Measuring the gluon spin contribution to the proton spin in polarized p+p collisions with the PHENIX experiment

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on behalf of PHENIX Collaboration
The **Relativistic Heavy Ion Collider** accelerator complex at Brookhaven National Laboratory

- **Collision Energy**: 62 ~ 510 GeV
- **Polarization**: 50 – 60 %
- **Luminosity**: 10 pb⁻¹/week
Collision Energy: 62 ~ 510 GeV
Polarization: 50 – 60%
Luminosity: 10 pb⁻¹/week
RHIC $p+p$ accelerator complex

- Absolute $p\overline{H}$ polarimeter
- RHIC $pC$ “CNI” polarimeters
- BRAHMS & PP2PP
- PHOBOS
- PHENIX
- STAR
- AGS
- AGS $pC$ “CNI” polarimeter
- Coulomb-Nuclear Interference
- Siberian Snakes
- Spin Rotators
- Pol. Proton Source
- LINAC
- BOOSTER
- 200 MeV polarimeter
- 20% Snake
- Rf Dipoles
- 5% Snake
RHIC $p+p$ accelerator complex

Spin direction

Collision

Spin direction

Siberian Snakes

Spin Rotators

Pol. Proton Source

200 MeV polarimeter

20% Snake

Rf Dipoles

AGS

AGS pC “CNI” polarimeter

Coulomb-Nuclear Interference
Highlights of RHIC Spin Program (Outline)

Longitudinal Spin Structure
- **Gluon Spin** (this talk)
- **Sea Quark** (following talks)

Transverse Spin Structure
- Sivers Effect
- Collins Effect
- Higher Twist ...

Future Upgrades
RHIC Polarized Spin Program

RHIC Polarized Proton Runs

Delivered Integrated Luminosity [pb]

Run5  Run6  Run8  Run9  Run11  Run12  Run13

- 500 (510) GeV
- 200 GeV
- 62 GeV
RHIC Polarized Spin Program

Beam Polarization

RHIC Polarized Proton Runs

Delivered Integrated Luminosity [pb]

Run5  Run6  Run8  Run9  Run11  Run12  Run13

ΔG

Δq

500 (510) GeV
200 GeV
62 GeV
Longitudinal Spin Structure

Longitudinally Polarized proton-proton

Helicity +

versus

Helicity −

Helicity Asymmetry

\[ A_{LL} = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}} = \sum_{a,b} \Delta f_a \otimes \Delta f_b \otimes d\hat{\sigma}^{f_af_b \rightarrow fX} \cdot \hat{a}_{f_f \rightarrow fX} \otimes D_f^h \]

Hadron Asymmetry

Fragmentation Function
Subprocess of pp

\[ A_{LL} \propto [\omega_{gg} \Delta g \Delta g] + [\omega_{gq} \Delta q \Delta g] + [\omega_{qq} \Delta q \Delta q] \]

Gluon is the major player compared to DIS/SIDIS
The PHENIX Detector

- Philosophy
  - high resolution & high-rate at the cost of acceptance
  - trigger for rare events

- Central Arms
  - $|\eta| < 0.35$, $\Delta\phi \sim \pi$
  - Momentum, Energy, PID

- Muon Arms
  - $1.2 < |\eta| < 2.4$
  - Momentum (MuTr)

- Muon Piston Calorimeter
  - $3.1 < |\eta| < 3.9$
## ΔG

### DOUBLE HELICITY $A_{LL}$ RESULTS

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Central Arm $\pi^0, \eta$

- Production cross section is high and from gluon interaction
- PHENIX EMCal trigger friendly
- Found in 2 photons invariant mass

\[ A^{\pi^0}_{LL} = \frac{A^{\pi^0+BG}_{LL} - w_{BG}A^{BG}_{LL}}{1 - w_{BG}} \]

Yield

$A_{LL}$: Central Arm $\pi^0$, $\eta$

- Statistically enriched observable
- Need to control Systematic uncertainties (relative luminosity)
- $\Delta G$ through
  - a different flavor structure
  - fragmentation function
- Statistically Challenging
More Challenging Attempt: \( \pi^0 - \pi^0 \) correlation

- Constrains event kinematics further
- Cost Statistics, need high \( P^4L \)

![3D histogram showing the correlation between invariant masses of \( \pi^0 - \pi^0 \) pairs with a peak at around 1 GeV.]

