Cold-nuclear-matter effects on heavy-quark production at forward and backward rapidity in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

A. Adare,13 C. Aidala,38,42,43 N.N. Ajitanand,60 Y. Akiba,55,56 R. Akimoto,12 H. Al-Bataineh,49 H. Al-Ta’ani,49 J. Alexander,60 K.R. Andrews,1 A. Angerami,14 K. Aoki,34,55 N. Apadula,60 E. Appelt,55 Y. Aramaki,12,55 R. Armendariz,7 E.C. Aschenauer,7,9 E.T. Atomska,35 R. Averbeck,61 T.C. Awes,51 B. Azmoun,7 V. Babintsev,24 M. Bai,6 G. Baksay,19 L. Baksay,19 B. Bannier,61 K.N. Barish,8 B. Bassalleck,48 A.T. Bayse,1 S. Bathe,5,8,56 V. Baublis,54 C. Baumann,44 A. Bazilevsky,7 S. Belilov,7,9 R. Belmont,62 J. Ben-Benjamin,45 R. Bennett 61 J.H. Bhom,69 D.S. Blau,33 J.S. Bok,69 K. Boyle,56,61 M.L. Brooks,38 D. Bromsey,45 H. Buesching,7 V. Bumazhnov,24 G. Bunce,7,56 S. Butyks,38 S. Campbell,61 A. Caringi,45 P. Castera,61 C.-H. Chen,61 C.Y. Chi,14 M. Chiu,7 I.J. Choi,25 J.B. Choi,10 R.K. Choudhury,4 P. Christiansen,40 T. Chuijo,64 P. Chung,60 O. Chvala,8 V. Cianciolo,51 Z. Citron,61 B.A. Cole,14 Z. Conesa del Valle,35 M. Connors,61 M. Csanád,17 T. Csörgő,68 T. Dahms,61 S. Dairaku,34,55 I. Danchev,65 K. Das,20 A. Datta,42 G. David,7 M.K. Dayananda,21 A. Denisov,24 A. Deshpande,56,61 E.J. Desmond,5 K.V. Dharmawardane,49 O. Dietzsch,58 A. Dion,28,61 M. Donadelli,38 O. Draper,35 A. Drees,61 K.A. Drees,8 J.M. Durham,38,61 A. Durum,24 D. Dutta,4 L. D’Orazio,41 S. Edwards,20 Y.V. Efremenko,51 F. Eilam,13 T. Engelmore,14 A. Enokizono,51 H. En’yo,55,56 S. Esumi,64 B. Fadem,45 D.E. Fields,48 M. Fries,9 M. Fries, Jr.,9 F. Fleuret,35 S.L. Fokin,33 Z. Franekel,67 E.J. Frantz,50,61 A. Franz,7, A.D. Frawley,20 K. Fujiiwa,55 Y. Fukao,55 T. Fusayasu,47 C. Gal,61 I. Garishvili,62 A. Glenn,37 H. Gong,61 X. Gong,60 M. Gouin,55 Y. Goto,55,56 R. Granier de Cassagnac,36 N. Grau,21,14 S.V. Greene,65 G. Grim,38 M. Grosse Perdekamp,25 T. Gujhi,12 L. Guo,38 H.-A. Gustafsson,40 J.S. Haggerty,7 K.I. Hahn,58 H. Hamagaki,12 J. Hamblen,62 R. Han,53 J. Hanks,14 C. Harper,45 K. Hashimoto,55,57 E. Haslum,40 R. Hayano,12 X. He,21 M. Heffner,73 T.K. Hemmick,61 T. Hester,8 J.C. Hill,28 M. Hohlmann,19 R.S. Hollis,8 W. Holzmann,14 K. Homma,23, Bong,32 T. Horaguchi,23,64 Y. Hori,12 D. Hornbuck,51,62 S. Huang,65 T. Ichihara,55,56 R. Ichimizu,55 H. Imura,31 Y. Ikeda,64 K. Imai,29,34,55 M. Inaba,60 A. Iordanova,8 D. Isenhower,1 M. Ishihara,55 M. Issah,65 D. Ivanishev,54 Y. Iwanaga,23 B.V. Jacak,61 J. Jia,7,60 X. Jiang,38 J. Jin,14 D. John,52 B.M. Johnson,7 T. Jones,1 K.S. Joo,46 D. Jouan,52 D.S. Jumper,4 F. Kajihara,12 J. Kamin,61 S. Kaneti,61 B.H. Kang,22 J.H. Kang,73 J.S. Kang,22 J. Kapustinsky,38 K. Karatsu,34,55 M. Kasai,55,57 D. Kawall,42,56 M. Kawashima,55,57 A.V. Kazantzis,63 J.T. Kempf,28 A. Khanzadeev,54 K.M. Kijima,23 J. Kikuchi,66 A. Kim,18 B.J. Kim,32,13, J. Kim,30 E.-J. Kim,10 Y.