The RHIC Spin Program

I would like to thank Les Bland, Werner Vogelsang, Abhay Deshpande, Sasha Bazilevsky, Matthias Grosse Perdekamp, for their advice and many plots.
RHIC Spin Outline

The key points for RHIC Spin are:

- Spin structure of proton
- Strongly interacting probes
  
- $P=60\%, \ L=2\times10^{31}, \ \text{root}(s)=200$ GeV in 2006
- Polarized atomic H jet: absolute $P$, pp elastic physics
- Very forward n asymmetry
  
- Cross sections for $\pi^0$, jet, direct photon described by $pQCD$—include new result for low $p_T$ region

- Helicity asymmetries: sensitivity to gluon spin contribution to proton

- Photon+jet: gluon pol. vs. $x_{\text{gluon}}$

- W boson parity violating production: ubar and dbar polarizations in proton

- Very large transverse spin asymmetries in $pQCD$ region

- Future: transverse spin Drell-Yan
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- **Future: transverse spin Drell-Yan**
EMC at CERN: J. Ashman et al., NPB 328, 1 (1989): polarized muons probing polarized protons

\[ \Delta \Sigma = \Delta u + \Delta d + \Delta s = 12 \pm 9 \text{(stat)} \pm 14 \text{(syst)}\% \]  

“proton spin crisis”
• What else carries the proton spin?

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g \]

→ How are gluons polarized?
→ How large are parton orbital angular mom.?

• What are the detailed patterns of quark & antiquark polarizations?
  → Flavor asymmetries in sea? Strangeness?

• What are the origins of large observed single-transverse-spin asymmetries?
What do they tell us about the nucleon?
  → Transverse quark pol.? Correlations spin / parton k_T?
    Orbital angular momentum? Spatial distributions?
Probing the spin structure of the nucleon in polarized pp collisions

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Dom. partonic process</th>
<th>probes</th>
<th>LO Feynman diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p\bar{p} \rightarrow \pi + X$</td>
<td>$\bar{q}q \rightarrow gg$</td>
<td>$\Delta g$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\bar{q}\bar{q} \rightarrow gg$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow \text{jet(s)} + X$</td>
<td>$\bar{q}q \rightarrow gg$</td>
<td>$\Delta g$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\bar{q}\bar{q} \rightarrow gg$</td>
<td>(as above)</td>
<td></td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow \gamma + X$</td>
<td>$\bar{q}q \rightarrow \gamma q$</td>
<td>$\Delta g$</td>
<td></td>
</tr>
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<td>$p\bar{p} \rightarrow \gamma + \text{jet} + X$</td>
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<td>$\Delta g$</td>
<td></td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow \gamma\gamma + X$</td>
<td>$\bar{q}\bar{q} \rightarrow \gamma\gamma$</td>
<td>$\Delta q, \Delta \bar{q}$</td>
<td></td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow DX, BX$</td>
<td>$\bar{q}q \rightarrow c\bar{c}, b\bar{b}$</td>
<td>$\Delta g$</td>
<td></td>
</tr>
<tr>
<td>$p\bar{p} \rightarrow \mu^+\mu^- X$</td>
<td>$\bar{q}\bar{q} \rightarrow \gamma^* \rightarrow \mu^+\mu^-$</td>
<td>$\Delta q, \Delta \bar{q}$</td>
<td></td>
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(Drell-Yan)
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- Future: transverse spin Drell-Yan
RHIC Polarized Collider

2006: 1 MHz collision rate; P=0.6
<table>
<thead>
<tr>
<th>Year</th>
<th>P</th>
<th>L(pb^{-1})</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>15%</td>
<td>0.15</td>
<td>first pol. pp collisions! disc. large n asymmetry</td>
</tr>
<tr>
<td>2003</td>
<td>30%</td>
<td>1.6</td>
<td>pi^0, photon cross section, A_LL(pi^0), 3 PRLs</td>
</tr>
<tr>
<td>2004</td>
<td>40%</td>
<td>3.0</td>
<td>polarized hydrogen jet, PLB</td>
</tr>
<tr>
<td>2005</td>
<td>50%</td>
<td>13</td>
<td>warm snake (RIKEN); large (P^4 x L = 0.8) gluon pol. ruled out</td>
</tr>
<tr>
<td>2006</td>
<td>60%</td>
<td>46</td>
<td>cold snake; first long spin run (prelim. to Kyoto)</td>
</tr>
</tbody>
</table>

