SIDIS Measurements at JLab12

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INT-17-3, Spatial and Momentum Tomography of Hadrons and Nuclei
Seattle, Washington - September 18, 2017
Outline

• The JLab SIDIS program at @ 12 GeV: some selected measurements

• Impact on existing and future measurements
  – **Investigation in the valence quark region**
    ▪ Precise data in a wide phase space
    ▪ Multi-dimensional mapping of 3D PDFs using CLAS12, SoLID
    ▪ Different targets species with different polarization
    ▪ Flavor tagging

• Nucleon structure: from measuring to understanding

• Conclusions
CEBAF @ 12 GeV

Project Scope: 99.7% Complete

- CEBAF Upgrade
  - $E_{\text{max}} = 12$ GeV
  - $I_{\text{max}} = 90 \, \mu$A
  - $P_{\text{ol, max}} = 85\%$
- Beam can be simultaneously delivered to 4 Exp. Halls

- October 2014
  - hall D commissioning
- April 2014
  - hall A commissioning
- February/March 2017
  - hall C & B commissioning

- Double cryo capacity
- 5 new cryomodules
- Add arc
- 5 new cryomodules
12 GeV Program: Approved PAC Days

A Decade of Experiments

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Quark-parton Model Interpretation of SIDIS: Transverse Momentum Dependent PDFs (TMDs)

\[ l + N \rightarrow l' + h + X \]

- Two scales
  - high Q - hard scale
  - Low \( p_T \) - sensitive to confining scale
- Two planes:
  - Lepton scattering plane and hadron production plane
  - The angular modulation allows TMD separation

### Leading Order – Leading Twist

<table>
<thead>
<tr>
<th>N/q</th>
<th>U</th>
<th>L</th>
<th>T</th>
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<tbody>
<tr>
<td>U</td>
<td>( f_1 )</td>
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<td>( h_1 )</td>
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<td>L</td>
<td>( g_1 )</td>
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<td>T</td>
<td>( f_{1T} )</td>
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<td>( h_1 ) ( h_{1T} )</td>
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### Higher Twist

<table>
<thead>
<tr>
<th>N/q</th>
<th>U</th>
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<tbody>
<tr>
<td>U</td>
<td>( f_{1}^{\perp} )</td>
<td>( g_{1}^{\perp} )</td>
<td>( h, e )</td>
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<tr>
<td>L</td>
<td>( f_{L}^{\perp} )</td>
<td>( g_{L}^{\perp} )</td>
<td>( h_L, e_L )</td>
</tr>
<tr>
<td>T</td>
<td>( f_{T}^{\perp}, f_{T}^{\perp} )</td>
<td>( g_{T}^{\perp}, g_{T}^{\perp} )</td>
<td>( h_T, e_T, h_T^{\perp}, e_T^{\perp} )</td>
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The nucleon is a complex object!

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How much do we know about the structure of the nucleon?

P. Rossi's poll
A Multi-Hall SIDIS Program

• From an exploratory phase to a consolidation phase
• Start Hall B & C: spring 2018

**Hall B: Large acceptance (CLAS12)**
- Unpolarized and polarized H & D targets
  → cross sections, single & double-spin asymmetries
  → start kaon SIDIS program with RICH detector

**Hall C: SHMS + HMS**
- Unpolarized target
  Precision magnetic-spectrometer setup, π and K, high luminosity,
  → L/T separations in SIDIS
  → precision cross sections and ratios of $\pi^+$ and $\pi^-$ (and $K^+$, $K^-$)

**Hall A: Solenoidal Large Intensity Device (SoLID) & SBS**
- Longitudinal & transversely polarized $^3$He
  → Access to n structure at high-x and high-$Q^2$
  → pion & kaon run with BigBite and SBS
Unpolarized TMDs

• Unpolarized TMDs are not yet constrained in a satisfactory way

• They are present in all measurements
  → it is not sufficient to describe their qualitative features
  → precision is required

• Transverse momentum dependence of the **Multiplicities**
  provides leverage in the quest to unfold, from the transverse
  hadron momentum $P_{hT}$, the intrinsic quark $p_T$ and
  fragmentation $k_T$
  - Access the shape of the unpolarized TMD
  - Constrain TMD models and calculations
Unpolarized SIDIS

\[
\frac{d\sigma}{dx_B\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = f_1 \otimes D_1 \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1 + \varepsilon)} \cos\phi_h F_{UU}^{\cos\phi_h} 
+ \varepsilon \cos(2\phi_h) F_{UU}^{\cos2\phi_h} + \lambda_\varepsilon \sqrt{2\varepsilon(1 - \varepsilon)} \sin\phi_h F_{LU}^{\sin\phi_h} \right\},
\]

