Recent PHENIX Results in Longitudinally Polarized Proton Collisions

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Outline:

- Quick Physics overview
- RHIC and PHENIX, and $A_{LL}$
- Run5 and Run6 new Results
Accessing $\Delta G$ in pp scattering

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L \]  
with $\Delta \Sigma \sim 25\%$, $\Delta G$ not well constrained, $L$?

\[ \rightarrow A_{LL} \sim a_{gg} \cdot \Delta G^2 + b_{gq} \cdot \Delta G \, \Delta q + c_{qq} \Delta q^2 \]

- From Run5 and Run6, we are currently studying an array of probes:
  - $\pi^0$  
    large statistics, specified trigger
  - $\pi^+, \pi^-$  
    large statistics, low trigger efficiency, PID only for $p_T<2.8$ and $p_T>4.7$ GeV/c
  - Direct photon  
    low statistics, no $\Delta G^2$ very clean signal
  - $\eta$  
    need FF
  - multiparticle “cone”
  - $J/\Psi$
Measuring $A_{LL}$

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{P_b P_y} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}$$

+ - = Opposite helicity
++ = Same helicity

- Helicity Dependent Particle Yields
  - $\pi^0$, $\pi^+$, $\pi^-$, $\gamma$, $\eta$, etc
- (Local) Polarimetry
- Relative Luminosity ($R = L_{++}/L_{+-}$)
- $A_{LL}$
<table>
<thead>
<tr>
<th>Year</th>
<th>$\sqrt{s}$ [GeV]</th>
<th>Luminosity [pb$^{-1}$] (recorded)</th>
<th>Polarization [%]</th>
<th>Figure of Merit ($P^4L$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>200</td>
<td>0.35</td>
<td>27</td>
<td>0.0019</td>
</tr>
<tr>
<td>2004</td>
<td>200</td>
<td>0.12</td>
<td>40</td>
<td>0.0031</td>
</tr>
<tr>
<td>2005</td>
<td>200</td>
<td>3.4</td>
<td>49</td>
<td>0.20</td>
</tr>
<tr>
<td>2006</td>
<td>200</td>
<td>7.5</td>
<td>62</td>
<td>1.11</td>
</tr>
<tr>
<td>2006</td>
<td>62.4</td>
<td>0.08</td>
<td>48</td>
<td>0.0042</td>
</tr>
</tbody>
</table>

* Longitudinal
PHENIX Detector

\( \pi^0/\gamma/\eta \) detection
- Electromagnetic Calorimeter (PbSc/PbGl):
  - High \( p_T \) photon trigger to collect \( \pi^0 \)'s, \( \eta \)'s, \( \gamma \)'s
  - Acceptance: \(|\eta|<0.35, \phi=2\pi/2\)
  - High granularity (~10*10 mrad\(^2\))

\( \pi^+/\pi^-\)
- Drift Chamber (DC) for Charged Tracks
- Ring Imaging Cherenkov Detector (RICH)
  - High \( p_T \) charged pions (\( p_T > 4.7 \) GeV).

Relative Luminosity
- Beam Beam Counter (BBC)
  - Acceptance: \( 3.0<\eta<3.9 \)
- Zero Degree Calorimeter (ZDC)
  - Acceptance: \( \pm 2 \) mrad

Local Polarimetry
- ZDC
- Shower Maximum Detector (SMD)
Local Polarimetry at PHENIX

- Use ZDC and SMD to measure a L-R and U-D asymmetry in forward neutrons (Acceptance: ±2 mrad).
- When transversely polarized, we see clear asymmetry.
- When longitudinally polarized, there should be no asymmetry.

