A Departure From Prediction: Electroweak Physics at NuTeV

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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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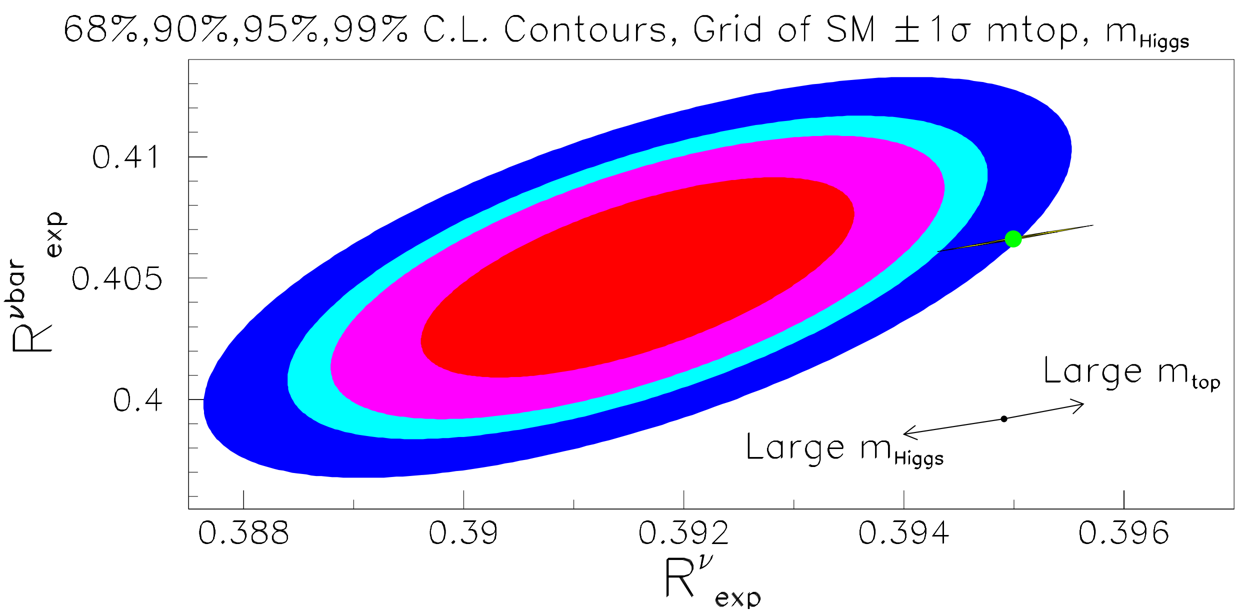
The Result

NuTeV Measures:

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

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

A discrepancy of 3σ...



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

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

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

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

$$\text{photon}_\mu = \frac{1}{\sqrt{g^2+g'^2}}(g'W^{(3)}_\mu + gB_\mu),$$

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

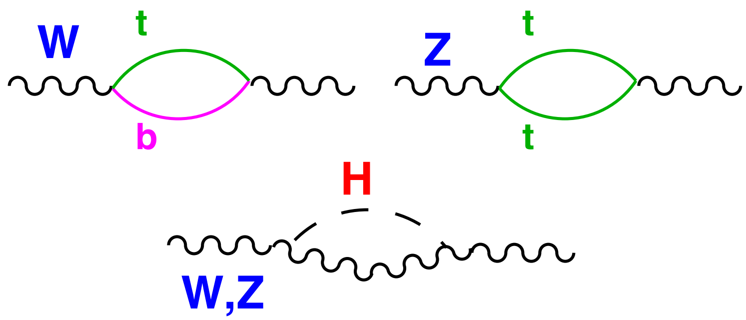
$$Z^0_\mu = \frac{1}{\sqrt{g^2+g'^2}}(gW^{(3)}_\mu - g'B_\mu).$$

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:

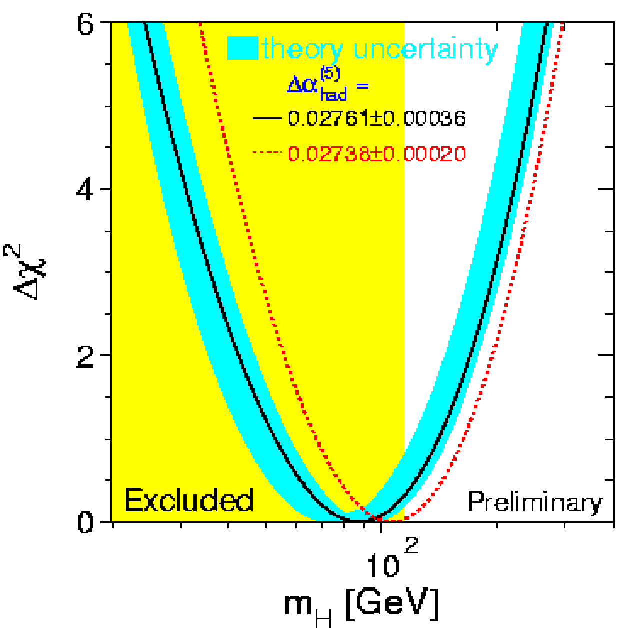
$$e = g\sin\theta_W,\ G_F = \frac{g^2\sqrt{2}}{8M_W^2},\ \frac{M_W}{M_Z} = \cos\theta_W$$

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

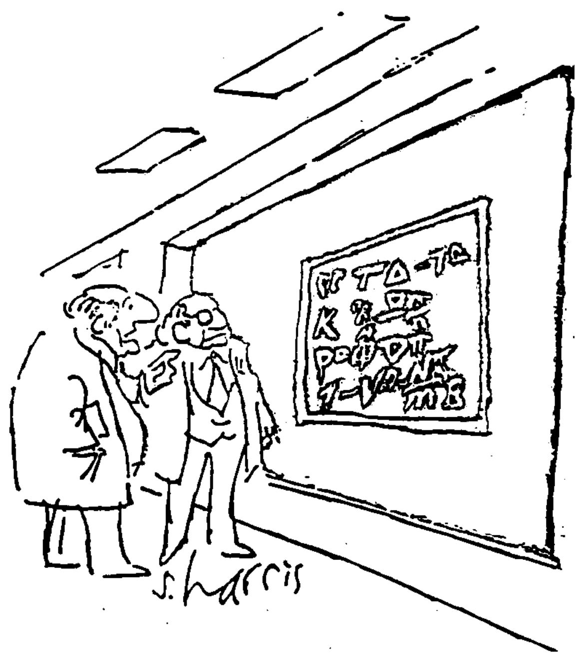
- Z^0 Bosons from e^+e^- collisions at LEP and SLC

  $\hookrightarrow$ 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)

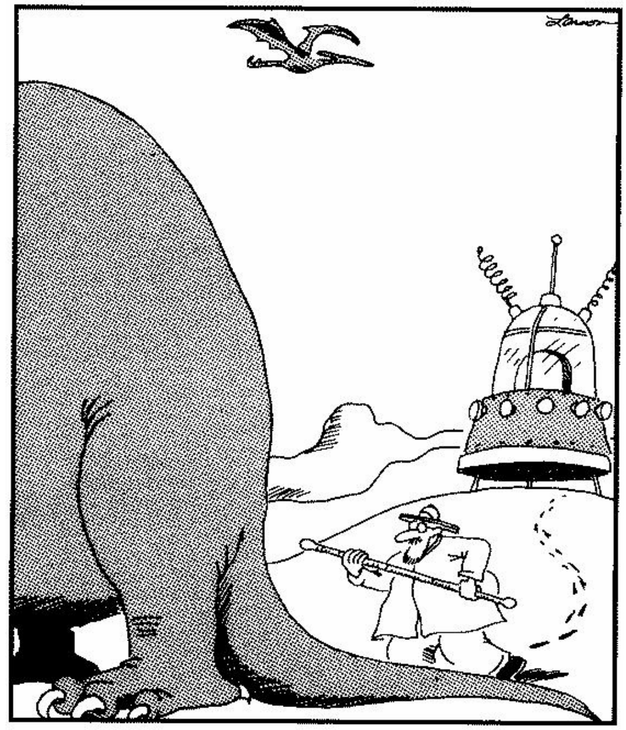
Why test in so many processes?

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."

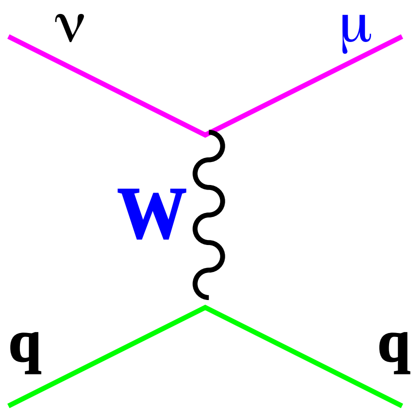
Why is NuTeV the Right Instrument for the Job?

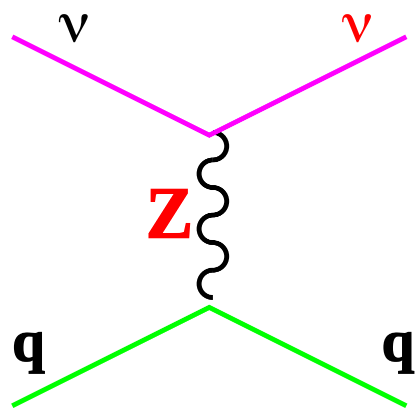


An instant later, both Professor Waxman and his time machine are obliterated, leaving the cold–blooded/warm–blooded dinosaur debate unresolved

- 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





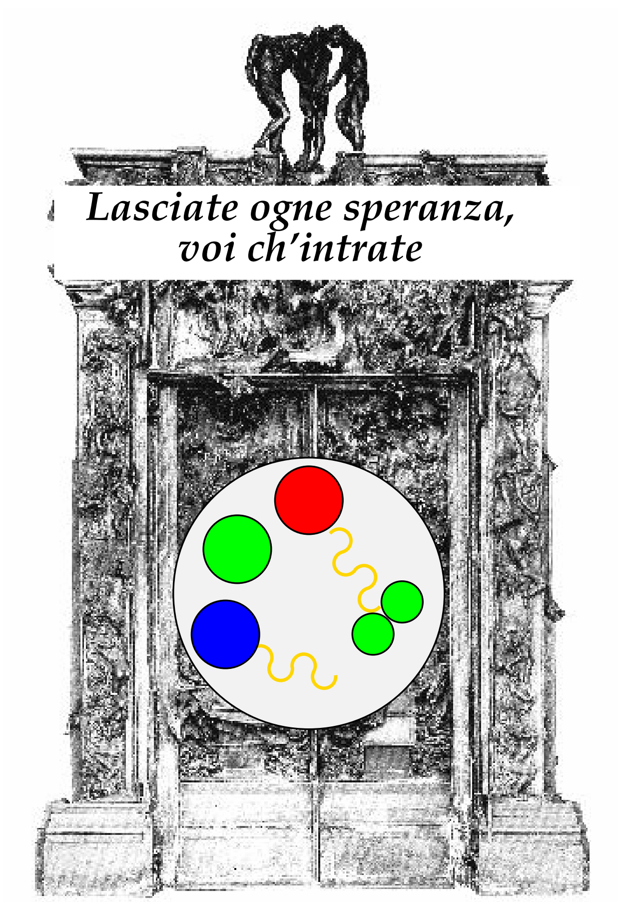
Coupling $\propto \; I^{(3)}_{\mathrm{weak}}$

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

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

(Llewellyn-Smith)

Cull the Herd
(Separate the Weak from the Strong)



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

  $x \equiv$fractional parton momentum;

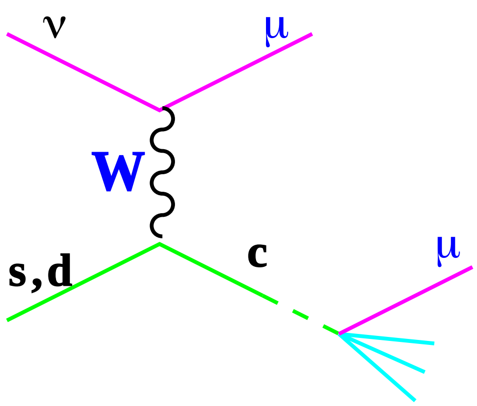
  $Q^2 = -q^2$, q is boson 4-momentum

Exploit Symmetry:

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

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

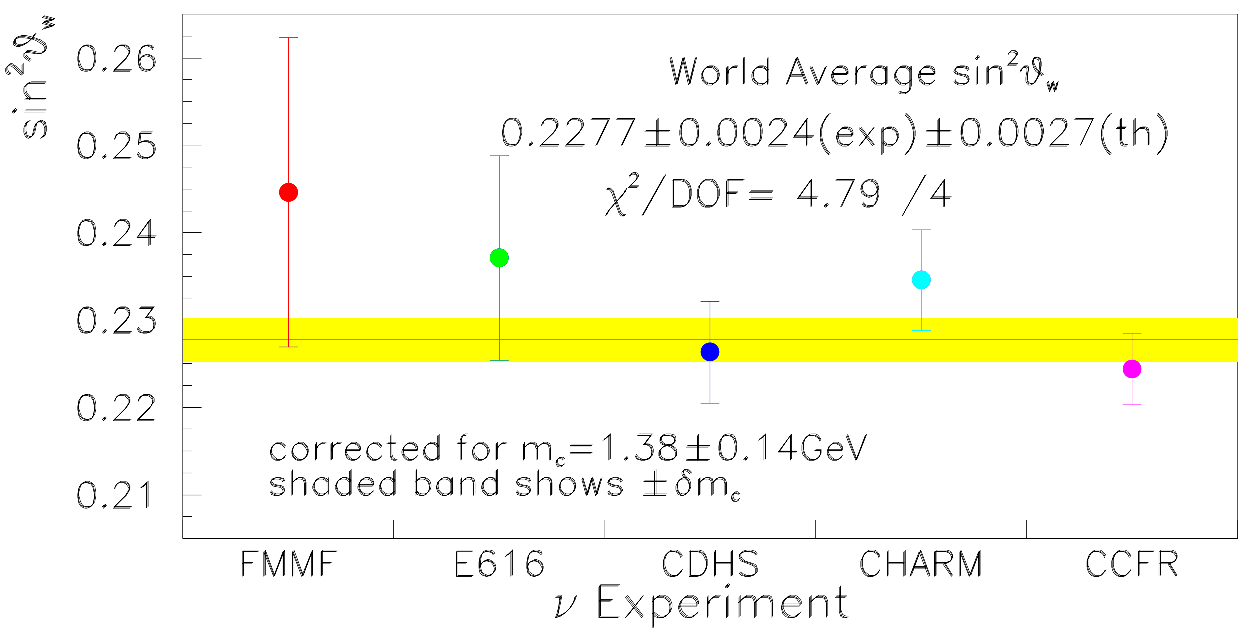
$$\xi = x(1 + \frac{mc^2}{Q^2}) \quad \textit{where} \quad x = \frac{Q^2}{2ME_{\mathrm{had}}}$$

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

νN Experiments Before NuTeV

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

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



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

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

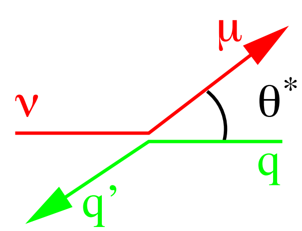
NuTeV's Technique

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

<u>Paschos-Wolfenstein Relation:</u>

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

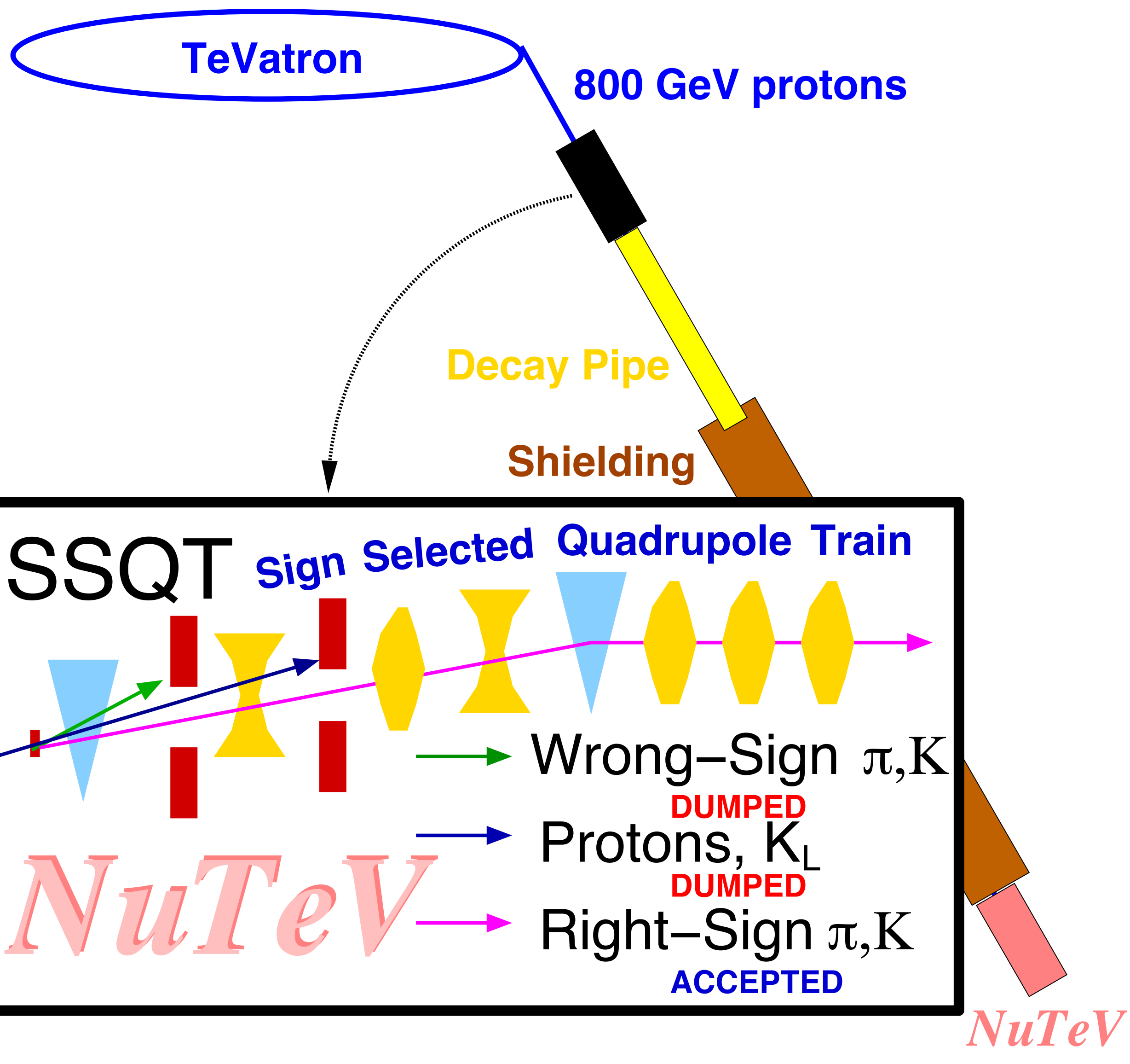
Interaction	Total Spin	$\frac{d\sigma}{dy}$
ν-q: or $\overline{\nu}$-$\overline{q}$	0	1
$\overline{\nu}$-q: or ν-$\overline{q}$	1	$(1-y)^2$



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

- 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

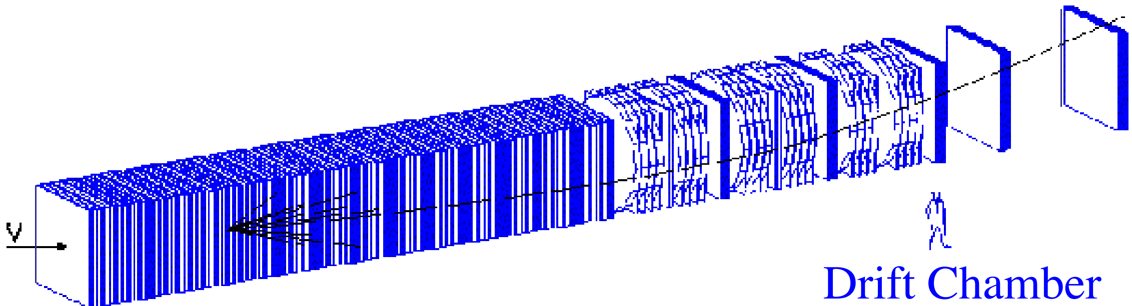
NuTeV Beamline

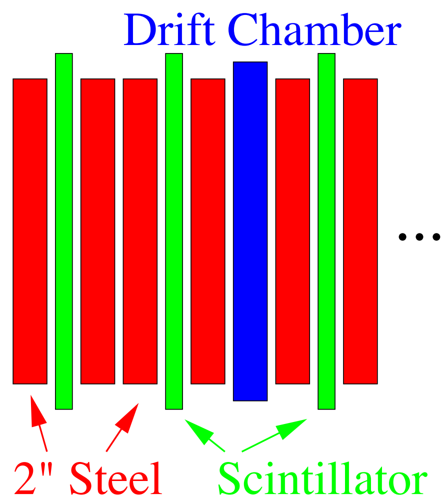


- Beam is almost purely ν or $\overline{\nu}$: ($\overline{\nu}$ in ν mode 3×10^{-4}, ν in $\overline{\nu}$ mode 4×10^{-3})
- Beam is $\sim$1.6% electron neutrinos

νN Deep Inelastic Scattering at NuTeV

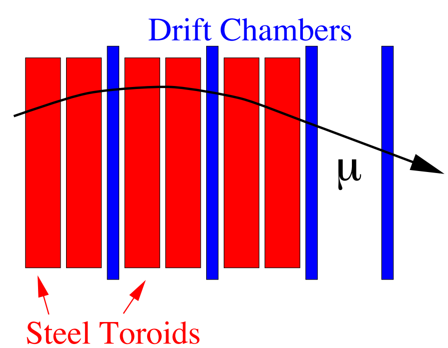
Lab E Detector - Fermilab E815(NuTeV)





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



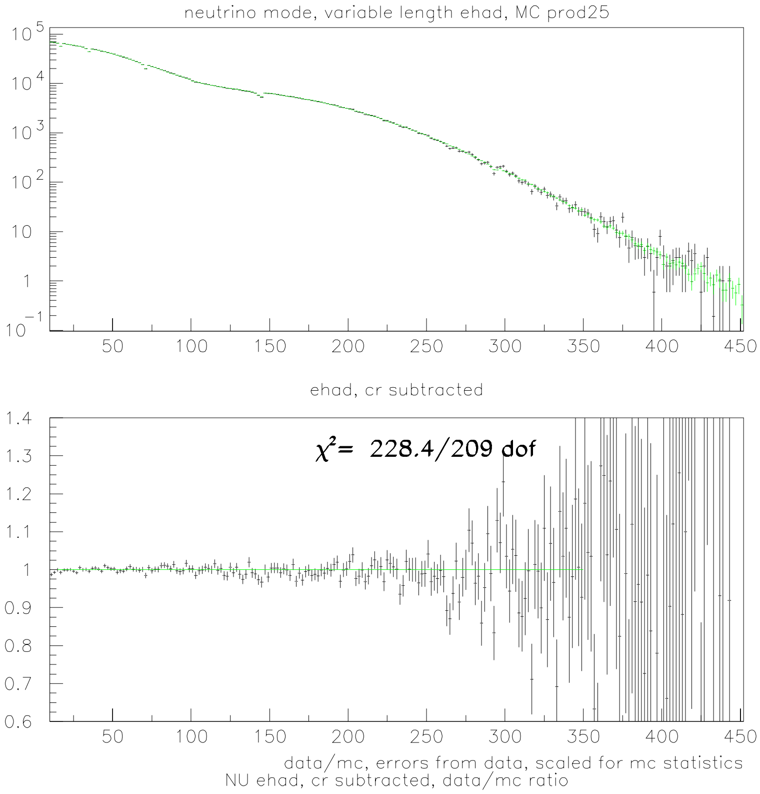
Toroidal Spectrometer:

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

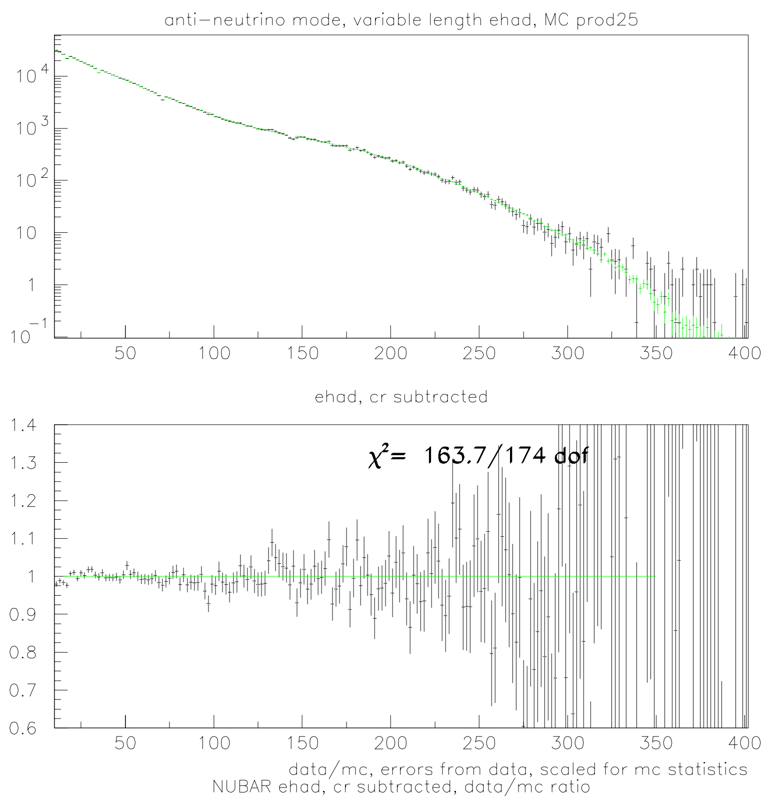
Continuous Test Beam: interspersed with ν beam

