Accessing Quark Information through Semi-Inclusive DIS Measurements at JLab-12 GeV

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- Opportunities of SIDIS at JLab-12GeV.
- How can we tell when we hit a quark?
- Cross sections of $\pi$-production at NLO.
- (Instrumentation considerations.)
- Letter-of-Intend (LOI12-07-103) and a new physics proposal for JLab PAC-35
SIDIS Programs at JLab-12 GeV

- $A_{UT}$ transversely polarized target SSA, Collins and Sivers asymmetries to access quark transversity and Sivers distributions.
- $A_{LL}$ longitudinally polarize target double-spin asymmetries to access quark helicity distributions $\Delta u, \Delta d, \Delta u - \Delta d$.
- Hadron azimuthal distributions in SIDIS, like $\cos(2\phi)$, to access transverse momentum dependent parton distributions.

The underline assumptions:
- Hard scattering.
- Independent fragmentation.
- Universality of Fragmentation Functions.

$$z = \frac{E_{\pi}}{\nu}$$
Can we really access quark information at JLab-12 GeV?

- Hard scattering. How can we tell when we hit a quark?
- Fragmentation. Quark information carried out by hadron?
- Extracted Frag. Func. agree with $e^+e^-$ and $p+p$ data?

Do we understand the fundamental cross sections in SIDIS, to the Next-to-Leading-Order?

Do we understand their relative relations, $x$, $Q^2$, $z$, $p_t$ and $\varphi$-dependencies?

The first step of the SIDIS program at JLab-12 GeV is to firmly establish the baseline of parton-model interpretation.

What will be the best evidences?
SIDIS hadron multiplicity ➔ cross section

Assuming the inclusive (e,e') cross section is well understood. (SLAC, HERA, JLab-6 GeV ...).

In SIDIS, obtain hadron multiplicity by integrate over hadron azimuthal angle and transverse momentum.

$$
\sigma^h(x,Q^2,z_h) = \frac{1}{\sigma_{tot}^{ee}(x,Q^2)} \int d\phi d^2p_T \frac{d\sigma^{ee'h}(x,Q^2,z_h,\phi,p_T)}{d\phi d^2p_T}
$$

$$
\sigma_{UU}^{ee'h} = A + B \cos \phi + D \cos(2\phi)...
$$

$x$-dependence comes from parton distribution.
$z_h$-dependence comes from fragmentation function.
$Q^2$-dependence comes from both PDFs and Frag. Func.
Leading Order Cross Sections, fractional contributions from each quark flavor

\[ \sigma_q / \sigma_{all} = e_f^2 q_f \cdot D_f^h / \sum_i e_i^2 q_i \cdot D_i^h \quad (\text{at } z_h = 0.5) \]
Since there’s no “free” neutron, one has to use Deuteron or $^3$He targets.

Sea quarks contribute <10%, strange quarks contribute <5% of the total cross section.
SIDIS cross sections at NLO

LO:

NLO-qq:

NLO-qq:

NLO-gq:

\[ q(x, Q^2) \cdot D(z, Q^2) \Rightarrow \int \frac{dx'}{x'} \int \frac{dz'}{z'} q\left(\frac{x}{x'}\right) C(x', z') D\left(\frac{z}{z'}\right) \]
NLO global fits for Fragmentation Functions

A global fit to e+e-, SIDIS and p+p data.

Predict cross sections at NLO for JLab-12GeV.

Fit compare with HERMES SIDIS data, R. Sassot et al. 2007.
For example, an experiment with CLAS12 (1000h): SIDIS $\pi^{+/0/-}$ production on proton and deuteron targets

$$ep \rightarrow e'\pi X \quad e(p + n) \rightarrow e'\pi X$$

Form ratios from measured yields $N_{\pi^+}, N_{\pi^-}$

$$\frac{(N_{\pi^+} + N_{\pi^-})^p}{(N_{\pi^+} + N_{\pi^-})^d} \quad \frac{(N_{\pi^+} - N_{\pi^-})^p}{(N_{\pi^+} - N_{\pi^-})^d}$$

Integrate over $\varphi$ and $p_t$: hadron multiplicities.

