STAR results on longitudinal spin dynamics

Joanna Kiryluk (MIT)
for the STAR Collaboration

DIS2006
20-24 April 2006, Tsukuba, Japan

Outline:
1. Goals of spin program (longitudinal pol)
2. STAR detector at RHIC
3. $A_{LL}$ in inclusive jet production
4. Longitudinal polarization (spin transfer) of Lambda and anti-Lambda
5. Summary and Outlook
Polarized proton-proton collisions with STAR (Solenoid Tracker At RHIC)

The STAR Collaboration

542 collaborators from 51 institutions and 12 countries

Brookhaven National Laboratory, Upton NY, USA
The goals of STAR-spin program with *longitudinally* polarized protons at RHIC

- gluon polarization - a major emphasis at STAR-Spin

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Dom. partonic process</th>
<th>probes</th>
<th>LO Feynman diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{p}p \rightarrow \pi + X$</td>
<td>$\bar{q}q \rightarrow gg$</td>
<td>$\Delta g$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\bar{q}g \rightarrow qg$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\bar{p}p \rightarrow \text{jet} + X$</td>
<td>$\bar{q}g \rightarrow gg$</td>
<td>$\Delta g$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$q\bar{g} \rightarrow qg$</td>
<td>(as above)</td>
<td></td>
</tr>
<tr>
<td>$\bar{p}p \rightarrow \gamma + X$</td>
<td>$\bar{q}g \rightarrow \gamma q$</td>
<td>$\Delta g$</td>
<td></td>
</tr>
<tr>
<td>$\bar{p}p \rightarrow \gamma + \text{jet} + X$</td>
<td>$q\bar{g} \rightarrow \gamma q$</td>
<td>$\Delta g$</td>
<td></td>
</tr>
</tbody>
</table>

\[ \sqrt{s} = 200(500) \text{ GeV} \]

- (anti-)quark polarization \((u,d)\) \[\bar{p} \ p \rightarrow W^\pm + X \rightarrow e^\pm + X\] \[\sqrt{s} = 500 \text{ GeV}\]
  
  *Talk by F. Simon, session SP-5*

- (anti-)lambda polarization \[\bar{p}p \rightarrow (\text{anti-})\bar{\Lambda} + X\] \[\sqrt{s} = 200 - 500 \text{ GeV}\]

  *Gives insight into pol. fragmentation and parton distribution functions e.g. $\Delta s$ (model dependent)*

  *this talk*

*STAR-spin program with transversly polarized protons: talk by C.Gagliardi, session SP-3*
RHIC (Relativistic Heavy Ion Collider) - polarized pp collider

- two siberian snakes in each ring: stable polarization direction at RHIC - vertical beam polarization measured by RHIC polarimeters -> talks by A. Bravar, session SP-2,-3

- a pair of spin rotators in each ring around STAR (and PHENIX) IR (Interaction Region): longitudinal polarization at two IRS

STAR local polarimeter - to (continuously) monitor beam polarization direction

<table>
<thead>
<tr>
<th>pp Run</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005-ongoing analysis</th>
<th>2006 run started in March &gt; 2006 LongTermGoals</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM Energy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam polarization/direction at STAR</td>
<td>0.15 T</td>
<td>0.30 T/L</td>
<td>0.40L</td>
<td>0.45 L/T</td>
<td>0.7 T/L</td>
</tr>
<tr>
<td>L_{max} [10^{30} s^{-1}cm^{-2}]</td>
<td>2</td>
<td>6</td>
<td>6</td>
<td>16</td>
<td>80</td>
</tr>
<tr>
<td>L_{int} [pb^{-1}] (STAR,delivered)</td>
<td>0.3</td>
<td>0.5/0.4</td>
<td>0.4</td>
<td>9/0.4</td>
<td>320</td>
</tr>
</tbody>
</table>

Results from these data analysis presented in this talk
**Solenoidal Magnet**
- $B = 0.5\, \text{T}$

**Tracking Detectors**
- **Time Projection Chamber** $|\eta| < 1.6$
- **Forward TPC** $2.5 < |\eta| < 4.0$
- **Silicon Vertex Tracker** $|\eta| < 1$

**Trigger Detectors**
- **Beam-Beam Counters** $3.4 < |\eta| < 5$
- **Zero-Degree Calorimeter** $|\eta| \sim 6$
- **E-M Calorimeters** - installation in stages completed before 2006
- **Barrel EMC** $|\eta| < 1$
- **Endcap EMC** $1.0 < \eta < 2.0$
- **Forward Pion Detector** $3.3 < |\eta| < 4.1$

