Probing the Properties of the Matter Created at RHIC.

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Abstract
I discuss the use of high momentum particles as calibrated probes of the medium created in heavy-ion collisions at RHIC. Since high Q^2 processes only happen in the first stages of the collisions the scattered partons must pass through the produced medium before leaving the collision region. Their modifications, with respect to those from p-p collisions, due to this interaction with the medium provides valuable information on the properties of the medium.

1 Introduction

At RHIC there is strong evidence that heavy-ion collisions at $\sqrt{s_{NN}}$ = 200 GeV produce a strongly coupled plasma whose constituents are quarks and gluons - known as the strongly coupled Quark-Gluon Plasma, sQGP. A number of striking discoveries were made within the first three years of RHIC's operations and are detailed in the four experiment's "white papers" [1–4]. Having established that a sQGP is created we are now in the process of determining the properties of this new state of matter. One technique we are using to probe the medium is that of comparing the products of hard scattered partons in p-p to those in A-A. Parton-parton scatterings with high Q^2 occur during the initial stages of the interactions at RHIC energies. Since the production takes place at an early stage we have direct access to the hot and dense core of the reaction. In p-p collisions the jet cross-section can be directly calculated from pQCD. In Au-Au collisions the hard scattered partons must first traverse the hot and dense medium created before escaping the collision region. By observing the suppression and modification patterns of the fragmentation products in Au-Au compared to those in p-p we can learn about the properties of the sQGP.

2 The p-p Baseline

Before examining the Au-Au data, we needed to ensure that we can indeed describe the jet properties in p-p collisions at $\sqrt{s_{NN}}$ =200 GeV. Measurements of the total jet cross-section [5] and the identified particle p_T spectra (for example [6,7]) show that there is remarkable agreement to the data confirming that hard processes with light quarks and gluons are a well calibrated probe. Recently preliminary charged particle fragmentation functions as a function of jet energy have also been reported [8]. Figure 1 shows the ξ=log(E^{jet}/p^{hadron}) distributions compared to PYTHIA (v6.4) [9] for reconstructed leading jet energies of 30-40 GeV, using two different radii for the jet finding midpoint cone algorithm. The PYTHIA simulations were passed through the experiment's GEANT detector response simulators. The overall agreement indicates that next-to-leading order corrections are not very large, since these effects are not included in the PYTHIA simulation.

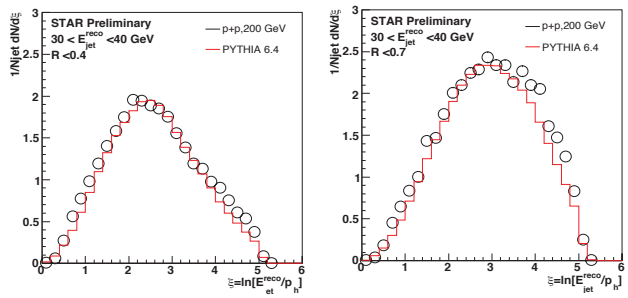

Fig. 1: Preliminary charged particle dN/dξ distributions for leading jets reconstructed with energies from 30-40 GeV. The left plot is for jet cone radii of R=0.4, the right for R=0.7. Only statistical errors are shown.

3 Nuclear Modification Factors and Di-hadron Correlations

Having convinced ourselves that we have a well calibrated probe via jet studies in p-p we turn our attention to the heavy-ion data. Before attempting full jet reconstruction we first looked at the inclusive high p_T particle spectra. At high p_T it is expected that particle production is dominated by fragmentation of hard scattered partons. If these partons do not interact with the medium the particle production rate should scale with the number of binary nucleon-nucleon collisions (N_{bin}) in the initial interaction. In this case the nuclear modification factor, $R_{AA}(p_T)$ (defined as the yields in A-A divided by the N_{bin} scaled p-p yields), at high p_T should be unity. If however the partons lose energy interacting with the sQGP the R_{AA} at high p_T should be suppressed.

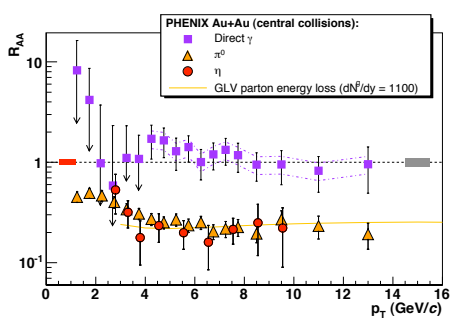

Fig. 2: The R_{AA} of direct γ, π^0, and η for central Au-Au events at $\sqrt{s_{NN}}$ = 200 GeV. The solid curves show the predictions from model calculations incorporating parton energy loss.

