The gluon spin contribution to the proton spin from the double helicity asymmetry in inclusive $^3\pi^0$ production in polarized $p + p$ collisions at $\sqrt{s} = 200$ GeV

A. Adare,12 S. Afanasiev,26 C. Aidala,37 N.N. Ajitanand,54 Y. Akiba,48, 49 H. Al-Bataineh,43 J. Alexander,54 K. Aoki,31, 48 L. Aphecetche,56 J. Asai,48 E.T. Atomssa,32 R. Averbeck,25 T.C. Aves,44 B. Azmoum,7 V. Babintsev,22 M. Bai,9 G. Baksy,18 L. Baksy,18 A. Baldisseri,15 K.N. Barish,5 P.D. Barnes,34 B. Bassalleck,42 A.T. Basye,1 S. Bathe,8 S. Batsouli,44 V. Baublis,17 C. Baumann,38 A. Bazilevsky,7 S. Belikov,7 R. Bennett,55 A. Berdnikov,51 Y. Berdnikov,51 A.A. Bickley,12 J.G. Boissevain,34 H. Borel,15 K. Boyle,55 M.L. Brooks,34 H. Buesching,7 V. Bumazhnov,22 G. Bunce,7, 49 S. Butsyk,34 C.M. Camacho,34 S. Campbell,55 P. Chand,4 B.S. Chang,63 W.C. Chang,4 J.-L. Charvet,15 S. Chernichenko,52 C.Y. Chi,13 M. Chiu,23 I.J. Choi,53 R.K. Choudhury,7 T. Chuiho,59 P. Chung,54 A. Chumy,22 V. Cianciolo,44 B.A. Cole,13 P. Constantin,34 M. Csándi,17 T. Csörgő,28 T. Dahms,55 S. Dairaku,31, 48 K. Das,19 G. David,7 A. Denisov,22 D. d’Enterria,32 A. Deshpande,49, 55 E.J. Desmond,7 O. Dietzsch,52 A. Dion,55 M. Donadelli,52 O. Draper,32 A. Drees,55 K.A. Drees,6 A.K. Dubey,62 A. Durum,22 D. Dutta,4 V. Dzhordzhadze,8 Y.V. Efremenko,44 J. Egger,55 F. Ellinghaus,12 T. Engelmore,13 A. Enokizono,33 H. En’yo,48, 49 S. Esumi,32 K.O. Eyser,8 B. Fadem,39 D.E. Fields,42, 49 M. Finger,9 M. Finger, Jr.,9 F. Fleuret,32 S.L. Fokin,30 Z. Fraenkel,62 J.E. Frantz,55 A. Franz,7 A.D. Frawley,19 K. Fujiiwara,48 Y. Fukuo,57 T. Fuyasu,41 I. Garishvili,57 A. Glenn,12 H. Gong,55 M. Goni,32 J. Gossel,15 Y. Goto,48, 49 R. Granier de Cassagnac,32 N. Grau,13 S.V. Greene,60 M. Grosse Perdekamp,23, 49 T. Gunji,11 H.-A. Gustafsson,36 A. Hadj Henni,56 J.S. Haggerty,7 H. Hamagaki,11 R. Han,46 E.P. Hartouni,33 K. Haruna,21 E. Hashmi,36 R. Hayano,11 M. Heffner,33 T.K. Hemmick,55 T. Hester,8 X. He,20 J.C. Hill,25 M. Hohlmann,18 W. Holznagel,54 K. Homma,21 B. Hong,29 T. Horaguchi,11, 48, 58, D. Hornback,57 S. Huang,60 T. Ichihara,48, 49 R. Ichiyama,48 Y. Ikeda,59 K. Imai,31, 48 J. Imrek,16 M. Inaba,59 D. Isehower,1 M. Ishihara,48 T. Isole,11 M. Issah,54 A. Isupov,26 D. Ivanischev,47 B.V. Jacak,14 J. Jia,13 J. Jin,13 B.M. Johnson,7 K.S. Joo,60 D. Joun,45 F. Kajihara,11 S. Kametani,48 N. Kamihara,49 J. Kamin,45 J.H. Kang,63 J. Kapustinsky,34 D. Kawall,37, 49 A.V. Kazantsev,30 T. Kempel,29 A. Khazadeev,47 K. Kijima,21 J. Kikuchi,61 B.I. Kim,29 D.H. Kim,40 D.J. Kim,43 E. Kim,53 S.H. Kim,33 E. Kinney,12 K. Kiriluk,12 A. Kiss,17 E. Kistenev,7 J. Klay,33 C. Klein-Boesing,38 L. Kochenda,47 V. Kochetkov,22 B. Komikov,47 M. Konno,59 J. Koster,23 A. Kozlov,62 A. Král,14 A. Kravitz,13 G.J. Kunde,34 K. Kurita,50, 48 M.H. Kweon,29 Y. Kwon,57 G.S. Kyle,43 