Transverse Spin Physics with CLAS12

Contalbrigo Marco
INFN Ferrara

Workshop on Partonic Transverse Momentum in Hadrons: Quark Spin-Orbit Correlations and Quark-Gluon Interactions

March 12-13, 2010 Duke University
Partonic Transverse Momentum
Quantum Phase-Space Distributions of Quarks

$W_p^u(x,k_T,r)$ “Mother” Wigner distributions

Probability to find a quark $u$ in a nucleon $P$ with a certain polarization in a position $r$ & momentum $k$

TMD PDFs: $f_p^u(x,k_T),…$

Measure momentum transfer to quark
Direct info about momentum distributions

GPDs: $H_p^u(x,\xi,t),…$

Measure momentum transfer to target
Direct info about spatial distributions

Form Factors $F_{1p}^u(t),F_{2p}^u(t)…$

PDFs $f_p^u(x),…$

Proton spin puzzle

$\frac{1}{2} = \frac{1}{2} \sum_f (q_f^+ - q_f^-) + L_q + \Delta G + L_g$

$P_T < 2$ GeV/c

$\sqrt{s} = 20$ GeV

SSA

Duke Workshop 2010
### Distribution Functions (DF)

<table>
<thead>
<tr>
<th>Nucleon</th>
<th>Quark</th>
<th>U</th>
<th>L</th>
<th>T</th>
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<tbody>
<tr>
<td>U</td>
<td>q</td>
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<tr>
<td>L</td>
<td>g_{1L}</td>
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3D description in momentum space

### Fragmentation Functions (FF)

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<tr>
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</table>

Off-diagonal elements are important objects:

Interference between wave functions with different angular momenta: contains info about parton orbital angular momenta

Testing QCD at the amplitude level:

- Sign change between DY and SIDIS
- Universality of TMDs

Fundamental prediction of QCD!
The 3D description of the nucleon

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<td></td>
<td></td>
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<tr>
<td>L</td>
<td>Δq</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>f_{IT}</td>
<td>g_{IT}</td>
<td>δq</td>
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BOER-MULDERSS
Spin orbit effect

SIVERS
Quark orbital
angular momentum

M. Contalbrigo
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The 3D description of the nucleon

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BOER-MULDERS
Spin orbit effect

\[ h_{1T}^- q \sim -\kappa_T q \]

SIVERS
Quark orbital angular momentum

\[ f_{1T}^- q \sim -\kappa_T q \]

Deformations by

GPD E \rightarrow GPD E_T + 2\tilde{H}_T

i.e. Sivers: spin-orbit correlations with same matrix element of anomalous magnetic moment, and GPD E
Correlation Functions and SIDIS

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\[ \Lambda_{QCD} \sim P_T \ll Q \]

\[ \sigma^{ep \rightarrow e'hX} = \sum_q q(x) \otimes \sigma^{eq \rightarrow eq} \otimes D_q^h(z) \]

Rich phenomenology but rather involved observables

Target type and hadron ID provide flavor tagging !!
- constrain valence and sea

Multidimensional analysis resolves kinematic correlations !!
- disentangle distribution and fragmentation functions (test factorization, HT)
Several observables already measured... with matches and mismatches

Collins

Sivers

Boer-Mulders
Executive summary

TMDs are a new class of phenomena providing novel insights into the rich nuclear structure.

Non-zero results from DIS experiments provide promises but also open questions.

Limited knowledge on transverse momentum dependences

Flavor decomposition often missing

Evolution properties to be defined

Role of the higher twist to be quantified

Universality ↔ Fundamental test of QCD
TMDs are a new class of phenomena providing novel insights into the rich nuclear structure.

Non-zero results from DIS experiments provide promises but also open questions.

- Limited knowledge on transverse momentum dependences.
- Flavor decomposition often missing.
- Evolution properties to be defined.
- Role of the higher twist to be quantified.

Universality ↔ Fundamental test of QCD.

Still incomplete phenomenology is asking for new inputs.

Crucial: completeness flavor tagging and five-fold differential extraction in all variables \((x,z,Q^2,P_T)\) to have all dependencies resolved.
JLAB 12
We recommend the completion of the 12 GeV Upgrade at Jefferson Lab.

- It will enable three-dimensional imaging of the nucleon, revealing hidden aspects of its internal dynamics.

