



CHORUS

This is the accepted manuscript made available via CHORUS. The article has been published as:

B-meson production at forward and backward rapidity in p+p and Cu + Au collisions at $\sqrt{s_{NN}}=200$ GeV

C. Aidala *et al.* (PHENIX Collaboration)

Phys. Rev. C **96**, 064901 — Published 4 December 2017

DOI: [10.1103/PhysRevC.96.064901](https://doi.org/10.1103/PhysRevC.96.064901)

***B*-meson production at forward and backward rapidity in $p+p$ and Cu+Au collisions
at $\sqrt{s_{NN}}=200$ GeV**

C. Aidala,^{39,44} N.N. Ajitanand,^{62,*} Y. Akiba,^{57,58,†} R. Akimoto,¹² J. Alexander,⁶² M. Alfred,²⁴ V. Andrieux,⁴⁴
K. Aoki,^{32,57} N. Apadula,^{29,63} H. Asano,^{35,57} E.T. Atomssa,⁶³ T.C. Awes,⁵³ C. Ayuso,⁴⁴ B. Azmoun,⁷
V. Babintsev,²⁵ A. Bagoly,¹⁷ M. Bai,⁶ X. Bai,¹¹ N.S. Bandara,⁴³ B. Bannier,⁶³ K.N. Barish,⁸ S. Bathe,^{5,58}
V. Baublis,⁵⁶ C. Baumann,⁷ S. Baumgart,⁵⁷ A. Bazilevsky,⁷ M. Beaumier,⁸ R. Belmont,^{13,68} A. Berdnikov,⁶⁰
Y. Berdnikov,⁶⁰ D. Black,⁸ D.S. Blau,³⁴ M. Boer,³⁹ J.S. Bok,⁵¹ K. Boyle,⁵⁸ M.L. Brooks,³⁹ J. Bryslawskyj,^{5,8}
H. Buesching,⁷ V. Bumazhnov,²⁵ C. Butler,²¹ S. Butsyk,⁵⁰ S. Campbell,^{14,29} V. Canoa Roman,⁶³ R. Cervantes,⁶³
C.-H. Chen,⁵⁸ C.Y. Chi,¹⁴ M. Chiu,⁷ I.J. Choi,²⁶ J.B. Choi,^{10,*} S. Choi,⁶¹ P. Christiansen,⁴⁰ T. Chujo,⁶⁷
V. Cianciolo,⁵³ Z. Citron,⁶⁹ B.A. Cole,¹⁴ M. Connors,^{21,58} N. Cronin,^{45,63} N. Crossette,⁴⁵ M. Csanád,¹⁷
T. Csörgő,^{18,70} T.W. Danley,⁵² A. Datta,⁵⁰ M.S. Daugherty,¹ G. David,^{7,63} K. DeBlasio,⁵⁰ K. Dehmelt,⁶³
A. Denisov,²⁵ A. Deshpande,^{58,63} E.J. Desmond,⁷ L. Ding,²⁹ A. Dion,⁶³ D. Dixit,⁶³ J.H. Do,⁷¹ L. D’Orazio,⁴²
O. Drapier,³⁶ A. Drees,⁶³ K.A. Drees,⁶ M. Dumancic,⁶⁹ J.M. Durham,³⁹ A. Durum,²⁵ T. Elder,²¹ T. Engelmores,¹⁴
A. Enokizono,^{57,59} H. En’yo,^{57,58} S. Esumi,⁶⁷ K.O. Eyser,⁷ B. Fadem,⁴⁵ W. Fan,⁶³ N. Feege,⁶³ D.E. Fields,⁵⁰
M. Finger,⁹ M. Finger, Jr.,⁹ F. Fleuret,³⁶ S.L. Fokin,³⁴ J.E. Frantz,⁵² A. Franz,⁷ A.D. Frawley,²⁰ Y. Fukao,³²
Y. Fukuda,⁶⁷ T. Fusayasu,⁴⁷ K. Gainey,¹ C. Gal,⁶³ P. Gallus,¹⁵ P. Garg,^{3,63} A. Garishvili,⁶⁵ I. Garishvili,³⁸ H. Ge,⁶³
F. Giordano,²⁶ A. Glenn,³⁸ X. Gong,⁶² M. Gonin,³⁶ Y. Goto,^{57,58} R. Granier de Cassagnac,³⁶ N. Grau,²
S.V. Greene,⁶⁸ M. Grosse Perdekamp,²⁶ Y. Gu,⁶² T. Gunji,¹² H. Guragain,²¹ T. Hachiya,^{57,58} J.S. Haggerty,⁷
K.I. Hahn,¹⁹ H. Hamagaki,¹² H.F. Hamilton,¹ S.Y. Han,¹⁹ J. Hanks,⁶³ S. Hasegawa,³⁰ T.O.S. Haseler,²¹
K. Hashimoto,^{57,59} R. Hayano,¹² X. He,²¹ T.K. Hemmick,⁶³ T. Hester,⁸ J.C. Hill,²⁹ K. Hill,¹³ R.S. Hollis,⁸
K. Homma,²³ B. Hong,³³ T. Hoshino,²³ N. Hotvedt,²⁹ J. Huang,^{7,39} S. Huang,⁶⁸ T. Ichihara,^{57,58} Y. Ikeda,⁵⁷
K. Imai,³⁰ Y. Imazu,⁵⁷ J. Imrek,¹⁶ M. Inaba,⁶⁷ A. Iordanova,⁸ D. Isenhower,¹ A. Isinhue,⁴⁵ Y. Ito,⁴⁸
D. Ivanishchev,⁵⁶ B.V. Jacak,⁶³ S.J. Jeon,⁴⁶ M. Jezghani,²¹ Z. Ji,⁶³ J. Jia,^{7,62} X. Jiang,³⁹ B.M. Johnson,^{7,21}
K.S. Joo,⁴⁶ V. Jorjadze,⁶³ D. Jouan,⁵⁴ D.S. Jumper,²⁶ J. Kamin,⁶³ S. Kanda,^{12,32} B.H. Kang,²² J.H. Kang,⁷¹
J.S. Kang,²² D. Kapukchyan,⁸ J. Kapustinsky,³⁹ S. Karthas,⁶³ D. Kawall,⁴³ A.V. Kazantsev,³⁴ J.A. Key,⁵⁰
V. Khachatryan,⁶³ P.K. Khandai,³ A. Khanzadeev,⁵⁶ K.M. Kijima,²³ C. Kim,^{8,33} D.J. Kim,³¹ E.-J. Kim,¹⁰
M. Kim,⁶¹ M.H. Kim,³³ Y.-J. Kim,²⁶ Y.K. Kim,²² D. Kincses,¹⁷ E. Kistenev,⁷ J. Klatsky,²⁰ D. Kleinjan,⁸ P. Kline,⁶³
T. Koblesky,¹³ M. Kofarago,^{17,70} B. Komkov,⁵⁶ J. Koster,⁵⁸ D. Kotchetkov,⁵² D. Kotov,^{56,60} F. Krizek,³¹
S. Kudo,⁶⁷ K. Kurita,⁵⁹ M. Kurosawa,^{57,58} Y. Kwon,⁷¹ R. Lacey,⁶² Y.S. Lai,¹⁴ J.G. Lajoie,²⁹ E.O. Lallow,⁴⁵
A. Lebedev,²⁹ D.M. Lee,³⁹ G.H. Lee,¹⁰ J. Lee,^{19,64} K.B. Lee,³⁹ K.S. Lee,³³ S. Lee,⁷¹ S.H. Lee,^{29,63} M.J. Leitch,³⁹
M. Leitgab,²⁶ Y.H. Leung,⁶³ B. Lewis,⁶³ N.A. Lewis,⁴⁴ X. Li,¹¹ X. Li,³⁹ S.H. Lim,^{39,71} L. D. Liu,⁵⁵ M.X. Liu,³⁹
V-R Loggins,²⁶ V.-R. Loggins,²⁶ S. Lokos,¹⁷ K. Lovasz,¹⁶ D. Lynch,⁷ C.F. Maguire,⁶⁸ T. Majoros,¹⁶ Y.I. Makdisi,⁶
M. Makek,^{69,72} M. Malaev,⁵⁶ A. Manion,⁶³ V.I. Manko,³⁴ E. Mannel,⁷ H. Masuda,⁵⁹ M. McCumber,^{13,39}
P.L. McGaughey,³⁹ D. McGlinchey,^{13,20,39} C. McKinney,²⁶ A. Meles,⁵¹ M. Mendoza,⁸ B. Meredith,²⁶
W.J. Metzger,¹⁸ Y. Miake,⁶⁷ T. Mibe,³² A.C. Mignerey,⁴² D.E. Mihalik,⁶³ A. Milov,⁶⁹ D.K. Mishra,⁴ J.T. Mitchell,⁷
G. Mitsuka,⁵⁸ S. Miyasaka,^{57,66} S. Mizuno,^{57,67} A.K. Mohanty,⁴ S. Mohapatra,⁶² P. Montuenga,²⁶ T. Moon,⁷¹
D.P. Morrison,⁷ S.I.M. Morrow,⁶⁸ M. Moskowitz,⁴⁵ T.V. Moukhanova,³⁴ T. Murakami,^{35,57} J. Murata,^{57,59}
A. Mwai,⁶² T. Nagae,³⁵ K. Nagai,⁶⁶ S. Nagamiya,^{32,57} K. Nagashima,²³ T. Nagashima,⁵⁹ J.L. Nagle,¹³ M.I. Nagy,¹⁷
I. Nakagawa,^{57,58} H. Nakagomi,^{57,67} Y. Nakamiya,²³ K.R. Nakamura,^{35,57} T. Nakamura,⁵⁷ K. Nakano,^{57,66}
C. Nattrass,⁶⁵ P.K. Netrakanti,⁴ M. Nishihashi,^{23,57} T. Niida,⁶⁷ R. Nouicer,^{7,58} T. Novák,^{18,70} N. Novitzky,^{31,63}
R. Novotny,¹⁵ A.S. Nyanin,³⁴ E. O’Brien,⁷ C.A. Ogilvie,²⁹ H. Oide,¹² K. Okada,⁵⁸ J.D. Orjuela Koop,¹³
J.D. Osborn,⁴⁴ A. Oskarsson,⁴⁰ G.J. Ottino,⁵⁰ K. Ozawa,^{32,67} R. Pak,⁷ V. Pantuev,²⁷ V. Papavassiliou,⁵¹
I.H. Park,^{19,64} J.S. Park,⁶¹ S. Park,^{57,61,63} S.K. Park,³³ S.F. Pate,⁵¹ L. Patel,²¹ M. Patel,²⁹ J.-C. Peng,²⁶
W. Peng,⁶⁸ D.V. Perepelitsa,^{7,13,14} G.D.N. Perera,⁵¹ D.Yu. Peressounko,³⁴ C.E. PerezLara,⁶³ J. Perry,²⁹
R. Petti,^{7,63} M. Phipps,^{7,26} C. Pinkenburg,⁷ R.P. Pisani,⁷ A. Pun,⁵² M.L. Purschke,⁷ H. Qu,¹ P.V. Radzevich,⁶⁰
J. Rak,³¹ I. Ravinovich,⁶⁹ K.F. Read,^{53,65} D. Reynolds,⁶² V. Riabov,^{49,56} Y. Riabov,^{56,60} E. Richardson,⁴²
D. Richford,⁵ T. Rinn,²⁹ N. Rivieli,⁵² D. Roach,⁶⁸ S.D. Rolnick,⁸ M. Rosati,²⁹ Z. Rowan,⁵ J. Runchey,²⁹ M.S. Ryu,²²
A.S. Safonov,⁶⁰ B. Sahlmueller,⁶³ N. Saito,³² T. Sakaguchi,⁷ H. Sako,³⁰ V. Samsonov,^{49,56} M. Sarsour,²¹ K. Sato,⁶⁷
S. Sato,³⁰ S. Sawada,³² B. Schaefer,⁶⁸ B.K. Schmoll,⁶⁵ K. Sedgwick,⁸ J. Seele,⁵⁸ R. Seidl,^{57,58} Y. Sekiguchi,¹²
A. Sen,^{21,29,65} R. Seto,⁸ P. Sett,⁴ A. Sexton,⁴² D. Sharma,⁶³ A. Shaver,²⁹ I. Shein,²⁵ T.-A. Shibata,^{57,66}
K. Shigaki,²³ M. Shimomura,^{29,48} T. Shioya,⁶⁷ K. Shoji,⁵⁷ P. Shukla,⁴ A. Sickles,^{7,26} C.L. Silva,³⁹ D. Silvermyr,^{40,53}
B.K. Singh,³ C.P. Singh,³ V. Singh,³ M.J. Skoby,⁴⁴ M. Skolnik,⁴⁵ M. Slunečka,⁹ K.L. Smith,²⁰ M. Snowball,³⁹

53 S. Solano,⁴⁵ R.A. Soltz,³⁸ W.E. Sondheim,³⁹ S.P. Sorensen,⁶⁵ I.V. Sourikova,⁷ P.W. Stankus,⁵³ P. Steinberg,⁷
 54 E. Stenlund,⁴⁰ M. Stepanov,^{43,*} A. Ster,⁷⁰ S.P. Stoll,⁷ M.R. Stone,¹³ T. Sugitate,²³ A. Sukhanov,⁷ T. Sumita,⁵⁷
 55 J. Sun,⁶³ S. Syed,²¹ J. Sziklai,⁷⁰ A. Takahara,¹² A. Takeda,⁴⁸ A. Taketani,^{57,58} Y. Tanaka,⁴⁷ K. Tanida,^{30,58,61}
 56 M.J. Tannenbaum,⁷ S. Tarafdar,^{3,68,69} A. Taranenko,^{49,62} G. Tarnai,¹⁶ E. Tennant,⁵¹ R. Tieulent,^{21,41}
 57 A. Timilsina,²⁹ T. Todoroki,^{57,67} M. Tomášek,^{15,28} H. Torii,¹² C.L. Towell,¹ R.S. Towell,¹ I. Tserruya,⁶⁹ Y. Ueda,²³
 58 B. Ujvari,¹⁶ H.W. van Hecke,³⁹ M. Vargyas,^{17,70} S. Vazquez-Carson,¹³ E. Vazquez-Zambrano,¹⁴ A. Veicht,¹⁴
 59 J. Velkovska,⁶⁸ R. Vértesi,⁷⁰ M. Virius,¹⁵ V. Vrba,^{15,28} N. Vukman,⁷² E. Vznuzdaev,⁵⁶ X.R. Wang,^{51,58}
 60 Z. Wang,⁵ D. Watanabe,²³ K. Watanabe,^{57,59} Y. Watanabe,^{57,58} Y.S. Watanabe,^{12,32} F. Wei,⁵¹ S. Whitaker,²⁹
 61 S. Wolin,²⁶ C.P. Wong,²¹ C.L. Woody,⁷ M. Wysocki,⁵³ B. Xia,⁵² C. Xu,⁵¹ Q. Xu,⁶⁸ L. Xue,²¹ S. Yalcin,⁶³
 62 Y.L. Yamaguchi,^{12,58,63} H. Yamamoto,⁶⁷ A. Yanovich,²⁵ P. Yin,¹³ S. Yokkaichi,^{57,58} J.H. Yoo,³³ I. Yoon,⁶¹ Z. You,³⁹
 63 I. Younus,^{37,50} H. Yu,^{51,55} I.E. Yushmanov,³⁴ W.A. Zajc,¹⁴ A. Zelenski,⁶ S. Zharko,⁶⁰ S. Zhou,¹¹ and L. Zou⁸

(PHENIX Collaboration)

¹Abilene Christian University, Abilene, Texas 79699, USA

²Department of Physics, Augustana University, 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, People's Republic of 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 Nevis Laboratories, Irvington, New York 10533, USA

¹⁵Czech Technical University, Zikova 4, 166 36 Prague 6, Czech Republic

¹⁶Debrecen University, H-4010 Debrecen, Egyetem tér 1, Hungary

¹⁷ELTE, Eötvös Loránd University, H-1117 Budapest, Pázmány P. s. 1/A, Hungary

¹⁸Eszterházy Károly University, Károly Róbert Campus, H-3200 Gyöngyös, Mátrai út 36, Hungary

