Electroweak Structure Functions

Measurement Aspects

Krishna S. Kumar
University of Massachusetts, Amherst

Recent work

A. Deshpande, S. Taneja (SUNY, Stonybrook)
K. Paschke (UVa)
K. Kumar, S. Riordan (UMass, Amherst)


(likely incomplete!)
EIC Electroweak Physics was largely unexplored until recently

Studies of the Electroweak Interaction
• Charged Lepton Flavor Violation $\tau \rightarrow e$
• Weak Neutral Current couplings

Studies using the Electroweak Interaction
• high-x structure functions - higher twist, charge symmetry violation, $d/u$ of the proton
• PV EMC effect in nuclei, $F_3^{YZ}$
• new spin structure functions

JLab User Workshop at College of William and Mary
(May 2010)

Significant theoretical interest

Since the workshop, we have finally found “some” manpower
**OUTLINE**

- **Introduction**
  - Weak Neutral Current Interactions at Low Energy
    - Parity-Violating Electron Scattering: Longitudinal beam spin asymmetries
- **Status of the Fixed Target Program**
  - Past, present and future
    - E158, Qweak, MOLLER, SOLID
- **EW Physics at a Lepton-Ion Collider**
  - Novel Longitudinal Single-Spin Asymmetries
    - New Spin Structure Functions
- **Conclusions/Outlook**
Parity-violating electron scattering and BSM physics
Other experimental observables predicted at 0.1% level: sensitive to heavy particles via higher order quantum corrections

4th and 5th best measured parameters: $\sin^2\theta_W$ and $M_W$

All weak neutral current amplitudes are functions of $\sin^2\theta_W$

Allows searches for new physics at the TeV scale via small measurement deviations

assuming no new physics beyond the standard model

courtesy: Jens Erler
There are often mechanisms to suppress Flavor Changing Neutral Currents

Many theories predict new forces that disappeared when the universe cooled

$\mathcal{L}_{\text{eff}} = \mathcal{L}_{SM} + \sum_{d \geq 5} \frac{c_n^{(d)}}{\Lambda^{d-4}} \hat{O}_n^{(d)}[\phi_{SM}]$

Flavor Diagonal Interactions

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

$L_{f_1 f_2} = \sum_{i,j=L,R} \frac{4\pi}{\Lambda^2} \eta_{ij} \tilde{f}_{1i} \gamma_{\mu} f_{1i} \tilde{f}_{2j} \gamma^{\mu} f_{2j}$

Many new physics models give rise to such terms: Heavy Z's, compositeness, extra dimensions, SUSY...
**COLLIDERS VS FIXED TARGET**

Neutral Current Amplitude at Low Energy

One goal of neutral current measurements at low energy AND colliders:
Access $\Lambda > 10$ TeV for as many $f_1f_2$ and L,R combinations as possible

*Colliders access scales $\Lambda$’s $\sim 10$ TeV*

- Tevatron, LEP, SLC, LEP200, HERA

Z boson production accessed some parity-violating combinations but...

<table>
<thead>
<tr>
<th>Electromagnetic amplitude interferes with Z-exchange as well as any new physics</th>
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- L,R combinations accessed are mostly parity-conserving

<table>
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<tr>
<th>New Physics/Weak-Electromagnetic Interference</th>
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<tr>
<td>• Spin-dependent electron scattering</td>
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<td>• opposite parity transitions in heavy atoms</td>
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Z on resonance: $A_Z$ imaginary

| $|A_{Z} + A_{\text{new}}|^2 \rightarrow A_{Z}^2 \left[ 1 + \left( \frac{A_{\text{new}}}{A_{Z}} \right)^2 \right]$ |

no interference!
Parity-Violating Longitudinal Beam Spin Asymmetry

At very forward angles, $A_{PV}$ is sensitive to $g_V^T$, the target vector coupling, called the weak charge.