- It will complete our understanding of the transition between the hadronic and the quark/gluon descriptions of nuclei.

- ...
12 GeV CEBAF

Beam current 90 µA
Beam polarization 85%

Add 5 cryomodules

20 cryomodules

Add arc

Enhance equipment in existing halls

Add 5 cryomodules

Add Hall D (and beam line)
Upgrade magnets and power supplies

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12 GeV CEBAF

Beam current 90 $\mu$A
Beam polarization 85 %

Add 5 cryomodules

20 cryomodules

Add arc

Enhance equipment in existing halls

2008-2014: Construction (funded at 99%)

May 2012
6 GeV Accelerator Shutdown starts

May 2013
Accelerator Commissioning starts

October 2013
Hall Commissioning starts

2013-2015
Pre-Ops (beam commissioning)
Limit defined by luminosity

Different $Q^2$ for same $x$ range

Complementary experiments

Matches valence

The SIDIS landscape
L $\sim 10^{35}$ cm$^{-2}$s$^{-1}$

10 nA electron beam
85% beam polarization

$\text{NH}_3\text{ND}_3$ target
85% polarization

multi-purpose detector
for fixed target electron scattering experiments

$Q^2 > 1$ GeV$^2$
$W^2 > 4$ GeV$^2$
y < 0.85
$M_X > 2$ GeV

Wide detector acceptance allows current & target fragmentation measur.
L ~ $10^{35}$ cm$^{-2}$s$^{-1}$

10 nA electron beam
85% beam polarization

NH$_3$ ND$_3$ target
85% polarization

multi-purpose detector for fixed target electron scattering experiments

Q$^2$ > 1 GeV$^2$
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y < 0.85
M$^2$X > 2 GeV

Wide detector acceptance allows current & target fragmentation measur.

Large kinematic ranges accessible with CLAS12 are important for separation of
- Valence region
- Higher Twist contributions ($Q^2$)
- Perturbative regime ($P_T \geq 1$)

High luminosity important for
- Multidimensional analysis
- Test factorization
- Reduce systematic

large luminosity
H and D targets
broad kinematical range
Pion and kaon, ..., SSA
L $\sim 10^{35}$ cm$^{-2}$s$^{-1}$

10 nA electron beam
85 % polarization

NH$_3$ ND$_3$ target
85 % polarization

large luminosity
H and D targets
broad kinematical range
Pion and kaon, .... SSA

Replace 2 sectors of LTCC with a proximity RICH detector to identify Kaons approved by JLab PAC34
TMDs with Unpolarized Targets
TMD correlators

\[
\frac{d\sigma}{dx
dy
d\psi
dz
d\phi_h
dP_{h,\perp}^2} = \frac{\alpha^2}{x y Q^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left\{ F_{UU, T} + \varepsilon F_{UU, L} \\
+ \sqrt{2} \varepsilon(1+\varepsilon) \cos \phi_h F_{UU}^{\cos \phi_h} + \varepsilon \cos(2\phi_h) F_{UU}^{2\phi_h} + \lambda_1 \sqrt{2} \varepsilon(1-\varepsilon) \sin \phi_h F_{LU}^{\sin \phi_h} \right\}
\]

\[
+ S_{\parallel} \left[ \sqrt{2} \varepsilon(1+\varepsilon) \sin \phi_h F_{UL}^{\sin \phi_h} + \varepsilon \sin(2\phi_h) F_{UL}^{2\phi_h} \right] + S_{\parallel} \lambda_2 \left[ \sqrt{1-\varepsilon^2} F_{LL} + \sqrt{2} \varepsilon(1-\varepsilon) \cos \phi_h F_{LL}^{\cos \phi_h} \right]
\]

\[
+ |S_{\perp}| \left[ \sin(\phi_h - \phi_S) \left( F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)} \right) + \varepsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h-\phi_S)} \right]
\]

\[
+ \sqrt{2} \varepsilon(1+\varepsilon) \sin \phi_S F_{UT}^{\sin \phi_S} + \sqrt{2} \varepsilon(1+\varepsilon) \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h-\phi_S)} \right] \right\}
\]

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20
Unpolarized target @ CLAS12

\[ F_{UU}^{\cos 2\phi} \propto h_{1}^\perp H_{1}^\perp \]

