Nuclear modification factors of $\phi$ meson in $d+Au$, $Cu+Cu$ and $Au+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV

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The PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC) has performed systematic measurements of $\phi$ meson production in the K$^+\text{K}^-$ decay channel at midrapidity in $p+p$, $d+Au$, Cu+Cu and Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV. Results are presented on the $\phi$ invariant yield and the nuclear modification factor $R_{AA}$ for Au+Au and Cu+Cu, and $R_{AA}$ for $d$+Au collisions, studied as a function of transverse momentum ($1<p_T<7$ GeV/c) and centrality. In central and mid-central Au+Au collisions, the $R_{AA}$ of $\phi$ exhibits a suppression relative to expectations from binary scaled $p+p$ results. The amount of suppression is smaller than that of the $\pi^0$ and the $\eta$ in the intermediate $p_T$ range (2–5 GeV/c), whereas at higher $p_T$ the $\phi$, $\pi^0$ and $\eta$ show similar suppression. The baryon (protons and anti-protons) excess observed in central Au+Au collisions at intermediate $p_T$ is not observed for the $\phi$ meson despite the similar mass of the proton and the $\phi$. This suggests that the excess is linked to the number of constituent quarks rather than the hadron mass. The difference gradually disappears with decreasing centrality and for peripheral collisions the $R_{AA}$ values for both particles are consistent with binary scaling.

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I. INTRODUCTION

Measurements of hadron spectra from $p+p$ and nucleus-nucleus collisions at RHIC provide a means to study the mechanisms of particle production and the properties of the medium formed in relativistic heavy ion collisions. At low transverse momentum, $p_T < 2$ GeV/c, where the bulk of particles are produced, hadron production is governed by soft processes characterized by low momentum transfer. The particle yields and the evolution of the interacting system are successfully described within the framework of thermal and hydrodynamical models [1–5].

At high transverse momentum, $p_T > 5$ GeV/c, hard scattering processes become the dominant contribution. Due to the large momentum transfer involved, the parton-parton scattering cross sections are amenable to perturbative QCD (pQCD) description and hadron production can be calculated using initial state parton dis-
trIBUTION functions and final state fragmentation functions. Modifications to the hadron yields are expected in nucleus-nucleus collisions due to the interaction of the scattered parton with the hot and dense medium formed \[6,8\]. In the absence of interaction with the medium the hard scatters and the resulting hadron yields should scale with the number of binary nucleon-nucleon collisions \([N_{\text{coll}}]\), whereas in the medium the yields are suppressed (“jet-quenching” \[4\]) due to parton energy loss through gluon bremsstrahlung. High-\(p_T\) hadron suppression consistent with this scenario has been discovered in Au+Au collisions at RHIC \[10–12\]. The same suppression by a factor of \(\sim 5\) is observed for \(\pi^0\) and \(\eta\) production whereas direct photons which do not interact with the medium, follow the expected binary scaling \[13\]. Single electrons originating from the semi-leptonic decays of mesons containing heavy quarks (charm and bottom) exhibit a large suppression at high \(p_T\), similar within the experimental uncertainties to that of \(\pi^0\) and \(\eta\), presenting a challenge for the bremsstrahlung explanation \[14\].

At intermediate transverse momentum \(2 < p_T \text{(GeV/c)} < 5\), suppression of binary scaled production is observed for light \(\pi^0\) and \(\eta\) mesons but not for protons and anti-protons in mid-central and central Au+Au collisions \[13\]. The \(p/\pi\) and \(\bar{p}/\pi\) ratios increase with centrality and exceed the values measured in \(p+p\) by a factor of 3–5 in the most central collisions. A different suppression pattern between baryons and mesons is also observed for strange hadrons, \(\Lambda\) and \(K^0_S\) \[16,17\]. These baryon/meson differences in suppression are inconsistent with the picture of hadron production through hard-scattering followed by partonic energy loss in medium and hadronization in vacuum according to the universal fragmentation functions. This poses the question whether hard-scattering is the dominant source of baryon production at intermediate \(p_T\). Studies of jet-like dihadron correlations in Au+Au collisions \[13,19\] imply nearly equal importance of the jet fragmentation as a production mechanism for mesons and baryons, except for the most central collisions. The interpretation of the baryon non-suppression results requires therefore another particle production mechanism in addition to jet fragmentation at intermediate \(p_T\).