• BM TMD describes correlation between the transverse momentum and transverse spin of quarks, requires FSI or ISI

\[
F_{UU}^{\cos\phi_h} \cos\phi_h \quad F_{UU}^{\cos2\phi_h} \cos2\phi_h
\]

Cahn + BM  BM + h.t. Cahn

• Nontrivial modulations from the Cahn and Boer-Mulders effects

\[\Rightarrow\] under intensive studies worldwide, including experiments, model calculations, lattice simulations
Flavor dependence of $k_T$-distributions

$\langle P_{hT}^2 \rangle = z^2 \langle k_T^2 \rangle + \langle p_T^2 \rangle$

JLab 6 GeV Hall C

From the transverse hadron momentum $P_{hT}$

- Higher probability to find more d-quarks at large $k_T$
- Data (assuming only valence quarks) indicate that $k_T$-width of u-quarks is larger than for d-quarks

> information on the intrinsic $k_T$ and the $p_T$ generated during fragmentation

- Indications from both experimental data and theory (lattice, $\chi$CQM) of the $k_T$ dependence of quark flavor distribution

R. Asaturyan et al. PRC 85, 015202 (2012)
Global analysis fitting

Pavia Group results, $Q^2 = 1$ GeV$^2$

- Fit simultaneously SIDIS (HERMES, COMPASS), DY, and Z boson data
- Factorized functional form with **Gaussian dependence** on the intrinsic transverse momentum
- Flavor-independent TMDs
- TMD evolution at NLL

- More experimental data needed to extend the coverage in $x$, $z$, $Q^2$
  → The 12 GeV physics program at JLab will be very important to constrain TMD distributions at large $x$

- Multiplicities alone may not be enough to separate $<k_{\perp}>$ from $<p_{\perp}>$

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arXiv:1703.10157v1
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**Hall C: SHMS + HMS (+ NPS)**

- High momentum capability & resolution
- Setup optimal for longitudinal-transverse separations and ratios of charged-meson cross sections (unique amongst the Hall experimental setups)

Precise measurements of absolute cross-sections ($\mathcal{O}$ 1%) and $p_T$ dependence $\pi^{\pm/0}$ and $K^{\pm}$ on $p$ & $d$

In the range: $0.2 < x < 0.5$, $2 < Q^2 < 5$ GeV$^2$, $0.3 < z < 0.5$, $p_T < 0.5$ GeV

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**E12-09-017**

- **Cross Section (a.u.)**
  - $x$, $Q^2$, $E$, $z$ = 0.3, 3.0, 11.0, 0.4
  - $P_T$ (GeV)
  - $d(p^+)$, $d(p^-)$, $p(p^+)$, $p(p^-)$

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- **Detector**
  - $\phi = 90^\circ$
  - $\phi = 180^\circ$
  - $\phi = 270^\circ$
  - $p_T = 0.4$
  - $p_T = 0.6$

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- **Magnet**
  - $\phi = 0^\circ$
  - $\phi = 90^\circ$
  - $\phi = 180^\circ$
  - $\phi = 270^\circ$
$\pi^+ / \pi^- \  &  K^+ / K^- \  \text{Ratios}$

- COMPASS and HERMES pion multiplicity ratios are found in good agreement
- COMPASS kaon results are systematically lower than those of HERMES.
- COMPASS \& HERMES data integrated over $z$,
  JLab data (E00-108) at $z=0.55$

- High statistics and high precision Hall C data @ 12 GeV can be compared with HERMES and COMPASS data in the $x$ overlapping points at the same averaged $z$ and $P_T$ to help understand the discrepancy for the $k^+ / k^-$ ratio

JLab data @ 12 GeV
Unpolarized SIDIS x-section from CLAS @ 6 GeV

\[ a(1 + b \cos \phi_h + c \cos^2 \phi_h) \]

N. Harrison

\[ F_{UU}^{\cos \phi_h} = \frac{2M}{Q} C \left[ \frac{\hat{h} \cdot p_T}{zM_h} \frac{k_T^2}{M^2} h_1^+ H_1^+ - \frac{\hat{h} \cdot k_T}{M} z f_1 D_1 \right] \]

- \( <\cos \phi> \) is more sensitive to the intrinsic \( k_T \)
- Symmetric behaviour indicates large BM contribution
• Approved experiments @ 12 GeV will continue these studies in a wider $Q^2$ and $P_T$ range.

