Departure From Prediction: Electroweak Physics at NuTeV

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Les Rencontres de Physique de la Vallée d'Aoste
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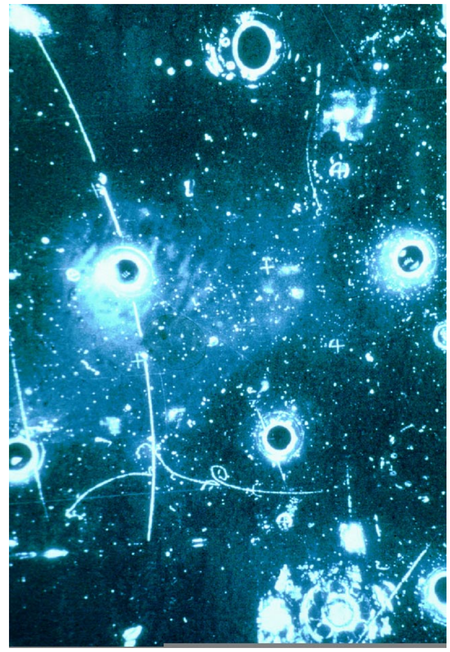
<u>Outline</u>

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

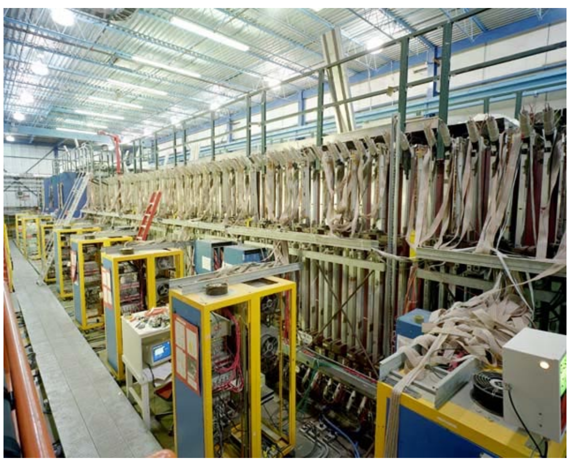
The Role of NuTeV

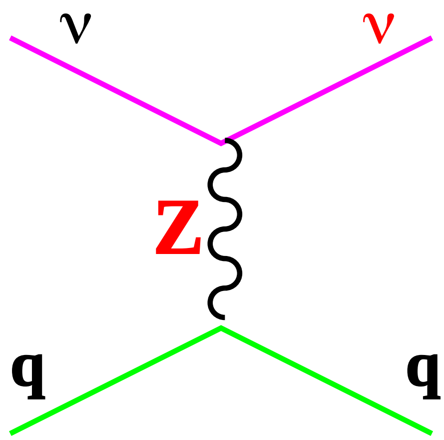
Neutrino scattering played a key historical role in electroweak unification



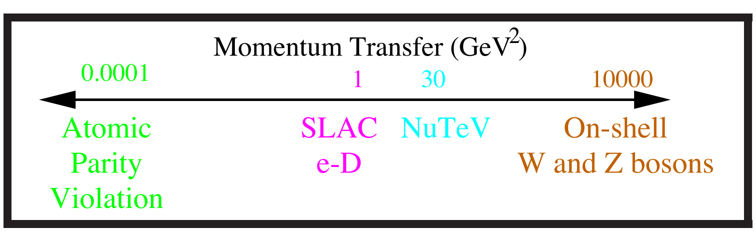
- Discovery of Neutral Current (Gargamelle, FNAL-E1A)
- First determimation of high-energy parameter
  $\sin^2\theta_W \sim 0.2 \;\Rightarrow\; \frac{M_W}{M_Z} \sim 0.9$

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



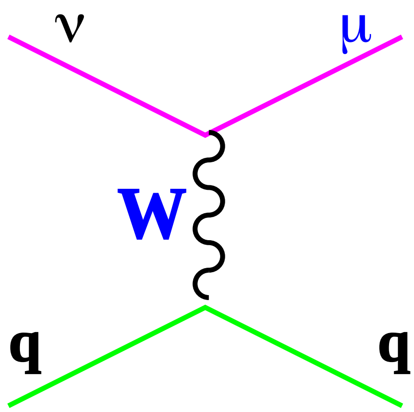


- Testing in a wide range of processes and momentum scales ensures universality of the electroweak theory

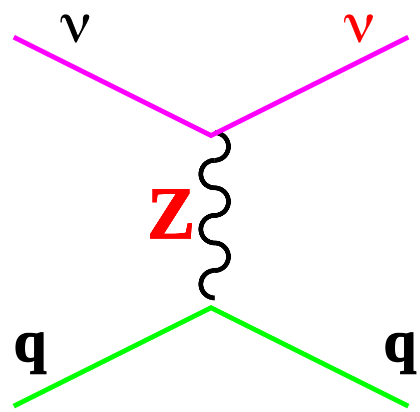


- NuTeV is sensitive to different processes
  - ↪ Measurement is off the Z pole (contributions besides Z?)
  - ↪ Measure neutral current neutrino couplings
    - ⋆ LEP I invisible line width is only other precise measurement

Methodology



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



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

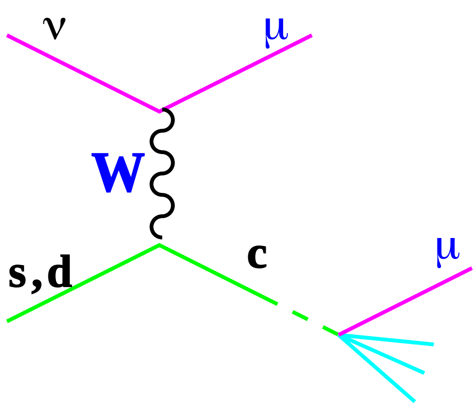
Isoscalar target composed of only u,d quarks at tree level:

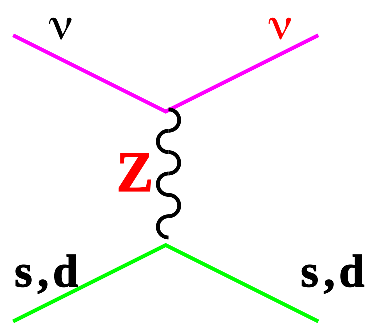
Llewellyn Smith Relation:

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

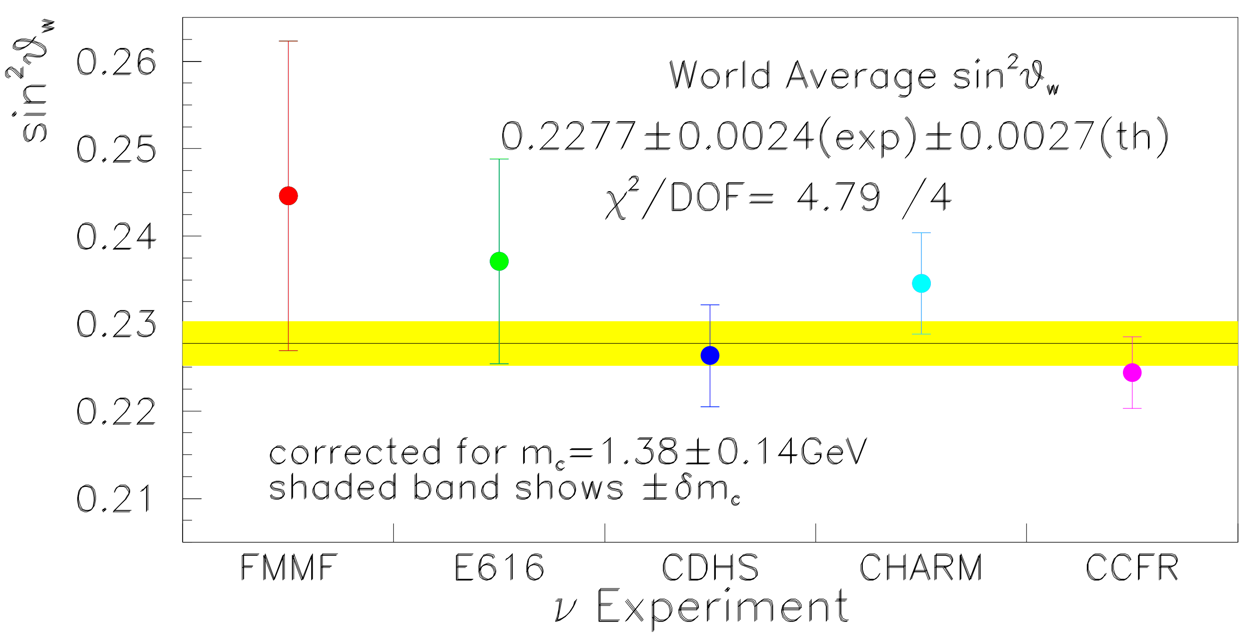
- R^ν, $R^{\overline{\nu}}$ easy to measure experimentally
- To extract $\sin^2\theta_W$ from the measured ratio:
  - ↪ isovector target ($2Z \neq A$)
  - ↪ heavy quark seas (and kinematic suppression)
  - ↪ radiative corrections, higher twist, R_L
- Most of the PDF dependence, many of systematic uncertainties, 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 ($x \longrightarrow \xi = \frac{Q^2+m_c^2}{2M\nu}$)
- Parameters measured by NuTeV/CCFR in dimuon events $c \to \mu X$
- Limited precision of previous νN measurements of $\sin^2\theta_W$ ...