¹⁹Ewha Womans University, Seoul 120-750, Korea

²⁰Florida State University, Tallahassee, Florida 32306, USA

²¹Georgia State University, Atlanta, Georgia 30303, USA

²²Hanyang University, Seoul 133-792, Korea

²³Hiroshima University, Kagamiyama, Higashi-Hiroshima 739-8526, Japan

²⁴Department of Physics and Astronomy, Howard University, Washington, DC 20059, USA

²⁵IHEP Protvino, State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, 142281, Russia

²⁶University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA

²⁷Institute for Nuclear Research of the Russian Academy of Sciences, prospekt 60-letiya Oktyabrya 7a, Moscow 117312, Russia

²⁸Institute of Physics, Academy of Sciences of the Czech Republic, Na Slovance 2, 182 21 Prague 8, Czech Republic

²⁹Iowa State University, Ames, Iowa 50011, USA

³⁰Advanced Science Research Center, Japan Atomic Energy Agency, 2-4

Shirakata Shirane, Tokai-mura, Naka-gun, Ibaraki-ken 319-1195, Japan

³¹Helsinki Institute of Physics and University of Jyväskylä, P.O.Box 35, FI-40014 Jyväskylä, Finland

³²KEK, High Energy Accelerator Research Organization, Tsukuba, Ibaraki 305-0801, Japan

³³Korea University, Seoul, 136-701, Korea

³⁴National Research Center "Kurchatov Institute", Moscow, 123098 Russia

³⁵Kyoto University, Kyoto 606-8502, Japan

³⁶Laboratoire Leprince-Ringuet, Ecole Polytechnique, CNRS-IN2P3, Route de Saclay, F-91128, Palaiseau, France

³⁷Physics Department, Lahore University of Management Sciences, Lahore 54792, Pakistan

³⁸Lawrence Livermore National Laboratory, Livermore, California 94550, USA

³⁹Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

⁴⁰Department of Physics, Lund University, Box 118, SE-221 00 Lund, Sweden

⁴¹IPNL, CNRS-IN2P3, Univ Lyon, Université Lyon 1, F-69622, Villeurbanne, France

⁴²University of Maryland, College Park, Maryland 20742, USA

⁴³Department of Physics, University of Massachusetts, Amherst, Massachusetts 01003-9337, USA

⁴⁴Department of Physics, University of Michigan, Ann Arbor, Michigan 48109-1040, USA

⁴⁵Muhlenberg College, Allentown, Pennsylvania 18104-5586, USA

⁴⁶Myongji University, Yongin, Kyonggido 449-728, Korea

⁴⁷Nagasaki Institute of Applied Science, Nagasaki-shi, Nagasaki 851-0193, Japan

- 114 ⁴⁸Nara Women's University, Kita-uoya Nishi-machi Nara 630-8506, Japan
 115 ⁴⁹National Research Nuclear University, MEPhI, Moscow Engineering Physics Institute, Moscow, 115409, Russia
 116 ⁵⁰University of New Mexico, Albuquerque, New Mexico 87131, USA
 117 ⁵¹New Mexico State University, Las Cruces, New Mexico 88003, USA
 118 ⁵²Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701, USA
 119 ⁵³Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA
 120 ⁵⁴IPN-Orsay, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, BP1, F-91406, Orsay, France
 121 ⁵⁵Peking University, Beijing 100871, People's Republic of China
 122 ⁵⁶PNPI, Petersburg Nuclear Physics Institute, Gatchina, Leningrad region, 188300, Russia
 123 ⁵⁷RIKEN Nishina Center for Accelerator-Based Science, Wako, Saitama 351-0198, Japan
 124 ⁵⁸RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973-5000, USA
 125 ⁵⁹Physics Department, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima, Tokyo 171-8501, Japan
 126 ⁶⁰Saint Petersburg State Polytechnic University, St. Petersburg, 195251 Russia
 127 ⁶¹Department of Physics and Astronomy, Seoul National University, Seoul 151-742, Korea
 128 ⁶²Chemistry Department, Stony Brook University, SUNY, Stony Brook, New York 11794-3400, USA
 129 ⁶³Department of Physics and Astronomy, Stony Brook University, SUNY, Stony Brook, New York 11794-3800, USA
 130 ⁶⁴Sungkyunkwan University, Suwon, 440-746, Korea
 131 ⁶⁵University of Tennessee, Knoxville, Tennessee 37996, USA
 132 ⁶⁶Department of Physics, Tokyo Institute of Technology, Oh-okayama, Meguro, Tokyo 152-8551, Japan
 133 ⁶⁷Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Ibaraki 305, Japan
 134 ⁶⁸Vanderbilt University, Nashville, Tennessee 37235, USA
 135 ⁶⁹Weizmann Institute, Rehovot 76100, Israel
 136 ⁷⁰Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Hungarian
 137 Academy of Sciences (Wigner RCP, RMKI) H-1525 Budapest 114, POBox 49, Budapest, Hungary
 138 ⁷¹Yonsei University, IPAP, Seoul 120-749, Korea
 139 ⁷²Department of Physics, Faculty of Science, University of Zagreb, Bijenička c. 32 HR-10002 Zagreb, Croatia
 140 (Dated: November 12, 2017)

141 The fraction of J/ψ mesons which come from B -meson decay, $F_{B \rightarrow J/\psi}$, is measured for J/ψ
 142 rapidity $1.2 < |y| < 2.2$ and $p_T > 0$ in $p+p$ and Cu+Au collisions at $\sqrt{s_{NN}}=200$ GeV with the
 143 PHENIX detector. The extracted fraction is $F_{B \rightarrow J/\psi} = 0.025 \pm 0.006(\text{stat}) \pm 0.010(\text{syst})$ for $p+p$
 144 collisions. For Cu+Au collisions, $F_{B \rightarrow J/\psi}$ is $0.094 \pm 0.028(\text{stat}) \pm 0.037(\text{syst})$ in the Au-going
 145 direction ($-2.2 < y < -1.2$) and $0.089 \pm 0.026(\text{stat}) \pm 0.040(\text{syst})$ in the Cu-going direction
 146 ($1.2 < y < 2.2$). The nuclear modification factor, R_{CuAu} , of B mesons in Cu+Au collisions is
 147 consistent with binary scaling of measured yields in $p+p$ at both forward and backward rapidity.

148 PACS numbers: 13.85.Ni, 13.20.Fc, 14.40.Gx, 25.75.Dw

* Deceased

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

I. INTRODUCTION.

149

150 Heavy quarks (charm and bottom quarks in the context of this work) are a powerful tool to investigate initial-state
 151 effects and quark-gluon plasma (QGP) medium formation in heavy ion collisions. Initial-state nuclear effects can alter
 152 the number of heavy quarks produced compared to extrapolations from $p+p$ collisions. Once produced, however, the
 153 number of heavy quarks is preserved in strong interactions in the medium. Final-state effects, such as energy loss in
 154 the QGP [1, 2], can only modify the momentum distribution of these quarks and open heavy mesons. On the other
 155 hand, the number of prompt J/ψ is not expected to be preserved in the medium because of the low $c\bar{c}$ binding energy,
 156 which can allow the J/ψ to be broken by medium interactions.

157 The B mesons which decay to J/ψ and subsequently decay into dimuon pairs, represent a relatively clean channel
 158 to extract b -quark yields. At the Relativistic Heavy Ion Collider (RHIC), the PHENIX forward silicon-vertex detector
 159 (FVTX) along with the central silicon-vertex detector (VTX) provide the ability to measure precise event vertex
 160 positions as well as displacement of the decay muon trajectories from the reconstructed event vertex. This allows for
 161 the statistical separation of J/ψ s from B -meson decays from prompt J/ψ s. The PHENIX muon detector acceptance
 162 for B mesons in this channel is nearly constant over all transverse momenta, allowing for the direct extraction of
 163 momentum integrated b -quark yields, corresponding to the number of b quarks in the rapidity acceptance. With these
 164 yields, we can verify whether initial-state effects are relevant to B -meson production in nucleus+nucleus collisions.

165 The only known source of nonprompt J/ψ is production via B -meson decay [3], which has a typical decay time
 166 $\tau_0 \sim 1.5\text{--}1.6$ ps [4]. The constituent bottom quarks have mass $m_b \sim 4.5$ GeV/ c^2 and are created from processes such as
 167 gluon fusion ($gg \rightarrow Q\bar{Q}$), flavor excitation where heavy quarks (Q) from the nucleon wave function scatter with gluons
 168 ($Qg \rightarrow Qg$), and gluon splitting ($gg \rightarrow Q\bar{Q}g$) [5, 6]. Gluon-gluon fusion and flavor excitation are equally dominant
 169 whereas the gluon splitting contribution is small at $\sqrt{s} = 200$ GeV according to PYTHIA8 hard scattering simulations
 170 [7].

171 Initial-state effects on the precursor gluons, before their hard scattering, include coherent multiple scattering, also
 172 called dynamical shadowing [6], incoherent multiple scattering [8, 9], initial state energy loss [10], and saturation of
 173 small momentum fraction x gluons [11]. Nuclear parton distribution functions, extracted from deep inelastic scattering
 174 and Drell-Yan experimental data, such as EPS09 [12] and impact-parameter-dependent EPS09s [13], indicate a pattern
 175 of suppression for small- x gluons and an enhancement of intermediate to large- x gluons. Semi-leptonic decays of
 176 particles carrying heavy flavor and produced inclusively in d +Au collisions at $\sqrt{s_{NN}} = 200$ GeV [14, 15] indicate yield
 177 suppression at forward rapidity, where Bjorken $x \sim 5 \times 10^{-3}$ gluons dominate. The same analysis also revealed a
 178 clear yield enhancement at mid- and backward rapidity, where gluons with fractional momentum $0.05 \lesssim x \lesssim 0.2$ are
 179 dominant. A similar enhancement was observed in the measurements of D mesons in d +Au at midrapidity [16].

180 Asymmetric Cu+Au collisions have the advantage of being a relatively large system which can access different x
 181 regions at positive and negative rapidities. Studies in these collisions provide a powerful test of how initial-state
 182 effects observed in small systems, such as $p+A$, can be projected in large heavy ion collisions. In the PHENIX muon
 183 arms, positive rapidity corresponds to the Cu-going direction, probing small- x in the Au nucleus and large- x in the
 184 Cu. Negative rapidity covers the Au-going direction, probing small- x in the Cu nucleus and large- x in the Au. Initial
 185 state parton distribution modifications are predicted to be stronger in the Au nucleus [17]. If these modifications
 186 have the same pattern as seen in $p(d)+A$ collisions, they may cause suppression in the Cu-going (positive rapidity)
 187 direction and enhancement in the Au-going direction. Initial-state energy loss [18] also results in larger suppression
 188 at positive rapidity.

189 In this study we quantify the fraction of muons from the decay of nonprompt J/ψ in $p+p$ and Cu+Au collisions at
 190 $\sqrt{s_{NN}} = 200$ GeV using the PHENIX muon arms measuring in the rapidity range $1.2 < |y| < 2.2$. The nonprompt
 191 fractions are then used to calculate the nuclear modification of B mesons in Cu+Au collisions. This result uses
 192 the capability to measure the approach between muons and the collision vertex using the FVTX [19]. Section II
 193 describes the experimental apparatus and the data set. Section III describes the data selection, backgrounds and
 194 defines the distance of closest approach (DCA_R). Section IV describes the simulation setup used to obtain the DCA_R
 195 distribution profiles. The fit to the real data distance of closest approach distributions is detailed in Section V.
 196 Systematic uncertainties are discussed in Section VI. Results and interpretations are presented in Section VII.

197

II. EXPERIMENTAL APPARATUS AND DATA SET.

198 This analysis was performed using data sets obtained with the PHENIX detector (Fig. 1) at the Relativistic Heavy
 199 Ion Collider during the 2015 $p+p$ and 2012 Cu+Au $\sqrt{s_{NN}} = 200$ GeV runs. Each collision was identified by the north
 200 and south beam-beam counters (BBC) which each comprise 64 quartz radiators instrumented with mesh dynode
 201 PMTs covering charged particles in the pseudorapidity region $3.0 < |\eta| < 3.9$ and with time resolution of ~ 50 ps.
 202 A fast online collision z vertex can be determined from the difference between the average north and south arrival

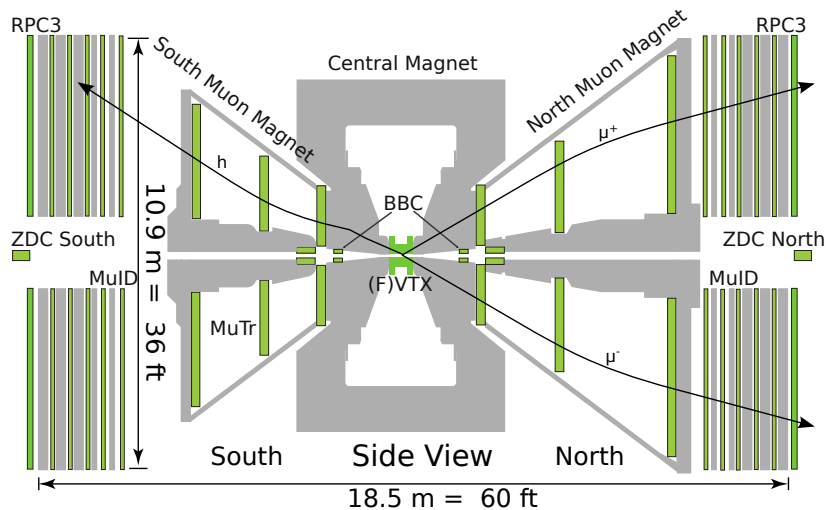


FIG. 1. Schematic view of the detector apparatus along with an illustrated dimuon and a hadron stopping in one of the muon identifier (MuID) gaps.

203 times. A minimum-bias (MB) event is triggered by two or more hits in each BBC and a measured vertex position
 204 $|z_{\text{vtx}}| \lesssim 10$ cm, and results in an acceptance of $93 \pm 3\%$ of the total Cu+Au cross section. For $p+p$ collisions, one or
 205 more hits are required in each BBC for the MB trigger, and $55 \pm 5\%$ of the total inelastic cross section is accepted.
 206 This analysis also used a sample of dimuon triggered events (MUIDLL1_2D) which required two roads of hits found
 207 in the Iarocci tubes in the muon identifiers (MuID), including at least one road that reached the most downstream
 208 tubes.

209 A. PHENIX muon spectrometers.

210 Each muon spectrometer covers a pseudorapidity range of $1.2 < |\eta| < 2.2$ and 2π in azimuth. Each spectrometer
 211 comprises hadron-absorber material, muon trackers (MuTr) inside a conical-shaped magnet, and a MuID. The first
 212 layer of hadron absorber, placed between the FVTX and the MuTr, comprises 19 cm of copper, 60 cm of iron from the
 213 central magnet and 36.2 cm steel, corresponding to a total of 7.2 nuclear interaction lengths. This material absorbs
 214 pions and kaons emitted into the acceptance of the muon arms. The muon magnet system provides a radial field
 215 inside the MuTr volume of approximately $\int \mathbf{B} \cdot d\mathbf{l} = 0.72$ T·m at 15 degrees from the beam axis, bending particles in
 216 the azimuthal direction.

217 Tracking and momentum measurements are performed by the MuTr, which comprises 8 octants of cathode strip
 218 chambers distributed in each of three z -stations. The first two stations have three sensitive planes each, and the
 219 farthest station from the interaction region has two sensitive planes. Each plane contains two cathode readout strip
 220 planes with varying stereo angle orientations among the planes in the station in order to provide measurements in
 221 two spatial dimensions. The momentum resolution achieved by the MuTr is $\delta p/p \approx 0.05$ for a typical muon from J/ψ
 222 decays.

223 The north and south MuID systems are located downstream of the MuTr and comprise five absorber plates totaling
 224 4.8 (5.4) nuclear interaction lengths in the south (north) arm. Two Iarocci tube planes with vertical and horizontal
 225 orientations distributed in six individual panels are placed after each of the five absorber gaps. Pion and kaon rejection
 226 after all absorber material is larger than a factor of 250. Only muons with momentum > 3 GeV/ c are able to penetrate
 227 all absorbers. Recorded hits in the tubes are used to reconstruct roads which are used in the MUIDLL1_2D trigger
 228 and in full muon track reconstruction. Technical details of the muon arms can be found in [20, 21].

