A Departure From Prediction: Electroweak Physics at NuTeV

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FNAL Wine and Cheese
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Outline

1. Our surprising result
2. Neutrinos and the weak neutral current
3. Technique
4. The NuTeV Experiment
5. The data sample
6. Experimental and theoretical simulation
7. Electroweak fits
8. Interpretation and conclusions

The NuTeV Collaboration

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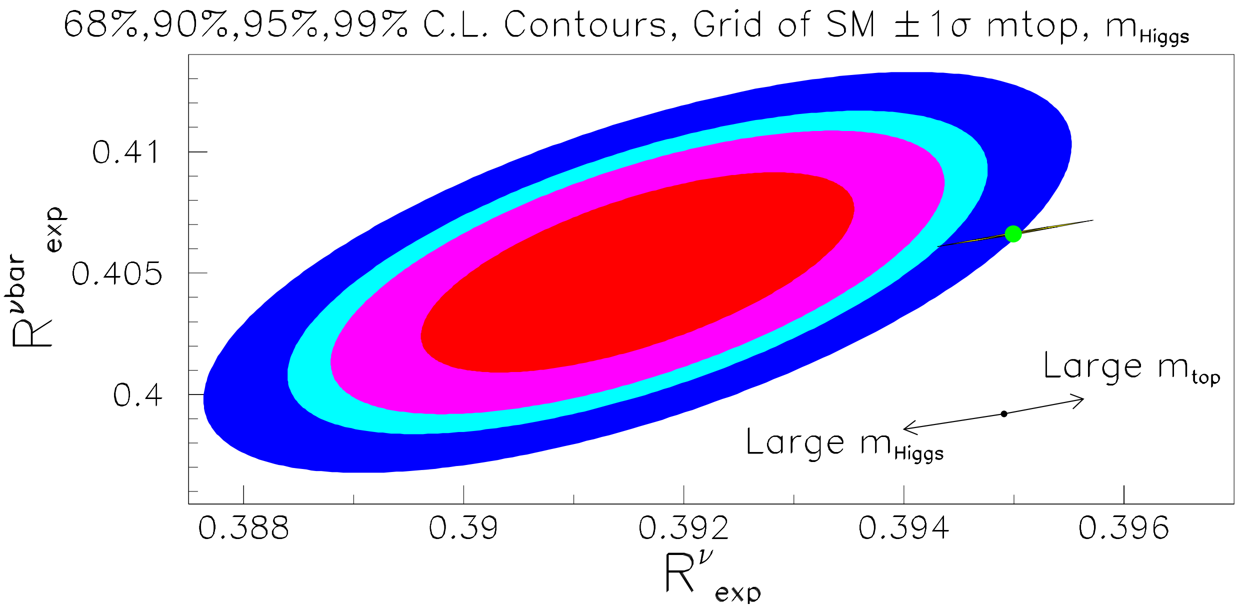
The Result

NuTeV Measures:

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

cf. standard model fit (LEPEWWG), 0.2227 ± 0.00037

A discrepancy of 3σ...



R^{ν}_{exp} and $R^{\overline{\nu}}_{\mathrm{exp}}$ measured to a precision of 0.3%, 0.65%, respectively

(systematics lead to correlated uncertainty)

Electroweak Theory

Unification of Weak and Electromagnetic Forces

- SU(2) group: "weak isospin" ⇒ isotriplet of gauge bosons
- U(1) group: "weak hypercharge" ⇒ single gauge boson

Electroweak Lagrangian:

$$\mathcal{L} = g\vec{J}_\mu \cdot \vec{W}_\mu + g' J_\mu^Y B_\mu,$$
$$J_\mu^Y = J_\mu^{\mathrm{em}} - J_\mu^{(3)}.$$

Physical Particles are: $W^\pm$, Z^0, photon

$$W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^{(1)} \pm \imath W_\mu^{(2)}).$$

$$\mathrm{photon}_\mu = \frac{1}{\sqrt{g^2 + g'^2}}(g' W_\mu^{(3)} + g B_\mu),$$

so that the photon couples only to the electromagnetic current. And what remains is:

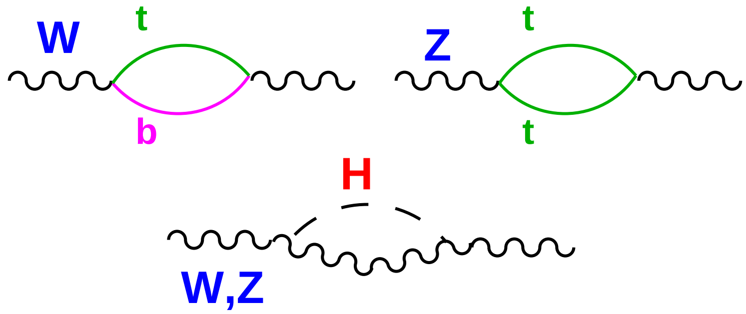
$$Z_\mu^0 = \frac{1}{\sqrt{g^2 + g'^2}}(g W_\mu^{(3)} - g' B_\mu).$$

Lagrangian in terms of physical bosons can be used to relate unification parameters to low energy measurements. Let $g' \equiv g \tan\theta_W$; then:

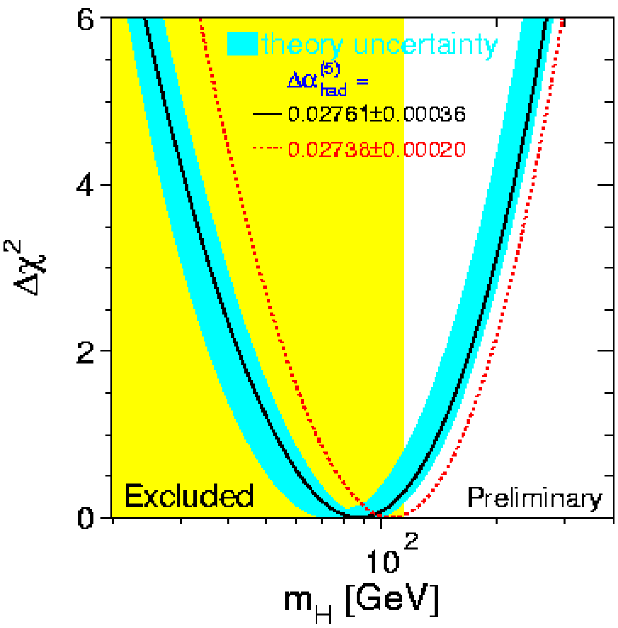
$$e = g\sin\theta_W, \; G_F = \frac{g^2\sqrt{2}}{8M_W^2}, \; \frac{M_W}{M_Z} = \cos\theta_W$$

Electroweak Theory (cont'd)

- $\alpha_{\rm em}$, known to 45 ppb
  (but only to 200 ppm at $Q^2 \sim M_Z^2$)
- G_F, known to 10 ppm
- M_Z, known to 23 ppm



- Radiative corrections large, well-understood
- Gives a large m_t, m_H dependence of boson masses

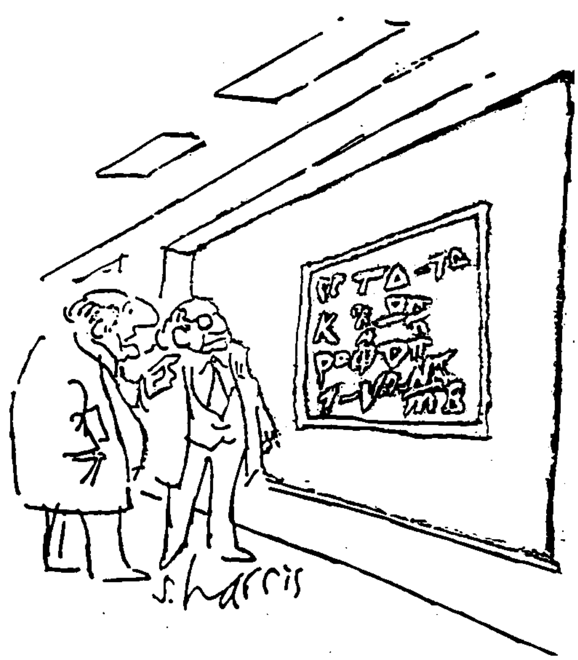


Precision Tests of EW Theory

- Z^0 Bosons from e^+e^- collisions at LEP and SLC
  $\hookrightarrow$ m_Z,Γ_Z, asymmetries in Z^0 decay
- $W^\pm$ Bosons at the Tevatron and LEP II
  $\hookrightarrow$ m_W, Γ_W
- ν-Nucleon Deeply Inelastic Scattering!
- Atomic Parity Violation and Polarized Electron Scattering ($\gamma - Z$ Interference)

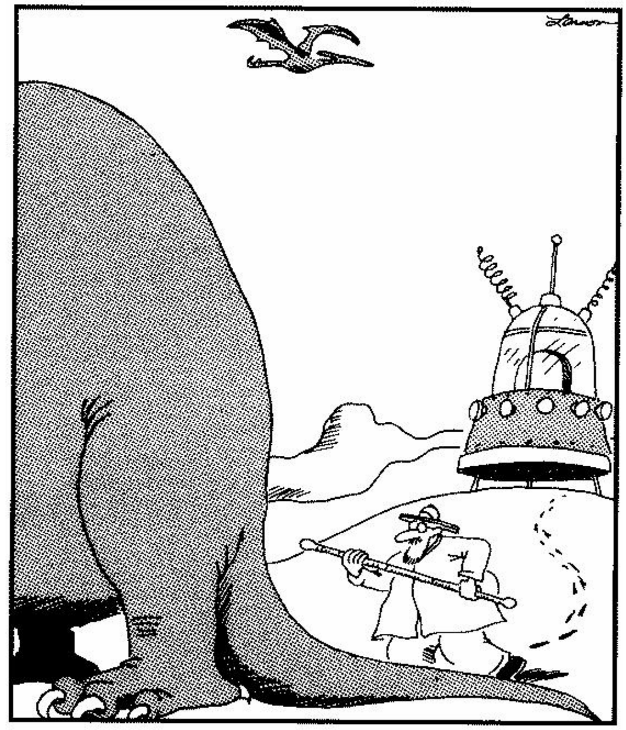
Why test in so many processes?

1. Testing in a wide range of processes and momentum scales ensures universality of the electroweak theory
2. Hope to observe new physics in discrepancies among measurements
   - Loop corrections
   - Tree level contributions



"Putting a box around it, I'm afraid, does not make it a unified theory."

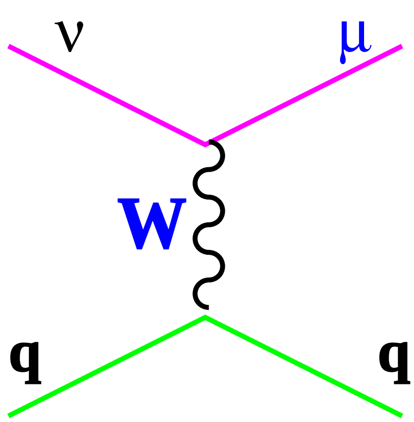
Why is NuTeV the Right Instrument for the Job?



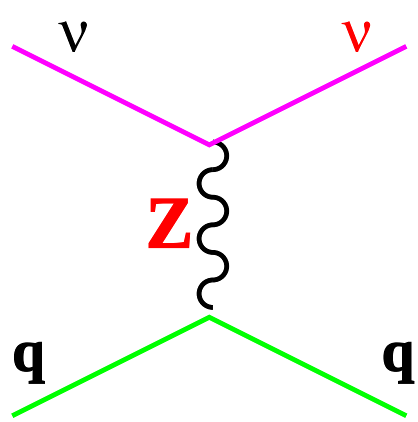
An instant later, both Professor Waxman and his time machine are obliterated, leaving the cold−blooded/warm−blooded dinosaur debate unresolved

- NuTeV is precise
  - ↪ M_W from NuTeV comparable to collider precision
- NuTeV is sensitive to different new physics from other precision experiments
  - ↪ Measurement is off Z pole
    - ⋆ I.e., exchange is not guaranteed to be a Z!
  - ↪ Neutral current neutrino couplings
    - ⋆ LEP I invisible width is only other precise measurement
  - ↪ Light quark neutral current coupling
    - ⋆ Also atomic parity violation, TeVatron Z production

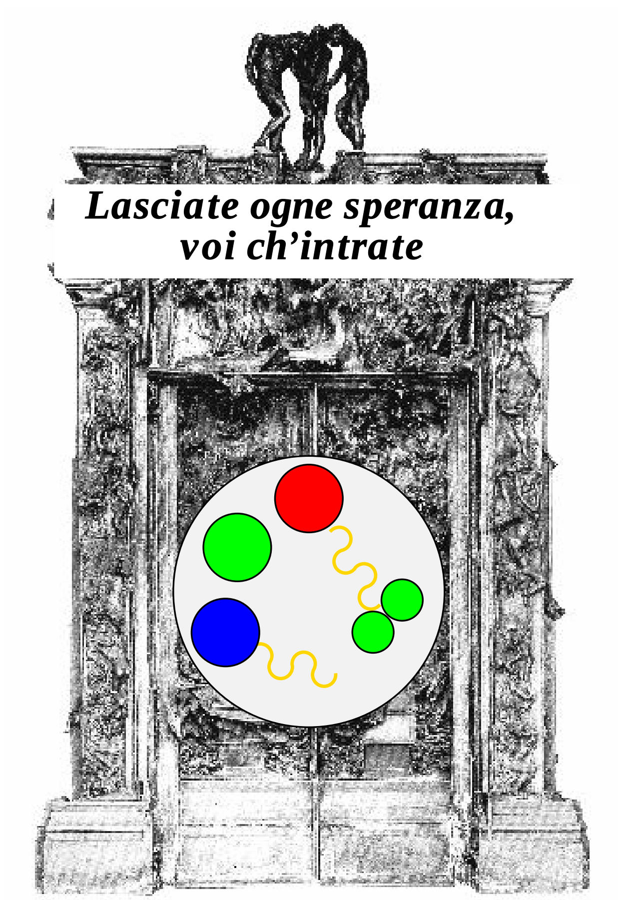
Methodology



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



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



- QCD controls your targets
- $q(x, Q^2)$, $\overline{q}(x, Q^2)$ enter into cross-sections

  $x \equiv$fractional parton momentum;

  $Q^2 = -q^2$, q is boson 4-momentum

Cull the Herd
(Separate the Weak from the Strong)

Exploit Symmetry:

- Charged-current and neutral-current have same target $\Rightarrow$ take cross-section ratios!
- Isoscalar Valence
  (if $u_v^p = d_v^n$, follows from heavy target)
- Isoscalar Sea ($u_s \approx d_s$)

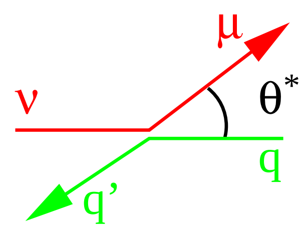
$$R^{\nu(\overline{\nu})} = \frac{\sigma_{NC}^{\nu(\overline{\nu})}}{\sigma_{CC}^{\nu(\overline{\nu})}} = \rho^2 \left(\frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W \left(1 + \frac{\sigma_{CC}^{\overline{\nu}(\nu)}}{\sigma_{CC}^{\nu(\overline{\nu})}} \right) \right)$$

(Llewellyn-Smith)

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

(Paschos-Wolfenstein)

