Measurement of the relative yields of $\psi(2S)$ to $\psi(1S)$ mesons produced at forward and backward rapidity in $p+p$, $p+Al$, $p+Au$, and $^{3}$He+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

A. Adare, A. C. Adlar, N.N. Ajitanand, Y. Akiba, M. Alfred, V. Andrieux, K. Aoki, N. Apadula, S. Asano, C. Ayus, B. Azmun, V. Babintsev, M. Bai, N. S. Bandara, B. Bannier, K. A. Barish, S. Bathe, A. Bazilevsky, M. Beaumier, S. Beckman, R. Belmont, A. Berdnikov, T. Berdnikov, D.S. Blau, M. Boer, J.S. Bok, E.K. Bowens, K. Boyle, M.L. Brooks, J. Byslaskjy, V. Bumazhkov, C. Butler, S. Campbell, V. Canoa Roman, R. Cervantes, C.-H. Chen, C.Y. Chi, M. Chiu, I.J. Choi, J.B. Choi, T. Chuo, Z. Citron, M. Connors, N. Cronin, M. Csanad, T. Csorgo, T.W. Danley, A. Datta, M.S. Daugherity, I. David, K. DeBlasio, D. Dehmlit, A. Denisov, A. Deshpande, E.J. Desmond, A. Dion, P.B. Diss, D. Dixit, J.H. Do, A. Drees, K.A. Drees, M. Dumnic, J.M. Durham, A. Durum, J.P. Dusing, T. Elder, E. Enokizono, H. En’yo, S. Emami, B. Fadem, W. Fan, N. Feige, D.E. Fields, M. Fingers, M. Fingers, J.R. S. Fokin, J.E. Frantz, A. Franz, A.D. Frawley, Y. Fukuda, C. Gal, P. Gallus, P. Garg, H. Ge, F. Giordano, A. Glenn, Y. Goto, N. Grau, S.V. Greene, M. Grosse Perdekamp, T. Gunji, H. Guragain, T. Hachiya, J.A. Key, V. Khachatryan, A. Khanzadeev, C. Kim, C. Kim, E.-J. Kim, G.W. Kim, M. Kim, J.M. Kimball, B. Kimelman, D. Kincses, E. Kistenev, R. Kitamura, J. Klatsky, D. Kleinj, P. Klimek, T. Koblesky, B. Komkov, J.R. Kotler, D. Kotlow, S. Kudo, K. Kurita, M. Kurose, M. Kuroswa, X. Liao, J.G. Lajoie, E.O. Lallow, A. Lebedev, S. Lee, S.H. Lee, J.M. Leitch, Y.H. Leung, N.A. Lewis, V.O. Li, X. Li, S.H. Lim, D. Liu, S. Liu, V.R. Logan, V.R. Logan, K. Lovasz, D. Lynch, T. Majoros, Y.I. Makdisi, M. Makek, M. Malaev, M. Manion, V.I. Manko, E. Mannel, M. McCumber, P.L. McGaughey, D. McGlinc, C. McKeen, A. Meles, R. Mendez, M. Mendoza, A.C. Mignerey, D.E. Milhau, A. Milov, D.K. Mishra, J.T. Mitrus, G. Mitsuka, M. Miyasaka, M. Mizuno, A.K. Mokhanty, P. Montuenga, T. Moon, D.P. Morrison, S.I.M. Morrow, T.V. Mokhanova, T. Murakami, J. Murata, A. Mvai, K. Nagai, K. Nagashima, T. Nagashima, J.L. Nagle, M.I. Nagy, I. Nakagawa, M. Nakagomi, K. Nakano, C. Nattrass, P.K. Netrakanti, T. Niida, S. Nishimura, R. Nourie, T. Novak, N. Novitzky, A.S. Novotny, A. Obrine, C.A. Ogilvie, J.D. O’Rourke, J. Osborne, O. Oskarsson, G.J. Ottino, A. Ozaawa, R.I. Pak, V. Pantuev, V. Papavassiliou, J.S. Park, S. Park, S.F. Pate, M. Patel, J-C. Peng, W. Peng, D.V. Perrelet, G. R. Perera, D.Y. Perez, C.E. PerezLara, J. Perry, R. Petri, M. Phipps, C. Pinkenburg, R. Pinson, R.P. Pisani, C.J. Press, A. Pun, M.L. Purschke, J. Rak, B.J. Ramson, I. Ravinovich, K.F. Read, D. Reynolds, V. Riabor, D. Richford, T. Rinn, S.D. Rolnick, M. Rosati, Z. Rowan, J.G. Rubin, J. Runchey, A.S. Safoenov, B. Sahlmuller, N. Saito, T. Sakaguchi, H. Sako, V. Samsonov, M. Sarso, K. Sato, S. Sato, B. Schaefer, B.K. Schmoll, K. Sedigwe, R. Seidl, A. Sen, R. Seto, P. Sett, A. Sexton, D. Sharma, I. Shein, T.A. Shibata, K. Shigaki, M. Shimomura, T. Shiroya, P. Shukla, A. Sickles, S.L. Silva, J.A. Silva, D. Silvermyr, B.K. Singh, C.P. Singh, V. Singh, M. Slunecka, K.L. Smith, M. Snowball, R.A. Solt, W.E. Sondheim, S.P. Sorensen, I.V. Sourikova, C.W. Stankus, M. Stepanow, H. Stien, S.P. Stoll, T. Sugitate, A. Sukhanov, T. Sumita, J. Sun, S. Syed, T.J. Szklar, A. Takeda, T. Taketani, K. Tanida, M.J. Tannenbaum, S. Tarafdar, A. Taranko, G. Tarnai, R. Tientul, A. Timilsina, T. Todorko, M. Tomasek, C.L. Towne, R. Towell, R.S. Towell, I. Tserruya, Y. Ueda, B. Ujvari, H.W. van Hecke, S. Vazquez-Carson, J. Velkovska, M. Virius, V. Vrba, N. Vukan, H.R. Wang, Z. Wang, W. Watanabe, Y.S. Watanabe, F. Wei, A.S. White, C.P. Wong, C.L. Woody, M. Wysocki, B. Xia, C.X. Xu, Q. Xu, L. Xue, S. Yalcin, Y.L. Yamaguchi, H. Yamamoto, A. Yanovich, P. Yin, J.H. Yoo, I.O. Yoon, H. Yu, I.E. Ushmanow, W.A. Zajec, A. Zelenski, S. Zhou, L. Zou

