Direct photon-hadron and Di-hadron correlations measured in PHENIX

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Abstract. We review results of PHENIX two-particle correlations for both di-hadrons and direct photon-hadron pairs. These measurements can reveal details of QGP induced jet energy loss in heavy ion collisions. The spectra of per-trigger yields on the awayside from trigger photons in the photon-hadron correlations or fragmentation function for direct photons of greater than 5 GeV/c in transverse momentum appear to show some modification compared to the same measurement in p+p collisions, including a suppression at high z (> ~0.4), and much less suppression, possibly even enhancement at low z. A framework for calculating parton or jet level observables from the PHENIX 2-particle yields results that can be compared to recent LHC jet reconstruction observables. Under certain assumptions, one of these observables, the mean fractional energy loss, appears to be larger for lower jet energies (~10 GeV) that the PHENIX data is sensitive to, than for much higher energy jets (~100 GeV) at the LHC. However the current PHENIX di-hadron measurements for this comparison which may have inherent biases need to be followed up by higher statistics direct photon-hadron measurements before definite statements could be made.

1. Fragmentation function

Over the course of the Relativistic Heavy Ion Collider (RHIC) physics program, two-particle correlations proved to be an effective probe to characterize the medium created in nucleus-nucleus collisions. Particularly, two-particle correlations can be used to study jet energy loss due to the medium. One can assign a certain threshold for a transverse momentum $p_T$ and select outgoing trigger particles that satisfy that threshold. In every event, a difference in measured azimuths $\Delta \phi$ between trigger particles and all other, so-called “associated”, particles describe how the trigger and associated particles correlate with each other. The spectrum of $\Delta \phi$ in unmodified hard scattering di-jet events has two pronounced peaks, one at about $\Delta \phi = 0$ and the second at about $\Delta \phi = \pi$. The first peak represents correlations between the triggers and those associated particles that belong to the same jet as the trigger particle. The second peak shows how the triggers correlate with the associated particles, members of the jet that opposes the trigger. In a heavy ion collision a suppression of the distribution around $\Delta \phi = \pi$, in regard to the similar distribution measured in p+p collisions, indicate energy loss of the jets that pass through the created medium.

The fragmentation function $D(z)$ describes the probability for outgoing parton in hard scattering collision to form a hadron with momentum fraction $z = p_h/p_{jet}$ ($p_h$ is the momentum of the hadron and $p_{jet}$ is the momentum of the jet; here it is implied that the momentum of the jet approximately equal to the momentum of the parton). PHENIX, as a collider detector with a modest geometrical acceptance, successfully studies hard scattering events with $z$ approximated by its transverse
component $z_T = |p_T^{h}| / |p_T^{jet}|$. As it is defined, the fragmentation function $D(z)$ is a characteristic of the final state of the hard scattering process; thus $D(z)$ is supposed to be independent of the colliding species. But various factors in other stages of the collision process might affect $D(z)$. For example, patrons can traverse through the dense medium and lose their energy. That would result in the lower transverse momentum at the start of the fragmentation. Thus one can quantify effects of the medium by comparing $D(z)$ measured in heavy ion collisions with $D(z)$ measured in p+p collisions.

2. Direct photons as a “tomographic” tool

Direct photons can be produced in hard scattering events through processes of quark-antiquark annihilation and Compton-like scattering. Also, direct photons can be produced through fragmentation of outgoing partons. Photons do not participate in strong interactions, so once produced in heavy ion collisions, they pass through the medium unaffected. Conservation of momentum requires a photon and an opposing jet to have equal transverse momenta. Thus, $D(z)$ can be directly measured with $z_T$ defined as $z_T = |p_T^{h}| / |p_T^{jet}|$. Contrary to $\gamma$-hadron correlations, hadron-hadron correlations can yield improved $D(z)$ measurements when the hard scattering events occur on or near the surface of the medium so one of the outgoing partons, presumably, do not suffer from a sizable loss of energy. It is evident that certain bias is inherent in $D(z)$ measurements from hadron-hadron correlations.

A method of using $\gamma$-hadron correlations to measure fragmentation functions is naturally very attractive. However, in practice such a task is very challenging; the rates of direct photon production processes are about a thousand times lower than the rates of two-jet events. PHENIX has been successful in measuring $\gamma$-hadron correlation yields for Au+Au and p+p collisions using a statistical subtraction method in which the $\gamma$-hadron yield is defined as

$$Y_{direct-h} = (R_\gamma Y_{inclusive-h} - Y_{decay-h})/(R_\gamma - 1) \quad (1)$$

where $R_\gamma$ is the ratio of the rate of the inclusive photons to the rate of the decay photons (a sample of the inclusive photons is a sum of a sample of the direct photons and a sample of the decay photons), $Y_{inclusive-h}$ is the $\gamma$-hadron yield, in which photons are inclusive, $Y_{decay-h}$ is the $\gamma$-hadron yield, in which photons are all decay.