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

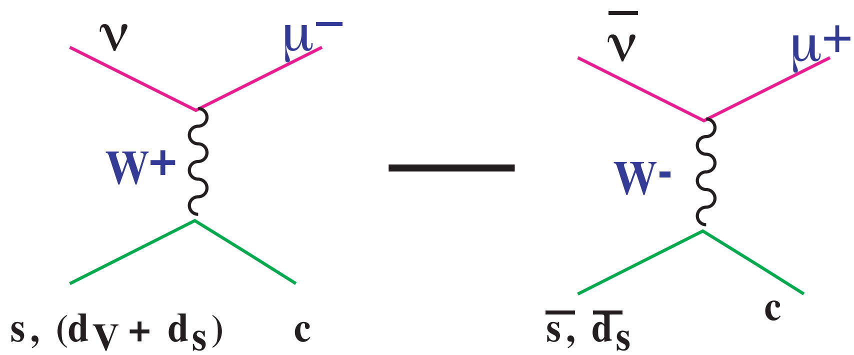
$$\rightarrow M_W = 80.14 \pm 0.19 \text{ GeV}$$

NuTeV's Approach

Large charm production errors $\Rightarrow$ need technique insensitive to sea

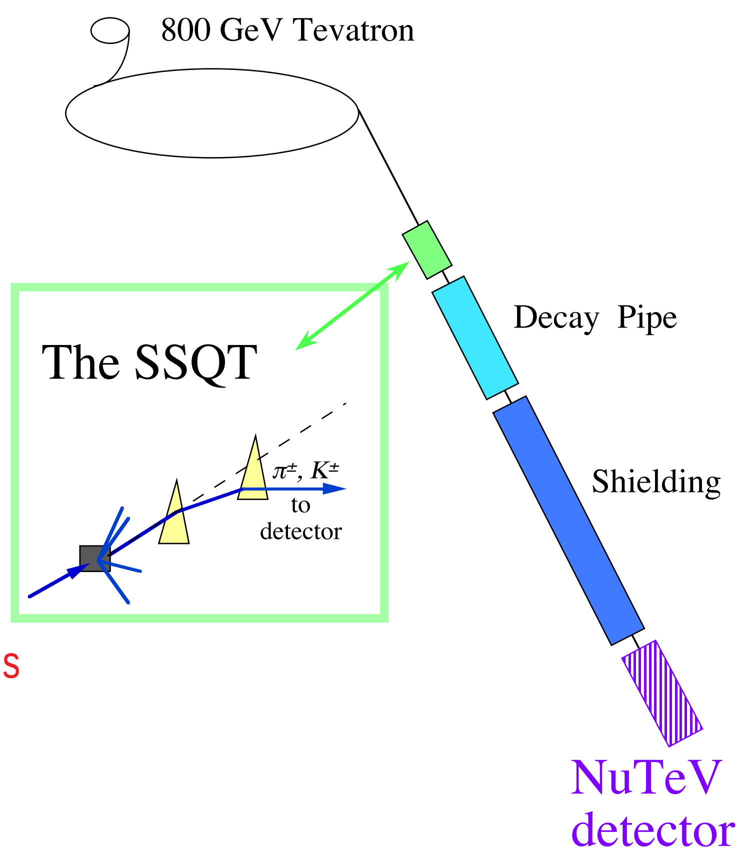
Paschos-Wolfenstein Relation:

$$R^{-} = \frac{\sigma^{\nu}_{NC} - \sigma^{\overline{\nu}}_{NC}}{\sigma^{\nu}_{CC} - \sigma^{\overline{\nu}}_{CC}} = \frac{R^{\nu} - rR^{\overline{\nu}}}{1-r}$$
$$= \rho^2 \left(\frac{1}{2} - \sin^2\theta_W\right)$$

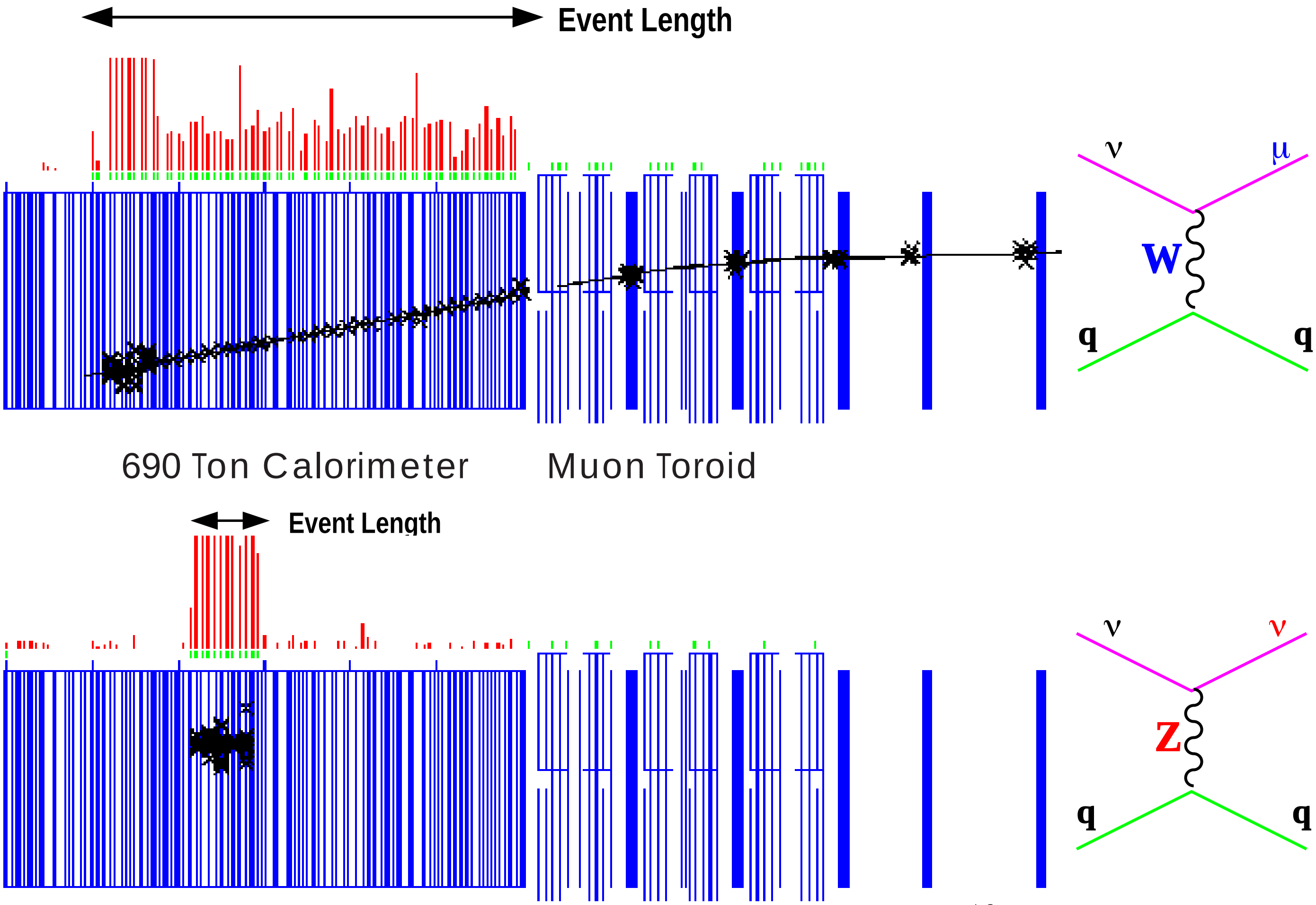


- R^{-} is manifestly insensitive to sea quarks
  - ↪ Charm and strange sea errors are negligible ...
    (Most of charm from s(x) scattering)
  - ↪ Massive charm production enters from d_V quarks only ...
    (Cabbibo suppressed and at high x)
- Requires separate ν, $\overline{\nu}$ beams $\Rightarrow$

