Electroweak Measurements at NuTeV: A Departure from Prediction

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for the NuTeV Collaboration

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- Introduction to Electroweak Measurements
- NuTeV Experiment and Technique
- Experimental and Theoretical Simulation
- Data Sample and Checks
- Electroweak Fits
- Interpretations and Summary


Electroweak Theory

• Standard Model

SU(2) ⊗ U(1) gauge theory unifying weak/EM
⇒ weak Neutral Current interaction

Measured physical parameters related to mixing parameter for the couplings, \( g' = g \tan \theta_W \)

\[
e = g \sin \theta_W, \quad G_F = \frac{g^2 \sqrt{2}}{8M_W^2}, \quad \frac{M_W}{M_Z} = \cos \theta_W
\]

<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
⇒ \( W^\pm \) and Z boson exchange

Charged-Current  Neutral-Current
History of EW Measurements

• Discovery of the Weak Neutral Current
  Summer 1973 (Gargamelle, CERN)
  SM predicted: $\nu_\mu N \rightarrow \nu_\mu X$

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

• Second Generation EW Experiments
  Experiments in the 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 \( M_{\text{top}} \)

• Third Generations Experiments
  Precision below 1% level
  Test consistency of SM
  Search for new physics and
  Constrain \( M_{\text{Higgs}} \)
  \( \Rightarrow \) Predict light Higgs boson
  (and possibly SUSY)
Current Era of Precision EW Measurements

• Precision parameters define the SM:
  \[ \alpha_{EM}^{-1} = 137.03599959(40) \quad \text{45ppb (200ppm@M_Z)} \]
  \[ G_\mu = 1.16637(1) \times 10^{-5} \text{ GeV}^{-2} \quad \text{10ppm} \]
  \[ M_Z = 91.1871(21) \quad \text{23ppm} \]

• Comparisons test the SM and probe for new physics
  LEP/SLD
  CDF/D0
  νN, APV

  \[ Z^0 \quad (M_Z, \Gamma_Z, \text{asymmetries}) \]
  \[ W^\pm \quad (M_W, \Gamma_W) \]

• Radiative corrections are large and sensitive to \( m_{\text{top}} \) and \( m_{\text{Higgs}} \)

\[ M_{\text{Higgs}} \text{ constrained in SM to be less than 196 GeV at 95\%CL} \]
Are There Cracks?

• All data suggest a light Higgs except $A_{FB}^b$

• Global fit has large $\chi^2$
  $\chi^2=23/15$ (9%)
  $A_{FB}^b$ is off about 3σ

• $\Gamma_{inv}$ also off by $\sim 2\sigma$

$N_v = 2.9841 \pm 0.0083$

Higgs Mass Constraint

Leptons     Quarks

Preliminary

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Pull</th>
<th>$O_{max}^0$</th>
<th>$\chi^2_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_{fb}^b(m_{Z})$</td>
<td>0.02761 ± 0.00036</td>
<td>-0.35</td>
<td></td>
</tr>
<tr>
<td>$m_Z$ [GeV]</td>
<td>91.1875 ± 0.0021</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>2.4952 ± 0.0023</td>
<td>-0.48</td>
<td></td>
</tr>
<tr>
<td>$\alpha_{em}$ [nb]</td>
<td>41.540 ± 0.037</td>
<td>1.60</td>
<td></td>
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<tr>
<td>$R_b$</td>
<td>20.767 ± 0.025</td>
<td>1.11</td>
<td></td>
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<tr>
<td>$A_{FB}^{b}$</td>
<td>0.1714 ± 0.00085</td>
<td>0.69</td>
<td></td>
</tr>
<tr>
<td>$A_{FB}^{c}$</td>
<td>0.21646 ± 0.00065</td>
<td>1.12</td>
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<tr>
<td>$R_{inv}$</td>
<td>0.1718 ± 0.0031</td>
<td>-1.12</td>
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<tr>
<td>$A_{FB}^{l\nu}$</td>
<td>0.0990 ± 0.0017</td>
<td>-2.90</td>
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<tr>
<td>$A_{FB}^{e\nu}$</td>
<td>0.6685 ± 0.0034</td>
<td>-1.71</td>
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<tr>
<td>$A_{FB}^{l\ell}$</td>
<td>0.670 ± 0.026</td>
<td>0.06</td>
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<tr>
<td>$A_{FB}^{l\nu}$</td>
<td>0.1513 ± 0.0021</td>
<td>1.47</td>
<td></td>
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<tr>
<td>$\sin^2\theta_{wb}(Q_{inv})$</td>
<td>0.2234 ± 0.0012</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>$m_{W}^{lep}$ [GeV]</td>
<td>80.450 ± 0.039</td>
<td>1.32</td>
<td></td>
</tr>
<tr>
<td>$m_{W}^{Q_{inv}}$ [GeV]</td>
<td>80.454 ± 0.060</td>
<td>0.93</td>
<td></td>
</tr>
<tr>
<td>$\sin^2\theta_{wb}(Q_{inv})$</td>
<td>0.2255 ± 0.0021</td>
<td>1.22</td>
<td></td>
</tr>
<tr>
<td>$Q_{inv}(C_s)$</td>
<td>72.50 ± 0.70</td>
<td>0.56</td>
<td></td>
</tr>
</tbody>
</table>
**NuTeV Adds Another Arena**

