A Totally Different Angle on Neutrinos:

*The Weak Mixing Angle*

\[ \sin^2 \theta_W \]

- Fundamental parameter describing the $\gamma/Z$ mixing
- Precision measurements are sensitive to New Physics

“The NuTeV Anomaly”

Mike Shaevitz
Columbia University
Three standard deviation from the Standard Model prediction at low $Q^2$ (off the Z pole)

• Introduction to Electroweak Measurements
• NuTeV Experiment and Technique
• Explanation of the NuTeV Anomaly (Old Physics? and/or New Physics?)
• Future Prospects
Standard Model Electroweak Theory

• Standard Model
  – Charged Current (CC) mediated by $W^\pm$ with (V-A)
  Neutral Current (NC) mediated by $Z^0$ with couplings below
  – One parameter to measure!
    • Weak / electromagnetic mixing parameter $\sin^2 \theta_W$

<table>
<thead>
<tr>
<th>$Z$ Couplings</th>
<th>$g_L$</th>
<th>$g_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e, \nu_\mu, \nu_\tau$</td>
<td>$1/2$</td>
<td>$0$</td>
</tr>
<tr>
<td>$e, \mu, \tau$</td>
<td>$-1/2 + \sin^2 \theta_W$</td>
<td>$\sin^2 \theta_W$</td>
</tr>
<tr>
<td>$u, c, t$</td>
<td>$1/2 - 2/3 \sin^2 \theta_W$</td>
<td>$-2/3 \sin^2 \theta_W$</td>
</tr>
<tr>
<td>$d, s, b$</td>
<td>$-1/2 + 1/3 \sin^2 \theta_W$</td>
<td>$1/3 \sin^2 \theta_W$</td>
</tr>
</tbody>
</table>

• Neutrinos are special in SM
  – Only have left-handed weak interactions
    $\Rightarrow W^\pm$ and $Z$ boson exchange
History of EW Measurements

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• Discovery of the Weak Neutral Current (1973 CERN)

CCFR, CDHS, CHARM, CHARM II
UA1, UA2, Petra, Tristan, APV, SLAC eD

• Second Generation EW Experiments (late 1980’s)
  – Discovery of W,Z boson in 1982-83
  – Precision at the 1-5% level
  – Radiative corrections become important
  – First limits on the $M_{\text{top}}$

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HPWF CIT-F

• First Generation EW Experiments (late 1970’s)
  – Precision at the 10% level
  – Tested basic structure of SM ⇒ $M_W, M_Z$

NuTeV, D0, CDF, LEP1 SLD
LEPII, APV, SLAC-E158

• Current Generation Experiments
  – Precision below 1% level
  – Discovery of the top quark
  – Constrain $M_{\text{Higgs}}$
    ⇒ Predict light Higgs boson (and possibly SUSY)
  – Use consistency to search for new physics!
G. Altarelli, 1989, and 10 years later:
There are some other indications of cracks.

- Quark and Lepton measurements don’t agree
  - All data suggest a light Higgs except $A_{FB}^b$
  - Global fit without NuTeV is good
    \[ \chi^2=15/13 \text{ (31\%)} \]
  - But disagreement
    $A_{fb}^b =$ Forward-back asymmetry for b-quarks
    is off about 3σ in opposite direction from
    $A_l =$ Left-right asymmetry for electrons

- Number of neutrinos from invisible width
  off 2σ $\Rightarrow$ 2.985 ± 0.008
  - May indicate reduced coupling of neutrinos to the Z-boson

\[
\begin{array}{ll}
0.995 +/- 0.003 & \text{LEP } Z \rightarrow \nu \nu \\
0.988 +/- 0.004 & \text{NuTeV}
\end{array}
\]
Neutrino Electroweak Measurements

• Standard model defined by Collider measurements (LEP/SLD/CDF/D0)
  – Not very precise on neutrino couplings
  – Only probe the theory at large (i.e. $Q^2 = M_Z^2$)

• Neutrino - lepton scattering
  – Clean probe of neutrino weak coupling at low $Q^2$
  – Very small cross section makes measurements difficult
  – Examples:
    • Inverse beta decay $\nu_\mu e^- \rightarrow \mu^- \nu_e$
    • Neutrino electron elastic scattering $\nu e^- \rightarrow \nu e^-$

