Results on Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV and 200 GeV from the PHENIX experiment

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Recent results from the PHENIX experiment at RHIC on Au+Au and p+p collisions are presented, including identified hadron spectra, ratios and particle correlations. The production of hadrons at high transverse momenta is investigated in detail. A strong suppression of high p_T hadrons in central heavy ion collisions compared to extrapolations from p+p collisions is observed. Evidence of jet structures in heavy ion collisions and the status of di-electron, di-muon and photon measurements is discussed.

1. INTRODUCTION

The PHENIX detector [1] at RHIC, the Relativistic Heavy Ion Collider at Brookhaven National Laboratory, is designed to measure the properties of nuclear matter at the highest temperatures and energy densities with a variety of experimental probes, and in particular to search for the predicted transition into a phase of deconfined quarks and gluons, the "quark-gluon-plasma" (QGP). The particular emphasis of PHENIX is the investigation of penetrating probes, like photons, electrons and muons. In addition, it has excellent hadron identification capabilities out to high transverse momenta.

PHENIX has measured Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV and at $\sqrt{s_{NN}} = 200$ GeV and p+p collisions at $\sqrt{s} = 200$ GeV. The PHENIX experiment consists of two central spectrometer arms that were completely instrumented in the most recent beam time (Run II) at RHIC. The central arms each cover pseudorapidity ($|\eta| < 0.35$), transverse momentum ($p_T > 0.2$ GeV/c), and 90 degrees in azimuthal angle ϕ. They are comprised from the inner radius outward of a Multiplicity and Vertex Detector (MVD), Drift Chambers (DC), Pixel Pad Chambers (PC), Ring Imaging Cherenkov Counter (RICH), Time Expansion Chamber (TEC), Time-of-Flight Scintillator Wall (TOF), and two types of Electromagnetic Calorimeters (EMCal). PHENIX has two forward muon spectrometers consisting of hadronic absorbers, a cathode strip chamber muon tracking system, and interleaved Iarocci tubes with steel plates for muon identification and triggering. Each spectrometer covers approximately $1.2 < |\eta| < 2.2$, and $p_{tot} > 2$ GeV/c. The south muon spectrometer was commissioned and operational in Run II, while the north arm is currently being completed.

Au-Au and proton-proton collisions are characterized with minimum bias triggers based on a set of zero degree calorimeters (ZDC), beam-beam counters (BBC), and a scintillator multiplicity counter (NTC) for larger coverage in proton-proton collisions.

The present paper reports on recent results regarding identified hadron spectra and ratios and correlations. Particular emphasis is laid on the investigation of hadron suppression at high transverse momentum and on evidence for jets in heavy ion collisions. The status of the measurements of penetrating probes like J/ψ, open charm and direct photons is discussed. The PHENIX experiment has obtained a large number of other interesting results, which can not be covered in these proceedings, recent reports can be found in [2].

2. IDENTIFIED CHARGED HADRONS

Using the central arm tracking detectors and the high resolution TOF PHENIX can identify charged hadrons over a large momentum range. Figure 1 shows p_T distributions in the 5% most central Au+Au collisions at 200 GeV. The spectra extend up to 1.8

*For full author and institution list see the Collaborations Appendix to the proceedings of the XVI International Conference on Ultrarelativistic Nucleus-Nucleus Collisions, Quark Matter 2002, Nantes, to be published in Nucl. Phys. A.

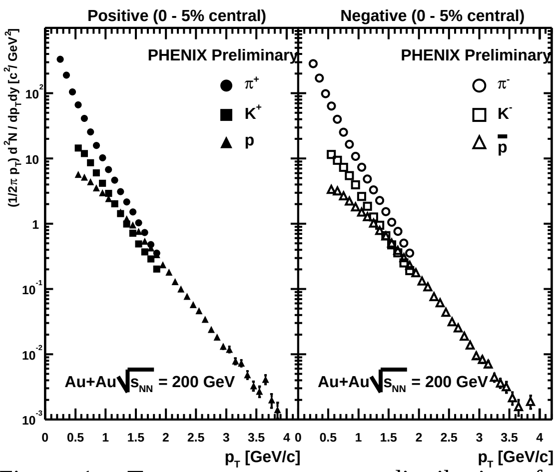

Figure 1. Transverse momentum distributions for identified charged hadrons in the 5% most central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. The error bars are statistical only.

