to RHIC and LHC data

674

Current State of the "Acoplanarity Art"

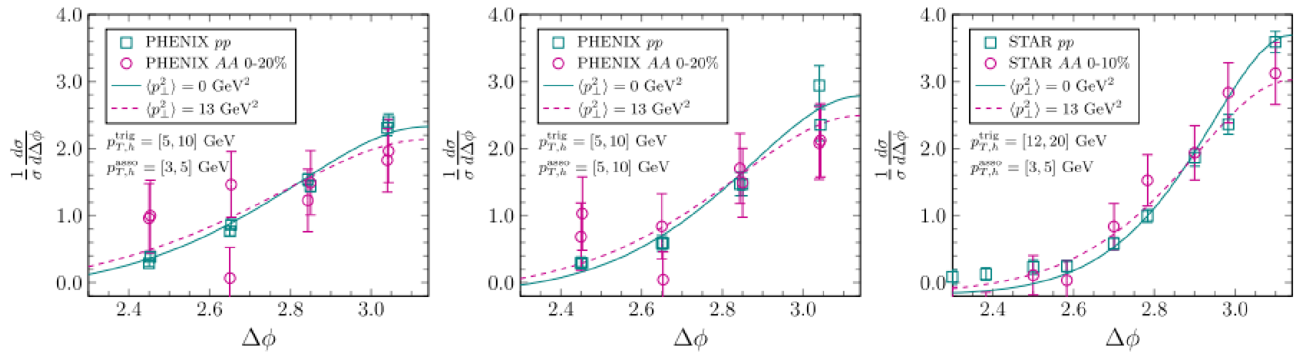


Fig. 1. Normalized dihadron angular correlation compared with PHENIX [51] and STAR [52] data.

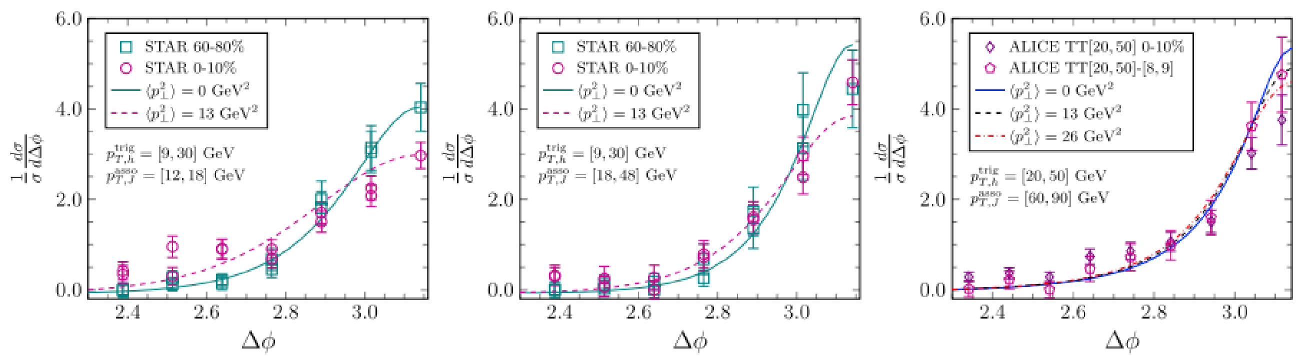


Fig. 2. Normalized hadron-jet angular correlation compared with STAR [53] and the ALICE [54] data. A factor of 3/2 is multiplied to the charged jet energy for our calculation to account for the energy carried by neutral particles. Two sets of ALICE data are shown: TT(trigger track)[20–50] (GeV) represents the signal and TT[20–50] (GeV)–[8–9] (GeV) subtracts the reference to suppress the contribution from the uncorrelated background.

[MG: Current exp precision does not constrain medium opacity better than RAA(pT) already does. Much higher precision data in the future needed to test color dof $n_a(T)$ and $d\sigma_{ab}/dq^2$]

A closer look

Jet-hadron acoplanarity azimuthal distribution from Chen,Qin,Xiao,Zhang PLB773, 2017
A+A Vacuum Sudakov+ BDMS(Qs) model compared to RHIC and LHC data

674

Current State of the "Acoplanarity Art"

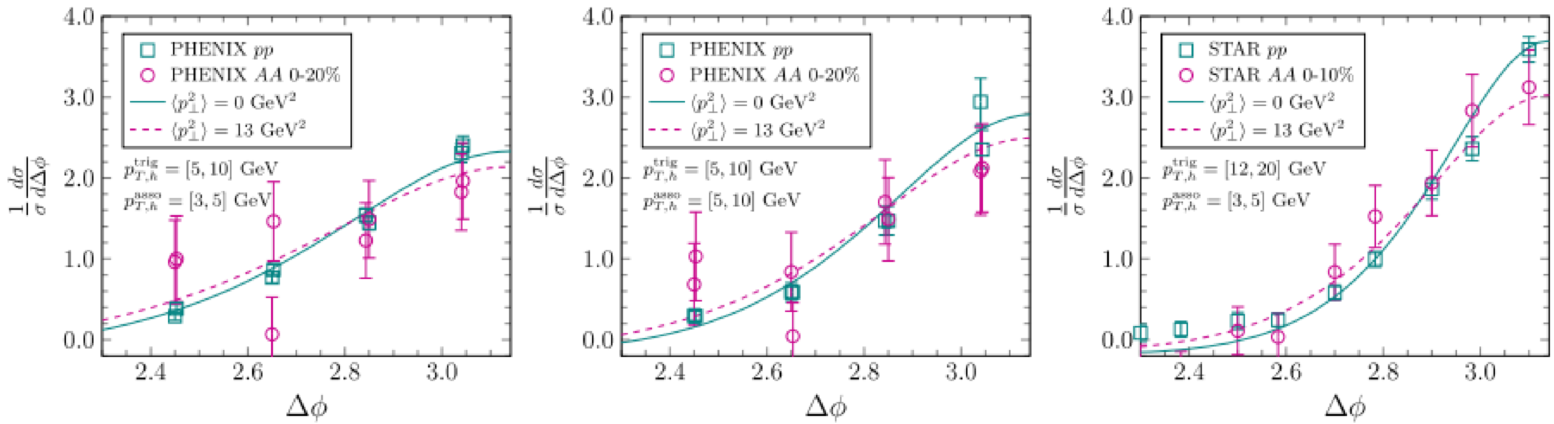
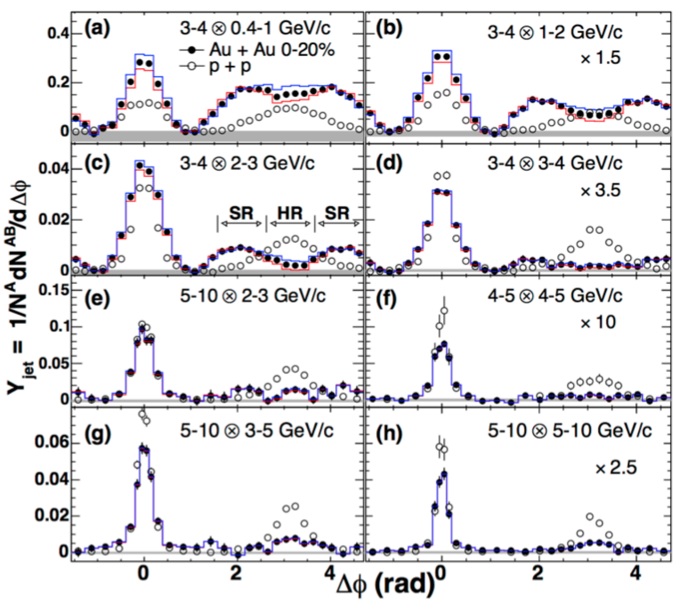


Fig. 1. Normalized dihadron angular correlation compared with PHENIX [51] and STAR [52] data.

[51] PHENIX, A. Adare, et al., Phys. Rev. C 77 (2008) 011901

The ``famous'' head-shoulders paper



A closer look

Jet-hadron acoplanarity azimuthal distribution from Chen,Qin,Xiao,Zhang PLB773, 2017
A+A Vacuum Sudakov+ BDMS(Qs) model compared to RHIC and LHC data

674

Current State of the "Acoplanarity Art"

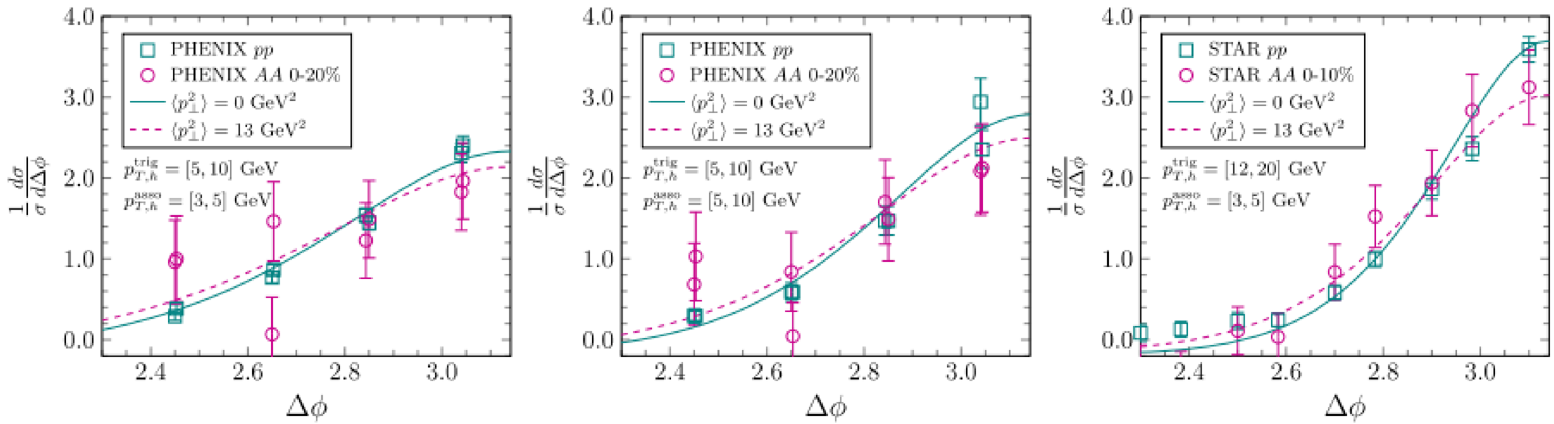
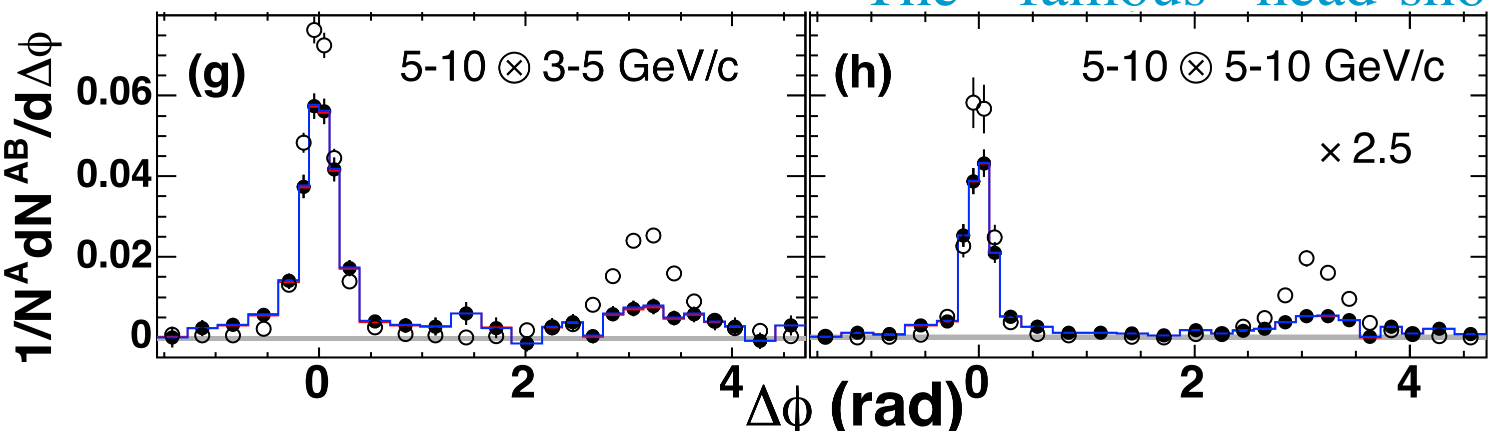


Fig. 1. Normalized dihadron angular correlation compared with PHENIX [51] and STAR [52] data.

[51] PHENIX, A. Adare, et al., Phys. Rev. C 77 (2008) 011901

The ``famous'' head-shoulders paper



Where are the errors in the $\Delta\phi \approx 3.14$ away peaks ?

How to understand this issue ?

I sent an email to the authors of PLB 773(2017)672-676 and I got a very prompt answer from Bo-Wen Xiao: “I believe that we are correct when we cited the PHENIX data in PRC 77(2008)011901(R). The data are taken from Fig. 1, Panel (g) and (h) (Previous slide here). We focus on the away side (near π) of these two plots, and plot them in self-normalized manner.” When I pressed Bo-Wen, I got the following important additional information:“We used the software called xyscan to get the data points and the error from the figure. Indeed we rescaled the points for both pp and AA data to make them normalize to 1. I am not sure whether the errors are exact or not. But this is the best we could do at that moment.”