• Neutrino - quark (nucleon) scattering
  – Pure weak process at low to moderate $Q^2$
  – High statistics but complications due to quark distribution modeling
  – Examples:
    • Elastic and quasi-elastic scattering: $\nu_\mu p \rightarrow \nu_\mu p$ and $\nu_\mu n \rightarrow \mu^- p$
    • Deep inelastic scattering (DIS) NC & CC: $\nu_\mu N \rightarrow \nu_\mu X$ and $\nu_\mu N \rightarrow \mu^- X$

Also, charged lepton parity violating measurements at Low $Q^2$:
  - Sensitive to charged lepton couplings at low $Q^2$
  - Use polarization to pick out parity violating weak part ($Q_{Weak}$)
  - Examples: Moller ($e^-e^-$), ep elastic, atomic parity violation
Neutrino – Lepton Scattering

- Inverse muon decay (NuTeV, CHARM II) \( \nu_\mu e^- \rightarrow \mu^- \nu_e \)
  
  - CHARM II: Check for anomalous couplings
    \[ \sigma = (16.5 \pm 0.9) \times 10^{-42} \text{ cm}^2/\text{GeV} \quad \text{(SM: } 17.2 \times 10^{-42}) \]
    \[ \Rightarrow \text{Constrains scalar coupling: } |g_{LL}^S| < 0.475 \text{ at } 90\% \text{ CL} \]

  - NuTeV: Search for lepton number violation
    \[ \frac{\sigma(\nu_\mu e^- \rightarrow \mu^- \nu_e)}{\sigma(\nu_\mu e^- \rightarrow \mu^- \nu_e)} < \sim 1\% \text{ at } 90\% \text{ CL} \]

- Neutrino – electron elastic scattering \( \nu_\mu e^- \rightarrow \nu_\mu e^- \)
  
  - CHARM II: Agreement with Standard Model but large errors
    - \( \sin^2 \theta_W = 0.2324 \pm 0.0083 \)
    - \( g_V = -0.035 \pm 0.017 \) (SM: -0.0398)
    - \( g_A = -0.503 \pm 0.017 \) (SM: -0.5065)

  - Neutrino magnetic moment limits (\(\gamma\) exchange)
    - Electron neutrino: Reactor exps, \( \mu_\nu < 1 \times 10^{-10} \mu_B \text{ at } 90\% \text{ CL} \)
    - Muon neutrino: LSND exp, \( \mu_\nu < 6.8 \times 10^{-10} \mu_B \text{ at } 90\% \text{ CL} \)
    - Standard model prediction: \( \mu_\nu = 3.2 \times 10^{-19} \mu_B \times m_\nu/eV \)
NuTeV Adds Another Precision Arena using DIS ν

- **Precision** comparable to collider measurements of $M_W$

- Sensitive to different **new physics**
  - Different radiative corrections

- Measurement **off the Z pole**
  - Exchange is not guaranteed to be a Z

- Measures **neutrino neutral current coupling**
  - LEP 1 invisible line width is only other precise ν measurement

- Sensitive to **light quark (u,d) couplings**
  - Overlap with APV, Tevatron Z production

- Tests universality of EW theory over large range of momentum scales
**EW Measurements using Neutrino DIS**

**Charged-Current (CC)**

\[ \nu \rightarrow \mu \]

**Neutral-Current (NC)**

\[ \nu \rightarrow \nu \]

**Charged-Current (CC)**

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

- Before NuTeV, \( \nu N \) exp's had hit a brick wall in precision
  - Due to systematic uncertainties
  - (mainly CC charm quark production)

**World Average \( \sin^2 \theta_W \) (excl. NuTeV)**

\[ 0.2277 \pm 0.0024 (exp) \pm 0.0019 (th) \]

\( \chi^2/DOF = 4.79/4 \)

**Corrected for CCFR + NuTeV**

\[ m_e = 1.38 \pm 0.14 \text{GeV} \]

**Shaded band shows** \( \pm \delta m_e \)
**NuTeV’s Technique to Reduce Systematics**

Cross section differences remove sea quark contributions
⇒ Reduce uncertainties from charm production and sea