-J. Kim,25 Y.K. Kim,22 E. Kinney,13 A. Kiss,17 E. Kistenev,7 D. Kleinjan,8 P. Kline,61 L. Kochenda,54 B. Komkov,54 M. Konno,64 J. Koster,25 D. Kotov,54 A. Krat,15 A. Kravitz,14 G.J. Kunde,38 K. Kurita,55,57 M. Kurosavas,55 Y. Kwon,69 G.S. Kyle,49 R. Lacev,60 Y.S. Lai,14 J.G. Lajoie,28 A. Lebedev,28 D.M. Lee,38 J. Lee,18 K.B. Lee,32 K.S. Lee,32 S.H. Lee,61 S.R. Lee,10 M.J. Leitch,38 M.A.L. Leite,58 X. Li,11 P. Lichtenwalser,15 P. Liebing,10 S.H. Lim,61 A. Lindem Levy,65 T.,9,13,15 L. Liu,38 M.X. Liu,38 B. Love,65 D. Lynch,7 C.F. Maguire,65 Y.I. Makdisi,6 M.D. Malik,38 A. Manion,61 V.I. Manko,33 E. Mannel,14 Y. Mao,53,55 H. Masui,64 F. Matathias,14 M. Mcfumber,13,61 P.L. McGaughy,38 D. McGlinchey,13,20 C. McKinney,25 N. Means,61 M. Mendoca,8 B. Meredith,51 Y. Miake,64 T. Mibe,31 A.C. Mignerey,31 K. Miki,55,64 A. Milov,7,67 J.T. Mitchell,7 Y. Miyachi,55,63 A.K. Mohanty,4 H.J. Moon,46 Y. Morino,12 A. Morreale,8 D.P. Morrison,7 S. Motschwiller,45 T.V. Mounkova,33 T. Murakami,34 J. Murata,55,57 S. Nagamiya,31 J.L. Nagle,12 M. Naglis,67 M.I. Nagy,68 I. Nakagawa,53,56 Y. Nakamichi,23 K.R. Nakamura,34,55 T. Nakamura,55 K. Nakano,55 S. Nam,18 J. Newby,37 M. Nguyen,61 M. Nihashi,23 R. Nouicer,7 A.S. Nyanin,33 C. Oakley,21 E. O’Brien,7 S.X. Oda,12 C.A. Ogilvie,28 M. Oka,64 K. Okada,56 Y. Otsuki,55 A. Oskarsson,40 M. Ouchida,23,55 K. Ozawa,12 R. Pak,7 V. Pantuev,26,61 V. Papavassiliou,49 B.H. Park,22 I.H. Park,18 S.K. Park,32 W.J. Park,32 S.F. Pate,49 L. Patel,21 H. Pei,28 J.-C. Peng,25 H. Pereira,16 D.Yu. Peressounko,33 R. Petti,61 C. Pinkenburg,7 R.P. Pisani,65 M. Proissl,61 M.L. Putschke,7 H. Qu,21 J. Rak,30 I. Rabinovich,69 K.F. Read,51,62 S. Rembeczki,19 K. Reyers,14 V. Riabov,54 Y. Riabov,54 E. Richardson,51 D. Roach,55 G. Roche,39 S.D. Rolnick,8 M. Rosati,28 C.A. Rosen,13 S.S.E. Rosendahl,40 R. Ružička,27 B. Sahlmueller,44,61 N. Saito,71 T. Sakaguchi,7 K. Sakashita,55,63 V. Samsonov,54 S. Sano,12,66 M. Sarsour,21 T. Sato,64 M. Savastio,61 S. Sawada,31 K. Sedgwick,8 J. Selee,13 R. Seidl,25,56 R. Seto,8 D. Sharma,67 I. Shein,24 T.-A. Shihata,55,63 K. Shigaki,23 H.H. Shim,62 M. Shimomura,64 K. Shoji,14,55 P. Shukla,4 A. Sickles,7 C.L. Silva,28 D. Silvermyr,51 C. Silvestre,16 K.S. Sim,32 B.K. Singh,3 C.P. Singh,3 V. Singh,3 M. Shnečča,9 T. Sodre,45 R.A. Soltz,37 W.E. Sondheim,38 S.P. Sorensen,62 L.V. Sourkova,7 P.W. Stankus,51 E. Stenhoud,40 S.P. Stoll,7 T. Sugitate,23 A. Sukhanov,7 J. Sun,61 J. Szkiel,68 E.M. Takagui,58 A. Takahara,12
The PHENIX experiment has measured open heavy-flavor production via semileptonic decay over the transverse momentum range \(1 < p_T < 6 \text{ GeV}/c\) at forward and backward rapidity (1.4 < \(|y|\) < 2.0) in \(d+\text{Au}\) and \(p+p\) collisions at \(\sqrt{s_{NN}} = 200 \text{ GeV}\). In central \(d+\text{Au}\) collisions an enhancement of heavy-flavor muon production is observed at backward rapidity, whereas suppression is seen at forward rapidity relative to the yield in \(p+p\) collisions scaled by the number of binary collisions. The difference observed between forward and backward rapidity exceeds predictions based on a model of initial parton density modification. These results can be used to probe predicted cold nuclear matter effects, which may significantly affect heavy-quark production at the Relativistic Heavy Ion Collider and the Large Hadron Collider, in addition to helping constrain the magnitude of charmonia breakup effects in nuclear matter.

