DIS and Electroweak Physics: Experimental Opportunities at a Polarized Electron-Ion Collider

Krishna Kumar
University of Massachusetts, Amherst

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E. Chudakov, A. Deshpande, M.J. Ramsey-Musolf, P. Souder
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Structure of Hadrons and Nuclei at the EIC
ECT*, Trento
Opening Thoughts

- Any new machine that pushes the intensity frontier is of interest to the precision EW community.
- EIC is no exception: I have been promising myself (and Abhay) for several years to start thinking about the potential for EW physics at the EIC.
- It took the coincidence of a great location, pushy organizers and Mike Ramsey-Musolf!
- I started thinking about this a few weeks ago: all conclusions are highly preliminary!
- (Un)fortunately, I have generated quite a bit of very interesting homework!
Outline

- Lepton Flavor Violation
- Precision weak mixing angle measurement
- Parity Violating deep inelastic scattering
- The Developing JLab 12 GeV PV Program
- Electroweak Physics at the EIC
  - First look at BSM reach
  - Full Slate of EW Observables
    - Relationship to Charged Current
  - Two specific applications to nucleon structure
    - EMC effect
    - Quark Helicity Distributions
- Preliminary Conclusions and Homework
Lepton Flavor Violation

- Mike has given you several aspects of the physics motivation
- From the experimental side, LFV physics is undergoing a revival
- LFV searches are ongoing at existing facilities (e.g. PSI), and are also being looked at seriously for the future (e.g. J-PARC, Fermilab)
- The muon-to-electron conversion experiment is being designed for Fermilab Project-X: The recent P5 report in the US gave mu2e at Fermilab the highest near term priority in HEP
- Thus, it is interesting to see if EIC has a role to play in this subfield
Identifying Tau Leptons

\[ e^- + p \rightarrow \tau^- + X \]

Topology: DIS event, except electron replaced by tau lepton

- **If mixed in with hadron remnants, the tau would be highly boosted (10 to 50 GeV)**
- **If forward in the incident electron direction, the tau would be isolated**
- **In either case:**
  - look for single pion, three pions in a narrow cone, single muon: should be able devise several good triggers
  - tau decay is self-analyzing: should study polarization dependence
  - tau vertex displaced 200 to 3000 microns: would greatly help background rejection and maintain high efficiency if vertex detector is included in EIC detector design
PV Asymmetries

Weak Neutral Current (WNC) Interactions at $Q^2 \ll M_Z^2$

Longitudinally Polarized Electron Scattering off Unpolarized Targets

\[ \sigma \propto |A_\gamma + A_{\text{weak}}|^2 \]

Longitudinally polarized

\[ -A_{LR} = A_{PV} = \frac{\sigma_- - \sigma_0}{\sigma_+ + \sigma_0} \sim \frac{A_{\text{weak}}}{A_\gamma} \sim \frac{G_F Q^2}{4 \pi \alpha} (g_A e g_V T + \beta g_V e g_A T) \]

$g_V$ and $g_A$ are function of $\sin^2 \theta_W$

\[ A_{PV} \sim 10^{-5} \cdot Q^2 \text{ to } 10^{-4} \cdot Q^2 \]

Specific choices of kinematics and target nuclei probes different physics:

- In mid 70s, goal was to show $\sin^2 \theta_W$ was the same as in neutrino scattering
- Early 90s: target couplings carry novel information about hadronic structure
- Now: precision measurements with carefully chosen kinematics can probe physics at the multi-TeV scale
PV Møller Scattering

\[ A_{PV} \propto m_e E_{\text{lab}} \left( 1 - 4 \sin^2 \vartheta_W \right) \]

Purely leptonic reaction

SLAC E158

\[ A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9} \]

\[ \frac{\delta(\sin^2 \vartheta_W)}{\sin^2 \vartheta_W} \cong 0.05 \frac{\delta(A_{PV})}{A_{PV}} \]


15 July 2008

DIS and Electroweak Physics (Experiment)
Møller Scattering at 12 GeV

- Comparable to single Z pole measurement: shed light on disagreement
- Best low energy measurement until ILC or $\nu$-Factory
- Could be launched ~ 2014

