Recent Electroweak Results from NuTeV

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- Introduction
- Past measurement of $\sin^2\theta_W$
- Present Improvements on $\sin^2\theta_W$
- Preliminary NuTeV $\sin^2\theta_W$
- Inverse Muon Decay
- Conclusions

NuTeV Collaboration

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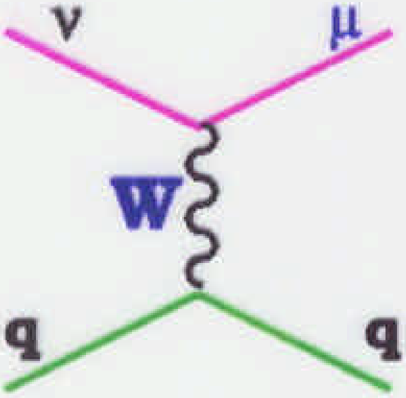
Introduction

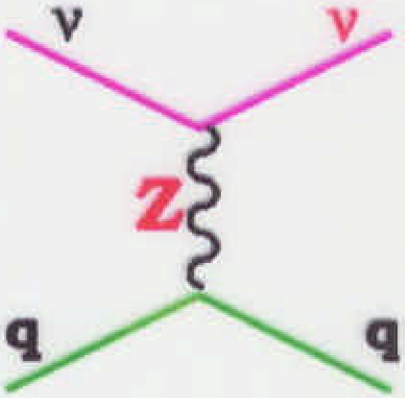
- νN scattering is a perfect testing field to probe electro-weak sector
- Within the SM on-shell renormalization scheme, $\sin^2\theta_W$ is:

$$\sin^2\theta_w^{On-Shell} = 1 - \frac{M_W^2}{M_Z^2}$$

- Provides independent and complementary measurement of M_W
- Comparable size of uncertainty to direct measurements
- Measures light quark couplings ➔ Sensitive to other types (anomalous) couplings
- In other words, sensitive to physics beyond SM ➔ New vector bosons, compositeness, ν-oscillations, etc
- Other electroweak processes ➔ Provide additional tools to probe beyond SM.

How do we measure $\sin^2\theta_W$?





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

$coupling \propto I^{(3)}_{weak} - Q_{EM}\sin^2\theta_W$

- Llewellyn Smith Formula (for isoscalar target):

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

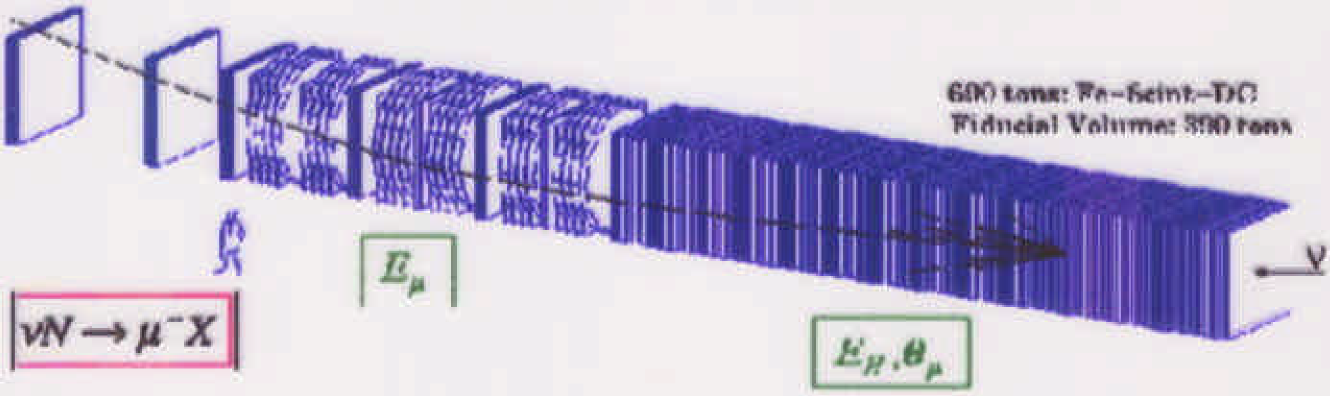
Some corrections are needed to extract $\sin^2\theta_W$ from measured ratios (radiative corrections, heavy quark effects, isovector target corrections, HT, R_L)

CCFR Experiment

E770: Quad Triplet Beam and Lab E Detector

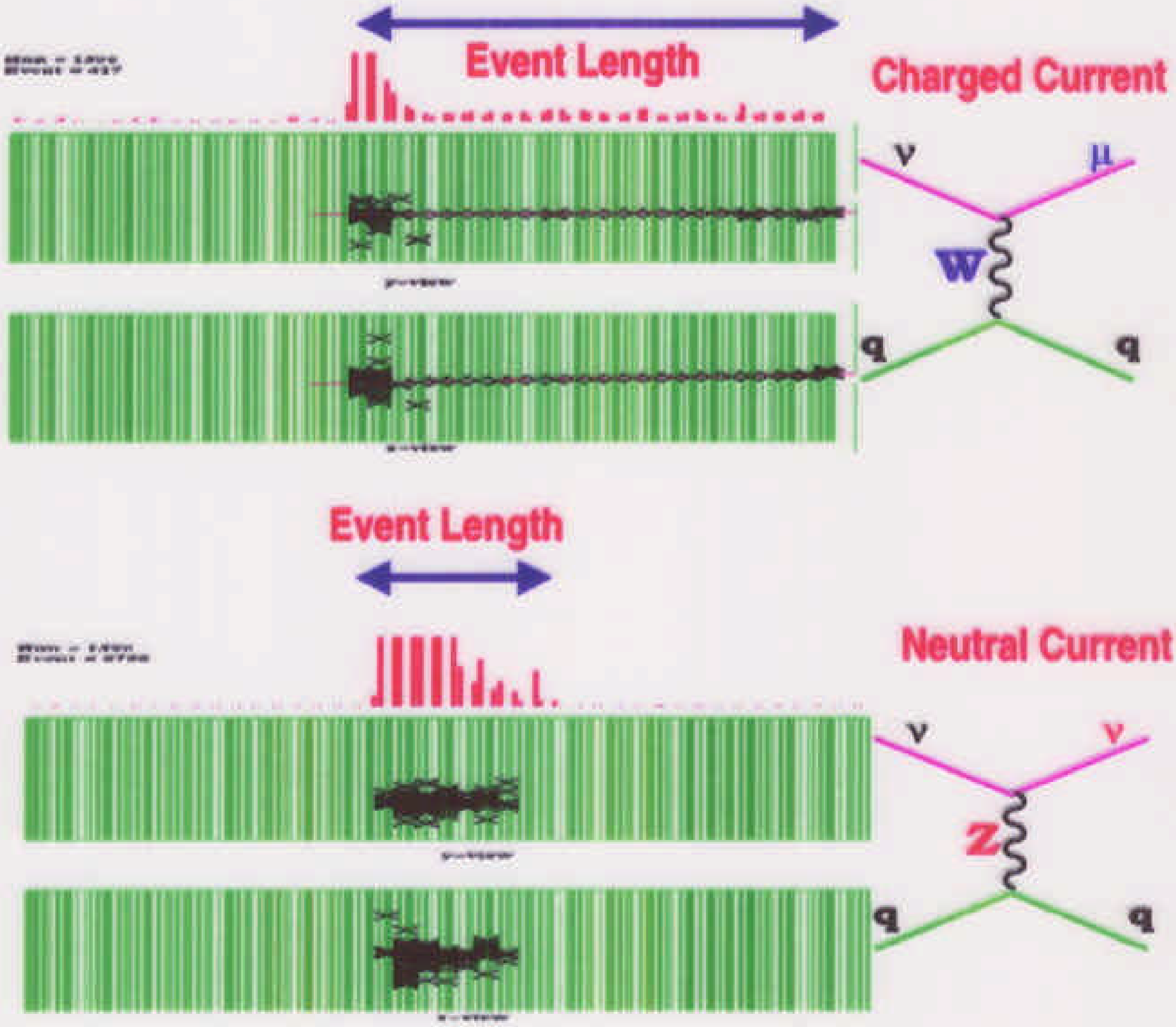
- Conventional neutrino beam from π/K decays
- Focus all signs of π/K for neutrinos and antineutrinos