PACS numbers: 25.75.Dw

Heavy quarks are essential probes of the evolution of the medium created in heavy-ion collisions, because they are produced in the early stages of nuclear collisions. Heavy-quark production has been measured via semileptonic decay electrons and muons, as well as fully reconstructed \(D\) mesons, at RHIC and the LHC. In \(p+p\) collisions, heavy-quark production tests perturbative quantum chromodynamics and provides a baseline for heavy-ion collisions. In central \(\text{Au}+\text{Au}\) collisions at \(\sqrt{s_{NN}} = 200 \text{ GeV}\), strong suppression of high transverse momentum (\(p_T\)) electrons from semileptonic decay of open heavy-flavor hadrons has been observed at midrapidity. At forward rapidity, a similar level of suppression has been measured for the production of heavy-flavor muons in central \(\text{Cu}+\text{Cu}\) collisions. Although suppression of high \(p_T\) particles was predicted as an effect of partonic energy loss in the dense medium created in heavy-ion collisions, it is difficult to account for this comparable suppression solely with hot nuclear matter effects. To interpret such measurements, it is essential to probe underlying cold-nuclear-matter (CNM) effects, which may also be present.

Control experiments with \(d+\text{Au}\) collisions allow us to probe those CNM effects, including modifications of the parton distribution function (PDF) and \(k_T\) broadening, with minimal impact from the hot nuclear medium. Because heavy quarks are produced primarily by gluon fusion at RHIC, modification of the gluon density in the nucleus can be observed in the charm and bottom production rates. Based on PYTHIA calculations, the average parton momentum fraction \(x\) in the Au nucleus leading to heavy-flavor muons with \(1 < p_T^\mu < 6 \text{ GeV}/c\) at backward \((-2.0 < y < -1.4, \text{Au-going direction})\) and forward \((1.4 < y < 2.0, \text{d-going direction})\) rapidity is \(\approx 8 \times 10^{-2}\) and \(\approx 5 \times 10^{-3}\) for the antishadowing and shadowing regions, respectively. Parton energy loss and multiple scattering in the nucleus can change the resulting heavy-flavor hadron momentum spectrum. Previous results in \(d+\text{Au}\) collisions at midrapidity show a significant enhancement of heavy-flavor electrons at moderate \(p_T\). In this Letter, we present measurements of the \(p_T\) spectra and the nuclear modification factor (\(R_{dA}\)) of negatively charged muons from open heavy flavor at forward and backward rapidity in \(d+\text{Au}\) collisions at \(\sqrt{s_{NN}} = 200 \text{ GeV}\).