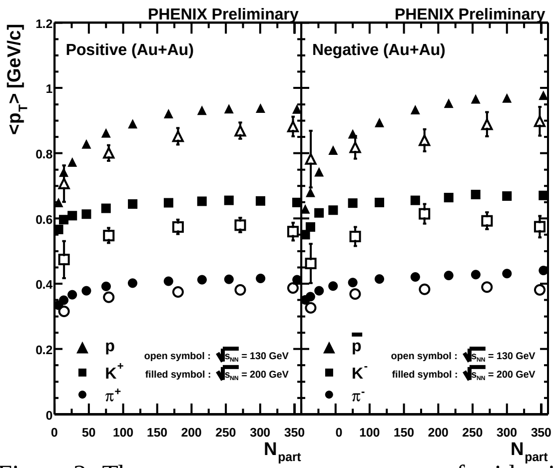

Figure 2. The mean transverse momentum for identified charged hadrons as a function of N_{part} in Au+Au collisions at 130 GeV [3] (open symbols) and 200 GeV (filled symbols).

GeV/c for charged pions and kaons and 3.8 GeV/c for (anti-)protons. Around 2.0 GeV/c in p_T, the proton yield becomes comparable to the pion yield in central collisions, and a similar observation is made for negative particles. This behavior is very different from the one observed in p+p or e^++e^- collisions, where the (anti)proton to pion ratio is much lower. It might be explained by a collectively expanding source, as will be discussed below.

This observation is of course related to the different shape of the spectra for different species, which can e.g. be quantified by the average transverse momentum. In figure 2, the centrality dependence of $\langle p_T \rangle$ for identified charged hadrons is shown, together with data taken at 130 GeV [3]. In both the 200 GeV and 130 GeV data, the $\langle p_T \rangle$ of all particles increases from the peripheral to the central events. The $\langle p_T \rangle$ also increases with increasing particle mass. This dependence would also be naturally explained by assuming a collective hydro-dynamical expansion. In such a scenario, the dependence on the number of participant nucleons (N_{part}) may be due to an increasing radial expansion from peripheral to central events.

3. HIGH P_T HADRON PRODUCTION

The experiments at RHIC have truely opened up the domain of hard scattering in heavy ion collisions. This is of particular interest as jets originating from hard scattered partons and their possible modification in nuclear collisions compared to p+p via energy loss is considered as a new signal for the quark-gluon-plasma [4]. PHENIX has the great advantage to be able to identify neutral pions with the EDMCal out to extremely high p_T, the range being essentially limited by statistics, which has been greatly enhanced in Run II. Fig. 3 shows the neutral pion spectrum for p+p collisions, which reaches out to 13 GeV/c. The data agree with pQCD calculations [5] (dotted lines) and also with the data from UA1 [6] (not shown), which were measured only for $p_T < 6\,\mathrm{GeV}/c$. Besides the important information this measurement provides by itself, the p+p measurement is also of great interest as a baseline for comparisons to the heavy ion results.

Fig. 4 shows the transverse momentum spectra of neutral pions for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and 130 GeV, the one for the 10% most central collisions at 200 GeV reaches out to $p_T = 8\,\mathrm{GeV}/c$.

Already in earlier measurements at 130 GeV [7,8] a suppression of the high p_T hadron yield relative to the expectation from naive estimates from perturbative QCD has been observed, which is qualitatively similar to the predicted jet-quenching from the plasma [4]. To quantify such effects a nuclear modification factor is usually introduced:

$$R_{AA}(p_T) = \frac{\mathrm{Yield\ per\ A + A\ collision}}{\langle N_{coll} \rangle (\mathrm{Yield\ per\ p + p\ collision})}$$

