Jet Energy Loss at RHIC

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One of the most well-known results from BNL-RHIC heavy ion collisions is the experimental confirmation of the energy loss of partons traversing a colored medium, *i.e.* jet energy loss. This has resulted from much study both experimentally and theoretically over the last decade during heavy ion collisions at RHIC. In this talk, the brief history of attempts to understand energy loss is given with an eye towards future experiments at both RHIC and the LHC.

One of the interests in studying jets in nuclear collisions is to answer a fundamental, non-trivial problem in QCD. The problem: how does a parton lose energy via interactions with an extended colored medium. This is analogous to the problem in QED of a charged particle losing energy in (charged) matter. This was studied extensively by Bethe.[1] He showed that the energy lost by the charged particle per unit path length, dE/dx depends on the density of scattering centers in the medium and the energy of the charged particle. Important for the discussion that follows is that the rate of energy lost is independent of length that particle has traveled in the medium. The problem has been analyzed in QCD. Because of the Albelian nature of QCD, not only are there diagrams where the parton directly interacts with the medium and emits a gluon, but the radiated gluon also interacts with the medium. This increases the rate of energy lost by the colored parton in the colored medium. A pQCD analysis, that is, weak coupling between the incoming parton (jet) and the medium, with a particular model of the scattering centers yields an energy loss rate that is proportional to the length the parton traverses in the medium, $dE/dx \sim x$.[2]

To study this experimentally, partons must be moving through an extended colored medium. Performing heavy ion collisions at an appropriate center-of-mass energy would achieve both. At high enough energy density and temperatures, evidence from the lattice indicates, a phase transition occurs in QCD where partons are not bound within color singlet states. This state is known as the quark-gluon plasma. This phase of matter could be created in relativistic heavy ion collisions to produce a colored medium much larger than the size of the proton. [a] Also at collider energies, hard-scattered partons, which will subsequently fragment into jets, are simultaneously produced in these events. Therefore, hard partons are auto-generated and lose energy as they traverse the quark-gluon plasma produced in heavy ion collisions.

Ideally the jets produced from these quenched partons would be measured. But the large detectors at RHIC, PHENIX and STAR, were not initially designed to perform full jet reconstruction measurements. Furthermore, the luminosity in heavy ion collisions is much lower than in e^+e^- annihilation and $p+p$ collisions, so obtaining statistics on jets above about 10 GeV has

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[a] Indeed parton energy loss was first discussed by Bjorken in terms of $p+\bar{p}$ collisions at the Tevatron.[3]

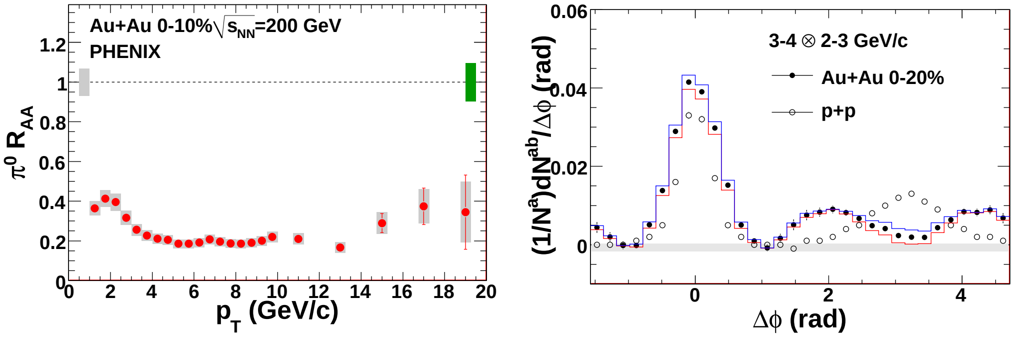

Figure 1: *Left:* Single high-p_T π^0 R_{AA}. *Right:* Relative azimuthal correlations between pairs of hadrons in $p+p$ (open) and $Au+Au$ (closed) collisions.

taken time to amass. As a first measurement, the rate of single, high-p_T particles, those that are the leading jet fragments, have been measured. This rate, for example, of π^0s in A+A collisions is compared to p+p collisions and quantified by R_{AA}, defined as

$$R_{AA} = \frac{1/N_{evt} dN^{AA\to\pi^0 X}/dp_T^{\pi^0}}{\langle N_{bin}\rangle\, 1/N_{evt} dN^{AA\to\pi^0 X}/dp_T^{\pi^0}} \tag{1}$$

