Departure From Prediction: Electroweak Physics at NuTeV

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Outline

1. The NuTeV Experiment
2. Key Elements of the Analysis
3. NuTeV’s Surprising Results
4. Interpretation and Conclusions
The Role of NuTeV

Neutrino scattering played a key historical role in electroweak unification

- **Discovery** of Neutral Current (Gargamelle, FNAL-E1A)
- First determination of high-energy parameter
  \[ \sin^2 \theta_W \sim 0.2 \Rightarrow \frac{M_W}{M_Z} \sim 0.9 \]

...but why continue to study when we make copious on-shell \( W \) and \( Z \) bosons at colliders?

- Testing in a wide range of processes and momentum scales ensures universality of the electroweak theory

<table>
<thead>
<tr>
<th>Momentum Transfer (GeV^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0001</td>
</tr>
<tr>
<td>Atomic</td>
</tr>
<tr>
<td>Parity</td>
</tr>
<tr>
<td>Violation</td>
</tr>
</tbody>
</table>

- NuTeV is sensitive to different processes
  - Measurement is off the \( Z \) pole (contributions besides \( Z \)?)
  - Measure neutral current neutrino couplings
    - LEP I invisible line width is only other precise measurement
**Methodology**

\[ \nu \quad \mu \]
\[ \text{W} \]
\[ q \quad q \]

Coupling \( \propto I^{(3)}_{\text{weak}} \)

\[ \nu \quad \nu \]
\[ Z \]
\[ q \quad q \]

Coupling \( \propto \left( I^{(3)}_{\text{weak}} - Q_{em} \sin^2 \theta_W \right) \)

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

**Llewellyn Smith Relation:**

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

- \( R^\nu, R^{\bar{\nu}} \) easy to measure experimentally
- To extract \( \sin^2 \theta_W \) from the measured ratio:
  - isovector target (\( 2Z \neq A \))
  - heavy quark seas (and kinematic suppression)
  - radiative corrections, higher twist, \( R_L \)
- Most of the PDF dependence, many of systematic uncertainties, and sensitivity to neutrino spectrum cancels in the ratio
Heavy Quark Effects

- Suppression of CC cross section for interactions with massive charm quark in final state
- Modeled by leading-order slow-rescaling \( x \rightarrow \xi = \frac{Q^2 + m_c^2}{2M_\nu} \)
- Parameters measured by NuTeV/CCFR in dimuon events \( c \rightarrow \mu X \)
- Limited precision of previous \( \nu N \) measurements of \( \sin^2 \theta_W \) ...

![Graph showing the world average \( \sin^2 \theta_W \) with error bars and a shaded band representing the correction for the mass of the charm quark.]

World Average \( \sin^2 \theta_W \)

\[ 0.2277 \pm 0.0024 \text{(exp)} \pm 0.0027 \text{(th)} \]

\( \chi^2/\text{DOF} = 4.79/4 \)

Corrected for \( m_c = 1.38 \pm 0.14 \text{GeV} \)

Shaded band shows \( \pm \delta m_c \)

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

\( M_W = 80.14 \pm 0.19 \text{GeV} \)
NuTeV’s Approach

Large charm production errors ⇒ need technique insensitive to sea quarks

**Paschos-Wolfenstein Relation:**

\[
R^- = \frac{\sigma^\nu_{NC} - \sigma^\nu_{NC}}{\sigma^{\nu CC} - \sigma^{\nu CC}} = \frac{R^\nu - r R^\nu}{1 - r} = \rho^2 \left( \frac{1}{2} - \sin^2 \theta_W \right)
\]

- \( R^- \) is manifestly insensitive to sea quarks
  - Charm and strange sea errors are negligible ...
    (Most of charm from \( s(x) \) scattering)
  - Massive charm production enters from \( d_V \) quarks only ...
    (Cabbibo suppressed and at high \( x \))
- Requires separate \( \nu, \bar{\nu} \) beams
  ⇒

NuTeV SSQT
Neutral Current/Charged Current Event Separation

Separate by simple length cut

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

in \( \nu \) and \( \bar{\nu} \) beams (1.62 and 0.35 million events)
Summary of Corrections to $R_{\nu}$

