Nuclear-modification factor of charged hadrons at forward and backward rapidity in p+Al and p+Au collisions at $\sqrt{s_{_{NN}}}=200$ GeV

C. Aidala,[40] Y. Akiba,[52,53,*] M. Alfred,[23] V. Andrieux,[40] N. Apadula,[28] H. Asano,[33,52] B. Azmoun,[7] V. Babintsev,[24] N.S. Bandara,[39] K.N. Barish,[8] S. Bathe,[5,53] A. Bazilevsky,[7] M. Beaumier,[8] R. Belmont,[12,46] A. Berdnikov,[55] Y. Berdnikov,[55] D.S. Blau,[32,43] J.S. Bok,[45] M.L. Brooks,[35] J. Bryslawskyj,[5,8] V. Bumazhnov,[24] S. Campbell,[13] V. Canoa Roman,[58] R. Cervantes,[58] C.Y. Chi,[13] M. Chiu,[7] I.J. Choi,[25] J.B. Choi,[10,†] Z. Citron,[63] M. Connors,[21,53] N. Cronin,[58] M. Csanád,[16] T. Csörgő,[17,64] T.W. Danley,[47] M.S. Daugherity,[1] G. David,[7,15,58] K. DeBlasio,[44] K. Dehmelt,[58] A. Denisov,[24] A. Deshpande,[7,53,58] E.J. Desmond,[7] A. Dion,[58] D. Dixit,[58] J.H. Do,[65] A. Drees,[58] K.A. Drees,[6] J.M. Durham,[35] A. Durum,[24] A. Enokizono,[52,54] H. En'yo,[52] S. Esumi,[61] B. Fadem,[41] W. Fan,[58] N. Feege,[58] D.E. Fields,[44] M. Finger,[9] M. Finger, Jr.,[9] S.L. Fokin,[32] J.E. Frantz,[47] A. Franz,[7] A.D. Frawley,[20] Y. Fukuda,[61] C. Gal,[58] P. Gallus,[14] E.A. Gamez,[40] P. Garg,[3,58] H. Ge,[58] F. Giordano,[25] Y. Goto,[52,53] N. Grau,[2] S.V. Greene,[62] M. Grosse Perdekamp,[25] T. Gunji,[11] H. Guragain,[21] T. Hachiya,[42,52,53] J.S. Haggerty,[7] K.I. Hahn,[18] H. Hamagaki,[11] H.F. Hamilton,[1] S.Y. Han,[18,52] J. Hanks,[58] S. Hasegawa,[29] T.O.S. Haseler,[21] X. He,[21] T.K. Hemmick,[58] J.C. Hill,[28] K. Hill,[12] A. Hodges,[21] R.S. Hollis,[8] K. Homma,[22] B. Hong,[31] T. Hoshino,[22] N. Hotvedt,[28] J. Huang,[7] S. Huang,[62] K. Imai,[29] M. Inaba,[61] A. Iordanova,[8] D. Isenhower,[1] S. Ishimaru,[42] D. Ivanishchev,[51] B.V. Jacak,[58] M. Jezghani,[21] Z. Ji,[58] X. Jiang,[35] B.M. Johnson,[7,21] D. Jouan,[49] D.S. Jumper,[25] J.H. Kang,[65] D. Kapukchyan,[8] S. Karthas,[58] D. Kawall,[39] A.V. Kazantsev,[32] V. Khachatryan,[58] A. Khanzadeev,[51] C. Kim,[8,31] E.-J. Kim,[10] M. Kim,[52,56] D. Kincses,[16] E. Kistenev,[7] J. Klatsky,[20] P. Kline,[58] T. Koblesky,[12] D. Kotov,[51,55] S. Kudo,[61] B. Kurgyis,[16] K. Kurita,[54] Y. Kwon,[65] J.G. Lajoie,[28] A. Lebedev,[28] S. Lee,[65] S.H. Lee,[28,58] M.J. Leitch,[35] Y.H. Leung,[58] N.A. Lewis,[40] X. Li,[35] S.H. Lim,[35,65] M.X. Liu,[35] V.