Electroweak Physics

Lecture III:
Electroweak Physics at Low $Q^2$: Weak Neutral Current Interactions
Review

• The electroweak theory has been tested to extraordinary precision
• Typical scale is 0.1%
• No significant deviations, but some tantalizing hints
• The Higgs boson is expected to be light
• We have a self-consistent effective quantum field theory of electroweak interactions up to a scale of 100 GeV
• There has been much progress, but many questions remain
Big Questions (EW physics)

- Why 3 generations of particles?
- Why is the weak boson mass ~ 100 GeV?
- What is the origin of mass?
- How did matter dominate over anti-matter?
- Is there a single unifying force?
- Why are neutrinos so light?
- Why is the Top so heavy?
- ......

June 3, 2005

Electroweak Physics: Lecture III
The High Energy Frontier

- Directly access the 1 TeV scale
- Explore the origin of SU(2) \( \times \) U(1) symmetry breaking
- Measure the arbitrary parameters as precisely as possible
- Confirm or rule out Supersymmetry
Low Energy EW Physics

• Symmetries & Conservation Laws
  - Atomic and Nuclear systems offer rare, unique access to EW interactions
  - Indirect access to very high energy scales
  - Clues to Grand Unified Theories
  - High statistics → Rare processes

• Evolution of fundamental coupling constants
  - Test theory at quantum loop level
  - Indirect access to high energy particles
Weak Neutral Current Interactions

- Many contrasts to W interactions:
  - Flavor conserving
  - Mixing with electromagnetism
  - Better control in the laboratory
- Most new theories have many heavy neutral bosons
- Precision knowledge of Z couplings to all fermions to interpret collider data
WNC Interactions at Low $Q^2$

$Q^2 << \text{scale of EW symmetry breaking}$

Consider

$Q^2 \sim M_Z^2$

on resonance: $A_Z$ imaginary

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

$A_Z^2 \left[ 1 + \frac{A_X^2}{A_Z^2} \right]$ (no interference!)

Logical to push to higher energies, away from the $Z$ resonance

LEPII, Tevatron, LHC access scales greater than $\Lambda \sim 10$ TeV

$\frac{\delta A_Z}{A_Z} \propto \frac{\pi/\Lambda^2}{g G_F}$

$\delta(g)/g \sim 0.1$

$\Lambda \sim 10$ TeV

$\delta(\sin^2 \theta_W) \sim 0.01$
Weak Neutral Current at low $Q^2$

Purely leptonic reaction

$Q_{eW}^e \sim 1 - 4\sin^2\theta_W$

Fixed Target Möller Scattering
APV: Boulder Cs Experiment  
(1982 -1997)

- measure APV component of $6s \rightarrow 7s$ transition in $^{133}$Cs; interferes with E1 (Stark) transition
- 5 reversals to isolate APV signal and suppress systematics
- APV signal is $\sim 6$ ppm of total rate, measured to 0.7% (40 ppb!)

$$Q_W = -N + Z(1 - 4\sin^2 \theta_W)$$

$$Q_W^{(133\text{ Cs})} = -72.74 \pm 0.29 \text{ (expt)} \pm 0.36 \text{ (theory)}$$
$$= -73.19 \pm 0.13 \text{ (SM)}$$

Aspen 2005

M. Woods (SLAC)
$$R^- = \frac{\sigma_{vN}^{NC} - \sigma_{vN}^{CC}}{\sigma_{vN}^{CC} - \sigma_{vN}^{CC}} \approx \rho^2 \left( \frac{1}{2} - \sin^2 \theta_w \right)$$

$$\sin^2 \theta_w^{(on-shell)} = 0.2277 \pm 0.0013 \text{(stat.)}$$
$$\quad \pm 0.0009 \text{(syst.)}$$

Standard Model prediction is 0.2227
(3σ deviation)
LETTERS TO THE EDITOR

PARITY NONCONSERVATION IN THE
FIRST ORDER IN THE WEAK-INTER-
ACTION CONSTANT IN ELECTRON
SCATTERING AND OTHER EFFECTS

Ya. B. ZEL’DOVICH

Submitted to JETP editor December 25, 1958

(March, 1959)
Parity Violation in Electron Scattering?

We assume that besides the weak interaction that causes beta decay,

$$g \langle \overline{PON} \rangle \langle \overline{e^-} \overline{0} \nu \rangle + \text{Herm. conj.,}$$

there exists an interaction

$$g \langle \overline{POP} \rangle \langle \overline{e^-} 0 e^- \rangle$$

(1)

with $g \approx 10^{-49}$ and the operator $O = \gamma_\mu (1 + i \gamma_5)$ characteristic of processes in which parity is not conserved.*

Then in the scattering of electrons by protons the interaction (2) will interfere with the Coulomb scattering, and the nonconservation of parity will appear in terms of the first order in the small quantity $g$. Owing to this it becomes possible to test the hypothesis used here experimentally and to determine the sign of $g$.

