RECENT TRANSVERSE SPIN RESULTS FROM THE STAR EXPERIMENT AT RHIC

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Outline

- Introduction
- The polarized RHIC collider and the STAR experiment
- Transverse Single Spin Asymmetries (TSSA) with forward detector, Forward Meson Spectrometer (FMS)
- TSSAs for Jets and di-hadrons
- STAR transverse physics in ongoing transverse run at $\sqrt{s} = 200$ GeV
Spin-dependent transverse momentum dependent (TMD) function $S_T(P\times k_T)$
+ Collins fragmentation functions

- Sivers function, Sivers90
- Collins function, Collins 93
- Gauge invariant definition of the TMDs: Brodsky, Hwang, Schmidt 02; Collins 02; Belitsky, Ji, Yuan 02; Boer, Mulders, Pijlman, 03
- The QCD factorization: Ji, Ma, Yuan, 04; Collins, Metz, 04

Twist-3 quark-gluon correlations
+ Twist three fragmentation functions

- Efremov-Teryaev, 82, 84
- Qiu-Sterman, 91,98
- Kouvaris,Qiu,Vogelsang,Yuan, 06

Need 2 scales $Q^2$ and $p_t$
Remember pp:
most observables one scale
Some Exceptions:
DY, W/Z-production, jet+hadron

Collinear/twist-3
$Q, Q_T >> \Lambda_{QCD}$
$p_T \sim Q$

Efremov, Teryaev; Qiu, Sterman

Need only 1 scale $Q^2$ or $p_t$
But
should be of reasonable size
should be applicable to most pp observables
$A_N(n^0/\gamma/jet)$
Sivers vs. Collins

**Sivers mechanism:** asymmetry in the forward jet or $\gamma$ production

D. Sivers, PRD 41, 83 (1990); 43, 261 (1991)

\[ \langle S_p \cdot (p \times k_{T,\text{parton}}) \rangle \neq 0 \]

Sensitive to proton spin–parton transverse motion correlations (needs $L_z$)

**Collins mechanism:** asymmetry in the forward jet fragmentation

J. Collins, NP B396, 161 (1993)

\[ \langle S_q \cdot (p \times k_{T,\pi}) \rangle \neq 0 \]

Sensitive to transversity ($h_1$)

\[ \pi^\pm \text{ Kinematic Variables} \]
\[ z = p_\pi / p_{\text{jet}} \]
\[ j_T (k_{T,\pi}) = \pi p_T \text{ relative to jet axis} \]
RHIC: the world’s first and the only polarized proton collider

- Siberian Snakes
- Polarized Source
- 200 MeV Polarimeter
- Strong Snake
- LINAC
- Fast Tune Jump Quads
- RF Dipole
- AGS Booster
- AGS Internal Polarimeter
- Spin Rotators
- Hydrogen Jet Polarimeter
- Carbon Polarimeters
- Spin Flipper
- Helical Partial Snake
- PHENIX
- STAR
STAR detector in cross view
STAR at forward rapidity

- Forward Meson Spectrometer (FMS), Forward Pre-Shower Detector (FPS, we have for 2015)
- Event topology dependent of TSSA
- Measurements from 2011 transverse data at $\sqrt{s} = 500\text{GeV}$:
  - $A_N$ for electromagnetic jets
  - $A_N$ for inclusive neutral pions
Forward Meson Spectrometer (FMS):
-- Pb glass EM calorimeter covering $2.5<\eta<4.0$
-- Detect $\pi^0, \eta$, direct photons and jet-like events in the kinematic region where transverse spin asymmetries are known to be large.