In some sense Bo-Wen was correct since there was no public list of the data for PRC77. However this paper was held up so long in trying to get into PRL that the final paper PRC 78(2008) 014901 did have a list of the data
https://www.phenix.bnl.gov/phenix/WWW/info/data/ppg083_data.html
so I decided to do a fit to our PHENIX data for Panels (g) and (h)

Here are my fit results compared to PLB773

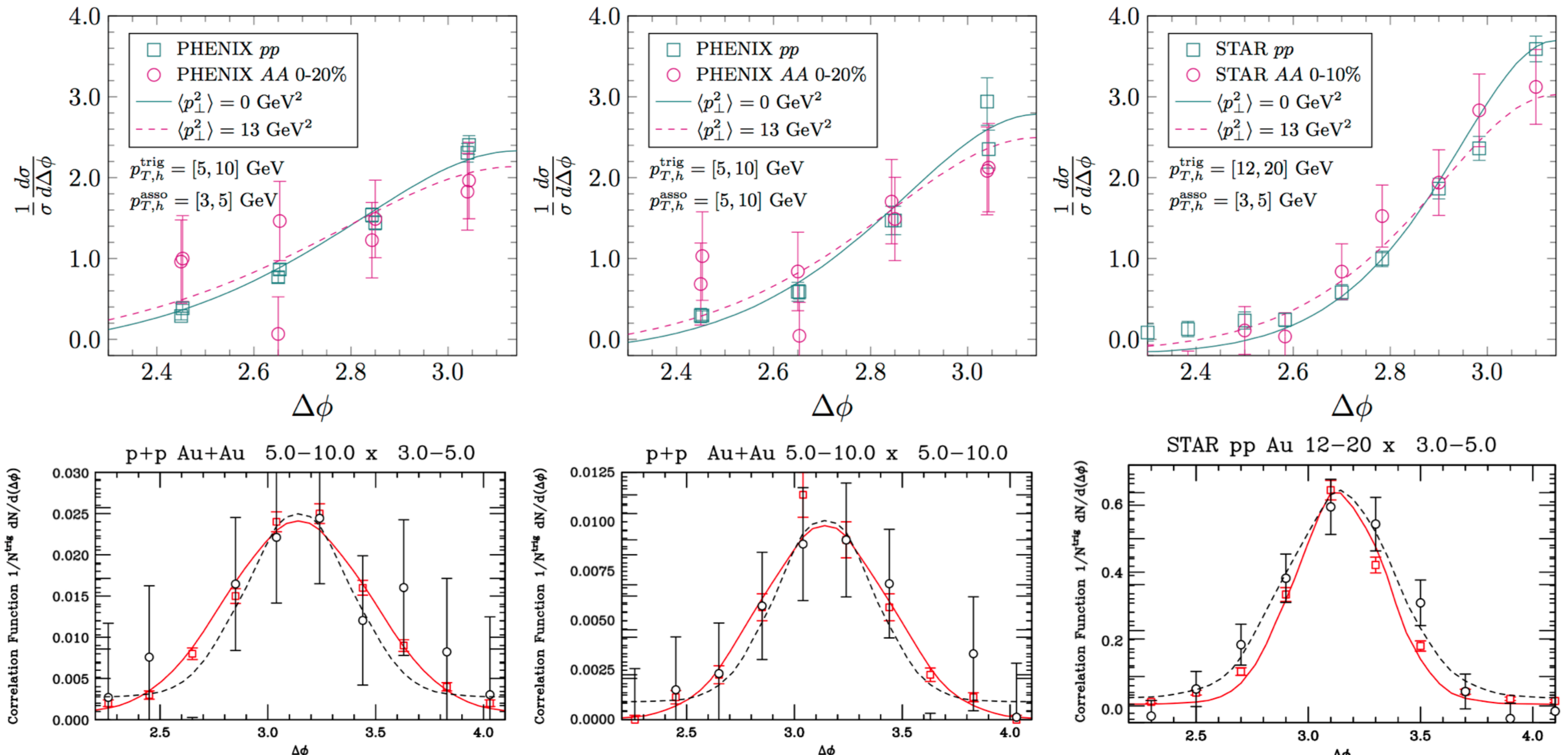


FIG. 3: Gaussian fits to actual dihadron angular correlation measurements of PHENIX [4] plus the previous fit [3] to the STAR data [5]. (p+p data open squares, fits solid lines; Au+Au data open circles, fits dashed lines). The y axes for the Au+Au data and fits are rescaled so that the peaks in the p+p and Au+Au fits lie on top of each other.

My Au+Au (dashed) fits to PHENIX are narrower than my p+p fits!!! My Au+Au fits to STAR are wider than p+p, like PLB773, where published data existed

Here are my fit results compared to PLB773

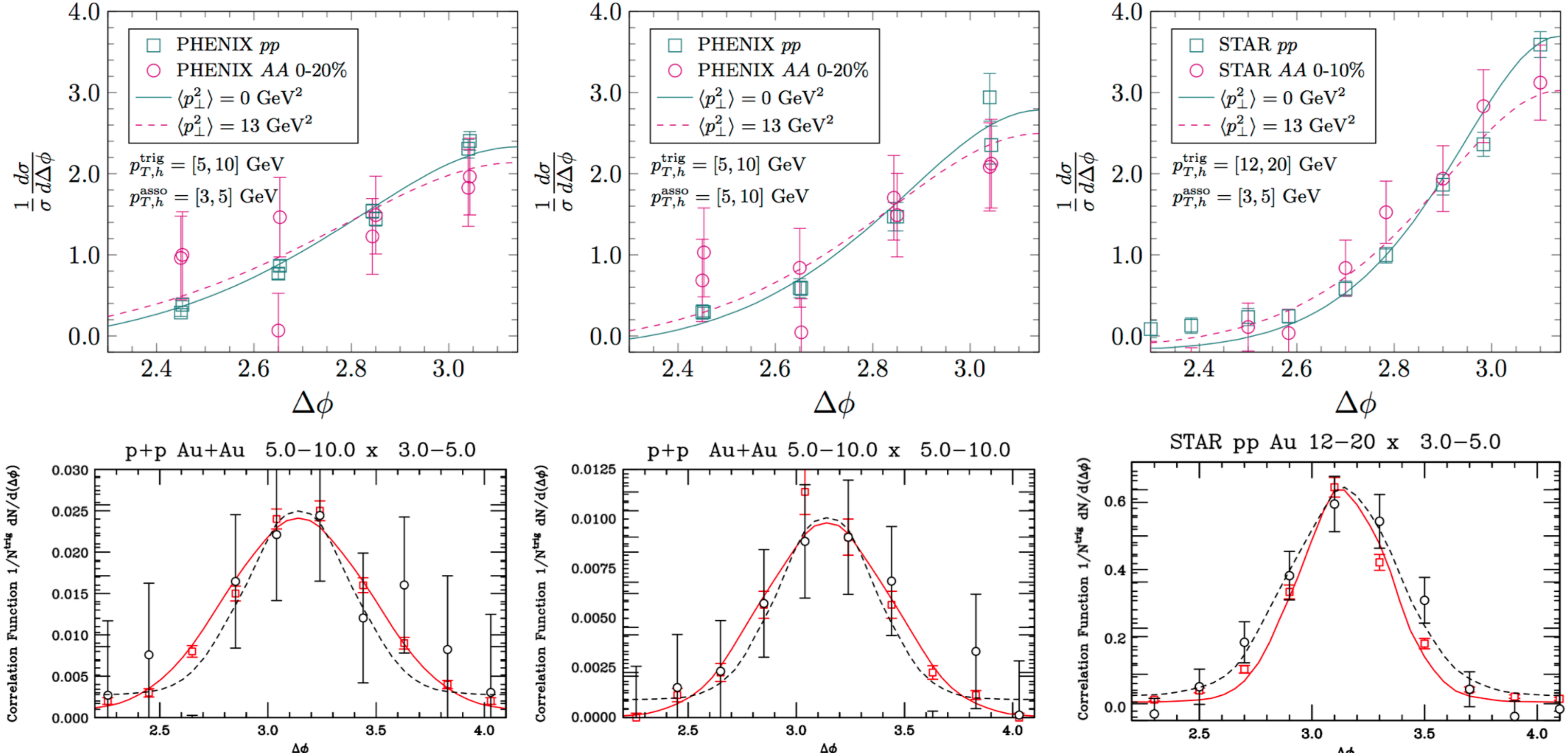


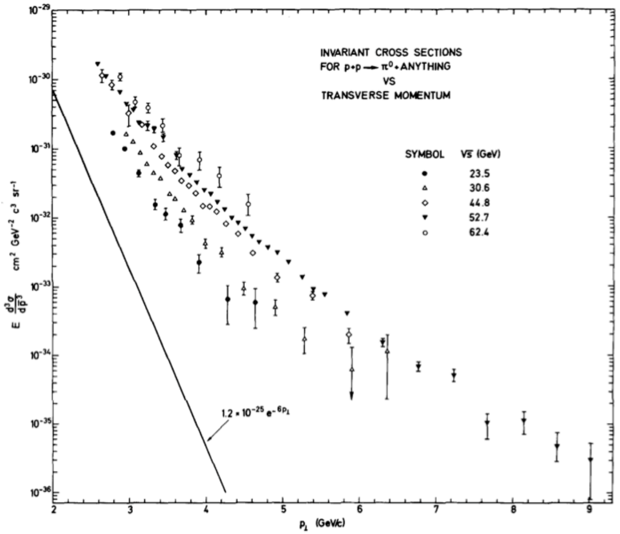
FIG. 3: Gaussian fits to actual dihadron angular correlation measurements of PHENIX [4] plus the previous fit [3] to the STAR data [5]. (p+p data open squares, fits solid lines; Au+Au data open circles, fits dashed lines). The y axes for the Au+Au data and fits are rescaled so that the peaks in the p+p and Au+Au fits lie on top of each other.

The rest of the talk is about what this means and why it is more interesting than you might expect, even for di-jets in sPHENIX

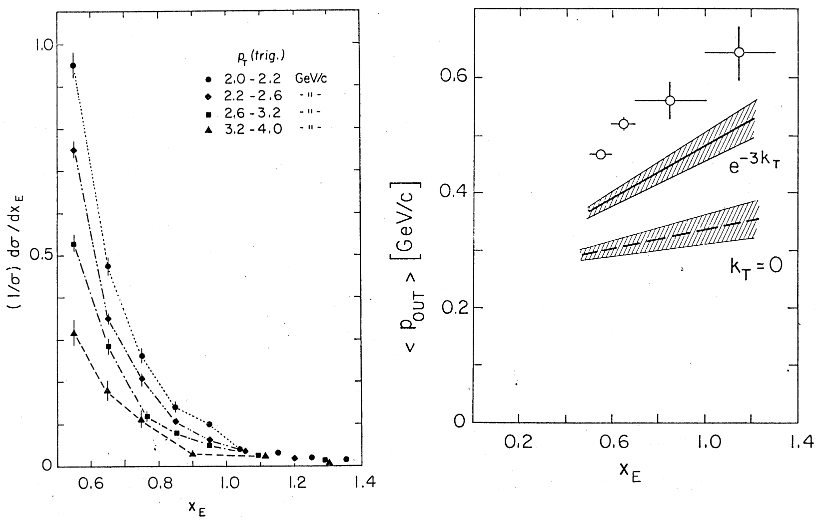
First, I discuss why I am so interested in azimuthal broadening in di-hadron correlations and qhatL

Azimuthal broadening of di-hadrons was first observed at the CERN ISR in 1976-77 by experiments (CCHK) trying to determine what was balancing the production of high p_T particles discovered in 1972-73 at the ISR

CCOR PLB46(1973)471

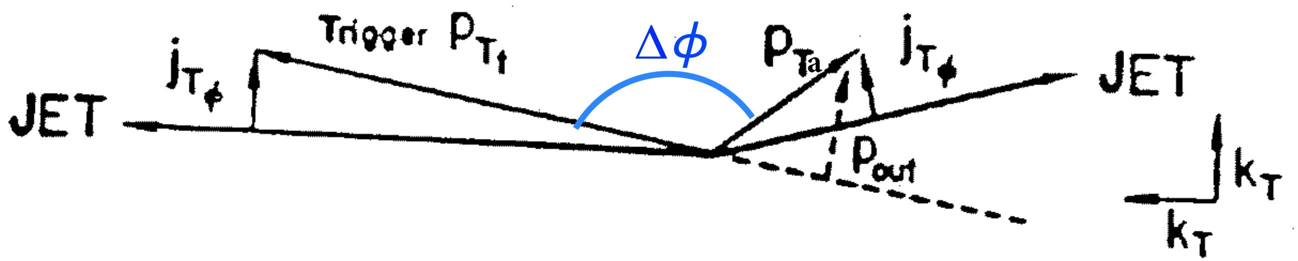


CCHK ``k_T'' NPB1279(2016)1-42



The variables used by CCHK for the measurements were $p_{\rm out} = p_{Ta}\sin(\Delta\phi)$ and $x_E \equiv \frac{p_{Ta}\cos(\Delta\phi)}{p_{Tt}} \approx \frac{p_{Ta}}{p_{Tt}} \equiv x_h$. They found azimuthal broadening, the $\langle p_{\rm out}\rangle$ increased with increasing x_E, which they attributed to transverse momentum k_T of a quark in a proton which Feynman, Field and Fox formalized.

Understanding k_T : FFF NPB128(1977)1-65



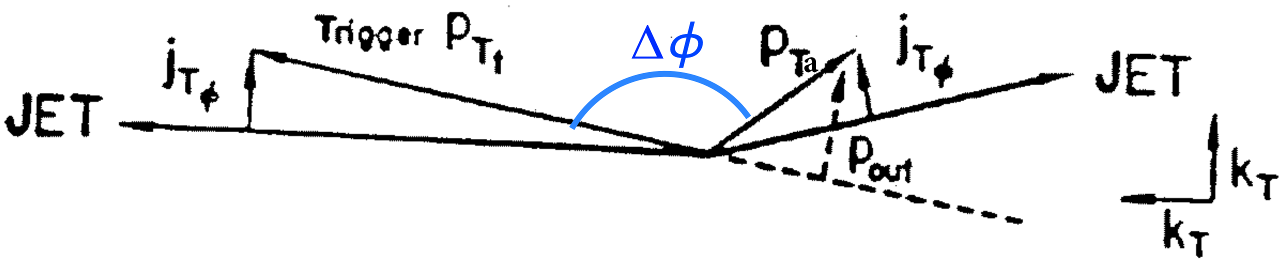
Following the ideas of Levin and Ryskin (Sov.Phys-JETP42(1975)783) and CCHK, Feynman, Field and Fox established the formalism for $\overrightarrow{k_T}$, the transverse momentum of a parton in a nucleon. In this formulation, the net transverse momentum of an outgoing parton pair, where the two $\overrightarrow{k_T}$ add randomly, is $\sqrt{2}k_T$, which is composed of two orthogonal components, $\sqrt{2}k_{T_\phi} = k_T$, out of the scattering plane, which makes the jets acoplanar, i.e. not back-to-back in azimuth, and $\sqrt{2}k_{T_x} = k_T$, along the axis of the trigger jet, which makes the jets unequal in energy.

FFF gave the approximate formula to derive k_T from the measurement of $p_{\rm out}$ as a function of x_E:

$$\langle|p_{\rm out}|\rangle^2 = x_E^2[2\langle|k_{T_\phi}|\rangle^2 + \langle|j_{T_\phi}|\rangle^2] + \langle|j_{T_\phi}|\rangle^2 \qquad .$$

This formula assumed that $\langle z_{\rm trig}\rangle = 1$ and that the jet energies are equal.