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

The Raw Data

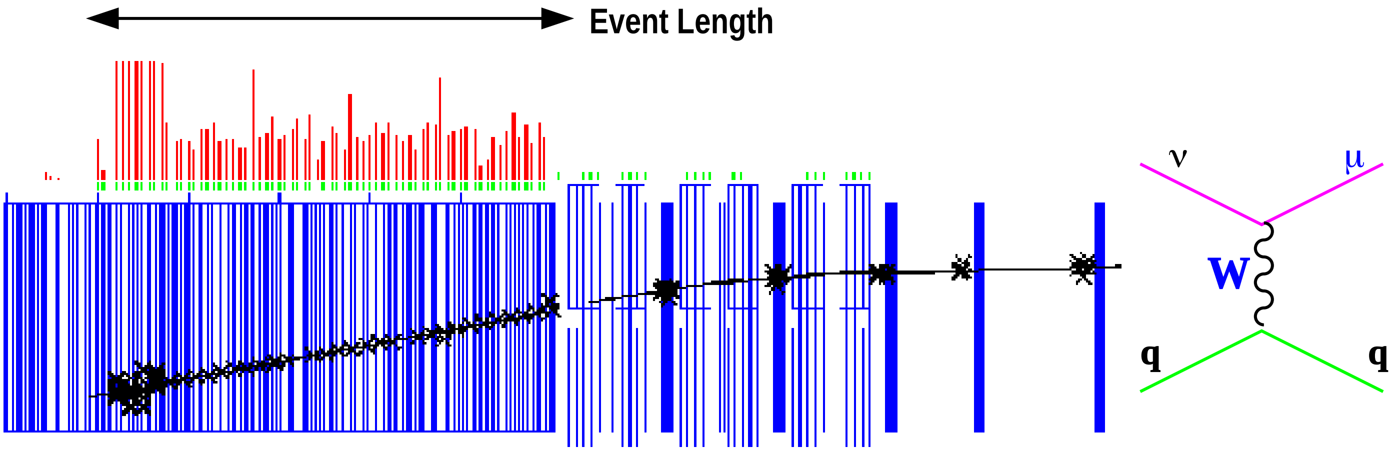


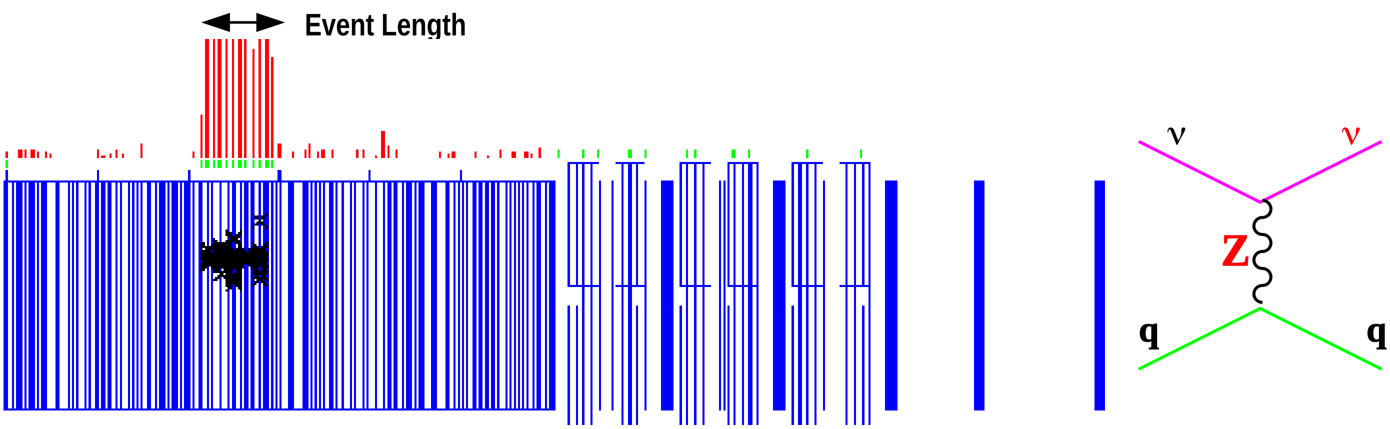
1.62×10^6 events
in the ν beam



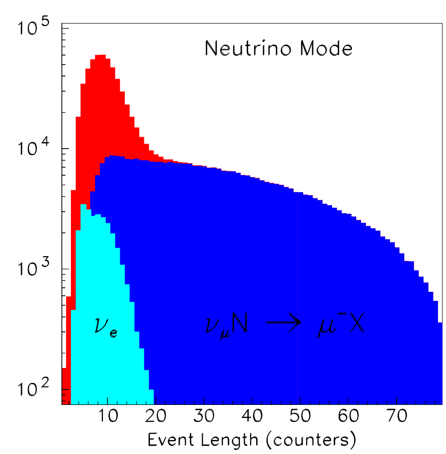
0.35×10^6 events
in the $\overline{\nu}$ beam

Neutral Current/Charged Current Event Separation





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



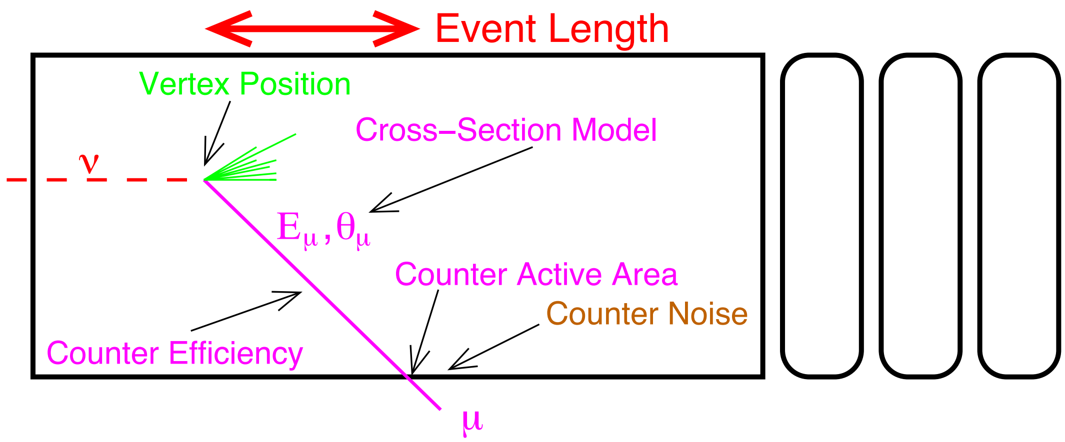
$$R_{\text{exp}} = \frac{\text{SHORT events}}{\text{LONG events}} = \frac{\text{NC candidates}}{\text{CC candidates}}$$

Experimental Technique

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

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

$R_{\rm exp}$ 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
- $d/u \neq 1$ $(\frac{Z+A}{2Z} \approx 5.67\%, \overline{u}/\overline{d})$
- Heavy quark corrections
- R_L; Higher Twist

<u>Detector response</u>

- CC$\leftrightarrow$NC cross-talk
- Muon simulation
- Event vertex
- Detector Response
- Electron Neutrinos

Summary of Corrections to $R_{\rm exp}$

Corrections Applied to Data

Effect	$\delta R^{\nu}_{\rm exp}$	$\delta R^{\overline{\nu}}_{\rm exp}$	Coping Techniques
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	$\delta R^{\nu}_{\rm exp}$	$\delta R^{\overline{\nu}}_{\rm exp}$	Coping Techniques
Short CC Background	−0.068	−0.026	†, $\surd$
Electron Neutrinos	−0.021	−0.024	♮, $\surd$
Long NC	+0.0028	+0.0029	†, $\surd$
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: $R^{\nu}_{\rm exp}$ and $R^{\overline{\nu}}_{\rm exp}$ measured to a precision of 0.0013 and 0.0027, respectively

Key to coping techniques

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

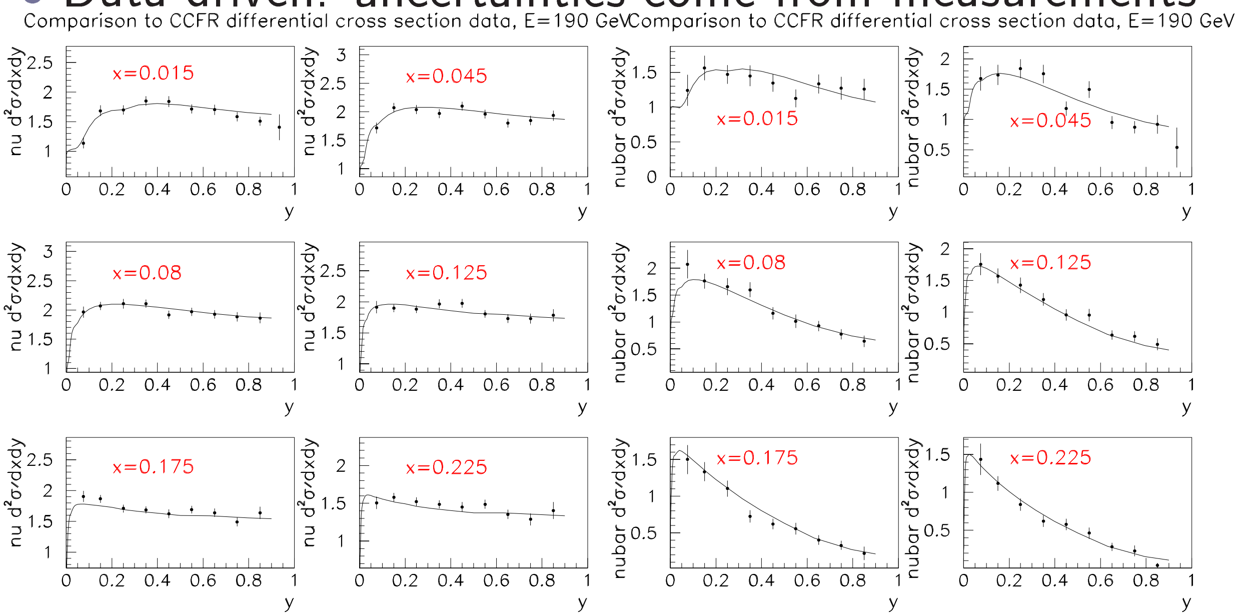
From Corrections to Uncertainties

- Theoretical model uncertainties dominate $R^{\nu}_{\rm exp}$, $R^{\overline{\nu}}_{\rm exp}$
- R^{-} technique $\Rightarrow \sin^2\theta_W^{\rm (on-shell)}$ *statistically* dominated

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
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

Enhanced LO Cross-Section

- $\overset{(-)}{\nu}$ 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 data ($d^n = u^p$)
- Data-driven: uncertainties come from measurements



High y CC ⇒ Soft muon ⇒ NC background

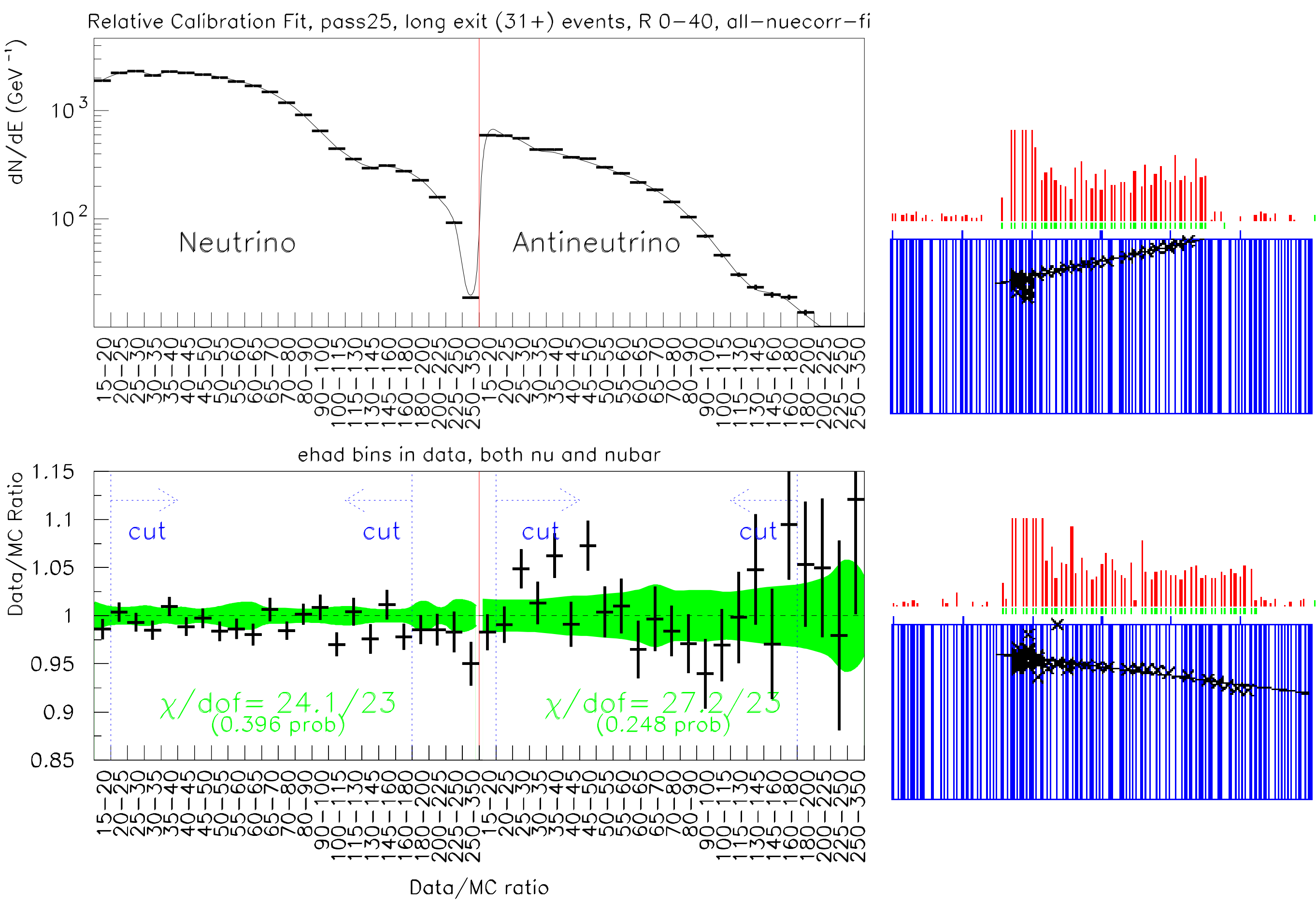
LO Quark-Parton model tuned to agree with data:

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

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

Charged-Current Control Sample

- High y charged-current is background to NC sample
  $\hookrightarrow$ 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

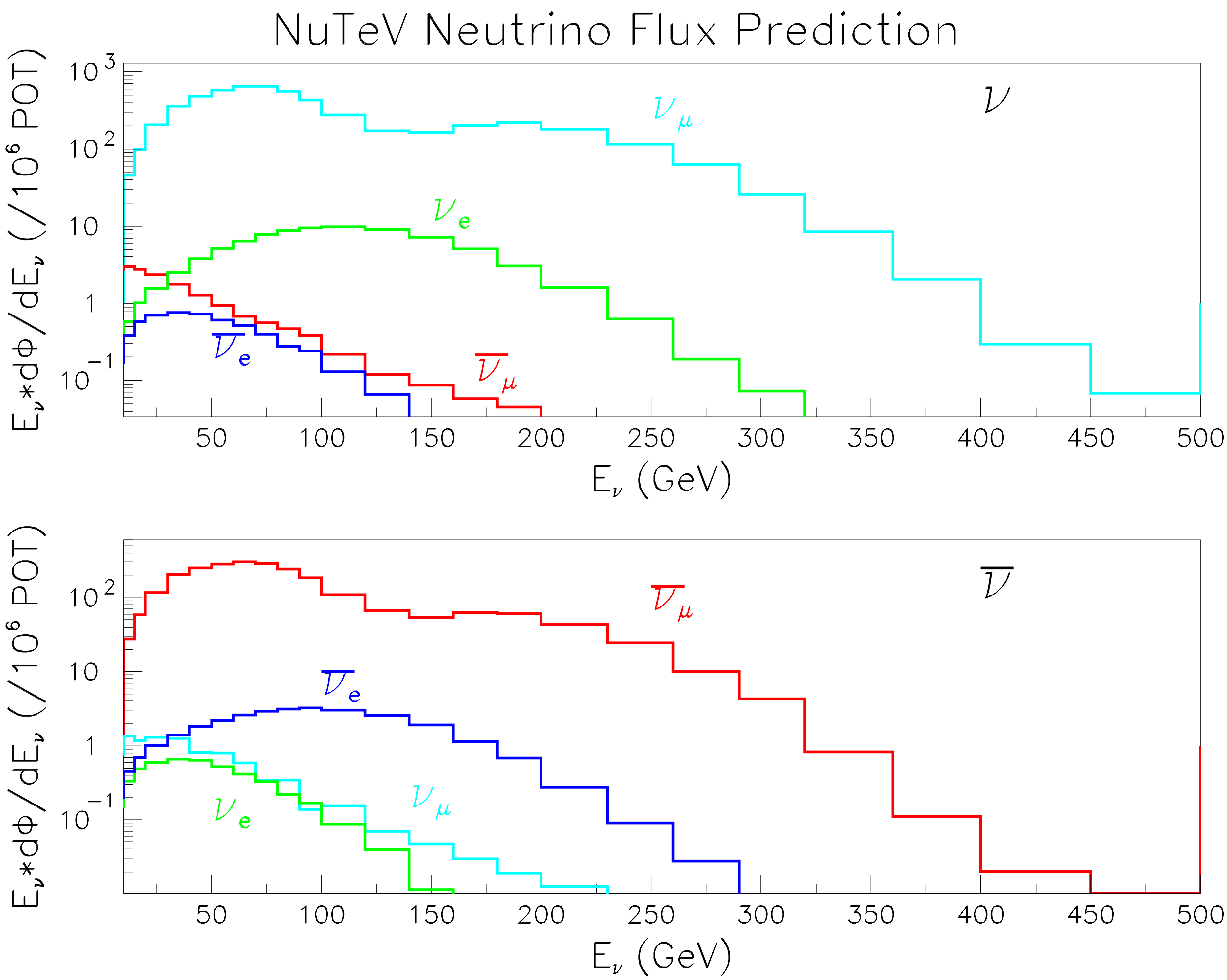


- Agreement in this "short" charged-current sample is good within systematic uncertainties

NuTeV Neutrino Flux

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*



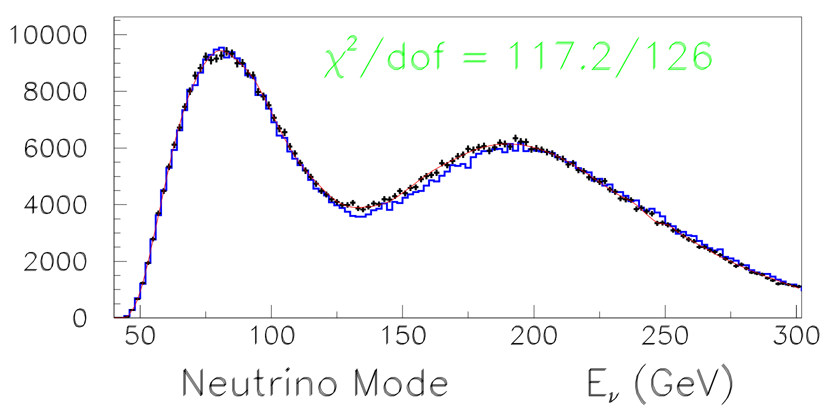
- Excess of ν_e over $\overline{\nu}_e$ in ν beam is due to K^+_{e3} decay
  - $\hookrightarrow$ Vast majority of $\nu_e/\overline{\nu}_e$ in $\nu/\overline{\nu}$ beams
  - $\hookrightarrow$ K_L and charm decay, which make both ν_e and $\overline{\nu}_e$, are small
- $K^\pm_{e3}$ decay is very well understood
  - $\hookrightarrow$ $K^\pm$ production. . . *is constrained by ν_μ and $\overline{\nu}_\mu$ flux*
- Have (less precise) direct measurements of ν_e and $\overline{\nu}_e$

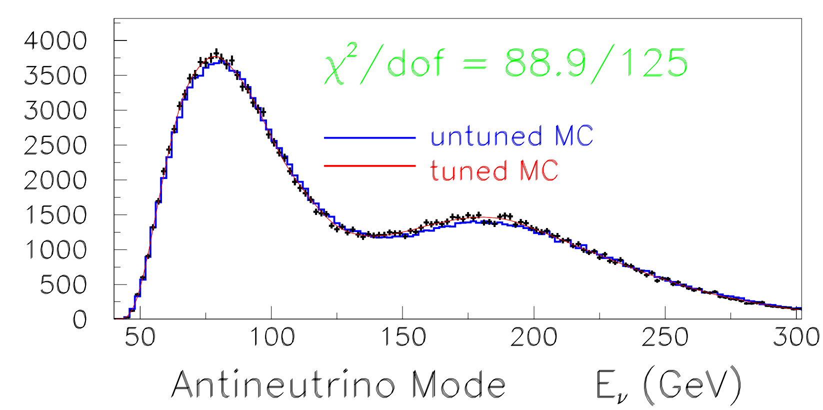
NuTeV Neutrino Flux

- Tune the observed ν_μ spectrum to match MC prediction
  - $\hookrightarrow$ Driven by small uncertainties in SSQT alignment and large production uncertainties
  - $\hookrightarrow$ 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%	$+2.8\%$

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



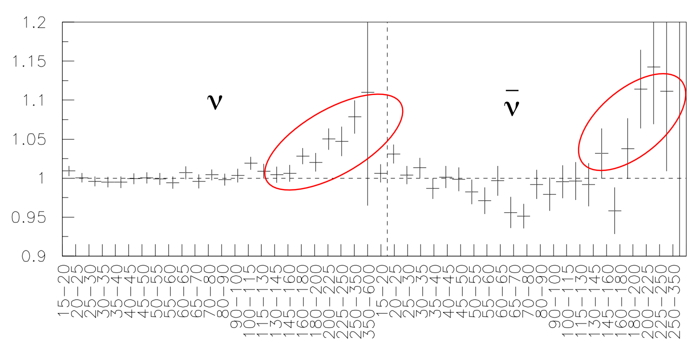


Direct Measurements of ν_e Flux

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

1. ν_μ in $\overline{\nu}$ beam (measures charm, K_L decay)
2. ν_e electron showers $(80 < E_\nu < 180$ GeV$)$
   - $N_{\text{meas}}/N_{\text{pred}}$: 1.05 ± 0.03 (ν_e), 1.01 ± 0.04 $(\overline{\nu}_e)$
3. ν_e from very short events $(E_\nu > 180$ GeV$)$
   - Precise measurement of ν_e on tail of flux
   - Observe $\sim 35\%$ more $\overline{\nu}_e$ than predicted in $\overline{\nu}$ beam, smaller excess in ν beam
   - *Conclude that we should require $E_{\text{had}} < 180$ GeV*
   - Preliminary NuTeV result did not know of this problem
     - ↪ ADC saturation in electron showers moved events to lower E_{had}, where they were not visible
     - ↪ $\delta R^{\nu}_{\text{exp}} \approx 0.0012$, $\delta R^{\overline{\nu}}_{\text{exp}} \approx 0.0010$ (!)
     - ↪ After incorporating high E_ν ν_e measurement, result is same with and without high E_{had} cut

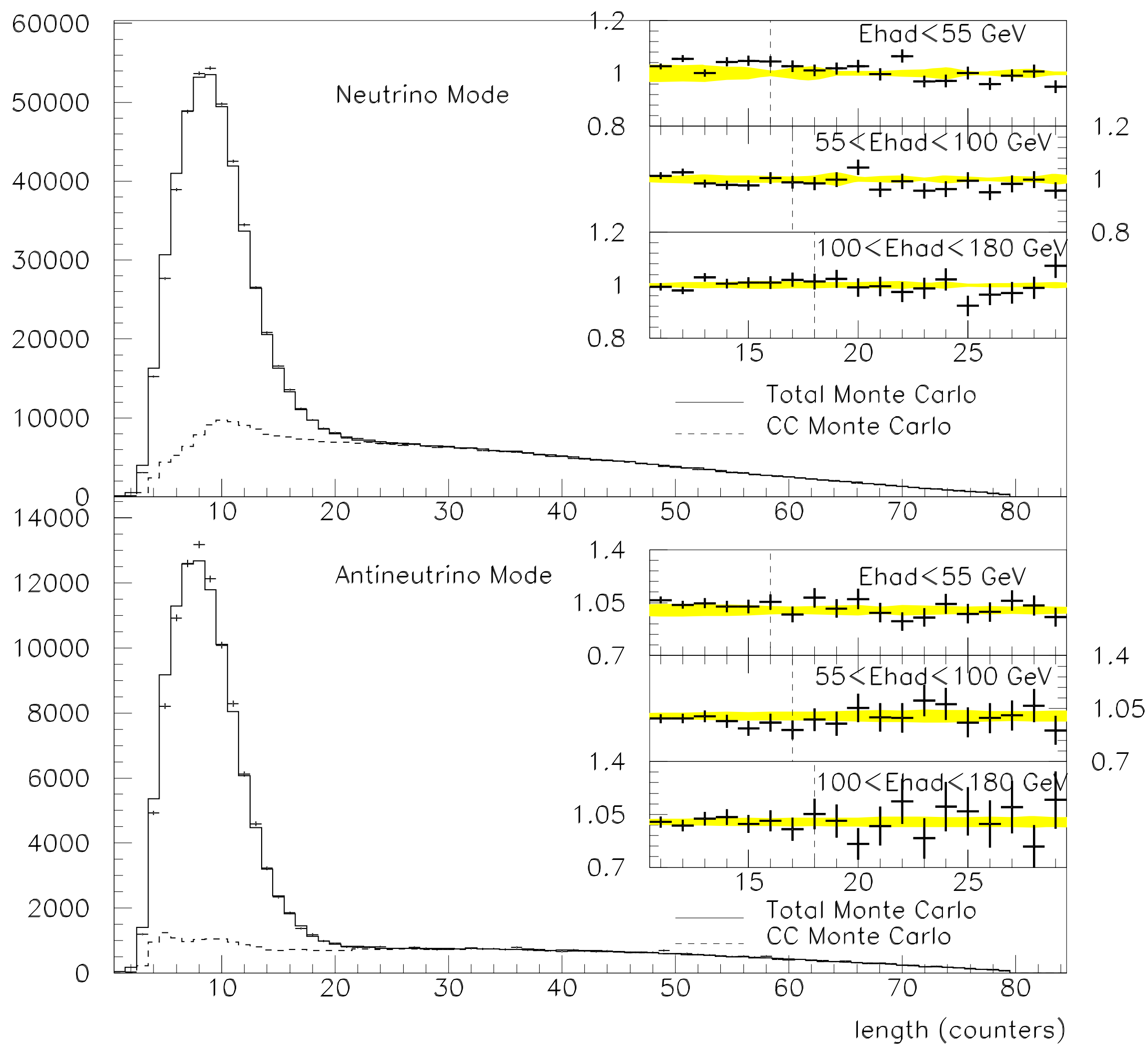
Without high E_ν ν_e correction



R_{exp} vs Visible Energy

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
- Testbeam hadrons measure punch-through
- Use LEPTO simulation to study difference between ν-induced and hadron-induced showers