Hard processes have a small cross section and are gen-

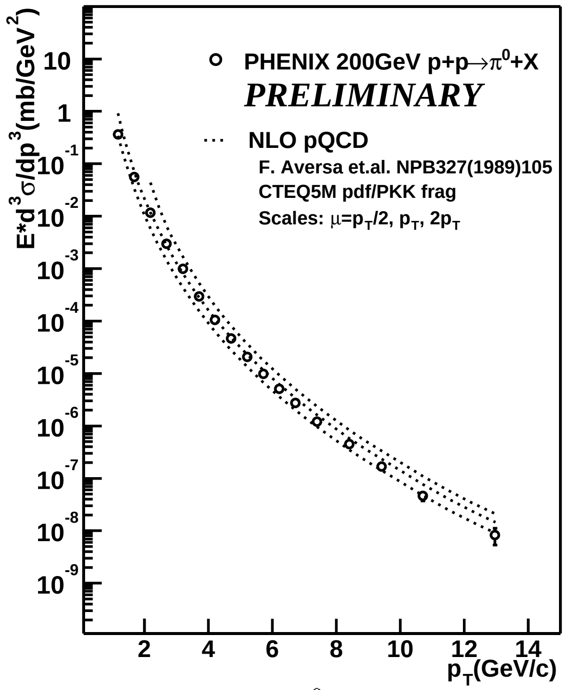

Figure 3. Cross section of π^0 as a function of p_T in p+p collisions at $\sqrt{s_{NN}} = 200$ GeV. The dotted lines show NLO pQCD calculations using $p_T/2$ (top line), p_T (middle line), and $2p_T$ (bottom line) renormalization and factorization scales.

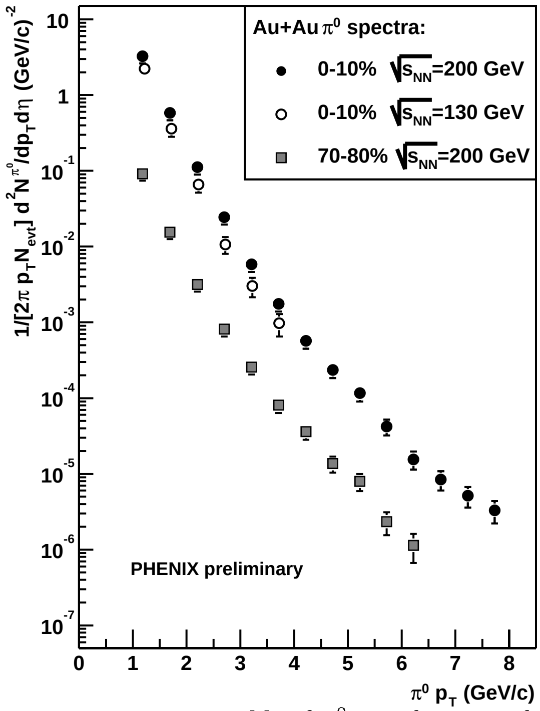

Figure 4. Invariant yields of π^0 as a function of p_T in central (0-10%) Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and 130 GeV and peripheral (70-80%) collisions at $\sqrt{s_{NN}} = 200$ GeV.

erally believed to be incoherent. Their probability in Au+Au collisions should thus be proportional to the average number of binary collisions N_{coll}. In the absence of any nuclear modification the ratio R_{AA} is therefore expected to be one for particles produced from such processes (i.e. at high p_T).

Fig. 5 shows $R_{AA}(p_T)$ for the 10% most central Au+Au collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$. A strong suppression relative to a scaling with N_{coll} is observed, which is qualitatively similar to the result at 130 GeV. In this measurement the suppression persists up to $p_T \approx 8\,\mathrm{GeV}/c$ reaching values of $1/5 - 1/6$. As the p+p reference spectrum has now been measured with the same detector, the systematic errors have been significantly reduced. In Fig. 5 this is compared to R_{AA} from central Pb+Pb collisions at $\sqrt{s_{NN}} = 17\,\mathrm{GeV}$ from WA98 [9], which shows a quite different behavior, namely a strong enhancement with values much larger than 1 increasing with increasing p_T. This enhancement at lower energies is similar to the “Cronin effect” [10] observed in p+A collisions, which has been attributed to p_T broadening due to initial state scatterings. One should however note that, if heavy-ion collisions do exhibit collective flow increasing for central collisions, this would also lead to p_T broadening and be similarly reflected in R_{AA}.