• Very Large Acceptance
• Full PID
• Moderately high luminosity ($10^{35}$ cm$^{-2}$s$^{-1}$)
Unpolarized SIDIS x-section with CLAS12

E12-06-112 : $H_2 (e, e'\pi)$

$4 < Q^2 < 5$

- $h_1^+ H_1^-$

6 GeV coverage

- $P_T$-dependence of BM asymmetry allows studies of transition from non-perturbative to perturbative description (Unified theory by Ji et al)

- Competing mechanisms (Cahn, Berger terms) and perturbative and radiative contributions to first order are expected to be "flavor blind" → in the first approximation, those effects cancel in the difference of the asymmetries for $\pi^-$ and $\pi^+$
Spin-orbit Correlations of the Strange Quarks

• SIDIS with K\(^{+/-}\) as leading particles, are of high interest.

• Kaon detection is generally challenged by the about one order of magnitude larger flux of pions → very little is known about the spin-orbit correlations related to the strange quark ratio K/\(\pi\) \~ 0.1-0.15

• HERMES and COMPASS results for Boer-Mulders asymmetries, despite the limited statistical accuracy, show surprising results
  - unexpectedly large Boer-Mulders asymmetries for kaons compared to pions
  - opposite signs for \(\pi\) and K

Relative sign \(H_{1,\text{fav}}/H_{1,\text{unfav}}\) for \(\pi\) and K inconsistent
Kaon Identification with CLAS12

• These puzzling issues will be addressed with CLAS12 thanks to the improved PID obtained with the RICH detector

Hadron identification @ CLAS12

• Pion contamination in kaon sample from \( \times 5-10 \) to \( \sim 1\% \) \( \Rightarrow 1:500 \) rejection factor (\( 4\sigma \) separation) can be achieved in full momentum range.

• Results confirmed at the CERN test beam with a RICH prototype (Eur. Phys. J. A (2016) 52: 23)

• Cherenkov ring at the cosmic test stand at Jefferson Lab
Boer – Mulders with CLAS12

E12-06-112 + E12-09-008

High precision data set on $\pi$ and K azimuthal asymmetries in SIDIS with unpolarized hydrogen and deuterium targets in the region $0.06 \leq x \leq 0.8$, $0 \leq P_T \leq 1.5$, $0.2 \leq z \leq 0.8$

- Excellent precision vs model uncertainties

- pions vs kaons
  - Different exclusive background
  - Different higher twist effects
  - Different hadronization effects
Higher Twist

\[ F_{LU}^{\sin^2} \propto \frac{M}{Q} \sum_a e_a^2 (e^a H_{1,a}^l + f_a^a G_{1,a}^l + g_a D_{1,a}^l + h_a E_{1,a}^l) \]

- SF related to quark-gluon-quark correlations
- Presently no satisfactory understanding of how much each function contributes

- \( A_{LU} \) measured with CLAS @ 5.5 GeV with better than 1% statistical precision over a large range of \( z, P_T, x_B, Q^2 \)
  - permits comparison with several reaction models
  - the commonly used Wandzura-Wilczek approximation is not applicable as it would demand that the entire asymmetry be zero

- \( A_{LU} \) vs \( P_T \) and \( Q^2 \) at fixed \( x_B \) and \( z \) with CLAS12

E12-06-112

W. Gohn et al., PRD89, 072011 (2014)
Measurements with Polarized Targets @ CLAS12

**Longitudinally polarized proton (NH$_3$) and deuteron (ND$_3$)**
(Dynamic Nuclear Polarization)

- Improvement with respect to 6 GeV
  - Can handle higher luminosity
  - Double-cell target: Two target samples at opposing polarizations with a single µwave frequency → reduced systematic effects

- Estimated completion date: Dec. 2018

**HD-Ice target**

Solid HD material in a frozen spin state → requires only modest (~1 T) • short (~15 cm) field to hold spin in-beam

- Work in progress: 1) to test the target in the UITF 2) to operate it in transverse pol. mode in the CLAS12 Solenoid

**Injector Test Facility (UITF)**

$E_e = 5-10$ MeV

**Expected polarization**
- $\geq 90\%$ (p)
- $\geq 40\%$ (d)

**Electron beam current operation up to 30 nA.**

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CLAS12: $A_{UT}$ with Transverse Proton Target

- Large acceptance of CLAS12 allows studies of $P_T$ and $Q^2$-dependence of SSAs in a wide kinematic range
- Comparison of JLab12 data with HERMES, COMPASS and EIC will pin down the $Q^2$ evolution of Sivers asymmetry
CLAS12: Kₜ Helicity Dependence

\[ A_1(\pi) \propto \frac{\sum q e_q^2 g_1^q D_1^q \to \pi(z)}{\sum q e_q^2 f_1^q D_1^q \to \pi(z)} e^{z^2 P_T^2 \frac{(\mu_0^2 - \mu_2^2)}{(\mu_D^2 + z^2 \mu_0^2)(\mu_D^2 + z^2 \mu_2^2)}} \]

