PROCEEDINGS OF SCIENCE

Measurement of $\hat{q}$ in RHI collisions using di-hadron correlations

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In the BDMPSZ model, the energy loss of an outgoing parton in a medium $-dE/dx$ is the transport coefficient $\hat{q}$ times L the length traveled. This results in jet quenching, which is well established. However BDMPSZ also predicts an azimuthal broadening of di-jets also proportional to $\hat{q}L$ which has so far not been observed. The azimuthal width of the di-hadron correlations in p+p collisions, beyond the fragmentation transverse momentum, j_T, is dominated by k_T, the so-called intrinsic transverse momentum of a parton in a nucleon, which can be measured. The broadening should produce a larger k_T in A+A than in p+p collisions. This presentation introduces the observation that the k_T measured in p+p collisions for di-hadrons with p_{Tt} and p_{Ta} must be reduced to compensate for the energy loss of both the trigger and away parent partons when comparing to the k_T measured with the same di-hadron p_{Tt} and p_{Ta} in A+A collisions. This idea is applied to a recent STAR di-hadron measurement in Au+Au at $\sqrt{s_{NN}}$ =200 GeV, *Phys. Lett.* B **760**, 689 (2016), with result $<\hat{q}L>= 2.1\pm0.6$ GeV^2. This is more precise but in agreement with a theoretical calculation of $<\hat{q}L>= 14^{+42}_{-14}$ GeV^2 using the same data. Assuming a length $<L>\approx 7$ fm for central Au+Au collisions the present result gives $\hat{q}\approx 0.30\pm0.09$ GeV^2/fm, in fair agreement with the JET collaboration result from single hadron suppression of $\hat{q}\approx 1.2\pm0.3$ GeV^2/fm at an initial time $\tau_0 = 0.6$ fm/c in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. There are several interesting details to be discussed: for a given p_{Tt} the $<\hat{q}L>$ seems to decrease then vanish with increasing p_{Ta}; the di-jet spends a much longer time in the medium ($\approx$ 7 fm/c) then $\tau_0 = 0.6$ fm/c which likely affects the value of $\hat{q}$ that would be observed.

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1. Jet Quenching: the first QCD based prediction BDMPSZ [1]

The first prediction of how to detect the QGP was via J/Ψ suppression [2] in 1986. However the first QCD based prediction for detecting the QGP was BDMPSZ Jet Quenching [1]. This is produced by the energy loss, via LPM coherent radiation of gluons, of an outgoing parton with color charge fully exposed in a medium with a large density of similarly exposed color charges (i.e. the QGP) (Fig. 1a). Jet quenching was observed quite early at RHIC by suppression of high p_T π^0 [3], with lots of subsequent evidence (Fig. 1b). It is interesting to note that all identified hadrons generally have different R_{AA} for $p_T \leq 5$ GeV/c but tend to converge to the same value for $p_T \gtrsim 5$ GeV/c. The fact that direct-γ are not suppressed indicates that suppression is a medium effect on outgoing color-charged partons as predicted by BDMPSZ [1].