Here the $p+p$ rate is scaled by the number of nucleon-nucleon scatterings that occur in the overlap region of the nuclear collision, N_{bin}. So, if nuclear collisions were simply a sum of multiple $p+p$ collisions, $R_{AA}=1$. Deviations from unity would indicate nuclear effects. Figure 1 shows the most recent π^0 R_{AA} from PHENIX [4]. Clearly, a factor of five fewer particles are produced at a given p_T in Au+Au compared to $p+p$ at the same energy. What is implicit are the particle invariant p_T spectra that have been measured over many orders of magnitude. The $p+p$ spectrum compares to NLO calculations down to 2 GeV, lending support to the fact that these are QCD jets that are contributing. R_{AA} <1 indicates that those $p+p$ jets, when created in Au+Au collisions, lose energy and resulting in a softer leading particle.

The next measurements to extract information about jets and their modifications from energy loss was to look at two-particle azimuthal correlations. Here, the event-averaged distribution of the relative azimuthal angle ($\Delta\phi$) between all pairs of particles in particular p_T ranges are constructed. In this way two particles fragmenting from a jet have $\Delta\phi \sim 0$. Particles which fragment from each of a di-jet pair have $\Delta\phi \sim \pi$. The right panel of Figure 1 shows these azimuthal correlations between unidentified charged hadrons with one p_T ranges from 3-4 GeV and 2-3 GeV in both $p+p$ and Au+Au.[5] The distribution in p+p looks as expected, i.e. peaks at 0 and π. But in Au+Au has a qualitatively different shape, especially at these p_T. There is a large yield of particles away from π not observed in p+p. This structure could indicate that energy loss modifies the angular distribution of fragments in a jet. Others have speculated that the supersonic parton would produces a Mach cone. [6] It is possible that this structure could arise from Cerenkov gluons from superluminal partons.[7] This has opened up a rich avenue of study both theoretically and experimentally in studying these aspects of QCD.

There are obvious, measurable effects on high-p_T particle production due to the medium. However, there is little quantitative information at this time due to a number of complications. These issues range from the level of understanding of the medium produced at RHIC to energy-loss biases in the measurements. Energy-loss biases result from the fact that, by requiring a high-p_T particle in the event with bias those particles to have lost little energy either due to fluctuations in the energy loss mechanism or that they have traversed little medium. Currently and in the future both at RHIC and the LHC, a program of quantitative and precision studies of energy loss is being planned and implemented. Some initial results are presented here.

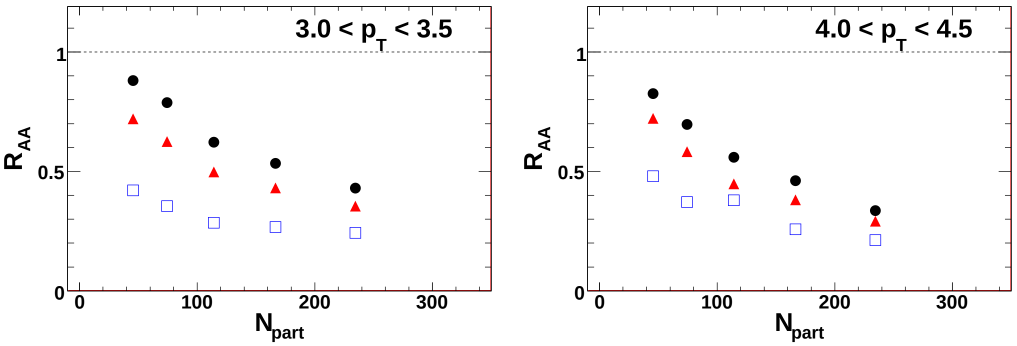

Figure 2: Th R_{AA} as a function of the number of participating nucleons (N_{part}) in the nuclear overlap regions, i.e. the centrality, for 3-3.5 GeV (left) and 4-4.5 GeV (right) π^0s emitted in the reaction plane (0-15 degrees,), out of the reaction plane (75-90 degrees,), and between (30-45 degrees,).

Initially it was presented that the Bjorken-like formula for QCD has a path-length dependence. Ideally, we would like to determine the exponent on $dE/dx \sim x^n$. An experimental observable that is sensitive to the path-length dependent energy loss is by measuring R_{AA} as a function of the particle's angle with respect to the reaction plane. The reaction plane is the plane defined by the impact parameter in the collisions. In moderately large impact parameter collisions, the overlap region is shorter along the reaction plane than perpendicular to it. Consequently, particles emitted in the reaction plane traverse less medium than perpendicular to it. Figure 2 shows the π^0 R_{AA} for two different p_T selections as a function of centrality (impact parameter) for those along the reaction plane (0-15 degrees), out of the reaction plane (75-90 degrees), and in between (30-45 degrees).[8] Qualitatively we see that the R_{AA} decreases from in-plane to out-of-plane, consistent with the path-length dependence of energy loss. However, a single exponent has not been extracted from this data.

