High-\(p_t\) hadron production and di-hadron azimuthal correlations from the STAR experiment

Marco van Leeuwen (STAR Collaboration)
Lawrence Berkeley National Laboratory, Berkeley, CA 94720
E-mail: mvanleeuwen@lbl.gov

Abstract. High-\(p_t\) hadrons are produced in large-momentum transfer parton scatterings in \(p+p\) and \(Au+Au\) collisions at RHIC. In \(Au+Au\) collisions, the production is modified compared to \(p+p\) collisions by interactions of the hard-scattered partons with the hot and dense medium. Relevant results on high-\(p_t\) hadron spectra, elliptic flow and azimuthal di-hadron correlations in \(Au+Au\) collisions at \(\sqrt{s_{NN}} = 62.4\) GeV are presented and compared to available results at 200 GeV. Qualitatively similar suppression patterns are observed at both energies.

Hadron production at high transverse momentum \(p_t\) is dominated by jet fragmentation products from large momentum transfer parton scatterings in the initial state in both \(p+p\) and \(Au+Au\) collisions at RHIC. While high-\(p_t\) hadron yields in \(p+p\) collisions follow expectations from perturbative QCD calculations [1], it has been long anticipated that high-\(p_t\) particle production in \(Au+Au\) collisions is modified by interactions of the produced partons with the hot and dense medium. To the extent that these QCD interactions can be calculated, the observed modifications of high-\(p_t\) particle production in nuclear collisions can be used to probe the properties of the medium [2].

Azimuthal correlations between high-\(p_t\) hadrons, which are the main topic of these proceedings, directly probe the kinematics of jet production and fragmentation. More inclusive measurements, such as spectra and azimuthal distributions with respect to the reaction plane, however, also provide important information about high-\(p_t\) particle production in \(Au+Au\) collisions and have the advantage that they require smaller data samples and therefore generally cover a larger \(p_t\)-range than the jet-like correlation measurements. New results on all these observables in \(Au+Au\) at \(\sqrt{s_{NN}} = 62.4\) GeV have recently become available and will be presented in comparison to existing results at the highest RHIC energy \(\sqrt{s_{NN}} = 200\) GeV.

1. Energy dependence of high-\(p_t\) particle production and suppression
The first experimental evidence for the suppression of high-\(p_t\) particle production came from measurements of the charged particle and neutral pion \(p_t\)-spectra in \(Au+Au\) collisions at \(\sqrt{s_{NN}} = 130\) and 200 GeV [3]. More recent results at \(\sqrt{s_{NN}} = 62.4\) GeV allow to explore the energy dependence of the observed suppression in some detail.

When comparing medium effects at the different energies, it is important to keep in mind that inclusive particle \(p_t\)-spectra at lower energies are significantly steeper than at higher energies, as is illustrated in Fig. 1, where inclusive hadron \(p_t\) spectra at different energies are compared. It can be seen that for \(p_t \approx 8\) GeV, the charged hadron yield in \(Au+Au\) collisions is about 10 times smaller at \(\sqrt{s_{NN}} = 62.4\) GeV than at 200 GeV.
Figure 1. Charged hadron $p_t$-spectra in Au+Au collisions at $\sqrt{s_{NN}} = 62.4, 130$ and 200 GeV from STAR and neutral pion spectra at 17 GeV, as measured by WA98 [4].

Figure 2. Nuclear modification factor $R_{CP}$ for Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ (circles) and 200 GeV (stars). For 62.4 GeV, results are shown in two different pseudo-rapidity intervals.

1.1. Nuclear modification factor
Fig. 2 shows a comparison of the nuclear modification factor $R_{CP}$ in Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV and 200 GeV. The nuclear modification factor $R_{CP}$ is used to quantify the suppression of particle production in central Au+Au collisions, by taking the ratio of the $p_t$-spectra in central to peripheral events, normalised by the number of binary collisions $N_{bin}$ in each centrality class:

$$R_{CP} = \frac{1/N_{bin} dN/dp_t|_{central}}{1/N_{bin} dN/dp_t|_{peripheral}}.$$

The nuclear modification factor would be unity if particle production in Au+Au collisions scales with the number of binary elementary collisions in the nuclear collision, as expected for high-$p_t$ hadron production from independent hard scatterings in the initial state.