Understanding k_T : FFF NPB128(1977)1-65



PHENIX (PRD74(2006)072002) computed $\langle k_T^2 \rangle$ for di-hadrons as fragments of the original di-jets with possible unequal energies :

$$\sqrt{\langle k_T^2 \rangle} = \frac{\hat{x}_h}{\langle z_t \rangle} \sqrt{\frac{\langle p_{\mathrm{out}}^2 \rangle - (1 + x_h^2) \langle j_T^2 \rangle /2}{x_h^2}}$$

where p_{Tt}, p_{Ta} are the transverse momenta of the trigger and away particles, $x_h \equiv p_{Ta}/p_{Tt}$, $\Delta\phi$ is the azimuthal angle between p_{Tt} and p_{Ta} and $p_{\mathrm{out}} \equiv p_{Ta} \sin(\pi - \Delta\phi)$. The di-hadrons are assumed to be fragments of jets with transverse momenta $\hat{p}_{Tt}$ and $\hat{p}_{Ta}$ with ratio $\hat{x}_h \equiv \hat{p}_{Ta}/\hat{p}_{Tt}$. $z_t \simeq p_{Tt}/\hat{p}_{Tt}$ is the fragmentation variable, the fraction of momentum of the trigger particle in the trigger jet. j_T is the jet fragmentation transverse momentum and we have taken $\langle j_{T\mathrm{ay}}^2 \rangle \equiv \langle j_{T\mathrm{a}\phi}^2 \rangle = \langle j_{T\mathrm{t}\phi}^2 \rangle = \langle j_T^2 \rangle /2$. The variable x_h (which STAR calls z_T) is used as an approximation of the variable $x_E = x_h \cos(\pi - \Delta\phi)$ from the original terminology at the CERN ISR where k_T was discovered and measured (CCOR PLB97(1977)163) more than 40 years ago.

So where does qhatL come in?

Rolf Baier asked me at a meeting in Paris in 1998 whether we could measure jets at RHIC.

I said, "Not really, but we probably could do just as well with high p_T hadrons which PHENIX was designed to measure."

I was correct for high p_T hadrons since our high p_T suppression discovery paper is the first and so far only regular paper at RHIC to have more than 1000 citations.

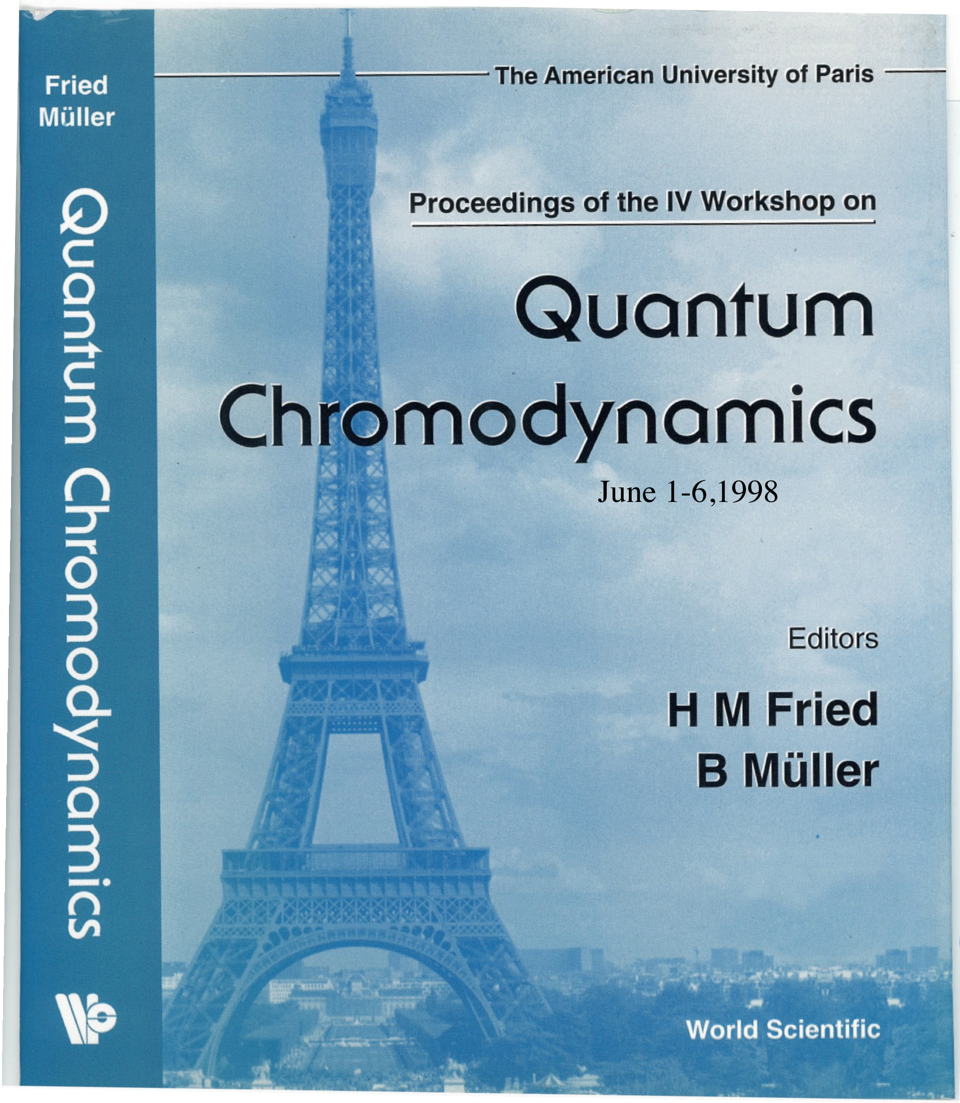
Suppression of hadrons with large transverse momentum in central Au+Au collisions at $\sqrt{s_{NN}}$ = 130-GeV

PHENIX Collaboration (K. Adcox (Vanderbilt U.) *et al.*). Sep 2001. 6 pp.

Published in **Phys.Rev.Lett. 88 (2002) 022301**

Detailed record - Cited by 1028 records

Conference where I first encountered BDMPSZ



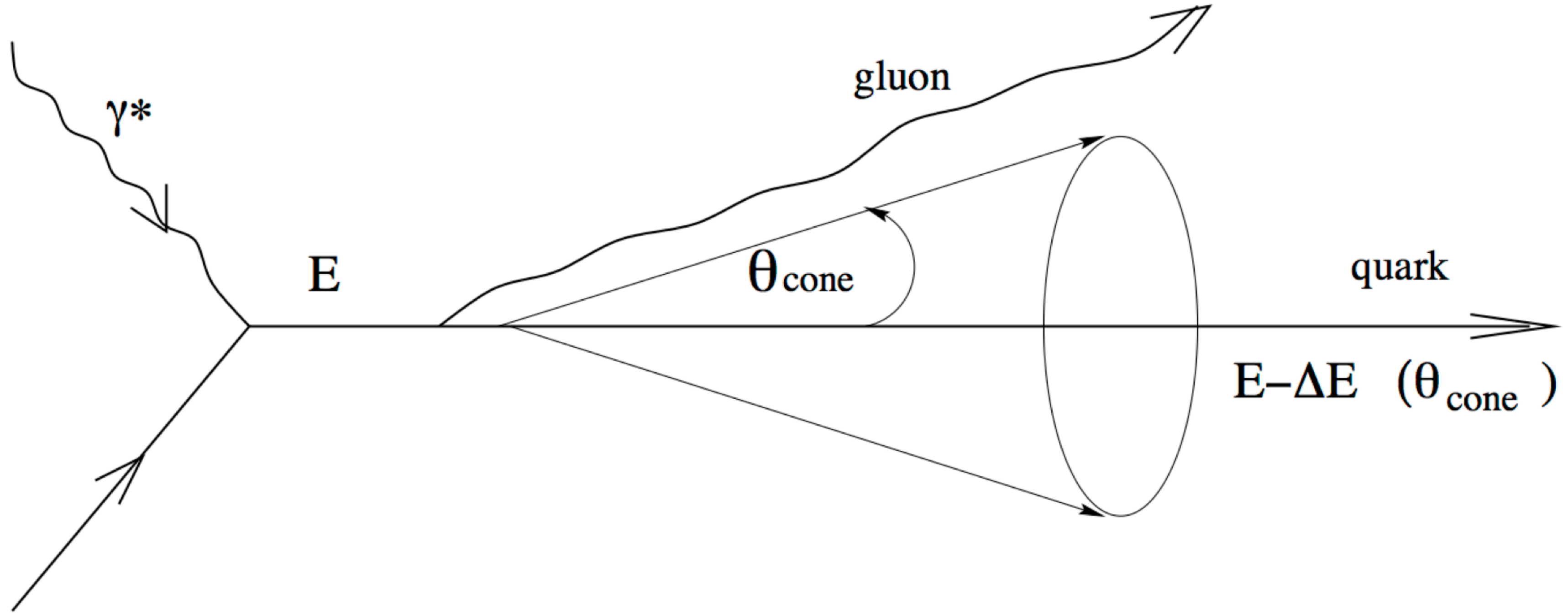
Jet Quenching: by coherent LPM radiative energy loss of a parton in the QGP-1997

In 1997, Baier, Dokshitzer, Mueller Peigne, Schiff also Zakharov, see ARNPS **50**, 37 (2000), said that the energy loss from coherent LPM radiation for hard-scattered partons exiting the QGP would "result in an attenuation of the jet energy and a broadening of the jets"

As a parton from hard-scattering in the A+B collision exits through the medium it can radiate a gluon; and both continue traversing the medium. It is important to understand that "Only the gluons radiated outside the cone defining the jet contribute to the energy loss." . In the angular ordering of QCD, the angular cone of any further emission will be restricted to be less than that of the previous emission and will end the energy loss once inside the jet cone. This doesn't work in the QGP So no energy loss occurs only when all gluons emitted by a parton are inside the jet cone. In addition to other issues this means that defining the jet cone is a BIG ISSUE—watch out for so-called trimming.

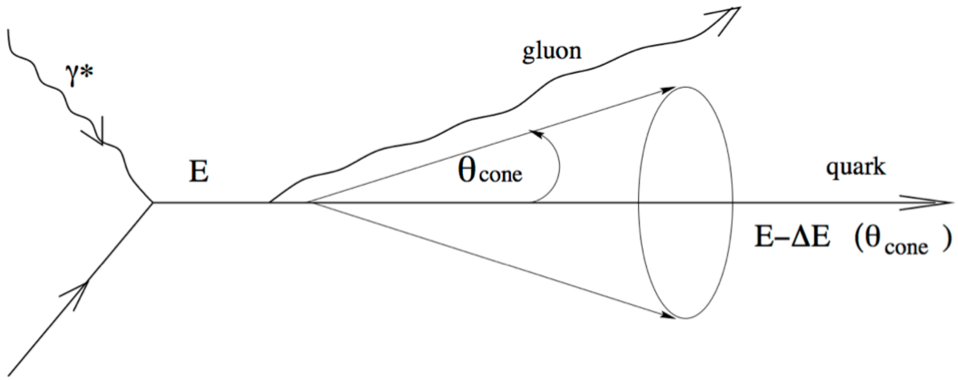
BDMPSZ-the cone, the energy loss, azimuthal broadening-QGP signature 1997

BSZ arXiv:hep-ph/0002198v2



BDMPSZ-the cone, the energy loss, azimuthal broadening-QGP signature 1997

BSZ arXiv:hep-ph/0002198v2



The energy loss of the original outgoing parton, $-dE/dx$, per unit length (x) of a medium with total length L, is proportional to the total 4-momentum transfer-squared, $q^2(L)$, with the form:

$$\frac{-dE}{dx} \simeq \alpha_s \langle q^2(L) \rangle = \alpha_s\, \mu^2\, L/\lambda_{\rm mfp} = \alpha_s\, \hat{q}\, L$$

where μ, is the mean momentum transfer per collision, and the transport coefficient $\hat{q} = \mu^2/\lambda_{\rm mfp}$ is the 4-momentum-transfer-squared to the medium per mean free path, $\lambda_{\rm mfp}$.

Additionally, the accumulated momentum-squared, $\langle p^2_{\perp W} \rangle$ transverse to the parton from its collisions traversing a length L in the medium is well approximated by

$$\langle p^2_{\perp W} \rangle \approx \langle q^2(L) \rangle = \hat{q}\, L.$$

The BDMPSZ model has 2 predictions

(1) The energy loss of the outgoing parton, $-dE/dx$, per unit length (x) of a medium with total length L, is proportional to the total 4-momentum transfer-squared, $q^2(L)$, and takes the form:

$$\frac{-dE}{dx} \simeq \alpha_s \langle q^2(L) \rangle = \alpha_s \, \mu^2 \, L/\lambda_{\rm mfp} = \alpha_s \, \hat{q} \, L$$

where μ, is the mean momentum transfer per collision, and the transport coefficient $\hat{q} = \mu^2/\lambda_{\rm mfp}$ is the 4-momentum-transfer-squared to the medium per mean free path, $\lambda_{\rm mfp}$.

(2) Additionally, the accumulated momentum-squared, $\langle p^2_{\perp W} \rangle$ transverse to a parton traversing a length L in the medium is well approximated by

$$\langle p^2_{\perp W} \rangle \approx \langle q^2(L) \rangle = \hat{q} \, L$$

$$\langle \hat{q} L \rangle = \langle k_T^2 \rangle_{AA} - \left\langle k'^2_T \right\rangle_{pp}$$

Although only the component of $\langle p^2_{\perp W} \rangle$ $\perp$ to the scattering plane affects k_T, the azimuthal broadening of the di-jet is caused by the random sum of the azimuthal components $\langle p^2_{\perp W} \rangle /2$ from each outgoing di-jet or $\langle p^2_{\perp W} \rangle = \hat{q} \, L$

The problem for azimuthal broadening

Many experiments at RHIC, including recent experiments with di-Jet [7] di-hadron [5] and jet-hadron [6] azimuthal correlations have searched for azimuthal broadening in Au+Au collisions compared to p+p collisions and have not found a significant difference in the Gaussian widths of the away peaks. (See MJT PLB771(2017)553-557 for the citations).
This effect, for $p_{Ta} \geq$ 2-3 GeV/c turns out to be interesting and related to another `well known effect' called I_{AA} and will be discussed later.

Another problem which took me a long time to figure out is that if you simply measure k_T with the same pTt and pTa in p+p and Au+Au collisions you get crazy answers.

