The 12 GeV Parity Violation Program

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Outline

• Precision tests of Standard Model
• Parity-violation in electron scattering
  Early work: SLAC E122 etc.
• Weak Charges & Physics Reach
  6 GeV: Qweak, PVDIS-6
• PVDIS with Base Equipment
• PVDIS with SoLID
• Moller at 11 GeV

• Conclusions
Precision Tests of the Standard Model

• Received Wisdom: *Standard Model is the effective low-energy theory of underlying more fundamental physics*

• Finding new physics: Two complementary approaches:
  - Energy Frontier (direct): *eg. Tevatron, LHC*
  - Precision Frontier (indirect): *(aka Intensity Frontier)*
    - *eg.*
      - $\mu(g-2)$, EDM, $\beta\beta$ decay, $\mu \rightarrow e \gamma$, $\mu A \rightarrow e A$, $K^+ \rightarrow \pi^+\nu\nu$, etc.
      - $\nu$ - oscillations
      - Atomic Parity violation
      - Parity-violating electron scattering

**Hallmark of Precision Frontier:**
choose observables that are *zero* or *suppressed* in Standard Model

When new physics found in direct measurements, precision measurements useful to determine *e.g.* couplings...
Parity Violating Electron Scattering: Weak Neutral Current Amplitudes

\[ M^{EM} = \frac{4\pi\alpha}{Q^2} Q_\ell \ell^\mu J^{EM}_\mu \]
\[ M^{NC}_{PV} = \frac{G_F}{2\sqrt{2}} \left[ g_A \ell^{\mu 5} J^{NC}_\mu + g_V \ell^{\mu} J^{NC}_{\mu 5} \right] \]

Interference: \( \sigma \sim |M^{EM}|^2 + |M^{NC}|^2 + 2\text{Re}(M^{EM*}M^{NC}) \)

scatter electrons of opposite helicities from unpolarized target

Interference with EM amplitude makes Neutral Current (NC) amplitude accessible

\[ A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \left| \frac{M^{NC}_{PV}}{M^{EM}} \right| \sim \frac{Q^2}{(M_Z)^2} \]

First discussed: Ya. B Zel'dovich JETP 36 (1959)
PARITY NON-CONSERVATION IN INELASTIC ELECTRON SCATTERING

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Received 14 July 1978

We have measured parity violating asymmetries in the inelastic scattering of longitudinally polarized electrons from deuterium and hydrogen. For deuterium near $Q^2 = 1.6$ (GeV/c)^2 the asymmetry is $(-9.5 \times 10^{-3}) Q^2$ with statistical and systematic uncertainties each about 10%.

Textbook Physics: High Energy Physics (D.H. Perkins); Quarks and Leptons (Halzen & Martin)
Pivotal to establishing Weinberg-Salam-Glashow SU(2) × U(1) gauge theory

### Techniques

Optically pumped electron source: rapid helicity reversal
integrate scattered flux
monitoring & feedback to control electron beam fluctuations

### Followed by:

1989: Mainz $^9$Be
W. Heil et al.

1990: MIT/Bates $^{12}$C
P.A. Souder et al.
Weak Charges: Vector

Govern strength of neutral current interaction with fermion

<table>
<thead>
<tr>
<th>Charge Particle</th>
<th>Electric</th>
<th>Weak (vector)</th>
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<tbody>
<tr>
<td>u</td>
<td>+2/3</td>
<td>$C_{1u} = -1/2 + 4/3 \sin^2 \theta_W$</td>
</tr>
<tr>
<td>d</td>
<td>-1/3</td>
<td>$C_{1d} = 1/2 - 2/3 \sin^2 \theta_W$</td>
</tr>
<tr>
<td>Proton uud</td>
<td>+1</td>
<td>$Q_{w}^p = 1 - 4 \sin^2 \theta_W \approx 0.06$</td>
</tr>
<tr>
<td>Electron e</td>
<td>-1</td>
<td>$Q_{w}^e = 1 - 4 \sin^2 \theta_W \approx 0.06$</td>
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Note “accidental” suppression of $Q_{w}^p, Q_{w}^e \rightarrow sensitivity to new physics
**Weak Charges: Axial**