There have been attempts to describe the different behavior of baryons and mesons through the strong radial flow that boosts particles with larger mass to higher \(p_T\) \[20,21\] or through the recombination of soft and hard massive partons \[22,24\], or through the interplay of the jet quenched hard component and phenomenological soft to moderate \(p_T\) baryon junction component \[27\] or through the QCD color transparency of higher-twist contributions to inclusive hadroproduction cross sections, where baryons are produced directly in short distance subprocess \[26\]. Although several models reproduce \(p_T\) spectra, particle ratios and elliptic flow for different hadrons reasonably well, the relative contributions from the different processes are difficult to infer.

The \(\phi\) meson is a very rich probe of the medium formed in heavy ion collisions, because it is sensitive to several aspects of the collision, including strangeness enhancement and chiral symmetry restoration, as well as energy loss and the nuclear modification factor \[27–31\], which is the focus of this paper. Due to its small inelastic cross section for interaction with non-strange hadrons \[27,32\], the \(\phi\) meson is less affected by late hadronic rescattering and reflects better the initial evolution of the system. Being a meson with a mass comparable to that of the proton, it is interesting to see how the \(\phi\) meson fits within the meson/baryon pattern described previously; being a pure \(s\bar{s}\) state, it puts additional constraints on the energy loss and recombination models.

This paper presents systematic PHENIX measurements of \(\phi\) meson production via the \(K^+K^-\) decay channel at \(\sqrt{s_{NN}} =200 \text{ GeV}\), including first PHENIX results in \(p+p\), \(d+Au\) and \(Cu+Cu\) collisions and new results in Au+Au collisions. The latter have much higher statistics and a finer centrality binning in comparison to the previously published PHENIX results \[28\]. The results benefit from three different techniques involving different levels of kaon identification in the analyses. These, combined with the high statistics of the analyzed data samples, allow for the extension of the \(p_T\) range of the measurements up to \(p_T = 7.0 \text{ GeV/c}\) in all collision systems. The higher \(p_T\) reach and the higher precision of the data allow for sharper conclusions with respect to earlier results \[28,30\]. The Cu+Cu measurements are complementary to those on Au+Au and allow the study of nuclear effects with different nuclear overlap geometry for the same \(N_{\text{part}}\) and with smaller \(N_{\text{part}}\) uncertainties for \(N_{\text{part}} < 100\).

The measurement of the \(\phi\) meson production in \(d+Au\) collisions is important for understanding cold nuclear matter effects which are of interest by themselves and are also essential for the interpretation of heavy ion collisions. As shown in \[33\], in the intermediate \(p_T\) range, charged pions are practically not enhanced in comparison to the binary scaled \(p+p\) yield, whereas protons and anti-protons exhibit some enhancement of \(\sim 30\%\) in the most central collisions. The mechanism of multiple soft re-scattering of partons in the initial state which is usually invoked as the origin of the Cronin effect does not explain this meson/baryon difference. One possible explanation comes from recombination models \[41\] in which baryons gain higher transverse momentum from recombination of three quarks in the final state in comparison to mesons consisting of only two quarks. Measurement of the Cronin effect for the \(\phi\) mesons can provide additional constraints for the models that try to explain these cold nuclear effects.
II. EXPERIMENTAL SET-UP AND DATA ANALYSIS

