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Jet properties from direct γ - hadron correlation in PHENIX at RHIC

D.J Kim*, **Sami Räsänen, Jan Rak**
Jyväskylä University, Finland
E-mail: djkim@jyu.fi

Two-particle correlations of direct photon triggers with associated hadrons are obtained by isolation method in $p+p$ collisions at $\sqrt{s}$= 200 GeV in PHENIX at RHIC. The initial momentum of the away-side parton is tightly constrained, because the parton-photon pair is balanced in momentum at the leading order in perturbative quantum chromodynamics (pQCD). Therefore making such correlations can be used as a tool to measure the away-side parton fragmentation function. The direct photon associated yields in $p+p$ collisions are compared with PYTHIA [1] and the effect of the k_T smearing in the spectra is discussed.

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1. Introduction

Fragmentation functions represent the probability for a parton to fragment into a particular hadron carrying a certain fraction of the parton's energy. Fragmentation functions incorporate the long distance, non-perturbative physics of the hadronization process in which the observed hadrons are formed from final state partons of the hard scattering process. It, like structure functions, cannot be calculated in perturbative QCD but can be evolved from a starting distribution at a defined energy scale [2]. If the fragmentation functions are combined with the cross sections for the inclusive production of each parton type in the given physical process, predictions can be made for the scaled momentum, z, spectra of final state hadrons. Small z fragmentation is significantly affected by the coherence (destructive interference) of soft gluons [3], while scaling violation of the fragmentation function at large z allows to measure α_s [4]. It has been believed that the shape of the high-p_T trigger hadron associated x_{E} distributions reflects the shape of the fragmentation function [5], by x_{E} we mean

$$x_{\mathrm{E}} = -\frac{\vec{p}_{T\mathrm{t}} \cdot \vec{p}_{T\mathrm{a}}}{p_{T\mathrm{t}}^2} = -\frac{p_{T\mathrm{a}}}{p_{T\mathrm{t}}} \cos\Delta\phi \simeq \frac{z_{\mathrm{a}}\,\hat{p}_{T\mathrm{a}}}{z_{\mathrm{t}}\,\hat{p}_{T\mathrm{t}}} \tag{1.1}$$

where $\hat{p}_{T\mathrm{t}}$, $\hat{p}_{T\mathrm{a}}$, $p_{T\mathrm{t}}$, $p_{T\mathrm{a}}$ are the transverse momenta of the trigger and associated parton, trigger and associated hadrons and z_{a}=$p_{T\mathrm{a}}/\hat{p}_{T\mathrm{a}}$ and z_{t}=$p_{T\mathrm{t}}/\hat{p}_{T\mathrm{t}}$. However, it has been demonstrated in [6] that the fixed momentum of the trigger particle $p_{T\mathrm{t}}$ does not fix the mother parton momentum $\hat{p}_{T\mathrm{t}}$ and $p_{T\mathrm{t}}$ varies with $p_{T\mathrm{a}}$. In this case both z_{a} and z_{t} vary with $p_{T\mathrm{a}}$ and this variation completely masks the actual shape of the fragmentation function. One of the alternative ways to explore the fragmentation function is to study the particle distributions associated to the direct photon. In the high-p_T region where the photon-production is dominated by the Compton scattering, the direct photon balances the back-to-back quark. The associated x_{E} distribution then approximates the fragmentation function of the away side jet. However, in this case there are important effects which need to be taken into account. One constraint comes from the fact that at low p_T the direct photon production may be contaminated by fragmentation photons from the large number of gluonic jets produced [7, 8]. Fragmentation photons obviously do not balance the away-side parton. Another constraint comes from the fact that even when considering the leading order Compton diagram there is always soft QCD radiation which breaks the jet-photon momentum balance and the azimuthal collinearity. This non-perturbative radiation manifests itself as a non-zero value of the net parton-photon pair transverse momentum magnitude. Originally this soft radiation induced transverse momentum was attributed to the individual incoming partons and the notation of k_T (parton transverse momentum) was introduced by Feynman, Field and Fox [9], where the colliding partons might have some initial transverse momentum k_T with respect to the incoming hadrons. This analog of the Fermi motion of nucleons in a nucleus would give rise to a smearing out of the p_T spectrum. There could be an additional smearing due to the k_T associated with the fragmentation in the final state [10].

