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void energy heavy-ion collisions [1–4]. Currently, a major
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formation composed of a nearly pure strange anti-strange (
meson is a useful probe for studying the QGP
section for interaction with nonstrange hadrons [6, 8],
meson production in bulk matter [5–7]. Due to its small inelastic cross
way. The
< p−2) and backward Au-going direction (−2 < y < −1.2),
rapidities. The measurements are performed via the dimuon decay channel and reported as a
function of the number of participating nucleons, rapidity, and transverse momentum. In the most
central events, 0%-20% centrality, the φ meson yield integrated over 1 < pT < 5 GeV/c prefers a
smaller value, which means a larger nuclear modification, in the Cu-going direction compared to
the Au-going direction. Additionally, the nuclear-modification factor in Cu+Au collisions averaged
over all centrality is measured to be similar to the previous PHENIX result in d+Au collisions for
these rapidities.

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I. INTRODUCTION

The Relativistic Heavy Ion Collider (RHIC) accelerator and its four experiments have previously provided
extensive experimental evidence to confirm the formation of a deconfined state of nuclear matter, referred to
as the quark-gluon plasma (QGP), in the initial stages of high-energy heavy-ion collisions [1–4]. Currently, a major
objective in the field of high-energy nuclear physics is to characterize the properties of the QGP in a quantitative
way. The φ meson is a useful probe for studying the QGP properties, because it is sensitive to several aspects of the
collision, including modifications of strangeness production in bulk matter [3, 4]. Due to its small inelastic cross
section for interaction with nonstrange hadrons [6, 8], the φ meson is less affected by late hadronic rescattering and
may reflect the initial evolution of the system. Being composed of a nearly pure strange anti-strange (ss) state, the φ meson puts additional constraints on models of quark recombination in the QGP.

The study of the QGP typically involves compar-

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ions of different observables measured in nucleus-nucleus (A+B) collisions and in proton-proton (p+p) collisions at the same center-of-mass energy. Modifications in the A+B collisions with respect to p+p collisions could be interpreted as being due to the hot nuclear matter (HNM) – possibly QGP – being produced. However, nuclear modifications could be present in the initial state of the collisions even if no QGP is produced. These effects, typically referred to as cold nuclear matter (CNM), may include the modification of parton distribution functions (PDFs) in a nucleus \[9\], initial-state energy loss \[10\], and the Cronin effect, which is often attributed to multiple scattering of the incoming parton inside the target nucleus \[11-12\]. CNM effects can be probed with d+Au collisions.

PHENIX has previously measured φ meson production in d+Au collisions at forward, mid- and backward rapidities \[13\]. Suppression was observed in the forward (d-going) direction, where small-x partons from the Au nucleus are probed, and an enhancement was seen in the backward (Au-going) direction. Similar behavior was previously observed for inclusive charged hadrons and open heavy flavor in d+Au collisions \[14, 15\], potentially indicating similar particle production and modification mechanisms.

The rapidity dependence \(y\) of particle production in asymmetric collisions with a smaller-A projectile and a large-A target, provides a way to investigate both hot and cold nuclear-matter effects. Previous \(J/\psi\) meson data in Cu+Au collisions \[16\] showed that the ratio of forward (\(1.2 < y < 2.2\), or Cu-going) to backward (\(-2.2 < y < -1.2\), or Au-going) \(J/\psi\) modification was comparable in both sign and magnitude to that expected from CNM effects. The φ meson is composed of lighter closed flavor (\(s\bar{s}\)) and its production from 1.0 GeV/c to 5.0 GeV/c involves a mix of soft and hard processes and would provide a link between heavy flavor and lighter mesons. Comparison of the φ meson production in Cu+Au and d+Au systems and to \(J/\psi\) production in Cu+Au collisions may shed light on the mixture of HNM and CNM effects on φ-meson production.

The production of φ mesons has already been measured at PHENIX in p+p, d+Au, Cu+Cu, and Au+Au at midrapidity \[17, 19\] and in p+p and d+Au at forward and backward rapidities \[13, 20\] over a wide range in \(p_T\). Previous measurements from Au+Au and Cu+Cu collisions \[18\] in a similar momentum range were found to be consistent with HNM effects and exhibited large flow anisotropies. The STAR Collaboration has also previously measured φ meson production at midrapidity in Cu+Cu and Au+Au collisions \[21, 22\]. φ meson production has also been measured by the ALICE Collaboration at large rapidity in p+p and p+Pb collisions \[23\] and at midrapidity in Pb+Pb collisions \[24\].

In this paper, the production of φ mesons is determined at forward and backward rapidities via dimuons reconstructed in the PHENIX muon spectrometers in Cu+Au collisions at \(\sqrt{s_{NN}}= 200\) GeV recorded in 2012. The particle multiplicity at these rapidities in heavy-ion collisions results in large combinatorial backgrounds and produces a challenging environment for φ meson measurements. Previous measurements were thus limited to smaller collision species. A procedure for removing the background is detailed and a measurement of the φ meson nuclear modification factor \(R_{CuAu}\) in Cu+Au collisions at forward and backward rapidities is presented versus \(y, p_T\), and the number of participating nucleons.

II. EXPERIMENTAL SETUP

The PHENIX detector is described in detail in \[25\], and a schematic of the 2012 setup is shown in Fig. 1. This analysis uses the dimuon decay channel of the φ meson. The detectors relevant for this measurement are forward and backward muon spectrometers \[26\], the two beam-beam counters (BBCs) \[27\], the silicon vertex tracker (VTX) \[28\], and the forward silicon vertex detector (FVTX) \[29\].

![Figure 1](image.png)

FIG. 1. (color online) The 2012 setup of the PHENIX detector.

This study used minimum bias (MB) events triggered by the BBCs. The BBCs comprise two arrays of 64 Čerenkov counters covering the pseudorapidity range \(3.1 < |\eta| < 3.9\). The MB trigger required two or more counters firing on each side and a \(z\)-vertex selection around the nominal center of the detector acceptance \[16\]. The MB trigger fired on 93±3% of the 5.2±0.2 b total inelastic Cu+Au cross section. In this case, the \(z\)-vertex was measured by the BBCs with a resolution of \(\sigma_z\approx 0.5–2.0\) cm, depending on the event multiplicity.