The spectrum for peripheral collisions (70-80%) is consistent with p+p collisions scaled by N_{coll}. It is of interest to investigate how the transition from these peripheral collisions to central collisions, where the suppression has been observed, takes place, and whether one can locate a centrality, where the suppression sets in. Fig. 6 shows R_{AA} as a function of the mean number of participating nucleons N_{part} for neutral pions with $p_T > 4\,\mathrm{GeV}/c$. The suppression smoothly increases from peripheral to central events. Results have also been obtained with an analog analysis using non-identified charged hadrons, where a qualitatively similar suppression in central reactions and the same trend with centrality is observed [11].

From the identified charged hadron spectra (see above) one has made the interesting observation that

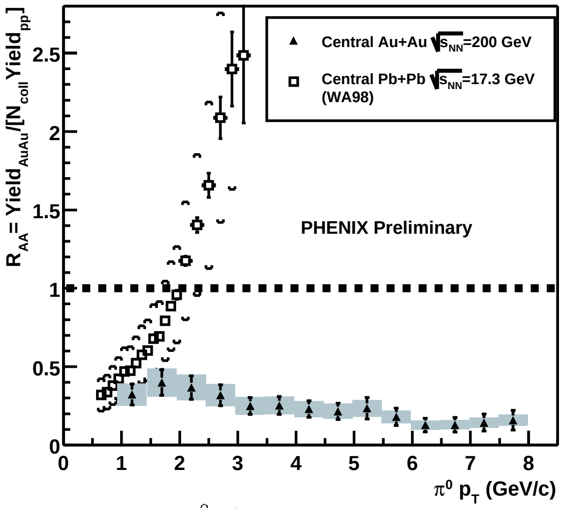

Figure 5. R_{AA} (π^0) for central Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV and central Pb+Pb collisions at $\sqrt{s_{NN}} = 17$ GeV. The error bars are the quadratic sum of statistical and p_T-dependent systematic errors. The brackets/boxes are the errors on the normalization of this ratio.

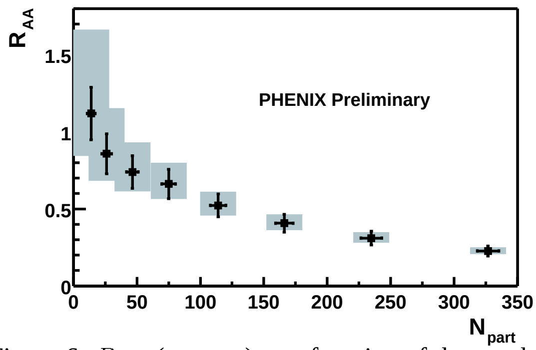

Figure 6. R_{AA} (see text) as a function of the number of participants for neutral pions with $p_T > 4$ GeV/c.

the proton and antiproton yield is comparable to the pion yield for $p_T = 3 - 4\,\mathrm{GeV}/c$. While at these transverse momenta one might imagine that hydrodynamics could be invoked as a possible explanation, it would be expected that this should break down at still higher p_T, where eventually perturbative QCD should start to dominate. The neutral pions allow to study the chemical composition of the spectra in this high p_T region via the ratio of π^0 to nonidentified charged hadrons $(\mathrm{h}^+ + \mathrm{h}^-)/2$. This ratio is shown in Fig. 7 for minimum bias events. From the knowledge of particle production in jets (as measured e.g. in $\mathrm{e}^+\mathrm{e}^-$ collisions [12]) one would expect this ratio

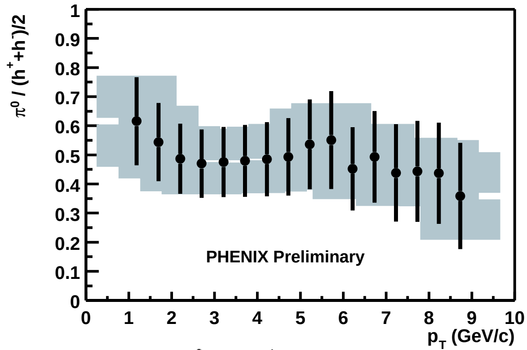

Figure 7. Ratio of π^0 to $(h^+ + h^-)/2$ as a function of p_T for minimum bias Au+Au collisions.

