PHYSICS at PHENIX, 15 years of discoveries

Understanding the composition of nucleon spin with the PHENIX detector at RHIC

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The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) has just finished 14 years of operation. A significant fraction of these operating years were with polarized proton collisions at 62.4, 200, and 500 GeV center of mass, investigating various aspects of nucleon spin through longitudinal and transversely polarized collisions. These data have helped to address some of the most puzzling and fundamental questions in quantum chromodynamics including: what fraction of the nucleon’s spin originates in the gluon’s helicity contribution?, how polarized are the sea quarks?, and what if any, is the evidence for transverse motion of quarks in polarized protons? These questions have been addressed by the PHENIX detector collaboration. We present in this review highlights of the PHENIX results and discuss their impact.

Subject Index D32

1. Quantum chromodynamics and nucleon spin

Quantum chromodynamics (QCD) has been established over the last four decades as the theory of strong interaction, quantitatively validated with remarkable precision, by a host of experiments at high energy. QCD differs from quantum electrodynamics (QED) most fundamentally in that the interaction carrier, the gluon, is itself a carrier of color charge, unlike the photon in QED, which is chargeless. It is this fundamental difference between the two that gives rise to the fundamental difference and enormous richness that is associated with QCD. Unlike any other many-body system, the individual quarks and gluons that make up nucleons and atomic nuclei cannot be removed from the systems and studied in isolation: this is the phenomenon of confinement, the details of which we do not yet understand. One of the most exciting discoveries in physics over the past few decades has been the understanding that most of the mass of the visible matter/universe—protons, neutrons, and hence the atomic nuclei—arises predominantly from the interaction energy of the gluons amongst themselves and with quarks. This implies that in all hadrons there is a large sea of gluons constantly fluctuating into quark–anti-quark pairs. This modern picture of a hadron made of a large number of highly relativistic and nearly massless spin-1/2 quarks exchanging spin-1 gluons is very different than the electromagnetic interactions binding electrons and nucleons together to form atoms. Investigation of the sea of gluons and quarks has emerged as a new frontier in QCD experimental physics.

Spin is one of the most fundamental concepts in physics, deeply rooted in the structure of the space-time itself. All elementary particles that we know carry spin, including those that participate
in strong interactions (QCD): spin-1/2 quarks and spin-1 gluons. It is indeed imperative to expect that spin would play a central role in QCD dynamics, and that needs to be understood. It is for such reasons that it is only natural for physicists to explore this aspect of QCD, using all tools available to them. It should be noted that the discovery of the fact that proton has a spatial structure, i.e., it is not a point particle, was due to “spin”. It was indeed due to the unexpected discovery by Stern et al. \[1\] in 1939 that it had an anomalously large magnetic moment. Today, after decades of intense experimental and theoretical investigations, the central question of how the proton spin-1/2 comes out from the quarks and gluons inside the proton as a combination of helicity and angular momenta of the components inside the proton is not understood. It is through such apparently simple, straightforward, but unsolved questions that nuclear scientists have explored and continue to explore the subtle and not-so-subtle aspects of the nucleon structure and hence understand QCD.

Quarks were originally introduced as theoretical constructs \[2,3\] based on symmetry considerations that allowed for the first time physicists to see patterns in the then-known zoo of particles. In order to distinguish amongst baryons such as $\Delta^{++}$ and $\Omega^-$, which are both made of 3 quarks of the same flavor, they had to carry a different quantum number (based on Pauli’s exclusion principle). The property of “color” had to be invented to make sense of this situation. Experiments performed at SLAC in the 1960s with electrons scattering off a nucleon, via exchange of virtual photons at high-enough energies, eventually discovered point-like spin-1/2 particles inside the nucleon that carried fractional electric charge. These constituents were eventually identified as quarks. The possible existence of gluons was indirectly inferred \[4–6\] from the 50% missing contribution to the proton’s momentum, even after accounting for the momentum carried by the quarks. This was followed by a search for and discovery of direct evidence of gluons through 3-jet events in electron–positron annihilation \[7\]. Over the following decades, the studies of nucleon structure became more precise, partly due to increased luminosities and energies of the lepton machines, leading finally to the $e^-p$ collider, HERA, at DESY.

As hadron colliders were realized, it was realized that the partonic structure of the nucleon seen in deep inelastic scattering (DIS) is universal in the sense that it can also be studied in inelastic proton–proton scattering. Based on which aspect of the nucleon structure is being studied, either electron–proton or proton–proton colliders became the appropriate tools. When our knowledge of nucleon structure improved, it became the tool to search for new physics. The discovery of electroweak bosons was the primary example, followed later by the discovery of the top-quark and most recently the Higgs boson at the LHC.

An important milestone occurred in electron–proton scattering in the mid–late 1960s. Polarized solid-state targets, which could surrogate for proton targets, were built and efforts to polarize them to a high degree were initiated \[8\]. Simultaneously, an independent effort to polarize electron beams was successfully launched by the production of the first polarized electron source \[9\] at Yale University for experiments at SLAC. Polarized DIS experiments were launched to explore and measure the quark’s spin contribution to the proton spin. The first experiments were performed at SLAC, which were then followed by CERN’s EMC experiment using much higher-energy (160–200 GeV/c) polarized muon beam. The EMC experiment at CERN discovered, to the surprise of the physics community, that hardly any of the proton’s spin was due to the spin of the quarks: the spin found was carried by the quarks and the anti-quarks, and only $\sim (14 \pm 19)\% \[10\]$ of the proton’s spin was carried by the quarks. The result became famous as the “spin crisis” in the literature and thus began the worldwide effort to understand the internal dynamics of the proton in terms of quarks and gluons. First, it was important for experiments to confirm the spin crisis by reducing the uncertainties. This was accomplished by the follow-up experiments: SMC at CERN, E142 and E143 at SLAC, and later by the HERMES
Fig. 1. Left: data on spin structure functions $xg_1$ around the late 1990s [42]. Right: results from an analysis of polarized DIS in terms of spin-dependent nucleon parton densities $\Delta S$ and $\Delta g$ at $Q^2 = 1 \text{ GeV}^2$. $\Delta S$ is the total quark and antiquark helicity contribution and $\Delta g$ is the total gluon contribution to the nucleon spin. The green shaded bands represent the uncertainty estimates at the time of the compilation of these data. Reproduced with permission from PHENIX Collaboration.