-R. Loggins,[25] S. Lökös,[16,17] K. Lovasz,[15] D. Lynch,[7] T. Majoros,[15] Y.I. Makdisi,[6] M. Makek,[66] V.I. Manko,[32] E. Mannel,[7] M. McCumber,[35] P.L. McGaughey,[35] D. McGlinchey,[12,35] C. McKinney,[25] M. Mendoza,[8] W.J. Metzger,[17] A.C. Mignerey,[38] A. Milov,[63] D.K. Mishra,[4] J.T. Mitchell,[7] Iu. Mitrankov,[55] G. Mitsuka,[30,52,53] S. Miyasaka,[52,60] S. Mizuno,[52,61] P. Montuenga,[25] T. Moon,[65] D.P. Morrison,[7] S.I. Morrow,[62] T. Murakami,[33,52] J. Murata,[52,54] K. Nagai,[60] K. Nagashima,[22,52] T. Nagashima,[54] J.L. Nagle,[12] M.I. Nagy,[16] I. Nakagawa,[52,53] K. Nakano,[52,60] C. Nattrass,[59] S. Nelson,[19] T. Niida,[61] R. Nishitani,[42] R. Nouicer,[7,53] T. Novák,[17,64] N. Novitzky,[58] A.S. Nyanin,[32] E. O'Brien,[7] C.A. Ogilvie,[28] J.D. Orjuela Koop,[12] J.D. Osborn,[40] A. Oskarsson,[36] G.J. Ottino,[44] K. Ozawa,[30,61] V. Pantuev,[26] V. Papavassiliou,[45] J.S. Park,[56] S. Park,[52,56,58] S.F. Pate,[45] M. Patel,[28] W. Peng,[62] D.V. Perepelitsa,[7,12] G.D.N. Perera,[45] D.Yu. Peressounko,[32] C.E. PerezLara,[58] J. Perry,[28] R. Petti,[7] M. Phipps,[7,25] C. Pinkenburg,[7] R.P. Pisani,[7] A. Pun,[47] M.L. Purschke,[7] P.V. Radzevich,[55] K.F. Read,[48,59] D. Reynolds,[57] V. Riabov,[43,51] Y. Riabov,[51,55] D. Richford,[5] T. Rinn,[28] S.D. Rolnick,[8] M. Rosati,[28] Z. Rowan,[5] J. Runchey,[28] A.S. Safonov,[55] T. Sakaguchi,[7] H. Sako,[29] V. Samsonov,[43,51] M. Sarsour,[21] S. Sato,[29] C.Y. Scarlett,[19] B. Schaefer,[62] B.K. Schmoll,[59] K. Sedgwick,[8] R. Seidl,[52,53] A. Sen,[28,59] R. Seto,[8] A. Sexton,[38] D. Sharma,[58] I. Shein,[24] T.-A. Shibata,[52,60] K. Shigaki,[22] M. Shimomura,[28,42] T. Shioya,[61] P. Shukla,[4] A. Sickles,[25] C.L. Silva,[35] D. Silvermyr,[36] B.K. Singh,[3] C.P. Singh,[3] V. Singh,[3] M.J. Skoby,[40] M. Slunečka,[9] K.L. Smith,[20] M. Snowball,[35] R.A. Soltz,[34] W.E. Sondheim,[35] S.P. Sorensen,[59] I.V. Sourikova,[7] P.W. Stankus,[48] S.P. Stoll,[7] T. Sugitate,[22] A. Sukhanov,[7] T. Sumita,[52] J. Sun,[58] Z. Sun,[15] S. Suzuki,[42] J. Sziklai,[64] K. Tanida,[29,53,56] M.J. Tannenbaum,[7] S. Tarafdar,[62,63] A. Taranenko,[43] G. Tarnai,[15] R. Tieulent,[21,37] A. Timilsina,[28] T. Todoroki,[53,61] M. Tomášek,[14] C.L. Towell,[1] R.S. Towell,[1] I. Tserruya,[63] Y. Ueda,[22] B. Ujvari,[15] H.W. van Hecke,[35] J. Velkovska,[62] M. Virius,[14] V. Vrba,[14,27] N. Vukman,[66] X.R. Wang,[45,53] Z. Wang,[5] Y.S. Watanabe,[11] C.P. Wong,[21] C.L. Woody,[7] C. Xu,[45] Q. Xu,[62] L. Xue,[21] S. Yalcin,[58] Y.L. Yamaguchi,[53,58] H. Yamamoto,[61] A. Yanovich,[24] J.H. Yoo,[31,53] I. Yoon,[56] H. Yu,[45,50] I.E. Yushmanov,[32] W.A. Zajc,[13] A. Zelenski,[6] Y. Zhai,[28] S. Zharko,[55] and L. Zou[8]

