

Transverse single-spin asymmetry of forward η mesons in $p^\uparrow + p$ collisions at $\sqrt{s} = 200$ GeV

N. J. Abdulameer,^{15,22} U. Acharya,¹⁹ C. Aidala,^{38,43} N. N. Ajitanand,^{62,*} Y. Akiba,^{57,58,†} R. Akimoto,¹¹ J. Alexander,⁶² D. Anderson,²⁷ S. Antsupov,⁶⁰ K. Aoki,^{31,57} N. Apadula,^{27,63} H. Asano,^{34,57} E. T. Atomssa,⁶³ T. C. Awes,⁵⁴ B. Azmoun,⁷ V. Babintsev,²³ M. Bai,⁶ X. Bai,¹⁰ B. Bannier,⁶³ E. Bannikov,⁶⁰ 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,^{12,52} A. Berdnikov,⁶⁰ Y. Berdnikov,⁶⁰ L. Bichon,⁶⁹ D. Black,⁸ B. Blankenship,⁶⁹ D. S. Blau,^{33,49} J. S. Bok,⁵¹ V. Borisov,⁶⁰ K. Boyle,⁵⁸ M. L. Brooks,³⁸ J. Bryslawskyj,^{5,8} H. Buesching,⁷ V. Bumazhnov,²³ S. Butsyk,⁵⁰ S. Campbell,^{13,27} P. Chaitanya,⁶³ C.-H. Chen,⁵⁸ D. Chen,⁶³ M. Chiu,⁷ C. Y. Chi,¹³ I. J. Choi,²⁴ J. B. Choi,^{29,*} S. Choi,⁶¹ P. Christiansen,³⁹ T. Chujo,⁶⁷ V. Cianciolo,⁵⁴ B. A. Cole,¹³ M. Connors,^{19,58} R. Corliss,⁶³ N. Cronin,^{45,63} N. Crossette,⁴⁵ M. Csanád,¹⁶ T. Csörgő,^{42,71} L. D'Orazio,⁴⁰ A. Datta,⁵⁰ M. S. Daugherty,¹ G. David,^{7,63} K. Dehmelt,⁶³ A. Denisov,²³ A. Deshpande,^{58,63} E. J. Desmond,⁷ L. Ding,²⁷ V. Doomra,⁶³ J. H. Do,⁷² O. Drapier,³⁵ A. Drees,⁶³ K. A. Drees,⁶ J. M. Durham,³⁸ A. Durum,²³ T. Engelmö, ¹³ A. Enokizono,^{57,59} R. Esha,⁶³ K. O. Eyser,⁷ B. Fadem,⁴⁵ D. E. Fields,⁵⁰ M. Finger, Jr.,⁹ M. Finger,⁹ D. Firak,^{15,63} D. Fitzgerald,⁴³ F. Fleuret,³⁵ S. L. Fokin,³³ J. E. Frantz,⁵³ A. Franz,⁷ A. D. Frawley,¹⁸ Y. Fukao,³¹ T. Fusayasu,⁴⁷ K. Gainey,¹ C. Gal,⁶³ P. Garg,^{3,63} A. Garishvili,⁶⁵ I. Garishvili,³⁷ F. Giordano,²⁴ A. Glenn,³⁷ X. Gong,⁶² M. Gonin,³⁵ Y. Goto,^{57,58} R. Granier de Cassagnac,³⁵ N. Grau,² S. V. Greene,⁶⁹ M. Grosse Perdekamp,²⁴ T. Gunji,¹¹ T. Guo,⁶³ H. Guragain,¹⁹ Y. Gu,⁶² J. S. Haggerty,⁷ K. I. Hahn,¹⁷ H. Hamagaki,¹¹ J. Hanks,⁶³ K. Hashimoto,^{57,59} R. Hayano,¹¹ T. K. Hemmick,⁶³ T. Hester,⁸ X. He,¹⁹ J. C. Hill,²⁷ A. Hodges,^{19,24} R. S. Hollis,⁸ K. Homma,²¹ B. Hong,³² T. Hoshino,²¹ J. Huang,^{7,38} T. Ichihara,^{57,58} Y. Ikeda,⁵⁷ K. Imai,²⁸ Y. Imazu,⁵⁷ M. Inaba,⁶⁷ A. Iordanova,⁸ D. Isenhower,¹ A. Isinhue,⁴⁵ D. Ivanishchev,⁵⁶ B. V. Jacak,⁶³ S. J. Jeon,⁴⁶ M. Jezghani,¹⁹ X. Jiang,³⁸ Z. Ji,⁶³ B. M. Johnson,^{7,19} K. S. Joo,⁴⁶ D. Jouan,⁵⁵ D. S. Jumper,²⁴ J. Kamin,⁶³ S. Kanda,^{11,31} B. H. Kang,²⁰ J. H. Kang,⁷² J. S. Kang,²⁰ J. Kapustinsky,³⁸ G. Kasza,^{42,71} D. Kaway, ⁴¹ A. V. Kazantsev,³³ J. A. Key,⁵⁰ V. Khachatryan,⁶³ P. K. Khandai,³ A. Khanzadeev,⁵⁶ K. M. Kijima,²¹ C. Kim,³² D. J. Kim,³⁰ E.-J. Kim,²⁹ Y.-J. Kim,²⁴ Y. K. Kim,²⁰ E. Kistenev,⁷ J. Klatsky,¹⁸ D. Kleinjan,⁸ P. Kline,⁶³ T. Koblesky,¹² M. Kofarago,^{16,71} B. Komkov,⁵⁶ J. Koster,⁵⁸ D. Kotchetkov,⁵³ D. Kotov,^{56,60} L. Kovacs,¹⁶ F. Krizek,³⁰ K. Kurita,⁵⁹ M. Kurosawa,^{57,58} Y. Kwon,⁷² Y. S. Lai,¹³ J. G. Lajoie,^{27,54} A. Lebedev,²⁷ D. M. Lee,³⁸ G. H. Lee,²⁹ J. Lee,^{17,64} K. B. Lee,³⁸ K. S. Lee,³² S. H. Lee,^{27,63} M. J. Leitch,³⁸ M. Leitgab,²⁴ B. Lewis,⁶³ X. Li,¹⁰ X. Li,³⁸ S. H. Lim,⁷² M. X. Liu,³⁸ D. A. Loomis,⁴³ D. Lynch,⁷ S. Lökös,⁷¹ C. F. Maguire,⁶⁹ Y. I. Makdisi,⁶ M. Makek,^{70,73} A. Manion,⁶³ V. I. Manko,³³ E. Mannel,⁷ M. McCumber,^{12,38} P. L. McGaughey,³⁸ D. McGlinchey,^{12,18,38} C. McKinney,²⁴ A. Meles,⁵¹ M. Mendoza,⁸ B. Meredith,²⁴ Y. Miake,⁶⁷ T. Mibe,³¹ A. C. Mignerey,⁴⁰ A. Milov,⁷⁰ D. K. Mishra,⁴ J. T. Mitchell,⁷ M. Mitrakova,^{60,63} Iu. Mitrakov,^{60,63} S. Miyasaka,^{57,66} S. Mizuno,^{57,67} A. K. Mohanty,⁴ S. Mohapatra,⁶² D. P. Morrison,⁷ M. Moskowitz,⁴⁵ T. V. Moukhanova,³³ B. Mulilo,^{32,57,74} T. Murakami,^{34,57} J. Murata,^{57,59} A. Mwai,⁶² T. Nagae,³⁴ S. Nagamiya,^{31,57} J. L. Nagle,¹² M. I. Nagy,¹⁶ I. Nakagawa,^{57,58} Y. Nakamiya,²¹ K. R. Nakamura,^{34,57} T. Nakamura,⁵⁷ K. Nakano,^{57,66} C. Nattrass,⁶⁵ P. K. Netrakanti,⁴ M. Nihashi,^{21,57} T. Niida,⁶⁷ R. Nouicer,^{7,58} N. Novitzky,^{30,63} T. Novák,^{42,71} G. Nukazuka,^{57,58} A. S. Nyanin,³³ E. O'Brien,⁷ C. A. Ogilvie,²⁷ H. Oide,¹¹ K. Okada,⁵⁸ M. Orosz,^{15,22} A. Oskarsson,³⁹ K. Ozawa,^{31,67} R. Pak,⁷ V. Pantuev,²⁵ V. Papavassiliou,⁵¹ I. H. Park,^{17,64} J. S. Park,⁶¹ S. Park,^{44,57,61,63} S. K. Park,³² L. Patel,¹⁹ S. F. Pate,⁵¹ J.-C. Peng,²⁴ D. V. Perepelitsa,^{12,13} G. D. N. Perera,⁵¹ D. Yu. Peressounko,³³ J. Perry,²⁷ R. Petti,^{7,63} C. Pinkenburg,⁷ R. P. Pisani,⁷ M. Potekhin,⁷ M. L. Purschke,⁷ H. Qu,¹ J. Rak,³⁰ I. Ravinovich,⁷⁰ K. F. Read,^{54,65} D. Reynolds,⁶² V. Riabov,^{49,56} Y. Riabov,^{56,60} E. Richardson,⁴⁰ D. Richford,^{5,68} N. Riveli,⁵³ D. Roach,⁶⁹ S. D. Rolnick,⁸ M. Rosati,²⁷ M. S. Ryu,²⁰ B. Sahlmueller,⁶³ N. Saito,³¹ T. Sakaguchi,⁷ H. Sako,²⁸ V. Samsonov,^{49,56} M. Sarsour,¹⁹ S. Sato,²⁸ S. Sawada,³¹ K. Sedgwick,⁸ J. Seele,⁵⁸ R. Seidl,^{57,58} Y. Sekiguchi,¹¹ A. Seleznev,⁶⁰ A. Sen,^{19,27} R. Seto,⁸ P. Sett,⁴ D. Sharma,⁶³ A. Shaver,²⁷ I. Shein,²³ T.-A. Shibata,^{57,66} K. Shigaki,²¹ M. Shimomura,^{27,48} K. Shoji,⁵⁷ P. Shukla,⁴ A. Sickles,^{7,24} C. L. Silva,³⁸ D. Silvermyr,^{39,54} B. K. Singh,³ C. P. Singh,³ V. Singh,³ M. Skolnik,⁴⁵ M. Slunečka,⁹ K. L. Smith,^{18,38} S. Solano,⁴⁵ R. A. Soltz,³⁷ W. E. Sondheim,³⁸ S. P. Sorensen,⁶⁵ I. V. Sourikova,⁷ P. W. Stankus,⁵⁴ P. Steinberg,⁷ E. Stenlund,³⁹ M. Stepanov,⁴¹ A. Ster,⁷¹ S. P. Stoll,⁷ M. R. Stone,¹² T. Sugitate,²¹ A. Sukhanov,⁷ J. Sun,⁶³ Z. Sun,^{15,22,63} A. Takahara,¹¹ A. Taketani,^{57,58} Y. Tanaka,⁴⁷ K. Tanida,^{28,58,61} M. J. Tannenbaum,⁷ S. Tarafdar,^{3,69} A. Taranenko,^{49,62} E. Tennant,⁵¹ A. Timilsina,²⁷ T. Todoroki,^{57,58,67} M. Tomášek,^{14,26} H. Torii,¹¹ R. S. Towell,¹ I. Tserruya,⁷⁰ B. Ujvari,^{15,22} H. W. van Hecke,³⁸ M. Vargyas,^{16,71} E. Vazquez-Zambrano,¹³ A. Veicht,¹³ J. Velkovska,⁶⁹ M. Virius,¹⁴ V. Vrba,^{14,26} E. Vznuzdaev,⁵⁶ R. Vértési,⁷¹ X. R. Wang,^{51,58} D. Watanabe,²¹ K. Watanabe,^{57,59} Y. Watanabe,^{57,58} Y. S. Watanabe,^{11,31} F. Wei,⁵¹ S. Whitaker,²⁷ S. Wolin,²⁴ C. L. Woody,⁷ M. Wysocki,⁵⁴ B. Xia,⁵³ Y. L. Yamaguchi,^{11,63} A. Yanovich,²³ S. Yokkaichi,^{57,58} I. Yoon,⁶¹ I. Younus,^{36,50} Z. You,³⁸ I. E. Yushmanov,³³ W. A. Zajc,¹³ A. Zelenski,⁶ and S. Zhou¹⁰

