Measurement of $K_S^0$ and $K^{*0}$ in $p+p$, $d+Au$, and $Cu+Cu$ collisions at $\sqrt{s}_{NN} = 200$ GeV

A. Adare, S. Afanasiev, A. Ajitanand, Y. Akiba, R. Akimoto, H.-Al-Bataineh, J. Alexander, M. Alfred, A. Angerami, K. Aoki, N. Apadula, Y. Aphecetche, Y. Aramaki, R. Armendariz, S.H. Aronson, J. Asai, H. Asano, E.T. Atomicsa, R. Averbeck, T.C. Awes, B. Aznoun, V. Babintsev, M. Bai, G. Bakays, L. Baksay, A. Baldiesser, N.S. Bandara, B. Bannier, K.N. Barish, P.D. Barnes, B. Bassalleck, A.T. Basye, S. Bathe, S. Batsoul, V. Baublis, C. Baumann, A. Bazelevskiy, M. Beaman, S. Beckman, S. Belikov, R. Belmont, R. Bennett, B. Berndikov, J.H. Bhom, A.A. Bickley, D. Black, D.S. Blau, J.G. Boissevain, J. Bok, J.S. Bok, H. Borel, K. Boyle, M.L. Brooks, J. Bryslewski, H. Buesching, V. Bunazhnov, G. Bune, S. Butsyk, S. Campbell, A. Carigni, B.S. Chang, J.L. Charvet, C.-H. Chen, S. Chernichenko, C.Y. Chi, J. Chiba, M. Chiu, T. Choi, J.C. Choi, R.K. Chtoudry, P. Christiansen, T. Chudo, P. Chung, A. Chury, O. Chvala, V. Cianciolo, Z. Citron, C.R. Cleven, B.A. Cole, M.P. Comets, Z. Conesa del Valle, M. Connors, P. Constantin, M. Csanad, T. Csorgo, T. Dahms, I. Danchev, K. Das, A. Datta, M.S. Daugherty, G. David, M.K. Dayananda, M.B. Deaton, K. DeBlasio, K. Dehmelt, H. Delagrange, A. Denisov, D. d’Entrematte, A. Deshpande, K.D. Desmond, K.V. Dharmawardane, O. Dietzsch, L. Ding, A. Dion, J.H. Do, M. Donadelli, O. Drapier, A. Drees, K.A. Drees, A.K. Dubey, J.M. Durham, A. Durum, D. Dutta, V. Dzhordzhadze, L. D’Orazio, S. Edwards, V.Y. Efremenko, J. Egdelin, E. Ellinghaus, W.S. Eman, T. Engelkiron, A. Enokizono, H. En’yo, S. Esumi, K.O. Eyser, B. Fadem, N. Fege, D.E. Fields, M. Finge, M. Finger, F. Fleuret, S.L. Fokin, Z. Frangen, J.F. Frantz, A. Franz, A.D. French, W. Fujiwara, Y. Fukao, T. Fuyasu, S. Gadrat, C. Gal, P. Gallus, P. Garg, I. Garishvili, H. Ge, F. Giordano, A. Glenn, H. Gong, M. Goun, J. Gosset, Y. Goto, R. Granier de Cassagnac, G. Grau, S.V. Greene, R. Hayano, X. He, M. Heffner, T.K. Hemmick, T. Hester, H. Hiejima, J.C. Hill, R. Hobbs, M. Hohlmann, R.S. Hollis, W. Holzmann, K. Homma, B. Hong, T. Horaguchi, D. Hornback, T. Hoshino, S. Huang, T. Ichihara, R. Ichimiyaya, H. Iinuma, Y. Ikeda, K. Imai, M. Inaba, Y. Inoue, A. Iordanova, D. Isenhower, M. Ishihara, T. Isobe, M. Issaah, A. Isupov, D. Ivanishceva, M. Ivanishchev, Y. Iwamu, E. Jacak, S.J. Jeon, M. Jezghani, J. Jia, X. Jiang, J. Jin, O. Jinnouchi, B.M. Johnson, T. Jones, E. Joo, K.S. Joo, D. Jouan, D.S. Juicer, F. Kajihara, S. Kametani, N. Kaminoh, J. Kamin, M. Kaneta, J.H. Kang, J.S. Kang, H. Kanou, J. Kaputsinski, K. Karatsu, M. Kasai, K. Kawall, M. Kawashima, A.V. Kazantsev, T. Kemp, Y. Kikuchiyama, A. Khanzadeev, K. Kihara, M.K. Kijima, J. Kikuchi, A. Kim, B.I. Kim, C. Kim, D.H. Kim, D.J. Kim, E. Kim, E.-J. Kim, H.-J. Kim, M. Kim, Y. Kim, Y.K. Kim, E. Kinney, A. Kiss, E. Kistenev, A. Kiyomichi, J. Klatsky, V. Klav, C. Klein-Boesing, D. Klein, T. Kolesy, L. Kochenda, V. Kochetkov, M. Kofarago, B. Komkov, M. Komno, J. Koster, D. Kotchetkov, D. Kotov, A. Kozlov, A. Král, A. Kravitz, J. Kubart, G.J. Kunde, N. Kurihara, K. Kurita, M. Kurosawa, M.J. Kweon, Y. Kwon, G.S. Kyle, R. Lacey, Y.S. Lai, J.G. Lajoie, A. Lebedev, D.M. Lee, J. Lee, K.B. Lee, K.S. Lee, M.K. Leick, H.S. Lee, M.J. Leicht, M.L. Leite, M. Leitge, B. Lenzi, X. Li, P. Lichtenwalner, P. Liebing, S.H. Lim, L.A. Lindey, T. Liska, A. Litvinenko, M. Lonina, M.X. Liu, B. Love, D. Lynch, C.F. Maguire, Y.I. Makdisi, M. Makek, M. Makish, M.D. Malik, A. Manion, V.I. Manko, E. Mannell, Y. Mao, L. Mašek, H. Masui, F. Matathias, M. McChesney, P.L. McGaughy, D. McGlinchey, C. McKinney, N. Means, A. Meles, M. Mendoza, B. Meredith, Y. Miao, T. Mibe, A.C. Migneray, P. Miles, K. Miki, A.J. Miller, T.E. Miller, A. Milov, S. Mioduszewski, D.K. Mishra, M. Mishra, J.T. Mitchell, M. Mitrovski, S. Miyasaka, S. Mizuno, A.K. Mohanty, P. Montuenga, H.J. Moon, T. Moon, Y. Morino, A. Morreale, D.P. Morrison, T.V. Moukhanova, M. Mukhopadhyay, J. Murata, A. Mwai, S. Nagamia, Y. Nagata, J.L. Nagle, M. Naglis, M.I. Nagy, I. Nakagawa, H. Nakagomi, Y. Nakamura, K.R. Nakamura, K. Nakano, S. Nam, C. Nattrass, P.K. Neatrakti, J. Newby, 40
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(PHENIX Collaboration)  

1Abilene Christian University, Abilene, Texas 79699, USA  
2Department of Physics, Augustana College, Sioux Falls, South Dakota 57197, USA  
3Department of Physics, Banaras Hindu University, Varanasi 221005, India  
4Bhabha Atomic Research Centre, Bombay 400 085, India  
5Baruch College, City University of New York, New York, New York, 10010 USA  
6Collider-Accelerator Department, Brookhaven National Laboratory, Upton, New York 11973-5000, USA  
7Physics Department, Brookhaven National Laboratory, Upton, New York 11973-5000, USA  
8University of California - Riverside, Riverside, California 92521, USA  
9Charles University, Ovocný trh 5, Praha 1, 116 36, Prague, Czech Republic  
10Chonbuk National University, Jeonju, 561-756, Korea  
11Science and Technology on Nuclear Data Laboratory, China Institute of Atomic Energy, Beijing 102413, P. R. China  
12Center for Nuclear Study, Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan  
13University of Colorado, Boulder, Colorado 80309, USA  
14Columbia University, New York, New York 10027 and News Laboratories, Irvington, New York 10533, USA  
15Czech Technical University, Zikova 4, 166 39 Prague 6, Czech Republic  
16Dapnia, CEA Saclay, F-91911, Gif-sur-Yvette, France  
17Debrecen University, H-4010 Debrecen, Egyetem tér 1, Hungary  
18ELTE, Eötvös Loránd University, H - 1117 Budapest, Pázmány P. s. 1/A, Hungary  
19Ewha Womans University, Seoul 120-750, Korea  
20Florida Institute of Technology, Melbourne, Florida 32901, USA  
21Florida State University, Tallahassee, Florida 32306, USA  
22Georgia State University, Atlanta, Georgia 30303, USA  
23Hanyang University, Seoul 133-792, Korea  
24Hiroshima University, Kagamiyama, Higashi-Hiroshima 739-8526, Japan  
25Department of Physics and Astronomy, Howard University, Washington, DC 20059, USA  
26IHEP Protein, State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, 142281, Russia  
27University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA  
28Institute for Nuclear Research of the Russian Academy of Sciences, prospekt 60-letiya Oktyabrya 7a, Moscow 117212, Russia  
29Institute of Physics, Academy of Sciences of the Czech Republic, Na Slovance 2, 182 21 Prague 8, Czech Republic
The PHENIX experiment at the Relativistic Heavy Ion Collider has performed a systematic study of $K^0_S$ and $K^{*0}$ meson production at midrapidity in $p+p$, $d+Au$, and $Cu+Cu$ collisions at $\sqrt{s_{NN}} = 200$ GeV. The $K^0_S$ and $K^{*0}$ mesons are reconstructed via their $K^0_S \rightarrow \pi^0(\rightarrow \gamma\gamma)$ and $K^{*0} \rightarrow K^\pm \pi^\mp$ decay modes, respectively. The measured transverse-momentum spectra are used to determine the nuclear modification factor of $K^0_S$ and $K^{*0}$ mesons in $d+Au$ and $Cu+Cu$ collisions at different centralities. In the $d+Au$ collisions, the nuclear modification factor of $K^0_S$ and $K^{*0}$ mesons is almost constant as a function of transverse momentum and is consistent with unity showing that cold-nuclear-matter effects do not play a significant role in the measured kinematic range. In $Cu+Cu$ collisions, within the uncertainties no nuclear modification is registered in peripheral collisions. In central collisions, both mesons show suppression relative to the expectations from the $p+p$ yield scaled by the number of binary nucleon-nucleon collisions in the $Cu+Cu$ system. In the $p_T$ range 2–5 GeV/$c$, the strange mesons ($K^0_S$, $K^{*0}$) similarly to the $\phi$ meson with hidden strangeness, show an intermediate suppression between the more suppressed light quark mesons ($\pi^0$) and the
nonsuppressed baryons \((p, \bar{p})\). At higher transverse momentum, \(p_T > 5 \text{ GeV}/c\), production of all particles is similarly suppressed by a factor of \(\approx 2\).

