E. RELATIVISTIC HEAVY ION COLLISIONS

The PHOBOS experiment at Brookhaven's Heavy-Ion Collider, RHIC, continues to be very productive. New data were collected for Au + Au collisions, supplemented by p + p and d + Au interactions all at maximum colliding beam energies of 200 GeV/u.

In addition, the PHOBOS collaboration continues their leadership role in publishing new results, with several new Letters appearing.

e.1. Mean Transverse Momentum at Large Pseudo-Rapidity, η (B. B. Back)

The almost hermetic coverage of the PHOBOS multiplicity detector allows for measurement of the total number and the pseudo-rapidity distribution of charged particles emitted in central Au + Au collisions (Fig. I-51, bottom panel). In fact, only about 1% of the charged particles are emitted in the high-η region, where there is no detector coverage. The present work exploits this large coverage to derive information on the mean transverse momentum, $\langle p_T \rangle$, by requiring energy conservation from the initial to the final stage of the collisions.

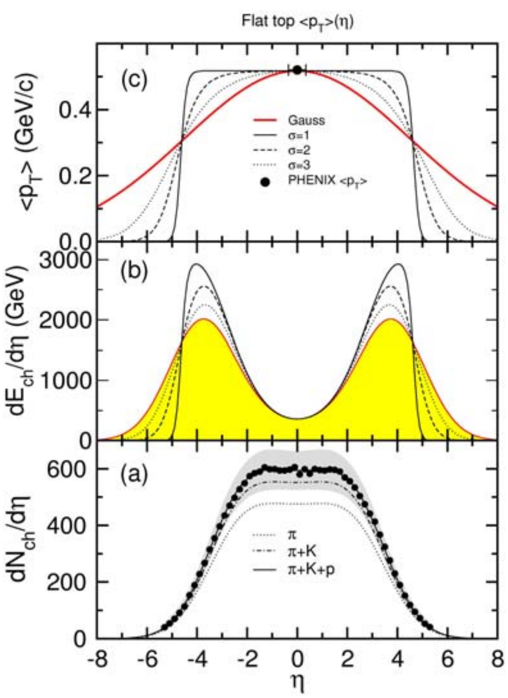

Fig. I-51. (a) The charged particle pseudo-rapidity distribution for 0-3% central Au + Au collisions at 130 GeV (PHOBOS Collab.) is shown as solid points. The grey band represents systematical and statistical errors. An analytical fit to the data using three Gaussians is shown as a solid curve with contributions from pions (dotted curve) and pion+kaons (dotted-dashed curve) shown separately. (b) The pseudo-rapidity distribution of charged particle energy is shown for four different assumptions of the shape of the <p_T> on pseudo-rapidity, as illustrated in panel (c). The solid data point in panel (c) represents a measurement by the PHENIX collaboration.

First, accounting for the energy carried by neutral particles that are not observed in the PHOBOS detector is based on isospin symmetry assumptions, such that $\pi^0 = 0.5(\pi^+ + \pi^-)$, $K_S^0 + K_L^0 = K^+ + K^-$, and $n = p$. From measurements by the PHENIX collaboration of identified charged particles we thus find that the charged particle fraction is $f_{ch} = 0.633$. Second, one should only expect to observe the energy (and particles) associated with the participating nucleons, N_{part}, of the incoming Au + Au ions. For the 0-3% centrality bin of 130 GeV Au + Au collisions $N_{part} = 355$ and we should thus expect to find a total energy of

$$E_{ch} = 0.633 \times 0.5 N_{part} \sqrt{s_{NN}} = 14{,}606 \text{ (GeV)}$$

is carried by the emitted charged particles. Since the total energy carried by a single particle is

$$E = \sqrt{m^2 + p_T^2 \cosh^2(\eta)}$$

one can therefore obtain the total energy in the exit channel as

$$E_{ch}^{out} = \sum_{i=1}^{3} \int_{-\infty}^{\infty} d\eta \int_{0}^{\infty} dp_T \frac{d^2N}{d\eta dp_T} \sqrt{m_i^2 + p_T^2 \cosh^2(\eta)} ,$$

where i denotes the three particle species, pions, kaons and nucleons and an integration over the η and p_T is carried out to account for all charged particles.

