Abstract. This manuscript contains a summary of the latest physics results from PHOBOS, as reported at Quark Matter 2006. Highlights include the first measurement from PHOBOS of dynamical elliptic flow fluctuations as well as an explanation of their possible origin, two-particle correlations, identified particle ratios, identified particle spectra and the latest results in global charged particle production.

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Over the last year, PHOBOS [1] has continued to analyze the large dataset obtained from the first five runs (2000-2005) of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. To a large extent, one of the primary goals of PHOBOS to obtain a broad survey of the global properties of charged particle production is nearing completion. We report two new results in this area, the first for the lowest energy Cu+Cu collisions, $\sqrt{s_{NN}} = 22.4$ GeV, and the second for the peripheral yields of midrapidity charged particle emission in Au+Au. In both cases the new data has followed the striking scaling rules reported in the past by PHOBOS [2, 3, 4], in particular the energy-independence of particle production when viewed in the rest-frame of one of the colliding nuclei [5] and the factorization of the energy and centrality dependence of midrapidity charged particle yields [6, 7]. We also report final results for identified hadron transverse momentum spectra down to very low $p_T$ in Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV as well as new results for antiparticle to particle ratios in Cu+Cu collisions [8]. The measurement of both elliptic and directed flow of charged particles over a uniquely large range in pseudorapidity ($-5.4 < \eta < 5.4$) has been an area of active analysis in PHOBOS from the very first Au+Au collisions [9, 10]. The large elliptic flow signals ($v_2$) measured near midrapidity at full RHIC energies, which are in agreement with hydrodynamical model calculations of a relativistic hydrodynamic fluid, have provided strong credence for our current view that we are producing a strongly interacting state of matter that reaches equilibration early in the collision process. The comparison between Cu+Cu and Au+Au of $v_2(\eta)$ and mid-rapidity $v_2(p_T)$ [11] further strengthens our understanding of the PHOBOS result reported at Quark Matter 2005 [12]: the $v_2$ results for both systems can be consistently unified when scaled by the “participant eccentricity”, $\langle \varepsilon_{\text{part}} \rangle$, where $\varepsilon_{\text{part}}$ is defined event-by-event as the initial overlap eccentricity measured in the rotated “participant” frame where that eccentricity is maximized. Furthermore, the importance of the initial event-by-event interaction points of the participant nucleons as defined by $\langle \varepsilon_{\text{part}} \rangle$, comes into clear focus when the fluctuations of this quantity are calculated and compared to the newly measured $v_2$ dynamical fluctuations in Au+Au [13, 14]. On the two particle correlations front, we present new data showing correlations between particles in p+p and Cu+Cu data at $\sqrt{s_{NN}} = 200$ GeV over a uniquely large region of $\Delta \eta$ and $\Delta \phi$ [15]. We also present the first physics results of a study of the centrality dependence of the short-range pseudorapidity correlations as measured by the effective cluster size, $K_{\text{eff}}$. Studies of cluster production indicate that the isotropic cluster model produces a cluster width in pseudorapidity that is larger than found in the resonance cascade model. PHOBOS also reported on the latest results of two ongoing studies of multiplicity fluctuations in Au+Au collisions, in particular the search for enhanced $dN_{ch}/d\eta$ fluctuations and the forward-backward multiplicity fluctuations in the context of two models of cluster production [16]. The current upper limit for the fraction of events with large deviations in the $dN_{ch}/d\eta$ distribution of 200 GeV Au+Au collisions is $10^{-5}$. In conclusion, we will give a brief overview of the future direction of the PHOBOS research program.

One of the primary motivations of colliding Cu+Cu and Au+Au nuclei at RHIC
was to enable a detailed study of the effect of system size on all measurable physics observables. The study of elliptic flow, with its sensitivity to the collectivity of the produced matter at very early times of the collision, is a physics measurement of particular interest. The result of this analysis and comparison for $\sqrt{s_{NN}} = 200$ GeV is shown in Figure 1 for the PHOBOS hit-based and track-based elliptic flow analysis, as a function of centrality defined by the number of participants, $N_{\text{part}}$. Two important features are immediately evident. First, the magnitude of flow in the smaller Cu+Cu system is large and qualitatively follows a similar trend with centrality as seen in the larger Au+Au system. Second, even for the most central collisions in Cu+Cu, the magnitude of $v_2$ is substantial, and exceeds that seen in central Au+Au.

