Measurement of $\sin^2\theta_W$ from NuTeV

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Outline

1. Precision Electroweak Tests and Neutrinos
2. The NuTeV Experiment
3. Analysis and Preliminary Result
4. Standard Model Interpretation

NuTeV Collaboration

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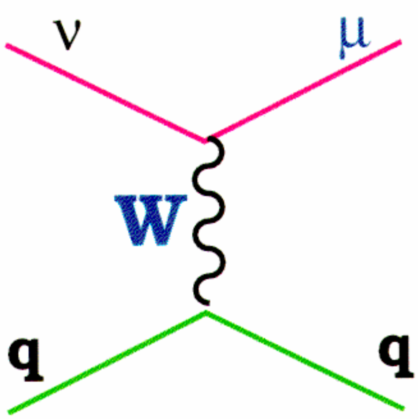
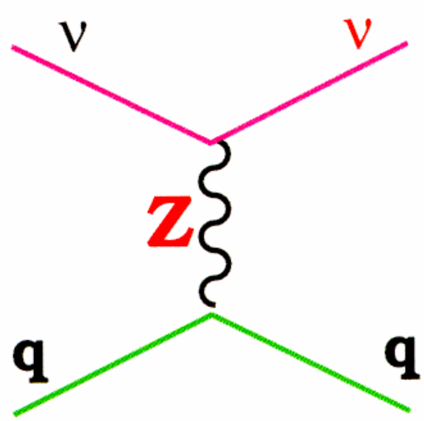
$\sin^2\theta_W$ in Neutrino Scattering





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

For an isoscalar target (equal number of protons and neutrons) of only u,d quarks at tree level:

Llewellyn Smith Relation (CCFR):

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

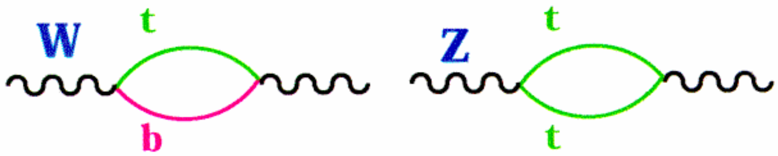
To extract $\sin^2\theta_W$ from the measured ratio a number of corrections must be applied (radiative corrections, heavy quark effects,isovector target correction, higher twist, R_L).

R. Drucker, SSI 1998

Electroweak Radiative Corrections

Three types of corrections to electroweak processes:

- QED Corrections
  (Bardin,Federenko, Sov.J.Nucl.Phys.**30**, 418,(1979))
- Weak Vertex Corrections and Box Diagrams
  (Sirlin, Phys. Rev. **D22**, 2695 (1980))
- Self-Energy Diagrams in boson propogators



▷ Fermion, gauge boson and Higgs loops contribute

▷ Different treatment ⇒ different renormalization schemes

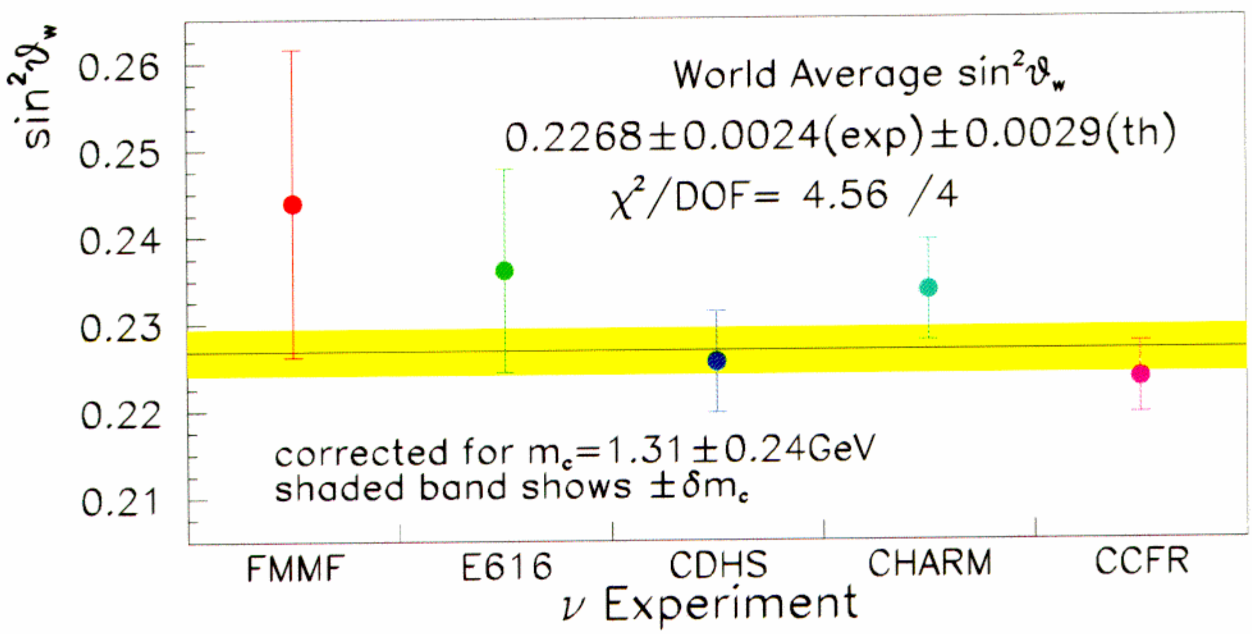
∗ On-shell scheme: $\sin^2 \theta_W^{\mathrm{on-shell}} \equiv 1 - \frac{{M_W}^2}{{M_Z}^2}$

∗ Dependence on m_{top} and m_{Higgs} is weak
(quadratic in m_{top}, logarithmic in m_{Higgs})

