Spin Physics With Jets at STAR

S. Vigdor, BNL, Ides of March 2007

I. RHIC Spin Goals

II. RHIC Spin Infrastructure

III. STAR Jet Infrastructure

IV. Inclusive Jet Results
   2003-5: Constraining the Gluon Contribution to Proton Spin

V. Single-Spin Asymmetry for Di-jets
   2006: Looking for Parton Orbital Momentum Effects

VI. Next Stages of Jet Program
Three constituent quarks in s-states $\Rightarrow$ good account for baryon magnetic moments -- attributes nucleon spin to quark spin alignment in rest-frame wave function.

Chiral symmetry breaking associated with pseudoscalar meson cloud $\Rightarrow$ $\bar{d}/u$ asymmetry, sea-quark orbital motion, sea quark spin opposes nucleon’s.

Hard high-energy probes sample light-cone wave function, provide momentum & spin “snapshots” of teeming assembly of partons $\Rightarrow$

$$\langle S_z^p \rangle = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta g + \langle L_z^{\text{quarks}} \rangle + \langle L_z^{\text{gluons}} \rangle$$

How do these quantities relate to above pictures?
Access to spin observables in hard partonic scattering processes treatable via perturbative QCD

probe non-perturbative nucleon spin structure via partonic degrees of freedom:

Do gluons account for “missing” proton spin?

Gluons provide ~ half of proton’s mass, momentum; do they also play important role in spin? If not \( \Delta g \), then orbital contributions!

Transverse quark motion and spin preferences in transversely polarized nucleon?

Transverse motion \( \Leftrightarrow \) orbiting mesons? Transverse spin decoupled from gluons, relativistically distinct from helicity preferences.

Gluon splitting vs. Goldstone bosons and flavor-dependent sea quark polarization?

Jet production studies illuminate first two major questions!
RHIC Spin Infrastructure
Polarization survival has been demonstrated to 250 GeV beam momentum (from 24 GeV injection)

RHKIC → Riken-BNL Helicity-Identified Collider

Pioneering accelerator development ⇒ unique spin capabilities!

Absolute Polarimeter (H↑ jet)

RHIC pC Polarimeters

PHOBOS

Siberian Snakes

BRAHMS

Siberian Snakes

PHENIX

Spin Rotators
(longitudinal polarization)

STaR

Spin Rotators
(longitudinal polarization)

Pol. H↑ Source

Solenoid Partial Siberian Snake

RHIC uses superconducting helical dipole magnets for Snakes and spin rotators

Cold Siberian snake in AGS, March 31, 2005

Absolute $P_{beam}$ calibration to $\pm 5\%$ goal in progress

200 MeV Polarimeter

Rf Dipole

AGS Internal Polarimeter

RHIC uses superconducting helical dipole magnets for Snakes and spin rotators

AGS pC Polarimeters

Strong Helical AGS Snake

Polarization survival has been demonstrated to 250 GeV beam momentum (from 24 GeV injection)
Steady Improvements in Polarized Beam Performance

2003 → 2006 ⇒ > 2 orders of magnitude improvement in $P^4 \mathcal{L}$ relevant to 2-spin asymmetries!

Factor ~ 5-6 remains to reach “enhanced design” goals

STAR $\sqrt{s} = 200$ GeV pp Sampled Luminosities

<table>
<thead>
<tr>
<th>Year</th>
<th>Long. $\int \mathcal{L} , dt$ [pb$^{-1}$]</th>
<th>Trans. $\int \mathcal{L} , dt$ [pb$^{-1}$]</th>
<th>$P_{\text{beam}}$</th>
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<tbody>
<tr>
<td>2002</td>
<td>0.3</td>
<td>0.15</td>
<td>15%</td>
</tr>
<tr>
<td>2003</td>
<td>0.3</td>
<td>0.25</td>
<td>30%</td>
</tr>
<tr>
<td>2004</td>
<td>0.4</td>
<td>0</td>
<td>40-45%</td>
</tr>
<tr>
<td>2005</td>
<td>3.1</td>
<td>0.1</td>
<td>45-50%</td>
</tr>
<tr>
<td>2006</td>
<td>8.5</td>
<td>3.3 (slow det.) 6.8 (fast det.)</td>
<td>60%</td>
</tr>
</tbody>
</table>
## The Beam Polarization Monitoring Chain