(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, Faculty of Mathematics and Physics, 180 00 Troja, Prague, Czech Republic
- ¹⁰Science and Technology on Nuclear Data Laboratory, China Institute of Atomic Energy, Beijing 102413, People's Republic of China
- ¹¹Center for Nuclear Study, Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan
- ¹²University of Colorado, Boulder, Colorado 80309, USA
- ¹³Columbia University, New York, New York 10027 and Nevis Laboratories, Irvington, New York 10533, USA
- ¹⁴Czech Technical University, Zikova 4, 166 36 Prague 6, Czech Republic
- ¹⁵Debrecen University, H-4010 Debrecen, Egyetem tér 1, Hungary
- ¹⁶ELTE, Eötvös Loránd University, H-1117 Budapest, Pázmány P. s. 1/A, Hungary
- ¹⁷Ewha Womans University, Seoul 120-750, Korea
- ¹⁸Florida State University, Tallahassee, Florida 32306, USA
- ¹⁹*Georgia State University*, Atlanta, Georgia 30303, USA
- ²⁰Hanyang University, Seoul 133-792, Korea
- ²¹Hiroshima University, Kagamiyama, Higashi-Hiroshima 739-8526, Japan
- ²²HUN-REN ATOMKI, H-4026 Debrecen, Bem tér 18/c, Hungary
- ²³IHEP Protvino, State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, 142281, Russia
- ²⁴University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA
- ²⁵Institute for Nuclear Research of the Russian Academy of Sciences, prospekt 60-letiya Oktyabrya 7a, Moscow 117312, Russia
- ²⁶Institute of Physics, Academy of Sciences of the Czech Republic, Na Slovance 2, 182 21 Prague 8, Czech Republic
- ²⁷Iowa State University, Ames, Iowa 50011, USA
- ²⁸Advanced Science Research Center, Japan Atomic Energy Agency, 2-4 Shirakata Shirane, Tokai-mura, Naka-gun, Ibaraki-ken 319-1195, Japan
- ²⁹Jeonbuk National University, Jeonju, 54896, Korea
- ³⁰Helsinki Institute of Physics and University of Jyväskylä, P.O. Box 35, FI-40014 Jyväskylä, Finland
- ³¹KEK, High Energy Accelerator Research Organization, Tsukuba, Ibaraki 305-0801, Japan
- ³²Korea University, Seoul 02841, Korea
- ³³National Research Center "Kurchatov Institute," Moscow, 123098 Russia
- ³⁴Kyoto University, Kyoto 606-8502, Japan
- ³⁵Laboratoire Leprince-Ringuet, Ecole Polytechnique, CNRS-IN2P3, Route de Saclay, F-91128, Palaiseau, France
- ³⁶Physics Department, Lahore University of Management Sciences, Lahore 54792, Pakistan
- ³⁷Lawrence Livermore National Laboratory, Livermore, California 94550, USA
- ³⁸Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
- ³⁹Department of Physics, Lund University, Box 118, SE-221 00 Lund, Sweden
- ⁴⁰University of Maryland, College Park, Maryland 20742, USA
- ⁴¹Department of Physics, University of Massachusetts, Amherst, Massachusetts 01003-9337, USA
- ⁴²MATE, Institute of Technology, Laboratory of Femtoscopy, Károly Róbert Campus, H-3200 Gyöngyös, Mátrai út 36, Hungary
- ⁴³Department of Physics, University of Michigan, Ann Arbor, Michigan 48109-1040, USA
- ⁴⁴Mississippi State University, Mississippi State, Mississippi 39762, 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
- ⁴⁸Nara Women's University, Kita-uoya Nishi-machi Nara 630-8506, Japan