Cutway side view of the detector where pseudorapidity $\eta = -\ln \tan \theta/2$

+ **STAR Upgrades**: Forward Meson Spectrometer, Time of Flight, Forward Tracker, Heavy Flavor Tracker ... *talk by F. Simon, session SP-5*

STAR is adding lots of EM calorimetry to trigger on and detect high-energy $\gamma$, $e^\pm$, $\pi^0$

- TPC+EMC for jet reconstruction
- TPC for Lambda reconstruction
- BBC + scaler board system for relative luminosity and polarization monitoring
**Inclusive jet production in pp interactions - motivation**

- Cross section

\[(\Delta)\sigma \propto \sum_{ab} (\Delta) pdf \otimes (\Delta) pdf \otimes (\Delta) \tilde{\sigma}_{ab} \]

hard scattering

\[p_T^3 \frac{d\sigma}{dp_T d\eta} = \frac{2}{\mathcal{O} \left( \frac{\lambda}{p_T} \right)^n} \]

jets - no fragmentation functions are needed (systematics!)

- Asymmetries

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

\(\Delta \sigma\) - very small (difficult to measure), measure asymmetries instead, where most of systematic effects cancel out

Similar sensitivity to the gluon polarization (no parton kinematics reconstruction)

- Convolutions “pdf \times pdf \times hard scattering” complicated and inversion \(A_{LL} \rightarrow g(x)\) not straightforward

- At the moment emphasis is on NLO predictions of \(A_{LL}\) in terms of “model” \(\Delta g\)

- Near-future: CTEQ-style global analysis of variety of \(A_{LL}\) data

  *talk by M.Stratmann, session SP-4*
Jet reconstruction at STAR
- via TPC $p_T$ for charged hadrons+EMC $E_T$ for e-m showers

1) Jets reconstruction - midpoint cone algorithm (Tevatron II)
   seed energy = 0.5 GeV, cone angle $R = 0.4$ in $\eta-\phi$
   splitting/merging fraction $f=0.5$

2) Trigger used in this analysis - High Tower:
   $E_T > 2.4$ GeV deposited in one tower $(\Delta \eta \times \Delta \phi ) = (0.05 \times 0.05)$
   + additional requirement of BBC coincidence.

3) Data set: 0.4 pb$^{-1}$ (2003 and 2004) recorded luminosity
   $<P_b> =0.3$ (2003) and $<P_b> = 0.4$ (2004)

4) Selections:
   - charged tracks $|\eta| < 1.6$ and $p_T > 0.1$ GeV/c
   - jets: $p_T$ jet > 5 GeV/c , 0.2 $<$ jet $\eta$ (det) $<$0.8
   - beam-background: $E_{jet}$ (neutral)/$E_{jet}$ (total) $<$ 0.8(0.9) for 2003 (2004)
   - $|z$-vertex$| < 60$cm

5) Final statistics (after cuts) $\sim 300k$ jets

Cross section for inclusive jet production: talk by M.Miller, session HSF-7
Double Longitudinal Spin Asymmetry Measurements

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

Statistical significance: \( P_1^2 P_2^2 \cdot \int L dt \)

Require concurrent measurements:

- magnitude of beam polarization, \( P_{1(2)} \) \( \rightarrow \) RHIC polarimeter(s)
- direction of polarization vector at interaction point
- relative luminosity of bunch crossings with different spin directions: \( R = \frac{L_{++}}{L_{+-}} \)
- spin dependent yields of process of interest: \( N_i \) and \( N_{ij} \) \( \{ \text{STAR} \} \)
Double spin asymmetry $A_{LL}$ (preliminary) results in inclusive jet production in $p+p$ collisions at $\sqrt{s}=200\text{GeV}$

Results limited by statistical precision

Total systematic uncertainty $\sim0.01$ (STAR) + beam pol. (RHIC)

$\text{GRSV-max}$ gluon polarization scenario disfavored

Sources of sys. uncertainties: background contribution, trigger bias, relative luminosity, residual (non-longitudinal) asymm., bunch to bunch syst. variations (random pattern analysis)+ beam pol.
Jet background contribution

(= 'jets' with no TPC tracks, only e-m energy)
- can cause a bias in the measurement of $A_{LL}$

$$A_{LL}^{meas}(p_T) = \frac{A_{LL}(p_T) + f_{bg}(p_T) \times A_{LL}^{bg}(p_T)}{1 + f_{bg}(p_T)}$$

- $f_{bg} < 0.05$ - remaining background fraction in the final jet sample
- $A_{LL}^{bg} \sim -0.06 \pm 0.03$ - extracted background asymmetry

Trigger bias

High Tower trigger ($E_T > 2.4$ GeV deposited in one tower) selects on e-m energy deposits and may thus distort the partonic sub-process contributions in inclusive jet production.

