Outline

§1. Precision Electroweak Measurements

§2. Neutrinos and the Weak Neutral Current

§3. Technique

§4. The NuTeV Experiment

§5. The Data Sample

§6. Experimental and Theoretical Simulation

§7. Electroweak Fits

§8. Interpretation and Conclusions
Robert Bernstein, A Departure From Prediction: Electroweak Physics at NuTeV

The NuTeV Collaboration


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Electroweak Measurements

- Measure $\sin^2 \theta_W$ in A Variety of Processes
  And Demand Consistency

\[
T = \rho - 1 \frac{1}{\bar{\alpha}}
\]

(S, T from Peskin and Takeuki)

\[
S \Rightarrow \sin^2 \theta_W
\]

Table I: Electroweak observables described in fit.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Experimental value</th>
<th>Theoretical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_W (\text{Cs})$</td>
<td>$72.2 \pm 0.8$ a)</td>
<td>$73.19$ b) $0.800 S$ $0.007 T$</td>
</tr>
<tr>
<td>$Q_W (\text{II})$</td>
<td>$115.0 \pm 4.5$ c)</td>
<td>$116.8$ d) $1.17 S$ $0.06 T$</td>
</tr>
<tr>
<td>$M_W$ (GeV/c²)</td>
<td>$80.451 \pm 0.033$ e)</td>
<td>$80.385$ f) $0.29 S + 0.45 T$</td>
</tr>
<tr>
<td>(Z) (MeV)</td>
<td>$83.991 \pm 0.087$ g)</td>
<td>$84.011$ f) $0.18 S + 0.78 T$</td>
</tr>
<tr>
<td>$\sin^2 \theta_W$</td>
<td>$0.23152 \pm 0.00017$ g)</td>
<td>$0.23140$ f) $+ 0.00362$ $0.00258 T$</td>
</tr>
<tr>
<td>“$M_W$” (GeV/c²)</td>
<td>$80.136 \pm 0.084$ h)</td>
<td>$80.385$ f) $0.27 S + 0.56 T$</td>
</tr>
</tbody>
</table>

J. Rosner, hep-ph/0109239
What’s Different About Neutrinos?

• Neutrinos Measure a Different Quantity from Direct Mass: $\rho$

$$\sin^2 \theta_W(\text{on-shell}) = 1 - \frac{M_W^2}{M_Z^2}$$

$$\sin^2 \theta_W = 1 - \frac{M_W^2}{\rho M_Z^2}$$

• $\sin^2 \theta_W$ describes the mixing between the $Z^0$ and the $\gamma$ in Spontaneous Symmetry Breaking

• $\rho = G_F(\text{NC})/G_F(\text{CC})$ sets the relative strength of charged, neutral current interactions

• Is $G_{\text{CC}}^F = G_{\text{NC}}^F$?

• Precise Measurements With Different EW Corrections: Probe for New Physics
Comparison in Different Processes

All happy families are alike. Each unhappy family is unhappy in its own way. —L. Tolstoy
Methodology

Coupling $\propto I_{\text{weak}}^{(3)}$

Want

$$R = \frac{\sigma(\nu, \text{NC})}{\sigma(\nu, \text{CC})}$$

Measure

$$R_{\text{meas}} = \frac{\text{Neutral Current Events}}{\text{Charged Current Events}} \Leftrightarrow \frac{\text{no} - \text{muon events}}{\text{with muon events}}$$

$$= R_{\text{meas}}(\sin^2 \theta_W, \rho, \text{flux}, \text{QPM}, \text{detector})$$
Taking Ratios

- $W, Z$ Scattering $\Leftrightarrow \rho$ and $\sin^2 \theta_W$:

**Llewellyn Smith Relations:**

$$R^\nu = \frac{\sigma^\nu_{NC}}{\sigma^\nu_{CC}} = \rho^2 \left( \frac{1}{2} - \sin^2 \theta_W + \frac{5}{9} \sin^4 \theta_W (1 + r) \right)$$

$$R^\bar{\nu} = \frac{\sigma^{\bar{\nu}}_{NC}}{\sigma^{\bar{\nu}}_{CC}} = \rho^2 \left( \frac{1}{2} - \sin^2 \theta_W + \frac{5}{9} \sin^4 \theta_W \left( 1 + \frac{1}{r} \right) \right)$$

$$r = \frac{\sigma^{\bar{\nu}}_{CC}}{\sigma^{\nu}_{CC}} \text{ Measured From Data}$$

*Isoscalar target composed of only $u,d$ quarks at tree level*

- Typically Have *Assumed* $\rho$ from SM and fit $\sin^2 \theta_W$

- Big Change With NuTeV:
  - Now Two Equations, Two Unkowns:

$$R^\nu, R^{\bar{\nu}} \Leftrightarrow \rho, \sin^2 \theta_W$$
Soundbite Version

- Fixing $\rho$ and reporting $R^-, R_\nu$ is very close to
  \[ \sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2} \]
- This Is What We Usually Quote
The Result

NuTeV Measures:

\[ \sin^2 \theta_W^{(on-shell)} = 0.2277 \pm 0.0013 \text{(stat)} \pm 0.0009 \text{(syst)} \]

\[ - 0.00022 \times \left( \frac{M_{\text{top}}^2 - (175 \text{ GeV})^2}{(50 \text{ GeV})^2} \right) \]

\[ + 0.00032 \times \ln \left( \frac{M_{\text{Higgs}}}{150 \text{ GeV}} \right) \]

cf. standard model fit (LEPEWWG): 0.2227 \pm 0.00037

A discrepancy of 3\(\sigma\)...

\[ \sin^2 \theta_W^{(on-shell)} \equiv 1 - \frac{M_W^2}{M_Z^2} \]

---

80.433 +/- 0.079  CDF
80.483 +/- 0.084  D0
80.471 +/- 0.049  ALEPH*
80.401 +/- 0.066  DELPHI*
80.398 +/- 0.069  L3*
80.490 +/- 0.065  OPAL*  OK, You can Leave Now...
80.451 +/- 0.033  Direct World Average
80.376 +/- 0.023  Indirect World Average 
                  (LEPI/SLD/APV/m_t)
                  (LEPEWWG)
80.136 +/- 0.084  NuTeV

* : Preliminary
Theory Recap:

- NuTeV is precise: $M_W$ comparable to collider precision
- NuTeV is sensitive to different new physics than other precision experiments
  - Sensitive to different radiative corrections
  - Measurement is off the Z pole
    - i.e. exchange is not guaranteed to be a Z
  - Measure neutral current neutrino couplings
    - LEP I invisible line width is only other precise measurement
  - Measure light quark couplings
    - also APV, Tevatron Z production
- Testing in a wide range of processes and momentum scales ensures universality of the electroweak theory

Momentum Transfer ($\text{GeV}^2$)

<table>
<thead>
<tr>
<th>Momentum Transfer ($\text{GeV}^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0001</td>
</tr>
<tr>
<td>Atomic Parity Violation</td>
</tr>
</tbody>
</table>
**What’s the Limiting Error?:**

**Charged-Current Production of Charm**

- Suppression of CC cross section for interactions with massive charm quark in final state
- Modeled by leading-order slow-rescaling

\[ \xi = x \left(1 + \frac{m_c^2}{Q^2}\right) \quad \text{where} \quad x = \frac{Q^2}{2M E_{\text{had}}} \]

- \( m_c \) a parameter, not real mass
- Can Measure Within Data, But Not Well Enough
- Need to Drastically Reduce this Error to Progress
$R_\nu$, $R^-$ and Systematics

With Just A Neutrino Beam:

$$R_\nu = \frac{\sigma(\nu, NC)}{\sigma(\nu, CC)} = \rho^2 \left( \frac{1}{2} - \sin^2 \theta_W + \frac{5}{9} \sin^4 \theta_W (1 + r) \right)$$

With Both Neutrinos and Antineutrinos:

$$R^- = \frac{\sigma(\nu, NC) - \sigma(\bar{\nu}, NC)}{\sigma(\nu, CC) - \sigma(\bar{\nu}, CC)} = \rho^2 \left( \frac{1}{2} - \sin^2 \theta_W \right)$$

And in the PW Denominator:

$$s, (d_\nu + d_s) \quad c \quad = d_\nu \sin^2 \theta_C \ Error \ Down \times 5$$
How Do You Get $R^-$?

$$R^- = \frac{R_\nu - rR_{\bar{\nu}}}{1 - r}$$

$$R^+ = \frac{R_\nu + rR_{\bar{\nu}}}{1 + r}$$

$$r = \frac{\sigma(\bar{\nu}, \text{CC})}{\sigma(\nu, \text{CC})}$$

($R^+$ is the companion to $R^-$ with cross-section sums)

- Experiment Measures $R_\nu, R_{\bar{\nu}}$
  
  Two Choices:

  §1. Use $R^+$ to Reduce Systematics on $R^-$

  §2. Feed in SM $\rho$

  §3. Extract Precise $\sin^2 \theta_W$

  §1. Use Both $R_\nu, R_{\bar{\nu}}$

  §2. By “Conservation of Information”, Same as $R^+, R^-$

  §3. Do Genuine Two-Parameter Fit and Extract $\rho$

We, of course, will do both …
What Do You Need for a Neutrino Experiment?