Obtain dependence on $Q^2$, $x_{bj}$, $z_{\pi}$

High Luminosity $10^{35} \, cm^{-2} \, s^{-1}$
Definition and cuts

\[ x_{bj} = \frac{Q^2}{2\nu M} \]
\[ z_{\pi} = \frac{E_\pi}{\nu} \]
\[ x_F = \frac{2p^*_{//}}{W} \]

* Virtual-photon nucleon CM

\[ Q^2 > 1\text{GeV}^2, W > 2\text{GeV}, W' > 1.5\text{GeV}, x_F > 0, p_\pi > 2\text{GeV} / c \]
Cuts for pion on $x_F, W'$

- $W' > 1.5$
- $x_F > 0$
$Q^2$ vs. $x$, $z$ vs. $x$, $P_t$ vs. $x$

$10 \times 10 \times 10$ bins in $x$, $Q^2$ and $z$ to obtain:
- $Q^2$ dependence at fixed $z$ and $x$
- $z$ dependence at fixed $Q^2$ and $x$
- $P_t$ dependence at fixed $Q^2$ and $x$
Expected results: z-dependence

Curve: Prediction in NLO from R. Sassot.

\[ Q^2 = 2.5, \]
\[ x = 0.2, 0.3, 0.4, 0.5 \]

\[ \pi^0 = \frac{(\pi^+ + \pi^-)}{2} \]

SU(2) symmetry in the fragmentation process?
Hall C data at 5.5 GeV: cross sections

$x=0.32$, $Q^2=2.3$ GeV$^2$.
smooth in $0.4<z<0.65$
agree with LO.

Expected results: $Q^2$ dependence

Curve: Prediction in NLO from R. Sassot.

$z=0.5,$
$x=0.2, 0.3, 0.4, 0.5$
with beam energy 11, 8.8 and 6.6 GeV
$Q^2$-dependence, same $Q^2$ point covered by different beam energy.
The combined-ratios of multiplicities

At LO no $z$-dependency.

Even at NLO, $z$-dependency mostly disappeared.

 Ratios become completely determined by quark distributions.

A clear evidence to prove that quark information is well-preserved in the fragmentation process.

At $E_0=5.5$ GeV, we already know from Hall C data...
Hall C data at 5.5 GeV: combined-ratio of multiplicities


Closed (open) symbols reflect data after (before) events from estimated coherent \( \rho \) production are subtracted.

\( x=0.32, Q^2=2.3 \text{ GeV}^2 \).
Flat in \( 0.4<z<0.7 \)
Agree with LO parton ratios.

GRV & CTEQ, @ LO or NLO
Fragmentation functions drop out at Leading Order (Isospin symmetry and charge conjugation) in ratios like:

\[
\frac{\sigma_p(\pi^+ + \pi^-)}{\sigma_d(\pi^+ + \pi^-)} = \frac{[4u(x) + d(x)]}{[5(u(x) + d(x))]} \\
\sim \frac{\sigma_p}{\sigma_d} \quad \text{independent of } z
\]

(in $\pi^+-\pi^-$ gluon related terms drop out at all orders.)

\[
\frac{\sigma_p(\pi^+) - \sigma_p(\pi^-)}{\sigma_d(\pi^+) - \sigma_d(\pi^-)} = \frac{[4u(x) - d(x)]}{[3(u(x) + d(x))]} \\
\text{independent of } z
\]
In $\pi^+ - \pi^-$ gluon related terms drop out at all orders

LO:

NLO-qq:

NLO-qg:

NLO-gq:

\[ q(x, Q^2) \cdot D(z, Q^2) \Rightarrow \int \frac{dx'}{x'} \int \frac{dz'}{z'} q \left( \frac{x}{x'} \right) C(x', z') D \left( \frac{z}{z'} \right) \]
Kaon multiplicities

Cut on $P_K < 3.0 \text{ GeV/c}$ (no RICH).

Kaon from the hit-quark?
A list of questions for SIDIS at JLab-12 GeV

- π Fragmentation Functions agree with $e^+e^-$, p+p data?
- Kaon multiplicities agree with NLO prediction?
- Fragmentation to other mesons: $\eta$, $K^0_s$, $\rho$, $\omega$ and $\phi$. Ratio of $\pi^0/\eta$.
- Connection between Frag. Func. to hadron structure. Transition from SIDIS to the exclusive limit, a theoretical picture?
- $\phi$(s-sbar) in SIDIS carry information of s-quarks? What about spin asymmetries, Sivers asymmetries?
- $\Lambda$ production and $\Lambda$ polarization. Spin-transfer, induced polarization, transverse spin asymmetry to access quark transversity.
Summary

- SIDIS@Jlab-12GeV offers many new physics opportunities.
- The first step is to firmly establish the baseline of interpretation.
- Understanding cross sections (multiplicities) of π-production to NLO is the key issue to be addressed.
- A new physics proposal, using the large acceptance CLAS12 detector, is to be submitted to JLab PAC-35.

A large acceptance detector provides:
- coverage in hadron azimuthal angle \( \varphi \).
- coverage in hadron transverse momentum \( p_t \).
Track resolution:
\[ \delta p \ (\text{GeV/c}) \quad 0.003p + 0.001p^2 \]
\[ \delta q \ (\text{mr}) \quad < \quad 1 \]
\[ \delta \phi \ (\text{mr}) \quad < \quad 3 \]

SIDIS kinematics
\[ Q^2 > 1 \]
\[ W^2 > 4 \]
\[ y < 0.85 \]
\[ M_X > 2 \]