By the end of the 1990s, it was known beyond doubt that quarks indeed carry only a small fraction $\sim (25 \pm 3)\%$ of the nucleon’s spin [11,12]. The spin crisis was thus confirmed.

There were two explanations proposed at the time to explain the small contribution from the quarks and anti-quarks. First was that the $\Delta S$, the quark + antiquark’s helicity contribution [13], was actually modified due to the axial anomaly, as indicated in the equation below:

$$\Delta S(Q^2) = \Delta S'(Q^2) - \frac{n_f}{2\pi} \cdot \alpha_s(Q^2) \cdot \Delta g(Q^2)$$

(1)

$\Delta S'$ is the real contribution that experimenters were seeking, while what was measured directly was $\Delta S$. If the term that is subtracted, which has the polarized gluon distribution $\Delta g$, is large, then one would get results consistent with the spin crisis. A large $\Delta g$ would hence result in a small $\Delta S$. The next-to-leading-order QCD fits performed under the above definition of relations between $\Delta S$ and $\Delta g$ (the Adler–Bardeen scheme) [14] resulted in values that typically fell around $1.0 \pm 1.0$ in $h$-bar units. Since the values in such schemes were significantly higher than the spin of the nucleon spin itself, this had very obvious unusual consequences. It was often called the unnatural solution of the nucleon spin problem. It implied that the angular momentum of partons would possibly have to be contributing in the opposite direction to that of the gluon’s helicity contribution, to effectively bring the proton spin down to $1/2 \ h$-bar units. Since the uncertainty in $\Delta g$ by itself rather large, an experiment to measure the gluon’s helicity contribution directly and precisely was urgently needed.

By the late 1990s it was also known from the unpolarized gluon distribution measurements from HERA that, at low $x$ ($x =$ the parton momentum fraction of the proton in its infinite momentum frame), the gluon distribution rises significantly, indicating that below $\sim 0.1$ the proton is essentially
a ball of glue. What better way to measure its helicity contribution (assuming that they constitute a large helicity contribution) than to collide polarized protons at high energy with themselves? Longitudinally polarized proton collisions at high energy, where the gluons dominate the proton’s landscape, hence became the sought-after method to determine the polarized gluon distribution.

The second possibility why $\Delta \Sigma$ may have been small was related to the interplay of helicity contributions between quarks and anti-quarks. $\Delta \Sigma$ is given in terms of quarks as:

$$\Delta \Sigma = \Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s}$$

The simple suggestion was that, for some reason, anti-quarks and quarks have opposite helicity contributions, thus reducing the $\Delta \Sigma$ in the above equation. This needed an explicit measurement of anti-quark polarizations, which is impossible in the polarized DIS experiment, in which the exchange particle is a virtual photon. However, if the proton collisions were performed at high-enough energy to create $W^{+/−}$, which result from selected quark–anti-quark flavors, then the single spin asymmetry in $W$ production allows direct access to the quark and anti-quark flavor’s helicity. Polarized DIS experiments attempt to do this, by tagging on one of the final-state particles (pions or kaons, including determining their charges) [15], but the lack of knowledge of polarized fragmentation functions at the time these experiments were performed led to speculations of possible large uncertainties in their knowledge, which directly translated to large uncertainties in the polarized anti-quark and quark distributions themselves. The $W$-physics method envisioned in a high-energy polarized proton–proton collision went around this limitation of the semi-inclusive deep inelastic scattering (SIDIS) method most naturally, and hence was considered a more reliable measure of anti-quark/quark polarization measurement.

In parallel to the above deep inelastic scattering (DIS) experiments there were many fixed-target polarized proton beam on stationary fixed-target experiments were launched in the US. The expectation for a single spin asymmetry in such experiments based on simple theoretical arguments [16] was small, $\sim 0.001$, based on:

$$A_N \sim \frac{\alpha_s \cdot m_q}{p_T}$$

where $m_q$ and $p_T$ are the mass of the quark that fragments into an observable meson and the transverse momenta of the meson measured in the experiment, $\alpha_s$ is the strong interaction constant, and $A_N$ is the left–right asymmetry measured in the meson production with respect to the transverse polarization of the polarized proton beam. However, unexpectedly large single transverse spin asymmetries were experimentally observed [17–21]. They were not fully understood, i.e., there was no theoretical framework to even begin to understand them, and hence remained an enigma for decades. It was conjectured that they were simply a result of some non-perturbative phenomena not relevant to high-energy physics. However, a new spin physics program at RHIC with polarized beams presented an obvious opportunity to study them systematically. As such, the understanding of the transverse spin phenomenon by exploring it with transverse single and double spin polarized beams at various center-of-mass energies became a third important goal for the RHIC spin program.

2. The Relativistic Heavy Ion Collider (RHIC) with polarized proton beams

High-polarization proton sources existed before the 1990s, although optically pumped polarized sources were being improved during that decade. Acceleration of polarized protons while preserving the polarization needed development and demonstration of special helical magnets, called “Siberian snake” magnets [22]. These were proposed first by S. Derbenev et al., and experimentally demon-
strated at the IUCF in the 1980s and early 1990s, although at low energy. With RIKEN’s help, motivated by the need to accelerate protons to 100–250 GeV/c, these magnets were developed for the RHIC spin program. Part of that development was the establishment of the RIKEN BNL Research Center [23], founded and headed by Prof. T. D. Lee of Columbia University. Demonstration of high-energy polarized protons at successively higher energies from 2 (in the Booster) to 24 (at the AGS at BNL) to 100 GeV at RHIC took a few years, from 1996–2001. A compatible polarimetry technique based on Coulomb nuclear interference (CNI) was also developed during the same time. All these essential and novel accelerator and polarimetry developments are described elsewhere in this volume.13

The US DOE and the Japanese funding agencies through the RIKEN-BNL Research Center funded the Siberian snakes, the spin rotator magnets for two experiments (PHENIX and STAR) that were critical for the realization of the RHIC spin program at BNL. In this article we will focus briefly on the performance of RHIC as a polarized collider and the PHENIX measurements with polarized beams only. For details of the accelerator achievements of RHIC, see Ref. [14].

