Longitudinal Double Spin Asymmetries with $\pi^0$ - Jet Correlations in Polarized Proton Collisions at $\sqrt{s} = 510$ GeV at STAR

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Outline

• Introduction
• STAR experiment at RHIC
• $\pi^0$ - Jet double spin asymmetry ($A_{LL}$) measurements at STAR
  ✓ Analysis methodology
  ✓ $\pi^0$ – Jet $A_{LL}$ analysis status
• Conclusion and Outlook
The observed spin of the proton can be decomposed into contributions from the intrinsic quark and gluon spin and orbital angular momentum.

$$\left\langle S_p \right\rangle = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L$$

unique measurement at RHIC

- DIS data measure the integral of quark polarization well to be around ~ 30%
- Both DSSV and NNPDF, with 2009 RHIC results integrated in the fits, find evidence for positive gluon polarization:
  - DSSV: $0.19^{+0.06}_{-0.05}$ at 90% c.l. for $x > 0.05$
- Uncertainties on integral over low x region are still sizeable.
The Relativistic Heavy Ion Collider (RHIC), the world’s first polarized hadron collider, is designed to collide many particle species energies.
The polarized p+p program at Solenoidal Tracker at RHIC (STAR):
- Study proton intrinsic properties
- QCD
- Forward program

Detectors used for gluon polarization study:
- **Time Projection Chamber**
  \(|\eta| < 1.1, 0 \leq \varphi < 2\pi\)
- **Barrel EM Calorimeter**
  \(|\eta| < 1, 0 \leq \varphi < 2\pi\)
- **Endcap EM Calorimeter**
  \(1.08 < \eta < 2, 0 \leq \varphi < 2\pi\)
- **FMS**
  \(2.5 < \eta < 4, 0 \leq \varphi < 2\pi\)
Exploring gluon Polarization at RHIC

Measure Longitudinal double spin asymmetries ($A_{LL}$):

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \propto \frac{\Delta f_a \otimes \Delta f_b}{f_a \otimes f_b} \otimes a_{LL} \otimes D^h_f$$

$\Delta f$: polarized parton distribution functions;
$D^h_f$: fragmentation functions.

Sensitive probes:
- inclusive jets
- neutral pions ($\pi^0$)
- correlations (di-jets, h-jet, ...)

For most RHIC kinematics, $gg$ and $qq$ dominate, making $A_{LL}$ for jets sensitive to gluon polarization.
Exploring gluon Polarization at RHIC

Longitudinally polarized p+p collisions at 200 GeV and 510 GeV allow both cross section and double spin asymmetry $A_{LL}$ measurements at STAR on:

- Inclusive Jet
  
  $x$ down to $\sim 0.05$ for jets in the mid-rapidity at 200/510 GeV

- Inclusive $\pi^0$
  
  $x$ down to $\sim 0.02$ for forward $\pi^0$ $0.8 < \eta < 2.0$ at 200/510 GeV

- Di-jet

  Correlation unfolds $x_1$, $x_2$ at the leading order

Run 2009: PRL 115, 092002
Run 2012: STAR Preliminary

PRD.89.012001

Run 2009: STAR Preliminary
Run 2012: STAR Preliminary
**π⁰ - Jet A_{LL} measurements at STAR**

**Channel:** Using a jet in the mid-rapidity region correlated with an opposite-side neutral pion in the forward rapidity region $1.08 < \eta < 2.0$ in the STAR EEMC provides a new tool to access the $\Delta G(x)$ distribution at Bjorken-$x$ down to 0.01.

\[
x_1 = \frac{p_T^{\text{jet}}}{\sqrt{s}} (e^{\eta_{\text{jet}}} + e^{-\eta_{\pi^0}}),
\]
\[
x_2 = \frac{p_T^{\text{jet}}}{\sqrt{s}} (e^{-\eta_{\text{jet}}} + e^{\eta_{\pi^0}}),
\]
\[
\sqrt{\hat{s}} = \sqrt{x_1 x_2 s}.
\]

- Compared to inclusive jet measurements, this $\pi^0$ - jet channel also allows to constrain the initial parton kinematics, such as $x_1$, $x_2$ and $\sqrt{\hat{s}}$.
π^0 - Jet A_{LL} measurements at STAR

Parton vs. Reconstructed kinematics:

- Find that most of the generated events in the Monte Carlo implementation of the NLO corrections give the same value for the 'real' and 'measured' momentum fractions.