(P^4 x L = 6)
RHIC Polarimetry

\[ P_{Beam} = P_{Jet} \times \frac{\epsilon_{Beam}}{\epsilon_{Jet}} \]

where \( \epsilon = \frac{N_{up} - N_{down}}{N_{up} + N_{down}} \)
Recoil Silicon Strip Spectrometer

For p-p elastic scattering only:

\[ \varepsilon = \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}} \]

\[ \varepsilon_{\text{beam}} = A_N \cdot P_{\text{beam}} \]

\[ \varepsilon_{\text{target}} = -A_N \cdot P_{\text{target}} \]

\[ P_{\text{beam}} = -\frac{\varepsilon_{\text{beam}}}{\varepsilon_{\text{target}}} \cdot P_{\text{target}} \]
Example of background for one recoil energy slice:

Yield (up / down)

E = 1.0–1.5 MeV
$A_N$ in the CNI region @ $\sqrt{s}=13.7$ GeV

$A_N \approx -\text{Im} \left( \phi_5^{em*} \phi_+^{had} + \phi_5^{had*} \phi_+^{em} \right) / |\phi_+|^2$

One photon exchange contribution!

2004 Data

H. Okada et al., PLB 638 (2006), 450-454
$A_N$ and $r_5$ results at $\sqrt{s}= 6.9$ GeV

- $r_5$ is not zero at $\sqrt{s}= 6.9$ GeV! $\chi^2/\text{ndf} = 35.5/9$

- $r_5$ has $\sqrt{s}$ dependence? $\Rightarrow$ Not improbable; theoretical prediction using $A_N^{p^c} @24\text{GeV}/c$, $100\text{GeV}/c$ and $A_N @100\text{GeV}/c$. 

Set $r_5$ as free parameter

$\Rightarrow$ Im $r_5 = -0.152 \pm 0.014$
$\Rightarrow$ Re $r_5 = -0.045 \pm 0.038$
$\Rightarrow$ $\chi^2/\text{ndf} = 2.87/7$

$r_5 = \frac{m_p \phi_{5}^{\text{had}}}{\sqrt{-t} \text{ Im } \phi_{5}^{\text{had}}}$
$A_N$ collection in the CNI region

$P_{beam} = 24$ GeV/$c$

$A_N^{pp}$

$|r_5| = 0$

preliminary

$P_{beam} = 100$ GeV/$c$

$P_{beam} = 21.7$ GeV/$c$

J. Tojo et al.

$A_N^{pC}$

$|r_5| = 0$

$\Rightarrow$ see talk by I. Alekseev

preliminary

$P_{beam} = 100$ GeV/$c$

O. Jinnouchi et al.
Polarization Measurements
2006 Run

Polarization (Blue) [Fill#7537 - 7872]

Polarization [%]

Online
Offline

Fill Number
Very forward neutron asymmetry from p-p collisions at RHIC-PHENIX

Manabu Togawa (Kyoto Spin06)
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PHENIX and STAR

PHENIX:
High rate capability
High granularity
Good mass resolution and PID
Limited acceptance

STAR:
Large acceptance with azimuthal symmetry
Good tracking and PID
Central and forward calorimetry
Cornerstones to the RHIC Spin program

Mid-rapidity: PHENIX

\[ pp \rightarrow \pi^0 X \]

Forward: STAR

To appear PRD Rapid, hep-ex-0704.3599

PRL 97, 152302 (2006)
And Jets and Direct $\gamma$

$pp \rightarrow$ jet $X$ : STAR

$pp \rightarrow \gamma X$ : PHENIX

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**Figure (a):**

$\frac{1}{2\pi} \frac{d^2\sigma}{d^2p_T}$ (pb/GeV)

- STAR
- $p+p \rightarrow$ jet + X
- $\sqrt{s} = 200$ GeV
- midpoint-cone
- $0.2 < \eta < 0.8$

- Combined MB
- Combined HT
- NLO QCD (Vogelsang)