2. PHENIX π^0 $-h$ and direct $\gamma-h$ correlation results

The identification of direct photons is difficult due to the large number of background photons from hadronic decays, mostly from π^0 decays. Therefore the extraction of the direct photon-hadron pairs per trigger yields relies on a statistical subtraction of the decay photon-hadron per trigger

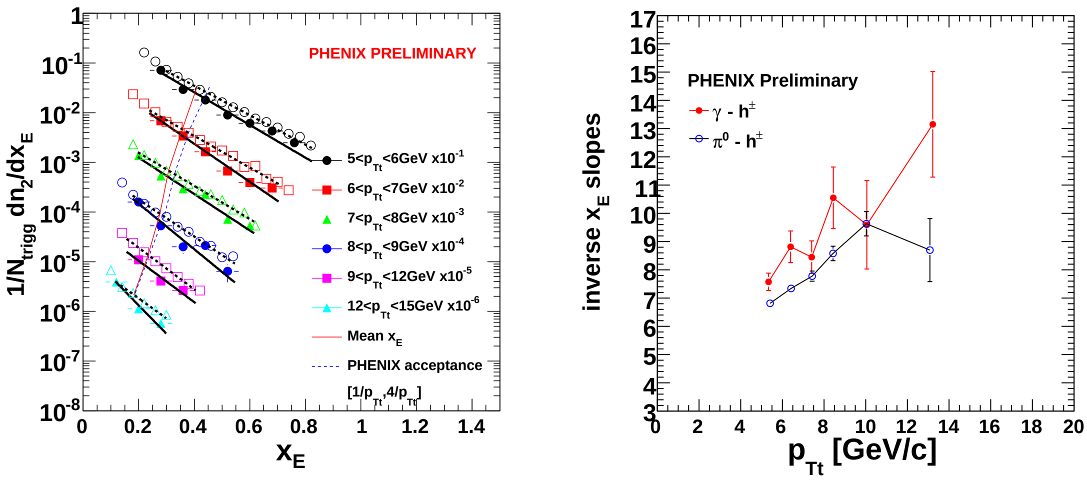
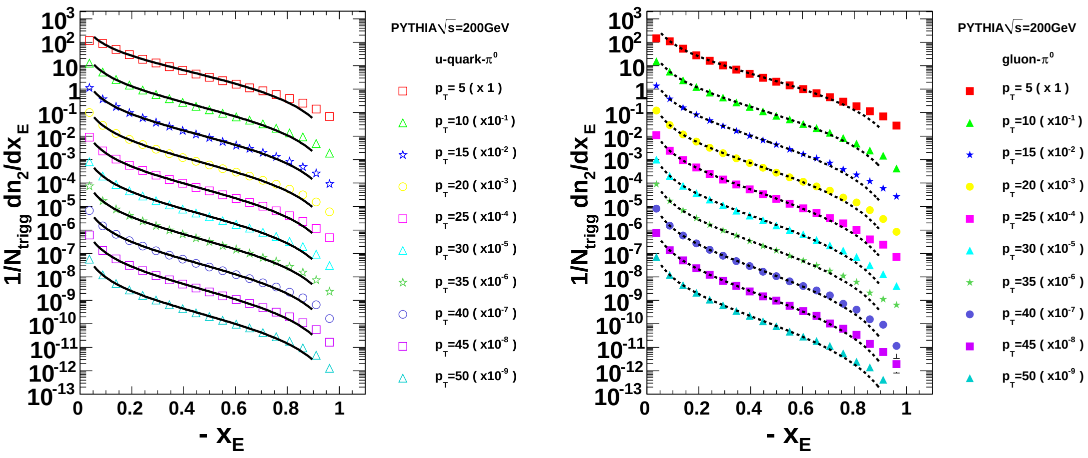