⁴⁹National Research Nuclear University, MEPhI, Moscow Engineering Physics Institute,
Moscow, 115409, Russia

⁵⁰University of New Mexico, Albuquerque, New Mexico 87131, USA

⁵¹New Mexico State University, Las Cruces, New Mexico 88003, USA

⁵²Physics and Astronomy Department, University of North Carolina at Greensboro,
Greensboro, North Carolina 27412, USA

⁵³Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701, USA

⁵⁴Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA

⁵⁵IPN-Orsay, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, BP1, F-91406, Orsay, France

⁵⁶PNPI, Petersburg Nuclear Physics Institute, Gatchina, Leningrad region, 188300, Russia

⁵⁷RIKEN Nishina Center for Accelerator-Based Science, Wako, Saitama 351-0198, Japan

⁵⁸RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973-5000, USA

⁵⁹Physics Department, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima, Tokyo 171-8501, Japan

⁶⁰Saint Petersburg State Polytechnic University, St. Petersburg, 195251 Russia

⁶¹Department of Physics and Astronomy, Seoul National University, Seoul 151-742, Korea

⁶²Chemistry Department, Stony Brook University, SUNY, Stony Brook, New York 11794-3400, USA

⁶³Department of Physics and Astronomy, Stony Brook University, SUNY,
Stony Brook, New York 11794-3800, USA

⁶⁴Sungkyunkwan University, Suwon, 440-746, Korea

⁶⁵University of Tennessee, Knoxville, Tennessee 37996, USA

⁶⁶Department of Physics, Tokyo Institute of Technology, Oh-okayama, Meguro, Tokyo 152-8551, Japan

⁶⁷Tomonaga Center for the History of the Universe, University of Tsukuba, Tsukuba, Ibaraki 305, Japan

⁶⁸United States Merchant Marine Academy, Kings Point, New York 11024, USA

⁶⁹Vanderbilt University, Nashville, Tennessee 37235, USA

⁷⁰Weizmann Institute, Rehovot 76100, Israel

⁷¹Institute for Particle and Nuclear Physics, HUN-REN Wigner Research Centre for Physics,
(HUN-REN Wigner RCP, RMI), H-1525 Budapest 114, P.O. Box 49, Budapest, Hungary

⁷²Yonsei University, IPAP, Seoul 120-749, Korea

⁷³Department of Physics, Faculty of Science, University of Zagreb,
Bijenička c. 32 HR-10002 Zagreb, Croatia

⁷⁴Department of Physics, School of Natural Sciences, University of Zambia,
Great East Road Campus, Box 32379, Lusaka, Zambia



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Utilizing the 2012 transversely polarized proton data from the Relativistic Heavy Ion Collider at Brookhaven National Laboratory, the forward η -meson transverse single-spin asymmetry (A_N) was measured for $p^\uparrow + p$ collisions at $\sqrt{s} = 200$ GeV as a function of Feynman- x (x_F) for $0.2 < |x_F| < 0.8$ and transverse momentum (p_T) for $1.0 < p_T < 5.0$ GeV/c. Large asymmetries at positive x_F are observed ($\langle A_N \rangle = 0.086 \pm 0.019$), agreeing well with previous measurements of π^0 and ηA_N , but with reach to higher x_F and p_T . The contribution of initial-state spin-momentum correlations to the asymmetry, as calculated in the collinear twist-3 framework, appears insufficient to describe the data.

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I. INTRODUCTION

In quantum chromodynamics (QCD), the behavior of the theory depends strongly on the distance scale of the physics

involved. At short distances where the strong coupling is small, the quarks and gluons, collectively known as partons, are readily described within the framework of perturbative QCD (pQCD). However, at long distances, the coupling becomes large and the theory becomes nonperturbative. Calculations of cross sections within QCD rely on factorizing the perturbative hard scattering at short distances from the nonperturbative physics at long distances, which is contained in the universal parton distribution functions (PDFs) and fragmentation functions (FFs) [1]. The standard factorization procedure explicitly defines only the collinear degrees of freedom of the nonperturbative functions and then expands the cross section in inverse powers of the momentum transfer

*Deceased.

†PHENIX Collaboration Spokesperson.

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Q , alongside the usual expansion of the hard scattering in powers of the strong coupling, α_s .

