Electroweak Measurements at NuTeV:
A Departure from Prediction

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WIN2002 Conference
Christchurch, New Zealand
January, 2002

- 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, $g' = g \tan\theta_W$

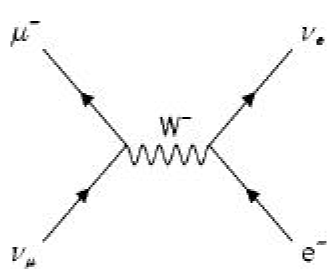
$$e = g\sin\theta_W,\; G_F = \frac{g^2\sqrt{2}}{8M_W^2},\; \frac{M_W}{M_Z} = \cos\theta_W$$

Z Couplings	g_L	g_R
ν_e, ν_μ, ν_τ	1/2	0
e, μ, τ	$-1/2 + \sin^2\theta_W$	$\sin^2\theta_W$
u, c, t	$1/2 - 2/3 \sin^2\theta_W$	$-2/3 \sin^2\theta_W$
d, s, b	$-1/2 + 1/3 \sin^2\theta_W$	$1/3 \sin^2\theta_W$

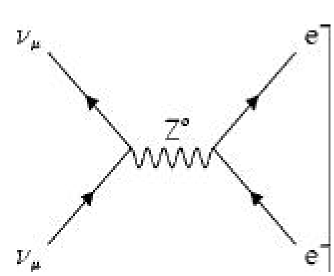
- Neutrinos are special in SM

  Only have left-handed weak interactions

  ⇒ $W^\pm$ and Z boson exchange



Charged-Current



Neutral-Current

History of EW Measurements

Gargamelle

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

Gargamelle
HPWF CIT-F

- 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

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

- 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_{top}

NuTeV D0 CDF
LEP1 SLD
LEPII APV
SLAC-E158

- Third Generations Experiments
  - Precision below 1% level
  - Test consistency of SM
  - Search for new physics and
  - Constrain M_{Higgs}
    - $\Rightarrow$ Predict light Higgs boson
      (and possibly SUSY)

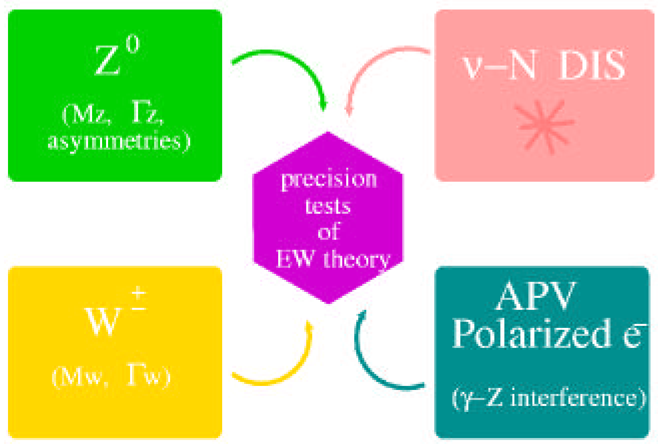
Current Era of Precision EW Measurements

- Precision parameters define the SM:

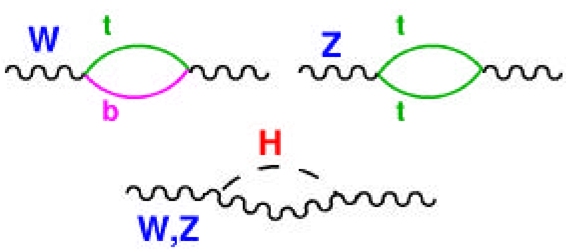
$\alpha_{EM}^{-1} = 137.03599959(40)$	45ppb (200ppm@M_Z)
$G_\mu = 1.16637(1)\times10^{-5}$ GeV^{-2}	10ppm
$M_Z = 91.1871(21)$	23ppm

- Comparisons test the SM and probe for new physics

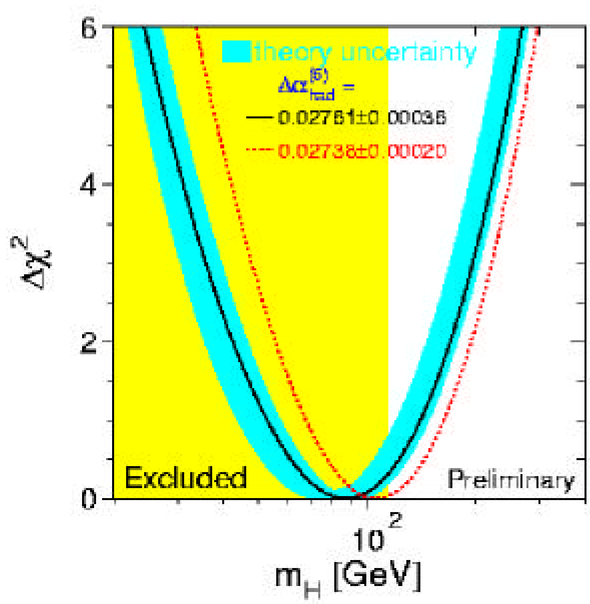
  LEP/SLD
  CDF/D0
  νN , APV



- Radiative corrections are large and sensitive to m_{top} and m_{Higgs}

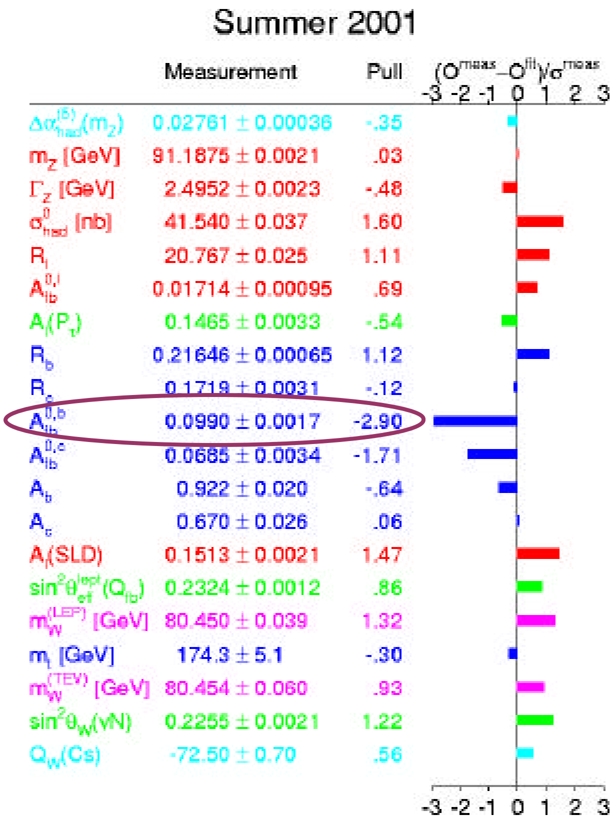


M_{Higgs} constrained in SM to be less than 196 GeV at 95%CL



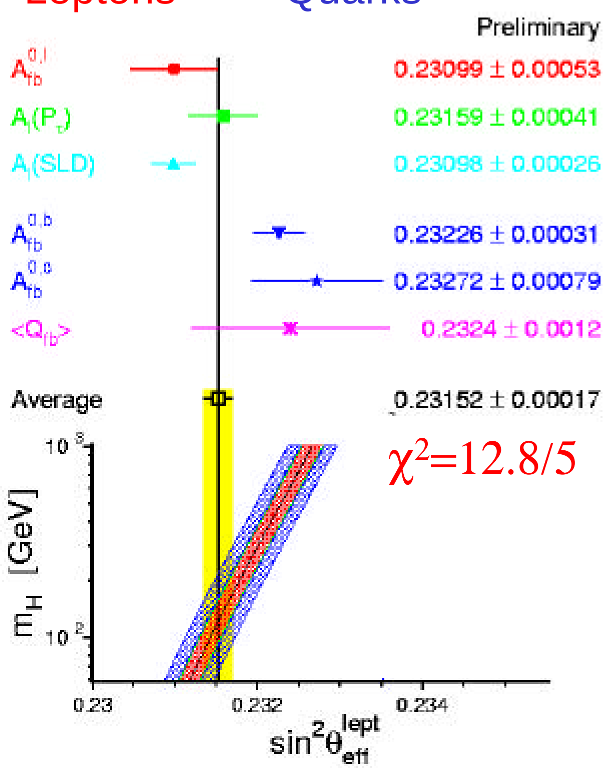
Are There Cracks?

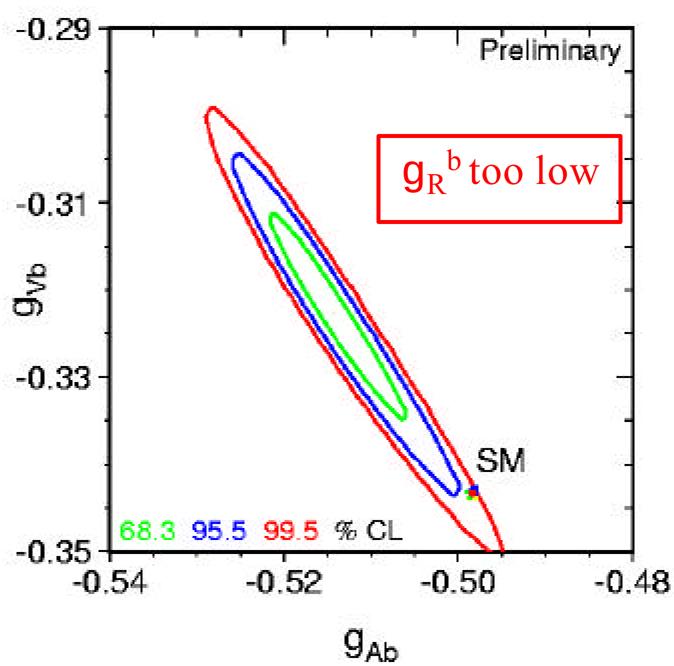
- All data suggest a light Higgs except A_{FB}^{b}
- Global fit has large χ^2
  χ^2=23/15 (9%)
  A_{FB}^{b} is off about 3σ
- Γ_{inv} also off by $\sim 2\sigma$
  $N_\nu = 2.9841 \pm 0.0083$



Higgs Mass Constraint

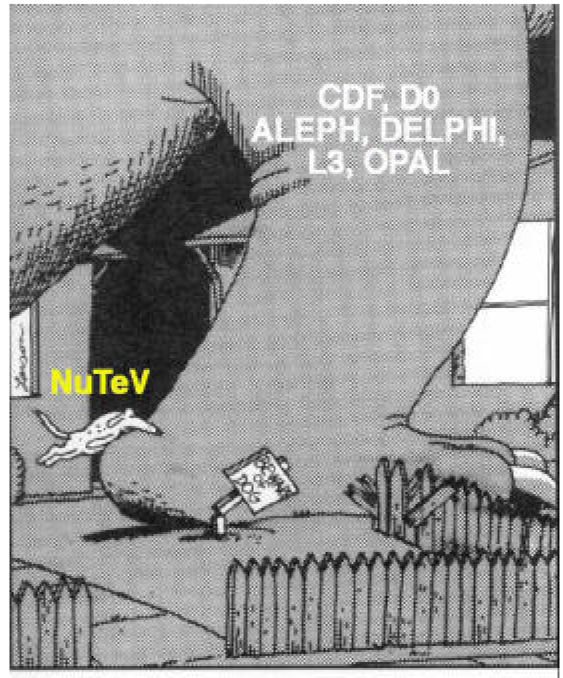
Leptons Quarks





NuTeV Adds Another Arena

- Precision comparable to collider measurements of M_W



Toby vs. Godzilla

- Sensitive to different new physics

  Different radiative corrections

- Measurement off the Z pole

  Exchange is not guaranteed to be a Z

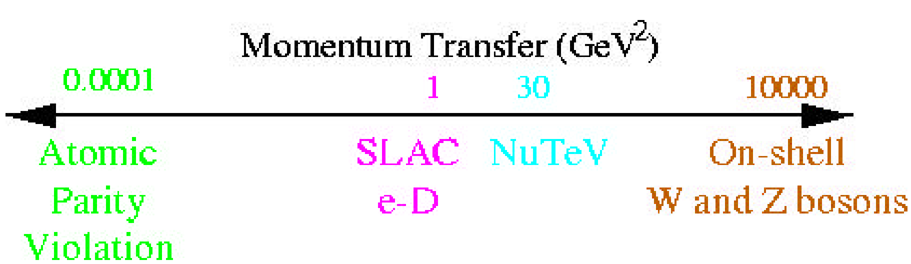
- Measures neutrino neutral current coupling