Requirements Driven by Small $\nu$ Cross-Section

- Neutrino Detector
  - Hundreds of Tons
- Neutrino Beam
  - Intense, Lots of Protons
- Auxiliary Measurements
  - Calibration of Detector Response
    §1. Muons
    §2. Hadrons
    §3. Electrons
Detector: Advantages and Disadvantages

Lab E Detector - Fermilab E815(NuTeV)
690 tons: Fe-Scint-DC

Massive, Simple, Understood, but Coarse

- Easy to Detect:
  - §1. Presence of Outgoing Muon ⇒ Charged Current
  - §2. Absence of Outgoing Muon ⇒ Neutral Current
- But coarse, and therefore
  - §1. Sometimes miss muon
    - Low Energy Muons Range Out in Shower
      \((\approx 3 \text{ GeV})\)
  - §2.  \(\nu_eN \rightarrow eX\) are a NC Background:
    - outgoing \(e\) gets Lost in Hadronic Shower \(X\)
Detector Details

Target/Calorimeter:
- 168 Fe plates (3m × 3m × 5.1cm)
- 84 liquid scintillation counters
  - Trigger the detector
  - Visible energy
  - Neutrino interaction point
  - Event length
- 42 drift chambers
  - Localized transverse shower position

Toroidal Spectrometer:
- 11 kG field ($P_T = 2.4 GeV/c$)

Continuous Test Beam: every beam spill
- Hadron, muon and electron beams
  - Map toroid and calorimeter response
- Understand Behavior of Hadronic Showers
**NuTeV Beamline: Overall**

800 GeV Tevatron

Target and Focusing

(\textit{miracle occurs here})

$\pi^\pm, K^\pm$ to detector

Decay Pipe

Shielding

1.4 km

NuTeV detector
What’s New About NuTeV?:
The Beam

Prior Beams

§1. Horn (MINOS)
  • Low Energy Portion
  • Separate $\nu$, $\bar{\nu}$

§2. Dichromatic (Cross-Section Measurements)
  • Selects Mesons of Particular Momentum
  • Low Flux

§3. Quadrupole Train (Structure Functions)
  • Mixed $\nu$, $\bar{\nu}$
  • High Energy, High Statistics
Why Not More Quad Triplet?

Quadrupole Triplet Was Best, but Problems

**Quadrupole Train**

1) Both Signs of Mesons
2) $\nu_e$ from $K_L$

§1. Mixed $\nu, \bar{\nu}$ Meant Can’t
   Experimentally Separate neutral current $\nu, \bar{\nu}$
   *Measure Combination of $R_\nu, R_{\bar{\nu}} \leftrightarrow \sin^2 \theta_W, \rho$

§2. Also Have Charm Mass Problem:
   - No Subtraction in $R_\nu = \sigma(\nu, \text{NC})/\sigma(\nu, \text{CC})$

§3. Allows $K_L \rightarrow \pi e \nu_e$
   - Source of $\nu_e$ which can fake neutral currents
   - Production not well known enough, big error!
NuTeV Beamline: SSQT

- Resulting beam is almost purely $\nu$ or $\bar{\nu}$: 
  
  $$(\bar{\nu} \text{ in } \nu \text{ mode } 3 \times 10^{-4}, \nu \text{ in } \bar{\nu} \text{ mode } 4 \times 10^{-3})$$

- Beam is $\sim 1.8\%$ electron neutrinos
  
  - But Troublesome $K_L \rightarrow \nu_e$ Gone,
    Since $K_L$ Head off Into Dumps,
    Away From Beam Direction

- About Half of QT flux/per proton
  
  - Experiment will end up being statistics-limited!
Experimental Errors

Beam

- Have to get Flux
- Estimate $\nu_e$ (from $K^\pm \rightarrow \pi^0 e\nu_e$)

Detector

- Crosstalk from Neutral to Charged
- $\nu_e$ (from $K \rightarrow \pi^0 e\nu_e$) all look like NC
- Acceptance Differences

QPM

- To extract $\sin^2 \theta_W$ from the measured ratio
  $\Rightarrow$ corrections: isovector target, radiative corrs, heavy quark effects, higher twist, $R_L$
- Most of SF dependence, many of systematic uncertainties, and sensitivity to neutrino spectrum cancel in the ratio
- Major theoretical uncertainty $m_c$
  $\rightarrow$ mainly affects CC
Neutral Current/Charged Current Event Separation

Statistical separation of NC and CC events based solely on “event length”:

\[ R_{\text{exp}} = \frac{\text{SHORT events}}{\text{LONG events}} = \frac{L \leq L_{\text{cut}}}{L > L_{\text{cut}}} = \text{NC candidates} \]

\[ \text{CC candidates} \]

(measure this ratio in both \( \nu \) and \( \bar{\nu} \) modes)
Fiducial Cuts: Energy and Length

Shower Containment

Muon ID (1)

Muon ID (2)

Muon Fakes Neutrino

Muon Not Identified Because Length is Too Short
Length Distribution and Sources

1. Model Shape of CC Distribution
   - How Many CC’s Under NC peak?
     ⇒ Structure Functions/PDFs

2. How Many $\nu_e$’s?
   - Flux Modeling

3. How Many “Long NC”’s?
   - Shower Length from Hadron Test Beam
Sources of Error in NC/CC Separation

**CROSS SECTION MODEL**
- LO pdfs (CCFR)
- Radiative corrections
- Isoscalar corrections \( \left( \frac{N-Z}{A} \approx 5.67\%, \; \bar{d}/\bar{u} \neq 1 \right) \)
- Heavy quark corrections
- \( R_L \)
- Higher twist

**DETECTOR RESPONSE**
- CC↔NC cross-talk
- Beam contaminations
- Muon simulation
- Calibrations
- Event vertex

**NEUTRINO FLUX**
- \( \nu_\mu \) and \( \nu_e \)
Backgrounds

- Even After Fiducial Cuts:

- Short $\nu_\mu$ CC’s (20% $\nu$, 10% $\bar{\nu}$)
  - Muons exit, range out

- Why Not Track?: **Systematics**
  - Differences in Efficiency for
  - NC (no track) vs. CC (track)
  - Error Would Dominate
  - Very Hard to Estimate/Control
Determine Structure Functions from this Data

- Measure Structure Functions \( \Rightarrow \) PDFs (Among Best PDF Inputs)
- Measured Internally With *Same Data Set*
  - Be Careful Applying External Corrections
  - Can’t Just Take Your Favorite PDFs and Apply
  - We Try to produce Model-Independent Results
Charged-Current Control Sample

- High $y$ charged-current is background to NC sample
  - CC subtraction is 20%/10% in $\nu/\bar{\nu} \Rightarrow$ want $\sim 1\%$ accuracy
- Check by looking at “long exit” CC events which start in the detector center and stop before toroid
- Kinematically Similar to Short Events, but no $\nu_e$

- Agreement in this “short” charged-current sample is good within systematic uncertainties
Approximately 5% of all short events are $\nu_e$ CC.

