

## Cross sections and double-helicity asymmetries of midrapidity inclusive charged hadrons in $p+p$ collisions at $\sqrt{s} = 62.4$ GeV

A. Adare,<sup>11</sup> S. Afanasiev,<sup>26</sup> C. Aidala,<sup>36</sup> N.N. Ajitanand,<sup>53</sup> Y. Akiba,<sup>47, 48</sup> H. Al-Bataineh,<sup>42</sup> J. Alexander,<sup>53</sup> K. Aoki,<sup>30, 47</sup> L. Aphecetche,<sup>55</sup> J. Asai,<sup>47</sup> E.T. Atomssa,<sup>31</sup> R. Averbeck,<sup>54</sup> T.C. Awes,<sup>43</sup> B. Azmoun,<sup>6</sup> V. Babintsev,<sup>21</sup> M. Bai,<sup>5</sup> G. Baksay,<sup>17</sup> L. Baksay,<sup>17</sup> A. Baldisseri,<sup>14</sup> K.N. Barish,<sup>7</sup> P.D. Barnes,<sup>33, \*</sup> B. Bassalleck,<sup>41</sup> A.T. Basye,<sup>1</sup> S. Bathe,<sup>7</sup> S. Batsouli,<sup>43</sup> V. Baublis,<sup>46</sup> C. Baumann,<sup>37</sup> A. Bazilevsky,<sup>6</sup> S. Belikov,<sup>6, \*</sup> R. Bennett,<sup>54</sup> A. Berdnikov,<sup>50</sup> Y. Berdnikov,<sup>50</sup> A.A. Bickley,<sup>11</sup> J.G. Boissevain,<sup>33</sup> H. Borel,<sup>14</sup> K. Boyle,<sup>54</sup> M.L. Brooks,<sup>33</sup> H. Buesching,<sup>6</sup> V. Bumazhnov,<sup>21</sup> G. Bunce,<sup>6, 48</sup> S. Butsyk,<sup>33</sup> C.M. Camacho,<sup>33</sup> S. Campbell,<sup>54</sup> B.S. Chang,<sup>63</sup> W.C. Chang,<sup>2</sup> J.-L. Charvet,<sup>14</sup> S. Chernichenko,<sup>21</sup> C.Y. Chi,<sup>12</sup> M. Chiu,<sup>22</sup> I.J. Choi,<sup>63</sup> R.K. Choudhury,<sup>4</sup> T. Chujo,<sup>58</sup> P. Chung,<sup>53</sup> A. Churny,<sup>21</sup> V. Cianciolo,<sup>43</sup> Z. Citron,<sup>54</sup> B.A. Cole,<sup>12</sup> P. Constantin,<sup>33</sup> M. Csanád,<sup>16</sup> T. Csörgő,<sup>62</sup> T. Dahms,<sup>54</sup> S. Dairaku,<sup>30, 47</sup> K. Das,<sup>18</sup> A. Datta,<sup>36</sup> G. David,<sup>6</sup> A. Denisov,<sup>21</sup> D. d'Enterria,<sup>31</sup> A. Deshpande,<sup>48, 54</sup> E.J. Desmond,<sup>6</sup> O. Dietzsch,<sup>51</sup> A. Dion,<sup>54</sup> M. Donadelli,<sup>51</sup> O. Drapier,<sup>31</sup> A. Drees,<sup>54</sup> K.A. Drees,<sup>5</sup> A.K. Dubey,<sup>61</sup> A. Durum,<sup>21</sup> D. Dutta,<sup>4</sup> V. Dzhordzhadze,<sup>7</sup> Y.V. Efremenko,<sup>43</sup> F. Ellinghaus,<sup>11</sup> T. Engelmores,<sup>12</sup> A. Enokizono,<sup>32</sup> H. En'yo,<sup>47, 48</sup> S. Esumi,<sup>58</sup> K.O. Eyser,<sup>7</sup> B. Fadern,<sup>38</sup> D.E. Fields,<sup>41, 48</sup> M. Finger,<sup>8</sup> M. Finger, Jr.,<sup>8</sup> F. Fleuret,<sup>31</sup> S.L. Fokin,<sup>29</sup> Z. Fraenkel,<sup>61, \*</sup> J.E. Frantz,<sup>54</sup> A. Franz,<sup>6</sup> A.D. Frawley,<sup>18</sup> K. Fujiwara,<sup>47</sup> Y. Fukao,<sup>30, 47</sup> T. Fusayasu,<sup>40</sup> I. Garishvili,<sup>56</sup> A. Glenn,<sup>11</sup> H. Gong,<sup>54</sup> M. Gonin,<sup>31</sup> J. Gosset,<sup>14</sup> Y. Goto,<sup>47, 48</sup> R. Granier de Cassagnac,<sup>31</sup> N. Grau,<sup>12</sup> S.V. Greene,<sup>59</sup> M. Grosse Perdekamp,<sup>22, 48</sup> T. Gunji,<sup>10</sup> H.-Å. Gustafsson,<sup>35, \*</sup> A. Hadj Henni,<sup>55</sup> J.S. Haggerty,<sup>6</sup> H. Hamagaki,<sup>10</sup> R. Han,<sup>45</sup> E.P. Hartouni,<sup>32</sup> K. Haruna,<sup>20</sup> E. Haslum,<sup>35</sup> R. Hayano,<sup>10</sup> X. He,<sup>19</sup> M. Heffner,<sup>32</sup> T.K. Hemmick,<sup>54</sup> T. Hester,<sup>7</sup> J.C. Hill,<sup>25</sup> M. Hohmann,<sup>17</sup> W. Holzmann,<sup>53</sup> K. Homma,<sup>20</sup> B. Hong,<sup>28</sup> T. Horaguchi,<sup>10, 47, 57</sup> D. Hornback,<sup>56</sup> S. Huang,<sup>59</sup> T. Ichihara,<sup>47, 48</sup> R. Ichimiya,<sup>47</sup> H. Iinuma,<sup>30, 47</sup> Y. Ikeda,<sup>58</sup> K. Imai,<sup>30, 47</sup> J. Imrek,<sup>15</sup> M. Inaba,<sup>58</sup> D. Isenhower,<sup>1</sup> M. Ishihara,<sup>47</sup> T. Isobe,<sup>10, 47</sup> M. Issah,<sup>53</sup> A. Isupov,<sup>26</sup> D. Ivanischev,<sup>46</sup> B.V. Jacak,<sup>54, †</sup> J. Jia,<sup>12</sup> J. Jin,<sup>12</sup> B.M. Johnson,<sup>6</sup> K.S. Joo,<sup>39</sup> D. Jouan,<sup>44</sup> F. Kajihara,<sup>10</sup> S. Kametani,<sup>47</sup> N. Kamihara,<sup>48</sup> J. Kamin,<sup>54</sup> J.H. Kang,<sup>63</sup> J. Kapustinsky,<sup>33</sup> D. Kawall,<sup>36, 48</sup> A.V. Kazantsev,<sup>29</sup> T. Kempel,<sup>25</sup> A. Khanzadeev,<sup>46</sup> K.M. Kijima,<sup>20</sup> J. Kikuchi,<sup>60</sup> B.I. Kim,<sup>28</sup> D.H. Kim,<sup>39</sup> D.J. Kim,<sup>63</sup> E. Kim,<sup>52</sup> S.H. Kim,<sup>63</sup> E. Kinney,<sup>11</sup> K. Kiriluk,<sup>11</sup> Á. Kiss,<sup>16</sup> E. Kistenev,<sup>6</sup> J. Klay,<sup>32</sup> C. Klein-Boesing,<sup>37</sup> L. Kochenda,<sup>46</sup> B. Komkov,<sup>46</sup> M. Konno,<sup>58</sup> J. Koster,<sup>22</sup> A. Kozlov,<sup>61</sup> A. Král,<sup>13</sup> A. Kravitz,<sup>12</sup> G.J. Kunde,<sup>33</sup> K. Kurita,<sup>47, 