<table>
<thead>
<tr>
<th>Paschos - Wolfenstein Relation</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ R^- = \frac{\sigma_{NC}^{\nu} - \sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^{\nu} - \sigma_{CC}^{\bar{\nu}}} = \rho^2 \left( \frac{1}{2} + \sin^2 \theta_W \right) = g_L^2 - g_R^2 ]</td>
</tr>
</tbody>
</table>

\[ g_{L,R}^2 = u_{L,R}^2 + d_{L,R}^2 \]

\[
\begin{align*}
\sigma(\nu_\mu d_{sea}) - \sigma(\bar{\nu}_\mu \bar{d}_{sea}) &= 0 \quad \Rightarrow \text{Only } d_{valence} \text{ contribute} \\
\sigma(\nu_\mu u_{sea}) - \sigma(\bar{\nu}_\mu \bar{u}_{sea}) &= 0 \quad \Rightarrow \text{Only } u_{valence} \text{ contribute} \\
\sigma(\nu_\mu s_{sea}) - \sigma(\bar{\nu}_\mu \bar{s}_{sea}) &= 0 \quad \Rightarrow \text{No} \text{ strange }-\text{sea contribution} \\
\end{align*}
\]

- \( R^- \) manifestly insensitive to sea quarks
  - Charm and strange sea error negligible \( \left( \text{If } x_s(x) = x_{\bar{s}}(x) \right) \)
  - Charm production small since only enters from \( d_\nu \) quarks only which is Cabbibo suppressed and at high-\( x \)

- **But** \( R^- \) requires separate \( \nu \) and \( \bar{\nu} \) beams so needed to develop a high-intensity separated beam
  ⇒ NuTeV SSQT (Sign-selected Quad Train)
**NuTeV Experimental Setup**

- Beam is almost pure $\nu$ or $\bar{\nu}$
  - $\bar{\nu}$ in $\nu$ mode $3 \times 10^{-4}$,
  - $\nu$ in $\bar{\nu}$ mode $4 \times 10^{-3}$
- Beam only has $\sim 1.6\%$ electron neutrinos
  - Important background for isolating true NC event

**NuTeV**

- **800 GeV Tevatron**
- **The SSQT**
  - Dipoles make sign selection
    - Set $\nu$ / $\bar{\nu}$ type
    - Remove $\nu_e$ from $K_{\text{long}}$
- **Decay Pipe**
- **Shielding**
- **690 ton $\nu$-target**
- **Steel-Scint-Chambers**
- **Solid Steel Magnet Drift Chamber Spectrometer**
NuTeV Collaboration

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Cincinnati\textsuperscript{1}, Columbia\textsuperscript{2}, Fermilab\textsuperscript{3}, Kansas State\textsuperscript{4}, Northwestern\textsuperscript{5}, Oregon\textsuperscript{6}, Pittsburgh\textsuperscript{7}, Rochester\textsuperscript{8}

(\textit{Co-spokespersons: R.Bernstein, M.Shaevitz})
Neutral Current / Charged Current Event Separation

- Separate NC and CC events statistically based on the “event length” defined in terms of # counters traversed

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

(measure this ratio in both \(\nu\) and \(\bar{\nu}\) modes)

<table>
<thead>
<tr>
<th></th>
<th>Short (NC) Events</th>
<th>Long (CC) Events</th>
<th>(R_{\text{exp}}) = Short/Long</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrino</td>
<td>457K</td>
<td>1167K</td>
<td>(0.3916 \pm 0.0007)</td>
</tr>
<tr>
<td>Antineutrino</td>
<td>101K</td>
<td>250K</td>
<td>(0.4050 \pm 0.0016)</td>
</tr>
</tbody>
</table>
Use Detailed Monte Carlo to relate $R_{\text{exp}}$ to $R^\nu$ and $\sin^2 \theta_W$

- **Quark Distribution Model**
  - Needed for including the NC and CC couplings
  - Needed to model the event cross sections (i.e. sets the amount short CC events)

- **Neutrino fluxes ($\nu_\mu, \nu_e, \bar{\nu}_\mu, \bar{\nu}_e$)**
  - Combined with cross sections to predict event numbers
  - Allows correction for electron neutrino CC events always look short NC events

- **Shower Length Modeling**
  - Needed to correct for NC short events that look long like CC events

- **Detector response vs energy, position, and time**
  - Test beam running throughout experiment crucial