("PHENIX Collaboration"

"Abilene Christian University, Abilene, Texas 79699, USA"

arXiv:1609.06550v1 [nucl-ex] 31 Jan 2017
| Number | Institute Name                                                                 | Country/Region                  |
|--------|--------------------------------------------------------------------------------|---------------------------------|
| 2      | Department of Physics, Augustaana University                                    | South Dakota, USA               |
| 3      | Department of Physics, Banaras Hindu University                                 | Varanasi, India                 |
| 4      | Bhabha Atomic Research Centre                                                   | Bombay, India                   |
| 5      | Baruch College, City University of New York                                     | New York, USA                   |
| 6      | Collider-Accelerator Department, Brookhaven National Laboratory, Upton         | New York, USA                   |
| 7      | Physics Department, Brookhaven National Laboratory, Upton                       | New York, USA                   |
| 8      | University of California-Riverside, Riverside, California                       | USA                             |
| 9      | Charles University, Ovací, Prague                                               | Prague, Czech Republic          |
| 10     | Chonbuk National University                                                      | Jeonju, Korea                   |
| 11     | Science and Technology on Nuclear Data Laboratory, China Institute of Atomic    | Beijing, People's Republic of    |
|        | Energy                                                                         | China                           |
| 12     | Center for Nuclear Study, Graduate School of Science, University of Tokyo        | Tokyo, Japan                    |
| 13     | University of Colorado, Boulder, Colorado                                        | USA                             |
| 14     | Columbia University, New York                                                    | New York, USA                   |
| 15     | Czech Technical University, Zikova                                              | Prague, Czech Republic          |
| 16     | Debrecen University, H-4010 Debrecen, Egyetem tér 1                            | Hungary                         |
| 17     | ELTE, Eötvös Loránd University                                                  | Budapest, Hungary               |
| 18     | Eszterházy Károly University, Károly Róbert Campus                              | Hungary                         |
| 19     | Ewha Womans University, Seoul                                                   | Seoul, Korea                    |
| 20     | Florida State University, Tallahassee                                           | Florida, USA                    |
| 21     | Georgia State University, Atlanta                                               | Georgia, USA                    |
| 22     | Hiroshima University, Kagaminiyama, Higashi-Hiroshima                           | Japan                           |
| 23     | Department of Physics and Astronomy, Howard University, Washington, DC          | USA                             |
| 24     | IHEP Protvino, State Research Center of Russian Federation, Institute for High | Russia                          |
|        | Energy Physics, Protvino                                                        | Russia                          |
| 25     | University of Illinois at Urbana-Champaign, Urbana, Illinois                    | USA                             |
| 26     | Institute for Nuclear Research of the Russian Academy, prospekt 60-letiya       | Moscow, Russia                  |
|        | Oktyabrnya 7a, Moscow 117312, Russia                                             | Russia                          |
| 27     | Institute of Physics, Academy of Sciences of the Czech Republic, Na Slovance     | Prague, Czech Republic          |
| 28     | Iowa State University, Ames, Iowa                                               | Ames, Iowa, USA                 |
| 29     | Advanced Science Research Center, Japan Atomic Energy Agency                     | Tokyo, Japan                    |
| 30     | Helsinki Institute of Physics and University of Jyväskylä, P.O.Box 35, FI-40114| Finland                         |
| 31     | KEK, High Energy Accelerator Research Organization, Tsukuba                       | Japan                           |
| 32     | Korea University, Seoul                                                         | Seoul, Korea                    |
| 33     | National Research Center “Kurchatov Institute”, Moscow                           | Russia                          |
| 34     | Kyoto University, Kyoto                                                         | Tokyo, Japan                    |
| 35     | Lawrence Livermore National Laboratory                                          | Livermore, California           |
| 36     | Los Alamos National Laboratory, Los Alamos, New Mexico                           | USA                             |
| 37     | Department of Physics, Lund University, Box 118                                | Lund, Sweden                    |
| 38     | University of Maryland, College Park, Maryland                                   | USA                             |
| 39     | Department of Physics, University of Massachusetts, Amherst                      | Massachusetts, USA              |
| 40     | Department of Physics, University of Michigan, Ann Arbor, Michigan               | Michigan, USA                   |
| 41     | Muhlenberg College, Allentown, Pennsylvania                                     | Pennsylvania, USA               |
| 42     | Nara Women's University, Kita-uyou Nishi-machi                                  | Nara, Japan                     |
| 43     | National Research Nuclear Institute, MPhI, Moscow Engineering Physics Institute  | Moscow, Russia                  |
| 44     | University of New Mexico, Albuquerque, New Mexico                                | Mexico                          |
| 45     | New Mexico State University, Las Cruces, New Mexico                              | USA                             |
| 46     | Department of Physics and Astronomy, Ohio University, Athens                     | Athens, USA                     |
| 47     | Oak Ridge National Laboratory, Oak Ridge, Tennessee                              | USA                             |
| 48     | IPN-Orsay, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay                  | France                          |
| 49     | Peking University, Beijing                                                      | People's Republic of China      |
| 50     | PNPI, Petersburg Nuclear Physics Institute, Gatchina, Leningrad region           | Russia                          |
| 51     | RIKEN Nishina Center for Accelerator-Based Science, Wako, Saitama                | Japan                           |
| 52     | RIKEN BNL Research Center, Brookhaven National Laboratory, Upton                 | New York, USA                   |
| 53     | Physics Department, Rikkyo University, 3-34-1 Nishi-Ikebuchiko                   | Tokyo, Japan                    |
| 54     | Saint Petersburg State Polytechnic University, St. Petersburg                    | Russia                          |
| 55     | Department of Physics and Astronomy, Seoul National University, Seoul            | Seoul, Korea                    |
| 56     | Chemistry Department, Stony Brook University, SUNY, Stony Brook                  | USA                             |
| 57     | Department of Physics and Astronomy, Stony Brook University, SUNY, Stony Brook   | New York, USA                   |
| 58     | University of Tennessee, Knoxville, Tennessee                                    | Tennessee, USA                  |
| 59     | Department of Physics, Tokyo Institute of Technology, Oh-okayama, Meguro         | Tokyo, Japan                    |
| 60     | Center for Integrated Research in Fundamental Science and Engineering, University | Tsukuba, Japan                  |
|        | of Tsukuba, Tsukuba, Ibaraki, Japan                                             | Japan                           |
| 61     | Vanderbilt University, Nashville, Tennessee                                      | Tennessee, USA                  |
| 62     | Weizmann Institute, Rehovot, Israel                                             | Israel                          |
I. INTRODUCTION