Figure 2 shows the polarization achieved and the integrated luminosity delivered by RHIC over the past fourteen years. Two notable effects are: a) that luminosity delivered each year in weeks has improved significantly, from \(\sim 45 \text{ pb}^{-1}\) in 2006 achieved in 14 weeks with 100 GeV/c beams with about 55% polarization, to about 470 \(\text{ pb}^{-1}\) delivered in 2013, in the same time, at about 52%. While some of the luminosity improvement is simply the higher boost of 2.5, there were clearly other significant improvements that made this significant achievement possible. Higher beam polarization not only increases the sensitivity of the spin physics measurements, but also allows a better handle on systematic uncertainties in the spin results that come from uncertainties in beam polarization. For more details on the methods and reasons for improved luminosity and beam polarization, see Ref. [14].

The RHIC comprises two counter-rotating storage rings, colored blue and yellow, each of which operates with as many as 120 polarized proton bunches of \(10^{11}\) protons or more. Protons have been
accelerated to 255 GeV/c per proton. Typically, however, the RHIC operated with \( \sim 110 \) bunches. Some of the unfilled bunches are used for background-related diagnostics essential to understanding the beam-related backgrounds in our physics sample.

The stable direction of beam polarization in the RHIC ring is vertical. The polarization direction for each bunch is aligned or anti-aligned with its vertical axis at injection, allowing collisions of multiple-orientation combinations of bunch spins within four consecutive crossings (i.e., 424 ns). Various combinations of spin orientations can be controlled and are called “spin patterns”, which are modified within and between runs to understand the various false asymmetry effects that may come from luminosity related to the bunch polarization orientation inherent in the beam from injection. Extensive studies of this effect and correlations have been performed in PHENIX and we have established an upper limit to such effects at the level of \( \sim 7 \times 10^{-4} \). This is currently the limiting factor for double-longitudinal spin asymmetry in PHENIX.

Beam polarization in RHIC relies on two separate measurements made by two polarimeters. First, the relative polarization is measured several times a fill using a fast high-statistics relative polarimeter in the CNI region of proton–carbon scattering. This measures the relative magnitude of polarization and any variation across the width of the beam [24]. This measurement is further normalized by comparing it with an absolute polarization measurement from a second polarimeter, which is based on scattering of the proton beam from a continuously running polarized hydrogen gas jet target [25].

3. The spin physics program at PHENIX

Figure 3 summarizes in a table the longitudinal spin program currently underway at RHIC with the polarized beams. The interactions of \( p–p \) and the final-state particles measured are shown in the first column, the partonic interactions responsible for it and the corresponding leading-order (LO) Feynman diagrams are indicated in the second and fourth columns, respectively, and the physical quantities of gluon distribution or anti-quark distributions are shown in the third column. The transverse spin program is not indicated in this table, as the quantities probed are normally a convolution of more than one physical quantity associated with the proton’s partonic property, or a correlation of the partonic momentum or spin with the proton’s spin or momentum. They will be described separately later.

3.1. PHENIX detector system

The PHENIX detector system was designed to perform a broad study of \( A–A, p–A, \) and \( p–p \) collisions to investigate nuclear matter under extreme conditions. A wide variety of probes sensitive to a range of timescales were expected to be used to study systematic variations in species and energy as well as to measure the spin structure of the nucleon. PHENIX was designed to measure electron and muon pairs, photons, and hadrons with excellent energy and momentum resolution. The detector consists of a large number of subsystems that are shown schematically in Fig. 4 and described below.

The PHENIX detector system consists of 4 instrumented spectrometer arms and three global detector systems. The detector consists of number of subsystems. The rapidity (\( \eta \)) and \( f \) coverage of each detector system is described in detail in Ref. [26]. The east and west arms visible in Fig. 4 (top) are centered around zero rapidity and are excellent spectrometers for the detection of electrons, photons, and charged hadrons. The north and south detectors visible in Fig. 4 (bottom) have full azimuthal coverage but limited \( \eta \) coverage and are instrumented to detecting muons. Each of the four arms has a geometric acceptance of about one steradian. The global detectors that sense the collisions
Table summarizing the science of the RHIC spin program with longitudinal spin orientation of the protons indicated in column 1, the partonic interactions of interest shown in column 2, the entity probed indicated in column 3, and the leading-order Feynman diagram indicated in column 4. Reproduced with permission from PHENIX Collaboration.

(start time for the rest of the detector), the vertex, and the multiplicity of the interactions comprise two detector systems, a beam–beam counter (BBC) and a zero-degree calorimeter (ZDC). The ZDCs detect neutrons produced in hadronic or nuclear collisions. They are located at $|z| = 18.0$ m from the interaction point (IP) along the beam axis and cover a region $|\eta| > 6$. The BBCs provide a measure of the time-of-flight of forward particles to determine the time of a collision, and provide a trigger as well as providing a measure of the collision position along the beam axis. The VTX tracker in the center is able to measure a more precise position of the event, and is thus able to determine the existence of a secondary vertex distinct from the primary if there is one in an event indicating heavy quark production in the collision. It is made up of 4 concentric barrels of 2 silicon stripixel and pixel layers installed in PHENIX in 2009/2010.

The PHENIX central magnet provides the axial magnetic field for the central spectrometer. The central arms consist of tracking systems for charged particles and electromagnetic calorimetry. The calorimeter is the outermost subsystem of the central arms and is intended for measuring both photons and electrons. A lead-scintillator (PbSc) calorimeter is used for good timing and a lead-glass (PbGl) calorimeter is used for good energy resolution. The tracking system consists of three sets of pad chambers (PC) to provide a 3D space point needed for pattern recognition; the precise projective tracking provided by the drift chamber (DC) provides excellent momentum resolution. A time-of-flight (ToF) and ring-imaging Cherenkov (RICH) provide excellent particle identification. Combining information from the RICH and electromagnetic calorimeter (EMCal), it has been demonstrated that the pion contamination in an electron sample is less than one in $10^4$ over a wide momentum range.
The forward muon spectrometers give PHENIX an acceptance for \( J/\Psi \) decaying to two muons at a rapidity range \(-2.25 < \eta < -1.15\) for the south arm, and \(1.15 < \eta < 2.44\) for the north arm. Each of these spectrometers includes a muon tracking system based on a radial magnetic field followed by a muon identifier, both with full azimuthal acceptance. The muon trackers consist of three multi-plane drift chambers for precise position resolution. The muon identifier (MuID) system consists of alternating layers of steel absorbers and low-resolution tracking layers of streamer tubes. As an upgrade to this system, directed towards reducing the beam-related backgrounds, more precise tracking was needed and was installed along with upgrades to the MuTR electronics. Overall, the pion contamination in an identified muon sample is less than one in \(10^3\).