We report on the measurements of $\phi$ mesons at midrapidity in the $K^+K^-$ decay channel in $p+p$, $d+Au$, $Cu+Cu$ and $Au+Au$ collisions at $\sqrt{s}_{NN}=$200 GeV using data collected by the PHENIX experiment during the 2004, 2005 and 2008 physics runs. A detailed description of the PHENIX detector can be found elsewhere [35]. The measurements were done using the two PHENIX central arms each covering 90° in azimuth at midrapidity ($|\eta| < 0.35$). The tracking of charged particles and the measurement of their momentum with typical resolution $(\delta p/p) = 0.7 \pm 1.1\% [\text{GeV}/c]$ are performed using the drift chambers and the first layer of the pad chambers (PC). In order to reduce the background at high $p_T$, tracks are required to have a matching confirmation in the third layer of PC or the electromagnetic calorimeter (EMCal). Kaons are identified using the time-of-flight detector (TOF), which covers approximately 1/3 of the acceptance in one of the central arms. With a time resolution of $\sim 115$ ps, the TOF allows for clear $\pi/K$ separation in the range of transverse momentum from 0.3 GeV/c to 2.2 GeV/c using a $2\sigma$ $p_T$-dependent mass-squared selection cut as described in [28].

The beam-beam counters (BBC) and zero degree calorimeters (ZDC) are dedicated subsystems that determine the collision vertex along the beam axis ($z_{vtx}$) and the event centrality, and also provide the minimum bias interaction trigger. Events are categorized into centrality classes using two-dimensional cuts in the space of BBC charge versus ZDC energy [30] for Au+Au collisions or only by the amount of charge deposited in the BBC [12, 37] for $d+Au$ and Cu+Cu collisions.

In any particular event one cannot distinguish between kaons from $\phi$ decays and other kaons, so the $\phi$ meson yields are measured on a statistical basis. In each event, all tracks of opposite charge which pass the selection criteria are paired to form the invariant mass distribution. This distribution contains both the signal (S) and an inherent combinatorial background (B). To maximize the statistical significance and the $p_T$ reach of the measurements we use three different track selection techniques: “no PID”, in which all tracks are assigned the kaon mass, but no TOF information is used, and “one kaon PID” or “two kaons PID”, in which one or both tracks are identified as kaons in the TOF.

Table I lists for each collision system and for each analysis technique the number of analyzed minimum bias events, accessible $p_T$ range and typical range of S/B ratio for the different $\phi \rightarrow K^+K^-$ analyses.

| Species | $N \times [10^9]$ | $p_T$ [GeV/c] | S/B | Technique |
|--------|-----------------|---------------|-----|-----------|
| $p+p$  | 1.50            | 0.9–1.5       | 1/9–1/2 | “one kaon PID” |
| $d+Au$ | 1.44            | 1.3–7.0       | 1/76–1/3 | “no PID” |
| Cu+Cu  | 1.69            | 1.1–7.0       | 1/245–1/12 | “no PID” |
| $Au+Au$| 0.77            | 1.1–2.95      | 1/91–1/9 | “one kaon PID” |
|        | 0.78            | 1.9–7.0       | 1/205–1/24 | “no PID” |
|        | 0.72            | 1.1–3.95      | 1/19–1/2 | “two kaons PID” |
|        | 0.82            | 2.45–7.0      | 1/385–1/32 | “no PID” |

FIG. 1: (Color online) Invariant mass distributions obtained with the “two kaons PID” and “no PID” methods in Au+Au collisions after subtraction of the combinatorial background estimated using the event-mixing technique. Plot on the top corresponds to integrated $p_T$ range whereas plot on the bottom is for the range $2 < p_T$ (GeV/c) < 3. The “no PID” spectrum is fit to the sum of a Breit-Wigner function convolved with a Gaussian function to account for the $\phi$ signal, and a polynomial function to account for the residual background.

a significant residual background remains in the subtracted mass spectra because the mixed-event technique does not account for the abundant correlated pairs from other particle decays ($K^0_s \rightarrow \pi^+\pi^-$, $\Lambda \rightarrow p\pi^-$, $\rho \rightarrow \pi^+\pi^-$, $\omega \rightarrow \pi^0\pi^+\pi^-$ etc.). In the “one kaon PID” analysis the residual background is considerably smaller [28] while in the “two kaon PID” method the background is negligible. Examples of subtracted mass spectra obtained in Au+Au collisions with the “two kaon PID” and “no PID” techniques are shown in Fig. 1. The
S/B ratio depends on the collision system, the analysis technique, the $\phi$ transverse momentum and the centrality. The typical ranges of the S/B values for each collision system and each analysis technique are summarized in Table I.