---

**Top Five Largest Corrections**

<table>
<thead>
<tr>
<th>Source</th>
<th>$\delta R^\nu_{\text{exp}}$</th>
<th>$\delta R^{\bar{\nu}}_{\text{exp}}$</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short CC Background</td>
<td>-0.068</td>
<td>-0.026</td>
<td>Check medium length events</td>
</tr>
<tr>
<td>Electron Neutrinos</td>
<td>-0.021</td>
<td>-0.024</td>
<td>Direct check from data</td>
</tr>
<tr>
<td>EM Radiative Correction</td>
<td>+0.0074</td>
<td>+0.0109</td>
<td>Well understood</td>
</tr>
<tr>
<td>Heavy m_e</td>
<td>-0.0052</td>
<td>-0.0117</td>
<td>$R^-$ technique</td>
</tr>
<tr>
<td>Cosmic-ray Background</td>
<td>-0.0036</td>
<td>-0.019</td>
<td>Direct from data</td>
</tr>
<tr>
<td>Compare to statistical error</td>
<td>±0.0013</td>
<td>±0.0027</td>
<td></td>
</tr>
</tbody>
</table>

Analysis uses **data directly to set and check the Monte Carlo simulation**
**Result**

\[
\sin^2 \theta_W^{(on-shell)} = 0.2277 \pm 0.0013 \text{ (stat.)} \pm 0.0009 \text{ (syst.)} \\
= 0.2277 \pm 0.0016
\]

- **NuTeV result:**
  - Error is statistics dominated
  - Is $\times 2.3$ more precise than previous $\nu N$ experiments
    where $\sin^2 \theta_W = 0.2277 \pm 0.0036$ and syst. dominated

- **Standard model fit (LEP-EWWG):** \(0.2227 \pm 0.00037\)
  A 3\(\sigma\) discrepancy ...........

\[R^\nu = \frac{\sigma^\nu_{NC}}{\sigma^\nu_{CC}}\text{ and } R^{\bar{\nu}} = \frac{\sigma^{\bar{\nu}}_{NC}}{\sigma^{\bar{\nu}}_{CC}}\]

\[
\frac{dR^\nu_{\exp}}{d \sin^2 \theta_W} \text{ large } \quad \text{dR}^{\bar{\nu}}_{\exp} \text{ small}
\]

\[R^\nu_{\exp} \rightarrow \sin^2 \theta_W \quad R^{\bar{\nu}}_{\exp} \rightarrow \text{systematics (i.e. } m_c)\]

\[
R^\nu_{\exp} = 0.3916 \pm 0.0013 \quad (SM : 0.3950) \Leftrightarrow 3\sigma \text{ difference}
\]

\[
R^{\bar{\nu}}_{\exp} = 0.4050 \pm 0.0027 \quad (SM : 0.4066) \Leftrightarrow \text{Good agreement}
\]

## Uncertainties in Measurement

<table>
<thead>
<tr>
<th>SOURCE OF UNCERTAINTY</th>
<th>$\delta \sin^2 \theta_W$</th>
<th>$\delta R^\nu_{\text{exp}}$</th>
<th>$\delta R^\nu_{\text{exp}}$</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>
</tr>
<tr>
<td>Interaction Vertex</td>
<td>0.00030</td>
<td>0.00022</td>
<td>0.00017</td>
</tr>
<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>
</tr>
<tr>
<td>Energy Measurement</td>
<td>0.00018</td>
<td>0.00015</td>
<td>0.00024</td>
</tr>
<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>$\sigma^\nu / \sigma^\nu$</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>
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<tr>
<td>Radiative Corrections</td>
<td>0.00011</td>
<td>0.00005</td>
<td>0.00006</td>
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<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>
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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>
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<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>

- **Criticisms not about the measurement details but about the theory uncertainties:**
  - Quark model uncertainties
  - Because result doesn't fit into expected types of new physics
Result from Fit to $R^\nu$ and $R^{\bar{\nu}}$

- Separating $\nu$ and $\bar{\nu}$ measurements:
  \[ R_{\text{exp}}^{\nu} = 0.3916 \pm 0.0013 \quad \text{and} \quad R_{\text{exp}}^{\bar{\nu}} = 0.4050 \pm 0.0027 \]
  \( (SM : 0.3950) \Leftarrow 3\sigma \text{ difference} \quad (SM : 0.4066) \Leftarrow \text{Good agreement} \)