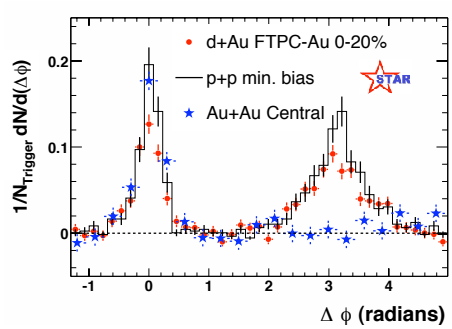

Fig. 3: Di-hadron correlations for p-p, d-Au, and Au-Au collisions at $\sqrt{s_{NN}}$ =200 GeV. p_T^{trig} = 4 GeV/c and $p_T^{ass} > 2$ GeV/c.

The measured R_{AA} for π^0, η, and direct γ are shown in Fig. 2 for central Au-Au collisions at $\sqrt{s_{NN}}$ =200 GeV [10]. The π^0 and η shown a large suppression of a factor five while the photons follow N_{bin} scaling. This scaling of the γ is predicted since they carry no color charge and have mean-free paths (or attenuations lengths) larger than the size of the medium. All hadrons measured to date, including those from heavy flavor decays, show an equivalent suppression at

high p_T for central data. The level of suppression decreases for peripheral collisions.

The theoretical description that is emerging to describe the R_{AA} results is that the partons undergo significant gluon radiation which is induced by their traversing a dense colored medium. The mean parton energy loss is proportional to the gluon density of the sQGP and dependent on the distance that the parton travels through it. Several theoretical models have been suggested to describe the data either via the gluon density or the transport coefficient $\hat{q}$, which is the mean k_T^2 transferred to the medium per unit length, see for example [11–14]. While all models are based on induced gluon radiation they differ in the methods used to calculate the energy loss. The obtained values of $\hat{q}$ calculated via these models vary between $\hat{q} \approx$ 1-13 [15]. Different observables are therefore required to uniquely identify those properties of the medium that cause the R_{AA} suppression as a function of N_{part}. Di-hadron correlations are one such measurement. These correlations are made by studying the distributions of the azimuthal difference, $\Delta(\phi)$, of all associated particles with $p_T > p_T^{ass}$ with respect to trigger particles with $p_T > p_T^{trig}$. Hadrons resulting from the fragmentation of the same parton will form a peak at $\Delta(\phi)$=0 while those associated with the backwards scattered parton form a peak at $\Delta(\phi)$=π. In p-p and d-Au collisions these two peaks are clearly observed (Fig. 3). In the most central Au-Au data however, the back scattered (away-side) peak disappears [16], indicated by the blue stars in Fig. 3. The fact that the away-side peak is evident in d-Au collisions means that the jet quenching signal observed in Au-Au is clearly not an intial but a final state effect due to the sQGP.

The near- and away-side peak particle yields were measured as a function of the number of participants, N_{part}, for Au-Au and Cu-Cu events at $\sqrt{s_{NN}}$ = 200 GeV. For the near-side the particle yield per trigger is the same for Au-Au and Cu-Cu collisions, independent of N_{part}, and the same as that measured for d-Au collisions. This suggests that the near-side peak is the result of unmodified vacuum fragmentation. The away-side yield is the same in Cu-Cu and Au-Au for a fixed N_{part} but the yields fall strongly as the centrality increases [17]. Both [11] and [14] have tried to describe these results. Neither group describes the low N_{part} behavior on the away-side well but they do show reasonable agreement with the shape of the N_{part} suppression in Au-Au. The authors of [14] also matches the data independence on colliding species while [11] predicted a stronger suppression at a fixed N_{part} for the Cu-Cu data.

Since these di-hadron correlations are not performed on an event-by-event basis we cannot calculate true fragmentation functions. Instead we approximate an average fragmentation function by calculating $z_T = p_T^{ass}/ p_T^{trig}$. This Au-Au di-hadron fragmentation function, $D_{AA}(z_T)$, is then compared to that from p-p collisions. The away-side $D_{AA}(z_T)$ for Au-Au and Cu-Cu for different centralities are shown in the left panel of Fig. 4. The right panel shows the away-side I_{AA}, the binary scaled yield of particles in the jet correlation ratio of Au-Au to p-p data, as a function of z_T. Several interesting effects emerge from these plots. First the similarity of the Cu-Cu and Au-Au data for the same N_{part} is preserved as a function of z_T. Second the suppression of the more central events is not a shape modification but a uniform suppression over the measured range of z_T. This suggests that what we are observing on the away-side is energy loss of the parton *in* the medium followed by vacuum fragmentation *outside* of the medium, albeit with a reduced jet energy.