<table>
<thead>
<tr>
<th>Charge Particle</th>
<th>Electric</th>
<th>Weak (axial)</th>
</tr>
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<tbody>
<tr>
<td>u</td>
<td>+2/3</td>
<td>(C_{2u} = -1/2 + 2 \sin^2 \theta_w)</td>
</tr>
<tr>
<td>d</td>
<td>-1/3</td>
<td>(C_{2d} = +1/2 - 2 \sin^2 \theta_w)</td>
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\[C_{2i} = 2g_v^{e}g_A^i\]

\[C_{2u} = -C_{2u} \approx -0.04\]

*Note*: weak axial charge of proton is not “protected” from hadronic effects via current conservation, unlike vector case (CVC)

\[\rightarrow \text{no clean Standard Model prediction}\]

**Access** \(C_{2u}\) and \(C_{2d}\) via parity-violating Deep Inelastic Scattering (PVDIS)
All Data & Fits Plotted at 1 $\sigma$

$Q_{W}^{T}=−2(2C_{1u} + C_{1d})$

Standard Model Prediction

HAPPEx: H, He
G$^0$: H,
PVA4: H
SAMPLE: H, D
Running of $\sin^2 \theta_W$

PDG 2008 Review: “Electroweak and constraints on New Physics Model”
J. Erler & P. Langacker
QWeak (proton)

- Forward-angle elastic scattering 1.16 GeV e's from proton at 8°
  \[ Q^2 = 0.026 \text{ (GeV/c)}^2 \]
- Expected Asymmetry: 234 parts per billion
- Installation begins November 2009
- Runs June 2010 to May 2012
  - Final expt. in Hall C before 12 GeV upgrade
Running of $\sin^2\theta_W$: recent developments

1) Atomic Parity Violation ($^{133}\text{Cs}$): W.G. Porsev, K. Beloy, A. Derevianko

   New calculation of many-body atomic theory (up to triple excitations)
   in $6S_{1/2} \rightarrow 7S_{1/2}$ transition  (100 Gb basis set)

   $Q_W(\text{Cs})^{exp}$: $-73.25 \pm 0.29 \pm 0.20$
   $Q_W(\text{Cs})^{SM}$: $-73.16 \pm 0.03$

2) NuTeV anomaly: originally quoted $3\sigma$ violation of Standard Model

   • Erler & Langacker: include corrections due to asymmetry in strange quark PDFs (from NuTeV and CTEQ)
   • Charge Symmetry violations  (eg Londergan & Thomas  PL B 558(2003)132 )
     ($u/d$ quark mass difference) account for $1\sigma$
     → vector mean fields in nucleus modifies in-medium PDFs
     claim: entire anomaly accounted for
Energy Scale of an Indirect Search

- Estimate sensitivity to new physics Mass/Coupling ratio
  → add new contact term to the electron-quark Lagrangian:


\[
\mathcal{L}_{\text{PV}}^{e-q} = \mathcal{L}_{\text{PV}}^{SM} + \mathcal{L}_{\text{New}}^{PV} \\
= -\frac{G_F}{\sqrt{2}} \bar{e} \gamma_\mu \gamma_5 e \sum_q C_1 q \bar{q} \gamma^\mu q + \frac{g^2}{4\Lambda^2} \bar{e} \gamma_\mu \gamma_5 e \sum_q h_V^q \bar{q} \gamma^\mu q
\]

\[\Lambda = \text{mass} \quad \Lambda = \text{coupling} \]

\[
\frac{\Lambda}{g} = \frac{1}{\sqrt{\sqrt{2}G_F}} \cdot \frac{1}{\sqrt{\Delta Q_W(p)}
\]

Few to 10's of TeV scale can be reached with PV electron scattering at JLab
New Physics: Examples

• Extra neutral gauge bosons: $Z'$  eg. $E6 \rightarrow SO(10) \times U(1)_\psi$ GUT, SUSY, left/right symmetric models, technicolor, string theories...

• Composite fermions

• Leptoquarks (scalar LQs can arise in R-parity violating SUSY)

New physics can show up differently in $Q_{W^e}, Q_{W^p}$, vector vs. axial couplings...