  NuTeV SSQT



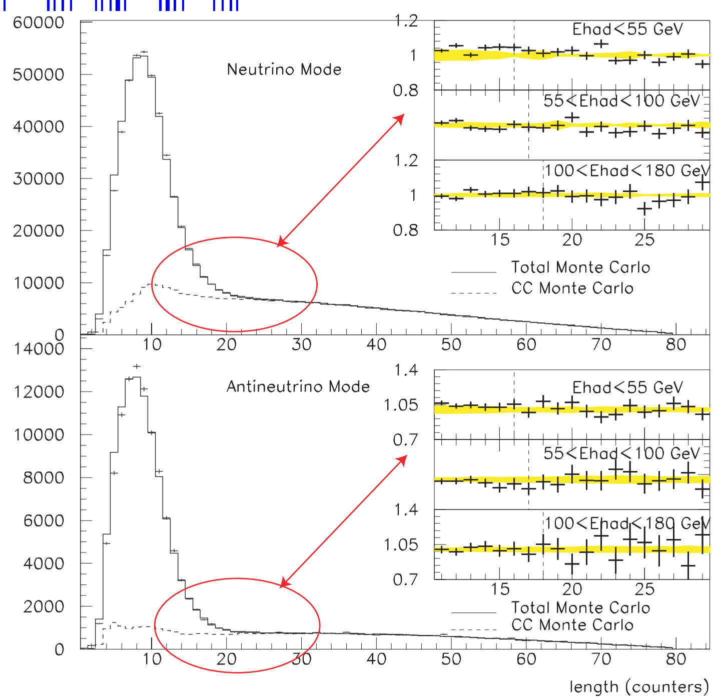
Neutral Current/Charged Current Event Separation



Separate by simple **length cut**

$$R_{exp} = \frac{SHORT\ events}{LONG\ events} = \frac{L \leq Lcut}{L > Lcut} = \frac{NC\ candidates}{CC\ candidates}$$

in ν and $\overline{\nu}$ beams (1.62 and 0.35 million events)



Summary of Corrections to R_{exp}

Corrections Applied to Data

Effect	δR^{ν}_{exp}	$\delta R^{\overline{\nu}}_{exp}$	Control
Cosmic Ray Background	–0.0036	–0.019	†
Beam μ Background	+0.0008	+0.0012	†
Vertex Efficiency	+0.0008	+0.0010	†

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

Effect	δR^{ν}_{exp}	$\delta R^{\overline{\nu}}_{exp}$	Control
Short CC Background	–0.068	–0.026	†, √
nu nubar Electron Neutrinos	–0.021	–0.024	♮, √
Long NC	+0.0028	+0.0029	†, √
Counter Noise	+0.0044	+0.0016	†
Heavy m_c	–0.0052	–0.0117	†, ♣
R_L	–0.0026	–0.0092	†, ♣
EM Radiative Correction	+0.0074	+0.0109	
Weak Radiative Correction	–0.0005	-0.0058	
d/u	–0.00023	–0.00023	†
Higher Twist	–0.00012	–0.00013	†

Recall: R^{ν}_{exp} and $R^{\overline{\nu}}_{exp}$ measured to a precision of 0.0013 and 0.0027, respectively

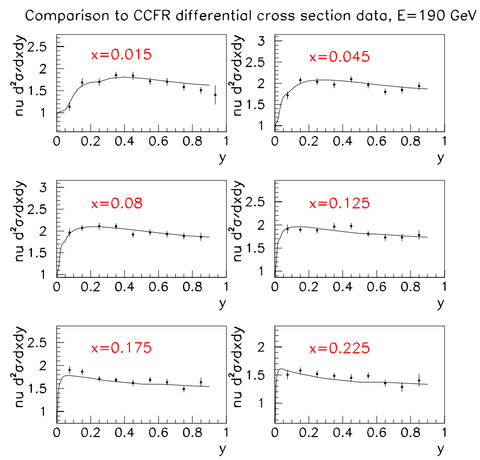
Key to coping techniques

†: Determined from data
√: Checked with data
♮: Independent Simulation
♣: R^{-} technique

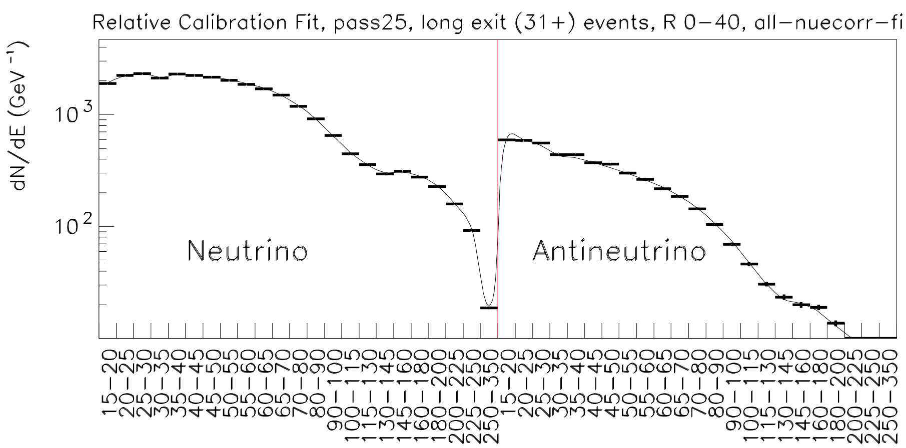
ν_μ Charged-Current Background

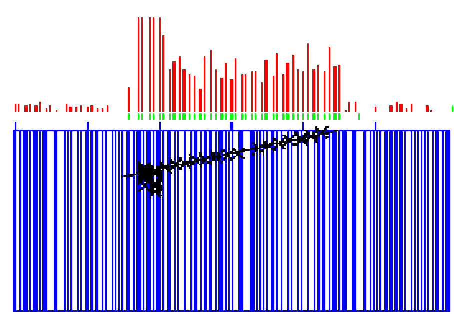
- High y charged-current is background to NC sample
  - $\overset{(-)}{\nu}$ NC & CC quark model cross-section

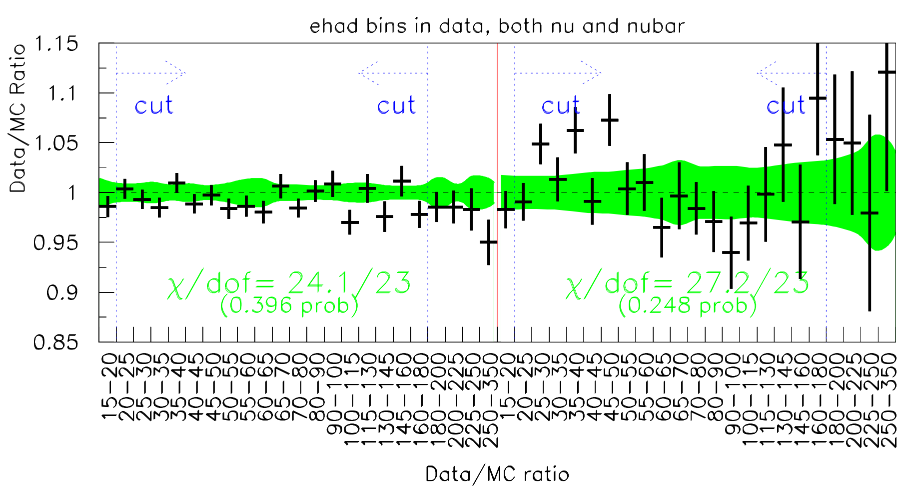
    $\hookrightarrow$ R_L term added to F_2, xF_3 to describe $g \to q\overline{q}$
  - PDFs extracted from CCFR σ_{CC}
  - Other data determines $s(x)$, d/u, R_L, higher twist, $F_2^{c\overline{c}}$