- **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 measure

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

- Tests universality of EW theory over large range of momentum scales
For an isoscalar target composed of u,d quarks:

- $\text{NC/CC ratio easiest to measure experimentally but ...}$
  - Need to correct for non-isoscalar target, radiative corrections, heavy quark effects, higher twists
  - Many SF dependencies and systematic uncertainties cancel
  - Major theoretical uncertainty $m_c \Rightarrow$ Suppress CC wrt NC

**Llewellyn Smith Relation:**

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

• CC is suppressed due to final state c-quark
  ⇒ Need to know s-quark sea and $m_c$
  Modeled with leading-order slow-rescaling

\[
x = \frac{Q^2}{2M_N} \quad \Rightarrow \quad \xi = \frac{Q^2 + m_c^2}{2M_N}
\]

Measured by NuTeV/CCFR using dimuon events
($\nu N \rightarrow \mu cX \rightarrow \mu\mu X$) (M. Goncharov et al., Phys. Rev. D64: 112006, 2001 and A.O. Bazarko et al., Z. Phys. C65: 189-198, 1995)
Before NuTEV

• νN experiments had hit a brick wall in precision
  ⇒ Due to systematic uncertainties (i.e. $m_c$ ....)

$$\sin^2 \theta_{W}^{on-shell} = 1 - \frac{M_W^2}{M_Z^2} = 0.2277 \pm 0.0036$$

⇒ $M_W = 80.14 \pm 0.19$ GeV

(All experiments corrected to NuTeV/CCFR $m_c$
and to large $M_{top} > M_W$)
NuTeV’s Technique

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

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

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

\(\text{Paschos - Wolfenstein Relation}\)

\(R^-\) manifestly insensitive to sea quarks

– Charm and strange sea error negligible
– Charm production small since only enters from \(d_V\) quarks only which is Cabbibo suppressed and at high-\(x\)

Note: NuTeV measures \(R^\nu\) and \(R^{\bar{\nu}}\) which, when used simultaneously, is equivalent to \(R^-\).

• \(R^-\) requires separate \(\nu\) and \(\bar{\nu}\) beams
⇒ NuTeV SSQT (Sign-selected Quad Train)
- 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
  $\Rightarrow$ Important background for isolating true NC event
NuTeV Lab E Neutrino Detector

168 Fe plates (3m x 3m x 5.1 cm)
84 liquid scintillation counters

- Trigger the detector
- Measure:
  - Visible energy
  - $\nu$ interaction point
  - Event length

42 drift chambers
- Localize transverse vertex

Toroid Spectrometer
- Measures $\mu$ momentum/charge
- $P_T = 2.4$ GeV
  for $\delta P/P \approx 10\%$

Continuous Test Beam
- simultaneous with $\nu$ runs
  - Hadron, muon, electron beams
  - Map toroid and calorimeter response

690 ton $\nu$-target
Picture from 1998 - Detector is now dismantled
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(Co-spokepersons: B.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

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

(measure this ratio in both $\nu$ and $\bar{\nu}$ modes)
NuTeV Data Sample

- Events selections:
  - Require Hadronic Energy, $E_{\text{Had}} > 20 \text{ GeV}$
  - Require Event Vertex with fiducial volume