<table>
<thead>
<tr>
<th>Physics process</th>
<th>Type of polarimeter</th>
<th>Accuracy, limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_N$ in $pp$ elastic scattering in CNI region</td>
<td>Polarized hydrogen gas jet target (calibrate $P_{\text{beam}}$ against $P_{\text{target}}$)</td>
<td>Absolute (~6%) calib., Some dedicated fills 1 value per year</td>
</tr>
<tr>
<td>CNI pol</td>
<td>Carbon $\mu$-ribbon target in RHIC beam, Recoil carbon detection in Si</td>
<td>Absolute ~20% (so far) Rel. ~3% + spin orient’n ~1 minute, affects beam, few per RHIC fill</td>
</tr>
<tr>
<td>BBC pol</td>
<td>Beam-Beam counters @ STAR Min-bias trigger</td>
<td>relative 10%, ~20 minutes every STAR run, Tune spin rotators</td>
</tr>
<tr>
<td>Polarization pattern of bunches</td>
<td>3 bits encode +,-,0 1bit : filled/empty for every beam</td>
<td>8bit word in every event Sometimes bits get stuck or lose sync</td>
</tr>
<tr>
<td>Finding bunch #1</td>
<td>Localize <strong>abort gap</strong></td>
<td>Needs ~5 minutes Sometimes ‘filled’ bunches are empty</td>
</tr>
</tbody>
</table>

*Diagram: Jet pol, CNI pol, BBC pol*
STAR Jet Infrastructure
\eta = - \ln(\tan(\theta/2))

-2<\eta<2

Time Projection Chamber

Forward Pion Detector

-4.1<\eta<-3.3

Tracking

Solenoidal Magnetic Field 5kG

Lum. Monitor
Local Polarim. Beam-Beam Counters

2<|\eta|<5

Beam-Beam Counters

1<\eta<2
**EMC's Essential for the Spin Program and Jet Detection**

STAR Barrel EMC (Wayne State U. + …)

STAR Endcap EMC (Indiana U. + ANL + …)

STAR Forward Pion Detector (BNL + …)

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STAR barrel (completed 2006), endcap (completed 2005) and forward (upgraded 2006) em calorimeters permit triggering/reconstruction for jets, $\gamma$, $\pi^0$, …

... in HI as well as $\bar{p}+\bar{p}$ collisions!
Jet Energy Scale Relies on EMC Calibration

Relative gain of every tower (4800 for BEMC, 720 for EEMC) determined from MIP response. Identify MIP’s via tracks for BEMC, via SMD + preshower + postshower response for EEMC

Set E-scale using 1.8<p<8 GeV/c electrons

Absolute E scale set by comparison to track momentum for identified electrons

Cross-check from reconstructed \(\pi^0\) invariant mass.

Overall gain precision = ±5% presently. Aim for 2% in near future.
Jet Triggering in STAR

Allocated Jet Rate to tape: ~15 Hz

Trigger either on

HT: ≥ 1 (of 4800 BEMC or 720 EEMC) tower $E_T > \text{thresh.}$

Or

JP: ≥ 1 (of 12 BEMC or 6 EEMC) hard-wired jet patch $\sum E_T > \text{thresh.}$

2006 rate ~ 150 Hz, combine with L2 trigger to fit in limited bandwidth

2006 rate ~ 2.5 Hz, sent to tape without prescaling

1x1 Jet patch $\sum E_T / \text{GeV}$
Jet Reconstruction in STAR

Use “midpoint-cone” algorithm (hep-ex/0005012):

- Search over all possible seeds ($p_T^{seed} > 0.5$ GeV) for stable groupings
- Check midpoints between jet-jet pairs for stable groupings
- Split/merge jets based on $E_{\text{overlap}}$
- Add all track/tower 4-momenta

Use cone radius:

$$R_{\text{cone}} = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$$

- = 0.4 for half-BEMC 2003-5
- = 0.7 for full B+EEMC 2006

Correction philosophy:

- PYTHIA+GEANT $\Rightarrow$ detector response
- Use to correct for “particle” $\rightarrow$ “detector” effects of resolution, efficiency, bias
- PYTHIA also $\Rightarrow$ study “parton” $\rightarrow$ “particle” effects of hadronization, event energy
Simulations Use Same EMC Status Tables as Data Analysis to Reproduce Details of Response

Efficiency dips between jet patches, sometimes enhanced by FEE hardware problems, reflected in status tables.