One complication from single- and two-particle observables is that, to compare to theory, one must integrate over jet energies. Ideally, the jet energy would be experimentally measured via jet reconstruction. An alternative approach is to use direct photon-charged hadron correlations. Here the direct photon is isolated and the charged hadron fragments from the opposing jet. To leading order the photon measures the jet energy. Figure 3 shows the number of correlated unidentified charged hadron pairs per direct photon as a function of $z_T = \left\langle p_T^h \right\rangle / \langle p_T^\gamma \rangle$, essentially the fragmentation function, in p+p and Au+Au for several different direct photon p_T ranges [9]. One would expect a softening of the fragmentation functions in Au+Au as energy is transported from high-z to low-z fragments. The current statistics are suggestive but insufficient to claim that this is indeed the case.

Recently, the study of fully reconstructed jets at RHIC has been undertaken. In PHENIX, the Gaussian filter algorithm [10], a IR and colinearly safe extension of the cone algorithm, is used. Because of the large underlying event background that has little to no correlation with the jet, additional care must be taken to reconstruct jets. For example, correlated fluctuations in the background can produce a jet signal which are not from an underlying hard scattering process[11]. These must be removed from the sample of total measured jets. However, removing these jets can result in a bias. For example, PHENIX makes a cut on a combination of the p_T and R distribution of the fragments which rejects soft and wide jets from the sample. These jets that are rejected could, however, be those modified jets that are of interest in studying energy loss. The R_{AA} of jets in Cu+Cu after rejection of the fake jets is shown in Figure 3. For the more central collisions, $R_{AA} < 1$. While one might expect the jet R_{AA} ~1 because of energy conservation, loses could be due to radiation that has leaked outside the jet area. Another interpretation, being explicit of the use of the fake jet rejection condition, is that about 50% of

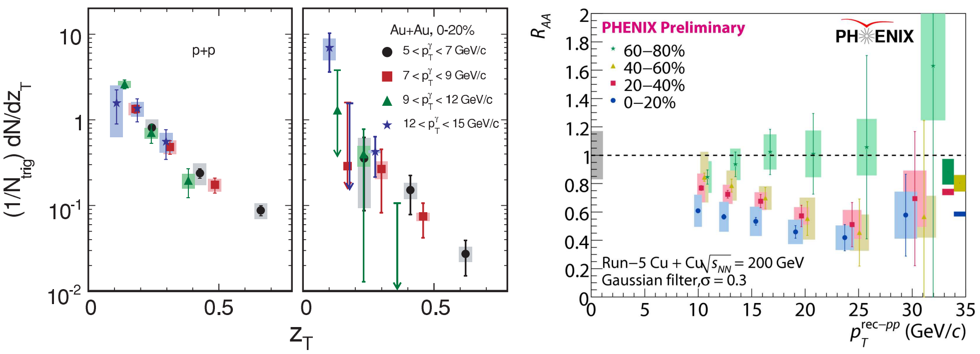

Figure 3: *Left panels:* The rate of correlated unidentified charged hadrons to a direct photon as a function of z_T (see text), which is the effective fragmentation function, measured in $p+p$ and Au+Au for various direct photon p_T ranges. *Right:* The R_{AA} of fully reconstructed jets in Cu+Cu collisions using the Gaussian filter algorithm (see text) and with fake jet rejection.

the jets are $p+p$-like. In the future it will be important to loosen the fake jet cuts to study those jets which are not $p+p$-like in order to reduce the energy-loss bias introduced by this cut.

At the end of the year, another exciting milestone will be reached at the LHC: nuclear collisions. At the LHC jets with energy well above 50 GeV will be reached, which is much higher than the current statistics at RHIC. Furthermore, the experiments, especially ATLAS and CMS are ideally suited to calorimetrically measure jets over a wide pseudo-rapidity range. The large increase in center-of-mass energy may well mean a qualitatively different medium will be produced and produce different effects on the jets at the LHC. Studying jets at both RHIC and the LHC simultaneously will ultimately help us to have a broad understanding of the effects of an interesting problem in QCD, how a parton loses energy in as it traverses an extended colored medium.

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