The well-known suppression of hadron production by about a factor five at high-$p_t$ in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV (stars) is clearly visible in Fig. 2. At the lower energy $\sqrt{s_{NN}} = 62.4$ GeV (circles), the suppression is smaller at intermediate $p_t$, up to about 4 GeV, while at high-$p_t$ the nuclear modification factors at both energies are similar. Although this seems to indicate that the medium density at both energies might be similar, model calculations indicate that due to the more steeply falling initial production spectra in $\sqrt{s_{NN}} = 62.4$ GeV collisions, the apparent suppression can be similar at both energies, even if the medium density is lower by about 30% at the lower energy [5].

1.2. Elliptic flow
In non-central collisions, the path-length dependence of the suppression of high-$p_t$ particles leads to azimuthal variations of the particle yields with respect to the reaction plane. This effect is quantified the second Fourier coefficient $v_2$ (elliptic flow) of the expansion of the azimuthal particle distribution with respect to the reaction plane. Figure 3 shows the $p_t$-dependence of $v_2$ for mid-central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The different markers show the result...
Figure 3. Elliptic flow $v_2$ as function of $p_t$ for mid-central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Results are shown from the two-particle cumulant method (triangles), the four-particle cumulant method (stars) and a two-particle correlation analysis with subtraction of the measured correlation in p+p (circles) [7].

from different analysis methods, which have different sensitivity to non-flow effects such as resonance decays and the correlations between particles in jets. A non-zero flow signal is clearly observed for $p_t$ up to about 8 GeV where particle production is dominated by jet fragmentation. The four-particle cumulant analysis (stars) explicitly reduces the effect of two-particle non-flow correlations, leading to smaller $v_2$ values compared to the two-particle cumulant results (triangles). In addition, however, event-by-event flow fluctuations may reduce the four particle cumulant result, so the four-particle cumulant result is often regarded as a lower bound on the actual collective elliptic flow [6]. The circles in Fig. 3 indicate results obtained from two-particle correlations after subtraction of the correlations measured in p+p collisions [7]. The values obtained from this procedure agree with the four-particle cumulant values at high $p_t$.

New measurements at $\sqrt{s_{NN}} = 62.4$ GeV are compared to the existing results at 200 GeV in Fig. 4. It can be seen that the $p_t$-dependence of the measured elliptic flow in 62.4 GeV collisions (solid symbols) is very similar to the result at 200 GeV (open symbols). At both energies, the four particle cumulant method (triangle) gives significantly lower $v_2$ values than the two-particle analysis (squares), indicating that non-flow contributions are similar. The similarity between the results at the different energies is striking, given the large differences in initial production and the expected differences in the densities at the early stage.

1.3. Azimuthal di-hadron correlations
Two-particle azimuthal correlations at high $p_t$ probe explicitly the jet-like nature of particle production at high $p_t$, as can be seen in Fig. 5, which shows distributions of the azimuthal angle $\phi$ of associated particles with $p_t > 2$ GeV with respect to trigger particles with $4 < p_t < 6$ GeV, for p+p collisions (line), d+Au collisions (circles) and Au+Au collisions (stars) [8]. While in p+p and d+Au collisions clear near- and away-side correlation peaks due to the back-to-back kinematics of jet production and fragmentation are visible, the away-side peak in Au+Au collisions is strongly suppressed. Since no suppression is observed in d+Au collisions, we conclude that initial state effects in the gold nucleus are of minor importance, and the observed suppression is entirely due to final state effects, most likely energy loss of the parton in interactions with the dense colored medium. This clearly provides a direct experimental observation of energy loss
Figure 4. Elliptic flow as a function of $p_t$ in Au+Au collisions in six different centrality ranges. Results at $\sqrt{s_{NN}} = 62.4$ GeV (solid symbols) are compared to results at 200 GeV (open symbols). Results from four-particle (triangles) and two-particle (squares) cumulant analyses are shown.