Stability of R_{exp}

- We have evaluated systematic uncertainties and believe they are under control
  - ↪ Now want to verify this with data. . .
- Strategy: verify that the R_{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_{had} dependence of R_{exp})
- Event observables:

  Longitudinal vertex: check detector uniformity

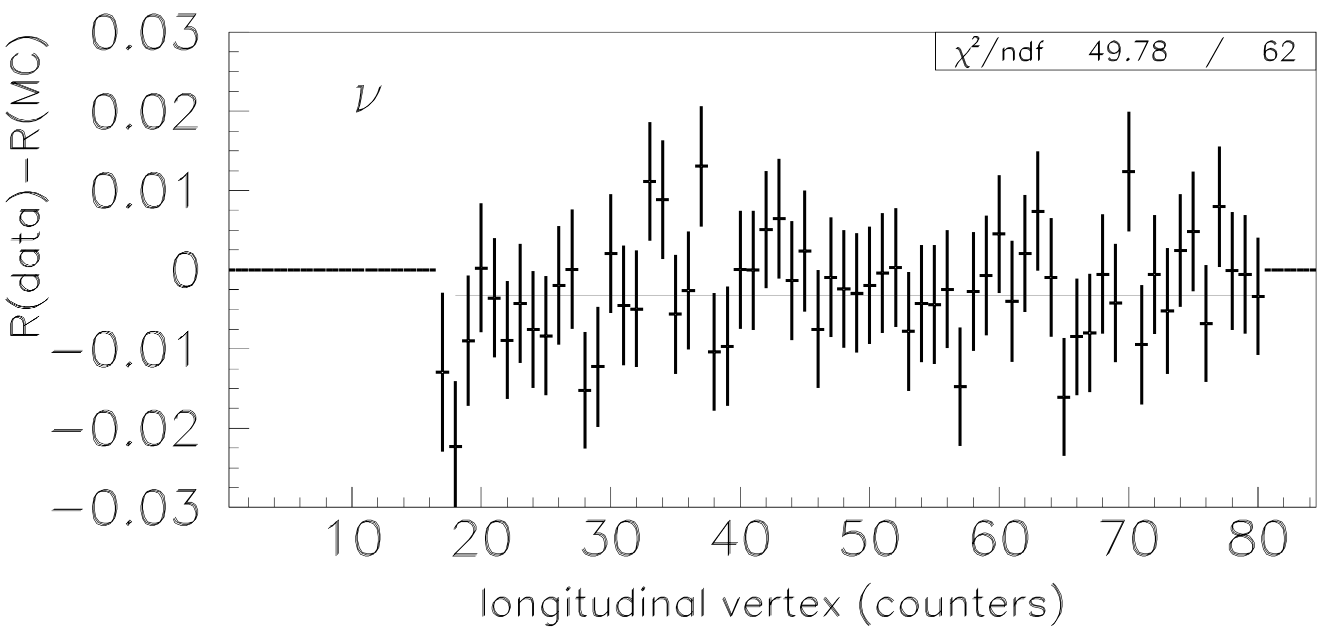
  Short/Long separatrix: check CC↔NC

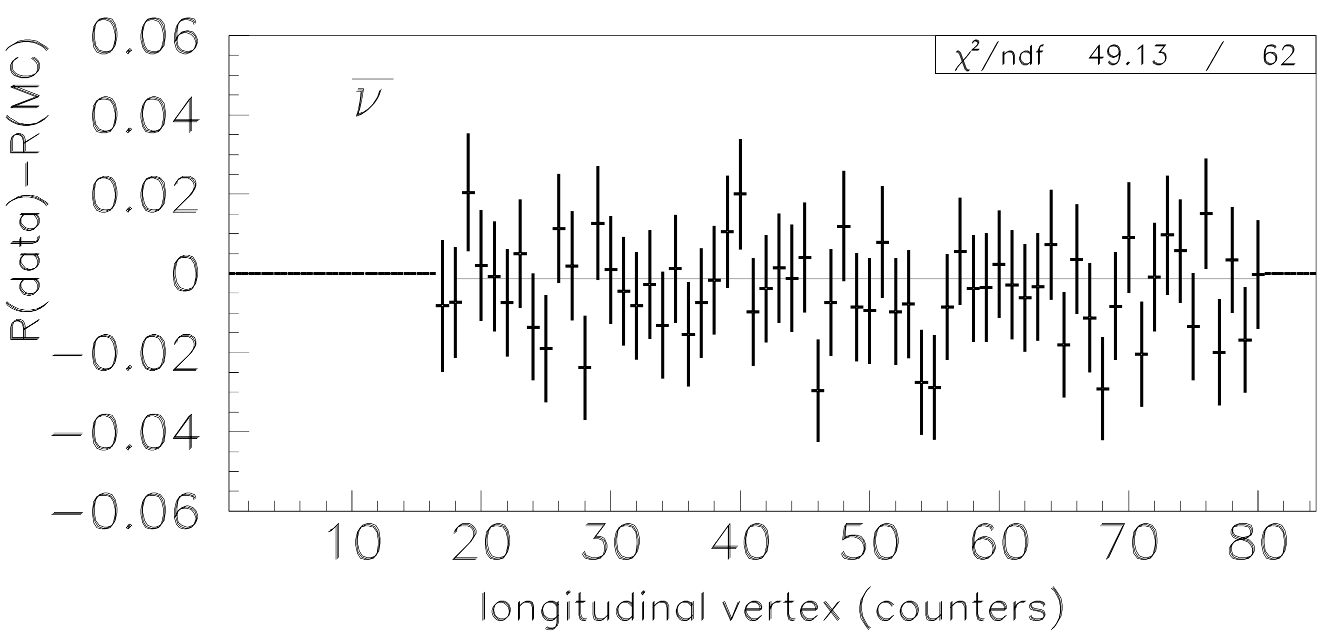
  Transverse vertex: more NC background near edge

  Visible Energy: checks EVERYTHING!

Stability of R_{exp} (cont'd)

R as a function of longitudinal vertex

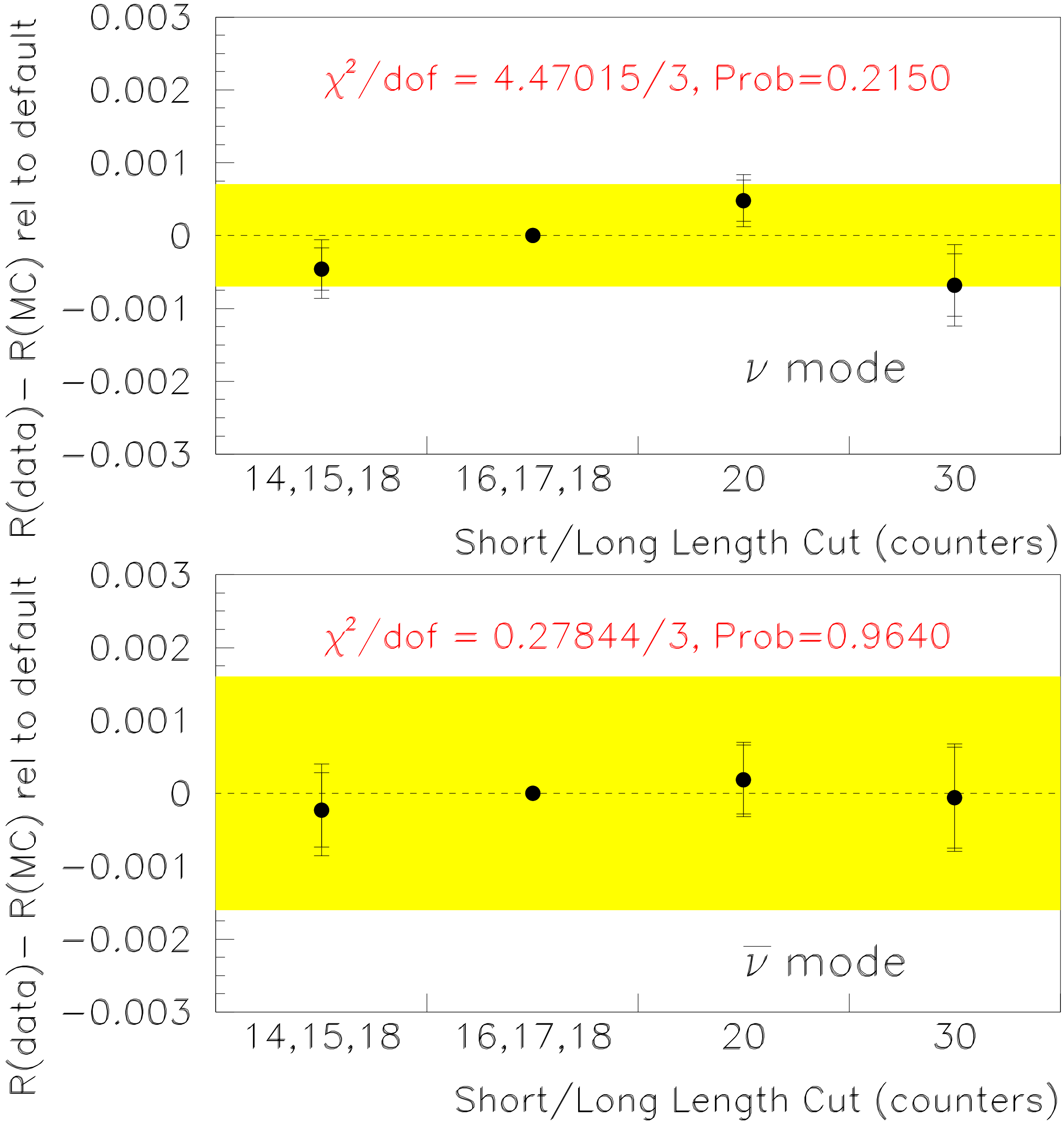




Stability of $R_{\rm exp}$ (cont'd)

R as a function of length cut

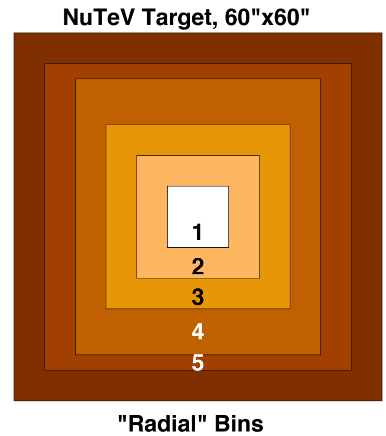
- "16,17,18" [counters] is default; tighten↔loosen NC selection
- Measurements are correlated; uncertainties are on *difference*

