\textbf{\large $\phi$ meson production and partonic collectivity at RHIC}

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\textbf{Abstract.} New results on $\phi$-meson production and elliptic flow $v_2$ measurements from RHIC 2004 run (Run-IV) have been reviewed. In addition, the di-hadron correlation function between the trigged $\phi$ and $\Omega$ and the associated soft particles was simulated. Knowledge about these results are discussed.

\section{1. INTRODUCTION}

The primary goal of the Relativistic Heavy-Ion Collider (RHIC) is to produce and study a state of high density deconfined nuclear matter called the Quark-Gluon Plasma (QGP). Measurements of the production of $\phi$-meson created at RHIC Au+Au collisions can provide insight on the dense matter created in the collisions. Because $\phi$-meson is expected to have a small cross-section for interactions with other non-strange particles, and its life time is relatively long ($\sim 41$ fm/$c$), it may keep information of the early stage of the system’s evolution. The observation of meson and baryon grouping in the nuclear modification factor ($R_{CP}$) and elliptic flow ($v_2$) measurements at intermediate transverse momentum ($p_T$) \cite{2} has been interpreted as a manifestation of bulk partonic matter hadronization through multi-parton dynamic such as recombination/coalescence of partons \cite{2, 3, 4}. $\phi$-meson provides unique sensitivity to test these theoretical scenarios, since $\phi$-meson has a mass heavier than proton and close to the Lambda while it is a meson. The hypothesis of kaon coalescence as a dominant source for $\phi$-meson production has been ruled out from the STAR 2002 measurements \cite{5}. If $\phi$ flows, it may be a strong signal of the partonic collectivity formed at RHIC. Based upon these reasons, the studies on the property of $\phi$-meson at RHIC energies is of great interest.

\section{2. TRANSVERSE MOMENTUM DISTRIBUTION}

Insight into particle production can be gained by examining the shape of the $\phi$-meson $p_T$ distributions as a function of centrality \cite{6}. Figure 1 shows the $\phi$-meson transverse momentum distributions as a function of centralities for Au + Au collisions (RunIV) at...
Figure 1. The $\phi$-meson transverse momentum distributions from Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. For clarity, distributions for different centralities are scaled by factors which are shown in the figure. Dashed lines represent the exponential fits to the distributions and dotted lines are the results of Levy function fits. Error bars represent statistic errors only.

Figure 2. Comparison of the binary scaled $P_T$ spectra among different collision systems (Au+Au, d+Au and pp at $\sqrt{s_{NN}} = 200$ GeV) in their most central centrality bins.

It is observed that the shape of the spectra evolves as a function of centrality. The central data can be fitted equally well by both exponential function and Levy functions, while the more peripheral spectra can only be fitted better by the
Levy function. Comparing with the peripheral data, the yield at high-$p_T$ region for central data is suppressed. Figure 2[7] shows the comparison among different reaction systems (Au+Au at 200 GeV/c, d+Au at 200 GeV/c and p+p at 200 GeV/c) in their most central bins. The fact that the $N_{\text{binary}}$ normalized spectra of Au+Au collisions at 200 GeV is an exponential shape and those of d+Au and p+p at 200 GeV/c are Levy shapes may indicate different reaction mechanism. The exponential shape at central 200GeV/c Au+Au data may be hints of thermalization of the system too.

Recently, it was predicted[6] that the dominant production mechanism for $\phi$-meson, (and similarly for the multi-strange baryon, $\Omega$), in the range $2 < p_T < 8$ GeV/c is the thermal recombination of strange quarks while the contribution from fragmentation processes in this $p_T$ range is suppressed by a few orders of the magnitude in comparison. Left panel of Figure 3[8] shows the central $\phi$-meson and $\Omega$ spectra compared with this model calculation (solid and dashed curves). The model appears to agree well with the data over the measured $p_T$ range. The right panel of Figure 3 shows the ratio of central $\Omega$ yield to $\phi$-meson yield. In this case, the model predicts a monotonic increase with $p_T$ up to $\sim 8$ GeV/c. It is clearly seen that the model describes data well with $p_T$ up to $\sim 4$ GeV/c while the deviation at higher $p_T$ range may imply that the contribution to particle production from fragmentation processes is larger than that expected by the model.

PHENIX presented result of $\phi$-meson production via its $e^+e^-$ decay channels (Figure 4) at Quark Matter 2005 Conference[9]. Although the statistic is still limited, no significant discrepancy between $\phi \rightarrow e^+e^-$ and $\phi \rightarrow K^+K^-$ has been observed. In recent CERES results, $\phi \rightarrow e^+e^-$ and $\phi \rightarrow K^+K^-$ also agree within errors[10]. The results agree with NA49's[11], but disagree with NA50's[12]. Thus there is still something for $\phi$ production to be learned. In this case, the di-electrons channel for $\phi$-meson production
measurement from STAR will be of great interest. This measurement will be achieved with the planned upgrade of the STAR detector with a full-barrel Time of Flight detector (TOF) which is expected to significantly increase the particle identification capability [13].