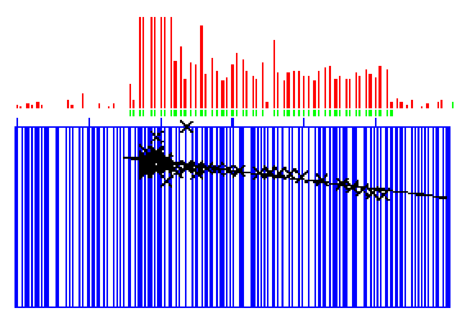


- Data-driven: uncertainties come from measurements







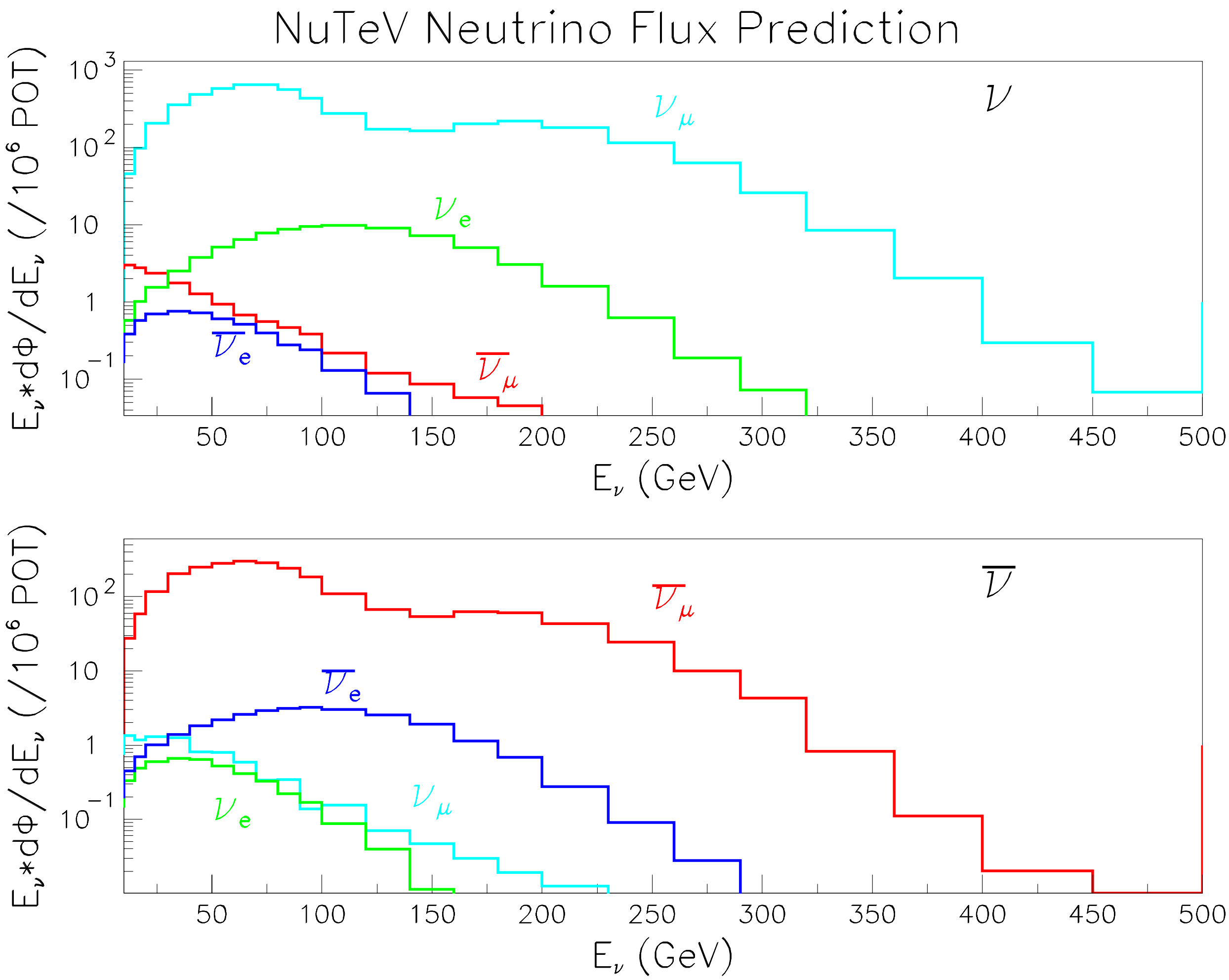


- Check by looking at "long exit" CC events which start in the detector center and stop before toroid

Electron Neutrinos

Approximately 5% of all short events are ν_e CC.

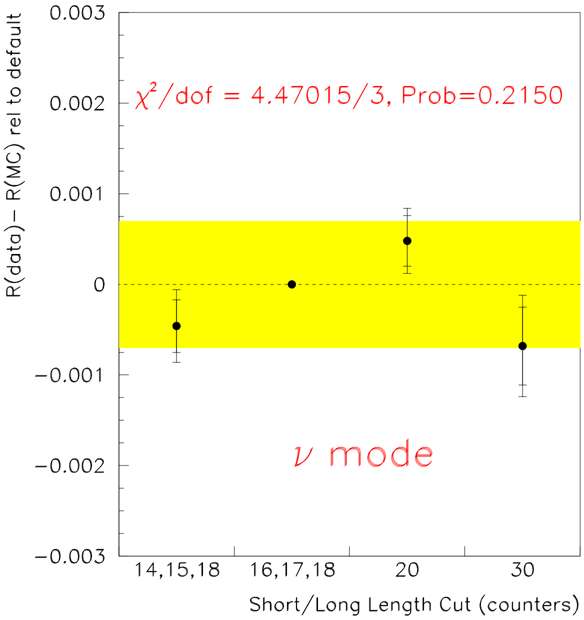
$\Rightarrow$ *It would take a* 20% *mistake in* ν_e *to move* $\sin^2\theta_W$ *to SM value*

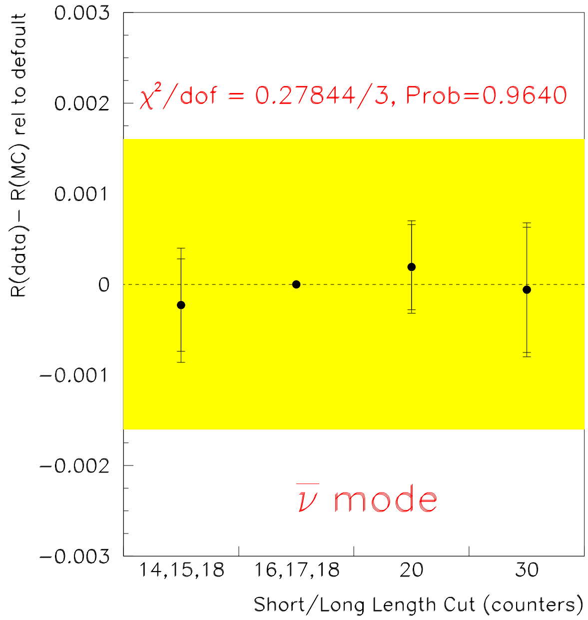


- Excess of ν_e over $\overline{\nu}_e$ in ν beam is due to K^+_{e3} decay
  - ↪ Vast majority of ν_e/$\overline{\nu}_e$ in ν/$\overline{\nu}$ beams
  - ↪ K_L and charm decay, which make both ν_e and $\overline{\nu}_e$, are small
- $K^\pm_{e3}$ decay is very well understood
  - ↪ $K^\pm$ production. . . *is constrained by* ν_μ *and* $\overline{\nu}_\mu$ *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 ν_e and $\overline{\nu}_e$
  - ↪ N_{meas}/N_{pred}: 1.05 ± 0.03 (ν_e), 1.01 ± 0.04 ($\overline{\nu}_e$) ($80 < E_\nu < 180$ GeV)

