JET MEASUREMENTS AT RHIC*

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We briefly report on the status of RHIC operations and summarize the rapidly developing measurements of parton propagation in dense QCD matter. These measurements are consistent with expectations of induced gluon radiation as the hard scattered parton traverses a dense colored medium.

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RHIC[1]is a flexible, multi-purpose hadron collider that studies QCD scatterings of various momentum transfer to make fundamental tests of perturbative QCD, study the partonic nature of hadronic matter, and make pioneering measurements of the properties of QCD matter at extreme energy and density. QCD hard-scatterings are dominated by final states with two or more energetic partons which hadronize to form collimated groups of energetic hadrons ("jets"). Jets can be studied by *(i)* full reconstruction using clustering algorithms, *(ii)* studying the most energetic ("leading") hadron in the jet and *(iii)* isolating multi-hadron correlations (*e.g.*, back-to-back leading hadrons) indicative of hard scattering and jet fragmentation. All three methods are applied at RHIC. While *(i)* provides direct access to the parton kinematics, methods *(ii)* and *(iii)* provide robust means to study properties of QCD hard scattering and jet fragmentation in the high multiplicity, large background environment of relativistic heavy ion collisions, where it is predicted that hard scattered partons will suffer significant radiative gluon energy loss while traversing a dense QCD medium, resulting in an effective modification of fragmentation [1]. In the case of a hard scattered parton traversing a deconfined quark–gluon medium, this loss can be large($dE/dx \sim 1$–10 GeV/fm), and is predicted to depend on the

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[1] Relativistic Heavy Ion Collider

color charge, energy, and mass of the hard scattered parton, as well as on the color charge, density, and expansion properties of the QCD medium [1]. The radiated gluons are predicted to fall primarily within a typical jet cone radius of ~ 0.7 radians [2]. Physical signatures would then include higher than average hadron multiplicity in the jet, jets with softened fragmentation functions, and increased di-jet acoplanarity (k_{T}). Induced gluon radiation is, therefore, an excellent probe of the properties of the hot, dense matter created at the earliest times following collision of high-energy heavy nuclei. In this letter we briefly report on the status of RHIC operations and summarize the rapidly developing measurements, gathered during the first 3 runs, of modified fragmentation in dense QCD matter.

RHIC consists of two independent concentric rings capable of accelerating different ionic species, from protons to gold ions, to ultra-relativistic energies. The peak collision energy for Au ions (protons) is $\sqrt{s_{NN}}$=200 (500) GeV, well into the region of validity for perturbative QCD calculation [3]. Additionally, RHIC is the first complex capable of colliding polarized beams of high energy protons. Mature accelerator performance was unequivocally demonstrated in Run 4 by fulfillment of the goal of 1400 $\mu\mathrm{b}^{-1}$ delivered during 11 weeks of physics running with Au beams at $\sqrt{s_{NN}}$=200 GeV/c. Additionally, a brief polarized $p+p$ commissioning run demonstrated the success of a new machine working point capable of simultaneously delivering high luminosity and sufficient polarization. The next run will, therefore, include 10 weeks of polarized $p+p$ physics running, with the conservative expectation of $15\,\mathrm{pb}^{-1}$ delivered with $> 40\%$ polarization. A summary of the rich and diverse jet physics program in polarized $p+p$ mode is given in [5]. Two small detectors (PHOBOS and BRAHMS) and two large detectors (STAR and PHENIX) instrument four of the six interaction regions of RHIC. While neither PHENIX nor STAR are fully hermetic detectors, both have active hard-scattering programs that make use of jet-surrogates (*e.g.*, leading hadrons) from tracking of charged hadrons and/or electromagnetic calorimetery. Additionally, the STAR detector combines charged particle tracking and electromagnetic calorimetery over full azimuth and $-1 < \eta < 1$, making it uniquely suited at RHIC for complete jet reconstruction in $p+p$ collisions. Subtle but important NLO effects complicate the clustering algorithms, requiring the adoption of common, fully specified algorithms for both theoretical calculations and experimental measurements of jet final states [4]. The STAR collaboration has accordingly implemented both the k_{T} cluster and midpoint-cone jet algorithms.