229 Particles produced at the primary vertex cross ~ 7.2 interaction lengths of absorber before reaching the first MuTr
 230 station located at $z = \pm 190$ cm. Due to multiple scattering in the absorber, the projection of tracks reconstructed
 231 in the MuTr to the FVTX has a standard deviation radius of 3 cm. The FVTX helps track these particles from the
 232 absorber to the vertex point.

233 A precise vertex measurement is provided offline (Sec. III C) by the central arm vertex detector (VTX) and the
 234 FVTX. The VTX [22, 23] is a silicon detector with four radial layers placed at 2.6, 5.1, 11.8 and 16.7 cm from the
 235 z -axis, covering $2 \times \Delta\phi \approx 1.6\pi$ and $|z_{\text{vtx}}| < 10$ cm. The innermost two layers have pixel segmentation of $\Delta\phi \times \Delta z =$
 236 $50 \mu\text{m} \times 425 \mu\text{m}$ and the two outer layers comprise stripixels with an effective pixel size of $80 \mu\text{m}$ in $R\Delta\phi$ and 1 mm

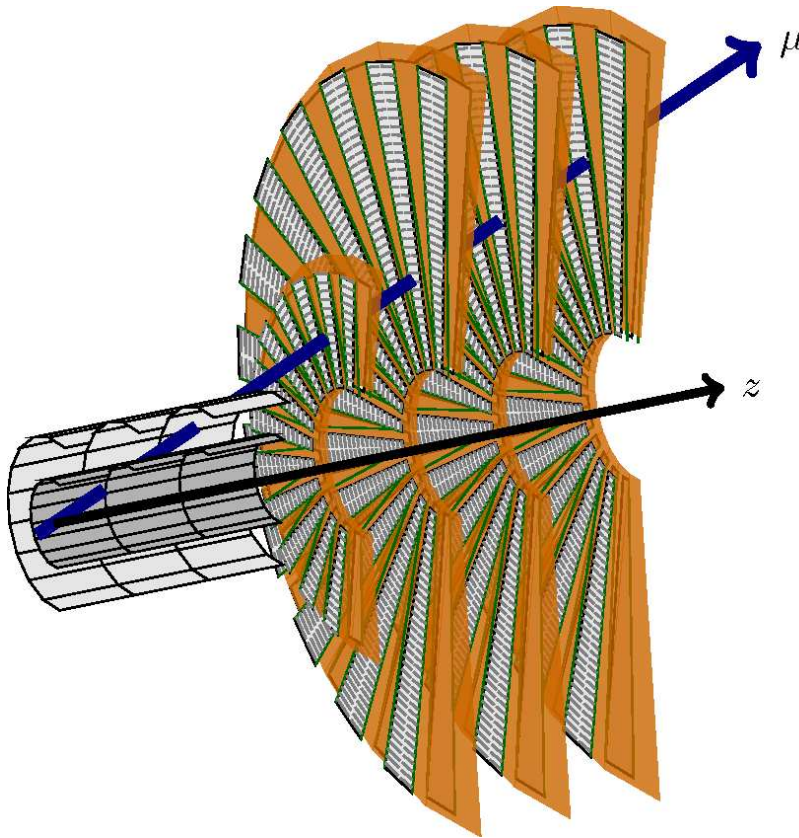


FIG. 2. Schematic view of the west VTX and north-west arm FVTX detectors used in this analysis.

237 in z .

TABLE I. Summary of FVTX geometry.

Mean z -position of discs [cm]	$\pm 20.1, \pm 26.1, \pm 32.2, \pm 38.2$
ϕ segmentation each disk	48 wedges \times 2 columns
inner radius	4.4 cm
strip pitch	75 μm
strip length	3.4 mm to 11.5 mm
total number of strips	1.08 M
silicon thickness	320 μm

238 The FVTX is a silicon detector installed in 2012 to precisely measure the radial distance of closest approach (DCA_R)
 239 of extrapolated particle trajectories to the collision vertex (Sec. III D), allowing statistical separation between prompt
 240 muons and muons from the decay of long-lifetime particles. Geometrical characteristics of the FVTX are listed in
 241 Table I. More technical details concerning the FVTX detector can be found in [19].

242 Tracks reconstructed in the silicon system are required to have at least three hits in different FVTX disks and/or
 243 VTX pixel layers (seen as half-cylinders in Fig. 2). The magnetic field in the region of the FVTX is primarily in the
 244 z -direction, resulting in only a very small bending of tracks in the ϕ direction. Therefore, the FVTX cannot measure
 245 particle momentum, which can be reconstructed only if the FVTX track is associated to a MuTr track.

246

B. Data set and quality assurance.

247 Only collisions with a vertex determined by the VTX and FVTX within $z = \pm 10$ cm from the nominal interac-
 248 tion point are selected. Collisions where the vertex determination (Sec. III C) has an uncertainty larger than 500

249 μm ($200 \mu\text{m}$) are also rejected in $p+p$ (Cu+Au) data. The fraction of collisions within the vertex range used in
 250 this analysis is 14% in $p+p$ and 18% in Cu+Au. Only MB triggers or MUIDLL1.2D triggers in coincidence with
 251 a MB trigger (MUIDLL1.2D&MB) were analyzed. In $p+p$ the number of analyzed events in the selected vertex
 252 region is 3.4×10^{11} , corresponding to an integrated luminosity of $\int \mathcal{L} dt = 14.8 \text{ pb}^{-1}$. In Cu+Au 5.7×10^9 MB
 253 and 284×10^6 MUIDLL1.2D&MB events were analyzed in the selected vertex range. The MB trigger is sensitive to
 254 $\sigma_{Cu+Au} = 5.23 \pm 0.15 \text{ b}$ of the total Cu+Au cross section, according to Glauber calculations reported in [17]. Therefore,
 255 the Cu+Au events used in this analysis correspond to $\int \mathcal{L} dt = 1.0 \text{ nb}^{-1}$, or the $p+p$ equivalent of 11.8 pb^{-1} .

256 The run-by-run average DCA_R (described in Sec.IIID) measured for of all charged particles by the FVTX was
 257 found to be stable throughout the data collection period in the Cu+Au run. For the case of $p+p$ collisions, $\sim 10\%$ of
 258 data are rejected due to instabilities of the measured DCA_R .

259 III. DATA SELECTION AND HOW TO OBTAIN THE DISTANCE OF CLOSEST APPROACH 260 DISTRIBUTIONS.

261 B mesons have a mean decay length $c\tau_0 \sim 450 \mu\text{m}$, a scale measurable by precision vertex detectors. At large
 262 rapidity the momentum boost $\gamma = \sqrt{p_z^2 + p_T^2 + m^2}/m$ to the decay length is larger than at midrapidity ($p_z \sim 0$),
 263 allowing B -meson identification via nonprompt decays even at zero transverse momentum.

264 Typically, the fraction of B -meson decays in J/ψ samples (here defined as $F_{B \rightarrow J/\psi}$) is determined by measuring
 265 the vertex given by the intersection of the two muon trajectories in the dimuon pair. This approach is not used in this
 266 analysis because: 1) the J/ψ dimuon vertex cannot be precisely determined because of the limited ϕ resolution of the
 267 FVTX; 2) a fraction of the sample of J/ψ decays would be lost in the sample when one of the muons reconstructed
 268 by the MuTr does not match to the FVTX.

269 In this analysis the J/ψ decay is identified by the dimuon invariant mass of selected MuTr+MuID tracks. In a
 270 second step, muon candidates from the identified J/ψ decay that have matching FVTX tracks are selected. The radial
 271 distance of closest approach DCA_R (Sec. IIID) is determined for combined FVTX+MuTr+MuID tracks after quality
 272 cuts. The following sections detail how the sample is selected, how the backgrounds are treated, and how DCA_R is
 273 defined.

274 A. Selection of J/ψ candidates.

275 Single muon candidates are MuTr tracks that are associated to MuID roads (Sec. II A). The MuTr track is required
 276 to have at least 11 out of a maximum of 16 hits in different cathode planes, and the fitted track should return a
 277 $\chi^2/\text{NDF} < 10$, cut based on the distribution obtained from simulated muons which also accounts for tracks crossing
 278 malfunctioning channels in the MuTr. Because a track is required to cross all absorbers, only muons with a total
 279 reconstructed momentum larger than $3 \text{ GeV}/c$ are accepted. The MuID roads are required to have at least 6 out of
 280 a possible 10 hits in different tube planes including a hit in one of the planes located behind the last MuID absorber.
 281 Three standard deviation cuts are applied to the distance and angle between the MuTr track and the MuID road
 282 projections at the first MuID gap. Dimuon pairs formed from MuTr+MuID selected muons are required to have an
 283 opening angle larger than 45° if the dimuon p_T is smaller than $5 \text{ GeV}/c$. Implementation of this cut helps remove
 284 contributions from ghost tracks. A fit involving the muon pair tracks and the collision vertex is required to have a
 285 $\chi^2/\text{NDF} < 5(3)$ in $p+p$ (Cu+Au) data, corresponding to a maximum distance between the dimuon crossing and the
 286 collision point of approximately 1 cm . This cut has no impact on B decay acceptance.

287 Dimuon spectra in the region of the J/ψ mass are shown in Fig. 3 for both muon arms. The combinatorial
 288 background, shown as open circles in panels (a) and (b), corresponds to random combinations of muons. This
 289 background is determined from mixed event dimuons and normalized by the geometric average between same event
 290 like-sign sources N_{++}^{same} , N_{--}^{same} and mixed event like-sign sources N_{++}^{mix} , N_{--}^{mix} :

$$\text{Norm}_{\text{CB}} = \frac{\sqrt{N_{++}^{\text{same}} \cdot N_{--}^{\text{same}}}}{\sqrt{N_{++}^{\text{mix}} \cdot N_{--}^{\text{mix}}}}. \quad (1)$$

291 Mixed event dimuons are required to come from two separate events with a z -vertex difference no larger than 1.5 cm
 292 and a difference between collision centrality percentiles that is no larger than 5%. Accumulated mixed event dimuon
 293 counts are five times larger than the same-event dimuons in order to reduce background statistical uncertainties.
 294 The number of selected J/ψ decays inside the dimuon invariant mass $2.8 < m_{\mu\mu} [\text{GeV}/c^2] < 3.5$, the signal over
 295 background, after all quality cuts, and the fraction of correlated continuum background f_{cont} are listed in Table II.

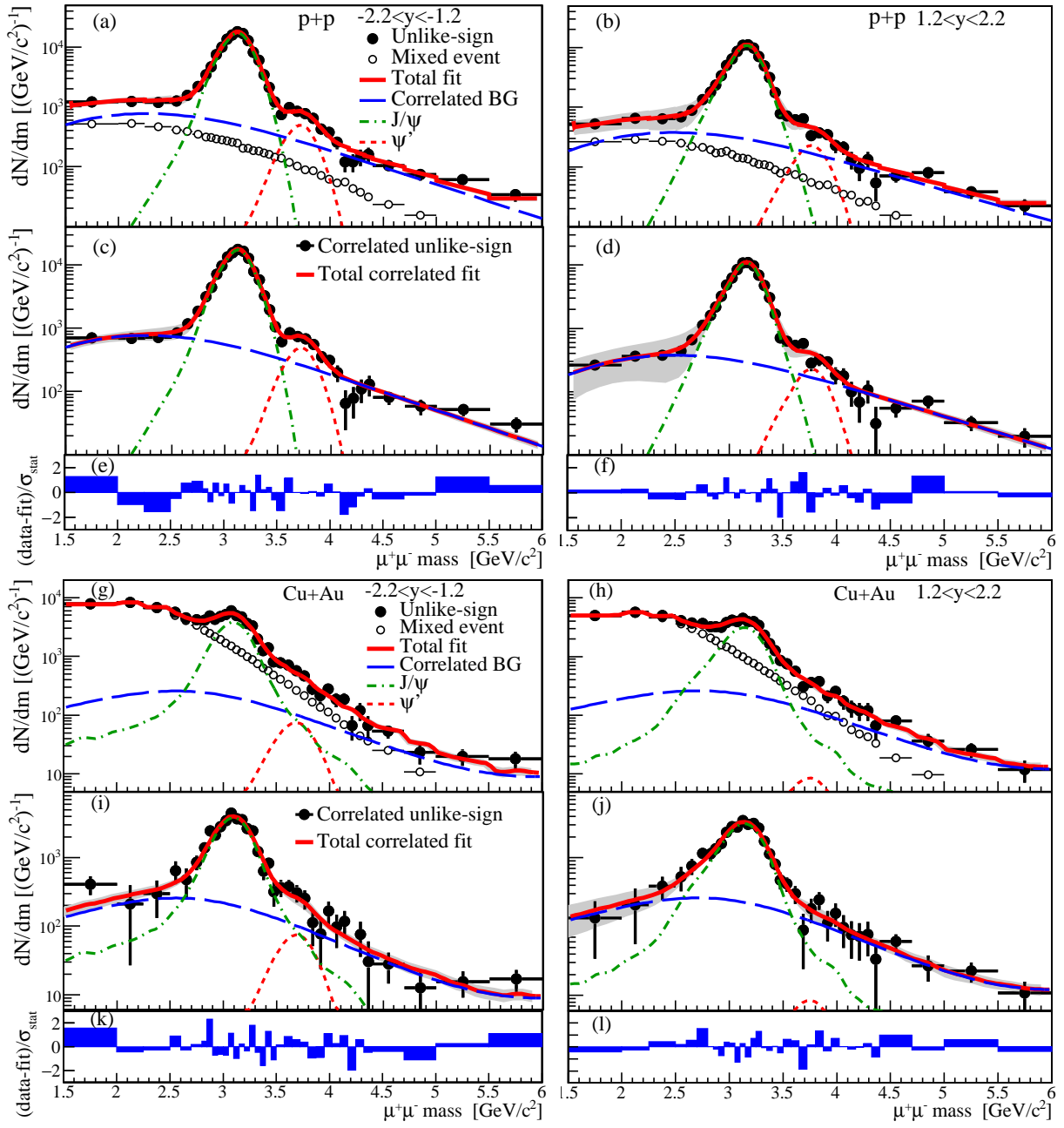


FIG. 3. The dimuon mass distributions in $p+p$ (a-f) and Cu+Au (g-l) collisions. The mass distribution along with mixed event dimuons which account for the combinatorial background is shown in panels (a,b,g,h). The distribution after removal of the combinatorial background is shown in panels (c,d,i,j). The lines represent the Eq. (2) components fit to the data points. Panels (e,f,k,l) show the pull between data and fit.