to approach one at high p_T where perturbative QCD should dominate (assuming $\pi^0 = (\pi^+ + \pi^-)/2$). Even for $p_T > 4\,\mathrm{GeV}/c$ this is not observed. The ratio remains nearly constant at a value around 0.5, indicating that approximately half of the charged hadrons at high p_T are protons and/or kaons. This may call for some other production mechanism for protons and/or kaons in Au+Au collisions at these large transverse momenta. It remains puzzling especially in view of the fact, that correlation studies (as discussed below) indicate, that jet fragmentation may still be the dominant production mechanism at these p_T. Alternatively, the large proton and/or kaon content at high p_T could be due to a difference of the modifications of jet fragmentation into pions relative to protons/kaons.

To understand particle production at high p_T it is of utmost importance to get more direct information on the hard scattering component. The high multiplicity in Au+Au collisions does not allow to identify indivdual jets based on event topology as in p+p. Therefore one has to search for hints of jet structures in a angular correlations. PHENIX has selected events with at least one neutral particle with $E > 2.5\,\mathrm{GeV}$ measured in the EMCal (mostly photons from neutral pion decays). In these events correlation functions of charged particles relative to the trigger photon are calculated. Measurements of such correlation functions in p+p exhibit peaks due to jets, which agree with those from the PYTHIA event generator [13]. One can then study the same correlation in Au+Au and again compare to PYTHIA to look for possible modifications. Figure 8 shows the background-subtracted correlation as a function of the relative azimuthal angle $\Delta\phi$ for charged particles with $p_T = 2 - 4\,\mathrm{GeV}/c$. Also shown is a correlation function combining ef-

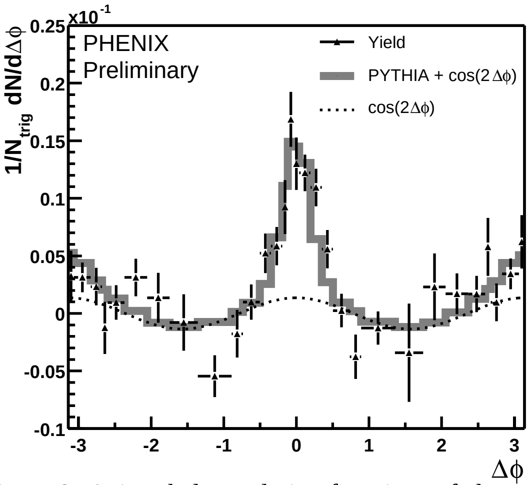

Figure 8. Azimuthal correlation functions of charged particles relative to a high p_T photon in triggered Au+Au collisions (acceptance corrected). The effect of elliptic flow (dotted line) and a fit of PYTHIA + elliptic flow (grey line) is also shown.

fects of jets as produced by PYTHIA with elliptic flow characterized by a $\cos(2\phi)$ term, which has been fit to the data. Apparently, the strong correlation at $\Delta\phi = 0$ is dominated by particles from jet fragmentation, which in shape looks very similar to the PYTHIA calculation. Thus there is high probability that a high p_T π^0 as represented by the trigger photon originates from a jet.

4. ELECTROMAGNETIC PROBES

PHENIX has excellent electron identification capabilities and has thus measured inclusive electron spectra. Electrons resulting from semi-leptonic decays of charm D mesons ($D \longrightarrow e + K + \nu$) and beauty B mesons ($B \longrightarrow e + D + \nu$) have significant contributions to these inclusive electrons above 1.0 and 2.5 GeV, respectively. The dominant sources of "background" electrons are from neutral pion Dalitz decay ($\pi^0 \longrightarrow \gamma e^+ e^-$) and photon conversions in material in the PHENIX aperture. One can account for these sources using the measured π^0 distributions. In addition, although their contributions are relatively small, additional electrons from $\eta, \eta', \omega, \phi, \rho$ must be estimated. Results from Au-Au collisions at $\sqrt{s_{NN}} = 130$ GeV have been published [14] and one finds a significant excess of electrons over "background" above $p_T \approx 0.7$ GeV/c that increases with p_T.

