SIDIS $\pi^+$ Beam Spin Asymmetry Measurements
with CLAS 12

Stefan Diehl

Justus Liebig University Giessen
University of Connecticut
Physics Motivation

• The 3D nucleon structure in momentum space can be described by TMDs
• A way to access these properties is the semi inclusive deep inelastic scattering

SIDIS cross section for an unpolarized target:

→ Contains model independent structure functions

\[
\frac{d\sigma}{dx_B \, dQ^2 \, dz \, d\phi_h \, dp_{h\perp}^2} = K(x, y, Q^2) \left\{ F_{UU,T} + \varepsilon F_{UU,L} \right. \\
+ \left. \sqrt{2 \varepsilon(1 + \varepsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} + \varepsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda \varepsilon \sqrt{2(1 - \varepsilon)} \sin \phi_h F_{LU}^{\sin \phi_h} \right\}
\]

\[
F_{LU}^{\sin \phi} = \frac{2M}{Q} C \left( -\hat{h} \cdot \hat{k}_T \right) \frac{M_h}{x e H_1} \left( \frac{1}{z} + \frac{f_1}{M} \frac{\tilde{G}_1}{z} \right) + \frac{\hat{h} \cdot p_T}{M} \left( \frac{x g_1 D_1}{z} + \frac{M_h}{M} \frac{h_1}{z} \frac{\tilde{E}}{z} \right)
\]
Physics Motivation

\[ F_{LU}^{\text{sin} \phi} = \frac{2M}{Q} \mathcal{C} \left( -\hat{h} \cdot k_T \frac{x e H^1_1}{M_h} + \frac{M_h}{M} f_1 \frac{G^1_1}{z} + \hat{h} \cdot p_T \frac{x g_1 D_1}{M} + \frac{M_h}{M} h_1^1 \frac{\tilde{E}^1_1}{z} \right) \]

- A convolution of 4 TMDs and 4 fragmentation functions
- Each term contains a twist 3 component
- The results can be used in a global fit to constrain the TMDs and FF

Additional constraints: i.e. from unpolarized structure functions

\[ F_{UU}^{\cos \phi_h} = \frac{2M}{Q} \mathcal{C} \left( -\hat{h} \cdot p_T \frac{x h H^1_1}{M_h} + \frac{M_h}{M} f_1 \frac{\tilde{D}^1_1}{z} - \hat{h} \cdot k_T \frac{x f^1_1 D_1 + M_h h_1^1 \tilde{H}}{M} \right) \]

\[ F_{UU}^{\cos 2\phi_h} = \mathcal{C} \left[ -\frac{2(\hat{h} \cdot p_T)(\hat{h} \cdot k_T) - p_T \cdot k_T h_1^1 H_1^1}{M M_h} \right]. \]

+ di-hadron SIDIS: \[ F_{LU}^{\text{sin} \phi_R} = -x \frac{\vec{R} \sin \theta}{Q} \left[ \frac{M}{M_{\pi \pi}} xe^q(x) H_1^{<q} (z, \cos \theta, M_{\pi \pi}) + \frac{1}{z} f_1^q(x) \tilde{G}(z, \cos \theta, M_{\pi \pi}) \right] \]

+ constraints from other experiments (SIDIS + Drell-Yan)
Physics Motivation

Goal of this study: Extract $\frac{F_{LU}^{\sin \phi}}{F_{UU}}$ from single $\pi^+$ beam spin asymmetries

$$d\sigma = d\sigma_0 (1 + A_{UU}^{\cos \phi} \cos \phi + A_{UU}^{\cos 2\phi} \cos 2\phi + \lambda_e A_{LU}^{\sin \phi} \sin \phi)$$

$$BSA = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} = \frac{A_{LU}^{\sin \phi} \sin \phi}{1 + A_{UU}^{\cos \phi} \cos \phi + A_{UU}^{\cos(2\phi)} \cos(2\phi)}$$

$$A_{LU}^{\sin \phi} = \sqrt{2\varepsilon(1-\varepsilon)} \frac{F_{LU}^{\sin \phi}}{F_{UU}}$$

Past: Measurements have been performed with CLAS, HERMES and COMPASS

Advantages of CLAS12
- Significantly higher statistics
- Extended kinematic coverage ($Q^2$, $P_T$