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I. INTRODUCTION

At very high energy densities, exceeding approximately 1 GeV/fm\(^3\), quantum chromodynamics predicts a phase transition from ordinary hadronic nuclear matter to a new state of matter where the degrees of freedom are quarks and gluons \(^\text{1}\). This state of matter exhibits very strong coupling between its constituents and is thus called the strongly coupled Quark-Gluon Plasma (sQGP) \(^\text{2}\). Matter at such high energy density can be produced in laboratory conditions by colliding heavy nuclei at relativistic energies. A wealth of measurements is available from the experiments at the Relativistic Heavy Ion Collider (RHIC) and recently from the experiments at the Large Hadron Collider (LHC) \(^\text{3}\).

High-momentum penetrating probes are among the observables attracting primary attention. Highly energetic partons traversing the sQGP medium suffer significant energy loss \(^\text{4, 5}\), leading to modification of the fragmentation functions \(^\text{6}\) and softening of the measured transverse momentum \((p_T)\) distribution. The softening of the spectrum is quantified by the “nuclear modification factor” \(R_{\text{AB}}\) defined as:

\[
R_{\text{AB}} = \frac{d^2N_{\text{AB}}/dydp_T}{N_{\text{coll}} \times d^2N_{\text{pp}}/dydp_T},
\]

where the numerator is the per-event yield of particle production in \(A+B\) (heavy ion) collisions, measured as a function of \(p_T\), \(d^2N_{\text{pp}}/dydp_T\) is the per-event yield of the same process in \(p+p\) collisions and \(N_{\text{coll}}\) is the number of nucleon-nucleon collisions in the \(A+B\) system \(^\text{7, 8}\). \(R_{\text{AB}}\) different from unity is a manifestation of medium effects. However, to untangle final state effects, such as energy loss, from possible contributions of cold nuclear matter and initial state effects (e.g. shadowing \(^\text{9}\) and the Cronin effect \(^\text{10}\)), the nuclear modification factor must also be measured in systems like \(p+A\) or \(A+A\).

A significant suppression of hadrons produced in heavy ion collisions was first measured at RHIC \(^\text{11, 20}\) and recently at the LHC \(^\text{21, 22}\) also with fully reconstructed jets \(^\text{23, 25}\). In central Au+Au collisions at RHIC, \(R_{\text{AB}}\) of hadrons reaches a maximum suppression of a factor of \(\approx 5\) at \(p_T \sim 5 \text{ GeV}/c\) \(^\text{13, 15, 16, 26}\). At higher \(p_T\), the suppression is found to be independent of the particle type, mesons or baryons, and their quark flavor content \(^\text{27, 22}\). In central Pb+Pb collisions at the LHC, the suppression reaches a factor of \(\approx 7\) at \(p_T \sim 6–7 \text{ GeV}/c\) \(^\text{21, 22}\). At higher \(p_T\), the \(R_{\text{AB}}\) starts to increase reaching a value of 0.5 at \(p_T > 40 \text{ GeV}/c\).

In the intermediate \(p_T\) range \((2 < p_T < 5 \text{ GeV}/c)\), mesons containing light quarks \((\pi, \eta)\) exhibit suppression \(^\text{15, 30}\), whereas protons show very little or no suppression \(^\text{30, 32}\). Other processes, such as the Cronin effect \(^\text{10}\), strong radial flow \(^\text{33}\), recombination effects \(^\text{34}\) have been invoked to explain the differences between mesons and baryons in this momentum range. Recent results obtained at the LHC in \(p+\text{Pb}\) collisions \(^\text{35, 37}\) and at RHIC in \(d+\text{Au}\) collisions \(^\text{30, 38}\) suggest that collective effects might be present even in small systems and can significantly modify the particle properties in the intermediate transverse momentum range.

Measurements of particles with different quark content provide additional constraints on the models of collective behavior, parton energy loss and parton recombination. Experimental measurements of particles containing strange quarks are important to find out whether or not recombination mechanisms boost strange hadron production at intermediate \(p_T\) and to understand their suppression at high \(p_T\). In heavy ion collisions, the \(\phi\) meson \(^\text{16}\) shows at high \(p_T\) the same suppression as particles containing only \(u\) and \(d\) quarks, however at intermediate \(p_T\) it is less suppressed than the \(\pi\) meson. On the other hand, the \(\eta\) meson, which has a significant strange quark content, is suppressed at the same level as \(\pi\) meson in the \(p_T\) range from 2–10 GeV/c \(^\text{15}\). Open questions are: Which physics mechanism prevails in the intermediate \(p_T\) region and which process is responsible for the suppression of particles with strange quark content.

This article presents results of the \(K^0_S\) and \(K^{*0}\) meson production as a function of \(p_T\) at midrapidity in \(p+p\), \(d+\text{Au}\) and \(\text{Cu}+\text{Cu}\) collisions at \(\sqrt{s_{NN}} = 200 \text{ GeV}\). The present measurements significantly extend the \(p_T\) reach of the previous PHENIX results on the measurement of \(K^0_S\) meson in \(p+p\) collisions \(^\text{19}\). The \(K^0_S\) meson is reconstructed via the \(K^0_S \rightarrow \pi^0(-\gamma\gamma)\pi^0(-\gamma\gamma)\) decay mode. The \(K^{*0}\) and \(K^{*0}\) mesons are reconstructed via the \(K^{*0} \rightarrow K^+\pi^-\) and \(K^0 \rightarrow K^-\pi^+\) decay modes, respectively. The yields measured for the \(K^{*0}\) and \(\bar{K}^{*0}\) mesons are averaged together and denoted as \(K^{*0}\). The invariant transverse momentum spectra for \(K^0_S\) mesons are measured over the \(p_T\) range of 2–13 (3–12) GeV/c in the \(d+\text{Au}\) (\(\text{Cu}+\text{Cu}\)) collision systems. The \(K^{*0}\) meson spectra are measured in the \(p_T\) range from 1.1 GeV/c up to 8–8.5 GeV/c depending on the collision system. The measurements extend the momentum coverage of the previously published results by the STAR collaboration \(^\text{40, 42}\). The nuclear modification factors are obtained for both particles in \(d+\text{Au}\) and \(\text{Cu}+\text{Cu}\) collisions at different centralities and are compared with those of

\(^\text{1}\) Deceased
\(^\text{2}\) PHENIX Co-Spokesperson: morrison@bnl.gov
\(^\text{3}\) PHENIX Co-Spokesperson: jie.nagle@colorado.edu
the $\phi$ and $\pi^0$ mesons. The measured $p_T$ ranges and the centrality bins used in the different systems are listed in Table II.

**TABLE I. Summary of centrality bins and measured $p_T$ ranges for the $K_S^0$ and $K^{*0}$ studies.**

| Collision System | Centrality bins (%) | Measured $p_T$ range (GeV/c) |
|------------------|---------------------|-------------------------------|
| $K_S^0$          | $d+Au$ 0–20, 20–40, 40–60, 60–88 | 2.0–13.0 |
|                  | Cu+Cu 0–20, 20–60, 60–94         | 3.0–12.0 |
| $K^{*0}$         | $p+p$ 0–20, 20–40, 40–60, 60–88  | 1.1–8.0 |
|                  | Cu+Cu 0–20, 20–40, 40–60, 60–94  | 1.4–8.0 |

The paper is organized as follows. The next section gives a brief description of the PHENIX detector. The analysis procedures used to measure $K_S^0$ and $K^{*0}$ mesons are described in Section III. The results, including the invariant $p_T$ distributions and $R_{AB}$, are given in Section IV. A summary is given in Section V.