Boer-Mulders spin-orbit effect

56 d @ 10^{35} s^{-1} cm^{-2}
LH_{2} LD_{2} targets

Measurements of kinematic \((x,Q^2,z,P_T)\) will probe HT distribution functions

In the perturbative limit \(1/P_T\) behavior expected

\[ A_{LU} \sim 1/Q \text{ (Twist-3)} \]

\[ P_{\text{beam}} = 85\% \]
PT-dependence of azimuthal moments allows studies of transition from non-perturbative to perturbative description (Unified theory by Ji et al, $P_T$ matches and mismatches by Bacchetta et al).

\[ F_{UU}^{\cos 2\phi} \propto h_1^\perp H_1^\perp \]

In the perturbative limit $1/P_T^2$ behavior expected

\[ \Lambda_{QCD} \ll P_T \ll Q \]

$4 < Q^2 < 5 \text{ GeV}^2$

$H_1^\perp u \to \pi^+ = -H_1^\perp u \to \pi^-$

2000h @ $10^{35}$ s$^{-1}$cm$^{-2}$

LH$_2$ target
TMDs with Longitudinal Polarized Targets
TMD correlators

\[
\frac{d\sigma}{dx \, dy \, d\psi \, dz \, d\phi_h \, dP_{h,\perp}^2} = \frac{\alpha^2}{x y Q^2} \frac{y^2}{2(1 - \varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \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}^{2\phi_h} + \lambda_\varepsilon \sqrt{2}\varepsilon(1 - \varepsilon) \sin \phi_h F_{LU}^{\sin \phi_h} \right. \\
+ S_{||} \left[ \sqrt{2}\varepsilon(1 + \varepsilon) \sin \phi_h F_{UL}^{\sin \phi_h} + \varepsilon \sin(2\phi_h) F_{UL}^{2\phi_h} \right] + S_{||} \lambda_\varepsilon \left[ \sqrt{1 - \varepsilon^2} F_{LL} + \sqrt{2}\varepsilon(1 - \varepsilon) \cos \phi_h F_{LL}^{\cos \phi_h} \right] \\
+ |S_{\perp}| \sin(\phi_h - \phi_S) \left( F_{UT,T}^{\sin(\phi_h - \phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h - \phi_S)} \right) + \varepsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h + \phi_S)} + \varepsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h - \phi_S)} \\
+ \sqrt{2}\varepsilon(1 + \varepsilon) \sin \phi_S F_{UT}^{\sin \phi_S} + \sqrt{2}\varepsilon(1 + \varepsilon) \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h - \phi_S)} \\
+ |S_{\perp}| \lambda_\varepsilon \left\{ \sqrt{1 - \varepsilon^2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h - \phi_S)} + \sqrt{2}\varepsilon(1 - \varepsilon) \cos \phi_S F_{LT}^{\cos \phi_S} + \sqrt{2}\varepsilon(1 - \varepsilon) \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h - \phi_S)} \right\}
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>q</td>
<td>h_1</td>
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<td>h_{1L}</td>
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<td>h_{1T}</td>
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Longitudinal Target Spin @ CLAS12

$F_{LL} \propto g_{1L} D_1$

2000h @ $10^{35} \text{s}^{-1}\text{cm}^{-2}$
NH$_3$ and ND$_3$ target

Helicity dependence of k$_T$-distribution of quarks

$A_{LL} \propto \frac{\mu_D^2 + z^2 \mu_0^2}{\mu_D^2 + z^2 \mu_2^2} \exp\left(-z^2 p_T^2 \frac{(\mu_0^2 - \mu_2^2)}{(\mu_D^2 + z^2 \mu_0^2)(\mu_D^2 + z^2 \mu_2^2)}\right) \sum e_q^2 g_{1L}^q D_q^h \sum e_q^2 f_{1L}^q D_q^h$

Constituent quark model (Pasquini et al).

