Access Quark Information Through semi-Inclusive Deep-Inelastic Scattering Experiments at JLab-12 GeV

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- Opportunities of SIDIS at JLab-12GeV.
- How do we know when we hit a quark?
- Cross sections of SIDIS $\pi$ production at NLO.
- Ratios of multiplicities carry quark information.
- My list of interesting SIDIS physics topics at JLab-12GeV.

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SIDIS Program at JLab-12 GeV

- $A_{UT}$ trans. target SSA, Collins and Sivers asymmetries to access quark transversity and Sivers distribution function. $\pi^{+/0/-}, K^{+/0/-}$ etc.

- $A_{LL}$ long. target double-spin asymmetries for quark spin-flavor decomposition, $\Delta u, \Delta d, \Delta u - \Delta d$

- Hadron azimuthal distribution in SIDIS, like $\cos(2\phi)$, access transverse momentum dependent parton distributions. and more...

Three underline assumptions:
- Hard scattering at the vertex.
- Independent fragmentation (soft).
- Universality of Frag. Func.
Can we access quark information at JLab-12 GeV?

- Hard scattering. How do we know when we hit a quark?
- Fragmentation. Quark information carried out by hadron?
- Universality of Frag. Func. Agree with $e^+e^-$, p+p data?

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

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

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

What is the best evidence?
Leading Order Cross Sections, contributions from each quark flavor

\[
\frac{\sigma_q}{\sigma_{all}} = \frac{e_f^2 q_f \cdot D_f^h}{\sum_i e_i^2 q_i \cdot D_i^h} \quad (\text{at } z_h = 0.5)
\]
LO contributions from each quark flavor, on Deuteron and $^3$He

\[
\frac{\sigma_q}{\sigma_{all}} = e_f^2 q_f \cdot D_f^h / \sum_i e_i^2 q_i \cdot D_i^h
\]
SIDIS cross sections at NLO

LO:

\[ q(x, Q^2) \cdot D(z, Q^2) \Rightarrow \int \frac{dx'}{x'} \int \frac{dz'}{z'} q\left(\frac{x}{x'}\right)C(x', z')D\left(\frac{z}{z'}\right) \]
\[ \sigma^h(x, z) = \sum_f e_f^2 q_f \left[ 1 + \frac{\alpha_s}{2\pi} C_{qq} \otimes \right] D^h_{q_f} \]

\[ + \left( \sum_f e_f^2 q_f \right) \otimes \frac{\alpha_s}{2\pi} C_{gg} \otimes D^h_G + G \otimes \frac{\alpha_s}{2\pi} C_{gq} \otimes \left( \sum_f e_f^2 D^h_{q_f} \right) \]

Wilson co-efficiencies \( C_{ij}(x, z) \) are well-known.

At NLO, gluon Frag. Func. are involved, limited number of unknowns. Many independent measurements help to constrain these unknowns within the framework of a global NLO-QCD fit.
NLO global fits of Fragmentation Functions

Fit compare with HERMES SIDIS data, R. Sassot et al. 2007.

Pion multiplicities, integrated over Pt and φ

Global fit to $e^+e^-$, SIDIS and p+p data, to predict cross sections at NLO for JLab-12GeV
For example, a measurement with CLAS12:
SIDIS $\pi^+, \pi^-, \pi^0$ production on proton and deuteron targets

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

Form ratios from measured yields $\frac{N_{\pi^+}, N_{\pi^-}}{(N_{\pi^+} + N_{\pi^-})^p}$

Check kinematic dependence on $Q^2$, $x_{bj}$, $z_\pi$, $P_t$

High Luminosity $10^{35} \text{cm}^{-2} \text{s}^{-1}$

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<th>$E_0=11 \text{ GeV}$</th>
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<tr>
<td>Beam on LH$_2$</td>
<td>1000 hours</td>
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<td>Beam on LD$_2$</td>
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Definition and cuts

\[ x_{bj} = \frac{Q^2}{2 \nu M} \]

\[ z_{\pi} = \frac{E_{\pi}}{\nu} \]

\[ x_F = \frac{2 p^*_l}{W} \]