$\rightarrow$ complementarity


Direct search at Tevatron: $M_{Z'\psi} > 0.82$ TeV
CDF  PRL 99 (2007)171802
Electroweak Global Fit

Figure courtesy of Jens Erler

1σ contours:
- $A_{LR}^{(had.)}$ [SLC]
- $A_{FB}^{(b)}$ [LEP]
- $M_W$
- low-energy
- $m_t$

all data: 90% CL

95% CL excluded
Parity-violating DIS

Goal: $c_{2u}$ and $c_{2d}$

$$A_d = -\left(\frac{3G_F Q^2}{\pi \alpha 2\sqrt{2}}\right) \left(2c_{1u} - c_{1d}\right) \left[1 + R_s(x)\right] + \frac{Y \left(2c_{2u} - c_{2d}\right) R_v}{5 + R_s(x)}.$$ 

$Y$ = kinematic variable (with $R_{LT}$)

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

$$R_s(x) = \frac{s(x) + \bar{s}(x)}{u(x) + \bar{u}(x) + d(x) + \bar{d}(x)}$$

$$R_v(x) = \frac{u_v(x) + d_v(x)}{u(x) + \bar{u}(x) + d(x) + \bar{d}(x)}$$

1. PVDIS-6 GeV - this Fall
2. PVDIS-12 GeV - Hall C SHMS/HMS (approved)
3. SoLID: Large Acceptance Solenoid Spectrometer (cond. approved)

_Caveat:_ hadron structure...
Hadronic Structure and PV DIS

- PDFs, $R_{LT}$: under sufficient control at moderate $x$

- Higher-twist: different $Q^2$ dependence than DGLAP effects on asymmetry of order 1% seem plausible
  $\rightarrow$ PVDIS may provide unique window into higher-twist

- Charge Symmetry Violation (CSV): $u^p(x) \neq d^n(x)$ etc.
  $\rightarrow$ effect expected to grow with $x$

- $[d/u$ ratio at high $x$ for proton
  $\rightarrow$ PVDIS can access with hydrogen target]

- Standard Model tests require robust understanding of nucleon structure effects

- Untangling structure effects: kinematic range
PVDIS - approved program

\[ (Q^2, x) = (1.1 \text{ GeV}^2, 0.25) \& (1.9 \text{ GeV}^2, 0.3) \]
- use HRS in Hall A, custom fast DAQ
- study \( Q^2 \) evolution (higher twist)
- 3\% (stat) precision on \( A_d \)

\[ (Q^2, x, W) = (3.3 \text{ GeV}^2, 0.25, 7.3 \text{ GeV}^2) \]
- 0.5\% stats on \( A_d \) in 670 hrs
- 0.7\% systematics goal
- expected \( A_d \): 285 ppm
- \( \sin^2 \theta_W \) to \( \pm 0.0045 \) (2\%)
  (if one assumes CSV and higher-twist under control)
Running of $\sin^2 \theta_W$
Goal: Measure $A_d$ over large kinematic range
\[ \rightarrow \text{disentangle New Physics from hadron structure} \]

Factor of 2 in $Q^2$ for each $x$; $W^2 > 4 \text{ GeV}^2$
**SoLID : Hadronic effects**

Disentangle via $x$, $Q^2$ and $y (=\nu/E)$ dependences

$$A = A \left[ 1 + \beta_{HT} \frac{1}{(1-x)^3 Q^2} + \beta_{CSV} x^2 \right]$$

<table>
<thead>
<tr>
<th></th>
<th>$x$</th>
<th>$Q^2$</th>
<th>$y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higher Twist</td>
<td>$\Rightarrow$</td>
<td>$\Rightarrow$</td>
<td></td>
</tr>
<tr>
<td>CSV</td>
<td>$\Rightarrow$</td>
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<tr>
<td>New Physics</td>
<td></td>
<td></td>
<td>$\Rightarrow$</td>
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</table>
SoLID: spectrometer

Solenoid: BaBar, CDF, or CLEO-II

Fast tracking, particle ID, calorimetry, pipeline electronics

Measure tracks after baffles: suppress low-energy backgrounds (Moller, π's...)

