Recent results and future prospects of the high-energy polarized p+p program at RHIC at BNL
Outline

- Selected recent results and future prospects
  - Transverse spin dynamics
  - Gluon polarization
  - Quark / Anti-quark polarization

- Experimental aspects: RHIC / PHENIX / STAR

- Theoretical foundation

- Summary and Outlook
How do we probe the structure and dynamics of matter in ep / pp scattering?

\[ d\sigma_{ep} \propto F_2 = \sum_q x e_q^2 f_q(x) \]

Momentum contribution:
\[ f(x) = f^+(x) + f^-(x) \]

Spin contribution:
\[ \Delta f(x) = f^+(x) - f^-(x) \]

Universality

Factorization

\[ W^2 \approx Q^2/x \]
Theoretical foundation

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Theoretical foundation

14th Workshop on Elastic and Diffractive Scattering - EDS 2011
Qui Nhon, Vietnam, December 15-21, 2011
Bernd Surrow
The world’s first polarized proton-proton collider
Overview

- Calorimetry system with 2π coverage: BEMC (-1<η<1) and EEMC (1<η<2)
- TPC: Tracking and particle ID
- ZDC: Relative luminosity and local polarimetry (500GeV)
- BBC: Relative luminosity and Minimum bias trigger

\[ \eta = -\ln \left( \tan \left( \frac{\theta}{2} \right) \right) \]
Overview

- $\pi^0, \eta, \gamma$
  - Electromagnetic Calorimeter (PbSc/PbGl) \(|\eta < 0.35, \varphi = 2 \times \pi/2|\)
- $\pi^\pm, e, J/\psi \rightarrow e^+e^-$
  - Drift Chamber (DC)
  - Ring Imaging Cherenkov Detector (RICH)
- Electromagnetic Calorimeter (PbSc/PbGl)
- $\mu, J/\psi \rightarrow \mu^+\mu^-$
  - Muon Id/Muon Tracker \((1.2 < |\eta| < 2.4 + 2\pi)|\)
- $\pi^0, \eta$
  - MPC \((3.1 < |\eta| < 3.9 + 2\pi)|\)
- Relative Luminosity
  - Beam Beam Counter (BBC) \((3.0 < \eta < 3.9)|\)
  - Zero Degree Calorimeter (ZDC)
Double and single longitudinal spin asymmetry measurements

\[ A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{P_1 P_2} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}} \]

Require concurrent measurements:

- Longitudinal beam polarization \( P_{1(2)} \) at STAR IR
- Direction of polarization vector
- Relative luminosity \( R \) of bunch crossings with different spin directions
- Spin dependent yields of process of interest \( N_{ij} \)
Measurement: Connection of $\Delta g$ and $A_{LL}$

Proton Spin decomposition in infinite momentum frame:

$$\frac{1}{2} \Delta \Sigma = \langle S_q \rangle + \langle S_g \rangle + \langle L_q \rangle + \langle L_g \rangle$$

$\Delta G(Q^2 = 1 GeV^2) \approx 1.8$

$\Delta G(Q^2 = 1 GeV^2) \approx 0.4$

$\Delta G(Q^2 = 1 GeV^2) \approx 0.1$

$\Delta G(Q^2 = 1 GeV^2) \approx -0.1$

$\Delta G(Q^2) = \int_0^1 \Delta g(x, Q^2) dx$

Recent results - Gluon polarization program

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- PHENIX: Mid-rapidity neutral pion $A_{LL}$ measurement

Data are well described by NLO pQCD calculations

Run 9 $A_{LL}$ results slightly above DSSV fit result (Incl. PHENIX and STAR Run 5/6 results)

PHENIX Collaboration, PRL103, 012003 (2009)
Recent results - Gluon polarization program

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- Run 9 $A_{LL}$ results slightly above DSSV fit result (Incl. PHENIX and STAR Run 5/6 results)
Recent results - Gluon polarization program

STAR: Mid-rapidity Inclusive Jet $A_{LL}$ measurement

- Data are well described by NLO pQCD plus hadronization and underlying event corrections
- Run 6 $A_{LL}$ measurement between GRSV-STD and GRSV-ZERO
- Run 9 $A_{LL}$ measurement between GRSV-STD and DSSV