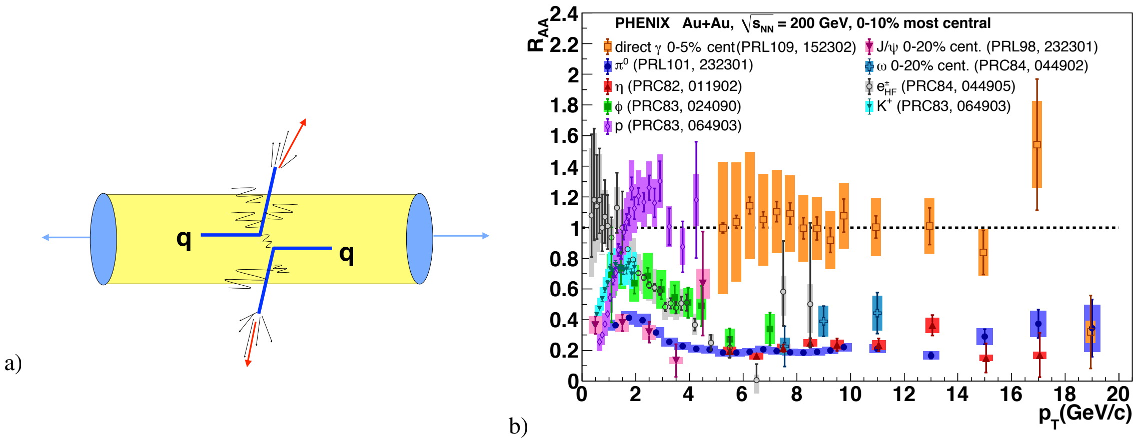

Figure 1: a) Schematic of $q+q$ scattering with scattered quarks losing energy in the medium. b) Suppression, $R_{AA}(p_T)$, for all identified particles so far measured by PHENIX in Au+Au central collisions at $\sqrt{s_{NN}} = 200$ GeV.

1.0.1 But the BDMPSZ model has two predictions

(I) 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, $q^2(L)$, with the form:

$$\frac{-dE}{dx} \simeq \alpha_s \langle q^2(L) \rangle = \alpha_s \mu^2 L/\lambda_{\rm mfp} = \alpha_s \hat{q} L \tag{1.1}$$

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, $\lambda_{\rm mfp}$.

(II) 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

$$\langle p^2_{\perp W} \rangle \approx \langle q^2(L) \rangle = \hat{q} L \qquad \text{so that} \qquad \langle \hat{q} L \rangle /2 = \langle k_T^2 \rangle_{AA} - \left\langle k'^2_T \right\rangle_{pp} \tag{1.2}$$

since only the component of $\langle p^2_{\perp W} \rangle$ $\perp$ to the scattering plane affects k_T. This is called azimuthal broadening. Here (see Fig. 2) k_T denotes the intrinsic transverse momentum of a parton in a proton plus any medium effect and k'_T denotes the reduced value correcting for the lost energy of the scattered partons in the QGP, a new idea this year [4].

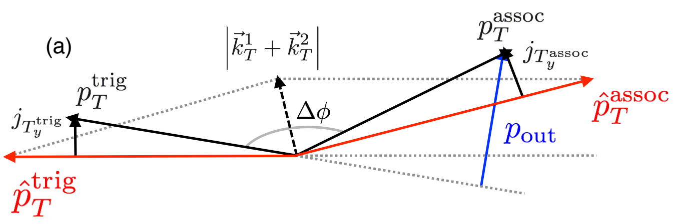

Figure 2: Initial configuration: trigger jet $\hat{p}_{Tt}$, associated (away) jet $\hat{p}_{Ta}$ with k_T effect (dashed arrow) and fragments p_{Tt} and p_{Ta}, with fragmentation transverse momentum j_{T_y}, and $p_{out} = p_{Ta}\sin(\pi - \Delta\phi)$.

Even though jet quenching has been established and confirmed for more than 15 years, many experiments have tried to find azimuthal broadening at RHIC e.g. Fig. 3 [5], [6], but have not been able to observe the effect because of systematic uncertainties.

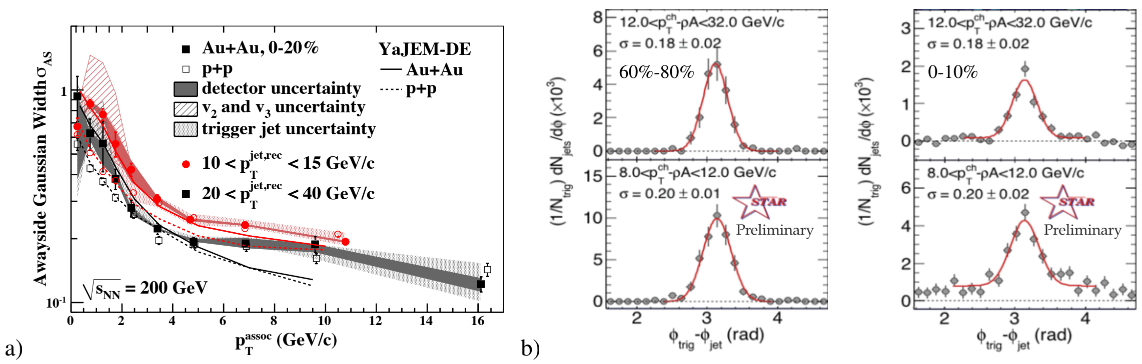

Figure 3: a) STAR measurement of the Gaussian widths $\sigma_{\rm AS}$ of away-side hadron peaks triggered by a jet in collisions of Au+Au (solid symbols) and p+p (open symbols) at $\sqrt{s_{NN}}$ =200 GeV [5]. b) Away-peaks in STAR di-jet measurement for two $\hat{p}_{Tt}$ ranges in Au+Au at $\sqrt{s_{NN}}$ =200 GeV: (left) peripheral, (right) central collisions, with the same σ [6].