  LEP 1 invisible line width is only other precise measure

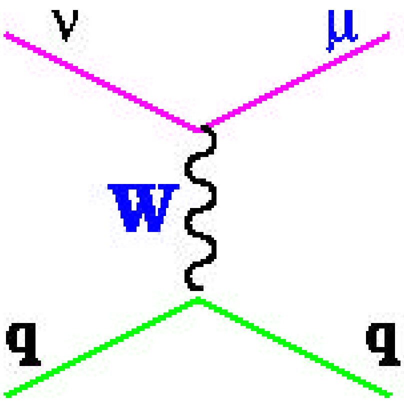
- Sensitive to light quark (u,d) couplings

  Overlap with APV, Tevatron Z production

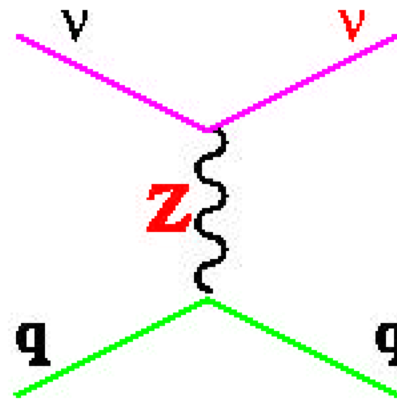
- Tests universality of EW theory over large range of momentum scales



Neutrino EW Measurement Technique



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



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

- For an isoscalar target composed of u,d quarks:

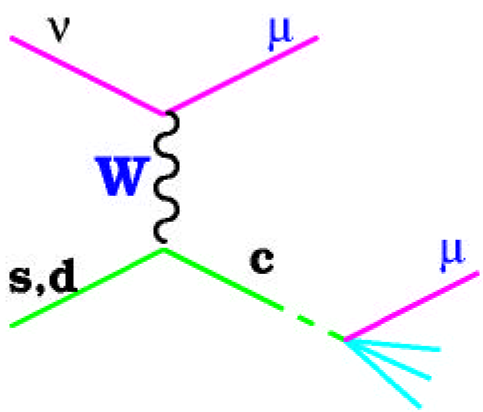
Llewellyn Smith Relation :

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

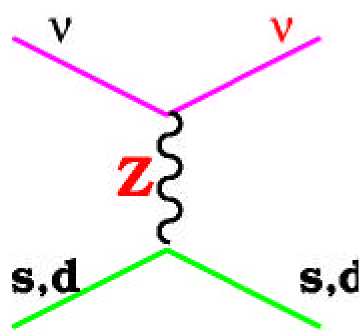
- *NC/CC* ratio easiest to measure experimentally but ...
  - Need to correct for non-isoscalar target, radiative corrections, heavy quark effects, higher twists
  - Many SF dependencies and systematic uncertainties cancel
  - **Major theoretical uncertainty m_c ⇒ Suppress CC wrt NC**

Charm Mass Effects

Charged-Current Production of Charm



Neutral-Current

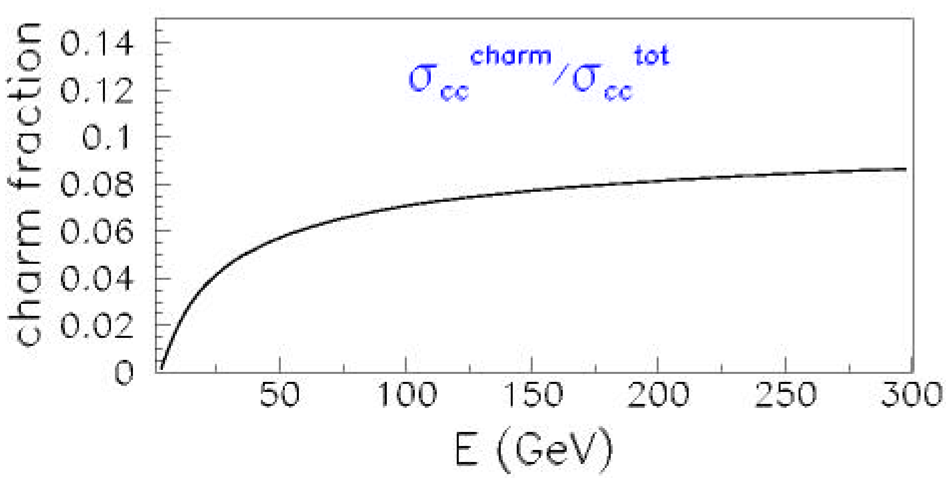


- CC is suppressed due to final state c-quark
  ⇒ Need to know s-quark sea and m_c

  Modeled with leading-order slow-rescaling

$$x = Q^2 / 2M\nu \;\rightarrow\; x = \left(Q^2 + m_c^2\right) / 2M\nu$$

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)*

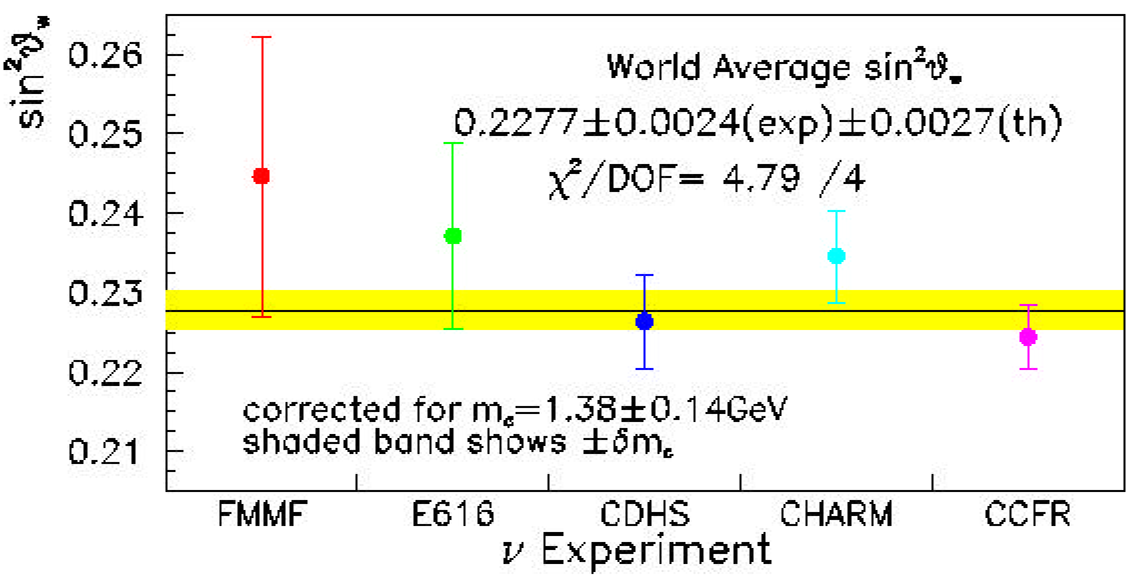


Before NuTEV

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

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

$$\Rightarrow M_W = 80.14 \pm 0.19\ GeV$$



(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
$\Rightarrow$ Reduce uncertainties from charm production and sea

Paschos - Wolfenstein Relation

$$R^{-} = \frac{\sigma_{NC}^{\nu} - \sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^{\nu} - \sigma_{CC}^{\bar{\nu}}} = \rho^{2}\left(\tfrac{1}{2} + \sin^{2}\theta_{W}\right) = \frac{R^{\nu} - rR^{\bar{\nu}}}{1-r}$$

$\sigma(\nu_{\mu} d_{sea}) - \sigma(\bar{\nu}_{\mu} \bar{d}_{sea}) = 0 \Rightarrow$ Only $d_{valence}$ contribute

$\sigma(\nu_{\mu} \bar{u}_{sea}) - \sigma(\bar{\nu}_{\mu} u_{sea}) = 0 \Rightarrow$ Only $u_{valence}$ contribute

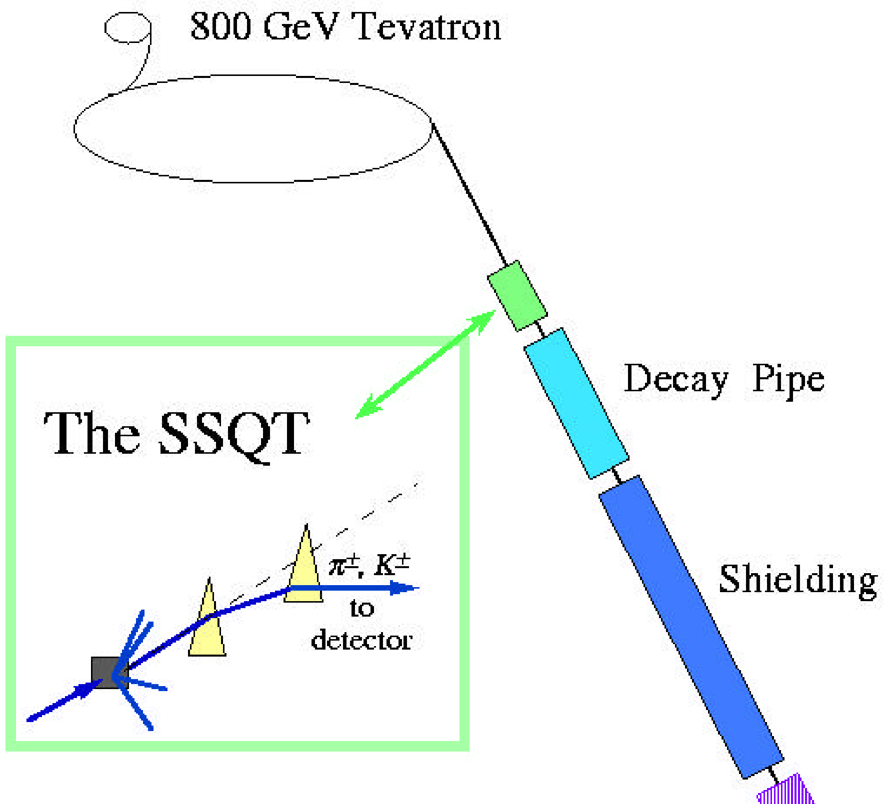
$\sigma(\nu_{\mu} s_{sea}) - \sigma(\bar{\nu}_{\mu} \bar{s}_{sea}) = 0 \Rightarrow$ No *strange – sea* contribution
(*Need to have* $xs(x) = x\bar{s}(x)$)

- 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^{ν} and $R^{\bar{\nu}}$ which, when used simultaneously, is equivalent to R^{-}.

- *But* R^{-} requires separate ν and $\bar{\nu}$ beams
  $\Rightarrow$ NuTeV SSQT (Sign-selected Quad Train)

NuTeV Sign-Selected Beamline



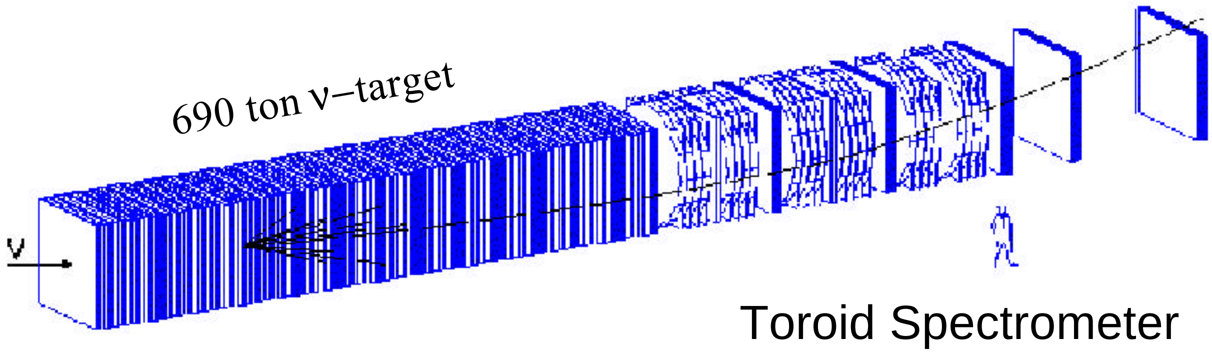
Dipoles make sign selection
- Set ν / ν type
- Remove ν_e from K_{long}
  (Bkgnd in previous exps.)

