Recent Results on Proton Helicity Structure Studies from PHENIX

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for the PHENIX collaboration
• RHIC Spin program
  - PHENIX and STAR
  - Longitudinal and Transverse
  - Achievements, Near term projections, and Future opportunities
Outline

• Introduction
  - Physics motivations
  - RHIC
  - PHENIX detectors
  - Recent longitudinal spin runs

• Proton helicity structure studies
  - Polarized gluon distributions (ΔG)
  - Polarized light sea quark distributions (Δq̅)

• Summary and Outlook
Introduction Physics motivations

- It’s not a big secret these days...
  
  \[- S_p = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_z \]

- PHENIX aims: both longitudinal spin structure and transverse spin phenomena

This talk

Tomorrow 11:30 AM by Dr. Yuji Goto
**Introduction**  

**Physics motivations**

\[ S_p = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_z \]

- **ΔΣ** = (Δq + Δ\bar{q})
  - (Δq + Δ\bar{q}):  
    - well constrained thanks to DIS results
  - Δ\bar{q}:
    - large uncertainty from fragmentation processes
    - \( \rightarrow \) measure \( A_L \) by \( W \) decay leptons

- **ΔG**
  - Largely unconstrained
  - \( \rightarrow \) measure \( A_{LL} \) by various probes

**This talk mainly presents Run13 highlights**
RHIC @ Brookhaven Lab., NY

- Polarized $p + p$ at $\sqrt{s} = 62.5 - 510$ (GeV)
- max. $\langle P \rangle$ (avg. beam polarization) $\approx 60\%$
**Introduction** PHENIX detectors

- **PHENIX detector**
  - High rate capability/granularity, Good mass resolution/pID, and Rare event triggers
  - Recent upgrades: forward muon trigger (2013) and inner tracking (VTX (2011) / FVTX (2012))
• **Central Arms** (midrapidity)
  - $|\eta| < 0.35$, $\Delta \phi = \frac{\pi}{2} \times 2$
  - VTX (from 2011)
  - Tracking: DC, PC
  - pID: RICH, ToF
  - EMCal: PbSc, PbGl

• **Muon Arms** (forward rapidity)
  - $1.2 < \eta < 2.2$ (S) or $2.4$ (N), $\Delta \phi = 2\pi$
  - FVTX (from 2012)
  - Tracking: MuTr
  - pID: MuID, RPCs (from 2011/2012)

• **MPCs** (forward EMCal)
  - $3.1 < |\eta| < 3.8$, $\Delta \phi = 2\pi$
Introduction Recent longitudinal spin runs

<table>
<thead>
<tr>
<th>Year</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>Int. $L$ (pb$^{-1}$)</th>
<th>$\langle P \rangle$ (%)</th>
<th>FoM1 ($L \cdot \langle P \rangle^2$)</th>
<th>FoM2 ($L \cdot \langle P \rangle^4$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>09</td>
<td>500</td>
<td>14</td>
<td>33 / 36</td>
<td>1.66</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>15.6</td>
<td>56 / 57</td>
<td>4.98</td>
<td>1.59</td>
</tr>
<tr>
<td>11</td>
<td>500</td>
<td>27.6</td>
<td>48 / 48</td>
<td>6.36</td>
<td>1.47</td>
</tr>
<tr>
<td>12</td>
<td>510</td>
<td>49.6</td>
<td>50.3 / 53.5</td>
<td>13.35</td>
<td>3.59</td>
</tr>
<tr>
<td>13</td>
<td>510</td>
<td>242.1</td>
<td>50.5 / 55.4</td>
<td>67.73</td>
<td>18.95</td>
</tr>
</tbody>
</table>

* MinBias with wide (no) vertex at PHENIX

- $\text{FoM1} = L \cdot \langle P_B \rangle \cdot \langle P_Y \rangle \iff$ Single spin asymmetry ($A_L$) $\iff \Delta \bar{q}$
- $\text{FoM2} = L \cdot \langle P_B \rangle^2 \cdot \langle P_Y \rangle^2 \iff$ Double spin asymmetry ($A_{LL}$) $\iff \Delta G$
Polarized gluons ($\Delta G$)

