Double Helicity Asymmetries of Forward Neutral Pions from $\sqrt{s} = 510$ GeV $pp$ Collisions at STAR

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Outline

- Current Status of Gluon Polarization
- Double Helicity Asymmetry – $A_{LL}$
- Forward EM Calorimetry at STAR
- Luminosity Detectors at STAR
- Relative Luminosity and $A_{LL}$ Systematics
- $\pi^0$ Event Selection
- Measurement of Forward $\pi^0 A_{LL}$
Gluon Polarization $\Delta g(x)$

Proton Spin Sum:  
$$ S_p = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g $$

- $\Delta \Sigma \sim 0.3$
- $L_q, L_g \sim ?$
- $\Delta G$ — status shown

Low-x poorly constrained; accessible via forward observables

de Florian, Sassot, Stratmann, Vogelsang  
Accessing $\Delta g$ by Measuring $A_{LL}$

Colliding proton helicities known for each bunch crossing (9.4 MHz at STAR)

\[
A_{LL} = \frac{1}{P_a P_b} \left( \frac{\sigma^{++} + \sigma^{--}}{\sigma^{++} + \sigma^{--} + \sigma^{+-} + \sigma^{-+}} \right) - \left( \frac{\sigma^{+-} + \sigma^{-+}}{\sigma^{++} + \sigma^{--} + \sigma^{+-} + \sigma^{-+}} \right) \propto \frac{\Delta f_1 \Delta f_2}{f_1 f_2}
\]

Beam Polarizations
(Measured by RHIC polarimetry group)

Re-express cross-section: $\sigma^{\pm\pm} = \frac{N^{\pm\pm}}{L^{\pm\pm}}$

Relative Luminosity: $R_3 = \frac{L^{++} + L^{--}}{L^{+-} + L^{-+}}$

Measured using STAR luminosity detectors

\[
A_{LL} = \frac{1}{P_a P_b} \left( \frac{N^{++} + N^{--}}{N^{++} + N^{--} + N^{+-} + N^{-+}} \right) - R_3 \cdot \left( \frac{N^{+-} + N^{-+}}{N^{++} + N^{--} + N^{+-} + N^{-+}} \right)
\]
Forward EM Calorimetry at STAR

**PRIMARY FOCUS:**

**FMS – Forward Meson Spectrometer**

- Forward pseudorapidity: \( 2.5 < \eta < 4 \)
- 1,264 **Lead-glass cells** coupled to photomultiplier tubes
  - Large (5.8 x 5.8 cm) outer cells (blue)
  - Small (3.8 x 3.8 cm) inner cells (black)
- Observes \( \pi^0 \rightarrow \gamma + \gamma \) as 2 cluster events
- Forward observables → access to **low-x gluons**
Measuring Relative Luminosity at STAR

3 Luminosity Detectors at STAR:
- Beam Beam Counter (BBC) – not used in this analysis
- Vertex Position Detector (VPD)
- Zero Degree Calorimeter (ZDC)

They are “Scalers”: for each bunch crossing, they count whether or not a “hit” was observed
- Scalers are placed symmetrically on both sides of the interaction point
- A hit on one side is called a “single count”
- A hit on both sides within a time window is called a “coincidence count”

\[ R_3 = \frac{L^{++} + L^{--}}{L^{+-} + L^{-+}} \]

VPD

4.2 < |\eta| < 5.1
5.7 m from Interaction Point
Hits: mostly charged particles and photons from pion decays

ZDC

6.5 < |\eta| < 7.5
18 m from Interaction Point
Hits: mostly neutrons and some neutral kaons;
photons only in 1st module
(charged particles are swept away by magnets)
Relative Luminosity Measurements

**2012 Relative Luminosity $R_3$**

- Measured with VPD, averaging over both singles sides and coincidences
- Cross-checked with other STAR scalers (ZDC, singles, coincidences)