R. Lacey,54 Y.S. Lai,13 J.G. Lajoie,55 D. Layton,23 A. Lebedev,25 D.M. Lee,34 K.B. Lee,29 T. Lee,53 M.J. Leitch,34 M.A.L. Leite,52 B. Lenzi,52 P. Liebing,49 T. Liška,14 A. Litvinenko,26 H. Liu,43 M.X. Liu,34 X. Li,10 B. Love,60 D. Lynch,7 C.F. Maguire,60 Y.I. Makiyie,37 S.F. Malik,38 M.D. Malik,31, 48 P. Manco,30 E. Mann,13 Y. Mao,46, 48 L. Mašek,9, 24 H. Masui,59 M. Matathias,13 M. McCumber,55 P.L. McGaughey,44 B. Meredith,23 Y. Miale,59 P. Mikes,24 K. Miki,59 A. Milov,7 M. Mishra,3 J.T. Mitchell,7 A.K. Mohanty,14 Y. Morino,13 A. Morreale,8 D.P. Morrison,7 T.V. Moukhanova,30 M. Mukhopadhyay,60 J. Murata,50, 48 S. Nagamiya,72 J.L. Nagle,12 M. Naglis,62 M. Nagy,17 I. Nakagawa,48, 49 Y. Nakama,21 T. Nakamura,21 K. Nakano,48, 58 J. Newby,33 M. Nguyen,55 T. Niita,59 R. Nourie,5 A.S. Nyanin,30 E. O’Brien,7 S.X. Oda,22 C.A. Ogilvie,25 H. Okada,31, 48 K. Okada,49 M. Oka,59 Y. Onuki,48 A. Oskarsson,36 M. Ouchida,21 K. Ozawa,11 R. Pak,5 A.P.T. Paloume,44 V. Pantuev,55 V. Papavassiliou,43 J. Park,53 W.J. Park,29 S.F. Pate,43 H. Pei,25 J.-C. Peng,23 H. Pereira,15 V. Peresedov,26 D.Yu. Peresoukko,30 C. Pinkenburg,7 M.L. Purschke,7 A.K. Purwar,34 H. Qu,70 J. Rak,42 A. Rakotozafrandibe,32 I. Ravinovich,62 K.F. Read,44, 57 S. Rembecki,18 M. Reuter,55 K. Reyes,38 V. Riabov,47 Y. Riabov,47 D. Roach,60 G. Roche,35 S.D. Rolnick,8 M. Rosati,25 S.S.E. Rosendahl,36 P. Rosnet,55 P. Rukoyatkina,26 P. Ružička,24 V.L. Rykov,48 B. Sahlmueller,38 N. Saiho,31, 48, 49 T. Sakaguchi,7 S. Sakai,59 K. Sakashita,48, 58 V. Samsonov,47 T. Sato,59 S. Sawada,27 K. Sedgwick,8 J. Seele,12 R. Seidl,23 A.Yu. Semenov,25 V. Semenov,23 R. Seto,8 D. Sharma,62 I. Shein,23 T.-A. Shibata,48, 58 K. Shigaki,21 M. Shimomura,59 K. Shoji,31, 48, 59 Shukla,4 A. Sickles,7 C.L. Silva,52 D. Silvermyr,44 C. Silvestre,15 K.S. Sin,29 B.K. Singh,3 C.P. Singh,3 V. Singh,5 M. Shunečka,9 A. Soldatov,22 R.A. Soltz,33 W.E. Sondheim,34 S.P. Sorensen,57 I.V. Sourikova,7 F. Staley,15 P.W. Stankus,44 E. Stenlund,36 M. Stepanov,43 A. Ster,28 S.P. Stoll,7 T. Sugitate,21 C. Suire,45 A. Sukhanov,5 J. Szklai,28 E.M. Takegai,52 A. Taketani,48, 49 R. Tanabe,59 Y. Tanaka,41 S. Tanega,55 K. Tanida,13 K. Tanimura,48, 49 M.J. Tannenbaum,7 A. Taranenko,54 P. Tarján,35 T.L. Thomas,42 M. Togawa,31, 48 A. Toia,55 L. Tomášek,24 Y. Tomita,59 H. Torii,48 R.S. Towell,1 V.-N. Tram,32 I. Tserunyan,62 Y. Tsuchimoto,21 C. Vale,25 H. Valle,60 H.W. van Hecke,34 A. Veitch,23 J. Velkovska,60 R. Vertesi,16 A.A. Vinogradov,30 M. Virius,14 V. Vrba,24 E. Vznuzdaev,47 D. Walker,55 X.R. Wang,43 Y. Watanabe,48, 49
F. Wei, J. Wessels, S.N. White, S. Williamson, D. Winter, C.L. Woody, M. Wysocki, W. Xie, Y.L. Yamaguchi, K. Yamaura, R. Yang, A. Yanovich, J. Ying, S. Yokkaichi, G.R. Young, I. Younus, I.E. Yushmanov, W.A. Zaje, O. Zaudtke, C. Zhang, S. Zhou, and L. Zolin