Observable: $A_{\text{LL}}$
**ΔG** Introduction

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

\[ = \frac{\sum_{abf} (\Delta f_a \otimes \Delta f_b) \otimes \hat{\sigma}^{a+b \rightarrow h+X} \otimes D_f^h}{\sum_{abf} (f_a \otimes f_b) \otimes \hat{\sigma}^{a+b \rightarrow h+X} \otimes D_f^h} \]

- \( f(\Delta f) \): unpol (pol) PDF
- \( \hat{\sigma}(\Delta \hat{\sigma}) \): unpol (pol) partonic cross section
- \( D_f^h \): fragmentation function

**Technically,**

\[ A_{LL} = \frac{1}{PBPY} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}} \]

- \( P \): avg. polarization of each beam
- \( N_{++} (N_{+-}) \): yields in same (opposite) helicity
- \( R \left( \frac{L_{++}}{L_{+-}} \right) \): relative luminosity

- **ΔG measurement at PHENIX:** via various probes
  - Midrapidity (Central Arms): γ, π⁰, π⁺⁻, η, heavy flavor decay leptons
  - Forward (MPC): electromagnetic clusters
**ΔG**  \( \pi^0 @ \text{midrapidity (}|\eta| < 0.35|\) **

**arXiv: 1501.01220**

**PHENIX: pp \( \rightarrow \pi^0 + X \) \( |\eta| < 0.35 \)**

- Inclusive \( \pi^0 A_{LL} \) in Run 12-13 (Int. \( L = 20, 108 \text{ pb}^{-1} \)) \( pp \) 510 GeV
  - First observation of significant **non-zero** \( A_{LL} \) (\( \Delta G \)) in hadron production
    * of course, let’s not forget ‘first non-zero \( A_{LL} \)’ was observed in **STAR jet** measurements
  - Extended Bjorken x coverage down to \( \sim 0.01 \)
DIS + pp global pQCD fit (DSSV2014)

- DSSV2014 (DSSV* and New fit):
  - Included:
    - RHIC data for original DSSV (before Run 9)
    - New COMPASS (SI)DIS data sets
- \( \int_{0.05}^{1} dx \Delta g(x) \)
  - DSSV*: RHIC Run 9 data excluded
  - DSSV New fit: RHIC Run 9 data included
    - \( 0.20 \pm 0.06 \) at 90% C.L.
    - LSS10p, DSSV, and NNPDF1.1 agree
- \( \int_{0.001}^{0.05} dx \Delta g(x) \)
  - Large uncertainty (no data points)
  - Upcoming forward data (next slide)
ΔG Other channels

- $A_{LL}$ at forward rapidity ($3.1 < \eta < 3.9$):
  - Run 9 data (left) / Run 13 projection (right, analysis is underway)
  - $\pi^0$ abundant (> 70 %) EM clusters
  - Probes Bjorken $x$ down to $\sim 0.001$
**ΔG**  Other channels

- **π± (Charged pions)**
  - Sensitive to the sign of ΔG
  - Run 13 analysis is underway

- **π⁰ pairs**
  - Better Bjorken x determination
  - Run 9 analysis is underway
### Other channels

#### Heavy flavor decay
- gg scat. dominated production

#### Forward $J/\psi$
- gg scat. dominated production
- Reach $\sim 2 - 3 \times 10^{-3}$ Bjorken $x$
ΔG What’s next?

Bin by Bin Δg fit: significant improvement expected

arXiv: 1501.01220
Polarized light sea quarks ($\Delta \tilde{q}$)

Observable: $A_L$
**Δq**

**Introduction**

\[ A_L = \frac{\Delta \sigma}{\sigma} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \]

\[ A_L^{W+} = \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta \bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)} \]

\[ A_L^{W-} = \frac{-\Delta d(x_1)\bar{u}(x_2) + \Delta \bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)} \]

technically,

\[ A_L^{W} = \frac{1}{P} \frac{N_+ - RN_-}{N_+ + RN_-} \]

- **P**: avg. polarization of each beam
- **N+ (N-)**: yields in same (opposite) helicity
- **R** (\(\frac{L^{++}}{L^{+-}}\)): relative luminosity