Address longstanding discrepancy between hadronic and leptonic Z asymmetries

Z pole asymmetries

Jefferson Lab

\[
\begin{align*}
A_{fb}^{0,1} &: 0.23099 \pm 0.00053 \\
A_{(P_T)} &: 0.23159 \pm 0.00041 \\
A_{(SLD)} &: 0.23098 \pm 0.00026 \\
A_{fb}^{0,b} &: 0.23221 \pm 0.00029 \\
A_{fb}^{0,c} &: 0.23220 \pm 0.00081 \\
Q_{had}^{\text{had}} &: 0.2324 \pm 0.0012 \\
\text{Average} &: 0.23153 \pm 0.00016
\end{align*}
\]
Ultrahigh Precision

Measure contribution from scalars to quantum loops

\[ \frac{\delta m_H}{m_H} \approx 10\% \text{ for } \delta \sin^2 \theta_W \approx 0.00004 \quad \text{(world average } \sim 0.00014) \]

Compare with mass observed at the LHC:

Critical crosscheck of electroweak theory

Colliders will attempt this with \( A_{\text{LR}} \) and \( M_W \) but...

Systematics are extremely challenging!

Energy scale to \( 10^{-4} \), polarimetry to 0.15%
ELIC in e-e Mode

E. Chudakov

- Single spin asymmetry $P_b \neq 0$, $P_t = 0$
  $$A_{LR}^{(1)} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R},$$
  $$\sigma_L = \sigma_{LL} + \sigma_{LR}, \ \sigma_R = \sigma_{RL} + \sigma_{RR}$$

- Double spin asymmetry $P_b \neq 0$, $P_t \neq 0$
  $$A_{LR}^{(2)} = \frac{\sigma_{LL} - \sigma_{RR}}{\sigma_{LL} + \sigma_{RR}}$$

- $A_{LR}^{(1)}$, $A_{LR}^{(2)}$ are calculable in SM

Add a central $e^-e^-$ collision point
- $\bar{e}^-e^-\ 3\times3$ GeV - $7\times7$ GeV
- Crab crossing
- $\mathcal{L} \sim 3 \cdot 10^{35}$ cm$^{-2}$s$^{-1} = 0.3$ pb$^{-1}$s$^{-1}$
- Collision rate 1.5 GHz
- Polarization flip $> 1.\ MHz$
- Bunch trains polar. structure (?)
ELIC e-e Issues

- $\sqrt{s} = 12.3$ GeV, $\mathcal{P} \sim 0.90(\pm 3\%)$
- Measure $A_{LR}^{(2)} = \frac{\sigma_{LL}-\sigma_{RR}}{\sigma_{LL}+\sigma_{RR}}$
  
  $\frac{N_{LL}-N_{RR}}{N_{LL}+N_{RR}} = A_{LR}^{(2)} \cdot \mathcal{P}_{\text{eff}} \cdot (1 - \delta)$
  
  $\delta \sim 0.02$ calculable
  
- $\mathcal{P}_{\text{eff}} = \frac{\mathcal{P}_1+\mathcal{P}_2}{1+\mathcal{P}_1\mathcal{P}_2} = 0.995 \pm 0.002$
- Acceptance $|\cos \theta| < 0.7$
- Trigger 3 kHz, reconstruction

Projected error on weak mixing angle: 
0.00014

- **polarization flips?**
  - How often?
  - Systematics

- **collision point feasibility**

- **effective polarization**
  - do we gain with systematics?

- **simplest detector?**
Comprehensive Search for New Neutral Current Interactions

Important component of indirect signatures of "new physics"

Many new physics models give rise to non-zero $\Lambda$'s at the TeV scale:
Heavy Z's, compositeness, extra dimensions...

One goal of neutral current measurements at low energy AND colliders:
Access $\Lambda > 10$ TeV for as many $f_1 f_2$ and $L,R$ combinations as possible

LEPII, Tevatron access scales $\Lambda$'s $\sim 10$ TeV

e.g. Tevatron dilepton spectra, fermion pair production at LEPII
- L,R combinations accessed are parity-conserving

LEPI, SLC, LEPII & HERA accessed some parity-violating combinations
but precision dominated by Z resonance measurements

Consider $f_1 \tilde{f}_1 \rightarrow f_2 \tilde{f}_2$ or $f_1 f_2 \rightarrow f_1 f_2$

$$L_{f_1 f_2} = \sum_{i,j=L,R} \eta_{ij} \frac{4\pi}{\Lambda_{ij}^2} \tilde{f}_1 \gamma^\mu f_1 \tilde{f}_2 \gamma^\mu f_2$$