The production of quark-antiquark bound states in nuclear collisions has long been studied for evidence of a phase transition between normal nuclear matter, where quarks and gluons are confined in hadrons, to a plasma phase where colored partons are deconfined. Early predictions of charmonium suppression as an unambiguous signature of deconfinement [1] have proven to be overly simplistic, as a variety of competing mechanisms have been identified which do not require color screening to disrupt bound state quark-antiquark pair formation and hadronization. It is necessary to quantitatively account for these effects to correctly interpret what measurements of quarkonia suppression in nuclear collisions imply about the quantum-chromodynamics phase diagram.

The heavy charm and bottom quarks are of particular interest, as they are produced through hard processes that are calculable with perturbative quantum-chromodynamics techniques [2] and their bound states are accessible experimentally through decays to dileptons. Models of cc and bb bound state production generally factorize charmonia production into two stages: first, the prompt initial heavy quark production via gluon fusion, and after a formation time $\tau_f$, the mechanism leading to hadronization into the final color singlet state [3–5]. In collisions involving nuclei, the initial heavy quark production can be affected by modifications of the parton distribution functions [6], energy loss in the nucleus [7], and scattering with other partons [8]. Effects which may be of hydrodynamic origin are also present in small systems [9–11], and may further alter the heavy quark final state [12, 13]. If these flow effects are due to quark-gluon-plasma formation, the presence of deconfined colored partons can inhibit coalescence into a bound state or dissolve fully-formed bound states [14]. The fully-formed pair may also be broken up through interactions with comoving hadrons outside the nucleus [15, 16].

One way to isolate final-state effects is through studies of states with the same quark content but different binding energies, such as the charmonium states $\psi(1S)$ and $\psi(2S)$, with binding energies of ~640 and ~50 MeV, respectively [17]. Before the charmonium formation time $\tau_f \sim 0.15$ fm/c, the precursor state is thought to be the same and so any effects on the precursor are likely identical. While significant initial-state effects on open charm have been found at the Relativistic Heavy Ion Collider (RHIC) [18, 19], these should equally affect all charm pairs before projection onto a final state. Therefore any differences in the modification of $\psi(2S)$ and $\psi(1S)$ production are likely due to late time effects which are sensitive to differences in the fully-formed meson radius and binding energy.

Previous measurements of $\psi(2S)$ suppression in $p+A$ collisions by the E866/NuSea [20] and NA50 [21] experiments were found to be well explained by models based on the breakup of fully formed charmonium states inside the nucleus, which naturally leads to a larger effect on the $\psi(2S)$ due to its larger radius [22]. However, this model fails to reproduce data from $d+Au$ collisions at midrapidity at RHIC [23], where the higher beam energy and shorter nuclear crossing time means the cc pairs project onto their final states outside the nucleus [24]. Breakup mechanisms which occur after the formation time can however explain the different suppression. Measurements over different rapidity intervals in asymmetric collisions can simultaneously provide information on the evolution of the cc state in different hadronic environments. In the $p/d/^{3}He$-going direction, there are relatively few produced particles, while in the A-going direction, there may be significant final state interactions between the quarkonia state and the higher number of comoving hadrons.

Here, we present measurements of the relative yields of $\psi(2S)$ to $\psi(1S)$ mesons at forward and backward rapidity in $p+p$, $p+Al$, $p+Au$, and $^{3}He+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV, from the 2014 and 2015 PHENIX data sets. We find that the relative production rate of $\psi(2S)$ to $\psi(1S)$ mesons in $p+p$ collisions is consistent with expectations from a modified color evaporation model of charmonium production [25]. In $p/^{3}He+A$ collisions, over the forward

---

[1] Deceased

* PHENIX Spokesperson: akiba@fnal.gov

---
hadron decays, allowing separation of the two peaks. Resolution and reduces combinatorial background from constituents of the pair opening angle to be made before the resonance near the larger, broad $\psi(2S)$ peak (cf. [28, 29]). Muons considered in this analysis pass through a the forward vertex tracking detector (FVTX) [27], a hadron absorber with a thickness of $\sim 10$ interaction lengths, then through three multi-plane cathode strip tracking chambers which reside in a radial magnetic field. After the tracking chambers are more layers of absorbers and Iarocci tubes for muon identification, where tracks must penetrate at least 2.5 interaction lengths of additional steel absorber. The dimuon trigger used in this analysis records events which have two tracks in the same spectrometer arm that pass through all absorber material.

Previous PHENIX measurements were not able to resolve the smaller $\psi(2S)$ peak in the dimuon mass spectrum near the larger, broad $\psi(1S)$ peak (cf. [28, 29]). However, the introduction of the four silicon tracking layers of the FVTX in 2012 now allows a precise measurement of the pair opening angle to be made before the muons undergo multiple scattering in the absorber. The additional FVTX tracking improves the dimuon mass resolution and reduces combinatorial background from hadron decays, allowing separation of the two peaks.