49</sup> M. Kurosawa,<sup>47</sup> M.J. Kweon,<sup>28</sup> Y. Kwon,<sup>56</sup> G.S. Kyle,<sup>42</sup> R. Lacey,<sup>53</sup> Y.S. Lai,<sup>12</sup> J.G. Lajoie,<sup>25</sup> D. Layton,<sup>22</sup> A. Lebedev,<sup>25</sup> D.M. Lee,<sup>33</sup> K.B. Lee,<sup>28</sup> T. Lee,<sup>52</sup> M.J. Leitch,<sup>33</sup> M.A.L. Leite,<sup>51</sup> B. Lenzi,<sup>51</sup> X. Li,<sup>9</sup> P. Liebing,<sup>48</sup> T. Liška,<sup>13</sup> A. Litvinenko,<sup>26</sup> H. Liu,<sup>42</sup> M.X. Liu,<sup>33</sup> B. Love,<sup>59</sup> D. Lynch,<sup>6</sup> C.F. Maguire,<sup>59</sup> Y.I. Makdisi,<sup>5</sup> A. Malakhov,<sup>26</sup> M.D. Malik,<sup>41</sup> V.I. Manko,<sup>29</sup> E. Mannel,<sup>12</sup> Y. Mao,<sup>45, 47</sup> L. Mašek,<sup>8, 24</sup> H. Masui,<sup>58</sup> F. Matathias,<sup>12</sup> M. McCumber,<sup>54</sup> P.L. McGaughey,<sup>33</sup> N. Means,<sup>54</sup> B. Meredith,<sup>22</sup> Y. Miake,<sup>58</sup> P. Mikeš,<sup>24</sup> K. Miki,<sup>58</sup> A. Milov,<sup>6</sup> M. Mishra,<sup>3</sup> J.T. Mitchell,<sup>6</sup> A.K. Mohanty,<sup>4</sup> Y. Morino,<sup>10</sup> A. Morreale,<sup>7</sup> D.P. Morrison,<sup>6</sup> T.V. Moukhanova,<sup>29</sup> D. Mukhopadhyay,<sup>59</sup> J. Murata,<sup>47, 49</sup> S. Nagamiya,<sup>27</sup> J.L. Nagle,<sup>11</sup> M. Naglis,<sup>61</sup> M.I. Nagy,<sup>16</sup> I. Nakagawa,<sup>47, 48</sup> Y. Nakamiya,<sup>20</sup> T. Nakamura,<sup>20</sup> K. Nakano,<sup>47, 57</sup> J. Newby,<sup>32</sup> M. Nguyen,<sup>54</sup> T. Niita,<sup>58</sup> R. Nouicer,<sup>6</sup> A.S. Nyanin,<sup>29</sup> E. O'Brien,<sup>6</sup> S.X. Oda,<sup>10</sup> C.A. Ogilvie,<sup>25</sup> M. Oka,<sup>58</sup> K. Okada,<sup>48</sup> Y. Onuki,<sup>47</sup> A. Oskarsson,<sup>35</sup> M. Ouchida,<sup>20</sup> K. Ozawa,<sup>10</sup> R. Pak,<sup>6</sup> A.P.T. Palounek,<sup>33</sup> V. Pantuev,<sup>23, 54</sup> V. Papavassiliou,<sup>42</sup> J. Park,<sup>52</sup> W.J. Park,<sup>28</sup> S.F. Pate,<sup>42</sup> H. Pei,<sup>25</sup> J.-C. Peng,<sup>22</sup> H. Pereira,<sup>14</sup> V. Peresedov,<sup>26</sup> D.Yu. Peressounko,<sup>29</sup> C. Pinkenburg,<sup>6</sup> M.L. Purschke,<sup>6</sup> A.K. Purwar,<sup>33</sup> H. Qu,<sup>19</sup> J. Rak,<sup>41</sup> A. Rakotozafindrabe,<sup>31</sup> I. Ravinovich,<sup>61</sup> K.F. Read,<sup>43, 56</sup> S. Rembeczki,<sup>17</sup> K. Reygers,<sup>37</sup> V. Riabov,<sup>46</sup> Y. Riabov,<sup>46</sup> D. Roach,<sup>59</sup> G. Roche,<sup>34</sup> S.D. Rolnick,<sup>7</sup> M. Rosati,<sup>25</sup> S.S.E. Rosendahl,<sup>35</sup> P. Rosnet,<sup>34</sup> P. Rukoyatkin,<sup>26</sup> P. Ružička,<sup>24</sup> V.L. Rykov,<sup>47</sup> B. Sahlmueller,<sup>37</sup> N. Saito,<sup>30, 47, 48</sup> T. Sakaguchi,<sup>6</sup> S. Sakai,<sup>58</sup> K. Sakashita,<sup>47, 57</sup> V. Samsonov,<sup>46</sup> T. Sato,<sup>58</sup> S. Sawada,<sup>27</sup> K. Sedgwick,<sup>7</sup> J. Seele,<sup>11</sup> R. Seidl,<sup>22</sup> A.Yu. Semenov,<sup>25</sup> V. Semenov,<sup>21</sup> R. Seto,<sup>7</sup> D. Sharma,<sup>61</sup> I. Shein,<sup>21</sup> T.-A. Shibata,<sup>47, 57</sup> K. Shigaki,<sup>20</sup> M. Shimomura,<sup>58</sup> K. Shoji,<sup>30, 47</sup> P. Shukla,<sup>4</sup> A. Sickles,<sup>6</sup> C.L. Silva,<sup>51</sup> D. Silvermyr,<sup>43</sup> C. Silvestre,<sup>14</sup> K.S. Sim,<sup>28</sup> B.K. Singh,<sup>3</sup> C.P. Singh,<sup>3</sup> V. Singh,<sup>3</sup> M. Slunečka,<sup>8</sup> A. Soldatov,<sup>21</sup> R.A. Soltz,<sup>32</sup> W.E. Sondheim,<sup>33</sup> S.P. Sorensen,<sup>56</sup> I.V. Sourikova,<sup>6</sup> F. Staley,<sup>14</sup> P.W. Stankus,<sup>43</sup> E. Stenlund,<sup>35</sup> M. Stepanov,<sup>42</sup> A. Ster,<sup>62</sup> S.P. Stoll,<sup>6</sup> T. Sugitate,<sup>20</sup> C. Suire,<sup>44</sup> A. Sukhanov,<sup>6</sup> J. Sziklai,<sup>62</sup> E.M. Takagui,<sup>51</sup> A. Taketani,<sup>47, 48</sup> R. Tanabe,<sup>58</sup> Y. Tanaka,<sup>40</sup> S. Taneja,<sup>54</sup> K. Tanida,<sup>47, 48, 52</sup> M.J. Tannenbaum,<sup>6</sup> A. Taranenko,<sup>53</sup> P. Tarján,<sup>15</sup> H. Themann,<sup>54</sup> T.L. Thomas,<sup>41</sup> M. Togawa,<sup>30, 47</sup> A. Toia,<sup>54</sup> L. Tomášek,<sup>24</sup> Y. Tomita,<sup>58</sup> H. Torii,<sup>20, 47</sup> R.S. Towell,<sup>1</sup> V.-N. Tram,<sup>31</sup> I. Tserruya,<sup>61</sup> Y. Tsuchimoto,<sup>20</sup> C. Vale,<sup>25</sup> H. Valle,<sup>59</sup> H.W. van Hecke,<sup>33</sup> A. Veicht,<sup>22</sup> J. Velkovska,<sup>59</sup> R. Vértesi,<sup>15</sup> A.A. Vinogradov,<sup>29</sup> M. Virius,<sup>13</sup> V. Vrba,<sup>24</sup> E. Vznuzdaev,<sup>46</sup> X.R. Wang,<sup>42</sup> Y. Watanabe,<sup>47, 48</sup> F. Wei,<sup>25</sup> J. Wessels,<sup>37</sup> S.N. White,<sup>6</sup> D. Winter,<sup>12</sup> C.L. Woody,<sup>6</sup> M. Wysocki,<sup>11</sup> W. Xie,<sup>48</sup> Y.L. Yamaguchi,<sup>60</sup> K. Yamaura,<sup>20</sup> R. Yang,<sup>22</sup> A. Yanovich,<sup>21</sup> J. Ying,<sup>19</sup> S. Yokkaichi,<sup>47, 48</sup>

