JLab 12 GeV Program:
Hard Exclusive and SIDIS Processes

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Physics Opportunities in Hall C at 12 GeV
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Quark structure of the proton

Large database on unpolarized structures functions constrain parton distributions \( u(x), d(x) \) …

Growing body of inclusive and semi-inclusive data constrain polarized pdfs \( \Delta u(x), \Delta d(x) \) …

\( \rightarrow \) JLab at 12 GeV can help put precision of polarized pdfs on par with unpolarized pdfs

Major facet of JLab 12 GeV program aimed at exploring proton structure beyond 1 dimension

\( \rightarrow \) TMD parton distributions which is linked to
\( \rightarrow \) Quark orbital angular momentum, and don’t forget about …
\( \rightarrow \) Nucleon tomography
Generalized Parton Distributions

GPDs provide the common framework for connecting DIS to elastic scattering

More importantly, provide information on the angular momentum of the nucleon via the Ji sum rule

\[ \int_{-1}^{1} dx x [H^q(x, \xi, t = 0) + E^q(x, \xi, t = 0)] = 2J^q \]

Can also do fun things like proton tomography:

\[ PDF(x, R_\perp) \equiv \int \frac{d^2 \Delta_\perp}{(2\pi)^2} e^{i(\Delta_\perp R_\perp)} GPD(x, t = -\Delta_\perp^2) \]
Hard Exclusive Reactions

Hard Exclusive Reactions

\[ e' + p = e' + p + \Delta \]

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DVCS:

\[ H, E, H, E \]

Meson production:

pseudoscalar mesons (\(\pi, \eta\)):

\[ H, E \]

vector mesons (\(\rho, \omega\)):

\[ H, E \]

Beam-spin asymmetry \(\rightarrow H\)

Long. target asymmetry \(\rightarrow H, \tilde{H}\)

Trans. target asymmetry \(\rightarrow E\)

Note: need \(\sigma_L\)
Hall A → Beam helicity dependent cross sections independent of $Q^2$

Hall B – Large phase space in one experiment

This is the first direct indication of scaling in DVCS!

Compton scattering is occurring at the quark level!

Purely experimental extraction of GPDs can really start!

Plastic scintillator array

LH2 target

Electromagnetic calorimeter

HRS

$A_1$ and $B_1$ are found independent of $Q^2$:

$$\sin \phi \quad \sin 2\phi$$

For fixed $x_B$ and $t$, $A$ and $B$ are found independent of $Q^2$.
Initial results on $\pi^0$ cross sections and beam-spin asymmetries from Hall A and B suggest transverse photon contributions not zero

→ LT separation required
6 GeV Highlights – Vector Mesons

Longitudinal cross section $\sigma_L (\gamma^*_L p \rightarrow p p_L^{0})$

$A$ modification of $H$ is possible, which will fix the low-$W$/high-$x_B$ behaviour, but is it real?
More to come at 6 GeV

Hall B:

1. DVCS beam spin asymmetry \(\rightarrow\) double statistics
2. DVCS longitudinal target asymmetry
3. DVCS transverse target asymmetry (maybe using HD-ice target?)

Hall A:

\(\rightarrow\) “LT like” separation of terms in DVCS cross section
\(\rightarrow\) Same experiment will also attempt LT for \(\pi^0\)
Hard Exclusive Reactions at 12 GeV

Approved experiments (so far – PACS 30 and 32)

Deeply Virtual Compton Scattering with CLAS at 11 GeV (E12-06-119)

Measurements of the Electron Helicity Dependent Cross Sections of Deeply Virtual Compton Scattering with CEBAF at 12 GeV (E12-06-114)

Hard Exclusive Electroproduction of $\pi^0$ and $\eta$ with CLAS12 (E12-06-108)

Scaling Study of the L-T Separated Pion Electroproduction Cross Section at 11 GeV (E12-7-105)
DVCS in Hall B

12 GeV Hall B experiment builds on 6 GeV experiment → expanded $Q^2$ and $x$ range

Max $Q^2$: 4 GeV$^2$ → 6 GeV$^2$
Max $x$: 0.4 → 0.6

12 GeV proposal includes measurements with polarized target
12 GeV experiment features greatly expanded kinematic coverage

Extract twist-2 and twist-3 BH-DVCS interference terms

Extract $\pi^0$ cross sections $\rightarrow$ assume $\sigma_L$ dominance in extracting GPDs
$Q^2$ dependence of $\pi^+ \sigma_L, \sigma_T$

Hall C: Horn et al

$\sigma_L \sim 1/Q^{5.1+/-0.9}$

$\sigma_T \sim 1/Q^{4.2+/-0.8}$

For $\pi^+$, $\sigma_L$ is not even close to dominating at $Q^2=4$ GeV$^2$
Meson Production Hall B

Measure cross sections for $\pi^0$ and $\eta$ electroproduction

$\rightarrow \sigma_T + \varepsilon \sigma_L$
$\rightarrow \sigma_L, \sigma_T$ separation
$\rightarrow \sigma_{TT}, \sigma_{LT}, \sigma_{LT'}$