Observed jet shapes well reproduced.
Subtleties of Jet Analysis: Jet Energies

Steep $p_T$ spectrum + crude jet energy resolution $\Rightarrow$ detector jets spawned, on average, by lower-$p_T$ particle jets (despite loss of neutral hadrons w/o hadron calorimeter).

- $p_T$ shift incorporated to date by cross section corrections, $A_{LL}$ syst. errors
- Future pubs. to correct E scale, with uncertainties in horizontal errors
- “Particle” $\rightarrow$ “detector” jet shift $\approx$ same for gg vs. qg vs. qq
- “Parton” $\rightarrow$ “particle” shifts from hadronization (E loss) and underlying event (E gain) are subprocess-dependent, to be incorporated in syst. errors

Error bars reflect rms spread of simulated detector jet $p_T$ in given bin of particle jet $p_T$
Subtleties of Jet Analysis: Trigger Bias

High Tower and Jet Patch triggers require substantial fraction of jet energy in neutral hadrons

⇒ Trigger efficiency turns on slowly above nominal threshold

⇒ Efficiency differs for quark vs. gluon jets, due to different fragmentation features

Simulations reproduce measured bias well, except for beam background at extreme EM energy fraction

Conclude:

➢ Cut out jets at very high or very low EMF

➢ Use simulations to estimate syst. errors from trigger bias
Inclusive STAR Jet
Results 2003-5
Published Jet Production Cross Sections (2003+4)
Rely on Simulated Correction Factors

\[ c(p_T) = \frac{M_{\text{geant}}(p_T^{\text{geant}})}{N_{\text{pythia}}(p_T^{\text{pythia}})} \]

\[ c(p_T): \varepsilon_{\text{trigger}} \otimes \varepsilon_{\text{jet}} \otimes \text{resolution} \]

\[ \varepsilon_{\text{jet}}: \text{decreases } c(p_T) \]

resolution: increases \( c(p_T) \)

\[ \varepsilon_{\text{Trig}}: \sim 1 \times 10^{-2} \text{ at } p_{T\text{-jet}} = 5 \text{ GeV} \]

\[ \sim 1 \text{ at } p_{T\text{-jet}} = 50 \text{ GeV} \]

- Jet \( p_T \) resolution \( \sim 25\% \)
- HT efficiency changes by 2 orders of magnitude!
- Consistent results from both PYTHIA and HERWIG
**Early RHIC pp Absolute Cross Section Results**

**PHENIX pp → π^0X**

$\sqrt{s}=200$ GeV

**Mid-rapidity**

- PHENIX Data
- KKP FF
- Kretzer FF

**STAR pp → jet+X,**

$\sqrt{s}=200$ GeV

**High rapidity**

- PHENIX Preliminary pp → γX
- $\sqrt{s}=200$ GeV

Syst. Unc. dominated by jet E scale uncertainty

**pQCD works! Absolute cross sections for channels critical to gluon polarization determination -- p+p → π^0+X, jet + X, γ +X at $\sqrt{s} =$ 200 GeV – are well reproduced in NLO pQCD calcs. down to $p_T$ ~ few GeV/c.**

**Low-$p_T$ reach of robust pQCD account was not anticipated!**
Parton Model \[ F_2^p(x,Q^2) = \sum e_i^2 x [q_i(x,Q^2) + \bar{q}_i(x,Q^2)] \]

World DIS database with DGLAP fits

\[ x_f(x) \text{ for quarks \& gluons in proton from current fits to world PDF database} \]

\[ g(x,Q^2) \text{ from scaling violations in } F_2 \]
Polarized DIS Data Are Too Sparse to Constrain Gluon Helicity Preferences Well:

\[ g_1^p = \frac{1}{2} \sum e_i^2 \left[ \Delta q_i(x, Q^2) + \Delta \bar{q}_i(x, Q^2) \right] \]

World Data on \( g_1^p \) as of 2005

Only \( \sim 20\%-30\% \) of proton spin arises from \( q \) and \( \bar{q} \) helicity preferences!