The electronics and triggering in PHENIX has evolved over the years from its beginning and is discussed in more detail in other articles in this volume and in Ref. [27]. Most of the spin physics described in this paper required the central arms to be focused on neutral pions for gluon spin measurement and part of the \( W \) physics program, and the muon arms for the anticipated results in the \( W \)-physics program in the near future. The transverse spin physics has been achieved with
electromagnetic calorimetry installed in the forward muon arms inside the muon piston, also called the muon piston calorimeter (MPC).

3.2. The gluon spin contribution to the nucleon spin

The RHIC experiments are connected to $\Delta g$ through inclusive double-longitudinal spin asymmetry measurements, $A_{LL}$, defined by:

$$A_{LL} = \frac{\Delta \sigma}{\sigma} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

(4)

where $\sigma$ and $\Delta \sigma$ are the polarized and unpolarized cross sections for a given observable, and “++” or “±” indicate the same and opposite helicities in $p—p$ collisions. In perturbative QCD (pQCD), the double spin asymmetry $A_{LL}$ can be written as:

$$A_{LL} = \frac{\sum_{abc} \Delta f_a(x_1, \mu_F^2) \otimes \Delta f_b(x_2, \mu_F^2) \otimes \Delta \sigma^{a+b+c+X}(x_1, x_2, p_c, \mu_F^2, \mu_R^2, \mu_T^2) \otimes D_h^b(z, \mu_F^2)}{\sum_{abc} f_a(x_1, \mu_F^2) \otimes f_b(x_2, \mu_F^2) \otimes \sigma^{a+b+c+X}(x_1, x_2, p_c, \mu_F^2, \mu_R^2, \mu_T^2) \otimes D_h^b(z, \mu_F^2)}$$

(5)

where $f_{a,b}$ and $\Delta f_{a,b}$ are unpolarized and polarized parton distribution functions (PDFs). $D_h^b$ is the fragmentation function (FF) describing the probability for a parton $c$ with momentum $p_c$ to fragment into a hadron $h$ with momentum $p_h$, and $z = p_h/p_c$. $\Delta \sigma$ and $\sigma$ are polarized and unpolarized cross sections calculable in pQCD at next-to-leading-order (NLO).

Before the above framework is used for the determination of $\Delta g$, it is imperative to demonstrate the applicability of pQCD in the region of measurement by the detector. This is accomplished by measuring the cross sections of the relevant final states—pions, $\eta$, photons, etc—and comparing them with the pQCD calculations. This has been demonstrated for 200 GeV collisions of protons for the production of neutral pions [28], $\eta$-mesons [29], jets [30], and direct photons [31], where the NLO calculations compare very favorably with the measured cross sections. It is only in the regions where these comparisons have been performed that we attempt to extract the polarized gluon distribution information from the double spin asymmetries of that particular final state. A number of different final-state channels can be used to access gluon polarization using Eq. (5), as the pQCD framework seems to agree with the data for the unpolarized cross section. They include jets in the final state and rare probes such as direct photons and heavy flavor. However, so far, neutral pions (predominantly used by PHENIX) and jets (predominantly used by STAR) have been the workhorses of collaborations that have resulted in precise measurements of $\Delta g$ based on RHIC data. We summarize below the most recently published results from PHENIX at $\sqrt{s} = 200$ GeV in $p—p$ collisions and recently released data, and also for the neutral pions at 510 GeV center of mass. The other final states are not effective yet, but are expected to independently measure $\Delta g$ in the near future based on data from higher-luminosity data sets.

The results presented below for $\Delta g$ are based on data taken in 3 years: 2005, 2006, and 2009. The data selection for identifying good neutral events with neutral pions in them has been extensively discussed in a recent publication [32]. The neutral pions are identified using the central arms of PHENIX in $|\eta| < 0.35$ and have an azimuthal coverage of $\Delta \phi = \pi/2$. The magnetic field configurations in 2005 and 2006 were similar and the central magnet provided a 1.15 Tm field in the central acceptance region. However, in 2009, the field configuration was different because of the existence of the hadron blind detector (HBD) in the run, which required a field-free region near the beam pipe. This had a negligible effect on the $\pi^0$ (and $\eta$-meson) decay measurements. The details of
Fig. 5. Two-photon invariant mass in the region of $\pi^0$ mass for $4 < p_T < 5$ GeV/$c$ [34]. Also shown are the red and blue shaded regions, which are the $\pi^0$ and the background regions used to study and understand the asymmetry of the background, and which are subtracted before the final asymmetry is estimated. Reproduced with permission from PHENIX Collaboration.

data selection based on the EMCal response; the EMCal trigger, its biases, and how they were dealt with; and various analysis selection criteria in the tracking detector PC are discussed in Ref. [31]. The main luminosity monitor is the BBC, which comprises two arms (each made of quartz-crystal Cherenkov radiators connected to photomultiplier tubes), is located $|z| = 144$ cm from the IP along the beam axis and covers a pseudorapidity range of $3.1 < |\eta| < 3.9$. The second luminosity monitor is the ZDC located 18 m from the IP in the $|\eta| > 6$ region. They consist of three hadronic calorimeter modules separated by a tungsten absorber. An optical fiber collects the Cherenkov light from the hadron calorimeters. The ZDCs sit behind the beam separator magnets at the end of the interaction region (IR); thus, the charged particles are indeed swept away at the ZDC point, creating a deposit of predominantly neutral particles in the ZDC (mostly neutrons). The ZDC trigger requires a minimum energy deposit of 20 GeV in each of its arms.

