Analyzing nucleon spin structure through SIDIS at Jefferson Lab

EUNPC 2012
Bucuresti,
September 20°, 2012.
In the last decades, Deep Inelastic Scattering (DIS) greatly contributed to depict a longitudinal representation of the nucleon.

At the leading order (twist)\(^1\), three Parton Distribution Functions (PDF) exhaust the description of quarks inside the nucleon:

- \( f_1^q(x) \): number density of an unpolarized quark in an unpolarized nucleon
  - known with high accuracy

- \( g_1^q(x) \): number density of longitudinally polarized quark in a longitudinally polarized nucleon
  - less well known (but there are measurements: see, e.g., Hermes data for 5 different quark flavours*)

- \( h_1^q(x) \): number density of transversely polarized quarks in a transversely polarized nucleon
  - the transversity is the only missing ingredient to complete the leading-twist picture of the nucleon.

\(^1\)Twist refers to the order in \( \frac{M}{Q} \) at which the distribution function contributes to the cross-section. See Jaffe, hep-ph/9602236.

\(^*\)A. Airapetian et al. PRD 71, 012003 (2005)
The proton has also a non-collinear structure

\[ p = xP \]

and its theoretical description is enriched. In the collinear approximation the proton is described as

\[
\Phi(x) = \frac{1}{2} \left\{ f_1 \gamma_+ + S_L g_1 \gamma_5 \gamma_+ - h_1 \frac{[S_T, \gamma_+]\gamma_5}{2} \right\}
\]

while, once a tranverse component for the quark momentum is considered, we got

\[
\Phi(x, p_T) = \frac{1}{2} \left\{ f_1 \gamma_+ \right. - \frac{1}{16T} \frac{c^p_T p_T p T S_T}{M} \gamma_+ + S_L g_1 \gamma_5 \gamma_+ - \frac{1}{11T} \frac{p_T \cdot S_T}{M} \gamma_5 \gamma_+ \\
+ \frac{h_1 T}{2} \frac{[S_T, \gamma_+]\gamma_5}{2} + S_L \frac{1}{11T} \frac{[p_T, \gamma_+]\gamma_5}{2M} \\
- \frac{h_1 T}{M} \frac{p_T \cdot S_T}{2M} \frac{[p_T, \gamma_+]\gamma_5}{2M} + \frac{h_1 T}{M} \frac{[p_T, \gamma_+]\gamma_5}{2M} \right\}
\]

1. TMDs depend on \( x \) and \( p_T \)
2. Describe correlations between \( p_T \) and quark or nucleon spin (spin-orbit correlations)
3. Provide a 3-D picture of the nucleon in momentum space (nucleon tomography)
Accessing the Tranverse Momentum Distributions (TMDs)

To access tranverse structure of the nucleon we rely on Semi-Inclusive DIS (SIDIS)

Through **Factorization** → \( \sigma^{e p \rightarrow e h X} = \sum q DF \otimes \sigma^{e q \rightarrow eq} \otimes FF \)

<table>
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<tr>
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<th>U</th>
<th>L</th>
<th>T</th>
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<td>( h_{1L}^- )</td>
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<td>( h_1, h_{1T}^+ )</td>
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Fragmentation Functions

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<td>L</td>
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<td>( H_{1L}^+ )</td>
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<td>( H_1^+ )</td>
<td>( G_{1T} )</td>
<td>( H_1, H_{1T}^+ )</td>
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</table>

FF describe the transition from the partonic to the hadronic d.o.f.
Depending on the degrees of freedom active in the process, various TMD\&FF can be accessed.

\[
\frac{d\sigma^h}{dx \, dy \, d\phi \, dz \, d\phi \, dP_{h\perp}^2} = \frac{\alpha^2}{x y Q^2 (1-\epsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) 
\]