II. PHENIX DETECTOR

A detailed description of the PHENIX detector can be found in Ref. [43]. The analysis here is performed using the two central-arm spectrometers, each covering an azimuthal angle $\phi = \pi/2$ and pseudorapidity $|\eta| < 0.35$ at midrapidity. Each arm comprises a Drift Chamber (DC), two or three layers of pad chambers (PC), a ring-imaging Čerenkov detector (RICH) and an Electromagnetic Calorimeter (EMCal) and a time-of-flight detector (TOF). This analysis uses the east arm of the TOF detector that covers $\pi/4$ in $\phi$.

The global event information is provided by the beam-beam counters (BBC) [45], which are used for event triggering, collision time determination, measurement of the vertex position along the beam axis and for the centrality determination [8, 46]. The typical vertex position resolution by the BBC depends on the track multiplicity and varies from $\sim 1.1$ cm in $p+p$ collisions to $\sim 3$ mm in central Au+Au collisions.

Track reconstruction in PHENIX is provided by two detectors: DC and PC [43]. The DC and the first layer of PC (PC1) form the inner tracking system, whereas PC2 and PC3 form the outer tracker. The DC is a multitire gaseous detector located outside the magnetic field between the radii of 2.02 m and 2.48 m in each PHENIX arm. The DC measures the track position with an angular resolution of $\sim 0.8$ mrad in the bending plane perpendicular to the beam axis. A combinatorial Hough Transform technique [47] is used to determine the track direction in azimuth and its bending angle in the axial magnetic field of the central magnet [48]. The track-reconstruction algorithm approximates all tracks in the volume of the DC with straight lines and assumes their origin at the collision vertex. This information is then combined with the hit information in PC1 which immediately follows the DC along the particle tracks. PC1 provides the $z$-coordinate information with a spatial resolution of $\sigma_z \sim 1.7$ mm. The resulting momentum resolution for charged particles with $p_T > 0.2$ GeV/c is $\delta p/p = 0.7 \pm 1.1$ % $p$ (GeV/c), where the first term represents multiple scattering and the second term is due to the intrinsic angular resolution of the DC. Matching the tracks to hits in PC2 and PC3 located at radii of 4.2 m and 5.0 m respectively helps to reject secondary tracks that originate either from decays of long-lived hadrons or from interactions with the detector material.

Detailed information on the PHENIX tracking can be found in Ref. [44, 49].

The TOF detector [50] identifies charged hadrons; pions, kaons and protons. It is located at a radial distance of 5.06 m from the interaction point in the east central arm. The total timing resolution of TOF east is 130 ps, which includes the start time determination from the BBC. This allows for a $2\sigma$ $\pi/K$ separation up to $p_T \approx 2.5$ GeV/c and $K/p$ separation up to $p_T = 4.5$ GeV/c using an asymmetric particle-identification (PID) cut, as described in Ref. [51]. The EMCal [52] uses lead-scintillator (PbSc) and lead-glass (PbGl) technologies and measures the position and energy of electrons and photons. It also provides a trigger on rare events with high momentum photons. The EMCal covers the full acceptance of the central spectrometers and is divided into eight sectors in azimuth. Six PbSc sectors are located at a radial distance of 5.1 m from the beam line and comprise 15,552 lead-scintillator towers with cross section of $5 \times 5$ cm$^2$. Most electromagnetic showers extend over several towers. Groups of adjacent towers with signals above a threshold that are associated with the same shower form an EMCal cluster. The energy resolution of the PbSc (PbGl) calorimeter is $\delta E/E = 2.1 (0.8)/\sqrt{E[GeV]}$. Most electromagnetic shower clusters exceed several towers. Groups of adjacent towers with signals above a threshold that are associated with the same shower form an EMCal cluster. The energy resolution of the PbSc (PbGl) calorimeter reaches $\sigma(E) = 1.55 (0.2) \div 5.74 (8.4)/\sqrt{E[GeV]}$ mm for particles at normal incidence.

Analyses presented in this paper use both the minimum bias (MB) and the rare event, EMCal-RICH trigger (ERT). For $p+p$, $d+Au$, and Cu+Cu collisions, the MB trigger requires a coincidence of at least one channel firing on each side of the BBC. It further requires the vertex position along the beam axis $z$, as determined from the BBC timing information, to be within 38 cm of the nominal center of the interaction region. Photon ERT utilizes the EMCal to select events with at least one registered high $p_T$ photon or electron. For every EMCal super module [52], the ERT sums the registered energy in adjacent $4 \times 4$ EMCal towers. This trigger is used to collect samples for the $K_S^0$ meson analysis. The trigger fires if the summed energy exceeds 1.4 and 2.8 GeV threshold
in $d$-$Au$ and Cu+Cu collisions, respectively. The calculation of the ERT efficiency for photons and $K_S^0$ mesons is described in Section III C.

III. ANALYSIS PROCEDURE

This section describes the analysis procedure for the measurement of $K_S^0$ meson and $K^{*0}$ meson transverse momentum spectra. The measurements are done using the data sets collected by the PHENIX experiment in the 2005 ($p+p$ and Cu+Cu) and in the 2008 ($d$+$Au$) physics runs. The data samples used in the analysis correspond to integrated luminosities of 3.78 pb$^{-1}$ in $p+p$, 81 nb$^{-1}$ in $d$+$Au$ and 3.06 nb$^{-1}$ in Cu+Cu collision systems. The mesons are reconstructed via the decay modes $K_S^0 \rightarrow \pi^0(\rightarrow \gamma\gamma)\pi^0(\rightarrow \gamma\gamma)$ and $K^{*0} \rightarrow K^\pm\pi^\mp$. The MB triggered data samples are used for the $K^{*0}$ meson study in $p+p$, $d$+$Au$ and Cu+Cu systems. The $K_S^0$ meson measurements are done using both the MB and ERT-triggered data samples in $d$+$Au$ and Cu+Cu collisions. The MB samples provide the measurements at low and intermediate $p_T$. The low $p_T$ reach of these measurements is limited by the rapidly decreasing signal to background ratio and subsequent difficulties in the extraction of the $K_S^0$ meson raw yield. The ERT-triggered data give access to intermediate and high $p_T$ production of $K_S^0$ mesons due to larger sampled luminosity. In the overlap region, results obtained with the MB and ERT data samples are found to be in very good agreement. For the final $K_S^0$ meson production spectrum in $d$+$Au$ (Cu+Cu) collisions, the MB results are used up to 4 (5) GeV/$c$ and the ERT results are used at higher transverse momenta. Details about the $K_S^0$ meson measurement in $p+p$ collisions can be found in Ref. [69].

A. Reconstruction of $K_S^0$ meson invariant mass

The $K_S^0$ meson with a lifetime of $\tau \sim 2.7$ cm decays to two $\pi^0$ mesons with a branching ratio BR = 30.69 ± 0.05% [52]. The neutral pions further decay into two photons with BR = 98.823 ± 0.034% [53]. The $\pi^0$ mesons are measured by combining the pair of photon clusters reconstructed in the EMCal. The energy of the clusters is measured in the EMCal and momentum components are calculated assuming that the particle originates at the event vertex. Besides electromagnetic showers created by photons and electrons, the EMCal also registers showers associated with hadrons. Because hadron showers are typically wider than the electromagnetic ones, a shower profile cut [54] is used to reject hadron-like clusters. The shower profile cut is based on a comparison of the registered cluster energy distribution in the EMCal towers to a reference shower shape expected for electromagnetic showers. Most hadrons are not absorbed in the EMCal and traverse it as minimum ionizing particles. The typical hadron energy loss in the EMCal is $\sim 0.3$ GeV [54]. To reduce hadron contamination and to account for the poorer EMCal resolution at lower energies, a minimum energy $E_\gamma > 0.2$ GeV is required for clusters reconstructed in all $d$+$Au$ events and in peripheral Cu+Cu events. In more central Cu+Cu collisions it is increased to $E_\gamma > 0.4$ GeV. The two clusters from the same $\pi^0$ meson are also required to fall within the acceptance of the same EMCal sector to suppress boundary effects. The energy balance between the two clusters forming a $\pi^0$ candidate is characterized by $\alpha = |E_1 - E_2|/|E_1 + E_2|$, where $E_1$ and $E_2$ are the cluster energies. For $\pi^0 \rightarrow \gamma\gamma$ decays the parameter $\alpha$ has an almost flat distribution between 0 and 1 [54]. Due to the steeply falling $p_T$ spectrum of all particles produced in the event, most of the EMCal clusters have a low energy partner, therefore the distribution of the parameter $\alpha$ calculated for combinatorial pairs has a distinct peak close to 1 for high $p_T$ pairs. To exclude those pairs, parameter $\alpha$ is required to be less than 0.8.