Historically, unpolarized observables, such as inclusive cross sections, have been well described by this collinear QCD factorization scheme at the leading $n = 2$ term of the $1/Q^{n-2}$ factorization expansion, where n is known as the twist. However, large azimuthal asymmetries in particle production from transversely polarized proton collisions ($p^\uparrow + p \rightarrow h + X$) [2–6], particularly at forward rapidities, disagree with the leading-twist collinear pQCD predictions of asymmetries on the order of 10^{-4} [7]. These transverse single-spin asymmetries (TSSAs) persist at high p_T [4,6,8] where pQCD is valid, suggesting additional considerations are needed in the nonperturbative initial- and final-state functions.

Multiple factorization frameworks have since been proposed with mechanisms to generate TSSAs. Transverse-momentum-dependent (TMD) factorization generalizes the definition of the PDFs and FFs to include explicit dependence on a nonperturbative transverse momentum. The resulting TMD distributions describe QCD spin-momentum correlations between the partons and hadrons. Two polarized TMD distributions have been identified as sources for large TSSAs. In the initial state, the Siverson TMD PDF [9,10] correlates the transverse polarization of the hadron with the transverse momentum of a constituent parton and explains the left-right asymmetry in particle production as arising from a transverse momentum imbalance of the partons. In the final state, the Collins TMD FF [11] correlates the transverse polarization of the struck parton and the angular distribution of the fragmenting hadrons. The Collins effect attributes the left-right asymmetries to the fragmentation of transversely polarized quarks with a preferred transverse direction. It arises from the coupling of the Collins TMD FF with the quark transversity distribution [12,13], which encodes the correlation between the transverse polarization of the initial-state proton and that of its constituent quarks.

Experimental probes of TMDs require observables with access to both a hard scale Q and a soft scale that defines the nonperturbative transverse momentum component, $k_T \ll Q$. In semi-inclusive deep-inelastic scattering (SIDIS), measurements of both pion and kaon single-spin asymmetries [14–17] led to the extraction of the first nonzero Siverson functions for u and d quarks [18–21]. Subsequently, nonzero Collins FFs for pions and transversity distributions for u and d quarks were extracted [22–24] from a combination of SIDIS [25–27] and e^+e^- data [28]. Recent measurements have confirmed significant Collins asymmetries at much higher precision [29–31].

For processes with one accessible hard scale, such as inclusive hadron production at high p_T in hadronic collisions, TSSAs can be described in collinear factorization with higher-twist multiparton correlators [32–34]. These twist-3 correlators represent the quantum interference between scattering with a single active parton and a

composite parton state that contains an additional gluon field. They have been shown to be related to the k_T moments of the TMD PDFs and FFs [35]. Asymmetries of inclusive hadrons from hadronic collisions can receive contributions from correlators in both the initial and final state. Previous phenomenological studies attempted to describe π^0 and η TSSAs in hadronic collisions with the initial-state Siverson-like twist-3 correlator [36,37]. More recent studies indicate that the final-state Collins-like twist-3 term may be of considerable importance [38,39] compared to other higher-twist terms.

Additional sources for TSSAs have been suggested, including diffractive processes [40] and nonperturbative color-exchange effects that may signal factorization breaking [41,42]. However, the extent to which such mechanisms contribute to inclusive forward hadron asymmetries in hadronic collisions is not yet well established. Thus, it remains an open question which combination of initial-state and final-state twist-3 correlators, or alternative contributions, dominates the generation of the observed asymmetries.

In this article, the PHENIX collaboration reports the measurement of the forward η -meson TSSAs from $\sqrt{s} = 200$ GeV $p^\uparrow + p$ collisions recorded in 2012. The TSSAs expand the kinematic reach on a previous $\sqrt{s} = 200$ GeV PHENIX measurement from the 2008 dataset [43] to higher x_F and p_T . This previous analysis at $\sqrt{s} = 200$ GeV also included a cross section measurement which exhibited good agreement with pQCD predictions, confirming the validity of factorization in this regime. We combine the measurements from both years of data taking and compare the resulting TSSAs to collinear twist-3 predictions of the asymmetry generated by only the initial-state Siverson-like contribution. They are also compared to the π^0 TSSAs in a similar rapidity range, which can illuminate any potential dependence of the asymmetry on isospin, strange quarks, and mass.

II. THE PHENIX EXPERIMENT AT RHIC

A. RHIC polarized proton beams

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory collides beams of polarized protons up to center of mass energies of 510 GeV. The two collider rings, called yellow and blue, store transversely polarized protons in 111 bunches with $\approx 10^{11}$ protons per bunch. Depolarizing resonances in the rings are mitigated through the implementation of two Siberian snakes, which rotate the proton polarization 180° without incurring orbit distortions [44].

The beam polarization P for (vertical) transversely polarized protons is defined as the difference in the number of protons with spin aligned versus antialigned with the vertical axis divided by the sum. Two separate polarimeters measure $\langle P \rangle$ throughout the run for each beam using the asymmetry of hadronic elastic scattering in the Coulomb-nuclear-interference region [44]. A proton-carbon polarimeter makes quick measurements of the relative

(uncalibrated) polarization several times within a store [45]. They are normalized by the absolute polarization which is determined using a hydrogen gas jet polarimeter [46]. The absolute polarization measurements can take up to several hours due to statistical limitations arising from the low density of the hydrogen gas. Typically, the beam polarizations at RHIC range from $\approx 50\%$ to 60% with an uncertainty of 4% – 7% for a few-hour store.

In each store during transverse-polarization running, the polarization direction of the proton bunches is alternated according to a predetermined pattern. Systematic effects stemming from bunch-by-bunch luminosity differences or detector efficiencies can be mitigated by having protons in both beams polarized in both directions. Because a TSSA measurement relies on the collision of a transversely polarized proton with an unpolarized proton, the sensitivity to polarization is removed in one beam by integrating over both spin-up and spin-down bunches.

B. PHENIX forward detectors

The PHENIX experiment at RHIC [47] utilized a versatile detector apparatus, purpose-built for the high-resolution measurement of leptons, photons, and charged hadrons at the central rapidity of $|\eta| < 0.35$, and with additional capabilities for the measurement of charged hadrons and muons at $1.2 < |\eta| < 2.2$. In the forward region, PHENIX consisted of an electromagnetic calorimeter known as the muon piston calorimeter (MPC) and two global detectors: the beam-beam counter (BBC) and the zero-degree calorimeter (ZDC).

Located 220 cm along the beamline on either side of the nominal PHENIX interaction point and covering $3.1 < |\eta| < 3.9$, the MPC was a scintillating electromagnetic calorimeter comprising 220 (196) PbWO_4 crystal towers in its north (south) arms. Previous measurements of cross sections and asymmetries have exhibited the capability of the MPC to reconstruct light neutral mesons in the forward region through their decays to photons [6,43,48]. To sample high-momentum η -meson candidates, an MPC trigger fired when a localized 4-by-4 group of towers had a cumulative energy deposition greater than a set threshold. In $\sqrt{s} = 200$ GeV collisions, this threshold corresponded to cluster energies of roughly 20 GeV.