Figure 1: PHENIX preliminary data from $p+p$ collisions at $\sqrt{s}$=200 GeV. Left : $x_{\rm E}$ distributions of charged hadrons associated with trigger π^0 (open markers) and isolated γ (closed markers) are fitted to a simple exponential function ($Ne^{-bx_{\rm E}}$) in the available range of $x_{\rm E}$. The mean $x_{\rm E}$ values extracted from the distributions are indicated by a solid line which goes across the $x_{\rm E}$ distributions labeled as "Mean $x_{\rm E}$". As for the dotted line, labeled as "PHENIX acceptance", the mean $x_{\rm E}$ is calculated by limiting the associated charged hadron momenta from 1 to 4 GeV/c of PHENIX acceptance in a given trigger momentum. Right : The extracted exponential slope b (called "inverse $x_{\rm E}$ slope" in the figure) is shown as a function of trigger particle momentum.

yields from the inclusive photon-hadron pairs per trigger yields. The first result from this "subtraction method" was presented in [11]. Recently PHENIX developed photon isolation cuts which were applied event by event in a new analysis in order to dramatically reduce the contamination of di-jet events with π^0 decay or fragmentation photons in the $\gamma-h$ event sample. The measured $x_{\rm E}$ distributions of charged hadrons associated with π^0 and isolated photon triggers in $p+p$ collisions at $\sqrt{s}=200$ GeV are presented in Fig. 1 for various isolated photon and π^0 trigger momenta. A fit of the $x_{\rm E}$ distribution to a simple exponential ($Ne^{-bx_{\rm E}}$) in the available range of $x_{\rm E}$ is presented in left panel of the Fig. 1. The extracted exponential slope b from the fitting as a function of trigger $p_{T{\rm t}}$ is shown in the right side of the Fig. 1. A very interesting feature from this result is observed. The $x_{\rm E}$ slopes are still increasing as the trigger momentum gets larger, which is very similar to the π^0-h case.

In order to understand this behavior of $x_{\rm E}$ slopes as a function of trigger momentum, we compare the PHENIX preliminary data with PYTHIA, where $\sqrt{\langle k_T^2\rangle}=3.0$ GeV/c is used based on the PHENIX measurement [6]. Fig. 2 shows the $x_{\rm E}$ distributions of quark and gluon fragmenting to π^0's for various quark and gluon momenta calculated by PYTHIA (note that $x_{\rm E}$ is negative because only near side particles associated with quarks and gluons are accounted for). The $x_{\rm E}$ distributions of π^0's resulting from quark and gluon fragmentation are parameterized by means of a fit function

$$\frac{dN}{dx_{\rm E}} \propto x_{\rm E}^{-\alpha}(1-x_{\rm E})^{\beta}, \tag{2.1}$$