At mid-rapidity, $\eta \approx 0$, the total hadronic charged particle spectra are known to have a power-law p_T dependence and that the mean transverse momentum, $\langle p_T \rangle$, increases linearly with particle mass to yield an overall value of $\langle p_T \rangle_{ch}^{\eta=0}$ = 508-520 MeV/c. Under simplifying, but weak, assumptions about the fixed abundances of particle species and spectral shapes for particles emitted at non-zero pseudo-rapidities, one can thus evaluate E_{ch}^{out} and compare to the value of 23,075 GeV required by energy conservation. The first observation is that assuming the p_T are independent of pseudo-rapidity leads to a gross over-estimation of the energy of outgoing charged particles, namely E_{ch}^{out} = 21,788 GeV, about 50% higher than the available energy. This leads to the conclusion that the mean p_T must fall off away from mid-rapidity. In Fig. I-51b,c is shown the results of a Gaussian η–dependence of $\langle p_T \rangle$ (thick solid curves), which fulfills the energy conservation requirement. However, other dependences approaching a flat-top distributions given by the relation $\langle p_T \rangle \alpha \; 1/\{1 + \exp[(\eta - a)/\sigma^2 + (\eta + a)/\sigma^2]\}$, where the parameter a is adjusted to yield the required total energy value for three different choices, σ = 1, 2, and 3, of the fall-off parameter are also possible. It is interesting to note that all four $\langle p_T \rangle$ dependences that satisfy the energy conservation requirement coincide at a value of $\langle p_T \rangle = 0.305$ at $|\eta| = 4.6$. We may therefore consider this analysis a measurement of the mean transverse momentum of charged particles, since it is based on a simple requirement of energy conservation and rather weak assumptions for the shapes of particle spectra. However, further analysis is required to establish a systematical error on this value.

e.2. The PHOBOS Experiment at RHIC (B. B. Back, A. H. Wuosmaa and the PHOBOS Collaboration*)

The PHOBOS experiment has made significant progress over the past year. Most of the effort was devoted to the analysis and interpretation of data obtained during RHIC runs 1 and 2, the latter of which concluded at the end of January 2002. This run included Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV for which ~10 M minimum bias events were acquired followed by a period of $\sqrt{s_{NN}}$ = 200 GeV $p + p$ collisions yielding ~4 M min bias events. A major milestone in 2002 was the Quark Matter 2002 conference that was held in Nantes, France, July 18-24 at which the PHOBOS collaboration presented several new and unique results from the $\sqrt{s_{NN}}$ = 200 GeV Au + Au running. The third RHIC run which started on November 1, 2002 was devoted to d + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. During this run ~130 M events minimum bias events and ~20 M spectrometer triggered events were collected. The justification for studying this asymmetric system was to acquire reference spectra to compare to the ones obtained for Au + Au collisions, which showed strong suppression of high p_T particles traversing the hot and dense volume created in these collisions. Several detector upgrade and maintenance projects were carried out in preparation of the RHIC run-3 in order to improve the data taking capability of the experiment. These projects included: 1) moving the time-of-flight walls to larger distances to improve their capabilities, 2) upgrading the data-acquisition system to be able to handle an event rate of 250 Hz (up from 30 Hz), 3) installation of an array of plastic scintillators outside of the PHOBOS spectrometer in order to enhance the spectrometer event sample, and 4) installation of calorimeters around the beam-pipe in order to improve the triggering on low multiplicity events from d + Au and p + p collisions. In addition, several Si ring modules were replaced.

ELLIPTICAL FLOW

The elliptical flow signal, v_2, is defined as the amplitude of the second Fourier component of the azimuthal distribution of particles, *i.e.*

$$dN/d(\varphi-\psi) \propto 1+2\nu_2 \cosh(\varphi-\psi)$$

where ψ is the azimuthal angle of the event-plane estimated for each event. The collective flow of particles from the collision zone provides an important indication for the underlying reaction mechanism as it signals the build-up of pressure gradients in the overlap-zone of the colliding ions. The PHOBOS detector is particularly well suited to measure the elliptical flow because of the near azimuthal symmetry of the multiplicity detectors (the octagon and ring detectors) and because it can obtain these measurements over a wide range of pseudo-rapidity, a feature that is unique to the PHOBOS experiment. The study and analysis of the elliptical flow signal for the 130 GeV Au + Au collisions was completed in 2002 and was published in Phys. Rev. Lett.[1] The analysis of the 200 GeV Au + Au data is in progress and nearing completion. The main results of the 130 GeV analysis are shown in Figs. I-52 and I-53.