The \(d+\text{Au}\) and \(p+p\) data presented here were recorded with the PHENIX detector during the 2008 and 2009 RHIC running periods, respectively. The minimum-bias collision is selected by using the beam-beam counter (BBC), and this selection covers 88 ± 4% (55 ± 5%)
of the total d+Au (p+p) inelastic cross section \[19\]. The integrated luminosity, sampled using single muon triggers \[8\] in coincidence with the minimum-bias trigger, used for this analysis of d+Au (p+p) collisions is 50 nb\(^{-1}\) (10 pb\(^{-1}\)). The d+Au collisions are categorized into five centrality classes: 0%-20%, 20%-40%, 40%-60%, 60%-88%, and 0%-100%, where 0%-20% represents the 20% highest multiplicity events, as determined by the amount of total charge deposited in the BBC on the Au-going side. For each centrality class, the average number of binary nucleon-nucleon collisions \(\langle N_{\text{coll}} \rangle\) is calculated from the BBC charge in a Glauber model \[20\]. Correction for the underlying event correlation and the efficiency of the BBC trigger to 100% is applied as in \[21, 22\]. The backgrounds are subtracted as follows.

The backgrounds are subtracted as follows.

For each data set, we measure the double differential number of decay and punch-through hadron background tracks determined using a hadron cocktail method (described below); \(N_p\) is the estimated number of fake tracks that pass the selection criteria; \(N_{J/\psi}\) is the number of muons from \(J/\psi\) decays; \(N_{\text{evt}}\) is the number of sampled events; \(\Delta c\) is the detector acceptance and efficiency correction; and \(c\) is the BBC bias correction factor for the trigger efficiency and centrality determination of events containing a heavy-flavor muon. The contribution from remaining background sources is less than 5% \[8, 25\]. Only negative muons are used, because the signal-to-background ratio is better than for positive muons \[8\]. The typical signal-to-background ratio, \(N_\mu/(N_C + N_F + N_{J/\psi})\), increases from 0.3 at \(p_T = 1\) GeV/c to 0.6 at \(p_T = 6\) GeV/c. The hadron cocktail method estimates the overall background owing to light hadron sources using a fully data-driven GEANT simulation based on measured \(p_T\) spectra. Details on background estimation procedure and associated systematic uncertainty are described in \[8, 25\].

Figure 1 shows the invariant yield of heavy-flavor muons in d+Au collisions at backward and forward rapidity along with the invariant yield in p+p collisions. The vertical bars represent statistical uncertainties, while boxes are systematic uncertainties in the acceptance and efficiency correction, background estimation, and trigger bias correction for each centrality class. The main source of the systematic uncertainties is the background estimate including initial hadron production (~10%) and hadron simulation (~10%). All components of the systematic uncertainty are added in quadrature. Solid lines show a modified Kaplan function \(A[1 + (p_T/8.3 \text{ (GeV/c)})^2]^{-3.9}\) \[26\], fit to the \(p_T\) spectrum in p+p collisions, and then scaled by \(\langle N_{\text{coll}} \rangle\) for each d+Au centrality class. The p+p results are consistent with previous PHENIX measurements \[8\].

To quantify nuclear effects in d+Au collisions, we calculate the ratio of heavy-flavor muon yields in d+Au to p+p collisions scaled by the average number of binary collisions for a given centrality bin,

\[
R_{dA} = \frac{dN_{dA}^-/dp_T}{\langle N_{\text{coll}} \rangle} \times \frac{dN_{pp}^-/dp_T}{dN_{pp}/dp_T}.
\]

Figure 2 shows \(R_{dA}\) as a function of \(p_T\) for heavy-flavor muons in different d+Au centrality classes. Vertical bars represent the statistical uncertainties for \(R_{dA}\), which are the quadratic sum of the statistical uncertainties for the invariant yields of p+p and d+Au collisions. Boxes around the data points are the systematic uncertainties. The global scaling uncertainty in \(\langle N_{\text{coll}} \rangle\) and the BBC efficiency is shown as a box centered around unity at the right edge of the plot.

