STAR Results from Polarized Proton Collisions at RHIC

- Long-term goals
- Polarized protons in RHIC
- STAR
- Results from first polarized proton collisions
- Summary

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Xth Workshop on High Energy Spin Physics
Dubna, September 16-20, 2003
Gluon Contribution to the proton’s spin

Coincident detection of $\gamma$ and away-side jet $\Rightarrow$ event determination of initial-state partonic kinematics.

Measure spin-correlation parameter ($A_{LL}$) with longitudinally polarized protons

$$P_{b_1} P_{b_2} A_{LL} = \frac{N_{++} - RN_+}{N_{++} + RN_+}$$

$P_{b_{1(2)}}$ — beam pol’n (~70%)
$N_{++(\pm)}$ — equal (opposite) helicity yield
$R$ — relative luminosity

Interpret measured asymmetry within leading-order pQCD

$A_{LL} = P_{\text{part.1}} P_{\text{part.2}} \hat{a}_{LL} = \frac{\Delta f_1}{f_1} \frac{\Delta f_2}{f_2} \hat{a}_{LL}(s, t, u)$

QCD Compton

$$\Delta G(x_g) \quad A_{1}^{P}(x_g) \quad \hat{a}_{LL}$$

unpol struct fncts.

pQCD result for specific process

Measured in polarized deep-inelastic scattering

gluon polarization
STAR Simulations of W Production

- Different $W^+$ vs. $W^-$ decay patterns ⇒ quite different $\eta$ distributions for daughters
- Quark vs. antiquark polarization sensitivity are separated most cleanly for $\eta > 1$, especially for $W^-$

$x$-values of quark and antiquark can be determined event-by-event from $\eta$ and $p_T$ of detected daughter.
Transversity at STAR

using spin dependent jet Fragmentation Function (FF)

\[ \frac{d^{6} \sigma_{H}( pp^{\uparrow} \rightarrow \pi^{+}\pi^{-}X) }{dx_{1}dx_{2}dtdzdm^{2}d\phi} \propto \delta q(x_{1})q(x_{2}) \]

Transversity

Hard Scattering Process xsection

\[ \frac{d^{3} \sigma (q_{1}q_{2} \rightarrow q_{3}q_{4}) }{dx_{1}dx_{2}dt} \]

Collins-Heppelmann FF

or

2 pion Interference FF
The **Relativistic Heavy Ion Collider** at Brookhaven National Laboratory

**R-HI**
New state of matter
QGP
De-confinement

…

**polarized proton**
Nucleon Spin Structure
Spin Fragmentation
pQCD

…

RHIC is a QCD lab
Polarized Proton Operation at RHIC

Equipment to be installed after FY03

- Helical dipole snake magnets
- CNI polarimeters in RHIC, AGS
  -> fast feedback
- \(\beta^*=1\)m operation
- spin rotators -> longitudinal polarization

Equipment/developments for runs 2 (1/02) and 3 (3/03 → 5/03)...
What is required for a spin experiment at RHIC?
(a summary of the multiple concurrent experiments)

Stages of the RHIC-spin Project
Concept → Learning → Production

- Production of high-energy/intensity/polarization proton bunches that collide
  ⇒ A successful accelerator physics experiment employing ‘snakes’, rotators, etc.
  Rarest probes require $P_{\text{beam}} = 70\%$ and $\int \mathcal{L} \, dt = 320(800) \, \text{pb}^{-1}$ at $\sqrt{s} = 200(500) \, \text{GeV}$

- Large experimental facilities capable of detecting hadrons/jets, $\gamma$, $e^\pm$, $\mu^\pm$, ...
  ⇒ Experimental sophistication comparable to other colliders (Tevatron, HERA, …)

- Polarimeters to monitor polarization and establish its absolute magnitude
  ⇒ Coulomb-nuclear interference / polarized gas jet target / local polarimeters
  Require $\Delta P_{\text{beam}} / P_{\text{beam}} \sim 5\%$

- Interaction-region monitors of spin-dependent relative luminosity
  ⇒ Precision experiments to minimize systematic errors in final answer
STAR adding lots of EM calorimetry to detect high-energy $\gamma$, $e^\pm$, $\pi^0$ plus Beam-Beam Counters for relative luminosity and polarization monitoring. EMC’s and FPD’s partially implemented for 2003 run, will be completed before 2005.

See NIM A499 (2003)
Run 2 Progress / Results

- \( \int \mathcal{L} \, dt \sim 350 \text{ nb}^{-1} \) and \( \langle P_{\text{beam}} \rangle \sim 18\% \) (Yellow) / 15\% (Blue) delivered to experiments. Polarization limited by performance of AGS.
- STAR / PHENIX / pp2pp experiments commissioned for \( pp \) collisions at \( \sqrt{s} = 200 \text{ GeV} \).
- Critical \( pp \) reference measurements for heavy-ion program completed providing important physics results.
- Transverse single-spin measurements completed providing physics results + local polarimeters for spin-rotator tuning in Run 3.