Corrections Applied to Data

<table>
<thead>
<tr>
<th>Effect</th>
<th>$\delta R_{\nu_{\text{exp}}}$</th>
<th>$\delta R_{\bar{\nu}_{\text{exp}}}$</th>
<th>Control</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 $R_{\bar{\nu}}$

<table>
<thead>
<tr>
<th>Effect</th>
<th>$\delta R_{\nu_{\text{exp}}}$</th>
<th>$\delta R_{\bar{\nu}_{\text{exp}}}$</th>
<th>Control</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>
</tbody>
</table>

Recall: $R_{\nu_{\text{exp}}}$ and $R_{\bar{\nu}_{\text{exp}}}$ 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
**\( \nu_{\mu} \) Charged-Current Background**

- High \( y \) charged-current is background to NC sample
- \((\bar{\nu}) \) NC & CC quark model cross-section
  \[ R_L \text{ term added to } F_2, x F_3 \]
  to describe \( g \rightarrow q\bar{q} \)
- PDFs extracted from CCFR \( \sigma_{CC} \)
- Other data determines \( s(x), d/u, R_L, \) higher twist, \( F_2^{\rho} \)
- Data-driven: uncertainties come from measurements

### Relative Calibration Fit, pass25, long exit (311) events, R 0 - 40, all—nucorr-fi

- Neutrino
- Antineutrino

### n-had bins in data, both nu and nubar

\[ \chi/dof = 24.1/23 \]
\[ \chi/dof = 27.2/25 \]

- Check by looking at “long exit” CC events which start in the detector center and stop before toroid
Electron Neutrinos

Approximately 5% of all short events are $\nu_e$ CC.

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

NuTeV Neutrino Flux Prediction

- Excess of $\nu_e$ over $\bar{\nu}_e$ in $\nu$ beam is due to $K^{+}_{e3}$ decay
  ⇔ Vast majority of $\nu_e/\bar{\nu}_e$ in $\nu/\bar{\nu}$ beams
  ⇔ $K_L$ and charm decay, which make both $\nu_e$ and $\bar{\nu}_e$, are small

- $K^{\pm}_{e3}$ decay is very well understood
  ⇔ $K^\pm$ production...is constrained by $\nu_\mu$ and $\bar{\nu}_\mu$ flux
  ⇔ Use predicted flux (few % shifts from production data),
      except high energy tail ($E_\nu > 180$ GeV direct measurement)

- Have (less precise) direct measurements of $\nu_e$ and $\bar{\nu}_e$
  ⇔ $N_{meas}/N_{pred}$: $1.05 \pm 0.03$ ($\nu_e$), $1.01 \pm 0.04$ ($\bar{\nu}_e$) ($80 < E_\nu < 180$ GeV)
Stability of $R_{\text{exp}}$ (cont’d)

- $R$ vs. length cut: Checks NC ↔ CC separation
  “16,17,18” $L_{\text{cut}}$ is default: tighten ↔ loosen selection

  ![Graph showing $\chi^2$/dof for $\nu$ and $\bar{\nu}$ modes]

  $\chi^2$/dof = 4.47015/3, Prob = 0.2150
  $\chi^2$/dof = 0.27844/3, Prob = 0.9640

- $R$ vs. “radial bin”: Checks electron neutrino and short CC events
  More NC background near edge

  ![Graph showing $R$ vs. radial bin for data and neutrino mode]

  $\chi^2$/dof = 4.01552/3 (Prob 0.2598), slope significance is 0.23σ
  $\chi^2$/dof = 1.18213/3 (Prob 0.7573), slope significance is 1.89σ

  NuTeV Target, 60"x60"

  "Radial" Bins
Stability of $R_{exp}$ (cont’d)

$R_{exp}$ vs. $E_{had}$: Checks stability of final measurement over full kinematic range
Checks almost everything - backgrounds, flux, detector modeling, cross section model, ...

