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
Introduction – Proton Spin Puzzle

The observed spin of the proton can be decomposed into contributions from the intrinsic quark and gluon spin and orbital angular momentum.

\[ \langle S_p \rangle = \frac{1}{2} = \frac{1}{2} \left( \Delta \Sigma + \Delta G + L \right) \]

- 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 of gluon polarization over low $x$ region are still sizeable
The Relativistic Heavy Ion Collider (RHIC), the world’s first and only polarized hadron collider, is designed to collide many particle species at different energies.

- World’s only polarized hadron-hadron collider
- Spin direction changes from bunch to bunch
- Spin rotators provide choice of spin orientation


The spin program at Solenoidal Tracker at RHIC (STAR):

- Gluon polarization ($\pi^0$/Jet production): $\Delta g(x)$
- Quark/Anti-quark polarization (W/Z production): $\Delta q(x)$
- Transverse spin dynamics (W/Z production): Sivers function

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**
  
  \[ 1.08 < \eta < 2, \ 0 \leq \varphi < 2\pi \]

- **Forward Meson Spectrometer**
  
  \[ 2.5 < \eta < 4, \ 0 \leq \varphi < 2\pi \]
Exploring gluon Polarization at RHIC

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

$$A_{LL} = \frac{\sigma^{++} - \sigma^{--}}{\sigma^{++} + \sigma^{--}} = \frac{\sum_{f_1, f_2} \Delta f_1 \otimes \Delta f_2 \otimes d\hat{\sigma}_{f_1 f_2 \rightarrow f X} \cdot \hat{a}_{f_1 f_2 \rightarrow f X} \otimes D^\pi_f}{\sum_{f_1, f_2} f_1 \otimes f_2 \otimes d\hat{\sigma}_{f_1 f_2 \rightarrow f X} \otimes D^\pi_f}$$

$\Delta f_i$: polarized parton distribution functions;
$D^\pi_f$: fragmentation functions.

Partonic fraction for jet production

$Mukherjee and Vogelsang, PRD.86.094009$
Exploring gluon Polarization at RHIC

Longitudinally polarized p+p collisions at 200 GeV and 500/510 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

- **Inclusive $\pi^0$**
  
  $x$ down to $\sim 0.02$ for forward $\pi^0$ $0.8 < \eta < 2.0$

- **Di-jet**
  
  $x$ down to $\sim 0.02$, correlation unfolds $x_1, x_2$ at the leading order

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**STAR p+p $\rightarrow$ Jet+X**

- 2012 510 GeV $R=0.5, |\eta|<0.9$ Prelim.
- 2009 200 GeV $R=0.6, |\eta|<1.0$
- Relative luminosity uncertainty
- LSS10p
- DSSV14
- NNPDF1.1

**$\bar{p}+p \rightarrow \pi^0 + X$**

- GRSV $\Delta g = g$
- GRSV $\Delta g = \text{std}$
- GRSV $\Delta g = -g$
- DSSV

$\sqrt{s} = 200$ GeV

$0.8 < \eta < 2.0$

6% Scale Uncertainty
Exploring gluon Polarization at RHIC

Longitudinally polarized p+p collisions at 200 GeV and 500/510 GeV allow both cross section and double spin asymmetry $A_{LL}$ measurements at STAR on:

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Run 2009: PRD 95 (2017) 71103
Run 2012: STAR Preliminary
Exploring gluon Polarization at RHIC

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\[ \pi^0 - \text{Jet} A_{\text{LL}} \text{ measurements at STAR} \]

**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.

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

- 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 \(\sqrt{s}\).
- Theoretical description of hadron-jet \(A_{\text{LL}}\) by next-to-leading order (NLO) model calculation: Daniel de Florian, PRD 79 (2009) 114014.
π⁰ - Jet $A_{LL}$ measurements at STAR

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
π^0 - Jet $A_{LL}$ measurements at STAR

Pythia simulation:

- The reconstructed $x_1$, $x_2$, and $\sqrt{s}$ of matched $\pi^0$-jet pair show a good linearity with MC (Pythia6426-Perugia0).

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

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

\[
\sqrt{s} = \sqrt{x_1x_2s}.
\]
Reconstructed kinematics from data:

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

\[
x_2 = \frac{p_T^{\text{jet}}}{\sqrt{s}} (e^{-\eta_{\text{jet}}} + e^{-\eta_{\pi^0}})
\]
STAR jet reconstruction efficiency was applied for the reconstructed spectrum (solid black histogram) in simulation.

- Weighted by the jet reconstruction efficiency, the $\pi^0$/jet $p_T$ spectrum and $\Delta\phi$ distribution from simulation are consistent with data.
Background subtraction:

The invariant mass spectrum (weighted by relative luminosities and beam polarizations), are fitted to estimate signal yield for each kinematic variable bin, respectively.

- **Signal:** A reconstructed photon pair is associated with the $\pi^0$ signal
- **Conversion background:** A reconstructed photon pair is associated with the conversion background
- **Other background:** Photon pairs that are not identified as signal or conversion background

- The raw yield of $\pi^0$-jet are well fitted by extended likelihood formalism in RooFit, in which the signal shape was described by skewed Gaussian function
- The shapes of signal and backgrounds are determined by fitting the spectrum summed over spin states
- Signal yield and background yields are estimated as free parameters by fitting over [0., 0.6] GeV/c² with the fixed signal and background shapes
- Signal (background) asymmetries, $A_{LL}^S$ ($A_{LL}^B$), are calculated by the estimated yields
\( \pi^0 - \text{Jet} \ A_{LL} \) measurements at STAR

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


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

Conclusion and Outlook

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

  More results can be found in talk: Adam Gibson, Saturday September 2

• $A_{LL}$ 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!