One more ingredient for energy loss quantification

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Abstract. The recent results at RHIC for direct $\gamma$-charged hadron azimuthal correlations in heavy-ion collisions are presented. We use these correlations to study the color charge density of the medium through the medium-induced modification of high-$p_T$ parton fragmentation. Azimuthal correlations of direct photons at high transverse energy ($8 < E_T < 16$ GeV) with away-side charged hadrons of transverse momentum ($3 < p_T < 6$ GeV/c) have been measured over a broad range of centrality for $Au + Au$ collisions and $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV in the STAR experiment. A transverse shower shape analysis in the STAR Barrel Electromagnetic Calorimeter Shower Maximum Detector is used to discriminate between the direct photons and photons from the decays of high-$p_T$ $\pi^0$. The per-trigger away-side yield of direct $\gamma$ is smaller than from $\pi^0$ triggers in the same centrality class. Within the current uncertainty the recoil suppression in central $Au + Au$ collisions $I_{CP}$ of direct $\gamma$ and $\pi^0$ are similar.

Key words. Heavy-ion Collision – gamma-Jet Correlations – Jet Quenching

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1 Introduction

High-$p_T$ particles produced in high energy collisions are of special importance in QCD. The production of these particles arises from the hard scattering of the incoming partons and their subsequent fragmentation. Therefore, their production rate can be calculated perturbatively, and their spectra reveal information about the parent parton distributions in momentum space. Furthermore in heavy-ion collisions these particles are formed at the early time of the collisions (“prompt production”) and therefore represent an ideal tool for probing the medium resulted from such collisions. The absorption of the high-$p_T$ particles in the medium can be used to obtain a tomographic image of the color charge density of the medium \cite{1}.

Bearing this in mind, the high-$p_T$ measurements in the heavy-ion program show some of the most important results at RHIC: The strong suppression of high-$p_T$ particles which is observed in central $Au + Au$ collisions via the dramatic suppression of particle production, and the modification of jet correlations at high transverse momentum \cite{2,3,4}. This strong suppression provides compelling evidence for large energy loss of scattered partons traversing matter that has a high density of color charges.

After various complementary measurements from RHIC data have revealed the formation of a strongly coupled medium \cite{5,6,7,8,9}, the primary goal of the RHIC heavy-ion program progresses from qualitative statements to rigorous quantitative conclusions. One of the most important requirements for quantitative conclusions is the precise measurements of the quantity of the medium-induced energy loss.

While the single-particle spectra do not provide enough sensitivity to discriminate between the different energy loss mechanisms \cite{10,11}, the di-hadron azimuthal correlation measurement is expected to provide somewhat better constraints on the energy loss. The initial parton energy is not accessible in single-particle spectra but is somewhat accessible in the di-hadron measurements. However a model dependent study \cite{12} has shown that at initial high color charge density both single particle spectra and di-hadron azimuthal correlation measurement have diminished sensitivity due to the geometrical bias.

The $\gamma$-hadron azimuthal correlation measurement has been suggested as a powerful tool to quantify the energy loss \cite{13}. In the dominant QCD process of Compton-like scattering, the photon transverse momentum balances the parton initial transverse energy. In addition, due to the large mean free path of the photon compared to the system size formed in heavy-ion collision, the direct photon measurement doesn’t suffer from the same geometrical bias of that
of single particle spectra and di-hadron azimuthal correlation measurements. In particular the γ-hadron azimuthal correlations provide a unique way to quantify the energy loss dependence on the initial parton energy and possibly the color factor. Therefore combining the energy loss measurements from many probes of different geometrical biases and different coupling to the formed medium and comparing these measurements with different theoretical models can lead to a successful quantitative interpretation of the heavy-ion data.

2 Data Analysis

The STAR experiment collected an integrated luminosity of 535 μb⁻¹ of Au + Au collisions at √s_{NN} = 200 GeV in 2007 using level-2 high-p_T tower trigger. The level-2 trigger algorithm was implemented in the Barrel Electromagnetic Calorimeter (BEMC) and optimized based on the information of the direct γ/π⁰ ratio in Au + Au collisions [14], the π⁰ decay kinematics, and the electromagnetic shower profile characteristics. The BEMC has full azimuthal coverage and pseudorapidity coverage |η| ≤ 1.0. As a reference measurement we use p + p data at √s_{NN} = 200 GeV taken in 2006 with integrated luminosity of 11 pb⁻¹. The Time Projection Chamber (TPC) was used to detect charged particle tracks and measure their momenta. The charged track quality cuts are similar to previous STAR analyses [15]. For this analysis, events with at least one cluster with E_T > 8 GeV were selected. To ensure the purity of the photon-triggered sample, trigger towers were rejected if a track with p > 3 GeV/c points to it.

A crucial step of the analysis is to discriminate between showers of direct γ and two close γ’s from a high-p_T symmetric π⁰ decay. At p_T ∼ 8 GeV/c the angular separation between the two photons resulting from a symmetric π⁰ decay (both decays photons have similar energy, smallest opening angle) at the BEMC face is typically smaller than the tower size (∆η = 0.05, ∆φ = 0.05); but a π⁰ shower is generally broader than a single γ shower. The Barrel Shower Maximum Detector (BSMD), which resides at ∼ 5X_0 inside the calorimeter towers, is well-suited for (2γ)/(1γ) separation up to p_T ∼ 26 GeV/c due to its fine segmentation (∆η ≈ 0.007, ∆φ ≈ 0.007). In this analysis the π⁰/γ discrimination was carried out by making cuts on the shower shape as measured by the BSMD, where the π⁰ identification cut is adjusted in order to obtain a very pure sample of π⁰ and a sample rich in direct γ (γ_{rich}). The discrimination cuts are varied to determine the systematic uncertainties. To determine the combinatorial background level the relative azimuthal angular distribution of the associated particles with respect to the trigger particle is fitted with two gaussian peaks and a straight line. The near- and away-side yields, Y^n and Y^rich, of associated particles per trigger are extracted by integrating the 1/N_{ triggers}dN/d(Δφ) distributions in |Δφ| ≤ 0.63 and |Δφ − π| ≤ 0.63 respectively. The yield is corrected for the tracking efficiency of associated charged particles as a function of multiplicity.