G.R. Young,<sup>43</sup> I. Younus,<sup>41</sup> I.E. Yushmanov,<sup>29</sup> W.A. Zajc,<sup>12</sup> O. Zaudtke,<sup>37</sup> C. Zhang,<sup>43</sup> S. Zhou,<sup>9</sup> and L. Zolin<sup>26</sup>

(PHENIX Collaboration)

- <sup>1</sup>Abilene Christian University, Abilene, Texas 79699, USA  
<sup>2</sup>Institute of Physics, Academia Sinica, Taipei 11529, Taiwan  
<sup>3</sup>Department of Physics, Banaras Hindu University, Varanasi 221005, India  
<sup>4</sup>Bhabha Atomic Research Centre, Bombay 400 085, India  
<sup>5</sup>Collider-Accelerator Department, Brookhaven National Laboratory, Upton, New York 11973-5000, USA  
<sup>6</sup>Physics Department, Brookhaven National Laboratory, Upton, New York 11973-5000, USA  
<sup>7</sup>University of California - Riverside, Riverside, California 92521, USA  
<sup>8</sup>Charles University, Ovocný trh 5, Praha 1, 116 36, Prague, Czech Republic  
<sup>9</sup>Science and Technology on Nuclear Data Laboratory, China Institute of Atomic Energy, Beijing 102413, P. R. China  
<sup>10</sup>Center for Nuclear Study, Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan  
<sup>11</sup>University of Colorado, Boulder, Colorado 80309, USA  
<sup>12</sup>Columbia University, New York, New York 10027 and Nevis Laboratories, Irvington, New York 10533, USA  
<sup>13</sup>Czech Technical University, Zikova 4, 166 36 Prague 6, Czech Republic  
<sup>14</sup>Dapnia, CEA Saclay, F-91191, Gif-sur-Yvette, France  
<sup>15</sup>Debrecen University, H-4010 Debrecen, Egyetem tér 1, Hungary  
<sup>16</sup>ELTE, Eötvös Loránd University, H - 1117 Budapest, Pázmány P. s. 1/A, Hungary  
<sup>17</sup>Florida Institute of Technology, Melbourne, Florida 32901, USA  
<sup>18</sup>Florida State University, Tallahassee, Florida 32306, USA  
<sup>19</sup>Georgia State University, Atlanta, Georgia 30303, USA  
<sup>20</sup>Hiroshima University, Kagamiyama, Higashi-Hiroshima 739-8526, Japan  
<sup>21</sup>IHEP Protvino, State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, 142281, Russia  
<sup>22</sup>University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA  
<sup>23</sup>Institute for Nuclear Research of the Russian Academy of Sciences, prospekt 60-letiya Oktyabrya 7a, Moscow 117312, Russia  
<sup>24</sup>Institute of Physics, Academy of Sciences of the Czech Republic, Na Slovance 2, 182 21 Prague 8, Czech Republic  
<sup>25</sup>Iowa State University, Ames, Iowa 50011, USA  
<sup>26</sup>Joint Institute for Nuclear Research, 141980 Dubna, Moscow Region, Russia  
<sup>27</sup>KEK, High Energy Accelerator Research Organization, Tsukuba, Ibaraki 305-0801, Japan  
<sup>28</sup>Korea University, Seoul, 136-701, Korea  
<sup>29</sup>Russian Research Center "Kurchatov Institute", Moscow, 123098 Russia  
<sup>30</sup>Kyoto University, Kyoto 606-8502, Japan  
<sup>31</sup>Laboratoire Leprince-Ringuet, Ecole Polytechnique, CNRS-IN2P3, Route de Saclay, F-91128, Palaiseau, France  
<sup>32</sup>Lawrence Livermore National Laboratory, Livermore, California 94550, USA  
<sup>33</sup>Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA  
<sup>34</sup>LPC, Université Blaise Pascal, CNRS-IN2P3, Clermont-Fd, 63177 Aubiere Cedex, France  
<sup>35</sup>Department of Physics, Lund University, Box 118, SE-221 00 Lund, Sweden  
<sup>36</sup>Department of Physics, University of Massachusetts, Amherst, Massachusetts 01003-9337, USA  
<sup>37</sup>Institut für Kernphysik, University of Muenster, D-48149 Muenster, Germany  
<sup>38</sup>Muhlenberg College, Allentown, Pennsylvania 18104-5586, USA  
<sup>39</sup>Myongji University, Yongin, Kyonggido 449-728, Korea  
<sup>40</sup>Nagasaki Institute of Applied Science, Nagasaki-shi, Nagasaki 851-0193, Japan  
<sup>41</sup>University of New Mexico, Albuquerque, New Mexico 87131, USA  
<sup>42</sup>New Mexico State University, Las Cruces, New Mexico 88003, USA  
<sup>43</sup>Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA  
<sup>44</sup>IPN-Orsay, Université Paris Sud, CNRS-IN2P3, BP1, F-91406, Orsay, France  
<sup>45</sup>Peking University, Beijing 100871, P. R. China  
<sup>46</sup>PNPI, Petersburg Nuclear Physics Institute, Gatchina, Leningrad region, 188300, Russia  
<sup>47</sup>RIKEN Nishina Center for Accelerator-Based Science, Wako, Saitama 351-0198, Japan  
<sup>48</sup>RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973-5000, USA  
<sup>49</sup>Physics Department, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima, Tokyo 171-8501, Japan  
<sup>50</sup>Saint Petersburg State Polytechnic University, St. Petersburg, 195251 Russia  
<sup>51</sup>Universidade de São Paulo, Instituto de Física, Caixa Postal 66318, São Paulo CEP05315-970, Brazil  
<sup>52</sup>Seoul National University, Seoul, Korea  
<sup>53</sup>Chemistry Department, Stony Brook University, SUNY, Stony Brook, New York 11794-3400, USA  
<sup>54</sup>Department of Physics and Astronomy, Stony Brook University, SUNY, Stony Brook, New York 11794-3400, USA  
<sup>55</sup>SUBATECH (Ecole des Mines de Nantes, CNRS-IN2P3, Université de Nantes) BP 20722 - 44307, Nantes, France  
<sup>56</sup>University of Tennessee, Knoxville, Tennessee 37996, USA  
<sup>57</sup>Department of Physics, Tokyo Institute of Technology, Oh-okayama, Meguro, Tokyo 152-8551, Japan  
<sup>58</sup>Institute of Physics, University of Tsukuba, Tsukuba, Ibaraki 305, Japan  
<sup>59</sup>Vanderbilt University, Nashville, Tennessee 37235, USA  
<sup>60</sup>Waseda University, Advanced Research Institute for Science and Engineering, 17 Kikui-cho, Shinjuku-ku, Tokyo 162-0044, Japan

<sup>61</sup>Weizmann Institute, Rehovot 76100, Israel

<sup>62</sup>Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Hungarian Academy of Sciences (Wigner RCP, RMKI), H-1525 Budapest 114, POBox 49, Budapest, Hungary

<sup>63</sup>Yonsei University, IPAP, Seoul 120-749, Korea

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Unpolarized cross sections and double-helicity asymmetries of single-inclusive positive and negative charged hadrons at midrapidity from  $p+p$  collisions at  $\sqrt{s} = 62.4$  GeV are presented. The PHENIX measurement of the cross sections for  $1.0 < p_T < 4.5$  GeV/ $c$  are consistent with perturbative QCD calculations at next-to-leading order in the strong-coupling constant,  $\alpha_s$ . Resummed pQCD calculations including terms with next-to-leading-log accuracy, yielding reduced theoretical uncertainties, also agree with the data. The double-helicity asymmetry, sensitive at leading order to the gluon polarization in a momentum-fraction range of  $0.05 \lesssim x_{gluon} \lesssim 0.2$ , is consistent with recent global parameterizations disfavoring large gluon polarization.

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## I. INTRODUCTION

The comparison of cross-section predictions with data on single-inclusive hadron production in hadronic collisions,  $p+p \rightarrow h + X$ , is important for understanding perturbative quantum chromodynamics (pQCD). For hadrons produced with transverse momenta  $p_T \gg \Lambda_{QCD}$ , the cross section factorizes into a convolution involving long-distance and short-distance components [1, 2]. Long-distance components include universal parton-distribution functions (PDFs) describing the partonic structure of the initial hadrons and fragmentation functions (FFs) for the final-state hadron. The short-distance part describes the hard scattering of partons. The long-distance components, PDFs and FFs, can be extracted from other processes, such as deep-inelastic scattering and hadron production in  $e^+e^-$  colliders. This allows for a test of the short-distance part of the convolution, which can be estimated using pQCD. In particular, differences between data and predictions can indicate the importance of neglected higher-order terms in the expansion or power-suppressed contributions [3].

Next-to-leading-order (NLO) pQCD and collinear factorization successfully describe RHIC cross-section measurements at a center-of-mass energy ( $\sqrt{s}$ ) of 200 GeV for midrapidity neutral pions [4, 5], jets [6–8], and direct photons [9], as well as forward rapidity pions and kaons [10, 11]. However, at lower  $\sqrt{s}$ , in particular in fixed-target experiments with  $20 \lesssim \sqrt{s} \lesssim 40$  GeV, NLO pQCD calculations significantly underpredict hadron production, by factors of three or more [3]. The consistency between NLO estimations and data at low  $\sqrt{s}$  was improved [3, 12, 13] by including the resummation of large logarithmic corrections to the partonic cross section to all orders in the strong coupling  $\alpha_s$ . The corrections are of the form  $\alpha_s^k \ln^{2k} (1 - \hat{x}_T^2)$  for the  $k$ th-order term in the perturbative expansion. Here  $\hat{x}_T \equiv 2\hat{p}_T/\sqrt{\hat{s}}$ , where

$\hat{p}_T = p_T/z$  is the transverse momentum of the parton fragmenting into the observed hadron with a fraction  $z$  of the parton transverse momentum, and  $\sqrt{\hat{s}} = \sqrt{x_1 x_2 s}$  is the partonic center-of-mass energy where  $x_1, x_2$  are momentum fractions carried by two interacting partons. The corrections are especially relevant in the threshold regime  $\hat{x}_T \rightarrow 1$  in which the initial partons have just enough energy to produce a high-transverse-momentum parton fragmenting into the observed hadron. In this regime gluon Bremsstrahlung is suppressed, and these corrections are large [12]. However, the addition of the resummed next-to-leading-log (NLL) terms to an NLO calculation may not provide the best means of describing data in a given kinematic region, for example, when the (unknown) higher-order terms that are omitted from the calculation have comparable magnitude and opposite sign to the NLL terms. It is therefore important to test pQCD calculations against data in a region of intermediate  $\sqrt{s}$ , to better define the kinematic ranges over which pQCD calculations can be applied with confidence.