<table>
<thead>
<tr>
<th>TMD</th>
<th>$\langle k_T^2 \rangle$</th>
<th>$\mu_0^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_1$</td>
<td>1.00</td>
<td>0.74</td>
</tr>
<tr>
<td>$g_1$</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td>$h_1$</td>
<td>2.20</td>
<td></td>
</tr>
<tr>
<td>$g_{1T}$</td>
<td>0.63</td>
<td></td>
</tr>
<tr>
<td>$h_{1T}$</td>
<td>2.20</td>
<td></td>
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<td>$h_{1T}$</td>
<td>0.63</td>
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M. Anselmino et al hep-ph/0608048

\[ f_1^q(x, k_\perp) = f_1^q(x) \frac{1}{\pi \mu_0^2} \exp\left(-\frac{k_T^2}{\mu_0^2}\right) \]

\[ g_1^q(x, k_\perp) = g_1^q(x) \frac{1}{\pi \mu_2^2} \exp\left(-\frac{k_T^2}{\mu_2^2}\right) \]

$\mu_0^2=0.25\text{GeV}^2$  $\mu_D^2=0.2\text{GeV}^2$
Longitudinal Target Spin @ CLAS12

Transversely polarized quarks in long polarized nucleon
Leading twist, sensitive to spin-orbit correlations

\[ F_{UL}^{\sin 2\phi} \propto h_{1L}^{\perp} H_{1}^{\perp} \]


\[ H_{1}^{\perp u \rightarrow \pi^{+}} / H_{1}^{\perp u \rightarrow \pi^{-}} = 0, -1, -5 \]

\[ H_{1}^{\perp d \rightarrow \pi^{+}} = 0 \]

2000h @ 10^{35} s^{-1}cm^{-2}
NH\textsubscript{3} and ND\textsubscript{3} target

Curves


black: Avakian et al, PRD77 (2008) 014012
Collins effect

Simple string fragmentation (Artru model)

$\rho$ production may produce an opposite sign $A_{UT}$

Collins function:

extracted from $e^+e^-$ collider data (BELLE)

- at much higher scale than SIDIS to be investigate at SIDIS scale too
  - evolution of TMDs
  - only for pions
    - unknown for kaons
      - strange vacuum
      - strangeness in the nucleon
    - unknown for vector mesons

Sub-leading pion opposite to leading (into page)

$H_1 \perp u \rightarrow \pi$

Leading $\rho$ opposite to leading $\pi$ (into page)

$H_1 \perp u \rightarrow \rho \sim -\frac{1}{3} H_1 \perp u \rightarrow \pi$

hep-ph/9606390

Fraction of direct kaons may be higher than the fraction of direct pions.
TMDs with Transversely Polarized Targets
CLAS transversely polarized HD-Ice target

**HD-Ice target vs std nuclear targets**

Heat extraction is accomplished with thin aluminum wires running through the target (can operate at $T \sim 500-750mK$)

<table>
<thead>
<tr>
<th>Material</th>
<th>gm/cm$^2$</th>
<th>mass fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD</td>
<td>0.735</td>
<td>77%</td>
</tr>
<tr>
<td>Al</td>
<td>0.155</td>
<td>16%</td>
</tr>
<tr>
<td>CTFE (C$_2$ClF$_3$)</td>
<td>0.065</td>
<td>7%</td>
</tr>
</tbody>
</table>

**Pros**

1. Small field ($\beta Bdl \sim 0.005-0.05 Tm$)
2. Small dilution (fraction of events from polarized material)
3. Less radiation length
4. Less nuclear background (no nuclear attenuation)
5. Wider acceptance much better FOM, especially for deuteron
6. H and D may be independently polarized

**Cons**

1. HD target is highly complex and there is a need for redundancy due to the very long polarizing times (months).
2. Need to demonstrate that the target can remain polarized for long periods with an electron beam with currents of order of 1-2 nA
3. Additional shielding of Moller electrons necessary (use minitorus)

HD-Ice target at ~ 1-2nA
NH$_3$ at ~ 5-10 nA
### TMD correlators

\[
\frac{d\sigma}{dx\ dy\ d\psi\ dz\ d\phi_h\ dP_{h\perp}^2} = \frac{\alpha^2}{x y Q^2} \frac{y^2}{2(1 - \varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} \right. \\
+ \sqrt{2\varepsilon(1 + \varepsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} + \varepsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda \varepsilon \sqrt{2\varepsilon(1 - \varepsilon)} \sin \phi_h F_{LU}^{\sin \phi_h} \\
\left. + S_{||} \left[ \sqrt{2\varepsilon(1 + \varepsilon)} \sin \phi_h F_{UL}^{\sin \phi_h} + \varepsilon \sin(2\phi_h) F_{UL}^{\sin 2\phi_h} \right] + S_{||} \lambda \varepsilon \left[ \sqrt{1 - \varepsilon^2} F_{LL} + \sqrt{2\varepsilon(1 - \varepsilon)} \cos \phi_h F_{LL}^{\cos \phi_h} \right] \right\}
\]