- Beam is almost pure ν or $\bar{\nu}$
  ($\bar{\nu}$ in ν mode 3×10^{-4}, ν in $\bar{\nu}$ mode 4×10^{-3})

- Beam only has ~1.6% electron neutrinos

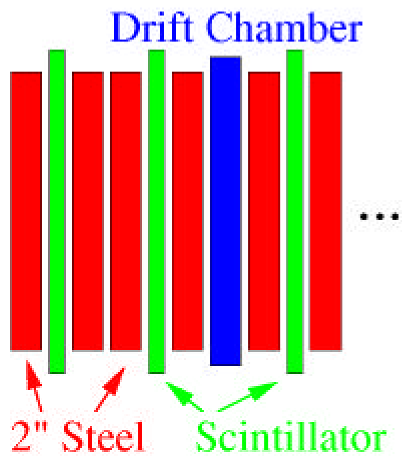
  $\Rightarrow$ Important background for isolating true NC event

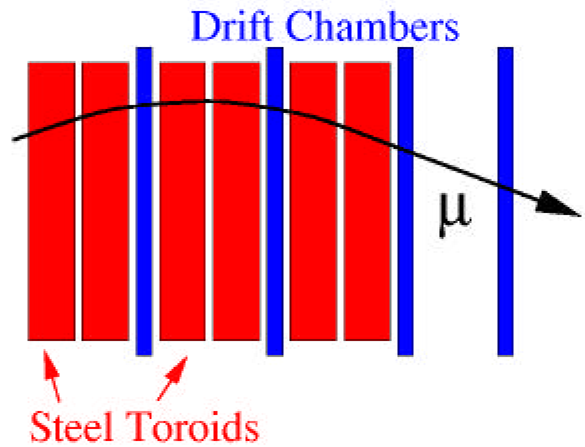
NuTeV Lab E Neutrino Detector



Toroid Spectrometer

Target / Calorimeter





168 Fe plates (3m×3m ×5.1cm)

84 liquid scintillation counters

- Trigger the detector
- Measure:
  Visible energy
  ν interaction point
  Event length

42 drift chambers

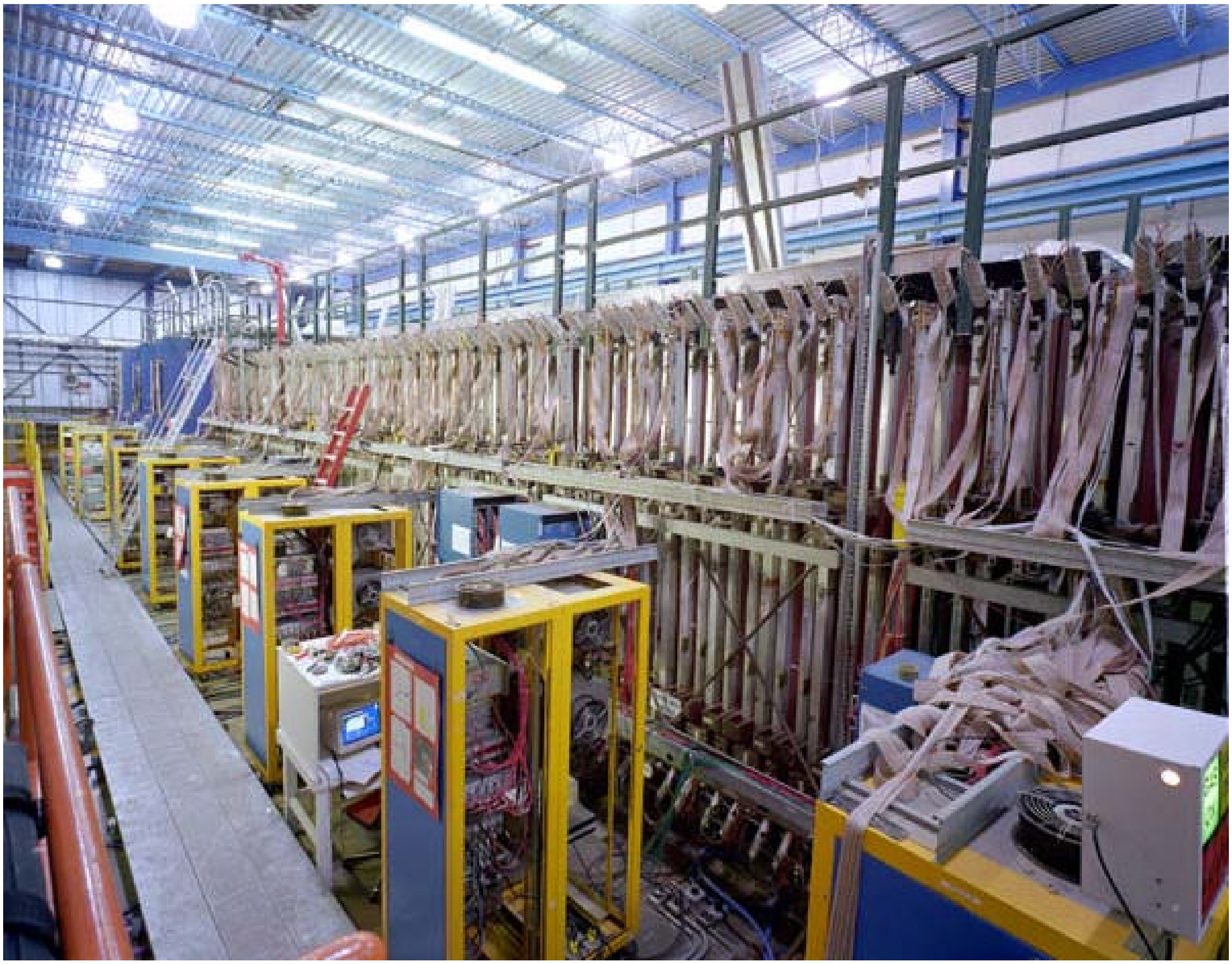
- Localize transverse vertex

Solid Fe magnet

- Measures μ momentum/charge
- P_T = 2.4 GeV for δP/P ≈ 10%

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

NuTeV Detector



Picture from 1998 - Detector is now dismantled

NuTeV Collaboration

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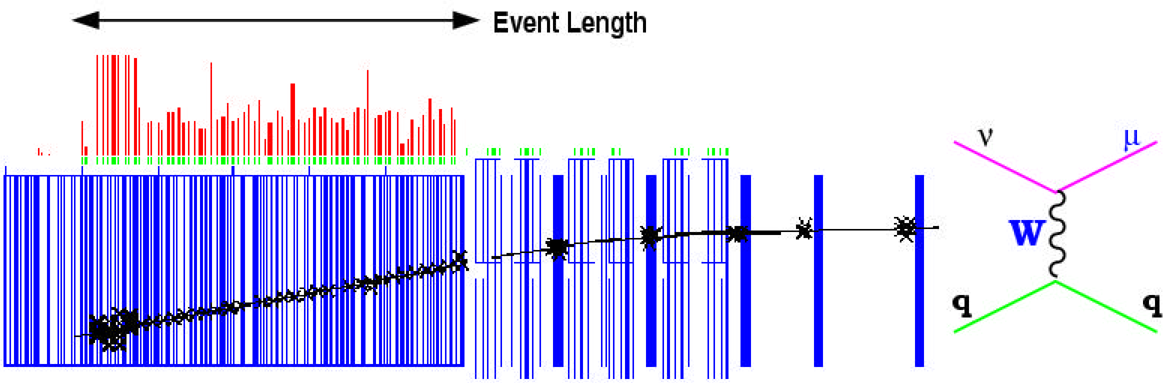
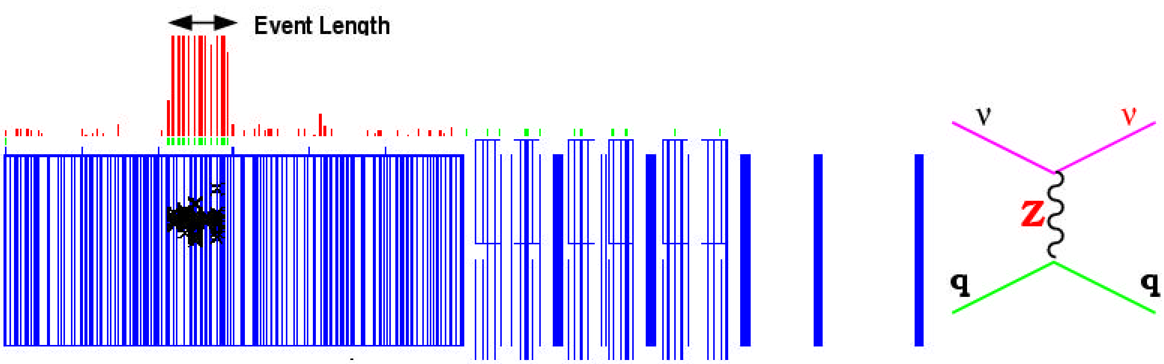
Cincinnati[1], Columbia[2], Fermilab[3], Kansas State[4], Northwestern[5], Oregon[6], Pittsburgh[7], Rochester[8]
(Co-spokepersons: B.Bernstein, M.Shaevitz)

Neutral Current / Charged Current Event Separation

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





$$R_{\exp} = \frac{\text{SHORT events}}{\text{LONG events}} = \frac{L \le L_{cut}}{L > L_{cut}} = \frac{\text{NC Candidates}}{\text{CC Candidates}}$$

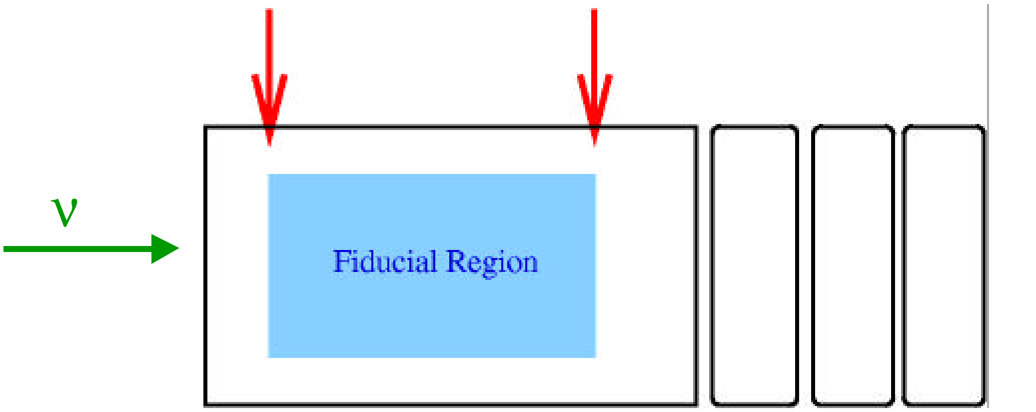
(measure this ratio in both n and $\bar{n}$ modes)

NuTeV Data Sample

- Events selections:

  Require Hadronic Energy, $E_{Had} > 20\ GeV$

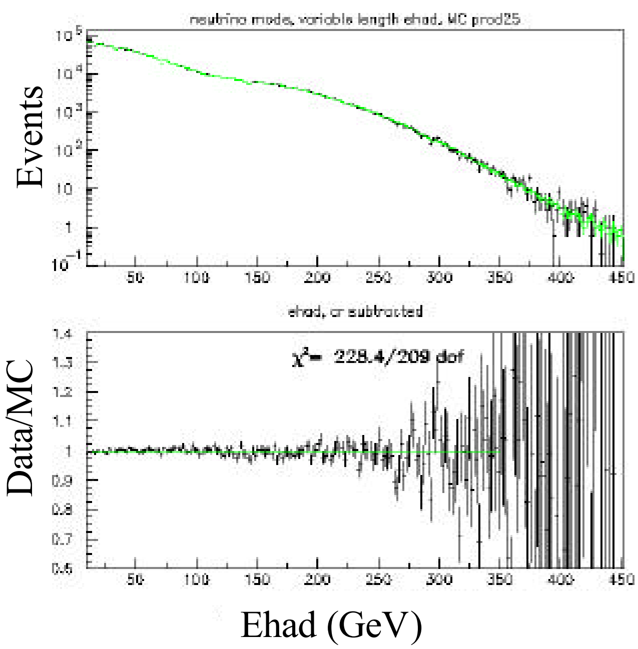
  Require Event Vertex with fiducial volume



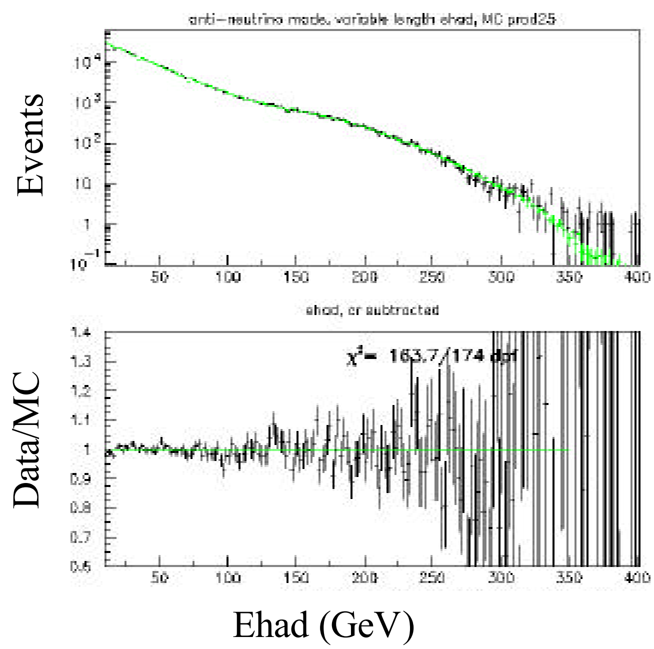
target - calorimeter *toroid spectrometer*