The PHENIX-detector data presented here for non-identified charged-hadron production make use of approximately five times the acceptance and different detection techniques compared to our previous identified-charged-hadron analysis [14]. The new results allow tests of NLO and NLL predictions based on an independent measurement. In addition, the theoretical calculations make use of different fragmentation functions than for identified particle calculations. Alternatively, assuming the reliability of the short-distance aspects of the theory, the data may be used to refine our knowledge of fragmentation functions. Present measurements also cover a greater  $p_T$  range than the identified charged-hadron cross sections, where the measured momentum ranges for pions, kaons, and protons are 0.3–3 GeV/ $c$ , 0.4–2 GeV/ $c$  and 0.5–4.5 GeV/ $c$  respectively [14]. These cross-section measurements of nonidentified charged hadrons (combinations of  $\pi^\pm, K^\pm, p^\pm$ ) are also important as baselines for extracting nuclear modification factors in high- $p_T$  hadron production in heavy ion collisions at RHIC [15, 16].

The charged hadrons in these measurements were produced from collisions of transversely- and longitudinally-

\*Deceased

†PHENIX Spokesperson: jacak@skipper.physics.sunysb.edu

polarized proton beams, a unique capability of RHIC [17]. While the cross-section measurements discussed above require averaging over the beam polarizations, sorting the hadron yields by colliding proton helicities (for longitudinal beam polarizations) provides sensitivity to the helicity PDFs [18]. The ability to probe helicity PDFs is essential for understanding the spin structure of the proton [19].

The spin of the proton originates from the spin and orbital angular momenta of its quark, antiquark, and gluon constituents. The contribution carried by quark and antiquark spin, determined from polarized deep-inelastic scattering (pDIS) experiments [20–30] using polarized leptons and polarized nucleons, is  $\sim 25\%$  [19, 31–33]. This is surprisingly small [19] and implies that the majority of the spin of the proton must originate from gluon spin and/or orbital angular momentum.

Colliding longitudinally-polarized proton beams provides sensitivity to the gluon-helicity distribution function at leading order. The helicity-dependent difference in hadron production is defined as:

$$\frac{d\Delta\sigma}{dp_T} \equiv \frac{1}{2} \left[ \frac{d\sigma^{++}}{dp_T} - \frac{d\sigma^{+-}}{dp_T} \right],$$

where the superscripts  $++$  and  $+-$  refer to same and opposite helicity combinations of the colliding protons [18]. Factorization allows this to be written as a convolution of the long- and short-distance terms summed over all possible flavors for the partonic interaction  $a + b \rightarrow c + X'$ , where  $c$  fragments into the detected hadron  $h$ :

$$\begin{aligned} \frac{d\Delta\sigma}{dp_T} &= \sum_{abc} \int dx_a dx_b dz_c \Delta f_a(x_a, \mu_f) \Delta f_b(x_b, \mu_f) \\ &\times \frac{d\Delta\hat{\sigma}^{ab \rightarrow cX'}}{dp_T}(x_a P_a, x_b P_b, P^h/z_c, \mu_f, \mu'_f, \mu_r) \\ &\times D_c^h(z_c, \mu'_f), \end{aligned} \quad (1)$$

where  $\Delta f(x, \mu_f)$  are the polarized PDFs of the colliding partons carrying light-cone momentum fraction  $x$  evaluated at factorization scale  $\mu_f$ . The fragmentation function of scattered parton  $c$  into hadron  $h$  with fraction  $z_c$  of the scattered parton momentum is  $D_c^h(z_c, \mu'_f)$  at fragmentation scale  $\mu'_f$ . The helicity-dependent difference in the cross section of the hard partonic scattering  $a + b \rightarrow c + X'$  is denoted by  $d\Delta\hat{\sigma}$  and is calculable in perturbative QCD. Cross section calculations to finite order in  $\alpha_s$  have a dependence on factorization and renormalization scales  $\mu_f$  and  $\mu_r$ .

Instead of directly measuring the helicity-dependent cross-section difference  $d\Delta\sigma/dp_T$ , we extract the double-longitudinal spin asymmetry defined as the ratio of the polarized to unpolarized cross sections  $A_{LL} \equiv d\Delta\sigma/d\sigma$ . Here,  $d\sigma$  is the helicity-averaged (unpolarized) cross section  $d\sigma \equiv [d\sigma_{(++)} + d\sigma_{(+-)}]/2$ . The ratio  $d\Delta\sigma/d\sigma$  has smaller systematic uncertainties since some of the uncertainties cancel.

At  $\sqrt{s} = 62.4$  GeV, the production of final-state hadrons at midrapidity in a transverse momentum range  $1.5 \leq p_T \leq 4.5$  GeV/ $c$  is dominated by quark-gluon scattering [34]. This makes the asymmetry reported here,  $A_{LL}(p+p \rightarrow h^\pm + X)$ , sensitive to the polarized gluon PDF  $\Delta G(x)$  at leading order, and more sensitive to its sign than processes dominated by gluon-gluon scattering or which produce isospin-symmetric particles. For example, preferential fragmentation of up quarks into positive pions and down quarks into negative pions, combined with the fact that the up quark helicity PDF is positive and the down quark helicity PDF is negative, would lead to an ordering of the asymmetries of pions (charged and neutral) directly sensitive to the sign of the gluon helicity PDF. Positive  $\Delta G(x)$  would lead to  $A_{LL}^{\pi^+} \geq A_{LL}^{\pi^0} \geq A_{LL}^{\pi^-}$ , whereas a negative  $\Delta G(x)$  would imply an opposite ordering. These results can be combined with data from polarized collider and fixed target experiments in a global analysis to reduce uncertainties on the gluon helicity distribution [35, 36].

## II. EXPERIMENTAL SETUP

This analysis uses the PHENIX central arm spectrometers. Each arm has an acceptance covering a pseudorapidity range  $|\eta| < 0.35$  and  $\Delta\phi = \frac{\pi}{2}$  in azimuth [37, 38]. The PHENIX central magnet creates an axial magnetic field with  $\int Bdl = 0.78$  T·m at  $\frac{\pi}{2}$  in this region.

Midrapidity charged hadrons are tracked in the drift chambers (DC), which are located outside the magnetic field with an inner radius of 2.0 m and outer radius of 2.4 m. The tracks are reconstructed as nearly straight lines and yield the deflection in the axial magnetic field to determine the transverse momentum with a resolution  $\frac{dp_T}{p_T} = 0.007 \oplus 0.009 p_T$  (GeV/ $c$ ) [39]. The first term in the resolution is dominated by multiple scattering in material before the DC, while the second arises from the finite angular resolution of the DC. The momentum scale is set by requiring the proton mass reconstructed from the measured momentum and time of flight to match the known proton mass.

Track reconstruction also utilizes two layers of pad chambers (PC), which are multiwire proportional chambers with pad readout [38]. The first layer, PC1, is located after the DC, with an average radius of 2.49 m. PC1 information is used in conjunction with the DC hits and vertex information to determine the polar angle for each charged track. The outermost layer PC3 is at an average radius of 4.98 m and is used for charged track selection by matching PC3 hit positions with tracks projected using information from the DC and PC1 and the measured event vertex. Matching projected tracks with hit positions in PC3 also helps in rejecting decay backgrounds from primary hadrons.

Vertex and timing information is provided by two beam-beam counters (BBCs) [37] placed around the beam pipe. The BBCs are located 1.44 m forward and

backward of the nominal interaction point. Each BBC comprises an array of 64 phototubes fitted with 3 cm long quartz radiators. The phototubes detect Čerenkov radiation from charged particles traversing the quartz. The detectors cover a pseudorapidity range of  $3.0 \leq |\eta| \leq 3.9$ , and a full  $\Delta\phi = 2\pi$  in azimuth. A coincidence of hits from the two BBCs forms the minimum bias trigger, with timing information providing the location of the event vertex along the beam line with a few cm precision.

To eliminate the  $e^\pm$  background due to photon conversion in material before the DC (primarily the beam pipe and DC entrance window), the analysis uses information from a ring imaging Čerenkov detector (RICH) [38] located after the DC. The RICH uses  $\text{CO}_2$  at atmospheric pressure as a radiator, with a momentum threshold of 17 MeV/c for  $e^\pm$  and 4.7 GeV/c for charged pions. A RICH veto (ensuring no RICH hits) is used to reject  $e^\pm$  and results in an upper transverse-momentum limit of  $p_T < 4.5$  GeV/c for charged hadrons in the analysis.

