Summary of Results on Hard Probes

T. Peitzmann $^a$ *

$a$University of Münster, 48149 Münster, Germany

Results on observables related to hard scattering processes as presented at this conference are reviewed. This includes in particular measurements related to jet quenching, a phenomenon which has been predicted as a signature for the hot and dense early phase of strongly interacting matter.

1. INTRODUCTION

With the new experiments at the RHIC accelerator at BNL, experimental heavy ion physics has truly reached the domain of hard probes. At RHIC energies hard scatterings as observed via jet structures are important in p+p collisions, and it was expected that hard scatterings should also be an important feature of heavy ion collisions at the collider. It has been predicted [1] that hard scattered partons should suffer energy loss from medium induced gluon radiation in a hot and dense system like the expected quark-gluon plasma phase of strongly interacting matter. This “jet-quenching”, which will lead to a suppression of hadron production at large transverse momenta, is therefore considered a signature of the partonic initial state. (For a review see [2].)

Two main avenues are being followed to get access to hard scattering processes:

- The study of high $p_T$ particle production via singles spectra and their comparison for different centralities and reaction systems (including p+p collisions).
- The study of azimuthal correlations reminiscent of jet topologies.

At the last Quark Matter conference [3] a suppression of high $p_T$ hadron production has already been reported [4], and the results have been published by the PHENIX and STAR experiments [5, 6].

At this conference, new results from all four RHIC experiments have been reported. The BRAHMS [7] and PHOBOS [8] experiments have presented spectra of hadrons out to relatively high $p_T$, while PHENIX [9] and STAR [10] have shown truly impressive results on hadrons out to very high $p_T$. I will try to summarize the highlights in the following.

2. SCALING OF PARTICLE PRODUCTION

The role of hard scattering even in understanding the global observables has been discussed in a number of papers [11], where it has been suggested that, in studying the
centrality dependence of the charged particle pseudorapidity density \( dN_{ch}/d\eta \), one might extract information on the relative contribution from hard scatterings. In particular, a parameterization as a function of the number of participants and the number of collisions has been proposed:

\[
\frac{dN_{ch}}{d\eta} = A \cdot N_{\text{part}} + B \cdot N_{\text{coll}},
\]

where the necessity of a term proportional to the number of collisions to explain the experimental data was taken as a hint for hard scattering production. In this context, the investigation of the scaling properties of particle production as presented by the PHOBOS experiment [12] is interesting. PHOBOS reported that the total charged multiplicity scales in good approximation with the number of participants and no additional term proportional to the number of collisions is necessary. The produced particles are however distributed differently in rapidity for varying centrality. This possibly implies that the observed stronger variation of \( dN_{ch}/d\eta \) with centrality may be due to a measurement in a limited phase space region combined with a redistribution of particles in phase space. In light of these observations, the interpretation of the parameterization (1) as related to hard scattering appears to be premature.

3. PRODUCTION OF HIGH \( p_T \) INCLUSIVE HADRONs

Momentum spectra of hadrons have been reported by all four RHIC experiments. Qualitatively, the suppression reported from the measurements at \( \sqrt{s_{NN}} = 130 \text{ GeV} \) has also been found at \( \sqrt{s_{NN}} = 200 \text{ GeV} \). Charged hadrons have been measured out to \( p_T = 9 \text{ GeV}/c \) by PHENIX [13] and to \( p_T = 11 \text{ GeV}/c \) by STAR [14]. Identified hadrons at very high \( p_T \), which do not suffer from uncertainties due to the unknown flavour composition, have only been presented by the PHENIX experiment [13], which has measured neutral pion spectra out to \( p_T = 10 \text{ GeV}/c \).