Inclusive Jet Cross Section
pp @ 200 GeV
Cone Radius = 0.7
$-0.8 < \eta < 0.8$

$\sqrt{s} = 200$ GeV $p^+p \rightarrow \text{jet}+X \ |\eta|<1$

$\pm 8.8\%$ scale uncertainty from polarization not shown

$\int \mathcal{L} dt = 5.39 \text{ pb}^{-1}$

Theory
- NLO pQCD + CTEQ6M
- Had. and UE. Corrections

Systematic Uncertainty

STAR Run 6

Preliminary Run 6
Recent results - Gluon polarization program

- First STAR Di-Jet $A_{LL}$ measurement

- Data are well described by NLO pQCD plus hadronization and underlying event corrections

- First Di-Jet $A_{LL}$ measurement in agreement with $\Delta g$ constrained by previous inclusive jet result, i.e. small gluon polarization preferred!
Recent results - Gluon polarization program

**First STAR Di-Jet $A_{LL}$ measurement**

- East - East and West - West Barrel
- East Barrel - West Barrel
- Full Acceptance

**Equation**

$$ M = \sqrt{x_1 x_2 s} \quad \eta_3 + \eta_4 = \ln \frac{x_1}{x_2} $$

- ALL measurements tend to fall in-between GRSV-STD and DSSV
- Run 9 data: First rapidity dependent di-jet measurement
  - Constrain x dependence!
Recent results - Quark / Anti-quark pol. program

Probing the quark flavor structure using W boson production

\[
\begin{align*}
\Delta d + \bar{u} &\rightarrow W^- \\
\Delta \bar{u} + d &\rightarrow W^- \\

p &\rightarrow W^+ (W^-) \\
\nu_e (\bar{\nu}_e) &\rightarrow e^+ (e^-) \\

\Delta d + u &\rightarrow W^+ \\
\Delta u + \bar{d} &\rightarrow W^+ \\

A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{1}{P N_+ - R N_-} \\
A_L^W = \frac{1}{2} \left( \frac{\Delta \bar{u}}{u} - \frac{\Delta d}{d} \right) \\
A_L^{\bar{W}} &= \frac{1}{2} \left( \frac{\Delta d}{d} - \frac{\Delta u}{u} \right) \\
A_L^{W^+} &= \frac{\Delta \bar{d}}{d} \\
A_L^{\bar{W}^+} &= \frac{\Delta d}{d} \\
\end{align*}
\]
Recent results - Quark / Anti-quark pol. program

- **Measurement: Background treatment / Signal distribution**

- Background dominated by QCD background (Data driven estimate) with smaller fractions from W boson induced τ decays and Z⁰ boson events (MC estimate)

- Total background \( B \):
  - \( e^+ : 39 \pm 9 \)
  - \( e^- : 23 \pm 6 \)

- Total \( e^+/e^- \) cand. events (S+B):
  - \( e^+ : 462 \)
  - \( e^- : 139 \)

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STAR Collaboration, PRL 106, 062002 (2011)
Recent results - Quark / Anti-quark pol. program

- First STAR $W^+$ / $W^-$ cross section measurement in pp collisions

- Measured and theory evaluated cross-sections agree within uncertainties

- Theory calculations: Full NLO framework
Recent results - Quark / Anti-quark pol. program

First STAR $A_L$ result

$\vec{p} + p \rightarrow W^\pm + X \rightarrow e^\pm + X$

STAR $\sqrt{s} = 500$ GeV
25 < $E_T^e$ < 50 GeV

$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$

$W^-$

$A_L^W = \frac{1}{2} \left( \frac{\Delta \bar{u}}{\bar{u}} - \frac{\Delta d}{d} \right)$

$W^+$

$A_L^W = \frac{1}{2} \left( \frac{\Delta d}{d} - \frac{\Delta \bar{u}}{\bar{u}} \right)$
Recent results - Quark / Anti-quark pol. program

First STAR $A_L$ result

$A_L^{W^-} = 0.14 \pm 0.19 \text{ (stat.)} \pm 0.02 \text{ (syst.)} \pm 0.01 \text{ (norm.)}$

$A_L^{W^+} = -0.27 \pm 0.10 \text{ (stat.)} \pm 0.02 \text{ (syst.)} \pm 0.03 \text{ (norm.)}$

$\vec{p} + p \rightarrow W^\pm + X \rightarrow e^\pm + X$

STAR $\sqrt{s} = 500$ GeV

$25 < E_T^e < 50$ GeV

$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$

Syst. uncertainty due to background, w/o pol. norm. uncertainty of 9.2%
Recent results - Quark / Anti-quark pol. program