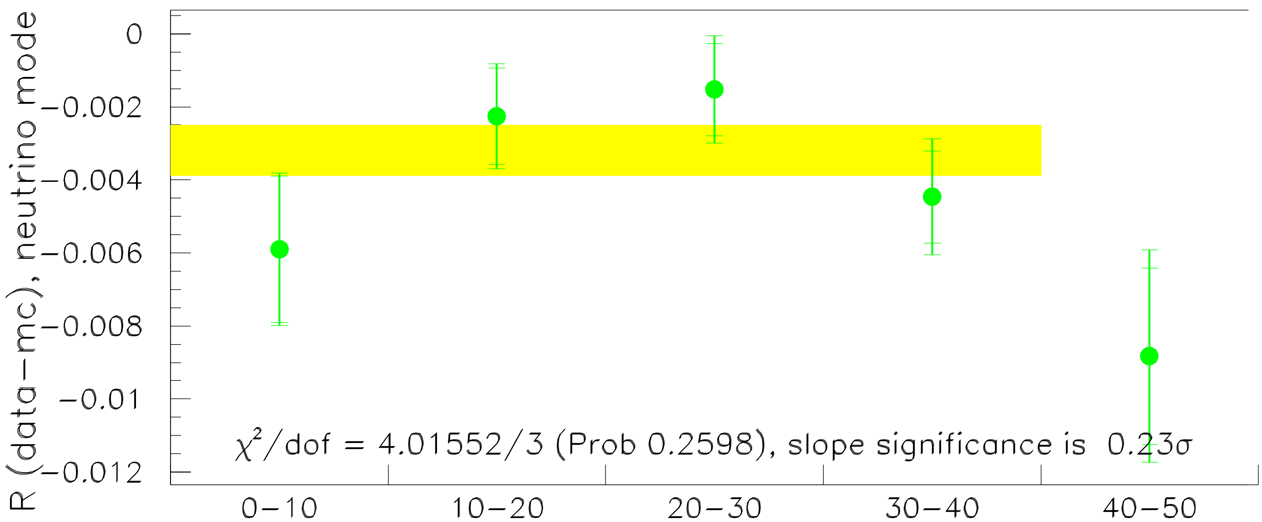


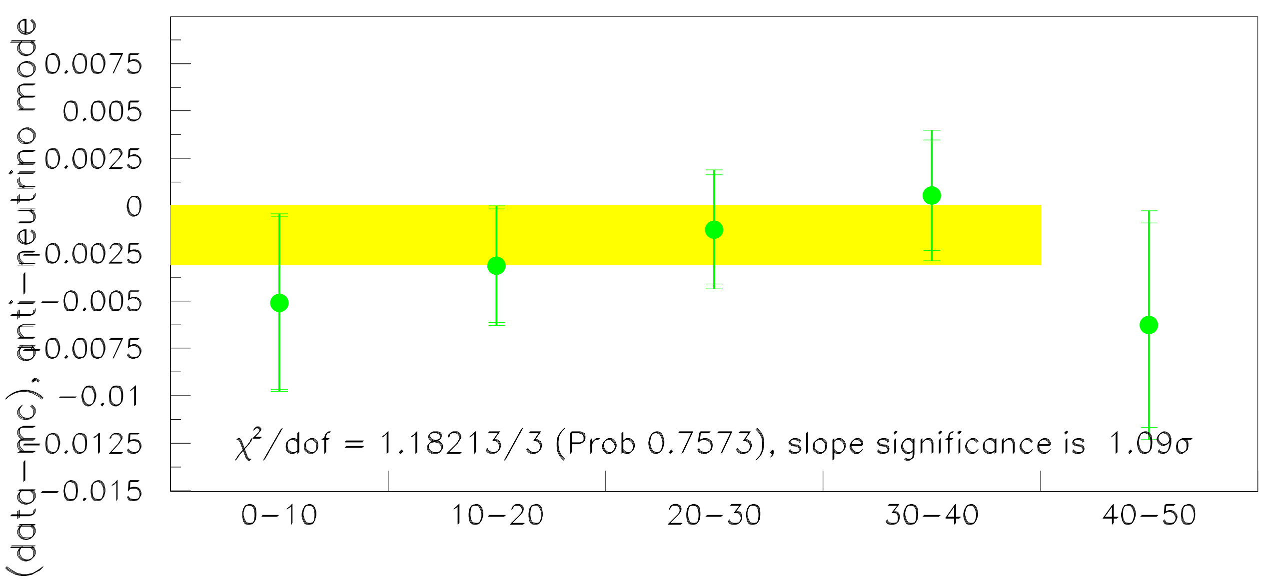
Stability of $R_{\rm exp}$ (cont'd)

R as a function of "radial" bin

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

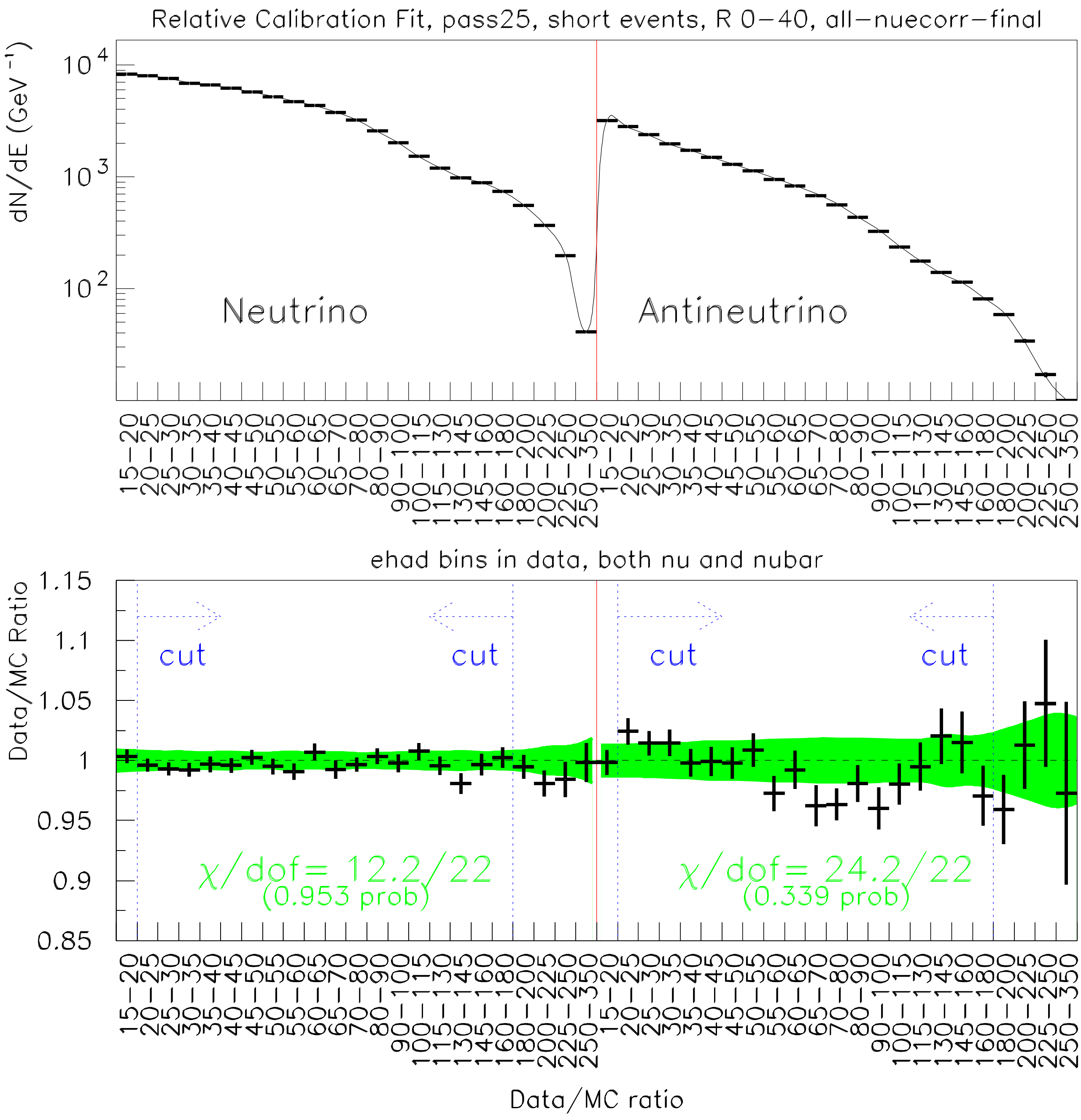






Stability of R_{exp} (cont'd)

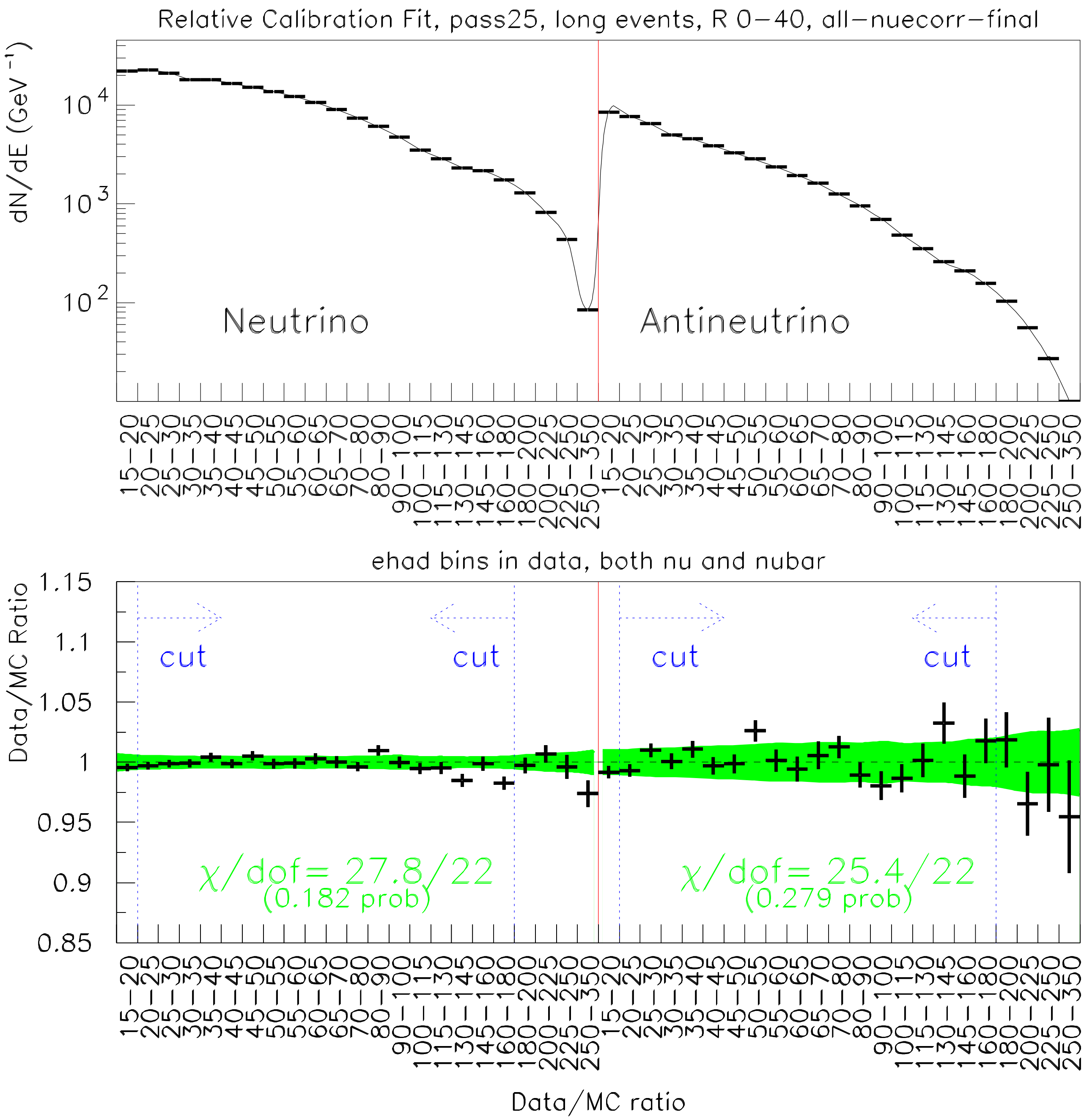
Short Events (NC Candidates) vs. E_{had}



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

Stability of R_{exp} (cont'd)

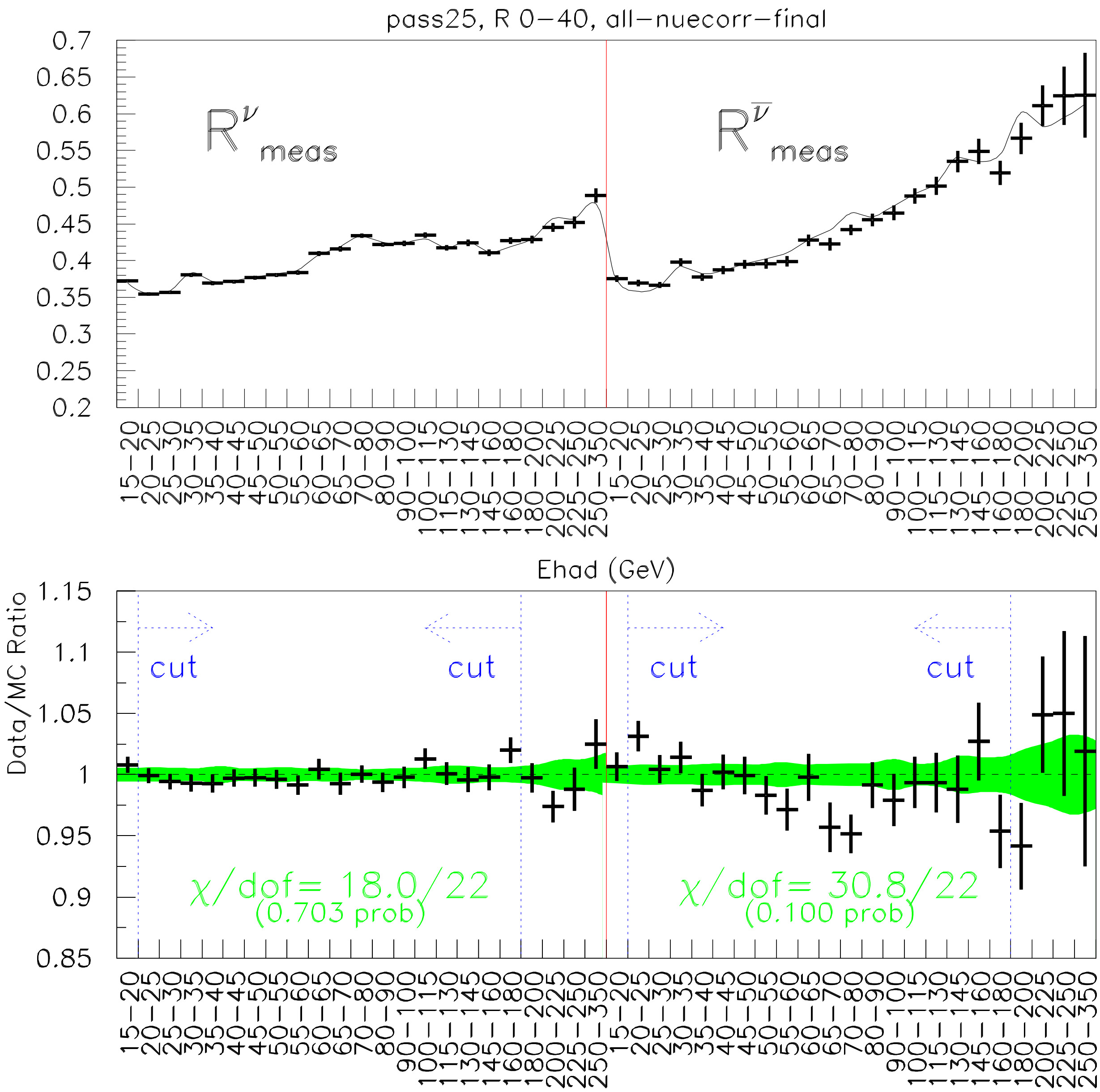
Long Event (CC Candidates) vs. E_{had}



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

Stability of R_{exp} (cont'd)