296 Correlated background expected to contribute in the J/ψ mass region is mainly from $c\bar{c} + X \rightarrow \mu^+\mu^- + X$ and
 297 $b\bar{b} + X \rightarrow \mu^+\mu^- + X$ processes. The amount of correlated background shown as dashed lines in Fig. 3 is estimated
 298 by fitting the function

$$\begin{aligned}
 f_{\mu^+\mu^-}(m) &= \text{CBG}(m) + N_{\text{corr}}f_{\text{corr}}(m) \\
 &\quad + N_{J/\psi}f_{J/\psi}(m) + N_{\psi'}f_{\psi'}(m) \\
 f_{\text{corr}}(m) &= A\varepsilon(m) \left[c_{1m}e^{-m/\lambda_{1m}} + (1 - c_{1m})m^{-\lambda_{hm}} \right]
 \end{aligned} \tag{2}$$

TABLE II. Dimuon net counts, signal to combinatorial background (S/CBG) and the correlated background contribution f_{cont} in the J/ψ mass region $2.8 < m_{\mu\mu}[\text{GeV}/c^2] < 3.5$.

data	arm	net count	S/CBG	f_{cont}
$p+p$	south	5978 ± 150	32.7	$5.5 \pm 0.3\%$
$p+p$	north	3714 ± 67	33.6	$5.3 \pm 0.4\%$
Cu+Au	south	3075 ± 92	1.13	$10.3 \pm 2.4\%$
Cu+Au	north	2675 ± 82	1.35	$10.7 \pm 2.5\%$

to the unlike-sign dimuon mass distribution m , where $\text{CBG}(m)$ is the combinatorial background, $f_{\text{corr}}(m)$ is the correlated background, $f_{J/\psi}(m)$ and $f_{\psi'}$ are the J/ψ and ψ' simulated peaks, $A\mathcal{E}(m)$ is the mass dependent detector acceptance and efficiency determined from simulation and trigger emulator. The correlated background functional form of $f_{\text{corr}}(m)$ accounts for an exponential behavior at low mass and a power law behavior at high mass, verified in PYTHIAS simulation of $c\bar{c}$ and $b\bar{b}$ pair production. The free parameters in the fit are N_{corr} , $N_{J/\psi}$, $N_{\psi'}$, c_{lm} , λ_{lm} and λ_{hm} . Fitting constrains are applied to c_{lm} , λ_{lm} and λ_{hm} according to a $f_{\text{corr}}(m)$ fit to correlated like-sign dimuon mass distribution in the same mass range. Table II also shows the extracted fractions of correlated background in the J/ψ mass region:

$$f_{\text{cont}} = \int_{m=2.8}^{3.5} dm N_{\text{corr}} f_{\text{corr}}(m). \quad (3)$$

B. FVTX-MuTr track association.

Requirements for standalone FVTX track selection include a minimum of three hits in different FVTX or VTX planes. The analysis require a FVTX track has a χ^2 probability (p-value) larger than 5%. The track quality selection keeps 95% of the true tracks according to simulations. FVTX-MuTr track matching is performed as follows:

1. MuTr and FVTX tracks are projected to three z -plane locations: 1) the fourth FVTX disk from the vertex, 2) the middle of the absorber materials in front of the MuTr and 3) the first MuTr station. Radial (R and p_R) and azimuthal (ϕ and p_ϕ) position and momentum projections, and uncertainties ($\sigma_{R_{\text{FVTX-MuTr}}}$, $\sigma_{\phi_{\text{FVTX-MuTr}}}$, $\sigma_{p_{R_{\text{FVTX-MuTr}}}}$, $\sigma_{p_{\phi_{\text{FVTX-MuTr}}}}$) are calculated for each FVTX and MuTr track using the GEANE Kalman Filter algorithm [24] taking into account the detector geometry, the amount of absorber material and the magnetic field map. The momentum magnitude used for FVTX track projections is taken from the associated MuTr track.
2. A combined FVTX+MuTr track χ^2 is calculated for each association from individual χ_{FVTX}^2 and χ_{MuTr}^2 track qualities and FVTX-MuTr projection residuals in the tree planes in an approximation considering the correlation between residuals in different planes is small:

$$\chi^2 = \chi_{\text{FVTX}}^2 + \chi_{\text{MuTr}}^2 + \chi_{\text{match}}^2 \quad (4)$$

$$\chi_{\text{match}}^2 = \sum_{i=1}^3 \frac{(R_i^{\text{FVTX}} - R_i^{\text{MuTr}})^2}{\sigma_{R_{\text{FVTX-MuTr}}}^2} + \frac{(\phi_i^{\text{FVTX}} - \phi_i^{\text{MuTr}})^2}{\sigma_{\phi_{\text{FVTX-MuTr}}}^2} + \frac{(p_{R_i}^{\text{FVTX}} - p_{R_i}^{\text{MuTr}})^2}{\sigma_{p_{R_{\text{FVTX-MuTr}}}}^2} + \frac{(p_{\phi_i}^{\text{FVTX}} - p_{\phi_i}^{\text{MuTr}})^2}{\sigma_{p_{\phi_{\text{FVTX-MuTr}}}}^2},$$

where $p\phi_i^{\text{FVTX}}$ and pr_i^{FVTX} are just track directions determined by the FVTX.

3. Only FVTX-MuTr combined tracks with $\chi^2/\text{NDF} < 6(3)$ are accepted for further analysis in $p+p$ (Cu+Au) data.
4. In the $p+p$ analysis, at least one VTX hit is required for tracks inside the VTX acceptance to reduce effects from additional material that was installed just before the 2015 run between the VTX and FVTX.

FVTX-MuTr track mismatches can occur if MuTr tracks are projected onto a region where the FVTX is not active. These MuTr tracks tend to incorrectly associate with tracks in neighboring live regions which can distort the DCA_R distributions. Fiducial cuts were applied to remove MuTr track projections onto nonactive ϕ regions in the FVTX and their edges to minimize these mismatches. Edge effects are further reduced by requiring the azimuthal residual between the FVTX and MuTr track projections is no larger than 100 mrad (corresponding to the MuTr azimuthal projection resolution).

Once the FVTX-MuTr association passes the matching criteria, the tracks are combined providing a momentum vector and projection at the vertex plane. The combined track has precise momentum and azimuthal direction mostly from the MuTr track information, and FVTX track information dominates the radial direction precision.

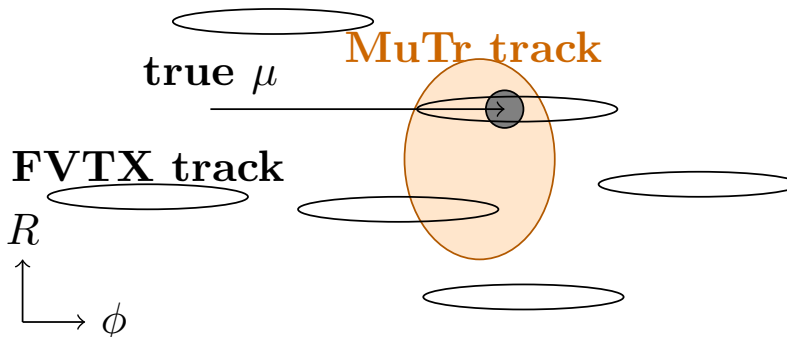


FIG. 4. MuTr (filled ellipse) and FVTX track (open ellipses) projection uncertainty areas at one of the FVTX planes along with the true particle (filled circle).

We determined that 65% of MuTr tracks in Cu+Au collisions find more than one potential FVTX track association passing the χ^2 quality and the matching criteria described above (Fig. 4), whereas the probability of having more than one association is about 15% in $p+p$ collisions. Because of this small fraction, the $p+p$ analysis uses only the best matching. The multiple associations are pronounced in central Cu+Au events because of the large FVTX track density, and for MuTr tracks with small momentum where projection uncertainties are larger because of the estimated multiple scattering in the absorber. In $B \rightarrow J/\psi \rightarrow \mu\mu$ events the best χ^2 association has a chance to happen between a MuTr track from the candidate muon and an FVTX track from an underlying event particle. In this situation the measured vertex displacement will correspond to a background particle and not the B -meson decay. In the Cu+Au analysis all FVTX-MuTr associations passing matching criteria (not just the best) are used in the DCA_R distributions in order to extract the correct FVTX and MuTr track associations. The contribution of mismatches to the track associations is then determined from event mixing, where MuTr tracks from one collision event are mixed with FVTX tracks from another event. Collisions are categorized in 10 FVTX track multiplicity and 200 z -vertex classes. The number of classes was chosen as the minimum number for which there was no observed change in the DCA_R distributions of simulations embedded in real data. MuTr tracks are mixed only with FVTX tracks belonging to the same collision event category. DCA distributions from mismatches are normalized by the relative FVTX track densities between same event and mixed event associations

$$\text{Norm}_{\text{mis}} = \frac{\text{N FVTX tracks in same event}}{\text{N FVTX tracks in mixed events}}. \quad (5)$$

The number of mixed event FVTX-MuTr associations is arbitrarily chosen to be five times larger than in same events in order to reduce background statistical fluctuations. The normalization 5 was tested with entire PYTHIA8+GEANT4 events containing prompt J/ψ and $B \rightarrow J/\psi$ embedded in real data, where the DCA_R distributions, after subtracting the normalized, event-mixed mismatch tracks, show excellent agreement with DCA_R distributions not embedded in real data.

C. Primary vertex determination.

The $p+p$ (Cu+Au) collision events are distributed in a volume, $\sigma_x \times \sigma_y \times \sigma_z$, of approximately $130 \mu\text{m} \times 130 \mu\text{m} \times 40 \text{cm}$ ($90 \mu\text{m} \times 90 \mu\text{m} \times 40 \text{cm}$) centered within the PHENIX detector. Collisions within $z = \pm 10 \text{cm}$ produce charged particle tracks in the nominal VTX and FVTX acceptance where the tracking can be utilized to precisely determine the collision point. The primary vertex location is found by the minimization of the squared impact parameter for

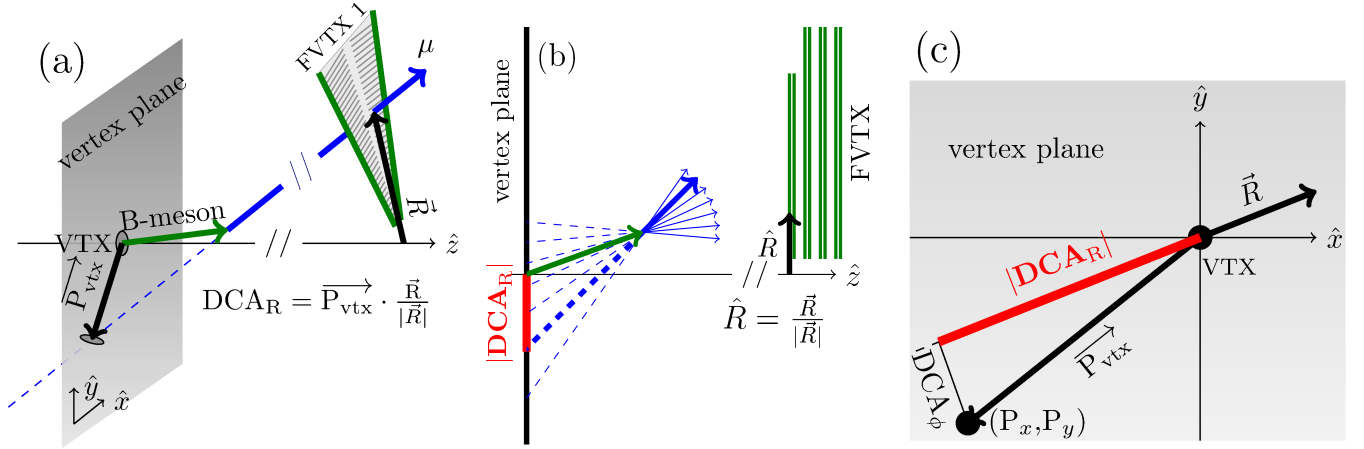


FIG. 5. Visual definition of the displaced vertex DCA_R used in this analysis: (a) 3D, (b) $r-z$ and (c) $x-y$ views. The collision point VTX is at the origin in this view for simplicity.

361 the collection of reconstructed charged particle tracks found in the VTX and the FVTX. In Cu+Au, bias created
 362 by tracks with off-vertex decay points is negligible due to the large number of particles created in the collisions of
 363 large nuclei and limits on the impact parameter cluster sizes used during the fitting procedure. In Cu+Au, the final
 364 primary vertex position is determined by a three dimensional minimization on an event-by-event basis. The majority
 365 of the position information in the minimization comes from tracklets within the VTX layers due to this detector's
 366 fine azimuthal segmentation of $50 \mu\text{m}$, short projection length of $\sim 2.6 \text{ cm}$, and typically large impact angles between
 367 reconstructed tracks. The event multiplicity is the key factor driving variance in the vertex resolution

$$\sigma_{\text{VTX}} = \sqrt{\sigma_{\text{VTX } x}^2 + \sigma_{\text{VTX } y}^2 + \sigma_{\text{VTX } z}^2}, \quad (6)$$

368 where the $\sigma_{\text{VTX } x}$, $\sigma_{\text{VTX } y}$, and $\sigma_{\text{VTX } z}$ vertex uncertainties are obtained event-by-event from the vertex minimization
 369 procedure. The vertex uncertainty is determined from independent measurements in north, south, east and west
 370 parts of the VTX and FVTX detector. A check of these uncertainties is performed with detector simulation, using
 371 HIJING [25] and PYTHIA8 generated events. The σ_{VTX} vertex resolution varies between $30 \mu\text{m}$ (central collisions) and
 372 $200 \mu\text{m}$ (peripheral collisions) in Cu+Au collisions. Due to the low multiplicity in $p+p$ collisions, the average x and y
 373 beam position in the transverse plane at the interaction point over a short data taking period ($\sim 90 \text{ min}$) are used in
 374 place of an event-by-event determination. Therefore, the x and y beam position resolutions correspond to the spread
 375 of the beam position ($130 \mu\text{m}$). The z -position is still determined event-by-event with typical resolution of $200 \mu\text{m}$.
 376 A summary of all vertex requirements for an event to be selected is listed in Table III.

TABLE III. List of vertex position requirements for event selection.

requirement	cut
z vertex position range	$ z < 10 \text{ cm}$
vertex resolution in $p+p$	$\sigma_z < 500 \mu\text{m}$
vertex resolution in Cu+Au	$\sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2} < 200 \mu\text{m}$

377

D. Distance of closest approach measurement.

378 The combined FVTX+MuTr track is projected to a plane perpendicular to the z -axis and placed at the measured
 379 z -position of the collision point. The displaced vertex vector \vec{P}_{vtx} is defined by the track projection $(x_{\text{track}}, y_{\text{track}}, z_{\text{vtx}})$
 380 and the collision point $(x_{\text{vtx}}, y_{\text{vtx}}, z_{\text{vtx}})$ as illustrated in Fig. 5a and 5c.

381 This projection is not precise in the ϕ direction because of the coarse segmentation of the FVTX in this direction,
 382 so the radial projection is used in this analysis, where the FVTX has the best segmentation. In Fig. 5 the radial axis
 383 \vec{R} is defined by the track projection at the first FVTX station $(x_{\text{FVTX1}}, y_{\text{FVTX1}}, z_{\text{FVTX1}})$ and the z -axis $(0, 0, z_{\text{FVTX1}})$.

384 The precise displacement vertex, which we call the radial distance of closest approach at the vertex plane DCA_R is a
 385 projection of the vector \vec{P}_{vtx} on the radial direction \vec{R}

$$\text{DCA}_R = \vec{P}_{\text{vtx}} \cdot \frac{\vec{R}}{|\vec{R}|}. \quad (7)$$

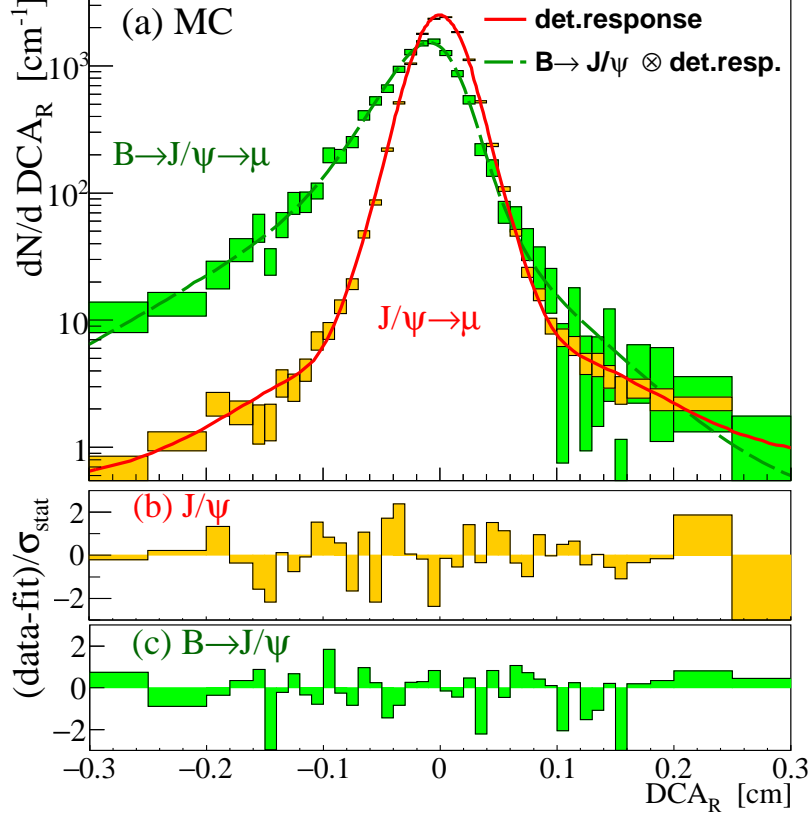


FIG. 6. (a) DCA_R distribution of PYTHIA8+GEANT4 simulated prompt J/ψ and $B \rightarrow J/\psi$ samples as described in Sec. IV (boxes) along with fitted functions (9) and Eq. (12), respectively. Boxes represent the bin widths and statistical uncertainties in simulation. (b,c) Pulls between data points from simulation and fitted functions.