**Figure (b):**

$E d^2\sigma/dp_T^2$ (pb GeV$^{-2}$ cm$^{-2}$)

- PHENIX Data (by W. Vogelsang)
- CTEQ 6M PDF
- BFGII FF
- $\mu = \frac{1}{2} p_T, p_T, 2p_T$

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PRL 97, 252001 (2006)

PRL 98, 012002 (2007)
From soft to hard

Exponent \( e^{-\alpha p_T} \) describes our pion cross section data perfectly well at \( p_T < \sim 1 \text{ GeV/c} \) (dominated by soft physics):

\[
\alpha = 5.56 \pm 0.02 \text{ (GeV/c)}^{-1}
\]

\[
\chi^2/\text{NDF} = 6.2/3
\]

Assume that exponent describes soft physics contribution also at higher \( p_T \)s \( \Rightarrow \) soft physics contribution at \( p_T > 2 \text{ GeV/c} \) is <10%

For \( \Delta G \) constraint use pi0 A_{LL} data at \( p_T > 2 \text{ GeV/c} \)
Probing $\Delta G$ in pp Collisions

Double longitudinal spin asymmetry $A_{LL}$ is sensitive to $\Delta G$
Measuring $A_{LL}$

$$A_{LL} = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}} = \frac{1}{P_1 P_2} \frac{N_{++} - RN_{+-}}{N_{++} - RN_{+-}}; \quad R = \frac{L_{++}}{L_{+-}}$$

(N) Yield
(R) Relative Luminosity
✓ BBC vs ZDC
(P) Polarization
✓ RHIC Polarimeter (at 12 o’clock)
✓ Local Polarimeters (SMD&ZDC in PHENIX and BBC in STAR)

✓ Bunch spin configuration alternates every 106 ns
✓ Data for all bunch spin configurations are collected at the same time

⇒ Possibility for false asymmetries are greatly reduced
\( A_{LL} : \text{jets} \)

STAR Preliminary Run5 (\( \sqrt{s}=200 \text{ GeV} \))

GRSV Models:

- “\( \Delta G = G \)”: \( \Delta G(Q^2=1\text{GeV}^2)=1.9 \)
- “\( \Delta G = -G \)”: \( \Delta G(Q^2=1\text{GeV}^2)=-1.8 \)
- “\( \Delta G = 0 \)”: \( \Delta G(Q^2=1\text{GeV}^2)=0.1 \)
- “\( \Delta G = \text{std} \)”: \( \Delta G(Q^2=1\text{GeV}^2)=0.4 \)

Large gluon polarization scenario is not consistent with data

\( \rightarrow \) J. Dunlop, next talk

Run3&4: PRL 97, 252001
GRSV model:

“$\Delta G = 0$”: $\Delta G(Q^2=1\text{GeV}^2)=0.1$

“$\Delta G = \text{std}$”: $\Delta G(Q^2=1\text{GeV}^2)=0.4$

Stat. uncertainties are on level to distinguish “std” and “0” scenarios? …

Run3,4,5: PRL 93, 202002; PRD 73, 091102; hep-ex-0704.3599
From $p_T$ to $x_{gluon}$

NLO pQCD: $\pi^0$ $p_T=2-9$ GeV/c $\rightarrow$ $x_{gluon}=0.02-0.3$

- GRSV model: $\Delta G(x_{gluon}=0.02\rightarrow0.3) \sim 0.6 \cdot \Delta G(x_{gluon}=0\rightarrow1)$

Each $p_T$ bin corresponds to a wide range in $x_{gluon}$, heavily overlapping with other $p_T$ bins

- These data is not much sensitive to variation of $\Delta G(x_{gluon})$ within our x range
- Any quantitative analysis should assume some $\Delta G(x_{gluon})$ shape
From $A_{LL}$ to $\Delta G$ (with GRSV)

Calc. by W. Vogelsang and M. Stratmann

$\chi^2$ (std) $- \chi^2_{\text{min}} > 9$

- Only exp. stat. uncertainties are included
  (the effect of syst. uncertainties is expected to be small in the final results)
- Theoretical uncertainties are not included

"std" scenario, $\Delta G(Q^2=1\text{GeV}^2)=0.4$, is excluded by data on >3 sigma level:

Only theoretical uncertainties included
Extending x range is crucial!