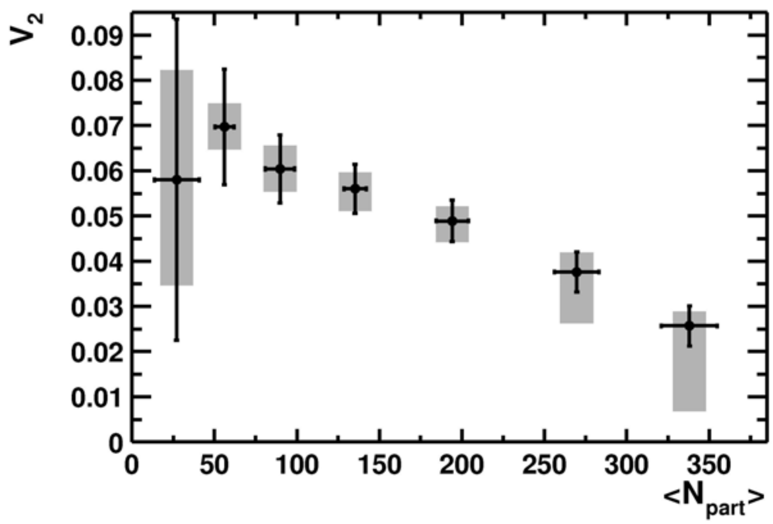

Fig. I-52. Fully corrected measurement of elliptic flow, v_2, as a function of the number of participants for $|\eta| < 1.0$. The black error bars represent the 1σ statistical errors and the gray bands give a measure of the systematic error for each point ~90% confidence level.

The amplitude of the flow signal, v_2, is shown in Fig. I-52 as a function of $\langle N_{part} \rangle$, which is a measure of the collision centrality, reaching a value of ~7% for peripheral collisions and decreasing to ~2.5% for the most central bin. Note that symmetry considerations demand that the flow signal vanish for truly central collisions. The large flow signals observed at RHIC energies, first observed by the STAR collaboration,[2] are surprisingly large and approach the hydrodynamic limit indicating that the interaction zone is characterized by a high density of strongly interacting particles, possibly of partonic nature, allowing for the build-up of pressure gradients that manifest themselves in the observed azimuthally asymmetrical emission patterns.

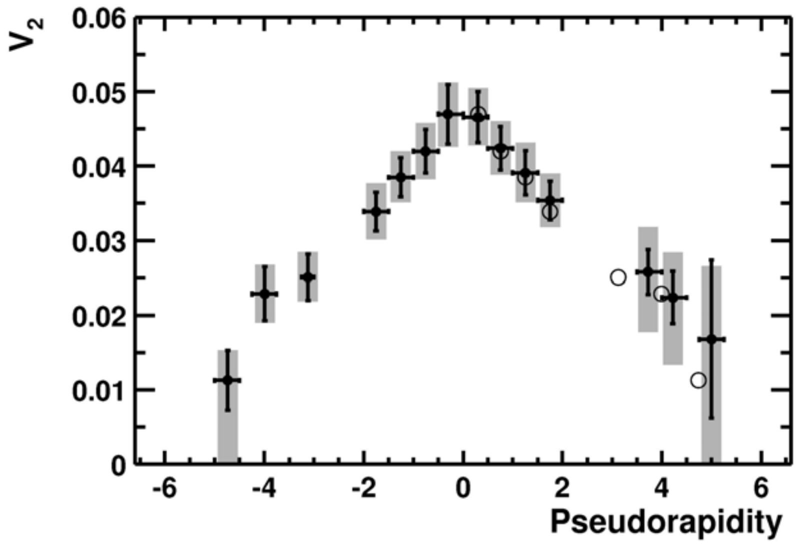

Fig. I-53. Elliptic flow, averaged over centrality, as a function of pseudo-rapidity, η. The graphical representation of the errors is similar to that shown in Fig. I-52. The points on the negative side are reflected about $\eta = 0$ and shown on the positive side as open circles.

The elliptical flow amplitude, v_2, is shown as a function of pseudo-rapidity, η, in Fig. I-53 for centrality averaged events. The ability to measure the flow signal over a wide range of pseudo-rapidity (angle) is unique to PHOBOS. The value of v_2 is seen to decrease away from the mid-rapidity region, an effect that has yet to find a theoretical explanation.

CHARGED PARTICLE MULTIPLICITY

The PHOBOS collaboration has carried out complete measurements[3-7] of the charged particle multiplicity in Au + Au collisions at three different energies $\sqrt{s_{NN}}$ = 19.6, 130, and 200 GeV in addition to a rudimentary measurement at $\sqrt{s_{NN}}$ = 56 GeV, which was obtained during the initial commissioning period of RHIC in 1999. A recent analysis[8] of the pseudo-rapidity distributions of the charged particle multiplicities, $dN/d\eta$, shows that the charged-particle multiplicity distribution exhibit "limited fragmentation" scaling behavior when displayed as a function of the parameter $\eta' = \eta - y_{beam}$, where y_{beam} is the beam rapidity. This scaling behavior has been seen previously in $p + p$ collisions over a wide energy range, but is even more pronounced for the high quality heavy-ion data obtained by PHOBOS. The full set of multiplicity distributions measured by PHOBOS is presented in Fig. I-54.