Study $Q^2$ (at low $-t$ ) dependence of all to look for evidence of factorization
\[ \frac{d\sigma_L}{\sigma_L} = \frac{d\sigma}{\sigma} \frac{1}{\epsilon_1 - \epsilon_2} \sqrt{(1/R + \epsilon_1)^2 + (1/R + \epsilon_2)^2} \]

\[ \frac{d\sigma}{\sigma} = 1\% \]

\[ \frac{\sigma_L}{\sigma_T} = 0.1 \]

\[ \frac{\sigma_L}{\sigma_T} = 1 \]

\[ \frac{\sigma_L}{\sigma_T} = 10 \]

\( \Delta \epsilon \)
$\frac{d\sigma_L}{\sigma_L} = \frac{d\sigma}{\sigma} \frac{1}{\epsilon_1 - \epsilon_2} \sqrt{(1/R + \epsilon_1)^2 + (1/R + \epsilon_2)^2}$
Charged Pion Production Hall C

Separated cross sections in $\pi^+$ production $\rightarrow$ examine $Q^2$ dependence at fixed $x,-t$ to test $1/Q^6$ scaling

Additional test data for $\pi^-$, perhaps L-T ratio more favorable
Transverse target asymmetries
→ DVCS → access to $E$
→ Pseudoscalar and vector meson production

*Important for mesons in particular: factorization not expected to set in until very large $Q^2$

Need the ratio of 2 (longitudinal) observables to take advantage of “precocious” factorization

Vector mesons? → most straightforward way to get at Ji sum rule?

And what about strangeness? → kaons!
Interest in semi-inclusive processes dominated originally by potential use in “flavor” tagging → deconvolution of polarized PDFs → constraints on unpolarized sea

More recently, interest has grown in azimuthal asymmetries → Transversity distribution → Transverse Momentum Distributions (TMDs)

\[ \sigma \sim \sum_{f} e_{f}^{2} q_{f} (x) D^{h}_{f} (z) \]

- Parton distribution
- Fragmentation function
**Distribution Functions**

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<tr>
<td>U</td>
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Diagonal elements = usual PDFs

Unpolarized nucleon $\rightarrow$ unpolarized quarks: $u(x)$, $d(x)$, ...

Longitudinally polarized nucleon $\rightarrow$ long. pol. quark: $\Delta u(x)$, $\Delta d(x)$, ...

Transversely polarized nucleon $\rightarrow$ trans. pol. quark: transversity distribution
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Off-diagonal elements = transverse momentum distributions, require non-zero angular momentum

- $f_{1T}$ → Sivers function, describes unpolarized quark in trans. pol. nucleon
- $h_{1\perp}, h_{1\perp L}, h_{1T}$ → Boer-Mulders functions describe transversely polarized quarks in un/long./trans./polarized nucleon
6 GeV Highlights – Meson Duality

ep,d → e′π+/-X in Hall C

Low energy semi-inclusive cross sections consistent with calculation using high energy params. of frag. functions and cteq PDFs (z<0.7)

Combinations of D/p, π+/π- yields give z-independent results
6 GeV Highlights – Hall B Multiplicities

\[ ep \rightarrow e' \pi^0 X \]

\( \pi^0 \) multiplicities in CLAS consistent with higher energy data
$\sigma_{\sin \phi}^{\text{LU(UL)}} \sim F_{\text{LU(UL)}} \sim 1/Q \text{ (Twist-3)}$

$A_{\text{UL}}$ (CLAS @5.7 GeV)

$A_{\text{UL}}$ CLAS @4.3 GeV

$A_{\text{LL}}$ CLAS @5.7 GeV

$A_{\text{UL}} \propto f_0^\perp D_1$

$A_{\text{UL}} \propto g_0^\perp D_1$

$A_{\text{LL}} \propto g_1 D_1$
More to come at 6 GeV

**Hall A**

1. Transversity in fall 2008 (polarized $^3$He)
2. Flavor asymmetry in nucleon sea $\bar{d} - \bar{u}$ (conditionally approved – run before 12 GeV?)

**Hall B**

1. More data on longitudinally polarized targets (x10 stats)
2. Transversely polarized target (along w/DVCS – see earlier)

**Hall C**

1. Semi-sane – data from longitudinally polarized targets to constrain $\Delta u, \Delta d$

$\rightarrow$ out of time before HKS/$Q_{\text{weak}}$, will take data parasitically during $g_1D$
Semi-inclusive Reactions at 12 GeV

Approved experiments (so far – PACS 30 and 32)

Measurement of the Ratio $R = \sigma_L / \sigma_T$ in Semi-Inclusive Deep-Inelastic Scattering (E12-06-104)

Probing the Proton’s Quark Dynamics in Semi-Inclusive Pion Production at 12 GeV (E12-06-112)

Studies of Spin-Orbit Correlations with Longitudinally Polarized Target (E12-07-107)
Analysis of semi-inclusive processes to extract polarized PDFs, etc., it is usually assumed that

\[ R = \frac{\sigma_L}{\sigma_T} \]

for semi-inclusive similar to R for inclusive DIS

→ No experimental verification that this assumption is true (except for low precision Cornell data)