In the most intuitive picture, our understanding of elliptic flow is that the magnitude of the final azimuthal angular distribution of produced particles relative to the reaction plane is a consequence primarily of the initial overlap eccentricity of the colliding nuclei. If this picture is correct, the elliptic flow results for both Cu+Cu and Au+Au should be compatible if each is scaled by the proper eccentricity. We have proposed that the most relevant eccentricity is not the one calculated relative to the initial impact parameter vector, which we will call the ‘standard’ calculation $\langle \epsilon_{\text{std}} \rangle$, but instead the eccentricity calculated event-by-event after rotating into the frame of reference that maximizes the eccentricity defined by the participant nucleon interaction points, $\langle \epsilon_{\text{part}} \rangle$. The difference between these calculations is shown in Figure 2, and deviations are clearly evident for smaller number of participants in Au+Au and all centralities of Cu+Cu collisions, a result that illustrates the importance of finite-number fluctuations of the participant interaction points. This result is robust to the details of the Glauber Monte Carlo simulation, as indicated by the bands which show the 90% C.L. systematic errors. When the $v_2$ data of Figure 1 is scaled by $\langle \epsilon_{\text{part}} \rangle$, the two very different systems are unified on a single curve as shown in the right-hand side of Figure 2.

The unification of the elliptic flow results in Cu+Cu and Au+Au collisions when scaled by the participant eccentricity holds not only for the average value of $v_2$ at
midrapidity, but also as a function of transverse momentum and pseudorapidity. This new result is shown in Figure 3, where for the same number of participants in both systems we find a consistent result out to 3.5 GeV/c in $p_T$ and across $\pm 5$ units of $\eta$.

The apparent relevance of the participant eccentricity model in unifying the average elliptic flow results for Cu+Cu and Au+Au collisions leads naturally to consideration of the dynamical fluctuations of both the participant eccentricity itself as well as in the elliptic flow signal from data. Simulations of the expected dynamical fluctuations in participant eccentricity as a function of $N_{\text{part}}$ were performed using the PHOBOS Monte Carlo Glauber based participant eccentricity model, and they predict large dynamical fluctuations, $\sigma(\epsilon_{\text{part}})/\langle \epsilon_{\text{part}} \rangle$ of the order of 0.4 in Au+Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV. There are several different approaches one could develop to measure dynamical elliptic flow fluctuations, and PHOBOS has recently created a new method that is based on a direct measure of $v_2$ on an event-by-event basis using a maximum likelihood fit that utilizes the unique large pseudorapidity coverage of the PHOBOS detector [14, 18]. The strength of this approach lies in the fact that this analysis removes the effects of statistical fluctuations and multiplicity dependence by applying a detailed

**Figure 2.** Left: Two different calculations for the average eccentricity for Cu+Cu and Au+Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV, see text for details. Right: The measured midrapidity $v_2$ divided by the participant eccentricity.

**Figure 3.** Eccentricity scaled elliptic flow results in Cu+Cu and Au+Au collisions at matched $\langle N_{\text{part}} \rangle$. Results are shown for $v_2/\langle \epsilon_{\text{part}} \rangle$ versus $p_T$ (left) and $\eta$ (right).
Latest Results from PHOBOS

Figure 4. Left: Event-by-event measurement of $\langle v_2 \rangle$ compared with hit and track based PHOBOS results. Right: Measured dynamical fluctuations in elliptic flow ($\sigma(v_2)/\langle v_2 \rangle$), participant eccentricity fluctuations calculated in the PHOBOS participant eccentricity model, and the sensitivity of the measurement in the case of no dynamical fluctuations.