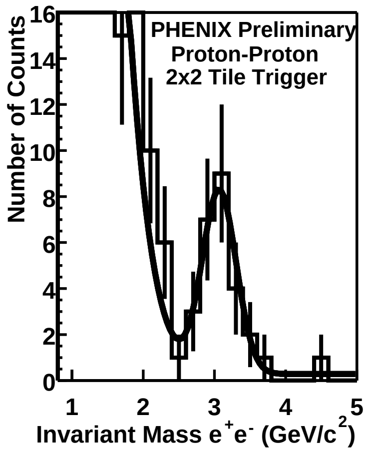

Figure 9. Dielectron invariant mass distribution from proton-proton events.

In Run II, PHENIX has a more powerful method of extracting the single electron charm contribution. Using a brass photon converter wrapped around the beam pipe near the interaction point for a fraction of the beam time, a good estimate of the photonic contributions to the background can be obtained. Since there is a fixed relation between the γ from π^0 decay (which is the dominant source of conversion photons), and the π^0 Dalitz contribution, we can subtract out both contributions.

After this subtraction the data appear reasonably described by a PYTHIA calculation of the expected charm contribution assuming scaling with N_{coll}, similar to the 130 GeV data analysis. The electron data in four centrality bins appears to qualitatively follow a scaling with N_{coll}. Significant work remains to reduce the systematic errors in order to exactly quantify this scaling relation. PHENIX is currently analyzing the proton-proton data set so that we can calculate the charm scaling without relying on the PYTHIA baseline.

Phenix has also performed the first measurements of J/ψ production in proton-proton collisions at $\sqrt{s} = 200$ GeV. As an example Figure 9 shows the dielectron invariant mass distribution for proton-proton collisions with at least one 2x2 calorimeter tower tile above our Level-1 trigger threshold. This represents about half of our proton-proton statistics. Similarly, measurements in the dimuon channel have been performed for proton-proton collisions.

We have corrected for the central and muon arm acceptances, tracking and particle identification efficiencies, and Level-1 trigger efficiencies and have thus measured the cross section $d\sigma/dy$ as a function of rapidity. The data are fit to a simple Gaussian form and also to the predicted rapidity shape from PYTHIA using parton distribution function GRV94LO. Integrating over rapidity, we find a preliminary result of:

$$\sigma_{pp}{}^{\mathrm{J}/\psi} = 3.8 \pm 0.6(\mathrm{stat}) \pm 1.3(\mathrm{sys})\ \ \mu\mathrm{b}.$$

Preliminary results on J/ψ production from the di-electron channel have also been obtained in Au+Au collisions. The limited statistics does presently not allow to draw any firm conclusions from this measurement. Increased statistics and the di-muon measurements are currently being analyzed. Future beam times with increased luminosity and a fully equipped PHENIX detector should significantly enhance this measurement.

The measurement of direct photons is another important goal of PHENIX. Present preliminary results show no significant excess of photons over those from hadron decays, which is mainly due to the large systematic error. This difficult analysis is under way and should allow to significantly reduce the systematic errors in the future.

5. CONCLUSIONS

PHENIX has obtained a wealth of interesting new results from the last RHIC beam time. Identified hadron spectra out to high p_T have been presented. High p_T neutral pion production in central Au+Au collisions at 200 GeV is suppressed by a factor of $1/5 - 1/6$ compared to p+p collisions scaled by the number of binary collisions. The suppression increases gradually with number of participants, or decreasing impact parameter, no threshold behavior is observed. High p_T neutral particles, which are predominantly photons from π^0 decays are accompanied by correlated charged particles in a jet-like pattern, which indicates that neutral pions at high p_T should originate to a large extent from jet fragmentation. However, the ratio of neutral pions to charged hadrons implies a large non-pionic contribution to hadrons out to $p_T = 8\,\mathrm{GeV}/c$, which is not in line with expectations from unmodified hard scattering production. Single electron spectra have been measured, which are consistent with predictions of charm production by perturbative QCD. A measurement of the cross section of J/ψ in p+p has been presented, and the status of the measurement of J/ψ and direct photons in Au+Au collisions has been discussed.

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