The collision point is determined in \(x, y, z\) by the two vertex detectors, VTX and FVTX, with a resolution of better than 100 microns. The VTX and FVTX detectors were installed in 2011 and 2012 to provide precise particle vertexing and tracking in the central and forward/backward rapidities. Covering approximately the same rapidity range as the existing muon spectrometers, the FVTX is composed of two endcaps, each with four stations that are perpendicular to the beamline and composed of silicon mini-strip sensors that have a 75 micron
pitch in the radial direction and lengths in the $\phi$ direction varying from 3.4 mm to 11.5 mm. The VTX, which surrounds the collision region at PHENIX, comprises four layers of silicon sensors. The inner two layers and outer two layers are composed of 30 pixel ladders and 44 stripixel ladders, respectively.

The muon system is separated into the north and south muon arms. Each arm comprises four subcomponents: an absorber material, a magnet, a muon tracker (MuTr), and a muon identifier (MuID). Initially, the absorbers were composed of 19 cm copper and 60 cm iron, but an additional 36.2 cm of stainless steel was added in 2010 to help decrease the hadronic background. Following the absorber in each muon arm is the MuTr, which comprises three sets of cathode strip chambers in a radial magnetic field with an integrated bending power of 0.8 T-m. The final component is the MuID, which comprises five alternating steel absorbers and Iarocci tubes to further reduce the number of punch-through hadrons that can be mistakenly identified as muons. The backplates of the magnets provide the first absorber layer for the muon identifier systems. The backplate of the south muon magnet is 10 cm shorter than the backplate of the north muon magnet, resulting in less total absorber material in the south arm than the north arm, and thus a slightly different momentum acceptance. The muon spectrometers cover the pseudorapidity range $1.2 < |\eta| < 2.2$ over the full azimuth. Muon candidates are identified by reconstructed tracks in the MuTr matched to MuID tracks, where at least one of the tracks from a pair of muon candidates in the same event penetrates through to the last MuID plane. The minimum momentum needed for a muon to reach the last MuID plane is $\sim 3$ GeV/$c$.

III. DATA ANALYSIS

A. Dataset and quality cuts

In this analysis, $\phi$ meson candidates are selected from two reconstructed muons in the RHIC Cu+Au dataset from 2012. The $\phi$ meson invariant yields are then measured and used to calculate the nuclear modification factor $R_{\text{CuAu}}$, which is compared to results from other systems. For this analysis, 4.73 billion ($L = 0.97$ nb$^{-1}$) sampled MB events were used within $\pm 10$ cm $z$-vertex and 0%-95% centrality. The total inelastic cross section for Cu+Au collisions at 200 GeV was estimated by a Glauber simulation to be $5.2 \pm 0.2$ b.

A set of quality assurance cuts is applied to the data to select good muon candidates and improve the signal-to-background ratio. These cuts are summarized in Table I. The collision $z$-vertex is required to be within $\pm 10$ cm of the center of the interaction region along the beam direction, as measured with the BBCs. The MuTr tracks are required to match the MuID tracks at the first MuID layer in both position and angle. In addition, only dimuon candidates in which at least one track penetrated to the final MuID layer are selected. Furthermore, the track is required to have greater than a minimum number of possible hits in the MuTr and MuID, and a maximum allowed $\chi^2$ is applied to both the track and vertex determination. There is a minimum allowed single muon momentum along the beam axis, $p_z$, which is reconstructed and energy-loss corrected at the collision vertex. Finally, this analysis is restricted to the dimuon $p_T$ range of $1 - 5$ GeV/$c$. This limitation is due to the large backgrounds and small acceptance at low $p_T$ and small statistics at high $p_T$, preventing signal extraction of the $\phi$ meson. The events are sorted into centrality classes using the combined charge from both BBCs [10]. The number of binary collisions $N_{\text{coll}}$ and number of participating nucleons $N_{\text{part}}$ are extracted from a Glauber simulation [10].

B. Background subtraction

The PHENIX muon spectrometers have a small acceptance for $\phi$ mesons. Going from the most peripheral centrality bin, 40%-93%, to the most central bin, 0%-20%, the signal-to-background ratio decreases from 0.28 to 0.067 in the Cu-going direction ($1.2 < y < 2.2$) and from 0.37 to 0.090 in the Au-going direction ($-2.2 < y < -1.2$). Due to the very low signal-to-background ratio, particularly in the most central events, the background subtraction is of crucial importance. Accordingly, several different background subtraction methods were explored and compared.

The invariant mass distribution is formed by combining muon candidate tracks of opposite charge. This unlike-sign invariant mass spectrum contains the $\phi$, $\rho$, and $\omega$ mesons as well as both uncorrelated and correlated backgrounds. The uncorrelated backgrounds come from random combinatorial associations of muon candidates, while the correlated backgrounds arise from open charm decay (e.g., $D\bar{D}$ where both decay semileptonically to muons), open beauty decay, $\eta$ meson and $\omega$ meson Dalitz decays and the Drell-Yan process. These correlated backgrounds are described in Sec. IIIC. The uncorrelated combinatorial background is accounted for via two methods: (1) like-sign dimuons and (2) event mixing.

First, the uncorrelated combinatorial background is estimated through the like-sign background subtraction technique, which is generally associated with the assumption that the like-sign dimuon pairs come purely from combinatorial processes without any correlation between muons. It follows that the like-sign distribution can be subtracted from the unlike-sign distribution according to the relationship described in Eq. [1]

$$N_{++} = FG_{++} - FG_{\pm\pm},$$

where $N_{++}$ is the uncorrelated background subtracted signal and $FG_{++}$ and $FG_{\pm\pm}$ are the unlike-sign and like-sign dimuon pairs, respectively, corresponding to pairs formed within the same event. The like-sign distribution
FG_{±±} \) is normalized to a quantity that is more precise and not sensitive to differences in the detector acceptance between like-sign and unlike-sign pairs. This background normalization is described in Eq. 2, where

\[
FG_{±±} = (FG_{++} + FG_{--}) \frac{2}{\int (FG_{++} + FG_{--})} \sqrt{\int FG_{++} \, dm \int FG_{--} \, dm}.
\]

where \( m \) is the dimuon invariant mass, and the integration is carried out in the range \( 0.2 < m < 5.0 \text{ GeV/c}^2 \).