A pair of $\gamma$-clusters is selected as a $\pi^0$ candidate if its reconstructed invariant mass is within $\pm 2$ standard deviations from a parameterized $\pi^0$ mass:

$$|M_{\gamma\gamma}(p_T) - M_{\pi^0}(p_T) \times R_M(p_T)| < 2\sigma_{\pi^0}(p_T) \times R_\gamma(p_T),$$

where $M_{\gamma\gamma}$ is the reconstructed invariant mass of a pair of the $\gamma$-clusters, $p_T$ is the transverse momentum of the pair, $M_{\pi^0}(p_T)$ and $\sigma_{\pi^0}(p_T)$ are the parameterizations of the mass and 1-$\sigma$ width of the $\pi^0$ peak as a function of transverse momentum. The parameterization is performed using an inclusive sample of $\pi^0$ mesons. $R_M(p_T)$ and $R_\gamma(p_T)$ are correction factors accounting for the difference between inclusive $\pi^0$ mesons and neutral pions produced in $K_S^0$ meson decays.

To determine $M_{\pi^0}(p_T)$ and $\sigma_{\pi^0}(p_T)$, the peak position and width of the $\pi^0$ peak in the invariant mass distribution of the cluster pairs are measured for different $p_T$ bins and are parameterized as a function of $p_T$. The mass and width of $\pi^0$ are determined by fitting the invariant mass distribution with a sum of a Gaussian function describing the signal and a second order polynomial describing the background. Figure 4 shows reconstructed mass and width of $\pi^0$ as a function of $p_T$ in Cu+Cu collisions for one of the EMCal sectors.

Because of the long lifetime of the $K_S^0$ meson, the neutral pions from its decay are produced at a displaced vertex and thus the momentum components of the clusters are mis-reconstructed. This results in a different reconstructed mass and width of $\pi^0$ mesons from $K_S^0$ decays compared to those reconstructed for inclusive $\pi^0$ mesons that mostly originate from the event vertex. In the data we have no means to isolate a sample of neutral pions from $K_S^0$ meson decays. Therefore a quantitative study of this effect is possible only in Monte Carlo simulation. Samples of $\pi^0$ mesons produced from the decay of $K_S^0$ mesons with a realistic $p_T$ distribution and neutral pions produced at the primary collision vertex with
FIG. 1. (color online) (a) Reconstructed mass and (b) 1-σ width of $\pi^0$ as a function of the reconstructed $p_T$ for inclusive $\pi^0$ mesons from data (open crosses), simulations (circles) and for $\pi^0$ coming from $K^0_S$ decays (squares). Neutral pions were reconstructed using the same analysis chain as in real data. From Fig. 1 (a) and (b), one can see the reconstructed masses and widths of simulated inclusive $\pi^0$ mesons (circles) originating from the event vertex are consistent with the values measured in real data (open crosses). Neutral pions from $K^0_S$ decays are reconstructed with smaller mass and larger width. The correction factors $R_M(p_T)$ and $R_\sigma(p_T)$ are calculated as the ratio of the parameterizations of $M_{\pi^0}(p_T)$ and $\sigma_{\pi^0}(p_T)$ for neutral pions from $K^0_S$ mesons and inclusive $\pi^0$ mesons. These correction factors improve the signal-to-background ratio by 30%–50%.

The $K^0_S$ mesons are reconstructed by combining the $\pi^0$ candidates in pairs within the same event. Pairs of $\pi^0$ candidates that share the same cluster are rejected. To improve the signal-to-background ratio $\pi^0$ candidates are required to have $p_T > 1.0$ GeV/$c$ in the $d+$Au sample.
and $p_T > 1.5 \text{ GeV}/c$ for Cu+Cu events with centrality $> 20\%$ and $p_T > 2 \text{ GeV}/c$ for Cu+Cu events with centrality $< 20\%$.

The red squares in Fig. 2 give an example of the invariant mass distribution for $\pi^0\pi^0$ pairs measured in the minimum bias $d+Au$ collisions at $8 < p_T < 9 \text{ GeV}/c$. Due to the steeply falling $p_T$ spectrum of produced particles, the finite energy/position resolution and nonlinear response of the EMCal, the reconstructed mass of pion candidates differs from the nominal PDG value $M_{PDG} = 134.98 \text{ MeV}$ [53]. To match the reconstructed mass of $\pi^0$ to the PDG value, the energy and momentum of clusters building a pair are multiplied by the ratio of measured and nominal $\pi^0$ mass: $M_{PDG}/M_{\gamma\gamma}$. This correction decreases the width of reconstructed $K_S^0$ meson peak by $\approx 50\%$. An example of the invariant mass distribution after energy correction is shown with blue open crosses in Fig. 2. The black circles correspond to the case when $\pi^0$ candidate selection is changed according to Eq. 2 to account for the difference between inclusive $\pi^0$ mesons and neutral pions produced in $K_S^0$ meson decays.

The $K_S^0$ meson raw yield in each $p_T$ bin is extracted by fitting the $\pi^0\pi^0$ invariant mass distribution to a combination of a Gaussian function for the signal and a polynomial for the background. A second order polynomial provided adequate description of the background shape outside of the $K_S^0$ peak and varied smoothly under the peak. The fitting range was set to about $\pm8$ standard deviations from the peak center and was enough to constrain the fit. A wider fitting range would require a higher order polynomial to describe the background. All fits resulted in $\chi^2/NDF$ values close to one. The $K_S^0$ meson yield in each $p_T$ bin is calculated as the integral of the Gaussian function. Examples of $\pi^0\pi^0$ invariant mass distributions are shown in Fig. 2(a) and (b) for $d+Au$ and Cu+Cu, respectively.

The typical signal/background ratio, integrated within $\pm2\sigma$ around particle mass, for different centrality classes grows from 0.5 to 0.86 (0.04–0.85) in $d+Au$ (Cu+Cu) collisions with increasing transverse momentum. The width and the mass of the reconstructed $K_S^0$ mesons were found to be in good agreement with the values expected from simulation.

### B. Reconstruction of $K^{*0}$ meson invariant mass

The $K^{*0}$ and $\bar{K}^{*0}$ mesons are reconstructed from their hadronic decay channels $K^+\pi^-$ and $K^-\pi^+$, respectively. We denote the average of $K^{*0}$ and $\bar{K}^{*0}$ as $K^{*0}$. Tracks selected for this analysis are required to have $p_T > 0.3 \text{ GeV}/c$. The TOF system covers approximately one half of the east central arm spectrometer acceptance and can identify charged kaons up to approximately $2.5 \text{ GeV}/c$ [51]. To extend the high $p_T$ reach of the $K^{*0}$ meson measurement, unidentified, oppositely charged tracks are also included in the analysis. These tracks are required to have associated hits in PC3 or EM-CAL and are referred to as the PC3-matched tracks. Depending on the track selection criteria, three different techniques are considered in this analysis.

1. **fully identified** where tracks are identified as kaon and pion in TOF.
2. **kaon identified** where one of the tracks is identified as kaon in TOF and the other is a PC3-matched track to which the pion mass is assigned.
3. **unidentified** where both tracks are the PC3-matched tracks.

The three techniques are exclusive to each other and statistically independent. The PC3-matched tracks are assigned the nominal mass of the $\pi$ or $K$ mesons depending on which technique is used. The $p_T$ ranges accessible in the different techniques in $p+p$, $d+Au$ and Cu+Cu collisions are given in Table III.

The “fully-identified” sample with both charged particles identified in the TOF has the highest signal-to-background ratio and provides access to $K^{*0}$ meson production at low and intermediate $p_T$. However, due to the limited PID capabilities of the TOF technique and the small acceptance of the TOF detector, this data set does not provide sufficient statistical precision for $p_T > 4 \text{ GeV}/c$. The “kaon identified” sample allows for the best signal extraction at intermediate $p_T$. The “unidentified” sample has a poor signal-to-background ratio that prevents signal extraction at low $p_T$. Signal extraction is possible at higher $p_T > 2.3 \text{ GeV}/c$ in $p+p$ or $d+Au$ collisions and $p_T > 2.9 \text{ GeV}/c$ in Cu+Cu collisions, because of the smaller combinatorial background. The highest $p_T$ reach of $K^{*0}$ measurements with the “unidentified” sample is limited only by the sampled luminosity. Measurements performed with the three techniques have a wide overlap region that is used for evaluation of the systematic uncertainties.

