Recent results and Future perspectives of the STAR high-energy polarized proton-proton program at RHIC

Bernd Surrow
Outline

- Collider
- Theoretical foundation
- Experiment
- Highlights of recent results and achievements
- Future polarized p-p physics program - FGT project
- Summary and Outlook
How do we probe the structure and dynamics of matter in ep / pp scattering?

\[ d\sigma_{ep} \propto F_2 = \sum_q x e_q^2 f_q(x) \]

\[ W^2 \approx Q^2 / x \]

**Momentum contribution**

\[ f(x) = f^+(x) + f^-(x) \]

**Spin contribution**

\[ \Delta f(x) = f^+(x) - f^-(x) \]

**Universality**

**Factorization**

Theoretical foundation
What do we know about the polarized quark and gluon distributions?

Spin carried by quarks is very small ($\Delta \Sigma \sim 0.4$!)

\[
\frac{1}{2} \Delta \Sigma = \langle S_q \rangle + \langle S_g \rangle + \langle L_q \rangle + \langle L_g \rangle
\]

\[
\Delta \Sigma = \Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s}
\]

Theoretical foundation

\[
\Delta q_i(Q^2) = \int_0^1 \Delta q_i(x, Q^2) dx
\]

\[
\Delta G(Q^2) = \int_0^1 \Delta g(x, Q^2) dx
\]


STAR India Collaboration Meeting at VECC
Kolkata, India, November 24, 2008

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Gluon polarization - Extraction

\[ \Delta G(Q^2) = \int_0^1 \Delta g(x, Q^2) dx \]

Extract \( \Delta g(x, Q^2) \) through Global Fit (Higher Order QCD analysis)!

\[ A_{LL} = \frac{d\Delta \sigma}{d\sigma} \]

\[ \Delta f_1 \otimes \Delta f_2 \otimes \sigma_h \cdot a_{LL} \otimes D_f^h \]

\[ \propto f_1 \otimes f_2 \otimes \sigma_h \otimes D_f^h \]

Input

\[ a_{LL} = \frac{\Delta \sigma_h}{\sigma_h} \]
Theoretical foundation

- **What is required experimentally to measure the gluon spin contribution?**

  - **Double longitudinal-spin asymmetry:** 
    \[ A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{P_1 P_2} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}} \]

  - **Study helicity dependent structure functions (Gluon polarization)!**

  - **Require concurrent measurements:**
    - Magnitude of beam polarization, \( P_{1(2)} \)
    - RHIC polarimeters
    - Direction of polarization vector
    - Relative luminosity of bunch crossings with different spin directions
    - Spin dependent yields of process of interest \( N_{ij} \)
    - RHIC polarimeters
    - STAR experiment
**Theoretical foundation**

- **Gluon polarization - Inclusive Measurements**

\[ x_T = \frac{2p_T}{\sqrt{s}} \]
Gluon polarization - Correlation Measurements

Correlation measurements provide access to partonic kinematics through Di-Jet/Hadron production and Photon-Jet production.

\[ x_1(2) = \frac{1}{\sqrt{s}} \left( p_T^3 e^{\eta_3(-\eta_3)} + p_T^4 e^{\eta_4(-\eta_4)} \right) \]

Di-Jet production / Photon-Jet production

- **Di-Jets:** All three (LO) QCD-type processes contribute: gg, qg and qq with relative contribution dependent on topological coverage.
- **Photon-Jet:** One dominant underlying (LO) process with large partonic \( a_{LL} \) at forward rapidity.
- Larger cross-section for di-jet production compared to photon related measurements.
- Photon reconstruction more challenging than jet reconstruction.
- Full NLO framework exists \( \Rightarrow \) Input to Global analysis.
**Theoretical foundation**