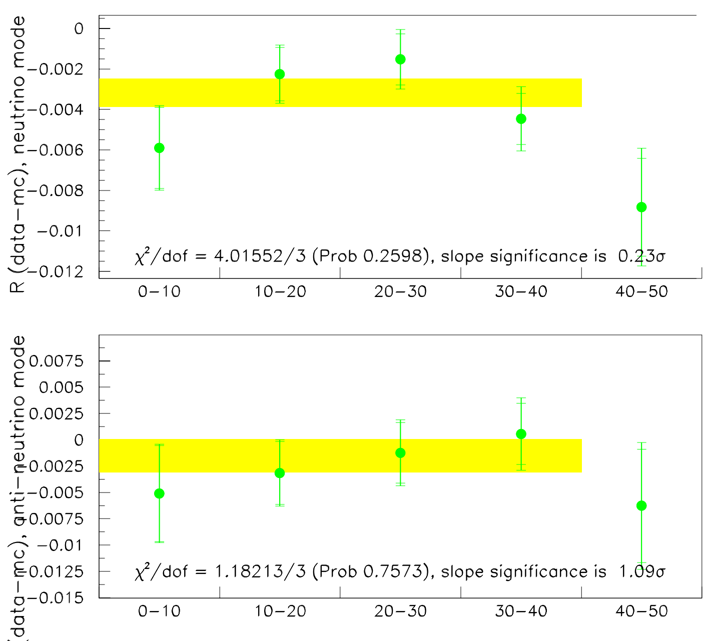
Stability of R_{exp} (cont'd)

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

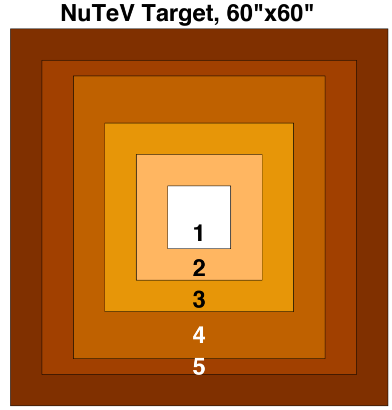




- R vs. "radial bin": Checks electron neutrino and short CC events
  More NC background near edge



NuTeV Target, 60"x60"

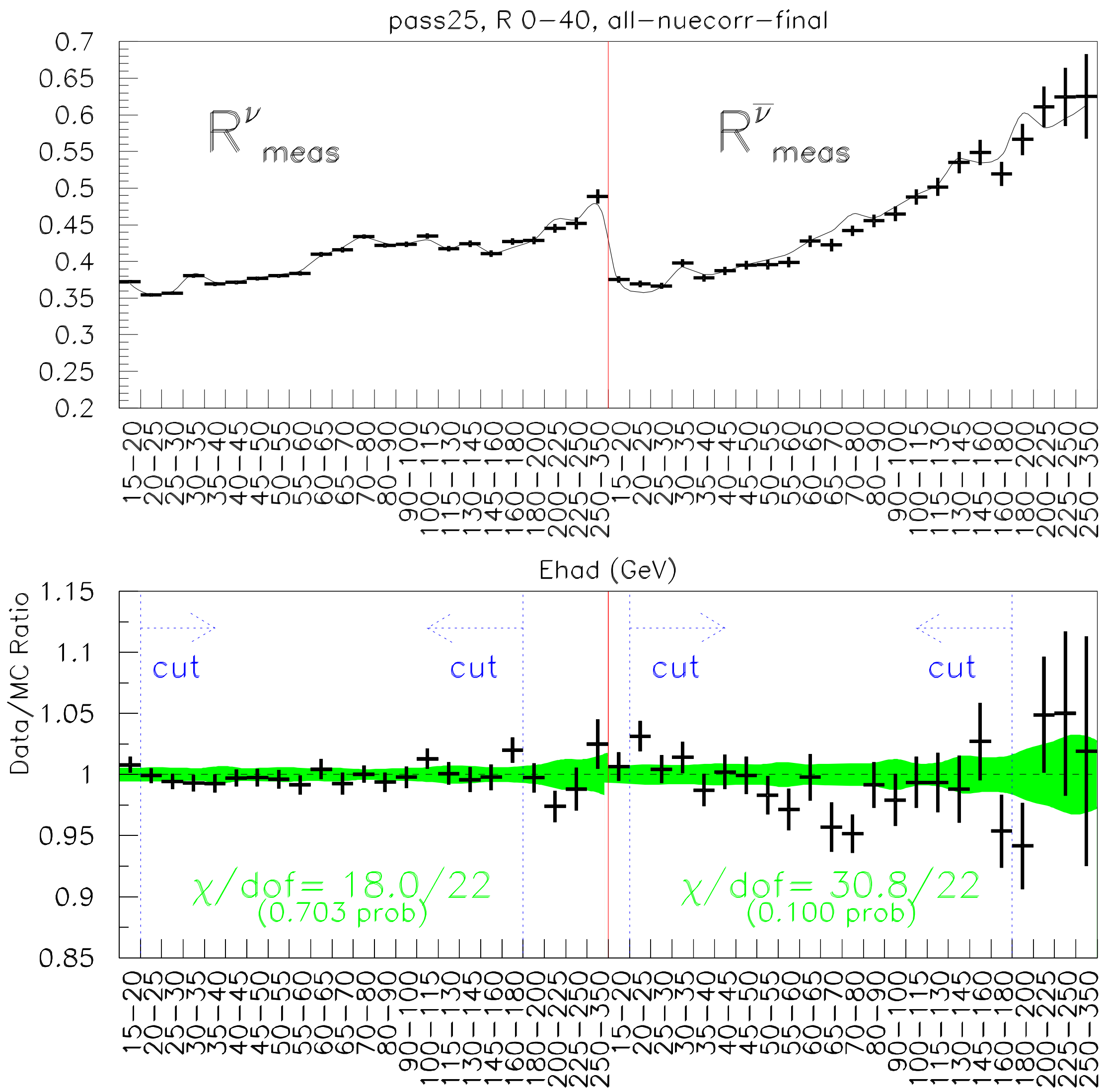


"Radial" Bins

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, ...



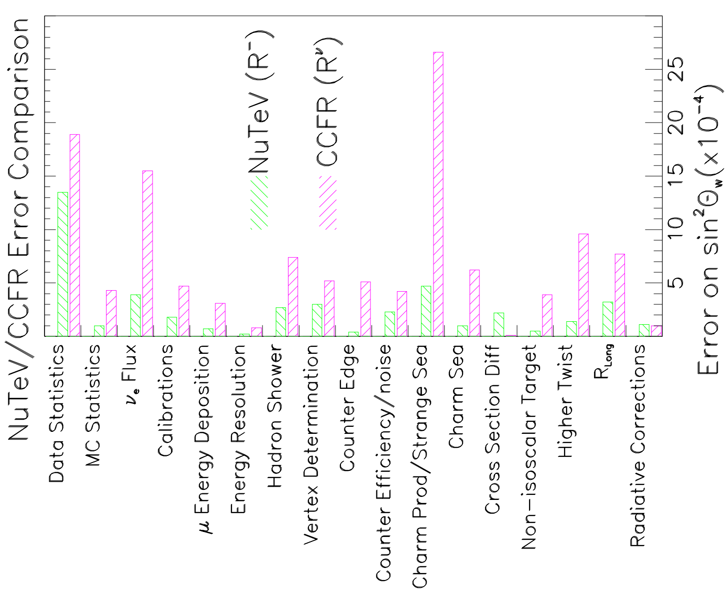
(Green band is $\pm 1\sigma$ systematic uncertainty)

The Result

$$\begin{aligned}\sin^2\theta_W^{(on-shell)} &= 0.2277 \pm 0.0013\,(stat) \pm 0.0009\,(syst) \\ &- 0.00022 \cdot \left(\frac{M_{top}^2 - (175\,GeV)^2}{(50\,GeV)^2}\right) \\ &+ 0.00032 \cdot \ln\left(\frac{M_{Higgs}}{150\,GeV}\right)\end{aligned}$$

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

SOURCE OF UNCERTAINTY	$\delta\sin^2\theta_W$	δR^{ν}_{exp}	$\delta R^{\overline{\nu}}_{exp}$
Data Statistics	0.00135	0.00069	0.00159
Monte Carlo Statistics	0.00010	0.00006	0.00010
TOTAL STATISTICS	0.00135	0.00069	0.00159
$\nu_e, \overline{\nu}_e$ Flux	0.00039	0.00025	0.00044
Interaction Vertex	0.00030	0.00022	0.00017
Shower Length Model	0.00027	0.00021	0.00020
Counter Efficiency, Noise, Size	0.00023	0.00014	0.00006
Energy Measurement	0.00018	0.00015	0.00024
TOTAL EXPERIMENTAL	0.00063	0.00044	0.00057
Charm Production, $s(x)$	0.00047	0.00089	0.00184
R_L	0.00032	0.00045	0.00101
$\sigma^{\overline{\nu}}/\sigma^{\nu}$	0.00022	0.00007	0.00026
Higher Twist	0.00014	0.00012	0.00013
Radiative Corrections	0.00011	0.00005	0.00006
Charm Sea	0.00010	0.00005	0.00004
Non-Isoscalar Target	0.00005	0.00004	0.00004
TOTAL MODEL	0.00064	0.00101	0.00212
TOTAL UNCERTAINTY	0.00162	0.00130	0.00272