  Discrepancy is neutrinos not antineutrinos

- In terms of left and right-handed couplings:
  \[ g_L^2 = u_L^2 + d_L^2 = 0.30005 \pm 0.00137 \quad \text{and} \quad g_R^2 = u_R^2 + d_R^2 = 0.0308 \pm 0.0011 \]
  \( (SM : 0.3042) \Leftarrow 2.6\sigma \text{ difference} \quad (SM : 0.0301) \Leftarrow \text{agreement} \)

  Discrepancy is left-handed coupling to $u$ and $d$ quarks

- Or in terms of the NC to CC $\nu/\bar{\nu}$ coupling strength (1-parameter fit)
  \[ \rho^2_0 = 0.9884 \pm 0.0026(stat.) \pm 0.0032(syst.) \quad (SM : \rho = 1.0) \]

  $\nu$ NC coupling is too small \Leftarrow 2.8\sigma \text{ difference}
SM Global Fit with NuTeV $\sin^2 \theta_W$

- **With NuTeV:**
  - $\chi^2$/dof = 25/15,
  - probability of 4%

- **Without NuTeV:**
  - $\chi^2$/dof = 15/13,
  - probability of 31%

- Upper $m_{\text{Higgs}}$ limit only weakens slightly

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Pull $(O^{\text{meas}} - O^{\text{fit}})/\sigma^{\text{meas}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta\alpha^{(8)}_{\text{had}}(m_Z)$</td>
<td>0.02761 ± 0.00036 -0.24</td>
</tr>
<tr>
<td>$m_Z$ [GeV]</td>
<td>91.1875 ± 0.0021 0.00</td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>2.4952 ± 0.0023 -0.41</td>
</tr>
<tr>
<td>$\sigma^0_{\text{had}}$ [nb]</td>
<td>41.540 ± 0.037 1.63</td>
</tr>
<tr>
<td>$R_l$</td>
<td>20.767 ± 0.025 1.04</td>
</tr>
<tr>
<td>$A_{tb}^{0,1}$</td>
<td>0.01714 ± 0.00095 0.68</td>
</tr>
<tr>
<td>$A_{l}(P_d)$</td>
<td>0.1465 ± 0.0032 -0.55</td>
</tr>
<tr>
<td>$R_b$</td>
<td>0.21644 ± 0.00065 1.01</td>
</tr>
<tr>
<td>$R_c$</td>
<td>0.1718 ± 0.0031 -0.15</td>
</tr>
<tr>
<td>$A_{tb}^{0,b}$</td>
<td>0.0995 ± 0.0017 -2.62</td>
</tr>
<tr>
<td>$A_{tb}^{0,c}$</td>
<td>0.0713 ± 0.0036 -0.84</td>
</tr>
<tr>
<td>$A_b$</td>
<td>0.922 ± 0.020 -0.64</td>
</tr>
<tr>
<td>$A_c$</td>
<td>0.670 ± 0.026 0.06</td>
</tr>
<tr>
<td>$A_{l}(\text{SLD})$</td>
<td>0.1513 ± 0.0021 1.46</td>
</tr>
<tr>
<td>$\sin^2\theta_{\text{eff}}^{l}(Q_{fb})$</td>
<td>0.2324 ± 0.0012 0.87</td>
</tr>
<tr>
<td>$m_W$ [GeV]</td>
<td>80.449 ± 0.034 1.62</td>
</tr>
<tr>
<td>$\Gamma_W$ [GeV]</td>
<td>2.136 ± 0.069 0.62</td>
</tr>
<tr>
<td>$m_t$ [GeV]</td>
<td>174.3 ± 5.1 0.00</td>
</tr>
<tr>
<td>$\sin^2\theta_W(vN)$</td>
<td>0.2277 ± 0.0016 3.00</td>
</tr>
<tr>
<td>$Q_W(Cs)$</td>
<td>-72.18 ± 0.46 1.52</td>
</tr>
</tbody>
</table>
Possible Interpretations

• Changes in Standard Model Fits
  – Changes in quark distributions sets
  – Cross section models: Leading Order (LO) vs Next to Leading Order (NLO)
  – Changes in standard model radiative corrections

• “Old Physics” Interpretations: QCD
  – Violations of “isospin” symmetry
  – Strange vs anti-strange quark asymmetry
  – Shadowing and other nuclear effects

• Physics Beyond the Standard Model
  – Neutrino Properties
    • Special couplings to new particles
    • Mixing and oscillation Effects
  – “New Particle” Interpretations
    • New Z’ or lepto-quark exchanges
    • New particle loop corrections
  – Mixtures of new physics
Can Quark Distributions or LO vs NLO Analysis Be a Problem?