Goal for a first CLAS12 publication: A multidimensional study in $Q^2$, $x_B$, $z$ and $P_T$
Experimental setup and available dataset

RG-A data from fall 2018 (pass 1 cooking):

- 10.6 GeV electron beam
- 85.9 / 89.2% average polarization
- liquid H₂ target

Available SIDIS eπ⁺X events with inbending field configuration:

<table>
<thead>
<tr>
<th></th>
<th>pass 1 (~170 runs)</th>
<th>DNP (64 runs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>eventbuilder:</td>
<td>1.01 \cdot 10^8</td>
<td>1.64 \cdot 10^7</td>
</tr>
<tr>
<td>after fid. cuts and PID ref:</td>
<td>5.67 \cdot 10^7</td>
<td>6.96 \cdot 10^6</td>
</tr>
</tbody>
</table>

Cooking of the outbending data is in progress
Electron ID

1. PCAL fiducial cuts
   \( (v, w > 9 \text{ cm}) \)

2. DC fiducial cuts for
   the 3 regions
   \( (\chi^2 / \text{NDF based method}) \)

3. PCAL energy
   deposition > 0.07 GeV
   eventbuilder: > 0.06 GeV

4. Calorimeter sampling fraction: 3-4 sigma region

5. \( p_e > 2.0 \text{ GeV} \)

6. z-vertex cut \([-13, +12]\)
   \( \Rightarrow \) Widening caused by \( \theta \) dependence
   of the vertex resolution

Stefan Diehl, JLU + UCONN
CLAS collaboration meeting, Newport News, VA
04/29/2020
1. DC fiducial cuts for the 3 regions

- Based on the local θ and Φ coordinates (from x, y, z hit positions)

Average $\chi^2$/NDF as a function of $\Phi_{\text{local}}$ for different bins in $\theta_{\text{local}}$ (sector 1, region1):

Plots by A. Kripko (Giessen)
Hadron ID

\[ a + b \cdot \log(\Theta) + c \cdot \Theta + d \cdot \Theta^2 \]

\[ \chi^2/\text{NDF} \]

\( \pi^+ \) region 1

\( \pi^+ \) region 2

\( \pi^+ \) region 3

plots by A. Kripko (Giessen)
Hadron ID

proton:

region 1

region 2

region 3

π⁺:

region 1

region 2

region 3

➔ Cuts individually adjusted for all hadron types
2. Cut on the z-vertex difference
The hadron vertex should not be outside the target region

3. Final selection based on TOF
→ Maximum likelyhood PID from eventbuilder with
\[ \chi^2_{\text{PID}} > -2.0 \quad \&\& \quad \chi^2_{\text{PID}} < +3.0 \]
Kinematic cuts

\[ P_{\text{min}}(e^-) = 2.0 \text{ GeV} \ (y < 0.8) \quad P_{\text{min}}(\pi^+) = 1.25 \text{ GeV} \]

**DIS cut:** \[ Q^2 > 1 \text{ GeV}^2 \quad W > 2 \text{ GeV} \]

**Classical SIDIS regime:** Cut on the final state hadron momentum fraction \( z \)

\[ 0.3 < z < 0.7 \]

\[ \rightarrow z > 0.3 \text{ removes the } "\text{target fragmentation region}" \]

\[ \rightarrow z < 0.7 \text{ removes contamination by pions from exclusive channels} \]

Cut on the \( e\pi^+X \) missing mass

\[ M_{\text{miss}} > 1.1 \text{ GeV} \]
Kinematic coverage for $\pi^+$

- DIS
- Preliminary data

Counts

- $Q^2$ [GeV$^2$]
- $W$ [GeV]
- $Q^2$ [GeV$^2$]
- $x_B$
- $P_T$ [GeV]

Experimental, CLAS-DIS MC data

Stefan Diehl, JLU + UCONN
CLAS collaboration meeting, Newport News, VA
04/29/2020
 Beam spin asymmetry

\[ BSA_i = \frac{1}{P_e} \cdot \frac{N_i^+ - N_i^-}{N_i^+ + N_i^-} \]

\[ P_e = \begin{cases} 
85.9 \% & \text{for run } \leq 5328 \\
89.2 \% & \text{for run } \geq 5331 
\end{cases} \]
In 1 dimension:

→ statistical uncertainty is very small!