The total combinatorial background in $p+p$ [38], as well as the residual background in $d+Au$, $Cu+Cu$ and $Au+Au$ analyses were estimated by fitting the mass spectra with the sum of a Breit-Wigner mass resolution function to account for the $\phi$ signal, and a polynomial function to account for the background. The typical experimental mass resolution for the $\phi$ meson was estimated to be $\sim 1$ MeV/$c^2$ using Monte-Carlo studies based on the known momentum resolution of the tracking system and time resolution of the TOF. To describe the background a second order polynomial was used in most analyses, except for the $Au+Au$ “no PID” case where a third order polynomial was used. Figure 1 shows an example of the fits.

The $\phi$ meson invariant yield in a given centrality and $p_T$ bin is obtained by:

$$
\frac{1}{2\pi p_T} \frac{d^2N}{dp_T dy} = \frac{N_\phi C_{bias}}{2\pi p_T N_{evt} \epsilon_{rec} \epsilon_{embed} B_{KK} \Delta p_T \Delta y},
$$

(1)

where $N_{evt}$ is the number of analyzed events in the centrality bin under consideration, $\epsilon_{rec}$ corrects for the limited acceptance of the detector and for the $\phi$ meson reconstruction efficiency, $\epsilon_{embed}$ accounts for the losses in reconstruction efficiency due to detector occupancy in heavy ion collisions, $B_{KK}$ is the branching ratio for $\phi \rightarrow K^+K^-$ in vacuum, $N_\phi$ is the raw $\phi$ yield measured in the given bin, $C_{bias} = C_{MB}/C_{BBC}$, where $C_{MB}$ and $C_{BBC}$ are the beam-beam trigger efficiencies for minimum bias and $\phi$ events respectively. This $C_{bias}$ correction is equal to 0.69 for $p+p$ [39] and varies from 0.92 to 0.85 as we go from peripheral to central $d+Au$ collisions [10]. In $Au+Au$ and $Cu+Cu$ collisions the minimum bias trigger is inefficient only for very peripheral collisions (centrality $> 92.2\%$ for $Au+Au$ and $> 94\%$ for $Cu+Cu$). For all other centralities, $0 - 92.2\%$ ($0 - 94\%$) for $Au+Au$ ($Cu+Cu$), there is no trigger bias and $C_{bias} = 1$. In $p+p$ the invariant differential cross section at midrapidity is related to invariant yield as $E \frac{d^2\sigma}{dp_T dy} = \sigma_{pp}^{inel} \times \frac{1}{2\pi p_T} \frac{d^2N}{dp_T dy}$, where $\sigma_{pp}^{inel} = 42.2$ nb.

The detector occupancy related loss ($1 - \epsilon_{embed}$) is calculated by embedding simulated $K^+K^-$ pairs into real events. It varies from 1% in peripheral to 29% (7%) in the most central $Au+Au$ ($Cu+Cu$) collisions without a significant $p_T$ dependence.

The acceptance and reconstruction efficiency ($\epsilon_{rec}$) of the $\phi$ meson, determined using a full GEANT simulation of the PHENIX detector, is shown in the bottom panel of Fig. 2 for different analysis techniques. There are very large differences, reaching more than one order of magnitude between the three cases. In spite of that, the invariant yield spectra obtained from the different techniques are in good agreement as demonstrated in the top panel of Fig. 2 which shows the ratios of yields obtained with “no PID” or with “one kaon PID” (“no PID” or “two kaons PID”) techniques in $p+p$ ($Au+Au$) to a fit performed to the combined data sets. This agreement implies good control over the systematic uncertainties which are quite different in the three cases and provides confidence on the robustness of the experimental results.