To quantitatively judge the measured hadron yield in central Au+Au collisions one tries to compare it to the expectations from p+p collisions, which must be appropriately scaled to the larger systems. As hard scatterings have a very small cross section and are expected to be incoherent, it is reasonable to assume that the multiplicity should scale with the number of binary nucleon-nucleon collisions. In fact, the scaling of high \( p_T \) hadron production in p+A collisions at somewhat lower energies has been shown to be stronger than with the number of collisions (“Cronin-effect”) [16]. A qualitatively similar enhancement compared to p+p collisions was found in central Pb+Pb collisions at 17.3 AGeV for neutral pion production by the WA98 experiment [17]. In the light of this known enhancement at lower energies, the suppression observed at RHIC is even more striking.

It has become customary to illustrate the suppression by using the so-called nuclear modification factor:

\[
R_{AA}(p_T) = \frac{d^2N^{A+A}/dp_Td\eta}{\langle N_{\text{coll}} \rangle d^2N^{N+N}/dp_Td\eta},
\]

In addition to the measurement of the hadron spectrum in heavy ion collisions this requires the knowledge of
Figure 1. Left: Neutral pion spectra for p+p collisions at 200 GeV measured by the PHENIX experiment [19]. Right: Pion spectra for minimum bias Au+Au collisions at √s_{NN} = 200 GeV measured by the PHENIX experiment. In addition to the neutral pions, charged pions identified by TOF at low p_T and by RICH at high p_T are included [9].

(1) the number of binary collisions and

(2) the spectrum in nucleon-nucleon collisions (or p+p collisions) at the same energy.

(1) is usually obtained by calculating the nuclear overlap in a Glauber-like approach. The systematic errors involved are among others related to uncertainties in the nucleon-nucleon cross section, the nuclear density profile and the trigger bias in the heavy ion measurement. While for peripheral collisions these do result in considerable uncertainties, the systematic error of the number of binary collisions N_{coll} in central collisions is estimated to be at most 10%. As a nucleon-nucleon spectrum (2) up to now data from earlier experiments at different energies were extrapolated to the RHIC conditions. At √s_{NN} = 200 GeV charged hadron spectra from UA1 [18] in p+p-collisions are available up to p_T = 6 GeV/c. The small momentum range and the possibly different systematic errors due to the measurement in a different experiment do however limit the usefulness of these data.

In this situation it is extremely important that PHENIX has measured the neutral pion spectra in p+p collisions at the same energy in the same apparatus [19]. This reduces the systematic uncertainties of the comparison (i.e. in R_{AA}). Together with the fact that the neutral pions are the only identified hadrons at high p_T this makes their measurement superior for the study of hadron suppression compared to the charged hadrons.
Figure 2. Left: Nuclear modification factor for neutral pions in the 10% most central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV as presented by PHENIX [9]. The curves show theoretical calculations without and with parton energy loss [21, 22, 23]. Right: Nuclear modification factor for charged hadrons. The PHENIX results [13] are shown as symbols with shaded areas as systematic errors, the results for STAR [14], PHOBOS [8] and BRAHMS [7] have been extracted from the presentations. The three latter have systematic errors of similar size as the PHENIX result.

The left hand side of Fig. 1 shows neutral pion spectra from p+p collisions. They agree relatively well with estimates from pQCD calculations [20]. For comparison a parameterization based on the UA1 data is also shown, which agrees with the neutral pions at low $p_T$ but starts to deviate for $p_T > 6$ GeV/c. The right hand side of Fig. 1 shows pion spectra in minimum bias Au+Au collisions. In the PHENIX experiment charged pions can be identified by time-of-flight at low momenta. They compare nicely with the neutral pions, which extend out to much higher momenta. In addition, at very high $p_T$ there are first attempts to identify charged pions in the RICH – the (scaled) spectra show also nice agreement in shape with the neutral pions.

Fig. 2 (left) shows the nuclear modification factor (see equation 2) for the 10% most central collisions of Au+Au at $\sqrt{s_{NN}} = 200$ GeV as presented by the PHENIX experiment. $R_{AA}$ is well below one for all of the covered $p_T$ range, decreasing from $\approx 0.4$ at $p_T = 1 - 2$ GeV/c to less than 0.2 for $p_T > 6$ GeV/c. The values are consistent with the results published for $\sqrt{s_{NN}} = 130$ GeV [3] for a much smaller $p_T$ range.