• NuTeV analysis uses an enhanced Leading Order (LO) formalism that implements:
  – Constraints from both CC 1\( \mu \) and 2\( \mu \) data
  – Uses external measurements for \( R_{\text{Long}} \), d/u, charm sea, higher twist

• NLO estimates from idealized analyses give small changes
  \( \delta \sin^2 \theta_W = -0.0004 \) to \(+0.0015\)

• Quark distribution variations are not sizeable for the idealized analyses

• To test possible NLO effects, we are developing a full NLO \( \nu \) event generator
  – Full NLO evolution with gluons
  – Include heavy charm at NLO
  – Many new NLO calculations are becoming available

Are the Standard Model Radiative Corrections Uncertain?

- EM radiative corrections are large
  - Bremsstrahlung from the final state lepton in CC events is the largest correction
    - Straightforward to calculate
  - Currently using the only available code from Bardin and Dokuchaeva (JINR-E2-86-260,1986)
    - Adding correction shifts $\delta \sin^2 \theta_W = -0.0030$

- New calculations becoming available
    - Improved treatment of initial state mass singularities
    - Point out additional uncertainties: input parameter, scheme dependence
    - Scaling their estimates $\Rightarrow \delta \sin^2 \theta_W = -0.0036$ (would reduce value by 1/3 $\sigma$)

- We are implementing Diener et al. code (and others) into NuTeV analysis
  - Only way to determine the quantitative effects of different corrections.
Possible Interpretations

- Changes in Standard Model Fits
  - Changes in quark distributions sets
  - Cross section models: LO vs NLO
  - Changes in standard model radiative corrections

- “Old Physics” Interpretations: QCD
  - Violations of “isospin” symmetry
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Symmetry Violating QCD Effects

\[ R^- = \frac{\sigma_{NC}^\nu - \sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^\nu - \sigma_{CC}^{\bar{\nu}}} = \frac{1}{2} + \sin^2 \theta_W \]

- Paschos-Wolfenstein Relation Assumptions:
  - Assumes isospin symmetry, \( u_p(x) \neq d_n(x) \)
  - Assumes sea momentum symmetry, \( s = \bar{s} \) and \( c = \bar{c} \)
  - Assumes nuclear effects common in W/Z exchange

\[ \Rightarrow \text{ Violations of these symmetries are possible but constrained} \]

**Bottom Line:** \( R^- \) technique is very robust
Isopin Symmetry Violation

- Isospin symmetry violation: $u^p \neq d^n$ and $d^p \neq u^n$
  ⇒ Could come about from $m_u \neq m_d$ or wave function differences

  - What is needed to explain the NuTeV data?
    • Need $d_v$ quarks in proton to carry ~5% more momentum than $u_v$ neutron
      ⇒ Model calculations are not very predictive
      ⇒ Typically predict from 0 to 1.5%

  - Full “Bag Model” calculations:
    • J.T. Londergan, A.W. Thomas, hep-ph/0407247
      ⇒ $\Delta \sin^2 \theta_W = 0.0$ to $-0.0017$ (0 to $-1 \sigma$)

  - “Meson Cloud Model”:
    (Cao et al., PhysRev C62 015203)
    ⇒ $\Delta \sin^2 \theta_W = +0.0002$ (~ 0 $\sigma$)

  - Global quark distribution fits also are not very predictive
    • Best fit from MRST would lower NuTeV value by 1 $\sigma$

⇒ Conclusion: Need more data to constrain these type of effects
s(x) vs \( \bar{s}(x) \) Asymmetry

- Non-perturbative QCD effects can generate a strange vs. anti-strange momentum asymmetry
  - Only available data is NuTeV and CCFR \( \nu \) and \( \bar{\nu} \) dimuon data
  - Fits to this data can measure the s vs. \( \bar{s} \) asymmetry.

\[
\nu \, s \rightarrow \mu \, c \rightarrow \mu \mu X
\]

NLO fits to \( \nu \) and \( \bar{\nu} \) dimuon data:

Measures \( s^- = \frac{s - \bar{s}}{2} \)

Give

\[
\int x s^- (x) dx = -0.0009 \pm 0.0014
\]

To explain NuTeV \( \sin^2 \theta_W \) would require +0.0060

Work of D. Mason et al. (NuTeV grad student)
(In collaboration with Amundson, Kretzer, Olness, Tung)
Nuclear Effects

- Need to worry about nuclear effects that could be different for W and Z exchange?