E12-09-009

\[ f_1^q(x, k_T) = f_1(x) \frac{1}{\pi \mu_0^2} e^{-\frac{k_T^2}{\mu_0^2}} \]

\[ g_1^q(x, k_T) = g_1(x) \frac{1}{\pi \mu_2^2} e^{-\frac{k_T^2}{\mu_2^2}} \]

\[ D_1^q(z, p_T) = D_1(z) \frac{1}{\pi \mu_D^2} e^{-\frac{p_T^2}{\mu_D^2}} \]

\( \mu_0^2 = 0.25 \text{GeV}^2 \)

\( \mu_2^2 = 0.2 \text{GeV}^2 \)

\( \mu_D^2 = 0.2 \text{GeV}^2 \)

Curves are calculated using different kₜ widths for helicity distributions

- \( A_{LL}(\pi) \) sensitive to difference in kₜ distributions for \( f_1 \) and \( g_1 \)
- Wide range in Pₜ allows studies of transition to perturbative approach
**Hall A: SoLID & SBS**

**SoLID:** Long Term

- Large acceptance (2\(\pi\))
- Moderately large \(P_T\) coverage
- Quite high luminosity (10\(^{36}\) cm\(^{-2}\) s\(^{-1}\))

\(\text{(e e' \(\pi^+/-\)) on Transversely Polarized }^3\text{He}\)

\(\text{(e e' \(\pi^+/-\)) on Longitudinally Polarized }^3\text{He}\)

\(\text{(e e' \(\pi^+/-\)) on Transversely polarized } \text{NH}_3\)

Dihadron with Transversely Pol. \(^3\text{He}\)

- CLEO Solenoid at JLab; Pre-CDR

**SBS:** Near Term

- Moderately large acceptance
- Full PID (\(\pi\) and \(k\))

\(\text{(e e' \(\pi^+/-\) & \(K^+/-\)) on Transversely Polarized }^3\text{He}\)

Under Construction; Physics > 2019

**3He:** effective polarized neutron target

\(~90\%\)
\(~1.5\%\)
\(~8\%\)

- 60 \(\mu\text{A}\) on 60 cm
- \(L \sim 6.6 \times 10^{36}\) cm\(^{-2}\)s\(^{-1}\)
- Polarization \(~60\%\)

**SoLID & SBS:** Complementary Kinematics

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Sivers Asymmetry with SBS e SoLID

**SBS**
- will achieve statistical FOM for the neutron ~100X better than HERMES proton data and ~1000X better than JLab E06-010 neutron data
- Kaon and neutral pion data will aid flavor decomposition, and understanding of reaction-mechanism effects.
Extraction and Validation framework

• The forthcoming years will be a time of unprecedented high precision and high volume data.

• Measurements from different experiments, different reactions at different energies will be soon available and the realization of a universal analysis framework to enable the *extraction* and the *interpretation* of the 3D PDFs, is mandatory.

  – The unambiguous interpretation of any SIDIS experiment (JLab in particular) in terms of leading twist TMDs requires:
    • understanding of evolution properties
    • control of various subleading $1/Q^2$ corrections
    • radiative corrections
    • knowledge of involved transverse momentum dependent FF
    • understanding of hadronic backgrounds not originating from current quarks

• This effort requires a comprehensive approach combining experimental, theoretical/phenomenological and computational efforts.

• The analysis framework will be used to both extract the 3D PDFs from measured observables and from models of 3D PDFs to prediction of observables.

• The framework will allow testing different extraction procedures and estimating systematics related to different assumptions and models used in the extraction procedure.
Framework (work flow)

- Framework is designed to have separate modules to tie together into functional code.
- Each part can be replaced by user implemented code.
- The pieces interact through data structures and take an input data.

Software developed by G. Gavalian

P. Rossi
December 11th to 15th, 2017
INFN Frascati National Laboratories (Italy)

http://www.lnf.infn.it/conference/transversity2017

Local Organizing Committee

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Emanuele Pace Rome Tor Vergata & INFN
Patrizia Rossi Jefferson Lab & INFN-LNF (co-chair)
Giovanni Salmè INFN-Rome
Conclusions

• A comprehensive SIDIS program at 12 GeV is in place:
  – Wide kinematic coverage and large acceptance
  – Precise un-polarized cross-sections and their kinematic dependence
  – Study leading and sub-leading twist TMDs
  – Many modulations will be extracted in more than one experimental hall, equipped with complementary performing detectors

• Flavor separation will be performed analyzing asymmetries with different target/beam polarization combinations on both neutron and proton targets

• A consistent procedure for extraction of TMDs from data with controlled systematic errors has started.