(PHENIX Collaboration)

[1]*Abilene Christian University, Abilene, Texas 79699, USA*
[2]*Department of Physics, Augustana University, Sioux Falls, South Dakota 57197, USA*
[3]*Department of Physics, Banaras Hindu University, Varanasi 221005, India*
[4]*Bhabha Atomic Research Centre, Bombay 400 085, India*
[5]*Baruch College, City University of New York, New York, New York, 10010 USA*
[6]*Collider-Accelerator Department, Brookhaven National Laboratory, Upton, New York 11973-5000, USA*
[7]*Physics Department, Brookhaven National Laboratory, Upton, New York 11973-5000, USA*
[8]*University of California-Riverside, Riverside, California 92521, USA*
[9]*Charles University, Ovocný trh 5, Praha 1, 116 36, Prague, Czech Republic*
[10]*Chonbuk National University, Jeonju, 561-756, Korea*
[11]*Center for Nuclear Study, Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan*

[12]University of Colorado, Boulder, Colorado 80309, USA
[13]Columbia University, New York, New York 10027 and Nevis Laboratories, Irvington, New York 10533, USA
[14]Czech Technical University, Zikova 4, 166 36 Prague 6, Czech Republic
[15]Debrecen University, H-4010 Debrecen, Egyetem tér 1, Hungary
[16]ELTE, Eötvös Loránd University, H-1117 Budapest, Pázmány P. s. 1/A, Hungary
[17]Eszterházy Károly University, Károly Róbert Campus, H-3200 Gyöngyös, Mátrai út 36, Hungary
[18]Ewha Womans University, Seoul 120-750, Korea
[19]Florida A&M University, Tallahassee, FL 32307, USA
[20]Florida State University, Tallahassee, Florida 32306, USA
[21]Georgia State University, Atlanta, Georgia 30303, USA
[22]Hiroshima University, Kagamiyama, Higashi-Hiroshima 739-8526, Japan
[23]Department of Physics and Astronomy, Howard University, Washington, DC 20059, USA
[24]IHEP Protvino, State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, 142281, Russia
[25]University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA
[26]Institute for Nuclear Research of the Russian Academy of Sciences, prospekt 60-letiya Oktyabrya 7a, Moscow 117312, Russia
[27]Institute of Physics, Academy of Sciences of the Czech Republic, Na Slovance 2, 182 21 Prague 8, Czech Republic
[28]Iowa State University, Ames, Iowa 50011, USA
[29]Advanced Science Research Center, Japan Atomic Energy Agency, 2-4 Shirakata Shirane, Tokai-mura, Naka-gun, Ibaraki-ken 319-1195, Japan
[30]KEK, High Energy Accelerator Research Organization, Tsukuba, Ibaraki 305-0801, Japan
[31]Korea University, Seoul, 02841
[32]National Research Center “Kurchatov Institute”, Moscow, 123098 Russia
[33]Kyoto University, Kyoto 606-8502, Japan
[34]Lawrence Livermore National Laboratory, Livermore, California 94550, USA
[35]Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
[36]Department of Physics, Lund University, Box 118, SE-221 00 Lund, Sweden
[37]IPNL, CNRS/IN2P3, Univ Lyon, Universit Lyon 1, F-69622, Villeurbanne, France
[38]University of Maryland, College Park, Maryland 20742, USA
[39]Department of Physics, University of Massachusetts, Amherst, Massachusetts 01003-9337, USA
[40]Department of Physics, University of Michigan, Ann Arbor, Michigan 48109-1040, USA
[41]Muhlenberg College, Allentown, Pennsylvania 18104-5586, USA