In parallel to the like-sign technique, the uncorrelated background is also estimated through the event mixing technique. In the standard event mixing method, muons from different events are randomly associated to produce a background distribution of uncorrelated dimuon pairs. Events were mixed with partners from within the same \( 2\% \)-centrality and 1-cm \( z \)-vertex bins in order to minimize the systematic uncertainties. The mixed-event background distributions \( BG \) were generated with about 8 times higher statistics than the actual background and then normalized to match the same-event foreground \( FG \). The normalization factor also accounts for slightly different multiplicities from mixing of slightly different events. Although a mass-dependent technique was developed for this analysis, a standard event mixing technique is described in advance. In previous PHENIX analyses, the normalization factor \( \alpha \) was calculated as described in Eq. 3:

\[
\alpha = \sqrt{\frac{\int FG_{++} \, dm \int FG_{--} \, dm}{\int BG_{++} \, dm \int BG_{--} \, dm}}.
\]

where \( FG_{++} \) and \( FG_{--} \) are the like-sign pairs from the same event and \( BG_{++} \) and \( BG_{--} \) are the like-sign pairs from mixed events.

After subtracting and fitting the resonances as well as the remaining correlated background, the yields from mixed-event background subtraction are consistent with the yields from the like-sign technique within statistical uncertainties. The event mixing technique is used in this analysis due to the statistical limitations of the like-sign technique. The differences between the like-sign and event mixing techniques are used to determine one component of the systematic uncertainty on the yield, as described later in Sec. IIIF.

In this method, each term in the square root of Eq. 3 was integrated over all mass, introducing a mass-independent normalization factor. Dimuons from same events are less likely to be reconstructed in close proximity to each other than those in mixed events, resulting in a larger relative number of mixed-event dimuons at low mass, where the opening angle is small, than at higher mass. Therefore, the normalization factor, which is simply a ratio of the like-sign same-event dimuons to like-sign mixed-event dimuons, drops at lower masses. Because this normalization factor depends on mass, particularly in the \( \phi \) meson region, it became necessary to introduce a mass-dependent normalization, as

### Table I. Quality cuts for \( \phi \) meson signal extraction in Cu+Au collisions.

| Variable          | Au-going | Cu-going | Meaning                                                                 |
|-------------------|----------|----------|-------------------------------------------------------------------------|
| \(|z_{\text{vtx}}| (cm)\) | < 10     | < 10     | Collision vertex along the beam direction as measured by the BBCs       |
| \(pDG0\)          | < 90     | < 50     | Track momentum times the spatial difference between the MuTr track and MuID track at the first MuID layer |
| \((\text{GeV/c cm})\) | (GeV/c cm) | (GeV/c cm) | Track momentum times the spatial difference between the MuTr track and MuID track at the first MuID layer |
| \(pDDG0\)         | < 30     | < 45     | Track momentum times the slope difference between the MuTr track and MuID track at the first MuID layer |
| \(\chi^2\)        | < 5      | < 10     | \(\chi^2/\text{NDF}\) of the \( \mu \) track                        |
| Lastgap           | one track \( \geq 2\) | one track \( \geq 2\) | Last MuID plane that the \( \mu \) track penetrated                     |
|                   | other track \( \geq 4\) | other track \( \geq 4\) |                                                                 |
| \(n\text{hid}\)   | \((2 \times \text{lastgap} - 1)\) | \((2 \times \text{lastgap} - 1)\) | Number of hits in the MuID, out of the maximum 10                       |
| \(n\text{trhid}\) | > 11     | > 10     | Number of hits in the MuTr, out of the maximum 16                        |
| \(\chi^2_{\text{vtx}}\) | < 4      | < 7      | \(\chi^2/\text{NDF}\) of the dimuon track with the vertex              |
| Dimuon \( p_T \)  | \(1 - 5\) | \(1 - 5\) | Transverse momentum of the dimuon pair                                   |
| \(|p_T| \text{ (GeV/c)}\) | > 2.4    | > 2.5    | Momentum of the \( \mu \) along the beam axis                           |

\[ \alpha = \sqrt{\frac{\int FG_{++} \, dm \int FG_{--} \, dm}{\int BG_{++} \, dm \int BG_{--} \, dm}}. \]

\[ (3) \]
described in Eq. 4 rather than the more commonly used mass-integrated normalization from Eq. 3.

\[ \alpha(m) = \frac{\sqrt{FG_+(m)FG_-(m)}}{BG_+(m)BG_-(m)} \]  

(4)

This mass-dependent normalization factor is then fit as a function of mass, and the fit function – rather than the integrated normalization factor – is multiplied to the unlike-sign mixed-event background to get the normalized background spectrum \( BG^{\text{normalized}}_+ \).

\[ BG^{\text{normalized}}_+(m) = \alpha(m) \times BG_+(m). \]  

(5)

Several fitting functions were tested, including a polynomial and an error function. The error function, which is used in the final analysis, is described in Eq. 6 where \( g(m) \) is the error function and \( p_0, p_1, \) and \( p_2 \) are free parameters of the fit. A plot of the normalization factor as a function of mass fit with an error function is shown in Fig. 2.

\[ g(m) = p_0 \times \text{Erf} \left( \frac{m - p_1}{p_2} \right) \]  

(6)

The application of event mixing to describe and subtract backgrounds in the \( \phi \) meson mass region is shown in Fig. 2 where the open squares represent the mixed-event background and the closed circles are the unlike-sign spectrum. Before background subtraction, the \( \rho + \omega, \phi \) and \( J/\psi \) peaks are clearly seen.

C. Signal extraction and correlated background

After the mixed-event background subtraction, there is still some correlated background remaining. In previous PHENIX analyses, it was shown that heavy flavor (charm and beauty) contributions were negligible in the \( \phi \) meson mass region for \( p+p \) and \( d+Au \) collisions at 200 GeV \( \sqrt{s} \) [13, 20]. Simulation studies showed that \( \eta \) meson Dalitz decays are one possible contributor to the correlated background. The correlated background is well described by the function in Eq. 7.

\[ f(m) = \exp(a \cdot m) + b + c \cdot m, \]  

(7)

where \( a, b \) and \( c \) are free parameters of the fit \( f(m) \). Accordingly, the correlated background in real data are also fit with the function described in Eq. 7 as shown in Fig. 3 where the mass distribution after mixed-event background subtraction is shown. Several other fit functions and fit ranges were tested and used to estimate a systematic uncertainty.

