Exploring Gluon and Antiquark Polarization in the Proton with \textit{STAR}

\textbf{Carl Gagliardi}
Texas A&M University
for the \textit{STAR} Collaboration

\textbf{Outline}

- Introduction
- Jets and gluon polarization
- W’s and antiquark polarization
Partonic origin of the proton spin?

\[ S_z = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + \langle L_z \rangle \]

- Measuring the gluon polarization distribution is a primary goal of the RHIC spin program

Blümlein & Böttcher, NPB 841, 205 (2010)
Fit to DIS data only

\[ \Delta G = 0.46 \pm 0.43 \]

Leader et al, PRD 82, 114018 (2010)
Fit to DIS and SIDIS data

\[ \Delta G = 0.32 \pm 0.19 \]
\[ \Delta G = -0.34 \pm 0.46 \]

Polarized DIS: \(~0.3\)
Poorly constrained by DIS

- Measuring the gluon polarization distribution is a primary goal of the RHIC spin program
Why is $\Delta \Sigma$ so small?

$$\Delta \Sigma = \int_{0}^{1} (\Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s}) \, dx$$

- Polarized inclusive DIS data measure $\Delta u + \Delta \bar{u}$ and $\Delta d + \Delta \bar{d}$
- Polarized semi-inclusive DIS data provide flavor separation, but uncertainties remain large

- FNAL E866 found surprising structure in the unpolarized antiquark distributions
- Might the polarized antiquark distributions also contain surprises?
- Measuring the antiquark polarization distributions is another primary goal of the RHIC spin program
Exploring gluon polarization at RHIC

\[ A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \propto \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL} \]

\( \Delta f \): polarized parton distribution functions

- \( \frac{\Delta G}{G} \)
- \( \frac{\Delta G}{q} \)
- \( \frac{\Delta G}{q} \)
- \( \frac{\Delta q}{G} \)
- \( \frac{\Delta q}{q} \)
- \( \frac{\Delta q}{q} \)

Partonic fractions in jet production at RHIC

For most RHIC kinematics, \( gg \) and \( qg \) dominate, making \( A_{LL} \) for jets sensitive to gluon polarization.
Exploring antiquark polarization at RHIC

- W’s only couple to left-handed quarks and right-handed antiquarks
  - Perfect spin separation!
- Detect W’s through $e^-$ and $e^+$ decay channels

The parity-violating single-spin asymmetry, $A_L$, for W production provides direct information about antiquark polarization

$$A_L^{W^-} \propto -\Delta d(x_1)\bar{u}(x_2) + \Delta\bar{u}(x_1)d(x_2)$$
$$A_L^{W^+} \propto -\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)$$
STAR detector side view

- High precision tracking with the TPC
- Electromagnetic calorimetry with the BEMC and EEMC (and FMS)
- Additional detectors (BBC, VPD, ZDC) for relative luminosity and local polarimetry
Jet reconstruction in **STAR**

**For 2006 data**

**Midpoint cone algorithm**
Adapted from Tevatron II - hep-ex/0005012
- Seed energy = 0.5 GeV
- Cone radius $R = 0.7$ in $\eta$-$\phi$ space
- Split/merge fraction $f = 0.5$

**For 2009 data and beyond**

**Anti-$k_T$ algorithm**
Cacciari, Salam, and Soyez, JHEP 0804, 063
- $R = 0.6$

Use **PYTHIA + GEANT** to quantify detector response
Sjostrand, Mrenna, and Skands, JHEP 05, 026
Jet cross section from 2006 data

- Good agreement between data and simulation
- Good agreement with NLO pQCD calculation after hadronization and underlying event correction is applied
- Jet production is well understood at RHIC energies
STAR inclusive jet $A_{LL}$ from 2006 data

- **STAR** inclusive jet $A_{LL}$ from 2006 excluded those scenarios that had a large gluon polarization within the accessible $x$ region.
DSSV – first global analysis with polarized jets

de Florian et al., PRL 101, 072001

- The first global NLO analysis to include inclusive DIS, SIDIS, and RHIC pp data on an equal footing
- Found relatively small gluon polarization within the region $0.05 < x < 0.2$ that was sampled by the 2006 data
Improvements for 2009

• 2009 jet patch trigger upgrades
  – Overlapping jet patches and lower $E_T$ threshold improve efficiency and reduce trigger bias
    • Net increase of 37% in jet acceptance
  – Remove beam-beam counter trigger requirement
    • Trigger more efficiently at high jet $p_T$
    • Measure non-collision background

• Increased trigger rate and reduced thresholds enabled by DAQ1000

• Sampled ~ 4 times the figure-of-merit relative to 2006

• Nearly **20-fold increase** in event statistics

• Improvements in jet reconstruction
  – Subtract 100% of track momentum from struck tower energy (2009) instead of MIP (2006)
  – Overall jet energy resolution improved from 23% to 18%
  – Switch from mid-point cone to anti-$k_T$
STAR inclusive jet $A_{LL}$ from 2009 data