The results from measurements at low $p_T$ using “two kaons PID” in $Au+Au$ collisions and “one kaon PID” in $p+p$ and $Cu+Cu$ are combined with the independent “no PID” measurements at intermediate and high $p_T$ to form the final $p_T$ spectra. The measurement in $d+Au$ is performed using the “no PID” technique only. The invariant mass spectra obtained with “one kaon PID” or “two kaon PID” methods are subsamples of the “no PID” distribution. Therefore results obtained with different methods can not be directly averaged. In the final spectra the transition between different techniques occurs at $p_T = 1.3$ GeV/$c$ in $p+p$, $p_T = 2.2$ GeV/$c$ in $Au+Au$ and at $p_T = 3.2$ GeV/$c$ in $Cu+Cu$ collisions in order to obtain the smallest combined statistical and systematical uncertainties for the points.

Systematic uncertainties on the $\phi$ invariant yield are grouped into three categories: type A (point-to-point uncorrelated), which can move each point independently; type B (point-to-point $p_T$-correlated), which can move points coherently, but not necessarily by the same relative amount; type C (global), which move all points by the same relative amount. The main contribution to the systematic errors of type A is the uncertainty in the raw yield extraction $N_\phi$ of 6–25%. Error of type B is dominated by uncertainties in reconstruction efficiency $\epsilon_{rec}$.
of 5–9%, embedding corrections $\epsilon_{\text{embed}}$ of 1–7% and momentum scale of 1–5%. The main contributions to the type C errors are the uncertainties in normalization for the $p+p$ ($d+Au$) cross section equal to 9.7% (7.8%) and in branching ratio $B_{\text{KK}}$ of 1.2%.

III. RESULTS AND DISCUSSION

Figure 3 shows the fully corrected $\phi$ invariant yield as a function of $p_T$ measured in $p+p$, $d+Au$, Cu+Cu and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The spectra are scaled by arbitrary factors for clarity and fitted to exponential and Tsallis functions shown by the dashed and solid lines, respectively. We used the Tsallis function adapted to the form [38]:

$$
\frac{1}{2\pi} \frac{d^2N}{dp_T} = \frac{1}{2\pi} \frac{dN}{dy} \frac{(n-1)(n-2)}{(nT + m_\phi(n-1))(nT + m_\phi)} \times \left(\frac{nT + m_T}{nT + m_\phi}\right)^{-n},
$$

where $\frac{dN}{dy}$, $n$ and $T$ are free parameters, $m_T = \sqrt{p_T^2 + m_\phi^2}$, and $m_\phi$ is the mass of the $\phi$ meson. The spectral shapes for all collision systems and centralities are well described by the Tsallis function, while the exponential fits underestimate the $\phi$ meson yields at high $p_T$ where the spectra begin to exhibit the power law behavior expected for particles produced in hard scattering processes. For $p+p$ collisions the departure from exponential shape occurs at $\approx 4$ GeV/c. For all centralities in Au+Au collisions the departure occurs at somewhat larger $p_T$, which suggests a larger contribution of soft processes to the $\phi$ meson production up to 4–5 GeV/c. Such behavior of the spectral shapes is in agreement with recombination models [22–24, 44–46] predicting $p_T$ spectra for different hadronic species based on the number and flavor of constituent quarks. At low transverse momentum, we do not observe a large change in the slopes of the spectra from central to peripheral collisions, supporting the expectation for smaller radial flow in $\phi$ mesons compared to other hadrons.

The large $p_T$ reach of the results presented here allows for the study of medium-induced effects on $\phi$ meson pro-
duction at intermediate and high $p_T$ using the nuclear modification factor:

$$R_{AB}(p_T) = \frac{dN_{AB}}{(N_{\text{coll}}) \times dN_{pp}},$$

where $dN_{AB}$ ($dN_{pp}$) is the differential $\phi$ yield in nucleus-nucleus ($p+p$) collisions and $(N_{\text{coll}})$ is the average number of nuclear collisions in the centrality bin under consideration. The latter is determined solely by the density distribution of the nucleons in the nuclei A and B and by the impact parameter and is calculated using the Glauber formalism. Deviations of $R_{AB}$ from unity quantifies the degree of departure of the A+B yields from a superposition of incoherent nucleon-nucleon collisions.