The \( \phi \) and \( \omega \) meson signals are each described by a Gaussian and the signal from the \( \rho \) meson by a Breit-Wigner distribution, as shown in Fig. 4 along with the correlated background description. The \( \phi \) meson mass resolution is \( \sim 90 \text{ MeV}/c^2 \). The PHENIX muon arms are not able to resolve the \( \rho \) and \( \omega \) peaks separately, so a combined fit is made. All fit parameters are constrained but allowed to vary, except the ratio of the yield of \( \rho \) mesons to that of \( \rho + \omega \), which is set as a constant based on the expected ratio between their cross sections and branching ratios. The data are binned as a function of \( p_T, \gamma \) and centrality over the range \( 1 < p_T < 5 \text{ GeV}/c, \) \( 1.2 < |\gamma| < 2.2 \), and \( 0\%–93\% \) centrality.
FIG. 3. (color online) The unlike-sign spectra and combinatorial background described with event mixing for $1.2 < y < 2.2$ (Cu-going direction) and $-2.2 < y < -1.2$ (Au-going direction). The $\rho^+ \omega$, $\phi$ and $J/\psi$ peaks are clearly visible before background subtraction. The mass bin width is 71 MeV as marked on the vertical axis.

FIG. 4. (color online) The dimuon mass spectra for $1.2 < y < 2.2$ (Cu-going direction) and $-2.2 < y < -1.2$ (Au-going direction) after subtracting mixed events and fitting the $\phi$ and $\rho + \omega$ peaks and the remaining correlated background. The mass bin width is 71 MeV as marked on the vertical axis.

D. Detector acceptance and reconstruction efficiency

The product of detector acceptance and reconstruction efficiency, $A_{\text{rec}}$, of dimuon decays of $\phi$ mesons is determined by the full event reconstruction of the $\phi$ meson signal obtained from PYTHIA 6.42 [32], run through a full GEANT3 [33] simulation of the 2012 PHENIX detector setup, and embedded in the MB real-data background. The embedded simulated events are then reconstructed in the same manner as data with the same cuts applied as in the real data analysis. The background subtraction and signal extraction are also handled in the exact same manner as in real data. The $A_{\text{rec}}$ is then calculated as the number of reconstructed $\phi$ meson candidates divided by the number of $\phi$ mesons generated in PYTHIA, both within an appropriate kinematic bin. As previously mentioned, the south arm has a smaller amount of absorber material, causing a larger acceptance in the south arm (Au-going direction) than in the north arm (Cu-going direction). In addition, the $A_{\text{rec}}$ has a centrality and $p_T$ dependence. Specifically, for the lower $p_T$ bin (1-2.5...
in this analysis corresponds to higher values going from 0%–93% centrality to $A_{\text{rec}} = 2.41 \times 10^{-3}$ in the Cu-going direction and 3.83 $\times 10^{-3}$ in the Au-going direction. The centrality dependence is not as strong, with the values going from $A_{\text{rec}} = 2.23 \times 10^{-3}$ in the Cu-going direction and 2.37 $\times 10^{-3}$ in the Au-going direction at 0%–20% centrality to $A_{\text{rec}} = 2.41 \times 10^{-3}$ in the Cu-going direction and 3.83 $\times 10^{-3}$ in the Au-going direction at 40%–93% centrality.

E. Invariant yields and nuclear modification factors

The invariant yield is calculated according to the relation:

$$BR \frac{d^2N}{dydp_T} = \frac{1}{\Delta y \Delta p_T A_{\text{rec}} N_{\text{evt}}} N,$$

(8)

where $BR$ is the branching ratio to dimuons ($BR(\phi \rightarrow \mu^+ \mu^-) = (2.89 \pm 0.19) \times 10^{-4}$), $N_{\text{evt}}$ is the number of sampled MB events within the relevant centrality selection ($N_{\text{evt}} = 4.73 \times 10^9$ for the 0%–93% selection), $N$ is the number of observed $\phi$ mesons, and $\Delta y$ and $\Delta p_T$ are the bin widths in $y$ and $p_T$, respectively. To evaluate the nuclear matter effects on $\phi$ meson production in Cu+Au collisions, the $\phi$ meson yields in Cu+Au collisions are compared to those measured in $p+p$ collisions at the same energy after scaling by the number of nucleon-nucleon collisions in the Cu+Au system, $N_{\text{coll}}$. This ratio is called the nuclear modification factor $R_{\text{CuAu}}$, and is defined as:

$$R_{\text{CuAu}} = \frac{\frac{d^2N_{\text{CuAu}}}{dydp_T}}{N_{\text{coll}} \times \frac{d^2N_{pp}}{dydp_T}},$$

(9)

The $p+p$ reference data used in the $R_{\text{CuAu}}$ are from Ref. 20. Because the rapidity and $p_T$ binning in the Cu+Au analysis differs from that in the $p+p$ analysis, the $p+p$ invariant yields were re-measured using the same binning as the Cu+Au yields and in a manner similar to Ref. 20. The sampled luminosity of the $p+p$ data used in this analysis corresponds to $\mathcal{L} = 14.1 \text{ pb}^{-1}$ 20.

F. Systematic uncertainties

The systematic uncertainties associated with this measurement are categorized as Type-A, Type-B or Type-C. Type-A refers to point-to-point uncorrelated uncertainties that allow the data points to move independently with respect to one another. They are added in quadrature with the statistical uncertainties and represented on the plots as an error bar. Type-B uncertainties are correlated point-to-point, which means the points move coherently. All sources of Type-B uncertainty are added in quadrature and displayed as boxes around the data points. Finally, Type-C refers to the global uncertainties which allow the data points to move together by an identical multiplicative factor. The Type-C uncertainties are given in the legends of the plots.