LAB–E Detector – Fermilab E815 (NuTeV)



- Very small cross section ➔ Heavy neutrino target
- ν_e are the killers (CC events look the same as NC events)

NC/CC Event Separation



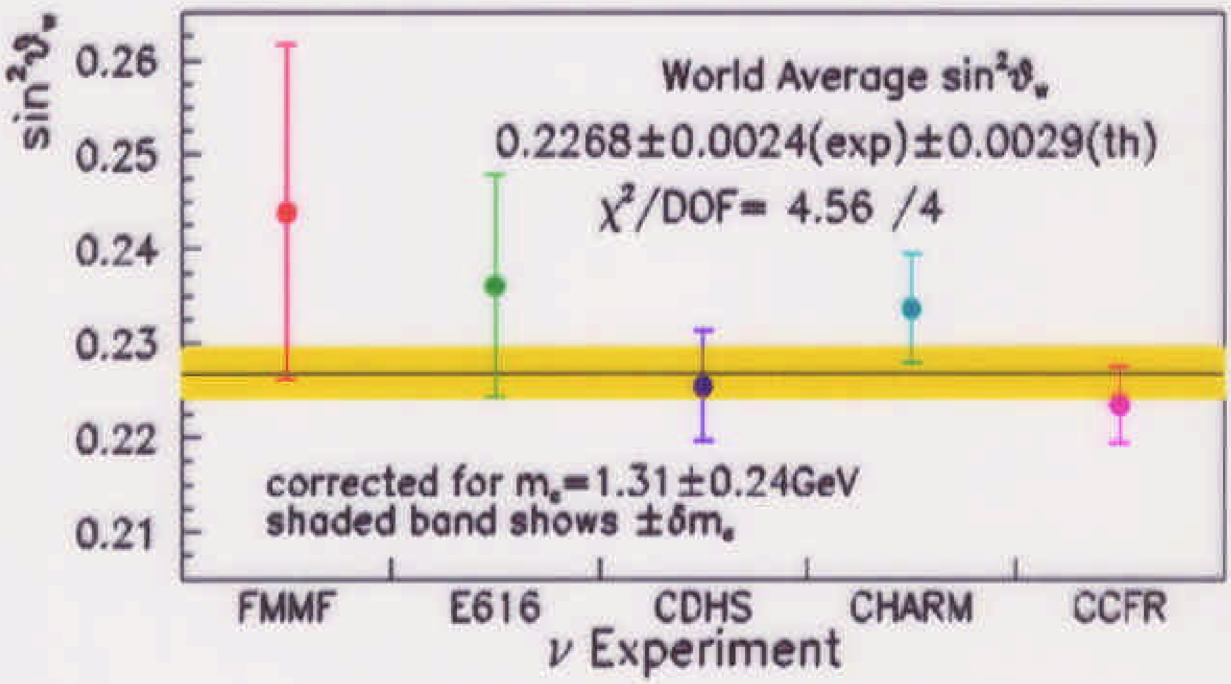
Statistical separation of NC and CC events based on "event length" (Longitudinal energy deposit)

$$R_{Meas} = \frac{N_{short}}{N_{long}} = \frac{N_{L\leq 20}}{N_{L>20}} = \frac{\text{NC candidates}}{\text{CC candidates}}$$

Previous Experimental Results

$$\sin^2\theta_W^{On-Shell} = 1 - \frac{M_W^2}{M_Z^2} = 0.2268 \pm 0.0037$$

$$\Rightarrow M_W^{On-Shell} = 80.18 \pm 0.19\ GeV/c^2$$



Significant correlated error from CC production of charm quark (m_c)

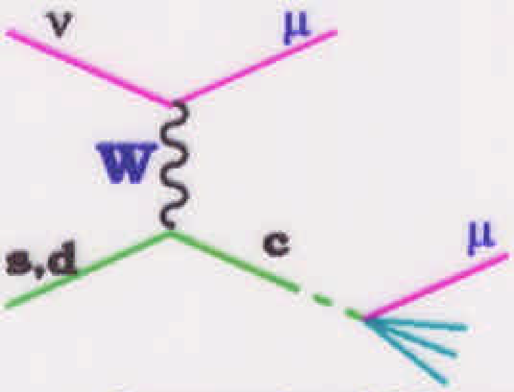
Issues from Previous Results

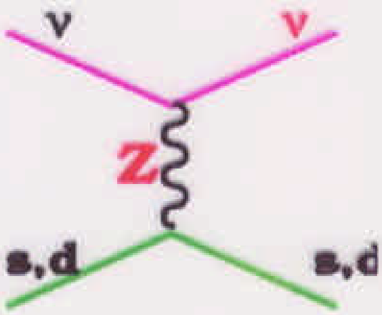
Systematic uncertainty dominated

- Poorly(~20%) known Neutral meson production cross sections ➔ Limit understanding ν_e content in the beam

  $\delta\sin^2\theta_W=0.0015$

- Charged Current Charm Production uncertainty due to mass threshold effect





  - Suppression of CC x-sec due to massive charm
  - Modeled by LO slow rescaling:

$$\xi = x\left(1+\frac{m_c^2}{Q^2}\right) \quad \text{where} \quad x=\frac{Q^2}{2ME_{had}}$$

  - Using parameters measured by CCFR

  $\delta\sin^2\theta_W=0.0027$

Calls for new technique!!