The key new idea (k'_T) gives elegant Solutions

The di-hadron correlations of p_{Tt} with p_{Ta} are measured in p+p and Au+Au collisions. The parent jets in the original Au+Au collision as measured in p+p will both lose energy passing through the medium but the azimuthal angle between the jets should not change unless the medium induces multiple scattering from $\hat{q}$. Thus the calculation of k'_T from the dihadron p+p mesurement to compare with Au+Au measurements with the same di-hadron p_{Tt} and p_{Ta} must use the value of $\hat{x}_h$ and $\langle z_t \rangle$ of the parent jets in the A+A collision.

$$x_h = p_{Ta}/p_{Tt} \quad \hat{x}_h = \hat{p}_{Ta}/\hat{p}_{Tt} \quad \langle z_t \rangle = p_{Tt}/\hat{p}_{Tt}$$

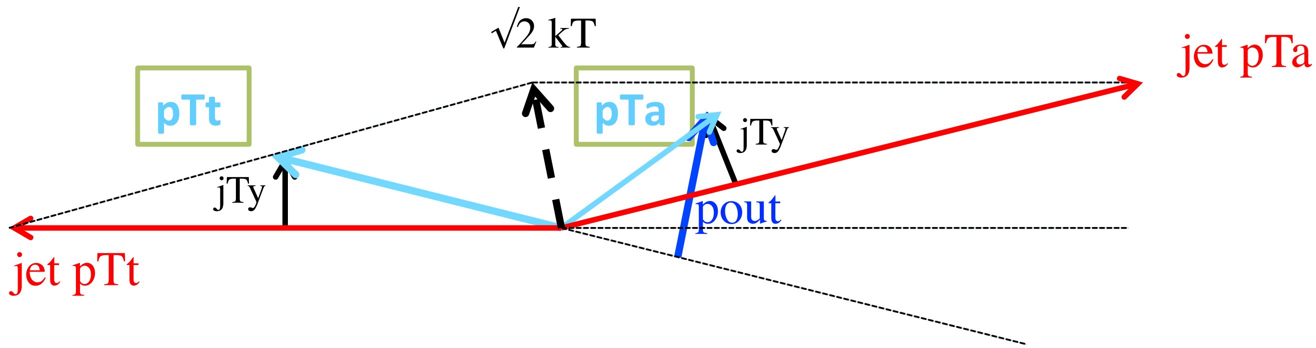
The same values of $\hat{x}_h$, and $\langle z_t \rangle$ in Au+Au and p+p gives the cool result:

$$\langle \hat{q}L \rangle = \left[\frac{\hat{x}_h}{\langle z_t \rangle}\right]^2 \left[\frac{\langle p_{\rm out}^2 \rangle_{AA} - \langle p_{\rm out}^2 \rangle_{pp}}{x_h^2}\right]$$

For di-jet measurements, the formula is even simpler:
i) $x_h \equiv \hat{x}_h$ because the trigger and away 'particles' are the jets; ii) $\langle z_t \rangle \equiv 1$ because the trigger 'particle' is the entire jet not a fragment of the jet;
iii) $\langle p_{\rm out}^2 \rangle = \hat{p}_{Ta}^2 \sin^2(\pi - \Delta\phi)$. This reduces the formula for di-jets to:

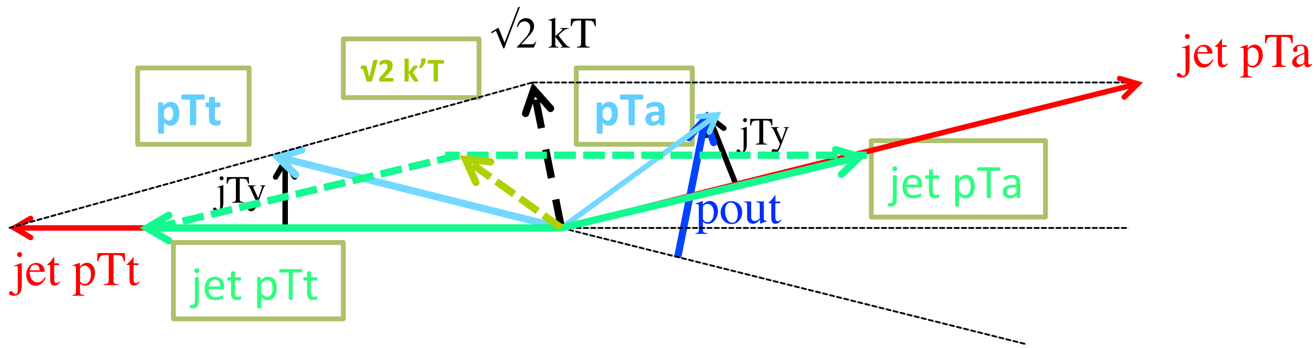
$$\langle \hat{q}L \rangle = \left[\langle p_{\rm out}^2 \rangle_{AA} - \langle p_{\rm out}^2 \rangle_{pp}\right] = \hat{p}_{Ta}^2 \left[\langle \sin^2(\pi - \Delta\phi) \rangle_{AA} - \langle \sin^2(\pi - \Delta\phi) \rangle_{pp}\right]$$

The solution in pictures



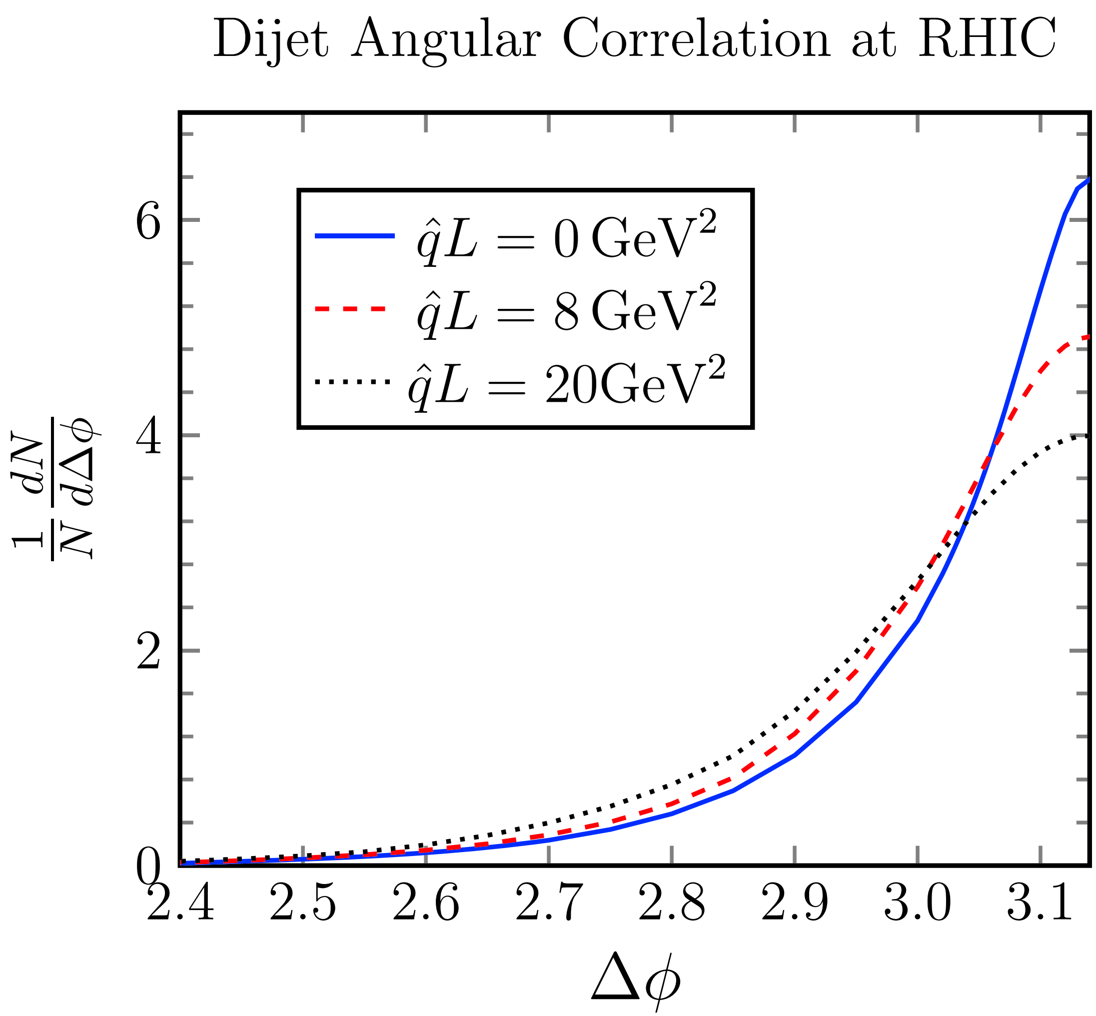
Initial configuration a di-jet with k_T and fragments with p_{out} .

The solution in pictures



Final configuration a di-jet with k'_T and fragments with p_{out} .

Homework

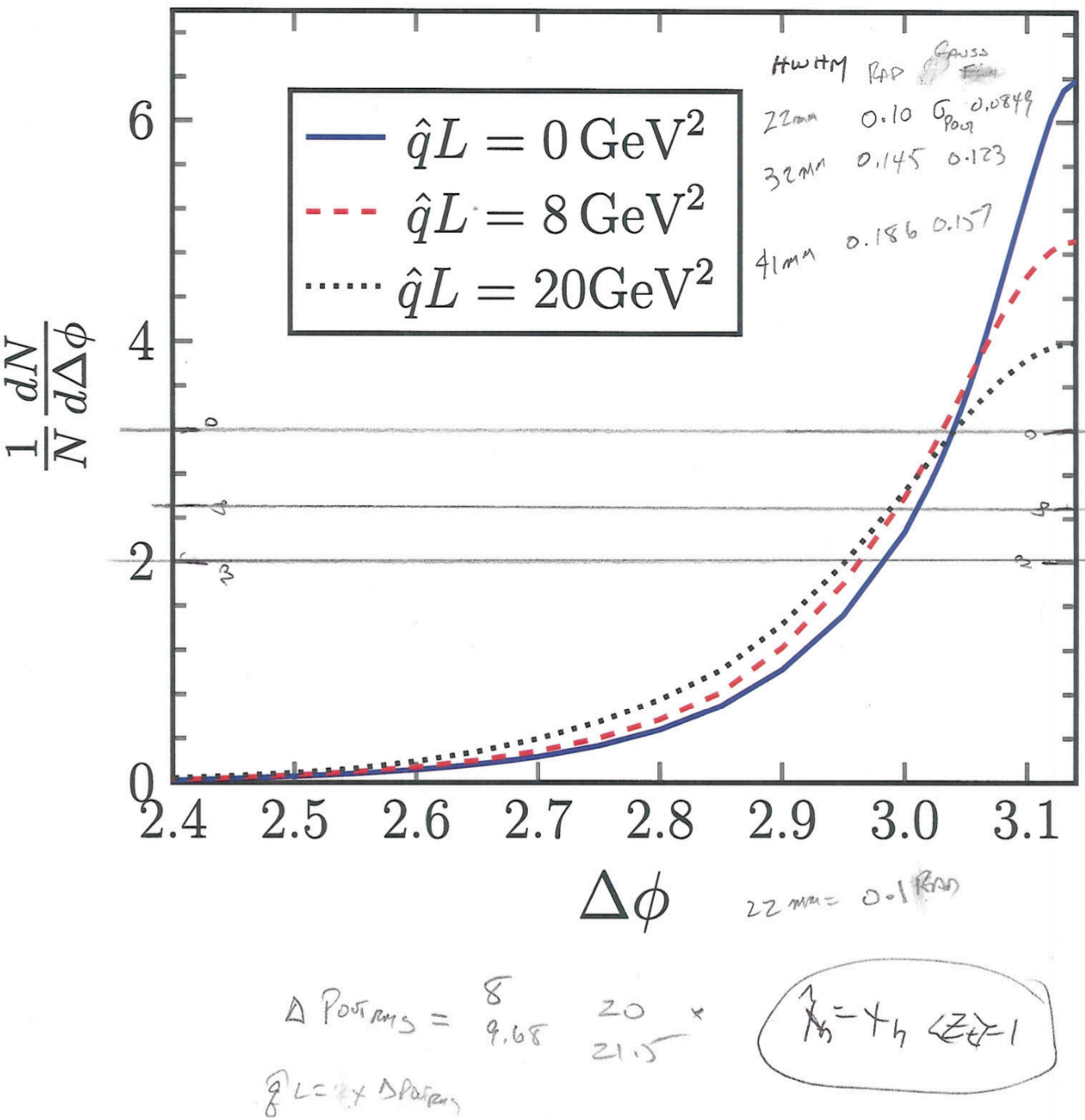


A.Mueller et al PLB **763** (2016) 208 predictions for 35 GeV/c Jets at RHIC

$$\langle \hat{q}L \rangle = \left[\left\langle p^2_{\mathrm{out}} \right\rangle_{AA} - \left\langle p^2_{\mathrm{out}} \right\rangle_{pp} \right]$$

Does the formula give the same answer for qhatL from $\langle p^2_{out} \rangle$ of the above predictions at RHIC for 35 GeV Jets?
I got 9.7 GeV^2 and 21.5 GeV^2 respectively for the 8 GeV^2 and 20 GeV^2 plots

My method and answer



A.Mueller et al PLB **763** (2016) 208 predictions for 35 GeV/c Jets at RHIC

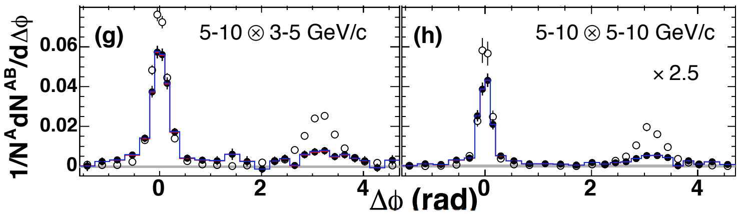
The theorists don't give numbers for the curves, so I assumed gaussians and measured the half width at half maximum, which for a gaussian is 1.177 σ. i.e. σ=hwhmax/1.177.

Assuming that the peak is symmetric about π, I calculated $\langle p_{out}^2 \rangle = (35 * \sin\sigma)^2$ and used

$$\langle \hat{q}L \rangle = \left[\langle p_{\mathrm{out}}^2 \rangle_{AA} - \langle p_{\mathrm{out}}^2 \rangle_{pp} \right]$$

I got 9.7 GeV^2 and 21.5 GeV^2 for the 8 GeV^2 and 20 GeV^2 plots

OK—Now back to the PHENIX data problem



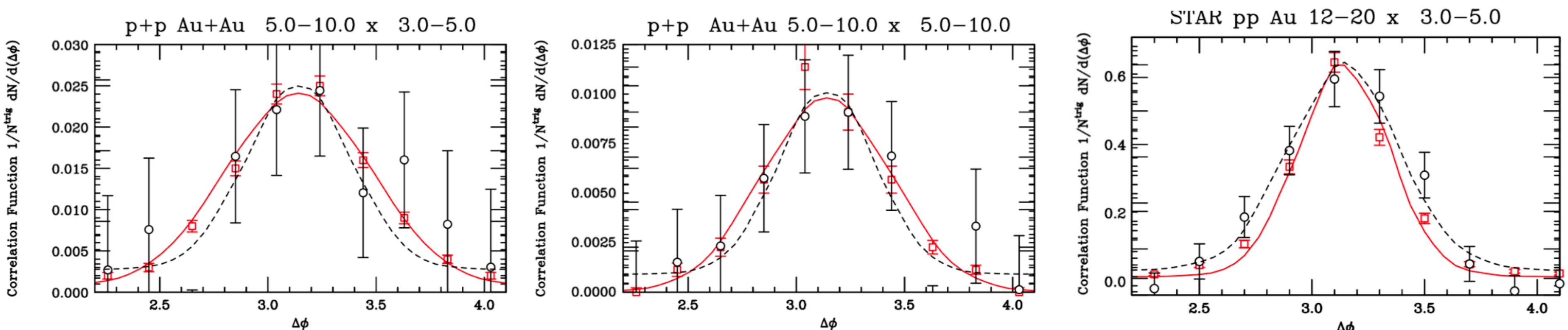
Normally, I would fit a two-particle correlation function $C^{ta}(\Delta\phi)$ for a trigger particle with p_{T_t} and associated particle p_{T_a} to the function:

$$C^{ta}(\Delta\phi) = J^{ta}(\Delta\phi) + B\left[1 + 2v_{22}^{ta}\cos(2\Delta\phi) + 2v_{33}^{ta}\cos(3\Delta\phi) + 2v_{44}^{ta}\cos(4\Delta\phi)\right]$$

For the Jet function $J^{ta}(\Delta\phi)$ I took the same and away side peaks as gaussians with rms σ_s and σ_a and integral N_s and N_a respectively, i.e.

$$J^{ta}(\Delta\phi) = \frac{N_s}{\sigma_s\sqrt{2\pi}}\exp\frac{-\Delta\phi^2}{2\sigma_s^2} + \frac{N_a}{\sigma_a\sqrt{2\pi}}\exp\frac{-(\pi-\Delta\phi)^2}{2\sigma_a^2},$$

However the PHENIX data was a Jet function that already had the v_2 accounted for [but didn't use v_3 and v_4], so the fit was simple.