Only valence quarks are strongly polarized

limited info on scaling violations, \( x \Delta g(x, Q^2) \) on shape or integral of gluon helicity preference \( \Delta g(x, Q^2) \).
**Constraining $\Delta g$ Via $p+p \rightarrow jet + X$ Spin Correlations**

Theory ingredients: pQCD factorization

- "soft" parton distribution functions
- "soft" frag. function
- "hard" $d^\wedge_{QCD}$ parton-parton

+ LO + NLO pQCD 2-spin asymmetries

$pQCD$ factoriz’n $\Rightarrow \mathcal{A}_{LL} = \frac{d\Delta \sigma_{pp \rightarrow \pi + X}}{d\sigma_{pp \rightarrow \pi + X}}$

$$= \sum_{f_1, f_2} \hat{\Delta} f_1 \otimes \hat{\Delta} f_2 \otimes d\hat{\sigma}_{f_1 f_2 \rightarrow fX} \cdot \hat{d_{LL}}^{f_1 f_2 \rightarrow fX} \otimes D_{f}^{\pi}$$

Fragmentation functions not needed for jet calcs.
STAR Preliminary 2005

3.1 pb⁻¹ sampled → 1.6 pb⁻¹ after run selection; \(\langle P_B P_Y \rangle \approx 0.25\)

Ongoing analysis is:

- recovering more runs
- correcting to particle jet E scale
- reducing systematic errors
- quantifying constraint on \(\Delta g\)

Results do not support \(\Delta g(1.0 \text{ GeV}^2)\) much > 0.4 within GRSV shape ansatz
STAR 2005 Inclusive Jet $A_{LL}$ Results are Consistent Among Different Jet Triggers, and With 2003+4 STAR Results and 2005+6 PHENIX $A_{LL}$ for Inclusive $\pi^0$

$pp \rightarrow \pi^0 + X \ @ \sqrt{s}=200 \ GeV$

$A_{LL}$

- 2003/2004 STAR Jet $A_{LL}$
- 2005 STAR Jet $A_{LL}$

Measured Jet $P_T$ (GeV/c)

Scaling error of 40% is not included.
Inclusive Jet Data from 2006 Will Provide Far Greater Discriminating Power for $\Delta g$

- High-statistics (esp. at high $p_T$) inclusive jet and $\pi^0$ $A_{LL}$ data from 2006 will select among $\Delta g$ models, assuming a shape of $\Delta g(x,Q^2)$.

- Inclusive channels suffer from integration over $x \Rightarrow$ model-dependent $\Delta G$ extraction.

With improved beam & detector performance, focus is now shifting to jet-jet and $\gamma$-jet coincidences for event-by-event constraints on colliding parton $x_{1,2}$:

$$x_1 = \frac{x_T}{2}(e^{\eta_1} + e^{\eta_2}); \quad x_2 = \frac{x_T}{2}(e^{-\eta_1} + e^{-\eta_2});$$

$$\cos \theta^* = \tanh \left[ \pm \frac{1}{2}(\eta_1 - \eta_2) \right]; \text{ with } x_T \equiv \frac{2p_T}{\sqrt{S_{pp}}}.$$
Single-Spin Asymmetry for Di-Jets 2006
Sizable Transverse Single-Spin Asymmetries Seen for Forward Hadron Production

Similar to SSA seen in FNAL E704 @ √s = 20 GeV, but here in regime where pQCD accounts for cross section!
Transverse Spin Measurements Have Stimulated Rapid Development of Theory

Factorization:

\[ \text{Hard hadronic } d\sigma = \text{PDF's } \otimes \text{hard partonic } d\sigma \otimes \text{fragment’n fcn.} \]

- Observed \( A_N \) values orders of magnitude too large to arise from explicit chiral-symmetry breaking quark mass terms in QCD Lagrangian.

