DIS-Parity: Physics Beyond the Standard Model with Parity NonConserving Deep Inelastic Scattering

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- Introduction: Weinberg-Salam Model and $\sin^2(\theta_W)$
- Parity NonConserving Electron Deep Inelastic Scattering
- 11 GeV Measurement at Jefferson Laboratory

Work done in collaboration with Peter Bosted, Dave Mack et al.
Weinberg-Salam model and $\sin^2(\theta_W)$

Unification of Weak and E&M Force
- SU(2)—weak isospin—Triplet of gauge bosons
- U(1)—weak hypercharge—Single gauge boson

Electroweak Lagrangian:

$$\mathcal{L} = g \vec{J}_\mu \cdot \vec{W}_\mu + g' J^Y_\mu B_\mu \quad J^Y_\mu = J^{EM}_\mu - J^{(3)}_\mu$$

$J_\mu, J^Y_\mu$ isospin and hypercharge currents
$g, g^0$ couplings between currents and fields

$$W^\pm_\mu = \frac{1}{\sqrt{2}} \left( W^{(1)}_\mu \pm i W^{(2)}_\mu \right) \quad \text{Weak CC}$$

$$A_\mu = \frac{1}{\sqrt{g^2 + g'^2}} \left( g' W^{(3)}_\mu + g B_\mu \right) \quad \text{EM NC}$$

$$Z^0_\mu = \frac{1}{\sqrt{g^2 + g'^2}} \left( g' W^{(3)}_\mu - g B_\mu \right) \quad \text{Weak NC}$$

$\theta_W$, relative strength of the SU(2) and U(1) couplings:

$$\tan \theta_W = \frac{g'}{g} \quad \sin \theta_W = \frac{g'}{\sqrt{g'^2 + g^2}}$$

$$\cos \theta_W = \frac{g}{\sqrt{g'^2 + g^2}}$$

$\theta_W$, relative strength of the SU(2) and U(1) couplings:

- Observables:
  - $Q_{EM} \ e = g \sin(\theta_W)$
  - $\sin^2(\theta_W) = 1 - \frac{M_W^2}{M_Z^2}$. 

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\( \sin^2(\theta_W) \text{ vs. } Q^2 \)

- Standard Model predicts \( \sin^2(\theta_W) \) varies (runs) with \( Q^2 \)
  - Well measured at Z-pole, but not at other \( Q^2 \).
  - Running sensitive to non-Standard Model Physics.
  - Different measurements sensitive to different non-S.M. physics.
- \( \sin^2(\theta_W) \) is *scheme dependent* observable—it’s value depends on the renormalization scheme.
\[ \sin^2(\theta_W) \] measurements below Z-pole

- **NuTeV νA scattering:**
  - 3σ from Standard Model!!!
  - *Fe* target: PDF’s in iron? Nuclear corrections—NC vs. CC?

- **Atomic Parity Violation (APV):**
  - Good measurement, hard to understand theoretically.
  - *Appears* to differ from S.M.??

- **\( Q_{\text{weak}} \) (Jlab):**
  - \( Q_{\text{weak}} \) PROTON
  - 1/42005-07

- **E158-Moller**
  - \( Q_{\text{Weak}} \) ELECTRON
  - *Final run 2004*

- **DIS-Parity:**
  - 11 GeV JLab Deep Inelastic Scattering Parity violation.
  - Deuterium/Hydrogen target.
  - \( Q^2 = 3.5 \text{ GeV}^2 \) (\( Q = 1.9 \text{ GeV} \))
Polarized $e^- deuterium$ DIS

Look for left-right asymmetry in polarized eD deep inelastic scattering

- Asymmetry caused by interference between $Z^0$ and $\gamma$ diagrams.