R_{exp} vs. E_{had}



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

The $\sin^2\theta_W$ Fit

(Llewellyn-Smith)

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

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

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

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

- Monte Carlo relates $R^{\overset{(-)}{\nu}}_{\mathrm{exp}}$ 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^{ν}_{exp}, $R^{\overline{\nu}}_{\mathrm{exp}}$ and experimental m_c constraint as inputs
- $\sin^2\theta_W^{(\mathrm{on-shell})} = 0.2277 \pm 0.0013 \pm 0.0009$

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

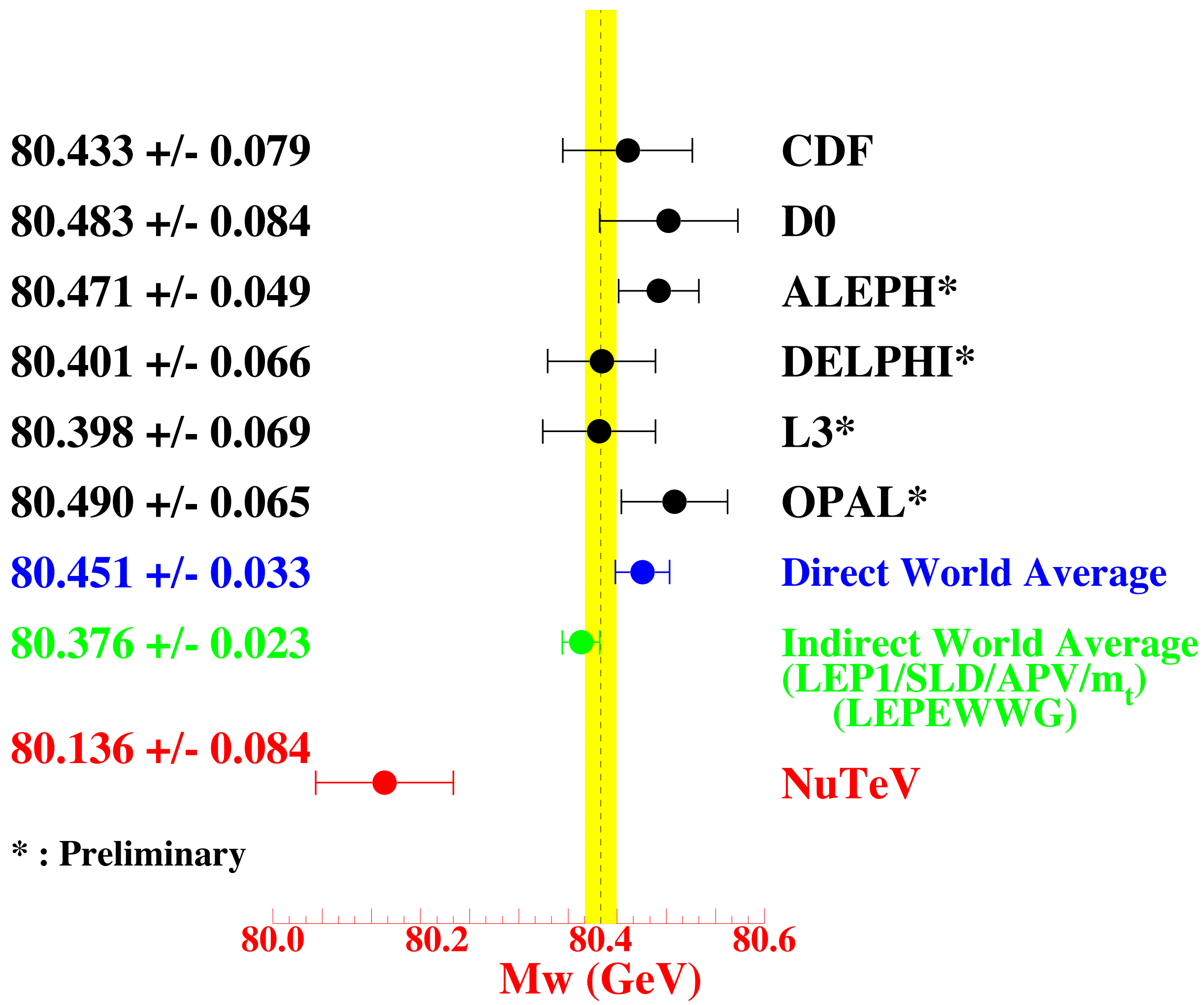
(Paschos-Wolfenstein)

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

Comparison with M_W

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

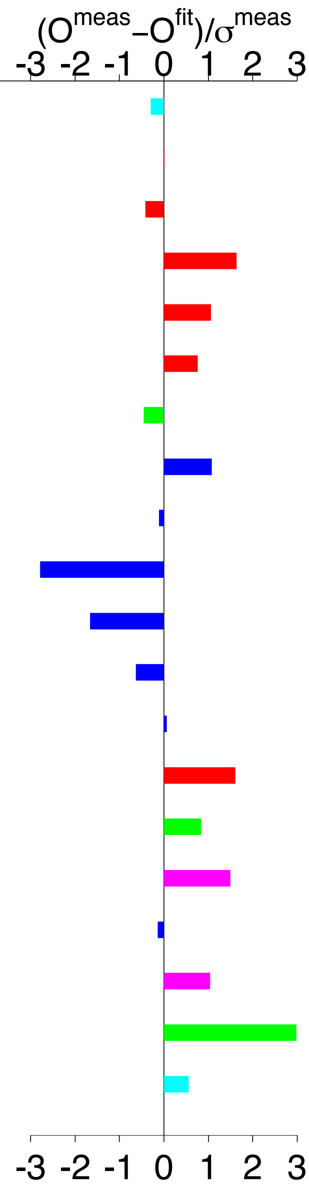


- In standard electroweak theory, NuTeV precision is comparable to a single direct measurement of M_W
- More inconsistent with direct M_W than other data

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



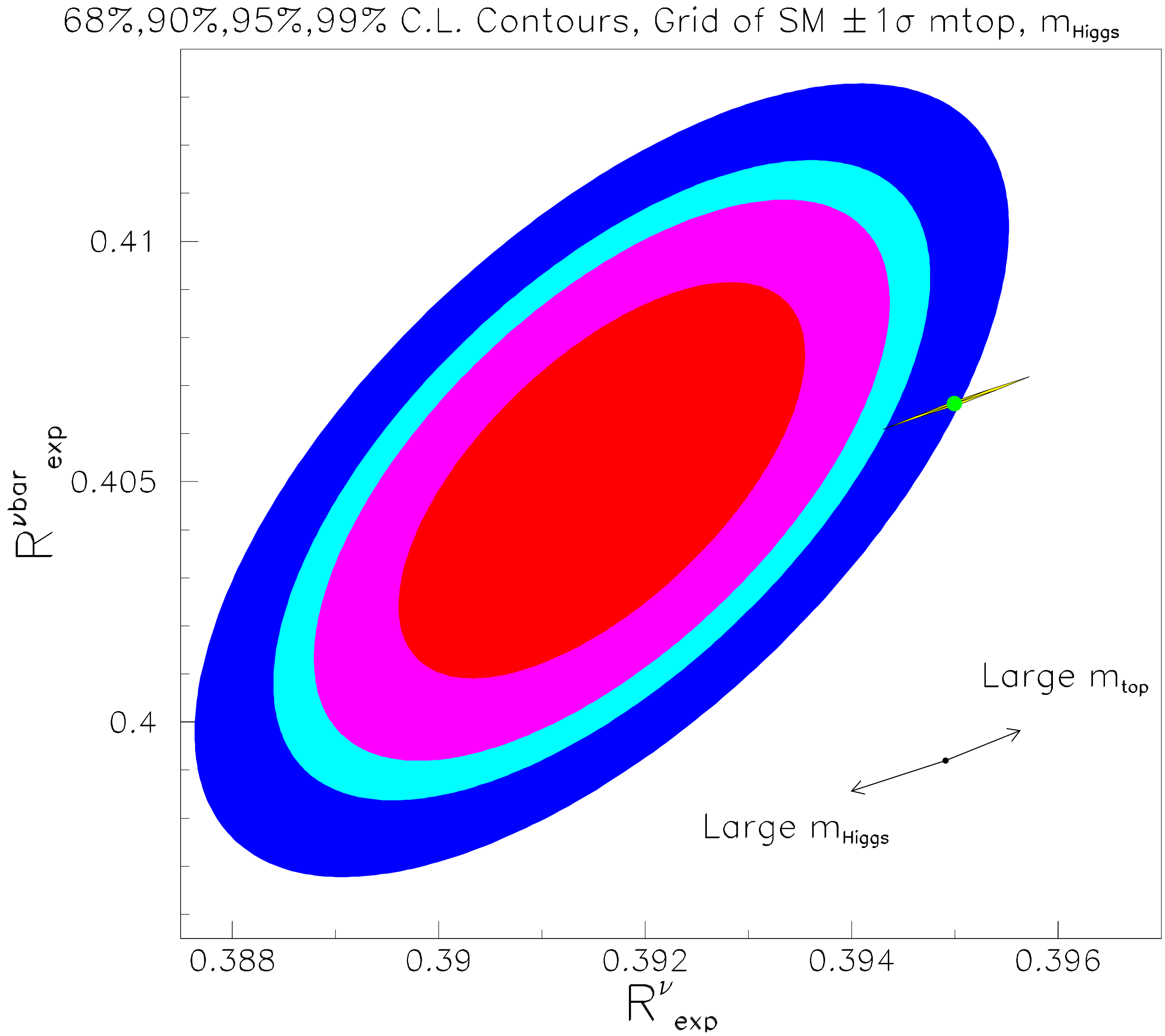
(Courtesy M. Grunewald, LEPEWWG)

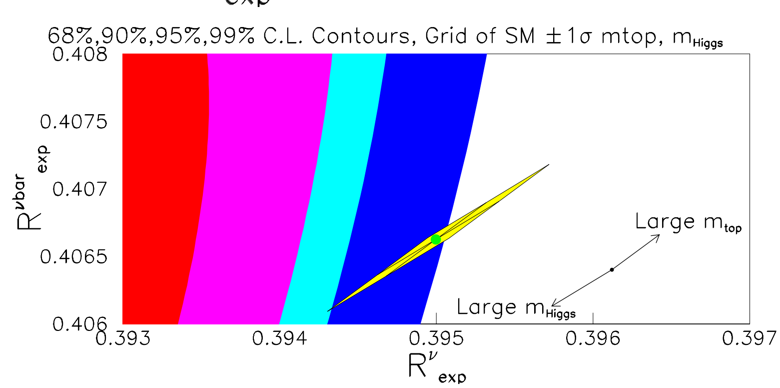
Without NuTeV: $\chi^2/\mathrm{dof} = 21.5/14$, probability of 9.0%