### II. EXPERIMENTAL SETUP

Dimuons from $\psi(2S)$ and $\psi(1S)$ decays were measured with the PHENIX muon spectrometer, which comprises two arms covering the forward and backward rapidity intervals $1.2 < |y| < 2.2$ [26]. Muons considered in this analysis pass through a the forward vertex tracking detector (FVTX) [27], a hadron absorber with a thickness of $\sim 10$ interaction lengths, then through three multi-plane cathode strip tracking chambers which reside in a radial magnetic field. After the tracking chambers are more layers of absorbers and Iarocci tubes for muon identification, where tracks must penetrate at least 2.5 interaction lengths of additional steel absorber. The dimuon trigger used in this analysis records events which have two tracks in the same spectrometer arm that pass through all absorber material.

Previous PHENIX measurements were not able to resolve the smaller $\psi(2S)$ peak in the dimuon mass spectrum near the larger, broad $\psi(1S)$ peak (cf. [28, 29]). However, the introduction of the four silicon tracking layers of the FVTX in 2012 now allows a precise measurement of the pair opening angle to be made before the muons undergo multiple scattering in the absorber. The additional FVTX tracking improves the dimuon mass resolution and reduces combinatorial background from hadron decays, allowing separation of the two peaks.

### III. DATA ANALYSIS

The measured dimuon mass spectra from $p+p$, $p+\text{Al}$, $p+\text{Au}$, and $^3\text{He}+\text{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV are shown in Fig. 1 with the a–d (e–h) plots showing data recorded in the South (North) PHENIX muon spectrometer arm. These distributions are comprised of peaks at the $\psi(1S)$ and $\psi(2S)$ masses ($\sim 3.1$ and $\sim 3.7$ GeV/$c^2$, respectively) on top of correlated background from charm and bottom hadron decays and Drell-Yan pairs, plus combinatorial background from light meson decays and hadrons which are not stopped in the absorbers. The fits to the data are shown as a solid [black] line with a shaded [gray] band representing the 90% confidence level of the fit, with the resonances and total background components of the fit represented by dashed [blue] and dotted [red] lines, respectively.

The combinatorial background contribution is extracted using event mixing techniques and is normalized to match the like-sign background. To determine systematic uncertainties on the relative yields that vary from 1% in $p+p$ collisions to 4% in $^3\text{He}+\text{Au}$ collisions, the mass range over which the normalization is done is varied from a nominal range of 2–5 GeV/$c^2$ to 1.5–5 GeV/$c^2$ and 2.5–5.5 GeV/$c^2$. The correlated background is modeled in the fit by an exponential. In the fitting procedure, the combinatorial background contribution is fixed using the methods previously described, while the shape and normalization parameters of the correlated background are allowed to vary.

The resonances are represented in the fit by the sum of a crystal-ball function [30] plus a Gaussian. The crystal ball is a continuous piecewise function that is comprised of a Gaussian on the high mass side and an exponential on the low mass side, which accounts for tails due to muon energy loss straggling in the absorbers. Due to 10 cm of additional steel absorber in the North arm as compared to the South, and the variations in the meson $p_T$ spectra in the different collision systems, the low mass tail on both peaks is expected to be different between the two arms and various systems. Therefore the parameters describing this low-side tail are allowed to float during fitting. The additional Gaussian is needed to account for tracks which have fewer than 14 hits out of a possible 16 in the muon tracker and therefore form pairs with poorer mass resolution. By analyzing pairs formed with one and two of these poorly reconstructed tracks, the width of the $\psi(1S)$ is found to vary from $\sim 200$ MeV/$c^2$ to $\sim 250$ MeV/$c^2$. Therefore, the width of this second Gaussian under the $\psi(1S)$ is set to 200 MeV/$c^2$ and varied by $\pm 25\%$ to determine a systematic uncertainty on the relative yields. From previous measurements and simulations [31], the width of the $\psi(2S)$ is expected to be 1.15 times the width of the $\psi(1S)$ peak; therefore the second Gaussian under this resonance is set to a nominal value of 230 MeV/$c^2$ and also varied by $\pm 25\%$. This is the dominant source of systematic uncertainty on this measurement, and ranges from 8% in $p+p$ collisions to 37% in the Au-going direction in $^3\text{He}+\text{Au}$ collisions, due to the larger combinatorial background.

The difference between the centers of the $\psi(2S)$ and $\psi(1S)$ peaks is set to the Particle Data Group value [32] of 0.589 MeV/$c^2$, and the width of the $\psi(2S)$ crystal-ball function is set to 1.15 times the width of the $\psi(1S)$ peak, again following expectations of the mass resolution in the muon spectrometer. This constraint is varied from 1.1 to 1.2 times the $\psi(1S)$ width to determine a systematic uncertainty on the relative yields of $\sim 3\%$ for all systems (variations outside this range do not converge on stable fit parameter values). Table 1 gives a summary of the counts measured in each collision system.

The physics quantity of interest here is the ratio of the cross sections $\sigma$ of the $\psi(2S)$ to $\psi(1S)$ mesons, multiplied by their respective branching ratio to dimuons $B_{\text{mu}}$. The counts $N_{\text{mea}}$ of each meson are determined by the fits to the dimuon mass spectra, and are corrected for the PHENIX muon spectrometer pair acceptance $\Omega$, pair detection efficiency $\epsilon$, and dimuon trigger efficiency $\epsilon_{\text{trig}}$. The measured dimuon mass spectra from $p+p$, $p+\text{Al}$, $p+\text{Au}$, and $^3\text{He}+\text{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV are shown in Fig. 1 with the a–d (e–h) plots showing data recorded in the South (North) PHENIX muon spectrometer arm. These distributions are comprised of peaks at the $\psi(1S)$ and $\psi(2S)$ masses ($\sim 3.1$ and $\sim 3.7$ GeV/$c^2$, respectively) on top of correlated background from charm and bottom hadron decays and Drell-Yan pairs, plus combinatorial background from light meson decays and hadrons which are not stopped in the absorbers. The fits to the data are shown as a solid [black] line with a shaded [gray] band representing the 90% confidence level of the fit, with the resonances and total background components of the fit represented by dashed [blue] and dotted [red] lines, respectively.