NuTeV's Improvements

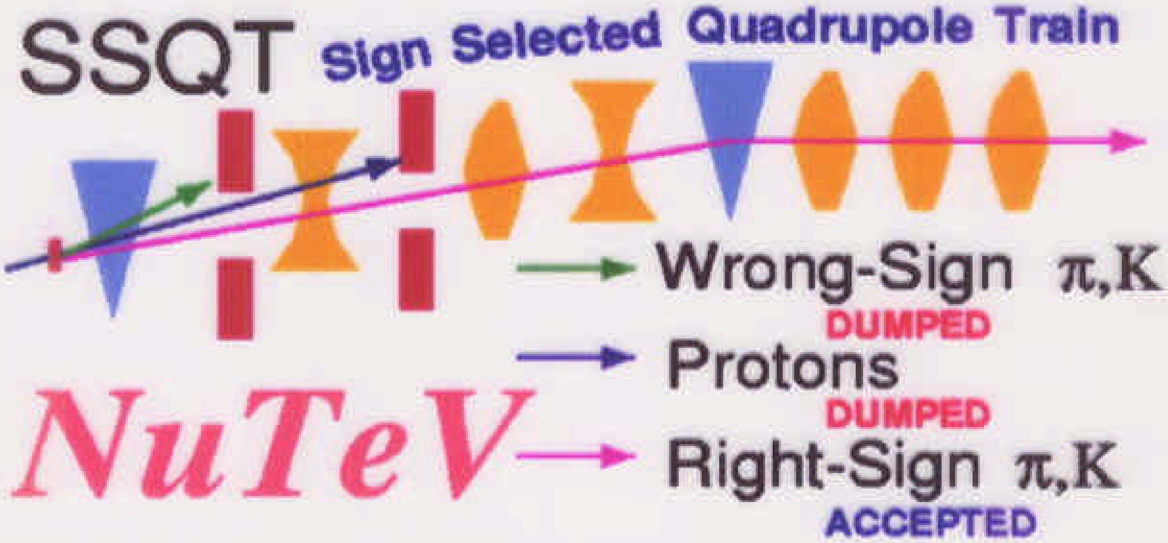
- Paschos-Wolfenstein formula:

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

➔ Reduce charm CC production error by subtracting sea quark contributions

➔ Need to distinguish ν and ν–bar NC events

➔ Requires a new beam line



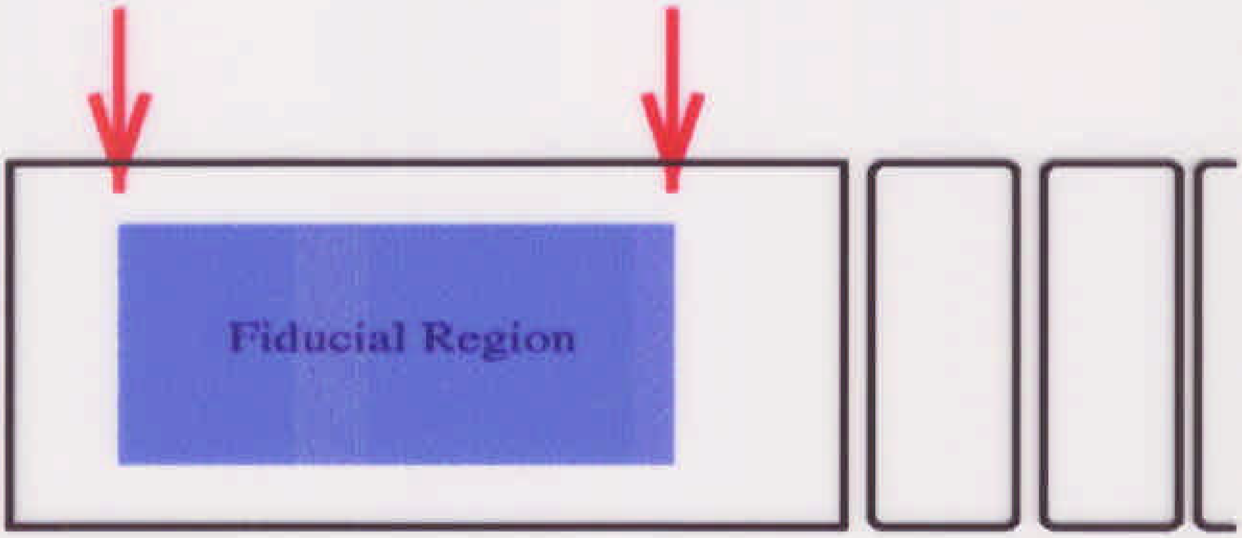
•Smarter beamline ➔ Removes neutral secondaries to eliminate most the ν_e content

•Beam wrong sign contamination: $<1\times10^{-3}$ (ν), $<2\times10^{-3}$ ($\bar{\nu}$)

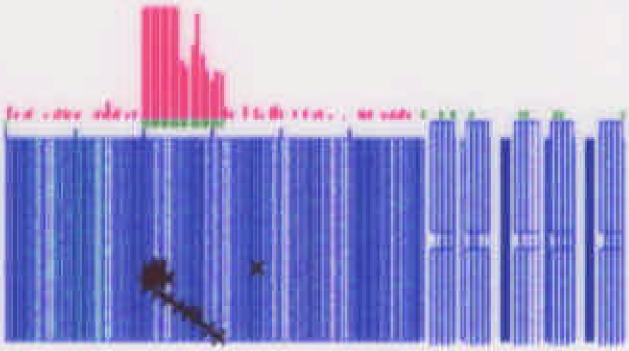
NuTeV Event Selection

Analysis Cuts:

- E_{had} > 20GeV
  - To ensure vertex finding efficiency
  - To reduce cosmic ray contamination
- X_{vert} and Y_{vert} within the central 2/3
  - Full hadronic shower and muon contrainment
  - Further reduce ν_e contamination
- Z_{vert} cut
  - To ensure neutrino induced interaction
  - Better discriminate CC and NC



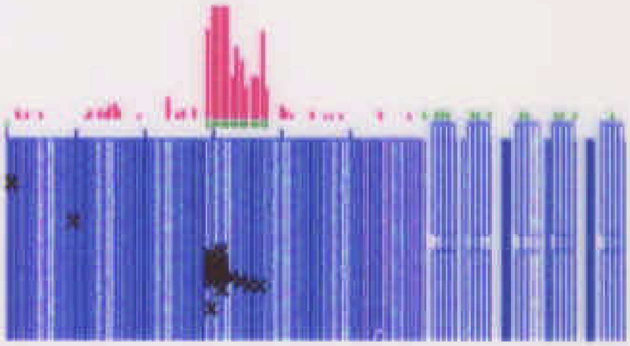
Event Contamination and Backgrounds



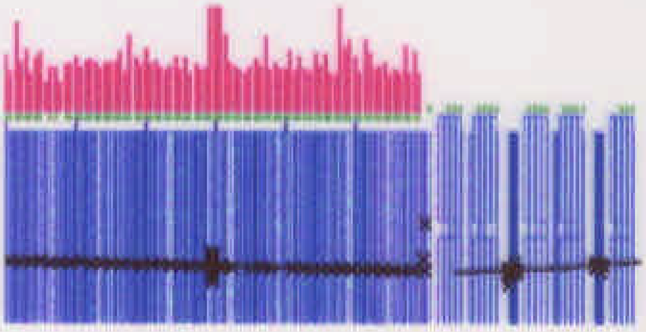
- •SHORT ν_μ CC's (20%)
  μ exit and rangeout
- •SHORT ν_e CC's (5%)
  $\nu_e N \rightarrow eX$

- •Cosmic Rays (0.8%)

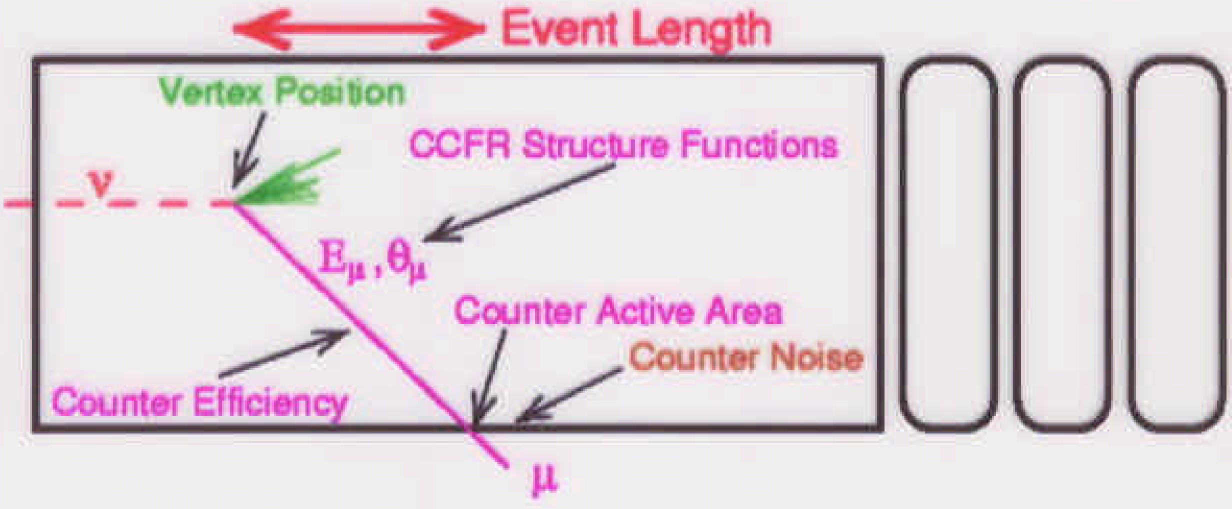
- •LONG ν_μ NC's (0.3%)
  hadron shower
  punch-through effects