- **Quark / Anti-Quark Polarization - W production**

\[
\begin{align*}
\Delta d + \bar{u} & \rightarrow W^- \\
\Delta \bar{u} + d & \rightarrow W^- \\
\Delta \bar{d} + u & \rightarrow W^+ \\
\Delta u + \bar{d} & \rightarrow W^+
\end{align*}
\]

\[
A_L^W = \frac{1}{P} \frac{N^+(W) - N^-(W)}{N^+(W) - N^-(W)}
\]

- **Key signature:** High \( p_T \) lepton (\( e^-/e^+ \) or \( \mu^-/\mu^+ \)) (Max. \( M_W/2 \)) - Selection of \( W^-/W^+ \)

- **W^+:** Charge sign discrimination of high \( p_T \) lepton

- **Required:** Lepton/Hadron discrimination
Theoretical foundation

- Quark / Anti-Quark Polarization - Sensitivity in $W$ production
  - Theoretical framework for leptonic asymmetries exists (RHICBOS) ⇒ Basis for input to global analysis!
  - Reconstruction of $W$-rapidity only possible in approximative way in forward direction
  - Important contribution from forward and mid-rapidity region

$$A_L^{W^-} = -\frac{\Delta d(x_1)\bar{u}(x_2) - \Delta \bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)}$$

$$x_1 = \frac{M_W}{\sqrt{s}} e^{yw} \quad x_2 = \frac{M_W}{\sqrt{s}} e^{-yw}$$

- Large uncertainties for polarized anti-quarks reflected in leptonic asymmetries!
Overview of collider complex

Collider: The First polarized p+p collider at BNL

$L_{\text{max}} = 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$

70% Beam Polarization

$50 < \sqrt{s} < 500 \text{ GeV}$
Collider: The First polarized p+p collider at BNL

RHIC collider aspects: p-p - Performance

- All RHIC polarized pp accelerator components are in place!
- 2006 performance (√s=200GeV): ~60% polarization (70% design) and ~1pb⁻¹/day (~3pb⁻¹/day design) delivered luminosity

<table>
<thead>
<tr>
<th>RHIC RUN</th>
<th>s [GeV]</th>
<th>(L_{\text{recorded}}) [pb⁻¹] (transverse)</th>
<th>(L_{\text{recorded}}) [pb⁻¹] (longitudinal)</th>
<th>Polarization [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>RUN 2</td>
<td>200</td>
<td>0.15</td>
<td>0.3</td>
<td>15</td>
</tr>
<tr>
<td>RUN 3</td>
<td>200</td>
<td>0.25</td>
<td>0.3</td>
<td>30</td>
</tr>
<tr>
<td>RUN 4</td>
<td>200</td>
<td>0</td>
<td>0.4</td>
<td>45</td>
</tr>
<tr>
<td>RUN 5</td>
<td>200</td>
<td>0.4</td>
<td>3.1</td>
<td>50</td>
</tr>
<tr>
<td>RUN 6</td>
<td>200</td>
<td>3.4/6.8</td>
<td>8.5</td>
<td>60</td>
</tr>
</tbody>
</table>
The STAR Experiment

- **Overview**
  - Wide rapidity coverage of STAR calorimetry (Jets / Neutral Pions / Photons) system:
    - FPD: -4.1 < \( \eta \) < 3.3
    - BEMC: -1.0 < \( \eta \) < 1.0
    - EEMC: 1.09 < \( \eta \) < 2.0
    - FMS: 2.5 < \( \eta \) < 4.0

- **Key elements for STAR \( \Delta g(x) \) program:**
  - Higher precision on \( \Delta g(x) \): Luminosity / DAQ upgrade (DAQ 1000)
  - Sensitivity to shape of \( \Delta g(x) \): Correlation measurements
  - Low-x region of \( \Delta g(x) \): 500GeV program / Asymmetric collisions (Forward calorimetry)

- **TPC:** Tracking and PID using dE/dx for |\( \eta \)| < 1.3 and \( p_T < 15 \text{ GeV}/c \)
Highlights of recent results and achievements

- STAR Run 5 Cross-section results: Mid-rapidity charged and neutral pion production