In the scattering of fast ($\sim 10^8$ ev) longitudinally polarized electrons through large angles by unpolarized target nuclei it can be expected that the cross-sections for right-hand and left-hand electrons (i.e., for electrons with $\sigma \cdot p > 0$ and $\sigma \cdot p < 0$) can differ by 0.1 to 0.01 percent. Such an effect is a specific test for an interaction not conserving parity.

$$A_{PV} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = -A_{LR}$$

4-momentum transfer

$$Q^2 = 4 EE' \sin^2 \frac{\theta}{2}$$
Weak Electromagnetic Interference

The matrix element of the Coulomb scattering is of the order of magnitude $\frac{e^2}{k^2}$, where $k$ is the momentum transferred ($\hbar = c = 1$). Consequently, the ratio of the interference term to the Coulomb term is of the order of $g k^2 / e^2$. Substituting $g = 10^{-3} / M^2$, where $M$ is the mass of the nucleon, we find that for $k \sim M$ the parity non-conservation effects can be of the order of 0.1 to 0.01 percent.

$$A_{PV} = \frac{\sigma_{\mu} - \sigma_{\nu}}{\sigma_{\mu} + \sigma_{\nu}} \sim \frac{A_{\text{weak}}}{A_{\text{EM}}} \sim \frac{G_F Q^2}{4 \pi \alpha}$$

$$A_{PV} \sim 10^{-4} \cdot Q^2 (\text{GeV}^2)$$

Many new theories (other than SU(2) x U(1)) predicted weak neutral currents, but many cases had no interference predicted.

Neutral weak force first measured in the early ‘70s: $\sin^2 \theta_W \sim 1/4$

Do the weak and electromagnetic amplitudes interfere?

A critical test for the correct gauge structure of the theory

June 3, 2005

Electroweak Physics: Lecture III
Accessing Parity Violation

• One of the incident beams longitudinally polarized
• Change sign of longitudinal polarization
• Measure fractional rate difference
Observation of Weak-Electromagnetic Interference

It was realized independently in the mid 70s at SLAC:

$$A_{PV} \text{ in Deep Inelastic Scattering off liquid Deuterium: } Q^2 \sim 1 \text{ (GeV)}^2$$

- Established the basic experimental technique
- Cleanly observed weak-electromagnetic interference
- Parity Violation in Weak Neutral Current Interactions
- $$\sin^2 \theta_W = 0.224 \pm 0.020$$: same as in neutrino scattering
E158 at SLAC

Parity-Violating Left-Right Asymmetry In Fixed Target Møller Scattering
At the Stanford Linear Accelerator Center

E158 Collaboration

• Berkeley
• Caltech
• Jefferson Lab
• Princeton
• Saclay

• SLAC
• Smith
• Syracuse
• UMass
• Virginia

8 Ph.D. Students
60 physicists

E158 Chronology

• Sep 97: EPAC approval
• Mar 98: First Laboratory Review
• 1999: Design and Beam tests
• 2000: Funding and construction
• 2001: Engineering run
• 2002-2003: Physics
• 2004: First PRL
• 2005: Final publications
Tiny Asymmetry

Imagine measuring the length of Central Park in NYC with 2 different meter scales: answer is expected to differ by 1 mm!

Highest electron beam energy with longitudinal beam polarization:
50 GeV at the Stanford Linear Accelerator Center

Raw asymmetry $\sim 1 \times 10^{-7}$ (100 ppb)

Need $10^{16}$ events

Count at $\sim 1$ GHz

Tiny signal (weak force) buried in known background (QED)
E158 New Physics Reach

- **LEP II**
  \[
  \left| e_R \bar{e}_R \right|^2 + \left| e_L \bar{e}_L \right|^2
  \]

- **Fermilab**
  \[
  q \quad \left\{ e \quad Z' \quad e \right\} \quad q
  \]
  *doubly charged scalar exchange*

- **E158**
  \[
  \left| e_R \bar{e}_R \right|^2 - \left| e_L \bar{e}_L \right|^2
  \]

- **15 TeV compositeness**

- **0.5–1.0 TeV GUTs**

- **0.5–2.5 TeV extra dimensions**

- **lepton flavor violation**
  \[
  \frac{g^2}{2 M^2_\Delta} < 0.01 \quad G_F
  \]
Optical Pumping

Modulate longitudinal polarization of the electron beam

- Beam helicity is chosen pseudo-randomly at 120 Hz
  - sequence of pulse quadruplets
  - Data analyzed as “pulse-pairs”

"strain" boosts polarization, but introduces anisotropy in response
Experimental Technique

- rates range from 1 MHz to 1 GHz
- Millions of electrons in each window

* Rapid helicity flip with each window
* Spatially separate signal
* Integrate scattered flux
* control beam jitter

Detector $D$, Current $I$: $F = D/I$

$$A_{\text{pair}} = \frac{\Delta F}{2F} + \Delta A(X,Y,\theta_X,\theta_Y,E)$$

each window-pair measures $A_{PV}$ with variance $\sim \frac{1}{\sqrt{2 \cdot N_{\text{window}}}}$

$$E158 \rightarrow \frac{200 \text{ ppm}}{\sqrt{320 M}} = 11 \text{ ppb}$$
Systematic Control