The BBC [49], located at $3.0 < |\eta| < 3.9$, had two arms of quartz Čerenkov radiator arrays 144 cm to the north and south side of the nominal PHENIX collision point. It was used primarily to define the condition of a minimum-bias (MB) event and to provide a vertex position along the beam axis by utilizing its precise timing resolution to measure the difference in the particle time of flight between the north and south arms. The ZDC [49] was a hadronic calorimeter in the far-forward region ($\eta \gtrsim 6$) used for neutron detection from diffractive or double-diffractive events. By sandwiching scintillating hodoscopes known as the shower-maximum detectors (SMD) within the ZDCs, PHENIX was also

sensitive to the position of these neutrons with ≈ 1 cm resolution. The ZDC/SMD system functioned as a local polarimeter for PHENIX through the measurement of known neutron single-spin asymmetries [50]. In 2012, results from the PHENIX local polarimeter confirmed the nominal vertical polarization direction of both beams.

III. ANALYSIS METHODS

In transversely polarized $p^\uparrow + p$ collisions, the cross section of inclusive particle production is modified to first order by an azimuthal-cosine modulation known as the raw asymmetry,

$$\epsilon(\phi) = PA_N \cos \phi, \quad (1)$$

where P is the beam polarization and A_N is the TSSA. A_N is measured by fitting a cosine function to the raw asymmetry and dividing the amplitude of the fit by the beam polarization. It quantifies the difference between azimuthally dependent cross sections when the proton is polarized up ($d\sigma^\uparrow$) versus down ($d\sigma^\downarrow$)

$$A_N \cos \phi = \frac{1}{P} \frac{d\sigma^\uparrow(\phi) - d\sigma^\downarrow(\phi)}{d\sigma^\uparrow(\phi) + d\sigma^\downarrow(\phi)}, \quad (2)$$

or, equivalently, when the final-state particle is produced to the left or right with respect to the polarized proton going direction. The angle ϕ is measured in the vertical plane, with the up direction being $\phi = \pi/2$. By convention, to the left (right) of the polarized proton going direction is defined as $\phi = 0$ ($\phi = \pi$). Rotating in this plane clearly gives $d\sigma^\uparrow(\phi) = d\sigma^\downarrow(\phi + \pi)$ and $d\sigma^\downarrow(\phi) = d\sigma^\uparrow(\phi + \pi)$.

During the 2012 data taking period, the south MPC underwent an upgrade, leaving only the north MPC to collect data for this measurement. It collected 1.23×10^{-2} pb $^{-1}$ of MB data and 12.95 pb $^{-1}$ of MPC triggered data. By treating the north-going (blue) beam as polarized and south-going (yellow) beam as unpolarized, A_N can be measured as a function of positive $x_F = 2p_z/\sqrt{s}$. Likewise, a polarized yellow and unpolarized blue beam provides access to negative x_F values. As such, A_N is measured at both positive and negative x_F with bin widths of 0.1 from 0.2 to 0.4 and -0.2 to -0.4 in the MB data and 0.3 to 0.8 and -0.3 to -0.8 in the MPC-triggered data. Additionally, A_N is measured as a function of p_T in MB from 1.0 to 2.5 GeV/ c and with MPC triggers from 2.0 to 5.0 GeV/ c in p_T bins of width 0.5 GeV/ c . The high- x_F behavior of the asymmetry is explored further by separating A_N versus p_T into x_F regions of 0.2 to 0.6 and 0.6 to 0.8.

A. Polarization

The polarizations of both RHIC beams were tracked throughout the 2012 data taking period using the proton-carbon and hydrogen gas jet polarimeters introduced in

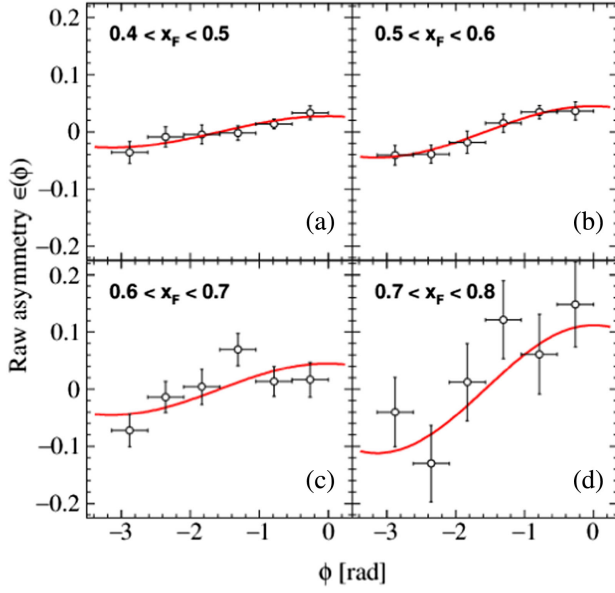


FIG. 1. A selection of MPC-triggered raw asymmetries and their cosine fits in the p_T range between 1.0 and 5.0 GeV/ c for (a) $0.4 < x_F < 0.5$ (b) $0.5 < x_F < 0.6$ (c) $0.6 < x_F < 0.7$ (d) $0.7 < x_F < 0.8$.

Sec. II A. The luminosity-weighted magnitude of the proton polarization was determined to be $\langle P_{\text{blue}} \rangle = 0.652 \pm 0.009$ (stat) ± 0.022 (syst) and $\langle P_{\text{yellow}} \rangle = 0.587 \pm 0.009$ (stat) ± 0.020 (syst). The ratio in luminosity between polarized-up and polarized-down bunches, known as the relative luminosity $\mathcal{R}$, is an important quantity when determining the raw asymmetry. It is calculated using bunch-dependent trigger counts from the BBC. For both the blue and yellow beams in 2012, $\mathcal{R} \approx 1$ within a tenth of a percent.

B. Raw asymmetries

Two independent methods are used to extract the raw asymmetry, $\epsilon(\phi)$. The first utilizes a geometric mean of yields on the left and right sides of the MPC from collisions of up and down polarized protons (Fig. 1),

$$\epsilon(\phi) = \frac{\sqrt{N^\uparrow(\phi)N^\downarrow(\phi + \pi)} - \sqrt{N^\downarrow(\phi)N^\uparrow(\phi + \pi)}}{\sqrt{N^\uparrow(\phi)N^\downarrow(\phi + \pi)} + \sqrt{N^\downarrow(\phi)N^\uparrow(\phi + \pi)}}, \quad (3)$$

where the yields $N^{\uparrow,\downarrow}$ are determined by integrating the invariant mass distribution of diphoton candidates from the decay $\eta \rightarrow \gamma\gamma$ in the signal region of $0.48 < M_{\gamma\gamma} < 0.70$ GeV/ c^2 (Fig. 2). This formula, to first order, cancels detector efficiency and relative luminosity effects. As a cross check, the raw asymmetry can also be measured with a formula that relies on counts from the same azimuthal region,

$$\epsilon(\phi) = \frac{N^\uparrow(\phi) - \mathcal{R}N^\downarrow(\phi)}{N^\uparrow(\phi) + \mathcal{R}N^\downarrow(\phi)}. \quad (4)$$

This method must account for the relative luminosity between up and down bunches. The final A_N is determined with Eq. (3) while the difference between the two methods is taken as an uncorrelated systematic uncertainty.