Figure 5. Azimuthal angle distribution of associated particles with $p_t > 2$ GeV with respect to trigger particles of $4 < p_t < 6$ GeV. Results from Au+Au collisions (stars) are compared to reference data from p+p (line) and d+Au (circles). All results are after subtraction of combinatorial background.
Figure 6. Two-particle azimuthal correlations with $4 < p_t(\text{trig}) < 6$ GeV and $p_t(\text{assoc}) > 2$ GeV. Results from $\sqrt{s_{NN}} = 62.4$ GeV Au+Au collisions (solid symbols) are compared to results at 200 GeV (open symbols).

Figure 7. Centrality dependence of the difference of the near and away-side correlated yields in Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV (solid symbols) and 200 GeV (open symbols).

phenomena in the medium.

In Fig. 6, recent results are shown for two-particle azimuthal correlations at $\sqrt{s_{NN}} = 62.4$ GeV (solid symbols), compared to the existing results at 200 GeV (open symbols). While for peripheral collisions (40-60% central, upper panel), a significant away-side correlated yield is measured, the correlated yield in central events (0-20% central, lower panel) is much reduced. The difference between the near-side yields at the two different energies is a result of the much more steeply falling partonic spectra at the lower energy: at $\sqrt{s_{NN}} = 62.4$ GeV, the average $p_t$ of partons fragmenting into 4 GeV leading particles is lower than in 200 GeV collisions, leaving less energy for the production of associated particles [9].

To compare the suppression of correlated particle production at the two different energies, Fig. 7 shows the difference between the near- and away-side yield as function of centrality for the two different energies. Although the absolute difference between the near and away-side yields is different at the different energies, the dependence of the suppression on the centrality of the collisions is strikingly similar.

The results presented here clearly demonstrate that high-$p_t$ particle production at RHIC has important contributions from jet fragmentation and that these are strongly affected by the hot and dense medium produced in Au+Au collisions. Therefore, high-$p_t$ particle production can be used to obtain quantitative information about the density and lifetime of the medium and the interactions of fast partons with the medium. At present, high-$p_t$ correlation studies are limited to trigger particles of $p_t \lesssim 6$ GeV because of statistical limitations. First results from the analysis of the large statistics data sample collected in 2004 will soon become available and these will allow more systematic studies of correlations as a function of trigger and associated $p_t$ threshold, which will help to map out the interactions of fast partons with the medium.
2. Di-hadron azimuthal correlations at intermediate $p_t$

A complementary way to investigate in-medium energy loss in more detail is by lowering the associated $p_t$ threshold and trying to recover jet-fragments that lost energy by interactions with the medium.

In Fig. 8, azimuthal distributions are shown for trigger hadrons with $4 < p_t < 6$ GeV and a low $p_t$-threshold for associated particles of 150 MeV (upper panel) in p+p and Au+Au collisions. For reference, results with $p_t(assoc) > 2$ GeV are shown in the lower panel. With the lower $p_t(assoc)$ threshold, the associated yields in Au+Au collisions are clearly larger than in p+p collisions, both on the near- and the away-side. This suggests that at a given trigger $p_t$, more energy is available for particle production in Au+Au collisions than in p+p collisions [10], which is again consistent with an energy loss scenario, but also with alternative hadronisation scenarios such as quark coalescence. Also note that the away-side peak for correlated yield in Au+Au collisions is much broader than in p+p collisions.