The combinatorial background contribution is extracted using event mixing techniques and is normalized to match the like-sign background. To determine systematic uncertainties on the relative yields that vary from 1% in $p+p$ collisions to 4% in $^3\text{He}+\text{Au}$ collisions, the mass range over which the normalization is done is varied from a nominal range of 2–5 GeV/$c^2$ to 1.5–5 GeV/$c^2$ and 2.5–5.5 GeV/$c^2$. The correlated background is modeled in the fit by an exponential. In the fitting procedure, the combinatorial background contribution is fixed using the methods previously described, while the shape and normalization parameters of the correlated background are allowed to vary.
TABLE I. Summary of the measured ratios of $\psi(2S)/\psi(1S)$ mesons. The first (second) values in the rightmost column represent statistical (systematic) uncertainties.

| Collision system | Rapidity interval | $N_{\text{meas}}^{\psi(1S)}$ | $N_{\text{meas}}^{\psi(2S)}$ | $B_{\mu\mu}^{\psi(2S)} / B_{\mu\mu}^{\psi(1S)}$ (%) |
|------------------|-------------------|-----------------------------|-----------------------------|----------------------------------|
| $p+p$            | $1.2 < |y| < 2.2$  | 17120±392                   | 519±51                      | $2.43\pm0.18\pm0.29$            |
| $p+Al$           | $1.2 < |y| < 2.2$  | 1497±142                    | 52±11                       | $2.73\pm0.64\pm0.13$            |
| $p+Al$           | $-2.2 < y < -1.2$ | 1463±109                    | 25±11                       | $1.37\pm0.61\pm0.16$            |
| $p+Au$           | $1.2 < |y| < 2.2$  | 3893±147                    | 117±18                      | $2.38\pm0.37\pm0.30$            |
| $p+Au$           | $-2.2 < y < -1.2$ | 3561±180                    | 51±18                       | $1.16\pm0.42\pm0.17$            |
| $^3\text{He}+Au$| $1.2 < |y| < 2.2$  | 959±64                      | 27±9.3                      | $2.24\pm0.78\pm0.32$            |
| $^3\text{He}+Au$| $-2.2 < y < -1.2$ | 1772±132                    | 35±15                       | $1.59\pm0.67\pm0.60$            |

for each species. The ratio of $\psi(2S)$ to $\psi(1S)$ mesons is given by

$$
\frac{B_{\mu\mu}^{\psi(2S)}}{B_{\mu\mu}^{\psi(1S)}} = \frac{N_{\text{meas}}^{\psi(2S)} \sigma_{\psi(2S)}}{N_{\text{meas}}^{\psi(1S)} \sigma_{\psi(1S)}} \frac{\Omega_{\psi(1S)} \epsilon_{\Omega(1S)} \epsilon_{\text{trig}}^{\psi(1S)}}{\Omega_{\psi(2S)} \epsilon_{\Omega(2S)} \epsilon_{\text{trig}}^{\psi(2S)}}
$$

(1)

The acceptance×efficiency factor $\Omega_{\psi(1S)} \epsilon_{\text{trig}}^{\psi(1S)}$ is determined via a full GEANT4 simulation of the PHENIX detector. A set of simulated dimuons, with a continuum of realistic mass, $p_T$, and rapidity distributions, is passed through the simulated PHENIX detector. The ratio of the acceptance×efficiency at the $\psi(1S)$ mass value to the $\psi(2S)$ mass value is found to be $\sim0.8$ for each arm. Since the $p_T$ distributions of $\psi(2S)$ and $\psi(1S)$ mesons have not been measured in all the collision systems presented here, a systematic uncertainty on the acceptance×efficiency factor is determined by changing the assumed $p_T$ spectra. Different dimuon samples are prepared assuming the $\psi(1S)$ spectrum follows the distribution previously measured in $p+p$ collisions and $d+Au$ collisions at forward and backward rapidity [28], and $m_T$-scaling [34] these distributions to approximate the $\psi(2S)$ spectrum. Adjusting the correction factors between these various assumptions gives a 2% systematic uncertainty on the relative yields.

The relative dimuon trigger efficiency $\epsilon_{\text{trig}}^{\psi(2S)} / \epsilon_{\text{trig}}^{\psi(1S)}$ is measured by finding the proportion of dimuon pairs in the Minimum Bias triggered data set which also fire the dimuon trigger. This small correction factor is $\sim0.97$, and a relative systematic uncertainty of 1% on the relative yields is assigned due to the statistical uncertainties on the dimuon sample in the Minimum Bias data set. Because no significant $\psi(1S)$ polarization has been measured at PHENIX [35], all corrections are calculated under the assumption that the mesons are unpolarized.

IV. RESULTS AND DISCUSSION

The $p_T$ integrated ratios of $\psi(2S)$ to $\psi(1S)$ mesons extracted from the North and South spectrometer arms
in the symmetric $p+p$ collision system agree within two standard deviations. These data points are averaged with a weighted least squared procedure, using the inverse of the square of the statistical uncertainties as weights (the same procedure that is used by the Particle Data Group to combine measurements of the same quantity [32]). The resulting data point is shown in Fig. 2, and is consistent with world data taken at other collision energies. Little difference is observed in the ratio of $\psi(2S)$ to $\psi(1S)$ mesons produced in collisions with center-of-mass energies that range over nearly three orders of magnitude, within uncertainties. This may imply that despite significant differences in the total charm cross section across these energies, once a precursor $cc$ is produced, the probability that it will project onto a given charmonium state is insensitive to the conditions which formed the initial $cc$ pair.

The same ratio is shown as a function of $p_T$ in Fig. 3 along with a calculation based on a modified color evaporation model of charmonium production at 200 GeV [25]. This model factorizes the initial production of the $cc$ pair from the color neutralization process via emission of soft gluons. The ratios reported here are somewhat higher than the model for $p_T > 2$ GeV/c, but the data’s limited statistical precision and significant theoretical error bands preclude any firm conclusions.

![Fig. 2](image-url)  
**FIG. 2.** Comparison of world data on the ratio of $\psi(2S)/\psi(1S)$ mesons in dilepton decays [21, 22, 38, 42].