C. Background correction

The asymmetry in the signal region must undergo a purity correction to account for the background underneath the η meson peak. The presence of a combinatorial background in the signal region dilutes the asymmetry. In contrast, correlated background clusters, composed primarily of π^0 decay photons that are reconstructed in the same cluster due to their small opening angle (merged π^0 clusters), could generate some false asymmetry in the η meson mass window that enhances the signal A_N . Both effects can be corrected for the TSSA (A_N) as

$$A_N = \frac{A_N^{\text{peak}} - rA_N^{\text{bkg}}}{1 - r}, \quad (5)$$

where $r = N_{\text{bkg}}/(N_\eta + N_{\text{bkg}})$ is the fraction of background in the signal region, A_N^{peak} is the transverse single-spin asymmetry in the signal region, and A_N^{bkg} is the transverse single-spin asymmetry in the sideband mass regions.

The background fraction is determined by fitting the invariant mass spectra with a gamma distribution background and Gaussian signal, as seen in Fig. 2. In the MB data, an additional Gaussian centered at 0.78 GeV/ c^2 was included in the background fit function to account for the $\omega(782) \rightarrow \pi^0 + \gamma$ decay. This $\omega(782)$ signal does not appear in the MPC 4-by-4 triggered sample because the merged π^0 and γ typically do not have enough energy to exceed the trigger threshold by themselves and the opening angle at $\sqrt{s} = 200$ GeV is such that they rarely are found in the same 4-by-4 tile. In the MB (MPC-triggered) data, the background fractions are $\approx 75\%$ (55%). A systematic uncertainty is taken as the difference between background fractions from the nominal extraction using a functional fit and a separate estimation using Gaussian-process regression [51].

The sideband regions are chosen to be sufficiently far from the signal region to remove nearly all $\eta \rightarrow \gamma\gamma$ pairs but close enough to the peak to sample a similar composition of the background under the peak. The low-mass sidebands are defined at $0.32 < M_{\gamma\gamma} < 0.42$ GeV/ c^2 and the high-mass sidebands are defined at $0.86 < M_{\gamma\gamma} < 0.96$ GeV/ c^2 ($0.76 < M_{\gamma\gamma} < 0.86$ GeV/ c^2) in the MB (MPC-triggered) data, where the MB high sideband is shifted higher to avoid

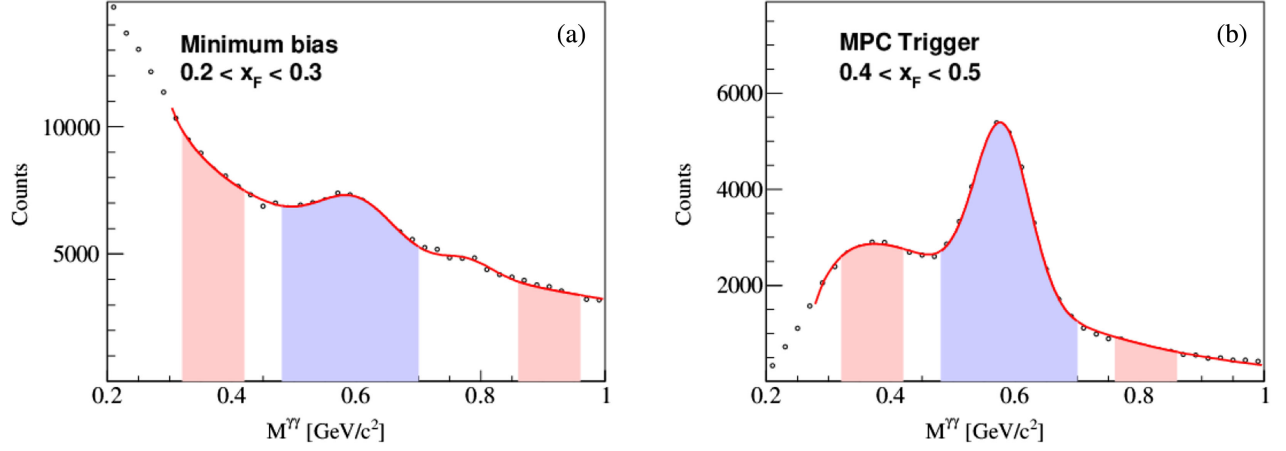


FIG. 2. Examples of two-photon invariant mass distributions in the MPC at $\sqrt{s} = 200$ GeV from the 2012 data taking period in (a) MB and (b) MPC-triggered data. The blue filled regions are used for the η meson-peak asymmetries while the red filled regions are designated as the sidebands for calculation of the background asymmetries.

the $\omega(782)$ region. In both sidebands, A_N^{bkg} is consistent with zero within statistical uncertainties for all x_F and p_T bins.

D. Systematic uncertainties

Three sources of systematic uncertainty on the TSSAs, all of which are uncorrelated across x_F and p_T , are added in quadrature for the total systematic uncertainty in each x_F or p_T bin. The difference in A_N when using the two raw asymmetry extraction methods is taken as a systematic and ranges from 0.005–0.060. Another systematic uncertainty comes from the difference between background fraction estimation when using functional fits and Gaussian-process regression (< 0.01 – 0.03). Any remaining systematic uncertainties are estimated by deviations of the

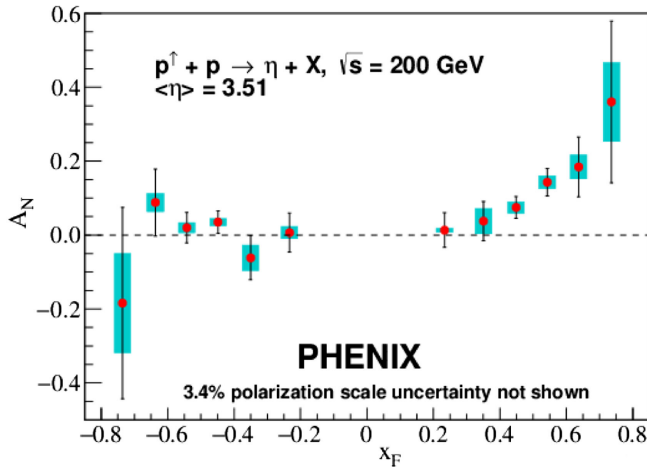


FIG. 3. The x_F dependent A_N of forward η mesons from PHENIX in the 2012 data taking period. The error bars show the statistical uncertainty and the error boxes show the uncorrelated systematic uncertainties added in quadrature. A 3.4% global polarization scale uncertainty is not shown.