**Parity-violating electron scattering has become a precision tool**

- **Beyond Standard Model**
- **Strange quark form factors**
- **Neutron skin of a heavy nucleus**
- **QCD structure of the nucleon in PV DIS**

**Thumb rule: measure** $\delta (\sin^2 \theta_W) \lesssim 0.002$ or better to access the multi-TeV scale

**Parity-violating electron scattering** has become a precision tool

- **part per billion systematic control**
- **1% normalization control**
- **photocathodes, polarimetry, high power cryotargets, nanometer beam stability, precision beam diagnostics, low noise electronics, radiation hard detectors**

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

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

$A_{PV} \sim 10^{-5} \cdot Q^2$ to $10^{-4} \cdot Q^2$
FIXED TARGET PROGRAM: BSM PHYSICS
Electroweak Weak Charge

Parity-Violating Electron-Electron (Møller) Scattering

Derman and Marciano (1978)

\[ A_{PV} = -m_e \frac{G_F}{\sqrt{2} \pi \alpha} \frac{16 \sin^2 \Theta}{(3 + \cos^2 \Theta)^2} Q^e_W \]

50 GeV at SLAC: \( \sim 150 \) ppb!

**E158 at SLAC**

Major technical challenges

45 & 48 GeV Beam
85% longitudinal polarization

Final Result:

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

THE WEAK MIXING ANGLE

Running of $\theta_W$: Bookkeeping for off-resonance measurements

- $\gamma-\gamma$ loop is the running of $\alpha_{EM}$
- $W-W$ loop provides indirect $m_t$
- $\gamma-Z$ loop is the running of $\sin^2\theta_W$

Published Measurements

- $^{133}$Cs Atomic Parity Violation
- NuTeV result requires careful consideration of nuclear corrections

Future Electron Scattering Measurements

- $e-q$ measurements: QWeak (elastic $e-p$) and deep-inelastic scattering
- Improve on E158 by a factor of 5: MOLLER at 12 GeV JLab

Published Measurements

- $^{133}$Cs Atomic Parity Violation
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Future Electron Scattering Measurements

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QUARK WEAK CHARGES

\[ C_{1i} = 2g_A^e g_V^i \]
\[ C_{2i} = 2g_V^e g_A^i \]

**PV elastic e-p, APV**

\[ \delta(C_{1q}) \propto (\eta_{RL}^eq + \eta_{RR}^eq - \eta_{LL}^eq - \eta_{LR}^eq) \]
\[ \delta(C_{2q}) \propto (-\eta_{RL}^eq + \eta_{RR}^eq - \eta_{LL}^eq + \eta_{LR}^eq) \]

**PV deep inelastic**

**A_{PV} in elastic e-p scattering:**

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

\[ Q_{\text{weak}}^p = 2C_{1u} + C_{1d} \propto 1 - 4\sin^2 \vartheta_W \]

Outcome of program to measure strange quark form factors of the nucleon

[Graph showing data points and fits for isovector and isoscalar weak charges]
Deep Inelastic Scattering

With Qweak and APV, $C_{1i}$'s measured, but $C_{2i}$'s still unconstrained

\[
A_{PV} \text{ in Electron-Nucleon DIS:} \\
A_{PV} = \frac{G_F Q^2}{\sqrt{2\pi\alpha}} \left[ a(x) + f(y) b(x) \right]
\]

$Q^2 \gg 1 \text{ GeV}^2, W^2 \gg 4 \text{ GeV}^2$

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

\[
a(x) = \frac{3}{10} \left[ (2C_{1u} - C_{1d}) \right] + \ldots \\
b(x) = \frac{3}{10} \left[ (2C_{2u} - C_{2d}) \frac{u_v(x) + d_v(x)}{u(x) + d(x)} \right] + \ldots
\]

Must measure $A_{PV}$ 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

- First experiment at 6 GeV: ran Oct-Dec '09; ~4% accuracy @ $Q^2 \sim 1-2 \text{ GeV}^2$
- Approved Hall C proposal at 11 GeV using planned upgrade for spectrometers
- SOLID: New large acceptance solenoidal spectrometer approved for Hall A
**Strategy:** sub-1% precision over broad kinematic range for sensitive Standard Model test and detailed study of hadronic structure contributions.
\( A_{PV} = 35.6 \) ppb

