Jet-Medium Interactions with Identified Particles

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Abstract

Identified particles have long been of great interest at RHIC in large part because of the baryon/meson differences observed at intermediate $p_T$ and the implications for hadronization via quark coalescence. With recent high statistics data identified particles are also now central to understanding the details of the jet-medium interactions and energy loss and hadron formation at intermediate and high $p_T$. In particular, high $p_T$ identified particle spectra along with two-particle correlations triggered with direct photons, neutral pions or electrons from heavy flavor decay with hadrons can provide information about how medium modifications to jet fragmentation depend on parton type. I will review recent results with identified particles both in heavy ion systems and the reference measurements in p+p collisions.

1. Hard Scattering at RHIC

Hard probes of relativistic heavy ion collisions have long been a valuable probe of the hot matter created in relativistic heavy ion collisions. Their main value comes from the fact that their production is both calculable in perturbative QCD and measurable in proton-proton collisions, providing quantified expectations for heavy ion collisions. Deviations from proton-proton expectations provide measurements of the effects of the hot dense matter on the propagation of fast partons. In high energy experiments hard probes are often measured through directly reconstructing full jets. Such measurements are not naturally suited to the large soft background of heavy ion collisions, especially when one wants to study the modification of jets from baseline proton-proton collisions measurements (for a discussion of jet reconstruction in heavy ion collisions see [1, 2]). More experimentally straightforward are single particle spectra and two particle correlations which provide complementary observables with relatively large rates. Particle identification provides a valuable experimental handle for changing the probe partons (e.g. light quarks, gluons, heavy quarks, photons) and for studying the effect of the matter on hadron formation [3, 4, 5, 6]. Current results from RHIC allow detailed quantitative studies of how jet modifications depend on parton type and provide insights on the interactions of the matter with fast partons and the hadron formation process.

2. Single Particle Production

The most stringent constraint on the opacity of the hot matter, within a particular theoretical model, comes from $\pi^0 R_{AA}$ [7]. The $R_{AA}$ of other particles can provide additional information.
about parton-medium interactions and hadron formation. Expectations for the $R_{AA}$ of protons and anti-protons were that they would be more suppressed than $\pi^0$ since gluon jets were thought to produce more baryons than quark jets do (however, recent fragmentation functions incorporating the STAR $p, \bar{p}$ spectra cast some doubt on this [8]). Since gluons have a larger QCD color factor, they should lose more energy. However, recent measurements from STAR show that $R_{AA}(p, \bar{p}) > R_{AA}(\pi^0)$, Fig. [1]. At intermediate $p_T$, $2 < p_T < 6$ GeV/c, this difference is widely thought to be from recombination (see Ref [9] and references therein), though realistic calculations taking into account spatial correlations, energy and momentum conservation and gluons have not yet been done.

For $p_T > 6$GeV/c, the difference between $R_{AA}(p, \bar{p})$ and $R_{AA}(\pi^0)$ is smaller but still significant and is not understood. One possible idea is that as the jet partons traverse the matter they change flavor after scattering on matter partons [10, 11], for example a fast quark could scatter off a medium gluon and emerge as a fast gluon. Discovery of these conversions would be extremely interesting as it would provide a means to study the mean free path of partons in the matter. However, this mechanism could make $R_{AA}(p, \bar{p}) \approx R_{AA}(\pi^0)$, but cannot make $R_{AA}(p, \bar{p}) > R_{AA}(\pi^0)$ so it cannot, in itself, explain the current data.

Alternatively, it has been proposed that baryons and anti-baryons observed at RHIC at high $p_T$ are produced in higher twist QCD processes in the initial state [5]. Processes such as $uu \rightarrow p\bar{d}$ can occur in QCD, but they are typically rare compared to production via jet fragmentation. However, since the protons produced directly in the hard scattering are small enough to propagate through the matter without interacting, similar to a direct photon. Such $p$ and $\bar{p}$ would also be produced in proton-proton collisions, however the dense matter in the heavy ion collision selects out these protons because the partons that would lead to fragmentation $p$ and $\bar{p}$ production lose energy. This mechanism naturally leads to $R_{AA}(p, \bar{p}) > R_{AA}(\pi^0)$. The decreasing $v_2$ of $p$ and $\bar{p}$ [12] observed by PHENIX is also easily explained if an increasing fraction of the $p$ and $\bar{p}$ is insensitive to the path length through the matter and this also explains the centrality dependence of $p$ and $\bar{p}$ triggered correlations at intermediate $p_T$ [13].