For the most peripheral collisions in both rapidity ranges, \(R_{dA}\) shows no overall modification. For the most central collisions, a clear enhancement is observed at
FIG. 1: (color online). Invariant yield of negatively charged heavy-flavor muons as a function of $p_T$ in $p+p$ collisions at $\sqrt{s_{NN}} = 200$ GeV (black squares) and in $d+Au$ collisions for different centralities at (a) backward rapidity (Au-going) and (b) forward rapidity (d-going). The solid lines represent a fit to the $p+p$ invariant yield, scaled by the number of binary collisions, $\langle N_{coll} \rangle$, for each centrality class.

This enhancement shows a $p_T$ dependence consistent with $p_T$ broadening and gluon anti-shadowing. A suppression is observed at forward rapidity in the most central collisions. At forward rapidity, $p_T$ broadening is indicated by the slope of $R_{dA}$, combined with a suppression that could be caused by gluon shadowing and/or partonic energy loss in CNM.

The dotted line in Fig. 2(c) is a prediction of $R_{dA}$ for muons from $D$ and $B$ mesons at backward (solid lines) and forward (dashed lines) rapidity as described in [29]. The EPS09s nPDF further incorporates a spatial dependence within the nucleus to the nPDF. The modification of nPDF is determined based on the input parameters $x$, momentum transfer ($Q^2$) of charm production generated by PYTHIA [15], and transverse radial positions of binary collisions in the nucleus for each centrality class. The un-

FIG. 2: (color online). The nuclear modification factor $R_{dA}$, for negatively charged heavy-flavor muons in $d+Au$ collisions for the (a) 60%-88%, (b) 0%-20%, and (c) 0%-100% most central collisions. The black boxes on the right side indicate the global scaling uncertainty. The red dashed (blue solid) lines in each panel are calculations at forward (backward) rapidity based on the EPS09s nPDF set [14]. The theoretical calculation shown in (c) is for forward rapidity [16].

matter, also describes the forward heavy-flavor muon results in central Cu+Cu collisions within uncertainties [8]. This agreement and the suppression at forward rapidity in central $d+Au$ collisions suggest that CNM effects may be important for the interpretation of the suppression of heavy-flavor muon production at forward rapidity at RHIC [8] and the Large Hadron Collider [28].

We use the EPS09s leading-order (LO) nuclear PDF (nPDF) set [14] to calculate $R_{dA}$ for muons from $D$ mesons at backward (solid lines) and forward (dashed lines) rapidity as described in [29]. The EPS09s nPDF further incorporates a spatial dependence within the nucleus to the nPDF. The modification of nPDF is determined based on the input parameters $x$, momentum transfer ($Q^2$) of charm production generated by PYTHIA [15], and transverse radial positions of binary collisions in the nucleus for each centrality class. The un-
Figure 3: (color online). Comparison of $R_{dA}$ as a function of $(N_{\text{coll}})$ for heavy-flavor leptons from different rapidity and $p_T$ bins. Data in the top (bottom) panel are from low ($1 < p_T \text{[GeV/c]} < 3$) and moderate ($3 < p_T \text{[GeV/c]} < 5$) $p_T$ ranges. Diamonds represent heavy-flavor electrons at midrapidity and squares (circles) represent heavy-flavor muons at forward (backward) rapidity.

The uncertainty bands are calculated as described in [13]. From this calculation, we can take solely the initial parton density modification into account. In central collisions, shown in Fig. 3(b), the EPS09s nPDF based calculation does not reproduce the data at backward rapidity, particularly in the moderate $p_T$ region; the difference is $\sim 2\sigma$ near $p_T = 2$ GeV/c. At forward rapidity, $R_{dA}$ calculated with the EPS09s nPDF is consistent with the data over the entire $p_T$ range within the systematic uncertainties of the data and calculation. The presence of other CNM effects is suggested, because the difference between forward and backward rapidity is significantly larger in the data than in the EPS09 nPDF calculation.

Figure 3 shows the heavy-flavor muon $R_{dA}$ as a function of $(N_{\text{coll}})$ for (a) $1.0 < p_T \text{[GeV/c]} < 3.0$ and (b) $3.0 < p_T \text{[GeV/c]} < 5.0$, compared to the heavy-flavor electron measurement at midrapidity [17]. Bars (boxes) around the data points represent the statistical (systematic) uncertainties determined as the quadratic sum of statistical (systematic) uncertainties on $R_{dA}$ for each centrality class. In both $p_T$ ranges midrapidity and backward rapidity results agree within systematic uncertainties, showing a large enhancement for more central collisions. At forward rapidity the low-$p_T$ bin shows suppression increasing with centrality, whereas the high-$p_T$ bin shows little or no centrality dependence. The EPS09s nPDF based calculations are consistent with the data at forward rapidity within uncertainties.