- Data with these cuts:
  - 1.62 million $\nu$ events
  - 351 thousand $\overline{\nu}$ events

![Diagram of event selection process with fiducial region, target, calorimeter, and toroid spectrometer.]
Determine \( R_{\text{exp}} \): The Short to Long Ratio:

Use \( E_{\text{had}} \) dependent \( L_{\text{cut}} \) to minimize short CC correction

<table>
<thead>
<tr>
<th></th>
<th>Short (NC) Events</th>
<th>Long (CC) Events</th>
<th>( R_{\text{exp}} = \text{Short/Long} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrino</td>
<td>457K</td>
<td>1167K</td>
<td>0.3916 ± 0.0007</td>
</tr>
<tr>
<td>Antineutrino</td>
<td>101K</td>
<td>250K</td>
<td>0.4050 ± 0.0016</td>
</tr>
</tbody>
</table>
From $R_{\text{exp}}$ to $R^\nu$

*Need detailed Monte Carlo to relate $R_{\text{exp}}$ to $R^\nu$ and $\sin^2\theta_W$*

- **Cross Section Model**
  - LO pdfs (CCFR)
  - Radiative corrections
  - Isoscalar corrections
  - Heavy quark corrections
  - $R_{\text{Long}}$
  - Higher twist corrections

- **Detector Response**
  - CC ↔ NC cross-talk
  - Beam contamination
  - Muon simulation
  - Calibrations
  - Event vertex effects

- **Neutrino Flux**
  - $\nu_\mu$ and $\nu_e$ flux

*Analysis goal is use data directly to set and check the Monte Carlo simulation*
Background Corrections

- Short $\nu_\mu$ CC's (20% $\nu$, 10% $\nu$) 
  muon exits, range out at high $y$

- Short $\nu_e$ CC's (5%) 
  $\nu_e N \rightarrow e X$

- Cosmic Rays (0.9%/4.7%)

- Long $\nu_\mu$ NC's (0.7%) 
  punch-through effects
Key Elements of Monte Carlo

- Parton Distribution Model
  Needed to correct for details of the PDF model
  Needed to model cross over from short $\nu_\mu$ CC events
- Neutrino fluxes
  $\nu_\mu, \nu_e, \bar{\nu}_\mu, \bar{\nu}_e$ in the two running modes
  Electron neutrino CC events always look short
- Shower Length Modeling
  Needed to correct for short events that look long
- Detector response vs energy, position, and time
  Test beam running throughout experiment crucial

**Top Five Largest Corrections**

<table>
<thead>
<tr>
<th>Source</th>
<th>$\delta R^v_{\text{exp}}$</th>
<th>$\delta R^{\bar{v}}_{\text{exp}}$</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_c</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>$\pm 0.0013$</td>
<td>$\pm 0.0027$</td>
<td></td>
</tr>
</tbody>
</table>
NC and CC quark model for $\nu / \bar{\nu}$ cross-sections needs:

$$q(x, Q^2) \text{ and } \bar{q}(x, Q^2)$$

- PDFs extracted from CCFR data exploiting symmetries:
  Isospin symmetry: $u^p = d^n$, $d^p = u^n$, and strange = anti-strange
- Data-driven: uncertainties come from measurements

• LO quark-parton model tuned to agree with data:
  – Heavy quark production suppression and strange sea (CCFR/NuTeV $\nu N \rightarrow \mu^+ \mu^- X$ data)
  – $R_L$, $F_2$ higher twist (from fits to SLAC, BCDMS)
  – $d/u$ constraints from NMC, NUSEA(E866) data
  – Charm sea from EMC $F_2^{cc}$

*This “tuning” of model is crucial for the analysis*
NuTeV Neutrino Flux

• Use beam Monte Carlo simulation tuned to match the observed $\nu_\mu$ spectrum

  Tuning needed to correct for uncertainties in SSQT alignment and particle production at primary target

Data vs Monte Carlo $E_\nu$ Spectrum

Simulation is very good but needs small tweaks at the $\sim 0.3 - 3\%$ level for $E_\pi$, $E_K$, $K/\pi$
Charged-Current Control Sample

- **Medium** length events (L>30 cntrs) check modeling and simulation of **Short** charged-currents sample
  
  Similar kinematics and hadronic energy distribution

![Graphs showing data and MC comparison](image)

- Good agreement between data and MC for the medium length events.
Approximately 5% of short events are $\nu_e$ CC events

Main $\nu_e$ source is $K^\pm$ decay (93% / 70%)

Others include $K_{L,S}$ (4%/18%) reduced by SSQT and Charm (2%/9%)

Main uncertainty is $K^{\pm}_{e3}$ branching ratio (known to 1.4%) !!