Gehrmann-Stirling models

- **GSC**: \[\Delta G(x_{\text{gluon}} = 0 \rightarrow 1) = 1\]
  \[\Delta G(x_{\text{gluon}} = 0.02 \rightarrow 0.3) \sim 0\]

- **GRSV-0**: \[\Delta G(x_{\text{gluon}} = 0 \rightarrow 1) = 0\]
  \[\Delta G(x_{\text{gluon}} = 0.02 \rightarrow 0.3) \sim 0\]

- **GRSV-std**: \[\Delta G(x_{\text{gluon}} = 0 \rightarrow 1) = 0.4\]
  \[\Delta G(x_{\text{gluon}} = 0.02 \rightarrow 0.3) \sim 0.25\]

Current data is sensitive to \(\Delta G\) for \(x_{\text{gluon}} = 0.02 \rightarrow 0.3\)
$pp \rightarrow \gamma + \text{jet}$

Simulation for STAR by Les Bland

Parton kinematics is well constrained, event-by-event

Lower x data provided by $\sqrt{s}=500$ GeV data is essential for reducing extrapolation (to lower x) errors

→ see next talk, J. Dunlop
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**Δq-Δq at RHIC via W production**

\[ Δd + \bar{u} \rightarrow W^- \]

\[ Δ\bar{u} + d \rightarrow W^- \]

\[ Δ\bar{d} + u \rightarrow W^+ \]

\[ Δu + \bar{d} \rightarrow W^+ \]

\[ A_L = \frac{σ_+ - σ_-}{σ_+ + σ_-} \]

**Expected start: 2009**

**Graph:**
- RHIC pp $\sqrt{s} = 500$ GeV
- \[ \int L dt = 800 \text{ pb}^{-1} \]
- $A_L (W^+)$
- $A_L (W^-)$
- $Δu/u$
- $Δ\bar{d}/\bar{d}$
- $Q^2 = M_W^2$
- GS95LO(A)
- BS(Δg=0)
Transverse spin: pion $A_N$
--very large forward asymmetries

$A_N(\pi)$ at 62 GeV

STAR
→ see next talk, J. Dunlop

Left:
$$A_N = \frac{N_{\text{forward}} - N_{\text{backward}}}{N_{\text{forward}} + N_{\text{backward}}}$$

$\rho+p \rightarrow \pi^0 + X$ at $\sqrt{s}=200$ GeV

Run6 $<\eta>=3.7$ PRELIMINARY
Run3+Run5 $<\eta>=3.7$

Right:
$$A_N(x_F)$$

BRAHMS Preliminary
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A Fundamental Test of Universality: Transverse Spin Drell Yan at RHIC vs Sivers Asymmetry in Deep Inelastic Scattering

• Important test at RHIC of recent fundamental QCD predictions for the Sivers effect, demonstrating… attractive vs repulsive color charge forces

• Possible access to quark orbital angular momentum

• Latest development from DIS: first direct evidence of Sivers and Collins effects (recent new results at DIS 2007 in München, April 2007, HERMES, Diefenthaler et al.)

• Requires very high luminosity (RHIC II)

• Both STAR and PHENIX can make important, exciting, measurements

• Discussion available at http://spin.riken.bnl.gov/rsc/
Attractive vs Repulsive Sivers Effects
Unique Prediction of Gauge Theory!

Simple QED example:

DIS: attractive
Drell-Yan: repulsive

Same in QCD:

As a result:
\[ \text{Sivers}_{\text{DIS}} = -\text{Sivers}_{\text{DY}} \]
Experiment SIDIS vs Drell Yan: $Sivers_{\text{DIS}} = -Sivers_{\text{DY}}$

*** Probes QCD attraction and QCD repulsion ***

HERMES Sivers Results

RHIC II Drell Yan Projections

Markus Diefenthaler
DIS Workshop
Munich, April 2007
Concluding Remarks

• High luminosity and high polarization achieved!

• Delta G: direct photon; global fits with RHIC, DIS; new vertex and forward detectors

• W boson parity violating production: ubar and dbar

• Very strong theoretical support

• Transverse spin renaissance!