Several systematic uncertainties are evaluated for this analysis. For the signal extraction uncertainty, different fits and parameters are tested for the background normalization factor, the correlated background, the $p+\omega$ signal, and the $\phi$ meson signal. This is done separately for each kinematic bin, and a 2–31% systematic uncertainty is assigned, with the largest uncertainty on yields extracted from the most central events. This is because the high multiplicity in central collisions results in large combinatorial backgrounds and a very small signal-to-background ratio. It is important to note here that the signal extraction uncertainty was primarily dominated by the fluctuations in the correlated background. The $p+p$ reference uncertainty comes from the uncertainty on the $\phi$ yields in the $p+p$ reference 20. There is a 4% systematic uncertainty from the MuID efficiency and a 2% un-
certainly from the MuTr efficiency in p+p collisions \[20\]. In Cu+Au collisions, the MuTr efficiency uncertainty remains the same, while the MuID efficiency uncertainty drops down to 2\% \[16\]. For the \( A_{\text{rec}} \) uncertainty, the \( p_T \) and \( y \) distributions in PYTHIA are changed to match the slope of the distributions in real data, and allowed to vary over the range of the error bars in data, yielding a 13\% systematic uncertainty. Real data and simulation inconsistencies in each of the muon identification cuts listed in Table II are also evaluated. They can affect the yields by 3\%, which is assigned as a systematic uncertainty on the \( \phi \) meson candidate selection. The like-sign background subtraction uncertainty of 5\% comes from differences in the yields when using the like-sign method or the event mixing method. The \( N_{\text{coll}} \) uncertainty of 5–10\% arises from the fact that \( N_{\text{coll}} \) carries a statistical uncertainty itself. Finally, the MB trigger efficiency uncertainty was 10\% in the p+p reference \[20\] and 3\% in Cu+Au collisions \[16\]. All of these systematic uncertainties are tabulated in Tables II and III.

IV. RESULTS

The invariant yields for \( 1 < p_T < 5 \text{ GeV/c} \) \( \phi \) mesons are calculated as a function of centrality, \( y \) and \( p_T \) as described in Eq. 8. The results are summarized in Tables IV – VI. Similarly, the nuclear modification factors are formed from the invariant yields using Eq. 9 and tabulated in Tables VII – IX.

Fig. 5 shows the invariant yield as a function of the number of participating nucleons \( N_{\text{part}} \). In Fig. 6, the dependence of the invariant yield on transverse momentum \( p_T \) is shown. The invariant yield as a function of rapidity is plotted in Fig. 7. More \( \phi \) mesons are produced in the Au-going direction \((-2.2 < y < -1.2)\) than in the Cu-going direction \((1.2 < y < 2.2)\). This may be explained by the larger multiplicity in the Au-going direction coupled with a mixture of both HNM and CNM effects.

Although the invariant yields are interesting on their own, the nuclear modification factor is studied in order to evaluate the effects of hot and cold nuclear matter on \( \phi \) meson production in Cu+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \).

The nuclear modification factor as a function of \( N_{\text{part}} \) is shown in Fig. 8. There is a dependence of \( R_{\text{CuAu}} \) on both centrality and rapidity. In the Au-going direction, the \( R_{\text{CuAu}} \) is greater than unity for all centralities. The rapidity dependence is similar to the trend observed by PHENIX for \( \phi \rightarrow \mu^+\mu^- \) in \( d+Au \) collisions \[12\] as well as measurements made by the ALICE Collaboration at large rapidity in \( p+Pb \) collisions at 5.02 TeV at the Large Hadron Collider \[22\], where an enhancement was observed in the Pb-going direction while the \( p \)-going direction was either suppressed or consistent with unity depending on the \( p_T \) range.

To further understand the relative roles of different nuclear matter effects in this collision system, the transverse momentum dependence of the nuclear modification factor is shown in Fig. 9. The data points are placed at the mean \( p_T \) of the bin. Here, the nuclear modification is calculated over integrated centrality, but it should be noted that the data are dominated by central collisions.

![Fig. 5](image-url) (color online) Invariant yield as a function of the number of participating nucleons for \( 1.2 < |y| < 2.2 \) and \( 1 < p_T < 5 \text{ GeV/c} \). The centrality bins are 0\%–20\%, 20\%–40\% and 40\%–93\%, and the data points are placed at the mean \( N_{\text{part}} \) calculated from a Glauber simulation. The data points for the Cu-going direction, \( 1.2 < y < 2.2 \), are shifted along the x-axis to \( N_{\text{part}} + 3 \) to make the points visible, while the Au-going direction, \(-2.2 < y < -1.2 \), remains unshifted. The values are shown in Table IV.

![Fig. 6](image-url) (color online) Invariant yield as a function of transverse momentum for \( 1.2 < |y| < 2.2 \) and 0\%–93\% centrality. The \( p_T \) bins are \( 1 < p_T < 2.5 \) and \( 2.5 < p_T < 5 \text{ GeV/c} \), and the data points are placed at the mean \( p_T \) of the bin. The Cu-going direction corresponds to the forward rapidity, \( 1.2 < y < 2.2 \), while the Au-going direction corresponds to the backward rapidity, \(-2.2 < y < -1.2 \). The values are shown in Table IV.
TABLE IV. Invariant yield as a function of centrality for $1 < p_T < 5$ GeV/c and $1.2 < |y| < 2.2$. The first value represents the statistical and Type-A systematic uncertainties, while the second is the systematic uncertainty of Type-B. An additional ±3% Type-C global systematic uncertainty also applies to the yields. The last column summarizes the forward/backward ratio shown in Fig. 11. The forward/backward ratio has no Type-C systematic uncertainty.

| Centrality Bin | $\langle N_{\text{part}} \rangle$ | $BR^{dN}_{d\Phi p p}$ (Cu-going) | $BR^{dN}_{d\Phi p p}$ (Au-going) | forward/backward ratio |
|----------------|-----------------------------|-------------------------------|--------------------------------|------------------------|
| 0%–20%        | 154.8 ± 4.1                | $(7.3 \pm 7.5 \pm 1.1) \times 10^{-5}$ | $(3.4 \pm 1.0 \pm 0.5) \times 10^{-4}$ | 0.230.3 < 0.1 |
| 20%–40%       | 80.4 ± 3.3                 | $(1.2 \pm 0.3 \pm 0.2) \times 10^{-4}$ | $(1.2 \pm 0.3 \pm 0.2) \times 10^{-4}$ | 1.070.4 ± 0.1 |
| 40%–93%       | 19.5 ± 0.5                 | $(1.5 \pm 0.6 \pm 0.2) \times 10^{-5}$ | $(2.7 \pm 0.7 \pm 0.4) \times 10^{-5}$ | 0.60.4 ± 0.3 |

TABLE V. Nuclear modification factors as a function of rapidity for 0%–93% centrality and 1 < $p_T$ < 5 GeV/c. The first error represents the statistical and Type-A systematic uncertainties, while the second is the systematic uncertainty of Type-B. An additional ±5.8% Type-C global systematic uncertainty also applies.