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

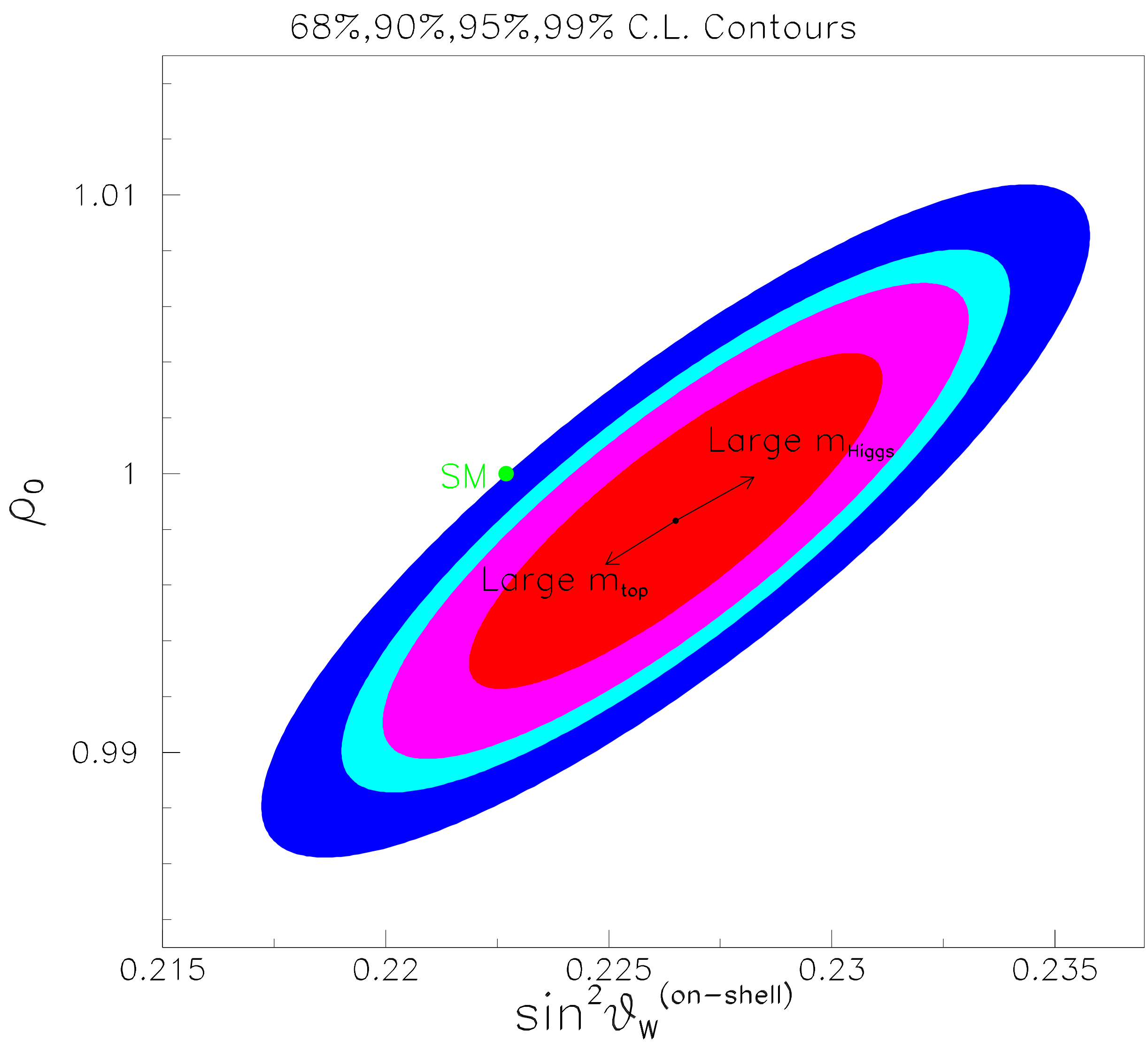
Upper m_{Higgs} limit weakens slightly

$R^{\nu}_{\rm exp}$ and $R^{\overline{\nu}}_{\rm exp}$





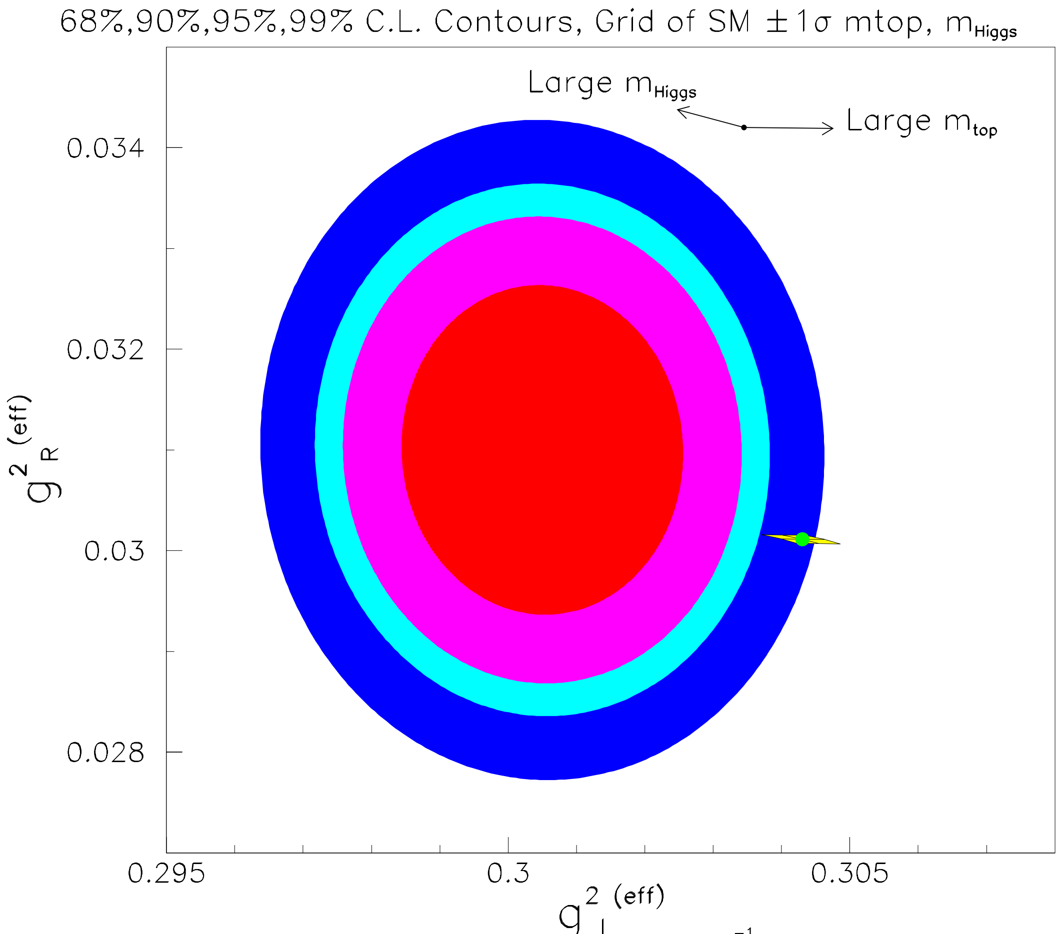
Tree-level parameters: ρ_0 and $\sin^2\theta_W^{(\text{on-shell})}$



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

  $\hookrightarrow$ but both agreeing is unlikely!

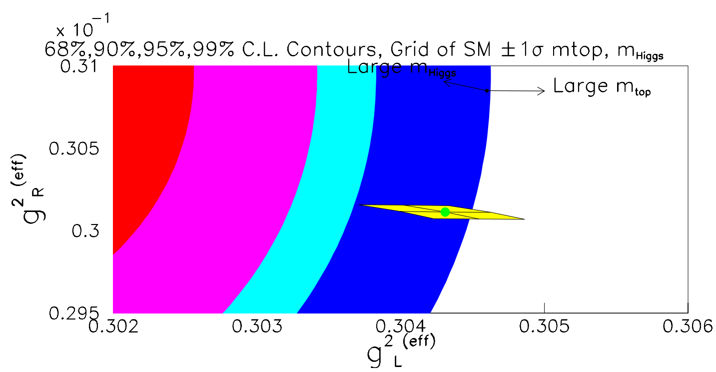
Quark Couplings: $(g_L^{\text{eff}})^2$ and $(g_R^{\text{eff}})^2$



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

NuTeV measures

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



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

Thomas *et al.*, Phys. Lett. **A9**, 1799

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

↪ ~ 0.0004 shifts at high, low x cancel

Meson Cloud model

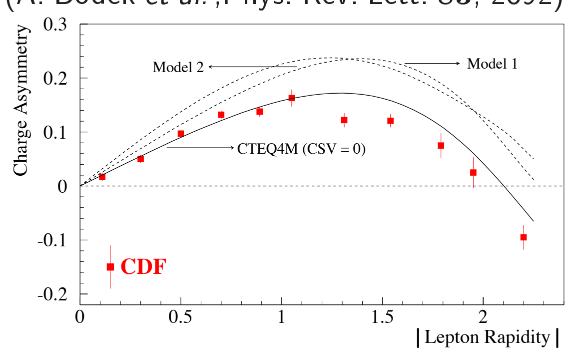
Cao & Signal, Phys. Rev. **C62**, 015203.

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

- How much can we rely on models?
- 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

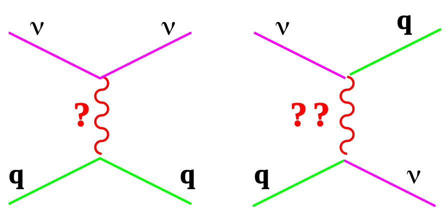
    (N.B., models at right are *different* than the ones above!)

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



  - ↪ Hard to exclude ALL models with such an argument

New Tree Level Physics?



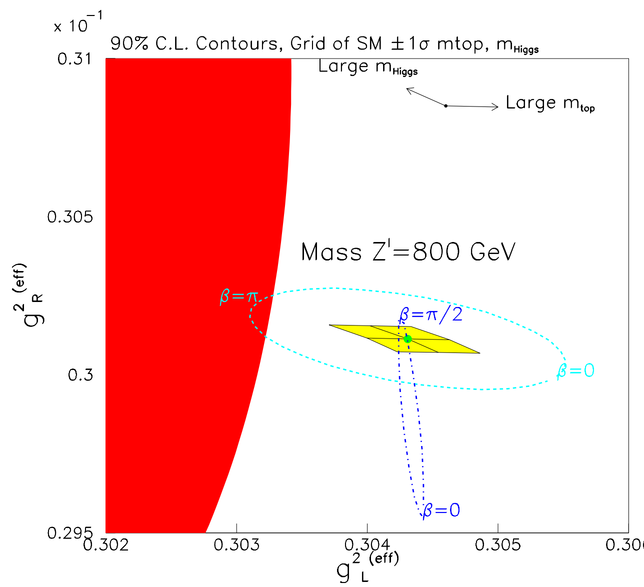
- "Natural" interpretation of result
- Z', LQ, etc.
- Must enhance LL not LR coupling

- $E(6)$ 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.)



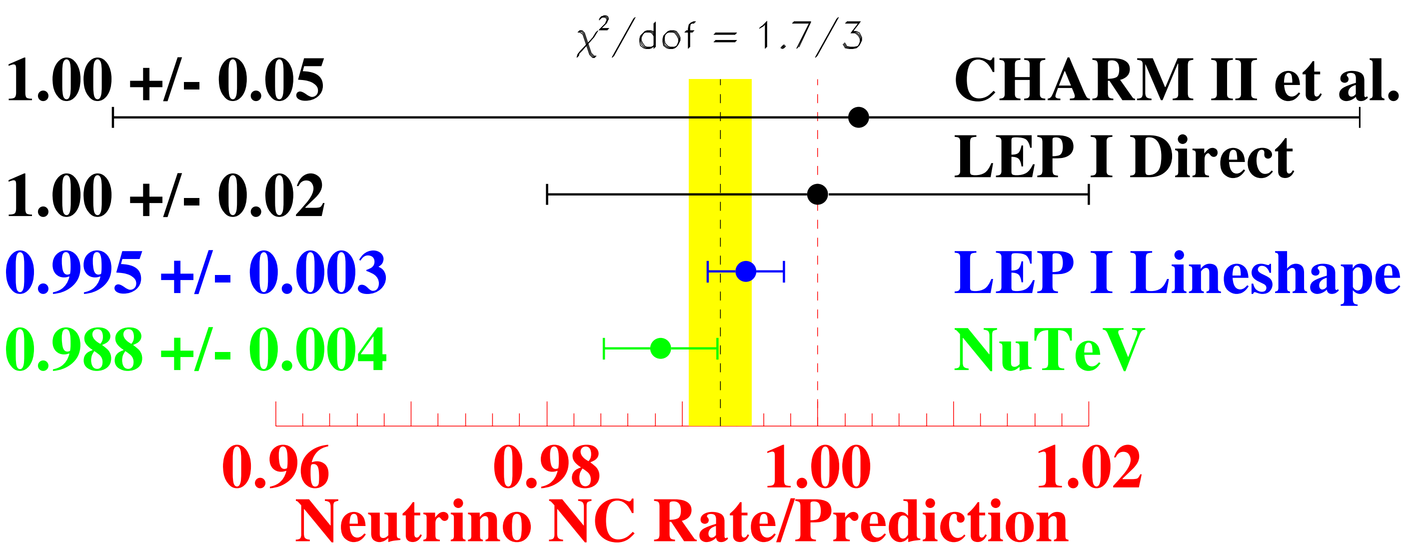
- "Almost sequential" Z' with opposite coupling to ν
  ↪ NuTeV preferred mass range: $1.2^{+0.3}_{-0.2}$ TeV
  ↪ CDF/D0 limits: $M_{Z'_{\rm SM}} \gtrsim 700$ GeV
- Contact interaction with LL coupling
  ↪ $\nu\nu qq$ Contact term, $\Lambda_{LL} = 4.5 \pm 1$ TeV

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

(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 $N_\nu = 3\frac{\Gamma_{\exp}(Z\to\nu\overline{\nu})}{\Gamma_{\mathrm{SM}}(Z\to\nu\overline{\nu})} = 3\times(0.9947\pm0.0028)$
  - ↪ LEP I "direct" partial width ($\nu\nu\gamma$) $\Rightarrow N_\nu = 3\times(1.00\pm0.02)$
- $\overset{(-)}{\nu}_\mu\, e^- \to \overset{(-)}{\nu}_\mu\, e^-$ scattering (CHARM II *et al.*)
  - ↪ PDG fit: $g_V^2 + g_A^2 = 0.259\pm0.014$, cf. 0.258 predicted
- NuTeV can fit for a deviation in $\nu\&\overline{\nu}$ NC rate
  - ↪ $\rho_0^2 = 0.9884\pm0.0026(\mathrm{stat})\pm0.0032(\mathrm{syst})$



- 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.