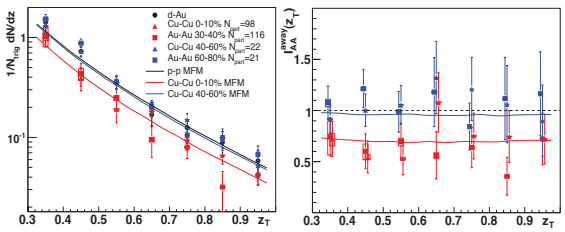

Fig. 4: Left: Away-side di-hadron fragmentation functions for Au-Au and Cu-Cu collisions at $\sqrt{s_{NN}}$ = 200 GeV. 6 $< p_T^{trig} <$ 10 GeV/c and 3 GeV/c $< p_T^{ass} < p_T^{trig}$. Right: The away-side I_{AA} as a function of z_T, from [17].

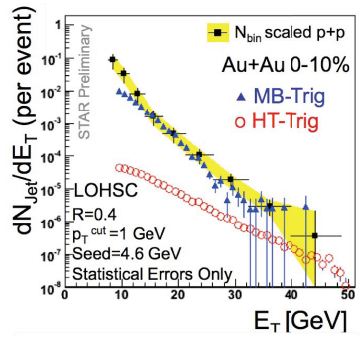

Fig. 5: Leading jet yields per event as a function of E_T for the most central Au-Au events at $\sqrt{s_{NN}}$ = 200 GeV compared to p-p events at the same energy. See text for more details.

4 Full Jet Reconstruction

With the full instrumentation and operation of the barrel calorimeter STAR now has the neutral and charged energy available allowing them to perform, for the first time in heavy-ion collisions, full jet reconstruction. Several new strategies had to adopted to control the large background from the softer particles in Au-Au event. It has been shown by CDF that $\sim$ 80 $\%$ of a given jet's energy is contained within a cone radius of R=0.3 [18]. Therefore to *find* the jets a small cone radius can be used. Finally the bulk of the background has p_T less than 2 GeV/c, and thus only tracks and calorimeter towers with p_T or $E_T >$ 1-2 GeV are assigned to jets. A correction is then applied to the reconstructed jet energy to account for the removed jet particles. This correction is calculated assuming PYTHIA fragmentation. The background from the Au-Au events is estimated by removing all the particles in the identified jet's cone and averaging over the rest of the event. The precision of this reconstruction is therefore strongly dependent on the event-by-event fluctuations and region-to-region correlations, such as elliptic flow, of this background [19, 20].

Figure 5 shows the resulting jet energy spectra for Au-Au and p-p events at $\sqrt{s_{NN}}$ = 200 GeV. The black circles show the N_{bin} scaled p-p data, the yellow band indicates the systematic error on this data. The blue triangles show the 0-10$\%$ centrality Au-Au data from a minimum bias trigger, only statistical errors are shown. These data have been corrected for efficiency, acceptance, and energy resolution. The open red circles show the uncorrected high tower trigger Au-Au dataset. This high tower trigger selected events online where at least one tower of the calorimeter had an energy greater than 7.5 GeV deposited in it. Therefore this data is extremely biased. This result is not corrected and is shown to indicate the potential jet energy reach of the data when all the corrections and biases have been accounted for. A comparison of the minimim bias and scaled p-p data shows that, within the currently large statistical and systematic uncertainties, the cross-section for hard processes scales with N_{bin} as predicted. The suppressions observed through the nuclear modification factors and di-hadron analysis are indeed likely due to energy loss of the scattered partons and not a reduction of the number of initial hard scatterings.

5 Summary

At RHIC we have much evidence that a strongly coupled deconfined state of quarks and gluons is created in the more central Au-Au collisions. We are now moving from the discovery phase into one of quantitative analysis of the properties of this medium. Studies of the nuclear modification factors and di-hadron correlations as a function of centrality and colliding species show that there is significant energy loss of hard scattered partons as they pass through the sQGP. However, the fragmentation functions themselves appear to be that of vacuum fragmentation in the ranges measured. Several models have been developed to try to describe our observations. However, they virtually all fail in describing all the details of the measurements now available. There is also the need for more selective experimental data. To this end an exciting new avenue of study has been opened with the first preliminary result on full jet reconstruction being announced. The measured Au-Au jet energy spectrum shows no strong suppression indicating that fully reconstructed jets indeed allow for the identification of all the particles resulting from the parton's fragmentation. Thus the observed high p_T single and di- hadron suppressions are likely due to a modification of this fragmentation both as a function of z=p^{had}/E^{jet} and particle composition. Studies are underway to try to quantify these effects. We can expect great progress in the future in high p_T correlation/jet studies due to the upgrades occurring at both STAR and PHENIX and the proposed RHIC luminosity upgrade. Finally there is the commencement of the LHC in 2009 where hard scatterings are much more prevalent and a new regime will begin.

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