Idea: Use neutron asymmetry to study transversely polarized component.
Measured Asymmetry During Longitudinal Running (2005)

\[ \chi^2/\text{NDF} = 88.1/97 \]
\[ p_0 = -0.00323 \pm 0.00059 \]

\[ \chi^2/\text{NDF} = 82.5/97 \]
\[ p_0 = 0.00423 \pm 0.00057 \]

\[ S_L = \sqrt{1 - S_T^2} \]
\[ S_T = \sqrt{S_X^2 + S_Y^2} \]

\[ \langle P_T/P \rangle = 10 \pm 2(\%) \]
\[ \langle P_L/P \rangle = 99.48 \pm 0.12 \pm 0.02(\%) \]

\[ \langle P_T/P \rangle = 14 \pm 2(\%) \]
\[ \langle P_L/P \rangle = 98.94 \pm 0.21 \pm 0.04(\%) \]

- Measurement of remaining transverse component → spin pattern is correct

Also confirmed in Run6 analysis
Relative Luminosity

- $R = \frac{L^{++}}{L^{+-}}$; $L$ = luminosity.
- Luminosity is given by the number of BBC triggered events ($N_{\text{BBC}}$).
- For estimate of uncertainty, measure $A_{\text{LL}}$ in the ratio of our two luminosity detectors

$$r(i) = \frac{N_{\text{ZDC}}(i)}{N_{\text{BBC}}(i)}$$

<table>
<thead>
<tr>
<th>Year</th>
<th>[GeV]</th>
<th>$\delta R$</th>
<th>$\delta A_{\text{LL}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005 *</td>
<td>200</td>
<td>1.0e-4</td>
<td>2.3e-4</td>
</tr>
<tr>
<td>2006 *</td>
<td>200</td>
<td>3.9e-4</td>
<td>5.4e-4</td>
</tr>
<tr>
<td>2006 *</td>
<td>62.4</td>
<td>1.3e-3</td>
<td>2.8e-3</td>
</tr>
</tbody>
</table>

* Longitudinal
Strategy:
1. Measure Cross Section to confirm that pQCD is applicable to data
2. Measure $A_{LL}$ to extract $\Delta G$
pQCD works

π⁰ @ 200 GeV

arXiv:0704.3599 [hep-ex]

Direct γ @ 200 GeV

Kieran Boyle

RHIC&AGS User’s Meeting—June 18, 2007
Recent $A_{LL}$ Measurements

PHENIX Preliminary (Run6 + Run5)

Many independent probes to understand gluon spin

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An in depth look at $\pi^0 A_{LL}$
Calculating $\pi^0 A_{LL}$

1. Calculate $A_{LL}(\pi^0+BG)$ and $A_{LL}(BG)$ separately.
2. Get background ratio ($w_{BG}$) from fit of all data.
3. Subtract $A_{LL}(BG)$ from $A_{LL}(\pi^0+BG)$:

$$A_{LL}(\pi^0+BG) = w_{\pi^0} \cdot A_{LL}(\pi^0) + w_{BG} \cdot A_{LL}(BG)$$

**Diphoton Mass Spectrum**

- $\pi^0+BG$ region: ±25 MeV around $\pi^0$ peak
- BG region: two 50 MeV regions around peak
Final Run5 \( \pi^0 \) \( A_{LL} \)

- Data is compared to GRSV model with several input values of \( \Delta G \).
- Question: At what \( p_T \) does soft physics contribution become small enough to allow comparison to pQCD models.

arXiv:0704.3599 [hep-ex]

9.4% scale uncertainty not included

By comparing p0 data with charged pion data, which has very good statistics at low pT, can estimate soft physics contribution.

Fitting an exponential to the low pT charged pion data (pT<1 GeV/c) gives an estimate on the soft physics contribution.

Fit result:
- $\alpha = 5.56 \pm 0.02 \text{ (GeV/c)}^{-1}$
- $\chi^2/\text{NDF} = 6.2/3$

From this, we see that for pT>2 GeV, the soft physics component is down by more than a factor of 10.
Final Run5 $\pi^0$ $A_{LL}$

- Measure below 1 GeV ($\sim$100% soft physics). $A_{LL} = 0.002 \pm 0.002$.
- Above $p_T=2$ GeV/c, soft physics contribution estimated to be <10%.
- Contamination from soft physics asymmetry is small.