Forward Preshower Detector in front of FMS in 2015 for direct photon detection.
Forward Meson Spectrometer (FMS):
-- Pb glass EM calorimeter covering 2.5< η <4.0
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**Forward Preshower Detector** in front of FMS in 2015 for direct photon detection
Inclusive π0 production

\[ p^\uparrow + p \rightarrow \pi^0 + X \]

\[ A_N \equiv \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} \]

\[ x_F = 2p_Z/\sqrt{s} \]

- Rising \( A_N \) with \( x_F \)
- \( A_N \) nearly independent of \( \sqrt{s} \)
- No evidence of fall in \( A_N \) with increasing \( p_T \)

PLB,261,201(1991)
PRL,101,222001(2008)
PRD,90,012006(2014)
More isolated pions have greater $A_N$ than those with nearby energy deposits
Pion $A_N$ is therefore event-topology dependent
**EM-Jet characteristics**

**p+p vs = 500 GeV transverse datasets**
- Jet algorithm: anti-kt
- R-parameter: 0.7
- $p_T^{EM-Jet} > 2.0$ GeV/c
- Photons with $p_T > 0.001$ GeV/c

**Leading EM-Jets:**
- Multi-photon Jets with highest energy
- $2.8 < \eta^{EM-Jet} < 4.0$
- $40$ GeV < Energy$^{EM-Jet}$ < $100$ GeV

- $\gamma\gamma$ invariant mass 2-photon EM-jets

**dE/d(\Delta R) distribution of EM-Jets**
- 2-photon jets are mostly $\pi^0$
- Events with more than 2 photons show jet-like energy flow
$A_N$ vs. EM-Jet Energy

- Isolated $\pi^0$'s have large asymmetries consistent with previous observation (CIPANP-2012 Steven Heppelmann)
  
  https://indico.triumf.ca/contributionDisplay.pycontribId=349&sessionId=44&confId=1383

- Asymmetries for “jettier” (event complexity) events are much smaller

- $\pi^0$-Jets –
  - 2$\gamma$-EM-Jets with
    - $m_{\gamma\gamma} < 0.3$
    - $Z_{\gamma\gamma} < 0.8$

- 2$\gamma$-EM-Jets ($\eta +$ continuum) –
  - with $m_{\gamma\gamma} > 0.3$

- EM-Jets –
  - with no. photons $> 2$
$A_N$ for different # photons in EM-Jets

1-photon events, which include a large $\pi^0$ contribution in this analysis, are similar to 2-photon events.

Three-photon jet-like events have a clear non-zero asymmetry, but substantially smaller than that for isolated $\pi^0$'s.

$A_N$ decreases as the event complexity increases (i.e., the "jettiness").

$A_N$ for #photons >5 is similar to that #photons = 5.
$A_N$ with mid-rapidity activities

- **Case-I**: having no central jet
- **Case-II**: having a central jet

**Central EM Jets**

- towers (BEMC+EEMC):
  - $|\eta| = 1.0, 2.0$
  - $\eta = 2.6-4.2$

**Leading central EM-Jets**: Jet with highest $p_T$

**Forward EMJets**:

- $\eta = 1.09, 2.0$

**BEMC**

- $\eta = -1.0, 1.0$

**EEMC**

**FMS**

- $\eta = 2.6-4.2$

**Central EM Jets**

- $\eta = 1.0, 2.0$

**towers (BEMC+EEMC)**:

- $\text{anti-}k_T$, $R = 0.7$, $p_T^{\text{EM-Jet}} > 2.0$ GeV/c, $-1.0 < \eta^{\text{EM-Jet}} < 2.0$
ΔΦ correlations between forward and central EM-Jets

Number of photons for forward EMJets:

- Correlation is stronger for more N_photon Jets
- For higher EMJets energy, correlation grows stronger

\begin{itemize}
  \item E = 40-60 GeV
    \begin{itemize}
      \item Entries 4163115
      \item Mean 2.16
      \item RMS 1.676
    \end{itemize}
  \item E = 60-80 GeV
    \begin{itemize}
      \item Entries 2404875
      \item Mean 2.18
      \item RMS 1.665
    \end{itemize}
  \item E = 80-100 GeV
    \begin{itemize}
      \item Entries 710428
      \item Mean 2.232
      \item RMS 1.639
    \end{itemize}
  \item E = 40-60 GeV
    \begin{itemize}
      \item Entries 7990953
      \item Mean 2.313
      \item RMS 1.594
    \end{itemize}
  \item E = 60-80 GeV
    \begin{itemize}
      \item Entries 6632622
      \item Mean 2.384
      \item RMS 1.55
    \end{itemize}
  \item E = 80-100 GeV
    \begin{itemize}
      \item Entries 2844054
      \item Mean 2.435
      \item RMS 1.515
    \end{itemize}
\end{itemize}
Asymmetries for the forward isolated π⁰ are low when there is a correlated away-side jet.
Asymmetries for $\pi^0$

- Isolated $\pi^0$ tend to have significantly larger asymmetries than $\pi^0$ associated with jet activities in the vicinity.
Collins asymmetries for $\pi^0$ relative to jet axis

- Total of Sivers and Collins asymmetries of EMjet and $\pi^0$ relative to jet axis are found to be insufficient to account for the observed inclusive $\pi^0$ single spin asymmetries.
Findings from forward rapidity

✧ Jets with isolated $\pi^0$ have large asymmetry.