The invariant mass distribution for $K\pi$ pairs comprises both signal and background. The uncorrelated part of

| Collision System | Technique used | $p_T$ range (GeV/c) | S/B |
|------------------|----------------|--------------------|-----|
| $p+p$            | fully identified | 1.1–4.0            | 0.011–0.023 |
|                  | kaon identified  | 1.1–4.0            | 0.005–0.0147 |
|                  | unidentified     | 2.3–8.0            | 0.006–0.021  |
| $d+Au$           | fully identified | 1.1–4.0            | 0.009–0.015  |
|                  | kaon identified  | 1.4–4.5            | 0.003–0.0118 |
|                  | unidentified     | 2.3–8.5            | 0.009–0.012  |
| Cu+Cu            | fully identified | 1.4–4.0            | 0.0048–0.0076 |
|                  | kaon identified  | 1.7–4.5            | 0.0006–0.0039 |
|                  | unidentified     | 2.9–8.0            | 0.0011–0.0036 |
the background that arises from the random combination of tracks in the same event is estimated using the mixed event technique \[53\]. The event mixing combines positively (negatively) charged tracks from one event with the charged tracks of opposite sign from another event within the same centrality class. The number of mixed events for each event in the data is set to 20 for \(p+p\) and \(d+Au\) and to 10 for \(Cu+Cu\) collisions, to have sufficient statistics. The mixed event invariant mass distribution is normalized by the number of events mixed and then it is subtracted from the unlike sign distributions. The correlated part of the background is dominated by track pairs from mis-reconstructed or not fully reconstructed decays of light hadrons. Two such processes, \(\phi \rightarrow K^+K^-\) and \(K_S^0 \rightarrow \pi^+\pi^-\), produce smeared peak structures in the invariant mass distribution in the close vicinity of the \(K^{*0}\) mass peak. Contributions of these two sources are estimated using measured yields of the \(\phi\) meson \[16\] and \(K_S^0\) meson \[39\]. The location and shape of these peaks are modeled by the PHENIX based simulations. The estimated contributions are then normalized by the number of events analyzed for \(K^{*0}\) meson and subtracted from the measured \(K^{*0}\) invariant mass distributions. Apart from these contributions, a residual background due to other correlated sources \[40\] remains in the subtracted spectra. The residual background is different depending on the collision systems, analysis techniques and also on the pair \(p_T\). Examples of invariant mass distributions after subtraction of the mixed event background and the correlated background from \(K_S^0\) and \(\phi\) mesons are shown in Fig. 4 (a), (b) and (c) for \(p+p\), \(d+Au\) and \(Cu+Cu\) collisions, respectively. The \(\phi\) contribution is shown by the magenta colored histogram. It is seen that this contribution is very small in \(Cu+Cu\) case, even smaller in \(d+Au\) case and negligible in \(p+p\) case. The residual background is clearly seen in the subtracted mass spectra. In the “fully-identified technique”, this residual background is relatively small. It is larger in the “kaon-identified technique” and even larger in the analysis based on unidentified tracks.

The invariant mass distribution in each \(p_T\) bin is fit to the sum of a relativistic Breit-Wigner (RBW) function for the signal and a 2nd or 3rd order polynomial for the residual background.

\[
RBW = \frac{1}{2\pi} \frac{M_{K\pi}M_{K^{*0}}\Gamma}{(M_{K\pi}^2 - M_{K^{*0}}^2)^2 + M_{K^{*0}}^2\Gamma^2},
\]

where \(M_{K\pi}\) is the reconstructed invariant mass, \(M_{K^{*0}}\) is the fitted mass of \(K^{*0}\) meson and \(\Gamma\) is the width of \(K^{*0}\) meson fixed to the value obtained from simulation. Because the experimental mass resolution (~5 MeV/c^2) is much smaller than the natural width of the \(K^{*0}\) meson the simulated \(\Gamma\) is very close to the nominal width of 48.7 MeV/c^2 \[53\].

The raw yield of the \(K^{*0}\) meson in each \(p_T\) bin is obtained as follows. The yield in each \(p_T\) bin is summed up in the invariant mass window of \(\pm 75\) MeV/c^2 around the nominal mass of \(K^{*0}\) meson which includes both sig-

FIG. 3. (color online) The invariant mass reconstructed from two \(\pi^0\) mesons in the range \(5 < p_T < 6\) GeV/c in (a) \(d+Au\) and (b) \(Cu+Cu\) collisions at \(\sqrt{s_{NN}} = 200\) GeV for the MB data. The distributions are approximated by a Gaussian plus a second order polynomial shown by solid red and blue dashed lines respectively.
nal and residual background. The invariant mass distribution is fitted, as explained above and the residual background contribution is obtained by integrating the background component of the fit (second or third order polynomial) in the same mass window. The residual background contribution is subtracted from the total signal to obtain the raw yield for $K^{*0}$ meson.

C. Calculation of invariant yield

The invariant yields of $K^0_S$ and $K^{*0}$ mesons are calculated by

$$\frac{1}{2\pi p_T} \frac{d^2 N}{d\phi dT dy} = \frac{1}{2\pi p_T} \frac{d^2 N}{d\phi dT dy} \times \frac{N_{\text{ev}} \epsilon(p_T) \Delta y \sigma_{\text{bias}}}{\epsilon_{\text{treff}}},$$

where $Y_{\text{raw}}$ is the meson raw yield (see Sections III A and III B), $N_{\text{ev}}$ is the number of sampled events in the centrality bin and $\epsilon(p_T)$ includes geometrical acceptance, reconstruction efficiency, and occupancy effects in the high multiplicity environment of heavy ion collisions. The branching ratio ($BR$) for $K^0_S \rightarrow \pi^0\pi^0$ is $30.69 \pm 0.05\%$ (BR for $\pi^0 \rightarrow 2\gamma$ is $98.823 \pm 0.034\%$). The branching ratio for the $K^{*0} \rightarrow K^+\pi^-$ is close to 67%. The trigger bias correction $C_{\text{bias}}$ is 0.69 [10] for $p+p$ collisions and for $d+Au$ collisions it varies from 1.03 to 0.94 [30] with increasing centrality. The trigger bias correction in Cu+Cu collision system is taken equal to unity in all analyzed centrality bins. The ERT efficiency for $K^0_S$ meson $\epsilon_{\text{treff}}$ determines the probability of $K^0_S \rightarrow \pi^0\pi^0 \rightarrow 4\gamma$ decay products to fire the ERT. For the $K^{*0}$ which uses no additional trigger, $\epsilon_{\text{treff}} = 1$.

The invariant cross section in the $p+p$ system is given by:

$$E^3 \frac{d^3 \sigma}{dp^3} = \sigma_{\text{pp}}^{\text{inel}} \times \frac{1}{2\pi p_T} \frac{d^2 N}{d\phi dT dy},$$

where $\sigma_{\text{pp}}^{\text{inel}} = 42.2 \pm 3\text{mb}$ [39] is the total inelastic cross section in $p+p$ collisions at $\sqrt{s} = 200\text{GeV}$.

The reconstruction efficiency for the $K^0_S$ and $K^{*0}$ mesons are obtained from Monte Carlo simulations. Both the $K^0_S$ and $K^{*0}$ mesons are generated using single particle event generator Exodus [56]. The primary mesons are decayed into the measured channel and all particles are traced through the PHENIX setup using the GENT [57] based PHENIX simulation package. The decayed particles are reconstructed using the same analysis procedures as used in the analysis of real data. The reconstruction efficiency is calculated as the ratio of the number of reconstructed mesons counted in the same way as in data, to the number of generated mesons. Due to high detector occupancy in Cu+Cu collisions, the reconstruction efficiency becomes smaller due to hit and cluster merging in detector subsystems. To take this effect into account the reconstruction efficiencies for $K^0_S$ and $K^{*0}$ mesons were determined after embedding the simulated signals in real events. The $K^{*0}$ meson reconstruction efficiency in Cu+Cu is reduced by $\sim 5\%$ in the most central collisions and by $\sim 1\%$ in peripheral collisions. These corrections are included in $\epsilon(p_T)$, as shown in Fig. 4.

The probability that one of the $K^0_S$ meson decay products fires the ERT trigger is estimated based on the measured single photon ERT efficiency, $\epsilon_\gamma$. The latter is evalu-
FIG. 5. (color online) Reconstruction efficiency for (a) $K^0_S$ and (b) $K^{*0}$ for $d+Au$ collisions. The gray band shows the systematic uncertainty. Please refer to Table III for systematic uncertainties. Fig. (b) shows the reconstruction efficiency for the “kaon identified”, “unidentified” and “fully identified” techniques for $K^{*0}$ analysis are shown by the red solid line, dotted dashed blue line and black dashed line, respectively.

uated as the ratio of the number of clusters that fired the ERT to the number of clusters of the same energy in the minimum bias data sample. The trigger efficiency is calculated as a function of cluster energy separately for each EMCal sector. An example of $\epsilon_\gamma$ in one of the EMCal sectors is shown in Fig. 6 (a) for the case of 2005 measurements for Cu+Cu collisions.

The trigger efficiency grows steeply with energy and reaches 50% at the energy approximately corresponding to the ERT threshold setting. The curves saturate at approximately twice the threshold energy. The level of saturation is below 100% because of inactive areas of the ERT. The trigger efficiency for $K^0_S$ meson ($\epsilon_{\text{treff}}$) is evaluated using Monte Carlo simulation. The $K^0_S$ meson is considered to fire the ERT if at least one of the photons in the final state fires the trigger. The resulting trigger efficiency for $K^0_S \rightarrow \pi^0(\rightarrow \gamma\gamma)\pi^0(\rightarrow \gamma\gamma)$ is shown in Fig. 6 (b). The trigger efficiency uncertainty for $K^0_S$ meson was evaluated by varying the single photon ERT efficiency within the uncertainties of the measurement.