Siberian Snakes work to preserve polarization through acceleration and store.
Di-jet Reference for Heavy-Ion Physics
(jet physics is central to spin program)

STAR p+p, $\sqrt{s} = 200$ GeV

Hadronic high-$p_T$ azimuthal correlations in $pp$ collisions

• di-jet events clearly observed in $pp$ collisions at $\sqrt{s} = 200$ GeV.

• di-hadrons serve as di-jet surrogates for heavy-ion collisions.

• clear near-side and away-side di-hadron correlations in $pp$ collisions serve as contrast for central AuAu collisions where away-side correlations are strongly suppressed.

Spin asymmetries in $\pi^0$ production: $p \uparrow + p \rightarrow \pi + X$

Non-zero $A_N$ measured in E704 at Fermilab at $\sqrt{s}=20$ GeV, $p_T=0.5-2.0$ GeV/c:

- Predictions by different theorists expect non-zero $A_N$ values, attributed to different dynamics, to persist at RHIC energies: $\sqrt{s}=200$ GeV...


See also:

...Non-zero analyzing power expected to persist up to RHIC collision energies...
STAR Forward $\pi^0$ Detector

24 layer Pb-scintillator sampling calorimeter

2 orthogonal planes of finely segmented triangular scintillator strips (Shower-Maximum Detector, or SMD)

2 Preshower layers

$\pi^0$ reconstruction at $E=20\sim80\text{GeV}$, $1<p_T<4\text{ GeV}$, $3<\eta<4$

Located east of STAR detector at $z=750\text{cm}$

Mid rapidity detectors

Event Display

SMD

EMC

Histogram = DATA fit (1165 points = SIMULATION (version 48))
STAR-Spin Results from Run 2

\[ p^+ + p \rightarrow \pi^0 + X, \sqrt{s} = 200 \text{ GeV} \]

- Measured cross sections consistent with pQCD calculations
- Large spin effects observed for \( \sqrt{s} = 200 \text{ GeV} \) pp collisions

Status: final analysis complete / paper in preparation
Relative Luminosity Monitoring

- RHIC stores up to 120 bunches per ring
- Different bunches injected with different spin orientation
- Collision luminosity can vary significantly with spin combination
- Precision of relative luminosity monitoring critical – demonstrated better than $10^{-3}$ in 2002 run
- Special problem for $A_{LL}$ measurements: asymmetry $\phi$-independent, shows up only as yield change per integrated luminosity unit
- Must demonstrate that $L$ monitor reaction does not have its own $A_{LL}$ of magnitude comparable to physics of interest $\Rightarrow$ comparisons of different $L$ monitors

Example of Relative Luminosity from Run 2

$R = \frac{L^{\uparrow\uparrow}}{L^{\uparrow\downarrow}} \neq 1$ and time dependent!
STAR Electromagnetic Calorimeters

Barrel EMC: 2400/4800 towers installed for 2003, with SMD but not yet preshower readout

Endcap EMC: 240/720 towers installed; no SMD, preshower or postshower readout yet
STAR Forward Pion Detector
(Construction for Run 3)

Run 3 Objectives:

• probe of Color Glass Condensate in d+Au
  ⇒ $p_T$ dependence of large $\eta$ yield

• improve understanding of dynamical origin of $A_N$
in $p_\uparrow + p \rightarrow \pi^0 + X$ ⇒
  ➢ Collins effect → sensitivity to transversity
  ➢ Sivers effect → sensitivity to orbital motion
  ➢ twist-3 effect → quark/gluon correlations

• serve as local polarimeter at STAR IR

$d+Au \rightarrow \pi^0 + X$, $\sqrt{s_{NN}} = 200$ GeV

- $10 < E_\pi < 80$ GeV
- $\eta_\pi \sim 4$ (relative to d)
Beam Beam Counter

1cm thick scintillator hex tiles with PMT readout \((2.1<|\eta|<5)\)

- Feed back to RHIC to make collision at STAR
- Measure relative luminosity \(~10^{-3}\) level
- Measure absolute luminosity \(~15\%\) level
- Minimum bias trigger (covers \(~50\%\) of total \(\sigma\))
- Reject beam gas events from biased trigger
- Measure multiplicity at forward rapidity
- \(A_N\) for forward charged particles
RHIC performance during run 3

Polarization
- Maximum at injection: ~50%,
- Maximum at 100 GeV: ~40%
- Average P ~25%
- Improved by factor of two compared to run 2
- Yellow ring affected by problem with snake magnet

Luminosity
- New problem ‘beam-beam tune shift’ surfaced, limiting luminosity
- Adequate to accomplish physics goals from Run 3.
Spin Rotators and Local Polarimetry

Calculations establish a working point and the dependence of transverse polarization components on spin rotator currents.

Local polarimeters are needed to measure vertical, radial polarization components at interaction region.
STAR Spin Rotator Magnet Tuning
(Run 3 Result)

• RHIC polarimeter (CNI) establishes polarization magnitude.
• Local polarimeter (BBC) establishes polarization direction at STAR.

