Jet properties from di-hadron correlations in $p+p$ collisions at $\sqrt{s}=200$ GeV

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Abstract

An analysis of high $p_T$ hadron spectra associated with high $p_T$ $\pi^0$ particles in $p+p$ collisions at $\sqrt{s}=200$ GeV is presented. The shape of the azimuthal angular correlation is used to determine the value of partonic intrinsic momentum $\sqrt{\langle k_T^2 \rangle} = 2.68 \pm 0.07 \text{(stat)} \pm 0.34 \text{(sys)} \text{ GeV/c}$. The effect of $k_T$-smearing of inclusive $\pi^0$ cross section is discussed.

Key words: jets, parton, intrinsic momentum, $k_T$-smearing, fragmentation

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1 Introduction

An observation of similar suppression pattern pattern of heavy and light quarks at RHIC (see e.g. [1]) initiated a discussion on detailed mechanism of parton energy loss in the exited nuclear medium [2,3]. In order to explain the relatively strong suppression patterns of high $p_T$ electrons from semi-leptonic $D$ and $B$ mesons decays, collisional energy loss has to be taken into account. However, this type of parton interaction with the exited nuclear medium should lead to the broadening of the away-side correlation peak [4]. Recent measurements of high $p_T$ trigger-associated particles do not indicate such a broadening [5] although for the trigger transverse momentum $p_{Tt} \sim 3 \text{ GeV/c}$ with lower $p_T$ associated particles, significant broadening is observed [6]. It is evident that the measurement of jet fragmentation properties and intrinsic parton transverse momentum $k_T$ for $p+p$ collisions is vital for the understanding of pQCD phenomena and it also provides an important baseline for comparison to the results in heavy ion collisions.
In the center-of-mass of the hard collision the two scattered partons propagate back-to-back with the opposite momenta. In the center-of-mass of the $p + p$ collision a finite net $p_{T\text{pair}}$ results in an acoplanarity and momentum imbalance of the di-jet which is measured as $k_T$. In the case of the Drell-Yan process the di-lepton net pair momentum reflects directly the magnitudes of $k_T$ vectors of $q\bar{q}$ parton pair in the annihilation process. In the case of di-hadron correlation the jet fragmentation process is involved and it is commonly accepted to characterize the di-hadron acoplanarity by quantity $= |p_{Tt} \times p_{Ta}|/p_{Tt}^2$, the transverse momentum component of the away-side particle $p_{Ta}$ perpendicular to trigger particle $p_{Tt}$ (for more details see [7]). It is believed that the origin of $k_T$ is three fold: I. Fermi motion induced by the finite transverse size of the nucleon wave-function. II. Soft gluon showering (see e.g [8]). III. Hard next to leading order radiation.

The contribution to the $k_T$ from the Fermi motion is $\approx \hbar/r_N \approx 300$ MeV/c where $r_N$, the transverse size of the nucleon wave-function, is of order of 1 fm. However, the measured values of $\langle k_T \rangle$ over the broad range of center-of-mass energies are as large as $5$ GeV/c [9]. The main contribution to $k_T$ comes

Fig. 1. Left panel: Muon pair transverse momentum distribution for the invariant mass in $7 < M_{\mu\mu} < 8$ (solid triangles) and $8 < M_{\mu\mu} < 9$ GeV/c (empty triangles) range measured in the fixed target experiment ($p_{\text{beam}}=400$ GeV/c) [10]. The solid lines represent the Gaussian fit in the $0 < p_{T\mu\mu} < 3$ GeV/c. Dashed line represent the extrapolation of the fit function up to $p_{T\mu\mu}=5$ GeV/c region. Right panel: $p_{\text{out}}$ distribution measured by PHENIX experiment in $d + Au$ collision at $\sqrt{s}=200$ GeV/c [11].

from the from the Gaussian-like soft gluon showering (see Fig 1) and can be reproduced relatively well by resummation technique [8]. The $\mu\mu$-pair $p_T$ distributions for the two different invariant mass bins (data taken from [10]) are shown on the upper panel and of Fig 1. It is evident that the Gaussian shape dominates over the entire range of measured $p_{T\mu\mu}$ with a hint of small excess above $p_{T\mu\mu}=3-4$ GeV/c. The $p_{\text{out}}$ measurement at higher $\sqrt{s}$ regime
reveals also similar Gaussian shape with more pronounced enhancement at 
large values of $p_{\text{out}}$ indicating presence of NLO radiation.

Fig. 2. Left panel: Measured values of $\hat{x}_h^{-1} \langle z_t \rangle \sqrt{\langle k_T^2 \rangle}$ (see Eq. (1)) for $1.4 < p_{T_a} < 5$ GeV/c as a function of $p_{T_t}$ in $p+p$ at $\sqrt{s}=200$ GeV. CCOR measurement of $\sqrt{\langle k_T^2 \rangle}$ values at $\sqrt{s}=62.4$ GeV (open triangles) [12]. The solid line represent the PYTHIA simulation with $\sqrt{\langle k_T^2 \rangle}=2.7$ GeV/c. The gray band correspond to the variation of the input $\sqrt{\langle k_T^2 \rangle}$ value by $\pm 0.1$ GeV/c. Right panel: Extracted $\sqrt{\langle k_T^2 \rangle}$ values when $\hat{x}_h$ and $\langle z_t \rangle$ were evaluated analytically (see [7]). The solid lines represent the systematic error bars originating mainly from the uncertainty on the fragmentation function. CCOR data (open triangles) the same as on the left panel.