- **Δq** measurement at PHENIX: by W/Z decay leptons
  - Midrapidity (Central Arms): electrons
  - Forward (Muon Arms): muons
$\Delta \bar{q}$  $W^\pm \rightarrow l^\pm$  @ PHENIX

- $W^\pm \rightarrow e^\pm$  @ midrapidity
  - Central Arms ($|\eta| < 0.35$)
  - Distinct Jacobian peak
  
  Triggered by energy
  Momentum by energy
  Charge by tracking in B-field

- $W^\pm \rightarrow \mu^\pm$  @ forward rapidity
  - Muon Arms ($1.2 < |\eta| < 2.2$)
  - Suppressed/No Jacobian peak

  Triggered by momentum
  Momentum by tracking in B-field
  Charge by tracking in B-field
$\Delta\bar{q}$: $W^\pm \rightarrow e^\pm$ @ midrapidity ($|\eta| < 0.35$)

- $W \rightarrow e A_L$ in Run 11-13 (total Int. $L = 240 \text{ pb}^{-1}$) pp 500/510 GeV
  - Charge isolation + Gaussian process regression
$\Delta \bar{q}$  \( W^\pm \to e^\pm @ \text{midrapidity (}|\eta| < 0.35|\) \\

[Image of a graph showing the comparison between experimental data and theoretical calculations for $e^+$ and $e^-$ in $W^+$ and $W^-$ reactions.]

- $W \to e A_L$ in Run 11-13 pp 500/510 GeV
  - Probed Bjorken $x : \sim 0.16$
  - $W^-$ suggests larger $\Delta \bar{u}$ contribution than theory in covered $x$ range
$\Delta \bar{q}$ $W^\pm \rightarrow \mu^\pm$ @ forward rapidity ($1.2 < \eta < 2.2 / 2.4$)

- $W \rightarrow \mu A_L$ in Run 11-13 (Int. L = 27, 53, and 290 pb$^{-1}$) pp 500/510 GeV
  - Analysis challenges: BG abundance, $p_T$ smearing, Limited acceptance...
  - Multivariate $W$ likelihood based analysis
$\Delta \bar{q}$ \hspace{1em} $W^\pm \rightarrow \mu^\pm$ @ forward rapidity (1.2 < $\eta$ < 2.2 / 2.4)

- \textbf{W} \rightarrow \mu \textbf{A}_L \text{ in Run 13 pp 510 GeV}
  - Cross section results agrees with calculations within large uncertainty
  - Still working on improving uncertainties:
    - improve S/BG, tracking alignment, dead map update...
\[ \Delta \bar{q} \rightarrow W^\pm \rightarrow l^\pm \text{ projections} \]

**arXiv: 1501.01220**

- **DSSV++ projections with \( W \) data at RHIC**
  - Significant constraint is expected in anti-quark polarization
Summary and Outlook  Helicity structure studies at PHENIX

• $\Delta G$
  - Run 13 inclusive $\pi^0$ at $\sqrt{s} = 510$ GeV
    a. First non-zero $A_{LL}$ observation in hadron production
    b. Extended Bjorken $x$ constraint down to $\sim 0.01$
  - Upcoming forward $\pi^0$ rich EM clusters data: push $x$ coverage down to $\sim 0.001$
  - Current DSSV14 fit: $0.20^{+0.06}_{-0.07}$ at 90 % C.L in $x > 0.05$
    a. Includes only RHIC Run 6-9 data at $\sqrt{s} = 62$ and 200 GeV
    b. Room for improvement: recent (after Run 9) results are not included yet!
      in addition, not only $\pi^0$ / jet, but also many other probes exist to help reduce systematic uncertainty of the fit

• $\Delta \bar{q}$
  - Run 11 – 13 by $W / Z \rightarrow$ leptons
  - larger $\Delta \bar{u}$ contribution: possibility of symmetry breaking between $\bar{u} \leftrightarrow \bar{d}$?
  - DSSV++ fit suggests significant constraint
Summary and Outlook

• Next?
  - PHENIX decommissions after Run 16
  - Transition to new detector system using the Babar solenoid
  - Upcoming Eletrcon-Ion Collider: back to DIS, but with much higher $L$ and $\sqrt{s}$
If you’re interested -
all about upcoming Electron – Ion Collider (EIC)
Backup LO dominant partonic processes