Theory

<table>
<thead>
<tr>
<th>Theory</th>
<th>$\chi^2$/NDF</th>
<th>C.L. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRSV-std</td>
<td>10.9/8</td>
<td>20</td>
</tr>
<tr>
<td>GRSV $\Delta G=0$</td>
<td>12.7/8</td>
<td>12</td>
</tr>
<tr>
<td>GRSV $\Delta G=G$</td>
<td>256/8</td>
<td>0.00</td>
</tr>
<tr>
<td>GRSV $\Delta G=-G$</td>
<td>58.4/8</td>
<td>0.00</td>
</tr>
</tbody>
</table>

arXiv:0704.3599 [hep-ex]

9.4% scale uncertainty not included.
Sign Ambiguity

• Dominance of two gluon interaction at low $p_T$ $\Rightarrow$ present $\pi^0$ $A_{LL}$ data cannot determine sign of $\Delta G$.

• Solution:
  – Higher $p_T$ $\Rightarrow$ higher FOM ($P^4L$)
  – Look to other probes:
    • Direct Photon (See Y. Goto, later in this session)
    • Charged pions
Sign Ambiguity II

- With PHENIX RICH, charged pions above 4.7 GeV can be identified.
- At higher $p_T$, $qg$ interactions become dominant and so $\Delta q \Delta g$ term in $A_{LL}$ becomes significant allowing access to the sign of $\Delta G$.
- Expect if $\Delta G > 0$, then: $A_{LL}(\pi^+) > A_{LL}(\pi^0) > A_{LL}(\pi^-)$.
- Run 6 will help.

Fraction of pion production

![Fraction of pion production graph](image)

![Graphs showing $A_{LL}$ vs. $p_T$ for different pion types](image)
Improved FoM → Run 6

Run: 5 → 6
Luminosity: 3.4 → 7.5
Polarization: 49% → 62%
FoM (P^4L): 0.20 → 1.11
Run6 $\pi^0 A_{LL}$

- Run6 scaling error based on online polarization values. Final scaling error expected to be $\sim 10\%$
- Grey band is systematic uncertainty due to Relative Luminosity, and is $p_T$ independent.
- Run6 Data favor “GRSV $\Delta G=0$” over GRSV-std

<table>
<thead>
<tr>
<th>Theory</th>
<th>$\chi^2$/NDF</th>
<th>CL(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRSV-std</td>
<td>23.8/8*</td>
<td>0.25</td>
</tr>
<tr>
<td>GRSV $\Delta G=0$</td>
<td>7.9/8*</td>
<td>44</td>
</tr>
</tbody>
</table>

*Theoretical uncertainties not included

$\chi^2/NDF$ values:
- Run5: $23.8/8^*$
- Run6: $7.9/8^*$

Online Polarization values used in Run6

Scaling errors not included

PHENIX Preliminary

- Run5 (9.4% scaling error)
- Run6 (40% scaling error)
Sensitivity of $\pi^0 A_{LL}$ to $\Delta G$

PHENIX Preliminary

- Run5 (9.4% scaling error)
- Run6 (40% scaling error)

Scaling errors not included

Online Polarization values used in Run6

GRSV std

present x-range

Kieran Boyle

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ΔG(x) C from Gehrmann Stirling

GSC-NLO: $\Delta G = \int \Delta G(x) dx = 1.0$

Much of the first moment $\Delta G = \int \Delta G(x) dx$ might emerge from low $x$!

GSC-NLO: $\Delta G = \int_{0.02}^{0.3} \Delta G(x) dx \sim small \rightarrow 0$
NEED TO EXTEND MEASUREMENTS TO LOW $x$ !!