(PHENIX Collaboration)

1 Abilene Christian University, Abilene, TX 79699, U.S.
2 Institute of Physics, Academia Sinica, Taipei 11529, Taiwan
3 Department of Physics, Banaras Hindu University, Varanasi 221005, India
4 Bhabha Atomic Research Centre, Bombay 400 085, India
5 Chemistry Department, Brookhaven National Laboratory, Upton, NY 11973-5000, U.S.
6 Collider-Accelerator Department, Brookhaven National Laboratory, Upton, NY 11973-5000, U.S.
7 Physics Department, Brookhaven National Laboratory, Upton, NY 11973-5000, U.S.
8 University of California - Riverside, Riverside, CA 92521, U.S.
9 Charles University, Ovocný trh 5, Praha 1, 116 36, Prague, Czech Republic
10 China Institute of Atomic Energy (CIAE), Beijing, People’s Republic of China
11 Center for Nuclear Study, Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan
12 University of Colorado, Boulder, CO 80309, U.S.
13 Columbia University, New York, NY 10027 and Nevis Laboratories, Irvington, NY 10533, U.S.
14 Czech Technical University, Zikova 4, 166 36 Prague 6, Czech Republic
15 Dapnia, CEA Saclay, F-91191, Gif-sur-Yvette, France
16 Debrecen University, H-4010 Debrecen, Egyetem tér 1, Hungary
17 ELTE, Eötvös Loránd University, H - 1117 Budapest, Pázmány P. s. 1/A, Hungary
18 Florida Institute of Technology, Melbourne, FL 32901, U.S.
19 Florida State University, Tallahassee, FL 32306, U.S.
20 Georgia State University, Atlanta, GA 30330, U.S.
21 Hiroshima University, Kagamiyama, Higashi-Hiroshima 739-8526, Japan
22 IHEP Protvino, State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, 142281, Russia
23 University of Illinois at Urbana-Champaign, Urbana, IL 61801, U.S.
24 Institute of Physics, Academy of Sciences of the Czech Republic, Na Slovance 2, 182 21 Prague 8, Czech Republic
25 Iowa State University, Ames, IA 50011, U.S.
26 Joint Institute for Nuclear Research, 141980 Dubna, Moscow Region, Russia
27 KEK, High Energy Accelerator Research Organization, Tsukuba, Ibaraki 305-0801, Japan
28 KFKI Research Institute for Particle and Nuclear Physics of the Hungarian Academy of Sciences (MTA KFKI RMKI), H-1525 Budapest 114, POBox 49, Budapest, Hungary
29 Korea University, Seoul, 136-701, Korea
30 Russian Research Center “Kurchatov Institute”, Moscow, Russia
31 Kyoto University, Kyoto 606-8502, Japan
32 Laboratoire Leprince-Ringuet, Ecole Polytechnique, CNRS-IN2P3, Route de Saclay, F-91128, Palaiseau, France
33 Lawrence Livermore National Laboratory, Livermore, CA 94550, U.S.
34 Los Alamos National Laboratory, Los Alamos, NM 87545, U.S.
35 LPC, Université Blaise Pascal, CNRS-IN2P3, Clermont-Fd, 63177 Aubière Cedex, France
36 Department of Physics, Lund University, Box 118, SE-221 00 Lund, Sweden
37 Department of Physics, University of Massachusetts, Amherst, MA 01003-9337, U.S.
38 Institut für Kernphysik, University of Muenster, D-48149 Muenster, Germany
39 Muhlenberg University, Allentown, PA 18104-5586, U.S.
40 Myongji University, Yongin, Kyonggido 449-728, Korea
41 Nagasaki Institute of Applied Science, Nagasaki-shi, Nagasaki 851-0193, Japan
42 University of New Mexico, Albuquerque, NM 87131, U.S.
43 New Mexico State University, Las Cruces, NM 88003, U.S.
44 Oak Ridge National Laboratory, Oak Ridge, TN 37831, U.S.
45 IPN-Orsay, Université Paris Sud, CNRS-IN2P3, BP1, F-91406, Orsay, France
46 Peking University, Beijing, People’s Republic of China
47 PNPI, Petersburg Nuclear Physics Institute, Gatchina, Leningrad region, 188300, Russia
48 RIKEN, The Institute of Physical and Chemical Research, Wako, Saitama 351-0198, Japan
49 RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973-5000, U.S.
50 Physics Department, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima, Tokyo 171-8501, Japan
51 Saint Petersburg State Polytechnic University, St. Petersburg, Russia
52 Universidade de São Paulo, Instituto de Física, Caixa Postal 66318, São Paulo CEP05315-970, Brazil
53 System Electronics Laboratory, Seoul National University, Seoul, Korea
54 Chemistry Department, Stony Brook University, Stony Brook, SUNY, NY 11794-3400, U.S.
55 Department of Physics and Astronomy, Stony Brook University, SUNY, Stony Brook, NY 11794, U.S.
56 SUBATECH (Ecole des Mines de Nantes, CNRS-IN2P3, Université de Nantes) BP 20722 - 44307, Nantes, France
57 University of Tennessee, Knoxville, TN 37996, U.S.
Thus $\Delta G$ or sign change, in $\Delta G$ for our sampled gluon momentum fraction ($x$) range, 0.02 to 0.3. The results are obtained using predictions for our measured asymmetries generated from four representative fits to polarized deep inelastic scattering data. We also consider the dependence of the $\Delta G$ constraint on the choice of theoretical scale, a dominant uncertainty in these predictions.

