First Hints of Jet Quenching at RHIC

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At this conference first data from RHIC has been presented. Spectra of charged hadrons and identified neutral pions obtained in central collisions exhibit a depletion at large transverse momenta compared to expectations deduced from $pp$ and $\bar{p}p$ data and lower energy heavy ion data. While spectra measured in peripheral collisions exhibit the expected power-law shape, spectra from central collisions are closer to exponential. In addition, a significant azimuthal anisotropy of high momentum charged particle production has been found. All observations are in qualitative agreement with theoretical predictions that quark matter formed in heavy ion collisions quenches jet production.

1. Introduction

Parton-parton scattering with large momentum transfer, so-called hard scattering processes, provide unique probes for studying heavy ion collisions. The reason is simple: hard scattering occurs early in the collision, well before quark matter is expected to form. The scattered partons will sense the full space-time evolution of the collision volume and thus probe the later formed hot and dense phase.

Scattering with large momentum transfer either results in the production of high mass particles, like charm quarks of which a small fraction bind in $J/\psi$ charmonium states, or in high momentum quarks or gluons which fragment into jets of hadrons. If the scattered partons penetrate quark matter significant modifications of $J/\psi$ production and jet fragmentation are expected. In fact, the discovery of charmonium suppression [1] is one of the corner stones of the argument that quark matter has been formed already at CERN energies [2]. Jet production should also be altered significantly. High momentum partons should lose a significant fraction of their energy by gluon bremsstrahlung effectively suppressing jet production. This phenomenon, commonly referred to as “jet quenching”, was predicted a decade ago [3].

Among the large number of produced particles present in the final state of a heavy ion collision jets can not be reconstructed directly. However, one of the jet fragments will always carry a major fraction of the jet momentum. These so-called leading particles manifest themselves in a power-law shape of the transverse momentum distribution. If jets are quenched a depletion of the high momentum tail of the spectra is expected. In addition, due to the binary nature of hard scattering processes, most jets are produced in pairs, thus azimuthal correlations between high $p_T$ particles might also serve as an experimental observable.

At CERN SPS energies measurements of high $p_T$ particle production were performed [4,5]. A conclusive interpretation failed so far, mostly because the data can be explained by hard scattering [6] as well as transverse flow [7]. In contrast, first data from RHIC show...
characteristic features consistent with the anticipated jet quenching. This talk summarizes the experimental evidence shown at QM2001. In the next two sections data from nucleon-nucleon collisions are evaluated and used to establish a reference to which RHIC data can be compared. Section 4 compares inclusive charged particle production to the reference. Additional information on identified particle production, and its implicites are discussed in section 5. The final section summarizes the talk.

2. Elementary reactions

Searching for new phenomena in heavy ion collisions requires a detailed understanding of elementary nucleon-nucleon collisions. Data on high momentum particle production from \( pp \) or \( \bar{p}p \) collisions exists for various beam energies, but not for the initial RHIC energy of \( \sqrt{s_{nn}} = 130 \) GeV. Fig. 1 shows inclusive charged particle \( p_\perp \) spectra obtained from \( pp \) collisions at the ISR [8], and from \( \bar{p}p \) collisions by UA1 [9] at CERN, and by CDF at FNAL [10]. With increasing beam energy high \( p_\perp \) particle production is enhanced, reflecting the increase of the jet production cross-section.

![Figure 1. Inclusive charged particle production for \( pp \) and \( \bar{p}p \) collisions [8-10]. The ISR data for \( \pi, K, p, \) and \( \bar{p} \) were added to obtain the charged spectrum. All data were fitted with a power-law function (dotted lines) and interpolated to \( \sqrt{s} = 130 \) GeV (thick line), systematic errors of the interpolation are shown as dashed lines.]

![Figure 2. Charged particle and neutral pion data from different experiments [9,11,10] at \( \sqrt{s} \) from 500 to 630 GeV. The consistency of the data is used to estimate the systematic errors on the absolute normalization of individual experiments.]