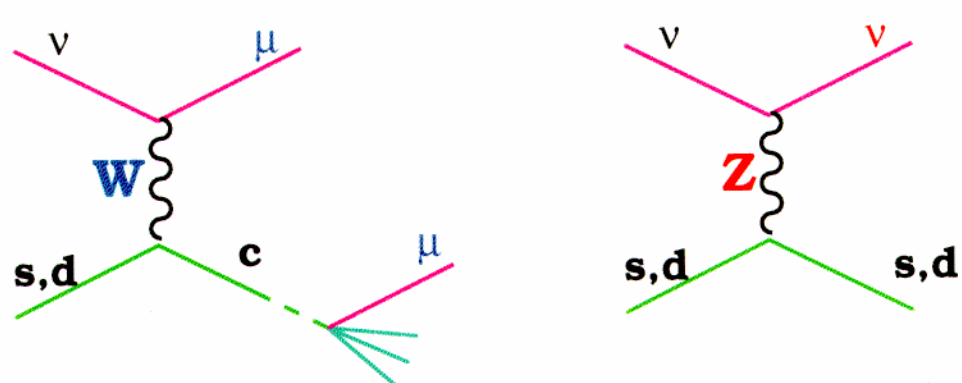
⇒ Effective measurement of M_W

Neutrino Experiments Before NuTeV

Results limited by large correlated uncertainty
⇒ technique had hit a brick wall



Charged-Current Production of Charm



- Modeled by leading-order slow-rescaling: $\xi = x(1+\frac{m_c^2}{Q^2})$
- Parameters model from CCFR in dimuon events $(c \to \mu X)$ (S. Rabinowitz), $m_c = 1.31 \pm 0.24$ GeV, $\kappa = 0.37 \pm 0.05$

NuTeV's Technique

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

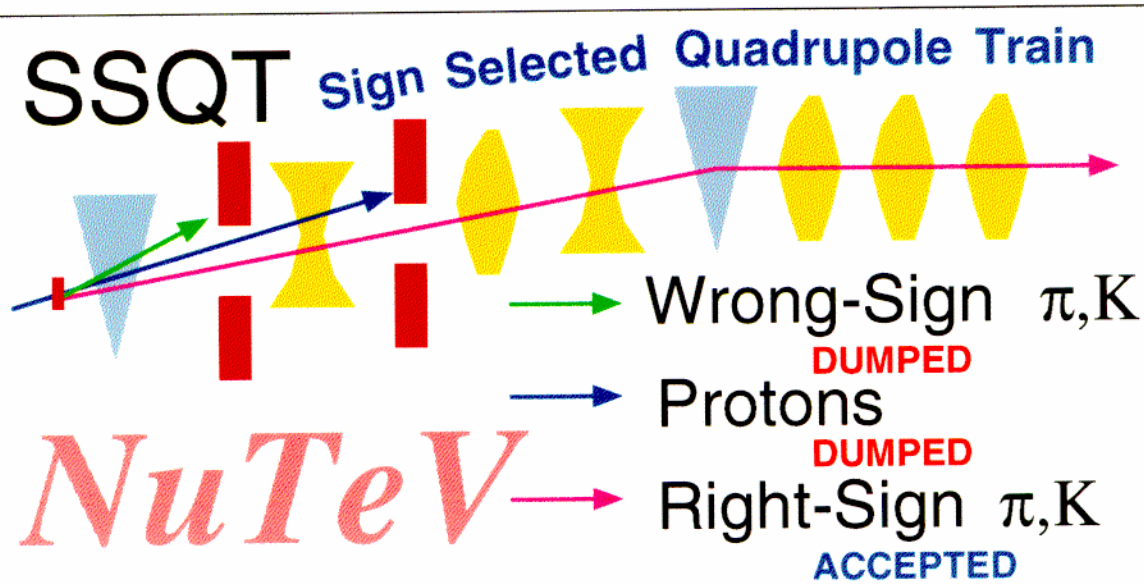
Paschos-Wolfenstein Relations:

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

- R^- manifestly insensitive to sea quarks
  - ▷ Charm production error from d_V-quarks only (Cabibbo suppressed and at large x)
  - ▷ Charm, strange sea errors negligible
  - ▷ Correlated cross section components cancel (higher twist, boson–gluon fusion, ...)
- Requires Separate ν and $\overline{\nu}$ Beams

  $\Rightarrow$ NuTeV SSQT

NuTeV Beamline



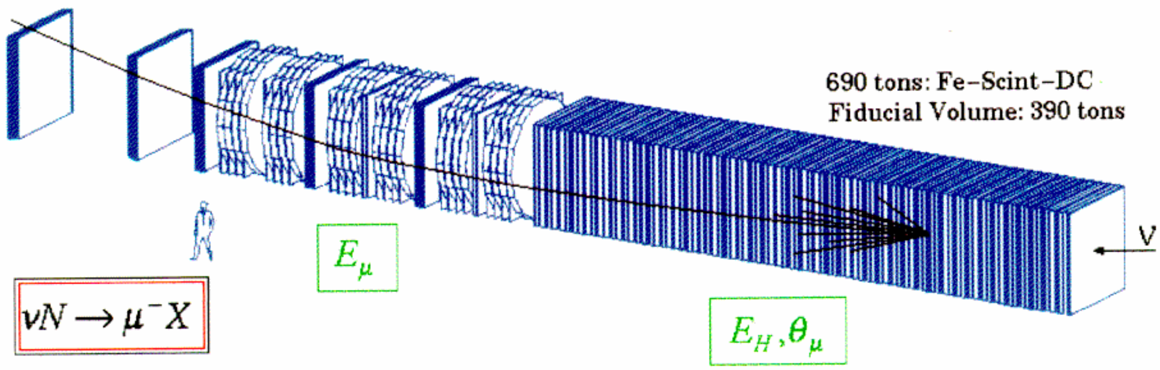
Resulting beam is almost purely ν or $\overline{\nu}$ depending on the sign selection:

Contamination Fractions:

Type	Measured fraction of events
$\overline{\nu}$ in ν mode	$< 1 \times 10^{-3}$
ν in $\overline{\nu}$ mode	$< 2 \times 10^{-3}$