FIG. 4: (Color online) Top: $R_{AA}$ vs. $p_T$ for $\phi$, $\pi^0$, $\eta$, (K$^+$+K$^-$) and (p+$\bar{p}$) in central Au+Au collisions. Middle: $R_{AA}$ vs. $p_T$ for $\phi$ and $\pi^0$ in 10-20% mid-central Au+Au collisions. Bottom: $R_{AA}$ vs. $p_T$ for $\phi$, and p+$\bar{p}$ in 60-92% and for $\pi^0$ in 80-92% peripheral Au+Au collisions. Values for (K$^+$+K$^-$), (p+$\bar{p}$), $\pi^0$ and $\eta$ are from Ref. [12, 33, 48, 50]. The uncertainty in the determination of $(N_{\text{coll}})$ is shown as a box on the left. The global uncertainty of $\sim$ 10% related to the $p+p$ reference normalization is not shown.

Figure 4 shows a comparison of the $R_{AA}$ for $\phi$ and $\pi^0$ from Ref. [49], proton and kaon from Ref. [33] and $\eta$ from Ref. [50], all measured in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The $\phi$ meson exhibits a different suppression pattern than that of lighter non-strange mesons and baryons. For central collisions (top panel) the $\phi$'s $R_{AA}$ shows less suppression than $\pi^0$ and $\eta$ in the intermediate $p_T$ range of $2 < p_T$ (GeV/c) $< 5$. At higher $p_T$ values, $p_T > 5$ GeV/c, the $\phi$'s $R_{AA}$ approaches and becomes comparable to the $\pi^0$ and $\eta$ $R_{AA}$. These two features remain true for all centralities up to the most peripheral collisions as displayed in the bottom panel of Fig. 4 (see also Fig. 5). The panel shows that the $\pi^0$ is slightly suppressed (at the level of $\sim$ 20%) in peripheral Au+Au collisions whereas the $\phi$ is not suppressed. The kaon data cover only a very limited range at low $p_T$ but in this range they seem to follow the $R_{AA}$ trend of the $\phi$ better than that of the $\pi^0$ and $\eta$ for central Au+Au collisions. The comparison with baryons, represented in Figure 4 by the protons and anti-protons, shows a different pattern. For central collisions, the protons show no suppression but rather an enhancement at $p_T > 1.5$ GeV/c, whereas the $\phi$ mesons are suppressed. This difference between $\phi$ mesons and protons gradually disappears with decreasing centrality and for the most peripheral collisions the $R_{AA}$ of $\phi$ and (anti)protons are very similar as demonstrated in the bottom panel.

The results presented here are in agreement with the previous PHENIX results [28], which were based on the 2002 RHIC run, within the relatively larger uncertainties of the latter. The use of different analysis techniques and the larger Au+Au data sample of the 2004 run resulted in a higher precision and a larger $p_T$ reach of $R_{AA}$ that allowed to unveil the different behavior of the $\phi$ meson, i.e. less suppression than $\pi^0$ but more suppression than baryons, in the intermediate $p_T$ range. Our results differ from the ones recently published by the STAR Collaboration [29, 30] which show that in Au+Au collisions $R_{AA}$ is consistent with binary scaling in the intermediate $p_T$ region whereas $R_{CP}$ shows considerable suppression. This difference is traced down to the almost factor of two higher invariant $p_T$ yield in the STAR experiment [29, 30] in Au+Au collisions, compared to our results presented in Fig. 4, whereas in $p+p$ both experiments are in reasonably good agreement.