(Green band is $\pm 1\sigma$ systematic uncertainty)
The Result

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

- In good agreement with previous $\nu N$: $\sin^2 \theta_W = 0.2277 \pm 0.0036$
- Standard Model fit (LEPEWWG): $0.2227 \pm 0.00037$

<table>
<thead>
<tr>
<th>SOURCE OF UNCERTAINTY</th>
<th>$\delta \sin^2 \theta_W$</th>
<th>$\delta R_{\text{exp}}^e$</th>
<th>$\delta R_{\text{exp}}^\mu$</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>
</tr>
<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>
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<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>$\sigma^r/\sigma^\mu$</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>
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<tr>
<td>Non-Isoscalar Target</td>
<td>0.00005</td>
<td>0.00004</td>
<td>0.00004</td>
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<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>

In the end, why is NuTeV so much more precise than CCFR?

- $R^-$ method makes charm production error small
- Few $K_L$ because of beam $\Rightarrow \nu_e$ greatly reduced
Given the precise measurement of the Z mass from LEP...

...can express NuTeV $\sin^2 \theta_W$ as an equivalent $M_W$

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

80.433 +/- 0.079
80.483 +/- 0.084
80.471 +/- 0.049
80.401 +/- 0.066
80.398 +/- 0.069
80.490 +/- 0.065
80.451 +/- 0.033
80.376 +/- 0.023
80.136 +/- 0.084

CDF
D0
ALEPH*
DELPHI*
L3*
OPAL*
Direct World Average
Indirect World Average (LEP1/SLD/APV/m_t)
(LEPEWWG)

NuTeV

* : Preliminary

- In standard electroweak theory, NuTeV precision is comparable to a single direct measurement of $M_W$
- More inconsistent with direct $M_W$ than other data
How Healthy is the EW Fit?

Winter 2002

<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>(\Delta\alpha_{\text{had}}(m_Z))</td>
<td>0.02761 ± 0.00036</td>
<td>-27</td>
</tr>
<tr>
<td>(m_Z [\text{GeV}])</td>
<td>91.1875 ± 0.0021</td>
<td>.01</td>
</tr>
<tr>
<td>(\Gamma_Z [\text{GeV}])</td>
<td>2.4952 ± 0.0023</td>
<td>-.42</td>
</tr>
<tr>
<td>(\sigma_{\text{had}} [\text{nb}])</td>
<td>41.540 ± 0.037</td>
<td>1.63</td>
</tr>
<tr>
<td>(R_b)</td>
<td>20.767 ± 0.025</td>
<td>1.05</td>
</tr>
<tr>
<td>(A_{\text{fb}})</td>
<td>0.01714 ± 0.00095</td>
<td>.70</td>
</tr>
<tr>
<td>(A_{\text{fb}}(P_{\tau}))</td>
<td>0.1465 ± 0.0033</td>
<td>-.64</td>
</tr>
<tr>
<td>(R_l)</td>
<td>0.21646 ± 0.00065</td>
<td>1.06</td>
</tr>
<tr>
<td>(R_c)</td>
<td>0.1719 ± 0.0031</td>
<td>-.11</td>
</tr>
<tr>
<td>(A_{\text{fb}}(0,b))</td>
<td>0.0994 ± 0.0017</td>
<td>-2.64</td>
</tr>
<tr>
<td>(A_{\text{fb}}(0,c))</td>
<td>0.0707 ± 0.0034</td>
<td>-1.05</td>
</tr>
<tr>
<td>(A_b)</td>
<td>0.922 ± 0.020</td>
<td>-.64</td>
</tr>
<tr>
<td>(A_c)</td>
<td>0.670 ± 0.026</td>
<td>.06</td>
</tr>
<tr>
<td>(A_{\text{fb}}(SLD))</td>
<td>0.1513 ± 0.0021</td>
<td>1.50</td>
</tr>
<tr>
<td>(\sin^2\theta_{\text{eff}}(Q_{\text{fb}}))</td>
<td>0.2324 ± 0.0012</td>
<td>.86</td>
</tr>
<tr>
<td>(m_W [\text{GeV}])</td>
<td>80.451 ± 0.033</td>
<td>1.73</td>
</tr>
<tr>
<td>(\Gamma_W [\text{GeV}])</td>
<td>2.134 ± 0.069</td>
<td>.59</td>
</tr>
<tr>
<td>(m_h [\text{GeV}])</td>
<td>174.3 ± 5.1</td>
<td>-.08</td>
</tr>
<tr>
<td>(\sin^2\theta_W(\nu N))</td>
<td>0.2277 ± 0.0016</td>
<td>3.00</td>
</tr>
<tr>
<td>(Q_W(\text{Cs}))</td>
<td>-72.39 ± 0.59</td>
<td>.84</td>
</tr>
</tbody>
</table>