\[
\begin{align*}
&\{ \\
&\quad \left[ F_{UU,T} + \epsilon F_{UU,L} \right] \\
&\quad + \sqrt{2\epsilon (1+\epsilon)} \cos(\phi) F_{UU}^{\cos(\phi)} + \epsilon \cos(2\phi) F_{UU}^{\cos(2\phi)} \\
&\quad + \lambda_L \left[ \sqrt{2\epsilon (1-\epsilon)} \sin(\phi) F_{LU}^{\sin(\phi)} \right] \\
&\quad + \lambda_L \left[ \sqrt{2\epsilon (1+\epsilon)} \sin(\phi) F_{UL}^{\sin(\phi)} + \epsilon \sin(2\phi) F_{UL}^{\sin(2\phi)} \right] \\
&\quad + S_L \lambda_L \left[ \sqrt{1-\epsilon^2} F_{LL} + \sqrt{2\epsilon (1-\epsilon)} \cos(\phi) F_{LL}^{\cos(\phi)} \right] \\
&\quad + S_L \lambda_L \left[ \sin(\phi - \phi_s) \left( F_{UT,T}^{\sin(\phi-\phi_s)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_s)} \right) \right. \\
&\quad + \epsilon \sin(\phi + \phi_s) F_{UT}^{\sin(\phi+\phi_s)} + \epsilon \sin(3\phi - \phi_s) F_{UT}^{\sin(3\phi-\phi_s)} \\
&\quad + \sqrt{2\epsilon (1+\epsilon)} \sin(\phi_s) F_{UT}^{\sin(\phi_s)} \\
&\quad + \sqrt{2\epsilon (1+\epsilon)} \sin(2\phi - \phi_s) F_{UT}^{\sin(2\phi-\phi_s)} \right] \\
&\quad + S_T \lambda_L \left[ \sqrt{1-\epsilon^2} \cos(\phi - \phi_s) F_{LT}^{\cos(\phi-\phi_s)} \right. \\
&\quad + \sqrt{2\epsilon (1-\epsilon)} \cos(\phi_s) F_{LT}^{\cos(\phi_s)} \right. \\
&\quad + \sqrt{2\epsilon (1-\epsilon)} \cos(2\phi - \phi_s) F_{LT}^{\cos(2\phi-\phi_s)} \left. \right] 
\}
\]

18 structure functions appear in the cross-section:

\[
F_{ij,K} \propto DF \otimes FF
\]
The **Cebaf Large-Acceptance Spectrometer (CLAS)** is installed in the Hall-B of the Thomas Jefferson National Accelerator Facility (Newport News, VA, USA).

The CEBAF:
- provides a continuous electron beam with a duty factor $\sim 100\%$;
- with a beam energy up to 6 GeV;
- has a good energy resolution ($\frac{\sigma_E}{E} \sim 10^{-5}$);
- and the beam has a polarization $\sim 85\%$

The CLAS detector is provided with:

- Toroidal magnetic field (6 superconducting coils)
- Drift chambers (argon/CO2 Gas, 35000 cells)
- Time-of-flight scintillators
- Electromagnetic calorimeters
- Cherenkov counters ($e/\pi$ separation)

Presently upgrading to 12 GeV!
During the 6 GeV era, CLAS accessed the **unpolarized** and **longitudinally polarized** parts of the cross-section

**Unpolarized targets**
- Liquid H target, 60 days data taking – 2001-2002
  - $\sigma_{UU}$ PRD 80, 032004 (2009)
- Liquid H target, 60 days data taking – 2005
  - $\pi^0$ BSA Phys. Lett. B 704, 397 (2011)

**Longitudinally polarized targets**
- NH3, ND3 targets, 5 days data taking 2001
  - $A_{UL}, A_{LL}$ PRD 80, 032004 (2009)
- NH3, ND3 targets (E05-113), 60 days data taking 2009
  - Experiment E05-113, analyses ongoing
By using a 5.7 GeV polarized electron beam impinging on a LONGITUDINALLY polarized target CLAS extracted

- **Single Spin Asymmetry** (SSA)

\[ A_{UL} = \frac{1}{fP_t} \frac{N^+-N^-}{N^++N^-} \propto A_{UL}^{\sin \varphi} \sin \varphi + A_{UL}^{\sin 2\varphi} \sin 2\varphi \]

1. \( A_{UL}^{\sin 2\varphi} \): it is the only term arising at LEADING ORDER, and it involves the coupling \( h_{1L}^+ \otimes H_1^- \). The only available measurements by Hermes* is consistent with zero.
2. \( A_{UL}^{\sin \varphi} \): expected to be dominated from higher-twist contributions

- **Double-Spin Asymmetry** (DSA)

\[ A_{LL} = \frac{1}{fD'(y)P_BP_t} \frac{N^+-N^-}{N^++N^-} \propto g_1 \otimes D_1 \]