Figure 6 compares the $R_{AA}$ of $\phi$ in $Au+Au$ and $Cu+Cu$ in two centrality bins which correspond approximately to the same number of participants in the two systems. Figure 6 shows the $R_{AA}$ of the $\phi$ integrated for $p_T > 2.2$ GeV/c in $Cu+Cu$ and $Au+Au$ collisions versus $N_{\text{part}}$. Under these conditions, there is no difference in the $R_{AA}$ of $\phi$ between the two systems indicating that the level of the suppression, when averaged over the azimuthal angle, scales with the average size of the nuclear overlap, regardless of the details of its shape. This behavior has been observed in other measurements, such as the $R_{AA}$ of the $\pi^0$. The $\pi^0$ suppression data in $Au+Au$ and $Cu+Cu$ taken from Ref. [12, 48] are also shown in Fig. 4 for comparison. The similarity of the $R_{AA}$ of $\phi$ in the two colliding systems implies that the features discussed previously for $Au+Au$ in the context of Fig. 4, namely that the $\phi$ exhibits an intermediate suppression between pions and baryons, remain valid also in the $Cu+Cu$ system.
Remains dominant up to a wider range and consequently the TT component becomes significant for both particles. It is interesting to note that the $\eta$ follows closely the $\pi^0$ in spite of its sizable ($\sim 50\%$) strangeness content [51].

Our data disfavor radial flow as the dominant source for the particle species dependence of the suppression factors at intermediate $p_T$, since the proton and $\phi$ $R_{AA}$ factors differ by a factor of $\sim 2$, in spite of their similar mass ($m_p \approx m_\phi$), whereas the kaon and $\phi$ show similar $R_{AA}$ factors although their masses differ by almost a factor of two ($m_\pi \approx 2m_K$).

Recombination models [23, 24, 44, 46] qualitatively explain the larger yield of baryons compared to mesons at intermediate $p_T$ by the higher gain in $p_T$ which comes from recombination of three quarks for baryons rather than two quarks for mesons. The same framework can be used to interpret the difference in suppression factors for $\pi^0$ and $\phi$ mesons. For $\pi^0$ production in the Hwa and Yang model [46] the contribution from the recombination of thermal (T) and shower (S) partons becomes comparable to that of the recombination of TT partons already at $p_T \approx 3$ GeV/c. For the $\phi$ however, the strangeness enhancement feeds preferentially the thermal quarks. Soft processes dominate over hard processes in a wider $p_T$ range and consequently the TT component remains dominant up to $p_T \approx 6$ GeV/c for the $\phi$ production [45]. The $R_{AA}$ of $\phi$ becomes similar to that for $\pi^0$ at $p_T \approx 5 - 6$ GeV/c where the contribution from fragmentation partons becomes significant for both particles. It is interesting to note that the $\eta$ follows closely the $\pi^0$ in spite of its sizable ($\sim 50\%$) strangeness content [51].

FIG. 5: (Color online) Top: $R_{AA}$ vs. $p_T$ for $\phi$ and $\pi^0$ for 30–40% centrality $Au+Au$ and 0–10% centrality $Cu+Cu$ collisions. Bottom: $R_{AA}$ vs. $p_T$ for $\phi$ and $\pi^0$ for 40–50% centrality $Au+Au$ and 10–20% centrality $Cu+Cu$ collisions. Values for $\pi^0$ are from [12, 49]. The uncertainty in the determination of $(N_{coll})$ is shown as a box on the left. The global uncertainty related to the $p+p$ reference normalization is not shown.

FIG. 6: (Color online) $R_{AA}$ for $\phi$ integrated at $p_T > 2.2$ GeV/c in Cu+Cu and Au+Au collisions vs. $N_{part}$. The global uncertainty related to the $p+p$ reference normalization is shown as a box on the right.