✧ $A_N$ decreases as the event complexity increases (i.e., the "jettiness").

✧ Isolated $\pi^0$ asymmetries are smaller when there is a correlated EM-jet at mid-rapidity.

✧ Both of these dependences raise serious question about how much of the large forward $\pi^0$ $A_N$ comes from $2 \to 2$ parton scattering (diffractive events?).

✧ Total of Sivers and Collins asymmetries of EMjet and $\pi^0$ relative to jet axis are found to be insufficient to account for the observed inclusive $\pi^0$ single spin asymmetries.
STAR at central rapidity

- Asymmetric distributions of di-hadrons ($\pi^+$ and $\pi^-$)
  coupling **transversity** to the so-called “interference fragmentation function” (IFF) in the framework of collinear factorization

- Collins Asymmetry from Jets
  coupling **transversity** to the transverse-momentum-dependent (TMD) Collins FF

**2011**
- 25 pb$^{-1}$ at $\sqrt{s} = 500$ GeV
- Average polarization = 53%

**2012**
- 22 pb$^{-1}$ at $\sqrt{s} = 200$ GeV
- Avg polarization = 63%

Access to transversity in region with limited constraints

Compare to $\approx 2$ pb$^{-1}$ at 57% polarization in 2006
Interference Fragmentation Function (IFF)

\[ P^\uparrow + P \rightarrow \pi^+\pi^- + X \]

\[ d\sigma_{UT} \propto P_T^{\pi^+\pi^-} \sin(\phi_{RS}) \int dx_a dx_b f_1(x_a) h_1(x_b) \frac{d\Delta \hat{\sigma}}{d\hat{t}} H_1^<(z, M_{inv}^{\pi^+\pi^-}) \]

\[ \phi_{RS} = \phi_R - \phi_S \]
\[ \vec{p}_h = \vec{p}_{h,1} + \vec{p}_{h,2} \]
\[ \vec{R}_h = \vec{p}_{h,1} - \vec{p}_{h,2} \]

\[ A_{UT} \sin (\phi_{RS}) = \frac{1}{Pol} \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \]

\[ \propto h_1 \otimes H_1^< \quad \text{Survives in collinear framework} \]
Asymmetry with $m_{_{inv}}$ and $p_T$ for $\pi^+$ and $\pi^-$ pairs

- Significant di-hadron asymmetries both at $\sqrt{s}=200\text{GeV}$ and $\sqrt{s}=500\text{GeV}$
- Increasing with $p_T$
- Enhancement to asymmetry is seen around $\rho$ mass

$\langle P_T \rangle = 10.49$
$\langle P_T \rangle = 3.57$

$P^+ p \rightarrow \pi^+ \pi^- + X$ at $\sqrt{s} = 200\text{GeV}$

$\langle \eta \rangle = 0.84$
$\langle \eta \rangle = -0.84$

4.5% scale uncertainty from beam polarization
Jets to access Transversity

Transversity = \begin{align*}
\text{Collins FF} = \pi^\pm
\end{align*}

Key search in region x (0.1 < x < 0.35)

- dependence of the Collins FF on pion transverse momentum ($j_T$)
- Collins asymmetry universal?
- do these asymmetries evolve with $\sqrt{s}$?