D. Systematic Uncertainties

Several factors contribute to the systematic uncertainty of the measurement of the $K^0_S$ meson invariant yield: the raw yield extraction, the reconstruction efficiency and detector acceptance and the $K^0_S \rightarrow \pi^0\pi^0$ decay branching ratio uncertainty. Evaluation of the systematic uncertainties associated with the $K^0_S$ meson raw yield extraction is done by varying the raw yield extraction method and by modifying the background shape around the $K^0_S$ peak. The $\pi^0\pi^0$ invariant mass distribution is approximated by a second order polynomial outside three standard deviations from the center of the peak region. The polynomial is then interpolated under the peak and subtracted from it. The yield is obtained by integrating the subtracted invariant mass distribution in a three standard deviation window around the mean of the peak. To modify the background shape the “cross $\pi^0$ meson” cut is used. This cut significantly changes the background shape in the invariant mass distributions of $\pi^0\pi^0$ pairs in the vicinity of the $K^0_S$ meson peak. If two photons with the largest energy, assigned to different $\pi^0$ candidates, produce an invariant mass within $\pm 4 \times \sigma_{\pi^0}(p_T)$ from the $M_{\pi^0}(p_T)$ given in Eq. 2 the entire combination of four clusters is rejected. The RMS of the corrected raw yields obtained in all combinations of yield extraction and background modification is taken as an estimate of the systematic uncertainty for the signal extraction.

The uncertainty in the reconstruction efficiency is dominated by mismatches in detector performance between data and Monte Carlo. The uncertainty on the EMCal acceptance is estimated by artificially increasing dead areas in the EMCal by 10% and redoing the analysis. To
FIG. 6. (a) Trigger efficiency for single photons as a function of cluster energy. (b) $K^0_S$ trigger efficiency as a function of $p_T$. The bands show the systematic uncertainty. Results are presented for the Cu+Cu data recorded in 2005.

estimate the contribution of the EMCal energy resolution to the systematic uncertainty, the $K^0_S$ meson reconstruction efficiency is recalculated with the energy resolution artificially worsened by 3%. The 3% variation of the energy resolution was chosen as a maximum value that would still provide consistency between the $\pi^0$ meson widths from real data and simulations. The contribution of the EMCal energy scale uncertainty was estimated by varying the energy scale within ±1% in simulation. The variation range is constrained by the $\pi^0$ meson peak positions in real data and simulation. Photon conversion in the detector material is accounted for in the calculation of the reconstruction efficiency. However, detector materials are described in the simulation with some precision and thus an uncertainty associated with the photon conversion is introduced. The conversion correction uncertainty was estimated in Ref. [54] to be equal to 3% for the neutral pions. Thus the $K^0_S$ meson conversion correction uncertainty is 6%.

The $\pi^0$ meson candidates are selected within two standard deviations around the $\pi^0$ meson peak position in the invariant mass distribution of two photons. The difference between the $\pi^0$ meson width parameterizations in real data and Monte Carlo simulations does not exceed 10%. To estimate the $\pi^0$ selection cut uncertainty, the window around the $\pi^0$ meson peak position is varied by 10%. The difference between the $K^0_S$ meson reconstruction efficiencies calculated with changed and default cuts is taken as the uncertainty related to the $\pi^0$ candidate selection cut. The $K^0_S$ meson trigger efficiency uncertainty is evaluated by varying the single photon $\epsilon_\gamma$ trigger efficiency within uncertainties of its measurement. Relative systematic uncertainties for the $K^0_S$ meson measurements in $d$+Au and Cu+Cu systems are given in Table III. The uncertainties are categorized by types: A, B and C. Type A denotes the $p_T$ uncorrelated uncertainty, type B denotes the $p_T$ correlated uncertainty and type C denotes the overall normalization uncertainty such as the minimum bias trigger efficiency in $p$+$p$ and $d$+Au collisions, branching ratio of the parent particle, $\gamma$-conversion factor etc.

The main systematic uncertainty of the $K^{*0}$ measurement include uncertainties in the raw yield extraction, EMCal-PC3 matching, TOF PID cuts, track momentum reconstruction, acceptance and BBC cross section. The systematic uncertainty associated with the raw yield extraction is estimated by varying the fitting ranges, varying the width of the $K^{*0}$ meson peak by ±2% around its simulated value and taking the integral of the fitted RBW function instead of summing up the yield in each $p_T$ bin. In addition, the yield difference when the $K^{*0}$ meson mass is fixed to the PDG value and when it is a free parameter in the fit of the mass spectrum, is included in the systematic uncertainty. To evaluate the uncertainties from EMCal-PC3 matching and TOF PID cuts, the corresponding cuts are varied within ±17%. The uncer-
TABLE III. Relative systematic uncertainties in percent for the $K_0^S$ meson measurement. The given ranges indicate the variation of the systematic uncertainty over the $p_T$ range of the measurement.

| Source                  | $d$+Au (%) | $Cu$+Cu (%) | Uncertainty Type |
|-------------------------|------------|-------------|-----------------|
| Raw yield extraction    | 4–31       | 14–26       | A               |
| Acceptance              | 6          | 5           | B               |
| ERT efficiency          | 2–7        | 3–4         | B               |
| EMCal energy resolution | 4–5        | 3–6         | B               |
| $\pi^0$ selection       | 5–11       | 6–10        | B               |
| $\gamma$ conversion     | 6          | 6           | C               |
| Branching ratio         | 0.2        | 0.2         | C               |
| BBC cross section       | 8          | –           | C               |

The uncertainty in momentum reconstruction is estimated by varying the momentum scale within 0.5% in the simulation.

A summary of the systematic uncertainties for the case of “kaon identified” analysis technique in $p$+$p$, $d$+Au and $Cu$+Cu collisions is given in Table IV.

IV. RESULTS AND DISCUSSIONS

In this section we present $p_T$ spectra of $K_0^S$ and $K^*$ mesons in $p$+$p$, $d$+Au and $Cu$+Cu collisions at $\sqrt{s_{NN}}$ = 200 GeV. The invariant $p_T$ spectra are used to calculate the nuclear modification factors in $d$+Au and $Cu$+Cu collisions at different centralities. These nuclear modification factors are compared to those previously measured for neutral pions, charged kaons, $\phi$ mesons and protons.

TABLE IV. Relative systematic uncertainties in percent for the $K^*$ meson measurement in “kaon identified” technique. The given ranges indicate the variation of the systematic uncertainty over the $p_T$ range of the measurement.

| Source                  | $p$+$p$ (MB) | $d$+Au (MB) | $Cu$+Cu (MB) | Uncertainty Type |
|-------------------------|--------------|-------------|--------------|-----------------|
| Raw yield extraction    | 5–8          | 7–12        | 2–4          | A               |
| Acceptance              | 1–5          | 3–7         | 1–3          | B               |
| Track Momentum          | 1–4          | 2–7         | 1–5          | B               |
| Track Matching          | 1–4          | 4–7         | 2–13         | B               |
| TOF PID                 | 1–6          | 4–9         | 1–4          | B               |
| BBC cross section       | 10           | 8           | –            | C               |

FIG. 7. (color online) (a) $K^*$ meson invariant yield as a function of $p_T$ obtained with the “kaon identified”, “fully identified” and “unidentified” analysis techniques in $p$+$p$ collisions at $\sqrt{s} = 200$ GeV. The systematic uncertainties shown with boxes are mostly uncorrelated between analysis techniques. The solid blue line is the Tsallis function fit to the combined data points. The star symbols are the $K^*$ meson measurements from the STAR collaboration [40]. (b) Ratio of the yields obtained with the three analysis techniques to the fit function. The scale uncertainty of 10% is not shown.

A. Invariant transverse momentum spectra

Figure 7 (a), shows the invariant yield of $K^*$ mesons as a function of $p_T$ in $p$+$p$ collisions at $\sqrt{s} = 200$ GeV. Experimental points shown with different symbols correspond to the different analysis techniques listed in Table IV. The systematic uncertainties, mostly uncorrelated for different techniques, are shown along with the data points and include raw yield extraction, track matching and TOF PID uncertainties listed in Table IV.

The solid line in Figure 7 (a) is the result of a common fit of the data with the Tsallis function in the form used
FIG. 8. (color online) $K_S^0$ meson invariant $p_T$ spectra (a) for $d+Au$ and (b) for Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV for different centrality bins. The systematic uncertainties are shown by the boxes. The solid curves are a fit of the $K_S^0 p+p$ data by the Tsallis function [39]. The dashed curves are the fit function scaled by $N_{coll}$. The global $p+p$ uncertainty of $\sim 10\%$ is not shown.

FIG. 9. (color online) $K^{*0}$ meson invariant $p_T$ spectra (a) for $d+Au$ and (b) for Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV for different centrality bins. The systematic uncertainties are shown by the boxes. The solid curve is a fit of the $K^{*0} p+p$ data by the Tsallis function [39]. The dashed curves are the fit function scaled by $N_{coll}$. The global $p+p$ uncertainty of $\sim 10\%$ is not shown.
FIG. 10. (color online) $K^0_S/\pi^0$ ratios for (a) $d+Au$ and (b) Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV for different centrality bins. The statistical uncertainties are shown by vertical bars and the systematic uncertainties are shown by the boxes.

in [39]:

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

where $dN/dy$, $n$, and $T$ are the free parameters, $m_T = \sqrt{p_T^2 + m^2}$ and $m$ is the mass of the particle of interest. The parameter $T$ determines the shape of the spectrum at low $p_T$ where particle production is dominated by soft processes whereas $n$ governs the high $p_T$ part of the spectrum dominated by particles produced in hard scattering. The fit parameters to the $p+p$ data are $dN/dy = 1.28 \pm 0.14$, $T = 121.077 \pm 19.17$ (MeV) and $n = 9.67 \pm 0.62$ with $\chi^2/\text{NDF} = 6.9/10$. The uncertainties in the parameters include both the statistical and systematic uncertainties in quadrature. Figure 7 (b) shows the ratio of the $K^*_{0}$ meson yields obtained with the different techniques to the fit. A good agreement is observed for the yields obtained with different analysis techniques that demonstrates the robustness of the results. The final $K^*_{0}$ production spectrum is obtained by standard weighted averaging [53] of the yields and uncorrelated errors for the same $p_T$ bin obtained from the different analysis techniques. The STAR experiment measured the $K^*_{0}$ meson over the $p_T$ range 0–1.5 GeV/c, shown by the solid star symbols in Fig. 7 (a). In the overlap region STAR results agree with our measurement within one sigma of combined statistical and systematic uncertainties.