\[
+ |S_{\perp}| \left[ \sin(\phi_h - \phi_S) \left( F_{UT,T}^{\sin(\phi_h - \phi_S)} + \varepsilon F_{UT,L,I}^{\sin(\phi_h - \phi_S)} \right) + \varepsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h + \phi_S)} + \varepsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h - \phi_S)} \right. \\
+ \sqrt{2\varepsilon(1 + \varepsilon)} \sin \phi_S F_{UT}^{\sin \phi_S} + \sqrt{2\varepsilon(1 + \varepsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h - \phi_S)} \\
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Collins asymmetry @ CLAS12

\[ F_{UT} \sin(\phi + \phi_S) \propto h_1 H_1^\perp \]

2000h @ 10^{34} s^{-1} cm^{-2}
HD-ice (P=85%)

Curves from A.V. Efremov et al
PRD76:094025, 2006

Study \( A_{UT} \) at large \( x \) (valence) where models are mostly unconstrained

\[ |\Delta_T d / \Delta_T u| \]

1. Anselmino et al
2. QCDSF / UKQCD
3. NRQM, MIT bag
4. Quark-Diquark
5. CQSM

M. Wakamatsu hep-ph:0811.4196

Tensor charge

\[ \delta u = 0.54^{+0.09}_{-0.22} \]
\[ \delta d = -0.23^{+0.09}_{-0.16} \]

M. Anselmino et al hep-ph:0812.4366
unpolarized beam, transv. target

non spherical shape of the nucleon

k⊥ = 0

k⊥ = 2.0 GeV

B. Pasquini et al.
arXiv:0806.2298

Relation in no-gluon models:
(in bag & spectator model)

\[ g_1^q(x) - h_1^q(x) = h_{1T}^{q(I)}(x) \]

\[ F_{UT}^\sin(3\phi - \phi_S) \propto h_{1T}^{\perp} H_1^{\perp} \]

2000h @ 10^{34}s^{-1}cm^{-2}
HD-ice (P=85%)

π^+ proton

± positivity

CLAS12 projections

models

Avakian et al.,
PRD78,114024
unpolarized beam, transverse target

\[ F_{UT} \sin(\phi - \phi_S) \propto f_{1T} \perp D_1 \]

2000h @ 10^{34} s^{-1} cm^{-2}
HD-ice (P=85%)

Sivers effect @ CLAS12

S. Arnold et al
arXiv:0805.2137

M. Anselmino et al
arXiv:0805.2677

\[ \text{ep} \rightarrow \text{e}^{+} \text{K}^{+} + \text{X} \]
GPDs @ CLAS12

D. Mueller, X. Ji, A. Radyushkin, A. Belitsky, …
M. Burkardt, … Interpretation in impact parameter space

Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions
Asymmetries highly sensitive to the $u$-quark contributions to the proton spin.

$$\Delta \sigma \sim \sin \phi \text{Im}\{k_1(F_2H - F_1E) + \ldots\}d\phi$$

$A_{UTx}$ Target polarization in the scattering plane

$A_{UTy}$ Target polarization perpendicular to the scattering plane

Sample kinematics

$Q^2 = 2.2 \text{ GeV}^2, x_B = 0.25, -t = 0.5\text{GeV}^2$
Exclusive $\rho^0$ production @ CLAS12

$A_{UT} \sim 2\Delta \left( \text{Im}(\text{AB}^*) \right)$

$E^u, E^d$ allow to map the orbital motion of quarks.