- Most nuclear effects are only large at small $Q^2$ and would effect W and Z the same
  - NuTeV is at relatively high $Q^2$
  - NuTeV $s_{\nu}^{2\theta_{\nu}}$ shows no effect with increasing the $E_{had}$ cut (which increases the sampled $Q^2$)
  - Quark distribution measurements show no $1/Q^2$ dependence in the NuTeV kinematic region

- Proposals with enhanced nuclear effects.
  - Vector meson dominance models could have differences for W and Z exchange
    \((\text{Miller and Thomas, hep-ex/0204007; also our rebuttal, G.P. Zeller et al. hep-ex/0207052})\)
    \((\text{Mainly effect sea quarks at low } x \text{ and cancel in } R^\nu)\)
    \(\Rightarrow\) Would increase both $R^\nu$ and $R^\bar{\nu}$

Conclusion:
These nuclear effects will change $R^\nu$ and $R^\bar{\nu}$ more than $R^-$
Making their deviation with the SM much more significant
\(\Rightarrow\) Hard to explain NuTeV discrepancy with nuclear effects
Possible Interpretations

• Changes in Standard Model Fits
  ✓ Changes in quark distributions sets
  ✓ Cross section models: LO vs NLO
  ✓ Changes in standard model radiative corrections

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  ? Violations of “isospin” symmetry
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Explanations Involving Neutrino Properties

**Reduced Neutrino Coupling**

- NuTeV result fit as a change in the $\nu / \bar{\nu}$ coupling
  \[ \rho_0^2 = 0.9884 \pm 0.0026(\text{stat.}) \pm 0.0032(\text{syst.}) \]
- LEP 1 measures $Z$ lineshape and partial decay widths to infer the “number of neutrinos”
  \[ 3 \times (0.995 \pm 0.003) \Rightarrow 1.9\sigma \text{ low} \]

- **Reduced Background from $\nu_e \rightarrow \nu_s$ Osc.**

  - Neutrino oscillations to Sterile Neutrinos (Giunti et al. hep-ph/0202152; )
    - $\nu_e \rightarrow \nu_s$ oscillation make real $\nu_e$ background subtraction smaller giving NuTeV anomaly
      - Requires high $\Delta m^2$ and ~20% mixing
    - Is this consistent with other oscillation limits
      - For (3+1) model inconsistent with Bugey reactor limits
    - Recent work has shown that shift is below $1/3 \sigma$ even for high mass (3+2) models (J.S. Ma et al., in progress)

$\Rightarrow$ Explain discrepancies by invoking an effectively lower coupling of the neutrino due to some new phenomena (i.e. mixing with heavy or sterile $\nu$’s)
Possible New Physics Interpretations

- **Constraints**
  - Z pole measurements (LEP/SLD)
    - Insensitive to effects not directly involving the Z
    - Not too constraining for neutrino couplings
  - Need to change $R^\nu$ and not $R^{\bar{\nu}}$ (or change $g_L$ and not $g_R$)

- **SUSY in loop corrections or RPV SUSY at tree level**
  - Generally small and in the wrong direction
  - Typically, change both $R^\nu$ and $R^{\bar{\nu}}$
  - Maybe extended SUSY models
    (i.e. K.S.Babu and J.C.Pati, hep-ph/0203029)
    - Also, can give LEP $\nu$ deficit
    - Will be tested at LHC

- **Contact Interactions:**
  - Fine tune a Left-handed q-q-lepton-lepton vertex, with strength $\sim$0.01 of the weak interaction ($\sim$ 5 TeV)

- **Leptoquarks:**
  - Generally, increase both NC and CC $\Rightarrow g_L$ discrepancy worsens
  - Hard to fit with leptoquark and evade $\pi$–decay constraints

- **Extra U(1) vector bosons ("Designer $Z'$") that evades other constraints**
  - Examples: Leptophobic, special couplings to 2nd generation, E(6) $Z'$
  - Could be seen at Tevatron (LHC) with masses up to 1 (5) TeV
“The NuTeV Anomaly, Neutrino Mixing and a Heavy Higgs”
W. Loinaz, N. Okamura, T. Takeuchi, and L. Wijewardhana