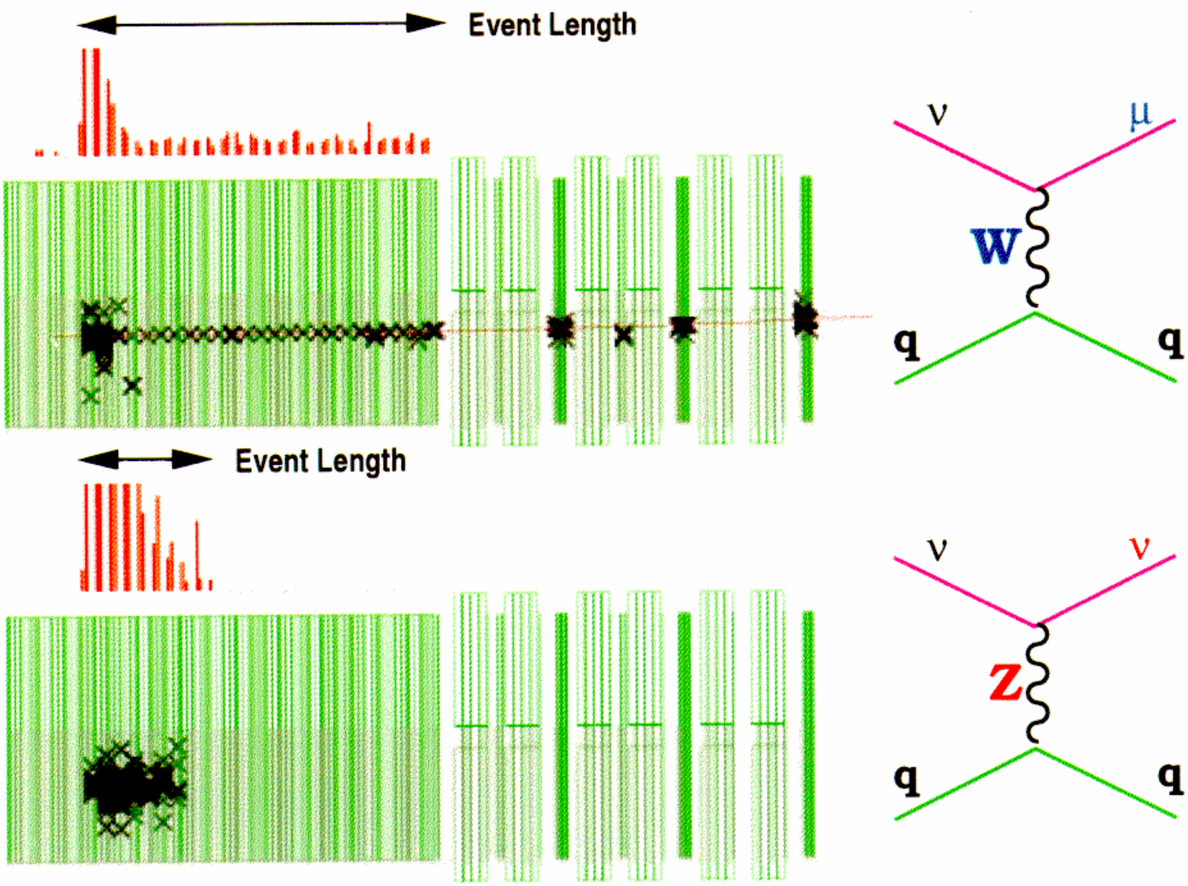
Beam is ~1.8% electron neutrinos

NuTeV Detector



- Target/Calorimeter:
  - ▷ 168 Fe plates (3m X 3m X 5.1cm)
  - ▷ 84 liquid scintillation counters (every 10.2cm steel)
    To trigger the detector
    To measure the visible energy
    To determine the longitudinal event vertex
    To ascertain the event length
  - ▷ 42 drift chambers (every 20.4cm steel)
    To establish transverse vertex of event
- Toroidal Spectrometer:
  15kG field ($P_T = 2.4\, GeV/c$)

Neutral Current/Charged Current Event Separation



Statistical separation of NC and CC events based on distribution of longitudinal energy deposition in the calorimeter ("event length").

$$R_{meas} = \frac{\text{SHORT events}}{\text{LONG events}} = \frac{\text{NC candidates}}{\text{CC candidates}} = \frac{\text{Length} \leq 20}{\text{Length} > 20}$$

NuTeV vs CCFR

Reduction of dominant systematic errors:

- Charm production → R^- technique
- Electron neutrino contamination → SSQT
  (20% uncertainty in K_L production)

Beamline is different:

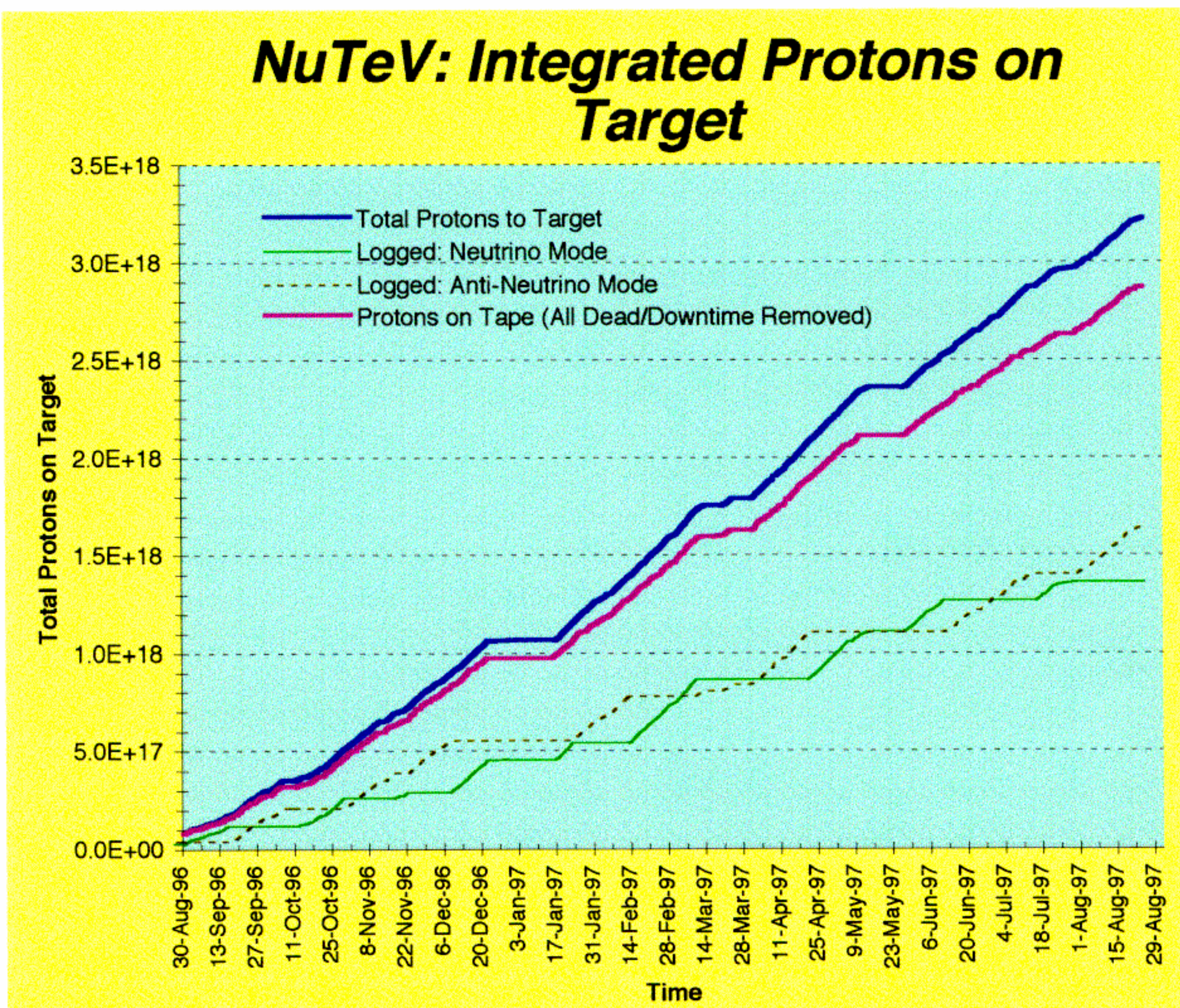
Beam	$\nu_\mu/\overline{\nu}_\mu$	Analyzed Neutrinos	$\langle E_\nu \rangle$	$\nu_e,\overline{\nu}_e$
CCFR QT	simultaneous	0.81M (mixed)	160 GeV	2.3%
NuTeV SSQT	separate	1.305M (ν), 0.299M ($\overline{\nu}$)	125 GeV	1.8%