### Sources of Neutrinos and Event Fractions

<table>
<thead>
<tr>
<th>Source</th>
<th>$\nu$ Mode</th>
<th>$\bar{\nu}$ Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^\pm, K^\pm \rightarrow \mu^\pm \nu_\mu$</td>
<td>0.982</td>
<td>0.973</td>
</tr>
<tr>
<td>$K^\pm_{e3}$</td>
<td>0.0157 ± 0.0003</td>
<td>0.0115 ± 0.0002</td>
</tr>
<tr>
<td>$K_{Le3}, K_{Se3}$</td>
<td>0.00065 ± 0.00007</td>
<td>0.00290 ± 0.0003</td>
</tr>
<tr>
<td>Charm Meson$\rightarrow \nu_e$</td>
<td>0.00042 ± 0.00006</td>
<td>0.00155 ± 0.0002</td>
</tr>
<tr>
<td>$\mu \rightarrow \nu_e$</td>
<td>0.00007 ± 0.00001</td>
<td>0.00010 ± 0.00001</td>
</tr>
<tr>
<td>$\Lambda_c, \Lambda, \Sigma$</td>
<td>0.00003 ± 0.00003</td>
<td>0.00023 ± 0.0002</td>
</tr>
</tbody>
</table>

⇒ It would take a 20% mistake in $\nu_e$ to move $\sin^2 \theta_W$ to SM value

But $K^\pm_{e3}$ constrained by $K^\pm \rightarrow \mu^\pm \nu_\mu$

---

Use **Measurement** to Remove Particle Production and Beam Optics
\[ \chi^2 / \text{dof} = 117.2 / 126 \]

\[ \chi^2 / \text{dof} = 88.9 / 125 \]
Direct Measurements of $\nu_e$ Flux

Longitudinal Shower Development

$e^-$ Showers Concentrate Energy At Beginning

$$\eta_3 = 1 - \frac{\sum \text{first three counters } E_i}{\sum \text{all counters } E_i}$$

- $\nu_e$ electron showers ($80 < E_\nu < 180$ GeV)

<table>
<thead>
<tr>
<th>$\nu_e$</th>
<th>$\nu_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1.05 \pm 0.03$</td>
<td>$1.01 \pm 0.04$</td>
</tr>
</tbody>
</table>

- $N_{\text{meas}}/N_{\text{pred}}$

- Approximately 5% of all short events are $\nu_e$ CC.
Hadron Shower Length

• All events have showers from recoil of hadronic system
  – Determines event length for NC
  – NC→CC sample (0.7% of NC)
  ⇒ Want to model punch-through at 10% level

• Testbeam hadrons measure punch-through
  – Use LEPTO simulation to study difference between
    $\nu$-induced and hadron-induced showers
Compare Hadronic Energy

ν Mode

Hadronic Energy

\[ \chi^2 = \frac{228.4}{209} \text{ dof} \]

Data/MC

1.62 \times 10^6 \text{ events in the } \nu \text{ beam}
The Raw Data: $\bar{\nu}$

$\bar{\nu}$ Mode

$\chi^2 = 163.7/174$ dof

$0.35 \times 10^6$ events in the $\bar{\nu}$ beam
Stability of $R_{\text{exp}}$

- We have evaluated systematic uncertainties and believe they are under control
  - Now want to verify this with data...

- Strategy: verify that the $R_{\text{exp}}$ comparison to Monte Carlo is consistent under changes in fiducial cuts and different ranges of event variables
  - Use $\chi^2$ probability test to evaluate comparisons
  - Compare to expected values

- Event observables:
  - Longitudinal Vertex: check detector uniformity
  - Short/Long at Intermediate/Long Length: check CC$\leftrightarrow$NC
  - Transverse Vertex: more NC background near edge
  - Visible Energy
Stability of $R_{\text{exp}}$ (cont’d)

$R$ as a function of longitudinal vertex

- Both Are Flat, So Stable: not leakage into front
- Note $\nu$ A Little Low: *that’s the answer!*

![Graph showing stability of $R_{\text{exp}}$](image-url)
Stability of $R_{\text{exp}}$ (cont’d)

$R$ as a function of length cut

- “16,17,18” [counters] is default; tighten ↔ loosen NC selection
- Measurements are correlated; uncertainties are on difference

\[
\chi^2/\text{dof} = 4.47015/3, \text{ Prob}=0.2150
\]

\[
\chi^2/\text{dof} = 0.27844/3, \text{ Prob}=0.9640
\]
Stability of $R_{\text{exp}}$ (cont’d)

$R$ as a function of “radial” bin

- These are exclusive bins
- Bins 1-4 in result (5 is a check)
- Sensitive to mistakes in $\nu_e$, short CC

![Graph showing $R_{\text{exp}}$ as a function of radial bin with data and Monte Carlo comparison, including chi-squared values and significance levels.]
Stability of $R_{\text{exp}}$ (cont’d)

Short Events (NC Candidates) vs. $E_{\text{had}}$

Relative Calibration Fit, pass25, short events, R 0–40, all-nuecorr–final

![Plot](Image)

- Neutrino
- Antineutrino

$\chi^{2}/\text{dof} = 12.2/22$

$\chi^{2}/\text{dof} = 24.2/22$

$\pm 1\sigma$ systematic uncertainty

(Data/MC ratio)

(Green band is $\pm 1\sigma$ systematic uncertainty)
Stability of $R_{\text{exp}}$ (cont’d)

Long Event (CC Candidates) vs. $E_{\text{had}}$

Relative Calibration Fit, pass25, long events, R 0–40, all–nuecorr–final

Neutrino

Antineutrino

e_{\text{had}}$ bins in data, both nu and nubar

$\chi^2/\text{dof} = 27.8/22$

(0.182 prob)

$x_{\text{dof}} = 25.4/22$

(0.279 prob)

(Data/MC ratio)

(Green band is $\pm 1\sigma$ systematic uncertainty)
Stability of $R_{\text{exp}}$ (cont’d)

$R_{\text{exp}}$ vs. $E_{\text{had}}$

Green band is $\pm 1\sigma$ systematic uncertainty
The $\sin^2 \theta_W$ Fit

\[
R_\nu = \frac{\sigma(\nu, \text{NC})}{\sigma(\nu, \text{CC})}
\]
\[
\frac{dR_\nu}{d\sin^2 \theta_W} \approx -0.65
\]

Strong $\sin^2 \theta_W$ Dependence but $m_c$ Systematics of pre-NuTeV

Weak $\sin^2 \theta_W$ Dependence

$\Rightarrow$ MEASURE $m_c$

- Largest theoretical uncertainty is in parameterization of charged-current charm production via $m_c$
- Use $R_\nu^\text{exp}$ (which is insensitive to $\sin^2 \theta_W$) to “measure” $m_c$ then feed back into $R_\nu^\text{exp}$

\[
\sin^2 \theta_W^{(\text{on-shell})} = 0.2277 \pm 0.0013 \pm 0.0009
\]
\[
m_c = 1.32 \pm 0.09 \pm 0.06 \text{ GeV (cf. input } m_c = 1.38 \pm 0.14)\]

- $\sin^2 \theta_W^{(\text{on-shell})}$ determined by a quantity that is $\approx R_\nu^-$
The Result (da capo)

NuTeV Measures:

\[
\sin^2 \theta_W^{(\text{on-shell})} = 0.2277 \pm 0.0013(\text{stat}) \pm 0.0009(\text{syst})
- 0.00022 \times \frac{M_{\text{top}}^2 - (175 \text{ GeV})^2}{(50 \text{ GeV})^2}
+ 0.00032 \times \ln \left( \frac{M_{\text{Higgs}}}{150 \text{ GeV}} \right)
\]

cf. standard model fit (LEPEWWG): 0.2227 \pm 0.00037

A discrepancy of 3\(\sigma\)...

\(R_{\nu}\) and \(R_{\bar{\nu}}\) measured to a precision of

0.3\%, 0.65\%, respectively

(systematics lead to correlated uncertainty)
## From Corrections to Uncertainties

- Theoretical model uncertainties dominate $R_{\nu}^{\exp}, R_{\bar{\nu}}^{\exp}$
- $R^{-}$ technique $\Rightarrow \sin^2 \theta_W^{(\text{on-shell})}$ statistically dominated