Zero degree calorimeters (ZDC), which detect neutral particles near the beam pipe ( $\theta < 2.5$  mrad) are used in conjunction with the BBC to estimate the systematic uncertainty on the relative luminosity for the asymmetry measurements [40]. The BBC and ZDC are also used to determine the integrated luminosity measurement [41, 42].

The stable spin direction of polarized protons in RHIC is vertical. The spin direction can be rotated into the longitudinal direction at the PHENIX interaction region using pairs of spin rotators. The polarizations of the beams at RHIC are measured every few hours by carbon target polarimeters [43], which are normalized to an absolute measurement with a hydrogen jet target polarimeter [44].

### III. CROSS SECTION

The results presented here are the first measurements of the cross section of inclusive charged-hadron production at midrapidity in the transverse momentum range  $0.5 \leq p_T \leq 4.5$  GeV/c from  $p+p$  collisions at  $\sqrt{s} = 62.4$  GeV. The analysis techniques are similar to methods described in Ref. [45] and are briefly explained in Sect. III A. The cross section results are presented and discussed in Sect. III B.

#### A. Cross Section Measurement

Approximately  $2.14 \times 10^8$  BBC-triggered events corresponding to an integrated luminosity of  $15.6 \text{ nb}^{-1}$  from polarization-averaged  $p+p$  data taken in 2006 have been analyzed. We calculate the midrapidity charged-hadron production cross section using the following formula:

$$\frac{E}{c} \frac{d^3\sigma}{dp^3} = \frac{\sigma_{\text{BBC}}}{N_{\text{BBC}}} \frac{d^3N(p_T)}{d\phi_T dp_T dy} R_{\text{smear}} C_{\text{trig}} \frac{1}{E_{\text{eff}}^{\text{acc}}}, \quad (2)$$

where  $\sigma_{\text{BBC}}$  is the  $p+p$  cross section seen by the BBC as measured in Ref. [40],  $N_{\text{BBC}}$  is the total number of BBC-triggered events analyzed,  $R_{\text{smear}}$  is the correction factor for the smearing of track  $p_T$  owing to the momentum resolution of the detectors as well as multiple scattering of the hadron tracks,  $C_{\text{trig}}$  is the correction factor for BBC trigger bias and  $E_{\text{eff}}^{\text{acc}}$  is the combined correction factor for geometrical acceptance of the detectors and reconstruction efficiency.

The reconstructed charged tracks in the transverse momentum range  $0.5 \leq p_T \leq 4.5$  GeV/c from events with vertices within  $\pm 30$  cm of the nominal interaction point are matched to projected hit positions in PC3 in azimuthal ( $\phi$ ) and beam direction ( $z$ ). Distributions of the matching variables (difference between the projected track position and actual hits on PC3, termed PC3d $\phi$  and PC3dz) are fit with the combination of a signal Gaussian and a second Gaussian for background. Figure 1 demonstrates the method for a sample  $p_T$  bin. The width of the fit to the signal distribution is used to impose a simultaneous selection window of  $2\sigma$  for both matching variables.

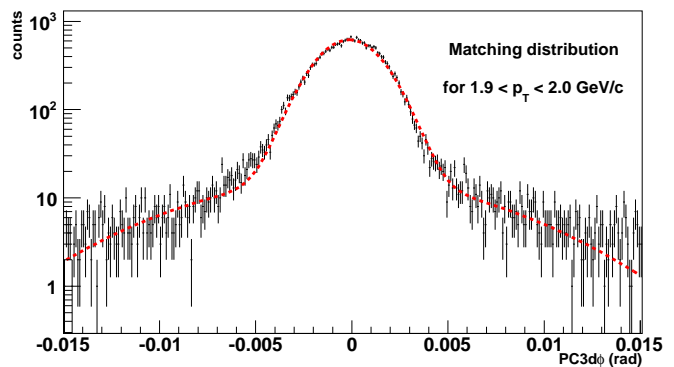


FIG. 1: (color online) Difference between the track-extrapolated and actual hit positions on PC3 in azimuth for a sample  $p_T$  bin. The histogram represents data; the dashed line represents a two-Gaussian fit.

The background to these measurements comes from several sources. One source is soft electrons from the magnet pole faces, and another is decays in flight of  $\pi^\pm$  and  $K^\pm$ . Not all of these electrons are rejected by the RICH cut. Off-vertex electrons and daughter particles with a perpendicular momentum kick from the decay are reconstructed as apparent high- $p_T$  tracks, but with wide Gaussian track matching distributions. The background fraction in each of the  $p_T$  bins is determined by using the distributions of the matching variables. Background fractions, which are 2–5% for  $p_T \leq 2.75$  GeV/c and  $\sim 30\%$  in the highest  $p_T$  bin, are subsequently subtracted from hadron yields.

An additional source of background is the feed-down background produced by weak decays of mostly  $\Lambda$  particles close to the event vertex with apparent momenta

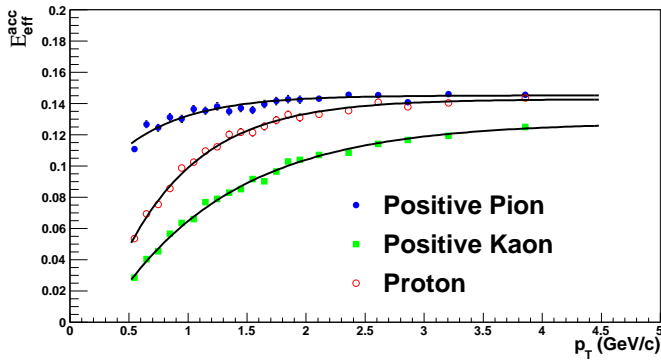


FIG. 2: (color online) Combined acceptance + detection efficiencies for separate hadron species.

close to their true momenta and matching distributions peaked under the signal. Feed-down contributions to the detected protons and antiprotons from weak decays of  $\Lambda$ 's and heavier hyperons are estimated using input  $\Lambda$  and  $\bar{\Lambda}$  spectra from  $p+p$  measurements at  $\sqrt{s} = 63$  GeV at the ISR [46, 47] and at  $\sqrt{s} = 62.4$  GeV at PHENIX with a GEANT3 [48]-based simulation of the PHENIX detector. The fractional contributions of the feed-down protons and antiprotons are independent of  $p_T$  above  $p_T = 2$  GeV/c and are close to 7 and 15% respectively. Below  $p_T = 2$  GeV/c the fractions increase with decreasing  $p_T$  and are roughly 25 and 60% for protons and antiprotons respectively at  $p_T = 0.5$  GeV/c.

Background-subtracted yields are corrected for angular resolution of the DC and for smearing of the reconstructed momenta resulting from multiple scattering of tracks, which depends on hadron mass. To account for the acceptance of the PHENIX detector system and the varying efficiency for different hadrons, single-particle Monte-Carlo simulations are performed and verified by comparing the live detector area between data and Monte Carlo, and appropriate correction factors are determined separately for each hadron species.

TABLE I: Fit-function parameters for the efficiency curves for different hadron species. See text for details.

hadron	A	B	C
$\pi^+$	-0.08	-1.8	0.1453
$K^+$	-0.17	-0.97	0.1280
$p$	-0.21	-1.54	0.1428
$\pi^-$	-0.07	-1.7	0.1449
$K^-$	-0.17	-1.01	0.1276
$p^-$	-0.21	-1.56	0.1424

Figure 2 shows the efficiencies for the three positive hadron species. The small efficiency for kaons is due to decays in flight. The large decrease in efficiency at low  $p_T$  is due to the fact that the fixed pseudorapidity accep-

TABLE II: Fit-function parameters for relative fractions of different species in the hadron mix. See text for details.

hadron	A	B	C	D
$\pi^+$	1.02	-2.39	0.57	-
$K^+$	-0.53	-2.39	0.20	0.009
$p$	-0.49	-2.39	0.23	-0.009
$\pi^-$	1.17	-2.49	0.61	0.012
$K^-$	-0.61	-2.49	0.20	-
$p^-$	-0.56	-2.49	0.18	-0.012

TABLE III: Systematic uncertainties of cross section measurements from various sources.

