Measuring Parton Energy Loss at RHIC compared to LHC

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Abstract. The method of measuring $\hat{x}_h$, the ratio of $\hat{p}_{T_a}$, the away-parton p_T, to $\hat{p}_{T_t}$, the trigger-parton p_T, using two-particle correlations at RHIC, which is sensitive to the away parton energy loss due to the surface bias, will be reviewed. This measurement is simply related to the new variable introduced at LHC for the di-jet transverse momentum imbalance, $A_J = (\hat{p}_{Tt} - \hat{p}_{Ta})/(\hat{p}_{Tt} + \hat{p}_{Ta}) = (1 - \hat{x}_h)/(1 + \hat{x}_h)$. Results from two-particle correlations at RHIC for $\hat{x}_h = (1 - A_J)/(1 + A_J)$ will be reviewed and new results will be presented and compared to LHC results. The importance of comparing any effect in A+A collisions to the same effect effect in p-p collisions will be illustrated and emphasized.

1. Introduction

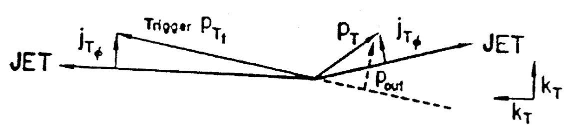
In 1998, at the QCD workshop in Paris, Rolf Baier asked me whether jets could be measured in Au+Au collisions because he had a prediction of a QCD medium-effect (energy loss via soft gluon radiation induced by multiple scattering [1]) on color-charged partons traversing a hot-dense-medium composed of screened color-charges [2]. I told him [3] that there was a general consensus [4] that for Au+Au central collisions at $\sqrt{s_{NN}} = 200$ GeV, leading particles are the only way to study jets, because in one unit of the nominal jet-finding cone, $\Delta r = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, there is an estimated $\pi\Delta r^2 \times \frac{1}{2\pi}\frac{dE_T}{d\eta} \sim 375$ GeV of energy !(!) The good news was that hard-scattering in p-p collisions was originally observed by the method of leading particles and that these techniques could be used to study hard-scattering and jets in Au+Au collisions [5].

2. Hard scattering via single particle inclusive and two-particle correlation measurements

Single particle inclusive and two-particle correlation measurements of hard-scattering have provided a wealth of discoveries at RHIC. Due to the steeply falling power-law ($\hat{p}_{T_t}^{-n}$) invariant transverse momentum spectrum of the scattered parton, the inclusive single particle (e.g. π^0) p_{T_t} spectrum from jet fragmentation is dominated by fragments with large $z_{\rm trig}$, where $z_{\rm trig} = p_{T_t}/\hat{p}_{T_t}$ is the fragmentation variable, and exponential fragmentation $D_q^{\pi^0}(z) \sim e^{-bz}$ is assumed. This gives rise to several effects which allow precision measurements of hard scattering to be made using single inclusive particle spectra and two particle correlations [6, 7].

The prevailing opinion from the 1970's until quite recently was that although the inclusive single particle (e.g. π^0) spectrum from jet fragmentation is dominated by trigger fragments with large $\langle z_{\rm trig}\rangle \sim 0.6-0.8$, the away-jets should be unbiased and would measure the fragmentation function, once the correction is made for $\langle z_{\rm trig}\rangle$ and the fact that the jets don't exactly balance p_T due to the k_T smearing effect [8]. Two-particle correlations with trigger p_{T_t}, are analyzed in terms of the two variables: $p_{\rm out} = p_T \sin(\Delta\phi)$, the out-of-plane transverse momentum of an associated track; and x_E, where:

$$x_E = \frac{-\vec{p}_T \cdot \vec{p}_{Tt}}{|p_{Tt}|^2} = \frac{-p_T\cos(\Delta\phi)}{p_{Tt}} \simeq \frac{z}{z_{\rm trig}}$$



$z_{\rm trig} \simeq p_{Tt}/p_{T\rm jet}$ is the fragmentation variable of the trigger jet, and z is the fragmentation variable of the away jet.