- •Hard μ Brem(0.2%)
  Deep μ events



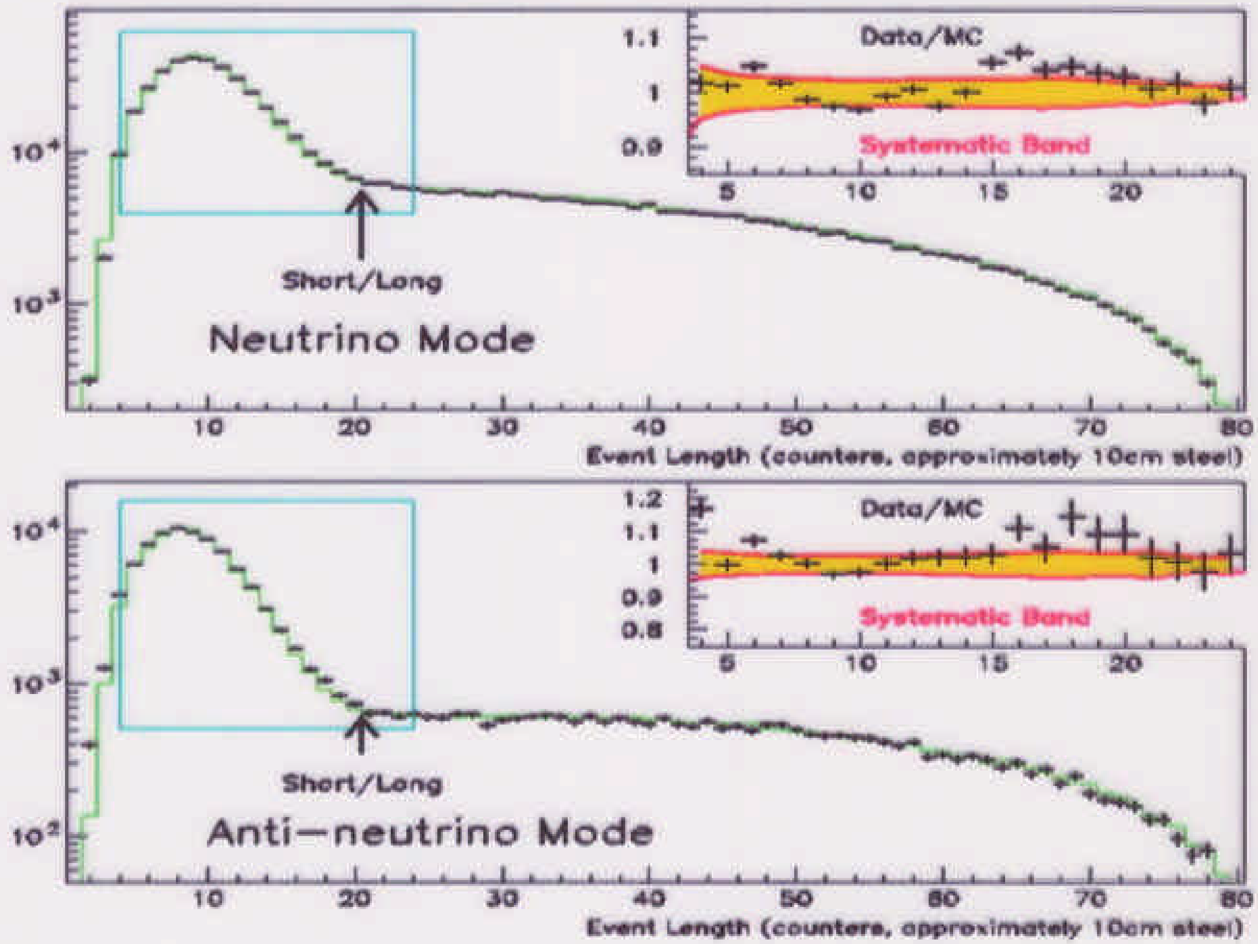
Other Detector Effects



Sources of experimental uncertainties kept small, through modeling using ν and TB data

Effect	Size($\delta\sin^2\theta_W$)	Tools
Z_{vert}	0.001/inch	$\mu^+\mu^-$ events
X_{vert} & Y_{vert}	0.001	MC
Counter Noise	0.00035	TB μ's
Counter Efficiency	0.0002	ν events
Counter active area	0.0025/inch	ν CC, TB
Hadron shower length	0.0015/cntr	TB π's and k's
Energy scale	0.001/1%	TB
Muon Energy Deposit	0.004	ν CC

Preliminary NuTeV Event Length Distributions



Mode	N_{short}	N_{long}	$R_{20}=N_{short}/N_{Long}$
ν	386k	919k	0.4198 ± 0.0008(stat)
$\overline{\nu}$	88.7k	210k	0.4215 ± 0.0017(stat)

Cross Section Model and $\sin^2\theta_W$ Fit

$$R^- = \frac{\sigma_{NC}^{\nu} - \sigma_{NC}^{\bar\nu}}{\sigma_{CC}^{\nu} - \sigma_{CC}^{\bar\nu}} = \frac{R^{\nu} - rR^{\bar\nu}}{1-r}$$

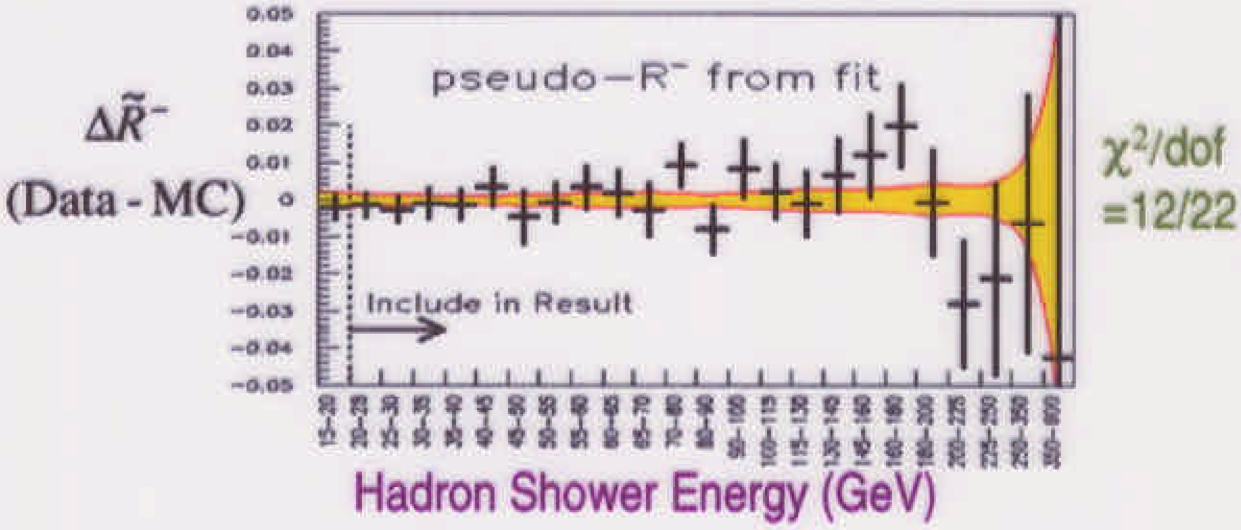
$$\text{where} \quad R^{\nu,\bar\nu} = \frac{\sigma_{NC}^{\nu,\bar\nu}}{\sigma_{CC}^{\nu,\bar\nu}}, \text{ and } \quad r = \frac{\sigma_{CC}^{\bar\nu}}{\sigma_{CC}^{\nu}}$$

- NuTeV's approach:Maximally utilize separate beam → Measure R^{ν}'s separately and form

$$\tilde{R}^- = R^{\nu} - xR^{\bar\nu}$$

- Choose "x" to minimize mc dependence; sea quark effect approximately cancels
- Use MC to find "x" and "R^-" dependence on $\sin^2\theta_W$

$$x \approx 0.514 \quad , \frac{d\left(\tilde{R}^-\right)}{d\sin^2\theta_W} \approx -0.636$$