π^- jet correlation in mid-rapidity from Daniel de Florian, PRD 79 (2009) 114014

Forward π^0 - barrel jet correlation using Daniel's NLO model calculation for this work
Analysis cuts for Run12 pp 510 GeV data:

\( \pi^0 \) reconstruction:
- \( \pi^0 \) p_T: > 4.0 GeV/c
- \( \pi^0 \) mass: (0, 0.6)
- \( \pi^0 \) physics eta: (1.086, 2.0)

\( \pi^0 \) - jet pairing:
- \(|\Delta \phi| > 2.0\) (back-to-back)

Jet reconstruction:
- Anti-k_T algorithm, R=0.6
- Leading jet with \( p_T > 8.0 \) GeV/c
- Jet physics eta: (-0.9, 0.9)
- Jet points to a jet patch (JP) trigger
- Contribution from the calorimeters to the total jet energy (R_t) was required to be less than 0.95
- Sum track \( p_T > 0.5 \) GeV/c

Triggers:
- JP triggers (EM calorimeter triggers, and the size of a JP is 1.0×1.0 in \( \eta-\phi \) coverage):
  - JP0: jet \( p_T > 5.4 \) GeV/c
  - JP1: jet \( p_T > 7.3 \) GeV/c
  - JP2: jet \( p_T > 14.4 \) GeV/c
Reconstructed kinematics from data:

\[ x_1 = \frac{p_T^{\text{jet}}}{\sqrt{s}} (e^{\eta_{\text{jet}}} + e^{\eta_{\pi^0}}) \]

\[ x_2 = \frac{p_T^{\text{jet}}}{\sqrt{s}} (e^{-\eta_{\text{jet}}} + e^{-\eta_{\pi^0}}) \]
The reconstructed $x_1$, $x_2$, and $\sqrt{\hat{s}}$ of matched $\pi^0$-jet pair show a good linearity with MC (Pythia6426-Perugia0).

$$x_1 = \frac{p_{T}^{\text{jet}}}{\sqrt{s}}(e^{\eta_{\text{jet}}} + e^{\eta_{\pi^0}}),$$

$$x_2 = \frac{p_{T}^{\text{jet}}}{\sqrt{s}}(e^{-\eta_{\text{jet}}} + e^{-\eta_{\pi^0}}),$$

$$\sqrt{\hat{s}} = \sqrt{x_1 \cdot x_2 \cdot s}.$$
\(\pi^0\) - Jet \(A_{LL}\) measurements at STAR

**Pythia simulation VS. data:**

![Graphs showing comparisons between Pythia simulation and data](image)

- Ratio of leading jet \(p_T\) from Run12 data to the leading jet \(p_T\) from generator MC was taken as jet reconstruction efficiency.

- Weighted by the jet reconstruction efficiency, the \(\pi^0/\text{jet } p_T\) spectrum and \(\Delta\phi\) distribution from MC are consistent with data.
The invariant mass spectrum (weighted by relative luminosities and beam polarizations), are fitted to estimate signal yield for each kinematic variable bin, respectively.

\[ \text{sig}(x) : k \times e^{-\frac{(x-\mu)^2}{2\sigma^2}} \times [1 + \text{Erf}\left(\frac{a(x-\mu)}{\sqrt{2}\sigma}\right)] \]

\[ \text{bkg}(x) : A \times x^B \times e^{Cx} \]

\[ \text{model}(x) = \frac{n_{\text{sig}}}{n_{\text{sig}} + n_{\text{bkg}}} \times \text{sig}(x) + \frac{n_{\text{bkg}}}{n_{\text{sig}} + n_{\text{bkg}}} \times \text{bkg}(x) \]

\[ n_{\text{raw}} \times \text{model}(x) = n_{\text{sig}} \times \text{sig}(x) + n_{\text{bkg}} \times \text{bkg}(x) \]

- The raw yield \((n_{\text{raw}})\) of \(\pi^0\)-jet are well fitted by model\((x)\), in which the signal shape was described by skewed Gaussian function \(\text{sig}(x)\), and background shape was fitted by Gamma function \(\text{bkg}(x)\):
- The shapes of \(\text{sig}(x)\) and \(\text{bkg}(x)\) were determined by fitting the spectrum summed over spin states.
- Signal yield \((n_{\text{sig}})\) and background yield \((n_{\text{bkg}})\) are estimated as free parameters by fitting over \([0.05, 0.6]\) GeV/c\(^2\) with the fixed \(\text{sig}(x)\) and \(\text{bkg}(x)\) shapes.
- Signal (background) asymmetries, \(A_{\text{LL}}^S\) (\(A_{\text{LL}}^B\)), are calculated by the estimated normalization \(n_{\text{sig}}\) (\(n_{\text{bkg}}\).
\( \pi^0 \)-Jet \( A_{LL} \) measurements at STAR

Uncertainty projections of \( \pi^0 \)-jet \( A_{LL} \):

- Statistics uncertainty projections for \( \pi^0 \)-jet \( A_{LL} \) in STAR Run12 pp 510 GeV data


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Conclusion

• STAR has been making significant contributions to the gluon polarization program via inclusive jets, inclusive neutral pions and di-jets measurements.

• $A_{LL}$ measurements via correlations between forward neutral pion and barrel jet allow to constrain the initial partonic kinematics. Analysis results using this channel is underway.

• More data have been taken by STAR and more precision measurements are expected.
Thanks for your attention!