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

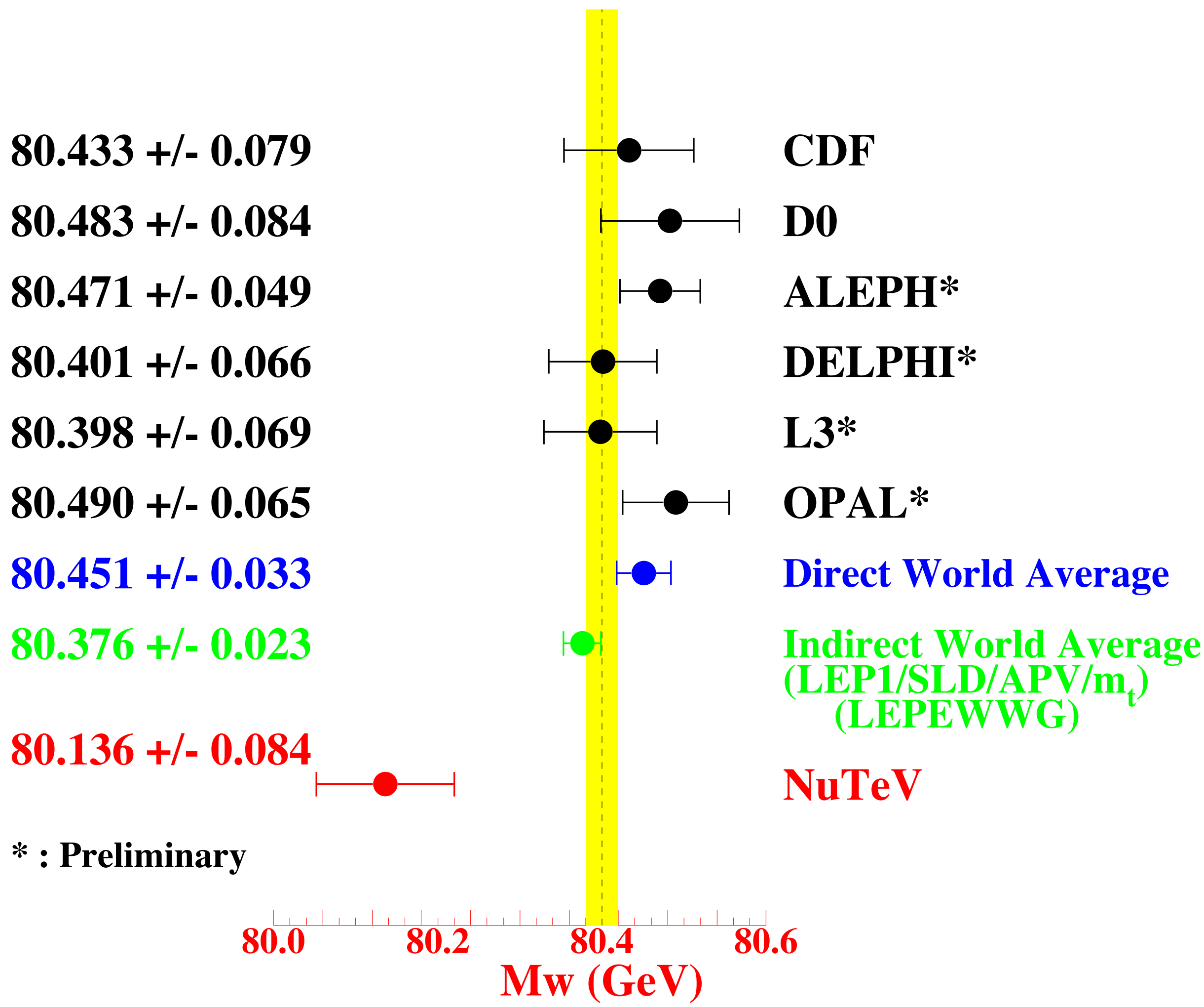
- R^- method makes charm production error small
- Few K_L because of beam $\Rightarrow \nu_e$ greatly reduced

Comparison to Direct M_W

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

Given the precise measurement of the Z mass from LEP...

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



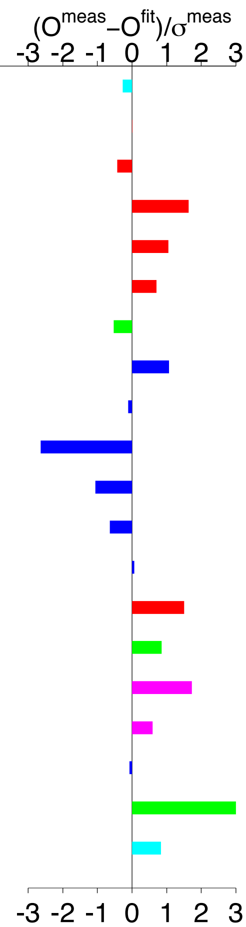
- In standard electroweak theory, NuTeV precision is comparable to a single direct measurement of M_W
- More inconsistent with direct M_W than other data

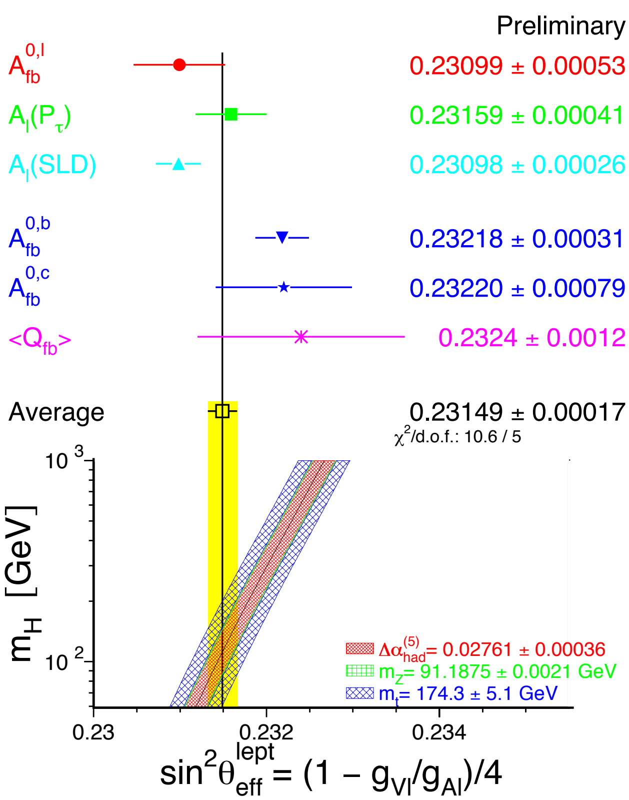
How Healthy is the EW Fit?