TABLE V. $N_{\text{coll}}$ and $N_{\text{part}}$ in $d+Au$ and Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV.

| Collisions | Centrality bin (%) | $\langle N_{\text{coll}} \rangle$ | $\langle N_{\text{part}} \rangle$ |
|------------|------------------|-------------------------------|-------------------------------|
| $d+Au$     |                  |                               |                               |
| 0–20       |                  | 15.1 ± 1.0                    | 15.3 ± 0.8                   |
| 20–40      |                  | 10.2 ± 0.7                    | 11.1 ± 0.6                   |
| 40–60      |                  | 6.6 ± 0.4                     | 7.8 ± 0.4                    |
| 60–88      |                  | 3.1 ± 0.2                     | 4.3 ± 0.2                    |
| 0–100      |                  | 7.6 ± 0.4                     | 8.5 ± 0.4                    |
| Cu+Cu      |                  |                               |                               |
| 0–20       |                  | 151.8 ± 17.1                 | 85.9 ± 2.3                   |
| 20–40      |                  | 61.6 ± 6.6                    | 45.2 ± 1.7                   |
| 40–60      |                  | 22.3 ± 2.9                    | 21.2 ± 1.4                   |
| 60–94      |                  | 5.1 ± 0.7                     | 6.4 ± 0.4                    |
| 0–94       |                  | 51.8 ± 5.6                    | 34.6 ± 1.2                   |
| 20–60      |                  | 42.0 ± 4.8                    | 33.2 ± 1.6                   |

The solid curves represent the Tsallis fit to the $p+p$ data. The dashed curves represent the same fit, scaled by the number of binary collisions corresponding to the central-
ity bins concerned. In $d+Au$ collisions, the production of both mesons follows the binary scaling for all centralities in the measured $p_T$ range. A similar behavior is also observed in peripheral $Cu+Cu$ collisions. In central and semi-central $Cu+Cu$ interactions, the production of $K^0_S$ and $K^{*0}$ mesons is suppressed at $p_T > 4$ GeV/$c$ and $p_T > 2-3$ GeV/$c$, respectively.

Figure 14 shows the ratio $K^0_S/p^0$ for different centrality bins in $Cu+Cu$ collisions at $\sqrt{s_{NN}} = 200$ GeV. The ratio is flat with respect to $p_T$ with a value of ~0.5, irrespective of the system and collision centrality. The statistical uncertainties are shown by vertical bars and the systematic uncertainties are shown by boxes.

### B. Nuclear Modification Factors

The nuclear modification factors for $K^0_S$ and $K^{*0}$ mesons were calculated using Eq. 1. The average number of inelastic nucleon-nucleon collisions ($N_{coll}$) and participants ($N_{part}$) estimated for each centrality bin analyzed in $d+Au$ and $Cu+Cu$ collisions are summarized in Table V [38, 50].

Figure 11 shows the nuclear modification factors $R_{dAA}$, measured for the $K^0_S$ and $K^{*0}$ mesons in the most central and peripheral $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Within uncertainties, the $R_{dAA}$ are consistent with unity for all centralities at $p_T > 1$ GeV/$c$. However, in the most central $d+Au$ collisions, there is a hint of a modest Cronin-like enhancement in the range $2 < p_T < 5$ GeV/$c$ and of suppression at $p_T > 6-8$ GeV/$c$. Results for $\phi$ and $\pi^0$ mesons [10, 60] and protons [30] are also shown for comparison in Fig. 11. The $R_{dAA}$ for all measured mesons shows similar behavior. Based on these results one can conclude that either the CNM effects do not play an important role in the production of these mesons or different CNM effects compensate each other in the studied $p_T$ range. Unlike mesons, baryons [30] exhibit a strong enhancement at intermediate transverse momenta in (semi)central $d+Au$ collisions that could be explained by recombination models [34].

Figure 12 shows the nuclear modification factors $R_{CuCu}$ measured for $K^0_S$ and $K^{*0}$ meson in $Cu+Cu$ collisions at $\sqrt{s_{NN}} = 200$ GeV. The results are presented for different centrality bins corresponding to the $\langle N_{coll} \rangle$ and $\langle N_{part} \rangle$ given in Table V. In peripheral $Cu+Cu$ collisions the production of $K^0_S$ and $K^{*0}$ mesons follows the binary scaling as expected from Figs. 8 and 9. The $R_{CuCu}$ factors become smaller with increasing centrality and in the most central $Cu+Cu$ collisions the production of both mesons is suppressed. For the most central collisions, $R_{CuCu}$ reaches a value of 0.5 at $p_T > 5$ GeV/$c$, both for $K^0_S$ and $K^{*0}$ mesons, for the most central collisions.

Figure 13 compares the $R_{CuCu}$ results for $K^0_S$ and $K^{*0}$ mesons to results obtained for the $\pi^0$ meson [8] and $\phi$ meson [10] in the most central, most peripheral, and MB $Cu+Cu$ collisions. In peripheral collisions, the nuclear modification factors are consistent with unity for all measured mesons at all $p_T$. In central and MB collisions, above $p_T > 5$ GeV/$c$, the $R_{CuCu}$ of all mesons is below unity, and within the uncertainties the suppression is the same for all measured mesons, indicating that its mechanism does not depend on the particle species. However, at lower $p_T$ between 1–5 GeV/$c$, there are differences among the different particles. The $K^{*0}$ meson $R_{CuCu}$ shows no suppression at $p_T \sim 1-2$ GeV/$c$ and then decreases with increasing $p_T$, as previously observed for the $\phi$ meson. The $\pi^0$ meson shows significantly stronger suppression over the same $p_T$ range.

Figure 14 compares the suppression patterns of light-quark mesons, strange mesons, and baryons. Shown are the $R_{AA}$ of $\pi^0$, $K^0$ and $\phi$ mesons measured in $Cu+Cu$ at $\sqrt{s_{NN}} = 200$ GeV. Because there are no measurements of $R_{AA}$ for protons and charged kaons in the $Cu+Cu$ system, we compare to proton and charged kaon measurements made in $Au+Au$ collisions at the same energy [30]. The comparisons are made for centrality bins corresponding to similar number of participating nucleons ($N_{part}$), in the $Cu+Cu$ and $Au+Au$ systems: $Cu+Cu$ 40%–94% ($\langle N_{part} \rangle = 11.93 \pm 0.63$) and $Au+Au$ 60%–92% ($\langle N_{part} \rangle = 14.5 \pm 2.5$) in the bottom panel and $Cu+Cu$ 0%–40% ($\langle N_{part} \rangle = 65.5 \pm 2.0$) and $Au+Au$ 40%–60% ($\langle N_{part} \rangle = 59.95 \pm 3.5$) in the top panel. In peripheral collisions the $R_{AA}$ factors for all mesons are consistent with unity at $p_T > 2$ GeV/$c$. A modest enhancement of $\approx 1.3$ is observed for protons. In central collisions, all hadrons show suppression. In the intermediate $p_T$ range ($p_T = 2-5$ GeV/$c$), there seems to be some hierarchy with baryons being enhanced, neutral pions being suppressed the most and $K^{*0}$ and $\phi$ mesons showing an intermediate behavior. At higher $p_T$, all particles are suppressed and they seem to reach the same level of suppression, within uncertainties, irrespective of their mass or quark content. The fact that $R_{AA}$ of all mesons becomes the same is consistent with the assumption that energy loss occurs at the parton level and the scattered partons fragment in the vacuum. We also note that the $R_{AA}$ of the $K^{*0}$ and $\phi$ mesons appear to be very similar to the $R_{AA}$ of electrons from the semi-leptonic decay of heavy flavor mesons [28]. The present results provide additional constraints to the models attempting to quantitatively reproduce the nuclear modification factors in terms of energy loss of partons inside the medium.

### V. SUMMARY AND CONCLUSIONS

The PHENIX experiment measured $K^0_S$ and $K^{*0}$ meson production via $\pi^0\pi^0$, and $K^{\pm}\pi^\mp$ decay, respectively, in $p+p$, $d+Au$ and $Cu+Cu$ collisions at $\sqrt{s_{NN}} = 200$ GeV. The invariant transverse momentum spectra and nuclear modification factors are presented for different centralities in the $d+Au$, and $Cu+Cu$ systems covering the $p_T$ range of 1.1–8.5 GeV/$c$ and 3–13 GeV/$c$ for $K^{*0}$ and $K^0_S$ respectively. In the $d+Au$ system, the nuclear modification factor of $K^0_S$ and $K^{*0}$ mesons is al-
FIG. 11. (color online) Nuclear modification factor as a function of $p_T$ for $K^0_S$ and $K^{*0}$ for (a) most central and (b) most peripheral $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Results from $\pi^0$ [60], $\phi$ [16] and protons [30] are also shown. The $\pi^0$ results are shown from the data collected in 2003 and the results of the rest of the particles are obtained from 2008 data. The corresponding systematic uncertainties are shown by boxes. The global $p+p$ uncertainty of $\sim 10\%$ is not shown.