- Data with these cuts:

1.62 million ν events

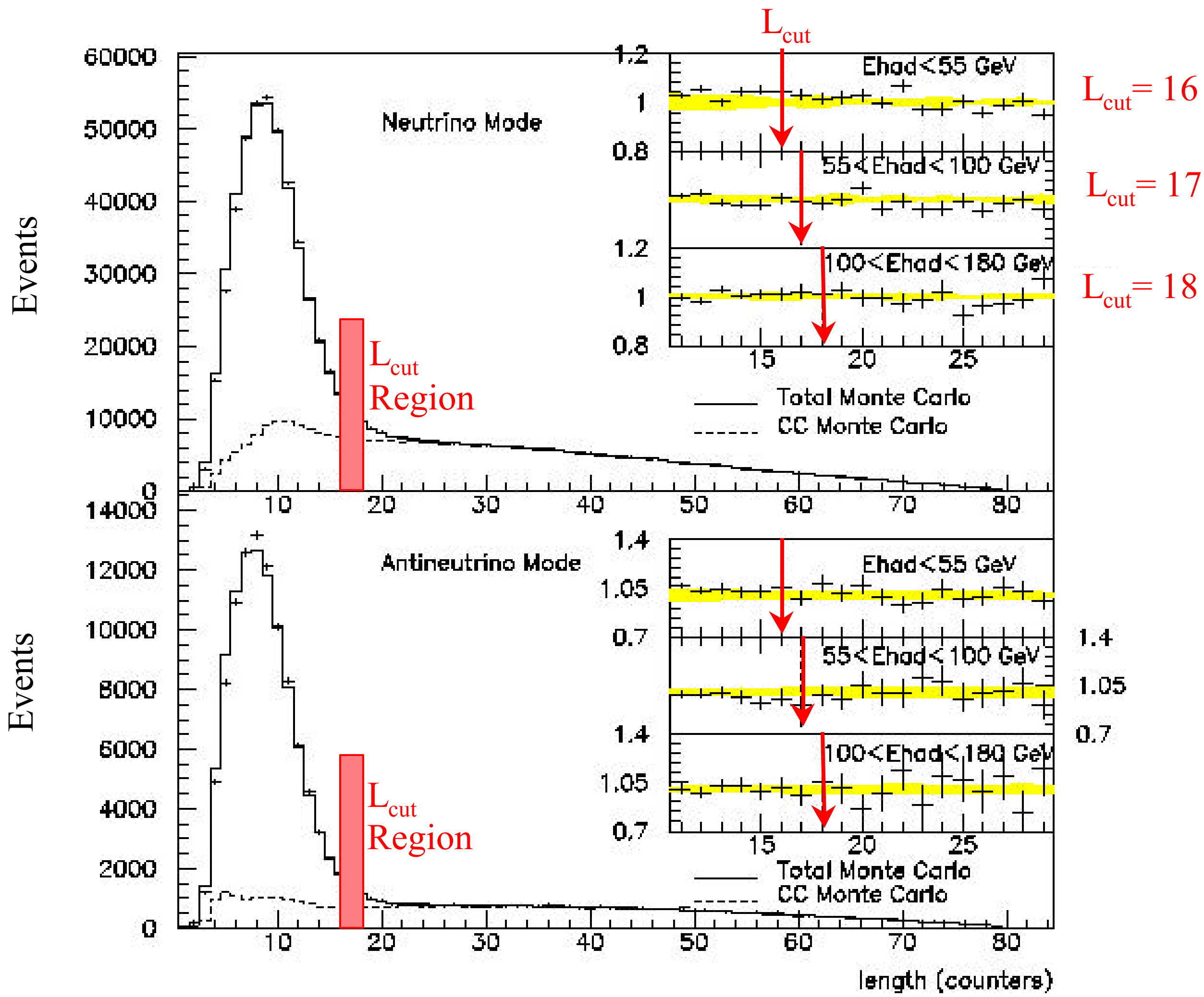


351 thousand $\bar{\nu}$ events



Determine R_{exp}: The Short to Long Ratio:

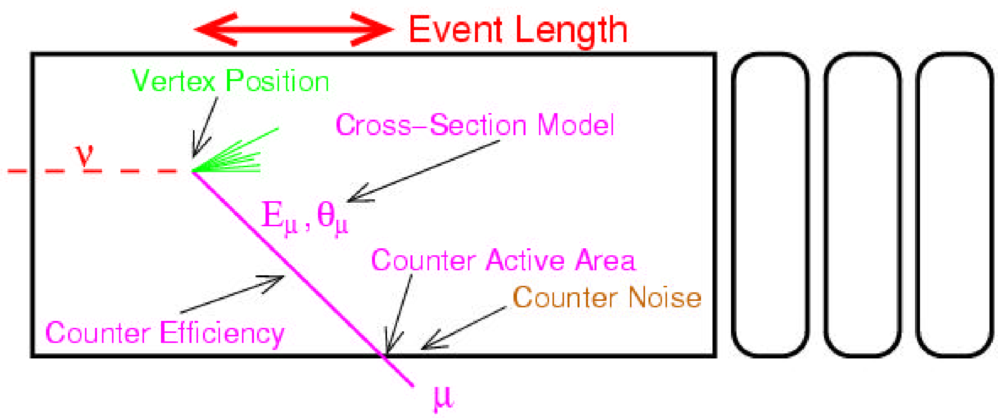
Use E_{had} dependent L_{cut} to minimize short CC correction



	Short (NC) Events	Long (CC) Events	**R_{exp}=Short/Long**
Neutrino	457K	1167K	**0.3916 ± 0.0007**
Antineutrino	101K	250K	**0.4050± 0.0016**

From R_{exp} to R^{n}

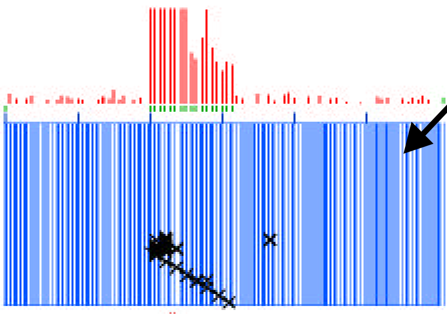
Need detailed Monte Carlo to relate R_{exp} to R^{n} and $\sin^2 q_W$



- Cross Section Model
  - LO pdfs (CCFR)
  - Radiative corrections
  - Isoscalar corrections
  - Heavy quark corrections
  - R_{Long}
  - Higher twist corrections
- Detector Response
  - CC ↔ NC cross-talk
  - Beam contamination
  - Muon simulation
  - Calibrations
  - Event vertex effects
- Neutrino Flux
  - ν_μ and ν_e flux

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

Background Corrections

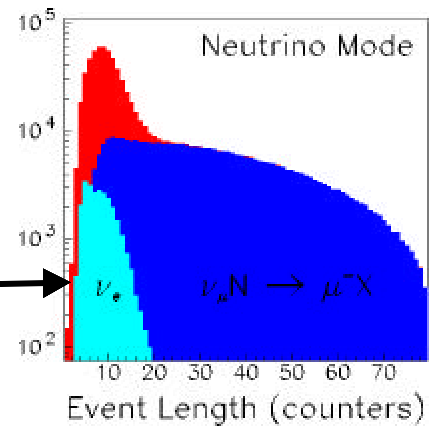


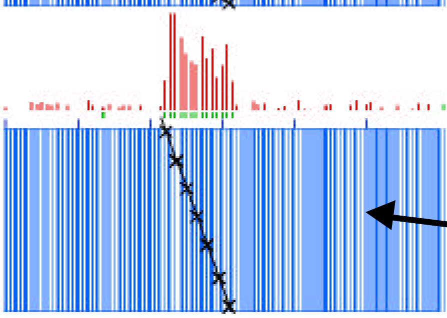
- Short ν_μ CC's (20% ν , 10% ν)

  muon exits, range out at high y

- Short ν_e CC's (5%)

  n_e N ® e X

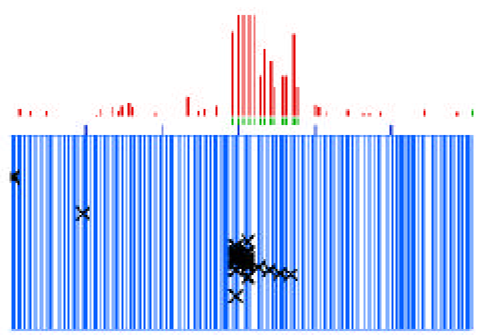




- Cosmic Rays (0.9%/4.7%)

- Long ν_μ 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 ν_μ CC events
- Neutrino fluxes
  - $n_m, n_e, \bar{n}_m, \bar{n}_e$ 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

Source	$dR^{n}_{\exp}$	$dR^{\bar{n}}_{\exp}$	Comments
Short CC Background	-0.068	-0.026	Check medium length events
Electron Neutrinos	-0.021	-0.024	Direct check from data
EM Radiative Correction	+0.0074	+0.0109	Well understood
Heavy m_c	-0.0052	-0.0117	R^- technique
Cosmic-ray Background	-0.0036	-0.019	Direct from data
Compare to statistical error	±0.0013	±0.0027	

Use Enhanced LO Cross-Section

NC and CC quark model for $n / \bar{n}$ cross-sections needs:

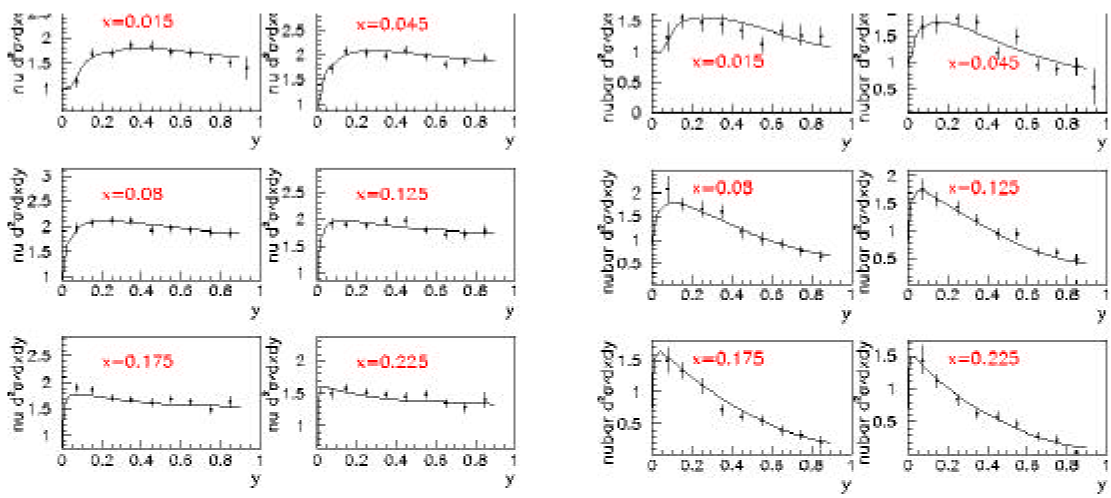
$$q(x, Q^2) \text{ and } \bar{q}(x, Q^2)$$

- PDFs extracted from CCFR data exploiting symmetries:

  Isospin symmetry: $u^p=d^n$, $d^p=u^u$, and strange = anti-strange
- Data-driven: uncertainties come from measurements