For the gluon polarization studies (and for the anti-quark spin studies described in Sect. 3.3) the vertical direction of the proton bunch spin had to be made horizontal and longitudinal. This was accomplished by the spin rotator magnets located in each ring just before and after the interaction region in the blue and yellow rings. A null measurement of a large but accidently measured left–right asymmetry in single spin neutron production in $p$–$p$ scattering at 200 GeV was the benchmark for the local polarimetry, telling us that the spin rotator magnets were doing its job. Typically, in 2009, the polarization fraction along the longitudinal direction was measured and monitored during the run using the ZDCs and was estimated to be larger than $(99.4 \pm 1.3)$% for the blue beam and $(97.4 \pm 4.3)$% for the yellow beam. A typical set of remaining analysis cuts and details of the analysis are described in Ref. [31]. The method to extract a $\pi^0$ sample of events includes understanding of the background, estimating its asymmetry, and then appropriately subtracting that from the signal region. Figure 5 shows a typical plot of this procedure. The red region is identified as the signal region in the reconstructed $M_{\gamma\gamma}$ spectrum. The shaded blue region is the region used to study the background asymmetry in each $p_T$ bin. In this figure, the two-photon invariant mass is plotted for $p_T$ regions $4 < p_T < 5$ GeV/$c$.

Figure 6 shows the remarkable consistency between the cross section for $\pi^0$ measured over a wide $p_T$ range and its comparison with the pQCD calculation performed at next-to-leading-order. The
The inclusive $\pi^0$ cross section measured with $p-p$ collisions at 200 GeV center-of-mass collisions in the central arms of PHENIX, compared with the NLO pQCD calculations and the $\pi^+/-$ cross sections measured separately [33]. Reproduced with permission from PHENIX Collaboration.

Consistency between them over five orders of magnitude over the cross section and a wide $p_T$ range gives us confidence in interpreting the double-longitudinal spin asymmetries measured over the same kinematic range in terms of polarized gluon distribution [33]. The cross section measurement, and its excellent agreement with the NLO pQCD calculation, hence becomes the foundation of all our results for polarized gluon distribution. Also shown in the figure is the fact that the charged pion cross section measured by PHENIX, also in the central arm, is consistent within the uncertainty with the neutral pions, when the positive and negative pion cross sections are averaged. While this gives us further motivation to use the charged pions to independently measure the gluon distributions, not having enough of those in the PHENIX trigger so far has prevented us from robustly using them for the determination of the polarized gluon distribution. Should a large-enough triggered sample of them become available in the future, they will be used. In fact, there are clear theoretical expectations that, for a positive value of $\Delta g$, the asymmetry in $\pi^+$ is greater than that in $\pi^0$, which in turn is greater than that in $\pi^-$. The pattern reverses itself if $\Delta g$ is negative. Future high-statistics measurements may explicitly demonstrate these aspects of the measurements.

Based on the above argument, we interpret the double-longitudinal spin asymmetry in terms of the polarization of the glue. Two significant issues need to be addressed in this task: 1) the polarization measurement of the beam as described in Ref. [22], and b) a possible variation of the proton-number correlation in a bunch with its polarization direction, often called the “relative luminosity study”. A very detailed analysis of the systematic uncertainties has been performed in PHENIX of this issue, with the help of the BBC, the ZDC, and the correlations with other fast detectors such as the EMCal in the central arm.

The final results from PHENIX on the double-longitudinal spin asymmetry in the neutral pion have been published in Ref. [34] and are presented in Fig. 7 [34].
Fig. 7. The combined $A_{LL}$ vs. $p_T$ of the $\pi^0$ mesons from 2005–2009 with statistical uncertainties [34]. Overlaid on them, in the left figure, are theory curves based on the Theory Group DSSV and GRSV and, in the right figure, the theory curves from NNPDF, BB10, and LSS10, respectively. Reproduced with permission from PHENIX Collaboration.

Fig. 8. Double spin asymmetry in neutral pions produced at 510 GeV center of mass. Left plot: vs. $p_T$, right plot: vs. $x_T$ [40]. Reproduced with permission from PHENIX Collaboration.

The final extraction of $\Delta g$ from the data necessarily requires the data from PHENIX and STAR (not shown here) to be utilized in a global fit at NLO in pQCD. This has been performed by various theoretical collaborations. The most comprehensive in terms of the use of existing data sets (to include all polarized DIS and semi-inclusive data, and the RHIC spin data) is that by de Florian et al [35]. The best-fit results in values of $\Delta g$ according to these analyses come out to be $0.19 \pm 0.06$ for $x > 0.05$. A slightly older version of the fit by DSSV (the one that was available at the time of writing) is shown in the PHENIX paper (Fig. 8 (left)). The other theoretical collaborations such as NNPDF [36,37], BB10 [38], and LSS10 [39] have also attempted such analyses; however, they have not included any of the RHIC data. We show them in Fig. 7 (right) only to indicate that the uncertainties in their analysis would be significant reduced should they use PHENIX (and also STAR) data sets in the future. Nevertheless, NNPDF has presented a value and its uncertainty in their extraction of $\Delta g \sim 0.23 \pm 0.07$ in the $x$ range $0.05 < x < 0.5$. We note that it is almost exactly the same in magnitude as the one extracted for $\Delta \Sigma$ before the RHIC data became available.

As this paper was being prepared, PHENIX released a preliminary version of the double-longitudinal spin asymmetry measured in neutral pions at 510 GeV center of mass [40]. A large asymmetry is observed, as shown in Fig. 8. It is also confirmed that, at higher center of mass, the
gluon distribution for the same $x_T$ should increase. The observed increase is consistent with the theoretical expectation based on evolution.

Other probes of $\Delta g$ from PHENIX include possible future extraction of this quantity by including $\eta$ and direct photons in the global fits. However, these are currently limited by the statistical uncertainties on the measurements. A substantial increase in the luminosity in the near future is not expected at 200 GeV center of mass, but if RHIC were to run for much longer at 500 GeV, then there is a possibility that these final states would become competitive and would give access to a somewhat lower $-x$ region in the proton [41]. We note that, while the direct photon was called the “golden channel” for extraction of the gluon polarization, since it does not involve any quark fragmentation function in the final state (unlike $\pi^0$ and $\eta$), the low rate of production in this channel is the only hindrance so far. In theory, indeed, it is one of the cleanest channels to access the gluon’s contribution to nucleon spin from polarized $p–p$ collisions. If the statistical uncertainties in the data sets presented so far can be reduced in future by about a factor of 5 or so (i.e., increase the data sample by about 25 times), it is possible that the direct-photon events would start having an effect on the global fits. There have also been speculations about the possible use of heavy quarks ($c–\bar{c}$, $d–\bar{d}$) to access the polarized gluon distribution. However, the double-longitudinal spin asymmetries associated with the currently expected polarized gluon distributions are small, in fact significantly smaller, than those expected before the RHIC spin data on $\pi^0$ (from PHENIX, presented above) and from STAR jets became available. So, unless there are novel QCD effects associated with fragmentation functions that have not been observed so far, we do not anticipate significant results from heavy quarks related to the gluon spin contribution based on future measurements in this area.