<table>
<thead>
<tr>
<th>SOURCE OF UNCERTAINTY</th>
<th>$\delta \sin^2 \theta_W$</th>
<th>$\delta R_{\nu}^{\exp}$</th>
<th>$\delta R_{\bar{\nu}}^{\exp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Statistics</td>
<td>0.00135</td>
<td>0.00069</td>
<td>0.00159</td>
</tr>
<tr>
<td>Monte Carlo Statistics</td>
<td>0.00010</td>
<td>0.00006</td>
<td>0.00010</td>
</tr>
<tr>
<td><strong>TOTAL STATISTICS</strong></td>
<td><strong>0.00135</strong></td>
<td><strong>0.00069</strong></td>
<td><strong>0.00159</strong></td>
</tr>
<tr>
<td>$\nu_e, \bar{\nu}_e$ Flux</td>
<td>0.00039</td>
<td>0.00025</td>
<td>0.00044</td>
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<tr>
<td>Interaction Vertex</td>
<td>0.00030</td>
<td>0.00022</td>
<td>0.00017</td>
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<tr>
<td>Shower Length Model</td>
<td>0.00027</td>
<td>0.00021</td>
<td>0.00020</td>
</tr>
<tr>
<td>Counter Efficiency, Noise, Size</td>
<td>0.00023</td>
<td>0.00014</td>
<td>0.00006</td>
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<tr>
<td>Energy Measurement</td>
<td>0.00018</td>
<td>0.00015</td>
<td>0.00024</td>
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<tr>
<td><strong>TOTAL EXPERIMENTAL</strong></td>
<td><strong>0.00063</strong></td>
<td><strong>0.00044</strong></td>
<td><strong>0.00057</strong></td>
</tr>
<tr>
<td>Charm Production, $s(x)$</td>
<td>0.00047</td>
<td>0.00089</td>
<td>0.00184</td>
</tr>
<tr>
<td>$R_L$</td>
<td>0.00032</td>
<td>0.00045</td>
<td>0.00101</td>
</tr>
<tr>
<td>$\sigma^{\bar{\nu}} / \sigma^{\nu}$</td>
<td>0.00022</td>
<td>0.00007</td>
<td>0.00026</td>
</tr>
<tr>
<td>Higher Twist</td>
<td>0.00014</td>
<td>0.00012</td>
<td>0.00013</td>
</tr>
<tr>
<td>Radiative Corrections</td>
<td>0.00011</td>
<td>0.00005</td>
<td>0.00006</td>
</tr>
<tr>
<td>Charm Sea</td>
<td>0.00010</td>
<td>0.00005</td>
<td>0.00004</td>
</tr>
<tr>
<td>Non-Isoscalar Target</td>
<td>0.00005</td>
<td>0.00004</td>
<td>0.00004</td>
</tr>
<tr>
<td><strong>TOTAL MODEL</strong></td>
<td><strong>0.00064</strong></td>
<td><strong>0.00101</strong></td>
<td><strong>0.00212</strong></td>
</tr>
<tr>
<td><strong>TOTAL UNCERTAINTY</strong></td>
<td><strong>0.00162</strong></td>
<td><strong>0.00130</strong></td>
<td><strong>0.00272</strong></td>
</tr>
</tbody>
</table>
How Well Did The New Beam Work?

Comparison to CCFR:

**NuTeV/CCFR Error Comparison**

- Data Statistics
- MC Statistics
- $\nu_e$ Flux
- Calibrations
- $\mu$ Energy Deposition
- Energy Resolution
- Hadron Shower
- Vertex Determination
- Counter Edge
- Counter Efficiency/noise
- Charm Prod/Strange Sea
- Charm Sea
- Cross Section Diff
- Non-isoscalar Target
- Higher Twist
- $R_{\text{Long}}$
- Radiative Corrections

Error on $\sin^2\Theta_w (\times 10^{-4})$
Comparison with $M_W$

\[ \sin^2 \theta_W^{(\text{on-shell})} \equiv 1 - \frac{M_W^2}{M_Z^2} \]

<table>
<thead>
<tr>
<th>$M_w$ (GeV)</th>
<th>CDF</th>
<th>D0</th>
<th>ALEPH*</th>
<th>DELPHI*</th>
<th>L3*</th>
<th>OPAL*</th>
<th>Direct World Average</th>
<th>Indirect World Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>80.433 +/- 0.079</td>
<td>80.483 +/- 0.084</td>
<td>80.471 +/- 0.049</td>
<td>80.401 +/- 0.066</td>
<td>80.398 +/- 0.069</td>
<td>80.490 +/- 0.065</td>
<td>80.451 +/- 0.033</td>
<td>80.376 +/- 0.023</td>
<td>80.136 +/- 0.084</td>
</tr>
</tbody>
</table>

* : Preliminary

- In standard electroweak theory, NuTeV precision is comparable to a single direct measurement of $M_W$

\[ \Delta M_W \]

<table>
<thead>
<tr>
<th>CDF/D0</th>
<th>NuTeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>79/84</td>
<td>84 MeV</td>
</tr>
</tbody>
</table>
And the result is consistent with past neutrino measurements ... but much smaller errors

\[ \sin^2 \theta_{W}^{\text{on-shell}} \equiv 1 - \frac{M_W^2}{M_Z^2} = 0.2277 \pm 0.0036 \]

\[ M_W(\text{LEPEWWG}) = 80.376 \pm 0.023 \text{ GeV} \]
\[ M_W(\text{before NuTeV}) = 80.14 \pm 0.19 \text{ GeV} \]
\[ M_W(\text{NuTeV}) = 80.136 \pm 0.084 \text{ GeV} \]

All other experiments are corrected to NuTeV/CCFR \( m_c \) and to large \( M_{\text{top}} \) \( (M_{\text{top}} > M_W) \)
Neutral Current $\nu$ Interactions: Is it Just Neutrinos?

- LEP I measures $Z$ lineshape and decay partial widths to infer the “number of neutrinos”
  - Their result is $N_\nu = 3 \frac{\Gamma_{\text{exp}}(Z\rightarrow\nu\nu)}{\Gamma_{\text{SM}}(Z\rightarrow\nu\nu)} = 3 \times (0.9947 \pm 0.0028)$
  - LEP I “direct” partial width ($\nu\nu\gamma$) $\Rightarrow N_\nu = 3 \times (1.00 \pm 0.02)$

- NuTeV can fit for a deviation in $\nu$&$\bar{\nu}$ NC rate
  - $\rho_0^2 = 0.9884 \pm 0.0026(\text{stat}) \pm 0.0032(\text{syst})$

\[
\begin{array}{c}
\text{CHARM II et al.} \\
\text{LEP I Direct} \\
\text{LEP I Lineshape} \\
\text{NuTeV}
\end{array}
\]

\[
\begin{array}{c}
1.00 \pm 0.05 \\
1.00 \pm 0.02 \\
0.995 \pm 0.003 \\
0.988 \pm 0.004
\end{array}
\]

\[\chi^2/\text{dof} = 1.7/3\]

- In this interpretation, NuTeV confirms and strengthens LEP I indications of “weaker” neutrino neutral current

NB: This is not unique or model-independent!
### SM Fit with NuTeV $\sin^2 \theta_W$

**Winter 2002**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Pull $(O^{\text{meas}} - O^{\text{fit}})/\sigma^{\text{meas}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \alpha_{\text{had}}^{(5)}(m_Z)$</td>
<td>$0.02761 \pm 0.00036$ -0.27</td>
</tr>
<tr>
<td>$m_Z$ [GeV]</td>
<td>$91.1875 \pm 0.0021$ .01</td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>$2.4952 \pm 0.0023$ -.42</td>
</tr>
<tr>
<td>$\sigma_{\text{had}}^{0}$ [nb]</td>
<td>$41.540 \pm 0.037$ 1.63</td>
</tr>
<tr>
<td>$R_l$</td>
<td>$20.767 \pm 0.025$ 1.05</td>
</tr>
<tr>
<td>$A_{\text{fb}}^{0,l}$</td>
<td>$0.01714 \pm 0.00095$ .70</td>
</tr>
<tr>
<td>$A_l(P_T)$</td>
<td>$0.1465 \pm 0.0033$ -.53</td>
</tr>
<tr>
<td>$R_b$</td>
<td>$0.21646 \pm 0.00065$ 1.06</td>
</tr>
<tr>
<td>$R_c$</td>
<td>$0.1719 \pm 0.0031$ -.11</td>
</tr>
<tr>
<td>$A_{\text{fb}}^{0,b}$</td>
<td>$0.0994 \pm 0.0017$ -2.64</td>
</tr>
<tr>
<td>$A_{\text{fb}}^{0,c}$</td>
<td>$0.0707 \pm 0.0034$ -1.05</td>
</tr>
<tr>
<td>$A_b$</td>
<td>$0.922 \pm 0.020$ -.64</td>
</tr>
<tr>
<td>$A_c$</td>
<td>$0.670 \pm 0.026$ .06</td>
</tr>
<tr>
<td>$A_l(SLD)$</td>
<td>$0.1513 \pm 0.0021$ 1.50</td>
</tr>
<tr>
<td>$\sin^2 \theta_W^{\text{eff}}(Q_{fb})$</td>
<td>$0.2324 \pm 0.0012$ .86</td>
</tr>
<tr>
<td>$m_W$ [GeV]</td>
<td>$80.451 \pm 0.033$ 1.73</td>
</tr>
<tr>
<td>$\Gamma_W$ [GeV]</td>
<td>$2.134 \pm 0.069$ .59</td>
</tr>
<tr>
<td>$m_t$ [GeV]</td>
<td>$174.3 \pm 5.1$ -.08</td>
</tr>
<tr>
<td>$\sin^2 \theta_W(\nu_N)$</td>
<td>$0.2277 \pm 0.0016$ 3.00</td>
</tr>
<tr>
<td>$Q_W(Cs)$</td>
<td>$-72.39 \pm 0.59$ .84</td>
</tr>
</tbody>
</table>

(Courtesy M. Grunewald, LEPEWWG)

Without NuTeV: $\chi^2$/dof = 19.6/14, probability of 14.3%

With NuTeV: $\chi^2$/dof = 28.8/15, probability of 1.7%

Upper $m_{\text{Higgs}}$ limit weakens slightly
Quark Couplings: \((g_{L}^{\text{eff}})^2\) and \((g_{R}^{\text{eff}})^2\)

\[
R_{\nu} = g_{L}^2 + g_{R}^2 r \\
R_{\bar{\nu}} = g_{L}^2 + \frac{g_{R}^2}{r}
\]

\(R_{\nu} \equiv u_{L}^2 + d_{L}^2\) \(g_{R}^2 \equiv u_{R}^2 + d_{R}^2\)

NuTeV measures:

\[(g_{L}^{\text{eff}})^2 = 0.3001 \pm 0.0014\]
\[(g_{R}^{\text{eff}})^2 = 0.0308 \pm 0.0011\]

• Assuming predicted \(\nu\) coupling, \((g_{L}^{\text{eff}})^2\) appears low
The Higgs Mass

Honest, Mom, it was broke when I got here!...