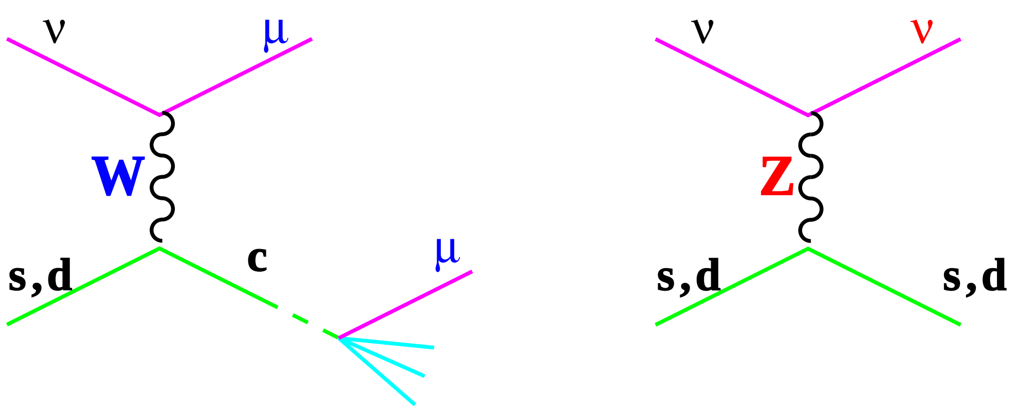
Interaction	Total Spin	$\frac{d\sigma}{dy}$
ν-q: or $\overline{\nu}$-$\overline{q}$	0	1
$\overline{\nu}$-q: or ν-$\overline{q}$	1	$(1-y)^2$



$2(1-y) = 1 + \cos^2\theta^*$

Heavy Quark Effects

Charged-Current Production of Charm



- Suppression of CC cross section for interactions with massive charm quark in final state
- Modeled by leading-order slow-rescaling

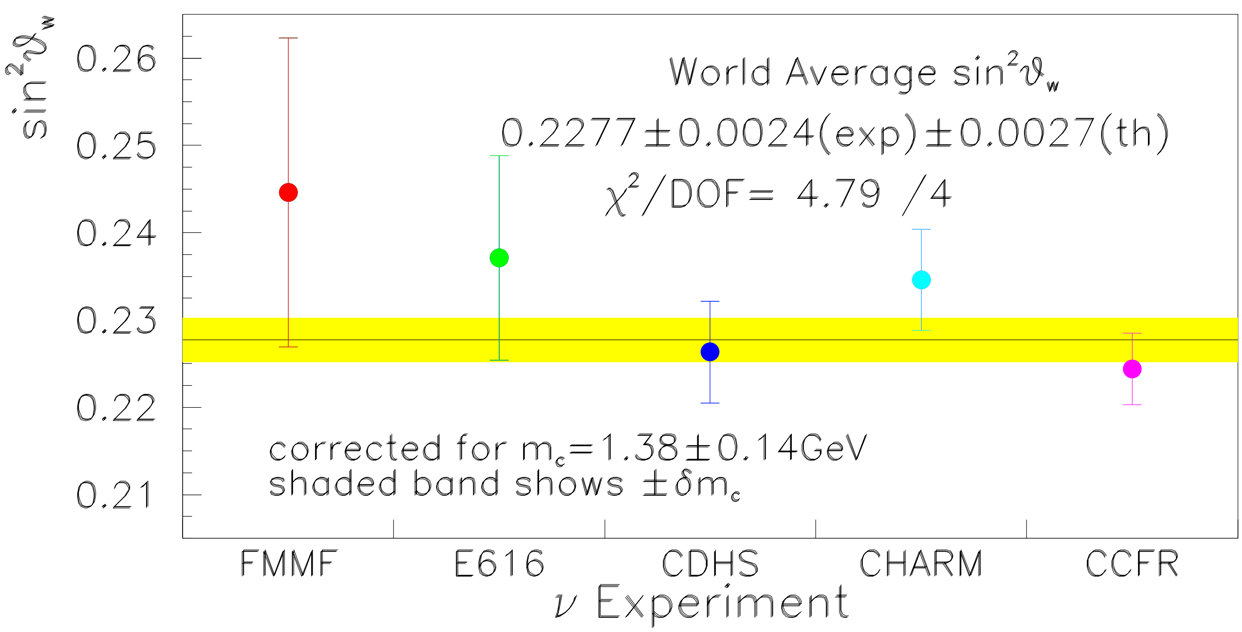
$$\xi = x(1 + \frac{mc^2}{Q^2}) \quad where \quad x = \frac{Q^2}{2ME_{\rm had}}$$

- Parameters of model and strange sea measured by NuTeV/CCFR in dimuon events $c \to \mu X$

νN Experiments Before NuTeV

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

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



All other experiments are corrected to NuTeV/CCFR m_c and to large $M_{\rm top}$ ($M_{\rm top} > M_W$)

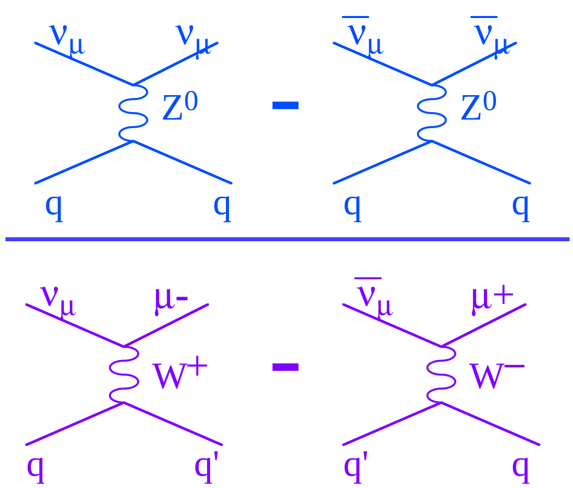
Results are limited by large correlated uncertainty $\Rightarrow$ technique has hit a brick wall

NuTeV's Technique

Charm Production and Charm Sea Errors are Large
$\Rightarrow$ Need a Technique Insensitive to Sea Quarks

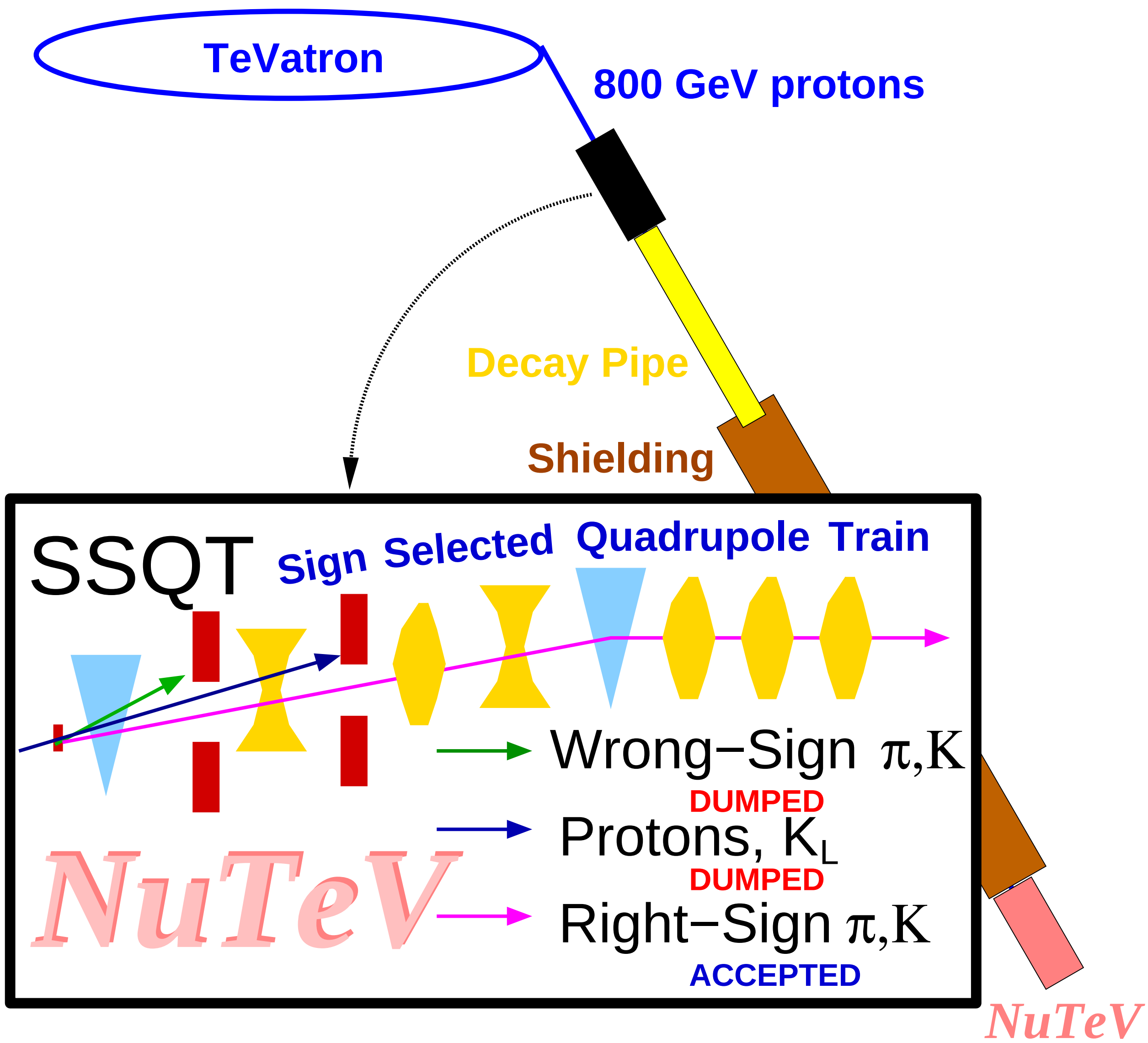
Paschos-Wolfenstein Relation:

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



- R^- manifestly insensitive to sea quarks
  - ↪ Massive quark production enters from d_V quarks only (Cabbibo suppressed and at high x)
  - ↪ Charm, strange sea errors negligible
- Requires Separate ν and $\overline{\nu}$ Beams $\Rightarrow$ NuTeV SSQT

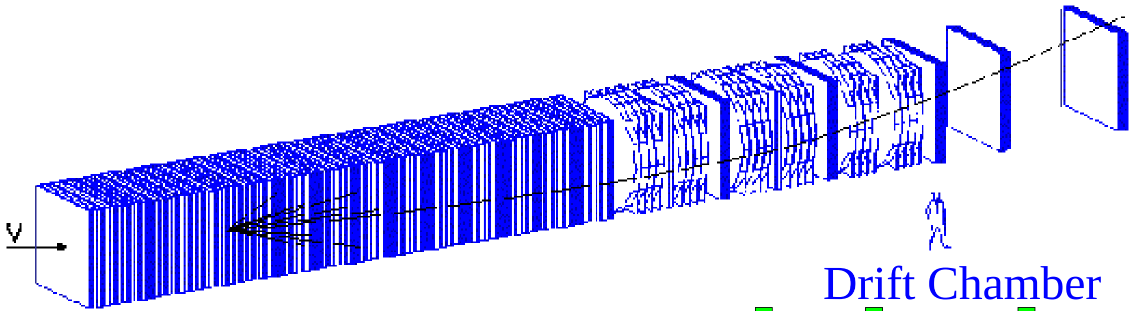
NuTeV Beamline



- Beam is almost purely ν or $\overline{\nu}$:
  ($\overline{\nu}$ in ν mode 3×10^{-4}, ν in $\overline{\nu}$ mode 4×10^{-3})
- Beam is $\sim$1.6% electron neutrinos

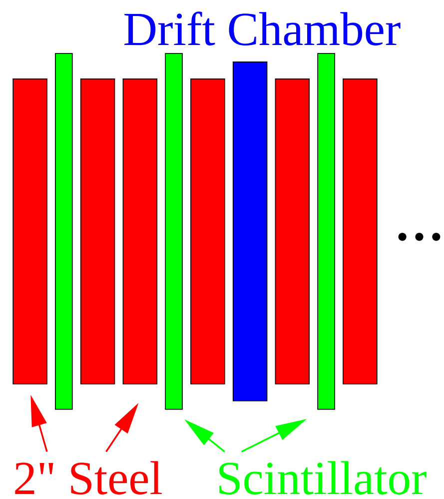
νN Deep Inelastic Scattering at NuTeV

Lab E Detector - Fermilab E815(NuTeV)



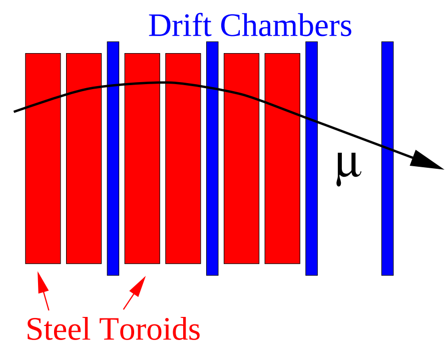
Target/Calorimeter:

- 168 Fe plates (3m × 3m × 5.1cm)
- 84 liquid scintillation counters
  Trigger the detector
  Visible energy
  Neutrino interaction point
  Event length
- 42 drift chambers
  Localized transverse shower position



Toroidal Spectrometer:

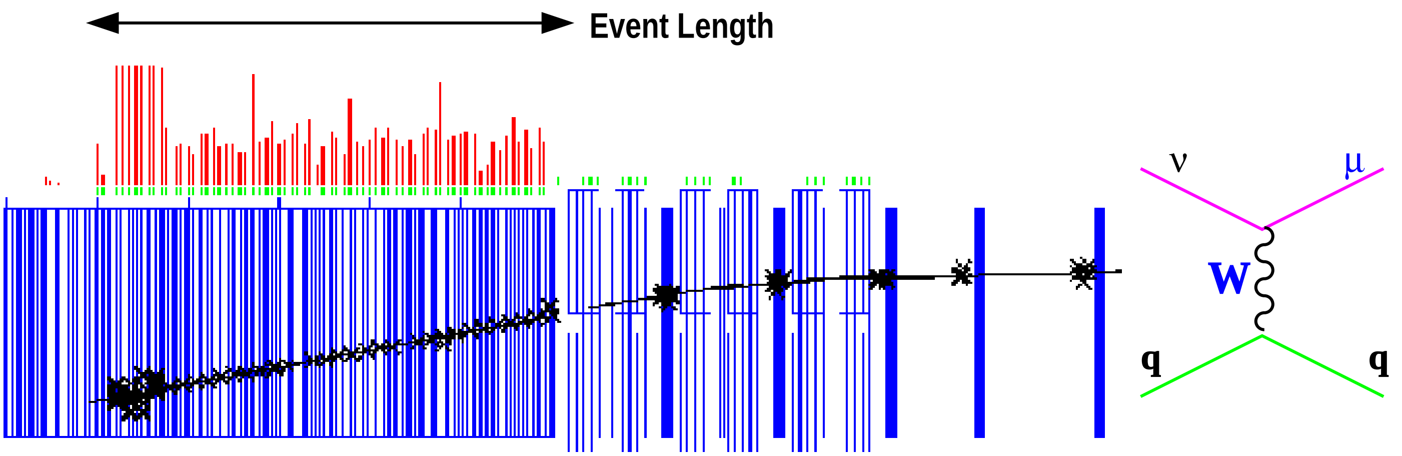
- 15kG field ($P_T = 2.4\, GeV/c$)