3.3. The anti-quark polarization measurements

One reason for investigating the anti-quark sea at RHIC was mentioned earlier in the introduction to this paper: to understand the small value of $\Delta S$. Could it be because the sea quarks (anti-quarks included) have their spins aligned opposite to the valence quarks? There is no way to directly distinguish quarks from anti-quarks using SIDIS (without using fragmentation functions, which have large uncertainties). An alternate method is needed, and polarized proton collisions at RHIC provide just such a method. Another unexplained and surprising discovery was made regarding the anti-quark densities by the E866 experiment at FNAL [42]. It was shown that the ratio of $\text{anti-}d/\text{anti-}u$ distribution as a function of $x$ is not flat, but rises from low to high $x$ up to about $x = 0.15$ and then decreases at high $x$. This is a very clear indication that the anti-$d$ sea quark is clearly more abundant than anti-$u$. This poses a natural question for the quark spin contributions: are the anti-$d$ and anti-$u$ spin contributions also asymmetric? Some configuration selected by nature for them could be the reason for the low value of $\Delta S$. It was important that this be measured and understood; see Ref. [43] for further discussion on this topic. Semi-inclusive DIS, in principle, does shed light on this question; however, the experimental requirement of flavor tagging and its understanding in terms of pQCD requires use of fragmentation functions, which were until recently only parametrically known, and required assignment of arbitrarily large uncertainty. At RHIC the polarization of $u$, $d$, anti-$u$, and anti-$d$ quarks in the proton can be measured directly and precisely using maximally parity-violating production of $u–\text{anti-}d \rightarrow W^+$ and $d–\text{anti-}u \rightarrow W$-[44–52].

Within the Standard Model (SM), the $W$ boson is produced via a pure $V–A$ interaction, which fixes the helicities of the quarks and anti-quark that participate in its production. Further, the $W$ boson couples directly to a weak charge that correlates to flavors (per generation). While the production
of $W$ at RHIC in $p-p$ collisions is predominantly through $u$, $d$, anti-$u$, and anti-$d$ quarks, a small mixture of heavier quark flavor contamination also exists, through quark mixing in the Cabibbo–Kobayashi–Maskawa (CKM) matrix. As such, $W$ production is an ideal tool for the study of the flavor structure of the proton.

The leading-order production of $W$ in polarized protons with positive and negative helicity is illustrated in Fig. 9. At RHIC, trains of bunches are alternately right- (+) and left- (−) handed. The parity-violating single spin asymmetry is the difference between left- and right-handed production of $W$ divided by the sum and normalized by the degree of beam polarization:

$$A^W_L = \frac{1}{P} \cdot \frac{N_-(W) - N_+(W)}{N_-(W) + N_+(W)}$$

(6)

We construct this asymmetry from either beam by summing over the polarizations of the other beam, thus naturally doubling the statistical sample of events. Because of the maximal parity-violating production of the left-handed $W$ boson, if the $W$ boson is produced as in Fig. 9(a) or (b), then the asymmetry would be equal to the longitudinal polarization asymmetry of the $u$ or $d$-bar quark in the proton (high-$x$):

$$A^{W+}_L = \frac{\Delta u(x_1)}{u(x_1)}$$

$$A^{W+}_L = \frac{\Delta u(x_1)}{u(x_1)}$$

(7)

In general, the asymmetry is a superposition of these two. Interchange of $u$ and $d$ in the above equation yields the expressions for the $W$-boson asymmetries. At RHIC, at 500 GeV, the quark is predominantly a valence quark. By identifying the rapidity of $W$, $y_W$, relative to the polarized proton we can get to the flavor-separated quark and anti-quark polarizations, particularly at high $y_W \gg 0$ (for $\Delta u/u$) and $y_W \ll 0$ (for $-\Delta(\text{anti}-d)/(\text{anti}-d)$). Higher-order corrections have been estimated and are expected to be small. In measurements of these asymmetries in which one cannot make an approximation of very high values of $|y_W| \gg 0$, the experimental separation amongst the quark and anti-quark flavors becomes more complicated and has to rely on a global analysis in which these are fitted to get the most optimal functions. The measurements of $W$ in the central arm of PHENIX, presented below, will be used in this way. Future measurements of $W$ in the muon arms of PHENIX will be more direct, although obviously they can be utilized in the global fits as well.

PHENIX has pursued two methods to get to the flavor-separated anti-quark polarization: 1) through the $W \rightarrow e$ decay in the central arms, where we have excellent calorimeter and tracking systems, and
Fig. 10. The measured cross sections for $W^+$ and $W^-$ in the $W \rightarrow e$ and $W \rightarrow m$ decays in PHENIX acceptances $|\eta| < 0.35$ and $1.1 < |\eta| < 2.5$, respectively. Also shown are the STAR published result and calculations based on RHICBOS, PYTHIA, and CHE using the SM parameters [53, 54]. Reproduced with permission from PHENIX Collaboration.

The preliminary results are consistent with the expectations from the existing parameterizations of the quark and anti-quark polarizations calculated in the corresponding kinematic regions based on various theoretical models.

It is expected that the statistical and systematic uncertainties in the PHENIX data will reduce in the near future. This is especially true of the systematic uncertainties in the high-$\eta$ muon results as the understanding of the various backgrounds from hadron and meson decays coming from secondary sources is improved. The primary message, that the asymmetries observed are consistent with the theory calculations, which are fitted to the SIDIS, is unlikely to be modified.