\( \delta(A_{PV}) = 0.73 \) ppb

\( \delta(Q^e_W) = \pm 2.1 \) (stat.) \( \pm 1.0 \) (syst.) %

\( \delta(\sin^2 \theta_W) = \pm 0.00026 \) (stat.) \( \pm 0.00012 \) (syst.) ~ 0.1%

\[ \mathcal{L}_{e_1e_2} = \sum_{i,j=L,R} \frac{g^2_{ij}}{2\Lambda^2} \bar{e}_i \gamma_\mu e_i \bar{e}_j \gamma^\mu e_j \]

\[ \frac{\Lambda}{\sqrt{|g^2_{RR} - g^2_{LL}|}} = 7.5 \text{ TeV} \]

best contact interaction reach at low \( Q^2 \)

Current limits on 4-electron contact interactions:

LEPII at 200 GeV

(Average of all 4 LEP experiments)

\[ \frac{\Lambda}{\sqrt{|g^2_{RR} + g^2_{LL}|}} = 4.4 \text{ TeV} \]

OR

\[ \frac{\Lambda}{g_{RL}} = 5.2 \text{ TeV} \]

 insensitive to \( |g^2_{RR} - g^2_{LL}| \)

Compositeness scale:

\[ \sqrt{|g^2_{RR} - g^2_{LL}|} = 2\pi \]

\[ \Lambda = 47 \text{ TeV} \]

Length scale probed:

\[ 4 \times 10^{-21} \text{ m} \]
MOLLER has discovery reach independent of LHC but...

\[ A_{0,\text{SLD}} = 0.23099 \pm 0.00053 \]
\[ A_{0,\text{P}} = 0.23159 \pm 0.00041 \]
\[ A_{0,\text{b}} = 0.23098 \pm 0.00026 \]
\[ A_{0,\text{c}} = 0.23221 \pm 0.00029 \]
\[ A_{0,\text{had}} = 0.23220 \pm 0.00081 \]
\[ A_{0,\text{b}} = 0.2324 \pm 0.0012 \]
\[ A_{0,\text{eff}} = 0.23153 \pm 0.00016 \]

\[ \chi^2/\text{d.o.f.} = 11.8/5 \]

**H → γγ:** 100 fb^{-1}, \( m_H = 120 \) GeV:

\[ A_{0,\text{SLD}} = 0.02758 \pm 0.00035 \]
\[ A_{0,\text{L}} = 0.23099 \pm 0.00053 \]
\[ A_{0,\text{P}} = 0.23159 \pm 0.00041 \]
\[ A_{0,\text{b}} = 0.23098 \pm 0.00026 \]
\[ A_{0,\text{c}} = 0.23221 \pm 0.00029 \]
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\[ \chi^2/\text{d.o.f.} = 11.8/5 \]

**Bill Marciano:**

*We forgot to nail* \( \sin^2 \theta_W \)

**Proposed MOLLER error bar is precise enough to affect the central value of the world average**
PARITY-VIOLATING ASYMMETRIES AT AN EIC
Polarized EIC EW Physics

- Much high $Q^2$: no higher twist issues
- “Huge” Asymmetries
- Large range in $y$
  - $y$-dependence separates V & A
- High precision @ $x \sim 0.01$ to 0.001
- $^1$H, $^2$H and $^3$He measurements
- Precision weak mixing angle
- Strange quark polarized and unpolarized pdf’s
- At highest luminosities: new precision QCD tests in inclusive DIS
  - $Q^2$ evolution
  - New “Callan-Gross” relations
  - New “Bjorken” sum rules

Machine configurations: GeV & fb$^{-1}$

- $11 \times 60$: 100 going to 500
- $5 \times 250$: 70 going to 350
- $11 \times 250$: 100 going to 500
- $20 \times 325$: 100 going to 500

High and “very high” integrated luminosities

discovering that unpolarized and polarized pdfs already benefit with modest samples
**Double-Spin Asymmetry**

**Reminder**

QED Double-spin Asymmetry

\[ A_{||} = \frac{f(y) g_\gamma^1}{F_1^\gamma} \]