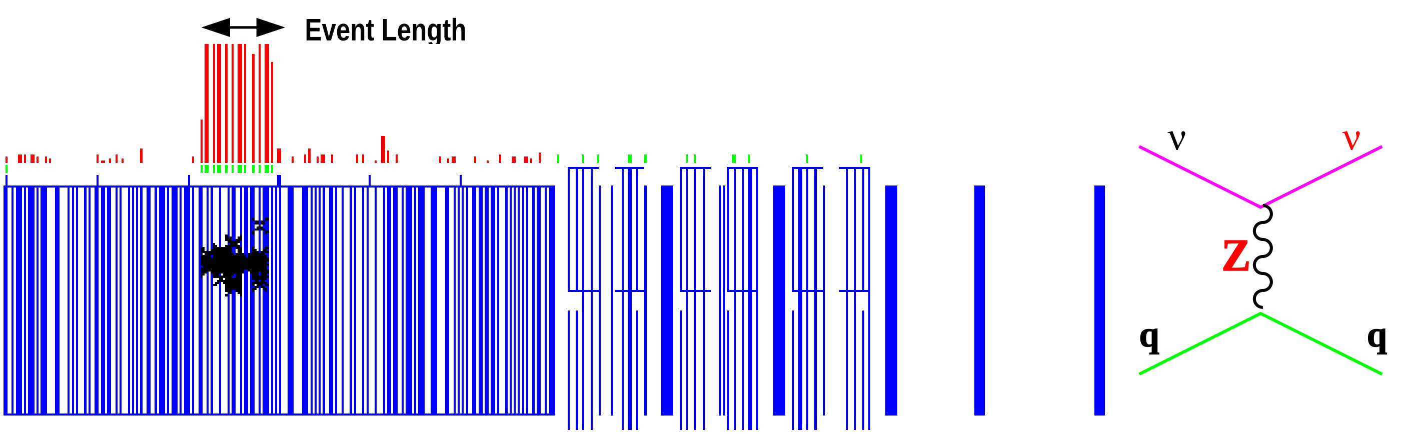


Continuous Test Beam: interspersed with ν beam

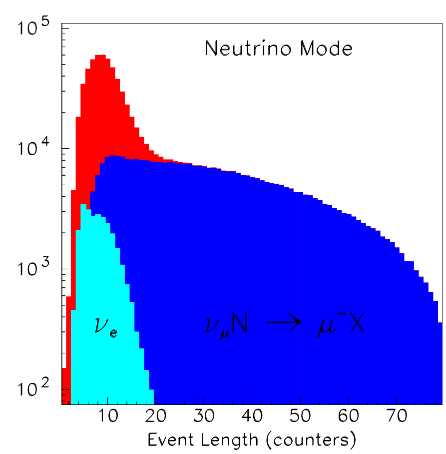
- Hadron, muon and electron beams
  Map toroid and calorimeter response

Neutral Current/Charged Current Event Separation





Statistical separation of NC and CC events based on ("event length").



$$R_{\text{exp}} = \frac{\text{SHORT events}}{\text{LONG events}} = \frac{\text{NC candidates}}{\text{CC candidates}}$$

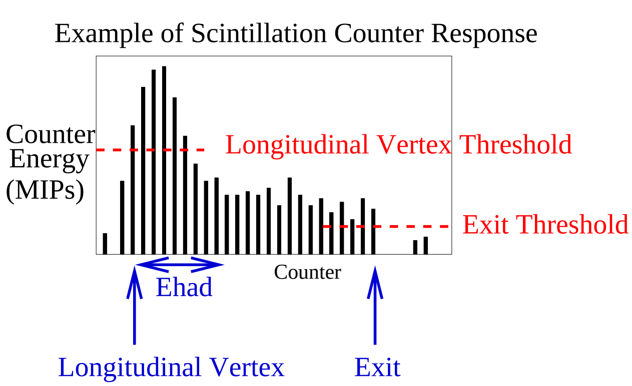
Event Selection

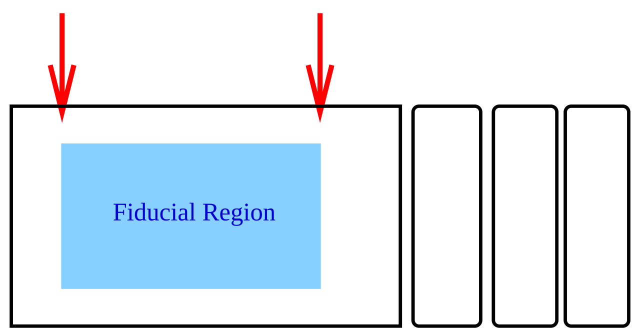
Trigger:

- Select events with large consecutive signals in counters

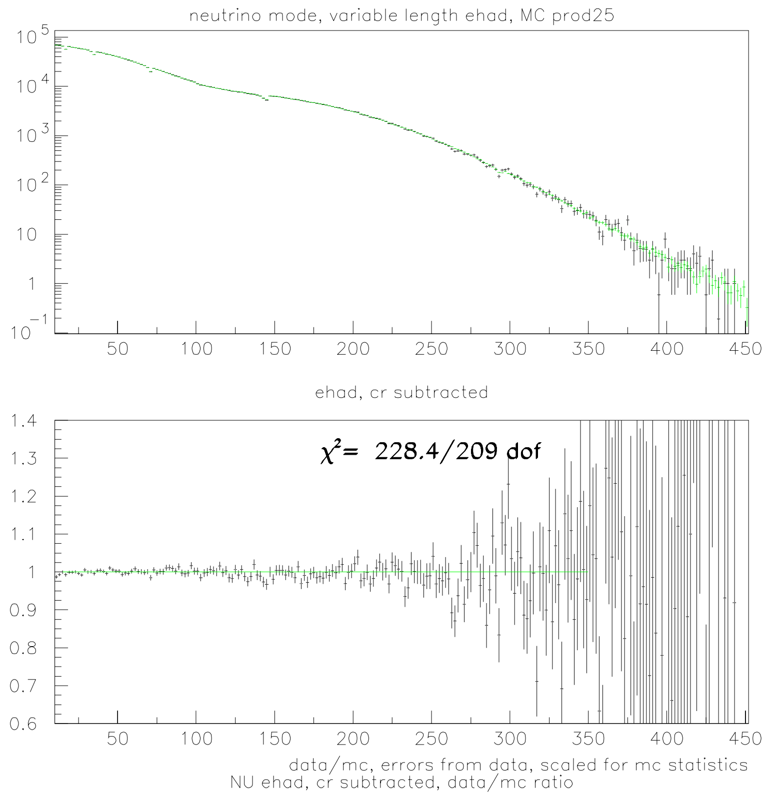
Event Variables:

- Hadronic Energy ($E_{\rm had}$)
  Sum of energies in number of counters tuned for containment: 0.7-1.2m steel equivalent
  Require $E_{\rm had} >$ 20 GeV for efficient vertex finding, low backgrounds
- Longitudinal Event Vertex
  Counter directly downstream of interaction
  Transverse vertex in central $\approx 2/3$ of calorimeter to ensure hadron and improve muon containment
- Event Exit
  Counter upstream of 3 consecutive quiet counters
  Upstream limit to reduce muons entering calorimeter, downstream limit to ensure meaningful length
- Event Length
  Number of counters from hadronic shower start
  to end of muon signal in scintillator

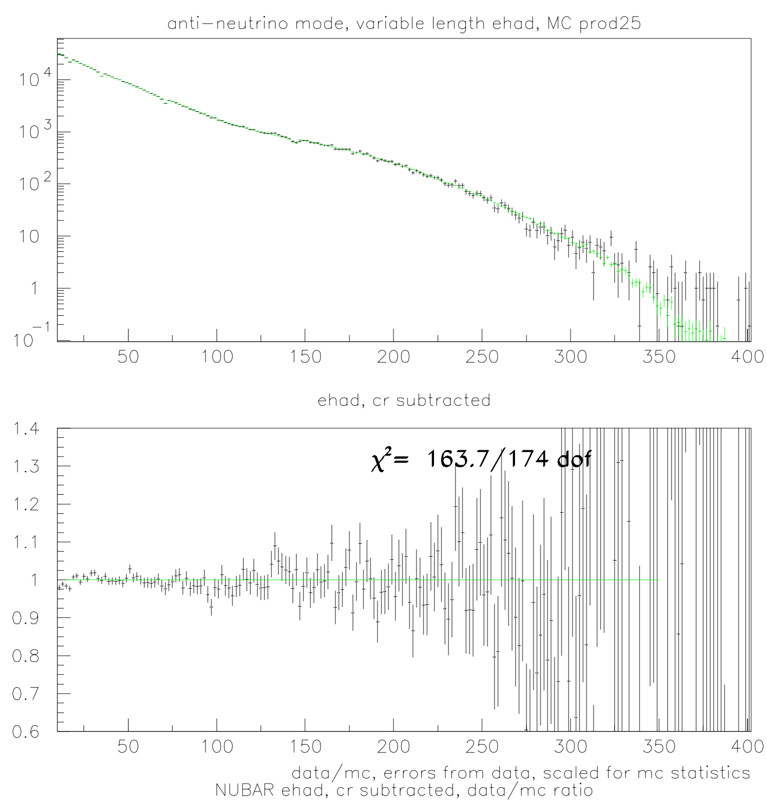




The Raw Data



1.62×10^6 events in the ν beam



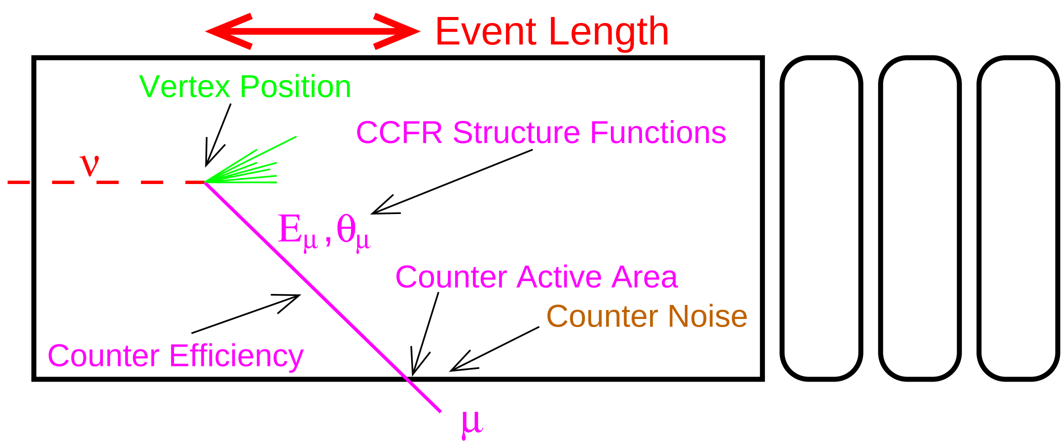
0.35×10^6 events in the $\overline{\nu}$ beam

Experimental Technique

	Short (NC) Events	Long (CC) Events
ν	457K	1167K
$\overline{\nu}$	101K	250K

	$R_{\rm exp} \equiv$ Short Events/Long Events
ν	$0.3916 \pm 0.0007(\rm stat)$
$\overline{\nu}$	$0.4050 \pm 0.0016(\rm stat)$

$R_{\rm exp}$ can be related to R^{ν} and $R^{\overline{\nu}}$ using a detailed cross-section model and detector Monte Carlo.



<u>Cross section model</u>

- LO PDF (CCFR)
- Radiative corrections
- Isovector corrections ($\frac{Z+A}{2Z} \approx 5.67\%$, $\overline{u}/\overline{d}$)
- Heavy quark corrections
- R_L; Higher Twist

<u>Detector response</u>

- CC↔NC cross-talk
- Beam Contaminations
- Muon simulation
- Calibrations
- Event vertex

Summary of Corrections $R_{\rm exp}$

Corrections Applied to Data

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

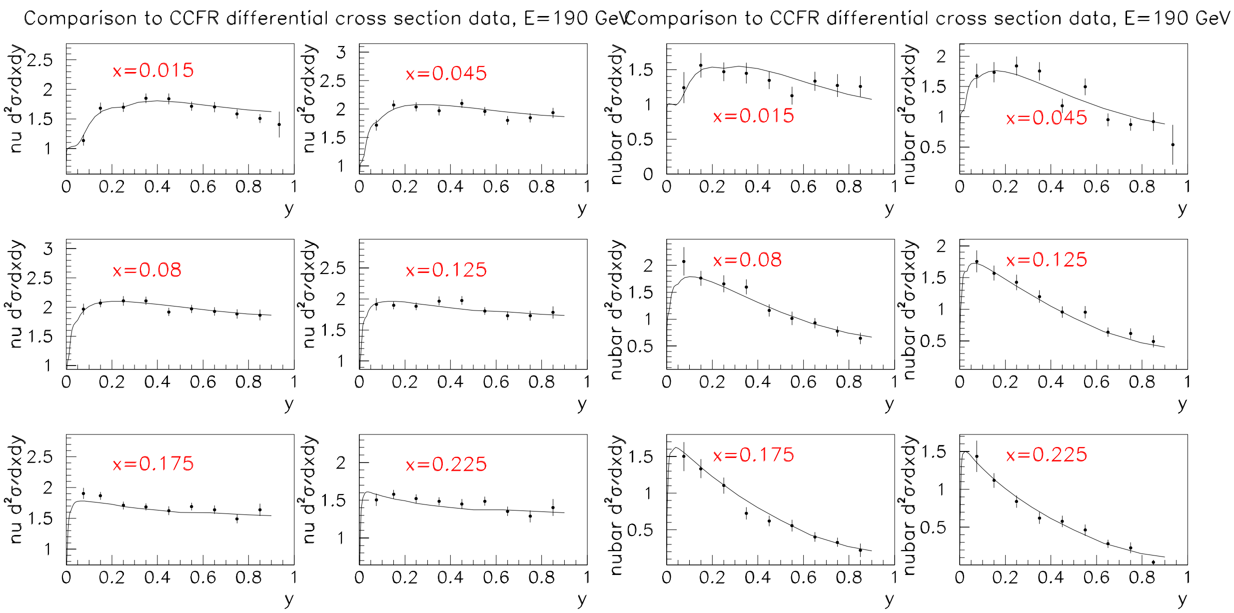
Effects in Monte Carlo that relate $R^{\overset{(-)}{\nu}}$ to $R^{\overset{(-)}{\nu}}_{\rm exp}$

Effect	$\delta R^{\nu}_{\rm exp}$	$\delta R^{\overline{\nu}}_{\rm exp}$
Short CC Background	–0.068	–0.026
Electron Neutrinos	–0.021	–0.024
Long NC	+0.0028	+0.0029
Counter Noise	+0.0044	+0.0016
Counter Efficiency	–0.0008	–0.0008
Longitudinal Vertex Offset	–0.0015	–0.0010
Heavy m_c	–0.0010	–0.0024
R_L	–0.0026	–0.0092
EM Radiative Correction	+0.0074	+0.0109
Weak Radiative Correction	–0.0005	+0.0058
High Q^2 “Longexit”	+0.00021	–0.00035
d/u	–0.00023	–0.00023
Higher Twist	–0.00012	–0.00013
Intrinsic Charm Sea	–0.00005	+0.00004

Recall: $R^{\nu}_{\rm exp}$ and $R^{\overline{\nu}}_{\rm exp}$ measured to a precision of 0.0012 and 0.0026, respectively

Enhanced LO Cross-Section

- LO PDFs extracted from CCFR data ($d^n = u^p$)
- PDFs are needed because u and d NC couplings differ
- PDF fit $\chi^2 = 2460/2559$ dof