- Sophisticated TPC (dE/dx) calibrations improve precision at high $p_T$ (arXiv:0807.4303-physics)

- Good agreement between data and NLO calculations for charged and neutral pion production
Highlights of recent results and achievements

- STAR Run 3/4 Cross-section results: Mid-rapidity Jet and Prompt Photon production

- Good agreement between data and NLO calculations for jet production and prompt photon production at central rapidity.
Highlights of recent results and achievements

Gluon polarization - Inclusive Measurements

- Examine wide range in $\Delta g$: $-g < \Delta g < +g$
- GRSV-STD: Higher order QCD analysis of polarized DIS experiments!

\[ \Delta G(Q^2) = \int_0^1 \Delta g(x, Q^2) dx \]

$\Delta G(Q^2 = 1 \text{GeV}^2) \approx 1.8$
$\Delta G(Q^2 = 10 \text{GeV}^2) \approx 0.4$

$x_{\text{parton}} \approx 2p_T/\sqrt{s}$
Highlights of recent results and achievements

- **STAR Run 5 / 6** $A_{LL}$ result: Mid-rapidity neutral pion production

\[
\Delta G(Q^2) = \int_0^1 \Delta g(x, Q^2) \, dx
\]

- **RUN 6 results**: GRSV-MAX ruled out

- Significant increase in statistical precision as well as greater $p_T$ reach compared to previous Run 5 Neutral Pion result

<table>
<thead>
<tr>
<th>$p_T$ range [GeV/c]</th>
<th>$A_{LL} \pm$ Stat. $\pm$ Sys.</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.2 - 6.75</td>
<td>0.0080 $\pm$ 0.0115 $\pm$ 0.002</td>
</tr>
<tr>
<td>6.75 - 8.25</td>
<td>0.0058 $\pm$ 0.0136 $\pm$ 0.004</td>
</tr>
<tr>
<td>8.25 - 10.5</td>
<td>0.0203 $\pm$ 0.0189 $\pm$ 0.004</td>
</tr>
<tr>
<td>10.5 - 16.0</td>
<td>-0.0084 $\pm$ 0.0306 $\pm$ 0.002</td>
</tr>
</tbody>
</table>
Highlights of recent results and achievements

- STAR Run 6 $A_{LL}$ result: Forward rapidity (FPD/EEMC) neutral pion production

- First $A_{LL}$ measurements at forward rapidity (STAR EEMC / STAR FPD)

- Probe small-$x$ region (Probe smaller $\Delta g(x) \Rightarrow$ Smaller $A_{LL}$ consistent with theoretical predictions)

- Important baseline measurements for STAR inclusive $\gamma$ and $\gamma$-jet program
Highlights of recent results and achievements

- STAR Run 6 $A_{LL}$ result: Mid-rapidity charged pion production

- Significant improvements compared to Run 5:
  - $50% \Rightarrow 60%$ beam polarization
  - $1.6 \text{ pb}^{-1} \Rightarrow 5.4 \text{ pb}^{-1}$
  - BEMC $\eta$ acceptance $[0,1] \Rightarrow [-1,1]$

- But ... increased JP trigger thresholds result in strong fragmentation bias for charged pions in trigger jet

  - Limit bias by measuring charged pions opposite a trigger jet
  - Plot asymmetry versus $z = p_T(\pi) / p_T(\text{trigger jet})$ to cleanly isolate favored fragmentation
Highlights of recent results and achievements

- STAR Run 6 $A_{LL}$ result: Mid-rapidity charged pion production

Conservative systematic uncertainties are evaluated for:

- Trigger bias: $6 - 15 \times 10^{-3}$
- PID background contamination: $2 - 10 \times 10^{-3}$
- Uncertainty on the jet $p_T$ shift: $3 - 16 \times 10^{-3}$
- Non-longitudinal components, relative luminosity: small