To generate a reference \( p_\perp \) distribution for the initial RHIC energy \( \sqrt{s_{nn}} = 130 \) GeV, the data shown in Fig. 1 were fitted with the empirical functional form \( d^2\sigma/dp^2_\perp = A/(p_0+p_\perp)^n \). The cross sections were then interpolated to 130 GeV at several fixed \( p_\perp \). Finally, the
interpolated cross sections were fitted with the identical power-law function to obtain a smooth reference distribution. The fit parameters obtained are $A = 2.75 \times 10^5$, $p_0 = 1.71$, and $n = 12.42$. The fits and the interpolation are shown in the figure. The dashed lines below and above the interpolation indicate the systematic uncertainty which results from (i) uncertainties in the interpolation procedure which increases with $p_\perp$ and more importantly (ii) systematic discrepancies of data sets take by different experiments. The latter error was estimated to by about 20% by comparing different data sets at similar $\sqrt{s}$. An example is given Fig. 3 [9–11].

The same magnitude of systematic errors on the nucleon-nucleon reference is estimated by comparing to other extrapolations done by the STAR collaboration [12,13] and X.N. Wang [14] as well as comparing it to theoretical calculations of the cross section [15,16].

3. Extrapolating to $AA$ and the Nuclear Modification Factor

To extrapolate from $pp$ to $AA$ collisions non-trivial assumptions need to be made. Lets first assume all high $p_\perp$ particle production results from binary hard collisions. In the absence of nuclear effects the cross section should then simply scale by the atomic number squared $A^2$. For a specific impact parameter selection corresponding to a fraction $f$ of the inelastic nucleus-nucleus cross section $\sigma_{AA}^{inel}$, the average number of binary collisions of the event sample $\langle N_{binary} \rangle$ can be calculated from the nuclear overlap integral and the inelastic nucleon-nucleon cross section $\sigma_{nn}^{inel}$ [17]:

$$\langle N_{binary} \rangle = \sigma_{nn}^{inel} \int_{b_1}^{b_2} d^2b \frac{T_{AA}(b)}{f \sigma_{AA}^{inel}} = \sigma_{nn}^{inel} \int_{b_1}^{b_2} d^2b \langle T_{AA} \rangle = \sigma_{nn}^{inel} \frac{\langle T_{AA} \rangle}{f}$$

In the following values of $\sigma_{nn}^{inel} = 42$ mb and $\sigma_{AA}^{inel} = 7200$ mb are used consistently. Experimentally, the number of binary collisions can be evaluated from measured global observables like the forward energy or the event multiplicity by a Glauber model approach (e.g. in [13]). To search for deviations from the $nn$-reference one may divide the $p_\perp$ spectra from heavy ion collisions by the scaled $nn$-reference. This ratio, denoted as $R_{AA}$, will be referred to as the nuclear modification factor following the suggestion from [14].

$$R_{AA}(p_\perp) = \frac{d\sigma_{AA}/dyd^2p_\perp}{\langle N_{binary} \rangle d\sigma_{pp}/dyd^2p_\perp}$$

If simple scaling with the number of binary collisions holds true the nuclear modification factor $R_{AA}$ should be unity. At low momenta, say below 1 GeV/c, $R_{AA}$ must be smaller than one since in this $p_\perp$ region the cross section is expected to scale with the number of participating nucleon rather than with the number of binary collisions. Thus scaling with $\langle N_{binary} \rangle$ is expected only at high $p_\perp$, say above 2-3 GeV/c.

Below $p_\perp$ of 10 GeV/c the situation is complicated by known nuclear effect. Already in the late 70’s it was discovered by Cronin et al. [14] that high $p_\perp$ particle production in p-nucleus collisions is enhanced beyond simple binary scaling. Traditionally this enhancement, now called Cronin effect, has been parameterized as $\sigma_{pA} = A^{\alpha(p_\perp)} \sigma_{pp}$. Fig.3 gives a compilation of the $p_\perp$ dependent exponent from different fixed target experiments [19,20]. Though, so far there is no quantitative theoretical description of the Cronin effect, it is
commonly accepted that it originates from initial state multiple scattering, i.e. multiple scattering of parton in the collision \cite{21}.

The Cronin effect has also been observed in heavy ion collisions \cite{23}. Data taken at CERN has been recently compiled and analyzed in terms of the nuclear modification factor \cite{14}. Fig.4 reproduces a figure from \cite{14} showing $R_{AA}$ for Pb-Pb collisions. $R_{AA}$ continuously increases, crosses unity around 1.5 GeV/c and eventually saturates above 2.5 GeV at a value $R_{AA} \sim 2$. At higher energies a similar behavior is expected, though one might expect a reduction with increasing energy \cite{14}.