1.1 Understanding k_T and k'_T.

Following the methods of Feynman,Field and Fox [7], CCOR [8] and PHENIX [9], the $\langle k_T^2\rangle$ for di-hadrons is computed from Fig. 2 as:

$$\sqrt{\langle k_T^2\rangle} = \frac{\hat{x}_h}{\langle z_t\rangle}\sqrt{\frac{\langle p_{\rm out}^2\rangle - (1+x_h^2)\langle j_T^2\rangle/2}{x_h^2}} \tag{1.3}$$

where p_{Tt}, p_{Ta} are the transverse momenta of the trigger and away particles, $x_h = p_{Ta}/p_{Tt}$, $\Delta\phi$ is the angle between p_{Tt} and p_{Ta} and $p_{\rm out} \equiv p_{Ta}\sin(\pi - \Delta\phi)$. The di-hadrons are assumed to be fragments of jets with transverse momenta $\hat{p}_{Tt}$ and $\hat{p}_{Ta}$ with ratio $\hat{x}_h = \hat{p}_{Ta}/\hat{p}_{Tt}$. $z_t \simeq p_{Tt}/\hat{p}_{Tt}$ 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 $\left\langle j_{Tay}^2\right\rangle \equiv \left\langle j_{Ta\phi}^2\right\rangle = \left\langle j_{Tt\phi}^2\right\rangle = \left\langle j_T^2\right\rangle/2$. 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 40 years ago.

A recent STAR paper [10] on π^0-hadron correlations in $\sqrt{s_{NN}}$ = 200 GeV Au+Au 0-12% central collisions had very nice correlation functions for large enough $12 \leq p_{Tt} \leq 20$ GeV/c so that the v_2, v_3 modulation of the background was negligible (Fig. 4). I made fits to these data [4] to determine $\langle p_{\rm out}^2 \rangle$ so that I could calculate k_T in p+p and Au+Au using Eq. 1.3. The results for $3 \leq p_{Ta} \leq 5.0$ GeV/c were $\sqrt{\langle k_T^2 \rangle} = 2.5 \pm 0.3$ GeV/c for p+p and $\sqrt{\langle k_T^2 \rangle} = 1.4 \pm 0.2$ GeV/c, for Au+Au, exactly the opposite of azimuthal broadening (Eq. 1.2)!