$\Delta G = \int \Delta G(x) dx = 1.0$

Large uncertainties resulting from the functional form used for $\Delta G(x)$ in the QCD analysis!
Extend x Range

• To measure $\Delta G$, need as wide an $x$ range as possible.
• Planned Upgrades will help (see talk on Wednesday)
• By measuring at different center of mass energies, we can reach different $x$ ranges.
• We can extend our $x$ coverage towards lower $x$ at $\sqrt{s} = 500$ GeV. Expected to start in 2009.
• We can extend our $x$ coverage towards higher $x$ at $\sqrt{s} = 62.4$ GeV. $\rightarrow$ Run6

![Graph showing x-range extension at different center of mass energies](image_url)
\[ \pi^0 A_{LL} \text{ at } \sqrt{s} = 62.4 \text{ GeV} \]
for high \( x \) measurement
\( \pi^0 \) ALL @ \( \sqrt{s}=62.4 \) GeV

- Short run with longitudinal polarized protons \( \rightarrow A_{LL} \)
- Grey band is systematic uncertainty due to Relative Luminosity

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PQCD works \( \rightarrow \) measure \( A_{LL} \)

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Comparison with 200 GeV

\[ x_T = \frac{p_T}{\sqrt{s}/2} \rightarrow x \]

- At fixed \( x_T \), \( \pi^0 \) cross section is 2 orders of magnitude higher at 62.4 GeV than at 200 GeV
- Converting to \( x_T \), we can get a better impression of the significance of the \( \sqrt{s} = 62.4 \) GeV data set, when compared with the Run5 final data set.

Run5 200GeV final 2.7pb\(^{-1}\) (49%)
Run6 62.4GeV preml. 0.04 pb\(^{-1}\) (48%)
Conclusions

• PHENIX has measured cross sections at $\sqrt{s}=200$ and 62.4 GeV, and found that pQCD describes our data well.

• PHENIX is able to probe the gluon polarization in the proton through many channels.

• Run5 and Run6 $\pi^0 A_{LL}$ are a significant constraint on the gluon polarization in the proton in the $x$ range $[0.02,0.3]$.
  – More luminosity at 200 GeV will enable us to address the $\Delta G$ sign ambiguity with charged pions and direct photons.
Outlook

• To understand the gluon polarization, we must cover a wide x-range by varying the center of mass energy.
  – PHENIX has begun this by measuring $\pi^0 A_{LL}$ at $\sqrt{s}=62.4$ GeV.
  – $\sqrt{s} = 500$ GeV running will also extend the low x reach.

• Detector Upgrades, such as the Silicon VTX, FVTX, and Nose Cone Calorimeter will extend the x reach at low x.
  – heavy quarks and Direct photons (see Y. Goto, later today)

• If we find $\Delta G$ is small, we must explore other possibilities, such as Orbital Angular Momentum. PHENIX is working on this:
  – transverse spin effects (see tomorrow’s session)
  – $k_T$ effects in longitudinally polarized protons (See D. Fields’ talk, later today).
Backups
Prompt $\gamma$ Production at $\sqrt{s}=200\text{GeV}$

- Gluon Compton scattering dominates
- At LO no fragmentation function
- Small contribution from annihilation

$A_{LL} \propto \frac{\Delta g(x_1)}{g(x_1)} \otimes \frac{\Delta q(x_2)}{q(x_2)} \otimes \hat{a}_{LL}(gq \rightarrow \gamma q)$
Attempting to Probe $k_T$ from Orbital Motion

- Spin-correlated transverse momentum (orbital angular momentum) may contribute to jet $k_T$. (Meng Ta-chung et al., Phys. Rev. D40, 1989)
- Possible helicity dependence
- Would depend on (unmeasured) impact parameter, but may observe net effect after averaging over impact parameter

### PHOENIX Preliminary

$\chi^2 / \text{ndf} = 1.347 / 5$

$p_0 = 0.6719 \pm 0.3874$

Run-5

Di-hadron $k_T$ asymmetry
Photon Trigger Efficiency

<table>
<thead>
<tr>
<th>Detector</th>
<th>1&lt;pT&lt;2 GeV/c</th>
<th>2&lt;pT&lt;3 GeV/c</th>
<th>3&lt;pT&lt;4 GeV/c</th>
<th>pT&gt; 4GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>PbSc</td>
<td>6%</td>
<td>50%</td>
<td>81%</td>
<td>88%</td>
</tr>
<tr>
<td>PbGl</td>
<td>21%</td>
<td>72%</td>
<td>87%</td>
<td>90%</td>
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