8.3% pol. uncertainty not included
Highlights of recent results and achievements

- STAR Run 6 $A_{\mathrm{LL}}$ result: Mid-rapidity charged pion production

- Full NLO pQCD predictions are not yet available for this measurement, but started!
- These curves generated by sampling $a_{\mathrm{LL}}$ and parton distribution functions at kinematics of PYTHIA event.
- $\pi^+$ offers significant sensitivity at high $z$
Highlights of recent results and achievements

- $A_{LL}$ Inclusive Jet 2005 result - STAR

\[ \Delta G(Q^2) = \int_{0}^{1} \Delta g(x, Q^2) dx \]

\[ \Delta G(Q^2 = 1 GeV^2) \approx 1.8 \]

\[ \Delta G(Q^2 = 1 GeV^2) \approx 0.4 \]

\[ \Delta G(Q^2 = 1 GeV^2) \approx 1.0 \]

- Maximum gluon polarization scenario (GRSV-MAX) ruled out

- $A_{LL}$ inclusive jet result (Run 5) consistent with previous Run 3/4 result

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STAR Collaboration, PRL 100, 232003 (2008).

# Highlights of recent results and achievements

- **$A_{LL}$ Inclusive Jet 2006 result - STAR**

![Graph showing $A_{LL}$ vs. $p_T$](image)

- **RUN 6 results:** GRSV-MAX / GRSV-MIN ruled out - $A_{LL}$ result favor a gluon polarization in the measured $x$-region which falls in-between GRSV-STD and GRSV-ZERO

- **Consistent with RUN 5 result** (Factor 3-4 improved statistical precision for $p_T$ > 13 GeV/c)

## Systematics

<table>
<thead>
<tr>
<th>Category</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{LL}$ systematics</td>
<td>$(x 10^{-3})$</td>
</tr>
<tr>
<td>Reconstruction + Trigger Bias</td>
<td>[-1,+3] (p_T dep)</td>
</tr>
<tr>
<td>Non-longitudinal Polarization</td>
<td>$\sim 0.03$ (p_T dep)</td>
</tr>
<tr>
<td>Relative Luminosity</td>
<td>0.94</td>
</tr>
</tbody>
</table>
| Backgrounds                     | 1<sup>st</sup> bin $\sim 0.5$  
else $\sim 0.1$                        |
| $p_T$ systematic                | $\pm 6.7\%$                     |
Highlights of recent results and achievements

- Quantify theory comparison of measured $A_{LL}$ for 2006 inclusive jet result

- The STAR data exclude a broad range of global fit results that have a larger first moment ($\Delta G$) than that in GRSV-STD

- Counterexample is GS-C: Large and positive at low $x$ and negative at high $x$ (Note at $x \sim 0.1$)
Highlights of recent results and achievements

- Global analysis incl. RHIC pp data

- Strong constraint on the size of $\Delta g$ from RHIC data for 0.05 < $x$ < 0.2

- Evidence for a small gluon polarization over a limited region of momentum fraction

- Important: Mapping $x$-dependence and extension of $x$-coverage needed!

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Future polarized p-p physics program - FGT

- Quark / Anti-Quark polarization program at STAR

**Forward GEM Tracker: FGT**

- Charge sign identification for high momentum electrons from $W^\pm$ decay (Energy determined with EEMC)

- Triple-GEM technology

- FGT project:
  - ANL, IUCF, LBL, MIT, MPI Munich, University of Kentucky, Valparaiso University, Yale

- Successful project review (Capital equipment funding): January 2008

- Expected installation: Summer 2010
Future polarized p-p physics program - FGT

- Layout

- FGT: 6 light-weight triple-GEM disks - WEST side of STAR

- New mechanical support structure
Future polarized p-p physics program - FGT

- Quark / Anti-Quark polarization program at STAR - e/h separation
  - Full PYTHIA QCD background and W signal sample including detector effects
    - e/h separation based on global cuts (isolation/missing $E_T$) and EEMC specific cuts as
    - With current algorithm: $E_T > 25\text{GeV}$ yields $S/B > 1$ (For $E_T < 25\text{GeV}$ $S/B \sim 1/5$) used for $A_L$ uncertainty estimates
Future polarized p-p physics program - FGT