Quarkonia and open heavy-flavor hadrons are sensitive to the same effects on heavy-quark production. However, quarkonium states are additionally influenced by breakup in nuclear matter. Therefore, open heavy-flavor production can provide a baseline for interpreting the nuclear breakup of quarkonia. Previous measurements suggest that nuclear breakup has a significant effect on quarkonia production in nuclear collisions [21, 29, 34].

Figure 4 shows a comparison of $R_{dA}$ between heavy-flavor muons and $J/\psi$ [21] for central collisions. A similar behavior across the entire $p_T$ range is observed at forward rapidity, within the systematic uncertainties, whereas a distinct difference is seen at backward rapidity, particularly for $p_T < 2.5$ GeV/c where charm contributions dominate over those from bottom [35]. The larger difference of the $R_{dA}$ between $J/\psi$ and open charm at backward rapidity compared to forward rapidity could be related to the longer time this $c\bar{c}$ state requires to traverse the nuclear matter or the larger density of comoving particles after the initial collision at backward rapidity [36]. This comparison suggests that an additional CNM effect, nuclear breakup, significantly affects $J/\psi$ production at mid- and backward rapidity. This measurement provides a key additional constraint on theoretical models attempting to describe quarkonia yields in nuclear collisions.

We have presented a measurement of negatively charged heavy-flavor muons produced at for-
ward and backward rapidity in $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV, for several centrality classes. We observe no significant modification in the most peripheral $d+Au$ collisions. However, in central $d+Au$ collisions, suppression (enhancement) of heavy-flavor muons is observed at forward (backward) rapidity. The large difference between forward and backward rapidity, which is not reproduced by PYTHIA calculations with the EPS09s nPDF sets, suggests that various CNM effects combine to produce the observed modifications. A comparison between the measured nuclear modification factors for $J/\psi$ and open heavy-flavor production provides strong indication that nuclear breakup significantly affects quarkonia production.

We thank the staff of the Collider-Accelerator and Physics Departments at Brookhaven National Laboratory and the staff of the other PHENIX participating institutions for their vital contributions. We acknowledge support from the Office of Nuclear Physics in the Office of Science of the Department of Energy, the National Science Foundation, Abilene Christian University Research Council, Research Foundation of SUNY, and Dean of the College of Arts and Sciences, Vanderbilt University (U.S.A), Ministry of Education, Culture, Sports, Science, and Technology and the Japan Society for the Promotion of Science (Japan), Conselho Nacional de Desenvolvimento Científico e Tecnológico and Fundação de Amparo à Pesquisa do Estado de São Paulo (Brazil), Natural Science Foundation of China (P. R. China), Ministry of Education, Youth and Sports (Czech Republic), Centre National de la Recherche Scientifique, Commissariat à l’Énergie Atomique, and Institut National de Physique Nucléaire et de Physique des Particules (France), Bundesministerium für Bildung und Forschung, Deutscher Akademischer Austausch Dienst, and Alexander von Humboldt Stiftung (Germany), Hungarian National Science Fund, OTKA (Hungary), Department of Atomic Energy and Department of Science and Technology (India), Israel Science Foundation (Israel), National Research Foundation and WCU program of the Ministry Education Science and Technology (Korea), Physics Department, Lahore University of Management Sciences (Pakistan), Ministry of Education and Science, Russian Academy of Sciences, Federal Agency of Atomic Energy (Russia), VR and Wallenberg Foundation (Sweden), the U.S. Civilian Research and Development Foundation for the Independent States of the Former Soviet Union, the Hungarian American Enterprise Scholarship Fund, the US-Hungarian Fulbright Foundation for Educational Exchange, and the US-Israel Binational Science Foundation.