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- $A_L(W^+)$ negative with a significance of $\sim 3\sigma$
- $A_L(W^-)$ central value positive

STAR Collaboration, PRL 106, 062002 (2011)
Recent results - Quark / Anti-quark pol. program

- First STAR $A_L$ result

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- $A_L(W^+)$ negative with a significance of $\sim 3\sigma$
- $A_L(W^-)$ central value positive

- Measured asymmetries are in agreement with theory evaluations using polarized pdf's (DSSV) constrained by polarized DIS data

\[ \Rightarrow \text{Universality of helicity distr. functions!} \]

$\bar{p} + p \rightarrow W^\pm + X \rightarrow e^\pm + X$
STAR $\sqrt{s} = 500 \text{ GeV}$
$25 < E_T^e < 50 \text{ GeV}$

$W^-$
$W^+$

Projected uncertainties
Simulated data

$L = 300 \text{ pb}^{-1}, P = 70\%$
Forward system: STAR Experience
Recent results - Quark / Anti-quark pol. program

- **PHENIX: Mid-rapidity $A_L$**

  - $A_L$ result consistent with all models
  - A non-zero asymmetry ($98.4\%$ CL) is observed in the positive candidates

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PHENIX Collaboration, PRL 106, 062001 (2011)
**Recent results - Quark / Anti-quark pol. program**

**PHENIX: Mid-rapidity $A_L$**

$S/B = 3.0$

$L=150\text{pb}^{-1} / P=50\%$

$W^+ \rightarrow \mu^+$

$W^- \rightarrow \mu^-$

$S/B = 0.3$

$W^+ \rightarrow \mu^+$

$W^- \rightarrow \mu^-$

$\eta_\mu$ (muon pseudo-rapidity)
Future - Quark / Anti-quark pol. program

PHENIX Muon trigger system

MuID Trigger: Selecting momentum above 2 GeV/c

MuTRG: Fast selection of high momentum tracks

RPC: Provide timing information and rough position information

Adding 35 cm Fe absorber: reduce the lower momentum hadron punch through (S/B=3:1 instead of 1:3 without absorber)
Hadron/Jet production: Gluon polarization

- Several final states (Hadron / Jet) have been measured all pointing to the same conclusion that the gluon polarization is small, much smaller than the proton spin itself, in contrast to earlier theoretical - controversial - speculations
- First Di-Jet measurement opens the path to constrain the shape of $\Delta g$
- Run 9 results: Precise $A_{LL}$ measurement above DSSV fit suggesting $\Delta G > 0$

W boson production: Quark/Antiquark polarization

- First measurement of W boson production in polarized p+p collisions at RHIC
- Establish a completely new and direct way to probe quark and anti-quark polarization in a high-energy polarized hadron collider environment

Long-term: Establish a new collider facility at BNL/JLAB - Electron-Ion Collider!
Backup: Jet/Hadron production

- RHIC Gluon polarization: Inclusive measurements

Inclusive Jet production (200GeV: Solid line / 500GeV: Dashed line)
RHIC Gluon polarization - Correlation Measurements

Correlation measurements provide access to partonic kinematics through Di-Jet/Hadron production and Photon-Jet production:

\[ x_1(2) = \frac{1}{s} \left( p_{T3} e^{\eta_3(-\eta_3)} + p_{T4} e^{\eta_4(-\eta_4)} \right) \]

\[ M = \sqrt{x_1 x_2 s} \]

\[ \eta_3 + \eta_4 = \ln \frac{x_1}{x_2} \]

Di-Jet production / Photon-Jet production

- **Di-Jets**: All three (LO) QCD-type processes contribute: \( gg \), \( qg \) and \( qq \)
- **Photon-Jet**: One dominant underlying (LO) process
- Larger cross-section for di-jet production compared to photon related measurements
- Photon reconstruction more challenging than jet reconstruction
- Full NLO framework exists \( \Rightarrow \) Input to Global QCD analysis
RHIC W Impact on polarized QCD sea

D. deFlorian and W. Vogelsang, PRD81, 094020 (2010)

Include W results at RHIC (PHENIX and STAR) assuming $-2 < \eta < 2$ with 200pb$^{-1}$

Strong constrain for $x > 0.05$