• But also have direct $\nu_e$ measurement techniques.
Direct Measurements of $\nu_e$ Flux

1. $\nu_\mu^{CC}$ (wrong-sign) events in antineutrino running constrain charm and $K_L$ production

2. Shower shape analysis can statistically pick out $\nu$ events ($80 < E_\nu < 180$ GeV)

3. $\nu_e$ from very short events ($E_\nu > 180$ GeV)
   
   Precise measurement of $\nu_e$ in tail region of flux
   
   Observe $\sim$35% more $\bar{\nu}_e$ than predicted above 180 GeV, and a smaller excess in $\nu$ beam
   
   Conclude that we should require $E_{\text{had}} < 180$ GeV

\[ N_{\text{meas}} / N_{\text{MC}} : 1.05 \pm 0.03 (\nu_e) \]
\[ 1.01 \pm 0.04 (\bar{\nu}_e) \]

NuTeV preliminary result did not have this cut
\[ \Rightarrow \text{shifts } \sin^2\theta_W \]
\[ \text{by } +0.002 \]
R_{\text{exp}} Stability Tests vs. Experimental Parameters

- Verify systematic uncertainties with data to Monte Carlo comparisons a function of exp. variables.
- Longitudinal Vertex: checks detector uniformity

![Graphs showing R_{\text{exp}} vs. Experimental Parameters](image)

Note: Shift from zero is because NuTeV result differs from Standard Model
Stability Tests (cont’d)

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

Yellow band is stat error

- $R_{\text{exp}}$ vs. radial bin: Check corrections for $\nu_e$ and short CC which change with radius.
Distributions vs. $E_{\text{had}}$

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

Long Events (CC Cand.) vs $E_{\text{had}}$
Stability Test: $R_{\text{exp}}$ vs $E_{\text{Had}}$

- Short/Long Ratio vs $E_{\text{Had}}$ checks stability of final measurement over full kinematic region
  Checks almost everything: backgrounds, flux, detector modeling, cross section model, .....
Fit for $\sin^2 \theta_W$

$$R^v(\bar{\nu}) = \frac{\sigma^v_{NC}}{\sigma^v_{CC}} = \rho_0^2 \left( \frac{1}{2} - \sin^2 \theta_W + \frac{5}{9} \sin^4 \theta_W \left( 1 + \frac{\sigma^v_{CC}}{\sigma^v_{CC}} \right) \right)$$

$$\frac{dR^v_{\text{exp}}}{d \sin^2 \theta_W} \quad \text{large}$$

$$R^v_{\text{exp}} \rightarrow \sin^2 \theta_W$$

$$\frac{dR^{\bar{\nu}}_{\text{exp}}}{d \sin^2 \theta_W} \quad \text{small}$$

$$R^{\bar{\nu}}_{\text{exp}} \rightarrow \text{systematics (i.e. } m_c \text{)}$$

Simultaneous fit of $R^v_{\text{exp}}$ and $R^{\bar{\nu}}_{\text{exp}}$ to two parameters:

$\sin^2 \theta_W$ and $m_c$

Also input $m_c = 1.38 \pm 0.14$ from $\nu$ dimuon measurements

This fit is equivalent to using $R^-$ in reducing systematic uncertainty

Result:

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

$$m_c = 1.32 \pm 0.09(\text{stat.}) \pm 0.06(\text{syst.})$$

Can also do a two parameter fit to $\rho$ and $\sin^2 \theta_W$:

$$\sin^2 \theta_W^{(on-shell)} = 0.2265 \pm 0.0031$$

$$\rho_0 = 0.9983 \pm 0.0040 \quad (\text{Correlation Coef.} = 0.85)$$
Uncertainties in Measurement

- $\sin^2 \theta_W$ error statistically dominated $\Rightarrow R^-$ technique
- $R^\nu$ uncertainty dominated by theory model