PACS numbers: 13.85.Ni,13.88.+e,21.10.Hw,25.40.Ep

The double helicity asymmetry in neutral pion production for $p_T = 1$ to 12 GeV/c has been measured with the PHENIX experiment in order to access the gluon spin contribution, $\Delta G$, to the proton spin. Measured asymmetries are consistent with zero, and at a theory scale of $\mu^2 = 4$ GeV$^2$ give $\Delta G^{[0.02,0.3]} = 0.1$ to 0.2, with a constraint of $-0.7 < \Delta G^{[0.02,0.3]} < 0.5$ at $\Delta x = 9$ ($< 3\sigma$) for our sampled gluon momentum fraction ($x$) range, 0.02 to 0.3. The results are obtained using predictions for our measured asymmetries generated from four representative fits to polarized deep inelastic scattering data. We also consider the dependence of the $\Delta G$ constraint on the choice of theoretical scale, a dominant uncertainty in these predictions.

The quark spin contribution to the proton spin was found to be only $\sim 25\%$ [1–3], indicating that the majority of the proton spin on average comes from the gluon spin contribution, $\Delta G$, and/or from gluon and quark orbital angular momentum. High energy polarized proton-proton collisions at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory access $\Delta G$ at leading order through spin-dependent gluon-gluon ($gg$) and quark-gluon ($qg$) scattering.

This paper presents results from the 2006 RHIC run (Run-6) on $\Delta G$ from measurements of the double helicity asymmetry ($A_{LL}$) in inclusive mid-rapiditiy $\pi^0$ production by the PHENIX experiment. $\Delta G$ can be extracted from $A_{LL}^\pi$, using next to leading order (NLO) perturbative quantum chromodynamics (pQCD) [4], which successfully describes unpolarized cross-sections measured at RHIC for many inclusive processes [5–7], including mid-rapiditiy $\pi^0$ production [8], at $\sqrt{s} = 200$ GeV. These data represent a factor of two improvement in the statistical uncertainty compared to previous results [8–10]. They significantly constrain $\Delta G$, as presented in a recent global fit (DSSV) [11] of both RHIC and polarized deep inelastic scattering (pDIS) data, which used a preliminary version of these results. We further present the impact of experimental systematic and several theoretical uncertainties on our determination of $\Delta G$.