\( g_1 \) is well known in the collinear case → its \( p_T \) dependence only recently explored

\[ \begin{array}{|c|c|c|c|}
\hline
N/q & U & L & T \\
\hline
U & f_1 & \text{ } & h_{1L}^+ \\
L & g_1 & \text{ } & h_{1L}^- \\
T & f_{1T}^+ & g_{1T} & h_1, h_{1T}^+ \\
\hline
\end{array} \]

\[ \begin{array}{|c|c|c|c|c|}
\hline
q/H & U & L & T \\
\hline
U & D_1 & \text{ } & H_1^- \\
L & G_{1L} & \text{ } & H_{1L}^- \\
T & H_1^+ & G_{1T} & H_1, H_{1T}^+ \\
\hline
\end{array} \]
Longitudinally-polarized contribution $\rightarrow A_1$ $x$-dependence

$$A_{LL} = \frac{1}{fD'(y)P_BP_T} \frac{N^+ - N^-}{N^+ + N^-} \propto g_1 \otimes D_1$$

$x$-dependence from 2001 data set

- $f = 0.14$ is the dilution factor
- $D'(y)$ is a depolarization factor
- $P_B \sim 70\%$ is the beam polarization
- $P_T \sim 75\%$ is the target polarization
- $N^\pm$ the luminosity integrated yields

NEW DATA (2009): analysis in progress

- Very precise data in the **high-$x$ region**
- Consistent with HERMES data in the **low-$x$ region** $\rightarrow$ weak $Q^2$ dependence of $A_1$
- Data consistent with calculation using leading-order GRSV* PDFs

Longitudinally-polarized contribution → $A_1 p_T$-dependence

$p_T$-dependence from 2001 data set

- Dependence could be related to different widths for TMD for different quark flavours & polarizations, resulting from different orbital motion of quarks polarized || or anti-|| to the proton spin.

- Compared with predictions from Torino group* → different values for the ratio

$$R = \frac{k_\perp \text{width of } g_1}{k_\perp \text{width of } f_1}$$

- $R = 0.40$
- $R = 0.68$
- $R = 1.0$

NEW DATA (2009): analysis in progress

With these new data set – 10 times more statistics – a 2-D analysis ($x, p_T$) will be performed

Longitudinally-polarized contribution \( \rightarrow \) SSA

\[
A_{UL} = \frac{1}{f P_t N^+ + N^-} \propto A_{UL}^{\sin \varphi} \sin \varphi + A_{UL}^{\sin 2\varphi} \sin 2\varphi \rightarrow h_{1L}^{\perp} \otimes H_{1}^{\perp}
\]

- **Clear \( \sin 2\varphi \) modulation for \( \pi^{\pm} \)**
- **Collins function suppressed for \( \pi^{0} \)?**
- **Small modulation in agreement with HERMES results \( \rightarrow \) cancellation among favored and unfavored Collins observed by HERMES & Belle**

**NEW DATA (2009): analysis in progress**

- Large \( \sin \varphi \) component \( \rightarrow \) HIGHER TWIST contribution important @CLAS kinematics
- 2-D extraction \( A_{UL}^{\sin \varphi} (x, p_T) \) & \( A_{UL}^{\sin 2\varphi} (x, p_T) \) ongoing
12 GeV CEBAF will explore a kinematical region complementary to other experiment

Valence region will be highly explored @CLAS

CLAS12 detector with
1. RICH for π/k separation in the 3-8 GeV momentum range
2. HD-ice target
In the future: transversely polarized term

In the CLAS12 era, the presence of a transversely polarized target will give access to the transverse part of the cross-section.

\[
\frac{d\sigma}{dxdy d\phi_S dz d\phi dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2} x (1 + \frac{\gamma^2}{2x}) \left( F_{UU,T} + \epsilon F_{UU,L} \right) + \sqrt{2\epsilon(1+\epsilon)} \cos(\phi) F_{UU} \cos(2\phi) + \epsilon \cos(2\phi) F_{UU} \cos(2\phi)
\]

\[
\begin{align*}
N/q & \quad U & \quad L & \quad T \\
U & \quad f_1 & & \quad h_1^- \\
L & \quad g_1 & \quad h_1^L & \\
T & \quad f_{1T}^+ & \quad g_{1T} & \quad h_1 & h_{1T}^+ \\
\end{align*}
\]