For each run (~30 min.), $R \sim 1 \pm 0.04$

Typical statistical uncertainty $\sim 4 \times 10^{-5}$

$$R_3 = \frac{L^{++} + L^{--}}{L^{+-} + L^{-+}}$$
Relative Luminosity $\rightarrow \pi^0 A_{LL}$ Systematic

2012 Run ZDC $A_{LL}$ Distribution (relative lum. by VPD)

- Measured $A_{LL}$ in ZDC scaler system using VPD coincidences as a relative luminosity
  - Denoted as "Scaler $A_{LL}$"

- Distribution of this Scaler $A_{LL}$ is shown on the left
  - 1 entry = 1 STAR run (~30 min)

- Red Lines indicate Gaussian fit results, defined with fit parameters $c$, $\mu$, and $\sigma$

Fit Function $f(A_{LL})$:

$$f(A_{LL}) = c \cdot \exp \left[ -\frac{1}{2} \left( \frac{A_{LL} - \mu}{\sigma} \right)^2 \right]$$

- In the 2013 Run, this Scaler $A_{LL}$ was correlated with spin pattern
  - The two peaks are fit with two separate Gaussians

\[ \begin{align*}
\mu &= 1.1 \times 10^{-5} \pm 1.3 \times 10^{-5} \\
\sigma &= 2.5 \times 10^{-4} \pm 1.1 \times 10^{-5}
\end{align*} \]

\[ \begin{align*}
\mu &= -1.1 \times 10^{-3} \pm 2.5 \times 10^{-5} \\
\sigma &= 5.1 \times 10^{-4} \pm 2.5 \times 10^{-5}
\end{align*} \]
Relative Luminosity $\rightarrow \pi^0 A_{LL}$ Systematic

- Measurement of Scaler $A_{LL}$ + its uncertainty = $\pi^0 A_{LL}$ shift systematic uncertainty
  - “Shift” denotes a constant bias on $A_{LL}$
  - Scaler $A_{LL}$ measurement is taken to be the overall mean of the distribution
  - For Scaler $A_{LL}$ uncertainty, we use the fit parameter $\sigma$
  - → For the 2013 run, the $\sigma$ of the wider peak is used
  - The overall $\pi^0 A_{LL}$ systematic is computed as:

$$\pi^0 A_{LL} \text{ Systematic} = \text{Scaler } A_{LL} \text{ “}\sigma\text{”} + | \text{Scaler } A_{LL} \text{ Mean} |$$

<table>
<thead>
<tr>
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<th>$A_{LL}$ Shift Systematic Uncertainty</th>
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</thead>
<tbody>
<tr>
<td>2012 Run</td>
<td>$2.8 \times 10^{-4}$</td>
</tr>
<tr>
<td>2013 Run</td>
<td>$6.2 \times 10^{-4}$</td>
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Combining 2012 and 2013 Runs' Systematics:
- For each $p_T$ (or $E_{yy}$) bin: weighted average of 2012 & 2013 systematics based on $\pi^0$ statistics
**π⁰ Event Selection**

- Full azimuth: \(-\pi \leq \phi < \pi\)
- FMS Psuedorapidity: \(2.5 \leq \eta < 4\)
- Transverse Momentum Ranges:
  - 2012 Run: \(2.5 \leq p_T < 10\) GeV/c
  - 2013 Run: \(2.0 \leq p_T < 10\) GeV/c
- Different low \(p_T\) cutoff to account for trigger threshold adjustment
- Di-photon Energy Range: \(30 \leq E_{\gamma\gamma} < 100\) GeV
- Energy Sharing: \(Z = |E_1 - E_2| / E_{\gamma\gamma} < 0.8\)
- Mass Cut: Dependent on \(E_{\gamma\gamma}\) (see invariant mass slide)
- 2-photon Isolation Cone: \(35\) mr and \(100\) mr analyzed
  - Isolation cone versus inclusive → See next slide
Motivating $\pi^0$ Isolation Cones

$A_N$ vs. Energy, averaged over pseudo-rapidity.
Compare 3 selection criterion based on photon energy outside the cone (all with 35mR cone and no soft E cut)