Eichten, Lane and Peskin, PRL50 (1983)
Colliders vs Low $Q^2$

Consider:

$$A_X \propto \frac{1}{Q^2 - M_X^2} \sim \frac{4\pi}{\Lambda^2}$$

$Q^2 \sim M_Z^2$

on resonance:

$$A_Z \text{ imaginary} \quad \rightarrow \quad A_Z^2 \left[1 + \frac{A_X^2}{A_Z^2}\right]$$

**no interference!**

$$\frac{\delta A_Z}{A_Z} \propto \frac{\pi/\Lambda^2}{g G_F} \quad \rightarrow \quad \delta(g)/g \sim 0.1 \quad \Lambda \sim 10 \text{ TeV}$$

$$\frac{\delta (\sin^2 \theta_W)}{\sin^2 \theta_W} \lesssim 0.01$$

Window of opportunity for weak neutral current measurements at $Q^2 \ll M_Z^2$

Processes with potential sensitivity:
- Neutrino-nucleon deep inelastic scattering
- Atomic parity violation
- Parity-violating electron scattering
Lepton-Quark WNC Couplings

- Atomic Parity Violation
  - $^{133}\text{Cs} 6s$ to $7s$ transition
- Future: isotope measurements
- Neutrino DIS: NuTeV
  - $3 \sigma$ deviation
- Many hadronic physics issues
- Look at other l-q couplings?

$\delta(C_{1q}) \propto (+\eta_{RL}^{eq} + \eta_{RR}^{eq} - \eta_{LL}^{eq} - \eta_{LR}^{eq})$

$\delta(C_{2q}) \propto (-\eta_{RL}^{eq} + \eta_{RR}^{eq} - \eta_{LL}^{eq} + \eta_{LR}^{eq})$

But elastic scattering cannot determine $C_{2q}$’s precisely

**Qweak at JLab**

$A_{PV}$ in elastic e-p scattering: $Q_{weak}$ at JLab

$A(Q^2 \rightarrow 0) = -\frac{G_F}{4\pi\alpha\sqrt{2}} \left[ Q^2 Q_{weak}^p + Q^4 B(Q^2) \right]$}

$Q_{weak}^p = 2C_{1u} + C_{1d} \propto 1 - 4\sin^2 \theta_W$

Data ~ 2010
PV Deep-Inelastic Scattering

A<sub>PV</sub> in Electron-Nucleon DIS:

\[ A_{PV} = \frac{G_F Q^2}{\sqrt{2} \pi \alpha} \left[ a(x) + f(y)b(x) \right] \]

\( Q^2 >> 1 \text{ GeV}^2 \), \( W^2 >> 4 \text{ GeV}^2 \)

For a \(^2\text{H}\) target, assuming charge symmetry, structure functions largely cancel in the ratio:

\[
\begin{align*}
   a(x) &= \frac{\sum C_{1i} Q_i f_i(x)}{\sum_i Q_i^2 f_i(x)} \\
   b(x) &= \frac{\sum C_{2i} Q_i f_i(x)}{\sum_i Q_i^2 f_i(x)}
\end{align*}
\]

\[
\begin{align*}
   a(x) &= \frac{3}{10} \left[ (2C_{1u} - C_{1d}) \right] + \cdots \\
   b(x) &= \frac{3}{10} \left[ (2C_{2u} - C_{2d}) \frac{u_v(x) + d_v(x)}{u(x) + d(x)} \right] + \cdots
\end{align*}
\]

Must measure A<sub>PV</sub> to 0.5% fractional accuracy!

Feasible at 6 GeV at Jlab \[\Rightarrow\] luminosity > \(10^{38}/\text{cm}^2/\text{s}\)

well-suited for 11 GeV after the upgrade
PV DIS at Jefferson Laboratory

- Approved Experiment with 6 GeV beam
- Proposal submitted for 11 GeV Beam

K. Paschke, P. Reimer, X. Zheng et. al

• ~0.5 MHz DIS rate, π/e ~ 0.1 - 1.0

A_{PV} = 280 ppm \rightarrow 30 \text{ days} \rightarrow \delta(A_{PV})_{\text{stat}} = 1.4 \text{ ppm}

\delta(2C_{2u} - C_{2d})_{\text{stat}} = \pm 0.009

Theory: +0.0986
PDG (2004): -0.08 \pm 0.24

Experimental systematic errors:
Challenging but doable

What about hadronic physics uncertainties?