Possible size of this effect was estimated from MonteCarlo (Pythia+GEANT) simulations of the trigger response, and from various polarized parton distribution functions such as GRSV-std and -max.

$$|A_{LL}(\text{with trigger bias}) - A_{LL}(\text{no trigger bias})| < 0.007$$
Systematic Study for $A_{LL}$ - Random Fill Pattern Analysis

- Method: take true fill pattern (56 bunches in 2004) and mix assignment of spin up and down bunches (red and green points) to the bunch crossing number

- Result for: one random fill pattern and 400 random fill patterns

The RMS is consistent with $A_{LL}$ statistical uncertainties indicating that bunch to bunch and fill to fill systematic uncertainties are negligible
Cross checks - parity violating asymmetries

\[ A_L = \frac{1}{P_{\text{beam}}} \frac{N^+ - RN^-}{N^+ + RN^-} \]

- \[ p_0 = 0.002(7) \quad \chi^2/\text{ndf} = 4/5 \]

- \[ p_0 = -0.006(6) \quad \chi^2/\text{ndf} = 6/5 \]

- \[ p_0 = 0.003(7) \quad \chi^2/\text{ndf} = 130/126 \]

- \[ p_0 = -0.005(6) \quad \chi^2/\text{ndf} = 154/126 \]

Consistent with zero - as expected
All other xcheck asymmetries were found consistent with zero
Prospects for Run5 (first long pp run) and Run6 (ongoing)

Run5 improvements:
- $P_b \sim 45\%$ ($\sim 40\%$ in Run4), $L = 3$/pb ($0.3$/pb in Run4)
  
- FoM (Run5)/FoM(Run4) = 16

- Acceptance: $3/4$ BEMC complete ($1/2$ in Run4)

- Two complementary jet triggers permit assessment of trigger bias due to q vs. g jet differences in shape, multiplicity, hardness in $z$.

Potential to discriminate between several $A_{LL}$ predictions based on DIS parametrizations
Anti-Lambda at RHIC: $\Delta \bar{s}$

The measurement of hyperon polarization at RHIC can give insights into polarized fragmentation and parton distribution functions

$$P^+_{\Lambda}(\eta) = \frac{\sigma_{p^+p \rightarrow \Lambda^+}(\eta)X - \sigma_{p^+p \rightarrow \Lambda^-}(\eta)X}{\sigma_{p^+p \rightarrow \Lambda^+}(\eta)X + \sigma_{p^+p \rightarrow \Lambda^-}(\eta)X} \equiv D_{LL}(\eta)$$

- Lambda-bar polarization (p+p) is sensitive (in a model dependent way) to $\Delta \bar{s}$
- Lambda polarization (p+p) less sensitive to $\Delta s$, because of u,d fragmentation, e.g.
  - D. de Florian et al, PRL81(1988)530
  - C. Boros et al, PRD62(2000)014021
  - B.Q. Ma et al, NPA703(2002)346
Lambda and anti-lambda reconstruction in p+p collisions at STAR

• $\Lambda$ reconstruction at STAR via decay channel: $\Lambda \rightarrow p + \pi$ (Br=64%)
  - combining TPC tracks with opposite charges
  - cuts for tracks and decay vertex topology
  - $|<x_F>| \sim 0.008$  $<p_T> \sim 1.5$ GeV/c

• Data sample (after all cuts) 2003+2004 $\sim 30k$ Lambda and $\sim 27k$ anti-Lambda

$M = 1.1157$ GeV (PDG)

\[ p_v(GeV) \]

Podolanski-Armenteros plot

\[ \alpha = \left( p^+_L - p^-_L \right) / \left( p^+_L + p^-_L \right) \]

$p^+_L$ ($p^-_L$) - momentum of positive (negative) tracks parallel to the $V_0$ momenta

$p_v$ - momentum of tracks perpendicular to the $V_0$ momentum
Measuring Longitudinal $\Lambda$ polarization without Acceptance Function

- **Standard Method:** Angular distribution of decay proton in the $\Lambda$ rest frame:
  \[
  \frac{dN}{d\cos\theta} = \frac{N_{\text{tot}}}{2} A(\cos\theta)(1 + \alpha \vec{P}_\Lambda \cdot \hat{p}_p),
  \]
  where $\alpha$ decay parameter (empirical) = 0.642 (PDG) and $A(\cos\theta)$ acceptance
  relies on knowledge of the Acceptance Function (usually from simulation).