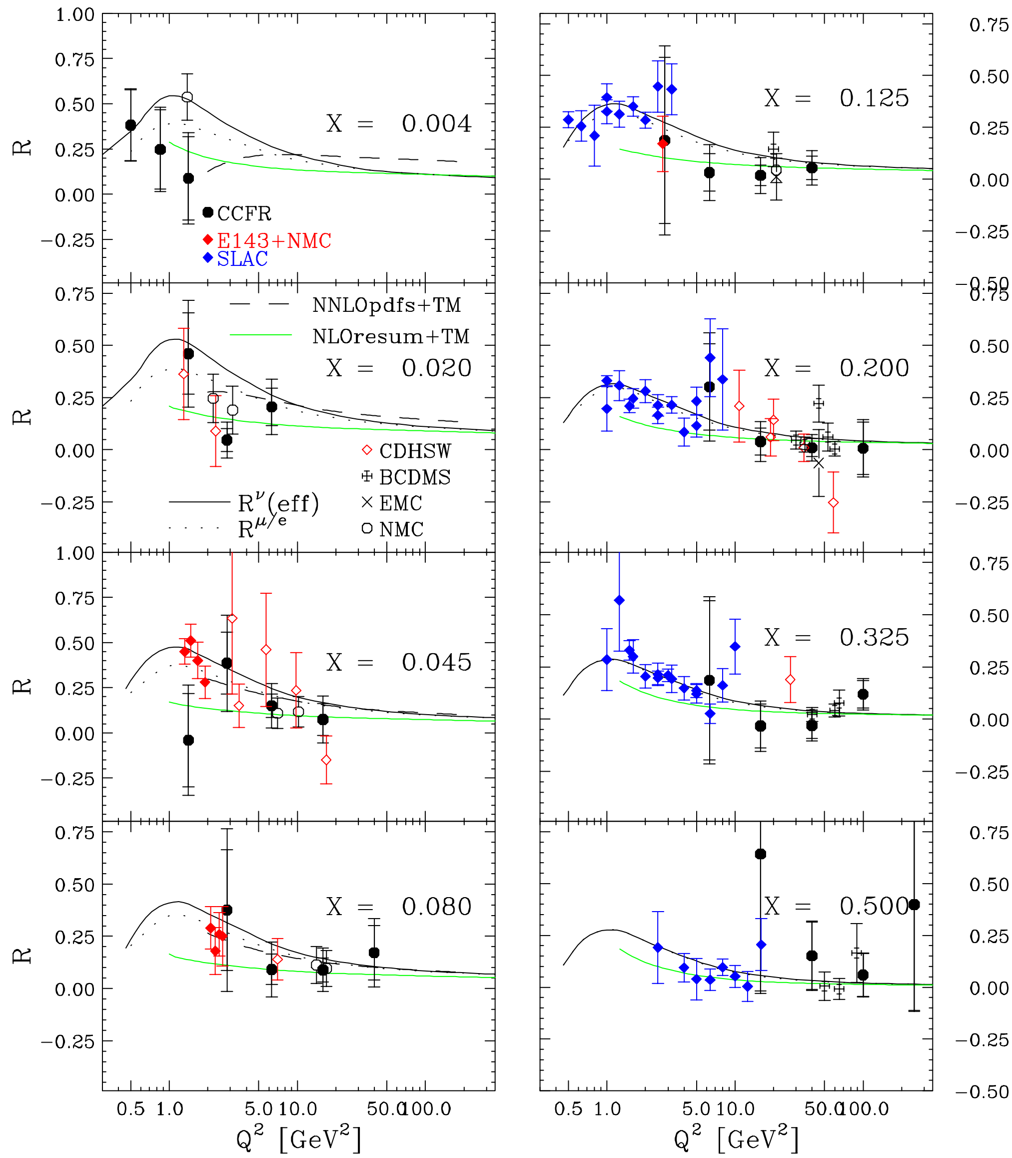
High y CC $\Rightarrow$ Soft muon $\Rightarrow$ NC background

Simple LO model must be augmented to agree with data

- Heavy quark production suppression and $\overline{s}(x)$ (CCFR, NuTeV $\nu N \rightarrow \mu^+\mu^- X$ data)
- R_L, Higher twist (from fits to SLAC, BCDMS)
- d/u constraints from NMC, NUSEA data
- $Q^2 < 1$ GeV^2 PDF evolution from GRV94LO model
- Intrinsic charm from EMC $F_2^{c\bar{c}}$

This "tuning" of model is *crucial* to analysis

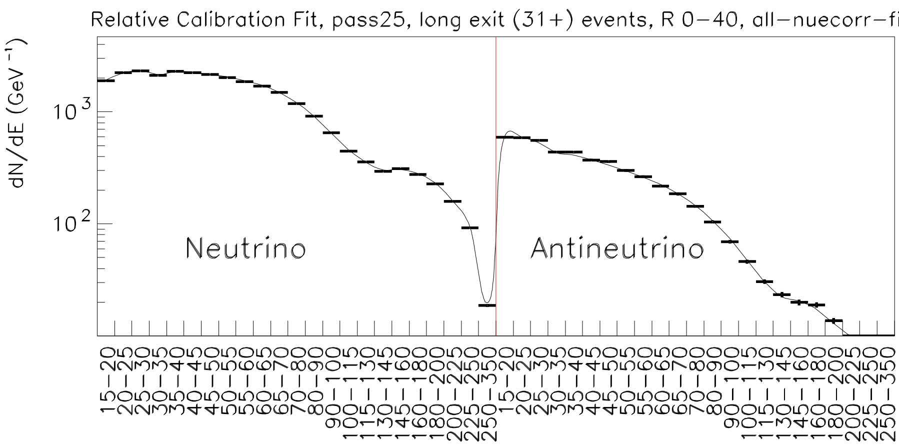
R_L

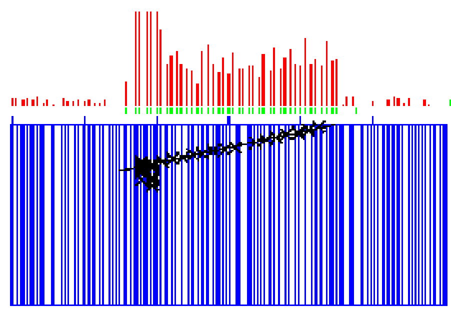


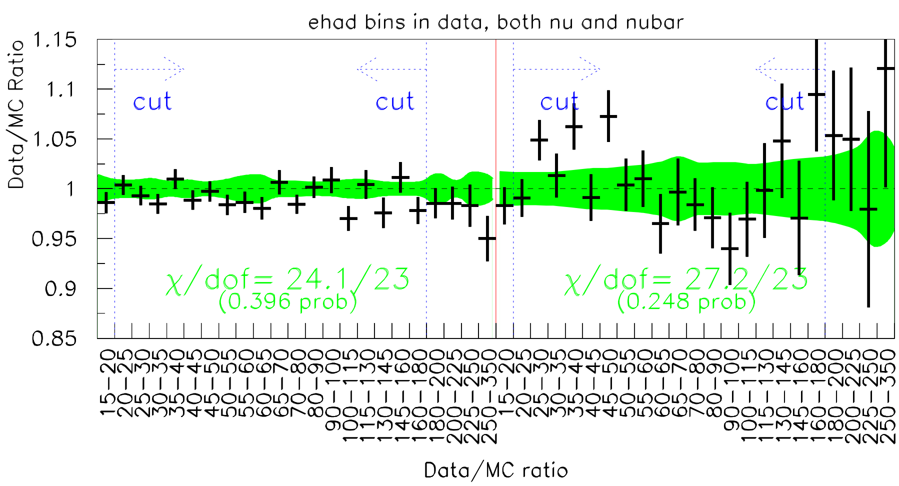
- Vary $R_L = F_L/F_T$ within data errors at low x
- At high x, where theoretical prediction of R_L is reliable, take NNLO-NLO difference as systematic
- Important for prediction of high y cross-section

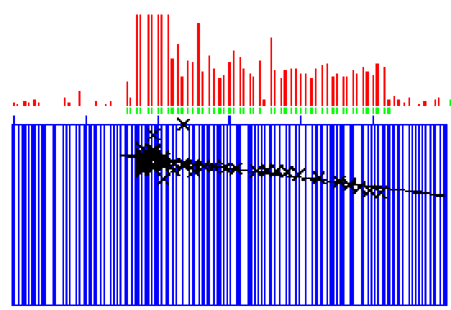
Charged-Current Control Sample

- High y charged-current is background to NC sample
  - ↪ CC subtraction is $20\%/10\%$ in $\nu/\overline{\nu}$ $\Rightarrow$ want $\sim 1\%$ accuracy
- Check by looking at "long exit" CC events which start in the detector center and stop before toroid





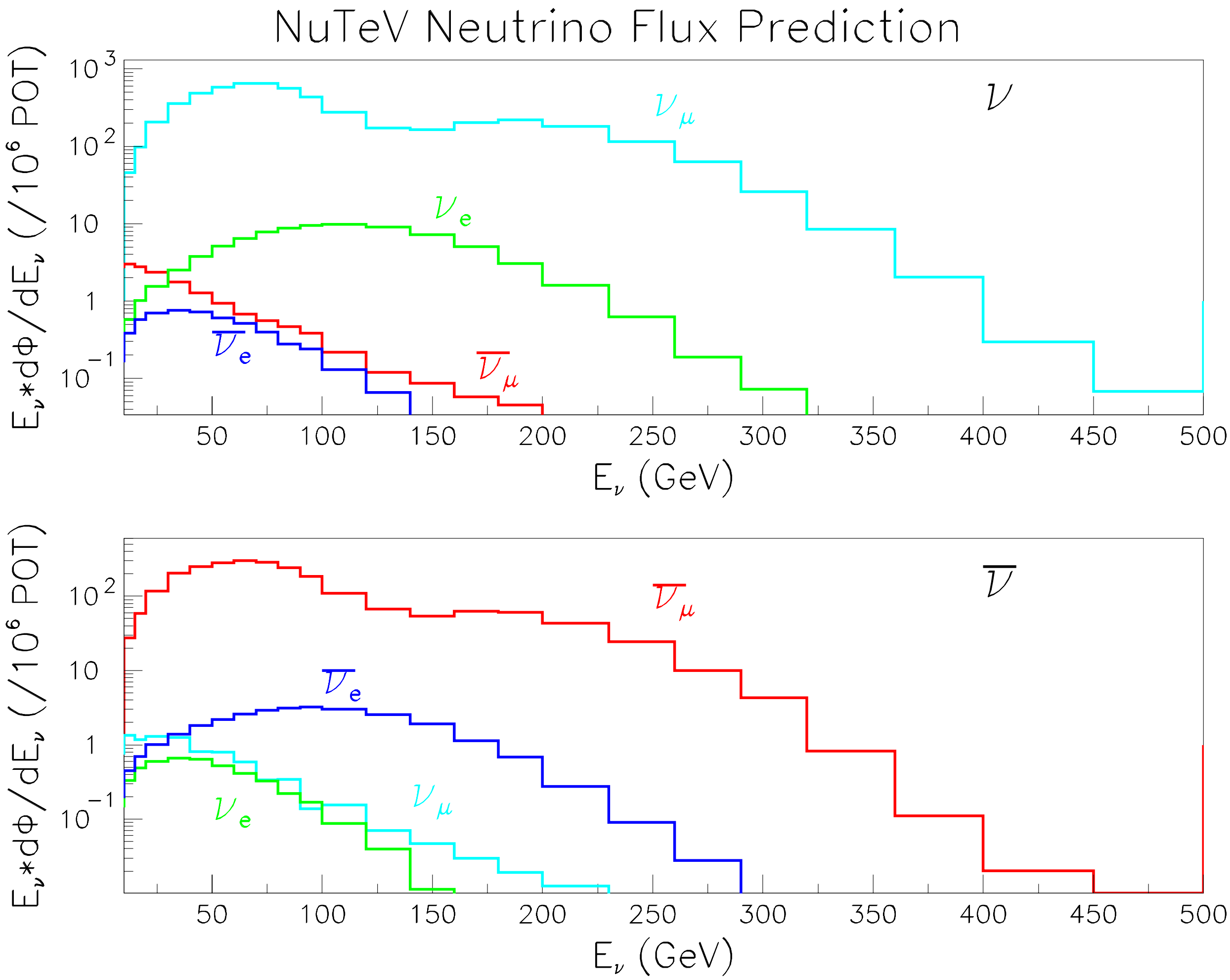




- Modify high Q^2, moderate x, PDFs to fix 2.6% disagreement at moderate $E_{\rm had}$ in ν mode
  - ↪ Only weak CCFR cross-section constraint here *(these events not in cross-section data)*
  - ↪ $\delta R^{\nu}_{\rm exp} = -0.00021$, $\delta R^{\overline{\nu}}_{\rm exp} = +0.00035$

NuTeV Neutrino Flux

Approximately 5% of all short events are ν_e CC.



Sources of Neutrinos and Event Fractions

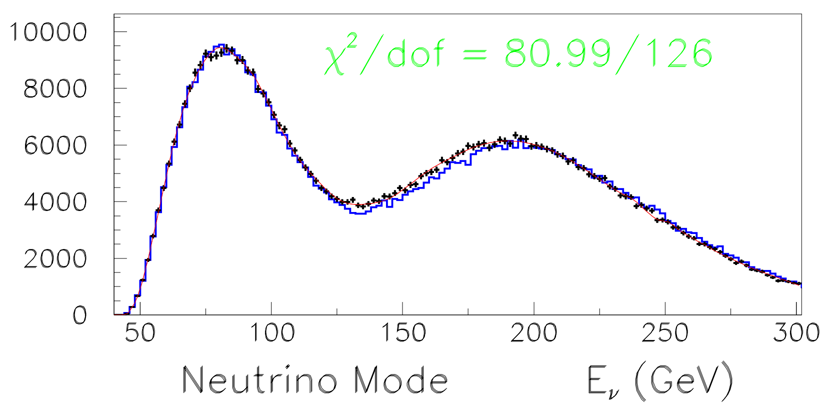
Source	ν Mode	$\bar{\nu}$ Mode
$\pi^\pm, K^\pm \to \mu^\pm \overset{(-)}{\nu}_\mu$	0.982	0.973
$K^\pm_{e3}$	0.0157 ± 0.0003	0.0115 ± 0.0002
K_{Le3}, K_{Se3}	0.00065 ± 0.00007	0.00290 ± 0.0003
Charm Meson$\to \nu_e$	0.00042 ± 0.00006	0.00155 ± 0.0002
$\mu \to \nu_e$	0.00007 ± 0.00001	0.00010 ± 0.00001
Λ_c, Λ, Σ	0.00003 ± 0.00003	0.00023 ± 0.0002

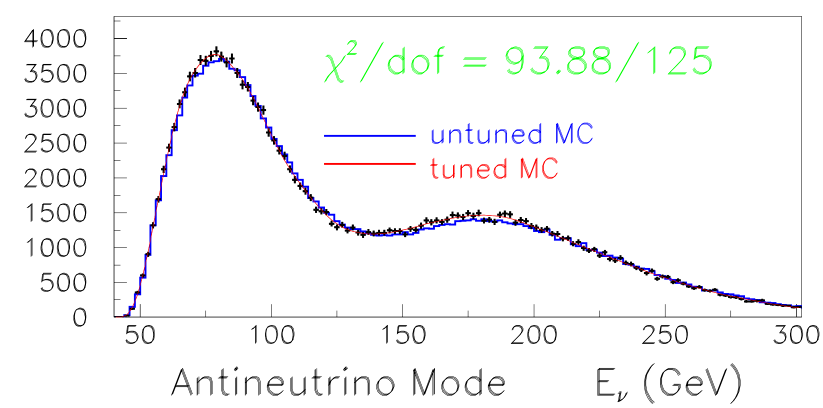
NuTeV Neutrino Flux

- Tune the observed ν_μ spectrum to match MC prediction
  - ↪ Driven by small uncertainties in SSQT alignment and large production uncertainties
  - ↪ Tuning procedure is robust at 0.5% level
- Find

Beam	E_π	E_K	K/π
ν	-0.2%	-1.3%	$+2.7\%$
$\overline{\nu}$	-0.4%	-0.9%	$+2.8\%$

  - ↪ Sensitive to calorimeter calibration ($\delta E_{\rm cal} = 0.43\%$)
- $K^{\pm}_{e3}$ branching ratio (1.4%) dominates ν_e flux uncertainty!!!