| $|y|_{\min}$ | $|y|_{\max}$ | $R_{CuAu}$ (Cu-going) | $R_{CuAu}$ (Au-going) |
|--------------|--------------|----------------------|----------------------|
| 1.8          | 2.2          | $(6.4 \pm 3.1 \pm 0.9) \times 10^{-5}$ | $(1.1 \pm 0.2 \pm 0.2) \times 10^{-4}$ |
| 1.2          | 1.8          | $(5.3 \pm 2.3 \pm 0.8) \times 10^{-5}$ | $(1.1 \pm 0.3 \pm 0.2) \times 10^{-4}$ |

TABLE VI. Invariant yield as a function of rapidity for 0%–93% centrality and 1 < $p_T$ < 5 GeV/c. The first error represents the statistical and Type-A systematic uncertainties, while the second is the systematic uncertainty of Type-B. An additional ±5.8% Type-C global systematic uncertainty also applies.

| $|y|_{\min}$ | $|y|_{\max}$ | $BR^{dN}_{d\Phi p p}$ (Cu-going) | $BR^{dN}_{d\Phi p p}$ (Au-going) |
|--------------|--------------|-------------------------------|-------------------------------|
| 1.8          | 2.2          | $(6.4 \pm 3.1 \pm 0.9) \times 10^{-5}$ | $(1.1 \pm 0.2 \pm 0.2) \times 10^{-4}$ |
| 1.2          | 1.8          | $(5.3 \pm 2.3 \pm 0.8) \times 10^{-5}$ | $(1.1 \pm 0.3 \pm 0.2) \times 10^{-4}$ |

TABLE VII. Nuclear modification factors as a function of centrality for 0%–93% centrality and 1 < $p_T$ < 5 GeV/c. The first error represents the statistical and Type-A systematic uncertainties, while the second is the systematic uncertainty of Type-B. An additional ±15% Type-C global systematic uncertainty also applies.

| Centrality Bin | $\langle N_{\text{col}} \rangle$ | $R_{CuAu}$ (Cu-going) | $R_{CuAu}$ (Au-going) |
|----------------|---------------------------------|----------------------|----------------------|
| 0%–20%        | 313.8 ± 28.4                   | 0.4 ± 0.4 ± 0.1      | 1.7 ± 0.5 ± 0.3      |
| 20%–40%       | 129.3 ± 12.4                   | 1.4 ± 0.4 ± 0.3      | 1.4 ± 0.3 ± 0.3      |
| 40%–93%       | 21.6 ± 1.0                     | 1.1 ± 0.5 ± 0.2      | 1.9 ± 0.5 ± 0.3      |

TABLE VIII. Nuclear modification factors as a function of $p_T$ for 0%–93% centrality and 1 < $|y| < 2.2$. The first error represents the statistical and Type-A systematic uncertainties, while the second is the systematic uncertainty of Type-B. An additional ±11% Type-C global systematic uncertainty also applies.

| $p_T_{\min}$ (GeV/c) | $p_T_{\max}$ (GeV/c) | $R_{CuAu}$ (Cu-going) | $R_{CuAu}$ (Au-going) |
|----------------------|----------------------|----------------------|----------------------|
| 1.0                  | 2.5                  | 1.1 ± 0.4 ± 0.2      | 2.3 ± 0.4 ± 0.4      |
| 2.5                  | 5.0                  | 0.6 ± 0.4 ± 0.1      | 1.4 ± 0.3 ± 0.2      |

TABLE IX. Nuclear modification factors as a function of rapidity for 0%–93% centrality and 1 < $p_T$ < 5 GeV/c. The first error represents the statistical and Type-A systematic uncertainties, while the second is the systematic uncertainty of Type-B. An additional ±11% Type-C global systematic uncertainty also applies.

| $|y|_{\min}$ | $|y|_{\max}$ | $R_{CuAu}$ (Cu-going) | $R_{CuAu}$ (Au-going) |
|--------------|--------------|----------------------|----------------------|
| 1.8          | 2.2          | 1.2 ± 0.6 ± 0.2      | 2.1 ± 0.5 ± 0.3      |
| 1.2          | 1.8          | 0.7 ± 0.3 ± 0.1      | 1.4 ± 0.4 ± 0.2      |
FIG. 8. (color online) The nuclear modification factor $R_{\text{CuAu}}$ as a function of the number of participating nucleons for $1 < |y| < 2.2$ and $1 < p_T < 5 \text{ GeV}/c$. The centrality bins are 0%–20%, 20%–40% and 40%–93%, and the data points are placed at the mean $N_{\text{part}}$ calculated from a Glauber simulation. The data points for the Cu-going direction, $1.2 < y < 2.2$, are shifted along the x-axis to $N_{\text{part}} + 3$ to make the points visible, while the data points for the Au-going direction, $-2.2 < y < -1.2$, remain unshifted. The values are shown in Table VII.

There is an enhancement at low $p_T$ in the Au-going direction. In the Cu-going direction, $R_{\text{CuAu}}$ is consistent with unity. The enhancement in the Au-going direction is similar in scale to that observed in the Au-going direction in $d+Au$ collisions [13], indicating similar nuclear modification between the two collision systems.

FIG. 9. (color online) The nuclear modification factor $R_{\text{CuAu}}$ as a function of transverse momentum for $1 < |y| < 2.2$ and 0%–93% centrality. The $p_T$ bins are $1 < p_T \leq 2.5$ and $2.5 < p_T < 5 \text{ GeV}/c$, and the data points are placed at the mean $p_T$ of the bin. The Cu-going direction corresponds to the forward rapidity, $1 < y < 2.2$, while the Au-going direction corresponds to the backward rapidity, $-2.2 < y < -1.2$. The values are shown in Table VIII.

FIG. 10. (color online) The nuclear modification factor $R_{\text{CuAu}}$ as a function of rapidity for $1 < |y| < 2.2$ and 0%–93% centrality. The rapidity bins are $1 < |y| < 1.8$ and $1.8 < |y| < 2.2$ and the data points are placed at the mean $y$ of the bin. The values are shown in Table IX. Also included are previous PHENIX results for $\phi$ mesons in $d+Au$ collisions [13] represented by open circles and $J/\psi$ mesons in Cu+Au collisions [16] represented by open triangles. Positive rapidity, $1.2 < y < 2.2$, corresponds to the Cu-going and d-going directions, while negative rapidity, $-2.2 < y < -1.2$, is the Au-going direction.