model of the detector response that enables both a measurement of the average $v_2$ on an event-by-event basis as well as a measure of the dynamical fluctuations in $v_2$. The experimental results for both the average $\langle v_2 \rangle$ and the measured dynamical fluctuations, which we quantify using the ratio $\sigma(v_2)/\langle v_2 \rangle$, obtained in this new analysis are given in Figure 4 for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The left-hand side of Figure 4 shows the results for the average midrapidity elliptic flow obtained from the event-by-event analysis together with the results from both the hit-based and track-based analyses. The error bars represent statistical errors and the shaded bands the 90% C.L. systematic uncertainties. Confidence that all three measurements are determining the average elliptic flow is increased through the observation that they agree within the systematic errors. The right-hand side of Figure 4 presents the new PHOBOS results for $v_2$ dynamical fluctuations together with the result obtained for fluctuations in the participant eccentricity. Systematics on the experimental measurement are improved by quantifying the result as a ratio of $\sigma(v_2)/\langle v_2 \rangle$. We observe large dynamical fluctuations in elliptic flow with a magnitude in remarkable agreement with calculations of participant eccentricity fluctuations. This result suggests that the initial state equilibrates very rapidly with a collision eccentricity largely defined by each collision event’s particular distribution of participant nucleon interaction points, and this detailed “snapshot” of the two nuclei’s overlap region is propagated by the subsequent hydrodynamic evolution of the produced matter.

PHOBOS has also made great progress in studying two-particle correlations between charged particles. We have recently published results on forward-backward multiplicity correlations in non-overlapping bins of pseudorapidity for $\sqrt{s_{NN}} = 200$ GeV
Au+Au collisions [19]. From this analysis we found that particles in Au+Au collisions are not produced independently, but instead appear to be produced in clusters. In particular, we found significant short-range correlations at all centralities, both as a function of $\eta$ and as a function of increasing pseudorapidity bin, $\Delta \eta$. Here we report a completely new two-particle correlation analysis that fully utilizes the extensive coverage in pseudorapidity ($|\eta| \leq 3.2$) and azimuthal angle ($\Delta \phi = 2\pi$) afforded by the PHOBOS Octagon detector and its corresponding ability to measure essentially the full bulk of charged particle emission down to very low momentum. At this point in time, we report the preliminary results of this measurement in both p+p and Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV, where we emphasize that no $p_T$ cut on any particle is imposed. The correlation is calculated in the following way:

$$R(\Delta \eta, \Delta \phi) = \left\langle (n - 1) \left( \frac{F_n(\Delta \eta, \Delta \phi)}{B_n(\Delta \eta, \Delta \phi)} - 1 \right) \right\rangle,$$

where $F_n$ is the same-event two particle correlation between all charged particles, $n$, and $B_n$ is the uncorrelated background. An example of the results of this analysis for central Cu+Cu collisions is shown in the left-hand side of Figure 5. One can already observe the $\Delta \phi$ correlations resulting from elliptic flow, something not present in the corresponding p+p data. Motivated by the interesting results found in the forward-backward correlations analysis, we initially have focused on studying the short-range correlations in pseudorapidity. To accomplish this, we project onto $\Delta \eta$ to obtain one-dimensional correlations in $\Delta \eta$, to which we perform fits in order to extract the parameter $K_{\text{eff}}$, the effective cluster size. This result is presented in the right-hand side of Figure 5. The results clearly show that on average, even in heavy-ion collisions such as Cu+Cu, particles tend to be produced in clusters with a size of $K_{\text{eff}} = 2 - 3$, which is surprisingly similar to that seen in elementary p+p collisions. In addition, there is a
nontrivial dependence of $K_{\text{eff}}$ on centrality, such that the value is larger than seen in p+p collisions for peripheral Cu+Cu collisions and decreases with centrality to a value below that found in p+p for central collisions. The observed variation of $K_{\text{eff}}$ with centrality is not seen in HIJING, and although the centrality dependence is qualitatively reproduced by AMPT, the magnitude is still below that seen in the data. For more details see Ref. [15].