![Graph showing the correlation between single \( \pi^0 \) and \( \pi^0 \) pair distributions with an 8.8% polarization uncertainty, not included in the preliminary data.]
\( \pi^\pm \) charge asymmetry is sensitive to sign of \( \Delta g(x, Q^2) \):

- \( D_u \pi^+ > D_u \pi^0 > D_u \pi^- \), \( \Delta u > 0 \)
- \( D_d \pi^+ < D_d \pi^0 < D_d \pi^- \), \( \Delta d < 0 \)

For positive \( \Delta g \):

- \( A^{\pi^+}_{LL} > A^{\pi^0}_{LL} > A^{\pi^-}_{LL} \)

\( p + p \rightarrow \pi^+ + X \)
\( \sqrt{s} = 200 \text{ GeV} \)

PHENIX Preliminary Run-09

- \( \Delta_{LL} \nu \ll 0.1 \)

\( \Delta_{LL} \nu \) range of this analysis covers \( <x_g> \sim 0.1 \)
Charged pion Cross Section

$p+p \rightarrow \pi^\pm$ and $\pi^0 + X$
at $\sqrt{s}=200\text{GeV}$, $|\eta|<0.35$

$\frac{(\pi^+ + \pi^-)}{2}$ Preliminary('09 Data)
$\pi^0$ PRD 76, 051106(2007)

Charge separated fragmentation functions are not well constrained in DSS FFs

In good agreement with STAR

NLO pQCD (by M. Stratmann)
CTEQ6.5 PDFs; DSS FFs
$\mu = p_T$ (solid); $p_T/2$, $2p_T$ (dashed)

$\pi^-/\pi^+$ ratio at Mid-$\eta$, $\sqrt{s}=200\text{GeV}$ (p+p)

PHENIX Preliminary, $|\eta|<0.35$
PRL 108 72302(2012) (STAR), $|\eta|<0.5$
DSS (pQCD NLO) $\mu = p_T$, $p_T/2$ and $2p_T$
Heavy Flavor Decay
Electrons

Subprocess fraction at NLO

signal
\[ D^+ \rightarrow \overline{K}^0 \nu_e e^+ \]
\[ D^0 \rightarrow \overline{K}^- \nu_e e^+ \]

backgrounds
\[ \pi^0 (\eta) \rightarrow \gamma \gamma \gamma e^+ e^- \] (in material)
This results largely benefited from using HBD in eliminating photo-conversion and Dalitz decay background.

Decay electrons include J/ψ, bottom production and other vector meson as well as open charm contributions.

Open charm production dominates in p_T range of 0.50 < p_T < 1.25 GeV/c

(J/ψ < 2%, b quark < 5%)

|Δg/g(⟨logx⟩,µ)|^2 < 3 × 10^{-2} (1σ)

(0.01 ~ x ~ 0.08)
Exploring Lower-x by Forward MPC

Muon Piston Calorimeter
$3.1 < |\eta| < 3.9$

- Low $P_T$ Reconstructed $\pi^0$
- High PT Merged $\pi^0$

cluster
Cluster $A_{LL}$

- Still consistent with zero at lower $x$
- Systematic error starts to defeat statistics
- Good control of relative luminosity required for better precision
Impact of RHIC 2009 Data

**PHENIX Preliminary**

- **DIS**
- **SIDIS**
- **pp**

**QCD Global Fit**

- **DSSV++ for jet**
- **DSSV++ for jet**
- **PHENIX Prelim.**

**Note:**
- Fully consistent
- Approximately 2% in DSSV analysis
- Approximately 10 GeV
- Strong constrain on first
- Completely consistent with
- First
- Strong constrain on
pQCD Fit on Latest (Run9) Data
DSSV++ (with latest results)

First Positive Polarization $\Delta G$ Result:

$$\int_{0.05}^{0.2} \Delta g(x) \, dx = 0.1 \pm \frac{0.06}{0.07}$$

**ΔG @ 510 GeV**

Access to smaller x region

Larger error @ overlapping x compared to 200GeV

**Central arm π₀**

**500 (510) GeV Integrated Luminosity (Delivered)**

Rich Integrated Luminosity

**MPC π₀ for ΔG at low x**

pp → π₀X

3.1<|η|<3.9

PHENIX proj. for √s=510 GeV:
L=630 pb⁻¹ P=0.55
Summary

• Measurements of gluon polarization at PHENIX through double longitudinal asymmetry.
• Various observables provide different sensitivities on $\Delta G$ sign, fragmentation functions.
• The first indication of positive $\Delta G$ from 2009 200 GeV data.
• More data to come from 510 GeV which cover smaller x region.
\[ \Delta G \at 62 \text{ GeV} \]

RHIC Polarized Proton Runs

![Diagram showing RHIC Polarized Proton Runs with data points for 500 (510) GeV, 200 GeV, and 62 GeV. The figure also includes a graph of the asymmetry \( A_{LL}(\pi^0) \) as a function of \( p_T \) for various model predictions and data points.](image)