E12-06-112: Pion SIDIS
E12-09-008: Kaon SIDIS

E12-06-112: Pion SIDIS
E12-09-008: Kaon SIDIS

Tranversely polarized targets

- PR12-11-111: Pion/Kaon SIDIS
- PR12-12-009: Pion/Kaon SIDIS

- Tranversity \( \rightarrow A_{UT}^{\sin(\varphi+\varphi_S)} \propto h_1 \otimes H_{1T} \)
- Sivers function \( \rightarrow A_{UT}^{\sin(\varphi-\varphi_S)} \propto f_{1T} \otimes D_1 \)
- Pretzelosity \( \rightarrow A_{UT}^{\sin(3\varphi-\varphi_S)} \propto h_{1T} \otimes H_{1T} \)
- Worm-gear \( \rightarrow A_{LT}^{\cos(\varphi-\varphi_S)} \propto g_{1T} \otimes D_1 \)
In the 12 GeV era, CLAS12 will be able to combine measurements with unpolarized, transversely- and longitudinally-polarized targets - to put important constraints on all chiral-odd, leading-twist TMDs in the range

- $1 < Q^2 < 8 \text{ GeV}^2$
- $0.05 < x < 0.6$
- $P_{h\perp} < 1.5 \text{ GeV}$

The Q-dependence will allow to isolate higher-twist effects, while the extended $p_{h\perp}$ range will open the exploration of the transition from non-perturbative to perturbative region.

The RICH subdetector will allow measurements involving kaons

- Their measurement is challenged by the almost one order of magnitude larger pion flux
- Very little is known about the spin-orbit correlations related to the strange quark
- Indication of non-trivial role of the sea quarks in the nucleon, and of the fragmentation mechanism in the presence of a strange quark
- Kaons may provide enhanced sensitivity to higher-twist effects.

A high-luminosity, large-acceptance experiment, also provided with an efficient hadron identification, will be able to explore the relevant kinematical dependence essential to interpret the results.
**Collins effect:** it is due to the correlation among quark transverse polarization and the transverse momentum of the final hadron

- It appears as an azimuthal asymmetry in the direction of the final hadron
- Effects already observed @HERMES & COMPASS
- Gives access to transversity

\[ A_{UT}^{\sin(\phi+\phi_S)} \propto h_1 \otimes H_{1T} \]

**With CLAS12:**
- Large statistics on the high-x region, important to constraint the tensor charge
- High resolution and broad range in \( p_T \) to test the transition from perturbative to non-perturbative regime

Projections for \( L = 5 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \), HD-ice target with a H polarization \( \sim 60\% \), \( f \sim 1/3 \), RICH detector
Sivers effect: it is due to the correlation among quark transverse momentum and nucleon transverse polarization

- It appears as an azimuthal asymmetry in the direction of the final hadron
- It implies the presence of an angular momentum
- Gives access to the Sivers function $f_{1T} \rightarrow A_{UT}^{\sin(\phi - \phi_S)} \propto f_{1T} \otimes D_1$

$Q^2$-dependence of Sivers asymmetry → test of the TMD evolution

Projections for $L = 5 \cdot 10^{33}$ cm$^{-2}$ s$^{-1}$, HD-ice target with a H polarization $\sim 60\%$, f$\sim 1/3$, RICH detector
## CLAS12 physics program

<table>
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<th>Proposal</th>
<th>Contact Person</th>
<th>Physics</th>
<th>Energy (GeV)</th>
<th>PAC days</th>
<th>Parallel Running</th>
<th>Run Group</th>
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**Total**

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Conclusions

- Correlations among parton transverse momentum & spin is essential to **relate the nucleon structure to its elementary degrees of freedom**

- Azimuthal asymmetries extracted so far suggest that such correlations may be important

- In the 6 GeV era, CLAS@Hall-B performed important measurements related to the **unpolarized** and to the **longitudinal** part of the cross-section, providing information for the structure function behaviour in the **valence region**

- In the 12 GeV era, the upgraded CLAS12 will widen the explored kinematical range for the **understanding of the nucleon spin structure**

- The high-luminosity and high precision of the measurements will allow multidimensional analysis of the moments, especially in the **high-x (valence) region and high \( p_T \) region** (transition between perturbative and non-perturbative regime)

(A lot of hadrons ahead!)