Source	Systematic Uncertainty
Acceptance & efficiency correction	11–24%
$\sigma_{\text{BBC}}$	11%
Trigger bias	2.5%
Monte Carlo/data scale factor	2%
PID fraction	1–5%
Background fraction	1–5%
Momentum smearing correction	1–2%

tance of the detector corresponds to a narrow range in rapidity for smaller  $p_T/m$ . The efficiencies are parameterized ( $Ae^{Bp_T} + C$ ) as a function of  $p_T$ . Table I shows the fit-function parameters. The fit values are used for the calculation of cross sections. The species-dependent corrections are applied according to their production fraction (Fig. 3) in the hadron mixture. The production fractions were determined from identified hadron spectra from PHENIX [14], as well as earlier data from the ISR [46]. Dotted and dashed lines in Fig. 2 represent fits with individual data sets. Parameterized fits of the form  $Ae^{Bp_T} + C$  (for positive pions and negative kaons) and  $Ae^{Bp_T} + C + Dp_T$  (for all other species) are performed under the constraint that the sum of the relative fractions is 1. Table II gives the fit-function parameters. Relative fractions from fit values are used to apply the corrections. The corrected yields are scaled by the BBC trigger bias as described in Ref. [40].

The integrated luminosity  $\mathcal{L}_{int} = \frac{N_{\text{BBC}}}{\sigma_{\text{BBC}}}$ , required for normalization of the invariant cross section, is calculated using the count of BBC-triggered events and the BBC normalization parameter  $\sigma_{\text{BBC}}$ . The parameter  $\sigma_{\text{BBC}}$  is the  $p+p$  cross section seen by the BBC and is measured by the Van der Meer (Vernier) scan technique [42]. The quantity  $\sigma_{\text{BBC}} = 13.7 \pm 1.5^{\text{syst}}$  mb for the relevant data set has been measured for previous PHENIX results and was discussed in detail in Ref. [40].

Table III shows the systematic uncertainties of cross section measurements from various sources. The largest contribution (11–24%) to the  $p_T$ -dependent systematic uncertainty comes from the correction for the acceptance



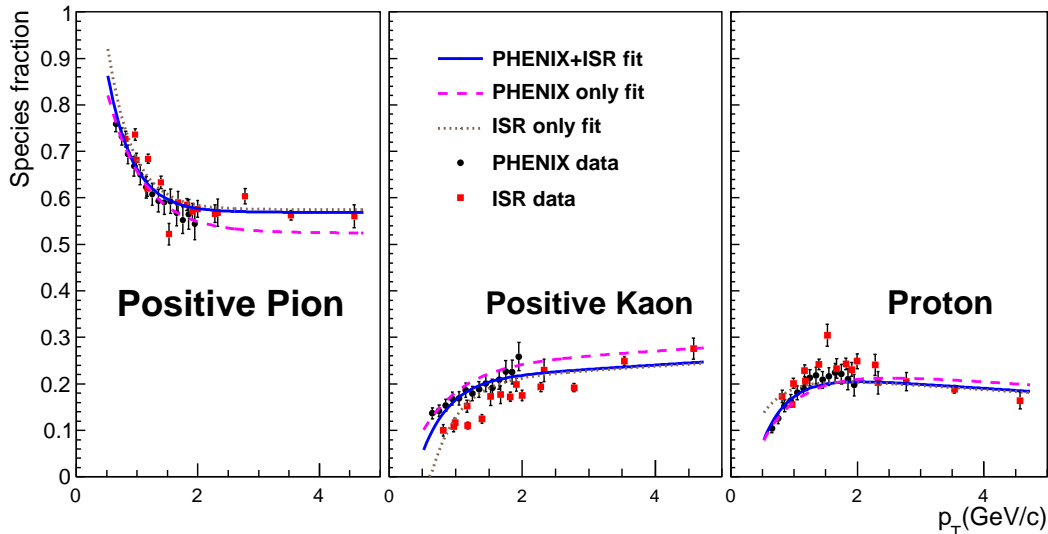


FIG. 3: (color online) Relative fraction of each species for positive hadrons. The error bars on the data points are combined statistical and systematic uncertainties. The solid line represents a fit to both the PHENIX and ISR data. The dashed (dotted) line represents a fit to only the PHENIX (ISR) data.

and detection efficiencies. The uncertainty on the cross section due to this correction factor is determined by varying the selection parameters in the MC simulations. The trigger bias introduces a 2.5% uncertainty in the overall normalization, in addition to the 11% uncertainty on  $\sigma_{\text{BBC}}$ . Determination of the background fraction and the production fraction of separate hadron species each introduces a 1–5%  $p_T$ -dependent systematic uncertainty. Uncertainties from other sources, for example the correction for momentum resolution, the correction for the active area of the detector in experiment and Monte Carlo, are  $\sim 1$ –2%.

## B. Cross Section Results

Figure 4 and Table IV show the inclusive charged-hadron cross sections from  $p + p$  collisions at  $\sqrt{s} = 62.4$  GeV as a function of  $p_T$ . A combined  $p_T$ -independent normalization uncertainty of 11.2% (uncertainties in the measurements of  $\sigma_{\text{BBC}}$  and BBC trigger bias) is not shown.

In the overlapping  $p_T$  range, the results were found to be consistent with the species-combined cross sections from identified results at PHENIX [14] as well as ISR results at  $\sqrt{s} = 63$  GeV [46]. On the upper panels of both plots in Fig. 4 the cross sections are compared to NLO and NLL calculations at a factorization, renormalization and fragmentation scale of  $\mu = p_T$  [49]. The calculations were performed using Martin-Roberts-Stirling-Thorne (MRST2002) PDFs [50] and deFlorian-Sassot-Stratmann (DSS) fragmentation functions [51]. The NLO predictions have been shown to describe midra-

pidity cross section results for neutral pions [52, 53] and charged hadrons [45] at  $\sqrt{s} = 200$  GeV within  $\sim 20\%$  for a scale choice of  $\mu = p_T$ . For the present results at  $\sqrt{s} = 62.4$  GeV, however, the NLO calculations underpredict the data by as much as  $\sim 80\%$  in the case of positive hadrons and  $\sim 60\%$  in the case of negative hadrons for the same scale choice. The lower two panels in the Fig. 4 plots show the dependence of the theoretical calculations on the choice of factorization, renormalization and fragmentation scale ( $\mu$ ) for three different values ( $p_T$ ,  $p_T/2$ , and  $2p_T$ ). The inclusion of higher-order terms in the NLL calculations leads to a considerably smaller scale dependence.

These new data at an energy intermediate to typical fixed-target and collider energies are timely, as the details of how to work with resummation techniques in different kinematic regimes are currently being explored by the theoretical community (see for example [3, 12, 13]). Comparison of the present results to the calculations at NLO with and without NLL terms included indicates that in the measured kinematic range, NLL terms make relevant contributions to the cross section. However, the tendency of the NLL calculations to overpredict the data, by as much as  $\sim 40\%$  in the case of positive hadrons and  $\sim 50\%$  in the case of negative hadrons for a scale choice of  $p_T$ , may indicate that there are terms in the full next-to-next-to-leading-order (NNLO) expansion that are of comparable magnitude and opposite sign to those in the NLL calculation. These measurements corroborate similar indications from neutral pion cross section results [40] and identified hadron cross section results [14] at PHENIX. The present measurements can also be useful in a future determination of inclusive charged-hadron fragmentation

