Recent Results from PHOBOS

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Abstract. In this manuscript we give a short summary of recent physics results from PHOBOS. Particular emphasis is put on elliptic flow, fluctuations in the initial geometry and the recent measurements of elliptic flow fluctuations.

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1. Summary of recent results

In the first five runs (2000–2005) of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory, the PHOBOS experiment [1] has collected data from 4 collision systems (p+p, d+Au, Cu+Cu and Au+Au) in a wide range of collision energies (19.6, 22.4, 62.4, 127, 200 and 410 GeV). To a large extent, analyses of this dataset dealt with the global properties of charged particle production. Recent results in this area extend the measurement of midrapidity charged particle multiplicity in Au+Au collisions to lower centrality, enabling a better overlap in $N_{\text{part}}$ with the Cu+Cu system and include the analysis of the $dN_{\text{ch}}/d\eta$ for all Cu+Cu energies, including the lowest energy data at $\sqrt{s_{\text{NN}}} = 22.4$ GeV [2]. Furthermore, we have also obtained preliminary results on elliptic flow [3] in Cu+Cu collisions at $\sqrt{s_{\text{NN}}} = 22.4$ GeV, completing our set of measurements on elliptic flow at RHIC for Cu+Cu and Au+Au collisions at all available energies [1, 5, 6, 7]. The final results for charged particle production down to very low transverse momenta in Au+Au collisions at $\sqrt{s_{\text{NN}}} = 62.4$ GeV [8], as well as preliminary measurements of antiparticle to particle ratios [9] in Cu+Cu collisions have been obtained. A completely new analysis of charged two-particle angular correlations has been developed that fully utilizes the extensive coverage in pseudorapidity ($\Delta \eta \leq 6.4$) and azimuthal angle ($\Delta \phi \leq 2\pi$) provided by the PHOBOS multiplicity (Octagon) detector and its corresponding ability to measure the full bulk of charged particle emission down to very low momentum. Studies related to this analysis initially have focused on the short-range correlations in pseudorapidity. Preliminary results for Cu+Cu [10] and final results for p+p [11] have recently been reported.

2. Elliptic flow and eccentricity fluctuations

Since the start of the RHIC program, studies of collective phenomena via the measurement of the azimuthal distribution of produced particles have been one of the most important probes of the dynamics of nucleus–nucleus collisions. In particular, elliptic flow is sensitive to the early stages of the collision and its study provides unique insights into the properties of the hot, dense matter that is produced in these collisions. At the root of the interpretation of elliptic flow lies the connection to the initial overlap geometry of the colliding nuclei. The azimuthal spatial asymmetry of the almond-shaped overlap region can only be reflected in the azimuthal distribution of detected particles if the produced particles do significantly interact already shortly after the initial production. At top RHIC energy, a large elliptic flow ($v_2$) signal near midrapidity has been observed [12]. Its magnitude is found to be in agreement with hydrodynamical model calculations of a relativistic hydrodynamic fluid which supports the current view that a strongly interacting state of matter is produced early in the collision process. 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. This is particularly interesting for elliptic flow. Figure 1 shows the magnitude of the
elliptic flow, $v_2$, obtained from the PHOBOS hit-based and track-based analyses, as a function of centrality defined by the number of participants, $N_{\text{part}}$ \cite{7}. 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 collisions.

In the most intuitive picture, the understanding of elliptic flow is that the anisotropy of the azimuthal angle distribution of the final particles relative to the event plane is a consequence primarily of the initial eccentricity of the overlap region. If this picture is correct, the elliptic flow results for both Cu+Cu and Au+Au collisions for the same volume of the overlap region ($N_{\text{part}}$) should be compatible if each is scaled by the proper eccentricity. The eccentricity ($\epsilon$) of the overlap region can be estimated with the collection of participating nucleons. There are several definitions for calculating $\epsilon$, two of which are illustrated in Figure 2. On the left, a schematic depiction of the “standard” (top, $\epsilon_{\text{std}}$) and “participant” (bottom, $\epsilon_{\text{part}}$) methods are shown. The former calculates the eccentricity of the overlap region assuming that the minor axis of the overlap region is aligned along the impact parameter. The impact parameter and the beam direction define the nuclear reaction plane. However, fluctuations in the nucleon interaction points frequently create a situation where the minor axis of the overlap ellipse is not aligned with the impact parameter vector. The participant eccentricity definition \cite{13} accounts for this by quantifying the eccentricity with respect to the major axes of the overlap ellipse.