However, in 2006, it was found by explicit calculation that this is not true [9, 6, 7]. The p_{T_a} spectrum of fragments from the away-side parton with $\hat{p}_{T_a}$, given a trigger particle with p_{T_t} (from a trigger-side parton with $\hat{p}_{T_t}$), is not sensitive to the shape of the fragmentation function (b), but measures the ratio of $\hat{p}_{T_a}$ of the away-parton to $\hat{p}_{T_t}$ of the trigger-parton and depends only on the same power n as the invariant single particle spectrum:

$$\left.\frac{dP_{p_{T_a}}}{dx_E}\right|_{p_{T_t}} \approx \langle m\rangle\,(n-1)\frac{1}{\hat{x}_h}\frac{1}{(1+\frac{x_E}{\hat{x}_h})^n} \quad . \qquad (1)$$

This equation gives a simple relationship between the ratio $x_E \approx p_{T_a}/p_{T_t} \equiv z_T$ of the transverse momenta of the away-side particle to the trigger particle, and the ratio of the transverse momenta of the away-jet to the trigger-jet, $\hat{x}_h = \hat{p}_{T_a}/\hat{p}_{T_t}$. The only dependence on the fragmentation function is in the mean multiplicity $\langle m\rangle$ of jet fragments. This functional form was shown previously [9, 10] (and with the present data, see below) to describe the π^0 triggered x_E distribution in p-p collisions and is based only on the following simplifying assumptions: the hadron fragment is assumed to be collinear with the parton direction; the underlying fragmentation functions ($D(z)$) are assumed to be exponential; and $\hat{x}_h$ is taken to be constant as a function of x_E over the range of interest. The key issue with Eq. 1 is that it is independent of the slope of an exponential fragmentation function, and only depends on the detected mean multiplicity $\langle m\rangle$ of the jet, the power, n, of the inclusive p_{T_t} spectrum and the ratio of the away jet to the trigger jet transverse momenta, $\hat{x}_h$.

3. Fits to PHENIX π^0-h correlations

The two-particle correlation distributions from π^0 triggers with p_{T_t} = 4-5, 5-7, 7-9 and 9-12 GeV/c with charged hadrons in a fixed range of of associated transverse momenta,

$p_{T_a} \approx 0.7, 1.3, 2.3, 3.5, 5.8$ GeV/c were recently published by PHENIX [11] in terms of the ratio of A+A to p-p collisions, $I_{AA}(p_{T_a})|_{p_{T_t}}$ (see Fig. 1). We now analyze these

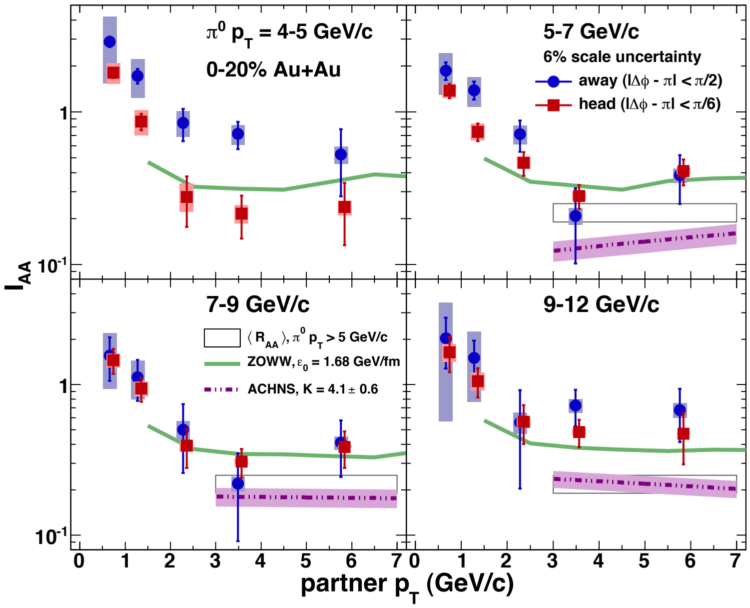


Figure 1. Away-side I_{AA} [11] for a narrow "head" $|\Delta\phi - \pi| < \pi/6$ selection (solid squares) and the entire away-side, $|\Delta\phi - \pi| < \pi/2$ (solid circles) as a function of partner momentum p_{T_a} for various trigger momenta p_{T_t}. Only the head region was used for the present analysis.