PHOBOS has also continued its analysis of identified charged particles. The left-hand side of Figure 6 gives one of the results for identified hadron transverse momentum spectra in Au+Au collisions at $\sqrt{s_{\text{NN}}} = 62.4$ GeV [20]. The unique coverage of PHOBOS at very low $p_T$ is evident, and the results of a blastwave fit to the higher $p_T$ data, measured using both the Spectrometer and time-of-flight detector, is found to be consistent with the combined yields of pions, kaons and protons at low $p_T$. The right-hand side of Figure 6 shows new results on antiparticle to particle ratios as a function of centrality measured in 62.4 and 200 GeV Cu+Cu [8]. The PHOBOS measurement of antiparticle to particle ratios is unique in that due to the two identical Spectrometer arms located on opposite sides of a dipole magnet we can, by simply reversing the magnetic field systematically during data taking, extract four independent measurements of identified particle ratios where all effects of acceptance and efficiency cancel out in the final ratio. The energy dependence of the proton and kaon particle ratios between $\sqrt{s_{\text{NN}}} = 62.4$ and 200 GeV is clearly evident in Figure 6 and we find in all cases that the ratios are only weakly dependent, if at all, on centrality.

![Figure 6](image_url)

**Figure 6.** Left: Identified particle spectra for Au+Au collisions at $\sqrt{s_{\text{NN}}} = 62.4$ GeV. Right: Antiparticle to particle ratios for protons, kaons and pions in Cu+Cu collisions at $\sqrt{s_{\text{NN}}} = 62.4$ and 200 GeV.

The latest results on global charged particle emission are shown in Figure 7. As shown in the left-hand figure, we have extended the analysis for the midrapidity charged
particle multiplicity in Au+Au collisions to lower centrality, enabling a better overlap in $N_{\text{part}}$ with the Cu+Cu system. On the right-hand side of Figure 7, we have also completed the analysis of $dN_{\text{ch}}/d\eta$ for all Cu+Cu energies with the addition of the lowest energy data at $\sqrt{s_{\text{NN}}} = 22.4$ GeV. The new results for even the lowest energy Cu+Cu data exhibit the same striking feature of extended longitudinal scaling [5] that appears to be a general feature of all heavy-ion results at RHIC energies.

The future PHOBOS physics program will continue to be based on the comprehensive dataset that already exists. This data consists of Au+Au collisions at $\sqrt{s_{\text{NN}}} = 19.6$, 62.4, 130 and 200 GeV, Cu+Cu collisions at $\sqrt{s_{\text{NN}}} = 22.4$, 62.4 and 200 GeV, d+Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV and p+p collisions at $\sqrt{s_{\text{NN}}} = 200$ and 410 GeV. The p+p dataset will allow for a measurement of $dN_{\text{ch}}/d\eta$ as a function of total multiplicity. On the heavy-ion side, we will extend the studies of dynamical flow fluctuations to other systems and energies. The two-particle correlations study between all particles will also be extended to Au+Au collisions. We are currently exploring the feasibility of performing two-particle correlations studies using a high $p_T$ trigger particle, as measured in the Spectrometer, correlated with the bulk charged particle production, as measured by the Octagon detector. We will continue to exploit the unique PHOBOS capabilities for particle identification at very low $p_T$ by using the high-statistics Au+Au data set at $\sqrt{s_{\text{NN}}} = 200$ GeV to extract yields of pions, kaons and protons as a detailed function of centrality. We plan to complete the PHOBOS comprehensive study of antiparticle to particle ratios with measurements in both Cu+Cu and Au+Au at $\sqrt{s_{\text{NN}}} = 62.4$ and 200 GeV, as a detailed function of centrality and $p_T$. We also continue to actively pursue studies of $\phi$-meson production at very low $p_T$. In short, although the active data-taking of PHOBOS at RHIC has come to a close, there is still a great deal of interesting and relevant physics to be explored and discovered.

Figure 7. Global charged particle production in Au+Au and Cu+Cu. Left: The ratio of midrapidity yields for different energies. Right: The pseudorapidity dependence for central collisions effectively shifted into the rest frame of one of the nuclei.
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