Neutrino xsec vs y at 190 GeV   Antineutrino xsec vs y at 190 GeV

CCFR Data



- 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}

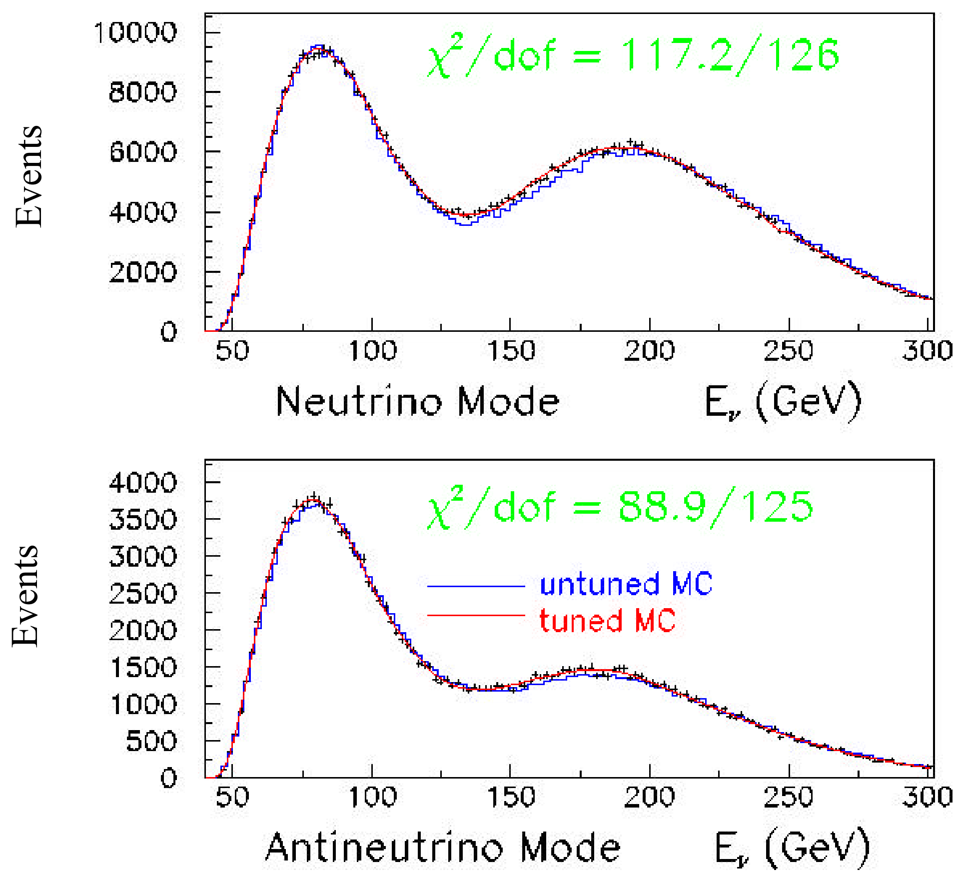
This “tuning” of model is crucial for the analysis

NuTeV Neutrino Flux

- Use beam Monte Carlo simulation tuned to match the observed ν_μ spectrum

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

Data vs Monte Carlo E_ν Spectrum

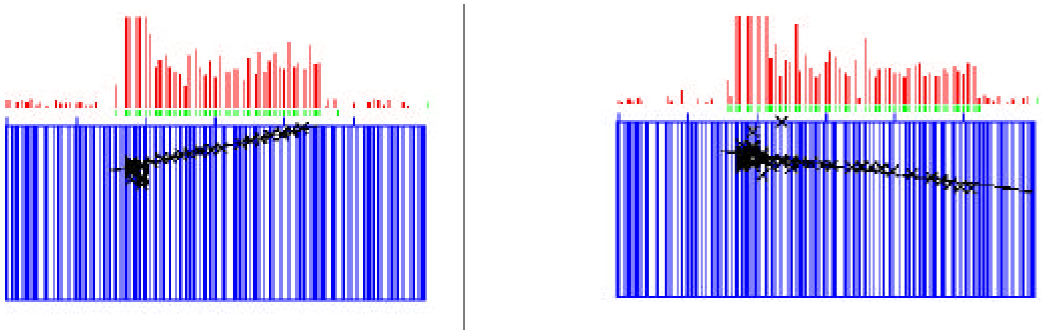


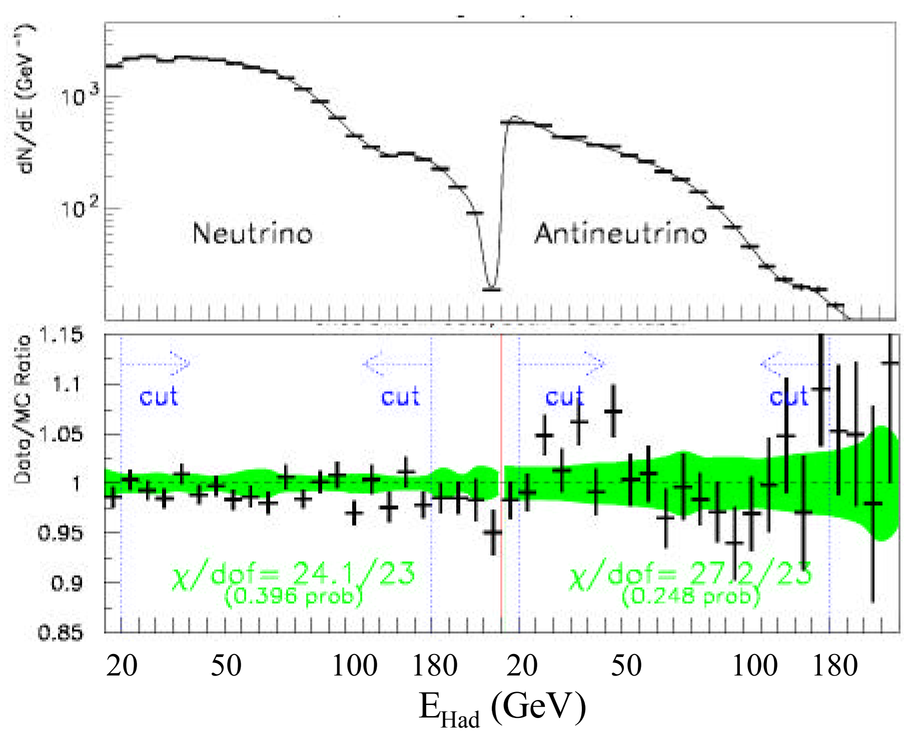
Simulation is very good but needs small tweaks at the ~0.3 –3% level for E_π , E_K , K/π

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





- Good agreement between data and MC for the medium length events.

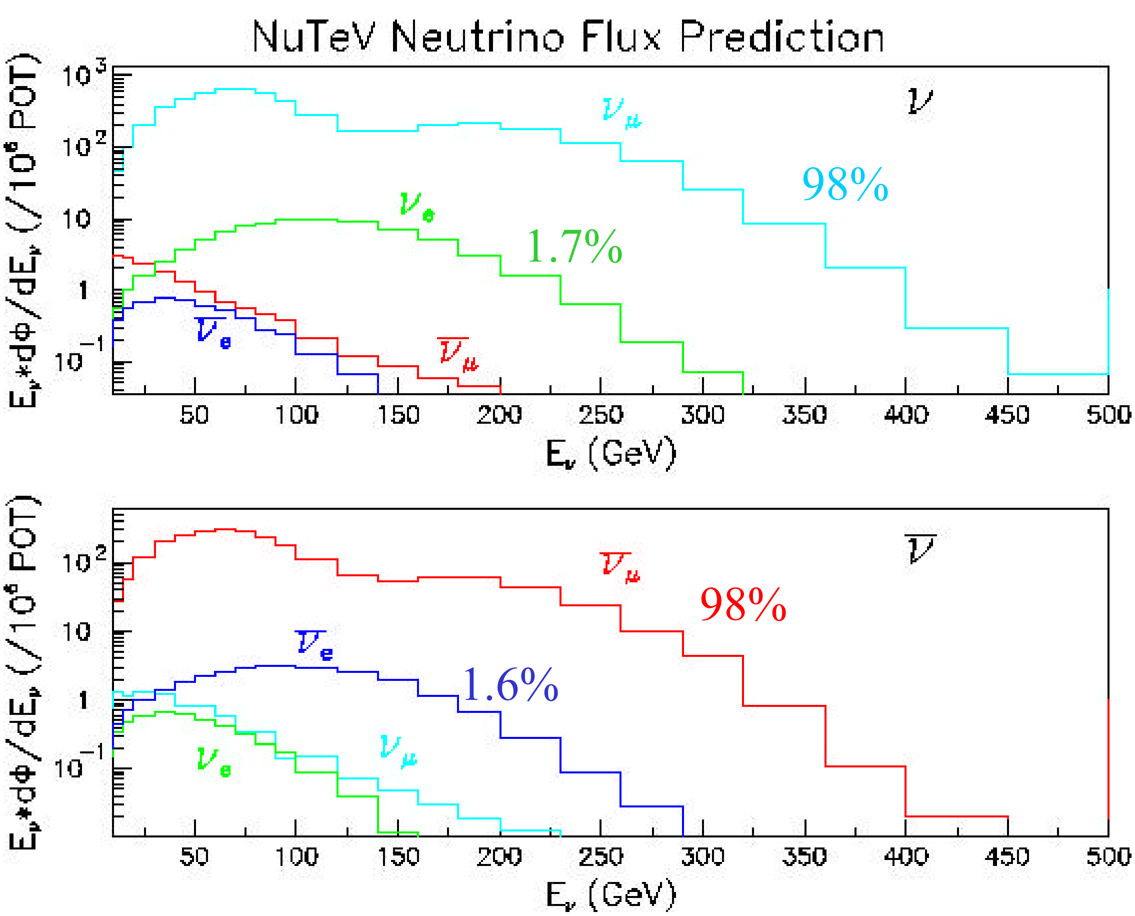
NuTeV Electron Neutrino Flux

- Approximately 5% of short events are ν_e CC events

  Main ν_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%) !!

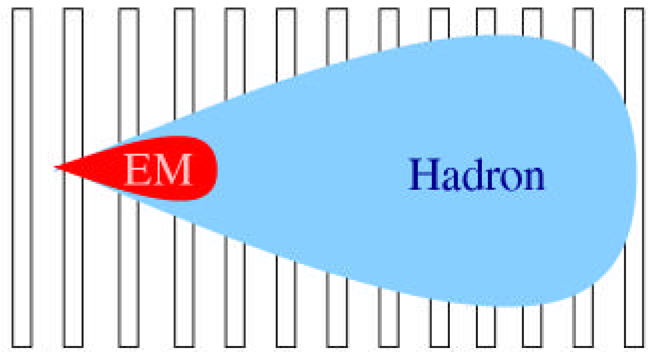


- But also have direct ν_e measurement techniques.

Direct Measurments of ν_e Flux

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

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



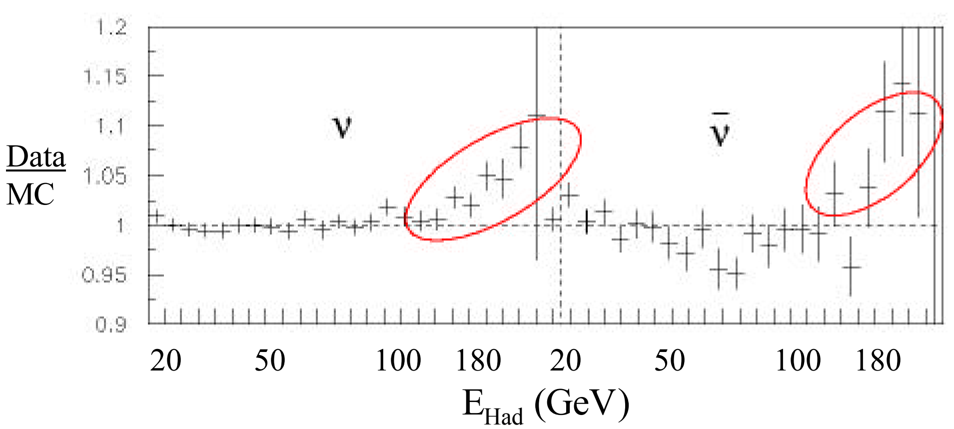
$$N_{meas} / N_{MC} : 1.05 \pm 0.03 \; (n_e)$$
$$1.01 \pm 0.04 \; (\bar{n}_e)$$

3. ν_e from very short events ($E_\nu > 180$ GeV)

Precise measurement of ν_e in tail region of flux

Observe ~35% more $\bar{\nu}_e$ than predicted above 180 GeV, and a smaller excess in ν beam

Conclude that we should require $E_{had} < 180$ GeV



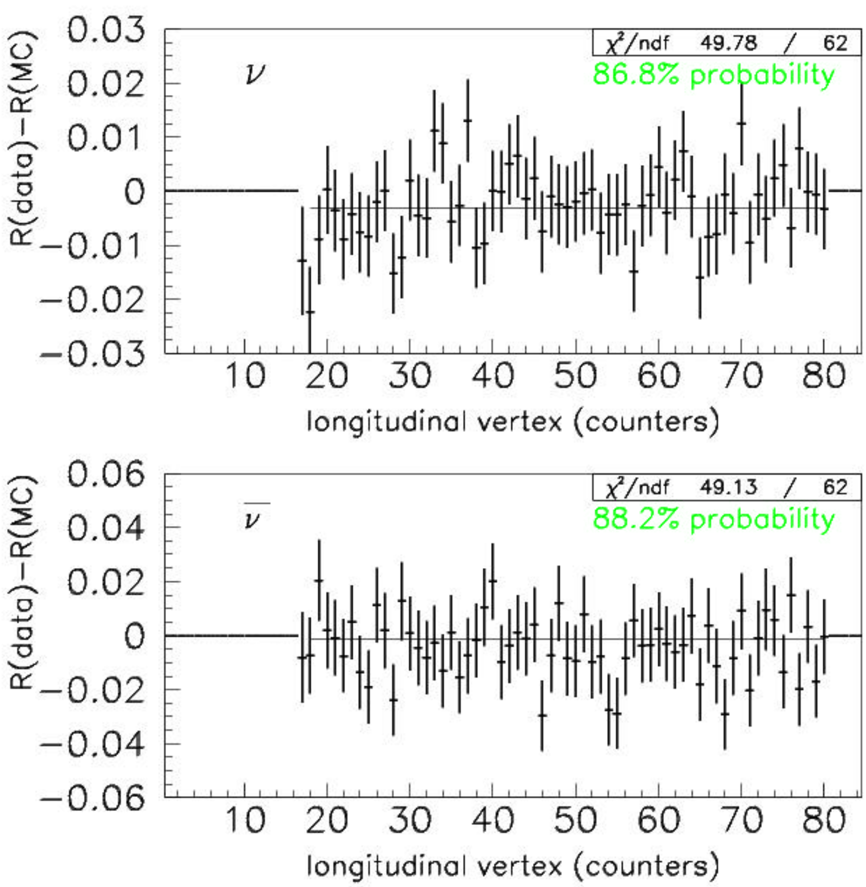
NuTeV preliminary result did not have this cut