$A_N = \frac{\sigma^\uparrow_L - \sigma^\downarrow_L}{\sigma^\uparrow_L + \sigma^\downarrow_L}$

(“L” = left half of detector)

More isolated $\pi^0$s have higher transverse single spin asymmetry $A_N$

We applied similar isolation cuts for $\pi^0 A_{LL}$, motivated by the dependence of $A_N$ on $\pi^0$ isolation

Goal: verify $A_{LL}$ is NOT dependent on $\pi^0$ isolation; inclusive $\pi^0$ to be explored after Spin2014

See Yuxi Pan’s Spin2014 presentation for more on “isolated” vs. “inclusive” $A_N$

Invariant Mass for 2-photon Events

**2012 Run**

- Trigger thresholds adjusted in 2013 run to increase sensitivity to $\pi^0$s in $2 < p_T < 3$ GeV/c region

- $\pi^0$ mass peak resolution decreases as Energy ($E_{\gamma\gamma}$) increases

- Mass peak smears toward higher mass as $E_{\gamma\gamma}$ increases

  - $E_{\gamma\gamma}$-dependent mass cut for $\pi^0$ candidates (FWHM of peak)

**2013 Run**

- Red Line – mass peak
- Blue & Green lines set at FWHM

$$m_{\pi^0} \approx 135 \text{ MeV}/c^2$$
Forward $\pi^0 A_{LL}$ Measurement – $p_T$-Dependence

$\pi^0$ Double Helicity Asymmetry $A_{LL}$ vs. $p_T$

- $pp \rightarrow \pi^0 + X$
- $\sqrt{s} = 510$ GeV
- $2.5 < \eta < 4$

**35 mr Isolation Cone**

**100 mr Isolation Cone**

**35 mr Constant Fit Result:** $A_{LL} = -2.5 \times 10^{-4} \pm 6.5 \times 10^{-4}$

$\chi^2 / NDF = 7.8 / 5$

**100 mr Constant Fit Result:** $A_{LL} = -3.3 \times 10^{-4} \pm 8.4 \times 10^{-4}$

$\chi^2 / NDF = 12.5 / 5$

* 100 mr points are offset by $p_T + 0.1$ GeV/c for visibility
Forward $\pi^0 A_{LL}$ Measurement – $E_{\gamma\gamma}$-Dependence

$\pi^0$ Double Helicity Asymmetry $A_{LL}$ vs. $E_{\gamma\gamma}$

35 mr Constant Fit Result: $A_{LL} = -2.5 \times 10^{-4} \pm 6.5 \times 10^{-4}$

$\chi^2 / NDF = 2.7 / 5$

100 mr Constant Fit Result: $A_{LL} = -3.3 \times 10^{-4} \pm 8.4 \times 10^{-4}$

$\chi^2 / NDF = 2.5 / 5$

* 100 mr points are offset by $E_{\gamma\gamma} + 1$ GeV for visibility
Conclusion

- Forward $(2.5 \leq \eta < 4)$ $\pi^0 A_{LL}$ measurement consistent with zero
  Independence of $A_{LL}$ on $\pi^0$ isolation verified
  (cf. large dependence of $A_N$ on $\pi^0$ isolation)

- Other systematic uncertainties are still under consideration
  Trigger Bias – likely sub-dominant
  Transverse spin component – likely negligible for $A_{LL}$

- Inclusive analysis coming soon!
backup
Outlook: Accessing low-\(x\) \(\Delta g(x)\) via Di-jets

- Forward hadrons from hard \(q\), soft \(g\) processes
- Dijet Kinematics → access to gluon \(x \leq 10^{-3}\)
- Lowest-x processes accessible in future FCS (Forward Calorimetry System; \(2.8 < \eta < 3.7\))

\[
\begin{align*}
\sqrt{s} &= 500 \text{ GeV} \\
\text{Cone alg. (R=0.7) / } E_{T_3} &> 5 \text{ GeV } E_{T_4} > 8 \text{ GeV}
\end{align*}
\]

\[
x_1 = \frac{p_T}{\sqrt{s}} (e^{\eta_3} + e^{\eta_4}) \\
x_2 = \frac{p_T}{\sqrt{s}} (e^{-\eta_3} + e^{-\eta_4})
\]