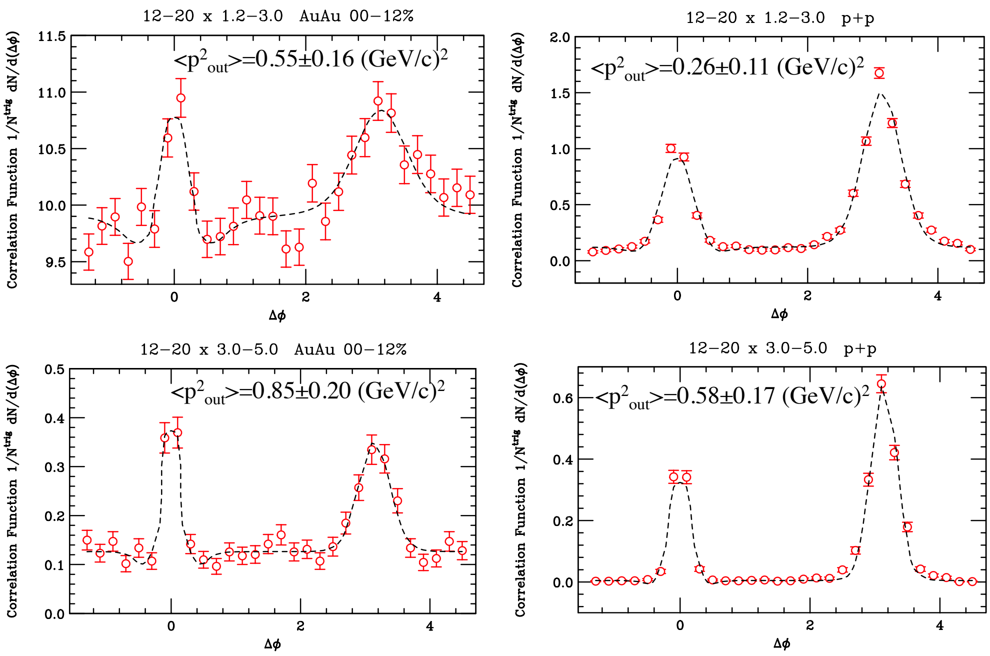

Figure 4: Fits [4] to STAR π^0-hadron correlation functions [10]: Gaussian in $\Delta\phi$ on trigger side ($\Delta\phi \approx 0$), and Gaussian in $p_{\rm out}$ on away-side with fitted values of $\langle p_{\rm out}^2 \rangle$ indicated.

After considerable thought, I finally figured out what the problem was and introduced the new k_T' [4]. For a di-jet produced in a hard scattering, the initial $\hat{p}_{Tt}$ and $\hat{p}_{Ta}$ (Fig. 2) will both be reduced by energy loss in the medium to become $\hat{p}'_{Tt}$ and $\hat{p}'_{Ta}$ which will be measured by the di-hadron correlations with p_{Tt} and p_{Ta} in Au+Au collisions. The azimuthal angle between the di-jets, determined by the $\langle k_T^2 \rangle$ in the original collision, should not change as both jets lose energy unless the medium induces multiple scattering from $\hat{q}$. Thus, without $\hat{q}$ and assuming the same fragmentation transverse momentum $\langle j_T^2 \rangle$ in the original jets and those that have lost energy, the $p_{\rm out}$ between the away hadron with p_{Ta} and the trigger hadron with p_{Tt} will not change; but the $\langle k'^2_T \rangle$ will be reduced because the ratio of the away to the trigger jets $\hat{x}'_h = \hat{p}'_{Ta}/\hat{p}'_{Tt}$ will be reduced. Thus the calculation of k'_T from the di-hadron p+p measurement to compare with Au+Au measurements with the same di-hadron p_{Tt} and p_{Ta} must use the values of $\hat{x}_h$, and $\langle z_t \rangle$ from the Au+Au measurement to compensate for the energy lost by the original dijet in p+p collisions.

The same values of $\hat{x}_h$, and $\langle z_t \rangle$ in Au+Au and p+p simplify Eqs. 1.2 and 1.3 to:

$$\langle \hat{q}L \rangle /2 = \left[\frac{\hat{x}_h}{\langle z_t \rangle}\right]^2_{AA} \left[\frac{\langle p_{\rm out}^2 \rangle_{AA} - \langle p_{\rm out}^2 \rangle_{pp}}{x_h^2}\right] \tag{1.4}$$

from which one could immediately get a reasonable answer for $\langle \hat{q}L \rangle/2$ from the $\langle p^2_{\rm out} \rangle$ results indicated on Fig. 4 if the values of $\hat{x}_h$ and $\langle z_t \rangle$ in the Au+Au measurement are known.

2. How to calculate $\langle \hat{q}L \rangle$ from the Au+Au (and p+p) measurements for di-hadrons with a trigger p_{Tt} and away-side p_{Ta} distribution.

From Eq. 1.4, we need $\langle p^2_{\rm out} \rangle_{pp}$, $\langle p^2_{\rm out} \rangle_{AA}$ plus $\hat{x}_h$ and $\langle z_t \rangle$ in Au+Au. This will be illustrated with the STAR data [10].

a) **$\hat{x}_h$ for a given p_{Tt} can be calculated from the p_{Ta} distribution:** The ratio of the away jet to the trigger jet transverse momenta, $\hat{x}_h = \hat{p}_{Tt}/\hat{p}_{Ta}$, can be calculated (Fig. 5) from the away particle $x_h = p_{Ta}/p_{Tt}$ distributions, which were also given in the STAR paper. The formula is [9], where n is the power of the p_T spectra:

$$\left.\frac{dP}{dp_{Ta}}\right|_{p_{Tt}} = N(n-1)\frac{1}{\hat{x}_h}\frac{1}{(1+\frac{x_h}{\hat{x}_h})^n} \quad . \tag{2.1}$$