• Fit all measurements with a “cocktail model”
  – Neutrino Mixing
  – Heavy Higgs
  – New heavy bound state physics

• Suppression of the $Z_{\nu\nu}$ coupling occur naturally in models which mix the neutrinos with heavy gauge singlet states
  – i.e. $\nu_L = \cos\theta \nu_{\text{light}} + \sin\theta \nu_{\text{heavy}}$
    • $Z_{\nu\nu}$ reduced by $\cos^2\theta = (1-\varepsilon)$
  – But this changes $G_F$ extracted from $\mu$-decay by $(1-\varepsilon)$ and messes up dozens of Z-pole agreements
    • Can fix this if $G_F$ is compensated by a shift in the $\rho$ parameter (T) ⇒ allowed with “new physics”
      – Contradicts $M_W$
        • Need extra U-type new physics

• Can fit all data with
  – Mixed neutrinos: $\theta = 0.055 \pm 0.010$
  – Heavy Higgs: $M_{\text{higgs}} \geq 200$ GeV
  – New physics (U-parameter type)
    ⇒ New heavy bound states???
Possible Interpretations

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Need New Experiments to Explore Low $Q^2$ and Neutrinos
Future Measurements

• Unfortunately, the high-energy neutrino beam at Fermilab has been terminated
  ⇒ Need to rely on other experiments for progress

• Upcoming new measurements:
  – Low $Q^2$ measurements:
    • SLAC E-158 Pol. Polarized electron-electron scattering
    • JLab QWEAK Polarized elastic ep
    • JLab DIS-Parity Polarized eD

    *(Test low $Q^2$ But for e’s and not $\nu$’s)*

  – High energy measurements:
    • Fermilab Tevatron Run 2 and LHC searches for $Z’$ and leptoquarks
New “Preliminary” Final E-158 Results

From talk by Y. Kolomensky at the SLAC Summer Institute (Aug. 6, 2004)
Other $\nu$ Measurement Possibilities

- Nomad $\nu N$ experiment (data taking completed)
  - Use $R^\nu$ only at $<Q^2>=15$ GeV$^2$
  - Make corrections for quark model effects
    - NNLO QCD model with $1/Q^2$ corrections
    - Use dimuon data to constrain $s(x)$ and $m_c$
  - Difficulties: NC/CC separation, $E_{\nu}$ spectrum
    $\Rightarrow \delta \sin^2 \theta_W = 0.002$

- Reactor $\bar{\nu}_e e^-$ elastic scattering
  [Conrad, Link, Shaevitz hep-ex/0403048]
  - Combination of W and Z exchange
  - Total rate is sensitive to $\sin^2 \theta_W$
  - Use $\bar{\nu}_e p \rightarrow e^- n$ for normalization
    $\Rightarrow$ Measure rate to $\sim 1\% \Rightarrow \delta \sin^2 \theta_W = 0.002$

- Dedicated $\nu_\mu e^-$ accelerator experiment (Super CHARM II)
  - Required sensitivity $\Rightarrow \times 25$ increase in statistics over CHARM II
  - Improved detector: Fine grained (ie LiqAr), larger mass (5 kton)
  - Improved beam: higher rep rate/intensity
    $\Rightarrow \delta \sin^2 \theta_W = 0.002$
Summary

- NuTeV measurement has the precision to be important for SM electroweak test
  Many experimental checks and the R^- technique is robust with respect to systematic uncertainties

- For NuTeV the SM predicts $0.2227 \pm 0.0003$ but we measure
  $$\sin^2 \theta_W^{(on-shell)} = 0.2277 \pm 0.0013 (\text{stat.}) \pm 0.0009 (\text{syst.})$$
  (Previous neutrino measurements gave $0.2277 \pm 0.0036$)

- In comparison to the Standard Model
  The NuTeV data prefers lower effective left-handed quark couplings
  Or neutral current coupling that is ~1.1% smaller than expected

- The discrepancy with the Standard Model could be related to:
  Quark model uncertainties but unlikely or only partially
  and / or
  Possibly new physics that is associated with neutrinos and
  interactions with left-handed quarks or neutrino mixing/oscillations

Jan/Feb 2002 CERN Courier article:
“Is the latest NuTeV result a blip or another neutrino surprise?
Only time will tell.”