Exclusive limit (\(z=1\)) : \(\sigma_L\) expected to dominate – how does this set in?
Unpolarized Azimuthal Moments in Hall B

$\cos 2\phi$ moment of semi-inclusive cross section from unpolarized target

$$\sigma_{UU}^{\cos 2\phi} \propto 2(1 - y)\cos 2\phi \sum_{q,\bar{q}} e_q^2 x h_{1q}^\perp(x) H_{1q}^\perp(z)$$

Boer-Mulders function

Collins Fragmentation Function

Contains information on Collins fragmentation function and TMD: related to interference of L=0 and L=1 wave functions
Polarized Target in Hall B

\[ \sigma_{UL}^{\sin 2\phi} \propto S_L 2(1 - y) \sin 2\phi \sum_{q, \bar{q}} e_q^2 x h_{1L}^{1q}(x) H_{1}^{1q}(z) \]

→ Single spin asymmetry contains information on alternate Boer-Mulders function
→ Double spin asymmetry yields polarized quark distributions

Figure 9: (Left) The projected \( x \)-dependence of the target SSA at 11 GeV. The triangles illustrate the expected statistical accuracy. The open squares and triangles show the existing measurement of the Mulders TMD from HERMES and the preliminary results from CLAS 5.7 GeV EG1 data sets, respectively. The curves are calculated using Ref. [61]. (Right) Projection for the Mulders distribution function for the \( u \)-quark from the \( \pi^+ \) SSA from CLAS12 (predicted) compared with the CLAS EG1 data set at 5.7 GeV.

Figure 10: The double spin asymmetry \( A_{UL} \) (left) and its \( \cos \phi \) moment (right) for the NH \( ^3\text{He} \) target as a function of the transverse momentum of hadrons, \( P_T \), averaged in the \( 0.4 < z < 0.7 \) range.

Figure 11: The double spin asymmetry \( A_{UL} \) (left) and its \( \cos \phi \) moment (right) for the ND \( ^3\text{He} \) target as a function of the transverse momentum of hadrons, \( P_T \), averaged in the \( 0.4 < z < 0.7 \) range.

Figure 12: The polarization of valence quarks (\( \Delta d^V \)) in the nucleon. The filled symbols are for the SIDIS data only and open symbols are for DIS data neglecting sea contributions. The curves are pQCD based predictions with (solid) and without (dashed) OAM contributions [29].
Agreement of JLab 6 GeV data with higher energy measurements/expectations suggests factorization should not be a problem at 12 GeV

Hall C semi-inclusive cross sections → agree well with simple parameterization using CTEQ and high energy frag. functions

Hall B multiplicities, SSA’s → Agree with EMC, HERMES data

HERMES agreement with E866 measurement of sea asymmetry taken as evidence that factorization works at “modest” energies
Recent analyses from HERMES suggests that factorization may not be working as well as we thought!

At $x \sim 0.3$, good agreement with simple factorization picture is seen.

Most JLab measurements so far are in this region or nearby.

Maybe we are just “lucky” to see evidence of factorization at 6 GeV?

Must proceed cautiously, even at 12 GeV…
Semi-Inclusive Processes: what’s missing?

Measurements with transverse targets
  → Obviously needed for transversity and Sivers effect measurements

Kaons
  → Most measurements so far emphasize pion production
  → Kaons needed for access to $\Delta s(x)$

Sea-asymmetry at 12 GeV? $\bar{d} - \bar{u}$
  → Proposal from PAC30 deferred based in part on questions about factorization (must be satisfied at very precise level)

This is exactly why we should do it! If it works and yields results consistent with E866/E906 Drell-Yan, gives us confidence in 12 GeV semi-inclusive program. If it yields “strange” results, gives information about where more study is needed.
Related Issues/Experiments Not Mentioned

**Color transparency**
2 experiments approved to study color transparency at 12 GeV
→ Exclusive $\rho$ production in Hall B
→ Exclusive $\pi$ production and e,e’p in Hall C (conditional)

Important for GPD studies: Factorization not possible without the onset of Color Transparency (CT) \([M. Strikman, Nuc. Phys. A663,64 (2000)]\)

**Hadronization**
2 experiments approved to study hadronization in nuclei
→ Semi-inclusive production in Hall B
→ Semi-inclusive production in Hall C

These experiments use the nucleus as a laboratory to understand how hadrons are formed in semi-inclusive processes (formation time, etc.)

→ Assumptions about factorization crucial as well as implicit assumption that the reaction mechanism is unchanged in nuclei
Conclusions

6 GeV program at JLab has provided first glimpse of physics we can do with hard exclusive, semi-inclusive processes

12 GeV program will provide data of great breadth and unparalleled precision

Our enthusiasm for the exciting physics we can do must be tempered by the knowledge that we must go out of our way to show that “factorization” is observed

→ What else can we do experimentally to convince ourselves and others that we are seeing factorization?
→ What about “precocious factorization”? $Q^2$ independence of ratios enough?