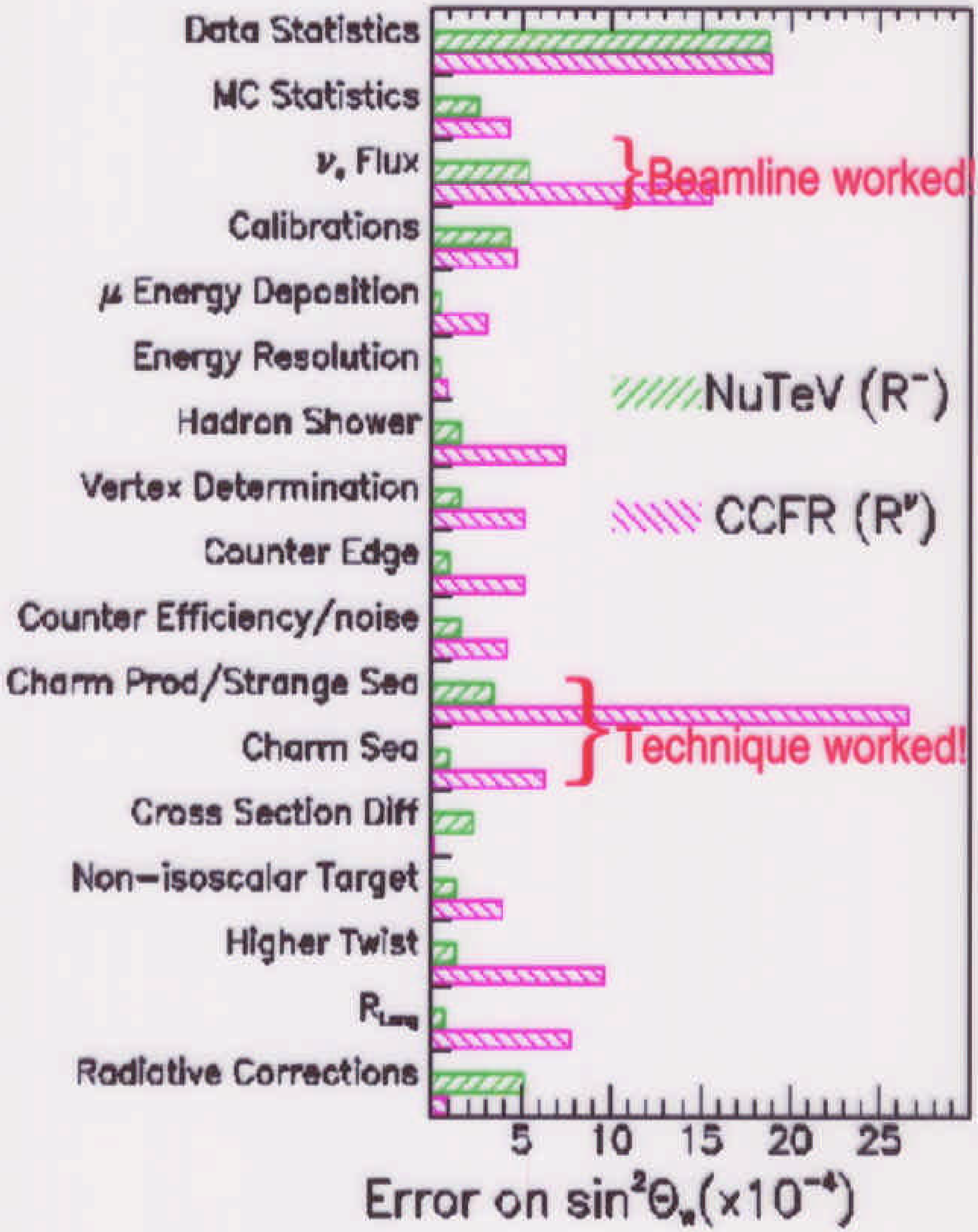
Preliminary NuTeV Uncertainties

Source of Uncertainty	$\delta \sin^2\theta_W$
Statistical	0.0019
ν_e flux	0.0005
Event Length	0.0004
Energy Scale	0.0005
Total Experimental Systematics	0.0008
CC Charm production	Negligible
Higher Twist	0.0001
Non-isoscalar target	0.0002
RadiativeCorrection	0.0005
Total Physics Model Systmatics	0.0007
Total Systematic Uncertainty	0.0021
ΔM_W (GeV/c^2)	0.11

1-Loop Electroweak Radiative Corrections based on Bardin, Dokuchaeva **JINR-E2-86-2 60 (1986)**

$$\delta \sin^2\theta_W^{(On-shell)} = -0.00142 \times \left(\frac{M_t^2 - (175\ GeV)^2}{(100\ GeV)^2} \right) + 0.00048 \times \ln\left(\frac{M_H}{150\ GeV} \right)$$