- $A_{FB}$ already a problem:
  
The set of measurements that are consistent with the global fit are inconsistent with the search limit while the measurements that are essential for consistency with the search limit are inconsistent with the global fit.
  —Chanowitz, hep-ph/0104024 v5

- $A_{FB}$ mostly responsible for Hadronic $m_H$ Dependence

- Chanowitz Lose-Lose theorem:
  
  Removing $A_{FB}$ data that drives high $\chi^2$ would drive Higgs mass further into LEP 2 excluded region
Standard Model Explanations

§1. Isospin Violation (1★) (reasonable, but no clear model)

§2. Strange Sea Asymmetry (0★)
   - Davidson et al., hep-ph/0112302 v4
   - Reasonable a priori, but ruled out within our data
   - See Next Talk

§3. Neutrino Oscillations (−2★)
   - $\nu_e \rightarrow \nu_S$ (Giunti et al., hep-ph/0202152)
   - Ruled Out By Direct Measurement of $\nu_e$ Flux
     (which is in our talks and paper...)

Unnamed Theorist Mailing Preprint to xxx.lanl.gov
Isospin Violating PDFs

- Isospin symmetry may not be good for PDFs ($u^p \neq d^n$).
  - PDF fits performed under this assumption ... but $m_n \neq m_p$
  - NuTeV is sensitive since make this assumption to assign
    $u, d$ types to scatterers
  - Has been calculated in several classes of non-perturbative
    model

<table>
<thead>
<tr>
<th>Bag model</th>
<th>Meson Cloud model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta \sin^2 \theta^{(\text{on-shell})}_W = -0.0001$</td>
<td>$\delta \sin^2 \theta^{(\text{on-shell})}_W = +0.0002$</td>
</tr>
<tr>
<td>$\sim 0.0004$ shifts at high, low $x$ cancel</td>
<td></td>
</tr>
</tbody>
</table>

- NC/CC Shadowing Differences:
  Talking with Miller and Thomas but disagreement about appli-
  cability of shadowing model in hep-ex/0204007:

Comment on “A Precise Determination of Electroweak Parameters in
Neutrino-Nucleon Scattering”

- Experimentally $x, Q^2$ distribution needs to be included –
  they use same value of correction for entire range, not convoluted over actual data
- No Comment about theoretical validity
- Looking forward to working together to nail this down
- Miller now agrees effect would increase anomaly
  ... (APS Conf., Priv. Comm.) ⇒ New Paper?
Is \( x_s(x) = x\bar{s}(x) \)?

- Davidson et al. suggest
  - Asymmetry in strange sea could explain 0.0026 (1/2) of result...
  - “eliminating anomaly”
  - Quote Re-Analysis of CDHS Data, hep/ph-0004268 (Barone, Pascaud, Zomer)
  - Effect is -1.75\(\sigma\), \(s > \bar{s}\)

\[
\begin{array}{ccc}
\text{CCFR} & 951000 & 170000 \\
\text{CDHS} & 638605 & 551390 \\
E_H > 25 & 187688 & 13625 \\
\text{CCFR/CDHS} & \times 5.1 & \times 12.5 \\
\end{array}
\]
• We use our own NuTeV/CCFR Dimuon Data

\[ \nu \rightarrow W \rightarrow s, d, c, \mu^+ \]

Goncharov et al.,
Phys.Rev.D64 (2001) 112006

• Effect is \( \approx +2.0\sigma \), \( \bar{s} > s \) at high-\( x \):
  Opposite Sign, Increasing Anomaly

• We claim consistent with zero,
  but \(-1.7\sigma\) of BPZ strongly disfavored


• We are not fitting models,
  we are fitting our \textit{data}

• We are open to suggestions for strange sea models which explain effect
  \textit{without} contradicting data
• Recall most of ocean at low $x$ and requires high $E_{\text{had}}$ to make charm

§1. Poor Statistics at high $E_{\text{had}}$

§2. What About low $x$?

– Quote 1 from BPZ:

“The small-$x$ ($x < 0.1$) $\nu$ Fe and $\bar{\nu}$ Fe are excluded in our analysis.”

– Quote 2 from BPZ:

Finally, we reject the CDHSW data with $x < 0.1$. The reason for this cut is threefold: i) the systematic errors in the low-$x$ region are large [44]; ii) the nuclear corrections at small $x$ are not completely under control, as discussed in section 3.2; iii) at low-$x$ the CDHSW results disagree with the CCFR findings for the cross sections [76] and for the structure functions [3].

• We couldn’t have said it better ourselves . . .
• CCFR Energy Much Higher
  —Above Charm Threshold

• Since Determine $s$, $\bar{s}$ from $s \rightarrow c$
  enormous advantage in statistics

§1. Less Sensitive to Slow-Rescaling Form
  In Determining Shape, Level of $s$, $\bar{s}$

§2. Data Analyzed Consistently Within
  Same Structure as WMA

§3. LO, NLO etc. Not Relevant if
  Parameterization Fits Data and
  used in same kinematic range
Conclusions

- NuTeV measures $R^\nu$, $R^{\bar{\nu}}$ to precisely determine $\sin^2 \theta_W$
- NuTeV expects $0.2227 \pm 0.0003$; measures
  $\sin^2 \theta_W^{(\text{on-shell})} = 0.2277 \pm 0.0013 \text{(stat)} \pm 0.0009 \text{(syst)}$
- Given inconsistency with Standard Model, we also present result in model-independent framework
  - Data prefers lower effective left-handed coupling
- Neutral-current couplings of neutrinos may be suspect
  - NuTeV result consistent with earlier $\nu N$ measurements
  - Only other precise measurement, LEP Invisible $Z$ Width, also suggests a discrepancy

Pending confirmation, refutation, or alternative explanations, it’s a puzzle.
## Summary of Corrections to $R_{\text{exp}}$

### Corrections Applied to Data

<table>
<thead>
<tr>
<th>Effect</th>
<th>$\delta R_{\text{exp}}^{\nu}$</th>
<th>$\delta R_{\text{exp}}^{\bar{\nu}}$</th>
<th>Coping Techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmic Ray Background</td>
<td>-0.0036</td>
<td>-0.019</td>
<td>†</td>
</tr>
<tr>
<td>Beam $\mu$ Background</td>
<td>+0.0008</td>
<td>+0.0012</td>
<td>†</td>
</tr>
<tr>
<td>Vertex Efficiency</td>
<td>+0.0008</td>
<td>+0.0010</td>
<td>†</td>
</tr>
</tbody>
</table>

### Effects in Monte Carlo that relate $R^{(-)}_{\nu}$ to $R^{(-)}_{\text{exp}}$

<table>
<thead>
<tr>
<th>Effect</th>
<th>$\delta R_{\text{exp}}^{\nu}$</th>
<th>$\delta R_{\text{exp}}^{\bar{\nu}}$</th>
<th>Coping Techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short CC Background</td>
<td>-0.068</td>
<td>-0.026</td>
<td>†, √</td>
</tr>
<tr>
<td>Electron Neutrinos</td>
<td>-0.021</td>
<td>-0.024</td>
<td>″, √</td>
</tr>
<tr>
<td>Long NC</td>
<td>+0.0028</td>
<td>+0.0029</td>
<td>†, √</td>
</tr>
<tr>
<td>Counter Noise</td>
<td>+0.0044</td>
<td>+0.0016</td>
<td>†</td>
</tr>
<tr>
<td>Heavy $m_c$</td>
<td>-0.0052</td>
<td>-0.0117</td>
<td>†, ♣</td>
</tr>
<tr>
<td>$R_L$</td>
<td>-0.0026</td>
<td>-0.0092</td>
<td>†, ♣</td>
</tr>
<tr>
<td>EM Radiative Correction</td>
<td>+0.0074</td>
<td>+0.0109</td>
<td></td>
</tr>
<tr>
<td>Weak Radiative Correction</td>
<td>-0.0005</td>
<td>-0.0058</td>
<td></td>
</tr>
<tr>
<td>$d/u$</td>
<td>-0.00023</td>
<td>-0.00023</td>
<td>†</td>
</tr>
<tr>
<td>Higher Twist</td>
<td>-0.00012</td>
<td>-0.00013</td>
<td>†</td>
</tr>
<tr>
<td>Charm Sea</td>
<td>-0.00005</td>
<td>+0.00004</td>
<td>″</td>
</tr>
</tbody>
</table>