(a) PYTHIA quark fragmentation function (b) PYTHIA gluon fragmentation function

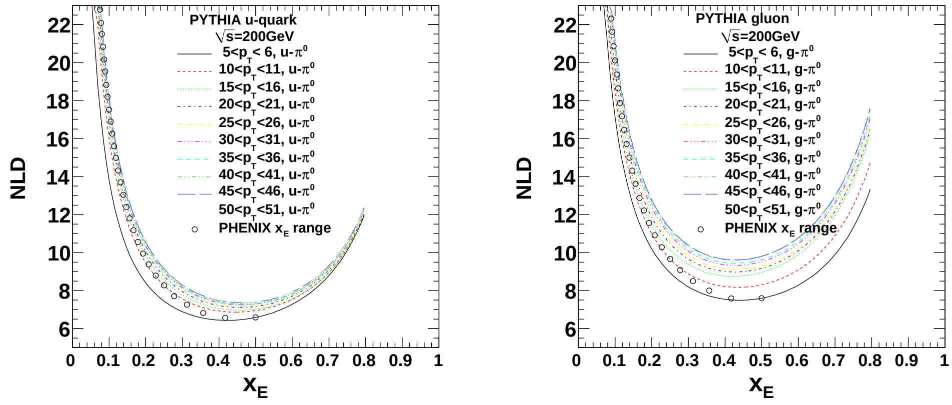
Figure 2: x_{E} distributions of π^0's resulting from quark and gluon fragmentation in various quark/gluon momenta, $p_{T\mathrm{t}}$ in PYTHIA ($p+p$ at $\sqrt{s}$=200 GeV). The results of the KKP parametrization [2] fitting to the distributions are shown as solid (for u-quarks) and dashed (for gluons) lines. The momenta in the figure label are given in GeV/c.

i.e. we use in fitting the same functional form as in KKP parametrization [2] for fragmentation functions. The results of the fitting are shown as solid (for u-quarks) and dashed (for gluons) lines. Negative Logarithmic Derivative (NLD) of x_{E} distributions

$$\mathrm{NLD} \equiv -\frac{d}{dx_{\mathrm{E}}} \ln \left(\frac{dN}{dx_{\mathrm{E}}} \right) \tag{2.2}$$

measures the local slope of the x_{E} distribution (NLD of an exponential distribution is constant). The NLD's extracted from the x_{E} distributions of neutral pions associated with quarks and gluons as a function of x_{E} is presented in Fig. 3. Because the x_{E} distributions in the x_{E} range above 0.8 cannot be properly described by the fit (see Fig. 2), the NLD distributions are shown only below $x_{\mathrm{E}} \approx 0.8$. The NLD's for low x_{E} regions (less than $x_{\mathrm{E}} \approx 0.2$) are much steeper than any other range, stay in lower values in the intermediate range ($0.2 \leq x_{\mathrm{E}} \leq 0.7$) and get larger for $x_{\mathrm{E}} \geq 0.7$ for all quark and gluon trigger momenta. The NLD's from PYTHIA in the range of available PHENIX data are shown in the same Fig. 3 as open circles for each quark/gluon momentum. The mean x_{E} extracted from the PHENIX data and the x_{E} values used to extract "NLD" from PYTHIA by limiting the hadron acceptance of PHENIX are comparable to each other, as can be seen from Fig. 1. In the latter comparisons of the PHENIX data to PYTHIA, the mean x_{E} values labeled as "PHENIX acceptance" are used for higher momenta in PYTHIA where PHENIX data are not available.

Finally, we have compared the exponential slopes of PHENIX data with PYTHIA where the used x_{E} values are close to the mean values of PHENIX x_{E} ranges in Fig. 4. They reveal the same increasing trend for the higher trigger $p_{T\mathrm{t}}$ and the local slopes of quarks and gluons from



(a) quarks (b) gluons

Figure 3: PYTHIA $p+p$ at $\sqrt{s}$=200 GeV. Negative Logarithmic Derivative ($NLD = -\frac{d}{dx_{\rm E}}\ln(\frac{dN}{dx_{\rm E}})$) of the $x_{\rm E}$ distributions of π^0's resulting from quarks and gluons fragmentation in various quark/gluon momenta. As for the open circle labeled as "PHENIX $x_{\rm E}$ range", the mean $x_{\rm E}$ is calculated by limiting the associated charged hadron momenta from 1 to 4 GeV/c of PHENIX acceptance in the given trigger momentum.