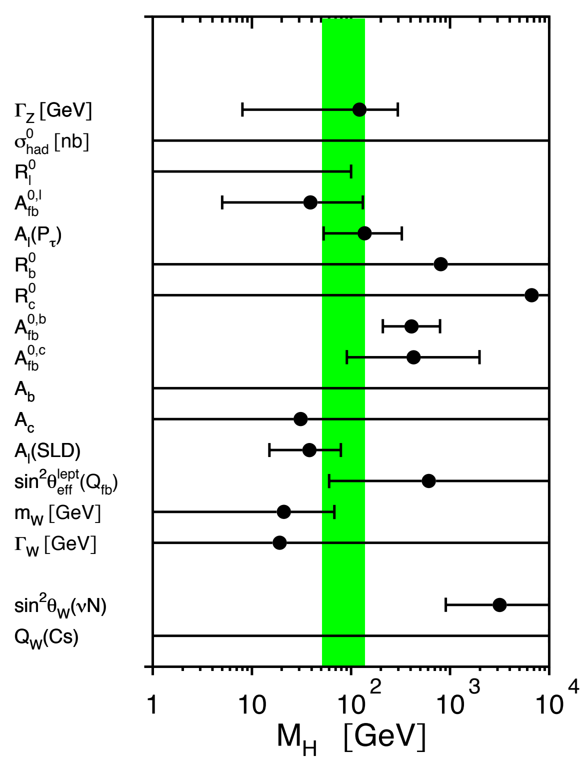
- Global fit has a χ^2 of $\chi^2/\mathrm{dof} = 19.6/14$ (probability of 14%)
- Two most precise measurements of $\sin^2\theta_W$ at Z pole differ by 3σ
- Data suggest light Higgs except $A_{FB}^{0,b}$
- σ_{had} also off by $\sim 2\sigma$
- Adding NuTeV: $\chi^2/\mathrm{dof} = 28.8/15$ (probability of 1.7%)

Winter 2002

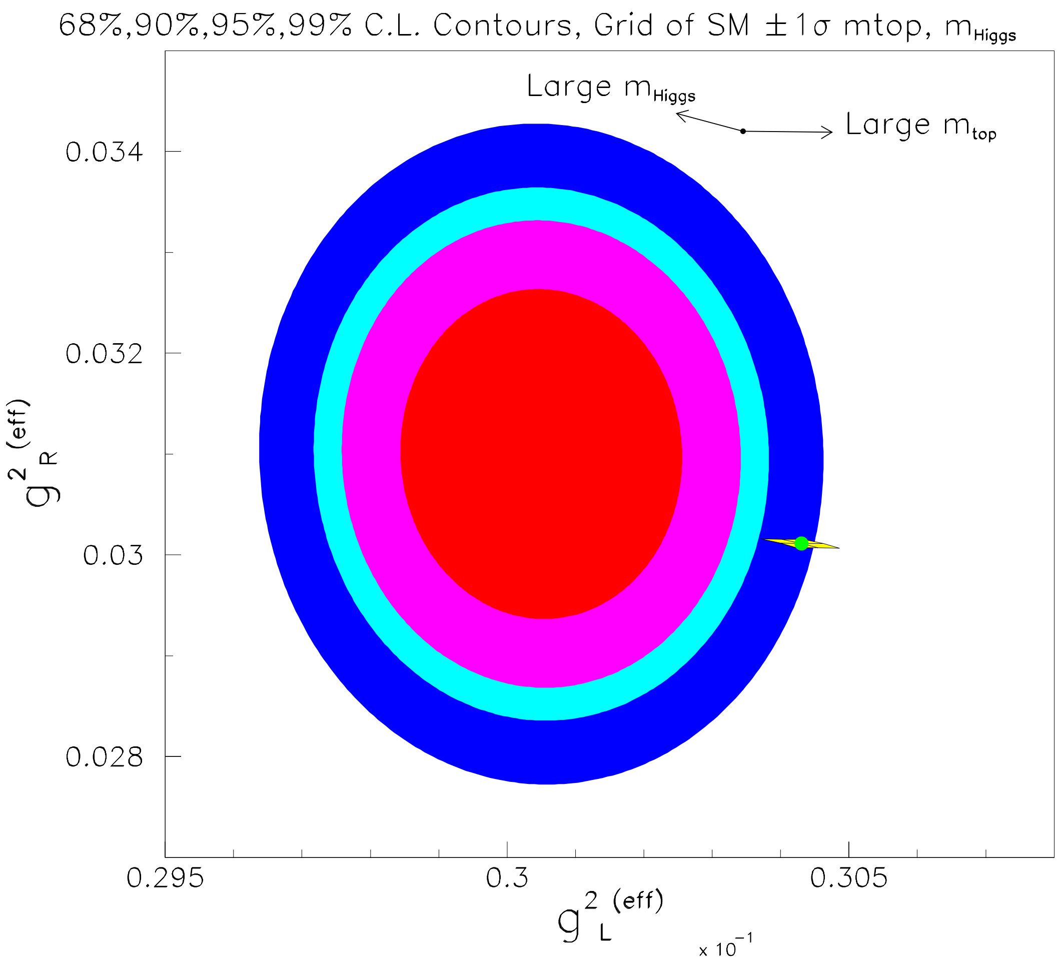
	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-.27
m_Z [GeV]	91.1875 ± 0.0021	.01
Γ_Z [GeV]	2.4952 ± 0.0023	-.42
σ^0_{had} [nb]	41.540 ± 0.037	1.63
R_l	20.767 ± 0.025	1.05
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.70
$A_l(P_\tau)$	0.1465 ± 0.0033	-.53
R_b	0.21646 ± 0.00065	1.06
R_c	0.1719 ± 0.0031	-.11
$A^{0,b}_{fb}$	0.0994 ± 0.0017	-2.64
$A^{0,c}_{fb}$	0.0707 ± 0.0034	-1.05
A_b	0.922 ± 0.020	-.64
A_c	0.670 ± 0.026	.06
A_l(SLD)	0.1513 ± 0.0021	1.50
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	.86
m_W [GeV]	80.451 ± 0.033	1.73
Γ_W [GeV]	2.134 ± 0.069	.59
m_t [GeV]	174.3 ± 5.1	-.08
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	3.00
Q_W(Cs)	-72.39 ± 0.59	.84







Quark Couplings: $(g_L^{eff})^2$ and $(g_R^{eff})^2$



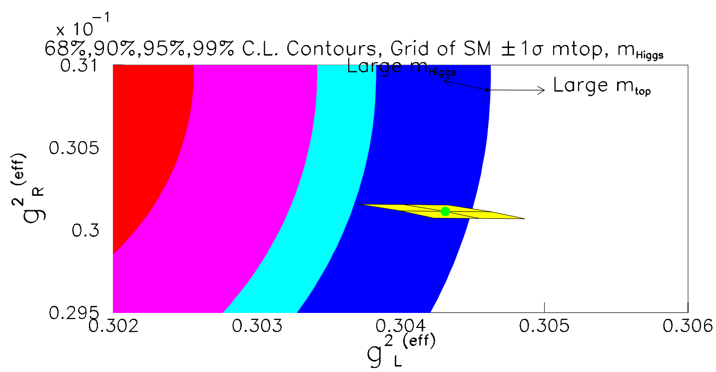
2 parameter fit to R^ν, $R^{\overline{\nu}}$:

$$R^\nu = g_L^2 + r\, g_R^2$$
$$R^{\overline{\nu}} = g_L^2 + \frac{1}{r}\, g_R^2$$

$$g_L^2 \equiv u_L^2 + d_L^2$$
$$g_R^2 \equiv u_R^2 + d_R^2$$

NuTeV measures:

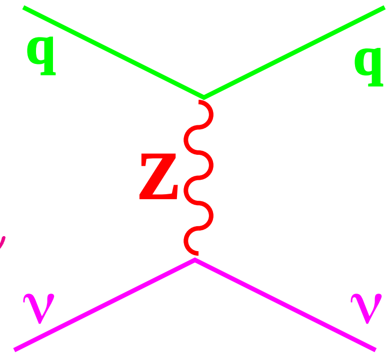
$$(g_L^{eff})^2 = 0.3005 \pm 0.0014$$
$$(g_R^{eff})^2 = 0.0310 \pm 0.0011$$
$$\rho_{corr} = -0.02$$



- Assuming predicted ν coupling, $(g_L^{eff})^2$ appears low

Interpretations

- Symmetry violating PDFs
- Extra Z' bosons
- Neutral current coupling of ν



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, $s = \overline{s}$ and $c = \overline{c}$

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., $s(x) \neq \overline{s}(x)$

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

where

$$
\begin{aligned}
\delta D_v &\equiv D_p - \overline{D}_p - U_n + \overline{U}_n \\
\delta U_v &\equiv U_p - \overline{U}_p - D_n + \overline{D}_n \\
\delta S &\equiv S - \overline{S} \\
\delta N &\equiv A - 2Z/A \\
V_p &\equiv U_p - \overline{U}_p + D_p - \overline{D}_p,
\end{aligned}
$$

Q_N is the total momentum carried by quark Q in nucleon N,

and $\epsilon_c \equiv \dfrac{\sigma(\nu s \to \mu c)}{\sigma(\nu s \to \mu c,\ m_c = 0)}$

The NuTeV analysis only corrects for δN

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. LettA9, 1799.

$\hookrightarrow$ $\delta \sin^2\theta_W^{(on-shell)} = -0.0001$

$\hookrightarrow$ ~ 0.0004 shifts at high, low x cancel

Meson Cloud model

Cao & Signal, Phys. Rev. **C62**, 015203.