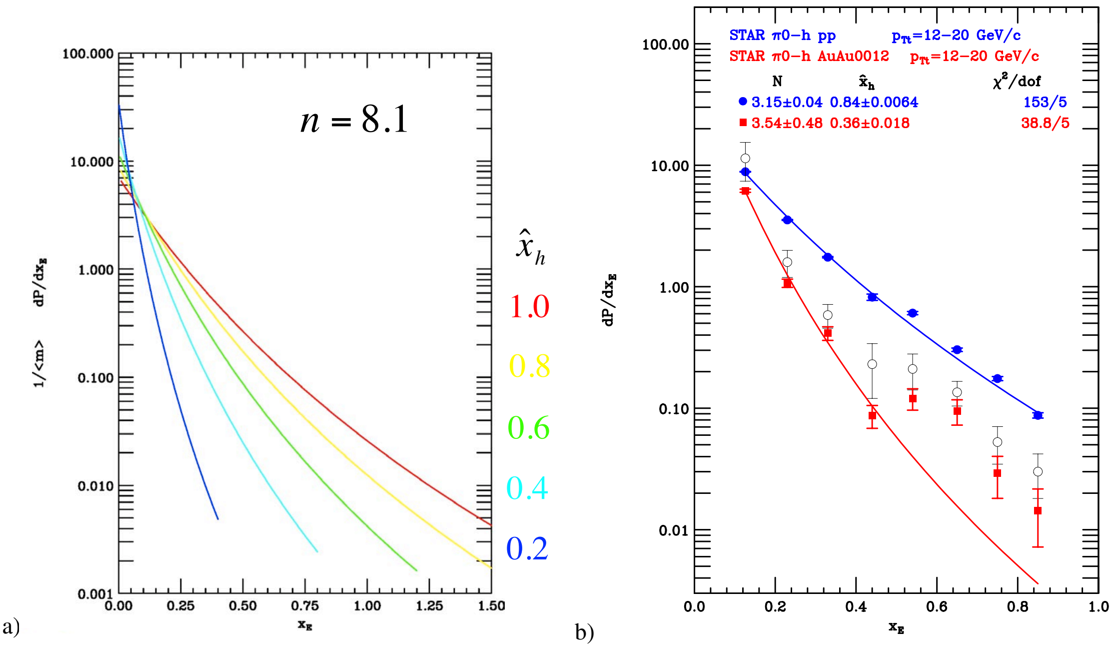

Figure 5: a) Plots of Eq. 2.1 for the values of $\hat{x}_h$ indicated. b) Fits of Eq. 2.1 [4] to the STAR away-side z_T distributions [10] in Au+Au 0-12% centrality, and p+p, for $12 < p_{Tt} < 20$ GeV/c. The Au+Au curve is a fit with $\hat{x}^{AA}_h = 0.36 \pm 0.05$ with error corrected by $\sqrt{\chi^2/{\rm dof}}$. The points with the open circles are the y_i and systematic errors σ_{b_i} of the data points while the filled points are $y_i + \varepsilon_b \sigma_{b_i}$ with errors $\tilde{\sigma}_i$ and $\varepsilon_b = -1.3 \pm 0.5$. [4]

b) **Fit the away-side peaks in the Au+Au and p+p correlation functions to gaussians in $\mathbf{p}_{\rm out}$:** The gaussian fit directly gives $\langle p^2_{\rm out} \rangle$ as was nicely shown for the STAR data in Fig. 4.

c) **The power of hard scattering: the Bjorken parent-child relation and "trigger bias":** The hard-scattering p_T spectra, $d\sigma/p_T dp_T$, at RHIC in the range $3 \leq p_T \lesssim 20$ GeV/c for p+p and Au+Au for all centralities follow the same power law $1/p_T^n$ with $n = 8.10 \pm 0.05$ [11]. This is why $R_{AA}(p_T)$ for π^0 and η in Fig. 1b are relatively constant over the same p_T range. The Bjorken parent-child relation [12] proved that the power n in p_T^{-n} is the same in the jet and fragment (π^0) p_T spectra. This is why π^0 can be used in place of the parent jet. However because the trigger π^0 spectrum for a given p_{Tt} in Au+Au for 0–10% centrality is shifted down by $\delta p_T/p_T^{pp} = 20\%$ in p_T compared to p+p [13], the $\langle z_t \rangle$ for A+A and compensated p+p should be calculated [9] from the measured p+p π^0 p_T spectrum at $p_{Tt}^{pp}/(1-\delta p_T/p_T^{pp})$. (For the present discussion, STAR measured $\langle z_t \rangle = 0.80 \pm 0.05$ from their p+p data [10].)