The y axes in the PHENIX data are rescaled so that the peaks in the p+p and Au+Au fits lie on top of each other. STAR fit details will follow.

Tabulation of MJT-PHENIX results

Tabulations for $\langle \hat{}qL \rangle$–PHENIX PRC77

PHENIX PRC77				
$\sqrt{s_{NN}} = 200$	$\langle p_{Tt} \rangle$	$\langle p_{Ta} \rangle$	$\langle p^2_{\rm out} \rangle$	$\langle \hat{q}L \rangle$
Reaction	GeV/c	GeV/c	$({\rm GeV/c})^2$	$\rm GeV^2$
p+p	8.08	3.75	1.54 ± 0.08	
p+p	8.08	6.68	3.92 ± 0.33	
Au+Au 0-20%	8.08	3.75	0.79 ± 0.64	-2.24 ± 2.01
Au+Au 0-20%	8.08	6.68	2.12 ± 1.13	-1.68 ± 1.21

Note that the qhatL results are negative but consistent with zero and completely in disagreement with the 13 $\rm GeV^2$ quoted in the figure from PLB 773.
The zero values for pTa>3 GeV/c are common and will be discussed in detail

q-hat L calculations from other measurements will be presented but first some details of how to find the needed di-jet quantities

Find di-jet info from di-hadrons and $\langle z_t \rangle$

$$\langle \hat{q} L \rangle = \left[\frac{\hat{x}_h}{\langle z_t \rangle} \right]^2 \left[\frac{\langle p_{\rm out}^2 \rangle_{AA} - \langle p_{\rm out}^2 \rangle_{pp}}{x_h^2} \right]$$

This is well known to older PHENIXians who have read PRD74(2006)072002, or my book [Rak & Tannenbaum, High pT physics in the Heavy Ion Era –Cambridge 2013] as outlined below

- A) Bjorken parent-child relation and `trigger-bias' gives $\langle z_t \rangle$ [NPB 113(1976) 395–412].
- B) The energy loss of the trigger jet from p+p to Au+Au can be measured by the shift [PRC87(2013) 034911]
- C) \hat{x}_h the ratio of the away-jet to the trigger jet transverse moments can be measured by the away particle p_{Ta} distribution for a given trigger particle p_{Tt}

$$\left. \frac{dP_\pi}{dx_E} \right|_{p_{T_t}} \approx N(n-1) \frac{1}{\hat{x}_h} \frac{1}{(1 + \frac{x_E}{\hat{x}_h})^n}$$

n=8.1 for 200 GeV

PHENIX π^0 Au+Au $\sqrt{s_{NN}}$=200 GeV 0801.4020

Power Law p_T>3GeV/c all centralities n=8.10±0.05

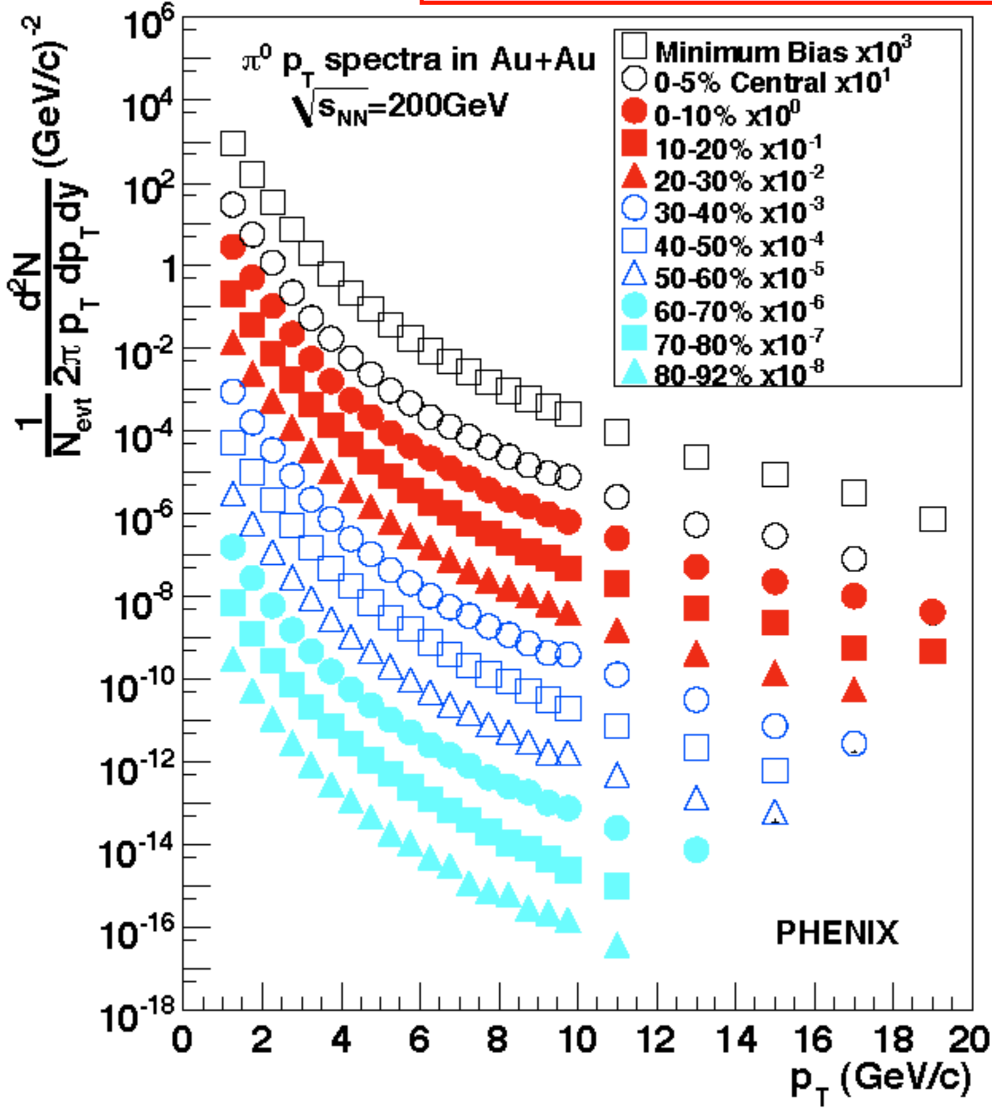
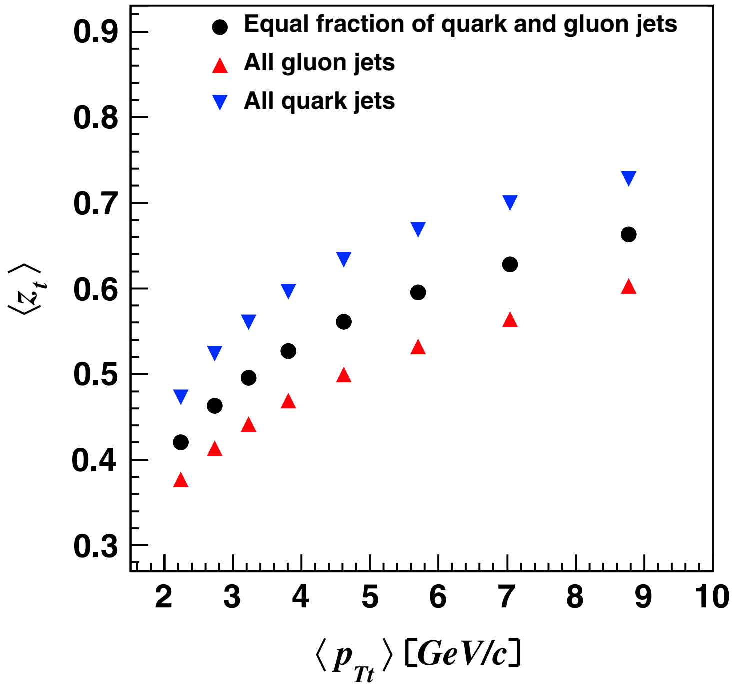
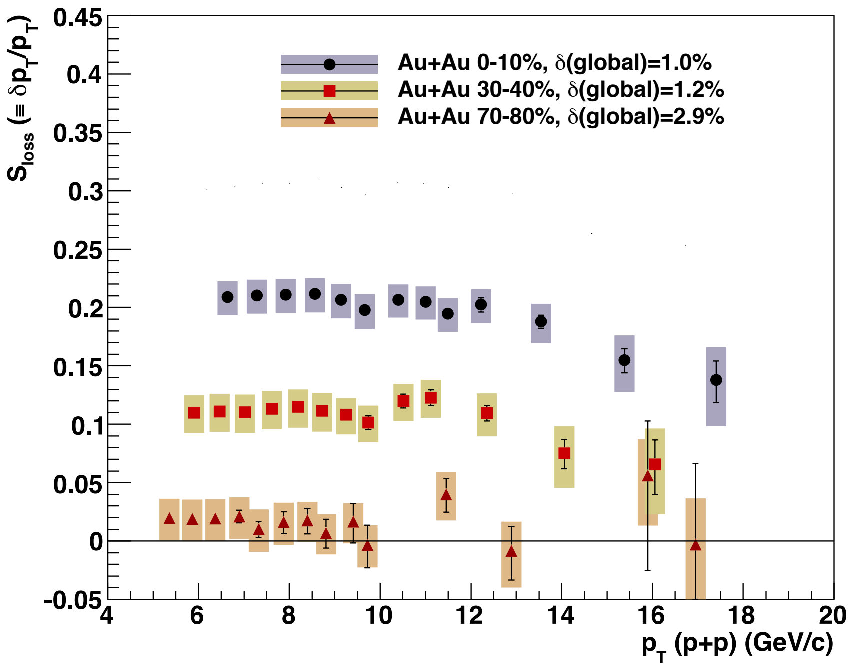


Table 5: Fit parameters for p_T>3 GeV/c

System	A	n	χ^2/NDF
p+p	14.61±1.45	8.12±0.05	5.68/17
Au+Au 0-5 %	81.18±10.30	8.20±0.07	9.66/16
Au+Au 0-10 %	75.28±8.89	8.18±0.06	10.62/17
Au+Au 10-20 %	64.62±7.64	8.19±0.06	10.04/17
Au+Au 20-30 %	49.33±5.78	8.18±0.06	6.63/16
Au+Au 30-40 %	30.85±3.53	8.10±0.06	10.63/16
Au+Au 40-50 %	22.58±2.61	8.13±0.06	3.50/15
Au+Au 50-60 %	12.40±1.48	8.06±0.07	8.09/15
Au+Au 60-70 %	6.25±0.78	8.03±0.07	2.89/14
Au+Au 70-80 %	3.38±0.45	8.12±0.08	8.42/13
Au+Au 80-92 %	1.19±0.18	8.03±0.09	9.84/13
Au+Au 0-92 %	29.31±3.07	8.17±0.05	6.83/17

Examples of A) and B)