386 Figure 5b shows a two-dimensional projection on the $r-z$ plane of the track. The extension of the DCA_R distribution
 387 depends on the decay length of the parent particle and the rapidity difference between the parent particle and the
 388 muon. Figure 6 shows the shape of DCA_R distributions of muons from simulated $B \rightarrow J/\psi$ and prompt J/ψ decays
 389 thrown in the detector response simulation. Negative DCA_R (where \vec{P}_{vtx} and \vec{R} have opposite directions) is larger for
 390 long range decays, producing an asymmetric DCA_R distributions for muons from heavy flavor decays which facilitates
 391 their separation from other contributions from prompt particles during the fitting procedure.

392 E. Backgrounds in the DCA_R distributions.

393 The DCA_R distributions comprise MuTr tracks, from dimuons in the J/ψ mass region, which are associated with one
 394 or more FVTX tracks. Each FVTX+MuTr association counts in the DCA_R distributions. There are two significant
 395 sources of uncorrelated background in the DCA_R distributions: 1) combinatorial background described in Section III A
 396 in the J/ψ mass region, corresponding to dimuons which are not from J/ψ decays; and 2) FVTX-MuTr mismatches
 397 described in Section III B corresponding to MuTr tracks from J/ψ decays but associated to the wrong FVTX track.
 398 Figure 7 shows the contribution of these backgrounds, extracted using the techniques described above, in the raw
 399 DCA_R distribution obtained in both arms. The combinatorial background distribution is obtained from mixed event
 400 dimuons, and the mismatch contribution is determined from event mixed MuTr-FVTX associations. Statistical

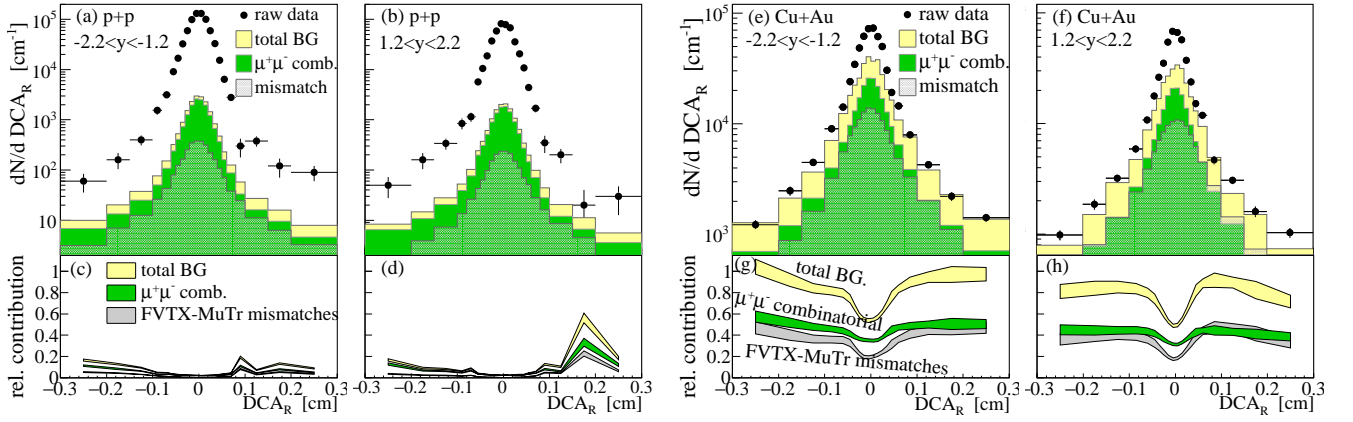


FIG. 7. (a,b,e,f) Uncorrelated background contributions to the DCA_R distributions from $p+p$ (a,b) and Cu+Au (e,f) data. (c,d,g,h) Background contribution relative to total yield. Bands in the relative contributions correspond to statistical uncertainties.

401 fluctuations are reduced by obtaining five times as many mixed event pairs and misassociations than in same event
 402 backgrounds. The normalization of these two distributions was explained in Sections III A and III B. According to the
 403 distributions shown in Fig. 7, most background contributions come from prompt particles, but the relative background
 404 contribution changes at large $|DCA_R|$ where fake or bad quality tracks and muons from light hadron decays are more
 405 significant.

406 The DCA_R line shape of correlated background contributions from $c\bar{c}$ and $b\bar{b}$ is obtained from simulation and
 407 discussed in Sec. IV B.

408 IV. SIMULATION.

409 In this Section we describe how the DCA_R line shape of each dimuon source in the J/ψ mass region is obtained
 410 from simulation.

411 A. Detector response of prompt particles.

412 The detector response to prompt decays, such as muons from prompt J/ψ , is estimated using prompt hadrons (pions,
 413 kaons and protons) generated by the PYTHIA8 event generator in MB mode and a GEANT4-based detector simulation
 414 package [26]. Several dead channel configurations are used to account for run-by-run detector acceptance fluctuations.
 415 This procedure was found to be crucial to simulate remaining edge effects (Sec. III B) and degradation of FVTX-VTX
 416 track quality which can potentially produce long tails in the measured DCA_R distributions. The simulated GEANT4
 417 signals from all generated hadrons in a single PYTHIA8 event are embedded in real data to account for occupancy and
 418 accidental hit-track-association effects in the DCA_R measurement. All particles generated by the detector simulation
 419 are shifted by $(\delta x, \delta y, \delta z)$, where each of the coordinates is a common Gaussian random number centered at the vertex
 420 position measured in the real data event and with a width determined from the vertex uncertainty of the real event
 421 the simulated particles are embedded in. Event reconstruction, including the simulated hits and the entire real data
 422 signal in the event, is then performed in the same manner as with real data.

423 Additional smearing and offsets are needed in the simulated DCA_R in order to account for irreducible detector
 424 misalignments, additional smearing of the primary vertex resolution that is not accounted for in the simulations, and
 425 any missing materials in the simulation that could be a multiple scattering source between the interaction region
 426 and the last FVTX plane. The measured DCA_R resolution depends on 1) the vertex uncertainty σ_{VTX} defined in
 427 Eq. (6); 2) a momentum independent parameter σ_a which represents the sum of the detector resolution contribution
 428 to the DCA_R resolution, additional vertex uncertainty which might not be captured by σ_{VTX} , residual detector
 429 misalignments and possible beam line tilt variations during the run; and 3) a multiple scattering term σ_b in the VTX
 430 and FVTX material which introduces the momentum dependence in the resolution:

$$\sigma_{DCA_R}(p, \sigma_{vtx}) = \sqrt{\sigma_{vtx}^2 + \sigma_a^2 + (\sigma_b/p)^2}. \quad (8)$$

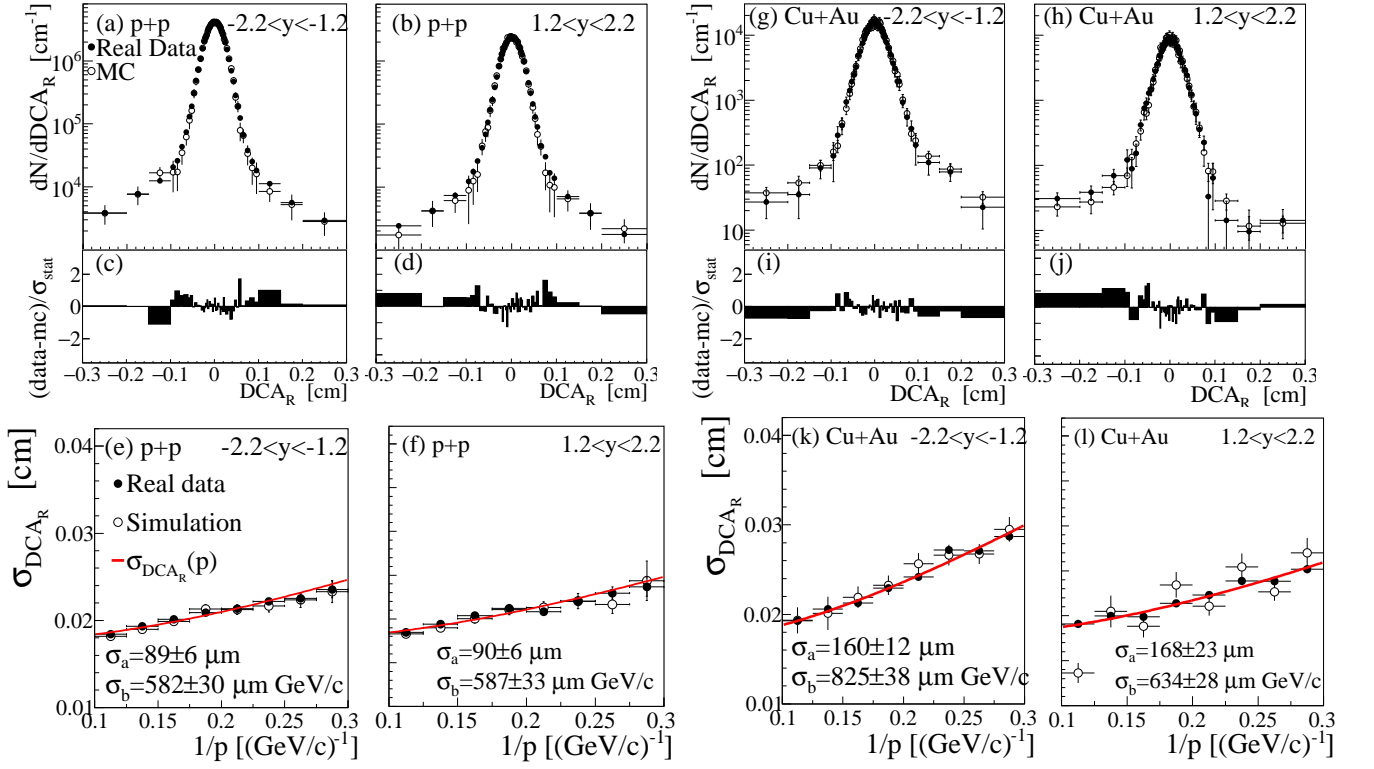


FIG. 8. DCA_R distribution of light hadrons in (a,b) $p+p$ and (g,h) Cu+Au real data after (closed circles) FVTX-MuTr mismatch subtraction. (open circles) momentum weighted simulation. (c,d,i,j) Pulls between real data and simulation. (e,f,k,l) Momentum dependence of $DCA_R \in [-0.04, 0.04]$ cm width in real and simulated hadron data along with fitted function (8).

431 Particles which stop at the third absorber plane in the MuID comprise mainly prompt light hadrons and $\sim 7\%$
 432 contribution from hadron $\rightarrow \mu$ decays according to PYTHIA8+GEANT4 simulation. This sample provides a relatively
 433 clean selection of prompt particles which can be used to compare DCA_R spectra between simulation and real data.
 434 The DCA_R distributions from the measured prompt hadrons are compared to simulated hadrons, and small smearing
 435 corrections are added to the simulated spectra until they match the real data spectra.

436 For real data and simulations, the σ_{VTX} value is set according to the event-by-event vertex resolution that is
 437 provided by the vertex finding code. The fit parameters σ_a and σ_b are extracted from the real data distributions, and
 438 the simulated data has additional smearing added until the distributions produce the same σ_a and σ_b fit results. An
 439 additional smearing of $70(110)$ μm was found to be necessary in the $p+p$ (Cu+Au) setup. After tuning the simulation,
 440 the DCA_R distribution of simulated hadrons stopping in the MuID is weighted according to the momentum distribution
 441 of real data stopped hadrons.

442 Figure 8 shows the DCA_R distribution of these prompt hadrons in real data compared to PYTHIA8 generated hadron
 443 events which have had tuned smearing parameters added. Figure 8 also shows the final fit parameters σ_a and σ_b for
 444 each of the north (positive rapidity) and south (negative rapidity) arms. Although the material present in the north
 445 and south arms is nominally identical, the momentum-dependent resolution parameter σ_b is found to be different for
 446 the two arms in the Cu+Au data set. The reason for this is that the vertex distribution for BBC-triggered events in
 447 Cu+Au events was found to be highly skewed toward the north arm, given the collision species asymmetry. Because of
 448 this, FVTX tracks had on average a shorter projection to the vertex for tracks in the north arm than in the south arm,
 449 resulting in a smaller contribution to the DCA_R resolution from multiple scattering in the north than in the south.
 450 Long tails in the DCA_R distribution contain part of the light hadron decay contribution but are mostly dominated
 451 by accidental hit-track associations which are reasonably well reproduced by the embedded simulation in the DCA_R
 452 range used in this analysis.

453

B. Prompt J/ψ and heavy flavor decay simulations.

454 Prompt J/ψ and $B \rightarrow J/\psi$ decays are generated using the PYTHIA8 event generator; open heavy flavor from $c\bar{c}$
 455 and $b\bar{b}$ processes are produced with leading order processes (gluon fusion) and the CT10 parton density distribution
 456 functions [27]. All particles generated in the $B \rightarrow J/\psi$ or prompt J/ψ event are used as input to the GEANT4 detector
 457 simulation and are embedded in real data. Generated events have the DCA_R values smeared and offset according to
 458 the parameters obtained for light hadrons as described in Section IV A. Simulated events are also weighted according
 459 to the momentum distribution of background-subtracted (combinatorial dimuon and FVTX-MuTr mismatch) muons
 460 from real data dimuons. Figure 6 shows the DCA_R distributions obtained from these prompt J/ψ and $B \rightarrow J/\psi$
 461 simulations. Several hypotheses of $B \rightarrow J/\psi$ nuclear modifications are considered in the momentum weighting for
 462 systematic uncertainty evaluations and described in Section VIA 2. Point-to-point statistical fluctuations in the
 463 generated DCA_R distributions are minimized by using fitted analytical functions for the final DCA_R fits. The DCA_R
 464 distributions obtained from prompt J/ψ simulation are well described by a three-Gaussian (G_1 , G_2 and G_3) function
 465 with a detector offset and resolutions σ_1 , σ_2 and σ_3 , and regulated by $f_1 + f_2 + f_3 = 1$:

$$\begin{aligned} \frac{\text{det.resp}(\text{DCA}_R)}{N} &= f_1 G_1(\text{DCA}_R; \text{offset}, \sigma_1) \\ &+ f_2 G_2(\text{DCA}_R; (dca0_2 - \text{offset}), \sigma_2) \\ &+ f_3 G_3(\text{DCA}_R; (dca0_3 - \text{offset}), \sigma_3). \end{aligned} \quad (9)$$

466 The following function defines the prompt J/ψ DCA_R line shape of prompt J/ψ decays

$$\text{decay}_{J/\psi}(\text{DCA}_R) = \delta(0) \otimes \text{det.resp}(\text{DCA}_R). \quad (10)$$

467 The true DCA_R distribution for heavy flavor decays is described by a set of three exponential functions:

$$\text{decay}^{\text{true}}(\text{DCA}_R) = \begin{cases} fd_1 e^{-\frac{\text{DCA}_R}{\lambda_{1l}}} + fd_2 e^{-\frac{\text{DCA}_R}{\lambda_{12}}} & \text{DCA}_R < 0 \\ (1 - fd_1 - fd_2) e^{-\frac{\text{DCA}_R}{\lambda_r}} & \text{DCA}_R > 0 \end{cases} \quad (11)$$

468 which must be convoluted with the detector response function (9) extracted from the prompt J/ψ fit in order to
 469 obtain the measured DCA_R distribution:

$$\text{decay}(\text{DCA}_R) = \text{decay}^{\text{true}}(\text{DCA}_R) \otimes \text{det.resp}(\text{DCA}_R). \quad (12)$$

470 The dashed line in Fig. 6 shows function (12) fitted to the simulated $B \rightarrow J/\psi$ decays. Function (12) is also used to fit
 471 the simulated correlated background components $c\bar{c}$ and $b\bar{b}$ as seen in Fig. 9. The heavy flavor decay functions used
 472 in the final fit are:

$$\begin{aligned} \text{decay}_D(\text{DCA}_R) &= \text{decay}(\text{DCA}_R; \vec{\text{par}}_{D \rightarrow \mu}) \\ \text{decay}_B(\text{DCA}_R) &= \text{decay}(\text{DCA}_R; \vec{\text{par}}_{B \rightarrow \mu}) \\ \text{decay}_{B \rightarrow J/\psi}(\text{DCA}_R) &= \text{decay}(\text{DCA}_R; \vec{\text{par}}_{B \rightarrow J/\psi \rightarrow \mu}) \end{aligned} \quad (13)$$

473 where $\vec{\text{par}}_{D \rightarrow \mu}$, $\vec{\text{par}}_{B \rightarrow \mu}$ and $\vec{\text{par}}_{B \rightarrow J/\psi \rightarrow \mu}$ are the parameters in Eq. (11) fitted to the corresponding heavy flavor
 474 decay simulations.