- The four combinations ($++$, $--$, $+-$, and $-+$) of beam helicities at RHIC, and symmetries (parity, proton indistinguishability) in the $\Lambda$ production process allow one to determine the *longitudinal* $\Lambda$ polarization (spin transfer) from measured asymmetries in (narrow) intervals in $\theta$,
  \[
  \varepsilon = \frac{N^+ - RN^-}{N^+ + RN^-} \approx \alpha \langle \cos\theta \rangle P_{\text{beam}}P^+_\Lambda
  \]
  in which the *Acceptance Function largely cancels*.

\[\begin{align*}
N^+ &= N^{++} + N^{+-} \\
N^- &= N^-- + N^{-+}
\end{align*}\]
Lambda polarization from 2003 and 2004 pp data with longitudinal polarization - Preliminary Results

\[ P_{\Lambda}^{+}(\eta) = \frac{\sigma_{p^{+}p^{-}\Lambda^{+}(\eta)X} - \sigma_{p^{+}p^{-}\Lambda^{-}(\eta)X}}{\sigma_{p^{+}p^{-}\Lambda^{+}(\eta)X} + \sigma_{p^{+}p^{-}\Lambda^{-}(\eta)X}} = D_{LL} \]

\[ D_{LL} \approx 0.01, \ p_{T} \approx 1.5 \text{GeV} \]

Gluon fragmentation at such low \( p_{T} \) should be important.

Results limited by statistical precision.

Prospects for Run5 (first long pp run), Run6 (on-going) and beyond

<table>
<thead>
<tr>
<th>Trigger Type</th>
<th>Number of ( \Lambda ) Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet-Patch</td>
<td>160k</td>
</tr>
<tr>
<td>High-Tower</td>
<td>80k</td>
</tr>
<tr>
<td>MinBias</td>
<td>36k</td>
</tr>
</tbody>
</table>

Run5

Run6 (10pb\(^{-1}\)) \( \delta D_{LL} \sim 0.04 \) for \( p_{T} > 6 \text{ GeV/c} \)

>100 pb\(^{-1}\) needed for \( \delta D_{LL} \sim 0.01 \) for \( p_{T} > 8 \text{ GeV/c} \)

Trigger on anti-Lambda?
Summary and Outlook

- We presented preliminary results for the measurement of the double spin asymmetry $A_{LL}$ in inclusive jet production in polarized $p+p$ collisions at $\sqrt{s}=200$ GeV over the measured kinematic range of jet $5 < p_T < 17$ GeV/c.

The results for $A_{LL}$ are limited by statistical uncertainties and currently do not distinguish between the different scenarios for gluon polarization in the proton allowed by polarized DIS data, but tend to disfavor GRSV-max gluon polarization scenario.

- A method to extract *longitudinal* lambda and anti-lambda polarizations in longitudinally polarized $p+p$ collisions with acceptance largely cancelled was developed and illustrated with the small data sample from 2003 and 2004.

Prospects for Run5 ....and beyond: new run6 started on March 1st 2006

In run-5 STAR collected $\sim$10 times more statistics (the first long pp run) with higher beam polarization (better source) than in 2003 and 2004.

STAR will be able to distinguish between the different scenarios for gluon polarization in the proton from $A_{LL}$ measurements in (i) inclusive jet production at mid-rapidity (ii) inclusive $\pi^0, \pi^+\pi^-$ production at mid-rapidity and $\pi^0$ in forward region (STAR unique!), (iii) inclusive $\gamma$ and (iv) $\gamma$+jet correlations.
Backup
Relative Luminosity Measurement from Beam Beam Counters

- Precision of relative luminosity monitoring critical: for \( A_{LL} \sim 1\% \) \( \delta A_{LL} / A_{LL} \sim 5\% \) if \( \delta R / R \sim 10^{-3} \)
- Luminosity \( \sim \) BBC coincidence rate (large cross section of \( \sim 27\text{mb} \)) counted every 107ns
- RHIC stores up to 120 bunches per ring - different bunches injected with different spin orientation
  - collision luminosity can vary with spin combination