2.1. Identified particle correlations

Correlations of identified leading baryons and mesons with charged particles are studied to clarify the relative importance of modified vacuum fragmentation and other hadronisation mechanisms such as quark coalescence. Due to statistical limitations, the first results on such correlations have a relatively low trigger $p_t$ range of $2.5 < p_t(trig) < 4$ GeV. The centrality dependence of the associated yield at the near- (upper panel) and away-side (lower panel) are shown in...
Fig. 9. In the same figure, the measured associated yields in p+p collisions are also shown (leftmost points). With the present statistical uncertainties, no strong centrality dependence of the associated yield is observed, although the yields in Au+Au collisions are clearly higher than in p+p collisions, in qualitative agreement with the observations for unidentified charged hadrons. No significant difference is observed between the associated yields for trigger baryons and trigger mesons. While this is intuitively not compatible with the idea that the observed baryon excess at intermediate $p_t$ (approx. $2 < p_t < 4$ GeV) is largely due to coalescence formation of baryons [11], a more quantitative theoretical analysis of the observed spectra and correlated yields is probably needed.

3. Discussion and outlook
Measurements of high-$p_t$ particle spectra, elliptic flow and di-hadron correlations clearly show effects of parton energy loss on particle production in Au+Au collisions at RHIC energies. Recent results at $\sqrt{s_{NN}} = 62.4$ GeV show qualitatively similar suppression patterns compared to existing results at 200 GeV. A quantitative interpretation of these effects in terms of medium densities and lifetimes needs to take into account the more steeply falling initial production cross section at the lower energies. First model calculations indicate that effective medium densities can be lower by up to 30% at $\sqrt{s_{NN}} = 62.4$ GeV than at 200 GeV.

While di-hadron correlation analyses at higher $p_t$ ($p_t^{(trig)} > 4$ GeV, $p_t^{(assoc)} > 2$ GeV) show similar yields for near side associated yields in central Au+Au and p+p collisions, analyses with lower $p_t$ thresholds find increased yields in Au+Au collisions. This is qualitatively consistent with an energy loss scenario, where the energy that is radiated in the medium can be detected as low-$p_t$ hadrons in the final state. No significant difference is found between correlations with leading baryons and mesons in this $p_t$ range.

It is expected that in the next few months, new results will become available from the large statistics data samples of Au+Au collisions taken in 2004. These will reduce the statistical uncertainties on many of the existing results, and allow to extend many analyses to higher $p_t$, which will allow for a more systematic quantitative assessment of energy loss effects in the hot and dense medium at RHIC.

References
[1] Adler S S et al (PHENIX Collaboration) 2003 Phys. Rev. Lett. 91 241803 Preprint hep-ex/0304038
[2] Gyulassy M and Plumer M 1990 Phys. Lett. B 243 432
  Wang X-N and Gyulassy M 1992 Phys. Rev. Lett. 68 1480
[3] Adcox K et al (PHENIX Collaboration) 2002 Phys. Rev. Lett. 88 022301
  Adler C et al (STAR Collaboration) 2002 Phys. Rev. Lett. 89 202301
  Adams J et al (STAR Collaboration) 2003 Phys. Rev. Lett. 91 172302
  Adler S S et al (PHENIX Collaboration) 2003 Phys. Rev. Lett. 91 072301
[4] Aggarwal M M et al. (WA98 collaboration) 1998 Phys. Rev. Lett. 81 4087, 2000 84 578(E)
[5] Wang X-N 2004 Phys. Rev. C 70 031901 Preprint nucl-th/0405029
  Eskola K J et al 2005 Nucl. Phys. A 747 511
[6] Adler C et al (STAR Collaboration) 2002 Phys. Rev. C 66 034904
[7] Adams J et al (STAR Collaboration) 2004 Phys. Rev. Lett. 93 252301
[8] Adams J et al (STAR Collaboration) 2003 Phys. Rev. Lett. 91 072304
  Adler C et al. (STAR Collaboration) 2003 Phys. Rev. Lett. 90 082302
[9] Filimonov K 2005 J.Phys. G 31 S513
[10] Adams J et al (STAR Collaboration) 2005 Preprint nucl-ex/0501016
[11] Hwa R C and Yang C B 2004 Phys. Rev. C 70 024905
  Fries R J, Bass S A and Muller B 2005 Phys. Rev. Lett. 94 122301