FIG. 12. (color online) The nuclear modification factor as a function of $p_T$ for $K^0_S$ and $K^{*0}$ meson for centrality bins (a) 0%-20% ($\langle N_{\text{part}} \rangle = 85.9 \pm 2.3$), (b) 20%-40% ($\langle N_{\text{part}} \rangle = 45.2 \pm 1.7$), (c) 0%-94% ($\langle N_{\text{part}} \rangle = 34.6 \pm 1.2$), (d) 20%-60% ($\langle N_{\text{part}} \rangle = 33.2 \pm 1.6$), (e) 40%-60% ($\langle N_{\text{part}} \rangle = 21.2 \pm 1.4$) and (f) 60%-94% ($\langle N_{\text{part}} \rangle = 6.4 \pm 0.4$) in Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV. In all panels the statistical uncertainties are shown with vertical bars and the systematic uncertainties are shown with boxes. The global $p+p$ uncertainty of $\sim 10\%$ is not shown.
most constant as a function of $p_T$ and consistent with unity showing that cold nuclear matter effects do not play a significant role in the measured kinematic range. A similar behavior is seen in $R_{dAu}$ for all measured mesons. In the Cu+Cu collisions system, no nuclear modification is registered in peripheral collisions within the uncertainties of the measurement. In central Cu+Cu collisions both mesons show suppression. In the range $p_T = 2-5$ GeV/c, the strange mesons show an intermediate suppression between the more suppressed $\pi^0$ and the non-suppressed baryons. This behavior provides a particle species dependence of the suppression mechanism and provides additional constraints to the models attempting to quantitatively reproduce nuclear modification factors. At higher $p_T$, all particles, $\pi^0$, strange mesons and baryons, show a similar level of suppression.

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[1] E. Shuryak, Phys. Repts. 61, 71 (1980).
[2] M. Gyulassy and L. McLerran, Nucl. Phys. A 750, 30 (2005); F. Karsch Lect. Notes Phys. 583, 209 (2002), arXiv: hep-lat/0106019.
[3] See e.g the Proceedings of the Quark Matter Conference 2012, Nucl. Phys. A 904 - 905, (2012).
[4] E. Braaten and M. H. Thoma, Phys. Rev. D 44, 2625 (1991).
[5] D. d’Enterria and B. Betz, Lect. Notes Phys. 785, 285 (2010).
[6] X. Wang and M. Gyulassy, Phys. Rev. Lett. 68, 1480 (1992).
[7] A. Adcox et al. (PHENIX Collaboration), Phys. Rev. Lett. 88, 022301 (2001).
[8] A. Adare et al. (PHENIX Collaboration), Phys. Rev. Lett. 101, 162301 (2008).
[9] N. Armesto, J. Phys. G 32, R367 (2006).
[10] J. W. Cronin et al., Phys. Rev. D 11, 3105 (1975).
[11] A. Adcox et al. (PHENIX Collaboration), Phys. Rev. Lett. 88, 022301 (2002).
[12] A. Adcox et al. (PHENIX Collaboration), Phys. Rev. Lett. B 561, 82 (2003).
[13] S. S. Adler et al. (PHENIX Collaboration), Phys. Rev. Lett. 91, 072301 (2003); A. Adare et al. (PHENIX Collaboration), Phys. Rev. Lett. 101, 232301 (2008).
[14] S. S. Adler et al. (PHENIX Collaboration), Phys. Rev. C 69, 034910 (2004).
[15] S. S. Adler et al. (PHENIX Collaboration), Phys. Rev. Lett. 96 202301 (2006).
[16] A. Adare et al. (PHENIX Collaboration), Phys. Rev. C 83, 024909 (2011).
[17] C. Adler et al. (STAR Collaboration), Phys. Rev. Lett. 89 202301 (2002).
[18] C. Adler et al. (STAR Collaboration), Phys. Rev. Lett. 90 082302 (2003).
[19] J. Adams et al. (STAR Collaboration), Phys. Rev. Lett. 91 172302 (2003).
[20] J. Adams et al. (STAR Collaboration), Phys. Rev. Lett. 92 112301 (2004).
[21] S. Chatrchyan et al. (CMS Collaboration), Eur. Phys. J. C 72, 1945 (2012).
[22] B. Abelev et al. (ALICE Collaboration), Phys. Rev. Lett. B 720, 52 (2013).
[23] S. Chatrchyan et al. (CMS Collaboration), Phys. Rev. C 84, 024906 (2011).
[24] S. Chatrchyan et al. (CMS Collaboration), Phys. Lett. B 712, 176 (2012).
[25] G. Aad et al. (ATLAS Collaboration), Phys. Rev. Lett. 105, 252303 (2010).
[26] A. Adare et al. (PHENIX Collaboration), Phys. Rev. C 84, 044902 (2011).
[27] A. Adare et al. (PHENIX Collaboration), Phys. Rev. Lett. 98, 172301 (2007).
[28] A. Adare et al. (PHENIX Collaboration), Phys. Rev. C 84, 044905 (2011).
[29] G. Agakishiev et al. (STAR Collaboration), Phys. Rev. Lett. 108, 072302 (2012).
[30] A. Adare et al. (PHENIX Collaboration), Phys. Rev. C 88, 024906 (2013).
[31] S. S. Adler et al. (PHENIX Collaboration), Phys. Rev. Lett. 91, 172301 (2003).
[32] S. S. Adler et al. (PHENIX Collaboration), Phys. Rev. C 69, 034909 (2004).
[33] T. Hirano and Y. Nara, Phys. Rev. C 69, 034908 (2004).
[34] R. J. Fries, V. Greco and P. Sorensen, Ann. Rev. Nucl. Part. Sci. 58, 177 (2008), arXiv: 0807.4939 [nucl-th].
[35] S. Chatrchyan et al. (CMS Collaboration), Phys. Rev. Lett. B 724, 213 (2013).
[36] ATLAS-CONF-2013-107.
[37] B. Abelev et al. (ALICE Collaboration), Phys. Rev. Lett.110, 082302 (2013).
[38] A. Adare et al. (PHENIX Collaboration), Phys. Rev. Lett. 111, 212301 (2013).
[39] A. Adare et al. (PHENIX Collaboration), Phys. Rev. D 83, 052004 (2011).
[40] J. Adams et al. (STAR Collaboration), Phys. Rev. C 71, 064902 (2005).
[41] B. I. Abelev et al. (STAR Collaboration), Phys. Rev. C 78, 044906 (2008).
[42] M. M. Aggarwal et al. (STAR Collaboration), Phys. Rev. C 84, 034909 (2011).
[43] K. Adcox et al. (PHENIX Collaboration), Nucl. Instrum. Methods A 499, 469 (2003).
[44] K. Adcox et al. (PHENIX Collaboration), Nucl. Instrum. Methods A 497, 263 (2003).
[45] M. Allen et al. (PHENIX Collaboration), Nucl. Instrum. Methods A 499, 549 (2003).
[46] S. S. Adler et al. (PHENIX Collaboration), Phys. Rev. Lett. 94, 082302 (2005).
[47] S. C. Johnson, Proc. Int. Conf. on Computing in High Energy Physics, CHEP 98, Chicago IL (1998).
[48] S. H. Aronson et al. (PHENIX Collaboration), Nucl. Instrum. Methods A 499, 480 (2003).
[49] K. Adcox et al. (PHENIX Collaboration), Nucl. Instrum. Methods A 499, 489 (2003).
[50] M. Aizawa et al. (PHENIX Collaboration), Nucl. Instrum. Methods A 499, 508 (2003).
[51] A. Adare et al. (PHENIX Collaboration), Phys. Rev. C 83, 064903 (2011).
[52] L. Aphecetche et al. (PHENIX Collaboration), Nucl. Instrum. Methods A 499, 521 (2003).
[53] J. Beringer et al. (Particle Data Group), Phys. Rev. D 86, 010001 (2012).
[54] S. S. Adler et al. (PHENIX Collaboration), Phys. Rev. C 76, 034904 (2007).
[55] S. S. Adler et al. (PHENIX Collaboration), Phys. Rev. C 72, 014903 (2005).
[56] A. Adare et al. (PHENIX Collaboration), Phys. Rev. C 81, 034911 (2010).
[57] GEANT 3.2.1, CERN Computing Library (1993), http://wwwasdoc.web.cern.ch/wwwasdoc/pdfdir/geant.pdf.
[58] R. Glauber and G. Matthiae, Nucl. Phys. B 21, 135 (1970).
[59] M. L. Miller, K. Reygers, S. J. Sanders and P. Steinberg, Ann. Rev. Nucl. Part. Sci. 57, 205 (2007).
[60] S. S. Adler et al. (PHENIX Collaboration), Phys. Rev. Lett. 98, 172302 (2007).