### Relative Luminosities Uncertainties:

\[
\delta R_{\text{stat}} \sim 10^{-4} - 10^{-3} \quad \text{and} \quad \delta R_{\text{syst}} < 10^{-3}
\]
BBC + Scaler Boards - Applications

- BBC Transverse Single Spin Asymmetries
  Single spin asymmetries measured for p+p -> A + X, where A – hit(s) in the BBC

\[
\varepsilon_{LR} = \frac{\sqrt{N_{L}^{\uparrow}N_{R}^{\downarrow}} - \sqrt{N_{L}^{\downarrow}N_{R}^{\uparrow}}}{\sqrt{N_{L}^{\uparrow}N_{R}^{\downarrow}} + \sqrt{N_{L}^{\downarrow}N_{R}^{\uparrow}}} \sim \begin{cases} 
\mathbf{P}_{\text{vert}}^{\text{beam}} \times A_N \times \left< \cos(\phi) \right> & \text{Left-Right} \\
\mathbf{P}_{\text{rad}}^{\text{beam}} \times A_N \times \left< \sin(\phi) \right> & \text{Top-Bottom} 
\end{cases}
\]

The BBC East and West data sets sorted by beam polarization states:
1. Polarized Yellow beam (sum over Blue beam polarization states) heads towards the East
2. Polarized Blue beam (sum over Yellow beam polarization states) heads towards the West

\[3.4 < \mid \eta \mid < 5.0 \text{ (small tiles only)}\]
Unexpected $A_N$ of unknown origin measured with the BBC

- Strong pseudorapidity dependence of $A_N$ for $x_F > 0$ and $A_N = 0$ for $x_F < 0$
- $\delta \varepsilon^{(syst)} < \delta \varepsilon^{(stat)}$ (next slide)
BBC - Local Polarimeter at STAR

- Stable spin direction at RHIC is vertical
- Spin Rotator brings to almost radial
- D0/DX magnet causes spin precession
- Longitudinal at IR
- DX/D0/Spin Rotator put back to vertical

Measured asymmetry $i \sim A_N P_i$
Left-Right asym - sensitive to vertical polarization
Top-Bottom asym - sensitive to radial polarization

<table>
<thead>
<tr>
<th>Rotators</th>
<th>OFF</th>
<th>ON</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNI polarimeter</td>
<td>non-zero</td>
<td>non-zero</td>
</tr>
<tr>
<td>BBC Left-Right (vertical)</td>
<td>NON_ZERO</td>
<td>ZERO</td>
</tr>
<tr>
<td>BBC Top-Bottom (radial)</td>
<td>zero</td>
<td>zero</td>
</tr>
</tbody>
</table>

Longitudinal polarization at STAR ($P_{vert}$ and $P_{rad}$ < 5%) - first step to $A_{LL}$ measurement
Reconstruction of \( \Lambda \)

- Approach to reconstruct \( \Lambda \):
  
  Combining TPC tracks with opposite charge to form a \( \Lambda \) candidate.

- Cuts for tracks and decay vertex topology:
  
  1. \( dE/dx < 3 \sigma \) for proton, and \(<5 \sigma \) for pion;
  2. \( \text{dca2helix} < 0.85\text{cm} \) : the closest distance between the two helices of possible proton and pion;
  3. \( \text{decay length}_{\text{radial}} > 2\text{cm} \)
  4. \( \text{V0\_DCA} < 2 \text{ cm} \) : the closest distance of the V0 to primary vertex;
  5. \( \cos(r.p) > 0 \), the angle between the vector from the primary vertex to the V0 point and the summed momentum of two tracks.
Masscut1

after dE/dx cut

M_A = 1.1157 GeV (PDG)

Masscut2

after dca2h cut

Masscut3

after decay len. cut

Masscut4

after V0_DCA < 2 cm

after cos(r.p) > 0
data in bins of $\cos\theta$ (Minbias+BHT):

- Fitting function: gaussian (signal) + bkg, 10 bins for $\cos\theta (-1,1)$

only the first 4 bins were used for analysis! ($\sim60\%$)

$\sim30K$ of $\Lambda$ candidates ($\sim27K$ for anti-lambda) used in our following analysis!