Complementarity of $\nu$ & $e$ probes of hadron structure

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Many areas of overlap for nucleon (& nuclear) structure studies with neutrino (LNBE) vs. electron (JLab) beams
→ strange content of the nucleon
→ parton distribution functions
→ higher twists & quark-hadron duality
→ nuclear modification of nucleon properties
→ generalized parton distributions

Cooperation between communities already exists
(e.g. MINERνA, CTEQX)

Workshop on Intersections of Nuclear Physics with Neutrinos and Electrons (2006)
http://conferences.jlab.org/neutrino/
Strange content of the nucleon

- Strange vector form factors measured to high precision in parity-violating $e$ scattering at JLab, MAMI & elsewhere

$G_E^s = \rho_s Q^2 + \rho_s' Q^4$
$G_M^s = \mu_s + \mu_s' Q^2$

$\rho_s = -0.03 \pm 0.63 \text{ GeV}^{-2}$
$\mu_s = 0.37 \pm 0.79$

- strange quark contribution to proton magnetic moment less than 10\%
- strange electric form factor consistent with zero
- consistent with theory (lattice + phenomenology)

Young et al., PRL 99, 122003 (2007)

Leinweber et al., PRL 94, 212001 (2005)
Strange content of the nucleon

Strange axial vector form factors not as well determined

\[ G_N^A = \tilde{g}_A^N (1 + Q^2/M_A^2)^{-2} \]

\[ M_A = 1.026 \text{ GeV} \]

\[ \tilde{g}_A^p = -0.80 \pm 1.68 \]

\[ \tilde{g}_A^n = 1.65 \pm 2.62 \]

Young et al., PRL 99, 122003 (2007)

→ includes “anapole” contribution (weak interaction within target)

→ complementary measurement in neutrino-nucleon elastic scattering
Strange content of the nucleon

Strange axial form factor at $Q^2 = 0$ related to spin carried by strange quarks through sum rule

$$\int_0^1 dx \ g_1^p(x, Q^2) = \left( \frac{1}{12} g_A^{(3)} + \frac{1}{36} g_A^{(8)} \right) C_{NS}(Q^2) + \frac{1}{9} g_A^{(0)} |_{\text{inv}} C_S(Q^2)$$

→ from elastic neutrino-proton scattering (NC) measure

$$2g_A^{(Z)} = (\Delta u - \Delta d - \Delta s)_{\text{inv}} + \mathcal{P} g_A^{(0)} |_{\text{inv}} + \mathcal{O}(m_t^{-1}, m_b^{-1})$$

→ using

$$(\Delta u - \Delta d - \Delta s)_{\text{inv}} = g_A^{(3)} + \frac{1}{3} g_A^{(8)} - \frac{1}{3} g_A^{(0)} |_{\text{inv}}$$

extract $g_A^{(0)} |_{\text{inv}} = (\Delta u + \Delta d + \Delta s)_{\text{inv}}$ to obtain independent determination of $\Delta s$

Strange content of the nucleon

- Neutrino/antineutrino DIS sensitive to strange-antistrange asymmetry in proton

\[ \text{integrated asymmetry } -0.001 \pm 0.04 \]

- asymmetry small but important indicator of nonperturbative physics

Alekhin, Kulagin, Petti, PLB 675, 433 (2009)
Parton distribution functions

- Vital to have precise $F_3$ structure function input into global PDF fits
  - most useful if measurements are on hydrogen (or deuterium) targets to avoid nuclear effects

- High-precision data on $F_2$ and $F_L$ from JLab at large $x$
  - desirable to have $F_2 / F_L$ separation for neutrinos at similar kinematics

- Data at low $Q^2$ and $W$ would also be useful
  - e.g. CTEQ6X global fit with $Q^2 > 1.69$ GeV$^2$, $W^2 > 3$ GeV$^2$ doubled number of DIS data points available

Accardi et al., PRD 81, 034016 (2010)
Parton distribution functions

- At large $x$ ($x > 0.5-0.6$) $d$ quark distribution (or $d/u$ ratio) is very poorly determined

- recent CTEQ6X fit attempts to better constrain $d$ quark to $x \sim 0.8$, but is limited by nuclear corrections in deuterium

Accardi et al., PRD 81, 034016 (2010)
Parton distribution functions

Several planned experiments at JLab with 12 GeV will measure $d/u$ to $x \sim 0.85$ with minimal nuclear corrections

- SIDIS from D with slow backward proton (“BONUS”); inclusive $^3\text{He} / ^3\text{H}$ ratio; and PVDIS from proton

Cleanest and most direct method is to use neutrino and antineutrino DIS on hydrogen

- Selects $d$ and $u$ quark PDFs at large $x$
- Need reach up to $x \sim 0.85$, with as large a $Q^2$ range as possible to control for higher twists
Higher twists and quark-hadron duality

Accuracy of quark-hadron duality being established in through high-precision measurements of electromagnetic structure functions in resonance region

higher-twist (duality-violating) corrections appear to be $\sim 10-20\%$ for low structure function moments

*Malace et al., PRL 104, 102001 (2010)*
Higher twists and quark-hadron duality

- Neutrino DIS will allow test of universality of duality, and determine size of higher twist matrix elements in $P$-odd vs. $P$-even structure functions

Model relies on very old neutrino resonance-production data

→ can lead to better constraints on large-$x$ PDFs
→ precise mapping out of resonance spectrum vital

Lalakulich, Paschos, WM PRC 75, 015202 (2007)
Generalized parton distributions

- Comprehensive program of hard exclusive reactions (e.g. DVCS) at JLab to extract GPDs
  - determine orbital angular momentum of quarks
  - map out 3D structure of nucleon

- Neutrino DVCS uniquely sensitive to $C$-odd combinations of GPDs, not accessible with $e$ scattering
  - flavor decomposition, non-diagonal transitions
  - can extract spin-dependent valence & sea distributions with an unpolarized target!

Psaker, WM, Radyushkin
*PRD 75*, 054001 (2007)
Nuclear effects

Important to understand differences between nuclear EMC effect for photons vs. $W/Z$ bosons

→ significant differences predicted, especially at low $Q^2$ and low $x$

→ critical for extracting nucleon information from nuclear target data (most neutrino experiments)
  - remain to be tested!

Kulagin, Petti
PRD 76, 094023 (2007)
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