FIG. 7. (color online) Invariant yield as a function of rapidity for $1 < p_T < 5 \text{ GeV}/c$ and 0%–93% centrality. The rapidity bins are $1 < |y| < 1.8$ and $1.8 < |y| < 2.2$ and the data points are placed at the mean $y$ of the bin. The Cu-going direction covers the region $1.2 < y < 2.2$, while the Au-going direction covers the region $-2.2 < y < -1.2$. The values are shown in Table VII.

FIG. 11.
FIG. 11. (color online) The forward/backward ratio as a function of the number of participating nucleons for $1 < p_T < 5$ GeV/c and $1.2 < |y| < 2.2$. The values are shown in Table IV. The Cu-going direction covers positive rapidity, $1.2 < y < 2.2$, while the Au-going direction covers negative rapidity, $-2.2 < y < -1.2$.

a function of $y$ for two rapidity regions, $1.2 < |y| < 1.8$ and $1.8 < |y| < 2.2$. The data points are placed at the mean $y$ of the bin. As in Fig. 9 the nuclear modification factor is inclusive of centrality. The rapidity-dependence of $R_{\text{Cu}Au}$ is similar to the trend observed in previous $\phi$ meson measurements in $p(d)+\text{Au}$ collisions. In particular, $\phi$ meson production is enhanced in the Au-going direction. None of the Cu-going points show significant suppression given the statistical uncertainties. For comparison, the PHENIX $J/\psi$ meson results in the same Cu+Au dataset from Ref. 16 are also shown in Fig. 10. While the closed charm shows suppression at both forward and backward rapidity for $1.2 < |y| < 2.2$, the closed strangeness is enhanced at backward rapidity. In Cu+Au collisions, the $J/\psi$ meson yield is strongly suppressed in the Au-going direction compared to the $\phi$ meson yield at the same rapidity. This is similar to the differences previously observed between $J/\psi$ and $\phi$ meson nuclear modification in $d+\text{Au}$ collisions 13. These differences could be attributed to a larger $J/\psi$ break up cross section, effects in the higher-energy-density backward-rapidity region, or changes between soft and hard production mechanisms between the two mesons.

The forward and backward differences can be quantified by the ratio of the yield values for the forward rapidity (Cu-going direction) to the backward rapidity (Au-going direction). Fig. 11 shows the forward/backward ratio as a function of participating nucleons for $1 < |y| < 2.2$ and $1 < p_T < 5$ GeV/c. The Type-C and Type-B systematic uncertainties, except for the $A\varepsilon_{\text{rec}}$ uncertainty, cancel when taking this ratio. The remaining systematic uncertainties are the Type-A signal extraction uncertainty and the Type-B $A\varepsilon_{\text{rec}}$ uncertainty. The difference in suppression between the forward and backward rapidity is more noticeable in the most central collisions, 0%–20%. In this centrality bin, the probability of observing the forward/backward ratio greater than or equal to unity was found to be $p$-value=1.2%, corresponding to a statistical significance of 2.3$\sigma$. The particle multiplicity for central collisions should be about 20% higher in the Au-going direction than in the Cu-going direction 33, however, the much smaller ratio observed may indicate that increased recombination effects or additional thermal strangeness production may also occur at higher energy density. In central collisions, the forward/backward ratio in $\phi$ production ($\sim0.2$) is smaller than that in $J/\psi$ production ($\sim0.8$) in Cu+Au collisions 16.

V. SUMMARY

In summary, $\phi$ meson production and its nuclear modification have been measured in Cu+Au collisions at $\sqrt{s_{NN}}=200$ GeV for $1 < |y| < 2.2$ and $1 < p_T < 5$ GeV/c via the dimuon decay channel. This first measurement of $\phi$ meson production and its nuclear modification in a heavy-ion system at forward/backward rapidity at RHIC extends measurements of $\phi$ from smaller systems, $p+p$ and $d+\text{Au}$, in the forward and backward rapidity. The invariant yields and nuclear modification factors have been presented here as a function of $N_{\text{part}}$, $p_T$ and rapidity.

The $\phi$ meson yields in Cu+Au collisions are found to be generally smaller in the Cu-going direction than in the Au-going direction. This is most pronounced in the most central events, 0%–20%, and at low momentum, 1.0–2.5 GeV/c. In central collisions (0%–20%), the forward/backward ratio is below unity at a confidence level of 99%. It has been shown that these results follow a trend similar to what was seen previously at PHENIX in $d+\text{Au}$ at the same rapidity and energy 13 as well as the ALICE measurement in $p+\text{Pb}$ collisions at larger rapidity ($-4.46 < y < -2.96$ and $2.03 < y < 3.53$) and higher energy ($\sqrt{s_{NN}}=5.02$ TeV) 24. While this agreement could imply a role for CNM effects on $\phi$ production in Cu+Au collisions, the production of $\phi$ in heavy-ion collisions for these kinematics is expected to have substantial contributions from HNM effects as which were demonstrated to dominate previous measurements at midrapidity for both Cu+Cu and Au+Au collisions 18. A competition between CNM and HNM production mechanisms appears relevant for $\phi$ production at forward rapidity for heavy-ion collisions and a comprehensive description is needed from soft and hard physics models. Although the $\phi$ meson is sensitive to both CNM and HNM effects, this study was statistically limited, a factor that also affects the precise determination of the systematic uncertainties. A high statistics measurement and theory calculations are both needed in order to make conclusions about the various physics processes that might be at play here, in-
cluding modifications of strangeness production in bulk matter and quark recombination.