Recall: $R_{\text{exp}}^{\nu}$ and $R_{\text{exp}}^{\bar{\nu}}$ measured to a precision of 0.0013 and 0.0027, respectively

Key to coping techniques

- †: Determined from data
- √: Checked with data
- ″: Independent Simulation
- ♣: $R^-$ technique
**NuTeV Neutrino Flux**

- $K_{e3}^+$ decay is very well understood
  $K^\pm$ production is constrained by $\nu_\mu$ and $\nu_\mu$ flux

- Tune the beam MC prediction to match observed $\nu_\mu$ spectrum
  (CC events in the data: $E_\nu = E_{\text{had}} + E_\mu$)

- Tune $K/\pi$ fraction and small spectral shift

- Similar Technique to E744/E770
  - Tuning procedure is robust at 0.5% level

<table>
<thead>
<tr>
<th>Beam</th>
<th>$E_\pi$</th>
<th>$E_K$</th>
<th>$K/\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$</td>
<td>-0.2%</td>
<td>-1.3%</td>
<td>+2.7%</td>
</tr>
<tr>
<td>$\bar{\nu}$</td>
<td>-0.4%</td>
<td>-0.9%</td>
<td>+2.8%</td>
</tr>
</tbody>
</table>

- Reflects small uncertainties in SSQT alignment and large production uncertainties

- Sensitive to calorimeter calibration ($\delta E_{\text{cal}} = 0.43\%$)

- $K_{e3}^{\pm}$ branching ratio (1.4%) dominates $\nu_e$ flux uncertainty!!!
**Data/MC Length Agreement**

**Neutrino Mode**

**Antineutrino Mode**
Event Kinematics

$\nu$: mean $Q^2 \sim 25\ \text{GeV}^2$

$\bar{\nu}$: mean $Q^2 \sim 15\ \text{GeV}^2$
Since the Preliminary Result...

- Statistical error reduced
  \( \delta \sin^2 \theta_W = 0.0019 \rightarrow 0.0014 \)
  - -14% from \( m_c \) constrained fit
  - -8% from change in length cut
  - -4% from added data statistics
  - -3% from added fiducial volume

- Systematic error comparable
  \( \delta \sin^2 \theta_W = 0.00010 \rightarrow 0.00009 \)

- Many improvements to the analysis:

<table>
<thead>
<tr>
<th>Change</th>
<th>( \delta R^\nu_{\text{exp}} )</th>
<th>( \delta R^\nu_{\text{exp}} )</th>
<th>( \delta \sin^2 \theta_W )</th>
</tr>
</thead>
<tbody>
<tr>
<td>new pdfs 9par ( \rightarrow ) 20par</td>
<td>+0.00001</td>
<td>+0.00112</td>
<td>-0.00044</td>
</tr>
<tr>
<td>( Q^2 &lt; 1 ) pdf evolution</td>
<td>-0.00047</td>
<td>-0.00104</td>
<td>-0.00034</td>
</tr>
<tr>
<td>( d/u )</td>
<td>+0.00023</td>
<td>+0.00023</td>
<td>+0.00028</td>
</tr>
<tr>
<td>higher twist</td>
<td>+0.00012</td>
<td>+0.00013</td>
<td>+0.00014</td>
</tr>
<tr>
<td>charm sea</td>
<td>+0.00005</td>
<td>-0.00004</td>
<td>+0.00010</td>
</tr>
<tr>
<td>correction to longexits</td>
<td>-0.00021</td>
<td>+0.00035</td>
<td>-0.00048</td>
</tr>
<tr>
<td>change in length cut</td>
<td>+0.00048</td>
<td>+0.00018</td>
<td>+0.00069</td>
</tr>
<tr>
<td>TOTAL</td>
<td>+0.00021</td>
<td>+0.00093</td>
<td>-0.00005</td>
</tr>
</tbody>
</table>

- Big shift is in \( \nu_e \) analysis, as previously noted
Low-Energy Experiments

\( \gamma - Z \) Interference

Suppressed by \( q^2 / M_Z^2 \)

- Magnitude of interference (parity-violating) relative to \( \gamma \)-exchange:
  \( \langle Q_W \rangle / \langle Q_{EM} \rangle \) (light quarks)

Neutrino Scattering

\( \sigma \approx 10^{-38} \text{ cm}^2 \)

- Magnitude of neutral current relative to charged-current gives
  \( \langle Q_Z \rangle / \langle Q_W \rangle \) (light quarks)
- Separate left and right-handed couplings (\( \nu \) and \( \bar{\nu} \))

<table>
<thead>
<tr>
<th>Momentum Transfer (GeV^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0001 1 30 10000</td>
</tr>
<tr>
<td>Atomic Parity Violation</td>
</tr>
<tr>
<td>SLAC NuTeV e-D On-shell</td>
</tr>
<tr>
<td>W and Z bosons</td>
</tr>
</tbody>
</table>
Atomic Parity Violation

Recent APV measurement (JILA/Boulder; Ce):

\[ Q_W = -72.06(28)_{\text{exp}(34)}_{\text{theory}} \Rightarrow 2.5\sigma \text{ deviation from SM} \]

Later authors have re-evaluated theory

“average” \[ Q_W = -72.5 \pm 0.8 \]
(Kozlov et al., PRL 85, 1618. Dzuba et al., PR A63, 044103.
Average: Rosner, hep-ph/0109239)

\[
\frac{Q_W^{\text{exp}} - Q_W^{\text{SM}}}{Q_W^{\text{SM}}} = 0.014 \pm 0.006 \quad \text{(or } 0.008 \pm 0.011) \\
= 5.1436(\delta u_L + \delta u_R) + 5.7729(\delta d_L + \delta d_R) - 2\delta g_A^e
\]
Counter Efficiency

• Why is this important?
Inefficiencies in response of counters can lead to a gap of 3 or more consecutive quiet counters signaling a false event end

• How do we study this?
Use sample of straight-through muons
Look for gaps in counter response

Average probability for seeing 3 consecutive counters not responding to a muon $\rightarrow 3 \times 10^{-5}$
Counter Noise

- **The importance**
  Noise in counters can artificially extend the length of an event causing a short event to become long

- **How do we study this?**
  - Large sample of neutrino events
  - Examine sections far away from interaction region

- **Two effects:**
  - Counters can fire even when a muon is not present
  - Real detector pile-up
Counter Active Area

- Measurement of counter position and effective size is important to properly simulate detector’s fiducial volume
- We are sensitive to this since muons exit outside of the detector
- Image counters with muons to map out counter response
Muons deposit about 250 MeV/counter

- NC/CC $E_{\text{had}}$ is different
- Measure in data using CC neutrino interactions far away from hadron shower

Systematic uncertainty of 2 MeV/counter (coherent)
Main energy uncertainty comes from hadron and muon energy calibrations.

- **Hadron Energy Scale**
  - Directly affects measured $E_{\text{had}}$
  - Measured to high precision with testbeam data over a wide range of energies
  - Assign a 0.43% uncertainty
What are the Funny Dips on the $E_{\text{had}}$ plot?

- They are real!