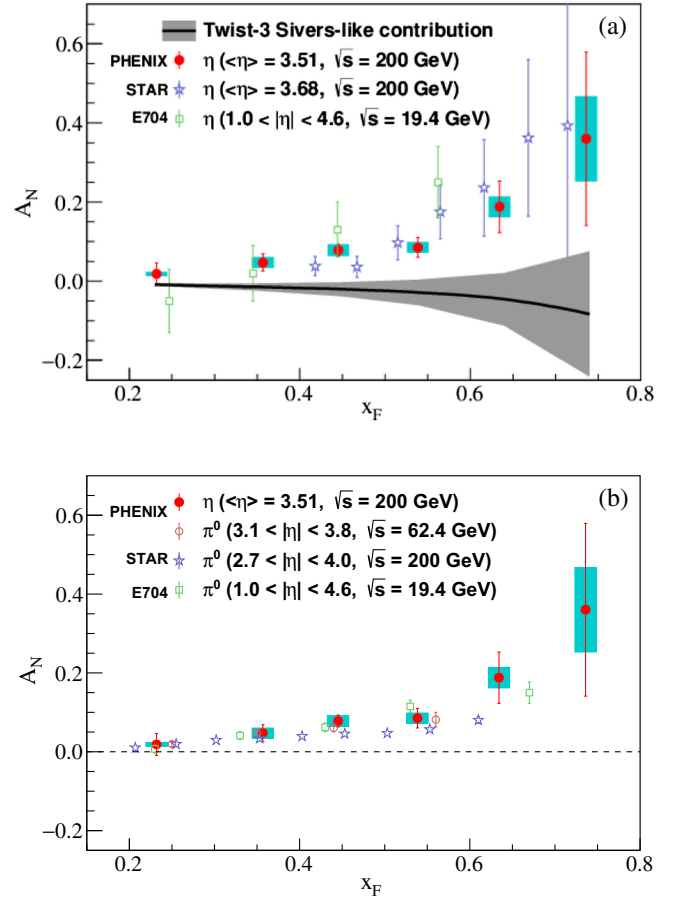


FIG. 4. The combined PHENIX measurement of the forward η meson TSSA from 2008 [43] and 2012 data. Panel (a) shows the asymmetry compared to measurements from STAR [5] and FNAL-E704 [3], and a twist-3 calculation of the initial-state Sivers-like contribution to the asymmetry [52,53]. Panel (b) shows the asymmetry compared to previous π^0 TSSAs from PHENIX [6], STAR [40], and FNAL-E704 [2]. The TSSA at $x_F < 0$ is consistent with zero in both 2008 and 2012 (not shown here).

TABLE I. The A_N of forward η mesons as a function of x_F at $\sqrt{s} = 200$ GeV using 2012 PHENIX data, as shown in Fig. 3, and combined 2008 + 2012 data, as shown in Fig. 4. A global 3.4% polarization scale systematic uncertainty is not included.

Data year	x_F bin	$\langle x_F \rangle$	$\langle p_T \rangle$ [GeV/c]	$A_N [10^{-3}]$	$\sigma_{\text{stat}} [10^{-3}]$	$\sigma_{\text{syst}} [10^{-3}]$
2012	-0.8 to -0.7	-0.736	4.278	-184	259	134
	-0.7 to -0.6	-0.637	3.717	88	91	24
	-0.6 to -0.5	-0.543	3.250	20	41	13
	-0.5 to -0.4	-0.448	2.787	35	31	9
	-0.4 to -0.3	-0.353	2.161	-62	60	34
	-0.3 to -0.2	-0.234	1.374	7	53	17
	0.2 to 0.3	0.234	1.374	14	47	5
	0.3 to 0.4	0.353	2.161	38	53	34
	0.4 to 0.5	0.448	2.787	75	30	15
	0.5 to 0.6	0.543	3.250	143	37	18
	0.6 to 0.7	0.637	3.717	185	81	33
	0.7 to 0.8	0.736	4.278	360	219	107
2008 + 2012	0.2 to 0.3	0.232	1.358	19	28	5
	0.3 to 0.4	0.357	2.311	47	21	13
	0.4 to 0.5	0.445	2.708	78	15	14
	0.5 to 0.6	0.539	3.134	85	25	13
	0.6 to 0.7	0.634	3.608	188	65	26
	0.7 to 0.8	0.736	4.278	360	219	107

asymmetries away from what could be explained by their statistical uncertainty. This is accomplished by randomizing the bunch-by-bunch polarization directions of the protons and then recalculating A_N . This bunch shuffling technique removes any knowledge of proton polarization and should generate asymmetries consistent with zero. Any artificial shift or unaccounted for systematic uncertainty can be seen by generating a sample of 10,000 bunch shuffled asymmetries and fitting A_N/σ_{A_N} to a Gaussian. This Gaussian should follow a standard normal distribution, $\mathcal{N}(\mu = 0, \sigma = 1)$. The resulting distributions are found to be consistent with $\mu = 0$ (consistent with no artificial asymmetry shift) for all x_F and p_T bins. However, all $|x_F| > 0.4$ bins and all p_T bins except for $1.0 < p_T < 1.5$ and $2.0 < p_T < 2.5$ GeV/c have distributions with widths exceeding unity by more than twice their fit uncertainty. These bins are assigned a bunch shuffling systematic uncertainty taken as what is necessary to be added in quadrature with the statistical uncertainty to account for this larger width. The bunch shuffling uncertainties range from 0.01–0.10.

IV. RESULTS AND DISCUSSION

Figure 3 shows the x_F -dependent A_N of forward η mesons at $\sqrt{s} = 200$ GeV from the 2012 data taking period. The asymmetry at positive x_F increases with x_F up to $\approx 35\%$ in the highest x_F region above 0.7. The asymmetry at negative x_F is consistent with zero within 0.86σ of the statistical uncertainty.

The combined results from 2008 and 2012 PHENIX data in Fig. 4 provide the most precise measurement of

the forward η meson A_N to date. Both the 2012 asymmetry from this measurement and combined 2008 + 2012 asymmetry are listed in Table I. Previous A_N measurements from STAR and FNAL-E704 [3,5] are consistent with this result in a similar kinematic regime, as seen in Fig. 4(a). A prediction of the twist-3 initial-state contribution to the asymmetry [52], utilizing the Sivers-like correlator from Ref. [53] and the newly updated collinear η meson fragmentation functions [54], significantly underestimates the data. Presently, a prediction for the contribution from the Collins-like correlator is unavailable for η mesons because of the lack of SIDIS and e^+e^- data to constrain the Collins TMD FF.

The η meson A_N is also compared to the $\pi^0 A_N$ from PHENIX [6], STAR [40], and FNAL-E704 [2] in Fig. 4(b). The compatibility of the η and $\pi^0 A_N$ seems to indicate that differences in strange-quark content, isospin, or mass have a limited impact on the generation of the asymmetry.