- Quark / Anti-Quark polarization program at STAR - $e^+/e^-$ separation

**Conclusion:**

Charge sign reconstruction impossible beyond $\eta = \sim 1.3$

![Graph showing reach of EEMC Acceptance](image)

TPC + FGT Tracking, $p_T = 30$ GeV/c

6 triple-GEM disks, assumed spatial resolution 60µm in $x$ and $y$ (Fairly insensitive for 60-100µm)

Charge sign reconstruction probability above 90% for 30 GeV $p_T$ over the full acceptance of the EEMC for the full vertex spread
Quark / Anti-Quark polarization program at STAR (Forward rapidity)

- Large asymmetries dominated by quark polarization - Important consistency check to existing DIS data with 100pb\(^{-1}\) (Phase I)

- Strong impact constraining unknown antiquark polarization requires luminosity sample at the level of 300pb\(^{-1}\) for 70% beam polarization (Phase II)
Future polarized p-p physics program

- Quark / Anti-Quark polarization program at STAR (Mid-rapidity)

- Polarization = 50%
- Luminosity: 10pb$^{-1}$

- 500 GeV running in Run 9 focus at mid-rapidity integrated [-1,+1]
- Demonstrate W production at mid-rapidity and first $A_L$ measurement at STAR

STAR projections for LT=10pb$^{-1}$, Pol=0.5, effi=70%, including QCD background, 2 beams, no vertex cut

$A_L(W^\pm)$ for positron $|\eta| < 1$
Future polarized p-p physics program - FGT

GEM technology

- Example: Triple-GEM application at COMPASS
- Advantages:
  - Reliable (COMPASS, multi-year experience)
  - High gas amplification (Multiple GEMs: up to \( \sim 10^6 \))
  - Fast (\(< 20\) ns FWHM, rate capability up to \(10^5\) Hz/mm)
  - Low mass (50\(\mu\)m Kapton + 10\(\mu\)m Cu; Thin low Z read-out plane)
  - Good spatial resolution (1D and 2D) (~60\(\mu\)m)
  - Simple construction and in-expensive

Standard layout:
- Pitch (P) 140 \(\mu\)m
- Outer diameter (D) 70 \(\mu\)m
- Inner diameter (d) 50 \(\mu\)m

Future polarized p-p physics program - FGT

- **GEM technology development**
  - SBIR proposal (Phase I/II):
    - Established commercial GEM foil source (Tech-Etch Inc.)
  - FNAL testbeam of three prototype triple-GEM chambers including APV25 chip readout
  - Performance meets requirements!
  - Good charge sharing!

- Image of residual Det1 X [mm] with fitted Gaussian function and Landau distribution with MPV and σ.
- Image of correlation plot of Det0 amplitude vs. Det1 amplitude with Kapton thickness label.

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Future polarized p-p physics program - FGT

- Mechanical design

- FGT: 6 light-weight disks
- Each disk consists of 4 triple-GEM chambers (Quarter sections)
- Procurement and assembly of full quarter section prototype in preparation
Future polarized p-p physics program - FGT

Triple-GEM detectors - Quarter section

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Radiation Length [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Support plate</td>
<td>5 mm Nomex</td>
<td>0.040</td>
</tr>
<tr>
<td></td>
<td>2x250 μm FR4</td>
<td>0.257</td>
</tr>
<tr>
<td>HV layer</td>
<td>5 μm Cu</td>
<td>0.035</td>
</tr>
<tr>
<td></td>
<td>50 μm Kapton</td>
<td>0.017</td>
</tr>
<tr>
<td>GEM foils</td>
<td>6x5 μm Cu (70%)</td>
<td>0.147</td>
</tr>
<tr>
<td></td>
<td>3x50 μm Kapton (70%)</td>
<td>0.036</td>
</tr>
<tr>
<td>Readout</td>
<td>5 μm Cu (20%)</td>
<td>0.007</td>
</tr>
<tr>
<td></td>
<td>50 μm Kapton (20%)</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td>5 μm Cu (88%)</td>
<td>0.031</td>
</tr>
<tr>
<td></td>
<td>50 μm Kapton</td>
<td>0.017</td>
</tr>
<tr>
<td></td>
<td>5 μm Cu (10%)</td>
<td>0.004</td>
</tr>
<tr>
<td></td>
<td>0.125 mm FR4</td>
<td>0.064</td>
</tr>
<tr>
<td>Drift gas</td>
<td>10 mm CO₂ (30%)</td>
<td>0.002</td>
</tr>
<tr>
<td></td>
<td>10 mm Ar (70%)</td>
<td>0.006</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>0.670</strong></td>
</tr>
</tbody>
</table>