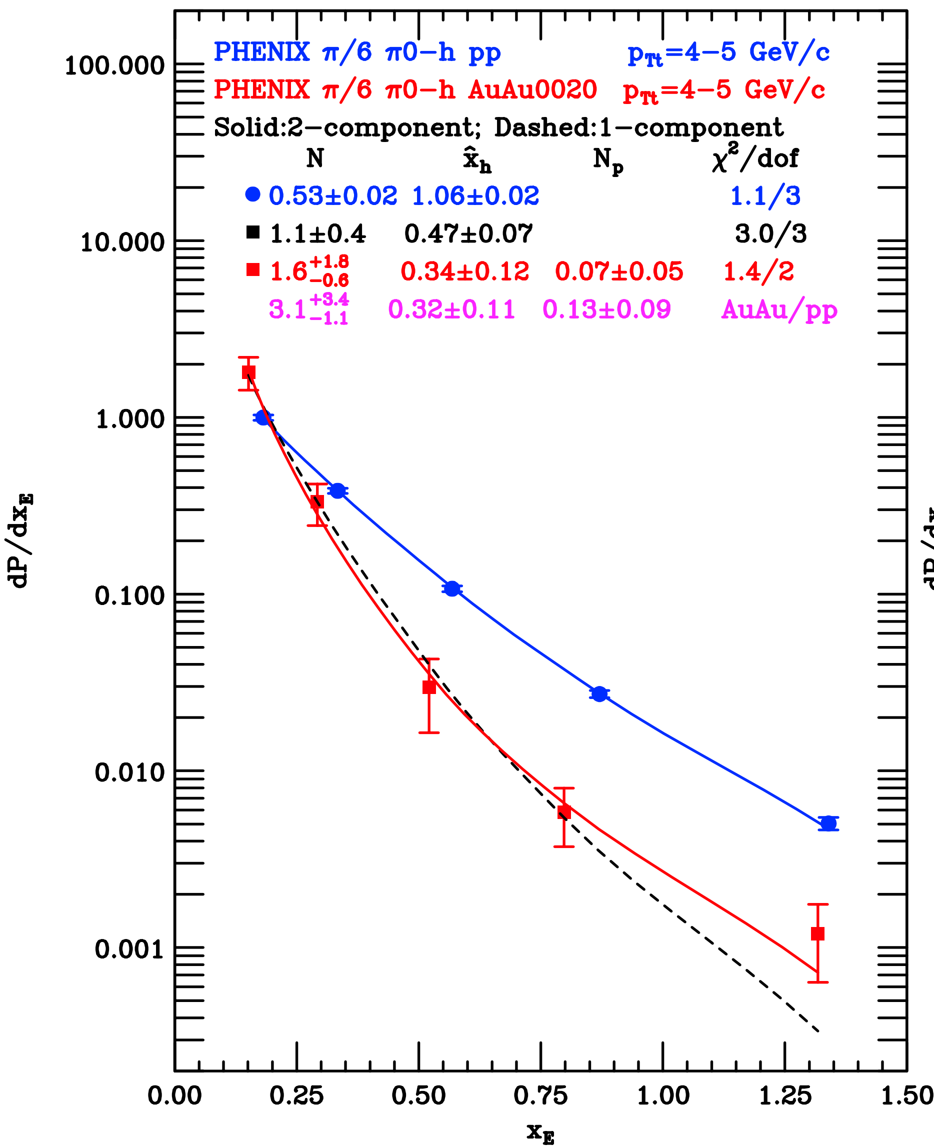


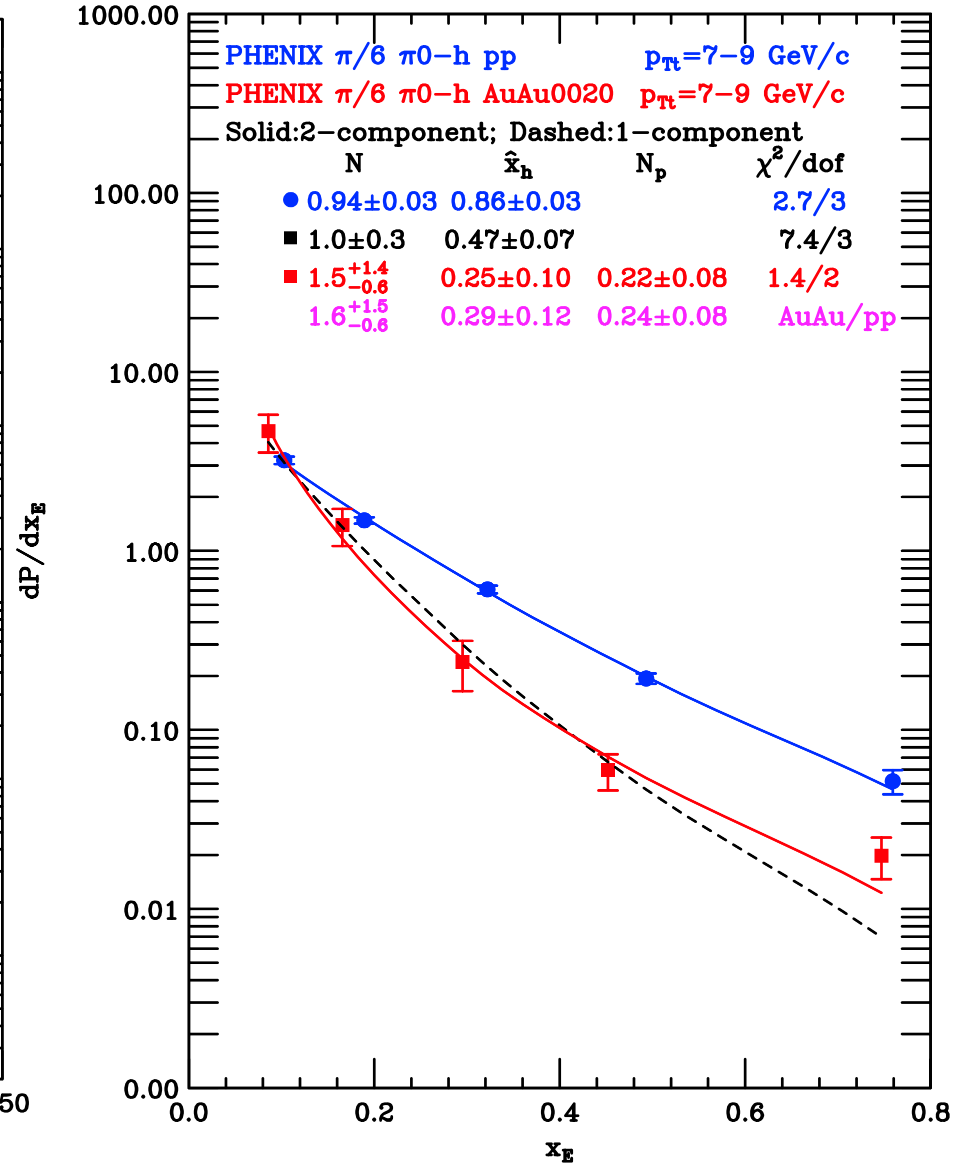
$<z_t>$= Fractional momentum of trigger fragment for π^0 p_{Tt} spectra with n=8.10 is calculated from gluon and quark fragmentation functions measured at LEP PRD81(2010)012002

Fractional Shift in π^0 p_{Tt} spectra from p+p to A+Au PRC87(2013)034911

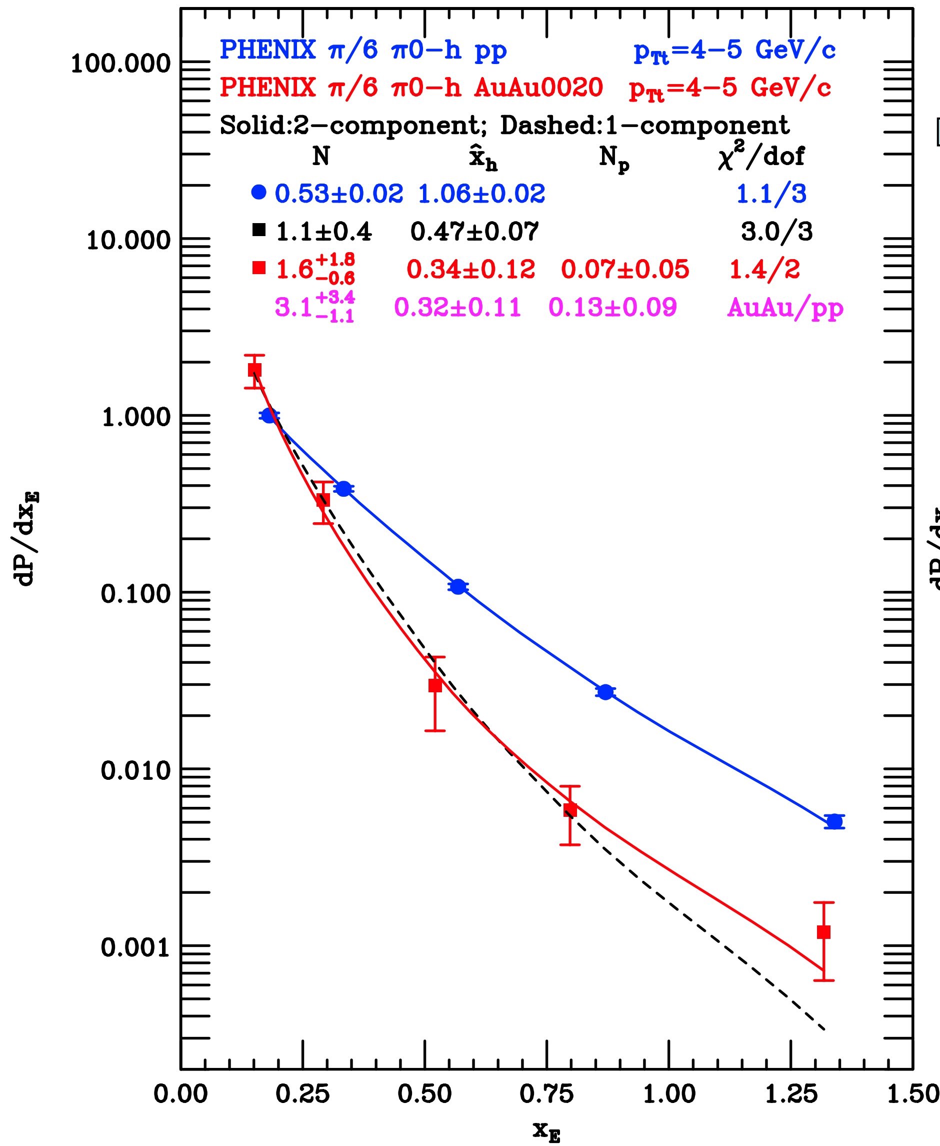
The $\langle z_t \rangle$ for p+p and Au+Au measurements may differ slightly because the maximum possible parton energy $\sqrt{s_{NN}}/2$ is reduced by the energy loss. The effect on $\langle z_t \rangle$ from p+p to Au+Au was estimated by increasing p_{Tt} in the calculation of $\langle z_t \rangle$ in p+p collisions by $\delta p_T/p_T^{pp} = 0.20$ for centrality 0-10%.

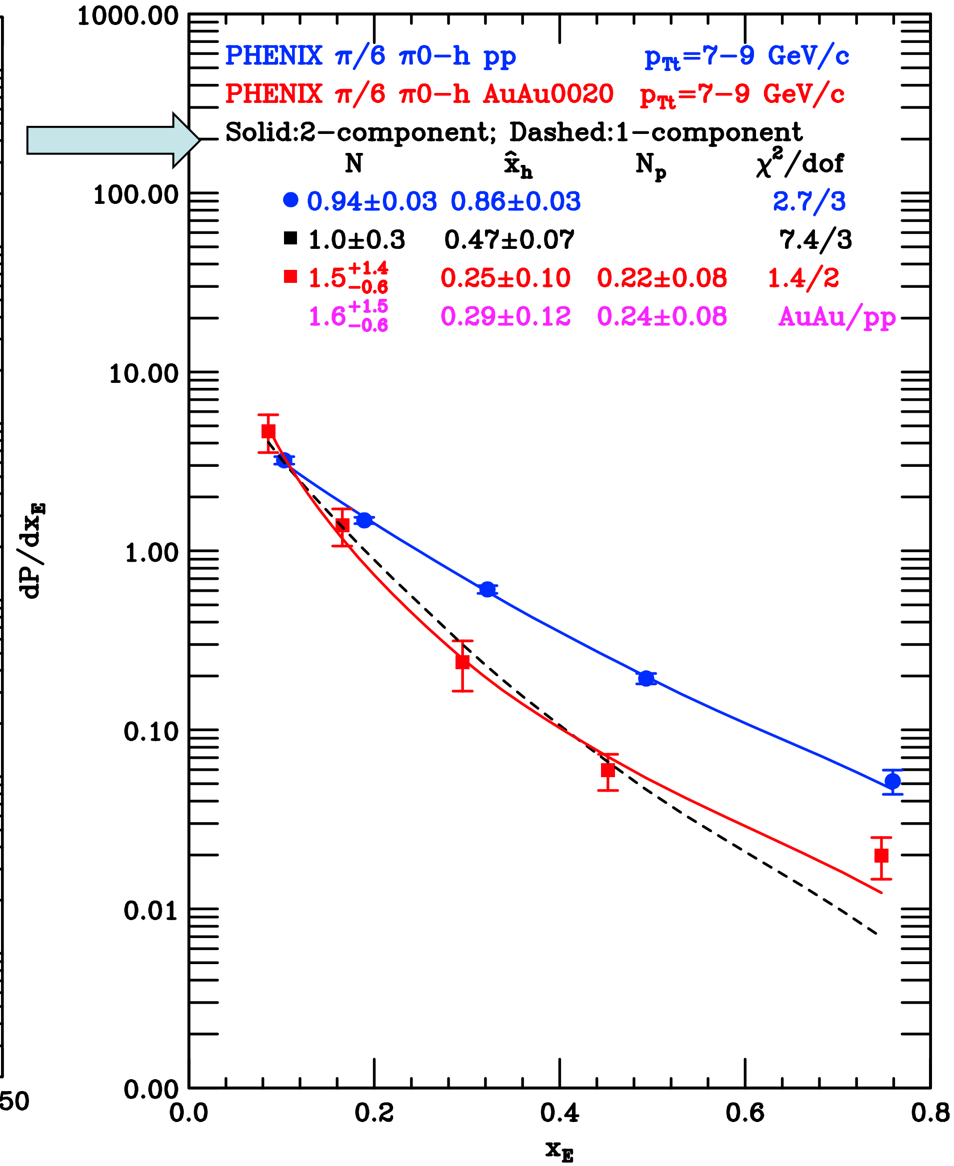
C) \hat{x}_h from fits to the PX PRL104 data





C) \hat{x}_h from fits to the PX PRL104 data



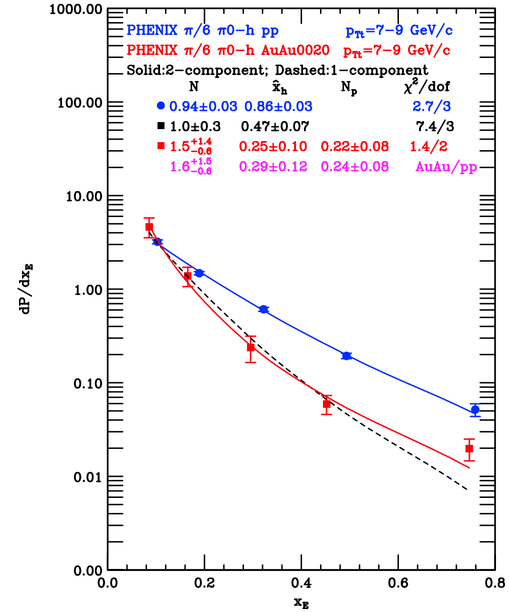


A more interesting result from the x_E fits

In the previous slide there is a fit to the PHENIX x_E Au+Au 0-20% and p+p distributions in a region with $7 < p_{Tt} < 9$ GeV/c, $\langle p_{Tt} \rangle \approx 7.8$ GeV/c, comparable to the $\langle p_{Tt} \rangle \approx 6.5$ GeV/c of the $5 < p_{Tt} < 10$ GeV/c range of the PHENIX PRC77 data. The results are $\hat{x}_h = 0.86 \pm 0.03$ in p+p and $\hat{x}_h = 0.47 \pm 0.07$ Au+Au (dashes). What is more interesting is a fit to a two-component formula for N and $\hat{x}_h^{AA}$ plus another term with $\hat{x}_h = 0.86$ fixed at the p+p value:

$$\left.\frac{dP_\pi}{dx_E}\right|_{p_{T_t}} = N\,(n-1)\frac{1}{\hat{x}_h^{AA}}\frac{1}{(1+\frac{x_E}{\hat{x}_h^{AA}})^n} + N_p\,(n-1)\frac{1}{\hat{x}_h^{pp}}\frac{1}{(1+\frac{x_E}{\hat{x}_h^{pp}})^n} \quad .$$

Here the first term represents the x_E distribution of a parton which has lost energy in the medium and then fragmented; and the second term represents the x_E distribution of a parton which has punched through the medium without losing energy and then fragmented, thus giving the same x_E distribution as in p+p collisions albeit reduced in magnitude by the fraction of partons that have punched through the medium. The fitted values are $N_p = 0.22 \pm 0.08$, compared to the $N = 1.5^{+1.4}_{-0.6}$ for the partons that have lost energy. The result is the solid Au+Au curve with a much better χ^2 which is notably parallel to the p+p curve for $x_E \geq 0.4$ ($p_{Ta} \approx p_{Tt} \times x_E = 3.1$ GeV/c).