- Global fit has a \(\chi^2\) of \(\chi^2/\text{d.o.f.} = 19.6/14\) (probability of 14%)
- Two most precise measurements of \(\sin^2\theta_W\) at Z pole differ by 3\(\sigma\)
- Data suggest light Higgs except \(A_{FB}\)
- \(\sigma_{\text{had}}\) also off by \(\sim 2\sigma\)
- Adding NuTeV:
  \(\chi^2/\text{d.o.f.} = 28.8/15\) (probability of 1.7%)
**Quark Couplings: \((g_L^{\text{eff}})^2\) and \((g_R^{\text{eff}})^2\)**

68%,90%,95%,99% C.L. Contours, Grid of SM ±1σ m_{top}, m_{Higgs}

2 parameter fit to \(R^\nu, R^{\overline{\nu}}\):

\[ R^\nu = g_L^2 + r g_R^2 \]
\[ R^{\overline{\nu}} = g_L^2 + \frac{1}{r} g_R^2 \]

\[ g_L^2 \equiv u_L^2 + d_L^2 \]
\[ g_R^2 \equiv u_R^2 + d_R^2 \]

**NuTeV measures:**

\[ (g_L^{\text{eff}})^2 = 0.3005 \pm 0.0014 \]
\[ (g_R^{\text{eff}})^2 = 0.0310 \pm 0.0011 \]
\[ \rho_{corr} = -0.02 \]

- Assuming predicted \(\nu\) coupling, \((g_L^{\text{eff}})^2\) appears low
Interpretations

- Symmetry violating PDFs
- Extra $Z$ bosons
- Neutral current coupling of $\nu$

$q \rightarrow Z \rightarrow q$

$\nu \rightarrow (\nu N) \sin^2 \theta_{\nu}$
Symmetry Violating Parton Distributions

Paschos-Wolfenstein, \( R^- = \frac{1}{2} - \sin^2 \theta_W \)

- Assumes total \( u \) and \( d \) momenta are equal in target
- Assumes momentum symmetry in sea, \( s = \bar{s} \) and \( c = \bar{c} \)

Violations of these symmetries can arise from

1. \( A \neq 2Z \), different numbers of neutrons and protons
2. Isospin violating PDFs, e.g., \( u_p(x) \neq d_n(x) \)
3. Asymmetric heavy seas, e.g., \( s(x) \neq \bar{s}(x) \)

\[
R^- \approx \frac{1}{2} - \sin^2 \theta_W + \left[ \frac{U_p - D_p}{U_p + D_p} \right] \left( 1 - \frac{8}{3} \sin^2 \theta_W \right) \Delta N + \left( 1 - \frac{8}{3} \sin^2 \theta_W \right) \left( \frac{\delta U_v - \delta D_v}{2V_p} \right) + \left( \frac{1}{2} - \frac{8}{3} \sin^2 \theta_W \right) \left( \frac{3}{2} - 3 \sin^2 \theta_W \right) \epsilon_c \left( \frac{\delta S}{V_p} \right)
\]

where

\[
\begin{align*}
\delta D_v &\equiv D_p - \bar{D}_p - U_n + \bar{U}_n \\
\delta U_v &\equiv U_p - \bar{U}_p - D_n + \bar{D}_n \\
\delta S &\equiv S - \bar{S} \\
\delta N &\equiv A - 2Z/A \\
V_p &\equiv U_p - \bar{U}_p + D_p - \bar{D}_p,
\end{align*}
\]

\( Q_N \) is the total momentum carried by quark \( Q \) in nucleon \( N \),
and \( \epsilon_c \equiv \frac{\sigma(\nu s \to \mu c)}{\sigma(\nu s \to \mu c, m_c = 0)} \)

The NuTeV analysis only corrects for \( \delta N \)
**Symmetry Violating PDFs (cont’d)**

### Isospin symmetry violations
- All PDF fits performed assuming symmetry, but $m_n \neq m_p$

#### Bag model
*Thomas et al., Mod. Phys. Lett**A**9, 1799.*

- $\delta \sin^2 \theta_W^{(on-shell)} = -0.0001$
- $\sim 0.0004$ shifts at high, low $x$ cancel

#### Meson Cloud model
*Cao & Signal, Phys. Rev. **C**62, 015203.*

- $\delta \sin^2 \theta_W^{(on-shell)} = +0.0002$

- Are models trustworthy? Can global fits accommodate large isospin violation to explain NuTeV?