At leading order, the partons emerging from a $2 \rightarrow 2$ hard scattering are azimuthally separated by $\Delta\phi \equiv \phi_1 - \phi_2 = \pi$. NLO corrections such as soft gluon emission either pre- or post-hard scattering imply $\Delta\phi \neq \pi$. If partonic energy loss proceeds via multiple gluon emission, we would expect greater acoplanarity in heavy ion collisions compared to $p+p$ collisions. It is, therefore, critical to measure the magnitude of di-jet acoplanarity in $p+p$ before drawing any conclusions from Au+Au. Fig. 1(a) shows the $\Delta\phi$ distribution for di-jets with $\langle p_{\mathrm{T}}^{\mathrm{jet}}\rangle = 13.6\,\mathrm{GeV}/c$ reconstructed with the midpoint-cone algorithm in STAR. The data corresponds to $\approx 0.8\,\mathrm{pb}^{-1}$ of $p+p$ data collected at $\sqrt{s_{NN}}$=200 GeV. An approximately Gaussian distribution is measured, with a width significantly larger than the intrinsic detector resolution — a clear signature of NLO contributions. A traditional measure of the magnitude of such NLO effects is $k_{\mathrm{T}} = \sqrt{\langle k_{\mathrm{T}}^2\rangle} = \langle p_{\mathrm{T}}^{\mathrm{jet}}\rangle \sin(\sigma_{\Delta\phi})$, where $\sigma_{\Delta\phi}$ is the Gaussian width of the di-jet $\Delta\phi$ distribution. For $p+p$ data, STAR reports $k_{\mathrm{T}} = 2.3 \pm 0.4 \pm^{0.67}_{1.11}$ GeV/c [6]. Fig. 1(b) finds good agreement of the STAR value of $\langle p_{\mathrm{T}}^{\mathrm{pair}}\rangle \equiv \sqrt{\frac{\pi}{2}\langle k_{\mathrm{T}}^2\rangle}$ with extrapolation from previous measurements at both lower and higher $\sqrt{s}$. Using a leading di-hadron analysis, PHENIX reports $\langle k_{\mathrm{T}}^2\rangle = \sqrt{\pi}\langle|k_{\mathrm{T}y}|\rangle = 1.92 \pm 0.09$ GeV/c [10]. The di-hadron analysis requires the additional knowledge $\langle z\rangle = \langle\frac{p_\perp^{\mathrm{hadron}}}{p_{\mathrm{parton}}}\rangle$. PHENIX estimates $\langle z\rangle = 0.75 \pm 0.05$ in good agreement with a previous measurement at $\sqrt{s} = 38.8\,\mathrm{GeV}/c$.

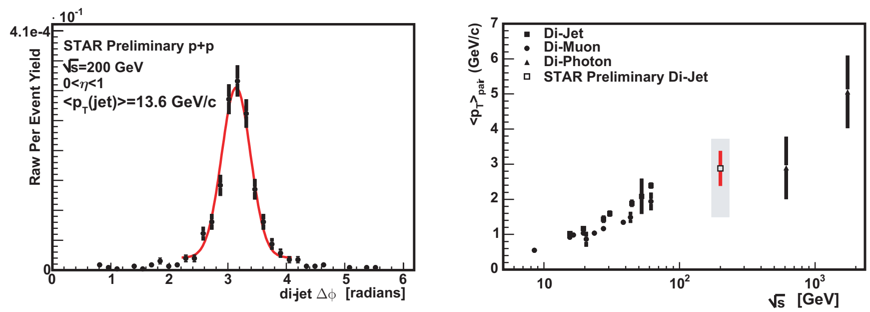

Fig. 1. The left panel shows the $p+p$ di-jet $\Delta\phi$ distribution at $\sqrt{s} = 200\,\mathrm{GeV}$. The right panel shows comparison to the world data for $\langle p_{\mathrm{T}}\rangle_{\mathrm{pair}}$ as a function of $\sqrt{s}$. Figure and caption taken from [6].

The good agreement between the di-hadron and di-jet k_{T} measurements in $p+p$ motivates the extension of multi-hadron correlations as jet probes into the heavy ion environment. Fig. 2(a) shows the $p_\perp$ distribution of charged hadrons associated with the leading "trigger" hadron ($p_\perp^{\mathrm{trig}} > 4\,\mathrm{GeV}/c$) in the event, where the association is defined by $p_\perp^{\mathrm{assoc}} > 0.15\,\mathrm{GeV}/c$, $|\eta_{\mathrm{trig}} - \eta_{\mathrm{assoc}}| < 1.4$ and $|\phi_{\mathrm{trig}} - \phi_{\mathrm{assoc}}| < 1.1$. Data are shown for $p+p$, peripheral Au+Au, and central Au+Au collisions, where centrality (related to impact parameter) is defined by gating on $\frac{dN_{\mathrm{ch}}}{d\eta}$ over $|\eta| < 1$ (0–5% $\to \frac{dN_{\mathrm{ch}}}{d\eta} \sim 700$).

In $p+p$ and Au+Au, the associated $p_\perp$ spectra are significantly stiffer than the inclusive (no trigger requirement) spectra — clear evidence for jet-like energy clusters. Additionally, the near-side spectra show similar slopes, suggesting similar fragmentation of the near-side jet in $p+p$, peripheral, and central Au+Au. However, Fig. 2(b) shows a clear softening of the away-side ($|\phi_{\rm trig} - \phi_{\rm assoc}| > 1.1$) associated $p_\perp$ spectra in central Au+Au, consistent with qualitative expectations of softened fragmentation associated with final-state induced gluon radiation. The data in Fig. 2 have a model dependent, but $p_\perp$ independent, background subtracted. The subtraction procedure is an open issue in the community, leading to caution in interpreting the integrals of the spectra. However, the spectral slopes are a robust probe of modified fragmentation in Au+Au relative to $p+p$.