Calibration using testbeam hadrons and muons:

- CCFR twice
- NuTeV continuous

How NuTeV Ran

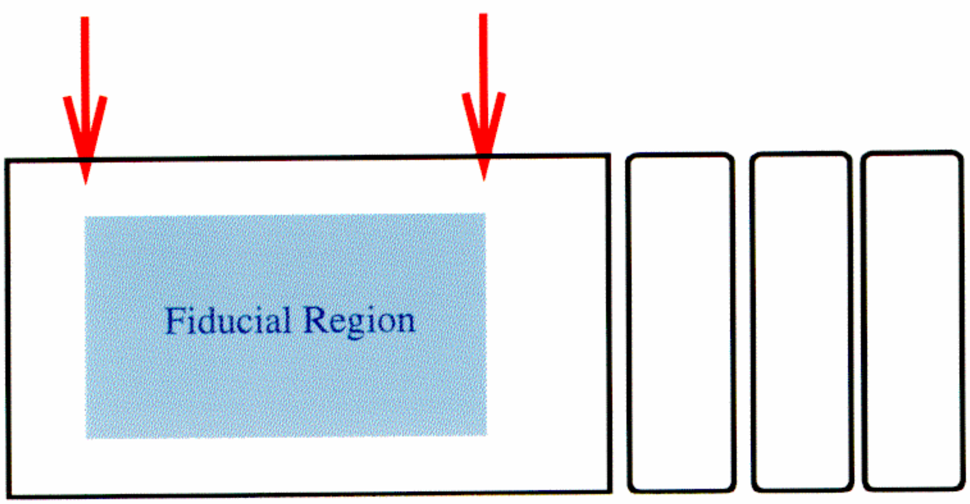
- 1996-1997 fixed target run
- Received total integrated proton intensity 3.22 x 10^{18}
- Overall data-taking efficiency of 89% → 2.86 x 10^{18} POT recorded



Event Selection

Analysis Cuts:

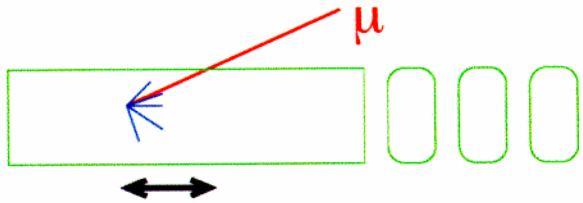
- Ehad> 20 GeV
  Ensures vertex-finding efficiency
  Reduces cosmic ray contamination
- Transverse interaction vertex in central 2/3 of detector
  Hadron shower and muon containment in calorimeter
  Reduces electron neutrino contamination
- Longitudinal interaction vertex restricted
  Ensures event is neutrino induced
  NC/CC discrimination



Final Sample:

- 1.3M νN events
- 0.3M $\bar{\nu} N$ events

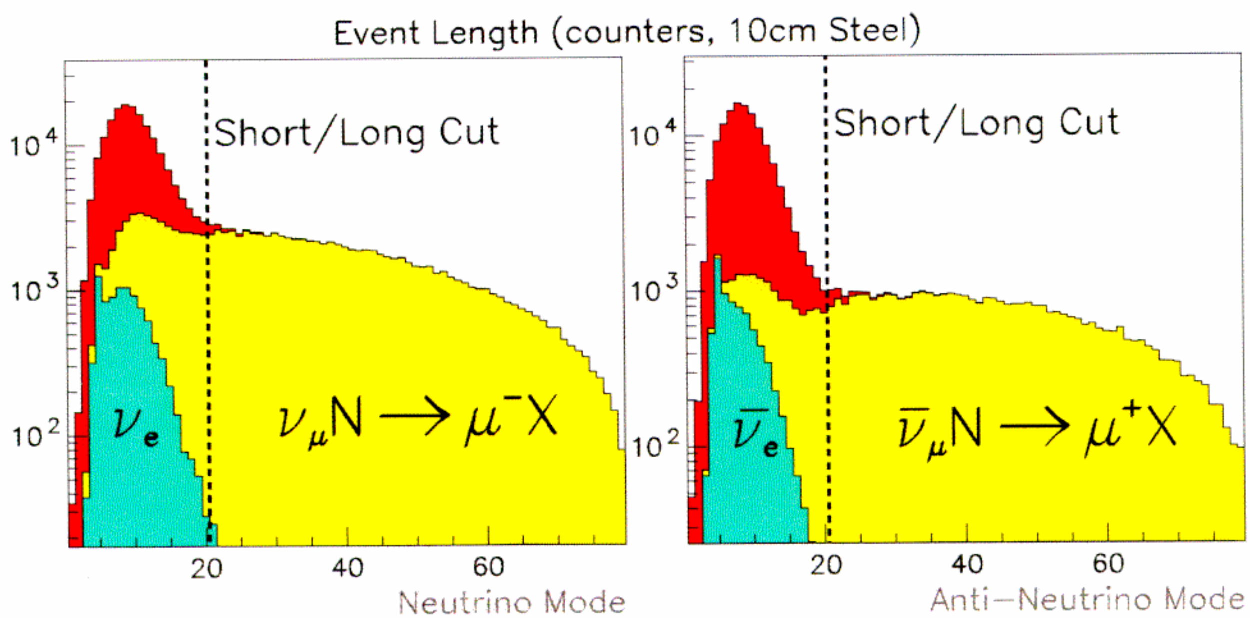
Event Contamination and Backgrounds



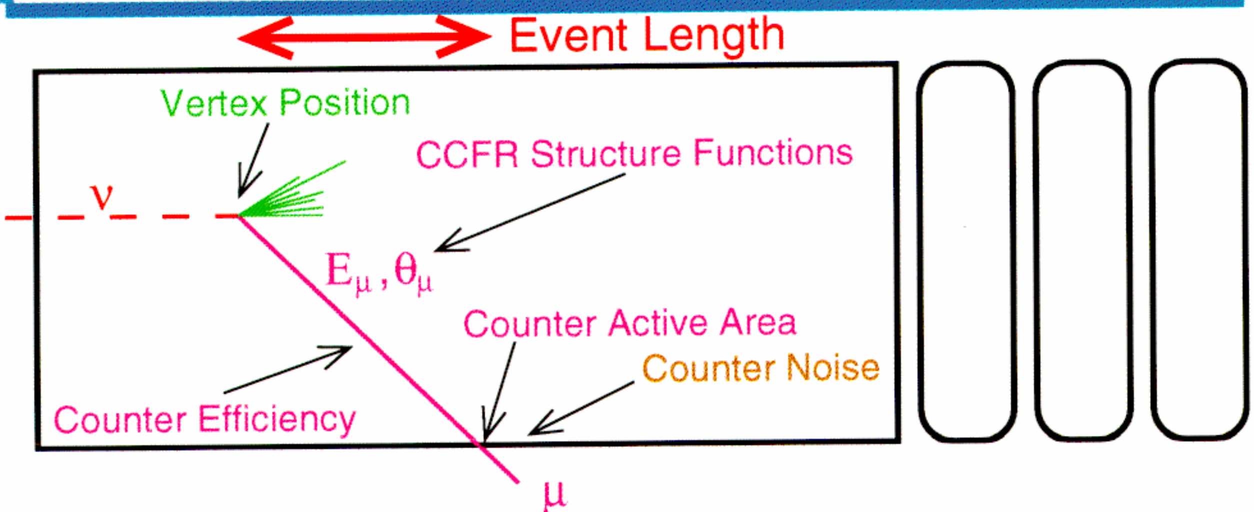
- SHORT ν_μ CC's (20%)
  muons that exit, range out
- SHORT ν_e CC's (5%)
  $\nu_e N \rightarrow eX$
- Cosmic rays (0.8%)

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

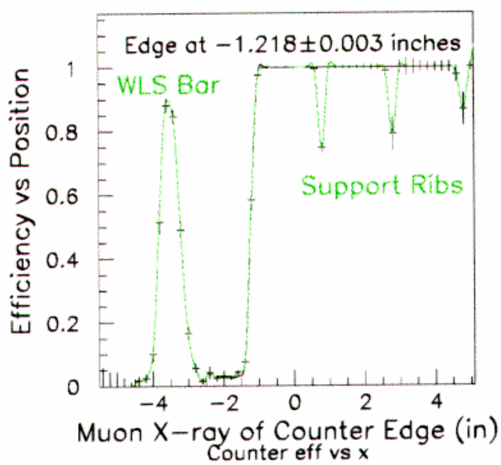
- LONG ν_μ NC's (0.3%)
- punch-through effects
- Hard μ bremsstrahlung (0.2%)