distributions separately for p-p and Au+Au collisions for 00-20% and 20–60% centrality, with the statistical error and the larger of the ± systematic errors of the data points added in quadrature. The p-p and Au+Au distributions were fit to the formula [9]:

$$\left.\frac{dP_\pi}{dz_T}\right|_{p_{T_t}} = N\,(n-1)\frac{1}{\hat{x}_h}\frac{1}{(1+\frac{z_T}{\hat{x}_h})^n} \qquad , \tag{2}$$

with a fixed value of $n = 8.10$ (± 0.05) as previously determined [12] , where n is the power-law of the inclusive π^0 spectrum and is observed to be the same in p-p and Au+Au collisions in the p_{T_t} range of interest. The fitted value for N is the integral of the z_T distribution which equals $\langle m \rangle$, the mean multiplicity of the away jet in the PHENIX detector acceptance, and $\hat{x}_h \equiv \hat{p}_{T_a}/\hat{p}_{T_t}$ is the ratio of the away jet to the trigger jet transverse momenta.

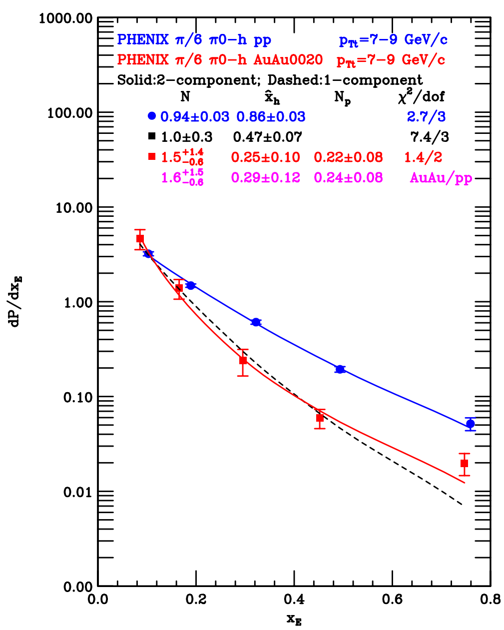
The p-p and the AuAu 00-20 and 20-60 data were first fit to Eq. 2, a 1-component fit. However, to take account of the fact that all measured I_{AA} distributions seen at RHIC (e.g. Fig. 1) exhibit a constant value for larger values of p_{T_a}, which indicates away jets which punch through (or are emitted tangentially through) the medium without energy loss and then fragment the same as p-p jets (vacuum fragmentation), fits to a two-component formula (Eq. 3) were also performed

$$\left.\frac{dP_\pi}{dz_T}\right|_{p_{T_t}} = N_{AA}\,(n-1)\frac{1}{\hat{x}_h^{AA}}\frac{1}{(1+\frac{z_T}{\hat{x}_h^{AA}})^n} + N_p\,(n-1)\frac{1}{\hat{x}_h^{pp}}\frac{1}{(1+\frac{z_T}{\hat{x}_h^{pp}})^n} \quad . \tag{3}$$

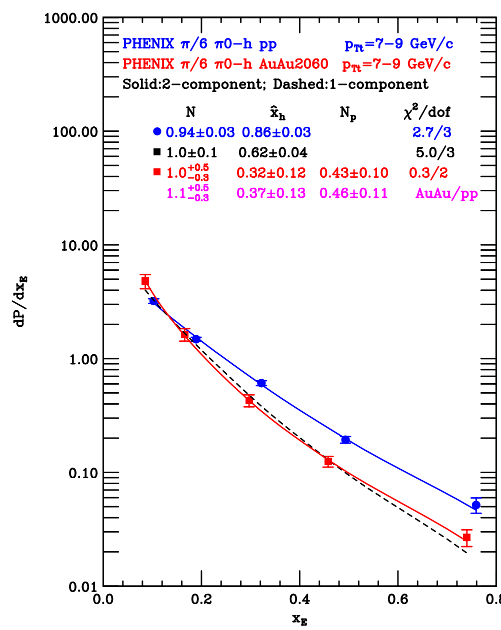
Here the first term represents the z_T distribution of a parton which has lost energy in the medium and then fragmented; and the second term represents the z_T distribution of a parton which has punched through the medium without losing energy and then fragmented, thus giving the same z_T distribution as in p-p collisions albeit reduced in magnitude by the fraction of partons that have punched through the medium. The symbols N_{AA} and $\hat{x}_h^{AA}$, represent the away-parton which has lost energy, and N_p the observed multiplicity of the jet from the punch-through parton as determined by the fit of the AuAu data to Eq. 3. The parameters of the p-p distribution, $\hat{x}_h^{pp}$ and N_{pp}, are determined by a fit of Eq. 2 to the p-p data; and $\hat{x}_h^{pp}$ is held constant at the p-p value in the fit to Eq. 3.