3. Medium effects on the fragmentation function measured from photon-hadron correlations

The PHENIX published results [1, 2] presented measurements from Au+Au data recorded in 2004 and from p+p data recorded in 2005 and 2006. Those results do not include $p_T$-dependent measurements of the fragmentation functions $D(z)$ in Au+Au collisions. During 2007 PHENIX detector accumulated Au+Au data sample as large as 4 times compared to that from 2004. Increased statistics allowed to complete $D(z)$ measurements for the Au+Au events.

Figure 1 shows the fragmentation functions $D(z) = (dN_{\gamma\\text{trig}})^{-1}dN/dz_T$ for p+p events (2005 and 2006 data) and for 0-20% most central Au+Au events (2007 data). The functions are computed in regard to the partons that oppose direct photons (i.e. in the away side jet) for different $p_T$ ranges of the trigger direct photons. The yield of the $\gamma$-hadron pairs d$V$ is extracted for the so-called “head” region that spans $|\Delta \phi - \pi| < \pi/5$. Data from p+p collisions were analyzed with transverse momenta of trigger photons equal to $p_T = 5 \div 15$ GeV. Associated hadrons were chosen with $p_T = 1 \div 10$ GeV. The fragmentation function for Au+Au data was extracted considering the trigger photons with $p_T = 5 \div 15$ GeV and the associated hadrons with $p_T = 1 \div 7$ GeV.

It is seen that trigger $p_T$ scales approximately with $z_T$. With the fit function $dN/dz_T = N_0 e^{bz_T}$ applied for both collision systems the slope parameter $b$ was measured to be $b = 6.9 \pm 0.6$ for p+p...
collisions and $b = 9.5 \pm 1.4$ for Au+Au collisions. A steeper slope $b$ in case of the Au+Au data is in agreement with a hypothesis that the medium created in the heavy ion collision causes constant fractional energy loss of the away-side parton. For the case of p+p collisions, the value $b = 6.9$ is more consistent with the slope $b = 8$ of the quark fragmentation function than with the slope $b = 11$ of the gluon fragmentation function [2].

![Figure 1](image.png)

Figure 1. Fragmentation functions measured for $\gamma$-hadron correlated pairs in p+p and 0-20% most central Au+Au collisions. For each collision system results are fitted with an exponential function.

It is reasonable to anticipate more manifested energy loss effects when $z_T$ is small. That is why the fragmentation functions can be studied in more detail when $z_T$ is replaced by an alternative variable $\xi = -\ln(z_T)$. In Figure 2 the fragmentation function $D(\xi) = (dN_{trig})/dN/\xi$ extracted for p+p events is plotted together with the fit function to the data from TASSO measurements [3]. Those measurements were done with e+e- collisions. The fit function is arbitrarily scaled by a factor of 10 to match the PHENIX p+p data. Similarity of $D(\xi)$ shapes between PHENIX and TASSO results hints on the fact that the $D(\xi)$ measured in p+p collisions is consistent with the quark fragmentation mechanism. Data from Au+Au collisions have an expanded range of $p_T = 0.5 \div 7$ GeV for the associated hadrons. At lower $\xi$ the fragmentation function is suppressed in regard to the p+p data, as energy loss in the medium is more pronounced for the hadrons with higher transverse momenta. The Au+Au data points are fitted well with the prediction (red line) from the model [4]. That model explains that in collisions of heavy ions the fragmentation function enhances with increasing $\xi$, because the energy, lost by the partons in the medium, is spent on soft particle production. Figure 3 shows the ratio of the fragmentation functions, which are plotted in Figure 2 (the ratio $I_{AA}$ is computed as Au+Au result over p+p result with a reduced number of $\xi$ bins). The ratio $I_{AA}$ manifests suppression of associated hadrons in the medium created in Au+Au collision, except when $\xi > 1.6$. However even starting at $\xi > 1.0$ there appears to be a rise in the $I_{AA}$. This behavior seems qualitatively similar to measurements by the STAR collaboration [6] of jet-hadron correlations using fully reconstructed jets. The statistical
strength of the statement made by our direct photon hadron data should be improved very soon with the use of a new larger 2010 dataset.

Figure 2. Fragmentation functions measured for $\gamma$-hadron correlated pairs in p+p and 0-20% most central Au+Au collisions; $\xi = -\ln(z_T)$ is used as a functional variable instead of $z_T$. The green line represents a scaled fit to TASSO data [3]. The red line is a prediction from the model [4].

