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

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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:**

\[ d\sigma \over dx_B dQ^2 dz d\phi_h dp_{h\perp} = K(x, y, Q^2) \left\{ F_{UU,T} + \varepsilon F_{UU,L} \right\} \]

\[ + \sqrt{2 \varepsilon (1 + \varepsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} + \varepsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda \varepsilon \sqrt{2 \varepsilon (1 - \varepsilon)} \sin \phi_h F_{LU}^{\sin \phi_h} \]

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

Collins FF  
unpolarized dist. function

Boer-Mulders  
twist-3 FF

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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

\[ F_{UU}^{\cos \phi_h} = \frac{2M}{Q} C \left[ \frac{\hat{h} \cdot p_T}{M_h} \left( xh_1^+ + \frac{M_h}{M} f_1 \tilde{D}_1^+ \right) - \frac{\hat{h} \cdot k_T}{M} \left( xf_1^+ D_1 + \frac{M_h}{M} h_1^+ \tilde{H} \right) \right] \]

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

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

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

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Goal of this study: Extract $F_{LU}^{\sin \phi}$ 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 the 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:

- 10.6 GeV electron beam
- 85% average polarization
- liquid H₂ target

Plots shown in this presentation: ~ 3% of the approved RG-A beam time (DNP 2019) inbending torus field

Data for first publication: complete fall 2018 inbending dataset (~ 3 x more) outbending data can be used to extend the kinematic region
Electron ID

1. PCAL fiducial cuts

2. DC fiducial cuts for the 3 regions

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

4. Calorimeter sampling fraction: 3 sigma region

5. $p_e > 2.0$ GeV

6. $z$-vertex cut $[-11, +9]$ 
   $\Rightarrow$ 2 % level of the maximum

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1. DC fiducial cuts for the 3 regions

2. Final selection based on TOF
   → Maximum likelyhood PID from eventbuilder with $|\chi^2_{PID}| < 2.0$
Kinematic cuts

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

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

**Additionally:** Cut on the final state hadron momentum fraction \( z \)

\[ 0.3 < z < 0.7 \]

\[ \rightarrow z > 0.3 \text{ removes the "target fragmentation region"} \]
\[ \rightarrow z < 0.7 \text{ removes contamination by pions from exclusive channels} \]
Kinematic coverage for $\pi^+$

- $Q^2$ vs. $W$ [GeV]
- $Q^2$ vs. $X_B$ [GeV²]

Counts vs. $Q^2$, $X_B$, $Z$, $P_T$ [GeV]

- Experimental
- CLAS-DIS MC data

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Beam spin asymmetry

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

\( P_e = 85\% : \) average e\(^{-}\) beam polarisation

\[ \Phi \text{ dependence without kinematic bins} \]

\( <Q^2> \sim 3.0 \text{ GeV}^2 \quad <x_B> \sim 0.27 \quad <z> \sim 0.42 \quad <P_T> \sim 0.45 \)

\( \Rightarrow \) Clear sinoid shape can be observed

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for a \( z, x_B, P_T \) and \( Q^2 \) binning

\[
\frac{F_{LU}^{\sin\phi}}{F_{UU}^{\sin\phi}}
\]

\( \text{CLAS12} \)

\( \text{CLAS} \)

[W. Gohn et al. PRD 98 (2014)]
**Step 1: A two dimensional binning**

0.3 < \( z < 0.7 \)

0.0 \( \text{GeV} \) < \( P_T \) < 1.4 \( \text{GeV} \)

1.0 \( \text{GeV}^2 \) < \( Q^2 \) < 12 \( \text{GeV}^2 \)
Step 2: A multidimensional binning in z, \( x_B \), \( P_T \) and \( Q^2 \)

**\( \Pi^+ \)**

0.3 < z < 0.4

Behaviour at large \( Q^2 \):
- Decrease for small \( P_T \)
- Increase for large \( P_T \)
A multidimensional study

0.3 < z < 0.4

$\pi^+$

$Q^2 = 1.8 \text{ GeV}^2$

$Q^2 = 2.4 \text{ GeV}^2$

$Q^2 = 3.2 \text{ GeV}^2$

$Q^2 = 4.5 \text{ GeV}^2$
A multidimensional study

$0.3 < z < 0.4$

$\pi^+$

Conclusion on $x_B$:

- Increase for small $Q^2$ independent of $P_T$
- Decrease at large $Q^2$ independent of $P_T$
- Nearly flat at intermediate $Q^2$
- Slope and magnitude are dominated by $Q^2$
A multidimensional study

$0.3 < z < 0.4$

$\pi^+$

- $Q^2 = 1.7 \text{ GeV}^2$
- $Q^2 = 2.3 \text{ GeV}^2$
- $Q^2 = 3.3 \text{ GeV}^2$
- $Q^2 = 4.4 \text{ GeV}^2$
A multidimensional study

$0.3 < z < 0.4$

Conclusion on $P_T$:

- Increase up to high $P_T$ if $Q^2$ and $x_B$ are small
- Flat behaviour at large $P_T$ for intermediate $Q^2$ and $x_B$
- Slight decrease at large $P_T$ for large $Q^2$ and $x_B$
- Slope and magnitude influenced by $Q^2$ and $x_B$
Kinematic coverage: outbending vs inbending

- $Q^2$
- $x_B$
- $z$
- $P_T$

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Possible 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
Available measurements:

- Change of the beam polarisation has to be considered.