$\rho^0 A \sim 2H^u - H^d$

$\rho^+ B \sim 2E^u - E^d$

$\omega^0 A \sim 2H^u + H^d$

$\omega^0 B \sim 2E^u + E^d$

Possible flavor decomposition

2000h @ $10^{34}$ s$^{-1}$ cm$^{-2}$

HD-ice (P=85%)

$Q^2 \approx 5$ GeV$^2$

-$t = 0.5$ GeV$^2$

$J^u = 0.1$

$J^d = 0$

K. Goeke, M.V. Polyakov, M. Vanderhaeghen, 2001
Conclusions

CLAS12: a wide-acceptance high-luminosity high-polarization experiment for a comprehensive study of the partonic transverse degree of freedoms in the nucleon

- Constrain models in the valence region
- Test factorization
- Study higher twist effects
- Investigate non-perturbative to perturbative transition (along $P_T$)
- Test of QCD: universality SIDIS vs Drell-Yan
- Test of Lattice QCD calculations: tensor charge
- Access to OAM

Precise mapping of TMDs (pdf & FF) and GPDs in a multi-D approach
\[ \pi \text{ multiplicities in SIDIS} \]

\[ \pi^0 \text{ multiplicities} \] less affected by higher twists

\( 0.4 < z < 0.7 \) kinematical range, where higher twists are expected to be small
SSA with long. polarized target

Quark polarization

<table>
<thead>
<tr>
<th>N/q</th>
<th>U</th>
<th>L</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>$f_1$</td>
<td></td>
<td>$h_T^\perp$</td>
</tr>
<tr>
<td>L</td>
<td></td>
<td>$g_1^\perp$</td>
<td>$h_{1L}^\perp$</td>
</tr>
<tr>
<td>T</td>
<td>$f_{1T}^\perp$</td>
<td>$g_{1T}^\perp$</td>
<td>$h_1^\perp$ $h_{1T}^\perp$</td>
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</tbody>
</table>

\[
A_{UL}^\sin \phi \propto \frac{M_h}{M} g_1 \frac{G_1}{z} + \frac{M}{M_h} x f_L^\perp D_1
\]

<table>
<thead>
<tr>
<th>q/h</th>
<th>U</th>
<th>L</th>
<th>T</th>
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</thead>
<tbody>
<tr>
<td>U</td>
<td>$D_1^\perp$</td>
<td>$D_L^\perp$</td>
<td>$D_T^\perp, D_{1T}^\perp$</td>
</tr>
<tr>
<td>L</td>
<td>$G_1^\perp$</td>
<td>$G_L^\perp$</td>
<td>$G_T^\perp, G_{1T}^\perp$</td>
</tr>
<tr>
<td>T</td>
<td>$H, E$</td>
<td>$H_L, E_L$</td>
<td>$H_T, E_T, H_{1T}^\perp, E_{1T}^\perp$</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>q/h</th>
<th>U</th>
<th>L</th>
<th>T</th>
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<tbody>
<tr>
<td>U</td>
<td>$D_1$</td>
<td></td>
<td>$D_{1T}^\perp$</td>
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<tr>
<td>L</td>
<td></td>
<td>$G_{1L}$</td>
<td>$G_{1T}^\perp$</td>
</tr>
<tr>
<td>T</td>
<td>$H_1^\perp$</td>
<td>$H_{1L}^\perp$</td>
<td>$H_1^\perp, H_{1T}^\perp$</td>
</tr>
</tbody>
</table>
Dilution factor in SIDIS

Fraction of events from polarized hydrogen in NH3

\[ f(x, Q^2, z, p_T, \phi) = 1 - \left( \frac{N_u}{N_p} \right) \left( \frac{\rho_p}{\rho_u} \right) C_n(x, Q^2, z) \]

N_u, N_p - total counts from NH3 and carbon normalized by lumi

\( \rho_u, \rho_p \) - total areal thickness of hydrogen (in NH3), and carbon target

Multiple scattering and attenuation in nuclear environment introduces additional \( P_T \)-dependence for hadrons
Uncertainties

Table 5: Uncertainties for asymmetry measurements.

