Partonic flow and $\phi$-meson production in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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(STAR Collaboration)
We present first measurements of the $\phi$-meson elliptic flow ($v_2(p_T)$) and high statistics $p_T$ distributions for different centralities from $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions at RHIC. In minimum bias collisions the $v_2$ of the $\phi$ meson is consistent with the trend observed for mesons. The ratio of the yields of the $\Omega$ to those of the $\phi$ as a function of transverse momentum is consistent with a model based on the recombination of thermal $s$ quarks up to $p_T \sim 4$ GeV/c, but disagrees at higher momenta. The nuclear modification factor ($R_{CP}$) of $\phi$ follows the trend observed in the $K^0_S$ mesons rather than in $\Lambda$ baryons, supporting baryon-meson scaling. Since $\phi$-mesons are made via coalescence of seemingly thermalized $s$ quarks in central Au+Au collisions, the observations imply hot and dense matter with partonic collectivity has been formed at RHIC.

PACS numbers:
The primary aim of ultra-relativistic heavy-ion collisions is to produce and study a state of high-density nuclear matter called the Quark-Gluon Plasma (QGP), the existence of which is supported by lattice QCD calculations \[1, 2, 3\]. In the search for this new form of matter, penetrating probes are essential in order to gain information from the earliest stage of the collisions. Phenomenological analysis \[4\] has suggested a relatively small hadronic interaction cross section for the central-triggered dataset comprised about 10 million events. Events were required to have a primary vertex \(z\) position (where \(z\) is the direction of the beam axis) within 30 cm of the center of the TPC. Events from the minimum bias dataset were divided into 8 centrality bins: 0-10\%, 10-20\%, 20-30\%, 30-40\%, 40-50\%, 50-60\%, 60-70\%, and 70-80\% of the measured cross-section. The central-triggered dataset was used to extract the 0-5\% and 0-12\% data.

The \(v_2\) yield in each \(p_T\) bin was extracted from the invariant mass \((m_{inv})\) distributions of \(K^+ + K^-\) candidates after subtraction of combinatorial background estimated using event mixing \[5\]. The kaons were identified through their \(dE/dx\) energy loss in the STAR TPC \[22\]. Including the detector resolution, the values of the reconstructed \(\phi\) mass and width are consistent with the PDG values \[23\]. The relative systematic uncertainty due to the \(dE/dx\) cut was estimated to be \(\sim 8\%\) by using different cuts and comparing the yields after a particle identification efficiency correction. Uncertainty in the residual background shape of the \(m_{inv}\) distributions resulted in a contribution of about 4.5\% to the errors on the final yields.

The \(\phi\)-meson \(v_2\) results were obtained using the \(v_2\) vs. \(m_{inv}\) method described in ref. \[24\]. The method involves calculating the \(v_2\) of the same-event distribution as a function of \(m_{inv}\) and then fitting the resulting \(v_2(m_{inv})\) distribution using:

\[
v_2(m_{inv}) = v_2S(m_{inv}) + v_2B(m_{inv})(1 - \alpha(m_{inv}))
\]

where \(v_2S = v_2\phi\) is the signal \(v_2\) and \(v_2B\) is the background \(v_2\). \(\alpha(m_{inv}) = S/(S+B)\) is the ratio of the signal over the sum of the signal plus background of the \(m_{inv}\) distributions. It was extracted from fits (Breit-Wigner plus a linear function) to the \(\phi\) mass-peak for each \(p_T\) bin. For each \(p_T\) bin, the \(v_2(m_{inv})\) was fitted using Eq. \[1\] in order to extract the fitting parameter \(v_2S\) and \(v_2B\) was parameterized using a linear or quadratic function in \(m_{inv}\). These results are consistent with results using an established method \[25\] where the \(\phi\)-meson yield is plotted as a function of the difference between its azimuthal angle and the estimated reaction plane angle, \((\phi - \Psi)\). The values of \(v_2\) are extracted from the fitting to the function \(dN/d\phi = P_0(1 + 2v_2\cos(2(\phi - \Psi)))\).

In the top panel of Fig. \[1\] we present the first measurement of the differential elliptic flow, \(v_2(p_T)\), of the \(\phi\)-meson from Au+Au collisions for four centrality bins. In this and the following figures, the vertical error bars on the \(\phi\) data points indicate the statistical errors while the shaded bands indicate the extent of the systematic uncertainties. The systematic errors vary from point to point including uncertainties in extracting the signal for obtaining \(\alpha(m_{inv})\) and differences in the reaction plane resolution determination. For minimum bias collisions, an additional contribution to account for the different methods of extracting the \(v_2(p_T)\) values is also included in the systematic error. Non-flow effects \[26\] are not
included in the systematic error. As expected, \( v_2(p_T) \) increases with increasing eccentricity (decreasing centrality) of the initial overlap region. This trend is also illustrated in Table I, which presents the \( p_T \)-integrated values of \( \phi \)-meson elliptic flow, \( \langle v_2 \rangle \), calculated by convoluting the \( v_2(p_T) \) with the respective \( p_T \) spectrum for three centrality bins. It should be noted that the centrality dependence of the \( \langle v_2 \rangle \) of \( \phi \)-mesons is consistent with that of charged hadrons [27].