We define $\Delta G^{[a,b]} = \int_a^b dx \Delta g(x,\mu^2)$, with $\Delta g(x,\mu^2)$, the polarized gluon distribution, a function of $x$, the gluon momentum fraction and $\mu^2$, the factorization scale. Thus $\Delta G^{[0,1]} = \Delta G$. Figure 1 shows the best fit $\Delta g(x)$ from four different pDIS fits: GRSV-std [12], BB (“ISET-4”) [13], LSS [14] and GS-C [15], which assumes a node, or sign change, in $\Delta g(x)$. As the pDIS data have limited sensitivity to $\Delta G$, there remains large uncertainty, which was estimated by BB, and is shown as the hatched band. The result from the recent global fit, DSSV, is also shown. It has a node, which is driven by the inclusion of RHIC PHENIX $\pi^0$ and STAR jet [16-17] $A_{LL}$ data along with evolution from pDIS at large $x$ [11]. Table I lists $\Delta G^{[a,b]}$ for several $x$ ranges.

We define $A_{LL}^\pi = (\sigma_{++} - \sigma_{+-})/\sigma_{++}$, with $\sigma_{++}$ and $\sigma_{+-}$ the beam helicity dependent differential cross sections for inclusive $\pi^0$ production from collisions of longitudinally polarized protons with the same (opposite) helicity. The asymmetry is measured using

$$A_{LL}^\pi = \frac{1}{(P_B P_Y) N_{++} + R N_{--}} \frac{N_{++} - R N_{--}}{R} = \frac{L_{++}}{L_{--}}$$

where $P_B$ and $P_Y$ are the polarizations of the two RHIC beams, called “Blue” and “Yellow,” and $R$, the relative luminosity, is the ratio of integrated luminosities ($L$) for same and opposite helicity collisions. Here we take $N$ to be the $\pi^0$ yield in a transverse momentum ($p_T$) bin.

Each $\pi^0$ $p_T$ bin samples a distribution in gluon $x$. Figure 1b shows the sampled gluon $x$ distributions for three $p_T$ bins from a NLO pQCD simulation.

\[\text{FIG. 1: (color online) (a) The polarized gluon distribution as a function of } x \text{ for five fits to polarized data. Hatched band is pDIS } 1\sigma \text{ uncertainty (BB). (b) Distributions of gluon } x \text{ in three } \pi^0 \text{ } p_T \text{ bins from a NLO pQCD simulation.}\]


\[ A_{LL}^{\pi^0} \] bins from a NLO pQCD simulation \[4, 18\]. They are peaked at \[ x_T/0.7 \] \[19\], with \[ x_T \equiv p_T/(\sqrt{s}/2) \]. The bins overlap, with our data covering primarily the range \[ 0.02 < x < 0.3 \], and so we probe \[ \Delta G_{GRSV}^{0.02,0.3} \].

The highly segmented PHENIX electromagnetic calorimeter (EMCal) \[20\] is used to detect \[ \pi^0 \rightarrow \gamma\gamma \] decays. The EMCal covers a pseudorapidity range of \[ \eta < 0.35 \] and azimuthal angle range of \[ \Delta \phi = \pi \], with segmentation \[ \Delta \eta \times \Delta \phi = 0.01 \times 0.01 \]. We required for each of the two decay photons an energy deposition pattern consistent with an electromagnetic shower, no charged track pointing to the location of the deposited energy, and standard quality assurance requirements \[9\]. Events were obtained from an EMCal based high \( p_T \) photon trigger \[21\] in coincidence with a minimum bias trigger \[8\] (also used to obtain the relative luminosity). This EMCal based trigger had an efficiency for \( \pi^0 \) at \( p_T \approx 1 \text{ GeV}/c \) and 90\% for \( p_T > 3.5 \text{ GeV}/c \). The minimum bias trigger was defined as the coincidence of signals from forward and backward beam-beam counters (BBC) with full azimuthal coverage located at pseudorapidities \[ \pm(3.0-3.9) \] \[22\]. The analyzed data sample corresponded to an integrated luminosity of 6.5 \( \text{pb}^{-1} \).

Each collider ring of RHIC was filled with up to 111 out of a possible 120 bunches, spaced 106 ns apart, with bunch helicities set such that all four beam helicity combinations occurred in sequences of four bunch crossings. The pattern of helicity combinations for each RHIC fill (typically 8 hrs) was cycled between four possibilities in order to reduce systematic uncertainties that could be correlated to the bunch structure in RHIC \[8\]. Events were tagged with the bunch crossing number to obtain the beam helicities for the event. The luminosity weighted beam polarization product was \( \langle P_B P_Y \rangle = 0.322 \pm 0.027 \) (8.3\%), with single beam polarizations of 0.560 and 0.575. Using very forward neutron production asymmetry \[8, 23\], the longitudinal polarization fractions \[ \langle \Delta P \rangle \] were found to be greater than 99\%.