The above results are consistent with a comprehensive global analysis of almost all polarized DIS and RHIC data [1, 10]. The RHIC data now pose the tightest constraint on \( g(x) \) in the range 0.05 < x < 0.2. The global analysis suggests a truncated first moment \( g[0.001, 1] = 0.013 \pm 0.070 \) at \( Q^2 = 10 \text{ GeV}^2 \), and full first moment \( g[0, 1] = 0.084 \). These results are very interesting. First, they suggest that large, anomaly-inspired values for \( g \) are very unlikely. Second, the difference between the truncated and full first moment highlights the importance of extending the measurements at RHIC to lower x. This may be possible in the near future as PHENIX' barrel and forward silicon vertex detectors are installed, and a proposed forward calorimeter (covering 1 < \( \theta \) < 3) is developed. These will increase the acceptance of the PHENIX detector substantially, and will allow new, correlated asymmetry measurements of \(-\)-jet, hadron-jet, and jet-jet. These new observables will allow us to constrain the kinematics of the hard-scattered partons, and improve our sensitivity to \( g(x) \) at lower momentum fraction x, perhaps to a few \( \times 10^{-3} \).

The PHENIX collaboration also has preliminary asymmetry results on several other inclusive channels. The \( A_{LL}(\pi^0) \) measurement has a slightly different sensitivity to \( g \) than \( \pi^0 \) since the flavor content of the \( \pi^0 \) is different. The asymmetry measured is consistent with 0, and is shown in Fig. 4 along with GRSV model predictions [8]. PHENIX' measurement of \( A_{LL} \) of direct photons is shown also in Fig. 4. This asymmetry too is consistent with 0, and is heavily statistics limited. The virtues of this measurement are that it is dominated by \( qg \) scattering, and so is linear in \( g \).
pQCD Fit on Latest (Run9) Data
DSSV++ (with latest results)

First Positive Polarization $\Delta G$ Result:
\[
\int_{0.05}^{0.2} \Delta g(x) \, dx = 0.1 \pm \frac{0.06}{0.07}
\]
Polarized gluon distribution (I)

- **Central Rapidity**

\[ \pi^0, \pi^{+/0} \] Sensitive to sign of \( \Delta g \)

\[ \eta \] Different fragmentation

Abundant Statistics

\[ A_{UL}^{\pi^0} \]

PHENIX Preliminary

- DSSV
  - Run5+6+9

\[ p_T \text{ (GeV/c)} \]

Polarized gluon distribution (II)

- **Central + Forward Rapidity, Low Energy**

Single e

High purity of glue-glue subprocess

Forward Cluster

Small $x \sim 10^{-3}$

$\pi^0$ at $\sqrt{s} = 62.4$ GeV

High $x$


DSSV Interpretation of $\pi^0 A_{LL}$

- Run5+Run6+Run9 Combined data constrain $\Delta G$
- Consistent with small $A_{LL}$, but still compatible with STAR jet probes somewhat lower values of $x$

D. De Florian et al.  
Progress in Particle and Nuclear Physics 67 (2012) 251
HBD Analysis for Heavy Flavor Decay $e^-$

- Hadron Blind Detector
  - gas Cerenkov detector read out with CsI evaporated GEM
  - electron identification
- this analysis is the first time of physics measurement with HBD

HBD cluster charge distributions

- each histograms are normalized as integral=1 (or 0.1)
- $75\%$
- $20\%$
Extraction of Gluon Polarization

QCD Global Fit

DIS
SIDIS
pp

HERMES
COMPASS
Jlab...

RHIC data constrain on gluon polarization!

PHENIX
STAR
(2005,2006)

Quark
Gluon

Consistent w/ 0

DSSV
DSSV +1
DSSV 2%

DNS
GRSV STD
GRSV VAL

Anti-quark
Strangeness
FIG. 4 (color online). The fractional contribution of gluon-gluon ($g g$), quark-gluon ($q g$), and quark-quark ($q q$) scattering to the $\eta$ production in the pQCD calculation of Fig. 3, and to the $\pi^0$ production [24], as a function of $p_T$.

FIG. 6. The double-helicity asymmetry for midrapidity inclusive $\eta$ production from the combined 2005 and 2006 data at $\sqrt{s} = 200$ GeV as a function of $p_T$. The gray boxes are point-to-point systematic uncertainties due to polarization and relative luminosity uncertainties and are correlated point-to-point, moving all points in the same direction but not by the same factor. An additional systematic uncertainty of 4.8% on the vertical scale due to the uncertainty in the beam polarizations is not shown. The results are compared to NLO pQCD calculations using two different sets of polarized PDFs [6,32]. See text for details.