From Fig. 2 it is apparent that the $\psi(2S)$ peaks are suppressed relative to the $\psi(1S)$ peak in the columns on the left (in the A-going direction). Quantitative comparisons are accomplished by calculating the double ratio of $\psi(2S)/\psi(1S)$ production in $p/3He+A$ collisions to the ratio found in $p+p$ collisions, as shown in Fig. 3. A previously published data point from midrapidity $d+Au$ collisions at the same energy is also included for comparison [28]. We see that at forward rapidity, the double ratio is consistent with all three collision systems, indicating that any possible nuclear effects on the two charmonium states are comparable. Because these states are not fully formed until after they exit the nucleus, the fact that any nuclear effects have an equal magnitude on both states suggests that there are no significant final state effects on the pair which occur in this rapidity region.

At backward rapidity, the ratios in all collision systems are suppressed by a factor of ~2. The mechanism for this preferential suppression of the $\psi(2S)$ relative to the $\psi(1S)$ is expected to occur after the $\psi(1S)$ formation time. A significant difference in the late stages of the collision between this region and forward rapidity is the presence of a larger number of comoving hadrons (see [10] for measurements of the charged particle rapidity distributions in $d+Au$, a similar collision system). Once the $cc$ pair exits the nucleus, it may be subject to interactions with these particles that can lead to breakup of the charmonium state, which are expected to be more pronounced on the less tightly bound $\psi(2S)$. While the exact nature of the interactions is not well understood, a model based on an absorption cross section that depends on the pair binding energy shows a preferential suppression that increases from forward to backward rapidity with comoving hadron multiplicity [17]. The model shows a similar trend with the $p+Au$ data, although it underestimates the relative suppression at backward rapidity (see the solid [black] line in Fig. 4). However, in $p+Al$, the model predicts almost no relative suppression at backward rapidity (dotted [red] line), while the data show a relative suppression similar to that in $p+Au$, within significant uncertainties.

Measurements in 5.02 TeV $p+Pb$ collisions at the Large Hadron Collider (LHC) have also observed that the $\psi(2S)$ is preferentially suppressed compared to the $\psi(1S)$ [18, 19]. However, at this collision energy, the preferential suppression shows no significant rapidity de-
dependence. This may indicate that the nuclear effects which preferentially suppress the $\psi(2S)$ are similar at forward and backward rapidity at the LHC. The charged particle pseudorapidity density per participant nucleon ($dN/d\eta$) in $p+Pb$ collisions at the LHC was found to be almost twice as high as $d+Au$ collisions at RHIC [50], so interactions with comoving particles may be more significant, even at forward rapidity.

For a direct comparison, the double ratios measured by PHENIX and at the LHC are plotted together in Fig. 4 as a function of comoving particle density, which is defined as the particle multiplicity $dN/d\eta$ evaluated over the same rapidity interval as the charmonia measurement, divided by the nuclear overlap $<S_T>$ . As measurements of the particle multiplicity do not exist for all these systems, the charged particle multiplicity $dN_{ch}/d\eta$ is determined by AMPT simulations [51, 52] and multiplied by $3/2$ to give the approximate total particle multiplicity $dN/d\eta$. The nuclear overlap $<S_T>$ is defined as

$$<S_T> = 4\pi \sqrt{<x^2> + <y^2> - 2<xy>^2}$$

where $x$ and $y$ are the spatial coordinates of the participating nucleons. This quantity is found via Monte Carlo Glauber simulations of the various collision species [53], with the $^3$He geometry modified as described in Ref. [54]. Table III summarizes the results of these simulations.

Figure 5 shows that the double ratio decreases as the comoving particle density increases, which is qualitatively consistent with expectations of charmonium breakup through final state interactions. The forward-rapidity PHENIX data at relatively low comover density shows no preferential suppression of $\psi(2S)/\psi(1S)$, but the forward rapidity LHC data show a relative suppression that is comparable to the backward rapidity PHENIX data at similar comover density, within uncertainties. The backward LHC data, at the highest comover density, also shows relative suppression.

Understanding suppression due to comovers could play a critical role in interpreting quarkonia data from $A+A$ collisions. Existing data on excited charmonia states in $A+A$ collisions generally suffer from poor statistics, large combinatorial backgrounds, and cover limited $p_T$ ranges [55, 56]. However, a clear sequential suppression of the excited bottomonium states has been observed in Pb+Pb collisions at the LHC [57]. While color screening is expected to play a role, given the high charged particle density in these collisions, it is reasonable to expect that similar breakup mechanisms can also have an effect on these states. In particular, the highly suppressed $\Upsilon(3s)$ state has a binding energy of only $\sim 200$ MeV, and may be especially sensitive to breakup through interactions with comoving particles.

V. CONCLUSIONS

In conclusion, we have found that the relative production of $\psi(2S)$ to $\psi(1S)$ mesons in $p+p$ collisions at $\sqrt{s} = 200$ GeV is consistent with expectations from a modified color evaporation model of charmonium production. In $p^3$He$+A$ collisions at forward rapidity we observe no difference in the $\psi(2S)/\psi(1S)$ ratio relative to $p+p$ collisions, which indicates that any possible nuclear effects that are present in this rapidity region are common between the two states, and therefore appear to occur on a timescale that is short compared to the charmonium...
formation time. At backward rapidity, where the comoving particle density is higher, we find that the $\psi(2S)$ is preferentially suppressed by a factor of $\sim 2$. This effect is likely not due to any interaction in the nucleus, because the $c\bar{c}$ pair exits the nucleus before final meson formation occurs. The preferential suppression appears consistent with interactions of the fully formed color-neutral meson with comoving particles. The magnitude of this breakup mechanism is dependent on the meson binding energy, and is likely important for interpretation of sequential screening of quarkonia in $A+A$ collisions.

**ACKNOWLEDGMENTS**

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 also thank Elena Ferreiro and Ramona Vogt for providing model calculations. 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), Croatian Science Foundation and Ministry of Science, Education, and Sports (Croatia), 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), National Science Foundation, OTKA, Károly Róbért University College, and the Ch. Simonyi Fund (Hungary), Department of Atomic Energy and Department of Science and Technology (India), Israel Science Foundation (Israel), Basic Science Research Program through NRF of the Ministry of Education (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, and the US-Israel Binational Science Foundation.