FIG. 7: (Color online) Top: $R_{AA}$ vs. $p_T$ for $\phi$, $\pi^0$ and $(p+\bar{p})$ for 0–20% centrality $d+Au$ collisions. Bottom: $R_{AA}$ vs. $p_T$ for $\phi$, $\pi^0$ and $(p+\bar{p})$ for 60–88% peripheral $d+Au$ collisions. Values for $(K^+K^-)$ and $(p+\bar{p})$ and $\pi^0$ are from [33, 48]. The uncertainty in the determination of $(N_{coll})$ is shown as a box on the left. The global uncertainty of $\sim 10\%$ related to the $p+p$ reference normalization is not shown.
Cold nuclear matter effects can also contribute to the differences in hadron suppression factors in A+A collisions. Figure 7 compares the $R_{dA}$ for $\phi$ and $\pi^0$ from Ref. [48] and protons from Ref. [33] for central (top panel) and peripheral (bottom panel) $d+Au$ collisions. For both centralities, the $R_{dA}$ for $\phi$ and $\pi^0$ are similar indicating that cold nuclear effects are not responsible for the differences between $\phi$ and $\pi^0$ seen in Au+Au and Cu+Cu collisions. The proton's $R_{dA}$ exhibits an enhancement for $p_T=4$ GeV/c usually associated with the Cronin effect [52–57], whereas the $R_{dA}$ for $\phi$ indicates little or no enhancement. The lack of Cronin enhancement is also seen in the $\pi^0$ data [48] shown in Fig. 7 and has also been observed for other mesons in central and mid-central $d+Au$ collisions at $\sqrt{s_{NN}}=200$ GeV [33, 58, 59].

IV. SUMMARY AND CONCLUSIONS

We have measured $\phi$ meson production at midrapidity via the K$^+K^-$ decay channel in $p+p$, $d+Au$, $Cu+Cu$ and Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV. Invariant $p_T$ spectra and nuclear modification factors have been presented over the $p_T$ range of $1 < p_T < 7$ GeV/c for different centralities.

The $\phi$ meson exhibits a different suppression pattern compared to lighter mesons ($\pi^0$ and $\eta$) and baryons (protons and anti-protons) in heavy ion collisions. For all centralities, the $\phi$ meson is less suppressed than $\pi^0$ and $\eta$ in the intermediate $p_T$ range (2–5 GeV/c) whereas at higher $p_T$, $\phi$, $\pi^0$ and $\eta$ show similar suppression values. The available kaon $R_{AA}$ data seem to follow the $R_{AA}$ trend of the $\phi$. The comparison with baryons shows that in central Au+Au collisions the latter are enhanced with respect to binary scaling whereas the $\phi$ meson is suppressed, but this difference gradually disappears with decreasing centrality and for peripheral collisions the baryons and the $\phi$ meson have very similar $R_{AA}$ values consistent with binary scaling.

The same features are observed in Cu+Cu collisions between the $\phi$ and $\pi^0$. The $\phi$ meson invariant $p_T$ spectra in Au+Au and Cu+Cu collisions for similar $N_{\text{part}}$ values exhibit similar shape and yield over the entire $p_T$ range of the measurement within the statistical and systematic uncertainties. This indicates that the production and suppression of the $\phi$ meson, when averaged over the azimuthal angle, scales with the average size of the nuclear overlap region, regardless of the details of its shape.

Cold nuclear effects cannot account for the observed differences. For all centralities, the $\phi$'s $R_{dA}$ in $d+Au$ collisions is consistent with binary scaling in agreement with other mesons. No meson species dependence is observed in $R_{dA}$ within uncertainties.

The observed features at intermediate $p_T$ in Au+Au and Cu+Cu collisions are qualitatively consistent with quark recombination models [22–24, 44–46], which are also supported by $\phi$ elliptic flow measurements [23, 31]. The systematic set of measurements presented here provides further constraints to these models. The similarity between the suppression patterns of different mesons at high $p_T$ favors the production of these mesons via jet fragmentation outside the hot and dense medium created in the collision. Complementary jet correlation measurements involving $\phi$ mesons as a trigger as well as extension of the kaon data to higher $p_T$ would be desirable to provide further insight into the $\phi$ meson production mechanism.

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