\* Deceased

\† PHENIX Co-Spokesperson: morrison@bnl.gov

\‡ PHENIX Co-Spokesperson: jenie.nagle@colorado.edu

\[1\] B. Abelev et al. (ALICE Collaboration), arXiv:1203.2160.

\[2\] B. Abelev et al. (ALICE Collaboration), arXiv:1305.2707.

\[3\] S. S. Adler et al. (PHENIX Collaboration), Phys. Rev. D 76, 092002 (2007).

\[4\] A. Adare et al. (PHENIX Collaboration), Phys. Rev. Lett. 97, 252002 (2006).

\[5\] H. Agakishiev et al. (STAR Collaboration), Phys. Rev. D 83, 052006 (2011).

\[6\] S. S. Adler et al. (PHENIX Collaboration), Phys. Rev. Lett. 96, 032301 (2006).

\[7\] A. Adare et al. (PHENIX Collaboration), Phys. Rev. Lett. 98, 172301 (2007).

\[8\] A. Adare et al. (PHENIX Collaboration), Phys. Rev. C 86, 024909 (2012).

\[9\] M. G. Mustafa, Phys. Rev. C 72, 014905 (2005).

\[10\] G. D. Moore and D. Teaney, Phys. Rev. C 71, 064904 (2005).

\[11\] H. van Hees, V. Greco, and R. Rapp, Phys. Rev. C 73, 034913 (2006).

\[12\] M. Djordjevic, arXiv:nucl-th/0603066.

\[13\] K. J. Eskola, H. Paukkunen, and C. A. Salgado, JHEP 0904, 065 (2009).

\[14\] I. Hellenius, K. J. Eskola, H. Honkanen, and C. A. Salgado, JHEP 1207, 073 (2012).

\[15\] T. Sjostrand, S. Mrenna, and P. Z. Skands, JHEP 0605, 026 (2006), version 8.176 with hard processes HardQCD:gg2ccbar and HardQCD:qqbar2ccbar decaying to muons and all other parameters set to the default values. url=http://www.hepforge.org/lists-archive/pythia8-announce/2013/000002.html.

\[16\] I. Vitev, Phys. Rev. C 75, 064906 (2007).

\[17\] A. Adare et al. (PHENIX Collaboration), arXiv:1208.1293.

\[18\] M. Allen et al. (PHENIX Collaboration), Nucl. Instrum. Methods A 499, 549 (2003).

\[19\] S. N. White, Amer. Inst. Phys. Conf. Proc. 792, 527 (2005).

\[20\] M. L. Miller, K. Reygers, S. J. Sanders, and P. Steinberg, Ann. Rev. Nucl. Part. Sci. 57, 205 (2007).

\[21\] A. Adare et al. (PHENIX Collaboration), Phys. Rev. C 87, 034904 (2013).

\[22\] A. Adare et al. (PHENIX Collaboration), arXiv:1304.3410.

\[23\] K. Adcox et al. (PHENIX Collaboration), Nucl. Instrum. Methods A 499, 469 (2003).

\[24\] H. Akikawa et al. (PHENIX Collaboration), Nucl. Instrum. Methods A 499, 537 (2003).

\[25\] A. Adare et al. (PHENIX Collaboration), Phys. Rev. C 84, 044905 (2011).

\[26\] J. K. Yoh, S. W. Herb, D. C. Hom, L. M. Lederman, J. C. Sens, et al., Phys. Rev. Lett. 41, 684 (1978).

\[27\] R. Sharma, I. Vitev, and B.-W. Zhang, Phys. Rev. C 80, 054902 (2009).

\[28\] B. Abelev et al. (ALICE Collaboration), Phys. Rev. Lett. 109, 112301 (2012).

\[29\] J. L. Nagle, A. D. Frawley, L. A. Linden Levy, and M. G. Wysocki, Phys. Rev. C 84, 044911 (2011).

\[30\] A. Adare et al. (PHENIX Collaboration), Phys. Rev. C 77, 024912 (2008).

\[31\] A. Adare et al. (PHENIX Collaboration), arXiv:1305.5516.
[32] A. Adare et al. (PHENIX Collaboration), Phys. Rev. Lett. 107, 142301 (2011).
[33] B. Z. Kopeliovich, I. K. Potashnikova, and I. Schmidt, Nucl. Phys. A 864, 203 (2011).
[34] C. Lourenco, R. Vogt, and H. K. Wochri, JHEP 0902, 014 (2009).
[35] A. Adare et al. (PHENIX Collaboration), Phys. Rev. Lett. 103, 082002 (2009).
[36] R. Vogt, Phys. Rev. C 61, 035203 (2000).