- Steep \( p_T \)-dependence of \( d\sigma \) ⇒ sensitivity to spin-correlated transverse momentum preferences in non-perturbative factors:
  
  a) Partons in the initial state -- Sivers effect:
  
  \[ \left\langle \vec{s}_\text{proton} \cdot \left( \vec{p}_\text{proton} \times \vec{k}_T\text{parton} \right) \right\rangle_{\text{observed process}} \neq 0 \]
  
  Sensitive to parton orbital components in proton wave function, but also needs initial- and/or final-state interactions to evade TRV.

  b) Hadrons emerging off-axis in quark → jet fragmentation -- Collins effect:
  
  \[ \left\langle \vec{s}_\text{quark} \cdot \left( \vec{p}_\text{quark} \times \vec{k}_T\text{fragment} \right) \right\rangle_{\text{jet formation}} \neq 0 \]
  
  Requires quark transverse spin orientation preference in transversely polarized proton (“transversity”) + spin transfer to outgoing quark in pQCD scattering.
Distinguishing Sivers from Collins Asymmetries

In SIDIS, can distinguish transverse motion preferences in PDF's (Sivers) vs. in fragmentation fcns. (Collins) via asym. dependence on 2 azimuthal angles:

HERMES results ⇒ both non-zero, but $\pi^+$ vs. $\pi^-$ difference suggests Sivers functions opposite for $u$ and $d$ quarks.

also: A. Airapetian et al, P. R. L. 94 (2005) 012002
**Motivation for pp → Di-Jet Measurement**

- HERMES transverse spin SIDIS asymmetries ⇒ u and d quark Sivers functions of opposite sign, different magnitude.

- Sivers effect in \( \bar{p}p \) ⇒ spin-dependent sideways boost to di-jets, suggested by Boer & Vogelsang (PRD 69, 094025 (2004))

- Both beams polarized, \( x^+z \neq x^-z \) ⇒ can distinguish high-x vs. low-x (primarily gluon) Sivers effects.

- Do we observe \( q \) Sivers consistent with HERMES, after inclusion of proper pQCD-calculable ISI/FSI gauge link factors for \( pp \rightarrow \) jets? Tests universality.

- First direct measurement of gluon Sivers effects.
The STAR EMC-Based (Level 0 + 2) Di-Jet Trigger in 2006

- **2006 p+p run, 1.1 pb⁻¹**
- **2.6M di-jet triggered events**
- **2 localized clusters, with**
  \[ E_T^{EMC} > 3.5 \text{ GeV}, |\Delta\phi| > 60^\circ \]

Reco cos(\(\phi_{\text{bisector}}\)) measures sign of net \(k_T^x\) for event

- **Broad \(\eta_{1,2}\) coverage**
- **Full, symmetric \(\phi_{1,2}\) coverage**

Signed azimuthal opening angle \(\zeta\)

\[ \eta_1 + \eta_2 = \ln \left( \frac{x^+}{x^-} \right) \]
Full offline di-jet reconstruction for ~2% of all runs shows triggered jet $p_T$ spectrum:

Jet finder
- TPC+EMC
- jet cone radius 0.6

Typical $x_T \sim 0.05 - 0.10$;
$\eta_1 + \eta_2$ range $\Rightarrow 0.01 < x_{Bj} < 0.4$

and $\Rightarrow$ angle resolution loss @ L2 OK:

$[\sigma(\phi) = 3.9^\circ, \sigma(\zeta) = 5.8^\circ]$ L2 vs. full jet $\ll \sigma_{\text{observed}}(\zeta) \approx 20^\circ$, mostly from $k_T$

PYTHIA+GEANT $\Rightarrow$ full jet reconstruction vs. parton-level resolution:

$[\sigma(\phi) = 5.0^\circ, \sigma(\eta) = 0.10]$ full reco. jet vs. parton angles