\[
\epsilon_{\text{std}} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2} \quad \epsilon_{\text{part}} = \sqrt{\left(\frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}\right)^2 + 4\frac{\sigma_{xy}^2}{\sigma_y^2 + \sigma_x^2}}
\] (1)
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Figure 2. Left: Visualization of the two approaches for calculating the eccentricity. The purple region (at center) in each collision illustrates the interacting nucleons. The orange and yellow nucleons (away from collision zone) are assumed not to directly influence the eccentricity. The solid line represents the impact parameter direction, the dashed line the direction of one of the axes in the calculation of the eccentricity (rotated by \( \Psi_0 \) with respect to the nuclear reaction frame). In the upper panel this direction is aligned with the impact parameter, while in the lower panel it is aligned along the minor axis of the participant region. Right: Comparison of \( \langle \epsilon_{\text{std}} \rangle \) and \( \langle \epsilon_{\text{part}} \rangle \) for Au+Au and Cu+Cu collisions at \( \sqrt{s_{NN}} = 200 \) GeV. The grey bands show the systematic uncertainty from variation of the Glauber simulation parameters as described in Ref. [7].

Figure 3. The average elliptic flow, \( v_2 \), scaled by the eccentricity from a Glauber model calculation for the (a) standard and (b) participant approaches. Data are for Au+Au and Cu+Cu collisions at \( \sqrt{s_{NN}} = 200 \) GeV. Shaded bands (error bars) represent the systematic (statistical) uncertainty from data.

Eqn 1 is the mathematical representation of the eccentricity for both definitions, where \( \sigma_{xy} = \langle xy \rangle - \langle x \rangle \langle y \rangle \), \( \sigma_x^2 \) and \( \sigma_y^2 \) are the (co-)variances of the \( x \) and \( y \) participant nucleon position distributions expressed in the nuclear reaction frame. The difference in mean
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Figure 4. Left: Event-by-event measurement of $v_2$ (with corresponding $\sigma_{v2}$ in the lower panel) at mid-rapidity compared with standard hit- and track-based PHOBOS results. Boxes and gray bands show 90% C.L. systematic errors and the error bars represent 1-$\sigma$ statistical errors. Right: Measured dynamical fluctuations in elliptic flow $\sigma(v_2)/(\langle v_2 \rangle)$, and participant eccentricity fluctuations calculated in the PHOBOS participant eccentricity model. The figures are taken from Ref. [15].

Deviations are clearly evident for peripheral and most central Au+Au collisions and for 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. Figure 3 compares the PHOBOS hit-based $v_2$ data scaled by $\epsilon_{\text{std}}$ and $\epsilon_{\text{part}}$. It is evident that the two very different systems are unified when scaled by the participant eccentricity. As recently presented, this unification 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 [3].

3. Elliptic flow fluctuations

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 measured 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. 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 assuming that the shape of \( v_2 \) in pseudo-rapidity is either triangular or trapezoidal and that utilizes the unique large pseudorapidity coverage of the PHOBOS detector \[14, 15\]. 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 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 \( \sigma_{v_2} \), which we also 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 \[15\]. 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 standard 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 supported by the observation that they agree within the systematic errors. The right-hand side of Figure 4 presents the PHOBOS results for \( v_2 \) dynamical fluctuations together with the result obtained for fluctuations in the participant eccentricity. Systematics on the experimental measurement are decreased 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. The observed agreement suggests that the fluctuations of elliptic flow primarily reflect fluctuations in the initial state geometry and are not affected strongly by the latter stages of the collision. Note that the systematic errors imposed in our results include estimates from non-flow contributions to the observed magnitude of the flow fluctuations that rely on a description of non-flow effects in HIJING. We are currently working on an MC-independent way to estimate this contribution from data using two-particle correlation measurements.

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