- 2009 *STAR* inclusive jet $A_{LL}$ measurements are a factor of 3 (high-$p_T$) to >4 (low-$p_T$) more precise than 2006

- $A_{LL}$ falls in the middle among several recent polarized PDF fit predictions

- $A_{LL}$ is somewhat larger than predictions from the 2008 DSSV fit
  - Points toward positive $\Delta g$ in the accessible $x$ region
BB and LSS model uncertainties

• Results are well within the quoted BB10 uncertainties
  – Can reduce inclusive jet $\chi^2$ from 89 to 18 while increasing the DIS data $\chi^2$ by less than 0.03% (0.36 in 1537, “BB10r”)
• Results fall outside the quoted LSS10 uncertainties for $p_T < \sim 12$ GeV/c
  – Very strong preference for LSS10p ($\chi^2=22.5$) over LSS10 ($\chi^2=57$)
Two new polarized distribution fits

• Both DSSV and NNPDF have released new polarized PDF fits
• Both find 2009 STAR jet $A_{LL}^{jet}$ results provide significantly tighter constraints on gluon polarization than previous measurements
• Both find evidence for positive gluon polarization in the region $x > 0.05$
  – DSSV: $0.20^{+0.06}_{-0.07}$ at 90% c.l. for $0.05 < x$
  – NNPDF: $0.23 \pm 0.07$ for $0.05 < x < 0.5$
Higher precision coming soon

- During 2012 STAR measured inclusive jet $A_{LL}$ in 510 GeV collisions
  - Higher beam energy provides sensitivity to smaller $x_g$
- STAR also anticipates significant future reductions in the uncertainties for 200 GeV collisions relative to the 2009 results
  - Hope to record triple the existing 200 GeV data during the 2015 RHIC run
Beyond inclusive $A_{LL}$ measurements

- Inclusive $A_{LL}$ measurements at fixed $p_T$ average over a broad $x$ range.
- Can hide considerable structure if $\Delta g(x)$ has a node.
- Correlation measurements can constrain the shape of $\Delta g(x)$.
2009 di-jet cross section in 200 GeV pp

\[ x_1 = \frac{1}{\sqrt{s}} \left( p_{T,3} e^{\eta_3} + p_{T,4} e^{\eta_4} \right) \]
\[ x_2 = \frac{1}{\sqrt{s}} \left( p_{T,3} e^{-\eta_3} + p_{T,4} e^{-\eta_4} \right) \]
\[ M = \sqrt{x_1 x_2 s} \]
\[ y = \frac{1}{2} \ln \frac{x_1}{x_2} = \frac{\eta_3 + \eta_4}{2} \]
\[ |\cos\theta^*| = \tanh \left( \frac{|\eta_3 - \eta_4|}{2} \right) \]

- Di-jets permit event-by-event calculations of \( x_1 \) and \( x_2 \) at LO
- Di-jet cross section is well-described by NLO pQCD with corrections for hadronization and underlying event
- Will have \( A_{LL} \) for 2009 di-jets at 200 GeV soon
- Also analyzing \( A_{LL} \) for di-jets at 510 GeV using data from 2013
STAR W $A_L$ from 2011+2012 data

- $A_L$ for $W^+$ is consistent with theoretical predictions constrained by polarized SIDIS data
- $A_L$ for $W^-$ is larger than the predictions for $\eta_e < 0$
  - This region is particularly sensitive to $\Delta u$
- Preference for a positive $\Delta \bar{u}$ in the range $0.05 < x < 0.2$
STAR W $A_L$ in recent polarized PDF fits

- DSSV++ is a preliminary fit that included a preliminary version of the STAR 2012 $W A_L$ results
- NNPDFpol1.1 uses the STAR W asymmetries ($A_L$ and $A_{LL}$) to constrain the antiquark polarizations
- Both find indication of a positive $\Delta \bar{u}$ in the vicinity of $x \sim 0.15$
Anticipated precision in the near future

- STAR recorded ~4 times as much W asymmetry data during the 2013 RHIC run than were included in the recent analysis.
- Will also extend kinematic coverage to larger $|\eta|$ with the FGT.
- Look for new $A_L$ results soon.
Conclusions

- **STAR 2009 inclusive jet $A_{LL}$ results** provide the **first experimental evidence for positive gluon polarization** in the RHIC range.

- **STAR 2011+12 W $A_L$ results** provide new constraints on antiquark polarizations, including a preference for a positive $\Delta \bar{u}$.

- Look for several more results in the near future:
  - First measurements:
    - Di-jet $A_{LL}$ at 200 and 510 GeV (2009&13 data)
    - Inclusive jet $A_{LL}$ at 510 GeV (2012 data)
  - Improved precision for:
    - W $A_L$ (2013 data)
    - Inclusive jet $A_{LL}$ at 200 GeV (2015 data)

- Stay tuned!