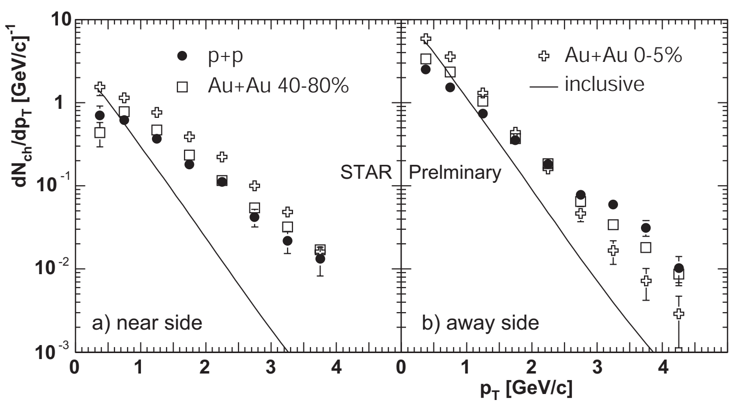

Fig. 2. (a) Near- and (b) away-side $p_\perp$ distribution of associated charged hadrons for $p+p$, peripheral and central Au+Au collisions. A model dependent background has been subtracted from the data. Statistical error bars are shown. Figure and caption reproduced from [7].

Fig. 3(a) shows model dependent background subtracted $\Delta\phi$ distributions for charged hadrons of $p_\perp^{\rm assoc} > 2$ GeV/c associated with trigger hadrons of $4 < p_\perp^{\rm trig} < 6$ GeV/c, for $|\eta| < 0.7$. A clear two-peaked structure, indicative of fragmentation of back-to-back jets, is seen in $p+p$ and d+Au data. Additionally, the near-side correlations for central Au+Au are in excellent agreement with the $p+p$ data. The striking lack of an away-side peak in central Au+Au motivates the often referenced "disappearance of the away-side-jet" claim. However, further analysis [9] has shown that the kinematic thresholds applied ($p_\perp^{\rm assoc} = p_\perp^{\rm trig}/2 = 2\,{\rm GeV}/c$) generate a high sensitivity to small changes in the large-z region of the away-side jet, thereby limiting the quantitative conclusions that can drawn from this analysis. However, the clear structure of the away-side jet in d+Au data is strong evidence that

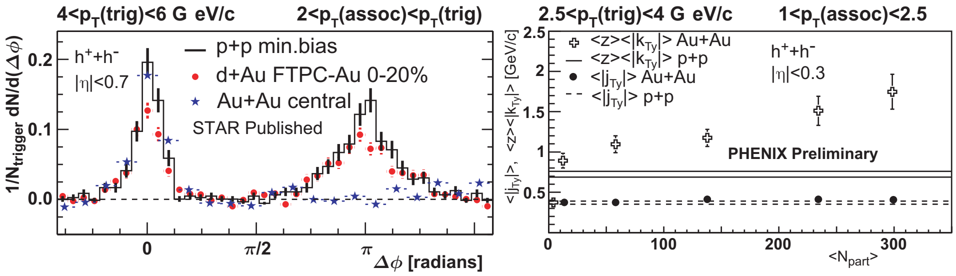

Fig. 3. Left: Comparison of background subtracted two-particle azimuthal distributions for central d+Au collisions to those seen in $p+p$ and central Au+Au collisions. Right: Centrality dependence of $\langle j_{\mathrm{T}y}\rangle$ and $\langle z_{\mathrm{trig}}\rangle\langle|k_{\mathrm{T}y}|\rangle$ in Au+Au. The dashed and solid lines represent the values measured in $p+p$ data. Statistical error bars are shown. Figures and captions reproduced from [8] and [10], respectively.

the modified fragmentation in Au+Au results from final-state interactions. A measurement of k_{T} is more easily interpreted theoretically. Fig. 2(b) shows $\langle|k_{\mathrm{T}y}|\rangle$ from $p+p$ and Au+Au collisions as a function of the centrality measure $N_{\mathrm{participant}} \sim \frac{dN_{\mathrm{ch}}}{d\eta}$. For $p+p$ we define $N_{\mathrm{part}} = 2$. $\langle|k_{\mathrm{T}y}|\rangle$ shows a smooth growth with centrality, indicative of an increase in the magnitude of the radiative corrections to the LO back-to-back picture of di-jet production. In a pQCD inspired analysis, the QCD matter density necessary to produce such large k_{T} is $\sim 20\,\mathrm{GeV/fm}^3$, more than 100 times the density of cold nuclear matter [11].

In conclusion, the jet-physics program at RHIC is rich, diverse, and rapidly developing. The world's first high-statistics study of jet physics in polarized $p+p$ collisions is planned for 2005. Additionally, studies of hard-scattering in heavy ion collisions show strong evidence for modified fragmentation resulting from induced gluon radiation in dense QCD media. Future work will focus on measuring jet yields, jet fragmentation functions via photon-jet events, and quark mass dependence of induced gluon radiation.

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