3.4. Exploring the transverse spin structure of the proton

The third and last major thrust of the nucleon spin studies at RHIC using the large detector systems is the transverse spin structure of the nucleon. Having tried to explain the $1/2$ $h$-bar units of spin purely based on the quark and gluon helicity, and having found that they may not explain all the spin, one is compelled to look elsewhere. The transverse spin structure of the proton is expected to be connected to quantities such as the confined transverse momentum of the partons. It was understood early on that, having seen about 400 hundred times larger spin asymmetries in proton–proton single spin scattering, clearly and overwhelmingly disagreeing with the KPL1978 argument of small asymmetries, there was
Fig. 11. Single-longitudinal spin asymmetries for the various $W \rightarrow e$ and $W \rightarrow \mu$ decays measured at RHIC. The central arm results shown for PHENIX (blue and red) represent Runs 12 and 13 for the electron in the final state. Forward and backward arm results for muons in the final state are shown for high-$\eta$ regions. Theoretical expectations for polarized quark and anti-quark polarizations at these rapidities are also shown [53,54]. Reproduced with permission from PHENIX Collaboration.

much more to the transverse spin structure of the proton than was earlier envisioned. If the partons do indeed have transverse motion $k_T$ and are still confined within the proton, the purely physical picture of this requires the connection of this to the orbital angular momentum of the partons, which may contribute to the remaining spin of the proton (beyond the quark and gluon helicity contributions). Further, when a proton is transversely polarized with respect to its momentum or the collisions axis, a novel helicity-flip chiral odd twist-2 quark distribution, known as the transversity distribution, $\delta q(x)$, appears. The transversity distribution is as fundamental as the unpolarized and polarized quark distributions in QCD and has its unique factorization scale dependence and a spin sum rule:

$$\frac{1}{2} = \frac{1}{2} \sum_{\alpha=q,\bar{q}} \int dx \delta q_{\alpha}(x \cdot Q^2) + \sum_{\alpha=q,\bar{q},g} (L_{\alpha^{\uparrow}})_\alpha(Q^2)$$

(8)

where $L_S$ is the component of orbital angular momentum along the transverse spin $s_T$ of the nucleon. $\delta q(x)$ and $\Delta q(x)$ are not identical because boosts and rotations are not commutative in relativistic theory. The difference between them hence gives us an insight into the non-perturbative structure of the proton structure, which is indeed of great interest. One of the most coveted aims of scientists in this field is to measure $\delta q(x)$ over a large range in $x$ so that we can extract the contribution to the nucleon’s tensor charge $\int_0^1 dx (\delta q(x) - \bar{\delta}q(x))$, which may be compared directly to the evaluations in lattice QCD.

Transversity can be measured in measurements with transverse spin scattering in two ways: 1) observables dominated by quark-initiated partonic process like $A_{TT}$ of Drell–Yan physics or 2) single transverse spin asymmetries (SSA), where $A_N \sim \delta q(x)$. The latter requires knowledge of another chiral odd unpolarized non-perturbative function known as the Collins function [55], which
contains information about the influence of the transverse spin component of the parton in a transversely polarized proton in imparting a left light final-state momentum bias to the fragmented hadron measured in a single spin asymmetry.

Another source of single transverse spin asymmetry, now known as the Sivers function [56], has been suggested by D. Sivers; this relates the influence of the initial-state parton transverse momentum to the left–right single spin asymmetry in the production of the final-state quark/meson. This is by its physical origin easily connected to the orbital motion of the parton and hence to the orbital angular motion of the partons in the initial state.

In proton–proton collisions, clearly the Collins and Sivers functions, if they are both non-zero, will play a role in determining the observed asymmetries, and by themselves cannot be without additional input from experiments performed with $e^+e^-$-collisions, which measure polarized and unpolarized fragmentation functions for meson production (pions in our case), thus allowing us to unfold the Collins asymmetries and hence transversity, and $e^-p$ collisions, which impart direct input to the initial-state $k_T$ of partons. There are some fundamental rules regarding the color flow that are of great interest to check if the Sivers asymmetries in DIS and in Drell-Yan measurable at RHIC have a reversed analyzing power, which may lead to further fundamental understanding about the factorizability of the transverse-momentum-dependent parton distributions.

All of these constitute a complex and multifaceted program for the PHENIX detector to be carried out in the remaining years of the RHIC operations. A slew of transverse spin measurements have been pursued that have gone in to our understanding of the rich dynamics of the parton and their correlations described so far. Typically, the transverse spin measurements are based on $\pi^0$, $\eta$, or “energy cluster” measurements in the central arms of PHENIX in the $|\eta| < 0.35$ or forward direction ($3.0 < |h| < 3.8$) using the muon piston calorimeter (MPC) [57].

Figure 12 shows the single spin asymmetries measured in neutral pion and $\eta$ production at 200 GeV center-of-mass collisions of transversely polarized protons at RHIC measured in the PHENIX detector’s central arms. Evidently, the $A_N$ in both cases is consistent with zero.

**Fig. 12.** Single spin asymmetry in $\pi^0$ and $\eta$ produced in the central arm of PHENIX [57]. Reproduced with permission from PHENIX Collaboration.
Figure 13 shows a comparison of the PHENIX $A_N$ measurement at 62.4 GeV center of mass with E704 (fixed-target single spin physics measurements at FNAL) and with the STAR detector at 200 GeV center of mass. All measurements are mostly consistent with each other within the experimental uncertainties and who now center of mass or $\eta$ dependence.

Figure 14 (left) shows the PHENIX $\pi^+$ transverse single spin asymmetry compared to the measurements by the BRAHMS detector collaboration in the early 2010s. The origin of this $A_N$ is inconsistent with the $u$ and $d$ quark Sivers functions (Fig. 15, right) extracted from SIDIS experiments.

Figure 15 (left) shows a comparison of the measured cross section of $h$ production at 200 GeV center of mass and a next-to-leading-order perturbative QCD calculation [57]. A very impressive consistency is demonstrated, indicating the validity of pQCD effects in the measured high-$h$ range indicated in the figure. The right-hand figure shows the single spin asymmetry measured in the same kinematic region. As expected, the negative $x_F$ asymmetries are zero, while the positive $x_F$
asymmetries are indeed positive. Although it is not shown, they are consistent with the $\pi^0$ asymmetries measured by PHENIX in the same region, shown in Fig. 13, and by the STAR and E704 experiments.