Figure 4. Invariant $m_T$ spectra. Statistical and systematic errors are shown by vertical bars and open rectangles, respectively [9].

3. NUCLEAR MODIFICATION FACTOR ($R_{CP}$)

$R_{CP}$ is calculated as the ratio of the yields from central collisions to peripheral collisions scaled by the mean number of binary collisions. Comparisons of the $R_{CP}$ for Au+Au collisions ($K_s^0$, $\phi$ and $\Lambda$) at 200 GeV/c are shown in Figure [7, 8].

From the figure, we can see that at intermediate $p_T$, the $R_{CP}$ of baryon ($\Lambda$) is larger than that of mesons ($K_s^0$ and $\phi$), which implies that particle production in this $p_T$ region is driven by the particles’ types, not by their masses since $\phi$-meson’s mass is close to $\Lambda$ while it is a meson. The $R_{CP}$ results are consistent with the partonic recombination model predictions [2, 3, 4] that the centrality dependence of the yield at intermediate $p_T$ depends more strongly on the number of constituent quarks than on the particle mass. There also may be a tendency for values of $R_{CP}$ for all particles to approach each other at higher $p_T$.

4. ELLIPTIC FLOW OF $\phi$ IN LOW AND MIDDLE $p_T$ FOR 200 GeV/c Au+Au

In non-central Au+Au collisions, the overlap region is anisotropic (nearly elliptic). Large pressure built up in the collision center results in pressure gradient which is dependent on azimuthal angle, which generates anisotropy in momentum space, namely elliptic flow. Once the spatial anisotropy disappears due to the anisotropic expansion, development of elliptic flow also ceases. This kind of self-quenching process happens quickly, therefore elliptic flow is primarily sensitive to the early stage equation of state (EOS) [14].

Figure 6 (left panel) shows the preliminary results for the first measurement of $\phi$-meson elliptic flow $v_2$ at RHIC [7, 8, 15]. $v_2$ of $K^+K^-$ and $p+\bar{p}$ from [10] are
Figure 5. The nuclear modification factor $R_{CP}$ of $\phi$-meson compared with $R_{CP}$ of $\Lambda$ and $K^0_S$ at $\sqrt{s_{NN}} = 200\text{GeV}$ [1]. Both statistic and systematic uncertainty have been included. The shaded bands represent the uncertainties in the Glauber model calculations for $\langle N_{\text{bin}} \rangle$ and $\langle N_{\text{part}} \rangle$.

Figure 6. Left panel: $p_T$ dependence of $v_2$ for $\phi$-meson which is compared with the results of $K^+ + K^-$ and $p + \bar{p}$. AMPT calculation are taken from Ref. [17]. Right panel: NCQ scaled $v_2$ as a function of NCQ scaled transverse momentum. Lines represent NCQ-scaling parameterization.

plotted together for comparison. The most striking thing in the figure is that the $\phi$-meson has a non-zero $v_2$ in the hydrodynamic region ($p_T < 2\text{ GeV/c}$) and it has a significant $v_2$ signal at $p_T > 2\text{ GeV/c}$ which is comparable to that of the $K^+ + K^-$. Since the formation of $\phi$-meson through kaon coalescence at RHIC has been ruled out by previous STAR measurements [5], and the low interaction cross-section of $\phi$-meson with other non-strange particles makes the contribution to flow due to hadronic re-scattering processes very small [17], therefore it may be possible to directly measure the flow of strange quark via the flow of $\phi$-meson. Additionally, since the $\phi$-meson $v_2$
values as a function of $p_T$ are similar to those of other particles, this indicates that the heavier $s$-quarks flow as much as the lighter $u$ and $d$ quarks. This can happen if there are a significant number of interactions between the quarks before hadronization. It is the signal of partonic collectivity of the system. A prediction from the naive coalescence model which is implemented in A Multi-Phase Transport (AMPT) model with the string melting scenario is also plotted here. The model describes the data quite well at $p_T > 1.5$ GeV/c. This is another hint of coalescence of strange quark as dominant production mechanism for $\phi$-meson. Further evidence can be obtained from the Number-of-Constituent-Quark (NCQ) picture in Figure (right panel).

5. DI-HADRON CORRELATION TRIGGED BY HIGH $p_T \phi$ or $\Omega$

The strong suppression of high-$p_T$ particle yield and the disappearance of one jet in back-to-back jet correlation have been observed in RHIC Au + Au central collisions at $\sqrt{s_{NN}} = 200$ GeV, which can be interpreted by jet quenching mechanism. On the other hand, the lost energy will be redistributed in the soft $p_T$ region. These soft associated particles which carry the lost energy have been reconstructed via two-particle azimuthal angular correlation of charged particles in STAR experiment, and the interesting Mach-like structure has been experimentally observed in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV as well as theoretically interpreted. For instance, it was proposed that a Mach shock wave happens when jet travels faster than sound in the medium, or it can also be produced with a Cherenkov radiation mechanism, or was attributed to medium dragging effect in Ref. etc. In addition, partonic transport model is able to give the Mach-like cone phenomenon for central Au+Au collisions at RHIC and shows the parton cascade is essential for describing experimental Mach-like structure.

