Proton Spin Physics in Polarized Proton-proton Collisions at STAR

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Introduction to the spin structure of the proton

❖ The naïve quark parton model
  - aka Static Constituent Quark Model
  - three stationary massive quarks
    ■ each weighs approx. \( \frac{1}{3} \) of the proton mass
  - able to reproduce many properties of baryons; e.g.,
    ■ magnetic moment of proton, neutron, hyperons
    ■ baryon spectrum
  - quarks in a \( s \)-state
    ■ no orbital angular momentum
    ■ \( \Sigma = 1 \) (quarks’ spin carries all proton spin)
Introduction to the spin structure of the proton

- "Spin Crisis"

- EMC experiment at CERN in 1988
  - polarized deep inelastic scattering (pDIS)
  - $\Sigma = 0.14 \pm 0.09 \pm 0.21$

- Quarks’ spin carries only a small fraction of proton spin

- $\Sigma = 0.33 \pm 0.03 \pm 0.05$ (recent value COMPASS, CERN, 2007)

- lately less sensationally called “Spin Puzzle”
**Static Constituent Quark Model**
- lack of motion of quarks
- lack of dynamics of quarks
- $\Sigma = 1$ (contradicts with the measured value)

**Relativistic Constituent Quark Model**
- relativistic motion of quarks
  - quarks’ mass is tiny
  - proton mass is largely due to kinetic energy of quarks
  - Dirac equation indicates orbital motion of quarks
  - $\Sigma \approx 0.65$ (still much larger than the measured value)
- lack of dynamics of quarks

**Quantum Chromodynamics (QCD)**
- dynamics are mediated by vector field, *gluons*
- axial anomaly; spin vector current is not conserved
- Gluons can share proton spin; $\Delta G \neq 0$
Introduction to the spin structure of the proton

- Decomposition of proton spin

\[
\frac{1}{2} = \frac{1}{2} \Sigma + \Delta G + L_q + L_g
\]

proton quark spin gluon spin orbital motion

- Quark spin and gluon spin contributions can be expressed in terms of polarized parton distribution functions

\[
\Sigma = \frac{1}{2} \left( \Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s} \right) \quad \Delta q = \int_0^1 (q^+(x) - q^-(x)) \, dx
\]

\[
\Delta G = \int_0^1 \Delta g(x) \, dx \quad \Delta g(x) = g^+(x) - g^-(x)
\]

- \( \Sigma \) has been measured by pDIS (\( \Sigma \approx 0.33 \))

- How do you measure \( \Delta G \)?

- Is it possible to measure \( L_q + L_g \)?
Measurement of $\Delta G$

- Polarized Deep Inelastic Scattering (pDIS)

- Polarized Semi-inclusive DIS (pSIDIS)

- Polarized Proton-proton Collisions
Measurement of $\Delta G$

**Polarized Deep Inelastic Scattering (pDIS)**

- Not as sensitive to $\Delta G$ as it is to $\Sigma$
  - Leptons do not couple to gluons

- $Q^2$-evolution of $\Delta q(x, Q^2)$ potentially yields $\Delta g(x, Q^2)$

- **Global analysis** of polarized parton distributions
  - E.g., GS, GRSV, LSS, AAC
  - Determined $\Delta q(x, Q^2)$ with some accuracy
  - Constrained $\Delta g(x, Q^2)$ little
    - $Q^2$-evolution is slow
    - Present pDIS data cover a limited range of $x$ and $Q^2$
  
  Almost any $\Delta g(x, Q^2)$ fits pDIS data
Measurement of $\Delta G$

Polarized Semi-inclusive Deep Inelastic Scattering (pSIDIS)

- detect hadrons simultaneously with scattered leptons
- photon-gluon fusion process
  - directly sensitive to $\Delta G$
  - higher-order processes
- HERMES at DESY
- SMC, COMPASS at CERN

![Graph showing measurements of gluon polarization from COMPASS, HERMES, and SMC](image)

<table>
<thead>
<tr>
<th>Experiment process</th>
<th>$\langle x_g \rangle$</th>
<th>$\langle \mu^2 \rangle$ (GeV$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERMES hadron pairs</td>
<td>0.17 ± 0.18</td>
<td>20 ± 0.28</td>
</tr>
<tr>
<td>HERMES inclusive hadrons</td>
<td>0.22 ± 0.07</td>
<td>1.35 ± 0.03</td>
</tr>
<tr>
<td>SMC hadron pairs</td>
<td>0.07 ± 0.12</td>
<td>0.20 ± 0.08</td>
</tr>
<tr>
<td>COMPASS hadron pairs, $Q^2 &lt; 10.85$</td>
<td>0.02 ± 0.05</td>
<td>0.16 ± 0.05</td>
</tr>
<tr>
<td>COMPASS hadron pairs, $Q^2 &gt; 10.82$</td>
<td>0.02 ± 0.05</td>
<td>0.18 ± 0.05</td>
</tr>
<tr>
<td>COMPASS open charm</td>
<td>0.11 ± 0.09</td>
<td>0.49 ± 0.07</td>
</tr>
</tbody>
</table>