But: Uncertainty of the integrated kinematics is very large and hard to model in theory
A multidimensional binning

without a cut on $M_{\text{miss}} > 1.1$ GeV:

$Q^2$ [GeV$^2$]

$X_B$

$z$ vs $P_T$

$P_T$ [GeV]

$P_T$ [GeV]
A multidimensional binning

The adjustment of the final binning scheme is in progress
A multidimensional binning

1.5 GeV² < Q² < 2.5 GeV²  z vs P_T bin 1  0.1 < x_b < 0.2

7 x 7 bins in the z – P_T plane

1.5 GeV² < Q² < 2.5 GeV²  z vs P_T bin 3  0.3 < x_b < 0.45

7 x 7 bins in the z – P_T plane
BSA for bin 1 (1.5 GeV < Q² < 2.5 GeV and 0.1 < x_B < 0.2)
BSA for bin 6 ($Q^2 > 4.5 \text{ GeV}^2$ and $x_B > 0.45$)
results for bin 1 (1.5 GeV < Q^2 < 2.5 GeV and 0.1 < x_B < 0.2)
results for bin 4 and 5

- $F_{LU}^{sin(\phi)} / F_{UU}$ versus $z$ for bin 4
- $F_{LU}^{sin(\phi)} / F_{UU}$ versus $P_T$ for bin 4
- $F_{LU}^{sin(\phi)} / F_{UU}$ versus $z$ for bin 5
- $F_{LU}^{sin(\phi)} / F_{UU}$ versus $P_T$ for bin 5

Increasing $z$ and small $z$.
results for bin 6 \((Q^2 > 4.5 \text{ GeV}^2 \text{ and } x_B > 0.45)\)

\(F_L^\sin(\phi)/F_U^\sin(\phi)\) versus \(z\) for bin 6

\(F_L^\sin(\phi)/F_U^\sin(\phi)\) versus \(P_T\) for bin 6

Increasing \(z\)

Small \(P_T\)

Medium + large \(P_T\)
Sources of systematic uncertainty

- Uncertainty of the beam polarisation
- Fiducial cuts and particle ID refinements
  (strictness of the PID / contamination in the pion sample)
- Acceptance Effects
- Extraction method and higher order moments
- Detector inefficiencies / sector dependence
- Radiative effects
- Binning / resolution effects

→ See my talk at the last collaboration meeting
→ Study is in progress based on the final inbending statistics
Comparison to theoretical predictions

Theoretical predictions will be compared to the multidimensional data.

A multidimensional binning will enable a much better comparability with the calculations and a more reliable TMD extraction from global fits.

Fig. 5 Predictions on the beam SSAs for charged pions (left panel), charged kaons (central panel), and proton/antiprotons (right panel) in SIDIS at JLab with a 12 GeV electron beam scattered off a proton target. The upper panels show the results calculated from the TMD DFs in Set 1 and the lower panels show the results calculated from the TMD DFs in Set 2. The dashed, dotted and solid curves show the asymmetries from the $eH_1^\perp$ term, the $g^\perp D_1$ term and the sum of the two terms, respectively.

Stefan Diehl, JLU + UCONN  CLAS collaboration meeting, Newport News, VA  04/29/2020
Timelines and path towards a first publication

April 1
- cooking of the fall inbending data

Mai 1
- cooking of the fall outbending data
- finalize PID cuts

June 1
- define final binning and extract results
- do systematic checks on final dataset

July 1
- complete analysis note and paper
- ongoing discussions and iterations
- cross check

August 1
- common production of large scale SIDIS MC
- MC based systematic checks

September 1
- collaboration review

Stefan Diehl, JLU + UCONN
CLAS collaboration meeting, Newport News, VA
04/29/2020
Conclusion and Outlook

- All analysis methods have been developed and tested on the DNP data
- Adjustment of cuts etc. for the pass 1 data is in progress / completed
- Common SIDIS MC production for pass 1 data is in progress
- The goal for the first publication is to show a multidimensional binning for $\pi^+$
  → A multidimensional binning will be available for the first time and is very important for global TMD fits.
- The final multidimensional binning is under investigation
  → Statistics (~ 10 x more than DNP) is sufficient for a fully multidimensional binning (we expect up to 588 bins)
- The analysis note and the paper are under preparation in coordination with the common RG-A analysis note