It is not surprising that $R_{AA} < 1$ at low $p_T$, as one would rather expect a scaling with the number of participants for soft particle production. A scaling of the yield with the number of participants would however lead to a value of $R_{AA} \approx 0.17$ for this centrality selection. This limit is not reached for the lowest momenta covered ($p_T \approx 1$ GeV/c), which is most likely due to the broadening of the spectra in Au+Au compared to p+p,
which will increase the yield at finite $p_T$ more strongly than the total multiplicity. At SPS energies it was observed [17] that $R_{AA}$ was increasing with $p_T$ reaching a value of 1 already at $p_T \approx 2$ GeV/$c$ – this increase is most likely due to a combined influence of increasing importance of hard scattering at higher $p_T$ with possible initial state multiple scattering and other momentum broadening effects like collective transverse flow. The new results at RHIC, however, show a continuous decrease of $R_{AA}$ for higher $p_T$. This result is not explained by theoretical calculations which are shown in Fig. 2 for comparison [21, 22, 23]. Calculations without energy loss fail completely, the calculations with energy loss are closer in magnitude to the experimental results, but can so far not explain the $p_T$ dependence.

It has been argued by the PHOBOS collaboration [24] that the particle yield even at high $p_T$ is compatible with participant scaling for Au+Au collisions with $N_{part} > 65$. This scaling is in general not seen in peripheral Au+Au data and for the transition from p+p to Au+Au, a closer look at data from all experiments also shows that even the approximate scaling is only valid in limited $p_T$ regions. So while the participant scaling of the total multiplicities may well have a fundamental origin, this is not at all clear for the same (approximate) scaling at a fixed $p_T$. Still it is interesting to note that $R_{AA}$ from neutral pions as shown in Fig. 2 is compatible with participant scaling for the highest $p_T$.

It has been discussed whether the emission of high $p_T$ hadrons is dominated by the surface of the reaction zone, and thus $R_{AA}$ would be determined by the surface-to-volume ratio. This in turn contains further uncertainties from the surface thickness assumed. To obtain a realistic numerical value of the scaling in this scenario one would have to take into account the transverse edge of the reaction zone and the varying density of the nuclear overlap. No precise value is available at present. Besides, it is noteworthy that even at relatively high $p_T$ hydrodynamic particle emission might contribute significantly to hadron spectra [25, 26]. For a locally thermalized system, which is the necessary condition for hydrodynamics, a scaling with the number of participants is very natural, so this might apply to the hydrodynamic fraction of the emitted hadrons. At the present moment, however, it is unclear, whether the observed scaling with the number of participants is purely a coincidence, or whether it can be related to a physical mechanism. In any case, even if this scaling holds, it does require a suppression mechanism of hard scattered particles when compared to the expectation from p+p collisions.

Similar analyses have been performed on charged hadron spectra. So far no direct p+p reference measurement is available. PHENIX has scaled the measured neutral pion spectrum in p+p to account for non-pions. The nuclear modification factor as displayed on the right hand side of Fig. 2 is slightly larger than the one for neutral pions, but both are compatible within errors. The other RHIC experiments have used a parameterization of UA1 data as their reference for $p_T < 6$ GeV/$c$. The curves included in Fig. 2 show fits extracted from the presented data, the systematic errors, which are not shown, are of similar size as for PHENIX. All results show qualitatively similar features: $R_{AA}$ increases at low $p_T$, has a maximum around $p_T = 2-2.5$ GeV/$c$ and decreases for higher $p_T$. There are considerable differences in the magnitude of the observed suppression for the different experiments, although probably not very significant in view of the systematic errors. For BRAHMS the relatively small value of the number of collisions used in the calculation may lead to an overestimate of $R_{AA}$. Part of the discrepancies may be due to the different
reference distributions used.