In summary, if previously observed phenomena are included, at RHIC $R_{AA}$ should be above the naive binary scaling, which probably underestimates $R_{AA}$ and below the empirically observed value from CERN, which might overestimate $R_{AA}$. This conclusion implicitly assumes that (i) the relative particle abundances – in particular at high $p_\perp$ – do not change going from nucleon-nucleon to nucleus-nucleus extracted from RHIC data collisions, and that (ii) collective radial flow as well as (iii) shadowing do not alter the spectra at high $p_\perp$ significantly.

4. Inclusive charged particle data from RHIC

Fig.5 compares the inclusive $p_\perp$ distribution of negatively charged hadrons from STAR \cite{13} to the spectra of all charged hadrons presented by PHENIX \cite{24}. Both data sets are obtained from the 5% most central Au-Au collisions at pseudo-rapidity zero. The data are consistent over the entire range observed out to 5 GeV/c. This is remarkable, given the preliminary nature of the data and the known difficulties of absolute measurements. There are subtle difference between the data sets which amount less than 40% and are largest around 2 GeV/c. This difference is used to estimate the systematic error on the absolute normalization. In the following the error is assumed to be $\pm 20\%$, which is consistent with the errors quoted by the experiments.

To compare to the $nn$-reference the nuclear modification factor is calculated. The $nn$-
Figure 5. Comparison of data on negatively charged hadrons obtained by STAR [13] and charged hadrons from PHENIX [24] for the most central 5% of the collisions. Both data sets are independently absolutely normalized.

Figure 6. Nuclear modification factor determined as ratio of the data from figure 5 over the nn-reference described in section 2, scaled by \( \langle N_{\text{binary}} \rangle = 945 \) (see text for details). The thin line indicates the estimated systematic uncertainty. Also given is the expectation for scaling with \( \langle N_{\text{binary}} \rangle \) (dashed line) and the nuclear modification factor deduced from CERN data (dash-dotted line).

reference was scaled by \( \langle N_{\text{binary}} \rangle = 945 \pm 140 \) determined by PHENIX [18]. STAR used a value of \( \langle T_{AA} \rangle = 26 \text{ mb}^{-1} \), corresponding to \( \langle N_{\text{binary}} \rangle = 1092 \) [13] to scale their reference. The difference of both values is used as systematic uncertainty of 15% on \( \langle N_{\text{binary}} \rangle \). This estimate is consistent with the \( \sim 15\% \) error given by PHENIX.

The resulting nuclear modification factor \( R_{AA} \) is shown in Fig. 6. On a linear scale the subtle differences between the data sets become more apparent. The systematic errors on \( R_{AA} \) are indicated by the full line, they results from (i) the error on the \( nn \)-reference (\( \sim 20\% \) but \( p_{\perp} \) dependent), (ii) a 20% error on the normalization, and (iii) a 15% error on \( \langle N_{\text{binary}} \rangle \). The errors quoted here are somewhat larger than those evaluated by PHENIX and STAR, the reason is two fold: (i) the errors take into account the differences between the data and (ii) the error on the \( nn \)-reference was estimated more conservatively.

Initially, \( R_{AA} \) increases up to a \( p_{\perp} \) of about 2 GeV/c where it saturates at a value of 0.6 to 0.8. At high \( p_{\perp} \) the nuclear modification factor \( R_{AA} \) seems to decrease again. In the region from 2 to 3 GeV \( R_{AA} \) might be consistent with unity within the rather large systematic uncertainties. However, it is not converging towards one at higher \( p_{\perp} \), as suggested by simple binary scaling. The figure also indicates \( R_{AA} \) observed at the CERN-SPS (dash-dotted line). Obviously, \( R_{AA} \) at RHIC is significantly below the value found for CERN SPS data.