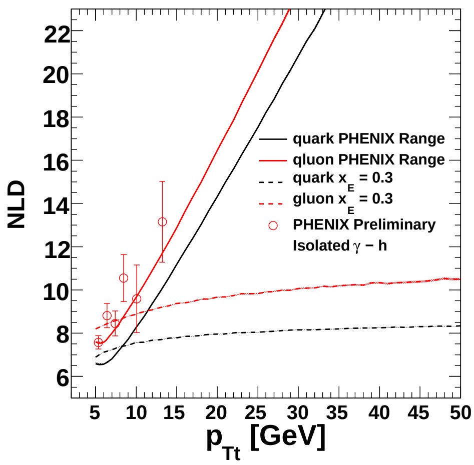


Figure 4: Inverse $x_{\rm E}$ slopes from PHENIX preliminary as a function of isolated γ trigger momentum are compared with NLD's from $x_{\rm E}$ distributions of π^0's resulting from PYTHIA quark and gluon fragmentation with two set of $x_{\rm E}$ ranges. The solid lines labeled as "PHENIX $x_{\rm E}$ range", represent the local slopes in the expected $x_{\rm E}$ value by considering PHENIX acceptance for charged hadron momentum in PYTHIA. The other shown as dotted line represents the NLD's for a fixed value of $x_{\rm E} = 0.3$ from PYTHIA.

PYTHIA are comparable to PHENIX data. The steepness of the exponential slopes in PHENIX data is driven by the experimental limit of the $x_{\rm E}$ range, i.e away-side hadron can be measured only from 1 to 4 GeV/c in PHENIX, therefore $x_{\rm E}$ value gets smaller as the trigger momenta gets higher. As for the intermediate $x_{\rm E}$ (≈ 0.3), the absolute slopes are slightly increasing as the trigger momentum gets larger and tend to converge into a constant above 10 GeV/c for quark and gluon fragmentation functions, shown as dotted lines. But the increment of the slopes for the gluon fragmentation functions (slope changes from 8 to 10) is rather larger about by factor of two than for the quark fragmentation functions (slope changes from 7 to 8) in the range $0.2 \leq x_{\rm E} \leq 0.7$ (see Fig. 3) when the trigger momentum varies from 5 to 50 GeV/c. The fact that the absolute NLD values in all trigger bins agree with those from quark and gluon fragmenation function suggests that the measured $x_{\rm E}$ distribution associated with direct photon is a representation of the quark or gluon fragmenation function. But a more detailed analysis with larger p_T trigger bins and wider $x_{\rm E}$ ranges is necessary to study trigger momentum and $x_{\rm E}$ dependent effects which can influence the fragmentation function.

3. Conclusions

The PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC) has measured $x_{\rm E}$ distributions of charged hadrons associated with π^0 and isolated photon triggers in $p+p$ collisions at $\sqrt{s} = 200$ GeV. It has been demonstrated in [6] that $x_{\rm E}$ distributions measured in di-hadron correlations are insensitive to the fragmentation function. Direct photon associated spectra are expected to follow fragmentation function more closely, because in leading order two-to-two processes the trigger photon fixes exactly the momentum of outgoing parton by momentum conservation. However, several complications, like fragmentation photons and soft QCD radiation, are expected. Nevertheless, the measured data presents a striking feature that slopes of the $x_{\rm E}$ distributions, in both π^0 and photon trigger cases, continue to rise as a function of trigger momentum. We have studied this rising trend in the case of photon trigger by fitting the same functional form as used in KKP parameterization [2] to the $x_{\rm E}$ distributions of neutral pions resulting from fragmentation of u-quark or gluon in PYTHIA. As the fit function is not exponential, we use Negative Logarithmic Derivative (NLD) to measure local slopes. We found that the observed rising trend of slopes of $x_{\rm E}$ distributions is driven by the experimental limits of the $x_{\rm E}$ range. PHENIX can measure photons up to very large momenta while for hadrons the measurable range is more limited. Therefore the measured $x_{\rm E}$ values for the higher trigger momenta are very small where the k_T effect dominates and make the local slopes of the fragmentation function larger. Improvement of the statistical and systematic precision of the measurements with wider $x_{\rm E}$ ranges and larger p_T trigger should allow further tests of fragmentation function as well as understanding of k_T effect quantitatively.

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