Þ shifts $\sin^2 q_W$ by +0.002

R_{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



$\chi^2 = 50 / 62$ dof

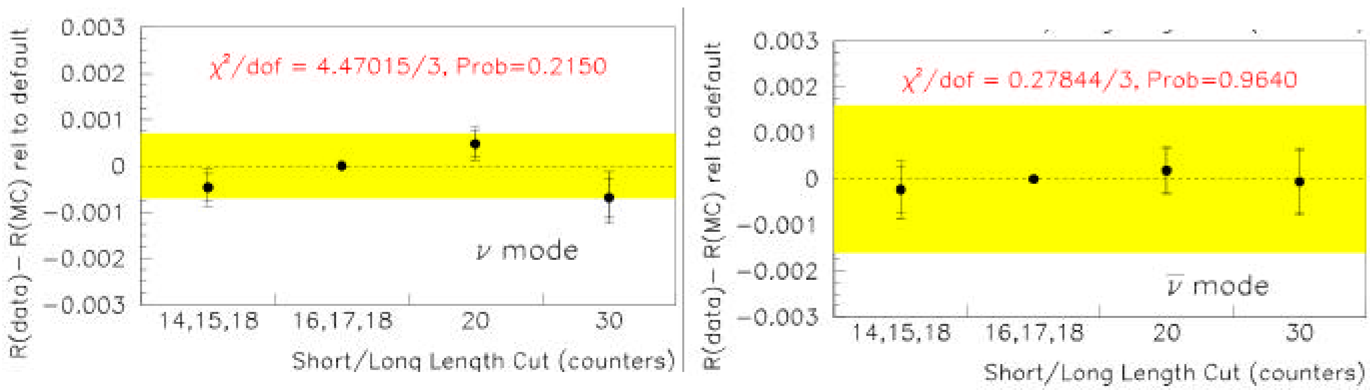
$\chi^2 = 49 / 62$ dof

Note: Shift from zero is because NuTeV result differs from Standard Model

Stability Tests (cont'd)

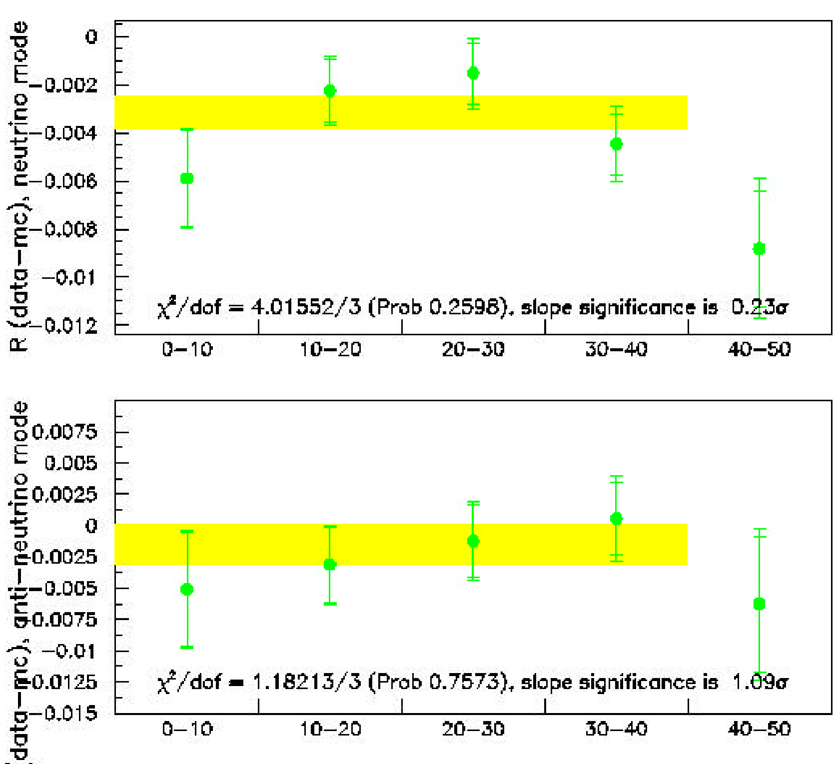
- R_{exp} vs. length cut: Check NC ↔ CC separation syst.

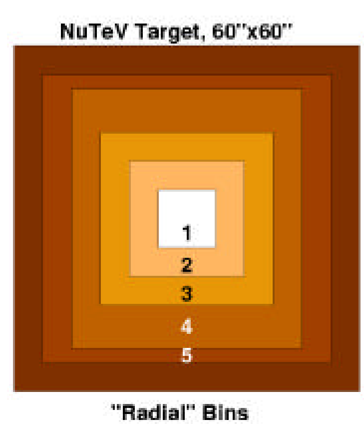
  "16,17,18" L_{cut} is default: tighten ↔ loosen selection



Yellow band is stat error

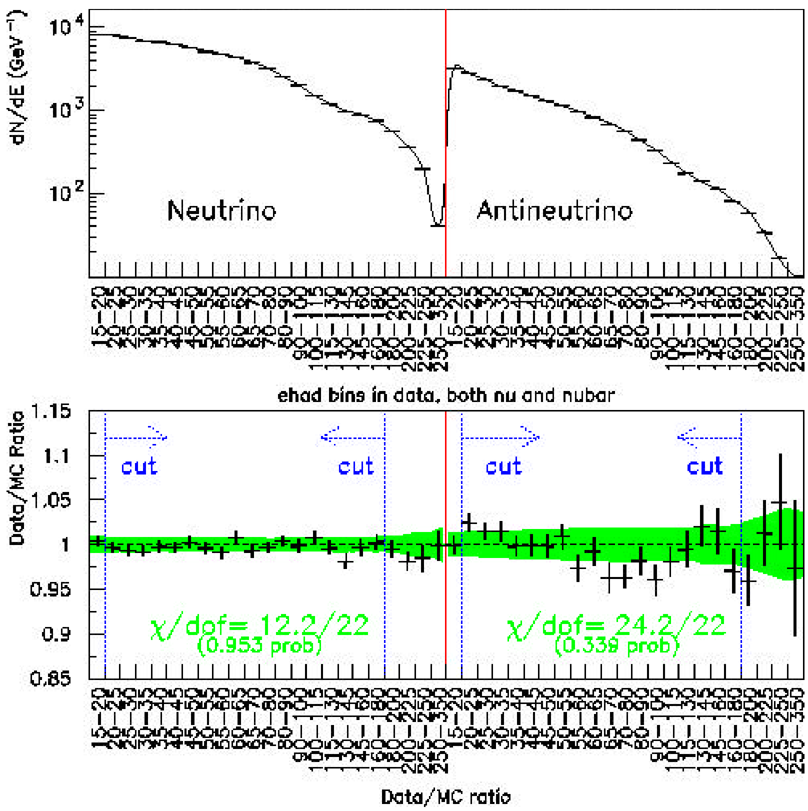
- R_{exp} vs. radial bin: Check corrections for ν_e and short CC which change with radius.