[42]Nara Women’s University, Kita-uoya Nishi-machi Nara 630-8506, Japan
[43]National Research Nuclear University, MEPhI, Moscow Engineering Physics Institute, Moscow, 115409, Russia
[44]University of New Mexico, Albuquerque, New Mexico 87131, USA
[45]New Mexico State University, Las Cruces, New Mexico 88003, USA
[46]Physics and Astronomy Department, University of North Carolina at Greensboro, Greensboro, North Carolina 27412, USA
[47]Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701, USA
[48]Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA
[49]IPN-Orsay, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, BP1, F-91406, Orsay, France
[50]Peking University, Beijing 100871, People’s Republic of China
[51]PNPI, Petersburg Nuclear Physics Institute, Gatchina, Leningrad region, 188300, Russia
[52]RIKEN Nishina Center for Accelerator-Based Science, Wako, Saitama 351-0198, Japan
[53]RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973-5000, USA
[54]Physics Department, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima, Tokyo 171-8501, Japan
[55]Saint Petersburg State Polytechnic University, St. Petersburg, 195251 Russia
[56]Department of Physics and Astronomy, Seoul National University, Seoul 151-742, Korea
[57]Chemistry Department, Stony Brook University, SUNY, Stony Brook, New York 11794-3400, USA
[58]Department of Physics and Astronomy, Stony Brook University, SUNY, Stony Brook, New York 11794-3800, USA
[59]University of Tennessee, Knoxville, Tennessee 37996, USA
[60]Department of Physics, Tokyo Institute of Technology, Oh-okayama, Meguro, Tokyo 152-8551, Japan
[61]Tomonaga Center for the History of the Universe, University of Tsukuba, Tsukuba, Ibaraki 305, Japan
[62]Vanderbilt University, Nashville, Tennessee 37235, USA
[63]Weizmann Institute, Rehovot 76100, Israel
[64]Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Hungarian Academy of Sciences (Wigner RCP, RMKI) H-1525 Budapest 114, POBox 49, Budapest, Hungary
[65]Yonsei University, IPAP, Seoul 120-749, Korea
[66]Department of Physics, Faculty of Science, University of Zagreb, Bijenička c. 32 HR-10002 Zagreb, Croatia

(Dated: October 29, 2019)

The PHENIX experiment has studied nuclear effects in p+Al and p+Au collisions at $\sqrt{s_{_{NN}}} = 200$ GeV on charged hadron production at forward rapidity ($1.4 < \eta < 2.4$, p-going direction) and backward rapidity ($-2.2 < \eta < -1.2$, A-going direction). Such effects are quantified by measuring nuclear modification factors as a function of transverse momentum and pseudorapidity in various collision multiplicity selections. In central p+Al and p+Au collisions, a suppression (enhancement) is observed at forward (backward) rapidity compared to the binary scaled yields in p+p collisions. The magnitude of enhancement at backward rapidity is larger in p+Au collisions than in p+Al collisions, which have a smaller number of participating nucleons. However, the results at forward rapidity show a similar suppression within uncertainties. The results in the integrated centrality are compared with calculations using nuclear parton distribution functions, which show a reasonable agreement at the forward rapidity but fail to describe the backward rapidity enhancement.