PHENIX has also presented a systematic survey of different centrality selections. The data are shown in Fig. 7. The spectra for the most peripheral collisions exhibit a pronounced power-law shape which seems to vanish for the most central selection. The significant difference between central and peripheral collisions is more clearly visible in the ratio, which is depicted in Fig. 8. To compare to the binary scaling assumption and
Figure 7. Inclusive charged particle production measured by PHENIX [24] for different centrality selections (specified in the figure). All data sets are absolutely normalized. The lowest data set represents the most peripheral selection and the highest data set the most central selection.

to $R_{AA}$ the cross sections were normalized by the number of binary collisions for the specific centrality selection. The large uncertainty in $\langle N_{binary} \rangle$ for the peripheral data sets ($\sim 60\%$) is reflected by the error band also shown in the figure; this is an uncertainty on the absolute scale of the ratio but not on its $p_{\perp}$ dependence.

Both ratios, central 5% to 80-92% and to 60-80% show the same trend: a rise up to $p_{\perp}$ of 1.5-2 GeV/c followed by a decrease at higher momenta. Such a behavior is qualitatively in agreement with a power-law spectrum becoming more exponential with increasing centrality. Within the systematic errors the ratio could be close to one, but as in Fig.6 the ratio does not converge towards unity at large $p_{\perp}$ as suggested by the binary scaling scenario. If one assumes that peripheral collisions resemble nucleon-nucleon interactions one can interpret the ratio shown in Fig.8 as an alternative measure of the $R_{AA}$. The ratio derived here and $R_{AA}$ shown in Fig.6 agree reasonably well. Although the systematic errors have similar size they have very different origin.

That something interesting is happening at high $p_{\perp}$ is corroborated by data on azimuthal angular correlations presented by STAR [25]. The data is presented in Fig.9 in terms of the $p_{\perp}$ dependence of $v_2$. Here $v_2$ is the second Fourier coefficient of the azimuthal track density distribution measured with respect to the reaction plane. The coefficient $v_2$ measures an anisotropy of particle production relative to the reaction plane, which is typically interpreted as elliptic flow. At low $p_{\perp}$ $v_2$ continuously increases at a rate predicted by model calculations based on hydrodynamics [26]. Around 2 GeV/c the pattern changes and $v_2$ seems to saturate. At high $p_{\perp}$, say above 2 GeV/c, particle production can no longer be described by hydrodynamics and consequently the anisotropy is expected to vanish. Interestingly, the saturation of $v_2$ and $R_{AA}$ occur at similar $p_{\perp}$ suggesting a
possible connection of both phenomena.

Angular correlations between jets should not contribute to $v_2$ because jet production is uncorrelated to the reaction plane. If, however, jets lose significant energy in the dense medium an anisotropy will be introduced by the geometry of the reaction volume. In transverse direction, perpendicularly to the beam axis, the reaction volume will be almond shaped for non-zero impact parameter. Thus, the average path length of a jet in the dense medium will be smaller in plane than out of plane. It is plausible that jets produced out of plane will loose more energy than those produced in plane, effectively leading to an anisotropy with respect to the reaction plane at medium and high momenta.

The figure compares the data to a recent theoretical calculation \cite{27} which combines a hydrodynamic calculation with perturbative QCD, and models jet production quenched by energy loss. The different curves correspond to different initial gluon densities; for a density of 500 the model simultaneously describes also the $p_\perp$ spectra reasonably well.

5. Identified pion data from RHIC

Additional information on high $p_\perp$ production of neutral pion, proton and anti-proton is available from PHENIX \cite{28,29}. These first data show that in Au-Au collisions a much smaller fraction of the high $p_\perp$ charged particles are pions than in $pp$ collisions. Minimum bias data for $\pi^-$, $K^-$ and $\bar{p}$ is presented in Fig.10. Above 2.0 GeV/c the ratio $\bar{p}/\pi^-$ (as well as the $p/\pi^+$ ratio) approaches unity, significantly larger than the value of $\sim 0.2$ observed in $pp$ collisions at the ISR \cite{1}. In addition, the spectra suggest that $\bar{p}/\pi^-$ continues to increase towards higher $p_\perp$, quite different from $m_\perp$ scaling found in $pp$ collisions. Large collective radial flow in heavy ion collision might offer a possible explanation \cite{31,32}.