In this analysis we used the two-particle azimuthal correlation function to 
determine $\langle p_{\text{out}} \rangle$ for different trigger ($p_{T_t}$) and associated ($p_{T_a}$) particle transverse momentum bins (for details see [7]). We have shown that the $\sqrt{\langle p_{\text{out}}^2 \rangle}$ value can be related to $\sqrt{\langle k_T^2 \rangle}$ as

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

where $x_h=p_{T_a}/p_{T_t}$ and $j_T$ is the jet fragmentation transverse momentum 
component in the azimuthal plane. All quantities on the right-hand side of 
Eq. (1) can be directly extracted from the correlation function while the left-hand side corresponds to the product of $\sqrt{\langle k_T^2 \rangle}$, $\hat{x}_h=(\langle \hat{p}_{T_a} \rangle/\langle \hat{p}_{T_T} \rangle)$, the ratio of the mean associated to trigger parton momenta, and $\langle z_t \rangle=(\langle \hat{p}_{T_t} \rangle/\langle \hat{p}_{T_T} \rangle)$, the mean momentum fraction carried by the trigger particle. The $\hat{x}_h$ quantity accounts for the jet momenta imbalance due to the $k_T$ bias ($k_T$ vector is more likely to be colinear with the trigger jet for events selected with the $p_{T_t}>p_{T_a}$ condition). The $\langle z_t \rangle$ quantity accounts for the fact that even when the trigger particle momentum $p_{T_t}$ is fixed, the trigger parton momentum $\hat{p}_{T_t}$ varies with $p_{T_a}$, the
transverse momentum of associated particles.

Measured $\hat{x}_h^{-1} \langle z_t \rangle \sqrt{\langle k_T^2 \rangle}$ values for different trigger particle momenta $p_{Tt}$ are shown on Fig. 2. In order to determine the $\sqrt{\langle k_T^2 \rangle}$ values we have to evaluate the $\hat{x}_h$ and $\langle z_t \rangle$ quantities. We assumed that

$$\langle z_t \rangle \approx \frac{1}{x_{Tt}} \int z_t^{-1} D_\pi^q(z_t) \frac{\sqrt{\pi/2}}{\sqrt{\langle k_T^2 \rangle}} \int_0^{\pi/2} \frac{1}{p_{Ta}^2} \frac{1}{D_q^\pi(p_{Tt})} d\phi d\hat{p}_T dz_t$$

(2)

where $\hat{p}_n = k_{Tt} + k_{Ta}$ is a net parton-pair momentum, $G(\hat{p}_n) = \exp(-\frac{\hat{p}_n^2}{2 \langle k_T^2 \rangle})$ describes the Gaussian probability of the net pair momentum magnitude distribution, $\Sigma_q(\hat{p}_t)$ is the unsmeared final state parton momentum distribution, $D_\pi^q$ is the fragmentation function.

The $\hat{x}_h$ quantity can be evaluated in the similar way as $\langle z_t \rangle$ (for details see $k_T$ smearing section of [7]). As it has been demonstrated in [7] it is not possible to extract the fragmentation function from di-hadron correlations, thus we used the $D_\pi^q$ parameters extracted from $e^+ e^-$ data [13,14]. The final values of $\sqrt{\langle k_T^2 \rangle}$ for various values of $p_{Tt}$ are displayed on Fig. 2 (solid circles). The average value obtained is $\sqrt{\langle k_T^2 \rangle} = 2.68 \pm 0.07(\text{stat}) \pm 0.34(\text{sys})$ GeV/c.

Fig. 3. **Left panel:** $\pi^0$ invariant cross section from [13]. The dashed lined ($\Sigma_q$) corresponds to the power law parameterization of the final state parton spectra before fragmentation. The dotted line ($\Sigma_{kT}$) is the $k_T$-smeared $\Sigma_q$ function. The solid line corresponds to the folding of $\Sigma_{kT}$ with the fragmentation function. **Right panel:** Net parton pair momentum $\langle p_T \rangle_{\text{pair}} = \sqrt{\pi/2} \sqrt{\langle k_T^2 \rangle}$ is compared to compilation from [9].

We have also studied the effect of $k_T$ smearing on the inclusive particle distributions. Although the NLO calculation without intrinsic $k_T$ shows relatively good agreement with an inclusive $\pi^0$ invariant cross section [13], we have found...
that there is a good agreement with the data when we perform a $k_T$-smearing of parametrized parton spectra by $k_T$ magnitude $2.7$ GeV/c (see left panel of Fig. 3).

The $\pi^0$ cross section was calculated as a folding $D(z) \otimes \Sigma_{kT}(p_T)$, where $\Sigma_{kT}(p_T)$ is the smeared final state parton spectrum. The unsmeared ($\Sigma_q$) and $k_T$-smeared ($\Sigma_{kT}$) final state parton spectra are shown as a dashed and dotted lines on the left panel of Fig. 3. The value of the net-transverse momentum of the pair found in this analysis is shown on the right panel of Fig. 3. This value appears to be with a good agreement with the world data from [9]. It is interesting to note that at LHC energies the magnitude of $k_T$ will be as large as 5-7 GeV/c.

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