4. Results of the fits

Examples of the fits for $7 < p_{T_t} < 9$ GeV/c for p-p collisions and Au+Au 0–20% and 20–60% are shown in Figs. 2a and b, respectively. The results for the fitted parameters



a)



b)

Figure 2. p-p (blue dircles) and AuAu (red squares) $z_T = p_{T_a}/\langle p_{T_t}\rangle$ distributions with fits to Eq. 2 p-p (solid blue line), AuAu (dashed black line); and to Eq. 3 AuAu (solid red line) with parameters indicated for $p_{T_t} = 7-9$ GeV/c ($\langle p_{T_t}\rangle = 7.71$ GeV/c): a) 00-20% centrality, b) 20–60% centrality.

are shown on the figures. In general the values of $\hat{x}_h^{pp}$ do not equal 1 but range between $0.8 < \hat{x}_h^{pp} < 1.0$ due to k_T smearing and the range of z_T covered. In the present data the p_{T_t} and z_T ranges are identical for the p-p and Au+Au collisions. In order to take account of the imbalance ($\hat{x}_h^{pp} < 1$) observed in the p-p data, the ratio $\hat{x}_h^{AA}/\hat{x}_h^{pp}$ is taken as the measure of the energy of the away jet relative to the trigger jet in A+A compared to p-p collisions.

It is important to note that the away jet energy fraction in AuAu relative to p-p from the 1-component fit, $\hat{x}_h^{AA}/\hat{x}_h^{pp} = 0.47/0.86 = 0.54 \pm 0.08$, is significantly less than 1, indicating energy loss of the away jet in the medium. For the two-component fit, the away jet energy fraction for the first component is smaller, $\hat{x}_h^{AA}/\hat{x}_h^{pp} = 0.25/0.86 = 0.29 \pm 0.12$, and the fraction of away jets which punch through the medium without losing energy, for a given trigger with p_{T_t}, is directly given by $f_{\rm punchthrough} = N_p/N_{pp}$.

5. LHC Results

In very exciting first results from the LHC heavy ion program, ATLAS [13] first observed dijet events in Pb+Pb central collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV with a large energy asymmetry which they characterized by a new quantity A_J, which is very closely related to $\hat{x}_h$, the ratio of the away-jet to the trigger jet transverse momenta:

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}} \approx \frac{1 - \hat{x}_h}{1 + \hat{x}_h} \qquad . \tag{4}$$

On the other hand CMS [14] presented a plot of $\langle 1 - p_{t,2}/p_{t,1}\rangle = \langle 1 - \hat{x}_h\rangle$, the fractional jet imbalance as a function of E_{T1} up to 200–220 GeV with a cut $E_{T2} \geq 50$ GeV (Fig. 3). This variable should be identical to the one we call $1 - \hat{x}_h^{AA}/\hat{x}_h^{pp}$, the away-parton fractional energy loss (or imbalance) in A+A relative to p-p, provided that the initial dijets are balanced in Pb+Pb as was shown by CMS for p-p. However, the cut

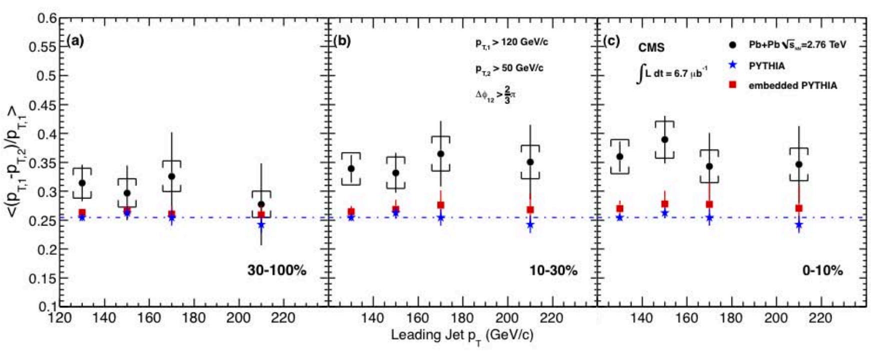


Figure 3. CMS [14] plot of $\langle 1 - p_{t,2}/p_{t,1}\rangle$, the fractional jet imbalance, as a function of $p_{T,1}$ for 3 centralities in p-p and Pb+Pb collisions.