Detector Effects

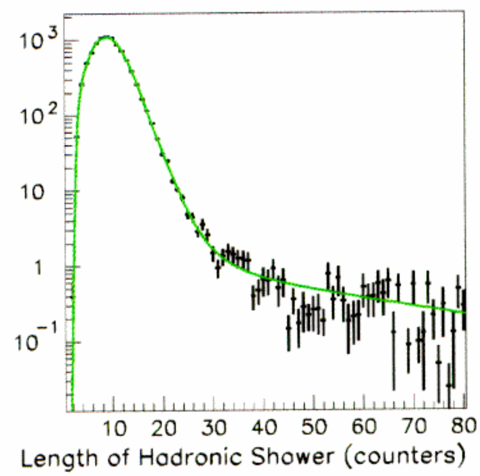


- Use ν data for muon measurements when possible

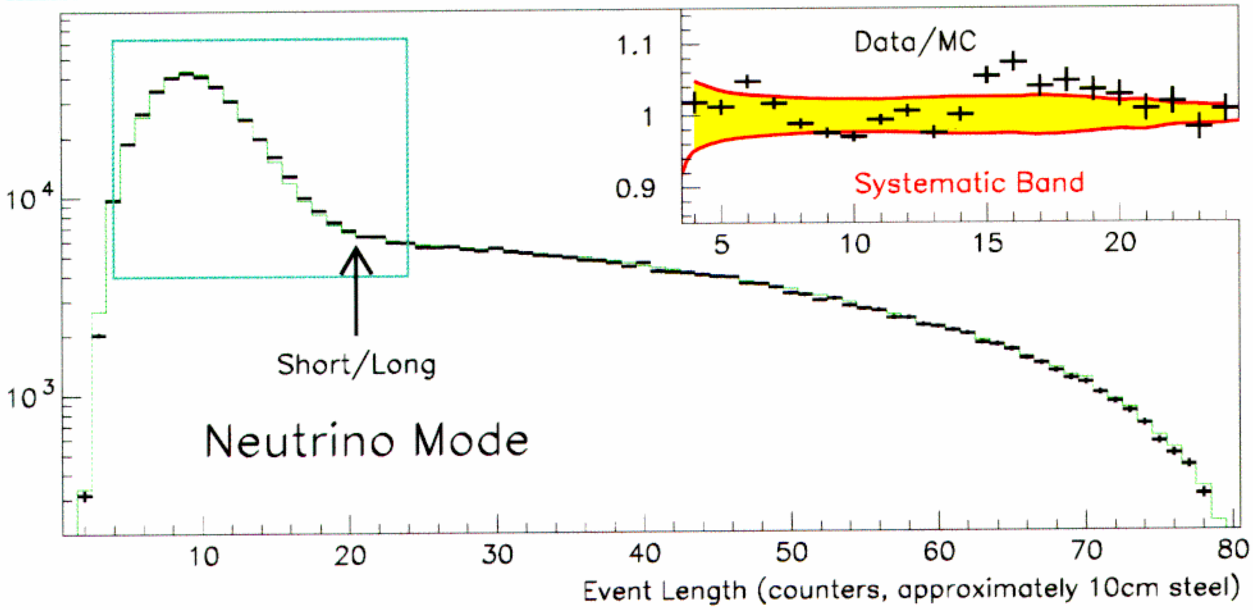


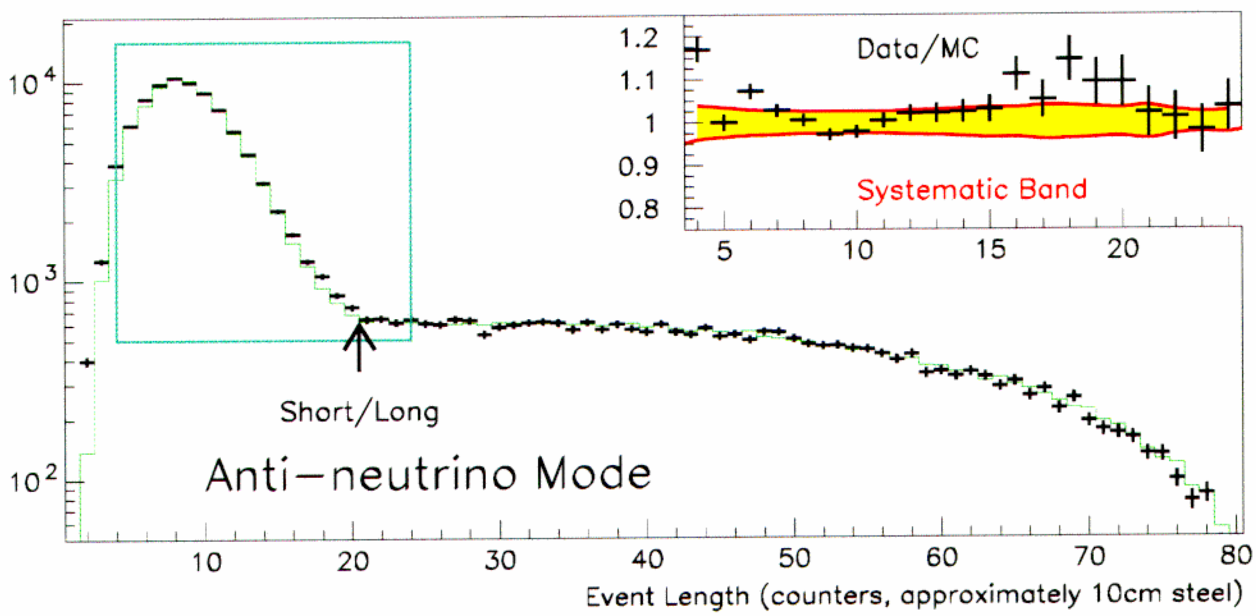
- Counter edges found with μ from ν and from testbeam
- Longitudinal ν vertex measured using $\mu^+\mu^-$ events
- μ energy deposited in counters comes from ν and μ data

- Hadron, μ testbeam data important also
- Hadronic shower length (neutral currents) from π, K in testbeam
- Energy scale, linearity and resolution measured from testbeam spectrometer