- Use deuterium target: $u(x) \neq d(x)$

- Large asymmetry: $A_d \frac{1}{10} 10^{-4}$
DIS Formalism

\[ A_d = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \]

Longitudinally polarized electrons on unpolarized isoscaler (deuterium) target (derivation is problem for listener).

\[
Y = \frac{1 - (1 - y)^2}{1 + (1 - y)^2 - y^2 R / (1 + R)}
\]

\[
R(x, Q^2) = \frac{\sigma_L}{\sigma_R} \approx 0.2
\]

\[
C_{1q} \begin{array}{c} \text{NC vector coupling to } q \\ \text{NC axial coupling to } e \end{array}
\]

\[
C_{2q} \begin{array}{c} \text{NC axial coupling to } q \\ \text{NC vector coupling to } e \end{array}
\]

\[
R_s(x) = \frac{2s(x)}{u(x) + d(x)} \overset{\text{large } x}{\longrightarrow} 0
\]

\[
R_v(x) = \frac{u_v(x) + d_v(x)}{u(x) + d(x)} \overset{\text{large } x}{\longrightarrow} 1
\]

\[
C_{1u} = -\frac{1}{2} + \frac{4}{3} \sin^2 (\theta_W) \approx -0.19
\]

\[
C_{1d} = \frac{1}{2} - \frac{2}{3} \sin^2 (\theta_W) \approx 0.35
\]

\[
C_{2u} = -\frac{1}{2} + 2 \sin^2 (\theta_W) \approx -0.04
\]

\[
C_{2d} = \frac{1}{2} - 2 \sin^2 (\theta_W) \approx 0.04
\]

Note that each of the $C_{ia}$ are sensitive to different possible S.M. extensions.
Repeat SLAC experiment (30 years later) with better statistics and systematics at 12 GeV Jefferson Lab:

- Beam current 100 µA vs. 4 µA at SLAC in ’78
- 60 cm target vs. 30 cm target
- $P_e$ (=electron polarization) = 80% vs. 37%
- $\delta P_e \frac{1}{4} 1\%$ vs. 6%

Finally we discuss a very delicate experiment to detect tiny parity-violation effects (asymmetries) due to the interference between $Z^0$ and $\gamma$-exchange in inelastic scattering of polarized electrons by deuterons. The experiment was carried out with beams of electrons of 16–22-GeV/c momentum at SLAC, the reaction being

$$e_{L,R}^- + d_{\text{unpolarized}} \to e^- + X,$$
Experimental Constraints and Kinematics

- Small sea quark uncertainties $x > 0.3$
- Better sensitivity to $\sin^2(\theta_W)$ Large $Y$
- DIS region, minimize higher twist $Q^2 > 2.0 \text{ GeV}^2$
- $W^2 > 4.0 \text{ GeV}^2$

- $d(x)/u(x)$ uncertainties deuterium target
- Pion and other backgrounds $E_0 > 0.3 \ (y < 0.7)$

Quick calculations show that these conditions are best matched with an 11 GeV beam and an electron scattering angle of approximately $10^\pm 15^\pm (12.5^\pm)$.

$$\begin{align*}
\hbar_{xi} &= 0.45 \\
\hbar_{Q^2i} &= 3.5 \text{ GeV}^2 \\
\hbar_{Yi} &= 0.46 \\
\hbar_{W^2i} &= 5.23 \text{ GeV}^2 \\
\frac{\delta \sin^2 \theta_W}{\sin^2 \theta_W} \bigg|_{Y=0.46} &\approx \frac{1}{2} \left( \frac{\delta A_d}{A_d} \right) \\
A_d &\approx 2.9 \times 10^{-4}
\end{align*}$$
Detector and Expected Rates

• **Expt. Assumptions:**
  - 60 cm $ld_2/lH_2$ target
  - 11 GeV beam @ 90$\mu$A
  - 75% polar.
  - $12.5^{\pm}$ central angle
  - 12 msr $d\Omega$
  - 6.8 GeV$£$ 10% momentum bite

• **Rate expectations:**
  - 1MHz DIS
  - $\pi/e \frac{1}{4} 1$ 1 MHz pions
  - 2 MHz Total rate
  - $dA/A = 0.5\%$ 345 hrs (ideal) plus time for $H_2$ and systematics studies.