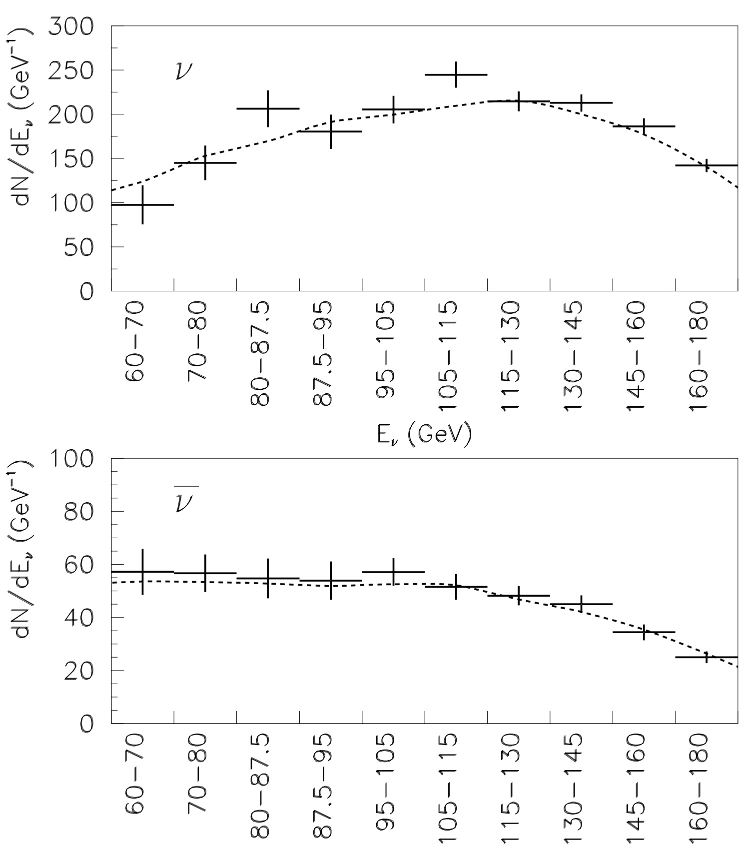


Direct Measurements of ν_e Flux

We have three additional *measurements* of the ν_e flux:

1. ν_μ in $\overline{\nu}$ beam (from charm, K_L decay)
2. Measurement of ν_e from quickly-developing showers
    - Constrains (mostly) $K^{\pm}_{e3}$ at moderate energy ($80 < E_\nu < 180$ GeV)
    - Direct measurement is less precise than, consistent with, slightly higher than the beam Monte Carlo
    - $N_{\text{meas}}/N_{\text{pred}}$: 1.05 ± 0.03 (ν_e), 1.01 ± 0.04 ($\overline{\nu}_e$)
    - Use weighted average of measurement with beam Monte Carlo

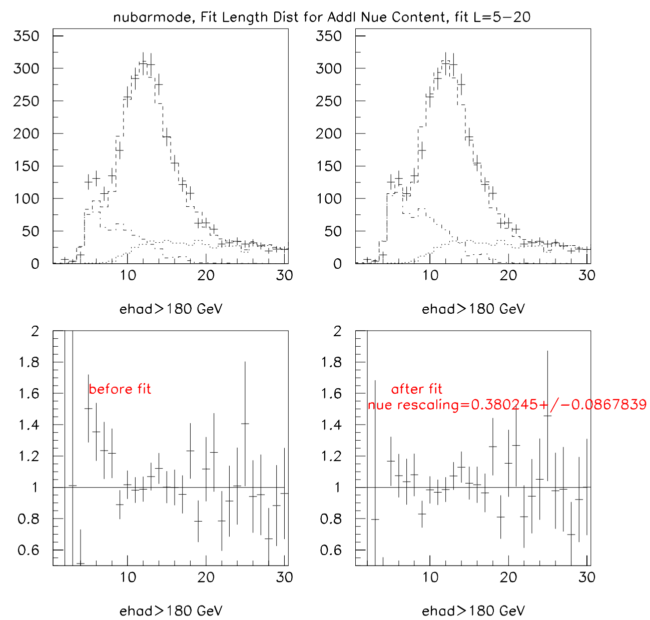
$\hookrightarrow$ $\delta R^{\nu}_{\text{exp}} \approx 0.0005$ from moderate E_ν constraint



Direct ν_e Flux (cont'd)

3. Measurement of ν_e from the length distribution!

   - Constrains $K_{e3}^{\pm}$ at high energy ($E_\nu > 180$ GeV)
   - Observe $\sim 35\%$ more $\overline{\nu}_e$ than predicted in $\overline{\nu}$ beam, smaller excess in ν beam
   - *Conclude that we should require $E_{\rm had} < 180$ GeV*



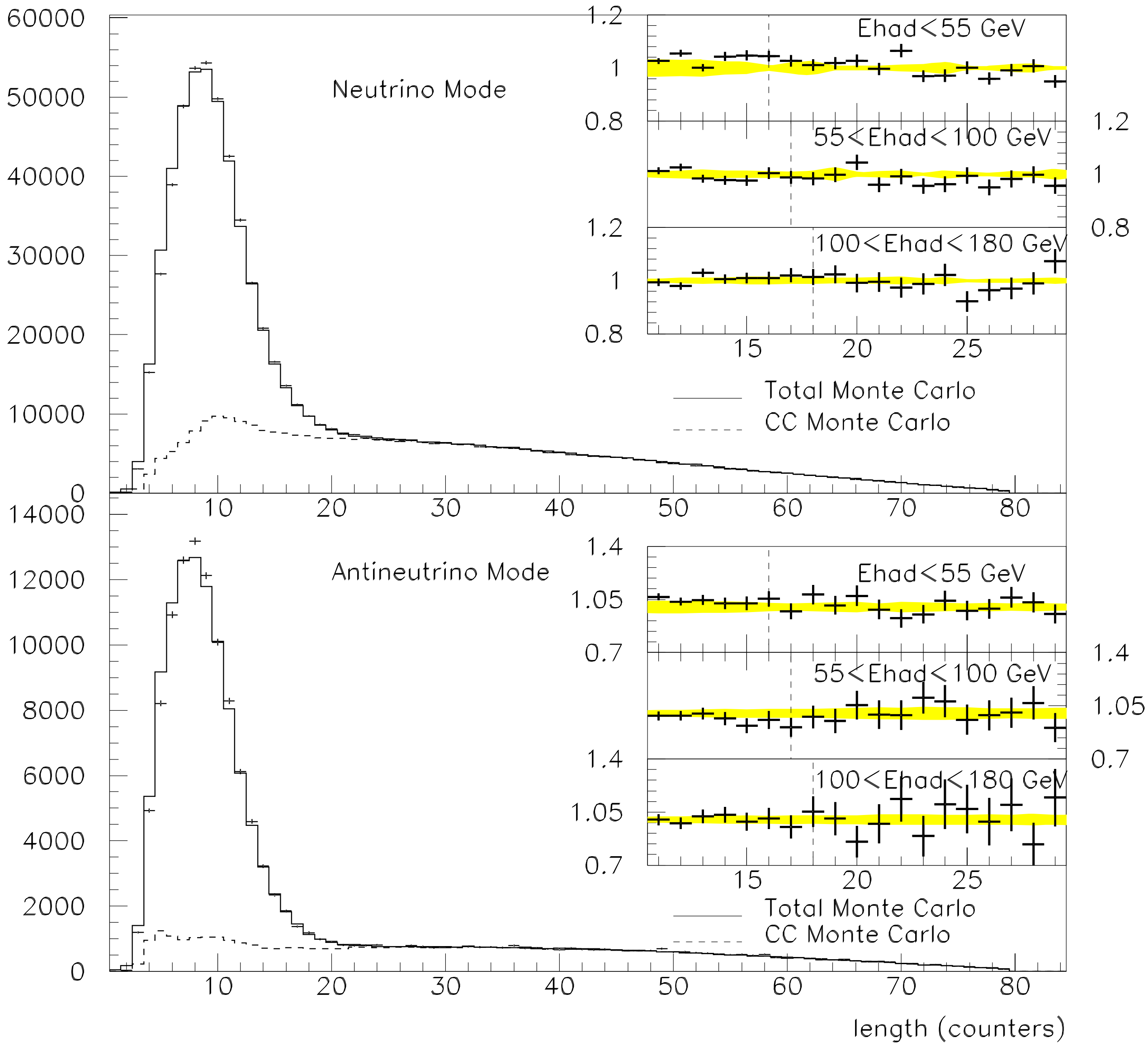
Preliminary result had significantly different ν_e prediction

- ADC saturation (now corrected) hid $E_{\rm had} > 180$ GeV excess
  - ↪ $\delta R^{\nu}_{\rm exp} \approx 0.0012$, $\delta R^{\overline{\nu}}_{\rm exp} \approx 0.0010$ (!)
  - ↪ After incorporating high E_ν ν_e measurement, result is same with and without high $E_{\rm had}$ cut.
- *This accounts for $+0.0020$ shift in $\sin^2\theta_W$ since preliminary result*

Hadron Shower Length

- All events have showers from recoil of hadronic system
  - ↪ Determines event length for NC
  - ↪ NC→CC sample (0.7% of NC)
  - ⇒ Want to model punch-through at 10% level
- Use LEPTO description of shower to generate hadrons and use testbeam hadron length
  - ↪ Robust at high E_{had} where NC→Long events occur
  - ↪ Not robust at low E_{had}; requires tuning of LEPTO description to match NC events in "long SHORT" region
  - ↪ No attempt to tune at low length
  - ↪ Systematics reflect uncertainty on tuning, testbeam

Hadron Shower Length (cont'd)



Stability of $R_{\rm exp}$

- Strategy: verify that the $R_{\rm exp}$ comparison to Monte Carlo is consistent under changes in fiducial cuts and different ranges of event variables
  - ↪ Use χ^2 probability test to evaluate comparisons
  - ↪ Compare to expected values
    - ⋆ Be wary that new physics can cause inconsistency! (e.g., $E_{\rm had}$ dependence of $R_{\rm exp}$)
- Event observables:

  Longitudinal vertex: check detector uniformity

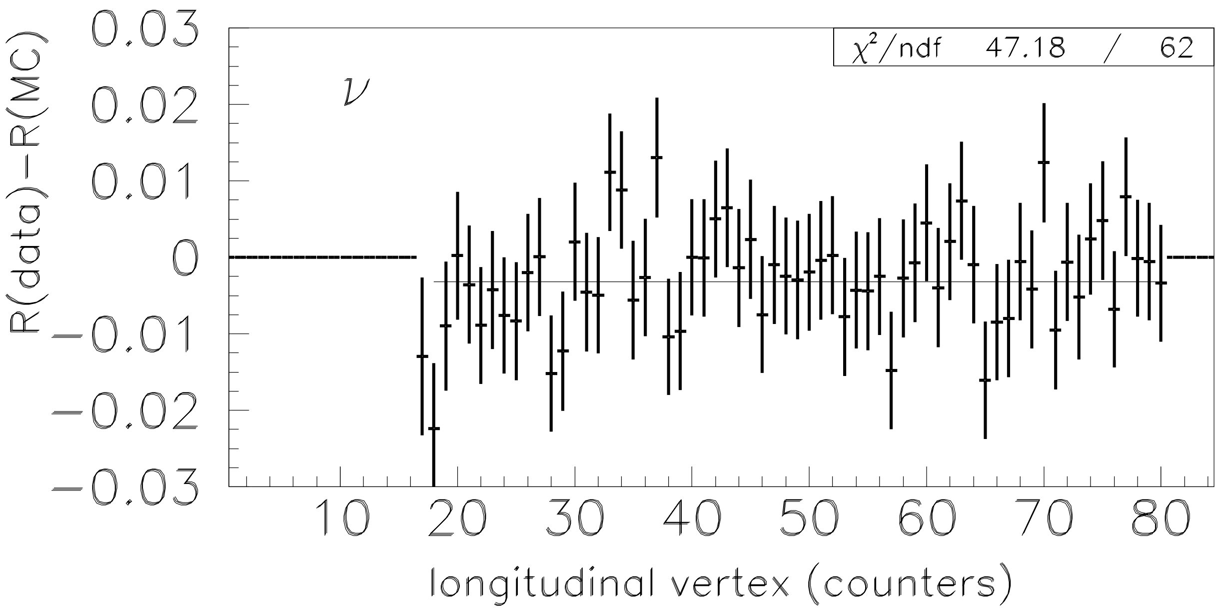
  Short/Long separatrix: check CC↔NC

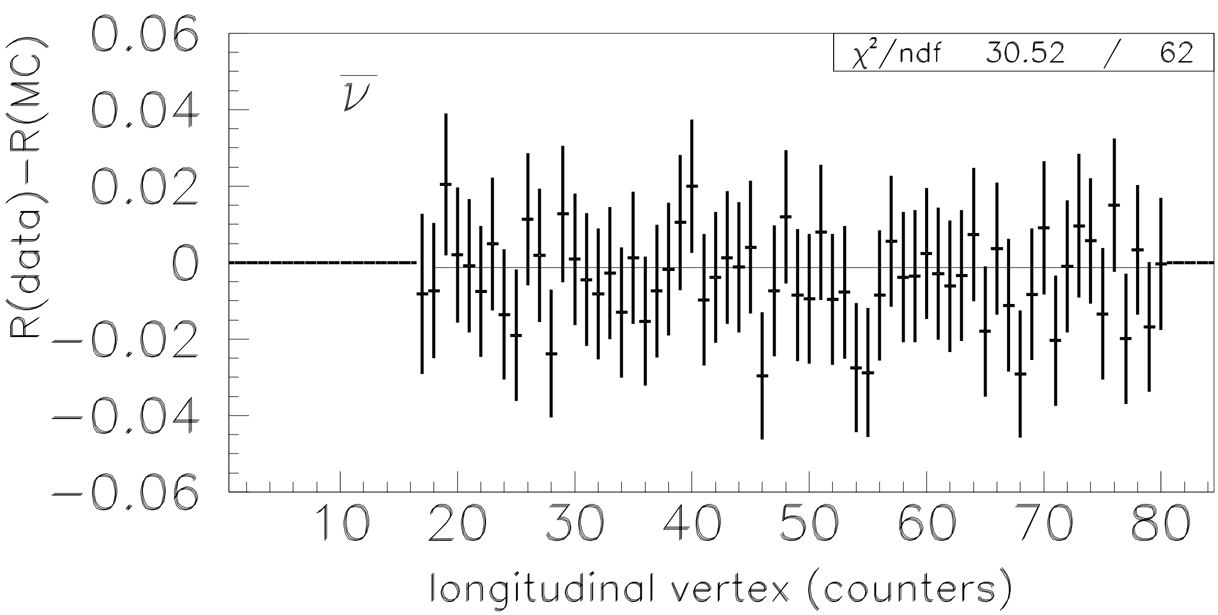
  Transverse vertex: more NC background near edge

  Visible Energy: checks EVERYTHING!

