Probing the Origin of the Proton Spin with Jets at STAR

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Outline

• Introduction
• Gluon polarization with jets and di-jets
• Collins effect and transversity with jets
Gluon polarization without RHIC data

- Two global analyses, both published in 2010
- Very large uncertainties for the gluon polarization
  - Both shape and magnitude

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

$Q^2 = 2.5 \text{ GeV}^2$

$\Delta G = 0.32 \pm 0.19$

$\Delta G = -0.34 \pm 0.46$
RHIC: the Relativistic Heavy Ion Collider

- Search for and study the Quark-Gluon Plasma
- Explore the partonic structure of the proton
- Determine the partonic structure of nuclei
STAR as a jet and di-jet detector

- Large and uniform acceptance makes STAR an excellent jet detector
- Good agreement with NLO predictions for both inclusive jet and di-jet cross sections
Exploring gluon polarization at RHIC

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

\[ \Delta f: \text{polarized parton distribution functions} \]

\[ \frac{\Delta G}{G} \frac{\Delta G}{G} \quad \frac{\Delta q}{q} \frac{\Delta G}{G} \quad \frac{\Delta q}{q} \frac{\Delta q}{q} \]

Partonic fractions in jet production at RHIC

For most RHIC kinematics, \( gg \) and \( qq \) dominate, making \( A_{LL} \) for jets sensitive to gluon polarization.
Inclusive jet $A_{LL}$ from the 2009 RHIC run

- STAR measured $A_{LL}$ for inclusive jets at 200 GeV during the 2009 RHIC run.
- Results draw a narrow road through the previous predictions.
- Far more precise than previous measurements.
- Systematically larger than expected by DSSV’08.
- Positive gluon polarization in the sampled region $x > 0.05$. 

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Gluon polarization with RHIC data

- Both DSSV and NNPDF have released new polarized PDF fits
- Both find the 2009 RHIC 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: $0.19^{+0.06}_{-0.05}$ at 90% c.l. for $0.05 < x$
  - NNPDF: $0.23 \pm 0.07$ for $0.05 < x < 0.5$
What’s next?

- Need to **increase precision in the currently sampled region** to consolidate the observation of non-zero gluon polarization
- Need to **extend sensitivity to lower $x_g$** where current extrapolations have very large uncertainties
Next steps

• RHIC had very successful runs with 510 GeV pp collisions during 2012 and 2013
  – Higher center-of-mass energy probes lower $x$ partons
• $A_{LL}$ at 510 GeV is well described by global fits that previously gave a good description of the 2009 measurements at 200 GeV
• STAR took additional 200 GeV pp data during 2015
  – Will reduce uncertainties for $A_{LL}$ at 200 GeV by a factor of $\sim 1.6$
Further constraining the $x$ dependence

- Di-jet measurements sample a much narrower range of $x$ values than inclusive jets
- Use to constrain the shape of $\Delta g(x)$
  - Minimize extrapolation errors outside the sampled region
Collins effect in jets at $\text{STAR}$

- With transversely polarized proton beams, pion production demonstrates an azimuthal modulation about the jet thrust axis
  - Arises through a convolution of quark transversity with the Collins fragmentation function
  - Appears as a $\sin(\varphi_S - \varphi_H)$ modulation
- Test the predicted universality of the Collins fragmentation function
- Extend $Q^2$ reach by two orders of magnitude compared to SIDIS
  - Probe TMD evolution
Transversity reach of $\textit{STAR}$

- Green band indicates the region that $\textit{STAR}$ has probed to date
  - Will expand in the future
- Study a region where current transversity uncertainties are large
- Strong interactions don’t experience $u$-quark dominance
  - Greater sensitivity to $d$-quark effects
First transversity signals in hadronic collisions

- Significant measurements of transversity convoluted with:
  - Di-hadron interference fragmentation function (IFF)
  - Collins fragmentation function
- Both have similar magnitudes in 200 and 500 GeV pp collisions
- Observations of transversity at very high scales
  - $Q^2$ up to $>900$ GeV$^2$ for Collins at 500 GeV
- Complementary results that obey different evolution equations
Final state: $\pi^{+/-}$ azimuthal distribution in jets

- First Collins effect measurements in pp collisions are well described by calculations that convolute the transversity distribution from SIDIS with the Collins FF from $e^+e^-$ collisions
  - Tests the predicted **universality of the Collins FF**
  - No TMD evolution in this calculation
    - Maybe small?
    - Maybe cancels between numerator and denominator for asymmetries?

Calculations from Kang et al, in preparation
Many azimuthal modulations possible

Transversity x Collins

\[ p^+ + p(Au) \rightarrow \text{jet} + \pi^+ + X \]

- Precision data at fixed \( x \), different \( \sqrt{s} \) ideal to constrain TMD evolution
- Upcoming 2017 data, when combined with existing 2011, ‘12, and ‘15 data, will provide stringent tests

Linearly polarized gluons: Possible explanation for the ridge in pp/pA?

Gluon Sivers function via Twist-3 relationship

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Conclusions

• We still have a great deal to learn about the structure of the proton

• **STAR is making significant contributions** to several poorly constrained pieces of the puzzle
  – **Gluon polarization**
    • May contribute as much or more to the proton spin as the quarks and anti-quarks
  – **Transversity and TMDs**
    • Clear evidence of transversity has been seen in pp collisions
    • Test universality and TMD evolution
    • Measure transversity where current uncertainties are large

• More data have been **recorded and are being analyzed** at this moment, and still more are expected soon. **Stay tuned!**
RHIC: the world’s first (and only!) polarized hadron collider

- Spin varies from rf bucket to rf bucket (9.4 MHz)
- Spin pattern changes from fill to fill
- Spin rotators provide choice of spin orientation
- Billions of spin reversals during a fill with little depolarization

**RHIC: the world’s first (and only!) polarized hadron collider**

- Absolute Polarimeter (H↑ jet)
- RHIC pC Polarimeters
- $A_NDY$

**RHIC**

- Siberian Snakes
- Spin Rotators (longitudinal polarization)
- PHENIX
- $A_NDY$

**PHENIX**

- Spin Rotators (longitudinal polarization)
- Solenoid Partial Siberian Snake
- STARR
- $A_NDY$

**STAR**

- Spin Rotators (longitudinal polarization)
- Siberian Snakes
- Spin flipper
- 200 MeV Polarimeter
- Pol. H⁻ Source

**AGS**

- Helical Partial Siberian Snake
- AGS Internal Polarimeter
- AGS pC Polarimeters
- Strong Helical AGS Snake

**AGS**

- Rf Dipole
- LINAC
- BOOSTER

**LINAC**

- 200 MeV Polarimeter
- Pol. H⁻ Source
Jet reconstruction in STAR

Data jets

MC jets

Jet direction

Detector

Particle
e, \nu, \gamma,
\pi, p, etc

GEANT

PYTHIA

For 2009 data and beyond

Anti-\(k_T\) algorithm

Cacciari, Salam, and Soyez, JHEP 0804, 063

- \(R = 0.6\) for 200 GeV
- \(R = 0.5\) for 500/510 GeV

Use PYTHIA + GEANT to quantify detector response

Sjostrand, Mrenna, and Skands, JHEP 05, 026

STAR as a jet detector

- Large and uniform acceptance makes STAR an excellent jet detector
- Good agreement with NLO predictions for inclusive jet cross section in 200 GeV pp collisions
First global analysis with RHIC pp data

de Florian et al., PRL 101, 072001

- DSSV’08 was the first global analysis to include inclusive DIS, semi-inclusive DIS (SIDIS), and RHIC pp data on an equal footing