This is in line with the observation, that the collision-normalized ratio of central to peripheral spectra is in much better agreement between PHENIX [13] and STAR [14]. Such a ratio is one possibility to investigate the centrality dependence of the observed suppression. The ratio central to peripheral has the advantage that no p+p reference is needed, however, it suffers from the larger uncertainty of the estimate of the number of collisions in peripheral reactions. While also in this representation a suppression is observed, the new features of the collisions at RHIC are not as striking here. Similar ratios for SPS energies by the WA98 experiment [17] show no enhancement, but also a suppression, which is qualitatively similar, though weaker than at RHIC.

The centrality dependence of the neutral pion suppression has been investigated by PHENIX [13], there is a gradual transition from no suppression in peripheral collision to a strong suppression in very central without any indication of threshold effects. The centrality dependence of the charged hadron spectra has been studied in detail by STAR [14] and PHENIX [13]. A significant change in shape is observed when going from peripheral to central collisions. This can be best illustrated by looking at the truncated \( \langle p_T \rangle \) as obtained by PHENIX [13]: For \( p_T < 2 \text{GeV}/c \) the \( \langle p_T \rangle \) increases with increasing number of participants, just like the \( p_T \)-broadening known from lower energies which may be attributed to multiple scattering or collective flow, which would be expected to get more important for larger systems. For \( p_T > 2 \text{GeV}/c \) the \( \langle p_T \rangle \) decreases with increasing number of participants.

4. FLAVOR COMPOSITION AT HIGH \( p_T \)

Differences in the suppression for charged hadrons and neutral pions may be partially due to a flavor dependence of the suppression mechanism. Moreover, if the particle production at high \( p_T \) is actually due to incoherent hard scattering processes, the flavor composition of hadronic spectra should approach values known from p+p collisions and should be calculable in pQCD. PHENIX has extended its previously reported baryon/pion ratios at 130 GeV to measurements at 200 GeV [27]. The same trend is observed: The proton- and antiproton-to-pion ratios increase with increasing \( p_T \) reaching values close to one at high \( p_T \) in central collisions, as seen for antiprotons in Fig. 3 on the left side. This is very different from the expectation of much smaller values seen in p+p and also in peripheral Au+Au reactions. Other ratios, which may be calculated for hard processes, have been looked at, like e.g. the antiproton/proton ratio, which is also expected to decrease at high \( p_T \) for hard scattering production. PHENIX results are compatible with a constant, relatively large value at high \( p_T \) [27], while STAR reports an indication of a decrease at the highest \( p_T \) [10]. But even taking this possible decrease into account, the (anti-)proton/pion ratios indicate a still unexpected behavior in the \( p_T \) range, where charged hadrons can presently be identified.

The strongest hint of the remaining puzzle comes again from the neutral pion measurement in PHENIX. They have compared the neutral pion yield to the charged hadron yield in minimum bias collisions up to \( p_T = 8 \text{GeV}/c \) [3], and report that even at very high \( p_T \) pions seem to make up only about 50% of the total charged hadron yield. Other hadrons, possibly baryons, need to contribute there in contrast to the expectations from p+p colli-
Figure 3. Left: Ratio of antiprotons to pions as a function of $p_T$ for peripheral and central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV as measured by PHENIX [27]. Right: Ratios of identified charged hadrons to neutral pions in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The different curves show simple fits to the hadron ratios as presented by PHENIX [27]. For comparison the ratio of non-identified charged hadrons to neutral pions in central collisions is estimated from the presented results similar to the same ratio for minimum bias collision as shown in [9].

sions. The right side of Fig. 3 tries to illustrate the current situation. The charged hadron to neutral pion ratio has been estimated from fits to the spectra presented by PHENIX for central collisions. The identified charged hadron to pion ratios have then been used to successively build up this ratio for the total charged hadrons. It can be seen that the total sum of pions, kaons, protons and antiprotons is consistent with the charged hadrons up to intermediate $p_T$. At high $p_T$ still a considerable non-pionic contribution is apparently needed, and the measurement of identified hadron spectra at these higher $p_T$ will be of great importance.