475

V. FITTING PROCEDURE.

476 The final fitting function used for the real data muon DCA_R distribution is

$$\begin{aligned} f_\mu(\text{DCA}_R) &= \text{BG}_{\text{uncor}}(\text{DCA}_R) + \text{BG}_{\text{corr}}(\text{DCA}_R) \\ &+ N_{J/\psi} \left[\left(1 - F_{B \rightarrow J/\psi}^{\text{meas}} \right) \text{decay}_{J/\psi}(\text{DCA}_R) \right. \\ &\left. + F_{B \rightarrow J/\psi}^{\text{meas}} \cdot \text{decay}_{B \rightarrow J/\psi}(\text{DCA}_R) \right] \end{aligned} \quad (14)$$

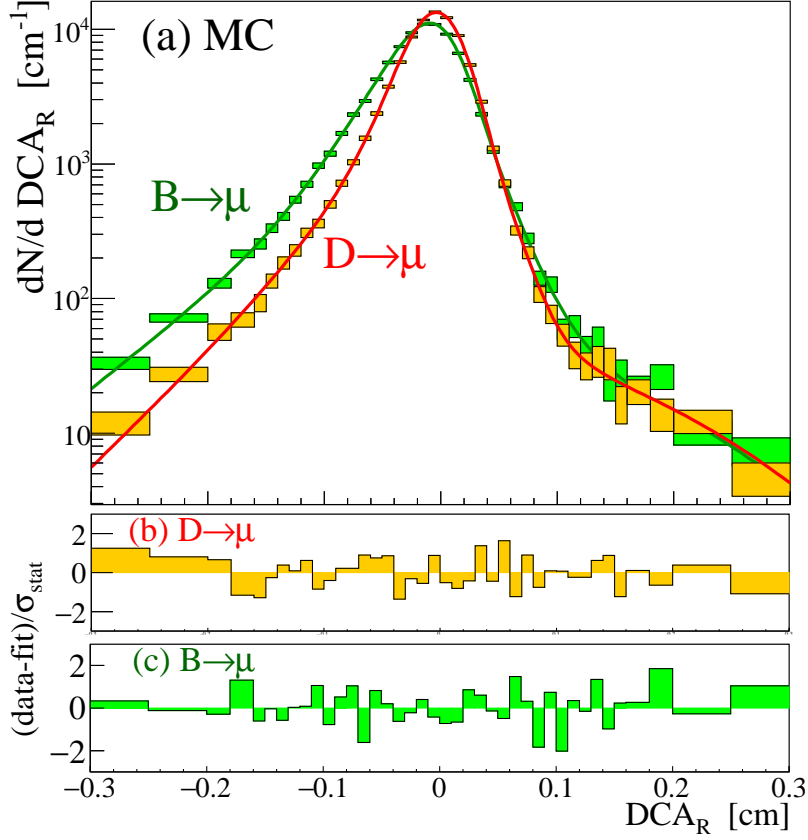


FIG. 9. (a) Simulated correlated background components, in the dimuon mass $\in [2.9, 3.5]$ GeV/ c^2 , after momentum weighting and vertex uncertainty along with fitted function (12). Boxes represent the bin widths and statistical uncertainties in simulation. (b,c) Pulls between simulated data points and fitted functions.

477 where $\text{BG}_{\text{uncorr}}$ includes the normalized dimuon combinatorial (Sec. III A) and FVTX-MuTr mismatch (Sec. III B)
 478 backgrounds. The correlated background BG_{corr} comprises $c\bar{c}$ and $b\bar{b}$ contributions:

$$\text{BG}_{\text{corr}}(\text{DCA}_R) = N_{\text{corr}} f_{\text{cont}} [(1 - f_{b\bar{b}}) \text{decay}_D(\text{DCA}_R) + f_{b\bar{b}} \text{decay}_B(\text{DCA}_R)].$$

479 where N_{corr} is the number of muons after subtracting $\text{BG}_{\text{uncorr}}$. The continuum correlated background f_{cont} is defined
 480 in Table II. The muon count from inclusive J/ψ decays is $N_{J/\psi} = (1 - f_{\text{cont}})N_{\text{corr}}$. The fraction of $b\bar{b}$ contribution in
 481 the correlated background $f_{b\bar{b}}$ was determined from extrapolations of previous $c\bar{c}$ and $b\bar{b}$ cross section measurements
 482 [28, 29] indicating a fraction $f_{b\bar{b}} = 0.32 \pm 0.21$ in $p+p$ collisions at $\sqrt{s} = 200$ GeV. The $b\bar{b}$ contribution in the correlated
 483 background is completely undetermined in Cu+Au collisions. So we set $f_{b\bar{b}} = 0.5$ in the standard fit and vary it in the
 484 range $f_{b\bar{b}} \in [0, 1]$ for the systematic uncertainty evaluation.

485 The measured fraction of B -meson decays $F_{B \rightarrow J/\psi}^{\text{meas}}$ is the only free parameter when fitting function (14) to the real
 486 data muon DCA_R distribution. The true $F_{B \rightarrow J/\psi}$ is obtained by correcting the measured $F_{B \rightarrow J/\psi}^{\text{meas}}$ with a factor given
 487 by the relative detector acceptance and efficiency of J/ψ from B -meson decays with respect to prompt J/ψ decays

$$\frac{1}{F_{B \rightarrow J/\psi}} = 1 + \left(\frac{1}{F_{B \rightarrow J/\psi}^{\text{meas}}} - 1 \right) \frac{\varepsilon_B}{\varepsilon_{J/\psi}}, \quad (15)$$

488 where $\varepsilon_B/\varepsilon_{J/\psi} \in [0.96, 0.98]$ depending on the data set ($p+p$ or Cu+Au) and muon arm.

489 The fit is performed with an unbinned extended log-likelihood method, where

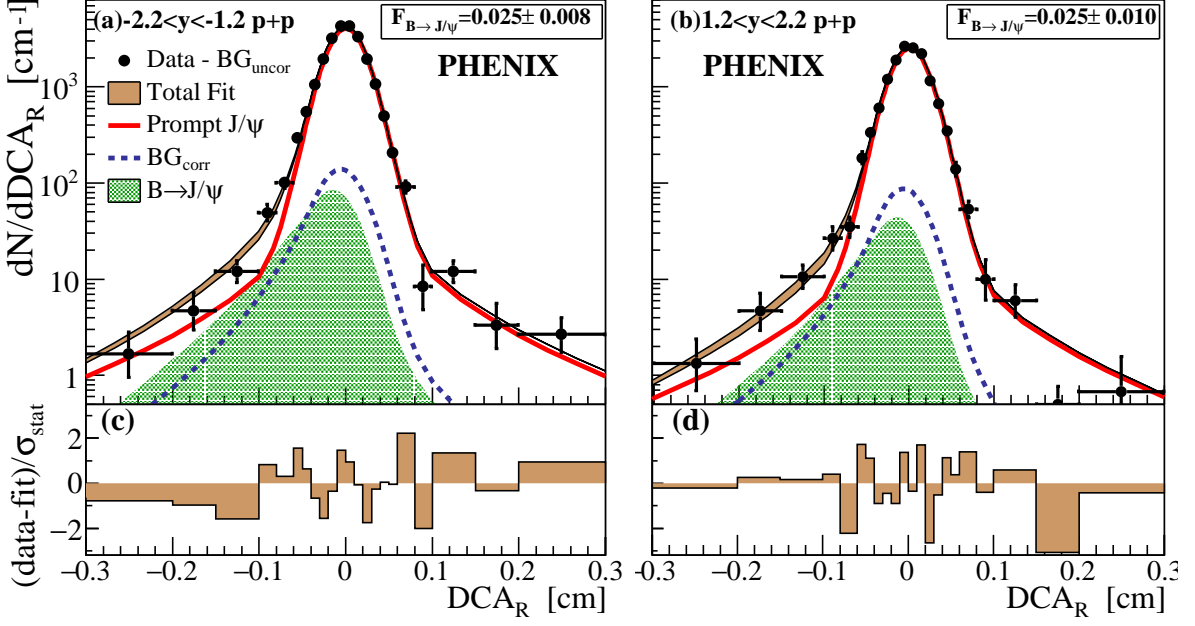


FIG. 10. (a,b) Function (14) fitted to the $p+p$ data in different rapidity ranges. The combinatorial and FVTX-MuTr mismatch backgrounds are subtracted from both data and the fitting function for clarity. The band around the total fit curve corresponds to the propagated fitting uncertainty. The resulting $F_{B \rightarrow J/\psi}$ is corrected by the relative acceptance and efficiency, and the evaluated uncertainty is only from the fit. (c,d) Pulls between data points and fitted functions.

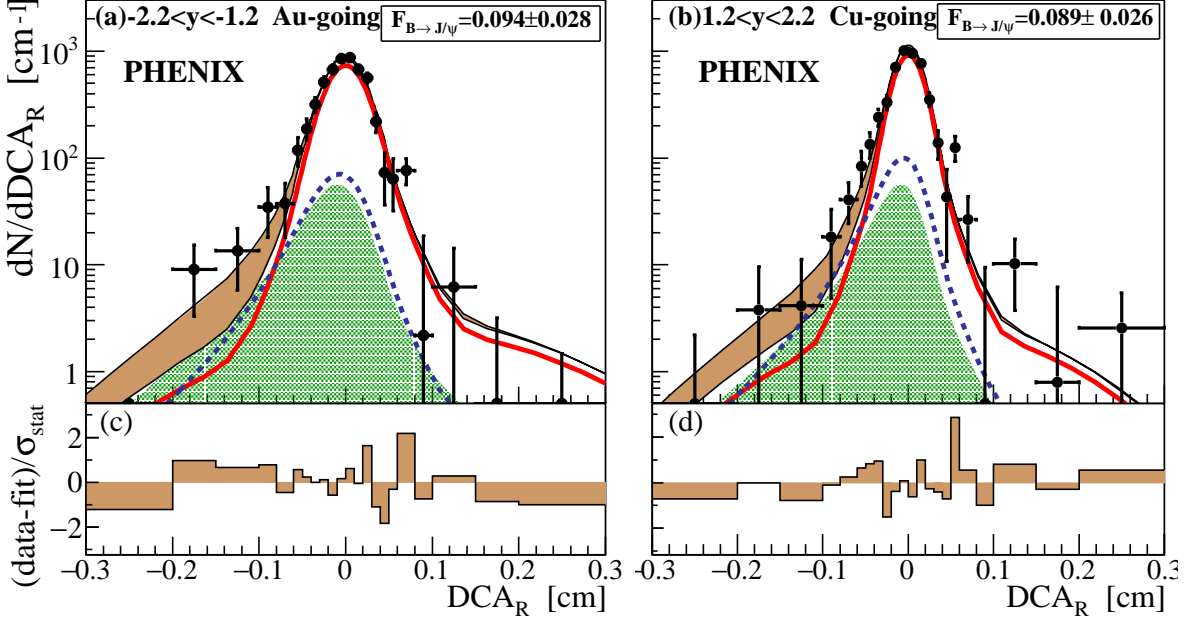


FIG. 11. (a,b) Function (14) fitted to the Cu+Au data in different rapidity ranges. The combinatorial and FVTX-MuTr mismatch backgrounds are subtracted from both data and the fitting function for clarity. The band around the total fit curve corresponds to the propagated fitting uncertainty. The resulting $F_{B \rightarrow J/\psi}$ is corrected by the relative acceptance and efficiency and the evaluated uncertainty is only from the fit. (c,d) Pulls between data points and fitted functions.

$$-\ln \mathcal{L} = \sum_{i=1}^{i=N_\mu} -\ln f_\mu (\text{DCA}_R; F_{B \rightarrow J/\psi}) - N_\mu \quad (16)$$

490 is minimized. N_μ is the number of muons in the DCA_R distribution, including the backgrounds. Figures 10 and 11

495 show the fitted function (14) to the DCA_R distributions in $p+p$ and Cu+Au collisions, respectively. The backgrounds
 496 due to combinatorial dimuons and FVTX-MuTr mismatches are subtracted for clarity in the figures. The bars in the
 497 figure show the total uncertainties of each data point.

494

VI. SYSTEMATIC UNCERTAINTIES.

495 The systematic uncertainties are determined by fitting $f_\mu(DCA_R)$ in function (14) several times, using random
 496 variations of the fitting parameters for each fit. This section lists all considered systematic uncertainty sources and
 497 how they affect the final results.

498

A. List of systematic uncertainty sources.

499

1. Testing of the fitting procedure.

500 The validity of the fitting procedure was tested by randomly generating DCA_R distributions for backgrounds,
 501 $B \rightarrow J/\psi$, and prompt J/ψ , with $F_{B \rightarrow J/\psi}$ tested in the range $[0, 0.4]$. The total number of entries in the summed
 502 DCA_R distributions were generated to match the real data distributions. The fit results over thousands of randomly
 503 generated DCA_R distributions in each $F_{B \rightarrow J/\psi}^{\text{generated}}$ return $F_{B \rightarrow J/\psi}^{\text{measured}}$ with average bias $\left| F_{B \rightarrow J/\psi}^{\text{generated}} - F_{B \rightarrow J/\psi}^{\text{measured}} \right| < 0.005$
 504 in Cu+Au data and negligible in $p+p$ data.

505

2. Weighting of simulated samples.

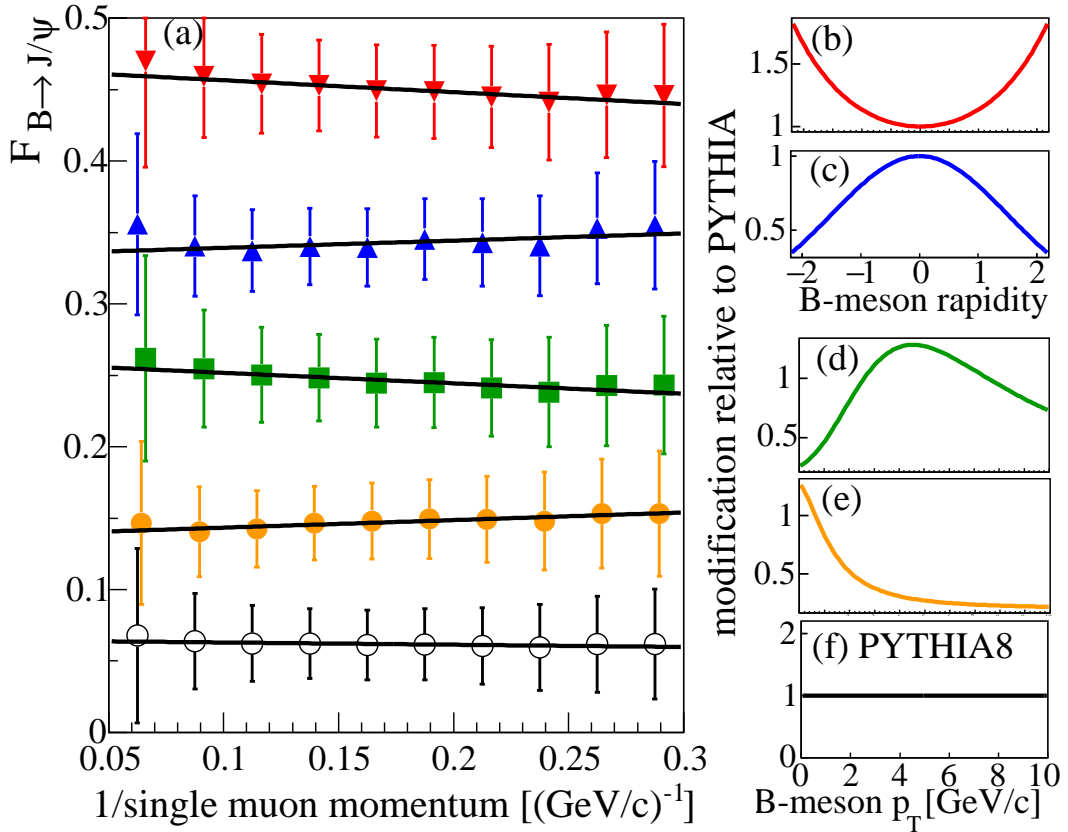


FIG. 12. (a) Momentum distribution of $F_{B \rightarrow J/\psi}$ from PYTHIA8 (open circles) and a set of p_T and rapidity B -meson yield modifications relative to prompt J/ψ (closed symbols) defined in panels (b,c,d,e,f). Scales on $F_{B \rightarrow J/\psi}$ are arbitrary.