LO helicity dependent double spin asymmetries for partonic reactions at RHIC

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Dom. partonic process</th>
<th>probes</th>
<th>LO Feynman diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p\bar{p} \rightarrow \pi + X$ [61, 62]</td>
<td>$g\bar{g} \rightarrow gg$</td>
<td>$\Delta g$</td>
<td>![Feynman diagram]</td>
</tr>
<tr>
<td></td>
<td>$g\bar{g} \rightarrow qg$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow \text{jet(s)} + X$ [71, 72]</td>
<td>$g\bar{g} \rightarrow gg$</td>
<td>$\Delta g$</td>
<td>(as above)</td>
</tr>
<tr>
<td></td>
<td>$g\bar{g} \rightarrow qg$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow \gamma + X$</td>
<td>$g\bar{g} \rightarrow \gamma q$</td>
<td>$\Delta g$</td>
<td>![Feynman diagram]</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow \gamma + \text{jet} + X$</td>
<td>$g\bar{g} \rightarrow \gamma q$</td>
<td>$\Delta g$</td>
<td>![Feynman diagram]</td>
</tr>
<tr>
<td></td>
<td>$g\bar{g} \rightarrow \gamma \gamma$</td>
<td>$\Delta q, \Delta \bar{q}$</td>
<td>![Feynman diagram]</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow DX, BX$ [77]</td>
<td>$g\bar{g} \rightarrow c\bar{c}, b\bar{b}$</td>
<td>$\Delta g$</td>
<td>![Feynman diagram]</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow \mu^+\mu^- X$ (Drell-Yan) [78, 79, 80]</td>
<td>$q\bar{q} \rightarrow \gamma^* \rightarrow \mu^+\mu^-$</td>
<td>$\Delta q, \Delta \bar{q}$</td>
<td>![Feynman diagram]</td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow (Z^0, W^\pm) X$ [78]</td>
<td>$q\bar{q} \rightarrow Z^0, q\bar{q} \rightarrow W^\pm$</td>
<td>$\Delta q, \Delta \bar{q}$</td>
<td>![Feynman diagram]</td>
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<tr>
<td>$p\bar{p} \rightarrow (Z^0, W^\pm) X$</td>
<td>$q\bar{q} \rightarrow W^\pm, q\bar{q} \rightarrow W^\pm$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
• **Inclusive $\pi^0$ analysis**
  - Charge veto ($\theta_{cv}$) + Time of flight + Relative Luminosity correction + Background asymmetry correction (by background sampling)
Backup \( \pi^0 \) analysis results – PHENIX/STAR
DIS + pp global pQCD fit (DSSV2014) – $x \Delta g$ vs. $x$

- DSSV2014 (DSSV* and New fit):
  - Included:
    RHIC data for original DSSV (before Run 9)
    New COMPASS (SI)DIS data sets
Backup \( \pi^0 \) abundance in forward EM clusters

- MC simulation for \( \sqrt{s} = 200 \text{ GeV} \) with full MPC
  - Kinematic cuts applied
Backup  $W$ partonic process

\[ A_{L}^{W^+} = \frac{u_{-}(x_1)d_{+}(x_2) - u_{-}(x_1)d_{+}(x_2)}{u_{-}(x_1)d_{+}(x_2) + u_{+}(x_1)d_{+}(x_2)} \]

\( \triangleq 1. \Delta u \text{ is being probed} \)

\[ A_{L}^{W^+} = \frac{d_{+}(x_1)u_{-}(x_2) - d_{+}(x_1)u_{-}(x_2)}{d_{+}(x_1)u_{-}(x_2) + d_{-}(x_1)u_{-}(x_2)} \]

\( \triangleq 2. \Delta \bar{d} \text{ is being probed} \)
Backup  W kinematic coverage
Backup  W kinematics in PHENIX acceptance
Backup  $W \rightarrow \mu$ muonic processes

$P_T$ distributions $\mu^-$

$P_T$ distributions $\mu^+$

$P_T$ spectrum (stacked) $\mu^-$

$P_T$ spectrum (stacked) $\mu^+$
Backup $W \rightarrow \mu$ hadronic processes
Backup $W \rightarrow \mu \text{S/BG extraction by unbinned max. likelihood fit}$