<table>
<thead>
<tr>
<th>SOURCE OF UNCERTAINTY</th>
<th>$\delta \sin^2 \theta_W$</th>
<th>$\delta R^\nu_{\text{exp}}$</th>
<th>$\delta R^{\bar{\nu}}_{\text{exp}}$</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>$\sigma^{\bar{\nu}} / \sigma^{\nu}$</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>
NuTeV Technique Gives Reduced Uncertainties

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
- $R_{long}$
- Radiative Corrections

Error on $\sin^2 \Theta_W (x10^{-4})$
\[ \sin^2 \theta_W^{(\text{on-shell})} = 0.2277 \pm 0.0013 (\text{stat.}) \pm 0.0009 (\text{syst.}) = 0.2277 \pm 0.0016 \]

- **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 (LEPEWWG):** 0.2227 \( \pm 0.00037 \)
  A 3\( \sigma \) discrepancy ............

\[
\begin{align*}
R_{\text{exp}}^\nu &= 0.3916 \pm 0.0013 \quad (SM : 0.3950) \quad \Leftarrow 3\sigma \text{ difference} \\
R_{\text{exp}}^\bar{\nu} &= 0.4050 \pm 0.0027 \quad (SM : 0.4066) \quad \Leftarrow \text{Good agreement}
\end{align*}
\]
Comparison to $M_W$ Measurements

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

- Extract $M_W$ from NuTeV $\sin^2 \theta_W$ value

\[M_W = 80.136 \pm 0.084 \text{ GeV}\]

QCD and electroweak radiative corrections are small

Precision comparable to collider measurements but value is smaller

- $80.433 \pm 0.079$ \hspace{1cm} CDF
- $80.483 \pm 0.084$ \hspace{1cm} D0
- $80.471 \pm 0.049$ \hspace{1cm} ALEPH*
- $80.401 \pm 0.066$ \hspace{1cm} DELPHI*
- $80.398 \pm 0.069$ \hspace{1cm} L3*
- $80.490 \pm 0.065$ \hspace{1cm} OPAL*
- $80.451 \pm 0.033$ \hspace{1cm} Direct World Average
- $80.376 \pm 0.023$ \hspace{1cm} Indirect World Average (LEP1/SLD/APV/m$_{\mu}$) (LEPEWWG)
- $80.136 \pm 0.084$ \hspace{1cm} NuTeV

* : Preliminary
SM Global Fit with NuTeV $\sin^2\theta_W$

Fall 2001

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Pull $(O_{\text{meas}} - O_{\text{fit}})/\sigma_{\text{meas}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta\alpha_{\text{had}}^{(B)}(m_Z)$</td>
<td>0.02761 ± 0.00036, -.30</td>
</tr>
<tr>
<td>$m_Z$ [GeV]</td>
<td>91.1875 ± 0.0021, .01</td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>2.4952 ± 0.0023, -.41</td>
</tr>
<tr>
<td>$\sigma_{\text{had}}^{0}$ [nb]</td>
<td>41.540 ± 0.037, 1.63</td>
</tr>
<tr>
<td>$R_t$</td>
<td>20.767 ± 0.025, 1.06</td>
</tr>
<tr>
<td>$A_{t/b}$</td>
<td>0.01714 ± 0.00095, .76</td>
</tr>
<tr>
<td>$A_{f}(P_f)$</td>
<td>0.1465 ± 0.0033, -.45</td>
</tr>
<tr>
<td>$R_b$</td>
<td>0.21646 ± 0.00065, 1.08</td>
</tr>
<tr>
<td>$R_c$</td>
<td>0.1719 ± 0.0031, -.12</td>
</tr>
<tr>
<td>$A_{t/b}^{0,b}$</td>
<td>0.0990 ± 0.0017, -2.78</td>
</tr>
<tr>
<td>$A_{t/b}^{0,c}$</td>
<td>0.0685 ± 0.0034, -1.67</td>
</tr>
<tr>
<td>$A_b$</td>
<td>0.922 ± 0.020, -.64</td>
</tr>
<tr>
<td>$A_c$</td>
<td>0.670 ± 0.026, .07</td>
</tr>
<tr>
<td>$A_f$ (SLD)</td>
<td>0.1513 ± 0.0021, 1.61</td>
</tr>
<tr>
<td>$\sin^2\theta_{\text{eff}}^{L_{\text{lep}}}(Q_{ic})$</td>
<td>0.2324 ± 0.0012, .83</td>
</tr>
<tr>
<td>$m_W^{(\text{LEP})}$ [GeV]</td>
<td>80.450 ± 0.039, 1.50</td>
</tr>
<tr>
<td>$m_t$ [GeV]</td>
<td>174.3 ± 5.1, -.14</td>
</tr>
<tr>
<td>$m_W^{(\text{TEV})}$ [GeV]</td>
<td>80.454 ± 0.060, 1.04</td>
</tr>
<tr>
<td>$\sin^2\theta_W$ (NuTeV)</td>
<td>0.2277 ± 0.0016, 2.98</td>
</tr>
<tr>
<td>$Q_W$ (Cs)</td>
<td>-72.50 ± 0.70, .56</td>
</tr>
</tbody>
</table>