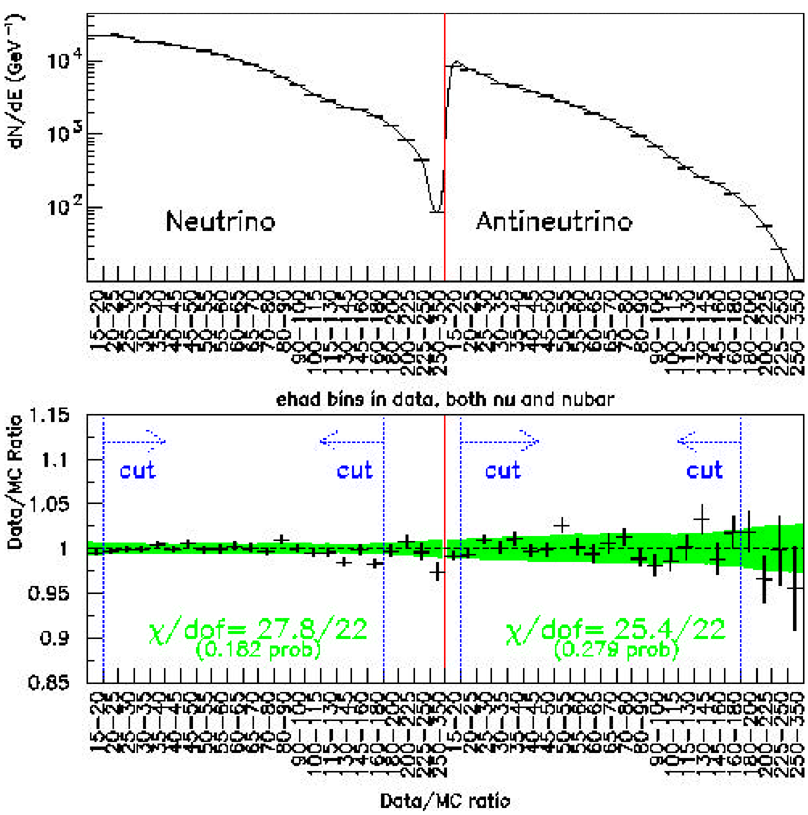


Distributions vs. E_{had}

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



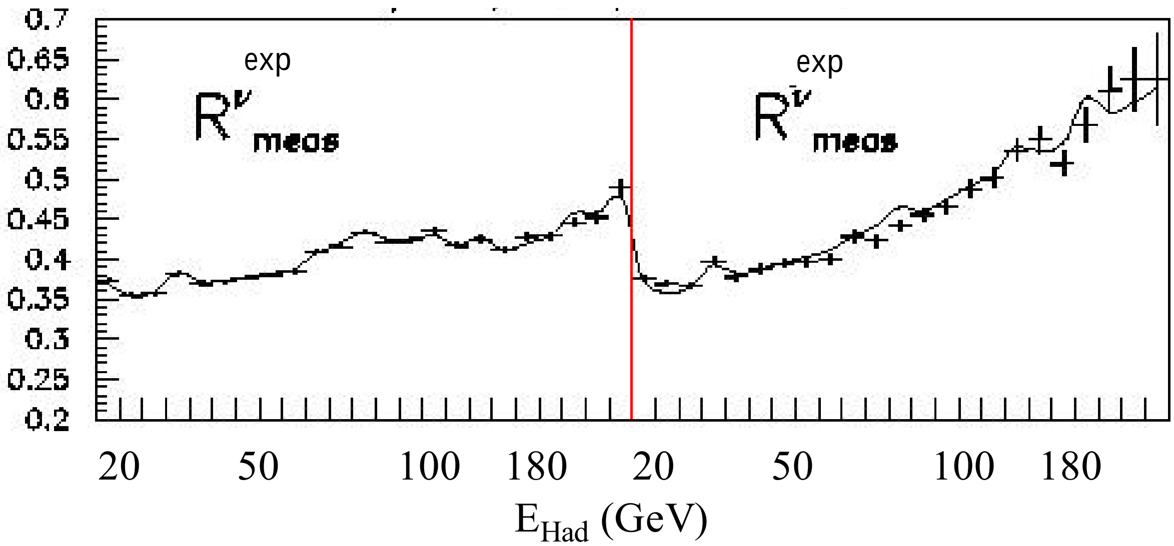
Long Events
(CC Cand.)
vs E_{had}

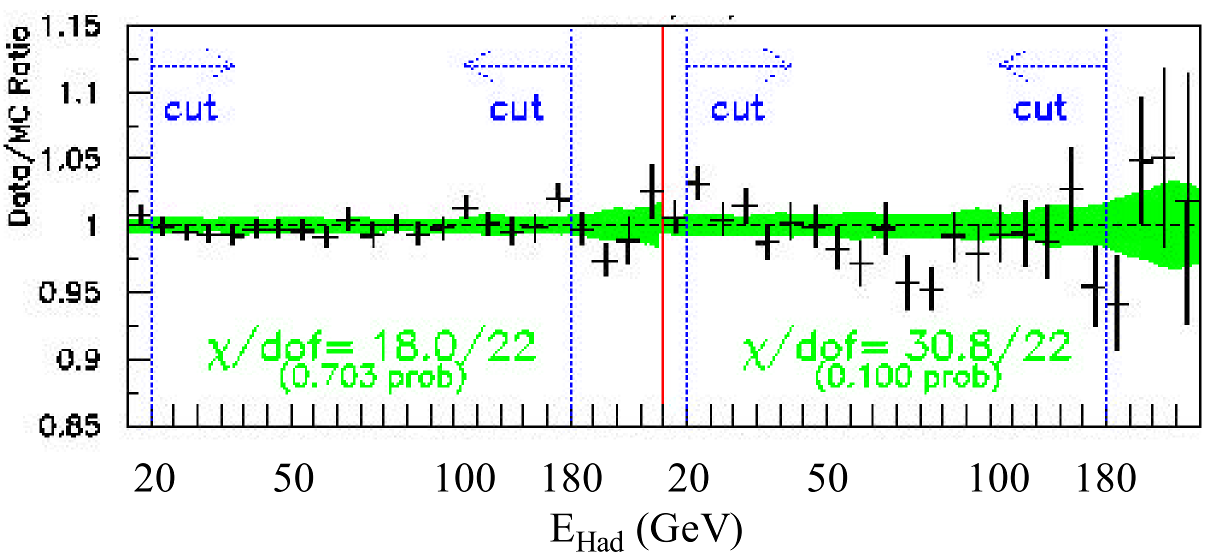


Stability Test: R_{exp} vs E_{Had}

- Short/Long Ratio vs E_{Had} checks stability of final measurement over full kinematic region

  Checks almost everything: backgrounds, flux, detector modeling, cross section model, ...





Fit for $\sin^2\theta_W$

$$R^{n(\bar{n})} = \frac{s_{NC}^{n(\bar{n})}}{s_{CC}^{n(\bar{n})}} = r_0^2\left(\frac{1}{2} - \sin^2 q_W + \frac{5}{9}\sin^4 q_W \left(1 + \frac{s_{CC}^{\bar{n}(n)}}{s_{CC}^{n(\bar{n})}}\right)\right)$$

$$\frac{dR_{\exp}^{n}}{d\sin^2 q_W} \text{ large}$$

$$R_{\exp}^{n} \to \sin^2 q_W$$

$$\frac{dR_{\exp}^{\bar{n}}}{d\sin^2 q_W} \text{ small}$$

$$R_{\exp}^{\bar{n}} \to \text{systematics (i.e. } m_c)$$

Simultaneous fit of $R_{\exp}^{n}$ and $R_{\exp}^{\bar{n}}$ to two parameters:

$$\sin^2 q_W \text{ and } m_c$$

Also input $m_c = 1.38 \pm 0.14$ from n dimuon measuremetnts

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

Result :

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

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

Can also do a two parameter fit to r and $\sin^2 q_W$:

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

$$r_0 = 0.9983 \pm 0.0040 \qquad (Correlatino\ Coef. = 0.85)$$

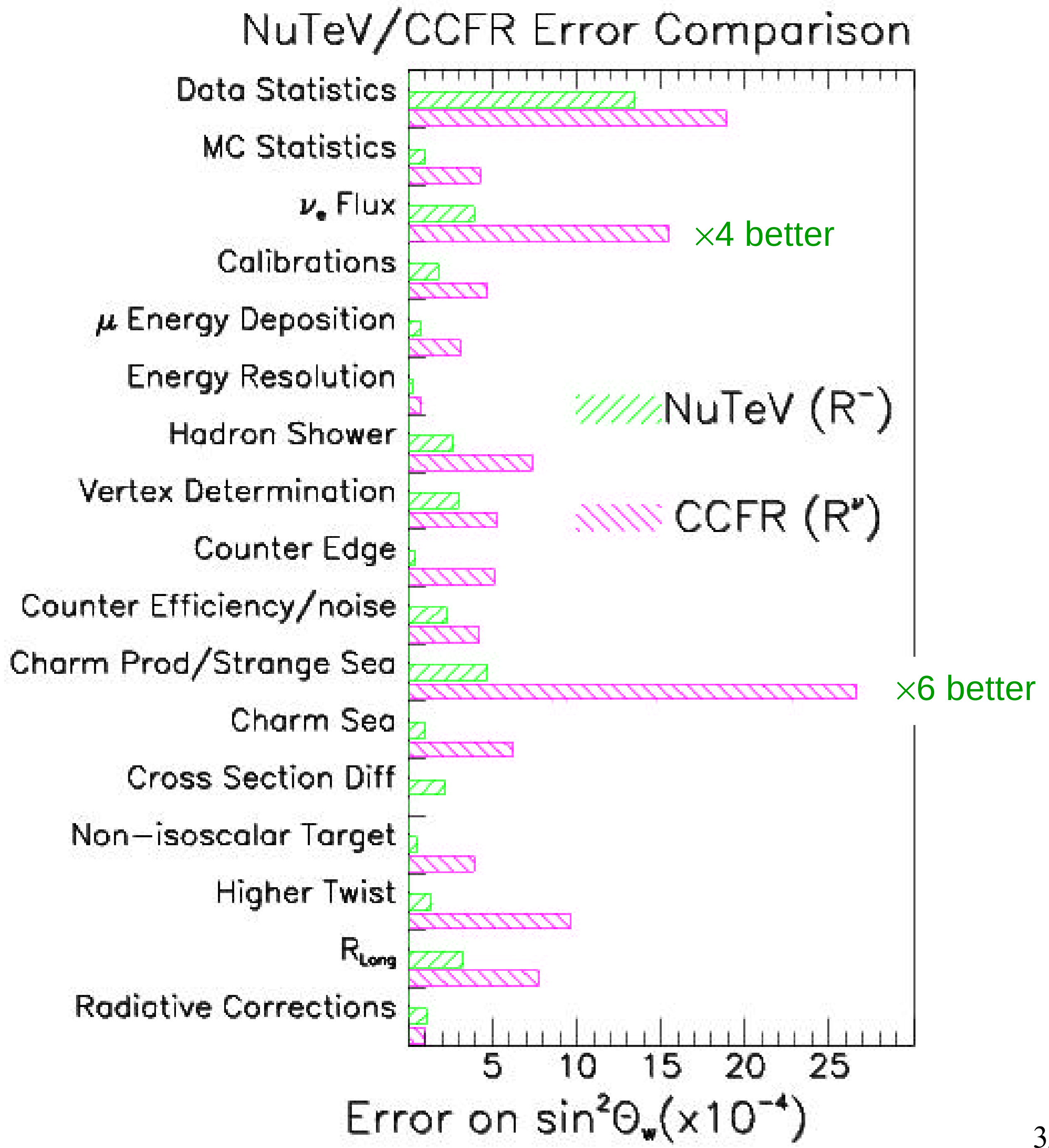
Uncertainties in Measurement

- $\sin^2 q_W$ error statistically dominated ⇒ R^- technique
- R^n uncertainty dominated by theory model

SOURCE OF UNCERTAINTY	$\delta \sin^2\theta_W$	$\delta R^{\nu}_{\rm exp}$	$\delta R^{\overline{\nu}}_{\rm exp}$
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

NuTeV Technique Gives Reduced Uncertainties

Comparison to CCFR :



The Result

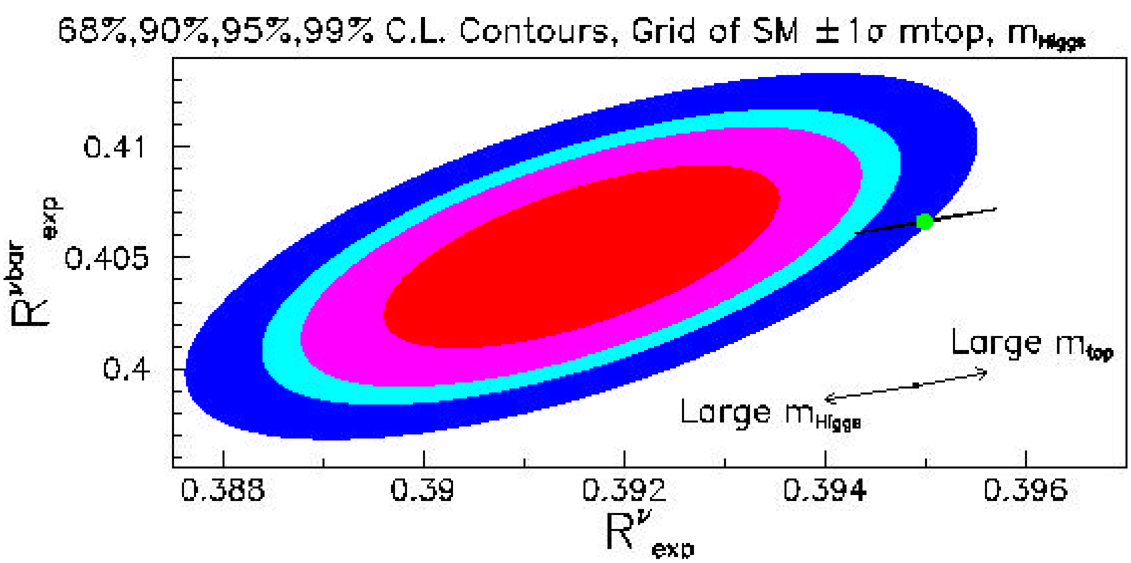
$$\sin^2 q_W^{(on-shell)} = 0.2277 \pm \pm 0.0013(stat.) \pm 0.0009(syst.)$$
$$= 0.2277 \pm 0.0016$$

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

- Standard model fit (LEPEWWG): 0.2227 ± 0.00037

  A 3σ discrepancy ....

$R^n_{exp} = 0.3916 \pm 0.0013$	$(SM : 0.3950)$	$\Leftarrow 3s$	*difference*
$\bar{R}^n_{exp} = 0.4050 \pm 0.0027$	$(SM : 0.4066)$	$\Leftarrow$ *Good*	*agreement*



Comparison to M_W Measurements

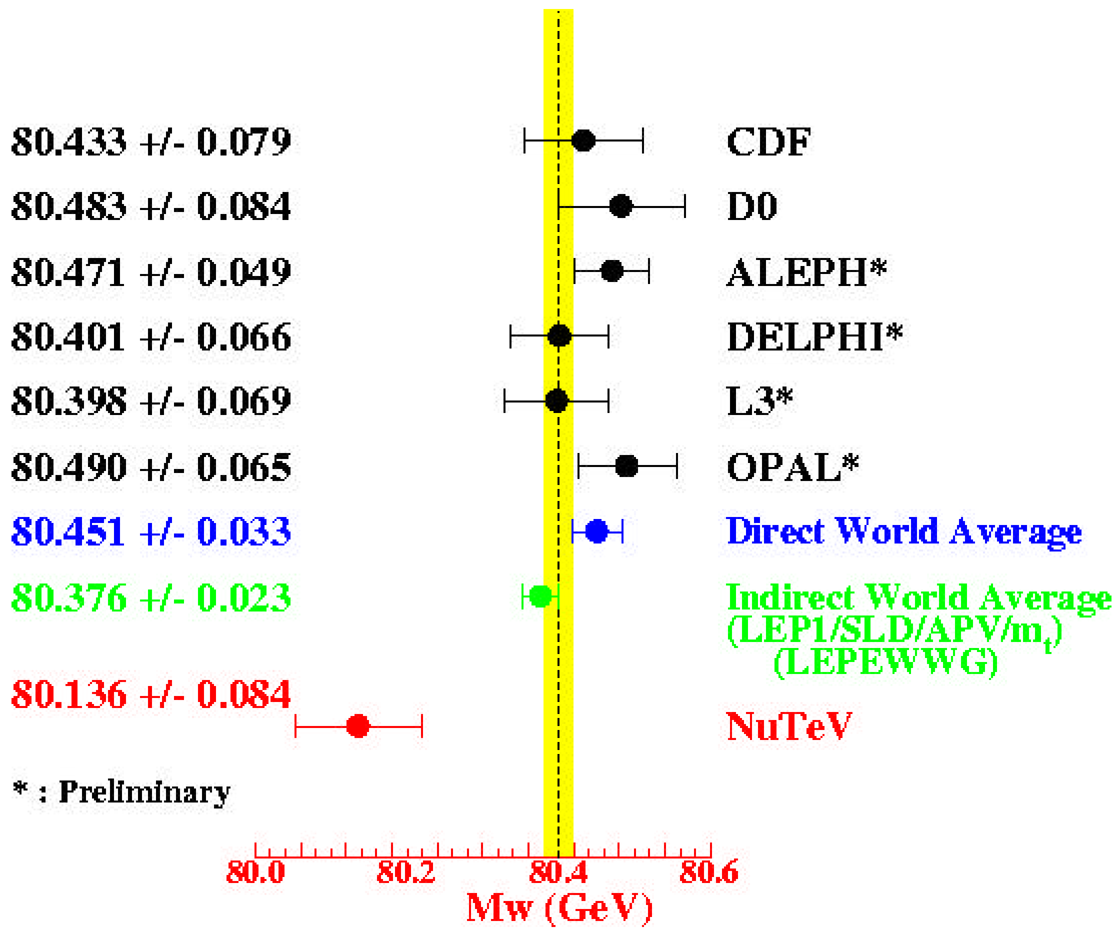
$$\sin^2 q_W^{(on-shell)} \equiv 1 - \frac{M_W^2}{M_Z^2}$$