### Table I: Integrated elliptic flow, \( \langle v_2 \rangle \), for the \( \phi \)-meson for three centrality bins.

| Centrality (%) | \( \langle v_2 \rangle \) (%) |
|----------------|-----------------------------|
| 0 - 5          | 2.1 \( ^{+0.2}_{-0.3}(stat) \) |
| 10 - 40        | 6.6 \( ^{+0.8}_{-0.9}(stat) \) |
| 40 - 80        | 8.5 \( ^{+1.1}_{-0.9}(stat) \) |

The lower panel of Fig. 1 shows the minimum bias (0-80%) result compared to parameterizations for number-of-quark scaling for mesons (NQ=2) and baryons (NQ=3) whose free parameters have been fixed by fitting to the \( \Lambda \) and \( K^0_S \) results simultaneously [28]. In this case, for \( p_T < 2 \text{ GeV}/c \), the \( \phi \) \( v_2 \) follows a mass-ordered hierarchy where the values of \( v_2 \), within errors, fall between those of the heavier \( \Lambda \) (open circles) and lighter \( K^0_S \) (open-squares). However, at intermediate \( p_T \), between 2-5 \text{ GeV}/c, the \( \phi \) \( v_2 \) appears to follow the same trend as \( K^0_S \). When we fit the \( v_2(p_T) \) of \( \phi \)-mesons with the quark number scaling ansatz [28], the resulting fit parameter NQ = 2.3 \( \pm 0.4 \). The fact that the \( \phi \) \( v_2(p_T) \) is the same as that of other mesons indicates that the heavier \( s \) quarks flow as strongly as the lighter \( u \) and \( d \) quarks. As previously mentioned, \( \phi \)-mesons are not formed through kaon coalescence and do not participate strongly in hadronic interactions. Therefore the results demonstrate partonic collectivity.

Figure 2 shows the \( p_T \) distributions of \( \phi \)-mesons as a function of centrality. The central-triggered dataset was used to obtain the most central spectrum while the other distributions were obtained using the minimum bias dataset. The error bars shown in Fig. 2 are statistical only. In the figure, the errors are smaller than the size of the data points.

![Fig. 1: (color online) Top panel: The elliptic flow, \( v_2(p_T) \), for the \( \phi \)-meson as a function of centrality. The vertical error bars represent the statistical errors while the shaded bands represent the systematic uncertainties. For clarity, data points are shifted slightly. Bottom panel: Minimum bias \( v_2(p_T) \) for the \( \phi \)-meson compared to results for \( \Lambda \) and \( K^0_S \). The dashed and dotted lines represent parameterizations inspired by number-of-quark scaling ideas from ref. [28] for NQ=2 and NQ=3 respectively.](image1)

![Fig. 2: (color online) Transverse momentum distributions of \( \phi \)-mesons from Au+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \). For clarity, distributions for different centralities are scaled by factors of ten. Dashed lines represent the exponential fits to the distributions and the dotted lines are Levy function fits. Error bars represent statistical errors only.](image2)
tions in peripheral collisions.

In Fig. 3, the ratios of $N(\Omega)/N(\phi)$ vs. $p_T$ for three centrality bins in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions. The solid and dashed lines represent recombination model predictions for central collisions [21] for total and thermal contributions, respectively.

FIG. 3: (color online) The $N(\Omega)/N(\phi)$ ratio vs. $p_T$ for three centrality bins in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions: (top) 0-5% vs. 40-60% and (bottom) 0-5% vs. 60-80%. The shaded bands represent the uncertainties in the Glauber model calculations for $N_{\text{part}}$ and $N(\text{mes})$ [32]. Also shown are results for $\Lambda$ and $K_S^0$ [11] and protons and $\pi^+$ [33].

In the 60-80% centrality bin (see lower, binary collision-scaled $\phi$ production is very similar to that in $p+p$ and $d+Au$ collisions where strangeness production is canonically suppressed [34]. Therefore a baryon-mesonscaling behaviour of $R_{CP}$ is not expected in the lower panel of Fig. 4. In addition, for baryons and mesons respectively, there seems to be an ordering in terms of strangeness content. This has also been observed in $R_{AA}$ for strange particles [35].

In summary, we have presented first measurements of the elliptic flow of $\phi$-mesons as a function of collision centrality in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. At low $p_T$ ($< 2$ GeV/c), $v_2$ is consistent with hydrodynamical expectations. At intermediate $p_T$ ($2 < p_T < 5$ GeV/c), $v_2$ of $\phi$-mesons is consistent with number-of-quark scaling for mesons. These observations indicate the development of partonic collectivity in the medium. Measurements of the $\phi$ $p_T$ spectra as a function of centrality show an evolution of the spectral shape from exponential to power-law-like with decreasing centrality, reflecting the increasing contributions from hard and possibly other non-equilibrium processes in more peripheral collisions. The result of a recombination model [21] is consistent with the trend of the central $N(\Omega)/N(\phi)$ ratio up to $p_T \sim 4$ GeV/c which covers more than 95% of the hadron yields. At higher $p_T$, the model fails. The $\phi$-meson $R_{CP}$ resembles the $K_S^0$ for the 0-5%/40-60% case which is consistent with meson scaling. Since $\phi$-mesons are made via coalescence of seemingly thermalized $s$ quarks in central Au+Au collisions, the observations imply hot and
dense matter with partonic collectivity has been formed at RHIC.

We thank the RHIC Operations Group and RCF at BNL, and the NERSC Center at LBNL for their support. This work was supported in part by the Offices of NP and HEP within the U.S. DOE Office of Science; the U.S. NSF; the BMBF of Germany; CNRS/IN2P3, RA, RPL, and EMN of France; EPSRC of the United Kingdom; FAPESP of Brazil; the Russian Ministry of Science and Technology; the Ministry of Education and the NNSFC of China; IRP and GA of the Czech Republic; FOM of the Netherlands, DAE, DST, and CSIR of the Government of India; Swiss NSF; the Polish State Committee for Scientific Research; SRDA of Slovakia, and the Korea Sci. & Eng. Foundation. HGR thanks the Alexander von Humboldt Foundation for generous support.

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