(Courtesy M. Grunewald, LEPEWWG)

- Without NuTeV: $\chi^2$/dof = 21.5/14, probability of 9.0%
- With NuTeV: $\chi^2$/dof = 30.5/15, probability of 1.0%
  
  Upper $m_{Higgs}$ limit weakens slightly 87 $\rightarrow$ 91 GeV
Possible Interpretations

• Changes in Standard Model Fits
  Change PDF sets
  Change $M_{\text{Higgs}}$

• “Old Physics” Interpretations: QCD
  Violations of “isospin” symmetry
  Strange vs anti-strange quark asymmetry

• Are ν’s Different?
  Special couplings to new particles
  Majorana neutrino effects

• “New Physics” Interpretations
  New $Z’$ or lepto-quark exchanges
  New particle loop corrections
Standard Model Fits to Quark Couplings

For an isoscalar target, the $\nu N$ couplings are:

\[
\begin{align*}
g_L^2 &= u_L^2 + d_L^2 = \rho^2 \left( \frac{1}{2} - \sin^2 \theta_W + \frac{5}{9} \sin^4 \theta_W \right) \\
g_R^2 &= u_R^2 + d_R^2 = \rho^2 \left( \frac{5}{9} \sin^4 \theta_W \right)
\end{align*}
\]

Two parameter fit to $R_{\text{exp}}^\nu$ and $R_{\text{exp}}^\bar{\nu}$:

\[
\begin{align*}
g_L^2 &= 0.3005 \pm 0.0014 \quad (SM : 0.3042) \iff 2.6\sigma \text{ difference} \\
g_R^2 &= 0.0310 \pm 0.0011 \quad (SM : 0.0301) \iff \text{agreement}
\end{align*}
\]

Example variations with LO/NLO PDF Sets (no NLO $m_c$ effects)

(S.Davidson et al. hep-ph/0112302)

- Difficult to explain discrepancy with SM using:
  - Parton distributions or LO vs NLO
  - Electroweak radiative corrections: heavy $m_{ \text{Higgs}}$
“Old Physics” Interpretations: QCD

$R^-$ technique could be sensitive to $q/\bar{q}$ differences:

$$R^- = g_L^2 - g_R^2 + \frac{\int xdx \left\{ (u_{val}^p - d_{val}^n) - (d_{val}^p - u_{val}^n) + (c - \bar{c}) - (s - \bar{s}) \right\}}{\int xdx \left( u_{val}^p + d_{val}^p \right)} \times \left\{ 3(g_{Lu}^2 - g_{Ru}^2) + (g_{Ld}^2 - g_{Rd}^2) \right\} + \ldots$$

- Valence quark momentum fraction $\int xdx \left( u_{val}^p + d_{val}^p \right) \approx 0.18$
  $\Rightarrow \int xdx \left\{ (u_{val}^p - d_{val}^n) - (d_{val}^p - u_{val}^n) + (c - \bar{c}) - (s - \bar{s}) \right\} \approx -0.038$
  could explain the NuTeV vs SM difference

- Isospin symmetry assumption: $u^p = d^n$ and $d^p = u^n$

  Expect violations around $(m_u - m_d)/\Lambda_{QCD} \approx 1\% \Rightarrow \delta \sin^2 \theta_W = 0.0004$

  Model dependent: Bag Models, Meson Cloud Models, ...

  give small $\delta \sin^2 \theta_W$ of this order.