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Future polarized p-p physics program - FGT

- 2D readout board and Front-End Electronics
Goal: Installation in summer 2010 ⇒ Ready for anticipated first long 500GeV polarized pp run in FY11 consistent with STAR 5-year Beam Use Request

Review: Successful review January 2008 / Beginning of construction funds FY08

Cost estimate and planning relies on the R&D and pre-design work:

- **Triple-GEM Detector**: Complete prototype tested on the bench and during FNAL testbeam experiment with extensive experience in mechanical design work (MIT-Bates) and assembly including previous experience at COMPASS

- **Front-End Electronics (FEE) System**: Complete prototype tested on the bench and during FNAL testbeam experiment based on existing APV25-S1 readout chip (MIT-Bates)

- **Data Acquisition (DAQ) System**: Conceptual layout is based on similar DAQ sub-detector systems with extensive experience (ANL/IUCF)

- **GEM foil development**: Successful development of industrially produced GEM foils through SBIR proposal in collaboration with Tech-Etch Inc. (BNL, MIT, Yale University)
Summary and Outlook

- **Summary - RHIC-SPIN**
  - Successful polarized proton collisions at high energies at RHIC at Brookhaven National Laboratory
  - **QCD**: Critical role to interpret measured asymmetries - First global analysis
  - **Strong constraint** on the size of $\Delta g$ from RHIC data for $0.05 < x < 0.2$
  - Evidence for a small gluon polarization over a limited region of momentum fraction ($0.05 < x < 0.2$)
  - Important: Mapping $x$-dependence and extension of $x$-coverage needed - Critical to reduce large uncertainties on first moment of $\Delta g$
  - Next critical step: Improved precision and Measurements to constrain shape of $\Delta g$ (Di-Jet production and Photon-Jet production)
### Summary and Outlook

**Outlook - RHIC SPIN**

- **Three key elements:**
  - Gluon polarization
  - Quark / Anti-Quark Polarization
  - Transverse spin dynamics

- **Critical:**
  - Beam polarization: 70% / Narrow vertex region / Spin flipper for high precision asymmetry measurements
  - Critical: Sufficient running time!

<table>
<thead>
<tr>
<th>Recorded Luminosity</th>
<th>Main physics Objective</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>~50pb⁻¹</td>
<td>Gluon polarization using di-jets and precision inclusive measurements</td>
<td>200 GeV</td>
</tr>
<tr>
<td>~100pb⁻¹</td>
<td>W production (Important consistency check to DIS results - Phase I) Gluon polarization (Di-Jets / Photon-Jets)</td>
<td>500 GeV</td>
</tr>
<tr>
<td>~300pb⁻¹</td>
<td>W production (Constrain antiquark polarization - Phase II) Gluon polarization (Di-Jets / Photon-Jets)</td>
<td>500 GeV</td>
</tr>
<tr>
<td>~30pb⁻¹</td>
<td>Transverse spin gamma-jet</td>
<td>200 GeV</td>
</tr>
<tr>
<td>~250pb⁻¹</td>
<td>Transverse spin Drell-Yan (Long term)</td>
<td>200 GeV</td>
</tr>
</tbody>
</table>

Critical: Sufficient running time!