MJT qhatL calculations from published STAR and PHENIX data

The results from STAR PLB760(2016)689 as given by MJT in PLB771(2017)553 also show a zero result for p_{Ta}> 3 GeV/c

with a few corrections

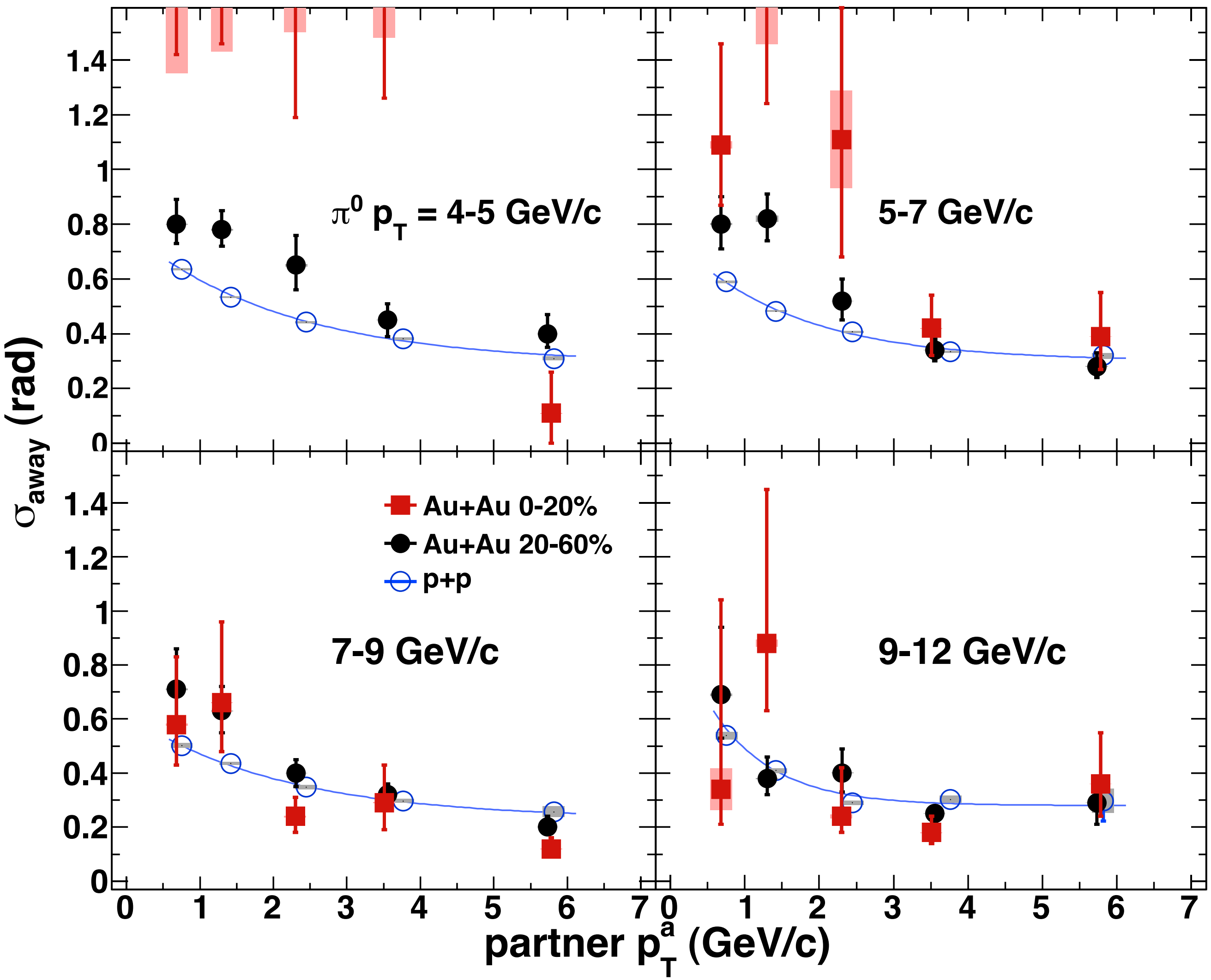
Table 18: Tabulations for $\hat{q}$–STAR π^0-h: $12 < p_{Tt} < 20$ GeV/c 00-12% Centrality

STAR PLB771						
$\sqrt{s_{NN}} = 200$	$\langle p_{Tt} \rangle$	$\langle p_{Ta} \rangle$	$\langle z_t \rangle$	$\hat{x}_h$	$\langle p^2_{\rm out} \rangle$	$\sqrt{\langle k_T^2 \rangle}$
Reaction	GeV/c	GeV/c		GeV/c		GeV/c
p+p	14.71	1.72	0.80 ± 0.05	0.84 ± 0.04	0.263 ± 0.113	2.34 ± 0.34
p+p	14.71	3.75	0.80 ± 0.05	0.84 ± 0.04	0.576 ± 0.167	2.51 ± 0.31
Au+Au 00-12%	14.71	1.72	0.80 ± 0.05	0.36 ± 0.05	0.547 ± 0.163	2.28 ± 0.35
Au+Au 00-12%	14.71	3.75	0.80 ± 0.05	0.36 ± 0.05	0.851 ± 0.203	1.42 ± 0.22
p+p comp	14.71	1.72	0.80 ± 0.05	0.36 ± 0.05	0.263 ± 0.113	1.006 ± 0.18
p+p comp	14.71	3.75	0.80 ± 0.05	0.36 ± 0.05	0.576 ± 0.167	1.076 ± 0.18
						$\langle \hat{q}L \rangle$ GeV^2
Au+Au 00-12%	14.71	1.72				4.21 ± 3.24*
Au+Au 00-12%	14.71	3.75				0.86 ± 0.87*

number 3 triptych plot

The errors on the STAR $\langle \hat{q}L \rangle$ GeV^2 are much larger than stated in my publication using the STAR data because I made an error by incorrectly calculating error Eq. which is correct. Interestingly neither referee caught this because all they had to do was use Eq. 5 since the necessary information with correct errors was given in the Tables. For the present work, the errors are correct. Also, the new values reflect that Eq. 5 defines $\langle \hat{q}L \rangle$ not $\langle \hat{q}L \rangle /2$.

Fig 2 from PHENIX PRL104,252301(2010) shows the away widths so qhatL calc is easy



Some qhatL results from PRL104 Fig2

Table 8: Tabulations for $\hat{q}$–PHENIX π^0-h: $5 < p_{Tt} < 7$ GeV/c 20-60% Centrality (Fig. 13)

PHENIX PRL104						
$\sqrt{s_{NN}} = 200$	$\langle p_{Tt} \rangle$	$\langle p_{Ta} \rangle$	$\langle z_t \rangle$	$\hat{x}_h$	$\langle p^2_{\rm out} \rangle$	$\sqrt{\langle k^2_T \rangle}$
Reaction	GeV/c	GeV/c		GeV/c		GeV/c
p+p	5.78	1.42	0.60 ± 0.06	0.96 ± 0.02	0.434 ± 0.010	3.13 ± 0.37
p+p	5.78	2.44	0.60 ± 0.06	0.96 ± 0.02	0.934 ± 0.031	3.18 ± 0.34
p+p	5.78	3.76	0.60 ± 0.06	0.96 ± 0.02	1.523 ± 0.061	2.74 ± 0.29
p+p	5.78	5.82	0.60 ± 0.06	0.96 ± 0.02	3.339 ± 0.351	2.73 ± 0.32
Au+Au 20-60%	5.78	1.30	0.62 ± 0.06	0.69 ± 0.05	0.867 ± 0.116	4.04 ± 0.61
Au+Au 20-60%	5.78	2.31	0.62 ± 0.06	0.69 ± 0.05	1.291 ± 0.308	2.88 ± 0.54
Au+Au 20-60%	5.78	3.55	0.62 ± 0.06	0.69 ± 0.05	1.370 ± 0.249	1.90 ± 0.32
Au+Au 20-60%	5.78	5.73	0.62 ± 0.06	0.69 ± 0.05	2.562 ± 0.620	1.66 ± 0.31
p+p comp	5.78	1.30	0.62 ± 0.06	0.69 ± 0.05	0.434 ± 0.010	2.39 ± 0.32
p+p comp	5.78	2.31	0.62 ± 0.06	0.69 ± 0.05	0.934 ± 0.031	2.34 ± 0.29
p+p comp	5.78	3.55	0.62 ± 0.06	0.69 ± 0.05	1.522 ± 0.061	2.03 ± 0.25
p+p comp	5.783	5.73	0.62 ± 0.06	0.69 ± 0.05	3.339 ± 0.351	1.93 ± 0.26
						$\langle \hat{q}L \rangle$ GeV^2
Au+Au 20-60%	5.78	1.30				10.6 ± 3.8
Au+Au 20-60%	5.78	2.31				2.8 ± 2.4
Au+Au 20-60%	5.78	3.55				-0.5 ± 0.9
Au+Au 20-60%	5.78	5.73				-1.0 ± 0.9

More qhatL results from PRL104 Fig2

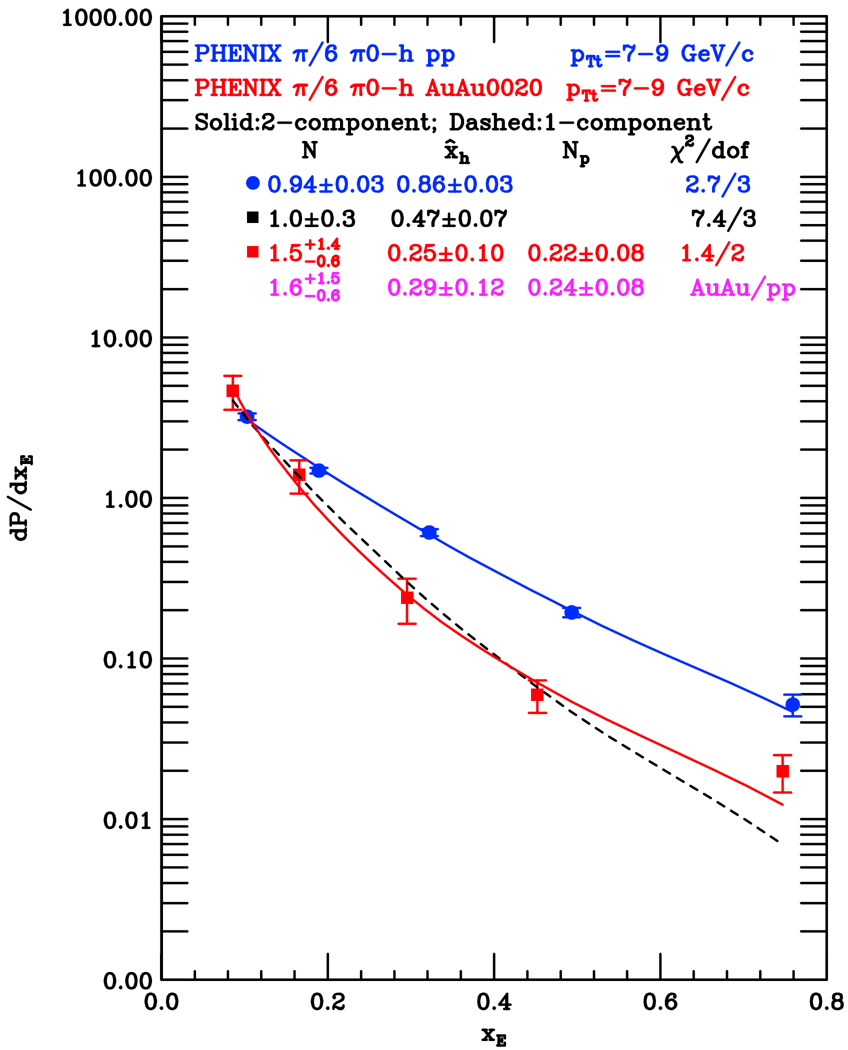
Table 10: Tabulations for $\hat{q}$–PHENIX π^0-h: $7 < p_{Tt} < 9$ GeV/c 20-60% Centrality (Fig. 13)

PHENIX PRL104						
$\sqrt{s_{NN}} = 200$	$\langle p_{Tt} \rangle$	$\langle p_{Ta} \rangle$	$\langle z_t \rangle$	$\hat{x}_h$	$\langle p^2_{\text{out}} \rangle$	$\sqrt{\langle k^2_T \rangle}$
Reaction	GeV/c	GeV/c		GeV/c		GeV/c
p+p	7.83	1.42	0.64 ± 0.06	0.86 ± 0.03	0.360 ± 0.017	2.98 ± 0.41
p+p	7.83	2.44	0.64 ± 0.06	0.86 ± 0.03	0.694 ± 0.048	2.99 ± 0.34
p+p	7.83	3.76	0.64 ± 0.06	0.86 ± 0.03	1.213 ± 0.109	2.76 ± 0.32
p+p	7.83	5.82	0.64 ± 0.06	0.86 ± 0.03	2.177 ± 0.424	2.48 ± 0.38
Au+Au 20-60%	7.83	1.30	0.66 ± 0.06	0.62 ± 0.04	0.548 ± 0.107	3.35 ± 0.64
Au+Au 20-60%	7.83	2.31	0.66 ± 0.06	0.62 ± 0.04	0.803 ± 0.177	2.45 ± 0.46
Au+Au 20-60%	7.83	3.55	0.66 ± 0.06	0.62 ± 0.04	1.237 ± 0.232	2.08 ± 0.34
Au+Au 20-60%	7.83	5.73	0.66 ± 0.06	0.62 ± 0.04	1.300 ± 0.350	1.29 ± 0.27
p+p comp	7.83	1.30	0.66 ± 0.06	0.62 ± 0.04	0.360 ± 0.017	2.28 ± 0.33
p+p comp	7.83	2.31	0.66 ± 0.06	0.62 ± 0.04	0.694 ± 0.048	2.22 ± 0.28
p+p comp	7.83	3.55	0.66 ± 0.06	0.62 ± 0.04	1.213 ± 0.109	2.05 ± 0.26
p+p comp	7.83	5.73	0.66 ± 0.06	0.62 ± 0.04	2.177 ± 0.424	1.76 ± 0.28
						$\langle \hat{q}L \rangle$ GeV^2
Au+Au 20-60%	7.83	1.30				6.0 ± 3.7
Au+Au 20-60%	7.83	2.31				1.1 ± 1.9
Au+Au 20-60%	7.83	3.55				0.11 ± 1.1
Au+Au 20-60%	7.83	5.73				-1.4 ± 1.0