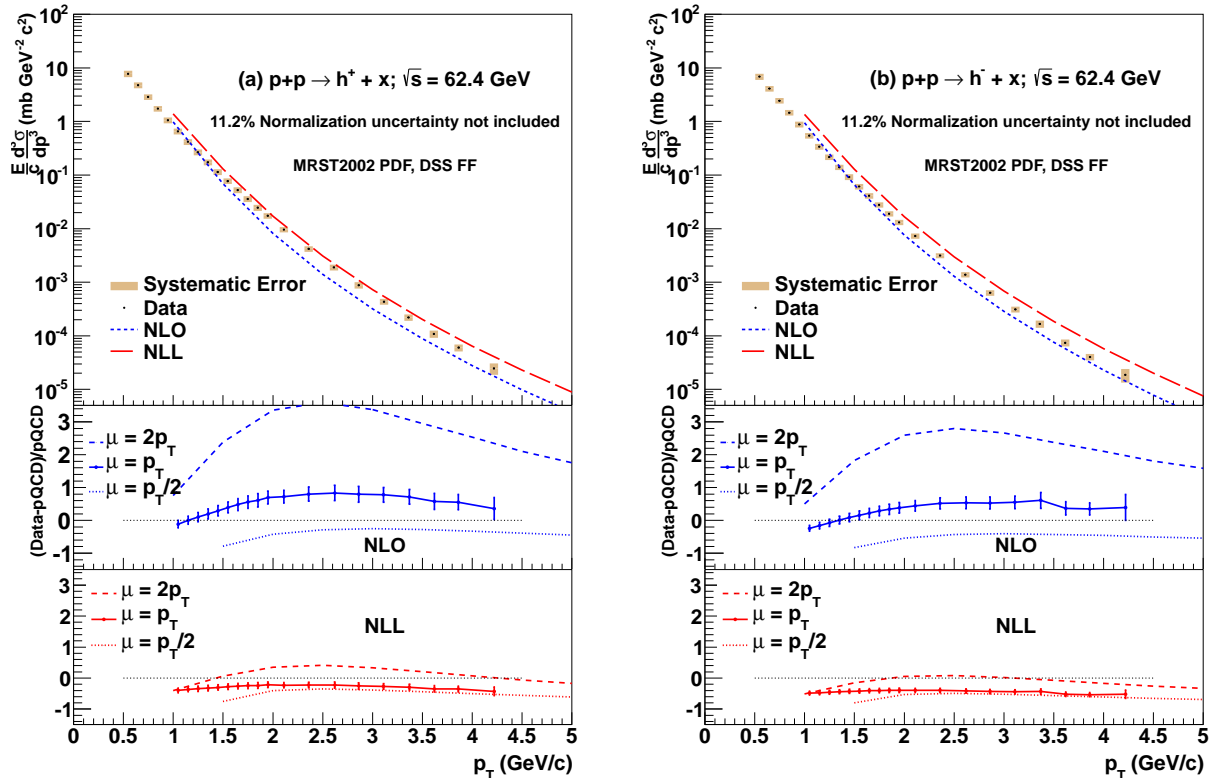


FIG. 4: (color online) Cross section of inclusive-charged-hadron production at midrapidity in  $p+p$  at 62.4 GeV for (a) positive and (b) negative hadrons. NLO and NLL theoretical predictions [49] at midrapidity, using MRST2002 parton distribution functions [50] and DSS fragmentation functions [51], at factorization, renormalization, and fragmentation scale  $\mu = p_T$  are shown as curves. The lower panels show the scale dependence of the NLO and NLL results.

functions, as progress in pQCD has allowed inclusion of  $p+p$  cross section measurements and semi-inclusive deep-inelastic lepton-nucleon scattering data in FF parameterizations along with the traditionally used  $e^+e^-$  data since 2007 [51, 54, 55].

#### IV. DOUBLE-HELICITY ASYMMETRY

We measured the double-helicity asymmetries,  $A_{LL}$ , of inclusive positive- and negative-hadron production in the transverse-momentum range of  $0.5 \leq p_T \leq 4.5$  GeV/ $c$  at midrapidity from longitudinally polarized  $p+p$  collisions at  $\sqrt{s} = 62.4$  GeV.

##### A. $A_{LL}$ Measurement

The double-helicity asymmetry of charged hadrons is defined as the relative difference between hadron-production cross sections from collisions of the same- and opposite-helicity state protons. Experimentally, the asymmetry is measured as

$$A_{LL} = \frac{1}{P_B \cdot P_Y} \frac{N_{++} - R \cdot N_{+-}}{N_{++} + R \cdot N_{+-}}, \quad (3)$$

where  $P_B$ ,  $P_Y$  are polarizations of the two colliding beams in RHIC (termed ‘Blue’ and ‘Yellow’),  $N_{++}$ ,  $N_{+-}$  are the midrapidity hadron yields from collisions of the same- and opposite-helicity protons, and relative luminosity  $R = \frac{L_{++}}{L_{+-}}$  is the ratio of luminosity of the same-helicity collisions to that of opposite-helicity collisions.

For the 2006  $p+p$  data set at  $\sqrt{s} = 62.4$  GeV, the luminosity-weighted average beam polarizations for both beams are measured to be  $\langle P \rangle = 0.48$ , and the average magnitude of the product of polarization of the two beams is  $\langle P_B \cdot P_Y \rangle = 0.23$  with a relative uncertainty of 13.9%. The colliding proton bunches at RHIC are assigned preset spin patterns repeated every four crossings. For consecutive fills with 120 bunches in the RHIC ring four such different spin patterns are alternated in order to reduce false asymmetries and systematic effects of possible correlations between the detector response and the RHIC bunch structures.

Hadron counts are obtained under similar criteria as described for the cross section measurements from the reconstructed tracks in Sect. III A. Approximately



TABLE IV: Cross section of midrapidity charged-hadron production from  $p + p$  collisions at  $\sqrt{s} = 62.4$  GeV as a function of  $p_T$ . The errors represent the statistical (first) and systematic uncertainties. The data are corrected for the contribution of feed-down protons and antiprotons. A normalization uncertainty of 11.2% is not included.

$p_T$ (GeV/ $c$ )	$h^+$ mb GeV $^{-2}$ $c^2$	$h^-$ mb GeV $^{-2}$ $c^2$
0.55	$7.80 \pm 1.2 \times 10^{-03} \pm 1.1$	$6.87 \pm 1.1 \times 10^{-03} \pm 9.3 \times 10^{-01}$
0.65	$4.78 \pm 8.7 \times 10^{-04} \pm 5.9 \times 10^{-01}$	$4.10 \pm 8.0 \times 10^{-04} \pm 5.0 \times 10^{-01}$
0.75	$2.87 \pm 6.3 \times 10^{-04} \pm 3.5 \times 10^{-01}$	$2.45 \pm 5.7 \times 10^{-04} \pm 2.9 \times 10^{-01}$
0.85	$1.73 \pm 4.6 \times 10^{-04} \pm 2.1 \times 10^{-01}$	$1.46 \pm 4.2 \times 10^{-04} \pm 1.7 \times 10^{-01}$
0.95	$1.06 \pm 3.4 \times 10^{-04} \pm 1.3 \times 10^{-01}$	$8.83 \times 10^{01} \pm 3.1 \times 10^{-04} \pm 1.1 \times 10^{-01}$
1.05	$6.55 \times 10^{-01} \pm 2.5 \times 10^{-04} \pm 8.2 \times 10^{-02}$	$5.43 \times 10^{-01} \pm 2.3 \times 10^{-04} \pm 6.6 \times 10^{-02}$
1.15	$4.18 \times 10^{-01} \pm 1.9 \times 10^{-04} \pm 5.2 \times 10^{-02}$	$3.40 \times 10^{-01} \pm 1.7 \times 10^{-04} \pm 4.1 \times 10^{-02}$
1.25	$2.67 \times 10^{-01} \pm 1.5 \times 10^{-04} \pm 3.4 \times 10^{-02}$	$2.16 \times 10^{-01} \pm 1.3 \times 10^{-04} \pm 2.6 \times 10^{-02}$
1.35	$1.73 \times 10^{-01} \pm 1.2 \times 10^{-04} \pm 2.2 \times 10^{-02}$	$1.41 \times 10^{-01} \pm 1.0 \times 10^{-04} \pm 1.6 \times 10^{-02}$
1.45	$1.14 \times 10^{-01} \pm 9.0 \times 10^{-05} \pm 1.4 \times 10^{-02}$	$9.21 \times 10^{-02} \pm 8.0 \times 10^{-05} \pm 1.1 \times 10^{-02}$
1.55	$7.73 \times 10^{-02} \pm 7.2 \times 10^{-05} \pm 9.3 \times 10^{-03}$	$6.11 \times 10^{-02} \pm 6.3 \times 10^{-05} \pm 7.2 \times 10^{-03}$
1.65	$5.25 \times 10^{-02} \pm 5.7 \times 10^{-05} \pm 6.4 \times 10^{-03}$	$4.11 \times 10^{-02} \pm 5.0 \times 10^{-05} \pm 4.7 \times 10^{-03}$
1.75	$3.59 \times 10^{-02} \pm 4.6 \times 10^{-05} \pm 4.4 \times 10^{-03}$	$2.79 \times 10^{-02} \pm 4.0 \times 10^{-05} \pm 3.3 \times 10^{-03}$
1.85	$2.46 \times 10^{-02} \pm 3.7 \times 10^{-05} \pm 3.1 \times 10^{-03}$	$1.90 \times 10^{-02} \pm 3.2 \times 10^{-05} \pm 2.2 \times 10^{-03}$
1.95	$1.74 \times 10^{-02} \pm 3.0 \times 10^{-05} \pm 2.0 \times 10^{-03}$	$1.31 \times 10^{-02} \pm 2.6 \times 10^{-05} \pm 1.5 \times 10^{-03}$
2.11	$9.61 \times 10^{-03} \pm 1.4 \times 10^{-05} \pm 1.1 \times 10^{-03}$	$7.32 \times 10^{-03} \pm 1.2 \times 10^{-05} \pm 8.3 \times 10^{-04}$
2.36	$4.19 \times 10^{-03} \pm 8.5 \times 10^{-06} \pm 5.0 \times 10^{-04}$	$3.14 \times 10^{-03} \pm 7.3 \times 10^{-06} \pm 3.5 \times 10^{-04}$
2.61	$1.89 \times 10^{-03} \pm 5.5 \times 10^{-06} \pm 2.4 \times 10^{-04}$	$1.38 \times 10^{-03} \pm 4.6 \times 10^{-06} \pm 1.6 \times 10^{-04}$
2.86	$8.80 \times 10^{-04} \pm 3.6 \times 10^{-06} \pm 1.2 \times 10^{-04}$	$6.36 \times 10^{-04} \pm 3.0 \times 10^{-06} \pm 7.5 \times 10^{-05}$
3.11	$4.33 \times 10^{-04} \pm 2.4 \times 10^{-06} \pm 5.4 \times 10^{-05}$	$3.12 \times 10^{-04} \pm 2.0 \times 10^{-06} \pm 3.8 \times 10^{-05}$
3.37	$2.20 \times 10^{-04} \pm 1.6 \times 10^{-06} \pm 2.9 \times 10^{-05}$	$1.67 \times 10^{-04} \pm 1.4 \times 10^{-06} \pm 2.5 \times 10^{-05}$
3.62	$1.09 \times 10^{-04} \pm 1.1 \times 10^{-06} \pm 1.7 \times 10^{-05}$	$7.41 \times 10^{-05} \pm 9.1 \times 10^{-07} \pm 1.1 \times 10^{-05}$
3.87	$6.03 \times 10^{-05} \pm 8.1 \times 10^{-07} \pm 9.0 \times 10^{-06}$	$4.02 \times 10^{-05} \pm 6.4 \times 10^{-07} \pm 5.5 \times 10^{-06}$
4.22	$2.46 \times 10^{-05} \pm 3.5 \times 10^{-07} \pm 6.0 \times 10^{-06}$	$1.88 \times 10^{-05} \pm 2.9 \times 10^{-07} \pm 5.3 \times 10^{-06}$