PRELIMINARY NuTeV Event Length Distributions



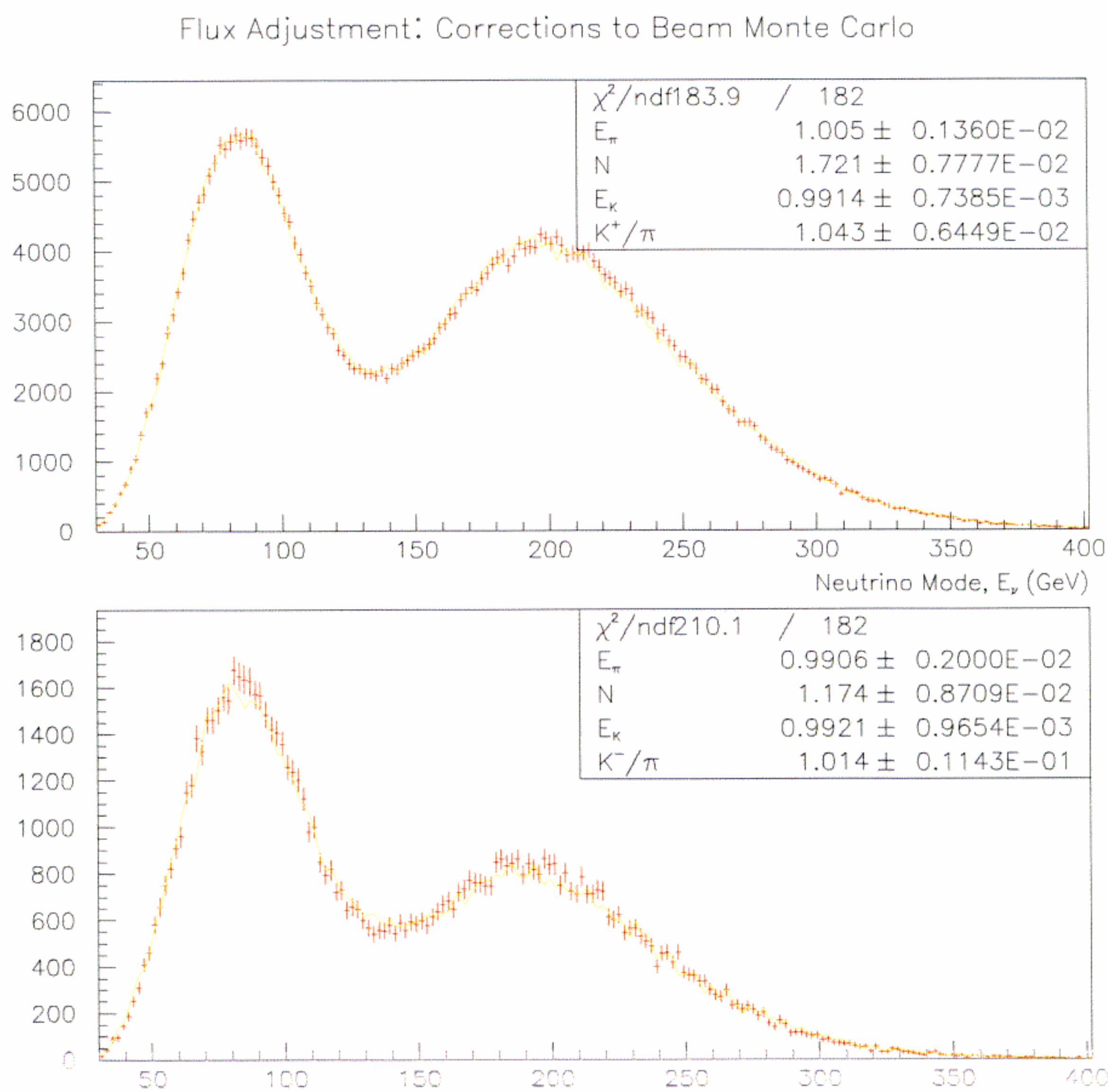


	Short (NC) Events	Long (CC) Events	$R_{20} \equiv$ Short/Long
ν	386K	919K	0.4198 ± 0.0008(stat)
$\overline{\nu}$	88.7K	210K	0.4215 ± 0.0017(stat)

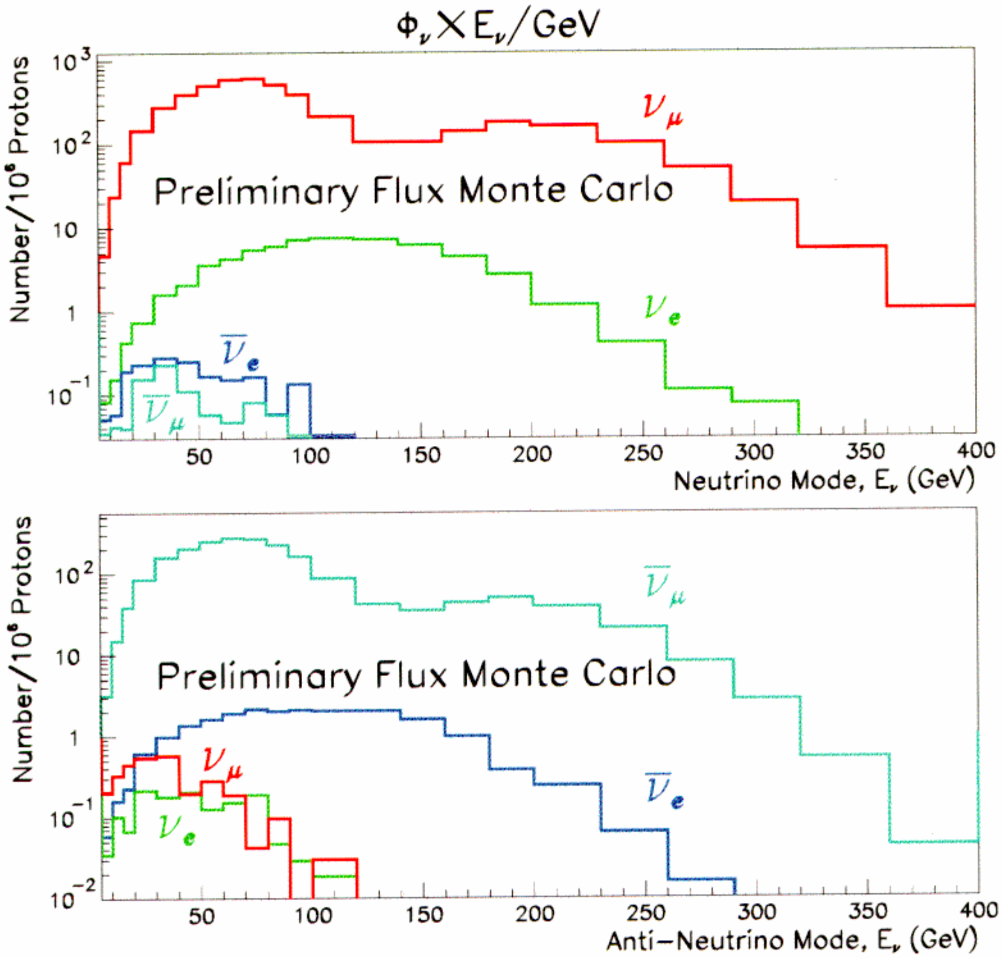
NuTeV Neutrino Flux

Tuning of Beam Monte Carlo

- Tune the observed ν_μ spectrum to match MC prediction
- Reflects small uncertainties in SSQT alignment and large production uncertainties
- Fit $\delta\langle E_\nu \rangle < 1\%$, K/π ratio +4% for ν, +1% for $\overline{\nu}$
- Tuning procedure is robust at 0.5% level
- $K^{\pm}_{e3}$ branching ratio (1.1%) dominates ν_e flux uncertainty!!!



PRELIMINARY NuTeV ν_e Flux



Sources of Neutrinos and Event Fractions

Source	ν Mode	$\overline{\nu}$ Mode
$\pi^{\pm}_{\mu 2}$	0.786	0.856
$K^{\pm}_{\mu 2,\mu 3}$	0.201	0.133
$K^{\pm}_{e3}$	0.0124 ± 0.00015	0.0081 ± 0.00012
K_{Le3}	0.00047 ± 0.00009	0.00153 ± 0.00030
$\mu \rightarrow \nu_e$	0.00020 ± 0.00004	0.00096 ± 0.00020
Charm Meson$\rightarrow \nu_e$	0.00021 ± 0.00004	0.00069 ± 0.00012
$\Lambda_c \rightarrow \nu_e$	0.00007 ± 0.00004	0.00022 ± 0.0001

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

$$R^- = \frac{\sigma^{\nu}_{NC} - \sigma^{\overline{\nu}}_{NC}}{\sigma^{\nu}_{CC} - \sigma^{\overline{\nu}}_{CC}} = \frac{R^{\nu} - rR^{\overline{\nu}}}{1-r}$$

where $R^{\nu/\overline{\nu}} = \sigma^{\nu/\overline{\nu}}_{NC}/\sigma^{\nu/\overline{\nu}}_{CC}$, and $r = \sigma^{\overline{\nu}}_{CC}/\sigma^{\nu}_{CC}$.