~3% systematic uncertainty from the measurement.
Systemtics: Uncertainty from the PID

\[ A_{LU} \]

\[ Q^2 \text{ [GeV]²} \]

\[ z \]

\[ \text{systematic PID uncertainty} \]

- Small effect (requires final statistics for precise results)

**red:** eventbuilder

**black:** redefined PID
Systematics: Dependence of the result on the data quality

\( \pi^+ \text{ or } \pi^- \)

- Dependence on data quality
- Comparison between fall 2018 (DNP 2019) and spring 2018 (DNP 2018)

Graphs showing variation with various variables:
- \( Z \)
- \( X_B \)
- \( P_T \) [GeV]
- \( Q^2 \) [GeV^2]
Comparison of different extraction methods

Method 1: $\chi^2$ fit of the BSA calculated for 12 $\phi$ bins

a) 1 moment only:  $BSA = A_{LU}^{\sin \phi} \cdot \sin(\phi)$

b) all 3 moments:  $BSA = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} = \frac{A_{LU}^{\sin \phi} \sin \phi}{1 + A_{UU}^{\cos \phi} \cos \phi + A_{UU}^{\cos(2\phi)} \cos(2\phi)}$

+ fast  
- using all 3 moments not reliable for low stat.

Method 2: Statistical extraction (unbinned in $\phi$)

a) 1 moment only:  $P = -\prod_{i=1}^{N} (1 + h \cdot P_e \cdot \text{gauss}(A_{LU}^{\sin \phi}, \sigma) \cdot \sin(\phi))$

b) all 3 moments:  $P = -\prod_{i=1}^{N} \left(1 + h \cdot P_e \cdot \frac{\text{gauss}(A_{LU}^{\sin \phi}, \sigma_1) \cdot \sin(\phi)}{1 + \text{gauss}(A_{UU}^{\cos \phi}, \sigma_2) \cdot \cos(\phi) + \text{gauss}(A_{UU}^{\cos(2\phi)}, \sigma_3) \cdot \cos(2\phi)} \right)$

⇒ Minimize $P$

+ partly a reduced error  
+ more reliable for low stat.  
- slow  
- no direct visualisation of the quality  
+ does not depend on the phi binning  
+ less sensitive to possible holes in the phi coverage
\[ \pi^+ \text{ - Comparison of all 4 extraction variants} \]
Systematics: Comparison of the sector dependence ($\pi^+$ sector)
Systematics: Acceptance effects

$\pi^+ \phi$ acceptance, based on SIDIS MC

- Smooth acceptance curves
- If they exist, acceptance effects due to the finite bin size only around $\phi = 0$
**Systematics: acceptance effects**

**MC for π⁺:**
- Generated (with experimental BSA)
  - fit to exp. result:
    \[ A_{LU}^{\sin\phi} = -0.00285 + 0.05787 \times z_{\text{gen}} \]
- ~ 60 – 80 million events

**reconstructed:**
- no variation within statistical uncertainty
- for a precise study 500 – 1000 million MC events will be produced (CLAS DIS).

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Comparison to theoretical predictions

A first theoretical model for single pion SIDIS was introduced in

Simplifying assumption:
• only contribution from $e(x) \otimes H_1^\perp$

$$F_{LU}^{\sin \phi} \sim \frac{2M}{Q} C \left( -\frac{\hat{h} \cdot k_T}{M_h} \left( xe H_1^\perp + \frac{M_h}{M} f_1 \frac{\tilde{G}_1^\perp}{z} \right) 
+ \frac{\hat{h} \cdot p_T}{M} \left( xg_1 D_1 + \frac{M_h}{M} h_1^\perp \frac{\tilde{E}}{z} \right) \right)$$

• sign is correctly reproduced
• magnitude at large $x$ is too low

Recent global fits show that the other terms can not be neglected

Some of the TMDs and FF got better constrained
Comparison to theoretical predictions

Newer predictions (2014):

On the beam spin asymmetries of electroproduction of charged hadrons off the nucleon targets

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- Updated calculations, including all known terms and the most recent TMDs and FF are in progress by P. Schweitzer et al.
- A multidimensional binning will enable a much better comparability with the calculations

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 $eH^\perp_1$ term, the $g^\perp D_1$ term and the sum of the two terms, respectively.
Timelines and path towards a first publication

- **April 1**: cooking of 90 runs inbend.
- **May 1**: cooking of the remaining fall inbend. data
- **June 1**: finalize redefined PID cuts
- **June 1**: do systematic checks on final dataset
- **June 1**: define final binning and extract results
- **June 1**: complete analysis note and paper
- **July 1**: ongoing review
- **03/20/2020**: final release for fall inbending is approved + cooking started
- **03/25/2020**: common production of large scale SIDIS MC
- **03/25/2020**: MC based systematic checks

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Conclusion and Outlook

• All analysis methods have been developed and tested on the DNP data

• Adjustment of cuts etc. will start as soon as the first bunch of the final data is available (next week)

• MC production will be done in parallel on OSG (common SIDIS MC)

• The goal for the first publication is to show a multidimensional binning for $\pi^+$
  $\rightarrow$ A multidimensional binning will be available for the first time and is very important for global TMD fits.

• The analysis note and the paper are under preparation