As in our previous analyses \[8, 9\], the relative luminosity ratio \( R \) was obtained from crossing-by-crossing collected minimum bias (BBC) trigger counts, which measure about half of the \( p+p \) inelastic cross section \[21\]. The uncertainty on \( R \) was derived from the comparison with a second trigger based on the Zero Degree Calorimeters \[24\], which selects different physics processes in a differ-

**TABLE I: \( \Delta G \) for different \( x \) ranges at \( \mu^2 = 4 \text{ GeV}^2 \) for each group’s best fit and the \( \chi^2 \) when comparing the expected \( A_L \) in Fig. 3(a) with our data (8 degrees of freedom). Also, the minimum \( \chi^2 \) and corresponding \( \Delta G_{GRSV}^{0.02,0.3} \) found in Fig. 3(b).**

| Group | \( \Delta G_{GRSV}^{0.02,0.3} \) | \( \chi^2 \) | From Fig. 3(b) |
|-------|-----------------|-------|----------------|
| GS-C  | 0.95            | 8.3   | 8.5            |
| DSSV  | -0.05           | -0.03 | NA             |
| LSS   | 0.60            | 32.4  | 7.0            |
| GRSV  | 0.67            | 14.8  | 7.1            |
| BB    | 0.93            | 69.0  | 7.2            |
ent kinematic range. It contributed a $p_T$ independent systematic uncertainty to $A_{LL}$ of $7 \times 10^{-4}$.

Equation (1) is used to determine, on a fill by fill basis, $A_{LL}$ for the yield in the $\pi^0$ mass peak for each $p_T$ bin. The asymmetries were averaged over fills and corrected for the asymmetry in the background contribution (determined from two 50 MeV/$c^2$ wide sidebands on either side of the $\pi^0$ peak) [9], which was consistent with zero.

Figure 2a shows the measured $A_{LL}^0$ from Run-6 [25] in comparison with our published data from the 2005 RHIC run (Run-5) [8]. The results are found to be statistically consistent with a 13% confidence level. The inset shows an expanded view of the low $p_T$ region, as well as the relative luminosity uncertainty from Run-6. Besides this and the scale uncertainty from polarization, other systematic uncertainties that can be found by using a bunch polarization sign randomization technique and by varying the $\pi^0$ identification criteria [8] appear negligible.

Also shown in Fig. 2a, are NLO pQCD predictions of $A_{LL}^0$ [4] based on fits of pDIS data by GRSV with three different values for $\Delta G$ at the input scale of $\mu^2 = 0.4$ GeV$^2$: 1) “std”, their best fit value with $\Delta G = 0.24$, 2) $\Delta G = 0$ and 3) $\Delta G = -1.05$. The measurements are most consistent with GRSV $\Delta G = 0$. CTEQ6 unpolarized parton distribution functions (PDF) [26] were used, along with DSS fragmentation functions (FF) [27], in all calculations. Using alternative PDF [28] or FF [29] did not lead to significant differences in the $A_{LL}$ expectations.

$A_{LL}$ expectations based on fits to the pDIS data with a range of inputs for $\Delta G^{[0.1]}$ evolved to $\mu^2 = 0.4$ GeV$^2$ in the GRSV parameterization were calculated. Similar to our previous analysis [8], $\chi^2$ values were calculated using our combined Run-5 and Run-6 data [25] for these expectations, effectively fitting $\Delta G$ with our data in this parameterization. In Fig. 2b, these values are plotted as a function of $\Delta G^{[0.02,0.3]}$ at $\mu^2 = 4$ GeV$^2$. Due to soft physics contamination at low $p_T$, we use only data with $p_T > 2$ GeV/$c$ [8]. Assuming that $\mu = p_T$, $\mu^2 = 4$ GeV$^2$ is then the minimum cutoff of our data. The solid curve shows the result considering only statistical uncertainties. Due to $gg$ interactions in $p+p$ collisions, $A_{LL}$ probes $\Delta G$ quadratically in $\pi^0$ production [8]. The $\chi^2$ profile is thus not parabolic, and so we show $\Delta \chi^2 \equiv \chi^2 - \chi^2_{\text{min}} = 1$ and 9 corresponding to “1σ” and “3σ” uncertainties. The $gg$ scattering increases toward low $p_T$, which dominates our statistics and causes the two minima seen in Fig. 2b. The larger allowed negative region arises from cancelation of $gg$ and $gq$ terms in $A_{LL}^0$ when $\Delta G$ is negative.