---

**Strange-Antistrange Sea Asymmetry**
- If $S - \bar{S} \sim +0.0020$, $\Longrightarrow \delta \sin^2 \theta_W = -0.0026$ ($\epsilon_c = 1$)
  
  (S. Davidson *et al.*, hep-ph/0112302)

- But NuTeV dimuon data measures $S, \bar{S}$ separately

\[
S - \bar{S} = -0.0027 \pm 0.0013 \\
\Longrightarrow \delta \sin^2 \theta_W \sim +0.0020 \pm 0.0009
\]

Then $\sin^2 \theta_W = 0.2297 \pm 0.0019$ (3.7$\sigma$ above SM)
New Tree Level Physics?

- $E(6)$ $Z'$ accounts for NuTeV?
  - Contact terms shift LR coupling
  - Mixing (here $3 \times 10^{-3}$) to $Z$ severely limited by LEP/SLD

$$Z' \equiv Z_{\chi}\cos\beta + Z_{\psi}\sin\beta$$

Langacker et al., Rev. Mod. Phys. 64 87.)

- Erler and Langacker:
  In global context, $\Delta \chi^2 \approx 7.5$
  $m_{Z'} = 600$ GeV, mixing $\sim 10^{-3}$, $\beta \approx 1.2$

- "Almost sequential" $Z'$ with opposite coupling to $\nu$
  - NuTeV preferred mass range: $1.2^{+0.3}_{-0.2}$ TeV
  - CDF/D0 limits: $M_{Z'_{SM}} \gtrsim 700$ GeV. LEP II?

- Contact interaction with LL coupling
  - $\nu\nuqq$ Contact term, $\Lambda_{LL} = 4.5 \pm 1$ TeV

$$-\mathcal{L} = \sum_{H \in \{ L,R \}} \frac{\pm 4\pi}{(\Lambda_{LL})^2} \times \left\{ l_L \gamma^\mu l_{L\bar{q}H\bar{q}} \gamma_\mu q_{H\bar{q}} + l_L \gamma^\mu l_{L\bar{q}H\bar{q}} \gamma_\mu q_{H\bar{q}} + C.C. \right\}$$

(Langacker et al., Rev. Mod. Phys. 64 87.)
Neutral Current $\nu$ Interactions

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

- $\nu_\mu e^- \rightarrow \nu_\mu e^-$ scattering (CHARM II et al.)
  \[ \Rightarrow \text{PDG fit: } g_V^2 + g_A^2 = 0.259 \pm 0.014, \text{ cf. } 0.258 \text{ predicted} \]

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

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

1.00 +/- 0.05 \quad \text{CHARM II et al.}

1.00 +/- 0.02 \quad \text{LEP I Direct}

0.995 +/- 0.003 \quad \text{LEP I Lineshape}

0.988 +/- 0.004 \quad \text{NuTeV}

- Neutrino NC Rate/Prediction

0.96 \quad 0.98 \quad 1.00 \quad 1.02

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

\[ \Rightarrow \text{NB: This is not a unique or model-independent interpretation!} \]
Conclusions

Surprise!

- NuTeV measurement has the precision to be an important test of the electroweak SM
- NuTeV measures $R^\nu, R^\tau$ to precisely determine $\sin^2 \theta_W$
- The SM predicts $0.2227 \pm 0.0003$, but we measure:

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

- NuTeV result consistent with earlier $\nu N$ measurements
- In comparison to the Standard Model:
  - NuTeV data prefers lower effective left-handed coupling
  - Neutral-current couplings of neutrinos may be suspect
  - Only other precise measurement, LEP Invisible $Z$ Width, also suggests a discrepancy
- Pending confirmation, refutation, or alternative explanations, it’s a puzzle.