In this section, we shall present two-particle correlation function, especially for those trigged by multi-strange particles, such as $\phi$ and $\Omega$ with higher $p_T$ which is beyond the $p_T$ region we discussed in the section of $v_2$, to further understand behavior of $\phi$ mesons. Fig. shows the di-hadron correlation functions in 10-20% centrality (left panel) or 40-80 or 40-90% centrality (right panel) for the results before the hadronic rescattering stage takes place in AMPT model. The mixed-event technique was used to extract the di-hadron correlation function as people made in RHIC data analysis. The full squares represent the trigger particles are multi-strange particles, namely $\phi$ or $\Omega$, while the open circles show the trigger particles are any hadrons. A clean split of the away-side peaks is observed in left panel, which is similar to the Mach-like cone behavior. It is possible to induce such kind of picture if the jet velocity is faster than the sound velocity when it passes through the dense matter. Also the deflect may occur when the associated particles try to traverse the dense QCD medium. From the comparison of different triggers, it is found that a little wider for away-side correlations trigged by any hadrons than the one trigged by $\phi$ or $\Omega$, while it keeps almost same width for near-side peaks. The former may indicate that $s$ or $\bar{s}$ quarks has weak partonic interactions with $u$ or $d$ quarks, which results in a narrower width of away-side peaks for $\phi/\Omega$-trigged correlation.
Of course, we selected a little wider $p_T$ range for $\phi$ and $\Omega$ triggers due to the limited statistics, which may have a small effect on the differences of di-hadron correlations. For the peripheral collisions, right panel of Fig. 7 demonstrated that the Mach-like cone peaks vanish and only mono peak exists in away-side which is also consistent with the experimental observation. The matter in peripheral collisions is more dilute so that the associated particles can be easily traverse the system directly. In this case, we have a single peak in the backward of the trigged particles. Based on the same reason for the central collisions, the associated particles trigged by $\phi$ and $\Omega$ have a narrower width for the away-side peak. From the above simulations, some differences in di-hadron correlation functions between $\phi/\Omega$ trigger and the normal particles trigger are predicted, which deserves to be explored in the data.

![Figure 7](image-url) Soft scattered associated hadron (0.15 < $p_T$ < 3 GeV/c) $\Delta \phi$ correlations trigged by high $p_T$ particles. Solid squares represent the trigger particles are either $\phi$ or $\Omega$ with 3 < $p_T$ < 10 GeV/c, and open circles any hadrons with 3 < $p_T$ < 6 GeV/c. Left panel: 10-20 % centrality; Right panel: 40-90 or 40-80% centrality.

6. CONCLUSIONS

STAR and PHENIX have measured wealth of data which help ones to learn the properties of $\phi$-meson production and the behavior of elliptic flow $v_2$ at RHIC. The measurement of $\phi$-meson transverse momentum spectra as a function of centrality for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV shows that for peripheral collisions, the spectra has a deviation of exponential shape because of the distinct power-law tail and are best described by a Levy function while for the central data, the power-law tail is suppressed and it can be well described by both Levy or exponential function. In other words, clear central suppression of transverse momentum spectra has been observed. Collisions among different systems (Au+Au, d+Au, p+p at $\sqrt{s_{NN}} = 200$ GeV) indicate that the central suppression only exists in the Au + Au systems. The SATR measurement of nuclear modification factor ($R_{CP}$) conclusively demonstrated that the $\phi$-meson $R_{CP}$ is much similar to the $R_{CP}$ of $K_S^0$ than $\Lambda$, which confirms the grouping of hadron $R_{CP}$ observable at RHIC is a baryon-meson type dependence but not a mass type dependence. The first measurement of $\phi$-meson elliptic flow $v_2$ from STAR shows that...
\( \phi \) flows as strong as other particle. At low \( p_T < 2 \text{ GeV}/c \) region, \( v_2 \) of \( \phi \) is consistent with hydrodynamical behavior of strange quarks in the early partonic stage while at intermediate region (2 GeV/c < \( p_T < 5 \text{ GeV}/c \)), it favors the number of constituent quark scaling. The sizeable \( v_2 \) from the data is a strong signal of partonic collectivity at RHIC. In addition, a Mach-like cone picture in central collisions is demonstrated for \( \phi \) or \( \Omega \) trigged di-hadron correlation with AMPT model and it reveals a narrower width of away-side peaks than the normal particles trigged di-hadron correlation function, which deserve to be explored experimentally in near future.

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