For a robust interpretation of our results in terms of $\Delta G$, we consider not only statistical but also experimental systematic and theoretical uncertainties. The effects of the two largest experimental systematic uncertainties, due to polarization and relative luminosity, are shown in Fig. 2b. The polarization uncertainty is insignificant when extracting $\Delta G$. However, the uncertainty on relative luminosity, though small, cannot be neglected. Accounting for statistical uncertainty, we find $\Delta G^{[0.02,0.3]} = 0.2 \pm 0.1$ (1σ) and $0.2^{+0.2}_{-0.8}$ (3σ) with an additional experimental systematic uncertainty of ±0.1.

Figure 3 shows $A_{LL}$ expectations [11] based on the parameterizations discussed above, along with the pDIS uncertainty on $\Delta g(x)$ in BB propagated to $A_{LL}$. Our combined Run-5 and Run-6 $\pi^0$ results [25] are also plotted for comparison. The $\chi^2$ values for comparing each curve with our data are given in Table II. The three fit results without a node in $\Delta g(x)$–LSS, GRSV and BB–have large values of $\Delta G^{[0.02,0.3]}$ which lead to relatively large asymmetries that lie mostly above the data, though they are consistent within the large uncertainty from pDIS. For GS-C and DSSV, which have a node in $\Delta g(x)$ near the center of the sampled $x$ region, a cancelation between the positive and negative contribution in the wide $x$ distribution in each $p_T$ bin leads to a small value of $\Delta G^{[0.02,0.3]}$ and thus small $A_{LL}$. As these two parameterizations have significantly different $\Delta G^{[0.1]}$ values, it is clear that we are sensitive only to $\Delta G^{[0.02,0.3]}$.

For each pDIS fit, by varying $\Delta G^{[0.1]}$ at the input scale while fixing the quark distributions and the shape of $\Delta g(x)$ to the best fit values, a range of $A_{LL}$ curves were generated. Figure 3b shows the resulting $\chi^2$ profiles. While this approach is different from that in Fig. 2b, resulting in a different $\chi^2$ profile shape for GRSV, the $\Delta \chi^2 = 1$ and 9 constraints are quite consistent. The $\Delta G^{[0.02,0.3]}$ values at the $\chi^2$ minimum for each parameterization are between 0.1 and 0.2, and are listed in Table II. At $\Delta \chi^2 = 9$, the profiles are consistent for all parameterizations, independent of shape, indicating that our data are primarily sensitive to the size of $\Delta G^{[0.02,0.3]}$.

The cross section for $\pi^0$ production has been pre-

![Fig. 3: (color online) (a) $\pi^0$ asymmetry expectations for different $\Delta g(x)$ in Fig. 1a. Hatched band is the pDIS uncertainty (BB). Combined Run-5 and Run-6 results are also plotted (statistical errors only). (b) The $\chi^2$ profile as a function of $\Delta G^{[0.02,0.3]}$ for same parameterizations. Arrows indicate 1σ uncertainty on BB best fit. $\Delta \chi^2$ values are shown for GRSV.](image-url)
sented $\Delta G^{[0.02.0.3]}$ and compared with NLO pQCD expectations with the theoretical scales (factorization, fragmentation, and renormalization) in the calculation set all equal to $\mu = k p_T$ with $k = 1$. The calculation agreed with our results within the sizable theoretical uncertainties in the choice of scale, which were estimated by varying $k$ up and down by a factor of two. As we rely on NLO pQCD to extract $\Delta G^{[0.02.0.3]}$ from our measured $A_{LL}^{p,t}$, we must consider the effect of this uncertainty. Figure 4 shows the change in the $\Delta G^{[0.02.0.3]}$ constraint when varying $k$ in the $A_{LL}$ calculation in the GRSV parameterization. The theoretical scale uncertainty for the constraint on positive values of $\Delta G^{[0.02.0.3]}$ is similar to that for varying the parameterization, while large uncertainty arises for negative values.