**TABLE II.** The charged particle multiplicity $dN_{ch}/d\eta$ determined from AMPT simulations [51, 52] and the nuclear overlap $S_T$ from Glauber simulations [53, 54] for the data shown in Fig. 5. Here we assume $dN/d\eta = \frac{1}{3}dN_{ch}/d\eta$, see text.

| Collision system | $\sqrt{s_{NN}}$ | Rapidity interval $\langle dN_{ch}/d\eta\rangle_{AMPT}$ | $<S_T>$ (fm$^2$) | $\left(\frac{dN/d\eta}_{AMPT}\right)_{<S_T>}$ (fm$^{-2}$) |
|------------------|----------------|---------------------------------------------------|-----------------|----------------------------------|
| $p+\text{Al}$    | 200 GeV        | $-2.2 < y < -1.2$                                | 5.9             | 0.82                            | 10.8                          |
| $p+\text{Al}$    | 200 GeV        | $1.2 < y < 2.2$                                  | 4.8             | 0.82                            | 8.8                           |
| $p+\text{Au}$    | 200 GeV        | $-2.2 < y < -1.2$                                | 10.2            | 1.01                            | 15.1                          |
| $p+\text{Au}$    | 200 GeV        | $1.2 < y < 2.2$                                  | 6.5             | 1.01                            | 9.7                           |
| $^3\text{He}+\text{Au}$ | 200 GeV        | $-2.2 < y < -1.2$                                | 20.3            | 2.35                            | 13.0                          |
| $^3\text{He}+\text{Au}$ | 200 GeV        | $1.2 < y < 2.2$                                  | 13.5            | 2.35                            | 8.6                           |
| $p+\text{Pb}$    | 5.02 TeV       | $-4.46 < y < -2.03$                              | 19.9            | 1.3                             | 23.0                          |
| $p+\text{Pb}$    | 5.02 TeV       | $2.03 < y < 3.53$                                | 15              | 1.3                             | 17.3                          |
| $p+\text{Pb}$    | 5.02 TeV       | $-4.0 < y < -2.5$                                | 20.4            | 1.3                             | 23.5                          |
| $p+\text{Pb}$    | 5.02 TeV       | $2.5 < y < 4.0$                                  | 13.7            | 1.3                             | 15.8                          |

[1] T. Matsui and H. Satz, “$J/\psi$ Suppression by Quark-Gluon Plasma Formation,” Phys. Lett. B 178, 416 (1986).
[2] M. Cacciari, P. Nason, and R. Vogt, “QCD predictions for charm and bottom production at RHIC,” Phys. Rev. Lett. 95, 122001 (2005).
[3] H. Fritzsch, “Producing Heavy Quark Flavors in Hadronic Collisions: A Test of Quantum Chromodynamics,” Phys. Lett. B 67, 217–221 (1977).
[4] G. T. Bodwin, E. Braaten, and J. Lee, “Comparison of the color-evaporation model and the NRQCD factorization approach in charmonium production,” Phys. Rev. D 72, 014004 (2005).
[5] Z. B. Kang, Y. Q. Ma, J. W. Qiu, and G. Sterman, “Heavy Quarkonium Production at Collider Energies: Factorization and Evolution,” Phys. Rev. D 90, 034006 (2014).
[6] I. Helenius, K. J. Eskola, H. Honkanen, and C. A. Salgado, “Impact-Parameter Dependent Nuclear Parton


A. Adare et al. (PHENIX Collaboration), “Quadrupole Anisotropy in Dihadron Azimuthal Correlations in Central d+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV,” Phys. Rev. Lett. 111, 112301 (2013)

A. Adare et al. (PHENIX Collaboration), “Measurement of long-range angular correlation and quadrupole anisotropy of pions and (anti)protons in central d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV,” Phys. Rev. Lett. 114, 192301 (2015)

A. Adare et al. (PHENIX Collaboration), “Measurements of elliptic and triangular flow in high-multiplicity $^{3}$He+Au collisions at $\sqrt{s_{NN}} = 200$ GeV,” Phys. Rev. Lett. 115, 142301 (2015)

X. Du and R. Rapp, “Sequential Regeneration of Charmonia in Heavy-Ion Collisions,” Nucl. Phys. A 943, 147–158 (2015)

A. Beramid et al., “Heavy-flavour production in high-energy d+Au and p+Pb collisions,” J. High Energy Phys. 03 (2016) 123.

A. Mocy, P. Petreczky, and M. Strickland, “Quarkonia in the Quark Gluon Plasma,” Int. J. Mod. Phys. A 28, 1340012 (2013)

A. Capella, A. Kaidalov, A. Kouvler Akli, and C. Gerschel, “$J/\psi$ and $\psi'$ suppression in heavy ion collisions,” Phys. Lett. B 393, 431–436 (1997)

E. G. Ferreiro, “Excited charmonium suppression in proton-nucleus collisions as a consequence of comovers,” Phys. Lett. B 749, 98–103 (2015)

H. Satz, “Colour deconfinement and quarkonium binding,” J. Phys. G 32, R25 (2006)

A. Adare et al. (PHENIX Collaboration), “Cold-nuclear-matter effects on heavy-quark production in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV,” Phys. Rev. Lett. 109, 242301 (2012)

A. Adare et al. (PHENIX Collaboration), “Cold-Nuclear-Matter Effects on Heavy-Quark Production at Forward and Backward Rapidity in d+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV,” Phys. Rev. Lett. 112, 252301 (2014)

M. J. Leitch et al. (NuSea Collaboration), “Measurement of $J/\psi$ and $\psi'$ suppression in $p$-Au collisions at 800 GeV/c,” Phys. Rev. Lett. 84, 3256–3260 (2000)

B. Alessandro et al. (NA50 Collaboration), “$J/\psi$ and $\psi'$ production and their normal nuclear absorption in proton-nucleus collisions at 400 GeV,” Eur. Phys. J. C 48, 329 (2006)

P. Arleo, P. B. Gossiaux, T. Gousset, and J. Aichelin, “Charmonium suppression in p-A collisions,” Phys. Rev. C 61, 054906 (2000)