Net L2-to-parton $\sigma(\phi_{\text{jet}}) = 6.3^\circ, \sigma(\zeta_{\text{di-jet}}) = 9.0^\circ$
2-parton events, transverse plane
match full jet reco. $p_T$ distribution
Gaussian + exp’l tail $k_T$ distribution fits $\zeta$ distribution
random $k_T^{x,y}$ (rms = 1.27 GeV/c) for each parton
Sivers spin-dep. $k_T^x$ offset $\Rightarrow \zeta$ shift, L-R di-jet bisector asym.
1-spin effects vary linearly with $k_T^x$ offset

\[
f P_{zz} | \cos \phi_b | A_N^{zz} (\zeta > \pi) = \left[ r_{zz} (\phi_b) - 1 \right] \left[ r_{zz} (\phi_b) + 1 \right] \text{ with } r_{zz} (\phi_b) = \frac{\sum N_{+j} (\zeta > \pi, \phi_b)}{\sum N_{-j} (\zeta > \pi, \phi_b)} \equiv \sqrt{\frac{\sum N_{-j} (\zeta < \pi, \phi_b)}{\sum N_{+j} (\zeta < \pi, \phi_b)}}, \text{ etc.}
\]

\[f = 0.85\] dilution corrected in data

\[
\phi \pm \delta \phi \text{ with } \phi \text{ smearing}
\]

\[A_N(\zeta > \pi)\]
STAR Results Integrated Over Pseudorapidity

Error-weighted avg of 16 independent $A_N(\zeta > \pi)$ values for $|\cos(\phi_{\text{bisector}})|$ slices, with effective $\perp$ beam polarization for each $= P_{\text{beam}} \times |\cos(\phi_{\text{bisector}})|$

- **Sivers asymmetries consistent with zero with stat. unc. = $\pm 0.002$**
- **Fast MC $\Rightarrow$ sensitivity to Sivers $\langle k_T^x \rangle$ offset $\approx$ few MeV/c $\approx 0.002 \langle (k_T^x)^2 \rangle^{1/2}$**
- **Systematic uncertainties smaller than statistics**
- **All null tests, including forbidden 2-spin asym. $\propto \cos(\phi_{\text{bisector}})$, consistent with zero, as are physics asymmetries for all polarization fill patterns**
- **Validity of spin-sorting confirmed by reproducing known non-zero $A_N$ for inclusive forward charged-particle production (STAR BBC's)**
What Did We Expect? Constraints from SIDIS Results

Fits to HERMES SIDIS Sivers asymmetries constrain $u$ and $d$ quark Sivers functions, for use in $\bar{p}p \rightarrow \text{dijet} + X$ predictions.

E.g., Vogelsang & Yuan use two different models of Sivers fcn. $x$-dependence:

\[ VY\ 1:\ \frac{u_T^{(1/2)}}{u(x)} = -0.81 x (1 - x) \]
\[ \frac{d_T^{(1/2)}}{u(x)} = 1.86 x (1 - x) \]

\[ VY\ 2:\ \frac{u_T^{(1/2)}}{u(x)} = -0.75 x (1 - x) \]
\[ \frac{d_T^{(1/2)}}{d(x)} = 2.76 x (1 - x) \]

Dijet calcs. include:
- no hadronization
- no gluon Sivers fcns.
- $5 < p_T^{\text{parton}} < 10$ GeV/c
- Initial-state interactions only (à la Drell-Yan)
- Trento sign convention (opposite Madison)

W. Vogelsang and F. Yuan, PRD 72, 054028 (2005).

≥1 jet forward, expected $|A_N| \sim 0.1$, little $p_T$ - dep.
**Theory of Transverse SSA Developing Very Rapidly!**

**Di-jet SSA Post-dictions shrinking!**

*Bacchetta, Bomhof, Mulders & Pijlman* [PRD 72, 034030 (2005)] deduce gauge link structure for $pp \rightarrow$ jets, hadrons:

\[ A_N (\text{ISI}+\text{FSI}) \approx -0.5 A_N (\text{ISI}) \]

⇒ Gauge links more robust for SSA weighted by $\sum p_T$ for 2 jets, or $|\sin \zeta|$.