Independent of the interpretation, at high $p_\perp$ the particle compositions in Au-Au at RHIC deviates from $pp$ collision where the ratio charged/$\pi$ was about 1.6 above 1.5 GeV/c. From Fig.10 one deduces charged/$\pi$ of about 2 at 1.5 GeV/c, increasing to $\sim 2.5$ at about

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1Value determined from data in \cite{8}
Figure 10. Inclusive $\pi^-$, $K^-$, and $\bar{p}$ production from minimum bias Au-Au collisions presented by PHENIX [29]. All three distributions are absolutely normalized.

2.2 GeV/c. Thus $R_{AA}$ measured for charged particles should not be interpreted as nuclear modification factor for pions. $R_{AA}$ underestimates the depletion of pion production by approximately a factor $\sim 1.5$.

Figure 12. Ratio of central to peripheral neutral pion data. The thin lines indicate the systematic uncertainty of the data.

Figure 11. Neutral pion transverse momentum distribution measured by PHENIX [28]. The data is compared to the appropriately scaled nucleon-nucleon reference for pion production (systematic errors given as dashed lines).

Figure 13. Comparison of neutral pion production to various model calculations from [16].
The measurement of neutral pions by PHENIX [28] reveals directly the more substantial suppression of high $p_{\perp}$ pion production. Two data sets are given in Fig.11, a 10% central and a peripheral (60-80%) event selection. The systematic uncertainty of the absolute normalization is included in the error bars.

Both data sets are compared to the nucleon-nucleon reference. Here the reference, which was deduced for charged particles in section 2, was scaled down by the charged/π ratio of 1.6 observed at the ISR. The systematic error bands shown in the figure contain the uncertainty of the reference (see section 2), a 10% error on the charged/π scale factor, as well as 15% and 60% error on the number of binary collisions for central and peripheral data, respectively. While the peripheral data are well described by the reference distribution, the central data are significantly below. From the ratio of the data to the $nn$-reference one deduces an average nuclear modification factor of $R_{AA} \sim 0.4$ for neutral pions in central collisions. This value is smaller by a factor of 1.5 compared to $R_{AA}$ obtained for charged particles, consistent with the large $p$ and $\bar{p}$ yield at high $p_{\perp}$. For the peripheral data, $R_{AA}$ is about unity reflecting the good agreement of the data and the $nn$-reference.

As alternative measure of $R_{AA}$ Fig.12 gives the ratio of central to peripheral data. For all $p_{\perp}$ the ratio is below unity, indicating the substantial suppression of the yield in central collisions relative to the binary scaling assumption. Very similar to the charged particle data the ratio peaks between 1.5 and 2 GeV/c and decreases towards higher $p_{\perp}$.

Finally in figure 13, the neutral pion data are compared to theoretical model calculations by X.N. Wang [16]. Three different calculations are shown: (i) an estimate of the scaled $nn$-reference, (ii) a scaled reference modified by modeling the Cronin effect (here called $p_{\perp}$-broadening) and shadowing, as well as (iii) a calculation inferring “jet quenching” by introducing an average energy loss of 0.25 GeV/fm for the scattered partons. The peripheral data agrees reasonably well with all three scenarios while the central data are significantly below the calculations not including energy loss.

6. Conclusion and Outlook

Only a few months after the end of its first Au-Au run, RHIC has produced a surprisingly rich sample of data, reaching out in $p_{\perp}$ well into a region where a significant contribution of hard scattering processes is expected. In central collisions a depletion of high $p_{\perp}$ particle production is discovered. This depletion is observed in charged particle production measured by STAR and PHENIX as well as in neutral pion data from PHENIX. The same depletion is found when comparing central to peripheral data. Additional information results from azimuthal anisotropy of particle production. All observations are consistent with a scenario in which quark matter formed during the collision suppresses jet production.

Whether these first hints for “jet quenching” will hold true remains to be seen. Drawing definite and quantitative conclusions from the present data certainly is premature in particular in view of the large systematic uncertainties. Besides better control of the absolute normalization it will be essential to measure the $nn$-reference in the same experiments. Data at higher $p_{\perp}$ will help to disentangle soft physics like radial flow from hard scattering.
At the end I would like to express my gratitude to many who have helped preparing my summary talk – before and during this exciting conference. I specially thank T.Ullrich, P.Jacobs, and R.Snellsings for providing the STAR data. X.N. Wang generously provided calculations and figures for my talk. Also many colleges in PHENIX deserve credit, in particular G.David, F.Messer, and J. Velkovska.

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