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[1] I. Arsene et al. (BRAHMS Collaboration), “Quark gluon plasma and color glass condensate at RHIC? The Perspective from the BRAHMS experiment,” Nucl. Phys. A 757, 1 (2005).
[2] B. B. Back et al., “The PHOBOS perspective on discoveries at RHIC,” Nucl. Phys. A 757, 28 (2005).
[3] J. Adams et al. (STAR Collaboration), “Experimental and theoretical challenges in the search for the quark gluon plasma: The STAR Collaboration’s critical assessment of the evidence from RHIC collisions,” Nucl. Phys. A 757, 102 (2005).
[4] K. Adcox et al. (PHENIX Collaboration), “Formation of dense partonic matter in relativistic nucleus-nucleus collisions at RHIC: Experimental evaluation by the PHENIX Collaboration,” Nucl. Phys. A 757, 184 (2005).
[5] P. Koch, B. Muller, and J. Rafelski, “Strangeness in Relativistic Heavy Ion Collisions,” Phys. Rept. 142, 167 (1986).
[6] A. Shor, “$\phi$ meson production as a probe of the quark gluon plasma,” Phys. Rev. Lett. 54, 1122 (1985).
[7] A. Andronic, “An overview of the experimental study of quark-gluon matter in high-energy nucleus-nucleus collisions,” Proceedings, 26th International Symposium on Lepton Photon Interactions at High Energy (LPI3), Int. J. Mod. Phys. A29, 1430047 (2014).
[8] C. M. Ko and D. Seibert, “What can we learn from a second $\phi$ meson peak in ultrarelativistic nuclear collisions?” Phys. Rev. C 49, 2198 (1994).
[9] J. J. Heckman, J. Seo, and C. Vafa, “Phase Structure of a Brane/Anti-Brane System at Large N,” J. High Energy Phys. 07 (2007) 073.
[10] I. Vitev, “Initial state parton broadening and energy loss probed in d+Au at RHIC,” Phys. Lett. B 562, 36 (2003).
[11] J. W. Cronin, Henry J. Frisch, M. J. Shochet, J. P. Boymond, R. Mermod, P. A. Piroue, and R. L. Summer, “Production of Hadrons with Large Transverse Momentum at 200 GeV, 300-GeV, and 400-GeV,” High energy physics. Proceedings, 17th International Conference, ICHEP 1974, London, England, July 01-July 10, 1974, Phys. Rev. D 11, 3105 (1975).
[12] A. Accardi and M. Gyulassy, “Cronin effect versus geometrical shadowing in d + Au collisions at RHIC,” Phys. Lett. B 586, 244 (2004).
[13] A. Adare et al. (PHENIX Collaboration), “$\phi$ meson production in d + Au collisions at $\sqrt{s_{NN}} = 200$ GeV,” arXiv:1506.08181.
[14] S. S. Adler et al. (PHENIX Collaboration), “Nuclear Modification Factors for Hadrons at Forward and Backward Rapidities in Deuteron-Gold Collisions at $\sqrt{s_{NN}} = 200$ GeV,” Phys. Rev. Lett. 94, 082302 (2005).
[15] A. Adare et al. (PHENIX Collaboration), “System-size dependence of open-heavy-flavor production in nucleus-nucleus collisions at $\sqrt{s_{NN}} = 200$ GeV,” Phys. Rev. C 90, 034903 (2014).
[16] A. Adare et al. (PHENIX Collaboration), “Nuclear matter effects on $J/\psi$ production in asymmetric Cu + Au collisions at $\sqrt{s_{NN}} = 200$ GeV,” Phys. Rev. C 90, 064908 (2014).
[17] S. S. Adler et al. (PHENIX Collaboration), “Production of $\phi$ mesons at midrapidity in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions at RHIC,” Phys. Rev. C 72, 014903 (2005).
[18] A. Adare et al. (PHENIX Collaboration), “Nuclear modification factors of $\phi$ mesons in d+Au, Cu+Cu and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV,” Phys. Rev. C 83, 024909 (2011).
[19] A. Adare et al. (PHENIX Collaboration), “Measurement of neutral mesons in p+p collisions at $\sqrt{s} = 200$ GeV and scaling properties of hadron production,” Phys. Rev. D 83, 052004 (2011).

[20] A. Adare et al. (PHENIX Collaboration), “Low-mass vector-meson production at forward rapidity in p+p collisions at $\sqrt{s} = 200$ GeV,” Phys. Rev. D 90, 052002 (2014).

[21] B. I. Abelev et al. (STAR Collaboration), “Partonic flow and $\phi$-meson production in Au+Au collisions at $\sqrt{s_{NN}} = 200$,” Phys. Rev. Lett. 99, 112301 (2007).

[22] B. I. Abelev et al. (STAR Collaboration), “Energy and system size dependence of $\phi$ meson production in Cu+Cu and Au+Au collisions,” Phys. Lett. B 673, 183 (2009).

[23] J. Adam et al. (ALICE Collaboration), “$\phi$-meson production at forward rapidity in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and in pp collisions at $\sqrt{s} = 2.76$ TeV,” arXiv:1506.09206.

[24] B. B. Abelev et al. (ALICE Collaboration), “$K^0$(892) and $\phi$(1020) production in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV,” Phys. Rev. C 91, 024609 (2015).

[25] K. Adcox et al. (PHENIX Collaboration), “PHENIX detector overview,” Nucl. Instrum. Methods Phys. Res., Sec. A 499, 469 (2003).

[26] H. Akikawa et al. (PHENIX Collaboration), “PHENIX muon arms,” Nucl. Instrum. Methods Phys. Res., Sec. A 499, 537 (2003).

[27] M. Allen et al. (PHENIX Collaboration), “PHENIX inner detectors,” Nucl. Instrum. Methods Phys. Res., Sec. A 499, 549 (2003).

[28] A. Taketani et al. (PHENIX Collaboration), “Silicon vertex tracker for RHIC PHENIX experiment,” Technology and instrumentation in particle physics. Proceedings, 1st International Conference, TIPP09, Tsukuba, Japan, March 12-17, 2009, Nucl. Instrum. Methods Phys. Res., Sec. A 623, 374 (2010).

[29] C. Aidala et al., “The PHENIX Forward Silicon Vertex Detector,” Nucl. Instrum. Methods Phys. Res., Sec. A 755, 44 (2014).

[30] C. Baglin et al. (NA38 Collaboration), “The Production of $J/\psi$ in 200-GeV/nucleon Oxygen Uranium Interactions,” Phys. Lett. B 220, 471 (1989).

[31] A. Adare et al. (PHENIX Collaboration), “$J/\psi$ suppression at forward rapidity in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV,” Phys. Rev. C 84, 054912 (2011).

[32] T. Sjostrand, P. Eden, C. Friberg, L. Lonnblad, G. Miu, S. Mrenna, and E. Norrbin, “High-energy physics event generation with PYTHIA 6.1,” Comput. Phys. Commun. 135, 238 (2001).

[33] R. Brun, F. Carminati, and S. Giani, “GEANT Detector Description and Simulation Tool,” CERN-W5013 (1994).

[34] J. Beringer et al. (Particle Data Group Collaboration), “Rev. of Particle Phys. (RPP),” Phys. Rev. D 86, 010001 (2012).

[35] L.-W. Chen and C. M. Ko, “Anisotropic flow in Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV,” Phys. Rev. C 73, 014906 (2006).