3. Two Particle Correlations

Two particle correlations have been used extensively to investigate jet production at RHIC. They are complementary to single particle observables, especially in that they are expected to have a different sensitivity to geometry. Single particle observables are thought to be strongly biased toward particles toward partons which have lost less than the average amount of energy which is dominated by those with a short path length through the matter. Requiring a correlated particle changes the surface bias depending on the $p_T$ and $\Delta \phi$ between the trigger and associated particle. At high $p_T$, two-particle back-to-back correlations can help constrain the path length dependence of energy loss. Previous measurements with charged hadrons have shown a strong suppression of the away side hadrons when a high $p_T$ trigger is required [15][16]. At intermediate $p_T$ with hadron-hadron correlations a third peak at $|\Delta \phi - \pi| \approx 1$ radian, termed the shoulder is observed [16][17][18]. Both the trigger particle and $p_T$ dependence of this structure are of great interest in determining its origin and sensitivity to properties of the matter. New measurements with the 2007 RHIC run allow further exploration of this with identified triggers and smaller $p_T$ bins. Identified trigger particles are important because of the dependence of $R_{AA}$ on the hadron species out to the highest measured $p_T$. 
3.1. Direct Photon-Hadron & $\pi^0$-Hadron Correlations

Direct photon-hadron ($\gamma_{\text{dir}}$-h) correlations have long been considered an important observable in studying energy loss. The photons are primarily produced in hard scattering processes in the initial state. Photons do not lose energy in the matter and therefore, at leading order, provides a measure of the away side jet energy (initial state $k_T$ and NLO effects modify this somewhat, see Ref. [19] for recent measurements). Because the photons do not lose energy they are not surfaced biased as hadron triggered measurements are.

However, the measurements are extremely difficult because of the large background from photons from meson (primarily $\pi^0$) decay: $\gamma_{\text{decay}}$. What is measured is the weighted average of the conditional yield associated with $\gamma_{\text{dir}}$-h and $\gamma_{\text{decay}}$-h:

$$Y_{\text{incl}} = \frac{N_{\text{direct}} Y_{\gamma_{\text{direct}}-h}}{N_{\text{incl}}} + \frac{N_{\text{decay}} Y_{\gamma_{\text{decay}}-h}}{N_{\text{incl}}}$$  \hspace{1cm} (1)

The two unknowns are then the fraction of the photons which are direct and the $\gamma_{\text{decay}}$-h conditional yield. The PHENIX and STAR methods for determining these quantities are quite different and are explained elsewhere [20,21,22]. PHENIX recently published results from the 2004 RHIC run which show first measurements of $\gamma_{\text{dir}}$-h correlations in Au+Au and p+p collisions [20]. Preliminary results from the 2007 RHIC run with higher statistics are available from both PHENIX and STAR. Since the $\gamma_{\text{dir}}$ provides a measurement of the jet energy, the conditional yield as a function of $z_T \equiv p_{T,h}/p_{T,\text{jet}}$ is approximately the jet fragmentation function into hadrons. At leading order the away side jet is expected to be a (anti-)quark jet because $\gamma_{\text{dir}}$ production is largely via $qg \rightarrow q\gamma$. The data are shown in Figure 2. The exponential slope of the quark fragmentation function is $\approx 8$ [23] and a fit to the p+p results gives a slope of $6.89\pm0.64$. 

Figure 1: (color online) Nuclear modification factor, $R_{AA}$ for charged $\pi$, $K$ and $p+\bar{p}$ for central collisions [14].
Figure 2: (color online) \( z_T \) distributions for PHENIX [21] (left) and STAR [22] (right) \( \gamma_{dir} \)-h correlations for Au+Au and p+p collisions.

Figure 3: (color online) \( I_{AA} \) for \( \gamma_{dir} \)-h and \( \pi^0 \)-h away side yields from PHENIX [21] (left) and STAR [22] (right). Both results show no \( p_T \) dependence or any significant difference between the suppression of \( \pi^0 \) and \( \gamma_{dir} \) triggers. (consistent with quark jet fragmentation functions [23]). Fitting the PHENIX Au+Au data gives a slightly softer slope: 9.5±1.4.

It is useful to compare \( \gamma_{dir} \)-h and \( \pi^0 \)-h correlations. \( \pi^0 \)-h correlations show a nearly constant suppression with \( p_{T,\pi^0} \) and \( p_{T,h} \) for a wide \( p_T \) range in central collisions. In contrast \( \pi^0 \)-h correlations are biased toward small medium path lengths and the \( \pi^0 \) does not carry the full jet energy. Therefore, differences between away side yields of \( \gamma_{dir} \)-h and \( \pi^0 \)-h provide information about the geometry and the energy dependences of energy loss. Within the current uncertainties the data are consistent between these two channels. With the present uncertainties, theoretical predictions do not predict a measurable difference between these channels in the \( p_T \) ranges measured [24-27].

Near side correlations, where the azimuthal angle between the \( \gamma_{dir} \) and the hadron is small are very interesting in heavy ion collisions. In hadron-hadron correlations, these correlations come from same jet fragmentation. In \( \gamma_{dir} \)-hadron correlations in p+p collisions, these correlations...
exist only when the photon is from jet fragmentation (for a discussion of fragmentation photons see Ref. [28]). Thus, the yield in p+p collisions of near side hadrons per trigger should be much smaller for $\gamma_{dir}$-h than $\pi^0$-h correlations, as observed in Fig. 4. The near side $\gamma_{dir}$-h correlations in Au+Au collisions are consistent with measurements from p+p collisions.