*(President Thomas Jefferson in the Hall-B Counting Room)*
backup
In the unpolarized term of the cross-section, two structure functions appear:

- $F_{UU}^{\cos(2\phi)}$ leading twist

$$d\sigma_{UU}^{\cos2\phi} \propto \cos2\phi \cdot \sum_q e_q^2 \left[ \frac{2(\hat{P}_{h\perp} \cdot \vec{k}_T)(\hat{P}_{h\perp} \cdot \vec{p}_T) - \vec{k}_T \cdot \vec{p}_T}{MM_h} h_{1T}^+ H_{1T}^- \right]$$

- $F_{UU}^{\cos(\phi)}$ sub-leading twist

$$d\sigma_{UU}^{\cos\phi} \propto \cos\phi \cdot \sum_q e_q^2 \frac{2M}{Q} \left[ \frac{(\hat{P}_{h\perp} \cdot \vec{p}_T)}{M_h} h_{1L}^+ H_{1L}^- \frac{(\hat{P}_{h\perp} \cdot \vec{k}_T)}{M} f_1D_1 + \ldots \right]$$

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<td>H_1^+</td>
<td>G_{1T}</td>
<td>H_1, H_{1T}^+</td>
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</table>
Boer-Mulders effect

\[ \langle \cos 2\phi \rangle_{UU} \propto h_1^l \otimes H_1^{lq} \]

1. Positive amplitudes in the low-z, high-\( p_T \) regions, zero elsewhere
2. Theoretical predictions expect zero amplitudes \( \rightarrow \) consistent with data but for low-z, high-\( p_T \) regions
$\langle \cos \phi \rangle_{UU} \propto h_1^{1} \otimes H_1^{1q} + f_1 \otimes D_1$

1. Non-zero amplitudes
2. Sign change in the high-$p_T$ regions
3. Theoretical predictions show same behaviours but larger amplitudes
CLAS12 is an ideal environment to study dihadron processes. Its large acceptance will allows the simultaneous detection of the scattered electrons and of the hadrons from the hadronization of the struck quarks.

PID in the forward region relies in the

- High-Threshold Cherenkov Counter
- Low-Threshold Cherenkov Counter
- Forward Time-Of-Flight system

**BUT**

- For momenta in the range 2.5–5 GeV/c the π/K separation relies only on the LTCC performance.
- In the 4.7–8 GeV/c momentum region it is not possible to separate protons from kaons.

A RICH detector is under development for CLAS12 to take the place of LTCC in SIDIS analysis.
CLAS12 will be composed of a **forward detector** and a **central detector**

**Forward Detector**
- Torus Magnet
- Forward Tracker
- High-Threshold Cherenkov Counter
- Low-Threshold Cherenkov Counter
- Forward Time-Of-Flight system
- Preshower Calorimeter
- Electromagnetic Calorimeter
- Inner e.m. Calorimeter

**Central Detector**
- SOLENOID Magnet
- Barrel Silicon Tracker
- Central TOF
clas12 kinematics & sistematics

<table>
<thead>
<tr>
<th>Error source</th>
<th>Systematic error (%)</th>
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<td>Target polarization $P_T$</td>
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<td>acceptance corrections</td>
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<td>Al background contribution</td>
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<tr>
<td>$\rho^0$ contamination</td>
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<tr>
<td>Radiative corrections</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>$\sim 9$</strong></td>
</tr>
</tbody>
</table>

RICH – $\pi/k$ ratio and aerogel
RICH – positioning & angular distributions
CLAS12 initial science program

<table>
<thead>
<tr>
<th>Physics Focus</th>
<th>Approved Experiments</th>
<th>Letters Of Intent Supported</th>
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<tr>
<td>GPD &amp; Exclusive Processes</td>
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<td>SIDIS &amp; TMD</td>
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<td>PDF &amp; DIS</td>
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<td>Elastic &amp; Resonances FF</td>
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<td>Hadronization &amp; Color Transparency</td>
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<td>Baryon Spectroscopy</td>
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<td>Total</td>
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<td>7</td>
</tr>
</tbody>
</table>

CLAS12 represents the ideal environment to study the structure of the nucleon at high $x_B$. 

Silvia Pisano, LNF - INFN

EUNPC 2012
As a chiral-odd object, transverse polarization of quarks cannot be probed through the cleanest hard process, the DIS.

Another chiral-odd object has to be inserted.
Odd-chiral nature of transversity

Helicity basis $|+\rangle$, $|-\rangle$

Transverse Spin basis $|\uparrow\rangle$, $|\downarrow\rangle$

Transversity in Helicity basis
$|\uparrow,\downarrow\rangle = \frac{1}{\sqrt{2}} (|+\rangle \pm i |-\rangle)$
Sivers-like distortion

A non-zero Sivers function means that the distribution of quarks in transverse momentum is affected by the direction of the nucleon’s spin.

HERMES data on the Sivers asymmetries°


A. Bacchetta, Conti, Guagnelli, Radici, arXiv:1003:1328