$1.63 \times 10^8$  BBC-triggered events with longitudinal beam polarization, corresponding to an integrated luminosity of  $11.9 \text{ nb}^{-1}$ , were analyzed for the asymmetry measurements. Luminosities for the same- and opposite-helicity events were obtained from crossing-by-crossing information of BBC trigger counts. The systematic uncertainty of the relative luminosity  $R$ , determined by comparing BBC-triggered events with events triggered by the ZDCs, was found to be  $1.4 \times 10^{-3}$ .

The asymmetry is determined on a fill-by-fill basis. The asymmetry of backgrounds from decays in flight, selected from the tail ends of the distribution of the matching variables (in beam direction  $z$  and azimuthal angle  $\phi$ ), is measured. The background asymmetry  $A_{LL}^{\text{bkg}}$  and background fraction are used to calculate the signal asymmetry and its statistical uncertainty. The feed-down from decays of  $\Lambda$ 's and heavier hyperons, however, cannot be separated from hadron yields. The backgrounds from feed-down protons and antiprotons are a small contribution (1–2.5%) to the total hadron yields and are not corrected for since the asymmetries of these backgrounds are unknown.

## B. $A_{LL}$ Results

Figure 5 and Table V show the  $p_T$ -dependence of the measured double-helicity asymmetries for inclusive-charged-hadron production at midrapidity in polarized  $p+p$  collisions at  $\sqrt{s} = 62.4$  GeV. The asymmetries are compared to NLO pQCD predictions [56] based on several different parameterizations of polarized PDFs at scale  $\mu = p_T$ .

The curves in Fig. 5 labeled “DSSV NLO” and “DSSV NLL” refer to deFlorian-Sassot-Stratmann-Vogelsang (DSSV) parameterizations of the helicity PDFs [35] and curves labeled “BB NLO” refer to Blümlein-Böttcher (BB) parameterizations of the helicity PDFs [32]. Both DSSV and BB calculations use DSS fragmentation functions [54]. DSSV calculations use MRST2002 unpolarized PDFs [50]; BB calculations use those from the coordinated-theoretical-experimental-project-on-QCD-6 [57]. Polarized PDFs use fits to the pDIS data to extract parameters of the functional forms of PDFs. DSSV [35] parameterizations use RHIC data along with the available pDIS data to constrain the polarized PDFs. The asymmetries are also compared to the NLL estimations with the DSSV PDFs [49].

For the purpose of comparison with the experimental results, pQCD calculations were obtained for separate hadron species (pions, kaons and (anti)protons) and were

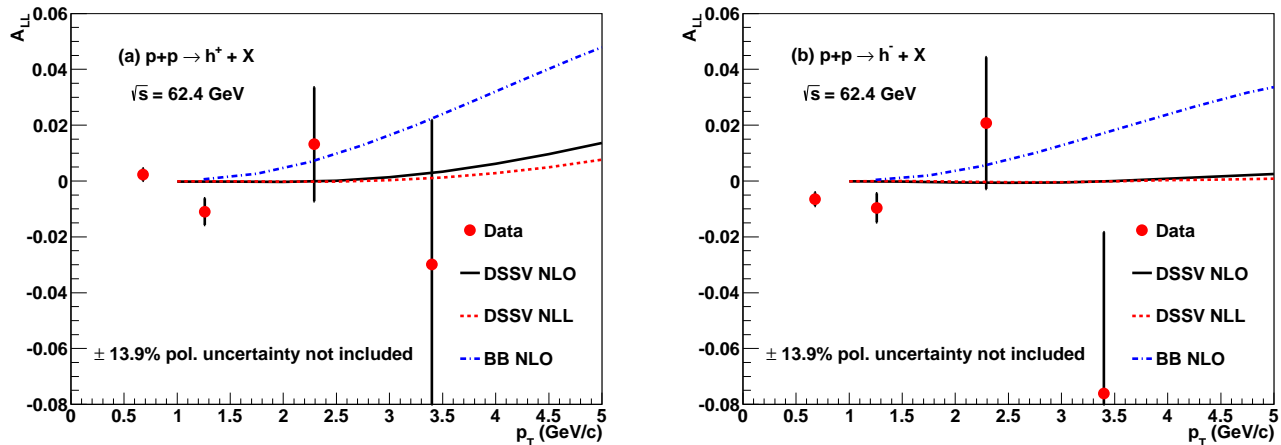


FIG. 5: (color online) Double-helicity asymmetry ( $A_{LL}$ ) of (a) positive and (b) negative charged-hadron production from polarized  $p+p$  collisions at  $\sqrt{s} = 62.4$  GeV. The results are compared to NLO and NLL pQCD predictions using several parameterizations of the helicity PDFs (see text for details).

TABLE V: The double-helicity asymmetries and the statistical uncertainties as a function of  $p_T$  for positive and negative inclusive charged hadrons from  $p + p$  collisions at  $\sqrt{s} = 62.4$  GeV. The fractional contribution to the yields from weak-decay feed-down to protons and antiprotons is shown; no correction to the asymmetries has been made for these contributions.

$p_T$ (GeV/c)	$A_{LL} \pm \delta A_{LL}(h^+)$	estimated		$A_{LL} \pm \delta A_{LL}(h^-)$	estimated	
		feed-down fraction( $h^+$ )			feed-down fraction( $h^-$ )	
0.68	$0.0023 \pm 0.0022$	0.022		$-0.0065 \pm 0.0024$	0.021	
1.26	$-0.01096 \pm 0.0048$	0.016		$-0.0096 \pm 0.0052$	0.025	
2.29	$0.0132 \pm 0.0204$	0.012		$0.0208 \pm 0.0236$	0.021	
3.40	$-0.0299 \pm 0.0517$	0.011		$-0.0761 \pm 0.0578$	0.018	

combined using the particle fraction in the hadron mixture (Fig. 3) and corresponding efficiency factor (Fig. 2). The measured asymmetries are small and consistent with zero. The results are also consistent with the predictions from the recent parameterizations within statistical limitations. The comparisons corroborate previous PHENIX measurements [4, 40] that disfavor very large gluon polarization. The presented asymmetry measurements probe a range of approximately  $0.05 \leq x_{gluon} \leq 0.2$  [12] of the interacting gluons.

## V. SUMMARY AND CONCLUSIONS

Cross sections and double-helicity asymmetries for the midrapidity production of positive and negative inclusive charged hadrons at  $\sqrt{s} = 62.4$  GeV are measured as a function of transverse momentum. The comparison with pQCD calculations shows that the NLO estimations are consistent with cross section results within a large scale uncertainty. NLL calculations with their reduced scale dependence are also consistent with the data, indicating that the threshold resummation of logarithmic terms is relevant in the kinematic region measured; however,

the overprediction of the data by up to  $\sim 50\%$  if the NLL terms are included suggests that contributions from NNLO terms may also be important. This corroborates other recent results from PHENIX [14, 40] with similar indications. The asymmetry results are the first measurements for charged hadron production in polarized  $p + p$  collisions at  $\sqrt{s} = 62.4$  GeV and are consistent with the asymmetries found using several other probes at different collision energies at RHIC [4, 5, 8, 10, 40, 53]. Experimental measurements of a variety of processes covering a broad kinematic range are essential to advancing our understanding of QCD in hadronic interactions and nucleon structure, and the present measurements contribute towards that end.

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