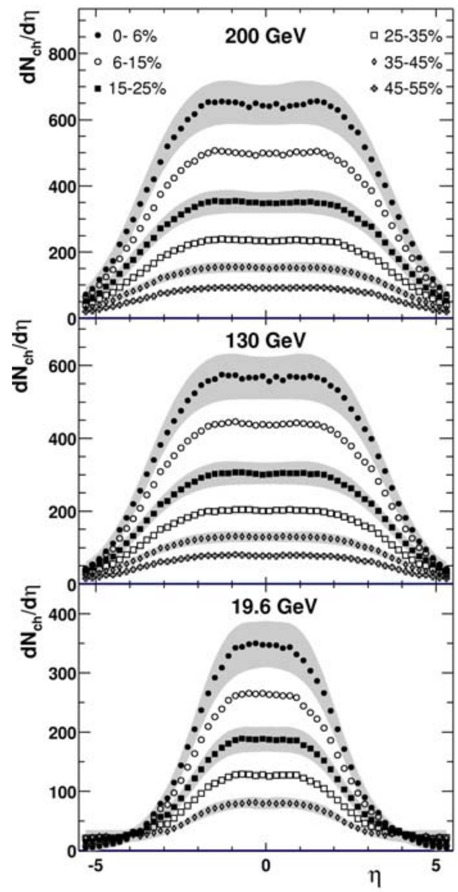

Fig. I-54. The charged particle pseudorapidity distribution, $dN_{ch}/d\eta$, measured for Au + Au at $\sqrt{s_{NN}}$ = 200, 130, and 19.6 GeV for the specified centrality bins. These bins range from 0-6% central to 45-55% in the case of the higher energy data and 0-6% to 35-45% for 19,6 GeV data. The statistical errors are negligible. The typical systematic errors (90% C.L.) are shown as bands for selected centrality bins.

The data show a typical plateau at mid-rapidity indicative of boost-invariance in this region. The width and height of the boost invariant region increases with collision energy followed by a gentle fall-off to larger pseudo-rapidities. Because of the large coverage of the PHOBOS Multiplicity Detector it is possible to estimate with good accuracy the total number of charged particles produced in the collisions. For the bin covering the 6% most central collisions the total number of charged particles are N_{tot} = 1680 ± 100, 4170 ± 210, and 5060 ± 250 for the 19.6, 130, and 200 GeV collision energy, respectively.

TRANSVERSE MOMENTUM SPECTRA

Using the PHOBOS spectrometer inclusive hadron p_T-spectra have been measured for Au + Au collisions at 200 GeV. The quality of the spectra is displayed in Fig. I-55. By comparison to proton-antiproton spectra measured at the same energy we observe a pronounced deficit for central collisions when accounting for the number of elementary two-body collisions (N_{coll} = 1050) expected in central (0-6%) Au + Au collisions. This suppression of the high-p_T part of the spectrum has also been observed by the STAR and PHENIX collaborations. It is conjectured to be caused by large energy losses of partons from hard scatterings in the hot and dense (and presumably partonic) medium formed in the collision. Further information on this topic may be expected from this year's *d + Au* data, where hard scattered partons traverse only the cold and less dense (Au) nuclear medium.

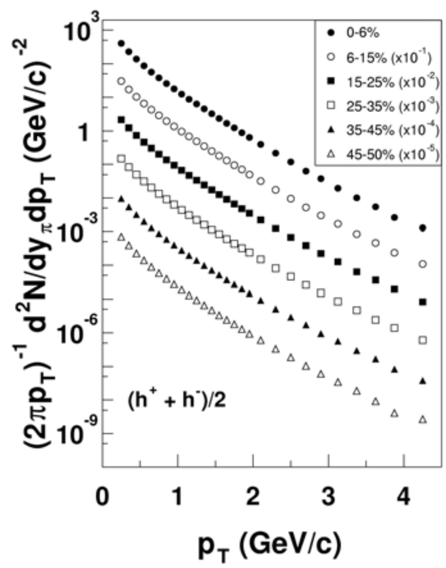

Fig. I-55. Invariant yields for charged hadrons as a function of p_T for six centrality bins. For clarity, consecutive bins are scaled by factors of 10. Statistical and systematic uncertainties are smaller than the symbol size.