Another sensitive measure of the path length dependence of the energy loss is $\pi^0$-h correlations where the trigger is selected based on its angle with respect to the reaction plane. When the trigger is aligned with (out of) the reaction plane the di-jet system sees a short (long) medium path length. When the energy loss through the core of the collision system is extremely large (all di-jets are completely suppressed if they cross the center), then the orientation with the trigger in the reaction plan will have a smaller away side yield than when the trigger is out of plane; tangential di-jets which do not cross the center of the collision system will be favored. If the di-jet suppression increases with the path length through the matter however the suppression will be greater when the trigger is oriented out of the reaction plane since that maximizes the away side path length. Results from PHENIX shown in Fig. 5 [29] show that the data favor the latter case and the data favor a stronger reaction plane dependence than expected from some theoretical models [30, 31, 32].

3.2. Heavy Flavor Conditional Yields

It has been known for some time that electrons from the decay of heavy mesons ($D_s$ and $B_s$) are suppressed more than can typically be accounted for in radiative energy loss calculations [34, 35]. There have been a variety of theoretical attempts to explain this including collisional energy loss [36], recombination [37, 38], and in-medium hadron formation [39]. The next experimental
step is to correlate the heavy quark electrons with other hadrons in the event in the same manner as is done for $\pi^0$-h and $\gamma_{dir}$-h correlations.

This measurement is severely complicated by the large number of background electrons from $\pi^0$ Dalitz decays and photon conversions and low statistics. STAR has developed a method of tagging photonic electrons via the invariant mass of $e^+e^-$ pairs [40]. PHENIX has established a method analogous to that used for the $\gamma_{dir}$-h correlations shown above to statistically subtract correlations from photonic sources [41]. Figure 6 shows results from $p+p$ collisions compared to charm production simulated in PYTHIA [42] (left) [41] and away side $I_{AA}$ which suggests some suppression of away side hadrons opposite to electrons from heavy flavor decay (right).

Interpretation of these measurements is complicated because electrons from heavy flavor decay come both from charm and bottom production. Experimental efforts [43, 44] to determine the relative contribution of these sources in $p+p$ collisions have agreed with Fixed Order Next to Leading Log calculations [45]. However, the relative contributions to the electron sample in heavy ion collisions could be modified from $p+p$ due to the effects of the medium. In the $p_T$ range measured here the electrons are expected to mainly be from $D$ meson decay. Higher statistics measurements in the 2010 RHIC run might allow these measurements to be extended to higher $p_T$ where bottom contributions are expected to be more significant. With detector upgrades capable of displaced vertex measurements it will be possible to distinguish charm and bottom triggered correlations. Those measurements will be crucial in understanding the suppression of the single electron spectra in Au+Au collisions.

3.3. Background Estimation and Two Source Model

Jet correlation measurements in heavy ion collisions depend on a procedure to estimate and remove the combinatorial background from pairs which do not come from the same di-jet production. Combinatorial pairs are assumed to only be angularly correlated through the reaction plane and the $v_2$ values of the trigger and partner hadrons are assumed to be independent. The shape of the combinatorial background in $\Delta\phi$ is then, $b_0(1 + 2v_{2,\text{trig}}v_{2,\text{part}} \cos(2\Delta\phi))$.

$b_0$ is often estimated by assuming the minimum in the jet function has zero yield [46]. There are a number of issues associated with this assumption. At the high momenta considered here the fluctuation of the background level due to statistical fluctuations in the correlation functions...
is a large source of uncertainty and bias \[47\]. Also in heavy ion collisions the jet induced correlations are much wider than in p+p collisions making the assumption of a zero yield region less desirable. The use of the Absolute Background Subtraction method \[47\] is preferable because of its stability in cases of low statistics and wide jets. Even when the combinatorial background is small compared to the jet yield (as it is at high $p_T$) the uncertainty can be large compared to the jet conditional yields.

4. Conclusions and Outlook

High $p_T$ identified spectra and correlation measurements give a significantly more nuanced picture of parton-medium interactions than unidentified hadron measurements alone. Contrary to expectations of high $p_T$ particle production by vacuum fragmentation alone, excess $p$ and $\bar{p}$ in heavy ion collisions persist out to $p_T \approx 10\text{GeV}/c$. This could be evidence of significant higher-twist baryon production and will be further investigated with higher statistics data, correlations, and $v_2$ measurements. In contrast both $\pi^0$-h and $\gamma_{\text{dir}}$-h correlations are consistent with each other and show little dependence on the $p_T$ of either the trigger or associated particle. Initial measurements of $e_{\text{HF}}$-h correlation results have large statistical errors, but show some evidence for away side suppression. Future measurements with higher statistics and charm and bottom separation will enable tomography of heavy flavor energy loss. While existing single and di-hadron measurements show that the created matter leads to a large energy loss, precision measurements with identified particles will allow robust determination of the mechanism of energy loss as well as the mechanisms of hadron formation.

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