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

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

Strange-Antistrange Sea Asymmetry

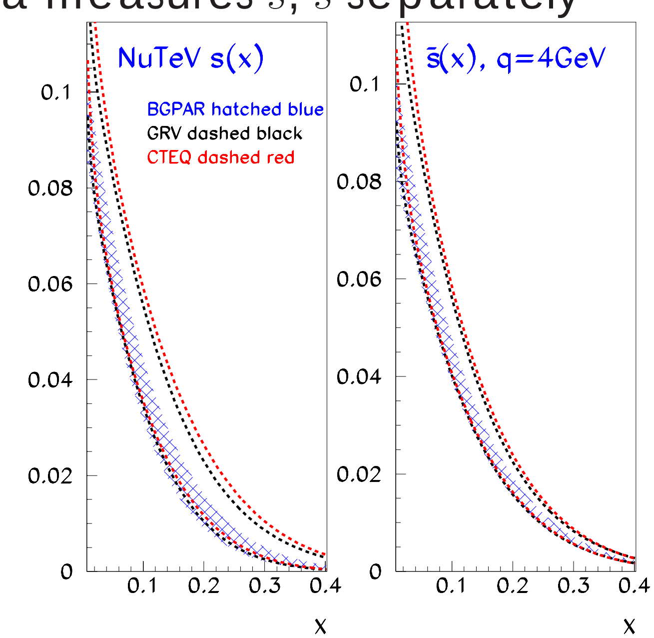
- If $S - \overline{S} \sim +0.0020$, $\Longrightarrow$ $\delta \sin^2\theta_W = -0.0026$ $(\epsilon_c = 1)$

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

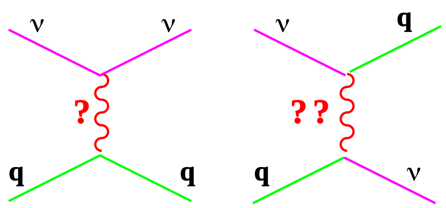
- But NuTeV dimuon data measures s, $\overline{s}$ separately

$$S - \overline{S} = -0.0027 \pm 0.0013$$
$$\Longrightarrow \delta \sin^2\theta_W \sim +0.0020 \pm 0.0009$$

Then $\sin^2\theta_W = 0.2297 \pm 0.0019$ (3.7σ above SM)



New Tree Level Physics?

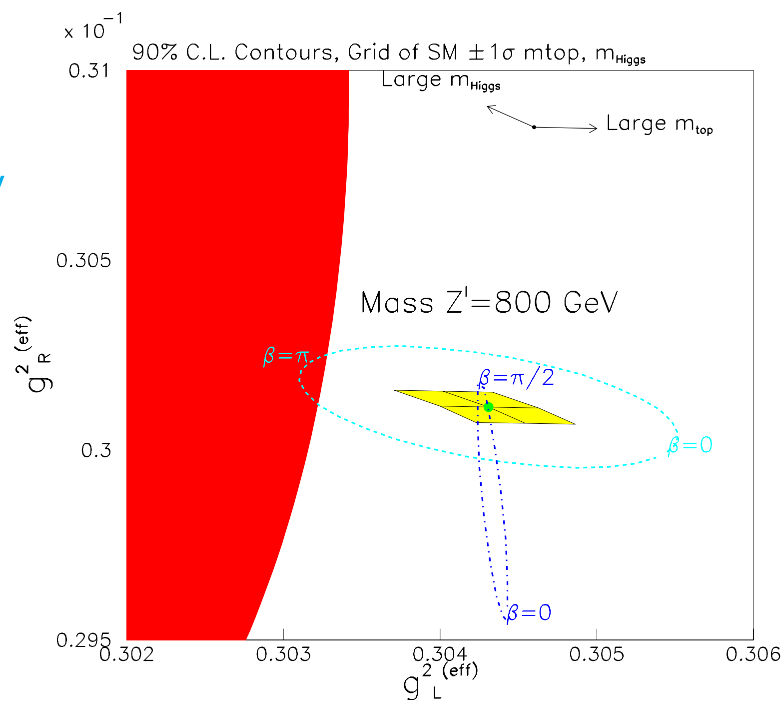


- "Natural" interpretation of result
- Z', LQ, etc.
- Must enhance LL not LR coupling

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

$$(Z' \equiv Z_\chi cos\beta + Z_\psi \sin\beta)$$

(Cho *et al.*, Nucl. Phys. **B531**, 65.
Zeppenfeld and Cheung, hep-ph/9810277.
Langacker *et al.*, Rev. Mod. Phys. **64** 87.)



- Erler and Langackger:
  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 ν
  - ↪ 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
  - ↪ $\nu\nu qq$ Contact term, $\Lambda_{LL} = 4.5 \pm 1$ TeV

$$-\mathcal{L} = \sum_{H_q\in\{L,R\}} \frac{\pm 4\pi}{\left(\Lambda^{\pm}_{LH_q}\right)^2} \times \{\overline{l_L}\gamma^\mu l_L \overline{q_{H_q}}\gamma_\mu q_{H_q} + l_L\gamma^\mu \overline{l_L}\overline{q_{H_q}}\gamma_\mu q_{H_q} + C.C.)$$

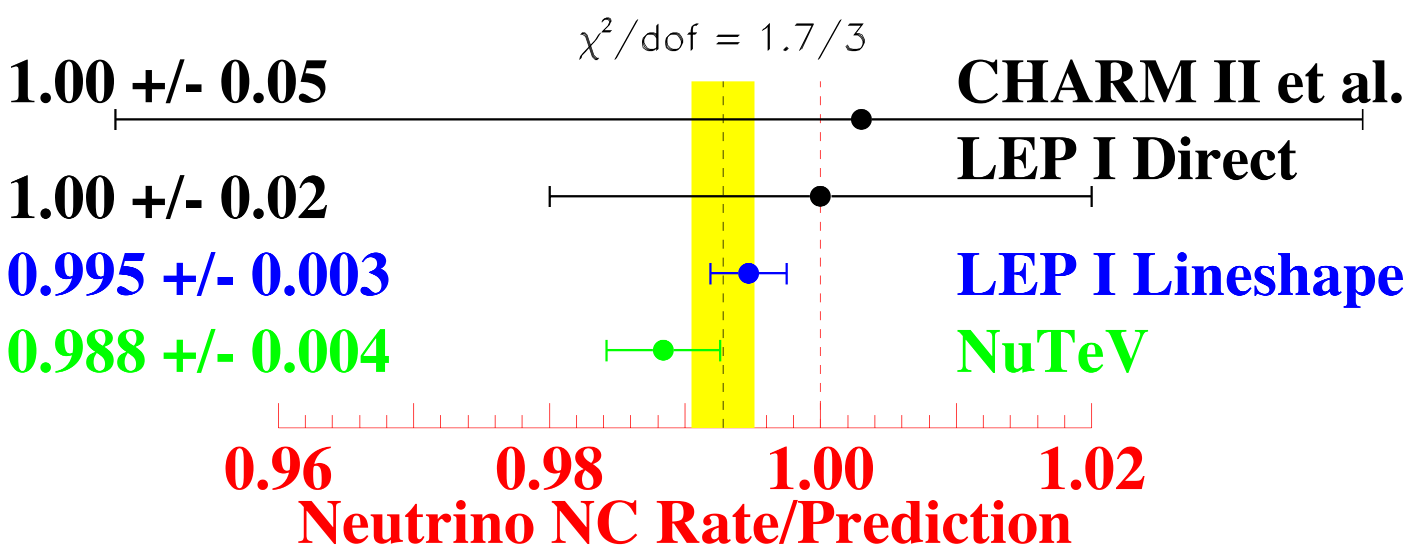
(Langacker *et al.*, Rev. Mod. Phys. **64** 87.)

Neutral Current ν Interactions

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

- $\overset{(-)}{\nu}_\mu e^- \to \overset{(-)}{\nu}_\mu e^-$ scattering (CHARM II *et al.*)
  - ↪ PDG fit: $g_V^2 + g_A^2 = 0.259 \pm 0.014$, cf. 0.258 predicted

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



- In this interpretation, NuTeV confirms and strengthens LEP I indications of "weaker" neutrino neutral current
  - ↪ 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^{ν}, $R^{\overline{\nu}}$ to precisely determine $\sin^2\theta_W$
- The SM predicts 0.2227 ± 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 νN 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.