Stability of R_{exp} (cont'd)

R as a function of longitudinal vertex

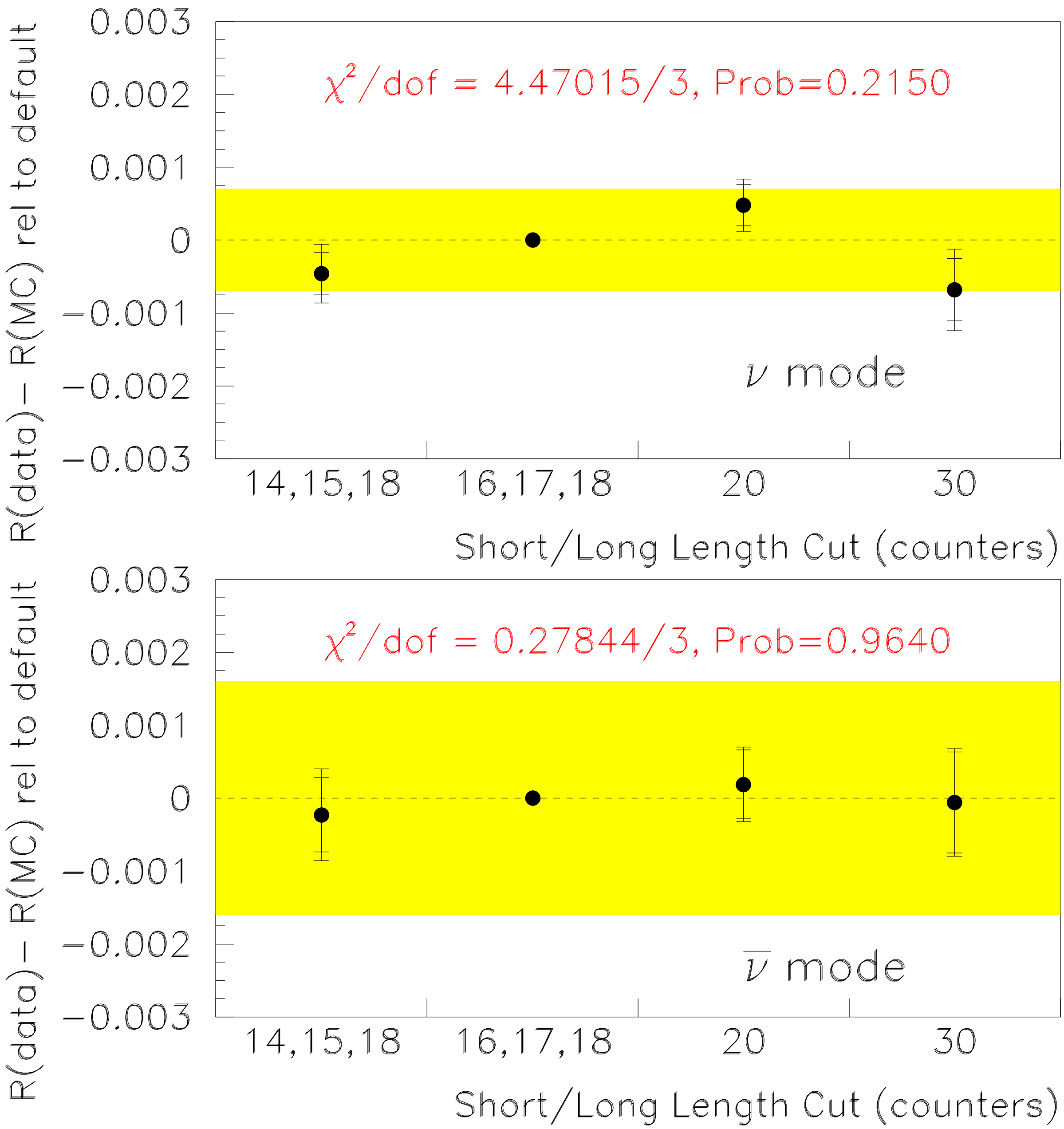




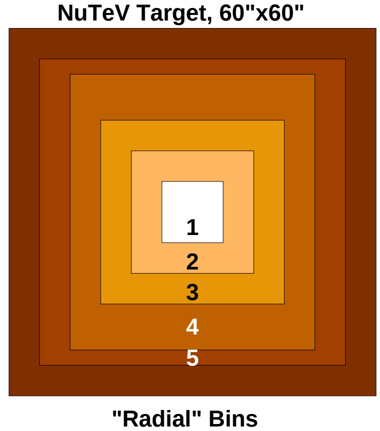
Stability of $R_{\rm exp}$ (cont'd)

R as a function of length cut

- "16,17,18" [counters] is default; tighten↔loosen NC selection
- Measurements are correlated; uncertainties are on *difference*

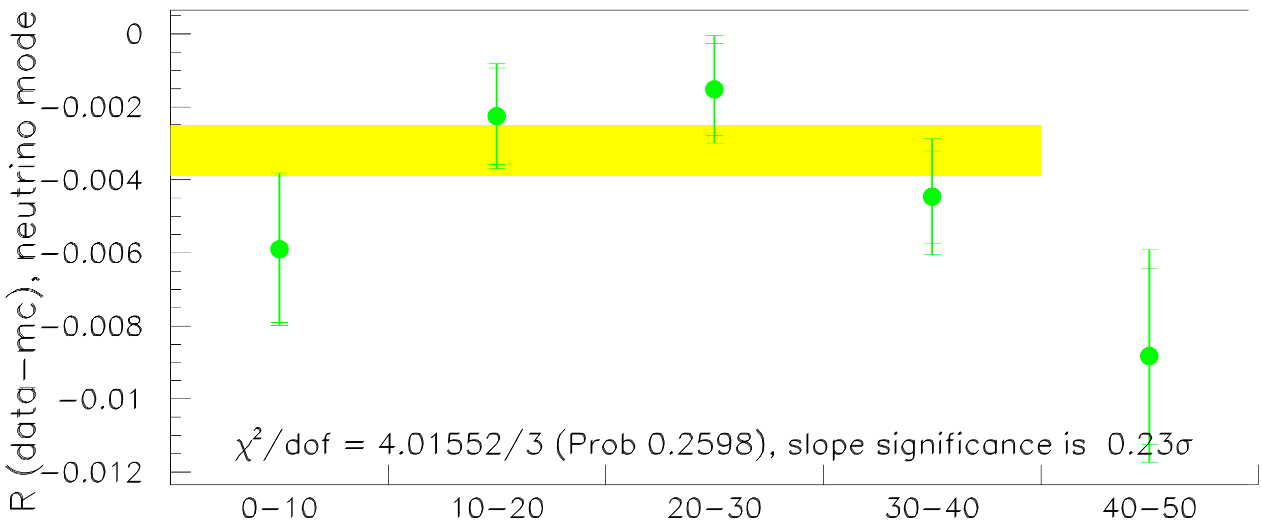


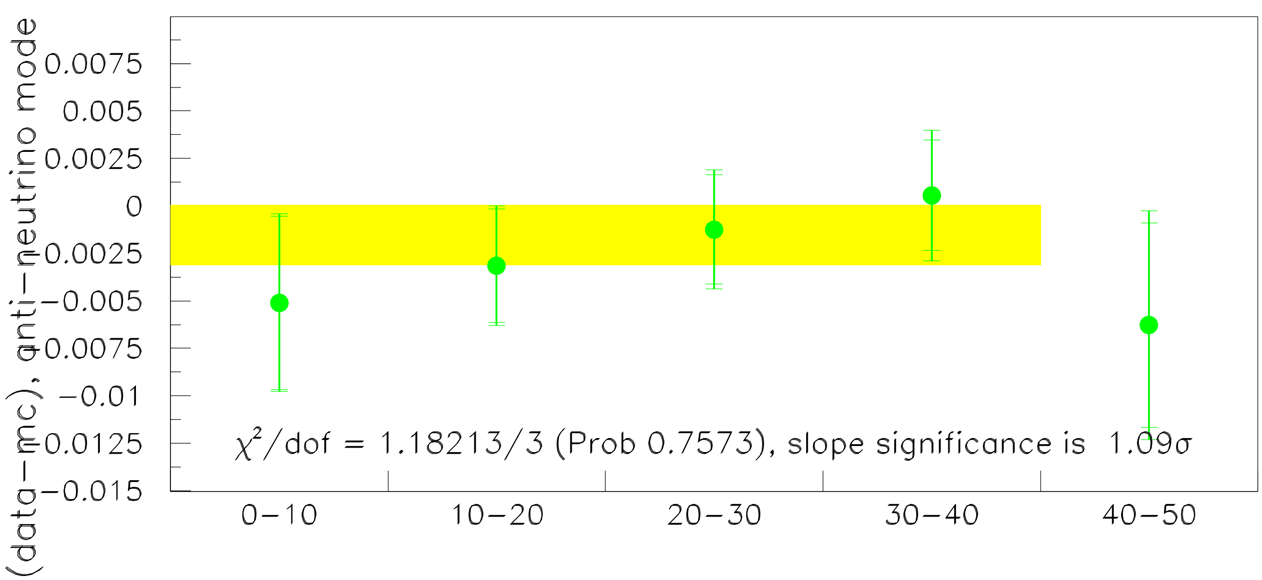
Stability of R_{exp} (cont'd)



R as a function of "radial" bin

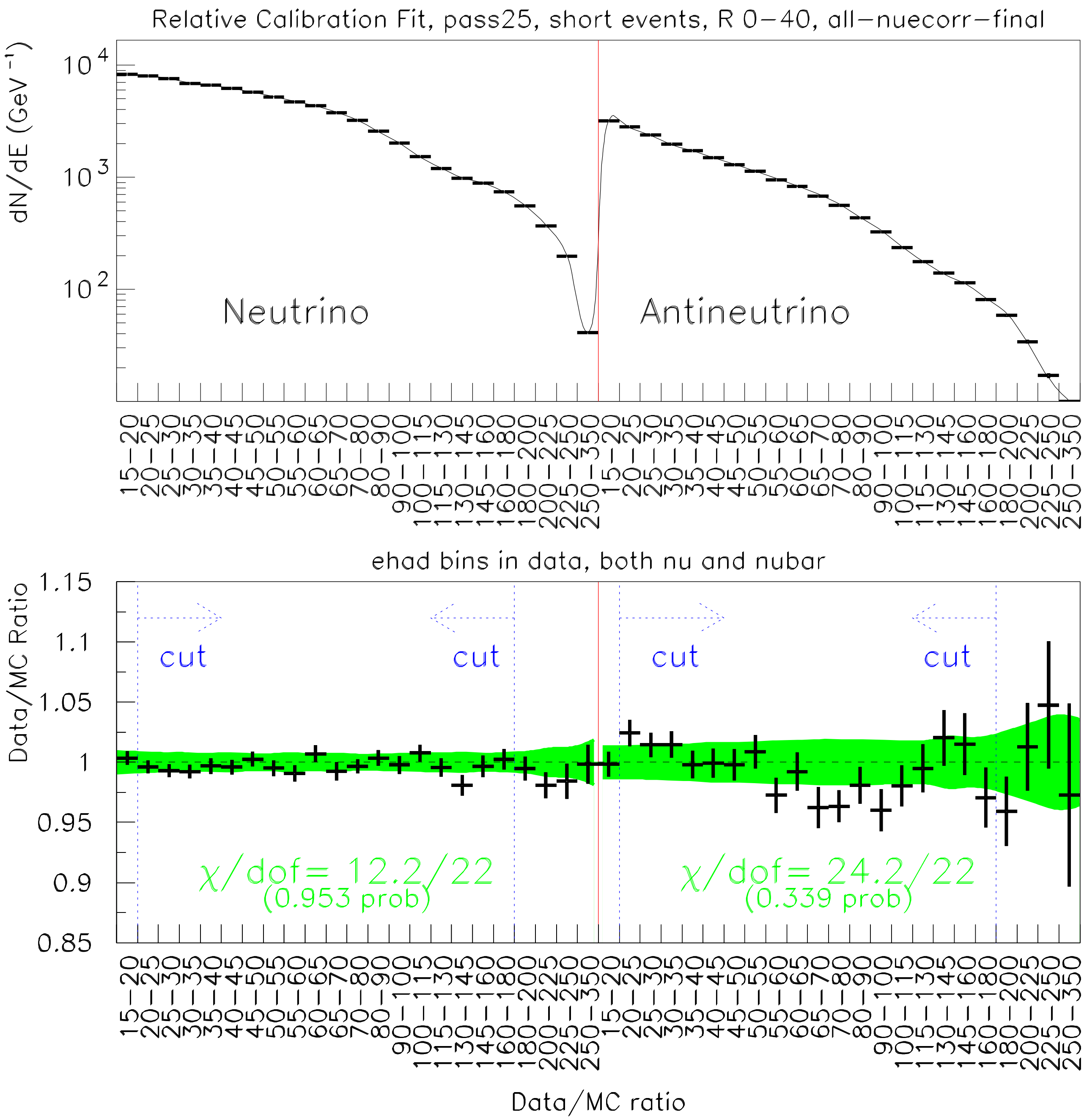
- Bins 1-4 in result (5 is a check)
- Sensitive to mistakes in ν_e, short CC





Stability of R_{exp} (cont'd)

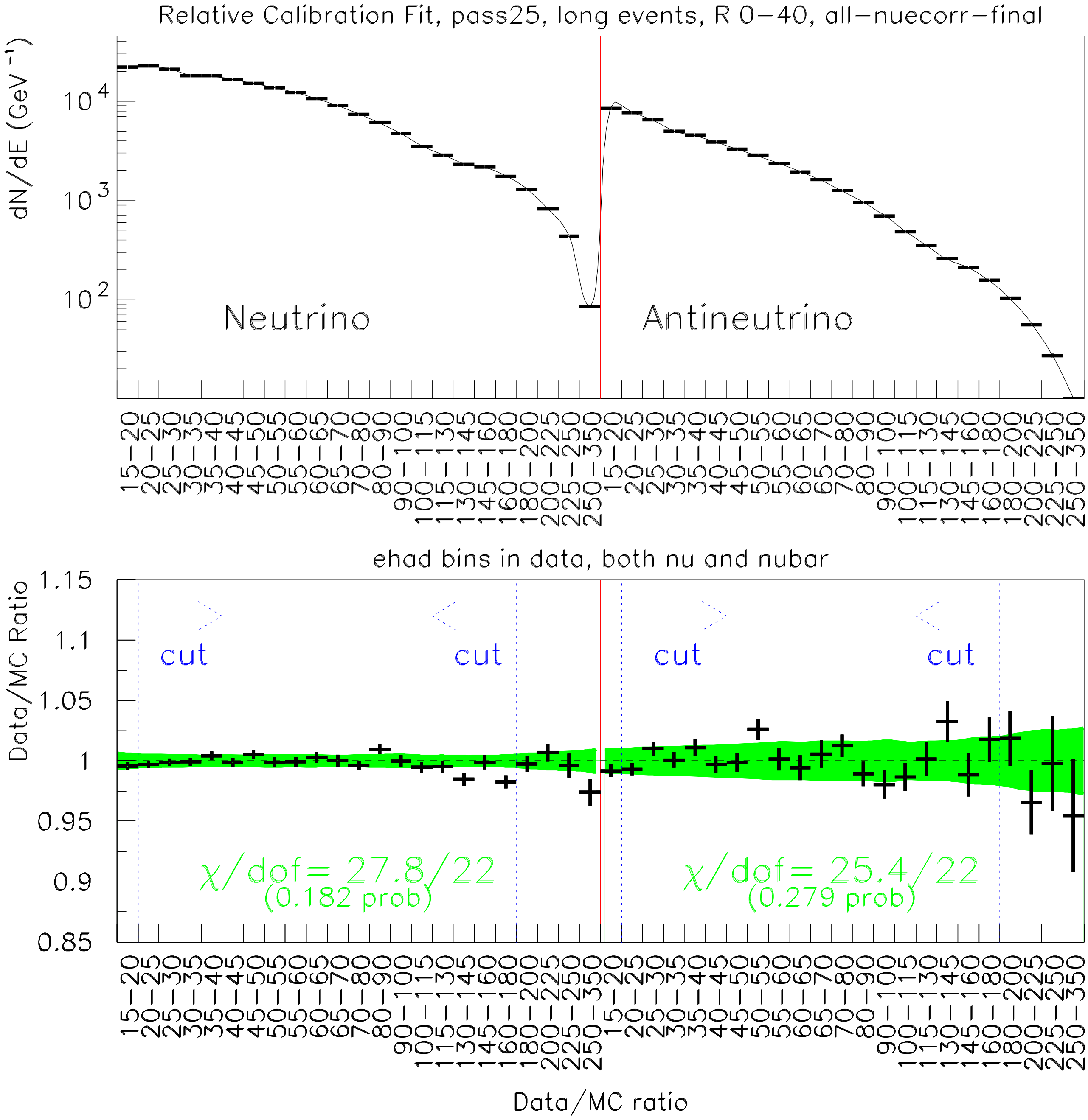
Short Events (NC Candidates) vs. E_{had}