- **Will work in either Hall C (HMS +SHMS) or Hall A (MAD)**
- $\pi/e$ separation requires gas Cherenkov counters $\frac{1}{4}6$ GeV thresh.
- Ignore tracking in detectors
- Rate requires flash ADC’s on Cherenkov and Calorimeters—this is a counting experiment!!
**Uncertainties in $A_d$**

- **Beam Polarization:**
  - QWeak also needs 1.4% polarization accuracy.
  - Hall C Moller has achieved 0.5% polarization accuracy.

- **Higher twists may enter in at this low of $Q^2$:**
  - Check by taking additional data at lower $Q^2$
  - 12.5±—11 GeV and 15±—8 GeV data
  - Possible 6 GeV experiment?

- **EMC effect in $d_2$**
  - Check with proton data in region where $d/u$ is known.

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Uncertainty Type</th>
<th>Uncertainty Value</th>
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</thead>
<tbody>
<tr>
<td>Statistical</td>
<td></td>
<td>0.5%</td>
</tr>
<tr>
<td>Beam polarization</td>
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<td>1.0%</td>
</tr>
<tr>
<td>$\delta Q^2$</td>
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<td>0.5%</td>
</tr>
<tr>
<td>Radiative corr.</td>
<td></td>
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<tr>
<td>$\delta R = \delta(\sigma_L/\sigma_T)$</td>
<td>§ 15%</td>
<td>&lt;0.02%</td>
</tr>
<tr>
<td>$\delta s(x) = $§ 10%</td>
<td></td>
<td>&lt;0.03%</td>
</tr>
<tr>
<td>Higher Twist</td>
<td></td>
<td>????</td>
</tr>
<tr>
<td>EMC Effect</td>
<td></td>
<td>????</td>
</tr>
</tbody>
</table>
Expected $\sin^2(\theta_W)$ Results

$$A = f \left[ \alpha + \beta \sin^2(\theta_W) \right] \quad A = 1.1 \times 10^{-4} Q^2 \left[ 2.2 - 6.1 \sin^2(\theta_W) \right]$$

$$\frac{\delta \sin^2(\theta_W)}{\sin^2(\theta_W)} = \frac{\delta A}{A} \frac{1}{\alpha + \beta \sin^2(\theta_W)} \frac{\alpha + \beta \sin^2(\theta_W)}{\sin^2(\theta_W)}$$

Measure $A_d$ to § 0.5% stat § 1.1% syst. (1.24% combined)

- Measurement uncertainties driven by polarization uncertainties

$$\left. \frac{\delta \sin^2 \theta_W}{\sin^2 \theta_W} \right|_{Y=0.46} = 0.56 \left( \frac{\delta A_d}{A_d} \right) = 0.7\%$$

What about $C_{iq}$'s?
Extracted Signal—It’s all in the binning

\[
\frac{A_d}{1.1 \times 10^{-4} Q^2} \approx - [(2C_{1u} - C_{1d}) + Y (2C_{2u} - C_{2d})]
\]

PDG: \( C_{1u} = -0.209 \pm 0.041 \) highly correlated
\( C_{1d} = 0.358 \pm 0.037 \) correlated

\( 2C_{2u} - C_{2d} = -0.08 \pm 0.24 \)

This measurement:
\( \delta(2C_{1u} - C_{1d}) = 0.03 \) (stat.)
\( \delta(2C_{2u} - C_{2d}) = 0.06 \) (stat.)

(without considering other expts.)