![Diagram showing measurements of gluon polarization](image)
Measurement of $\Delta G$

Polarized Proton-proton collisions

- gluons at the leading order
- challenging to determine $x$ and $Q^2$
- PHENIX, STAR at RHIC, BNL
Measurement of $\Delta G$

Polarized Proton-proton collisions

- **Double Longitudinal Spin Asymmetries $A_{LL}$**
  - the primary quantity to measure
  - defined as
    \[
    A_{LL} = \frac{\Delta \sigma}{\sigma} = \frac{(\sigma^{++} + \sigma^{--}) - (\sigma^{+-} + \sigma^{-+})}{(\sigma^{++} + \sigma^{--}) + (\sigma^{+-} + \sigma^{-+})}
    \]
  - sensitive to $\Delta g(x, Q^2)$; the first moment is $\Delta G$
  - in the QCD factorization:
    \[
    A_{LL} = \frac{\sum \int dx_1 \int dx_2 \Delta f_i(x_1, Q^2) \Delta f_j(x_2, Q^2) \hat{a}_{LL} \hat{\sigma}(\cos \theta^*)}{\sum \int dx_1 \int dx_2 f_i(x_1, Q^2) f_j(x_2, Q^2) \hat{\sigma}(\cos \theta^*)}
    \]

- **Cross Sections $\sigma$**
  - test QCD factorization
    \[
    \sigma = \sum \int dx_1 \int dx_2 f_i(x_1, Q^2) f_j(x_2, Q^2) \hat{\sigma}(\cos \theta^*)
    \]
Measurement of $\Delta G$

*Polarized Proton-proton collisions*

- determination of *parton-level kinematics*
- in DIS, it can be always determined

\[
\chi = \frac{Q^2}{2M \nu}
\]

- in pp, not unless two outgoing partons are measured

\[
\begin{align*}
\chi_1 &= \frac{\hat{p}_T}{\sqrt{s}}(e^{+y_3} + e^{+y_4}) \\
\chi_2 &= \frac{\hat{p}_T}{\sqrt{s}}(e^{-y_3} + e^{-y_4})
\end{align*}
\]

$\rightarrow$ *dijets, $\gamma$ - jet*
RHIC as a polarized proton-proton collider

- The world’s first and only polarized proton-proton collider

- \( \sqrt{s} = 23 \sim 500 \text{ GeV} \)

<table>
<thead>
<tr>
<th>Run</th>
<th>( \sqrt{s} ) [GeV]</th>
<th>( \int L dt ) [pb(^{-1})](^a)</th>
<th>Polarization(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run-2</td>
<td>200</td>
<td>0.47</td>
<td>14%</td>
</tr>
<tr>
<td>Run-3</td>
<td>200</td>
<td>2.5</td>
<td>34%</td>
</tr>
<tr>
<td>Run-4</td>
<td>200</td>
<td>3.2</td>
<td>46%</td>
</tr>
<tr>
<td>Run-5</td>
<td>200</td>
<td>12.7</td>
<td>46%</td>
</tr>
<tr>
<td>Run-6</td>
<td>200</td>
<td>44.9</td>
<td>58%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>62</td>
<td>50%</td>
</tr>
<tr>
<td>Run-8</td>
<td>200</td>
<td>19.2</td>
<td>44%</td>
</tr>
<tr>
<td>Run-9</td>
<td>500</td>
<td>52.6</td>
<td>40%</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>53.5</td>
<td>56%</td>
</tr>
</tbody>
</table>

\(^a\) Delivered luminosity at STAR
\(^b\) Average polarization
STAR Detector

a full-azimuth calorimeter

a full-azimuth tracking device
Jets are sprays of particles which are moving approximately in the same direction from the collision point.
Jets at STAR

Parameters of Recent Jet Analysis

- 140 billion polarized proton-proton collisions at 200 GeV, RHIC Run-6
- Jet Patch Trigger
  - $E_T > 8.3$ GeV in a jet patch
  - minimum bias condition
- Jet Definition
  - Charged tracks in TPC
  - Energy deposits in BEMC towers
  - *Mid-point cone* ($R=0.7$)
- Dijet Definition
  - Two-leading $p_T$ jets
Jets at STAR

- two quantities to measure
  - *Jet Spin Asymmetries* $A_{LL}$
    - to extract $\Delta g(x, Q^2)$
  - *Jet Cross Sections*
    - test theory used to extract $\Delta g(x, Q^2)$ from $A_{LL}$
      - pdf, pQCD, jet definitions, hadronization and underlying events

- two final states to observe
  - *Dijets*
    - the best channel at RHIC
      - started at Run-6
  - *Inclusive jets*
    - best alternative at STAR
      - measured for Run-3/4/5/6/9
Jets at STAR

Jets at three levels

Data and theory are corrected to hadron level using Monte Carlo (MC) simulation
Jets at STAR

Data-MC comparison of inclusive jets

Correction factors are determined with MC samples which well reproduce data.