I. INTRODUCTION

Measurements of particle production in heavy-ion collisions enable the study of properties of a hot and dense nuclear medium called the quark-gluon plasma (QGP) [? ? ? ?]. An initial striking observation at the Relativistic Heavy Ion Collider (RHIC) was that production of high transverse momentum (p_T) hadrons in Au+Au collisions is strongly suppressed compared to that in p+p collisions scaled by the number of binary collisions. This suppression indicates that partons experience substantial energy loss as they traverse the QGP, a phenomenon called jet-quenching [?]. A control experiment involving a deuteron projectile on a heavy-ion target, d+Au, was carried out to test whether the feature of strong energy loss is still present in a collision system of much smaller size. The results in d+Au collisions at midrapidity presented in Ref. [?] showed no suppression at high p_T, initially leading to the conclusion that QGP itself—and associated jet quenching—were unique to collisions of larger heavy ions. In the ten years because these initial measurements, indications of QGP formation in smaller collision systems including d+Au have been found, though without evidence of jet quenching phenomena [?].

Although there were no indications of strong suppression of high p_T particles in d+Au collisions, detailed measurements do indicate other particle-production modifications relative to p+p collisions [? ? ? ? ?]. At midrapidity, a centrality-dependent enhancement of charged hadron production was observed at intermediate p_T ($2 < p_T < 5$ GeV/c) [?] in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. These nuclear effects may be due to initial- and/or final-state multiple scatterings of incoming and outgoing partons [? ?]. Processes such as radial flow [?] and recombination [?] developed for heavy-ion collisions were also investigated to explain a stronger enhancement of p and $\bar{p}$ over $\pi^{\pm}$ and $K^{\pm}$ [?]. Recent results of collectivity amongst identified particles in small collision systems at RHIC and the Large Hadron Collider [?] have been also explained within the hydrodynamic evolution model [? ?].

The study of particle production at forward and backward rapidity can provide additional information on nuclear effects such as initial-state energy loss [?] and modification of nuclear parton distribution functions (nPDF) [? ? ? ? ?]. Of particular interest are gluons at small Bjorken $x_{\rm Bj}$ (fraction of the proton's longitudinal momentum carried by the parton), where the dramatic increase of gluon density leads to expectation of saturation. This is often described within the color glass condensate (CGC) framework [?]. A strong centrality dependent suppression of single and dihadron production has been observed at forward rapidity in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [? ? ?]. A CGC calculation provides a good description of the experimental data [? ?]. Also, a perturbative quantum chromodynamics (pQCD) calculation considering coherent multiple scattering with small-$x_{\rm Bj}$ gluons reproduces the suppression of particle production at forward rapidity [? ?]. Another very different explanation for the suppression at forward rapidity is that color fluctuation effects modify the size of the high-$x_{\rm Bj}$ partons in the proton [? ?].

Accessible quark and gluon $x_{\rm Bj}$ ranges depend on the pseudorapidity (η) and transverse momentum of final state hadrons or jets. Therefore, measurements over a wide kinematic range are quite useful to further understand nuclear effects in small collision systems. PHENIX experiment has two muon spectrometers that provide wide coverage at forward ($x_{\rm Bj} \approx 0.02$, shadowing region) and backward rapidity ($x_{\rm Bj} \approx 0.1$, antishadowing region). In the previous study of nuclear effects on charged hadron production in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [?], a significant suppression was observed at forward rapidity in high multiplicity collisions compared to that in low multiplicity collisions, whereas a moderate enhancement is seen at backward rapidity. Although the direction of modification is consistent with the expectation from nPDF modification, no specific model comparison was presented.

High statistics data samples of p+p, p+Al, and p+Au collisions at $\sqrt{s_{NN}} = 200$ GeV were collected in 2015 by PHENIX. These data samples combined with the availability of a new forward silicon vertex tracking detectors, which enable the selection of particle tracks coming from the collision point, significantly improved p_T and η resolutions. The charged hadron analysis with these data sets can extend the previous study in d+Au collisions [?], and a comparison between p+Al and p+Au of very different size of nuclei can provide new information on nuclear effects on charged hadron production in p+A collisions.

In this paper, we present nuclear modification factors of charged hadron production at forward and backward rapidity in p+Al and p+Au collisions at $\sqrt{s_{NN}} = 200$ GeV of various multiplicities. Section **??** describes the experimental setup and the data sets used in this analysis. Section **??** details the analysis methods.

* PHENIX Spokesperson: akiba@rcf.rhic.bnl.gov
† Deceased