Note—Polarization uncertainty enters as in slope and intercept
\[
A_{\text{obs}} = PA_d / P(2C_{1u} - C_{1d}) + P(2C_{2u} - C_{2d})Y
\]
but is correlated
Constraints with DIS-Parity

\[ C_{1q} \] \text{NC vector coupling to } q
\[ \not{\mathbf{f}} \text{NC axial coupling to } e \]

\[ C_{2q} \] \text{NC axial coupling to } q
\[ \mathbf{f} \text{NC vector coupling to } e \]
Constraints with DIS-Parity

DIS-Parity provides intersecting constraints on \( C_{ia} \) parameters:

\[
\delta(2C_{1u} - C_{1d}) = 0.03 \text{ (stat.)} \quad \delta(2C_{2u} - C_{2d}) = 0.06 \text{ (stat.)}
\]

(1\( \sigma \) limits)
QWeak & APV will Constrain $C_{1u}$ & $C_{1d}$

Combined expected Qweak (proton) and APV measurements give a better value for $C_{1u}$ and $C_{1d}$. Will provide an “anchor” point for fit. Very useful in determining $2C_{2u} - C_{2d}$. 

\[ \delta(2C_{1u} - C_{1d}) = 0.005 \]
\[ \delta(2C_{2u} - C_{2d}) = 0.014 \]
DIS-Parity determines $2C_{2u} - C_{2d}$

Combined result significantly constrains $2C_{2u} - C_{2d}$.

PDG $2C_{2u} - C_{2d} = -0.08 \pm 0.24$ Combined $\delta(2C_{2u} - C_{2d}) = \pm 0.014$

£ 17 improvement (S.M $2C_{2u} - C_{2d} = 0.0986$)
DIS-Parity: Conclusions

- Measurements of $\sin^2(\theta_W)$ below $M_Z$ provide strict tests of the Standard Model.
- Parity NonConserving DIS provides complimentary sensitivity to other planned measurements.
- DIS-Parity Violation measurements can be carried out at Jefferson Lab with the 12 GeV upgrade (beam and detectors) in either Hall A or Hall C.

\[
\begin{align*}
\delta (2C_{1u} - C_{1d}) &= 0.005 \\
\delta (2C_{2u} - C_{2d}) &= 0.014
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\]
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$g$, $g^0$ couplings between currents and fields

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$$\tan \theta_W = \frac{g'}{g} \quad \sin \theta_W = \frac{g'}{\sqrt{g'^2 + g^2}}$$

$$\cos \theta_W = \frac{g}{\sqrt{g'^2 + g^2}}$$

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- $\sin^2(\theta_w)$ is scheme dependent observable—it’s value depends on the renormalization scheme.
Additional Possibilities with $H_2$

- Asymmetry in $\sigma_d - 2\sigma_p$
  - Interpretation does not require knowledge of parton distributions.

\[
A_{d2p} = \frac{\sigma_d^L - \sigma_d^R - 2(\sigma_p^L - \sigma_p^R)}{\sigma_d^L + \sigma_d^R - 2(\sigma_p^L + \sigma_p^R)}
\]
\[
= \left(\frac{G_F Q^2}{\pi \alpha^2 2\sqrt{2}}\right) \left[\frac{1}{2} + 2\sin^2(\theta_W)\right] \times [1 + Y]
\]
\[
\approx -0.65 \times 10^{-5} Q^2 (1 + Y)
\]

- Ratio of asymmetries: $A_p/A_d$
  - If $C_{1a}$'s are known, measures $r(x) \frac{1}{4} d(x)/u(x)$ at large $x$.
  - Polarization cancels out.

\[
\left(\frac{A_p}{A_d}\right) = \left(\frac{2C_{1u} - r(x) C_{1d}}{2C_{1u} - C_{1d}}\right) \left(\frac{5}{4 + r(x)}\right)
\]
\[
r(x) \approx d(x)/u(x)
\]

- s-quark distribution at low $x$: $A_p$
  - $Q^2$ possibly not high enough at Jlab 11 GeV.
$R_s(x)$ and $R_v(x)$

$$R_s(x) = \frac{2s(x)}{u(x) + d(x)} \xrightarrow{\text{large } x} 0$$

$$R_v(x) = \frac{u_v(x) + d_v(x)}{u(x) + d(x)} \xrightarrow{\text{large } x} 1$$

Uncertainties in PDF’s are now known and would be factored into overall error budget.