- The $E_{\text{had}}$ algorithm sums over an energy-dependent number of scintillation counters

- At the transition between numbers of counters summed, get a “jump”, because most events ($\sim 70\%$) have a muon in the final state
  
  - So each counter has a MIP of energy, or about 0.2 GeV

- We simulate this very well
Energy Scale

- **Muon Energy Scale**
  - Indirectly effects analysis through flux extraction
  - Constrained by $E_{\text{had}}$ distribution of CC events

- Agrees with testbeam
- Assign a 0.25% (0.4%) uncertainty in $\nu$ ($\bar{\nu}$) mode
### Vertex Location

- Longitudinal vertex important since simulation muons originate from vertex
  - Can systematically shift CC background prediction

\[
\begin{align*}
\nu & \rightarrow v \\
\nu & \rightarrow Z \\
\nu & \rightarrow W \\
\nu & \rightarrow \mu
\end{align*}
\]

Measure 1.0 ± 0.2 inch shift from true vertex

- Transverse vertex important, particularly muon effect since not common to CC and NC
Single $E_{\text{cal}}$ bin measurement of effect of muon on vertex in CC data
Cross Section with Outside PDFs

Solid(Default MC, BG pdfs)  Dotted(CTEQ4LO pdfs), $E=75$ GeV

CTEQ4LO pdfs (with Callan-Gross $R_L = 0$, not tuned)
$d/u$ Corrections to Cross-Section

- $d/u$ constrained by NMC $F_2 D_2/H_2$ ratio

- NUSEA $d \bar{d}/\pi$ in Drell-Yan $p+D_2/H_2$
\[ \Delta R_{\nu}^\text{exp} \sim 0.00023, \quad \Delta R_{\nu}^\text{exp} \sim 0.00023 \]

\[ \Rightarrow \Delta \sin^2 \theta_W \sim 0.00028 \]
NC Charm Production

Need to model:

\[ \nu N \rightarrow \nu c\bar{c}X \]

- Use LO model of “intrinsic” charm sea

- Heavy quark suppression uses slow rescaling 
  \textit{(as with our CC charm production model)}

- “Intrinsic charm” is chosen to match EMC \( F_2^{c\bar{c}} \)

- Assume 100\% uncertainty on size of process

- TINY! \( \Delta R_{\nu}^{\text{exp}} \sim 0.00005, \Delta R_{\bar{\nu}}^{\text{exp}} \sim 0.00004 \)
  \[ \Rightarrow \Delta \sin^2 \theta_W \sim 0.00010 \]
Higher Twist Effects in Cross-Section

- Need higher twist contributions added to LO cross-section at high $x$ and low $Q^2$
Higher Twist Effects in Cross-Section

- Fit higher twist contribution from SLAC/BCDMS $F_2$

- Assume 100% uncertainty on higher twist correction

- TINY! $\Delta R_{\exp}^{\nu} \sim 0.00012$, $\Delta R_{\exp}^{\bar{\nu}} \sim 0.00013$

  $\Rightarrow \Delta \sin^2 \theta_W \sim 0.00014$
\( Q^2 < 1 \) PDF Evolution

- At very low \( Q^2 \), our Buras-Gaemers model for PDF evolution breaks down

- Effect is evident in the lowest \( x, y \) points of \( \sigma_{CC} \) measurement

- Use GRV94LO PDF evolution to model low \( Q^2 \)
  - Vastly improved description of low \( Q^2 \) cross-section
  - New since preliminary result

- \( \Delta R_{\nu}^{\exp} \sim 0.00020, \Delta R_{\bar{\nu}}^{\exp} \sim 0.00012 \)
  \[ \Rightarrow \Delta \sin^2 \theta_W \sim 0.00027 \]
Quasi-Elastic Cross-Section

\[ \nu N \rightarrow \ell N \]

- Why do we care? These have very low \( E_{\text{had}} \)!
  - \( \nu_e \) quasi-elastics are 1.3\% of \( \nu_e \) events
- Use Serpukhov data (low energy) to check theoretical cross-section

- Total size of QE contribution: \( R_{\exp}^{\nu} \sim 0.00032, R_{\exp}^{\bar{\nu}} \sim 0.00089 \)
  \( \Rightarrow \sin^2 \theta_W \sim 0.00015 \)
- Assign a 15\% error
QED Radiative Corrections


(also smaller contributions from radiation from quarks, vertex corrections, box diagrams)
Weak Radiative Corrections

- Tree level couplings (LEPEWWG $\sin^2 \theta_W^{(on-shell)}$):
  \[ g_L^2 = 0.3049, \quad g_R^2 = 0.0276 \]

- Use ZFITTER/DIZET 6.34 (Jan 2001)

- With weak radiative corrections for $\langle q^2 \rangle \sim 20$ GeV$^2$:
  \[ g_L^2 = 0.3039, \quad g_R^2 = 0.0301 \]

- $M_{\text{top}} = 175$ GeV, $M_{\text{Higgs}} = 150$ GeV
NuTeV/CCFR Dimuon Analysis

\[ \nu N \rightarrow \mu^+ \mu^- X \quad (c \rightarrow \mu^+ X) \]

Fits of cross-section model to data as a function of \( x \) in \( E, y \) bins.

(Thesis work of Max Goncharov, Kansas State)
Neutrino Oscillations?

- CC $\nu_e$, $\nu_\tau$ events would be misidentified as NC $\nu_\mu$
- Would observe excess of short events $\Rightarrow$ larger NC rate
- Used lack of excess in CCFR to search for oscillations

**NuTeV Result and $M_{\text{top}}, M_{\text{Higgs}}$**

**NuTeV Measures**

\[
\sin^2 \theta_W^{(\text{on-shell})} = 0.2277 \pm 0.0013 \text{(stat.)} \pm 0.0009 \text{(syst.)} \\
- 0.00022 \times \left( \frac{M_{\text{top}}^2 - (175 \text{ GeV})^2}{(50 \text{ GeV})^2} \right) \\
+ 0.00032 \times \ln \left( \frac{M_{\text{Higgs}}}{150 \text{ GeV}} \right)
\]

- Therefore, the top and Higgs mass corrections to the measurement are $\ll 0.001$.

**Standard Model Predictions**

![Diagram showing the relationship between $\sin^2 \theta_W^{(\text{on-shell})}$ and $m_{\text{top}}$]
“Stability” Test $\chi^2$ Probabilities

• What is the $\chi^2$ Distribution for Changing Cuts, etc?
• Does it look too good or too bad?

No obvious indication of a problem
Stability of $R_{\text{exp}}$ (out to bin 5)

$R$ as a function of “radial” bin:

\[ \chi^2/\text{dof} = 7.58831/4 \text{ (Prob 0.1079), slope significance is } -0.78\sigma \]

\[ \chi^2/\text{dof} = 1.67222/4 \text{ (Prob 0.7958), slope significance is } 0.54\sigma \]
Was the Analysis Blind?

Sort of.

- We had a preliminary result, based on $R^-$, that included 80% of the data in this analysis.

- After the preliminary result, we rewrote significant parts of the simulation relating $R^{(-)}_{\nu} \exp$ to $R^{(-)}_{\nu}$
  - At this time, we “hid” the true $\sin^2 \theta_W^{(\text{on-shell})}$ from ourselves in the Monte Carlo.
  - We “revealed” the result after making all analysis choices.

- Nevertheless, we knew preliminary result had a larger $\sin^2 \theta_W^{(\text{on-shell})}$ than the standard model prediction.
Background Subtraction from Data

**Cosmic Rays**
- Short ⇒ NC candidates
- Beam-off gate

**Hard μ Bremsstrahlung**
- Long ⇒ CC candidates
- Identify and subtract

Size of correction:

- Cosmic Ray Correction:
  - Hadron Energy (GeV)
  - 0.9% of Short $\nu$ Events
  - 4.7% of Short $\bar{\nu}$ Events

- Muon Brem Correction:
  - Hadron Energy (GeV)
  - 0.2% of Long $\nu$ Events
  - 0.3% of Long $\bar{\nu}$ Events
Vertex Inefficiencies From Data

Longitudinal Vertex Inefficiency
- Effect for low energy events
- Corrected using sbit quantities to tell us location and length of event

Transverse Vertex Inefficiency
- Event “lost” if missing hits in first 3 drift chambers
- Correct using PMT vertex
Size of correction:

<table>
<thead>
<tr>
<th>Hadron Energy (GeV)</th>
<th>Fraction of short events</th>
<th>Longitudinal Vertex Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.006% of Short $\nu$ Events</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.042% of Short $\bar{\nu}$ Events</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hadron Energy (GeV)</th>
<th>Fraction of all events</th>
<th>Transverse Vertex Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.44% (0.26%) of Short (Long) $\nu$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.58% (0.37%) of Short (Long) $\bar{\nu}$</td>
</tr>
</tbody>
</table>
High Energy Flux

CC Muon–Antineutrino Flux Spectrum

Data/MC Ratio

$E_\nu$ (GeV)
High energy $\nu_\mu$ (and $\bar{\nu}_\mu$) show an excess in data

- From high $p$, high $p_t$ $K^{\pm}$ in beam

- These $K^{\pm}$ produce highest energy $\nu_e$'s

\[ E_{\nu} \]
Direct $\nu_e$ Measurement ($\eta$)