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

Stability of $R_{\rm exp}$ (cont'd)

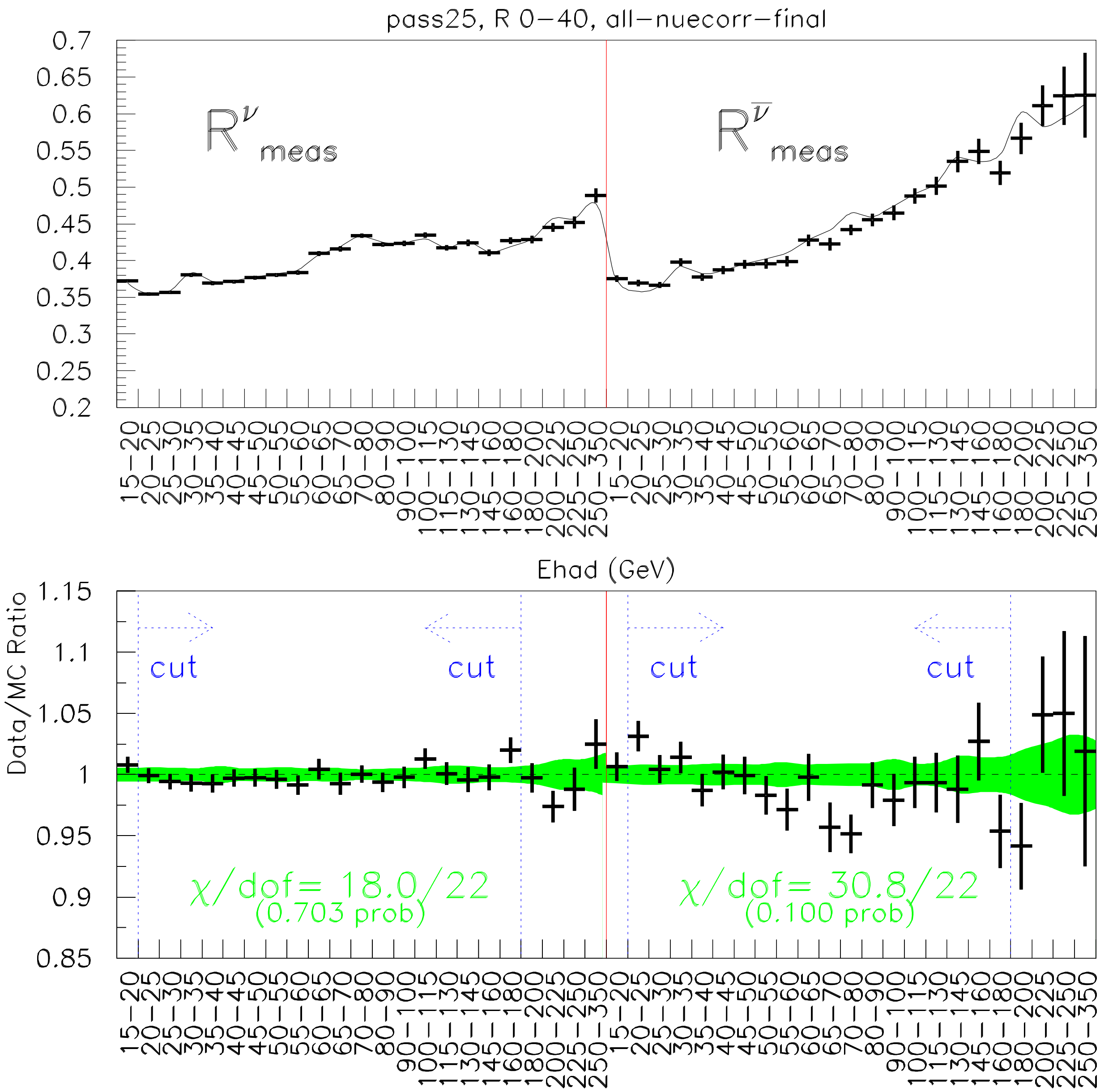
Long Event (CC Candidates) vs. $E_{\rm had}$



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

Stability of $R_{\rm exp}$ (cont'd)

$R_{\rm exp}$ vs. $E_{\rm had}$



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

Summary of uncertainties

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

The $\sin^2\theta_W$ Fit

(Llewellyn-Smith)

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

$\frac{dR^{\nu}_{\rm exp}}{d\sin^2\theta_W}$ large

$\frac{dR^{\overline{\nu}}_{\rm exp}}{d\sin^2\theta_W}$ small

$R^{\overline{\nu}}_{\rm exp}$ "measures" systematic effects, independent of $\sin^2\theta_W$

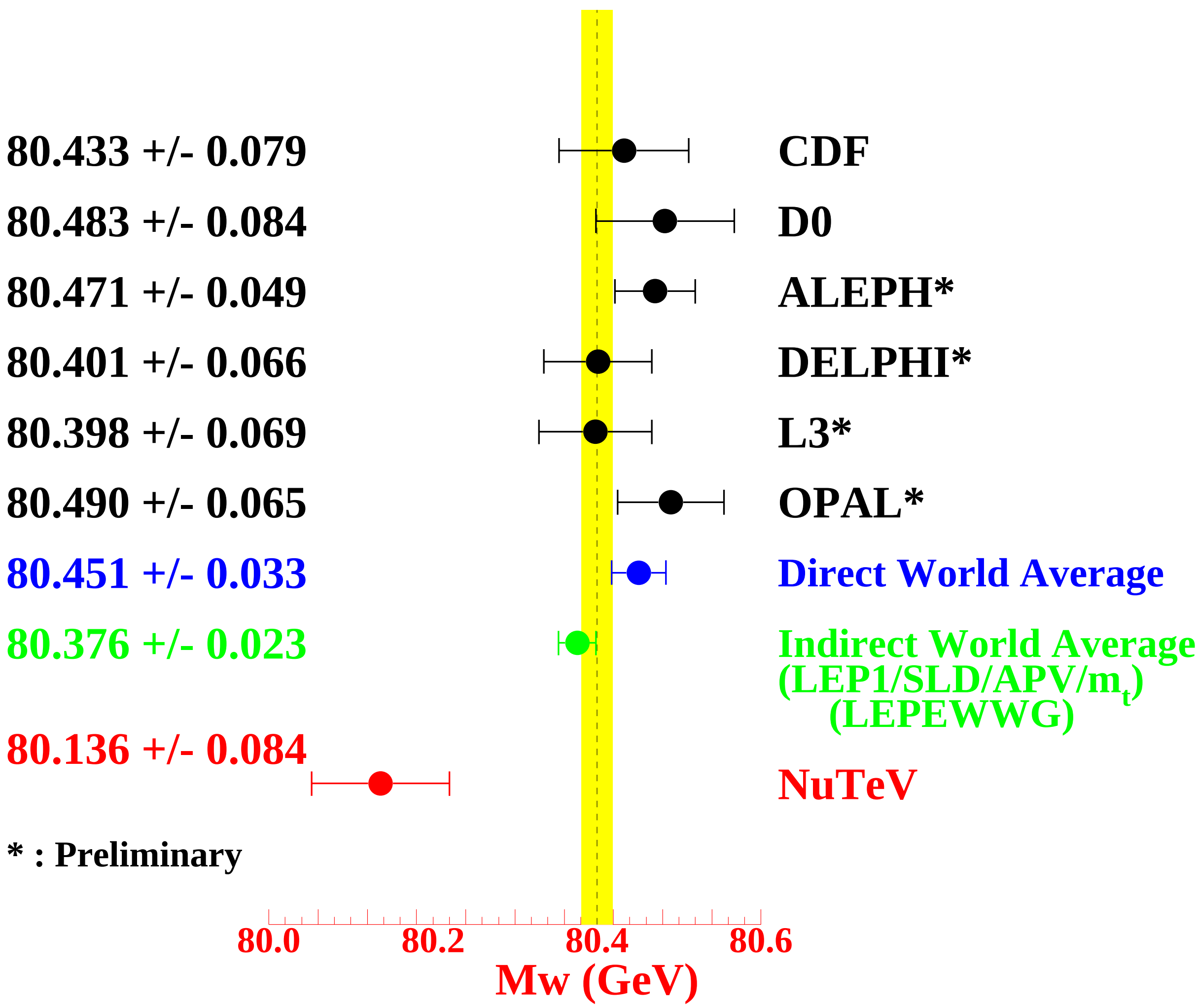
- Monte Carlo relates $R^{\overset{(-)}{\nu}}_{\rm exp}$ to $R^{\overset{(-)}{\nu}}$
- Largest theoretical uncertainty is in parameterization of charged-current charm production *via* m_c
- Therefore, fit for m_c and $\sin^2\theta_W$ simultaneously, with $R^{\nu}_{\rm exp}$, $R^{\overline{\nu}}_{\rm exp}$ and experimental m_c constraint as inputs
- $\sin^2\theta_W^{(\rm on-shell)} = 0.2277 \pm 0.0013 \pm 0.0009$

  $\hookrightarrow$ $m_c = 1.32 \pm 0.09 \pm 0.06$ GeV (cf. input $m_c = 1.38 \pm 0.14$)
- $\sin^2\theta_W^{(\rm on-shell)}$ determined by a quantity that is $\approx R^-$

(Paschos-Wolfenstein)

Comparison with M_W

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

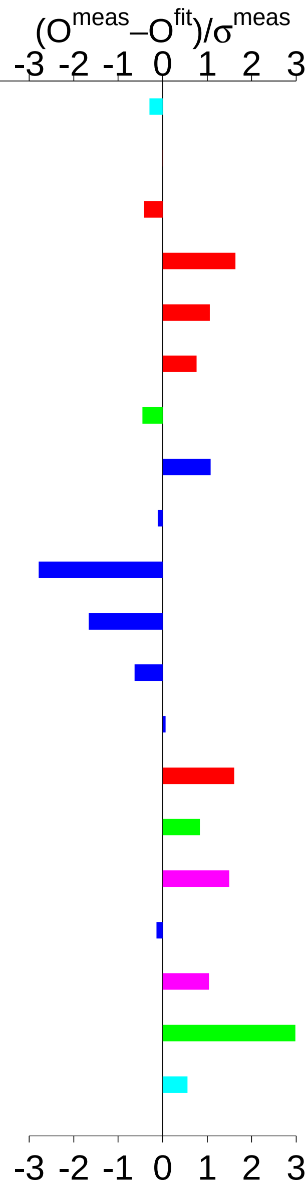


- In standard electroweak theory, NuTeV precision is comparable to a single direct measurement of M_W
- More inconsistent with direct M_W than other data

SM 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



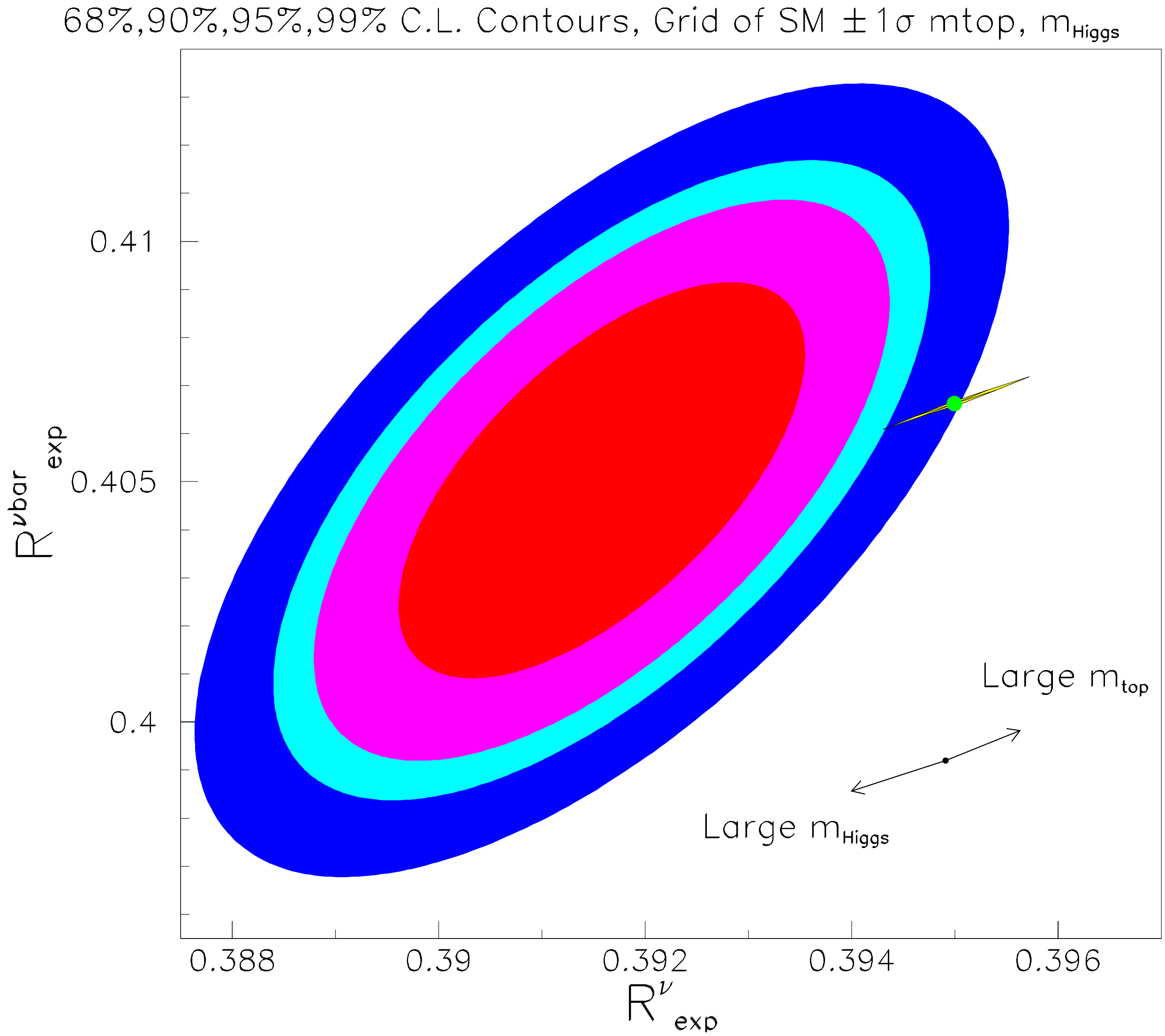
(Courtesy M. Grunewald, LEPEWWG)

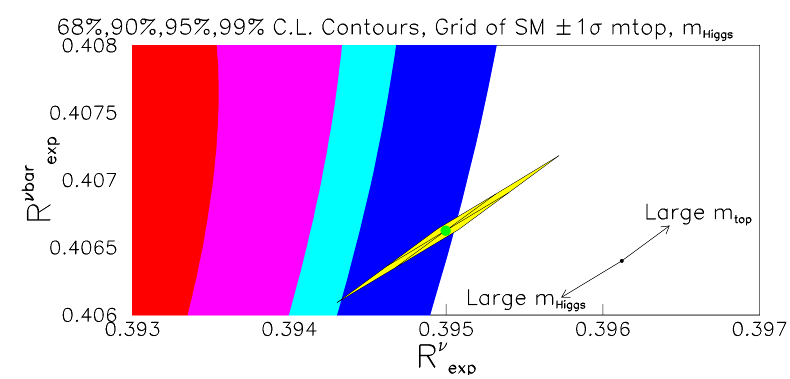
Without NuTeV: $\chi^2/\mathrm{dof} = 21.5/14$, probability of 9.0%