Detector D, Current I: $F = D/I$

$$A_{\text{pair}} = \frac{F_R - F_L}{F_R + F_L} = \frac{\Delta F}{2F} + \text{fluctuations}$$

$$A_{\text{pair}} \approx \frac{\Delta D}{2D} - \frac{\Delta I}{2I} + \frac{\Delta E}{2E} + \alpha_i \Delta X_i$$

- jitter (ppm) 200
- accuracy (ppm)
- cumulative (ppb) 110 $\pm 11$

Precision monitoring and control of electron beam fluctuations
Experimental Apparatus

• Polarized Beam
• Precision Beam Monitoring
• Liquid Hydrogen Target
• Spectrometer
• Detectors
Beam Monitoring

Pulse by pulse monitoring at 1 GeV and 45 GeV

Graphs showing:
- Resolution 1.05 MeV
- Resolution 1.54 μm
- Resolution 26.6 ppm

Equations:
- $\sigma_{\text{energy}} \leq 1$ MeV
- $\sigma_{\text{BPM}} \leq 2$ microns
- $\sigma_{\text{toroid}} \leq 30$ ppm
Liquid Hydrogen Target

Simplest source of target electrons is liquid hydrogen $\frac{Z}{A} = 1$

- Refrigeration Capacity: 1 k
- Operating Temperature: 20
- Length: 1.5
- Flow Rate: 5 m
- Vertical Motion: 6 inches
Kinematics

Quadrupole Quadruplet

- primary & scattered electrons enclosed in quadrupoles
- Mollers (e-e) focused, Motts (e-p) defocused
- full range of azimuth

[Graphs showing electron distributions at various distances from the beam axis]
E158 Plan View in ESA

target

Concrete shielding

Spectrometer magnets

Detector cart
E158 Spectrometer
Downstream Configuration
Detector Concept

* 4 integrating detectors
* profile detectors for calibration
Detector Cart

- Cu-fused silica sandwich
- 20 million 17 GeV electrons at 120 Hz
- 100 MRad radiation dose

Profile

integrating calorimeter

PMT shields

signal exit window

Beam

pion detector
Analysis of Calorimeter Response

Basic Idea:

- Corrections for beam fluctuations
- Average over runs
- Statistical tests
- Beam polarization and other normalization
Physics Runs

Run 1: Apr 23 12:00 – May 28 00:00, 2002
Run 2: Oct 10 08:00 – Nov 13 16:00, 2002
Run 3: July 10 08:00 - Sep 10 08:00, 2003

Run 1: Spring 2002
Run 2: Fall 2002
Run 3: Summer 2003

Data divided into 75 “slugs”:
- Wave plate flipped ~ few hours
- Beam energy changed ~ few days
Beam Asymmetries

Charge asymmetry at 1 GeV
Avg. = 0.013 +/- 0.311 ppm

Charge asymmetry agreement at 45 GeV
Avg. = -8.363 +/- 7.844 ppb

Energy difference in A line
Avg. = -0.092 +/- 1.370 keV

Energy difference agreement in A line
Avg. = -0.006 +/- 0.239 keV

Position differences < 20 nm
Position agreement ~ 1 nm
Raw Asymmetry Statistics

\[ \sigma_i \approx 200 \text{ ppm} \]

\[ \sigma_i \approx 600 \text{ ppb} \]

\[ N = 85 \text{ Million} \]

\[ N = 818 \]

June 3, 2005  Electroweak Physics: Lecture III
Final Analysis of All 3 Runs

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

\[ \chi^2/df = 78.5/74 \]

---

g-2 spin precession

45 GeV: 14.0 revs

48 GeV: 14.5 revs

June 3, 2005
Electroweak Physics

\[ \sin^2 \theta_W = \frac{e^2}{g^2} \]

test gauge structure of SU(2) × U(1)

\[ \frac{1}{2} - q \sin^2 \theta_W \]

Czarnecki & Marciano (2000)

\[ \sin^2 \theta_W \text{ is about } 3\% \]
Final Physics Results

\[ \sin^2 \theta_{\text{eff}} = 0.2397 \pm 0.0010 \pm 0.0008 \]

\[ \sin^2 \theta_{W}^{\text{MS}}(M_Z) \]

- E158
- NuTeV
- Qw(Cs)

6σ

*hep-ex/0504049 submitted early May*

June 3, 2005

Electroweak Physics: Lecture III
Beyond the Standard Model

(95% confidence level)

* Limit on $\Lambda_{LL} \sim 7$ or 16 TeV

* Limit on SO(10) $Z' \sim 1$ TeV

* Limit on lepton flavor violating coupling $\sim 0.01G_F$
Summary

• Progress beyond low energy electroweak theory requires:
  - Exploring the 1 TeV frontier
  - Exploring rare processes at lower energy

• Weak Neutral Current experiments play a central role in testing the electroweak theory

• SLAC E158 is the most sensitive test to date: what can we do next?

• Lower energy implies understanding of atoms, nuclei and nucleons