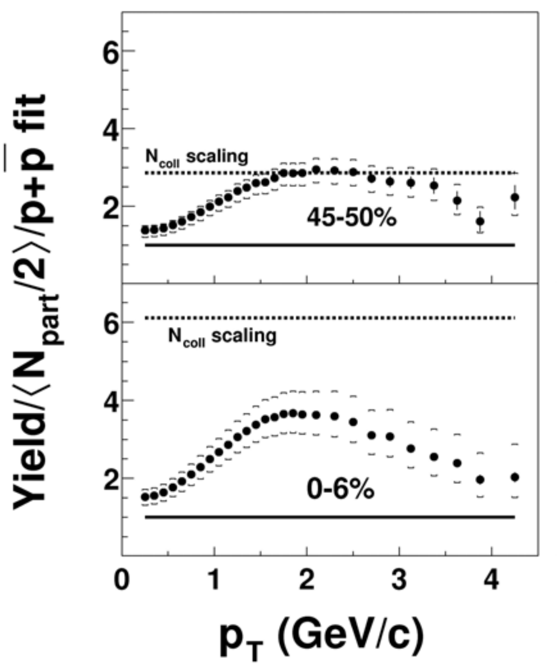

Fig. I-56. Ratio of the yield of charged hadrons as a function of p_T for the most peripheral bin ($<N_{part}> = 65 \pm 4$, upper panel) and the most central bin ($<N_{part}> 344 \pm 11$, lower panel) to a fit of proton-antiproton data scaled by $<N_{part}/2>$. The dashed (solid) line shows the expectation for N ($N_{par}t$) scaling relative to p + p collisions. The brackets show the systematic uncertainty of the Au + Au data.

The PHOBOS collaboration has observed that the high-p_T part of the spectra appears to scale instead rather well with the number of participants N_{part} in collisions ($N_{part} = 344 \pm 11$ for 0-6% centrality), which is largely consistent with a picture in which only hard-scattered partons from the surface are observable because those from the interior of the overlap zone suffer large energy losses and are shifted down to the soft part of the spectrum, see Fig. I-56. A manuscript presenting these data was submitted to Phys. Rev. Lett.[9]

ANTI-PARTICLE TO PARTICLE RATIOS

The anti-particle to particle ratio for pions, kaons and protons has been measured for 200 GeV Au + Au collisions using the PHOBOS spectrometer. The following results were found[10]: $\langle \pi^+ \rangle / \langle \pi^- \rangle$ = 1.025 ± 0.006(stat) ± 0.018(syst), $\langle K^+ \rangle / \langle K^- \rangle$ = 0.95 ± 0.03(stat) ± 0.03(syst), and $\langle \bar{p} \rangle / \langle p \rangle$ = 0.73 ± 0.02(stat) ± 0.03(syst). When analyzed within a statistical model of particle production assuming thermal equilibrium between various particle species,[11] one obtains a value of the ratio of the baryo-chemical potential, μ_B, to the temperature, T, of μ_B/T = 0.17 ± 0.01(stat.), see Fig. I-57. For a typical chemical freeze-out temperature of T = 165 MeV, one obtains a value of μ_B = 27 ± 2(stat.) MeV, which is about half of the value of μ_B = 45 ± 5(stat.) MeV found at 130 GeV. These results therefore show that an almost baryon-free region is generated in Au + Au collisions at the highest RHIC energy.

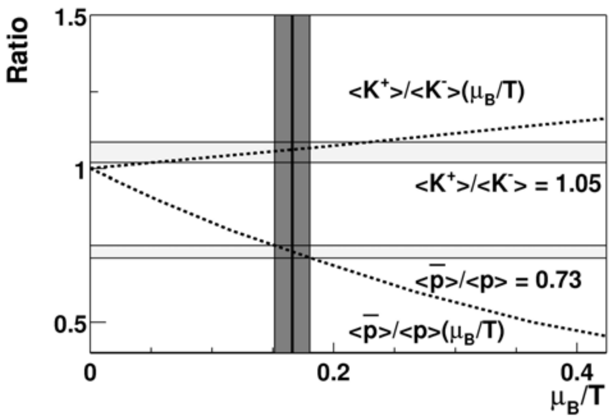

Fig. I-57. Statistical model calculation (dotted curves) of $\langle K^+ \rangle / \langle K^- \rangle$ and $\langle \bar{p} \rangle / \langle p \rangle$ as a function of μ_B/T from Becattini et al.[9] The horizontal bands show the ratios observed in the data (statistical errors only). The vertical shaded area indicates the allowed region in μ_B/T.

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