Figure 3. Ratio of the $\gamma$-hadron fragmentation function measured in 0-20% most central Au+Au events to the $\gamma$-hadron fragmentation function measured in p+p collisions.
4. PHENIX measurements in the LHC era

The Large Hadron Collider (LHC) provides nuclear physics community with unparallel research opportunities. At the LHC the energy of Pb+Pb collisions far exceeds the RHIC energy of Au+Au collisions. Two LHC general purpose detectors, ATLAS and CMS, both have very large acceptances and arrays of versatile detectors which allow in-depth studies of jets. PHENIX, in contrast, can detect hadrons and photons in a narrow pseudorapidity range of $\eta < |0.35|$ and in a modest azimuth range of $\phi = 2 \times 90^\circ$. Lack of a hadronic calorimeter further limits PHENIX jet physics program. However, recent LHC data already showed that the LHC and RHIC can successfully complement each other.

![Figure 4](https://i.imgur.com/3B5x.png)

Figure 4. Fractional energy loss for PHENIX data calculated with two-particle hadron-hadron correlations for partons compared with the same quantities calculated for reconstructed jets measured by the CMS collaboration directly. For the CMS data, the partner jet is also restricted to have energy $> 50$ GeV.

The LHC energy loss data has been mostly made use of full jet reconstruction, and the RHIC data we are concerned with are mostly measured with 2-particle correlations. Ignoring details of the influence of the actual experimental definitions of jets via various jet finding algorithms, one should be able to make a connection to the underlying “parton” parent of the jets via either type of
measurement. Fortunately PHENIX has developed a calculation framework [7] that can calculate averages of various jet (parton) level observables from two particle observables such as the shape of the spectral yield of associated particles conditional on the trigger. The quantities include for example, mean $<z>$ of trigger jets, mean di-jet intrinsic momentum imbalance $<k_T>$ between trigger and second jet in a di-jet pair, and the mean fraction of transverse momenta of the away-side jet over the trigger jet $\langle \hat{z}_h \rangle = \langle \frac{E_{assoc\ jet}}{E_{trigger\ jet}} \rangle$ or equivalently $1-\langle \hat{z}_h \rangle$ the mean fractional energy loss of the away-side jet. Since in PHENIX the rapidity range is limited so that $p_{Tjet} \approx E_{jet}$, these latter quantities can be related to recent LHC jet data, measured both in the jet asymmetry $A_J$ [8,9] which is defined as $|E_1 - E_2|/(E_1 + E_2) = (1-\hat{z}_h)/(1+\hat{z}_h)$ or in direct measurements of itself of $\hat{z}_h$ itself [9,10]. This allows one to compare the mean fractional energy loss between jets of different energy as is done in Figure 4, if one assumes that the medium effects are not strongly dependent on the center of mass energy of the collisions, e.g. if the sQGP exists at the phase boundaries in both cases for the dominant times of the evolution. This could test energy loss models ability to reproduce a “Bethe-Bloch formula”-like dependence. On the other hand if such a quantity can be measured for at both LHC and RHIC for the same energy jets, and this quantity is different, it could elucidate differences in the medium for the two center of mass energy ranges. As Fig.4 shows, the first assumption of similar QGP effects, it appears that the lower energy jets suffer a larger fractional energy loss. More details of this analysis can be found in [10]. The RHIC data is derived from hadron-hadron correlations, and therefore for the RHIC data, a scale factor of $1/<z_{leading\ particle}>$ taken approximately as 1/0.7 is used to scale the leading trigger $\pi^0$ momentum to its parent jet energy. Deriving the same data from direct photon –hadron correlations can be cleaner since, to leading order, no such scale factor is needed, and the photons avoid possible biases (e.g. geometric) coming from the source distribution of the trigger hadrons, since their parent jet distributions could already be modified. However improvement of the statistical precision of the direct photon data is necessary before such comparisons can be made. The new 2010 dataset which will be analyzed soon could also offer such improved statistics.

5. Conclusions

Measurements of two particle correlations, both hadron-hadron and especially direct photon-hadron correlations reveal details of QGP induced jet energy loss in heavy ion collisions. The fragmentation function for relatively low $p_T$, direct photons (> 5 GeV/c) appear to show some modification, including a suppression at large $z$, and much less suppression, possibly even enhancement. The statistical precision of the result needs improved to make a more definite statement, something that may be forthcoming with the availability of a new higher statistics 2010 dataset.

A framework for calculating parton or jet level observables from the PHENIX 2-particle yields results that can be compared to recent LHC jet reconstruction observables. Under certain assumptions, the fractional energy loss for lower jet energies that the PHENIX data is sensitive to, appears to be larger than for much higher energy jets at the LHC. This statement needs many caveats, many of which may be able to be removed in the future with the availability of higher statistics direct photon – hadron measurements and possibly jet reconstruction analyses at RHIC.

6. References

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