A. Adare et al. (PHENIX Collaboration), “Nuclear Modification of $\psi$, $\chi_c$ and $J/\psi$ Production in d+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV,” Phys. Rev. Lett. 111, 202301 (2013)

D. C. McGlinchey, A. D. Frawley, and R. Vogt, “Impact parameter dependence of the nuclear modification of $J/\psi$ production in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV,” Phys. Rev. C 87, 054910 (2013)

Y. Q. Ma and R. Vogt, (2016), private communication and in preparation.

H. Akiba et al. (PHENIX Collaboration), “PHENIX muon arms,” Nucl. Instrum. Methods Phys. Res., Sec. A 499, 537–548 (2003)

C. Aidala et al., “The PHENIX Forward Silicon Vertex Detector,” Nucl. Instrum. Methods Phys. Res., Sec. A 755, 44–61 (2014)

A. Adare et al. (PHENIX Collaboration), “Transverse-Momentum Dependence of the $J/\psi$ Nuclear Modification in d+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV,” Phys. Rev. C 87, 034904 (2013)

A. Adare et al. (PHENIX Collaboration), “Ground and excited charmonium state production in $p+p$ collisions at $\sqrt{s} = 200$ GeV,” Phys. Rev. D 85, 092004 (2012)

Tomasz Skwarnicki, A study of the radiative CASCADE transitions between the Upsilon-Prime and Upsilon resonances, Ph.D. thesis, Cracow, INP (1986).

R. K. Choudhury et al., Technical Design Report of the Forward Silicon Vertex Tracker, 2007.

K. A. Olive et al. (Particle Data Group), “Rev. of Particle Phys.” Chin. Phys. C 38, 090001 (2014)

S. Agostinelli et al. (GEANT4 Collaboration), “GEANT4: A Simulation toolkit,” Nucl. Instrum. Methods Phys. Res., Sec. A 506, 250–303 (2003)

A. Adare et al. (PHENIX Collaboration), “Measurement of neutral mesons in $p+p$ collisions at $\sqrt{s}$= 200 GeV and scaling properties of hadron production,” Phys. Rev. D 83, 052004 (2011)

A. Adare et al. (PHENIX Collaboration), “Transverse momentum dependence of $J/\psi$ polarization at midrapidity in $p+p$ collisions at $\sqrt{s} = 200$ GeV,” Phys. Rev. D 82, 012001 (2010)

L. Antoniazzi et al. (E705 Collaboration), “Production of $J/\psi$ via $\psi'$ and $\chi$ decay in 300 GeV/c $p$ and $\pi^{\pm}$ nuclear interactions,” Phys. Rev. Lett. 70, 383–386 (1993)

M. C. Abreu et al. (NA51 Collaboration), “$J/\psi$, $\psi'$ and Drell-Yan production in $p+p$ and $p+d$ interactions at 450 GeV/c,” Phys. Lett. B 438, 35–40 (1998)

A. G. Clark et al., “Electron Pair Production at the CERN ISR,” Nucl. Phys. B 142, 29 (1978).

C. Albajar et al. (UA1 Collaboration), “$J/\psi$ and $\gamma$ production at the CERN pp collider,” Phys. Lett. B 256, 112–120 (1991).

F. Abe et al. (CDF Collaboration), “$J/\psi$ and $\psi$(2S) production in $pp$ collisions at $\sqrt{s} = 1.8$ TeV,” Phys. Rev. Lett. 79, 572–577 (1997)

R Aaij et al. (LHCb Collaboration), “Exclusive $J/\psi$ and $\psi$(2S) production in $pp$ collisions at $\sqrt{s} = 7$ TeV,” J. Phys. G 40, 045001 (2013)

B. B. Abelev et al. (ALICE Collaboration), “Measurement of charmonium production at forward rapidity in $pp$ collisions at $\sqrt{s} = 7$ TeV,” Eur. Phys. J. C 74, 2974 (2014)

R Aaij et al. (LHCb Collaboration), “Measurement of $\psi$(2S) meson production in $pp$ collisions at $\sqrt{s} = 7$ TeV,” Eur. Phys. J. C 72, 2100 (2012) (1204.1258)

I. Abt et al. (HERA-B Collaboration), “A Measurement of the $\psi$ to $J/\psi$ production ratio in 920 GeV proton-nucleus interactions,” Eur. Phys. J. C 49, 545–558 (2007)

M. H. Schub et al. (E789 Collaboration), “Measurement of $J/\psi$ and $\psi'$ production in 800 GeV/c proton-gold collisions...
[45] Z. W. Lin, C. M. Ko, B. A. Li, B. Zhang, and S. Pal, “A Multi-phase transport model for relativistic heavy ion collisions,” Phys. Rev. C 72, 064901 (2005).

[46] C. Loizides, J. Nagle, and P. Steinberg, “Improved version of the PHOBOS Glauber Monte Carlo,” SoftwareX 1-2, 13–18 (2015).

[47] J. L. Nagle, A. Adare, S. Beckman, T. Koblesky, J. O. Koop, D. McGlinchey, P. Romatschke, J. Carlson, J. E. Lynn, and M. McCumber, “Exploiting Intrinsic Triangular Geometry in Relativistic 3He+Au Collisions to Disentangle Medium Properties,” Phys. Rev. Lett. 113, 112301 (2014).

[48] J. Adam et al. (ALICE Collaboration), “Differential studies of inclusive J/ψ and ψ(2S) production at forward rapidity in Pb-Pb collisions at √sNN = 2.76 TeV,” J. High Energy Phys. 05 (2016) 179.

[49] V. Khachatryan et al. (CMS Collaboration), “Measurement of Prompt ψ(2S) → J/ψ Yield Ratios in Pb-Pb and p–p Collisions at √sNN = 2.76 TeV,” Phys. Rev. Lett. 113, 262301 (2014).

[50] S. Chatrchyan et al. (CMS Collaboration), “Observation of sequential Upsilon suppression in Pb-Pb collisions,” Phys. Rev. Lett. 109, 222301 (2012).