Different \( g_1(x, Q^2) \) curves for different \( \Delta G \)

\[
F_1^\gamma = \frac{1}{2} \sum_q e_q^2 (q + \bar{q}) \quad F_2^\gamma = 2x F_1^\gamma \\
g_1^\gamma = \frac{1}{2} \sum_q e_q^2 (\Delta q + \Delta \bar{q}) \quad g_2^\gamma = 0
\]
Polarized Collisions

General Electroweak Hadronic Tensor

\[
\frac{1}{2m_N} W^i_{\mu\nu} = -\frac{g_{\mu\nu}}{m_N} F^i_1 + \frac{p_\mu p_\nu}{m_N (p \cdot q)} F^i_2 \\
+ i \frac{\epsilon_{\mu\nu\alpha\beta}}{2(p \cdot q)} \left[ \frac{p^\alpha q^\beta}{m_N} F^i_3 + 2q^\alpha S^\beta g^i_1 - 4xp^\alpha S^\beta g^i_2 \right] \\
- \frac{p_\mu S_\nu + S_\mu p_\nu}{2(p \cdot q)} g^i_3 + \frac{S \cdot q}{(p \cdot q)^2} p_\mu p_\nu g^i_4 + \frac{S \cdot q}{p \cdot q} g_{\mu\nu} g^i_5
\]

Ji, Vogelsang, Blümlein, ...


QPM Interpretation

\[
F^{\gamma Z}_1 = \sum_q e_q(g_V)_q (q + \bar{q}) \quad F^{\gamma Z}_2 = 2x F^{\gamma Z}_1 \\
F^{\gamma Z}_3 = 2 \sum_q e_q(g_A)_q (q - \bar{q}) \\
g^{\gamma Z}_1 = \sum_q e_q(g_V)_q (\Delta q + \Delta \bar{q}) \\
g^{\gamma Z}_2 = g^{\gamma Z}_4 = 0 \\
g^{\gamma Z}_3 = 2x \sum_q e_q(g_A)_q (\Delta q - \Delta \bar{q}) \quad 2x g^{\gamma Z}_5 = g^{\gamma Z}_3
\]
Beam Spin Asymmetry

Beam spin asymmetry

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

\[ \delta(\sin^2 \theta_W) \sim \pm 0.0004 \]

\[ \delta(F_1^{\gamma Z}) \sim \pm 0.25\% \]

\[ \delta(F_3^{\gamma Z}) \sim \pm 2.5\% \]

Proton

\[ F_1^{\gamma Z} \propto u + d + s \]

\[ F_3^{\gamma Z} \propto 2u + d \]

Deuteron

\[ F_1^{\gamma Z} \propto u + d + 2s \]

\[ F_3^{\gamma Z} \propto u + d \]

Quantitative estimates: unpolarized pdf's? BSM probe?
**WEAK-EM INTERFERENCE**

Charge Current Structure functions at **100 GeV2**
including kinematical factors $\eta^i$

![Graph of charge current structure functions at 100 GeV^2 with labeled functions g_1^W, g_2^W, g_3^W, g_5^W, and g_1^γ/10000.]

**Weak-EM interference amplitudes much more accessible; high statistics**

Structure functions at **100 GeV2** including kinematical factors $\eta^i$

![Graph of structure functions at 100 GeV^2 with labeled functions g_1^γ/100, g_3^γZ, g_5^γZ, and g_1^γZ.]

**Pure W and Z exchange amplitudes challenging to measure even at EIC**

Note: Here $g_1^\gamma$ had to be scaled down by $10^2$ to see $\gamma Z.$

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Krishna S. Kumar  Electroweak Structure Functions: Experimental Aspects  22
Rates and Asymmetries

Such polarization asymmetries not feasible in previous machines

Asymmetries are small!