The p_T -dependent A_N from 2012 data is presented in Fig. 5(a) and Table II. At positive x_F , the asymmetry is nonzero and increasing with p_T until ≈ 4 GeV/c at which point it levels out. At negative x_F , the asymmetry is consistent with zero within statistical uncertainty. The high- p_T behavior is explored further by splitting the asymmetry into an intermediate- x_F ($0.2 < x_F < 0.6$) and a high- x_F ($0.6 < x_F < 0.8$) region. As seen in Fig. 5(b), the asymmetry shows the flattening or potential suppression at high p_T in the high- x_F region that is expected from twist-3 calculations [36,37,39] and is hinted at in the recent STAR forward π^0 results [8].

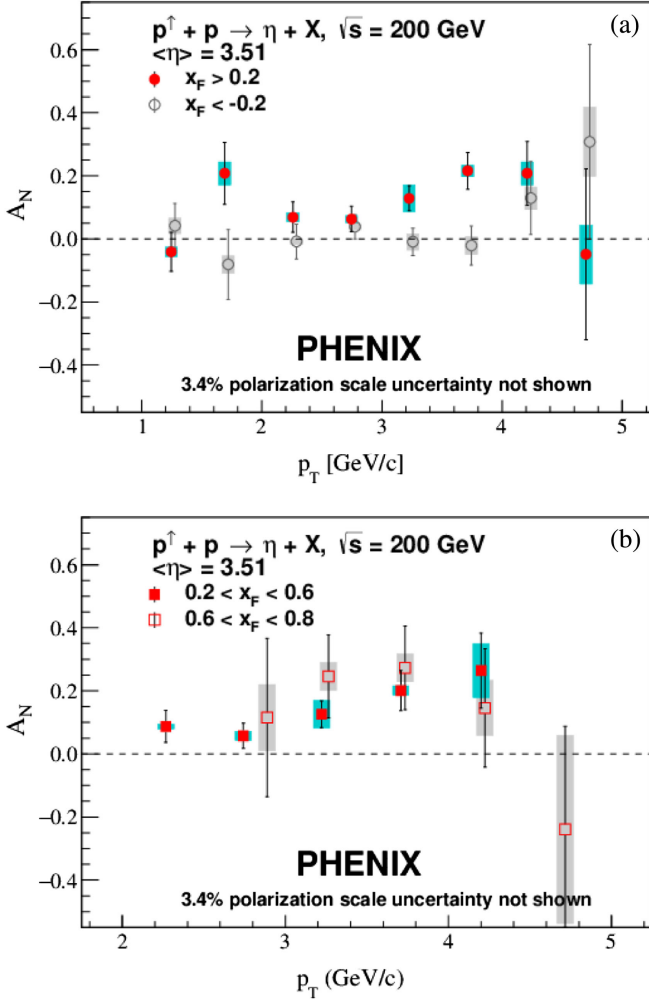


FIG. 5. The p_T dependent A_N of forward η mesons from PHENIX 2012 data. The error bars show the statistical uncertainty and the error boxes show the uncorrelated systematic uncertainties added in quadrature. A 3.4% global polarization scale uncertainty is not shown. Panel (a) shows A_N at positive and negative x_F while panel (b) shows A_N at positive x_F split into intermediate- x_F and high- x_F .

V. SUMMARY

The transverse single-spin asymmetries of η mesons at forward rapidity in $\sqrt{s} = 200$ GeV $p^\uparrow + p$ collisions have been measured by the PHENIX collaboration. The TSSAs are measured as a function of η meson x_F and p_T . Previous measurements of large asymmetries in the forward region are confirmed with greater precision at high x_F . Twist-3 predictions of the TSSA using only the initial-state Sivers-like correlator do not fully describe these asymmetries and comparisons between the η and π^0 TSSAs indicate that effects on the asymmetry that could be caused by mass, isospin, or strange quarks are relatively minor. At high x_F and increasing p_T , the η meson A_N is consistent with the flat or decreasing behavior that has been seen in previous RHIC results and twist-3 predictions of light meson A_N .

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TABLE II. The A_N of forward η mesons from PHENIX 2012 data as a function of p_T at $\sqrt{s} = 200$ GeV, as shown in Fig. 5. A global 3.4% polarization scale systematic uncertainty is not included.

x_F	p_T bin [GeV/c]	$\langle p_T \rangle$ [GeV/c]	$\langle x_F \rangle$	$A_N [10^{-3}]$	$\sigma_{\text{stat}} [10^{-3}]$	$\sigma_{\text{syst}} [10^{-3}]$
$x_F < -0.2$	1.0 to 1.5	1.247	-0.229	41	71	25
	1.5 to 2.0	1.691	-0.264	-81	111	27
	2.0 to 2.5	2.259	-0.407	-8	55	9
	2.5 to 3.0	2.746	-0.459	39	38	10
	3.0 to 3.5	3.227	-0.503	-10	44	25
	3.5 to 4.0	3.714	-0.543	-21	62	28
	4.0 to 4.5	4.209	-0.583	129	116	35
	4.5 to 5.0	4.699	-0.625	308	309	110
$x_F > 0.2$	1.0 to 1.5	1.247	0.229	-41	62	15
	1.5 to 2.0	1.691	0.264	208	98	37

(Table continued)

TABLE II. (*Continued*)

x_F	p_T bin [GeV/c]	$\langle p_T \rangle$ [GeV/c]	$\langle x_F \rangle$	$A_N[10^{-3}]$	$\sigma_{\text{stat}}[10^{-3}]$	$\sigma_{\text{syst}}[10^{-3}]$
	2.0 to 2.5	2.259	0.407	69	49	14
	2.5 to 3.0	2.746	0.459	63	40	11
	3.0 to 3.5	3.227	0.503	129	40	42
	3.5 to 4.0	3.714	0.543	216	58	19
	4.0 to 4.5	4.209	0.583	208	101	37
	4.5 to 5.0	4.699	0.625	-50	271	93
$0.2 < x_F < 0.6$	2.0 to 2.5	2.267	0.407	87	51	8
	2.5 to 3.0	2.743	0.455	58	40	14
	3.0 to 3.5	3.222	0.483	126	42	44
	3.5 to 4.0	3.708	0.508	202	64	14
	4.0 to 4.5	4.200	0.534	264	119	85
$0.6 < x_F < 0.8$	2.5 to 3.0	2.888	0.619	115	251	104
	3.0 to 3.5	3.264	0.640	246	132	44
	3.5 to 4.0	3.734	0.656	273	133	44
	4.0 to 4.5	4.224	0.666	146	188	87
	4.5 to 5.0	4.716	0.671	-239	326	298

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The numerical values for data shown in Figs. 3 and 4 are given in Table I and for data shown in Fig. 5 are given in Table II. All values of this data are stored in HEPData [55].

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