*Sivers fcns. from twist-3 qg correl’n fits to $pp \rightarrow$ forward hadron*

*Bomhof, Mulders, Vogelsang & Yuan*, hep-ph/0701277

VY 2 SIDIS Sivers fit

JSI only

FSI only

ISI+FSI

Bomhof, Mulders, Vogelsang & Yuan, hep-ph/0701277

**Ji, Qiu, Vogelsang & Yuan** [PRL 97, 082002 (2006)] show strong overlap between Sivers effects & twist-3 quark-gluon (Qiu-Sterman) correlations:

⇒ twist-3 fits to $A_N (\vec{p}+p \rightarrow \text{fwd. } h)$ can constrain Sivers fcn. moment relevant to weighted di-jet SSA

⇒ *Kouvaris et al.* [PRD 74, 114013 (2006)] fits give nearly complete u vs. d cancellation in weighted di-jet SSA
STAR Di-Jet Sivers Results vs. Jet Pseudorapidity Sum

- All calcs. for STAR $\eta$ acceptance
- Reverse calc. $A_N$ signs for Madison convention
- Scale Bomhof calcs by $1/\langle |\sin \zeta| \rangle \approx 3.0$ to get $A_N$ of unit max. magnitude
- $u$ vs $d$ and FSI vs ISI cancellations $\Rightarrow$ sizable SSA in inclusive fwd. h prod’n and SIDIS (weighted SSA) compatible with small weighted di-jet SSA -- test via LCP flavor select

STAR $A_N$ all consistent with zero $\Rightarrow$ both net high-$x$ parton and low-$x$ gluon Sivers effects $\sim 10x$ smaller in $\bar{p}p \rightarrow$ di-jets than SIDIS quark Sivers asym!
Transverse spin:

- Full jet reconstruction for 2006 di-jets for $p_T$ - sorting, leading hadron charge determ. for flavor selectivity
- New Forward ($\eta = 2.5 - 4$) Meson Spectrometer extends coverage to region where large inclusive $A_N$ seen

Longitudinal spin:

- Exploit full di-jet kinematic range to enhance sensitivities:

  at LO: 
  \[
  \eta_1 + \eta_2 = \ln \left( \frac{x_a}{x_b} \right) \\
  \frac{(\eta_1 - \eta_2)}{2} = \tanh^{-1}(\cos \theta^*) \\
  x_T = 2 p_T / \sqrt{s} = \sqrt{2 x_a x_b / [1 + \cosh(\eta_1 - \eta_2)]} 
  \]

  E.g., $\eta_1 \approx \eta_2 > 1$ enhances $qq$ scattering sensitivity to $\Delta g(\text{low } x)$

- High $p_T$, large $|\eta_1 - \eta_2|$, $\eta_1 + \eta_2 \approx 0$, HT trigger enhances qq sensitivity to test pQCD
2006-10: Coincidence Measurements to Map $\Delta g(x)$ Fully

- E.g., detect $\gamma$-jet coincidences in polarized proton collisions at $\sqrt{s} = 200$ and 500 GeV
- Measure two-spin asymmetry in production rates between equal vs. opposite helicities, as function of $\eta$(jet), $\eta(\gamma)$, $p_T(\gamma)$
- Assuming 2-body parton kinematics, can infer initial $x$ values of gluon and quark

- Next-Leading-Order (NLO) pQCD analyses of data, with DIS database, can extract $\Delta g(x)$ for $Q^2 \sim 100$ GeV$^2$
- LO pQCD analysis of simulations at right ⇒ STAR sensitivity for 3 diff. models of initial gluon helicity distributions

GS-A, B, C models of $x\Delta G(x)$ from Gehrmann and Stirling, PR D53, 6100 (1996).
Summary & Conclusions

- STAR jet spin program is well under way, fueled by ample cross sections, large STAR acceptance & efficient EMC triggering.
- NLO QCD describes cross section well over 7 orders of magnitude.
- Inclusive jet $A_{LL}$ beginning to provide best constraints on gluon polarization in the proton. 2006 data will $\Rightarrow$ dramatic improvement.
- Di-jet $A_N^{\text{Sivers}}$ all consistent with zero $\Rightarrow$ compatible with sizable $A_N$ for inclusive forward hadrons and SIDIS? Add flavor enhancement to test $u$ vs. $d$ cancellation.
- Early successes $\Rightarrow$ shift focus now to:
  - Improve EMC calibration and quantitative understanding of syst. errors from energy scale ambiguities, trigger/reconstruction bias
  - Extend coincidence acceptance with Forward Meson Spectrometer
  - Exploit full kinematic characterization of parton scattering in di-jet and $\gamma$-jet coincidences to enhance interpretation of gluon polarization and transverse motion preferences in polarized proton
  - Extend measurements to 500 GeV c.m. energy $\Rightarrow$ smaller $x$
Backup Slides
Theory Systematics