First Conclusion

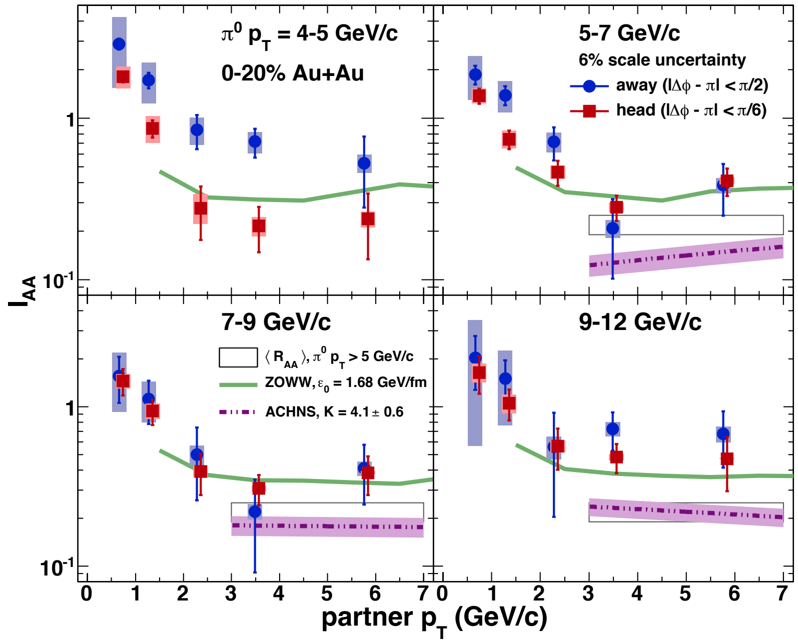
It appears that my $\hat{q}L$ method works and gives consistent results for all the data shown. In the lowest $p_{Ta} \sim 1.5$ GeV/c bin the results are all consistent with the JET collaboration [Phys. Rev. C**90**, 014909 (2014)] result, $\hat{q} = 1.2 \pm 0.3$ GeV^2/fm or $\hat{q}L \approx 8.4 \pm 2.1$ GeV^2 for $L = 7$fm, the diameter of an Au nucleus. However for $p_{Ta} > 2.0$ GeV/c all the results are consistent with $\hat{q}L = 0$. Personally I think that this is where the first gluon emitted in the medium was inside the jet cone, so that there is no evident suppression; or that jets with hard fragments close to the axis don't lose energy in the QGP. I think that this also agrees with the observation that three orders of magnitude down in the x_E (STAR z_T) distributions the A+A best fit is parallel to the p+p measurement which means no energy loss from the jets beyond this value. This is consistent with all the I_{AA} (ratio of Au+Au/p+p x_E) distributions ever measured which decrease with increasing p_{Ta} until $p_{Ta} \approx 3$ GeV/c and then become constant because the A+A and p+p distributions are parallel.

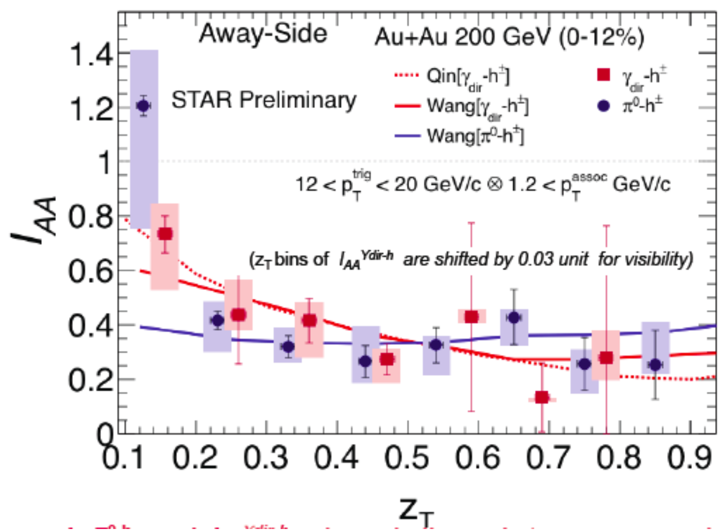
I_{AA} is simply the ratio of the Au+Au to p+p x_E distributions

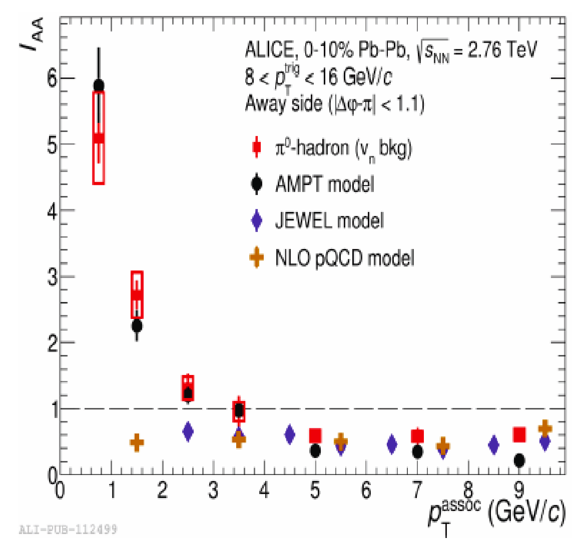


All I_{AA} distributions are flat for p_{Ta}>3 GeV/c

PHENIX PRL104,252301(2010)







Suggestion for Improvement: di-jets (at RHIC)

The measurement of $\hat{q}L$ and possibly $\hat{q}$ can be greatly improved by measuring di-jet angular distributions rather than di-hadron distributions. The energy loss of the trigger jets can be determined by the shift in the $\hat{p}_T$ spectrum from p+p to A+A the same way as for π^0. Then a plot of the $\hat{p}_{Ta}$ of the away jets for a given trigger jet with $\hat{p}_{Tt}$, analogous to the π^0 x_E distributions, and an evaluation of $\Delta E = \alpha_s\, \hat{q}\, L^2$ from $\hat{p}_{Tt} - \hat{p}_{Ta}$; and also $\hat{q}L$ by the equation

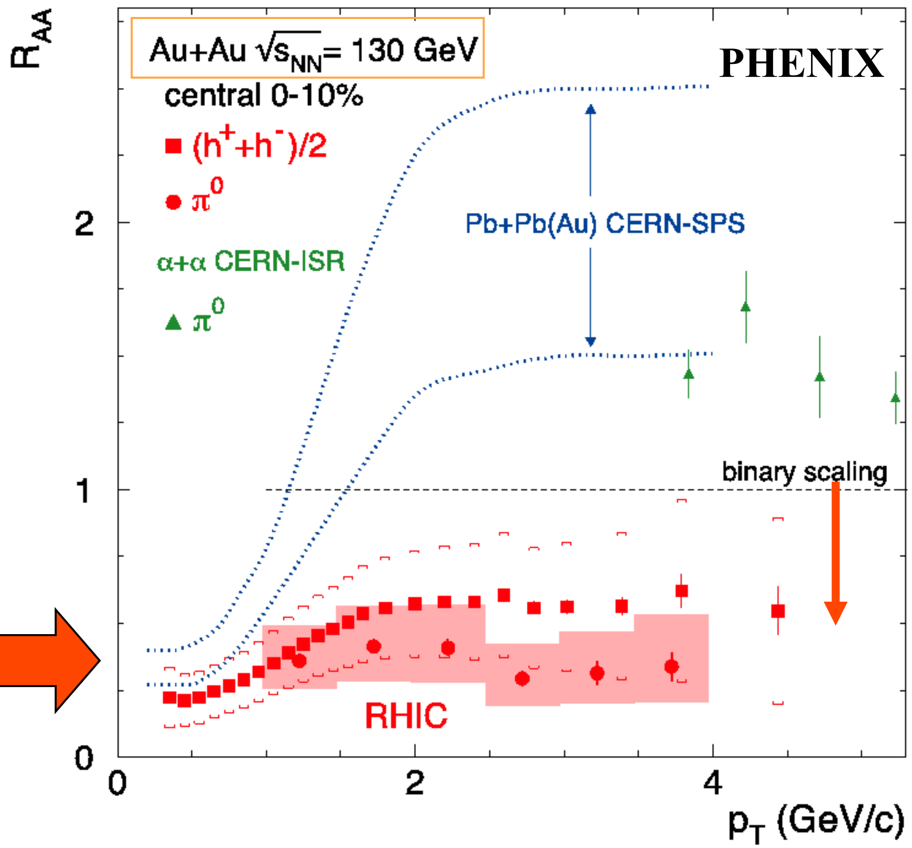
$$\langle \hat{q}L \rangle = \left[\left\langle p^2_{\rm out} \right\rangle_{AA} - \left\langle p^2_{\rm out} \right\rangle_{pp} \right]$$

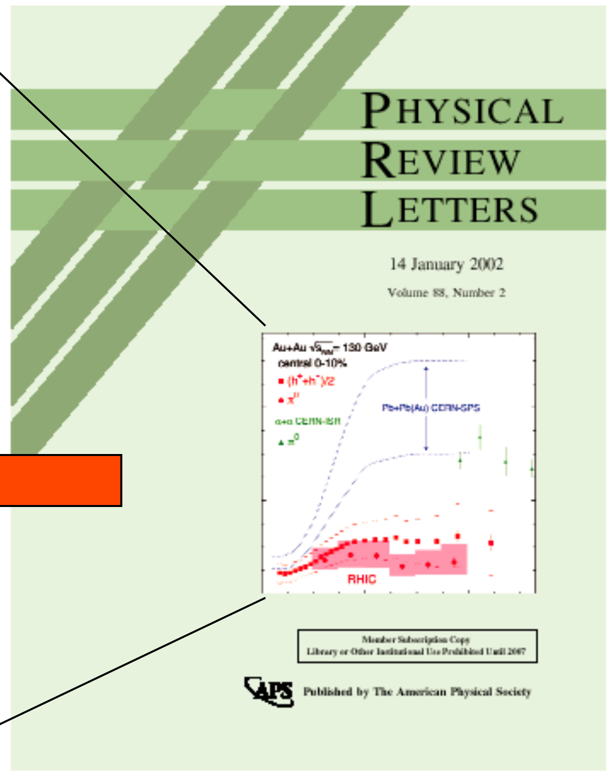
as a function of $\hat{p}_{Ta}$ might allow the L dependence to be factored out or determined which would lead to a experimental measurement of $\hat{q}$.

According to Al Mueller et al. PLB 763 (2016) 208 this measurement can only be made at RHIC because the much larger Sudakov effect at LHC obscures the QGP jet broadening, which is only slightly increased at LHC.

The End

Run-1: RHIC Headline News … January 2002
THE major discovery at RHIC (so far)



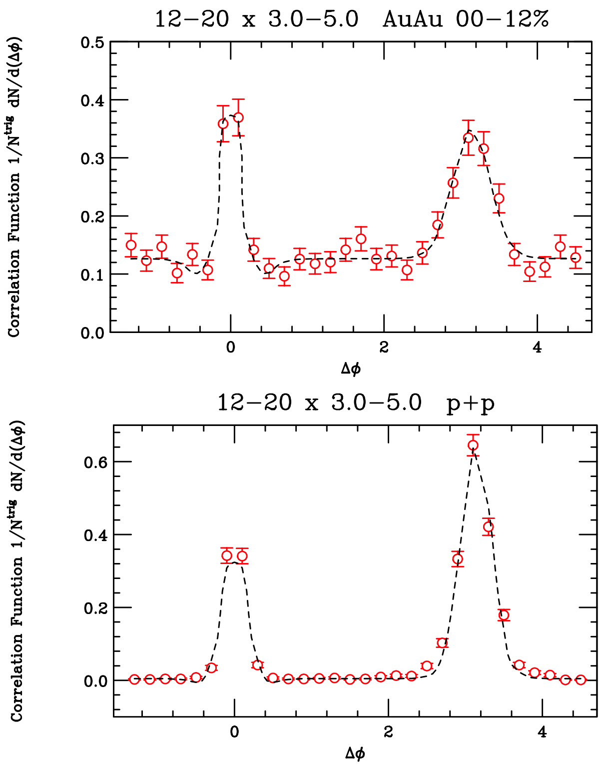


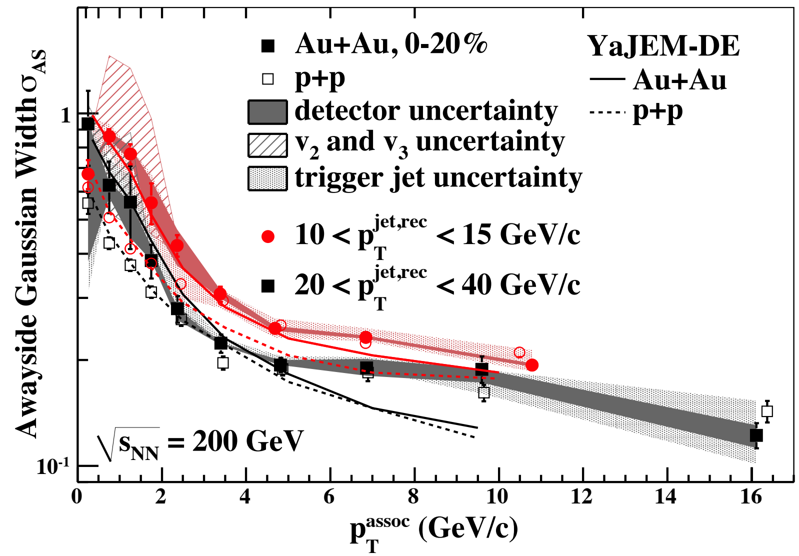
PHENIX PRL 88, 022301 (2002)

First observation of *large* suppression of high p_T hadron yields

"Jet Quenching"? == Quark Gluon Plasma?

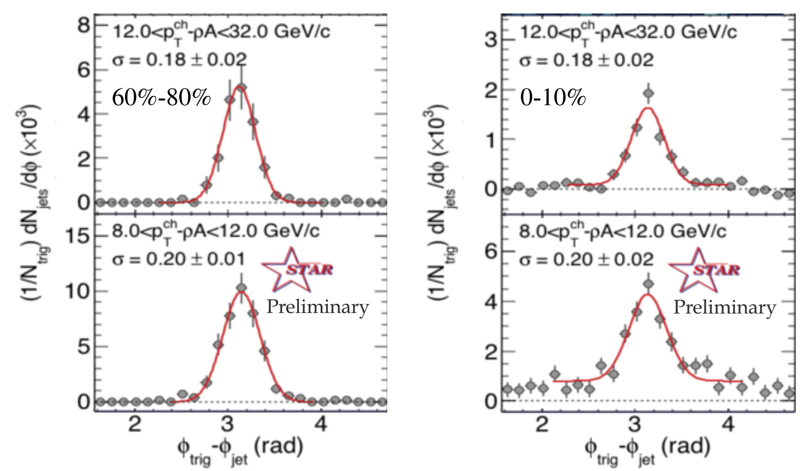
STAR results





STAR Jet-hadron PRL112(2014)122301

STAR PLB760(2016) 689
p_{Tt}=12-20 GeV/c, p_{Ta}=3-5 GeV/c
AuAu central, $\sqrt{\langle k_T^2\rangle}$=1.42±0.22
p+p $\sqrt{\langle k_T^2\rangle}$=2.51±0.31 GeV/c



MJT-$\langle \hat{q}L \rangle$ with this data 1702.00840v2

STAR Jet-Jet NPA956(2016)641