STAR spin rotator:
⇒ P_{vert} ← ON
⇒ P_{long}

• use segmentation of inner tiles of BBC as a Local Polarimeter monitoring pp collisions.
• Rotators OFF ⇒ BBC L/R spin asymmetries comparable to RHIC polarimeter (CNI).
• Rotators ON ⇒ adjust rotator currents to minimize BBC L/R and T/B spin asymmetries.

⇒ Longitudinal Polarization at STAR
BBC & ZDC for relative luminosity monitor

Is there $A_{LL}$ in Relative Luminosity ($R = N_{++}/N_{+-}$) measurement? BBC sees ~50% of total cross section (~87% of inelastic, non-diffractive cross section). ZDC sees ~0.5% of total cross section.

$R_{\text{BBC}} - R_{\text{ZDC}} \leq 10^{-3}$

Green light for $A_{LL}$ measurements
Projections for Sensitivity to $\Delta G$ from Run 3

Longitudinal spin asymmetry ($A_{LL}$) for mid-rapidity jet production

$\Rightarrow$ first measurements sensitive to gluon polarization

Status:

- data analysis underway
- understand trigger bias
- understand jet yields
# Possible Timeline for STAR Spin Program

<table>
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<tr>
<th>RHIC RUN YEAR</th>
<th>NEW EQUIPMENT TO BE COMMISSIONED</th>
<th>STAR/RHIC SPIN MEASUREMENTS</th>
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<tr>
<td>FY04</td>
<td>New AGS warm snake; $\vec{\Lambda}$ gas jet; rf spin flipper; BEMC preshower; EEMC SMD + preshower; completed FPD</td>
<td>Test $L$ improvement schemes; calibrate $P_{\text{beam}}$ to 10%; continue $A_{LL}(\text{jets})$</td>
</tr>
<tr>
<td>FY05</td>
<td>New strong AGS cold snake; Completed BEMC, EEMC (incl. postshower); forward hadron calorimeter?</td>
<td>Calibrate $P_{\text{beam}}$ to 5%; improve $L$; Collins frag. with forward $\pi^0$’s; more $A_{LL}(\text{jets})$; first look at $\gamma$+jet</td>
</tr>
<tr>
<td>FY06+07</td>
<td>Whatever is needed to achieve full design $L$ and $P_{\text{beam}}$; $\sqrt{s} = 500$ GeV polarized collisions;</td>
<td>$A_{LL}(\gamma + \text{jet})$, transversity measurements at mid-rapidity, at $\sqrt{s} = 200$ GeV</td>
</tr>
<tr>
<td>FY08+09</td>
<td>Improved STAR forward tracker ($1&lt;\eta&lt;2$)</td>
<td>$A_{LL}(\gamma + \text{jet})$, $A_L(W^{\pm})$ at $\sqrt{s} = 500$ GeV</td>
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Summary

1) STAR spin program well under way. Essential equipment and procedures commissioned during RHIC runs 2,3: snakes, rotators, polarimeters, accurate relative luminosity monitors; STAR EMC’s, FPD, BBC’s.

2) 1st pp collisions with transversely polarized beams in run 2 ⇒ large analyzing power in hard scattering at $\sqrt{s} = 200$ GeV. Additional data on $A_N^{\text{fwd. } \pi^0}$ in run 3, including correlations with midrapidity tracks, negative Feynman-x spin asymmetry.

3) 1st pp collisions with longitudinally polarized beams in run 3 ⇒ begin search for $\Delta G$ sensitivity in jet production.

4) For next ~2 years, STAR spin physics focus on $\Delta G$ via $A_{LL}^{\text{jets}}$ and $A_N^{\text{fwd. } \pi^0}$ vs. Collins angle from jet axis, while $P^4L$ brought to ~design goals.

5) High priority programs on $A_{LL}^{\gamma + \text{jet}}, A_L^{PV}(W^\pm)$ and transversity via mid-rapidity jet fragmentation likely to take rest of decade to complete.
The STAR Collaboration

~ 500 collaborators
48 institutions
12 countries

Note strong new STAR spin interest from:
CalTech, LBNL, MIT, Valparaiso U., Zagreb

Brazil: Sao Paolo
China: IHEP-Beijing, IMP-Lanzhou, Shanghai INR, Tsinghua, USTC, IPP-Wuhan
Croatia: Zagreb
Czech Republic: Nuclear Physics Institute-AS-CR
England: Birmingham
France: IReS - Strasbourg, SUBATECH-Nantes
Germany: Frankfurt, MPI-Munich
India: Bhubaneswar, Jammu, IIT, Panjab, Rajasthan, VECC-Kolkata
Netherlands: NIKHEF
Poland: Warsaw U. of Technology
Russia: JINR - Dubna, IHEP – Protvino, MEPHI - Moscow
U.S.: Argonne, Berkeley, Brookhaven National Laboratories
UC Berkeley, UC Davis, UCLA, CalTech, Creighton, Carnegie-Mellon, Indiana, Kent State, MIT, Michigan State, CCNY, Ohio State, Penn State, Purdue, Rice, Texas, Texas A&M, Valparaiso, Washington, Wayne State, Yale Universities