Changing the pdf

Changing the scale
### Jet Energy Scale Systematics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Charged Track Momentum</td>
<td>$\Delta p/p$ TPC</td>
<td>1%</td>
</tr>
<tr>
<td>Charged Track Inefficiency</td>
<td>$10% \times 60%$ jet</td>
<td>6%*</td>
</tr>
<tr>
<td>Neutral Tower Energy</td>
<td>$\Delta G_{\text{ain}}/G_{\text{ain}} = 10%$</td>
<td>40% in yield</td>
</tr>
<tr>
<td>Neutral Energy Inefficiency</td>
<td>$\sum E_T$ from $n+K^0_{L/S}+\eta+\Omega+\nu$</td>
<td>6-10%*</td>
</tr>
<tr>
<td>MIP Subtraction</td>
<td>10% Correction to Jet $E_T$</td>
<td>1%</td>
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<tr>
<td>Fiducial Detector Effects</td>
<td>Edges/Dead regions</td>
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<tr>
<td>Jet $\eta$ calculation</td>
<td>1 tower = $\Delta \eta=0.05$</td>
<td>3%</td>
</tr>
<tr>
<td>Background Trigger</td>
<td>Background trigger +MINBIAS event</td>
<td>5% in yield</td>
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<tr>
<td>Background Energy</td>
<td>Jet + underlying Background</td>
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<tr>
<td>Underlying Event</td>
<td>Work in Progress</td>
<td>NA</td>
</tr>
<tr>
<td>Fragmentation</td>
<td>Comparison to HERWIG ongoing</td>
<td>NA</td>
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</tbody>
</table>

* Included in Correction Factor
• Increase in sampled luminosity over 2005

• Polarization ~ 60%
  (FOM is P^4L)

• Entire BEMC instrumented

• Beamline shielding installed

• Greater emphasis on high p_T jets and dijets with triggers

\[ \vec{p} + \vec{\bar{p}} \rightarrow \text{jet} + X \text{ at } \sqrt{s}=200 \text{ GeV} \]

-1 < |\eta| < 1

\[ \Delta G = G \]

\[ \Delta G = \bar{G} \]

\[ \Delta G = 0 \]

Jet p_T [GeV/c]

Jet E(EMC)/E(total)

A_{\text{like-sign}}, GRSV-STD

Trigger bias (δA_{LL}), GRSV-STD

- HT2
- JP2

Jet pT (GeV/c)
### 2005 Results: Inclusive Jet $A_{LL}$

**Spin 2006, preliminary result, STAR inclusive jets**

All numbers in units of $1\times10^{-3}$ absolute on $A_{LL}$

<table>
<thead>
<tr>
<th></th>
<th>bin 1</th>
<th>bin 2</th>
<th>bin 3</th>
<th>bin 4</th>
<th>bin 5</th>
<th>bin 6</th>
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<td>10.4</td>
<td>12.8</td>
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* Middle point of the histogram bin: $= \text{max} - \text{min}$
data ↔ x-range probed

a closer look:
diff. subprocesses populate different x-ranges

$\Delta g(\mu) = 0.24$
$x = 0.04 \pm 0.23$

$gg$ vs. $qq$ interplay explains all:

- large pos. $\Delta g$ → pronounced $gg$ peak
- small pos. $\Delta g$ → double peak
- not too large neg. $\Delta g$ → oscillations

estimates of $x \pm dx$ very difficult w/o knowing $\Delta g$

d$\Delta \sigma / dp_T \ d\log_{10} x$
$p_T = 2.5 \text{ GeV}$

sum for $\Delta g(\mu) = 0.24$

$gg \rightarrow \pi X$
$qg \rightarrow \pi X$
$qq, qq', q\bar{q} \rightarrow \pi X$