\(\) (leading-order \(x_1\) and \(x_2\) equations)

Surrow – arXiv: 1407.4176
Energy-Dependent $\pi_0$ Mass Cuts – 2012 Run

**Vertical Lines Legend**

- **M low bound**
- **M max bin**
- **M high bound**

Bounds are set at the full width at half max of the $\pi^0$ mass peak for each 10 GeV $E_{\gamma\gamma}$ bin.
Energy-Dependent $\pi_0$ Mass Cuts – 2013 Run

*Vertical Lines Legend*

- **M low bound**
- **M max bin**
- **M high bound**

Bounds are set at the full width at half max of the $\pi^0$ mass peak for each 10 GeV $E_{\gamma\gamma}$ bin.
**π⁰ p_T Distributions**

For above plots:
Black vertical lines are p_T bin boundaries; red lines indicate p_T bin means & RMSs

**2012 Run Cut:**
2.5 ≤ p_T < 10 GeV/c

**2013 Run Cut:**
2.0 ≤ p_T < 10 GeV/c

Trigger thresholds adjusted in 2013 to increase sensitivity in 2<p_T<3 GeV/c region
For above plots:
Black vertical lines are $E_{\gamma\gamma}$ bin boundaries; red lines indicate $E_{\gamma\gamma}$ bin means & RMSs

2012 and 2013 Run Cut:
$30 \leq E_{\gamma\gamma} < 100$ GeV
Forward $\pi^0 A_{LL}$ Measurement for 2012 vs. 2013

$\pi^0$ Double Helicity Asymmetry $A_{LL}$ vs. $p_T$

**2012 Run**

**STAR PRELIMINARY**

35 mr Isolation Cone
100 mr Isolation Cone

$p_T$ Dependence

statistical uncertainty

bin RMS

systematic uncertainty
Forward $\pi^0 A_{LL}$ Measurement for 2012 vs. 2013

$\pi^0$ Double Helicity Asymmetry $A_{LL}$ vs. $E_{\gamma\gamma}$

**2012 Run**

- 35 mr Isolation Cone
- 100 mr Isolation Cone

**STAR PRELIMINARY**

**E_{\gamma\gamma} Dependence**

- statistical uncertainty
- bin RMS

**2013 Run**

- 35 mr Isolation Cone
- 100 mr Isolation Cone

**STAR PRELIMINARY**
Combining Data to Measure $A_{LL}$

- STAR takes data in ~30 minute periods, called runs
- Combine runs via maximum likelihood method (MLM)

MLM value: 

$$\bar{A}_{LL} = \frac{\sum_i P_a^{(i)} P_b^{(i)} \left[ N_{++}^{(i)} + N_{--}^{(i)} - R_3^{(i)} \left( N_{+-}^{(i)} + N_{-+}^{(i)} \right) \right]}{\sum_i \left( P_a^{(i)} P_b^{(i)} \right)^2 \left[ N_{++}^{(i)} + N_{--}^{(i)} + R_3^{(i)} \left( N_{+-}^{(i)} + N_{-+}^{(i)} \right) \right]}$$

(sums over runs)

Statistical Uncertainty: 

$$\delta^{stat}_{\bar{A}_{LL}} \approx \frac{1}{\langle P_a \rangle \langle P_b \rangle \sqrt{N_{tot}}}$$

Need 3 coincident measurements:
- h-dependent yields $\leftarrow$ calorimetry (viz. FMS)
- Relative Luminosity $\leftarrow$ scaler detectors (BBC, ZDC, VPD)
- Beam Polarizations $\leftarrow$ RHIC polarimetry (~55% +/- 5%)