With electron scattering, possibility to localize x, Q^2 bins, unlike neutrino scattering
Large Acceptance Solenoidal Spectrometer

- **High Luminosity on Cryotargets**
- **Better than 1% errors**
  - It is unlikely that any effects are larger than 5-6%
- **x-range 0.25-0.75**
- **$W^2$ well over 4 GeV$^2$**
- **$Q^2$ range a factor of 2 for each $x$**
  - (Except $x \approx 0.75$)
- **Moderate running times**

**Need BaBar, CDF or CLEOII Solenoid**

- state-of-the art fast tracking, particle ID and “parity” counting electronics
- precision polarimetry
- diverse physics topics addressed:
  - **Standard Model test, CSV, d/u, higher twist effects, nuclear EMC effect, semi-inclusive transverse physics, precision spin structure functions...**
12 GeV JLab Projections

Also: PV-DIS off the proton (hydrogen target)

\[ a(x) = \frac{u(x) + 0.91d(x)}{u(x) + 0.25d(x)} \]

Very sensitive to d(x)/u(x)

• Allows d/u measurement on a single proton, Vector quark current!

Strategy:

• Measure \( A_{PV} \) in NARROW \( x, Q^2 \) bins, EACH with 1% accuracy
• measure or constrain higher twist effects at \( x \sim 0.5-0.6 \)
• precision measurement of \( A_{PV} \) at \( x \sim 0.7 \) to search for CSV

Simulation and design development begun
• First proto-collaboration meeting: Aug 12-13 @ JLab
• Letter of Intent targeted for Jan 2009
Where do electrons and quarks go?

$\theta$ 

10 GeV $\times$ 250 GeV

177°  160°  10 GeV  5 GeV  scattered electron

10°  90°  10 GeV  5 GeV  scattered quark

EIC DIS Kinematics
PV DIS at the EIC

- Confine to $Q^2 > 10 \text{ GeV}^2$
- Below $100 \text{ GeV}^2$, will need hadron jet to extract $x$: can one keep asymmetry systematics at ppm level?
- To avoid sticky trigger systematics, keep lepton energy $> 5 \text{ GeV}$ and scattering angle between 10 and 170 degrees
- Figure of merit ($A^2\sigma$) roughly flat vs $Q^2$
- Measurements at different $y$ for same $x$ very useful
- Two $Q^2$ ranges: 10 to 100 GeV$^2$ & $> 100 \text{ GeV}^2$ : $y$ range
- Assume a 100 fb$^{-1}$ data set: Would much prefer to have at least $3-4 \times 10^{33}$ luminosity!
- As you will see by the end of the talk, I dont want to run just one hadron species!
First Look at Statistics

- ~ billion events at $Q^2 \sim 10$ GeV$^2$
- ~ few hundred thousand events at $\sim 200$ GeV$^2$
- figure of merit is roughly flat for fixed $x$
- $y$ is virtually zero for small $Q^2$ sample

Number of events vs $Q^2$ (GeV$^2$)

- 100 fb$^{-1}$

figure of merit vs $Q^2$ (GeV$^2$)

0.25 < $x$ < 0.35
Some Comments

- sub-1% stat. error at $x = 0.3$ and $Q^2 > 100 \text{ GeV}^2$, independent sub-2% measurement, same $x$ & $Q^2 = 10 \text{ GeV}^2$
- sub-2% stat error at $x = 0.6$: stringent tests of charge symmetry violation and $d/u$?
- Can one control polarimetry syst. error at that level?
- Is there a double-spin asymmetry calculation that makes the effective polarization large and the systematic error small?

Preliminary conclusions:

- A 100 fb$^{-1}$ data set with $e$-$d$ collisions can provide sensitivity to standard model EW couplings at an interesting level: one would have to revisit this after LHC data and JLab 12 GeV measurements
- A similar data set with $e$-$p$ collisions would measure $d/u$ precisely and the combination of the two data sets would provide new limits on charge symmetry violation at $x = 0.6$ and $Q^2 = 300 \text{ GeV}^2$
\[ \frac{1}{2m_N} W^i_{\mu\nu} = -\frac{g_{\mu\nu}}{m_N} F_1^i + \frac{p_\mu p_\nu}{m_N (p \cdot q)} F_2^i + i \frac{\epsilon_{\mu\nu\alpha\beta}}{2(p \cdot q)} \left[ \frac{p^\alpha q^\beta}{m_N} F_3^i + 2q^\alpha S^\beta g_1^i - 4xp^\alpha S^\beta g_2^i \right] 
\]

\[ + \frac{p_\mu S_\nu + S_\mu p_\nu}{2(p \cdot q)} g_3^i + \frac{S \cdot q}{(p \cdot q)^2} p_\mu p_\nu g_4^i + \frac{S \cdot q}{p \cdot q} g_{\mu\nu} g_5^i \]