The shower shape cuts used to select a sample of direct photon “rich” triggers reject most of the π⁰’s, but do not reject photons from highly asymmetric π⁰ decays, γ’s, and fragmentation photons. All of these sources of background are removed as follows from Eq.(1) below, but only within the systematic uncertainty on the assumption that their correlations are similar to those for π⁰’s. Assuming zero near-side yield for direct photon triggers and a very pure sample of π⁰, the away-side yield of hadrons correlated with the direct photon is extracted as

\[ Y_{\gamma_{direct} + h} = \frac{Y_{\gamma_{rich} + h}^n - RY_{\pi^0 + h}^n}{1 - R}, \quad R = \frac{Y_{\gamma_{rich} + h}^n}{Y_{\pi^0 + h}^n}. \]  

Where Y_{γ_{rich} + h}^n and Y_{π^0 + h}^n are the away (near)-side yields of associated particles per γ_{rich} and π⁰ triggers respectively, so that R is the fraction of γ_{rich} triggers that are actually from π⁰, γ, and fragmentation photons.

3 Results

Figure 1 (left) shows the azimuthal correlation for inclusive photon triggers for the most peripheral and central bins in Au+Au collisions. Parton energy loss in the medium causes the away-side to be increasingly suppressed with centrality as it was previously reported [3,15]. The suppression of the near-side yield with centrality, which has not been observed in the charged hadron azimuthal correlation, is consistent with an increase of the γ/π⁰ ratio with centrality at high E_T^{assoc}. The shower shape analysis is used to distinguish between the (2γ)/(1γ) showers as in Figure 1 (right) which shows the azimuthal correlation for γ-rich sample triggers and π⁰ triggers for the most peripheral and central bins. The γ-rich sample has a lower near-side yield than π⁰-triggered sample, but it is not zero. The non-zero near-side yield for the γ-rich sample is expected due to the remaining contributions of the widely separated photons from other sources, because the shower shape analysis is only effective for the two close γ showers.

The purity of π⁰ identification with the shower shape analysis is verified by comparing to previous measurements of azimuthal correlations between charged hadrons (cH − cH) [15]. Figure 2 shows the z_T dependence of the associated hadron yield normalized per π⁰ trigger D(z_T), where \( z_T = p_T^{assoc}/p_T^{trig} \) [16], for the near-side and away-side compared
to the per charged hadron trigger [15]. The near-side yield as in Figure 2 (left) shows no significant difference between $p+p$, $d+Au$, and $Au+Au$ indicating in-vacuum fragmentation even in heavy-ion collisions. This can be due to either a surface bias as generated in several model calculations [17,18,19,20] or the parton fragmenting in vacuum after losing energy in the medium. However, the medium effect is clearly seen in the away-side in Figure 2 (right) where the per trigger yield in $Au+Au$ is significantly suppressed compared to $p+p$ and $d+Au$. The general agreement between the results from this analysis ($\pi^0$-ch) and the previous analysis ($ch$) is clearly seen in both panels of Figure 2 which indicates the purity of the $\pi^0$ sample and therefore the effectiveness of the shower shape cut to identify $\pi^0$.

The away-side associated yields per trigger photon for direct $\gamma$-charged hadron correlations are extracted using Eq. 1. Figure 3 (left) shows the $z_T$ dependence of the trigger-normalized fragmentation function for $\pi^0$-charged correlations ($\pi^0$-ch) compared to measurements with direct $\gamma$-charged correlations ($\gamma$-ch). The away-side yield per trigger of direct $\gamma$ is smaller than with $\pi^0$ trigger at the same centrality class. This difference is due to the fact that the $\pi^0$ originates from higher initial parton energy and therefore has a larger associated jet multiplicity.

In order to quantify the away-side suppression, we calculate the quantity $I_{CP}$, which is defined as the ratio of the integrated yield of the away-side associated particles per trigger particle in $Au+Au$ peripheral (40-80% of the geometrical cross section) relative to $Au+Au$ central (0-10% of the geometrical cross section) collisions. Figure 3 (right) shows the $I_{CP}$ for $\pi^0$ triggers and for direct $\gamma$ triggers as a function of $z_T$. The ratio would be unity if there were no medium
In summary, the first measurement of fragment distributions for jets with energy controlled via $(\gamma,\pi^0)$-jet in Au + Au collisions has been performed by the STAR experiment. The STAR detector is unique to perform such correlation measurements due to the full coverage in azimuth. Within the current uncertainty the recoil suppression ratio $I_{\gamma\gamma}$ of direct $\gamma$ and $\pi^0$ are similar. A full analysis of the systematic uncertainties is under way and may lead to a reduction in the systematic and statistical uncertainties.

4. Summary and Outlook

In summary, the first measurement of fragment distributions for jets with energy controlled via $\gamma$-jet in Au + Au collisions has been performed by the STAR experiment. The STAR detector is unique to perform such correlation measurements due to the full coverage in azimuth. Within the current uncertainty the recoil suppression ratio $I_{\gamma\gamma}$ of direct $\gamma$ and $\pi^0$ are similar. A full analysis of the systematic uncertainties is under way and may lead to a reduction in the systematic and statistical uncertainties.
of the total uncertainty. Future RHIC runs will provide larger data samples to further reduce the uncertainties and extend the $z_T$ range.

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