<table>
<thead>
<tr>
<th>Item</th>
<th>$A_1^p$</th>
<th>$A_{UL}^{\sin \phi}$</th>
<th>$A_{UL}^{\sin 2\phi}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam x target polarization</td>
<td>2%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>target polarization</td>
<td>-</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>depolarization and R dilution factor</td>
<td>4%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>radiative corrections</td>
<td>3%</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>fitting procedure</td>
<td>-</td>
<td>4%</td>
<td>5%</td>
</tr>
<tr>
<td>transverse (to $\gamma^*$) spin effects</td>
<td>3%</td>
<td>3%</td>
<td>-%</td>
</tr>
</tbody>
</table>
CLAS12 Acceptance MC studies

\[ \langle \cos n\phi \rangle(\omega) = \frac{\iiint \sigma(\omega, \phi) e_{\text{acc}}(\omega, \phi) e_{\text{RAD}}(\omega, \phi)L \cos(n\phi) \, d\omega d\phi}{\iiint \sigma(\omega, \phi) e_{\text{acc}}(\omega, \phi) e_{\text{RAD}}(\omega, \phi)L \, d\omega d\phi} \]

\[ \omega = (x, y, z, P_{h\perp}) \]

After acceptance correction the generated azimuthal moments are recovered with an error < 10% (dominant contribution to systematics)

Even better results expected with a fully-differential analysis

CLAS12 SIDIS MC (LUND-PEPSI) used to study azimuthal moments from acceptance and radiative corrections for different pions.
Table 5: Uncertainties for asymmetry measurements.

<table>
<thead>
<tr>
<th>Item</th>
<th>$A_{UU}^{\cos 2\phi}$</th>
<th>$A_{UU}^{\cos \phi}$</th>
<th>$A_{LU}^{\sin \phi}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam polarization</td>
<td>-</td>
<td>-</td>
<td>3%</td>
</tr>
<tr>
<td>acceptance corrections</td>
<td>4%</td>
<td>4%</td>
<td>2%</td>
</tr>
<tr>
<td>radiative corrections</td>
<td>3%</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>fitting procedure</td>
<td>4%</td>
<td>4%</td>
<td>3%</td>
</tr>
</tbody>
</table>
# Systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>Size</th>
<th>relative</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam/Target polarization</td>
<td>2-4 %</td>
<td>relative</td>
<td></td>
</tr>
<tr>
<td>Dilution factor Nuclear effects</td>
<td>2-4 %</td>
<td>relative</td>
<td>HD-ice to suppress these effects</td>
</tr>
<tr>
<td>Detector performance</td>
<td>1-2 %</td>
<td>absolute</td>
<td>RICH to improve hadron ID</td>
</tr>
<tr>
<td>Acceptance effects Fitting procedure</td>
<td>3-4 %</td>
<td>absolute</td>
<td>Statistical origin Multidimensional approach</td>
</tr>
<tr>
<td>Radiative corrections</td>
<td>1-2 %</td>
<td>relative</td>
<td></td>
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</tbody>
</table>
# TMDS Physics with SIDIS

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Reactions</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>Planned</th>
<th>Status</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERMES @ DESY</td>
<td>$e^+p^+$</td>
<td>7.5</td>
<td>&lt; 2012</td>
<td>Data-taking is over</td>
<td>Completing analyses</td>
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<tr>
<td>COMPASS @ CERN</td>
<td>$\mu^+p^+$, $\mu^+d^+$</td>
<td>17-20</td>
<td>&gt; 2009</td>
<td>Proposal</td>
<td>Improved statistics</td>
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<tr>
<td>Hall-A,B,C @ JLab</td>
<td>$e^-p^+$, $e^-d^+$, $e^-n^+$</td>
<td>5</td>
<td>&gt; 2013</td>
<td>Approved</td>
<td>Detector upgrades HD-ice polarized target</td>
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<tr>
<td>EIC</td>
<td>$e^+p^+$</td>
<td>30-100</td>
<td>&gt; 2017</td>
<td>Under study</td>
<td>NSAC Long Range plan 2012</td>
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<tr>
<td>eN @ FAIR</td>
<td>$e^+p^+$</td>
<td>12</td>
<td>&gt; 2020</td>
<td>Under study</td>
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<td>LHeC @ CERN</td>
<td>$e^-p^+$</td>
<td>1400</td>
<td>&gt; 2020</td>
<td>Under study</td>
<td>Conceptual Design Report in 2010</td>
</tr>
</tbody>
</table>
TMD palette

Hadron probe

pp reactions: PDFs (x FFs)
Strong SSA at large $x_F$

SIDIS: PDFs x FFs
Not zero Sivers
Not zero $h_1$, Collins & IFF
Non zero Boer-Mulders

Lepton probe

e+e- annihilation: FFs
Not zero Collins & IFF