**QPM Interpretation**

\[
F_1^{\gamma Z} = \sum_q e_q(g_V)_q (q + \bar{q}) \quad F_2^{\gamma Z} = 2x F_1^{\gamma Z}
\]

\[
F_3^{\gamma Z} = 2 \sum_q e_q(g_A)_q (q - \bar{q})
\]

\[
g_1^{\gamma Z} = \sum_q e_q(g_V)_q (\Delta q + \Delta q)\]

\[
g_2^{\gamma Z} = g_4^{\gamma Z} = 0
\]

\[
g_3^{\gamma Z} = 2x \sum_q e_q(g_A)_q (\Delta q - \Delta \bar{q}) \quad 2x g_5^{\gamma Z} = g_3^{\gamma Z}
\]

Anselmino, Gambino and Kalinoski, hep-ph/9401264v2
Observables

\[ A_{11} = \frac{f(y)}{F_1^y} \]

Double-spin

\[ A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha} \left[ g_A \frac{F_1^y}{F_1^y} + f(y) g_V \frac{F_3}{F_1^y} \right] \]

polarized electron, unpolarized hadron

unpolarized electron, polarized hadron

\[ A_{1VP} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha} \left[ g_V \frac{g_5^y}{F_1^y} + g_A f(y) \frac{g_1^y}{F_1^y} \right] \]

- Enough y range to separate vector and axial-vector couplings
- Could go down in x as low as 0.01
- Electroweak \( g_1 \) is complementary to electromagnetic \( g_1 \):
weights of up, down and strange quark helicity distributions
- With sufficient precision, could eliminate the need for input from Hyperon decays for extracting strange quark helicity distributions!
Homework on Observables

- There are 3 beam PV asymmetries and 3 target PV asymmetries that can be measured \((p, ^3He, ^2H)\)
- There are equal number of W asymmetries that can be measured
- Within the standard model and the quark-parton model i.e. with no physics beyond the standard model and no novel QCD effects, these observables will form an over-constrained set.
- Is there a clever set of these observables that optimizes sensitivity for testing QCD models as well as TeV scale BSM models, and at the same time reduce sensitivity to common systematic errors such as beam polarization?
Possible Novel Aspect of the EMC Effect

- Suppose one completes a polarized electron-unpolarized deuteron run and measure $A_{PV}$ precisely as a function of $x$

- Now suppose we switch to a heavy nucleus for an e-A run and maintain a polarized electron beam
  - To first order, DIS rate should be the same: measure $A_{PV}$
  - $A_{PV}$ is in itself a ratio (weak to EM amplitude)
    - What would the ratio of ratios (deuterium to nucleus) look like as a function of $x$?
    - Measuring the EMC effect along a different isospin axis
    - Major contributions to the radiative corrections would cancel in the ratio of ratios
    - Intriguing theory question: How is $F_L(\gamma-Z)$ related to $F_L(\gamma)$? Perhaps $F_L$ effects cancel?
**Preliminary Conclusions and Outlook (I)**

- **Lepton Flavor Violation**
  - DIS tau lepton conversion possible at EIC kinematics with high efficiency and large background rejection
  - With vertexing and 1000 fb^{-1} : 10^{-10} sensitivity

- **Precision weak mixing angle measurement**
  - ELIC with central collision point for electron beam would allow precision beyond anything conceived for next decade
  - Several technical issues:
    - *Polarization flips*
    - *longitudinal polarization stability*
    - *luminosity fluctuations and monitoring*
    - ...
Conclusions (II)

• Parity Violating deep inelastic scattering at EIC
  - 100 fb$^{-1}$ data set with polarized e-d collisions needed
    • sensitivity would reach beyond 12 GeV JLab program
    • interest level might be magnified depending on LHC results and results of the JLab program
    • theoretically very clean (e.g. higher twist effects)
    • detailed look at experimental systematics needed!
    • Is the polarization systematic suppressed to 0.1%?
  - An optimized data set with polarized proton and He-3
    • new parity-violating structure functions
    • separation of quark helicity distributions from $x = 0.01$ to 0.5
    • Critical for disentangling new physics in $W$ asymmetries
  - e-A with polarized electrons
    • novel probe of EMC effect?
    • different systematics? e.g. radiative corrections, $F_L$