* Virtual-photon nucleon CM

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

$W' > 1.5$ at least

$x_F > 0$

$x_F^\pi, p > 1 \text{GeV}$
Q2 vs. x, z vs. x, Pt vs. x

Check $Q^2$ dependence for a given $z$ and $x$

Check $z$ dependence for a given $Q^2$ and $x$

Check $P_t$ dependence for a given $Q^2$ and $x$
Expected results: $z$-dependence

Curve: Prediction in NLO from R. Sassot.

$Q_2=2.5,$
$x=0.2,0.3,0.4,0.5$

$\pi^0=\left(\pi^+ + \pi^-\right)/2$

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

\( x = 0.32, \; Q^2 = 2.3 \text{ GeV}^2 \)

smooth in \( 0.4 < z < 0.65 \)

agree with LO calculations.
Expected results: Q2 dependence

Curves: predictions from NLO, R. Sassot et al.

z=0.5,
x=0.2,0.3,0.4,0.5
(x, Q^2) coverage.

with beam energy 11, 8.8 and 6.6 GeV

E_0=11 GeV
E_0=8.8 GeV
E_0=6.6 GeV

Q^2>1.0 GeV^2
W>2.0 GeV
W''>1.5 GeV
X_F>0
$Q^2$-dependence, same $Q^2$ point covered by different beam energy.
Combined-ratio of multiplicities

At LO no $z$-dependency. SU(2) symmetry in pdf and F.F.

Even at NLO, $z$-dependency mostly canceled in the ratio.

Ratios become completely determined by parton distributions.

A clear evidence to prove that parton information is preserved in the fragmentation process.

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

\[ X = 0.32, \quad Q^2 = 2.3 \text{ GeV}^2. \]

Flat in 0.4<z<0.7

Agree with LO parton distribution ratios.
and the reason is ...

Neglect sea quarks and assume no $p_t$ dependence of parton distribution functions

\rightarrow \text{Fragmentation functions drop out at Leading Order, due to SU(2) symmetry.}

\rightarrow \frac{[\sigma_p(\pi^+) + \sigma_p(\pi^-)]}{[\sigma_d(\pi^+) + \sigma_d(\pi^-)]}

= \frac{[4u(x) + d(x)]}{[5(u(x) + d(x))]} \text{ independent of } z.

\rightarrow \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.
Kaon multiplicities

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

A planned RICH detector helps in:
1. Eliminate $\pi$ contamination.
2. Expand coverage to high-$z$, to study the transition to exclusive KY channels.

Kaon from the hit-quark? Any hope to access s-quark information?
Need a detailed understanding of cross sections to \(~2\%\) level.
Recall LO Cross Sections, contributions from each quark flavor.

\[
\frac{\sigma_q}{\sigma_{all}} = e_f^2 q_f \cdot D_f^h \div \sum_i e_i^2 q_i \cdot D_i^h \quad (\text{@} z_h = 0.5)
\]
A list of questions in SIDIS

- π Frag. Func. agree with e^+e^-, p+p data?
- Fragmentation to other mesons: η, K_s^0, ρ, ω and φ. Ratio π^0/η.
- Connection between Frag. Func. to hadron structure.
- φ(s-sbar) in SIDIS carry information of s-quarks? What about spin asymmetries, Sivers asymmetries?
- Transition from SIDIS to the exclusive limit, a theory picture?
- Λ production and Λ polarization. Spin-transfer, induced polarization, transverse spin asymmetry to access quark transversity.
Summary

• SIDIS@JLab-12GeV offers many new physics opportunities.
• Firmly establish the baseline of interpretation is the critical step.

• Understanding cross sections of $\pi$-production to NLO level is the first step.