5. ELLIPTIC FLOW

A lot of new and improved results on elliptic flow have been presented. A detailed summary is given in [28], so I will not discuss this in any detail. It should, however, be mentioned that, while azimuthal asymmetries for low and intermediate $p_T$ appear to be dominated by hydrodynamical effects, the persistence of a finite elliptic asymmetry $v_2$ out to very high $p_T$ indicates that modifications of hard scattering production are likely relevant for these analyses. This is nicely demonstrated in Fig. 4, which shows $v_2$ as measured by STAR [29] out to beyond $p_T = 10$ GeV/c. It will be interesting to see at which momenta the asymmetry disappears, and how much of the $v_2$ is actually due to partial jet quenching.
Figure 4. Elliptic flow parameter $v_2$ as a function of $p_T$ for charged particles as measured by STAR [29] for two different semi-central samples of Au+Au collisions at 200 GeV.

Figure 5. Azimuthal correlations of charged particles relative to a high $p_T$ trigger particle as measured by STAR [30] for peripheral (left) and central (right) collisions. Estimates from p+p collisions are shown as grey histograms.

6. JET STRUCTURES FROM AZIMUTHAL CORRELATIONS

While the suppression of high $p_T$ hadron production as seen in inclusive spectra is certainly established and will yield important constraints on the property of the hot and dense matter created in these collisions, it is even more interesting to investigate jet structures themselves. Analyses searching for jet patterns in azimuthal correlations have been performed by STAR [31, 32] and PHENIX [33]. Both experiments see small angle correlations of particles relative to high $p_T$ hadrons or photons, which in turn originate predominantly from pions. The magnitude and shape of this correlation in Au+Au collisions is very similar to the one in p+p. This is the first observation of jet structures in heavy ion collisions.

Also large angle correlations are seen by both experiments. STAR has performed a detailed analysis of these correlation phenomena [31]. As shown in Fig. 5 they attempt to describe the correlation function in heavy ion collisions by a superposition of a flat
Figure 6. The relative strength of the trigger-jet (open symbols) and the counter-jet (closed symbols) as a function of centrality in Au+Au collisions at 200 AGeV [30].

background, a component of elliptic flow and the jet correlation as measured in p+p. In peripheral collisions (left side of Fig. 5) both the trigger-jet (Δφ ≈ 0) and the counter-jet (|Δφ| ≈ π) are very similar to the expectations from p+p. In central collisions (right side of Fig. 5), the trigger-jet remains unaltered, but the counter-jet has almost completely disappeared. The existence of the trigger-jet ensures that a hard scattering has really taken place, such that the suppression of the balancing counter-jet is a very direct indication of jet quenching.

STAR has also presented the centrality dependence of the relative strength of the two jet structures compared to p+p. As can be seen in Fig. 6, the strength of the trigger-jet shows even a small increase towards more central collisions, which is surprising and should be further investigated. The counter-jet strength exhibits a gradual decrease with increasing number of participants, qualitatively very similar to the centrality dependence of the high \( p_T \) neutral pion suppression. This measurements provides a very important step towards understanding jet quenching, more detailed systematic investigation of observed first trends in the data and comparisons to theory are now required.

7. SUMMARY

A lot of exciting results on hard probes have been presented at this conference. The high \( p_T \) hadron suppression in central Au+Au collisions relative to p+p collisions has been established, most notably through the neutral pion measurements from PHENIX. Detailed theoretical calculations are now eagerly awaited. Elliptic azimuthal asymmetries persist at very high \( p_T \), which may be related to partial jet quenching. Correlation structures due to jets have been observed by STAR and PHENIX. The most important highlight of the conference is the suppression of the counter-jet in triggered central events as seen by STAR, which provides the most direct observation of jet quenching to date. The most
urgent open question concerns the explanation of the large non-pionic contribution to hadron spectra at very high $p_T$ as reported by PHENIX.

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