While no concrete conclusions can be drawn from the above measurements regarding the transverse dynamics of partons in the proton, it is clearly a topic of great experimental and theoretical interest. Short- and long-term future investigations will allow many aspects of this puzzle to be uncovered. However, a complete picture of the transverse momentum and position distribution of the partons needs more measurements from RHIC, complementary to those currently planned at the Jefferson Lab and with the COMPASS detector at CERN, as well as the future electron ion collider (EIC).

4. Summary and outlook

The realization of RHIC with polarized beams has been a major advance in the field of nucleon spin. It has addressed some of the most fundamental open questions that have faced the nucleon spin community since the 1990s. It has decisively measured the contribution of polarized gluons to the nucleon spin in $x > 0.05$. We now know that $\Delta g \sim 25\%$ of the proton’s spin $1/2$, far less than what was envisioned before RHIC came about. The current best estimates of the quark and gluon’s contribution to the nucleon spin are about $20–25\%$ each. This leaves room for a substantial contribution to the nucleon spin from the orbital angular momentum from quarks and gluons.

RHIC has also initiated a program to directly measure the sea quark’s contribution to the nucleon’s spin. Unambiguous separation of the quark vs. anti-quark’s contribution to the nucleon spin was not possible in the past. It had to depend on SIDIS data from fixed-target experiments, which relied heavily on insufficient and model-dependent polarized and unpolarized fragmentation functions. RHIC has worked around this problem very naturally by invoking the parity-violating generation and decay of W bosons. Early results summarized in this paper indicate that the expected quark and anti-quark polarized distributions are indeed what the pre-RHIC models had predicted, with at most minor
modifications. The data collected recently in 2014 may solidify this observation further over a wide kinematic region, as results from PHENIX and STAR get published in the coming year.

The transverse spin collisions have been pursued intermittently at RHIC and have provided surprising and exciting new results, which promise to help shed light on the transverse dynamics of partons inside the proton when combined with the transverse spin physics results from the DIS and SIDIS fixed-target experiments at COMPASS and the Jefferson Lab in the near future. The complementary but essential nature of these methods has been highlighted by the global analyses now underway with the participation of both theorists and experimentalists.

The need for even higher precision in understanding the longitudinal spin structure of the proton, and many tests of QCD possible only through transverse spin collisions in $p-p$ and $e-p$, has become apparent over the years. It has also been acknowledged that some of these DIS and SIDIS data that may be needed for these physics goals would have to be at very high energy. As a result, a high-luminosity high-energy polarized electron ion collider (EIC) is currently under consideration by the US nuclear science community as their next major research facility in the US after the construction of the FRIB (the radioactive beam facility at Michigan State University). The science of the EIC has been laid out in a recent White Paper [58], prepared and released recently for the Nuclear Science Advisory Committee’s (NSAC) deliberations. This White Paper presents measurements that will help us fully elucidate and understand the nucleon’s spin structure in terms of the helicity of quarks and gluons, and construct a very detailed picture of the quark and gluon’s positions and momentum distributions in the transverse direction to its motion, akin to realizing tomographic images of the proton in its polarized state. A natural consequence of the precision enabled by the EIC will be to allow us to access and possibly also measure the orbital angular momentum of the partons. Progress in lattice QCD also promises to evaluate various parton distribution functions [59–62] in polarized protons by the mid-2020s. The EIC thus provides an exciting possibility to enable a direct comparison of these quantities from experimental data and lattice QCD. High-energy nuclei colliding with the electron beam is another major thrust of the EIC’s physics program. Precise measurements leading to unprecedented understanding of the role of gluons in QCD at the highest energy (partonic density) would be possible. We refer readers to the White Paper [29] for further details of the science case.

Currently, there are two designs for the US EIC. One uses one of the beams of RHIC and collides with a 5–20 GeV/c (upgradable to 30 GeV/c at a lower luminosity) electron beam facility to be constructed within the RHIC tunnel. The other proposal uses the recently upgraded 12 GeV CEBAF facility at the Jefferson Lab and collides it with a new hadron beam facility to be built near it. The physics program could start with the lower-energy electron beam and then be upgraded to the full 20 (30) GeV/c at a later date. The luminosity aimed at for the physics is $10^{33–34}$ cm$^{-2}$ sec$^{-1}$ (about 100–1000 times the luminosity achieved at the HERA collider at DESY). The US EIC would be the first polarized electron–proton collider, as well as the first electron–nucleus collider.

Should the site for EIC be RHIC, i.e., eRHIC, then the existing IRs (currently occupied by PHENIX and STAR) would be natural places to consider locating the EIC detectors. Recently, the PHENIX collaboration and Brookhaven National Laboratory submitted a proposal for a major upgrade of the PHENIX detector [63], called the sPHENIX detector, and a letter of intent to further enhance this detector to be optimized as a first-stage eRHIC detector [64]. The sPHENIX consists of new large-acceptance electromagnetic and hadronic calorimetry built around the superconducting solenoid acquired from the decommissioned BaBar experiment at SLAC. sPHENIX proposes to make key new measurements of probes of strongly coupled quark–gluon plasma (sQGP) and study its internal
It is possible that, after the sPHENIX detector is constructed, the forward (hadron-going side; red detectors on the right in Fig. 16 (bottom)) and backward (electron-going side; green detectors on the left in Fig. 16 (bottom)) detectors of the eRHIC detector may be realized sequentially in time. If the forward detectors (hadron-going side) can be realized earlier than the transition of RHIC to eRHIC (in which case, according to the current plans of the BNL management, the yellow RHIC ring will be dismantled), then sPHENIX with its forward detector upgrade could become a detector for transverse spin physics and a \( p-A \) physics program at RHIC before eRHIC comes online. Interested scientists in the PHENIX collaboration are considering this stage beyond the sPHENIX upgrade, as yet another upgrade: forward-sPHENIX or fsPHENIX. Arguments for the scientific case for such an interim program, based on measurements of transverse spin phenomena extending to the Drell–Yan physics, direct-photon measurements in single spin polarized collisions, and also exploration of the nuclear-size dependence of the saturation scale in polarized \( p-A \) collisions, are currently being developed \cite{65}.

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