506 All detector reconstructed simulated samples were weighted according to the single muon momentum distributions
 507 of real data muons from J/ψ decays used in the DCA_R distributions. This weighting already accounts for the
 508 realistic momentum distribution of measured dimuons in the J/ψ mass region. Figure 12 shows how the momentum
 509 distribution of muons from $B \rightarrow J/\psi$ decays are distributed relative to muons from prompt J/ψ decays in several
 510 conservative B -meson p_T and rapidity yield modification hypotheses. The inverse momentum dependence obtained
 511 from the several hypotheses can be described by polynomials of degree one $f_{B \rightarrow J/\psi}(p)$. The maximum deviation from
 512 the assumption used in the standard result is $|f_{B \rightarrow J/\psi}(p) - F_{B \rightarrow J/\psi}| < 0.005$. This value is used in the systematic
 513 uncertainty determination.

514 3. DCA_R resolutions and offsets in simulation.

515 A relative variation of 15% in the detector offset, 5% for σ_a and 7% for σ_b are found when different fitting ranges are
 516 used to determine the offset and the momentum dependence of the DCA_R detector resolution shown in Figs. 8c,d,g,h.
 517 Varying these parameters within their uncertainties produces fluctuations on the $F_{B \rightarrow J/\psi}$ result of up to 0.015.

518 4. DCA_R tail contribution to the detector response function.

519 The detector response function (9) is fitted to simulated and real data hadrons shown in Fig. 8. The third Gaussian,
 520 which accounts for the long range tails in the DCA_R distributions, has a contribution which is 20% different between
 521 real and simulated data. This difference can be caused by 1) modified light hadron decay in real data, 2) bias in the
 522 FVTX-MuTr mismatch distribution normalization (5); or 3) missing accidental hit-track associations in simulation.
 523 The third Gaussian contribution in Eq. (9), f_3 , is varied by 20% to account for these uncertainties. This variation
 524 produces a change in the $F_{B \rightarrow J/\psi}$ of up to 0.004.

525 5. Relative detector acceptance and efficiency.

526 Variations in the PYTHIA8 parameters, such as renormalization factor and additional weighting in order to match
 527 measured J/ψ rapidity and p_T distributions in [30], used to determine the relative detector acceptance and efficiency
 528 $\varepsilon_B/\varepsilon_{J/\psi}$ introduce 1% relative fluctuation in the $F_{B \rightarrow J/\psi}$ result in the $p+p$. When considering different scenarios for
 529 the B -meson nuclear modification in Cu+Au; including variations with centrality, p_T and rapidity; the fluctuation in
 530 $F_{B \rightarrow J/\psi}$ relative to the default result is 5%.

531 6. Dimuon combinatorial background and FVTX-MuTr mismatch distribution normalizations.

532 The dimuon combinatorial background normalization (1) varies by up to 3% when changing the mass range
 533 used to determine it. Another concern is how particle activity surrounding a B meson can affect the normaliza-
 534 tion (5) of FVTX-MuTr mismatch distributions. The normalization shows a 5% variation when embedding entire
 535 PYTHIA8+GEANT4 events containing prompt J/ψ and $B \rightarrow J/\psi$. When applying these variations in the DCA_R fitting
 536 (14), the $F_{B \rightarrow J/\psi}$ result has a standard deviation of 0.01.

537 7. Correlated background.

538 The dimuon mass fitting uncertainty for the correlated background contributions shown in Table II is introduced as
 539 Gaussian random numbers before each fit. The fraction of $b\bar{b}$ in the correlated background is varied by $f_{b\bar{b}} = 0.32 \pm 0.21$
 540 in $p+p$ collisions based on the uncertainties in the total $c\bar{c}$ and $b\bar{b}$ cross section [28, 29]. For Cu+Au collisions, $f_{b\bar{b}} \in [0,1]$
 541 is considered, which accounts for unknown $c\bar{c}$ and $b\bar{b}$ nuclear modifications. When applying these variations in the
 542 fitting procedure defined in Eq. (14) the $F_{B \rightarrow J/\psi}$ standard deviation is 0.01 in $p+p$ and 0.025 in Cu+Au.

543 B. Total systematic uncertainties.

544 Table IV summarizes all systematic uncertainty contributions. The total systematic uncertainty also listed in the
 545 table is obtained by varying the parameters as described in the fitting function (14) simultaneously, assuming all

TABLE IV. Summary of all absolute systematic uncertainties on the $F_{B \rightarrow J/\psi}$ measurement.

source	$p+p$		Cu+Au	
	south	north	south	north
fitting procedure		<0.001	0.005	0.005
simulation weighting	0.003	0.002	0.005	0.005
DCA _R resolution	0.004	0.004	0.012	0.015
detector offset		<0.002	0.011	0.013
DCA _R tail contribution		<0.001	0.002	0.004
relative acc. \times eff.		<0.001	0.005	0.005
background normalizations		<0.001	0.010	0.009
correlated bg	0.002	0.003	0.018	0.018
fraction of corr. $b\bar{b}$	0.008	0.008	0.017	0.018
TOTAL	0.009	0.010	0.033	0.034

546 variations are independent, and running several independent fits.

547

C. Other checks.

548 Other tests such as variations in the DCA_R fitting range, and the use of simulated histograms rather than functions
 549 as fitting input, provided results that are statistically consistent with the default result. No additional systematic
 550 uncertainties are assigned from these checks.

551

VII. RESULTS.

552

A. Fraction of B mesons in the J/ψ sample.

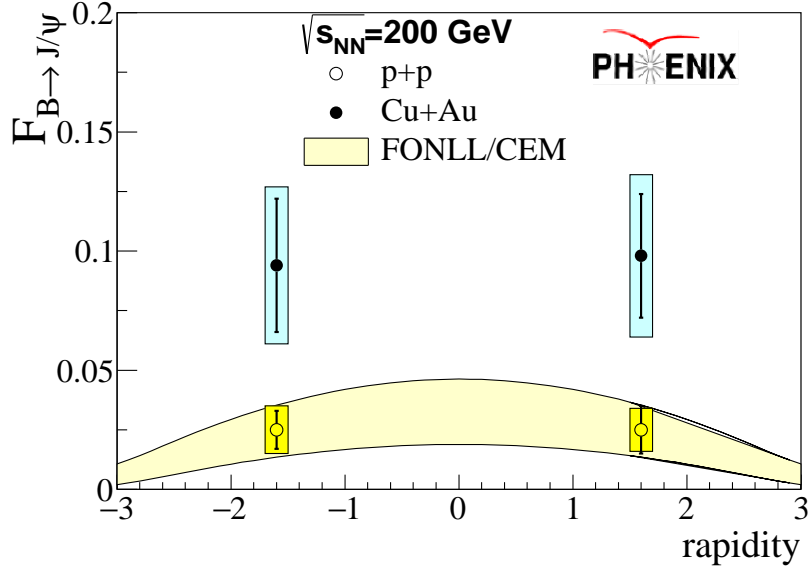


FIG. 13. Fraction $F_{B \rightarrow J/\psi}$ of B -meson decays in the inclusive J/ψ sample in $p+p$ and Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV versus rapidity along with a theoretical estimation based on fixed-order plus next-to-leading logs (FONLL) [31, 32] for the $B \rightarrow J/\psi$ cross section and Color-Evaporation-Model (CEM) [33] for the prompt J/ψ . The statistical errors are represented by the error bars and the systematic uncertainties are represented by filled boxes.

TABLE V. Fraction of B -meson decays in J/ψ samples obtained in $p+p$ and Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

data sample	$F_{B \rightarrow J/\psi}$
$-2.2 < y < -1.2$ $p+p$	$0.025 \pm 0.008(\text{stat}) \pm 0.010(\text{syst})$
$1.2 < y < 2.2$ $p+p$	$0.025 \pm 0.010(\text{stat}) \pm 0.009(\text{syst})$
$1.2 < y < 2.2$ $p+p$	$0.025 \pm 0.006(\text{stat}) \pm 0.009(\text{syst})$
$-2.2 < y < -1.2$ (Au-going)	$0.094 \pm 0.028(\text{stat}) \pm 0.033(\text{syst})$
$1.2 < y < 2.2$ (Cu+going)	$0.089 \pm 0.026(\text{stat}) \pm 0.034(\text{syst})$

553 The acceptance and efficiency corrected B -meson contributions to the J/ψ yields collected in $p+p$ and Cu+Au data
554 are listed in Table V and plotted in Fig. 13. The detector acceptance and efficiency of B -meson decays producing
555 a J/ψ in the muon arm apertures is shown in Fig. 14 as a function of rapidity and transverse momentum. The
556 estimation is obtained from the simulation setup described in Section IV embedded in Cu+Au raw data. As can be
557 seen in the right panel, the measurement presented in this analysis is the first which covers B mesons starting from
558 zero p_T in heavy ion collisions.

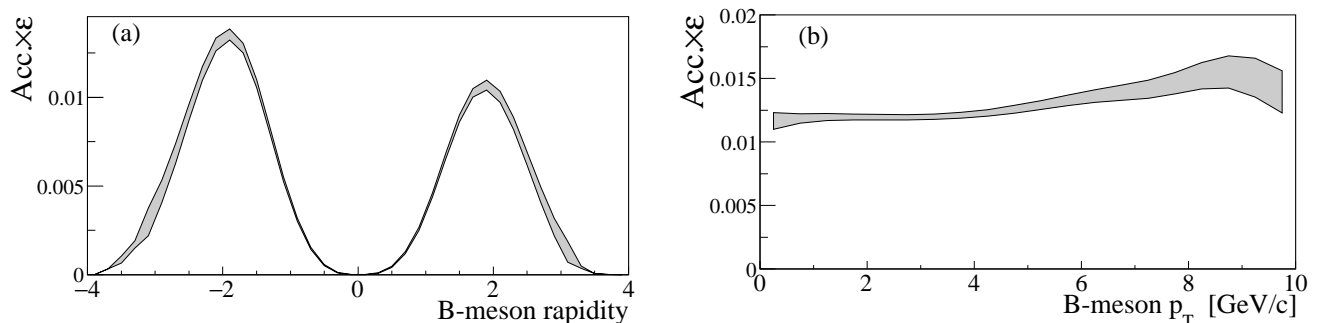


FIG. 14. Detector acceptance \times efficiency of B -meson decays producing a J/ψ in the muon arms ($1.2 < |y| < 2.2$) versus B -meson (a) rapidity and (b) p_T . The statistical uncertainties in simulation are shown in filled gray bands.

559 The $F_{B \rightarrow J/\psi}$ obtained in $p+p$ collisions is well described by a theoretical calculation based on FONLL [31, 32] for
560 the $B \rightarrow J/\psi$ and color-evaporation-Model (CEM) [33] for the prompt J/ψ differential cross sections. Uncertainties in
561 the theoretical calculation come from the bottom quark mass ($4.5 - 5.0 \text{ GeV}/c^2$) and scale uncertainties. The CTEQ6
562 parton-density function [34] was adopted in both FONLL and CEM calculations.

563

B. Differential cross section of $b\bar{b}$ in $p+p$ collisions.

The corresponding $p+p \rightarrow b\bar{b}$ differential cross section can be calculated by

$$\frac{d\sigma_{b\bar{b}}}{dy} = \frac{\frac{1}{2}d\sigma_{J/\psi}/dy \times F_{B \rightarrow J/\psi}}{\text{Br}(B \rightarrow J/\psi + X)}, \quad (17)$$

564 where $d\sigma_{J/\psi}/dy$ is obtained from J/ψ measurement by PHENIX [30]. The branching ratios $\text{Br}(B \rightarrow J/\psi + X)$ and
565 $\text{Br}(J/\psi \rightarrow \mu^+\mu^-)$ are reported in the particle data group [3]. The factor $\frac{1}{2}$ accounts for the fact that both b quarks in
566 the $b\bar{b}$ pair contribute to the $F_{B \rightarrow J/\psi}$. The results are shown in Table VI, where the average rapidity $\langle y \rangle$ are obtained
567 from the detector acceptance of $B \rightarrow J/\psi$ events generated by PYTHIAS. Table VI also presents the corresponding
568 FONLL calculation.

TABLE VI. Differential cross section for $p+p \rightarrow b\bar{b}$ at $\sqrt{s}=200$ GeV obtained from (17) along with the FONLL theoretical calculation [31, 32].

$\langle y \rangle$	$d\sigma_{b\bar{b}}/dy$ [μb]
-1.6	$0.51 \pm 0.16(\text{stat}) \pm 0.20(\text{sys})$
1.6	$0.52 \pm 0.21(\text{stat}) \pm 0.21(\text{sys})$
1.6	$0.51 \pm 0.13(\text{stat}) \pm 0.20(\text{sys})$
1.6 (FONLL)	$0.26^{+0.14}_{-0.10}(\text{theory uncert.})$

569

C. B -meson nuclear modification.

The nuclear modification factor is defined by

$$R_{\text{CuAu}} = \frac{(dN/dy)^{\text{CuAu}}}{\langle N_{\text{coll}} \rangle (dN/dy)^{pp}}, \quad (18)$$

where dN/dy is the yield in Cu+Au and $p+p$ collisions and $\langle N_{\text{coll}} \rangle$ is the average number of binary collisions in the Cu+Au data sample. The Glauber estimated average number of collisions in Cu+Au collisions is $\langle N_{\text{coll}} \rangle = 108 \pm 11$. The centrality and p_T integrated R_{CuAu} for inclusive J/ψ in Cu+Au collisions is obtained from the results presented in [17]: $0.365 \pm 0.019(\text{stat}) \pm 0.026(\text{syst})$ in the Au-going direction and $0.295 \pm 0.026(\text{stat}) \pm 0.021(\text{syst})$ in the Cu-going direction with a global uncertainty of 7.1%. The separated prompt J/ψ and B -meson R_{CuAu} can be extracted from inclusive J/ψ R_{CuAu} and $F_{B \rightarrow J/\psi}$ through

$$R_{\text{CuAu}}^{\text{prompt}} = \frac{1 - F_{B \rightarrow J/\psi}^{\text{CuAu}}}{1 - F_{B \rightarrow J/\psi}^{\text{pp}}} R_{\text{CuAu}}^{\text{incl.}}, \quad R_{\text{CuAu}}^B = \frac{F_{B \rightarrow J/\psi}^{\text{CuAu}}}{F_{B \rightarrow J/\psi}^{\text{pp}}} R_{\text{CuAu}}^{\text{incl.}}, \quad (19)$$

570 where $R_{\text{CuAu}}^{\text{prompt}}$, R_{CuAu}^B and $R_{\text{CuAu}}^{\text{incl.}}$ are the nuclear modification factors for prompt J/ψ , B mesons and inclusive J/ψ
571 respectively.

572 The average of the results for $F_{B \rightarrow J/\psi}$ shown in the first two rows of Table V is used as a $p+p$ reference $F_{B \rightarrow J/\psi}^{\text{pp}}$.
573 The uncertainties in the DCA_R resolution in simulation are correlated between the $p+p$ and Cu+Au analysis and
574 cancel out in the R_{CuAu} results. The global uncertainty includes statistical and systematic uncertainties of the $p+p$
575 reference. Table VII and Fig. 15 summarizes the B -meson and prompt- J/ψ nuclear modifications obtained using
576 Eq. (19).

TABLE VII. Nuclear modification factors of B mesons and prompt J/ψ obtained from Eq. (19).