Systematic control at $10^{-5}$ needed

- Instantaneous rates are $\sim$ kHz
- Must have pipeline electronics to avoid dead-time corrections
Extensive experience with high rates and small asymmetries
SIGN FLIPS AT AN EIC

Fast and Slow Helicity Reversals

Rapid helicity flips provides basis for measurements

Bunch-by-bunch helicity control at EIC essential

Systematic control from “slow” flips: each provides ~ factor of 10 suppression

e.g. half-wave plate, g-2 energy toggle, Double-Wien

At EIC, relative luminosity fluctuations will be a challenge

RHIC experience ~ 10⁻⁴

- Flippers DURING fill?
- half-wave plate toggle each fill?
- Double-Wien for electrons?
- Ion species slow flips?
POWER OF COLLIDER KINEMATICS

Assumptions: electron energy > 2 GeV, 3 to 177 degrees

Overall normalization affects intercept (y-independent piece) but not slope (y-dependent piece)
Electron polarization

Challenge for ultra-precise weak mixing angle

State of the art: 1% at JLab, 0.5% at SLC

SOLID target: 0.4%

Compton polarimetry can make incremental improvements

R&D on atomic hydrogen Møller polarimetry:
  two continuous monitors

Highly desirable to have two continuous electron polarization monitors at the EIC

Must build significantly further on combining HERA experience with that of JLab 6 and 12 GeV
**F2 STRUCTURE FUNCTION**

proton

\[ u + d + s \]

deuteron

\[ u + d + 2s \]

small samples at first stage could already help unpolarized pdf fits

11x60 option similar
F3 STRUCTURE FUNCTION

Again, should help pdf fits

Relationship to F3 for neutrinos?

Any impact on fundamental sum rules?
**Weak Mixing Angle**

highest luminosities at highest COM energy

\[ \delta(\sin^2 \theta_W) \sim \pm 0.0004 \]

\[ \delta(F_1^{\gamma Z}) \sim \pm 0.25\% \]

\[ \delta(F_3^{\gamma Z}) \sim \pm 2.5\% \]

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Polarimetry error ~ 0.2% needed!

Need to worry about heavy quarks

Axial quark current dynamics

potentially reach 3%

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\[ \text{Relative Extraction Uncertainty, EIC } 20 \text{ GeV} \times 325 \text{ GeV} \ (E_E \times E_p), L \times t = 500 \text{ fb}^{-1} \]

Y. Li and W. Marciano
**Target Spin Asymmetries**

*Entirely new at the EIC*

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

**unpolarized electron, polarized hadron**

**Fundamentally new properties of the nucleon that have never been measured**

**proton**

\[ g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s \]
\[ g_5^{\gamma Z} \propto 2\Delta u_v + \Delta d_v \]

**deuteron**

\[ g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s \]
\[ g_5^{\gamma Z} \propto \Delta u_v + \Delta d_v \]

**Quantitative estimates:**

- polarized pdf’s?
- unambiguous evidence for strange quark polarization?
- New fundamental sum rule and other QCD tests?
\( g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s \)

first measurements significant already with \(10 \text{ fb}^{-1}\)

what precision is needed to help pdf fits?

is it needed to go to lower angles (than 3 degrees)?

Is there a new sum rule worth measuring?
**G5 Structure Function**

\[ g_5^Z \propto 2\Delta u_v + \Delta d_v \]

\[ g_5^Z \propto \Delta u_v + \Delta d_v \]

Same questions as in \(g_1\) case
POLARIZED STRANGENESS?

A cross-check showing unambiguously non-zero delta-s in an inclusive measurement

Semi-inclusive measurements lose statistical power at $x \sim 0.1$
Would be nice to have 3% accuracy; needs to be checked
CONCLUSIONS/OUTLOOK

- **Weak Mixing Angle**
  - Importance of measurement will depend on outcome of LHC and JLab measurements but the best strategies should be identified
  - Likely to impose major demands on experimental systematics
- **Unpolarized pdf’s: impact at first stage & low luminosity**
- **Polarized pdf’s: need high luminosity, but very important new input (e.g. singlet combination) for global fits**
- **Further work**
  - Work with theorists to identify the best physics impact
    - new fundamental QCD tests?
  - Sustain momentum created by recent simulation effort
    - optimize statistical accuracy (angular range, better fitting, beam energy....)
  - Make list of experimental requirements
  - Begin to think about writing this up