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

$$M_W = 80.136 \pm 0.084\ GeV$$

QCD and electroweak radiative corrections are small

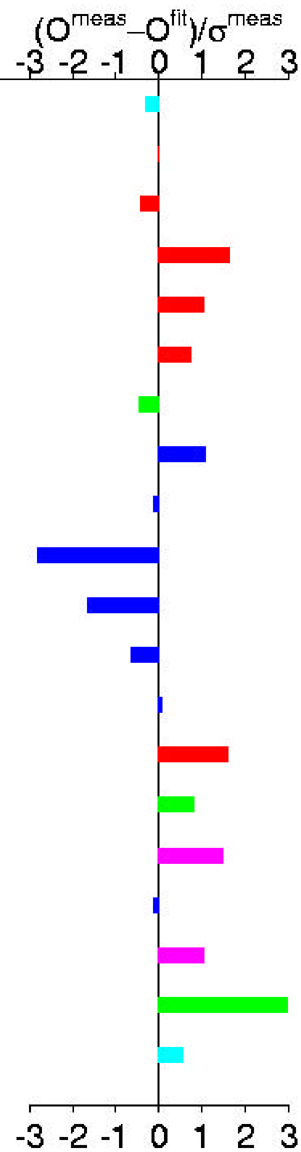
Precision comparable to collider measurements but value is smaller



SM Global Fit with NuTeV $\sin^2\theta_W$

Fall 2001

	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-.30
m_Z [GeV]	91.1875 ± 0.0021	.01
Γ_Z [GeV]	2.4952 ± 0.0023	-.41
σ^0_{had} [nb]	41.540 ± 0.037	1.63
R_l	20.767 ± 0.025	1.06
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.76
$A_l(P_\tau)$	0.1465 ± 0.0033	-.45
R_b	0.21646 ± 0.00065	1.08
R_c	0.1719 ± 0.0031	-.12
$A^{0,b}_{fb}$	0.0990 ± 0.0017	-2.78
$A^{0,c}_{fb}$	0.0685 ± 0.0034	-1.67
A_b	0.922 ± 0.020	-.64
A_c	0.670 ± 0.026	.07
A_l(SLD)	0.1513 ± 0.0021	1.61
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	.83
$m_W^{(LEP)}$ [GeV]	80.450 ± 0.039	1.50
m_t [GeV]	174.3 ± 5.1	-.14
$m_W^{(TEV)}$ [GeV]	80.454 ± 0.060	1.04
$\sin^2\theta_{W}$(NuTeV)	0.2277 ± 0.0016	2.98
Q_W(Cs)	-72.50 ± 0.70	.56



(Courtesy M. Grunewald, LEPEWWG)

- Without NuTeV: χ^2/dof = 21.5/14, probability of 9.0%
- With NuTeV: χ^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_{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
$\left(g_L^{eff}\right)^2$ and $\left(g_R^{eff}\right)^2$

For an isoscalar target, the νN couplings are:

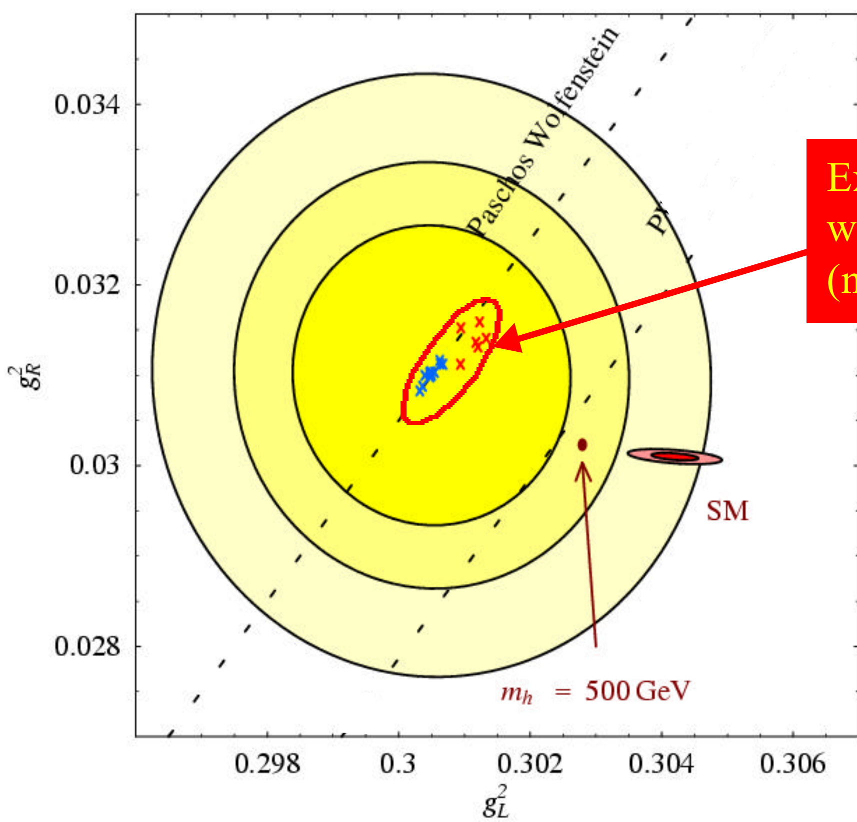
$$g_L^2 = u_L^2 + d_L^2 = \rho^2\left(\tfrac{1}{2} - \sin^2\theta_W + \tfrac{5}{9}\sin^4\theta_W\right)$$

$$g_R^2 = u_R^2 + d_R^2 = \rho^2\left(\tfrac{5}{9}\sin^4\theta_W\right)$$

Two parameter fit to R^{ν}_{exp} and $R^{\bar{\nu}}_{exp}$:

$g_L^2 = 0.3005 \pm 0.0014$ (SM : 0.3042) $\Leftarrow 2.6\sigma$ *difference*

$g_R^2 = 0.0310 \pm 0.0011$ (SM : 0.0301) $\Leftarrow$ *agreement*



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 or

  Electroweak radiative corrections: heavy m_{Higgs}

"Old Physics" Interpretations: QCD

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

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

◦ Valence quark momentum fraction $\int xdx\,(u_{val}^p + d_{val}^p) \approx 0.18$

$$\Rightarrow \int xdx\{(u_{val}^p - d_{val}^n) - (d_{val}^p - u_{val}^n) + (c - \bar{c}) - (s - \bar{s})\} \approx -0.038$$

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 $\Delta s = \int xdx\,(s - \bar{s})$

  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 ν-dimuons limit the size of $\Delta s << 0.002$
    (M.. Goncharov et al., Phys. Rev. D64: 112006,2001)

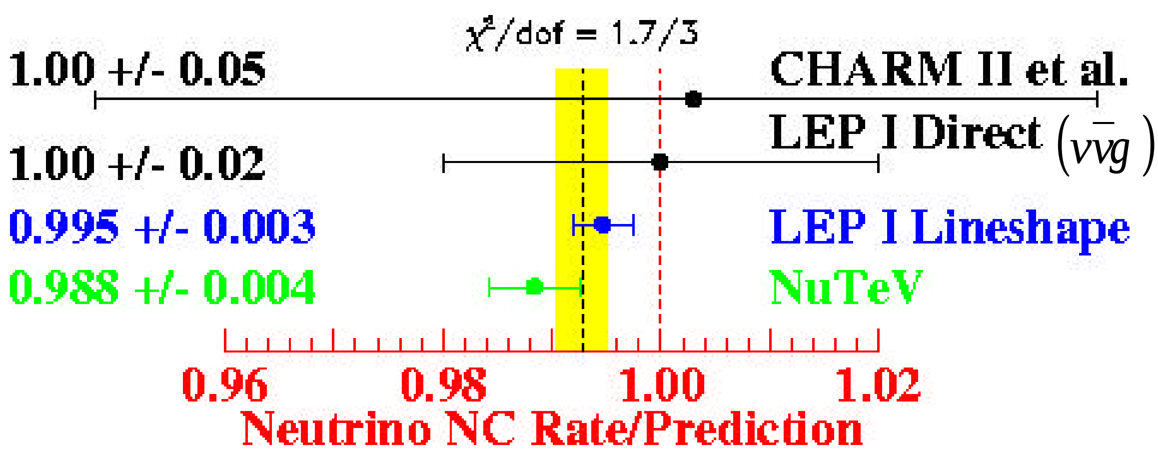
Are ν's Different?

- NuTeV result fit as a change in the $n/\bar{n}$ coupling

  $\rightarrow\ r_0^2 = 0.9884 \pm 0.0026(stat.) \pm 0.0032(syst.)$

- LEP 1 measures Z lineshape and partial decay widths to infer the "number of neutrinos"

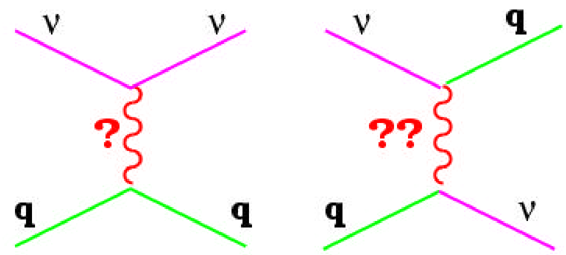
$$N_n = 3\frac{\Gamma_{\exp}(Z \rightarrow n\bar{n})}{\Gamma_{SM}(Z \rightarrow n\bar{n})} = 3 \times (0.9947 \pm 0.0028) \Leftarrow 1.9s \text{ low}$$



- 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 ν's?

"New Physics" Interpretations

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



- Oblique (propagator) corrections

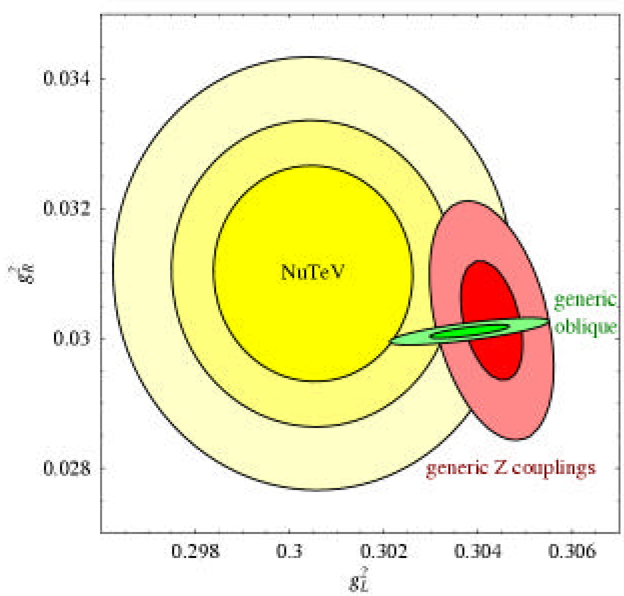
  Constrained by SM fits

- Gauge boson interactions

  Allow generic couplings

  Example: Extra Z' boson

  - Mixing with E(6) Z'
  - $Z'=Z_\chi \cos\beta + Z_y \cos\beta$
  - 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 GeV, mixing ~10^{-3}, $\beta \approx 1.2$

  "Almost sequential" Z' with opposite coupling

  - NuTeV would want $m_{Z'}$ ~1.2 TeV
  - CDF/D0 Limits: $m_{Z'}$ > 700 GeV

(Cho et al., Nucl.Phys.B531, 65.; Zeppenfeld and Cheung, hep-ph/9810277; 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 ν 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, $\varepsilon^{LL}_{\nu\nu qq}$, with strength ~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 π–decay constraints
- Extra U(1) vector bosons:
  - An unmixed Z' with B-3L_μ 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 ± 0.0003 but we measure

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

(Previous neutrino measurements gave 0.2277 ± 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