NuTeV vs CCFR Uncertainties Comparisons



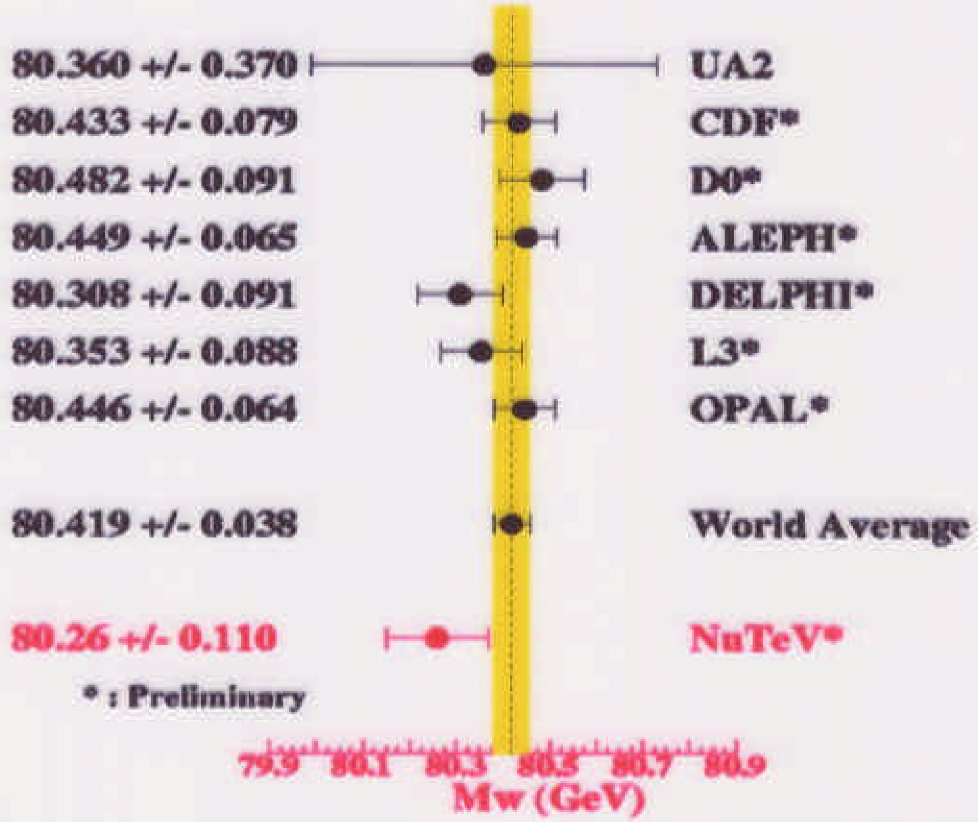
Preliminary NuTeV $\sin^2\theta_W$

$$\sin^2\theta_W^{On-Shell} = 0.2253 \pm 0.0019\,(stat) \pm 0.0010\,(syst)$$

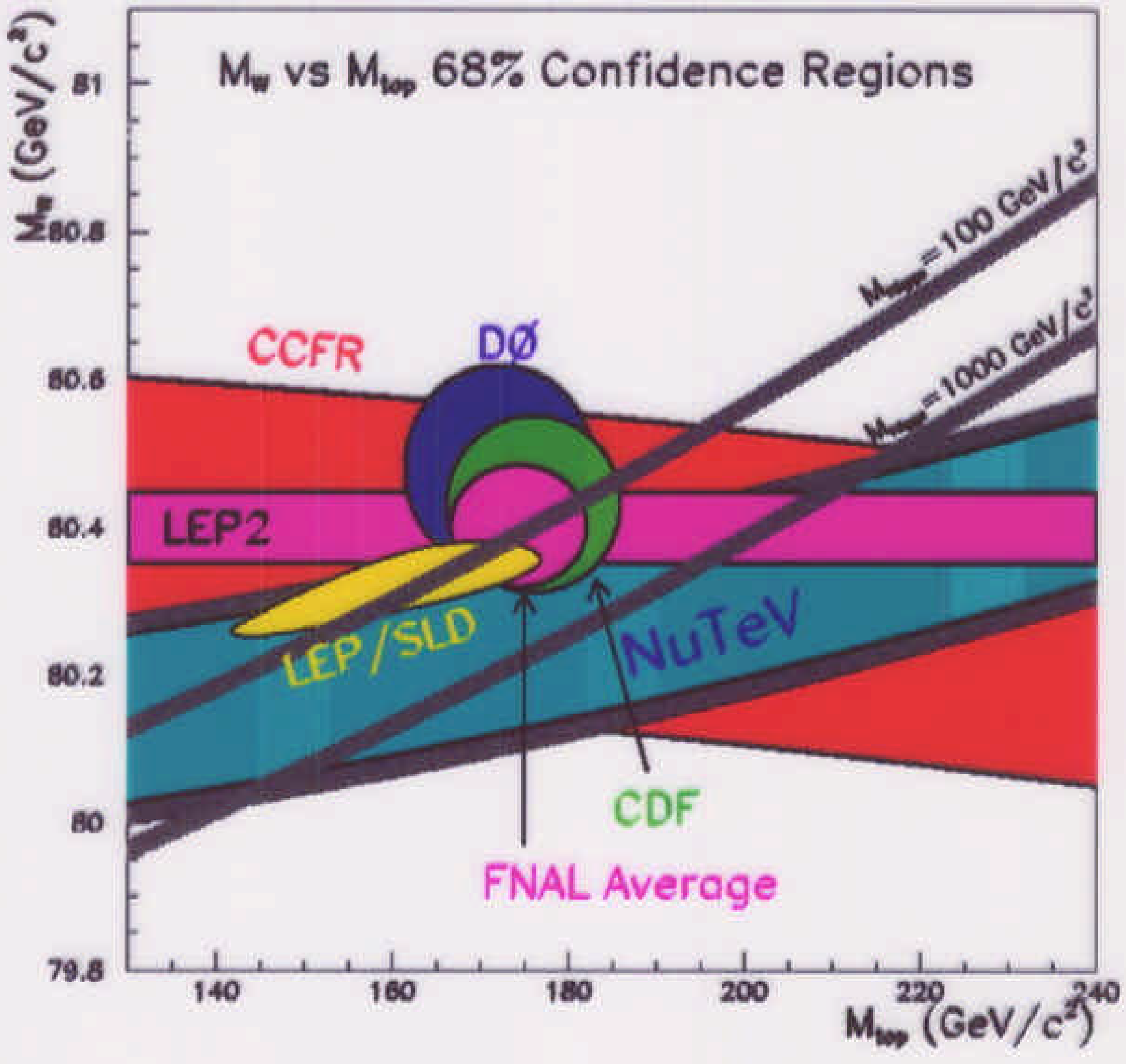
$$\sin^2\theta_W^{On-shell} = 1 - \frac{M_W^2}{M_Z^2}$$

$$\Rightarrow M_W^{On-Shell} = 80.26 \pm 0.11\,GeV/c^2$$

Comparable precision to other measurements, providing complementary information within SM



M_{top} vs M_W



Results from various measurements are in reasonable agreements, pointing to light Higgs

Inverse Muon Decay

- A clean test of weak sector→ purely leptonic interaction

  $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$
- Only occurs in neutrino mode (no positrons in atoms)
- Theoretical prediction unambiguous
  - Lorentz structure of weak current
  - ν_μ Helicity
  - Cross section depends on parameters sensitive to handedness, polarization, etc.
- Tool for background estimate for LNV ($\Delta L=2$) in $\bar{\nu}$ mode ($\bar{\nu}_\mu + e^- \rightarrow \mu^- + \bar{\nu}_e$)
- A possible tool for flux measurement for future high rate neutrino facility
- For ($s \gg m_\mu^2$):

  $$\sigma(\nu_\mu + e^- \rightarrow \mu^- + \nu_e) = G_F^2 s/\pi = 17.2\times10^{-42}\,E_\nu\,cm^2$$

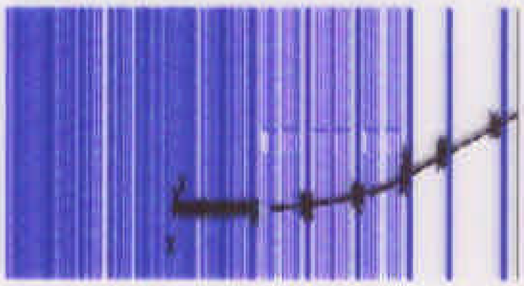
•Clear Experimental Signatures:

–Right sign μ–CC in ν mode

–no hadronic energy

–Low scattering angle of μ → Low P_T^μ, Low Q^2

–Well known threshold; $E_\nu > E_\mu > m_\mu^2/2m_e > 10.8$GeV



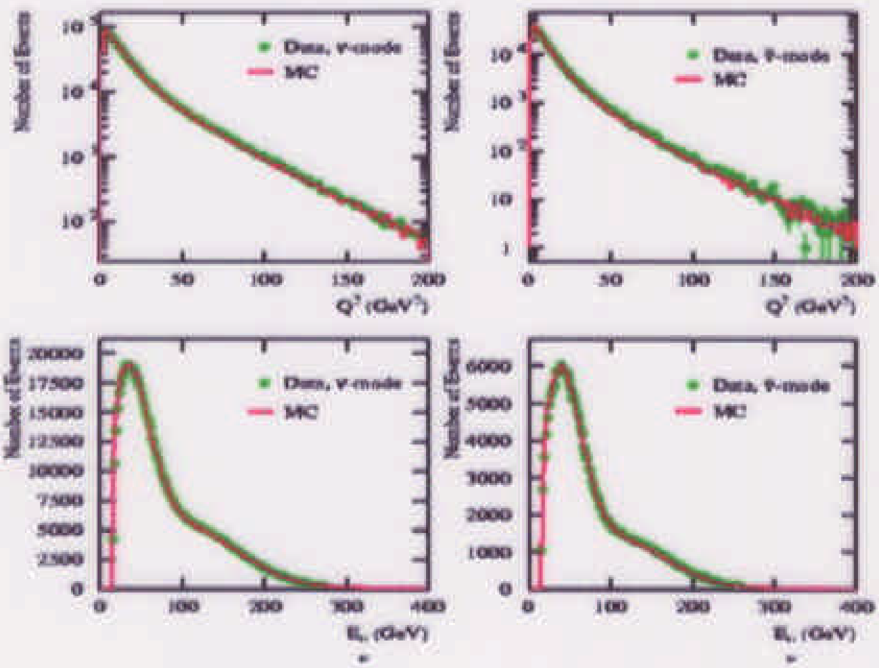
The analysis

- Event selection, within the fiducial volume:
  - Well measured and fully contained μ^- in ν mode
  - Low hadronic energy (<3GeV)
  - Low P_T^μ ($P_T^{\mu\,2}$<f(Eν) to retain ~95% IMD)
  - Overall cut efficiency ~ 81%
- Backgrounds:
  - Qusi-elastic scattering: $\nu_\mu + n \rightarrow \mu^- + p$
  - Resonance production: $\nu_\mu + N \rightarrow \mu^- + R$
  - Coherent meson production off the nucleus

  → All expected equally produced by high E neutrino and anti-neutrinos
  - Low E_{had} DIS
  - Backward going cosmic-ray muons
  - Di-muons
- 2 methods for background subtraction:
  - Direct subtraction: Using low E_{had} anti-neutrino events (statistics limited)
  - Use MC (Modeling systematics limited)

Low E_{had} Modeling

- Includes detailed detector modeling
- Low E_{had} cross section models
  - Qusi-Elastic production (Llewllyn Smith x-sec)
  - Resonance production & DIS (Rein & Sehgal)
- Nuclear effects
  - Fermi Motion (Bodek et. al)
  - Pauli Suppression
- Verify the modeling, using Structure Function candidates (high E_{had} CC events) ➔ Good description of data obtained

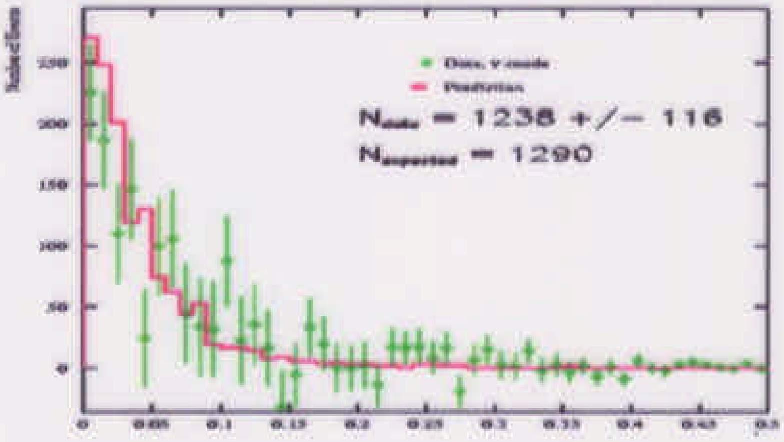


Preliminary NuTeV IMD Result

- MC Background subtraction Method:
  - N_{signal} = 1238+/- 116 (stat) +/- 300(syst)

    σ_{IMD}/E_{ν}=(16.5+/-1.5+/-4.0)x10^{-42} cm^2/GeV
  - N(snti-neutrino) = 295 +/- 98 (stat)+/- 233(syst)

  ➔ consistent with 0.



- Direct subtraction method:
  - N_{signal} = 1066+/-188(stat)+/-107(syst)

    σ_{IMD}/E_{ν}=(14.2+/-2.5+/-1.4)x10^{-42} cm^2/GeV
- The two methods are consistent to each other
- CHARM-II:σ_{IMD}/E_{ν}=(16.01+/-0.33+/-0.83)x10^{-42} cm^2/GeV
- SM Prediction: σ_{IMD}/E_{ν}=17.2 x10^{-42} cm^2/GeV

Conclusions

- NuTeV has measured $\sin^2\theta_W$:

$$\sin^2\theta_w^{On-shell} = 0.2253 \pm 0.0019(stat) \pm 0.0010(syst)$$

$$\Rightarrow M_W^{On-Shell} = 80.26 \pm 0.11 GeV/c^2$$

  - NuTeV result is comparable to other measurements
  - Interpretations of this result implicated on extra Z' boson mass, μ antineutrino to τ anti-neutrino oscillation, etc, presented in other conferences
- NuTeV measured IMD cross section:

  From MC method:

  σ_{IMD}/E_ν=(16.5+/-1.5+/-4.0)x10^{-42} cm^2/GeV

  From direction subtraction method:

  σ_{IMD}/E_ν=(14.2+/-2.5+/-1.4)x10^{-42} cm^2/GeV

  → σ_{IMD}/E_ν=(14.2+/-2.9) x10^{-42} cm^2/GeV

  - Consistent with other experimental measurements and the standard model predictions
  - Tool to handle LNV backgrounds in hand

  → LNV (ΔL=2) analysis in progress
- NuTeV has been vigilantly working on exploiting rich data sample → More results to come soon