- $\nu_e$ showers develop more quickly than $\nu_\mu$ showers because of electron
- Fit to hadron shower from $\nu_\mu$ events and electrons from Monte Carlo tuned on calibration beam
- Constrains (mostly) $K_{e3}^\pm$ at moderate energy ($80 < E_\nu < 180$ GeV)
- $N_{\text{meas}}/N_{\text{pred}}$: $1.05 \pm 0.03$ ($\nu_e$), $1.01 \pm 0.04$ ($\bar{\nu}_e$)
### SM Fit with \((g_L^{\text{eff}})^2\) and \((g_R^{\text{eff}})^2\)

**Fall 2001**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Pull</th>
<th>((O_{\text{meas}} - O_{\text{fit}})/\sigma_{\text{meas}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\varphi_{\text{had}}(m_2))</td>
<td>(0.02761 \pm 0.00036)</td>
<td>-2.9</td>
</tr>
<tr>
<td>(m_Z) [GeV]</td>
<td>(91.1875 \pm 0.0021)</td>
<td>.01</td>
</tr>
<tr>
<td>(\Gamma_Z) [GeV]</td>
<td>(2.4952 \pm 0.0023)</td>
<td>-.44</td>
</tr>
<tr>
<td>(\sigma_{\text{had}}) [nb]</td>
<td>(41.540 \pm 0.037)</td>
<td>1.64</td>
</tr>
<tr>
<td>(R_L)</td>
<td>(20.767 \pm 0.025)</td>
<td>1.05</td>
</tr>
<tr>
<td>(A_{f_b}^{0,I})</td>
<td>(0.01714 \pm 0.00095)</td>
<td>.74</td>
</tr>
<tr>
<td>(A_{f_b}(P_t))</td>
<td>(0.1465 \pm 0.0033)</td>
<td>-.47</td>
</tr>
<tr>
<td>(R_b)</td>
<td>(0.21646 \pm 0.00065)</td>
<td>1.08</td>
</tr>
<tr>
<td>(R_c)</td>
<td>(0.1719 \pm 0.0031)</td>
<td>-.12</td>
</tr>
<tr>
<td>(A_{f_b}^{0,b})</td>
<td>(0.0990 \pm 0.0017)</td>
<td>-2.81</td>
</tr>
<tr>
<td>(A_{f_b}^{0,c})</td>
<td>(0.0685 \pm 0.0034)</td>
<td>-1.68</td>
</tr>
<tr>
<td>(A_b)</td>
<td>(0.922 \pm 0.020)</td>
<td>-.64</td>
</tr>
<tr>
<td>(A_c)</td>
<td>(0.670 \pm 0.026)</td>
<td>.06</td>
</tr>
<tr>
<td>(A_{f_b}(\text{SLD}))</td>
<td>(0.1513 \pm 0.0021)</td>
<td>1.58</td>
</tr>
<tr>
<td>(\sin^2 \theta_{\text{eff}}(Q_{f_b}))</td>
<td>(0.2324 \pm 0.0012)</td>
<td>.84</td>
</tr>
<tr>
<td>(m_{W}^{(\text{LEP})}) [GeV]</td>
<td>(80.450 \pm 0.039)</td>
<td>1.47</td>
</tr>
<tr>
<td>(m_{W}^{(\text{TEV})}) [GeV]</td>
<td>(80.454 \pm 0.060)</td>
<td>1.02</td>
</tr>
<tr>
<td>(g_2^2(\nu N))</td>
<td>(0.3005 \pm 0.0014)</td>
<td>-.26</td>
</tr>
<tr>
<td>(g_\rho^2(\nu N))</td>
<td>(0.0310 \pm 0.0011)</td>
<td>.82</td>
</tr>
<tr>
<td>(Q_W(Cs))</td>
<td>(-72.50 \pm 0.70)</td>
<td>.56</td>
</tr>
</tbody>
</table>

(Courtesy M. Grunewald, LEPEWWG)

Without NuTeV: \(\chi^2/\text{dof} = 21.5/14\), probability of 9.0%

With NuTeV: \(\chi^2/\text{dof} = 29.1/16\), probability of 2.3%

Upper \(m_{\text{Higgs}}\) limit weakens slightly
Running of $\sin^2 \theta_W$

(Jens Erler and Paul Langacker)

- E158, $Q_{\text{weak}}$ (JLab) numbers are projected uncertainties
- “old” APV is Bennett and Wieman with corrections
- “new” APV is Bennett and Wieman, with “new” corrections
S-T Plane


- S and T parameterize oblique radiative corrections (sensitive to all forms of new physics)
- T parameter contains $\delta \rho$ effects
- S parameter modifies relationship between masses and couplings
- Note lack of overlap between direct $M_W$ and NuTeV
- Vary $R_L = F_L/F_T$ within data errors at low $x$
- At high $x$, where theoretical prediction of $R_L$ is reliable, take NNLO-NLO difference as systematic
- Important for prediction of high $y$ cross-section
Direct High Energy $\nu_e$ Flux

- Extremely short events at very high visible energy are very likely to be nearly-elastic electron neutrino charged-current interactions
- Observe significant excess in both beams over MC prediction

Length fit, Antineutrino Mode, $E_{\text{had}}>180$ GeV

(before fit) Data/MC ratio vs. $L$ (counters)

(after fit) Data/MC ratio vs. $L$ (counters)
$E_\nu > 180 \text{ GeV}$ is tail of flux
Sather Nucleon Isospin Breaking Model

- Estimate of diquark mass difference in MIT bag model
- Calculated at $Q^2 = 0$ and evolved to experimental $Q^2$

$$u^p_v - d^n_v = \delta u_v \quad d^p_v - u^n_v = \delta d_v$$

$$\int x\delta d_v dx = 0.0023$$
$$\int x\delta u_v dx = -0.0011$$

- To shift the NuTeV $\sin^2 \theta_W$ to agree with prediction would an effect $\approx 2.5 \times$ larger than Sather’s
Isospin breaking occurs in proton, nucleon and nuclear PDFs

1. In proton PDFs

\[ u_v^p \neq d_v^p \quad \left( F_2^d / F_2^p \right) \]
\[ \bar{u}^p \neq \bar{d}^p \quad \text{(NUSEA Drell – Yan)} \]

*These enter in $R^-$ when target is not $n \leftrightarrow p$ isoscalar*

(NuTeV, 5.67% $n$ excess)

2. In nucleon or nuclear PDFs

\[ u_v^p \neq d_v^n, \quad d_v^p \neq u_v^n \]
\[ \bar{u}^p \neq \bar{d}^n, \quad \bar{u}^n \neq \bar{d}^p \]

i.e., move $d$ quarks to higher $x$ and $u$ quarks to lower $x$ or vice versa

*These enter in $R^-$ event for $Z = N$ target*

($m_d \neq m_u$ in nucleon, Coulomb in nucleus both thought to be small)
Write

\[ \Delta N = \frac{A - 2Z}{A} \]

\[ \delta D_v = \frac{\int x(d_v^p - u_v^n)dx}{\int x(u_v^p + d_v^p)dx} \] (analogous \( \delta U_v \))

\[ \delta D = \frac{\int x(\overline{d}^p - \overline{u}^n)dx}{\int x(\overline{u}^p + \overline{d}^p)dx} \] (analogous \( \delta \overline{U} \))

Then, for \( s, c = 0 \),

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

\[ + \left[ \frac{\int x(u_v^p - d_v^p)dx}{\int x(u_v^p + d_v^p)dx} \right] \left( \frac{7}{3} \sin^2 \theta_W - 1 \right) \Delta N \]

\[ + \left( \frac{1}{2} - \frac{7}{6} \sin^2 \theta_W \right) (\delta U_v - \delta D_v). \]

No dependence on \( \delta \overline{U}, \delta \overline{D}, \frac{\int x(\overline{u}^p - \overline{d}^p)dx}{\int x(\overline{u}^p + \overline{d}^p)dx} \).

At NuTeV \( \langle Q^2 \rangle \),

\[ \int x(u_v^p + d_v^p) = .333; \quad \int x(\overline{u}^p + \overline{d}^p) = .063 \]
NuTeV’s $\sin^2 \theta_W$ measurement isn’t exactly sensitive to

$$0.72 \times (\delta d_v - \delta u_v) = \int x \left[ (d_v^p - u_v^n) - (u_v^p - d_v^m) \right] dx$$

$$d\sin^2 \theta_W / d\delta q$$
Thomas et al. Nucleon Isospin Breaking Calculation

- Effect of $d$-$u$ mass difference evaluated in MIT bag model
- Full calculation includes: nucleon mass difference, nucleon radius difference, quark and diquark mass difference

\[
\int x(d_v^p - u_v^n)dx = 0.0006
\]
Comparison of Isospin Breaking Models

- MIT Bag Model:
  Sather estimate and Thomas et al. full calculation

- Meson cloud model