	R_{CuAu}^B	
Au-going		$1.37 \pm 0.41(\text{stat}) \pm 0.33(\text{syst}) \pm 0.47(\text{pp})$
Cu+going		$1.05 \pm 0.31(\text{stat}) \pm 0.28(\text{syst}) \pm 0.47(\text{pp})$
	$R_{\text{CuAu}}^{\text{prompt}}$	
Au-going		$0.339 \pm 0.021(\text{stat}) \pm 0.026(\text{syst}) \pm 0.075(\text{pp})$
Cu+going		$0.276 \pm 0.026(\text{stat}) \pm 0.023(\text{syst}) \pm 0.075(\text{pp})$

577 Both nuclear modifications factors from forward and backward rapidities are consistent with binary scaling of $p+p$
578 yields given the large uncertainties. The results are also consistent with initial-state effects predicted by the EPS09
579 model [12], shown in Fig. 15, which suggests a modest enhancement. The EPS09 calculation uses as input x and Q
580 from $gg \rightarrow b\bar{b}$ events generated by PYTHIA8. The same model underpredicts the large yield enhancements observed
581 for leptons from inclusive heavy flavor, dominated by charm quarks, at midrapidity and negative rapidity in $d+Au$
582 collisions [14, 15] at the same energy. Heavy flavor yield enhancement at large- x , which dominates the negative
583 rapidity yield, is also expected from incoherent multiple scattering of initial gluons [9].

584 Binary scaling of momentum-integrated heavy flavor production was previously observed in electron yields from
585 charm quarks by PHENIX [35] and reconstructed D mesons by STAR [36] in Au+Au collisions at RHIC. The p_T
586 integrated B -meson nuclear modification result obtained in this work, when combined with these earlier results,

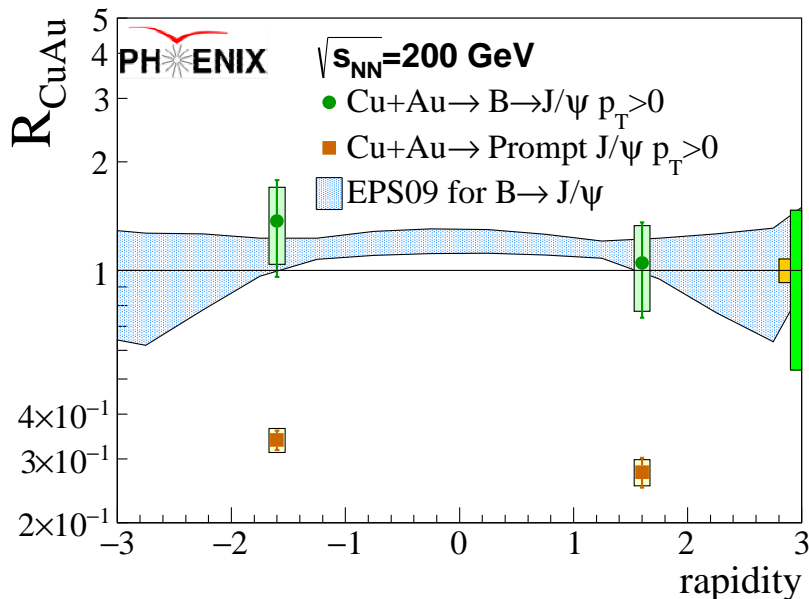


FIG. 15. Rapidity dependence of B -meson and prompt- J/ψ meson nuclear modification factors R_{CuAu} along with the initial state effect estimated from EPS09 [12]. The statistical uncertainties are shown as bars, and the systematic uncertainties are shown as filled boxes. The boxes at rapidity=3 are global uncertainties for the prompt J/ψ and $B \rightarrow J/\psi$.

587 indicate there is binary scaling of B - and D -mesons separately. Because charm and bottom number are conserved in
 588 heavy ion collisions at $\sqrt{s_{NN}} = 200$ GeV, the interaction with the QGP medium only alters the momentum distribution
 589 of D mesons and B mesons causing a relative yield suppression for $p_T \gg m_Q$.

VIII. SUMMARY AND CONCLUSIONS.

590
 591 We report the fraction of B -meson decays in the inclusive J/ψ yield in $p+p$ and Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.
 592 The measurement is centrality and p_T integrated with acceptance starting from zero p_T B mesons. The $b\bar{b}$ differential
 593 cross section obtained from the measured fractions at rapidity $1.2 < |y| < 2.2$ in $p+p$ collisions is consistent with
 594 FONLL theoretical calculation within uncertainties [31, 32]. A systematically larger fraction is observed in Cu+Au
 595 collisions than in $p+p$ collisions, which reflects a smaller nuclear modification of B mesons in Cu+Au collisions
 596 compared to prompt J/ψ . The nuclear modification factor calculated from the Cu+Au and $p+p$ fractions, along with
 597 the measured inclusive J/ψ R_{CuAu} , are listed in Table VII and shown in Fig. 15. The results are consistent with
 598 binary scaling of B -meson yields. No significant difference is observed between the Cu-going and Au-going direction
 599 within the result uncertainties. However, yield enhancement at negative rapidity is favored, which is in agreement
 600 with cold-nuclear-matter effects observed for inclusive heavy flavor in $d+Au$ collisions at the same energy [14, 15],
 601 an EPS09-based calculation, and incoherent multiple scattering of initial gluons. This result and others on charm
 602 yields indicate that heavy-quark number is conserved in heavy ion collisions at $\sqrt{s_{NN}} = 200$ GeV. Interaction with
 603 the QGP medium only alters momentum distributions of D and B mesons. The nuclear modification observed for
 604 B mesons contrasts with the strong suppression measured for prompt J/ψ mesons indicating that final-state effects,
 605 where the $c\bar{c}$ binding is broken by the medium formed, are dominant for prompt J/ψ mesons.

ACKNOWLEDGMENTS

606
 607 We thank the staff of the Collider-Accelerator and Physics Departments at Brookhaven National Laboratory and
 608 the staff of the other PHENIX participating institutions for their vital contributions. We acknowledge support from
 609 the Office of Nuclear Physics in the Office of Science of the Department of Energy, the National Science Foundation,
 610 Abilene Christian University Research Council, Research Foundation of SUNY, and Dean of the College of Arts and
 611 Sciences, Vanderbilt University (U.S.A), Ministry of Education, Culture, Sports, Science, and Technology and the
 612 Japan Society for the Promotion of Science (Japan), Conselho Nacional de Desenvolvimento Científico e Tecnológico

613 and Fundação de Amparo à Pesquisa do Estado de São Paulo (Brazil), Natural Science Foundation of China (People's
 614 Republic of China), Croatian Science Foundation and Ministry of Science and Education (Croatia), Ministry of Edu-
 615 cation, Youth and Sports (Czech Republic), Centre National de la Recherche Scientifique, Commissariat à l'Énergie
 616 Atomique, and Institut National de Physique Nucléaire et de Physique des Particules (France), Bundesministerium
 617 für Bildung und Forschung, Deutscher Akademischer Austausch Dienst, and Alexander von Humboldt Stiftung (Ger-
 618 many), National Science Fund, OTKA, EFOP, and the Ch. Simonyi Fund (Hungary), Department of Atomic Energy
 619 and Department of Science and Technology (India), Israel Science Foundation (Israel), Basic Science Research Pro-
 620 gram through NRF of the Ministry of Education (Korea), Physics Department, Lahore University of Management
 621 Sciences (Pakistan), Ministry of Education and Science, Russian Academy of Sciences, Federal Agency of Atomic
 622 Energy (Russia), VR and Wallenberg Foundation (Sweden), the U.S. Civilian Research and Development Foundation
 623 for the Independent States of the Former Soviet Union, the Hungarian American Enterprise Scholarship Fund, and
 624 the US-Israel Binational Science Foundation.

-
- 625 [1] J. D. Bjorken, "Energy Loss of Energetic Partons in Quark-Gluon Plasma: Possible Extinction of High $p(t)$ Jets in
 626 Hadron-Hadron Collisions," (1982), FERMILAB-PUB-82-059-THY, FERMILAB-PUB-82-059-T.
 627 [2] Yu. L. Dokshitzer and D. E. Kharzeev, "Heavy-quark colorimetry of QCD matter," *Phys. Lett. B* **519**, 199 (2001).
 628 [3] K. A. Olive *et al.* (Particle Data Group), "Review of Particle Physics," *Chin. Phys. C* **38**, 090001 (2014).
 629 [4] R. Aaij *et al.* (LHCb Collaboration), "Measurements of the B^+ , B^0 , B_s^0 meson and Λ_b^0 baryon lifetimes," *J. High Energy*
 630 *Phys.* **04** (2014) 114.
 631 [5] E. Norrbin and T. Sjöstrand, "Production and hadronization of heavy quarks," *Eur. Phys. J. C* **17**, 137 (2000).
 632 [6] I. Vitev, T. Goldman, M. B. Johnson, and J. W. Qiu, "Open charm tomography of cold nuclear matter," *Phys. Rev. D*
 633 **74**, 054010 (2006).
 634 [7] T. Sjöstrand, S. Mrenna, and P. Z. Skands, "A Brief Introduction to PYTHIA8.1," *Comput. Phys. Commun.* **178**, 852
 635 (2008).
 636 [8] Z.-B. Kang, I. Vitev, and H. Xing, "Multiple scattering effects on inclusive particle production in the large- x regime,"
 637 *Phys. Rev. D* **88**, 054010 (2013).
 638 [9] Z.-B. Kang, I. Vitev, E. Wang, H. Xing, and C. Zhang, "Multiple scattering effects on heavy meson production in $p + A$
 639 collisions at backward rapidity," *Phys. Lett. B* **740**, 23 (2015).
 640 [10] Z.-B. Kang, I. Vitev, and H. Xing, "Effects of cold nuclear matter energy loss on inclusive jet production in $p + A$ collisions
 641 at energies available at the BNL Relativistic Heavy Ion Collider and the CERN Large Hadron Collider," *Phys. Rev. C* **92**,
 642 054911 (2015).
 643 [11] L. D. McLerran and R. Venugopalan, "Gluon distribution functions for very large nuclei at small transverse momentum,"
 644 *Phys. Rev. D* **49**, 3352 (1994).
 645 [12] K. J. Eskola, H. Paukkunen, and C. A. Salgado, "EPS09: A New Generation of NLO and LO Nuclear Parton Distribution
 646 Functions," *J. High Energy Phys.* **04** (2009) 065.
 647 [13] I. Helenius, K. J. Eskola, H. Honkanen, and Carlos A. Salgado, "Impact-Parameter Dependent Nuclear Parton Distribution
 648 Functions: EPS09s and EKS98s and Their Applications in Nuclear Hard Processes," *J. High Energy Phys.* **07** (2012) 073.
 649 [14] A. Adare *et al.* (PHENIX Collaboration), "Cold-Nuclear-Matter Effects on Heavy-Quark Production at Forward and
 650 Backward Rapidity in $d+Au$ Collisions at $\sqrt{s_{NN}} = 200$ GeV," *Phys. Rev. Lett.* **112**, 252301 (2014).
 651 [15] A. Adare *et al.* (PHENIX Collaboration), "Cold nuclear matter effects on heavy-quark production in $d+Au$ collisions at
 652 $\sqrt{s_{NN}} = 200$ GeV," *Phys. Rev. Lett.* **109**, 242301 (2012).
 653 [16] J. Adams *et al.* (STAR Collaboration), "Open charm yields in $d+Au$ collisions at $\sqrt{s} = 200$ GeV," *Phys. Rev. Lett.* **94**,
 654 062301 (2005).
 655 [17] C. Aidala *et al.* (PHENIX Collaboration), "Nuclear matter effects on J/ψ production in asymmetric Cu+Au collisions at
 656 $\sqrt{s_{NN}}=200$ GeV," *Phys. Rev. C* **90**, 064908 (2014).
 657 [18] H. Xing, Y. Guo, E. Wang, and Wang. X. N., "Parton energy loss and modified beam quark distribution functions in
 658 Drell-Yan process in collisions," *Nucl. Phys. A* **879**, 77 (2012).
 659 [19] C. Aidala *et al.*, "The PHENIX Forward Silicon Vertex Detector," *Nucl. Instrum. Methods Phys. Res., Sec. A* **755**, 44
 660 (2014).
 661 [20] H. Akikawa *et al.*, "PHENIX Muon Arms," *Nucl. Instrum. Methods Phys. Res., Sec. A* **499**, 537 (2003).
 662 [21] S. S. Adler *et al.* (PHENIX Collaboration), "Measurement of Single Muons at Forward Rapidity in $p + p$ Collisions at
 663 $\sqrt{s} = 200$ GeV and Implications for Charm Production," *Phys. Rev. D* **76**, 092002 (2007).
 664 [22] Z. Li, H. Enyo, Goto. Y., Radeka. V., W. Chen, D. Elliott, T. Kawabata, M. Togawa, N. Saito, V. Rykov, Tanida. K.,
 665 and J. Tojo, "Novel silicon stripixel detector for PHENIX Upgrade," *Nucl. Instrum. Methods Phys. Res., Sec. A* **518**, 300
 666 (2004).
 667 [23] R. Ichimiya *et al.*, "Silicon Pixel Detector for the PHENIX experiment at the BNL RHIC," *4th International Workshop*
 668 *on Semiconductor Pixel Detectors for Particles and Imaging (PIXEL 2008) Batavia, Illinois, September 23-26, 2008*, *J.*
 669 *Instrum.* **4**, P05001 (2009).

- 670 [24] V. Innocente, M Maire, and E Nagy, “GEANE: average tracking and error propagation package,” CERN Program Library
671 **W5013-E**, 0 (1991).
- 672 [25] X.-N. Wang and M. Gyulassy, “HIJING: A Monte Carlo model for multiple jet production in p p, p A and A A collisions,”
673 Phys. Rev. D **44**, 3501 (1991).
- 674 [26] S. Agostinelli *et al.*, “GEANT4-a simulation toolkit,” Nucl. Instrum. Methods Phys. Res., Sec. A **506**, 250 (2003).
- 675 [27] H.-L. Lai, M. Guzzi, J. Huston, Z. Li, P. M. Nadolsky, J. Pumplin, and C.-P. Yuan, “New parton distributions for collider
676 physics,” Phys. Rev. D **82**, 074024 (2010).
- 677 [28] A. Adare *et al.* (PHENIX Collaboration), “Measurement of high- p_T single electrons from heavy-flavor decays in $p + p$
678 collisions at $\sqrt{s} = 200$ GeV,” Phys. Rev. Lett. **97**, 252002 (2006).
- 679 [29] A. Adare *et al.* (PHENIX Collaboration), “Measurement of Bottom versus Charm as a Function of Transverse Momentum
680 with Electron-Hadron Correlations in $p + p$ Collisions at $\sqrt{s} = 200$ GeV,” Phys. Rev. Lett. **103**, 082002 (2009).
- 681 [30] A. Adare *et al.* (PHENIX Collaboration), “Ground and excited charmonium state production in $p+p$ collisions at $\sqrt{s} = 200$
682 GeV,” Phys. Rev. D **85**, 092004 (2012).
- 683 [31] M. Cacciari, M. Greco, and P. Nason, “The P(T) spectrum in heavy flavor hadroproduction,” J. High Energy Phys. **05**
684 (1998) 007.
- 685 [32] M. Cacciari, P. Nason, and R. Vogt, “QCD predictions for charm and bottom production at RHIC,” Phys. Rev. Lett. **95**,
686 122001 (2005).
- 687 [33] A. D. Frawley, T. Ullrich, and R. Vogt, “Heavy flavor in heavy-ion collisions at RHIC and RHIC II,” Phys. Rept. **462**,
688 125 (2008).
- 689 [34] P. M. Nadolsky, H.-L. Lai, Q.-H. Cao, J. Huston, J. Pumplin, D. Stump, W.-K. Tung, and C. P. Yuan, “Implications of
690 CTEQ global analysis for collider observables,” Phys. Rev. D **78**, 013004 (2008).
- 691 [35] A. Adare *et al.* (PHENIX Collaboration), “Heavy Quark Production in $p + p$ and Energy Loss and Flow of Heavy Quarks
692 in Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV,” Phys. Rev. C **84**, 044905 (2011).
- 693 [36] L. Adamczyk *et al.* (STAR Collaboration), “Observation of D^0 Meson Nuclear Modifications in Au+Au Collisions at
694 $\sqrt{s_{NN}} = 200$ GeV,” Phys. Rev. Lett. **113**, 142301 (2014).