We have presented results for $A_{LL}^{p,t}$ from Run-6, which, combined with Run-5 results, at $\mu^2 = 4$ GeV$^2$ give

$$\Delta G_{\text{GRSV}}^{[0.02.0.3]} = 0.2 \pm 0.1(\text{stat}) \pm 0.1(\text{sys})$$

$$+0.4(\text{shape}) \pm 0.1(\text{scale}).$$

(2)

Using four parameterizations of $\Delta g(x)$, we find a shape independent constraint of $-0.7 < \Delta G^{[0.02.0.3]} < 0.5$ at $\Delta \chi^2 = 9$ ($\sim 3\sigma$). The theoretical scale induced uncertainty is small for positive values of $\Delta G_{\text{GRSV}}^{[0.02.0.3]}$, but is sizable for negative values. Future measurements will be required to measure $\Delta g(x)$ for $x < 0.02$ where large uncertainty remains [11] and which may still contribute a significant amount of the proton spin. The quark spin contribution was well constrained by pDIS, and our result begins to significantly constrain the gluon spin contribution as well.

We thank the staff of the Collider-Accelerator and Physics Departments at BNL for their vital contributions. We acknowledge support from the Office of Nuclear Physics in DOE Office of Science, NSF, and a sponsored research grant from Renaissance Technologies (U.S.), MEXT and JSPS (Japan), CNPq and FAPESP (Brazil), NSFC (China), MSMT (Czech Republic), IN2P3/CNRS, and CEA (France), BMBF, DAAD, and AvH (Germany), OTKA (Hungary), DAE (India), ISF (Israel), KRF and KOSEF (Korea), MES, RAS, and FFAE (Russia), VR and KAW (Sweden), U.S. CRDF for the FSU, US-Israel Fulbright, US-Israel BSF.

FIG. 4: (color online) $\chi^2$ profile as a function of $\Delta G_{\text{GRSV}}^{[0.02.0.3]}$ when the theoretical scale is set to $\mu = p_T$, $p_T/2$ and $2p_T$.

[1] S. S. Adler et al., Phys. Rev. Lett. 91 (2003).
[2] M. Sarsour, Phys. Rev. D 74, 202001 (2006).
[3] J. Bluemlein and H. Bottcher, Nucl. Phys. B636, 225 (2002).
[4] A. Airapetian et al., Phys. Rev. D 75, 012007 (2007).
[5] Y. Alexakhin et al., Phys. Lett. B647, 8 (2007).
[6] B. Jäger, A. Schiffer, M. Stratmann, and W. Vogelsang, Phys. Rev. D 67, 054005 (2003).
[7] J. Adams et al., Phys. Rev. Lett. 92, 171801 (2004).
[8] M. Stratmann (2007), private communication.
[9] M. Sarsour, Phys. Rev. D 74, 072002 (2006).
[10] S. S. Adler et al., Phys. Rev. D 75, 051106 (2007).
[11] M. Stratmann and W. J. Stirling, Phys. Rev. D 53, 091102 (2004).
[12] M. Stratmann, Phys. Rev. D 73, 091102 (2006).
[13] M. Stratmann, Phys. Rev. Lett. 101, 072001 (2008).
[14] M. Glöckle, E. Reya, M. Stratmann, and W. Vogelsang, Phys. Rev. D 63, 094005 (2001).
[15] J. Ashman et al., Nucl. Phys. B828, 1 (1989).
[16] B. Abelev et al., Phys. Rev. Lett. 97, 252001 (2006).
[17] T. Gehrmann and W. J. Stirling, Phys. Rev. D 57, 024019 (2003).
[18] M. Stratmann, private communication.
[19] M. Stratmann, Phys. Rev. D 74, 072002 (2006).
[20] L. Apecetche et al., Nucl. Instrum. Meth. A499, 521 (2003).
[21] S. S. Adler et al., Phys. Rev. Lett. 91, 241803 (2003).
[22] M. Allen et al., Nucl. Instrum. Meth. A499, 549 (2003).
[23] Y. Fukao et al., Phys. Lett. B650, 325 (2007).
[24] M. Allen et al., Nucl. Instrum. Meth. A470, 488 (2001).
[25] Tables of data available at http://www.phenix.bnl.gov/WWW/info/data/ppg091_data.html.
[26] J. Pumplin et al., JHEP 07, 012 (2002).
[27] D. de Florian, R. Sassot, and M. Stratmann, Phys. Rev. D 75, 114010 (2007).
[28] A. D. Martin, R. G. Roberts, W. J. Stirling, and R. S. Thorne, Eur. Phys. J. C28, 455 (2003).
[29] B. A. Kniehl, G. Kramer, and B. Potter, Nucl. Phys. B582, 514 (2000).