11.44 < pT < 17.31 GeV
26.19 < pT < 39.63 GeV
39.63 < pT < 59.96 GeV

MC: Pythia 6.4 + Geant 3

−0.8 < η < 0.8
Jets at STAR

**Data-MC comparison of dijets**

Data are well described by MC

**MC:** Pythia 6.4 + Geant 3

<table>
<thead>
<tr>
<th>Condition</th>
<th>( \max(p_T) &gt; 10.0 ) GeV</th>
<th>( \min(p_T) &gt; 7.0 ) GeV</th>
<th>(-0.8 &lt; \eta &lt; 0.8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(</td>
<td>\eta_3 - \eta_4</td>
<td>&lt; 1.0)</td>
<td>(</td>
</tr>
</tbody>
</table>
Inclusive Jet Cross Section

- pp 200 GeV, RHIC Run-6
- update from the previous measurements based on Run-3/4 data [PRL 97 (2006) 252001] with smaller acceptance and cone size
- well described by theory which is used to extract polarized parton distributions from inclusive jet $A_{LL}$
- provide reference for heavy-ion collisions

\[
\frac{d^2\sigma}{2\pi dp_T d\eta} = \frac{1}{\int L dt} \cdot \frac{1}{2\pi \Delta p_T \Delta \eta} \cdot \frac{1}{C} \cdot N_{\text{jets}}
\]

- $N_{\text{jets}}$: Detector-level jet yields
- $C$: Correction factors
- $2\pi \Delta p_T \Delta \eta$: Phase space volume
- $\int L dt$: Luminosity
Dijet Cross Section

- pp 200 GeV, RHIC Run-6
- the first measurement at RHIC
- well described by theory which can be used to extract polarized parton distributions from dijet $A_{LL}$

\[
\frac{d^3\sigma}{dM_{jj}d\eta_3d\eta_4} = \frac{1}{\int Ldt} \cdot \frac{1}{\Delta M_{jj}\Delta \eta_3\Delta \eta_4} \cdot \frac{1}{C} \cdot N_{jets}
\]

- $N_{jets}$: Detector-level dijet yields
- $C$: Correction factors
- $\Delta M_{jj}\Delta \eta_3\Delta \eta_4$: Phase space volume
- $\int Ldt$: Luminosity
Inclusive Jet Double Longitudinal Spin Asymmetry $A_{LL}$

- pp 200 GeV, RHIC Run-6
- second update
  - Run-5 data [PRL 100 (2008) 232003]
- inconsistent with large $\Delta G$
- probed $0.02 < x < 0.3$

- provided significant constraint on $\Delta g(x, Q^2)$ in a global analysis of polarized pdf, DSSV [PRL 101 (2008) 072001]
- confirmed the relevance of a probing wider range of $x$
- stimulated the discussion of the measurements of the orbital motions of partons
Dijet Double Longitudinal Spin Asymmetry $A_{LL}$

- the first measurement of dijet $A_{LL}$
- consistent with DSSV prediction
- as a function of invariant mass $M_{jj}$
  - relevant for the first measurement
  - not optimal for the purpose
- will be extended to wider acceptance with $\eta$ dependence

\[
\begin{align*}
\text{Dijet } A_{LL} @ 200 \text{ GeV} \\
\text{Cone Radius} = 0.7 \\
\max(p_T) > 10 \text{ GeV} \\
\min(p_T) > 7 \text{ GeV} \\
-0.8 < \eta < 0.8, |\Delta \eta| < 1.0 \\
|\Delta \phi| > 2.0 \\
\int \text{Ldt} = 5.39 \text{pb}^{-1}
\end{align*}
\]
Summary

- The *spin puzzle* remains unsolved
- polarized DIS showed quarks’ spin carry only \(~30\%\) of the proton’s spin
- RHIC-Spin suggested a possibility of small gluon’s spin contribution
- RHIC-Spin will extend the kinematical coverage of the measurement
- The possibility of measuring orbital motions is being explored

\[
\frac{1}{2} = \frac{1}{2} \Sigma + \Delta G + L_q + L_g
\]