\[ A_{\pi^\pm} \approx \frac{h_{q_1}^q (x_1, k_T) f_{q_2} (x_2, k_T) \hat{\sigma}_{UT} (\hat{s}, \hat{t}, \hat{u}) \Delta D_{q_1}^{\pi^\pm} (z, j_T)}{f_{q_1} (x_1, k_T) f_{q_2} (x_2, k_T) \hat{\sigma}_{UU} D_{q_1}^{\pi^\pm} (z, j_T)} \]
20 pb⁻¹ transversely polarized p+p collisions at $\sqrt{s} = 200$ GeV
Average event weighted polarization: 63%
Anti-$k_T$ (R = 0.6) jet reconstruction
$|\eta_{\text{jet}}| < 1$
Jet $p_T > 10$ GeV/c ($x_T > 0.1$) reduces gluon contamination
$\Delta R_{\text{min}} > 0.1$

$A_{\text{UT}}$ vs. $j_T$

$A_{\text{UT}}$ vs. $z$

$A_{\text{UT}}$ vs. $p_T$

The first statistically significant non-zero Collins asymmetries in pp collisions
200 vs. 500 GeV Comparison

- These measurements coupled with the interference fragmentation function (IFF) measurements at both 200 and 500 GeV will provide insight into the $Q^2$ evolution and universality of TMD functions.

- These results could lend sensitivity to the size of potential factorization-breaking in Collins in $p+p$. 

\[ p^\uparrow + p \rightarrow \text{jet} + \pi^\pm + X \]

STAR Preliminary

$A_{UT}$

$\Delta R = 1.3 \text{ GeV/c}$

Closed points: $\pi$; Open points: X

$\sin(\phi_H - \phi_X)$

$3.2 \text{ GeV/c}$

$\langle p_{T,jet} \rangle = 12.9 \text{ GeV/c}$

$\langle p_{T,jet} \rangle = 31.0 \text{ GeV/c}$

$\langle p_{T,\pi} \rangle = 1.3 \text{ GeV/c}$

$Z$

$0.2$ $0.4$ $0.6$
Projections till year 2017

• These measurements coupled with the interference fragmentation function (IFF) measurements at both 200 and 500 GeV will provide insight into the $Q^2$ evolution and universality of TMD functions.

• These results could lend sensitivity to the size of potential factorization-breaking in Collins in p+p.
2015 Rich Transverse physics data with STAR forward upgrades
 Observable without fragmentation func.: Drell-Yan, $W^\pm/Z$, jets, direct photons

measurements $\gamma_{\text{direct}}$ measurements as a test of twist-3 framework

$Sivers_{\text{DIS}} = - \text{Sivers (DY or W or Z)}$
STAR forward goals for data taking on 2015

- **Direct Photon** x-section & $A_N$ at $p_T>2.0$GeV (FMS + Pre-shower)
- **Pi0 $A_N$ - Jetty vs Isolated**:
  - $pp$ vs $pA(p+Au, p+Al)$, diffractive vs non-diffractive (Roman Pots)
- Study di-electron channel ($J/\psi$) towards DY

understand the underlying sub-process leading the big forward SSA in transverse polarized $p+p$ collisions.
Summary

- STAR measurements play an important role in understanding nucleon spin structure.

- **TSSA for π⁰’s and EMJets at forward rapidity** for \( \sqrt{s} = 500 \text{GeV} \) shed light to the origin of large transverse asymmetry.

- **IFF measurements** show high asymmetry for \( \pi^+ \) and \( \pi^- \) pairs and an enhancement at \( p \) mass region.

- **First Measurement of Transversity in \( p+p \)**: consistent with \( x_T \) scaling from 200 to 500 GeV.

- Data for 2015 moving toward \( A_N \) measurement of direct photons and DY at forward rapidity.

- **Collisions \( p\uparrow+p\uparrow \) and \( p\uparrow+Au \) and \( p\uparrow+Al \) would provide new insight** in understanding the underlying sub-process leading the big forward SSA in transverse polarized \( p+p \).
**FMS photon reconstruction:**

- **towers**
- **clusters**
- shower shape fitting
- **photon**

BEMC+EEMC towers: to find central electromagnetic jets

FMS photons: to find forward electromagnetic jets

2015 RHIC & AGS Annual Users' Meeting
Collins-like Asymmetries at $\sqrt{s} = 500\text{GeV}$

FIRST MEASUREMENT!

Present data sit well below maximized contribution of $\sim 2\%$ at low $z$

Present data should provide first constraints on Collins-like effect
(sensitive to linearly polarized gluons)