used in the CMS variable results in a large imbalance of 0.25 for p-p, independent of E_{T1} (Fig. 3); so we correct this by calculating $\hat{x}_h^{AA}$ and $\hat{x}_h^{pp}$ for CMS from their given values of $1 - \hat{x}_h^{AA}$ and $1 - \hat{x}_h^{pp}$ and then correcting to $1 - \hat{x}_h^{AA}/\hat{x}_h^{pp} \equiv 1 - \hat{x}_h$.

These points are shown together with the PHENIX data for $1 - \hat{x}_h^{AA}/\hat{x}_h^{pp}$ which we call $1 - \hat{x}_h$, the observed fractional jet imbalance relative to p-p (Fig. 4). Of course the CMS result is directly measured with jets, while the PHENIX value is deduced from the fragments of the dijets using a few simple assumptions, as noted above. The PHENIX data are plotted at the presumed mean trigger parton transverse momentum $\langle \hat{p}_{T_t}\rangle = p_{T_t}/\langle z_{\rm trig}\rangle$, where the average fragmentation fraction of the trigger particle,

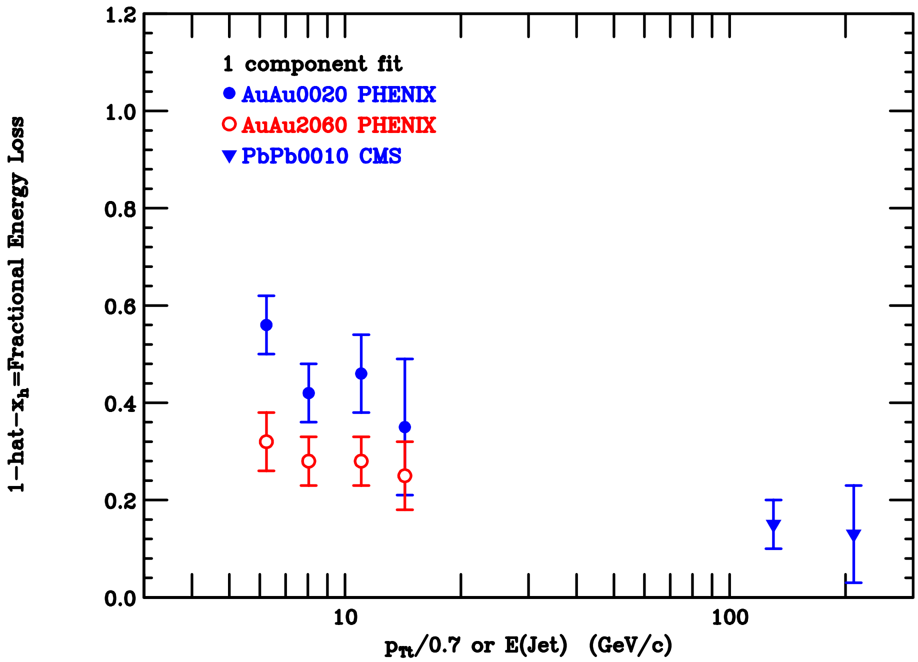


Figure 4. Away-jet fractional energy loss or imbalance in A+A relative to p-p, $1-\hat{x}_h$, as a function of $p_{T_t}/0.7$ for PHENIX and E(Jet) for CMS with centralities indicated.

$\langle z_{\rm trig}\rangle \approx 0.7$, was derived in Ref. [9]. There is a clear difference in fractional energy loss in going from RHIC to LHC in central collisions—the jet-imbalance or fractional energy loss is much smaller at LHC. Also at RHIC, there is less fractional energy loss or jet imbalance in less central collisions. The large difference in fractional jet imbalance between RHIC and LHC c.m. energies could be due to the difference in jet $\hat{p}_{T_t}$ between RHIC ($\sim$ 20 GeV/c) and LHC ($\sim$ 200 GeV/c), the difference in n for the different $\sqrt{s}$, or to a difference in the properties of the medium. This is different from the first impression [13] and clearly requires extending both the RHIC and LHC measurements to overlapping regions of p_T.

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