With NuTeV: $\chi^2/\mathrm{dof} = 30.5/15$, probability of 1.0%

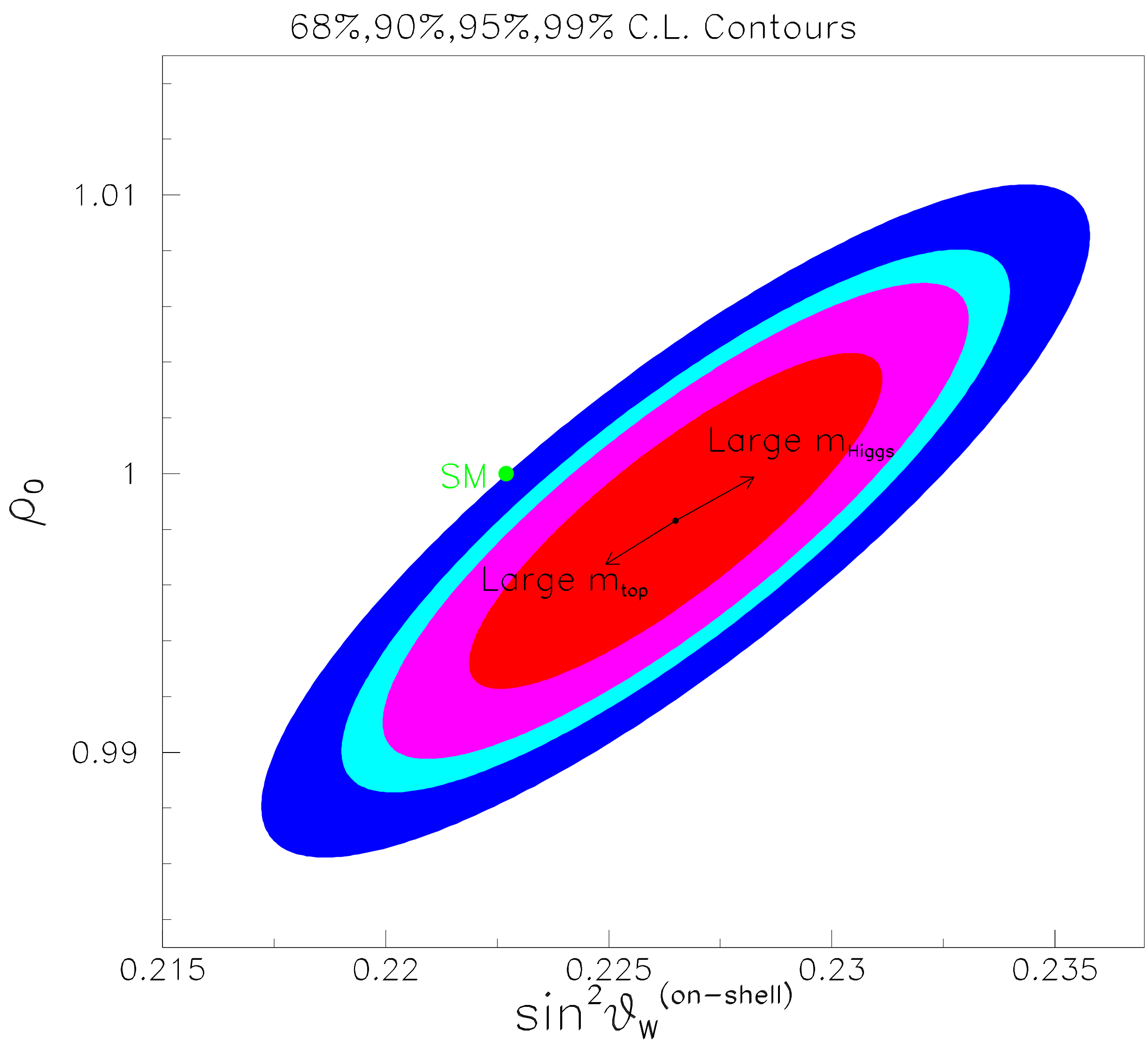
Upper m_{Higgs} limit weakens slightly

R^{ν}_{exp} and $R^{\overline{\nu}}_{\text{exp}}$





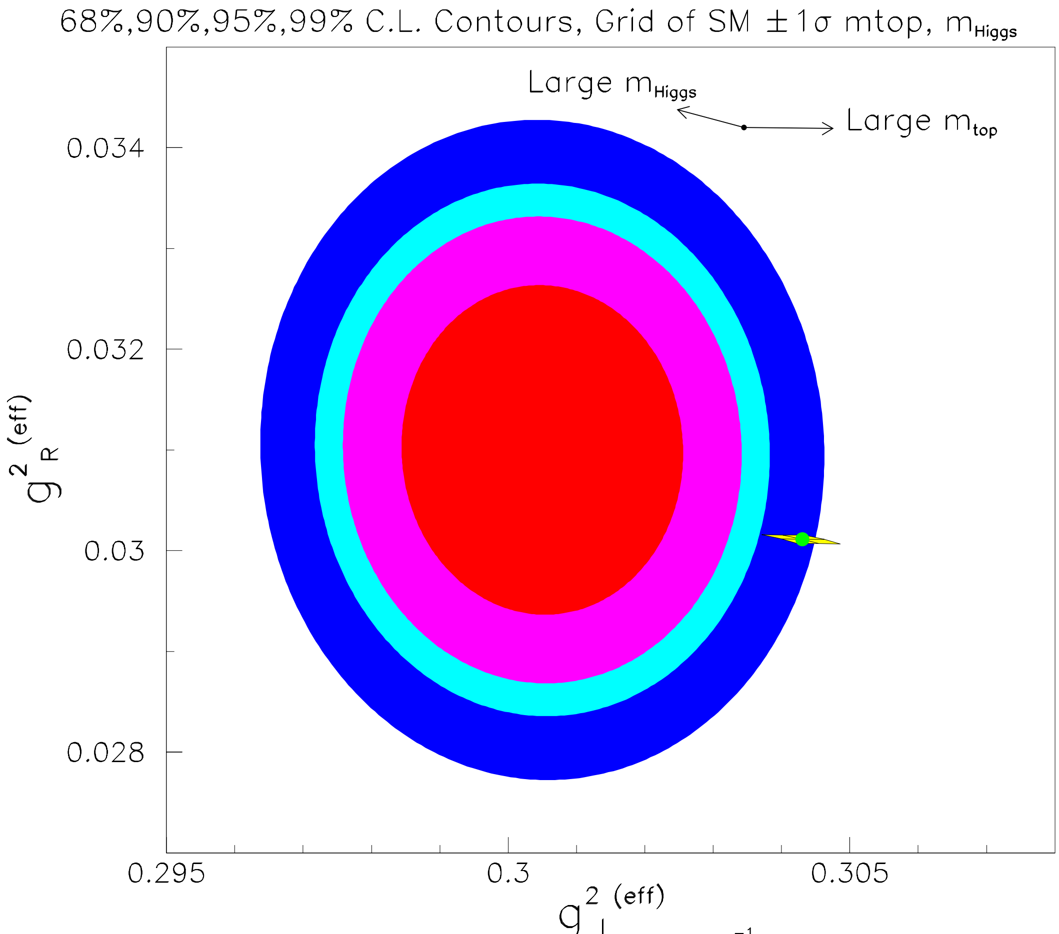
Tree-level parameters: ρ_0 and $\sin^2\theta_W^{(on-shell)}$



- Either $\sin^2\theta_W^{(on-shell)}$ or ρ_0 could agree with predictions

  $\hookrightarrow$ but both agreeing is unlikely!

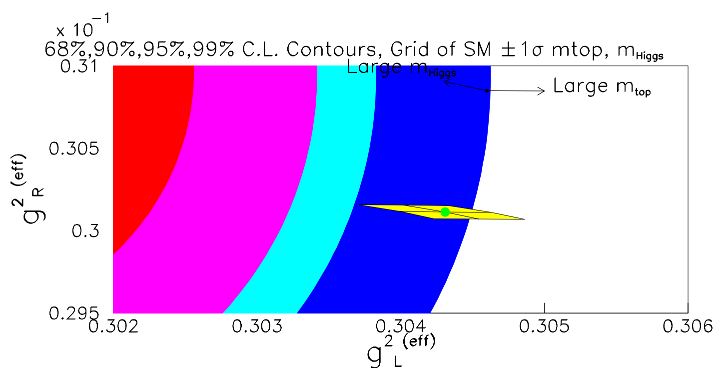
Quark Couplings: $(g_L^{\rm eff})^2$ and $(g_R^{\rm eff})^2$



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

NuTeV measures

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



- 3–5% more sensitive to d than u ($\frac{n}{p} > 1$, strange sea)
- Assuming predicted ν coupling, $(g_L^{\rm eff})^2$ appears low

Isospin Violating PDFs

- Isospin symmetry may not be good for PDFs ($u^p \neq d^n$).
  - ↪ PDF fits use this assumption
  - ↪ Obviously, electromagnetic effects violate isospin. $m_n \neq m_p$.
  - ↪ Has been calculated in several classes of non-perturbative model
- NuTeV is sensitive since $\epsilon^u \neq \epsilon^d$

Bag model

E. Sather, Phys. Lett **B274**, 433

↪ $\delta \sin^2 \theta_W^{(\text{on-shell})} = -0.0020$

⇒ This and a fluctuation?

⇒ True isospin violation larger?

Meson Cloud model

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

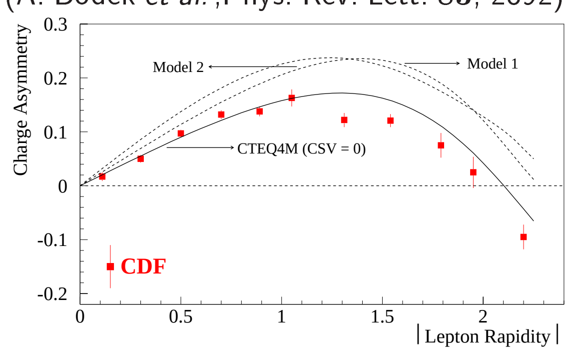
↪ $\delta \sin^2 \theta_W^{(\text{on-shell})} = +0.0002$

↪ Criticizes bag model calculations for ignoring large 2nd order effects in diquark mass shifts

- Implications for collider data?
  - ↪ Valence distributions (from neutrino data on heavy targets) are extracted assuming $u^p = d^n$
  - ↪ Isospin violating models can cause big changes in predicted $p\overline{p}$ production characteristics

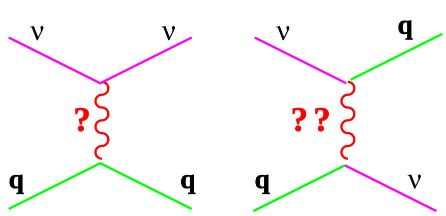
    (N.B., models at right are *different* than the ones above!)

(A. Bodek *et al.*, Phys. Rev. Lett. **83**, 2892)



  - ↪ Hard to exclude ALL models with such an argument

New Tree Level Physics?



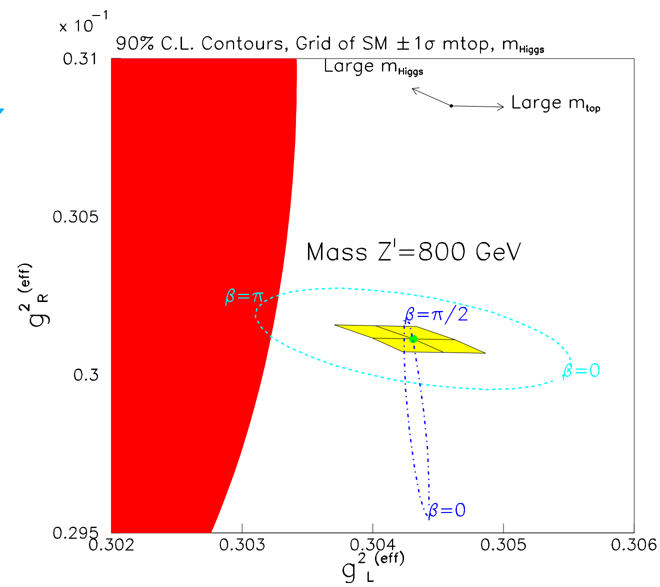
- "Natural" interpretation of result
- Z', LQ, etc.
- Must enhance LL not LR coupling

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

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

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

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



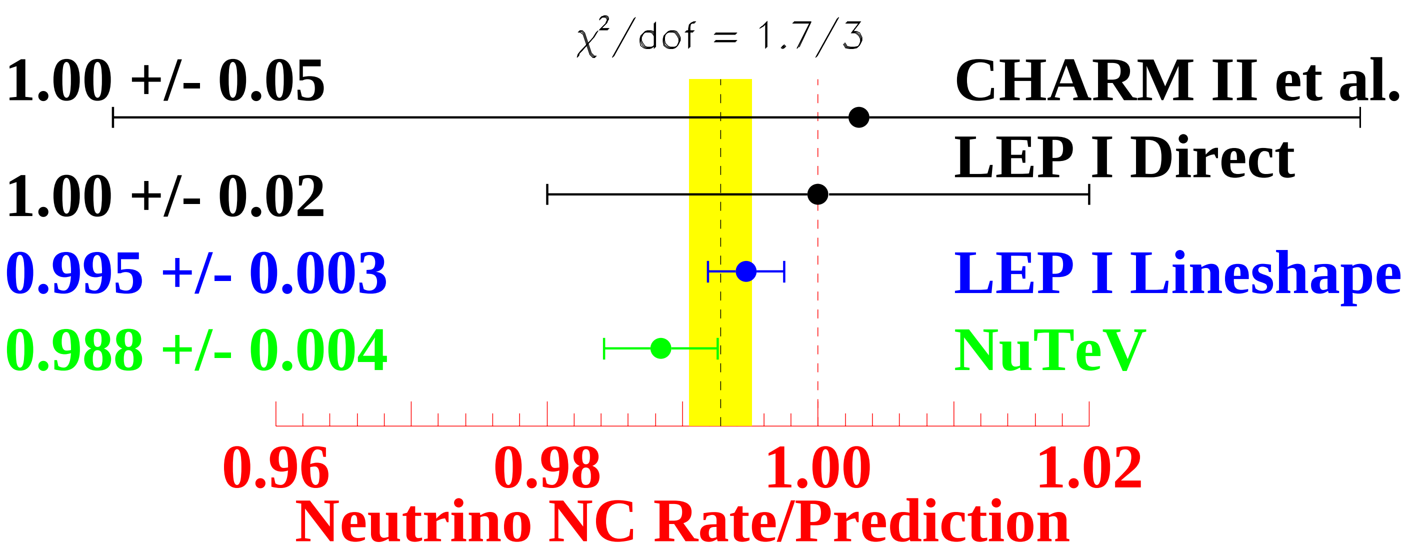
- "Almost sequential" Z' with opposite coupling to ν
  - ↪ NuTeV preferred mass range: $1.2^{+0.3}_{-0.2}$ TeV
  - ↪ CDF/D0 limits: $M_{Z'_{\rm SM}} \gtrsim 700$ GeV
- Contact interaction with LL coupling
  - ↪ $\nu\nu qq$ Contact term, $\Lambda_{LL} = 4.5 \pm 1$ TeV

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

(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 $N_\nu = 3\frac{\Gamma_{\rm exp}(Z\to\nu\overline{\nu})}{\Gamma_{\rm SM}(Z\to\nu\overline{\nu})} = 3\times(0.9947\pm 0.0028)$
  - ↪ 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
  - ↪ $\rho_0^2 = 0.9884\pm 0.0026({\rm stat})\pm 0.0032({\rm syst})$



- 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 measures R^{ν}, $R^{\overline{\nu}}$ to precisely determine $\sin^2\theta_W$
- NuTeV expects 0.2227 ± 0.0003; measures

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

- Given inconsistency with Standard Model, we present result also in model-independent frameworks
  - ↪ 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
  - ↪ Consistent with earlier νN measurements
- Pending *confirmation*, *refutation*, or *alternative explanations*, it's a puzzle.