This method enabled me to calculate $\langle \hat{q}L \rangle$ from the $\langle p_{\rm out}^2 \rangle$ values indicated on Fig. 4, now with sensible results (Table 1). The results in the two p_{Ta} bins are at the edge of agreement, different by 2.4σ; but both are $> 2.6\sigma$ from zero. These results leave several open issues as mentioned in the abstract.

Table 1: Tabulations for $\hat{q}$ [4] from STAR π^0-h data [10]

$\sqrt{s_{NN}} = 200$GeV	$\langle p_{Tt} \rangle$	$\langle p_{Ta} \rangle$	$\sqrt{\langle k_T^2 \rangle_{AA}}$	$\sqrt{\langle k'^2_T \rangle_{pp}}$	$\langle \hat{q}L \rangle$
Reaction	GeV/c	GeV/c	GeV/c	GeV/c	GeV^2
Au+Au 0-12%	14.71	1.72	2.28 ± 0.35	1.01 ± 0.18	8.41 ± 2.66
Au+Au 0-12%	14.71	3.75	1.42 ± 0.22	1.08 ± 0.18	1.71 ± 0.67

3. Homework

However there is a nice prediction of $\Delta\phi$ for for 35 GeV Jets at RHIC [14] for several values of $\langle \hat{q}L \rangle$ (Fig. 6). An amusing test would be to see if the present method gives the same answers for $\langle \hat{q}L \rangle$ by calculating $\langle p_{\rm out}^2 \rangle$ of the predictions.

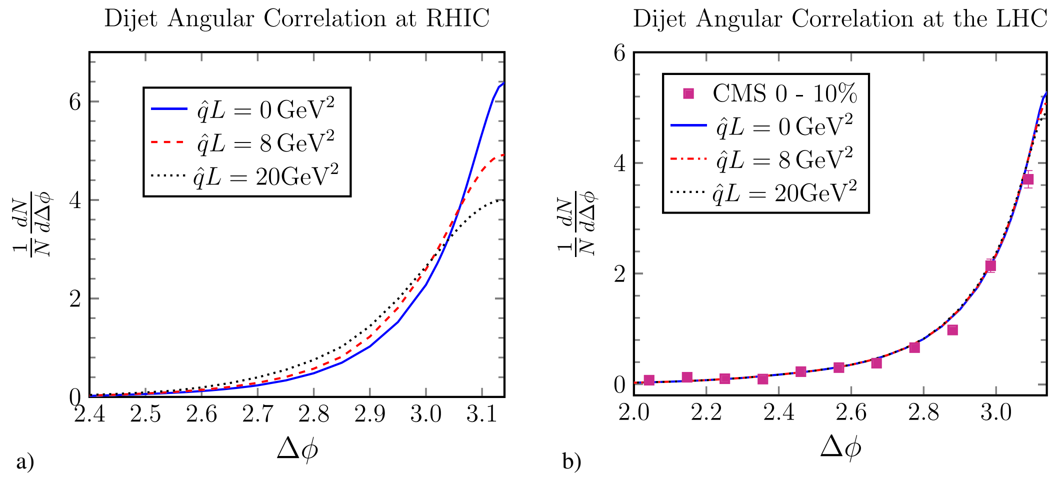

Figure 6: Prediction by Al Mueller and collaborators [14] of the di-jet azimuthal decorrelation as a function of $\hat{q}L$ for a) 35 GeV jets at RHIC $\sqrt{s_{NN}} = 200$ GeV; and b) 50 GeV jets at the LHC $\sqrt{s_{NN}} = 2.76$ TeV where "p_T broadening effects are negligible" [14].

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