> 200 msr
Resolution < 2%
100 kHz
d/u at high x with SoLID

Switch to hydrogen target:

\[ a^P(x) \approx \frac{u(x) + 0.91d(x)}{u(x) + 0.25d(x)} \]

3-month run

- QCD fit
- CTEQ4M
- CTEQ4M (modified)
- This proposal, 90 days (follows MRST-2004)
Parity-violating Moller at 11 GeV

**Goal:** measure 36 ppb asymmetry with 0.7 ppb error  
Would determine $Q^e_{\text{weak}}$ to 2.3%  
$\sin^2 \theta_W$ to $\pm 0.00026(\text{stat}) \pm 0.00013(\text{syst})$

Novel two-toroid spectrometer exploits topology of identical particles to capture full azimuthal acceptance

\[ A_{PV} = mE \frac{G_F}{\sqrt{2}\pi\alpha} \frac{4\sin^2 \theta}{(3 + \cos^2 \theta)^2} Q^e_W. \]

Physics reach to 7.5 TeV
Moller: spectrometer concept

Identical particles: avoid double-counting, only take forward or backward in c-o-m.

select backward $\theta_{CM}$

*Exploit* to gain full azimuthal acceptance: odd-sectored toroid

Lost $\theta_{CM} > 90^\circ$ electrons in one sector detected via partner ($\theta_{CM} < 90^\circ$) in opposing sector!

Angle range: 5.5 – 17 mrad
Energy range: 2.8 – 8.2 GeV
Moller: some details

- 85 $\mu$A 150 cm lH2 target: 5 kW
- 150 GHz rate (integrating DAQ)
- 5040 hours
- azimuthal defocusing - full $\phi$ population at focal plane: complex hybrid toroid
- background discrimination: $r$, $\phi$

Hybrid (2nd) toroid

600 kW

![Diagram of hybrid toroid](image)
Running of $\sin^2 \theta_W$

Moller-12: competitive with most precise collider data at Z-pole
Complementarity: an example
Timeline/status: SoLID and Moller-12

Moller-12

• PAC 34 - full approval - strong endorsement:

  "The proposed physics reach is outstanding and capable of making this effort a flagship experiment at JLab." "The PAC believes the mission of this experiment... is so important that the Laboratory should make every effort to support the securing of the resources required"

• Working with lab management to prepare funding request (DOE nuclear, +...)

• Goals: CD-0 Spring 2010  construction 2012-2015

• First review (JLab-initiated): late this year

SoLID

• PAC 34 - conditional approval.  Issues: clarify hadronic issues, esp. higher-twist; portability of apparatus (effect on other experiments)

• Plan to resubmit to next PAC

• Theory workshop last week at UW Madison (M. Ramsey-Musolf).  Focus: higher twist in PVDIS

• Securing engineering help on mechanical design/portability of detector package
Summary

• Precision Parity-Violation experiments at JLab will probe new physics at the TeV scale

• May provide critical information for interpretation of “Beyond the Standard Model physics at the LHC

• PVDIS experiments also can address topical issues in hadron structure: higher-twist, charge symmetry violation, u/d at high-x

- finis -
## Precision on $\sin^2\theta_w$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\delta \sin^2\theta_w$ (10^{-4})</th>
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<tbody>
<tr>
<td>APV (Cs)</td>
<td>11</td>
</tr>
<tr>
<td>NuTeV</td>
<td>16</td>
</tr>
<tr>
<td>SLAC E158</td>
<td>15</td>
</tr>
<tr>
<td>PVDIS - 6</td>
<td>18</td>
</tr>
<tr>
<td>Qweak</td>
<td>7</td>
</tr>
<tr>
<td>PVDIS -12</td>
<td>11</td>
</tr>
<tr>
<td>Moller - 12</td>
<td>3</td>
</tr>
</tbody>
</table>

Caveat: not all theoretical errors on equal basis
Complementarity with Direct Searches (LHC)

This is with luminosity-upgraded SLHC (1000 fb⁻¹)
Comparison to Z-pole data for $\sin^2 \theta_W$
"Oblique" new physics

Gauge field self-energies affected, but no direct coupling to fermions

Gauge field self-energies affected, but no direct coupling to fermions
SUSY “phase space”

- RPV SUSY (no SUSY Dark Matter)
- Future 2.5% $Q_e^{\text{Weak}}$
- Future 2.5% $Q_p^{\text{Weak}}$
- 4% $Q_p^{\text{Weak}}$ Measurement
- RPC SUSY
JLab Qweak will provide a stringent stand alone constraint on Leptoquark based extensions to the SM.

- $Q^p_{\text{weak}}$ (semi-leptonic) and E158 (pure leptonic) together make a powerful program to search for and identify new physics.
Lower Bound for “Parity Violating” New Physics

Qweak (4%) with PVES

Atomic only

Qweak constrains new PV physics to beyond 2 TeV

Analysis by R.D. Young et al.