  (Thomas et al., PL A9 1799, Cao et al., PhysRev C62 015203)

- Strange vs anti-strange quark asymmetry $\Delta s = \int xdx \left( s - \bar{s} \right)$

  The number of strange vs anti-strange needs to be the same but the momentum distributions could differ.

  - An asymmetry of $\Delta s = 0.002$ gives $\delta \sin^2 \theta_W = 0.0026$
  - CCFR/NuTeV $\nu$-dimuons limit the size of $\Delta s \ll 0.002$

Are $\nu$’s Different?

- NuTeV result fits 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”
  \[ N_\nu = 3 \frac{\Gamma_{\exp}(Z \to \nu\bar{\nu})}{\Gamma_{SM}(Z \to \nu\bar{\nu})} = 3 \times (0.9947 \pm 0.0028) \leq 1.9\sigma \text{ low} \]

- If neutrinos are Majorana, they may have different fundamental couplings from other particles to an extra U(1) type $Z'$
  - Majorana neutrinos could have zero charge wrt to extra U(1)
  - Can this explain why charged leptons are different from $\nu$’s?
“New Physics” Interpretations

- Z’, LQ, ... exchange
- NuTeV needs LL enhanced relative to LR coupling

- Oblique (propagator) corrections
  Constrained by SM fits

- Gauge boson interactions
  Allow generic couplings
  Example: Extra Z’ boson
  - Mixing with E(6) Z’
  - Z’=$Z_x\cos\beta + Z_y\cos\beta$
  - LEP/SLC mix<$10^{-3}$

- Hard to accommodate entire NuTeV discrepancy.
  Global fits somewhat better with E(6) Z’ included
  Example: Erler and Langacker: SM $\Delta \chi^2 \approx 7.5$
  $m_{Z'}=600 \text{ GeV}$, mixing $\sim 10^{-3}$, $\beta \approx 1.2$
  “Almost sequential” Z’ with opposite coupling
  - NuTeV would want $m_{Z'} \sim 1.2 \text{ TeV}$
  - CDF/D0 Limits: $m_{Z'} > 700 \text{ GeV}$

Langacker et al., Rev.Mod.Phys.64,87; Davidson et al., hep-ph/0112302.)
Recent Summary of Possible Interpretations

*S.Davidson, S.Forte, P.Gambino, N.Rius, A.Strumia (hep-ph/0112302)*

• **QCD effects:**
  – Small asymmetry in momentum carried by strange vs antistrange quarks \(\Rightarrow\) CCFR/NuTeV \(\nu\) dimuons limits
  – Small isospin violation in PDFs \(\Rightarrow\) expected to be small

• **Propagator and coupling corrections to SM gauge bosons:**
  – Small compared to effect
  – Hard to change only \(\nu Z\nu\)

• **MSSM:**
  – Loop corrections wrong sign and small compared to NuTeV

• **Contact Interactions:**
  – Left-handed quark-quark-lepton-lepton vertices, \(\epsilon_{\text{LL}}^{\nu\nuqq}\), with strength \(\sim 0.01\) of the weak interaction \(\Rightarrow\) Look Tevatron Run II

• **Leptoquarks:**
  – SU(2)\(_L\) triplet with non-degenerate masses can fit NuTeV and evade \(\pi\)–decay constraints

• **Extra U(1) vector bosons:**
  – An unmixed \(Z'\) with B-3L\(_\mu\) symmetry can explain NuTeV
  – Mass: \(600 < M_{Z'} < 5000\) GeV or \(1 < M_{Z'} < 10\) GeV
  – Light \(Z'\) may relate to:
    • GZK cutoff UHE cosmic-rays (\(\nu\nu\rightarrow qq\))
    • Source of heavy neutral leptons: NuTeV anomalous dimuon signal.
Summary

• NuTeV measurement has the precision to be important for SM electroweak test

• For NuTeV the SM predicts $0.2227 \pm 0.0003$ but we measure

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

  (Previous neutrino measurements gave $0.2277 \pm 0.0036$)

• In comparison to the Standard Model

  The NuTeV data prefers a lower effective left-handed quark coupling

• The discrepancy with the Standard Model could be related to:

  Quark model uncertainties but looks like only partially and / or

  Possibly new physics that is associated with neutrinos and interactions with left-handed quarks