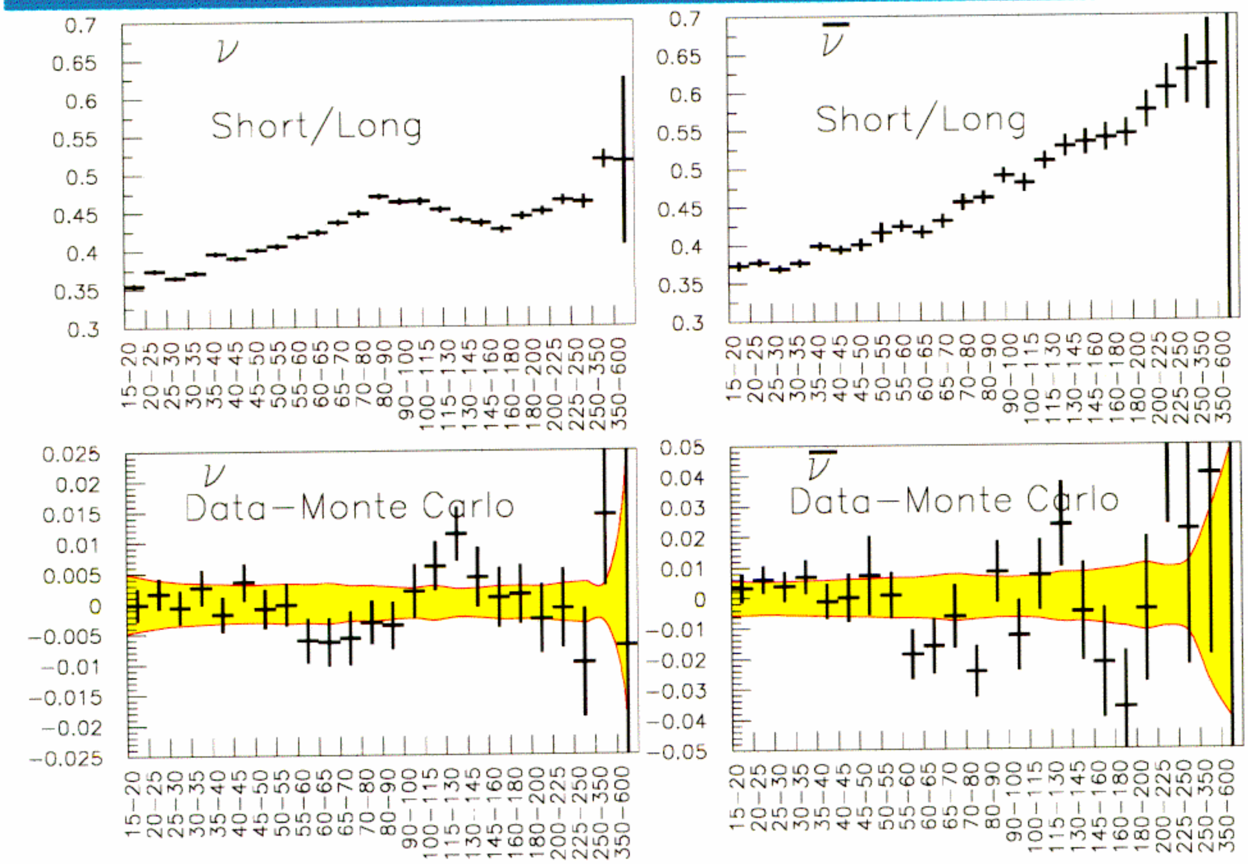
- One approach: subtract backgrounds and and calculate R^{ν}, $R^{\overline{\nu}}$, r explicitly to get R^-.
- NuTeV's approach: effectively use cross-section model and detector and beam Monte Carlo to predict x,

  such that pseudo $R^- = R^{\nu}_{20} - xR^{\overline{\nu}}_{20}$

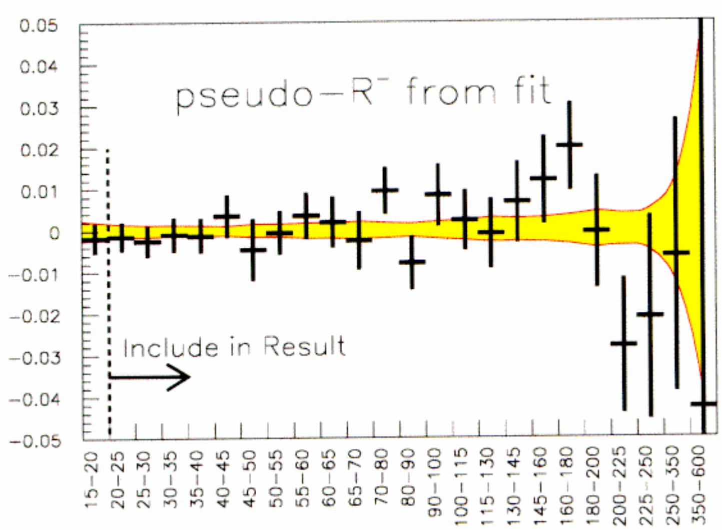
  is insensitive to charm production suppression (largest cross-section uncertainty).

  - ▷ In the prescription, sea contributions approximately cancel
  - ▷ Monte Carlo used to find pseudo R^- dependence on $\sin^2\theta_W$
  - ▷ $x \approx 0.514$, $d(pseudoR^-)/d\sin^2\theta_W \approx -0.636$

PRELIMINARY Short/Long Ratios



- Correlated structure as a function of E_{had} approximately covered by systematics in cross-section - χ^2/dof is 60/44 (stat only)



- R^- style subtraction removes correlated structure χ^2/dof is 12/22

PRELIMINARY NuTeV Uncertainties

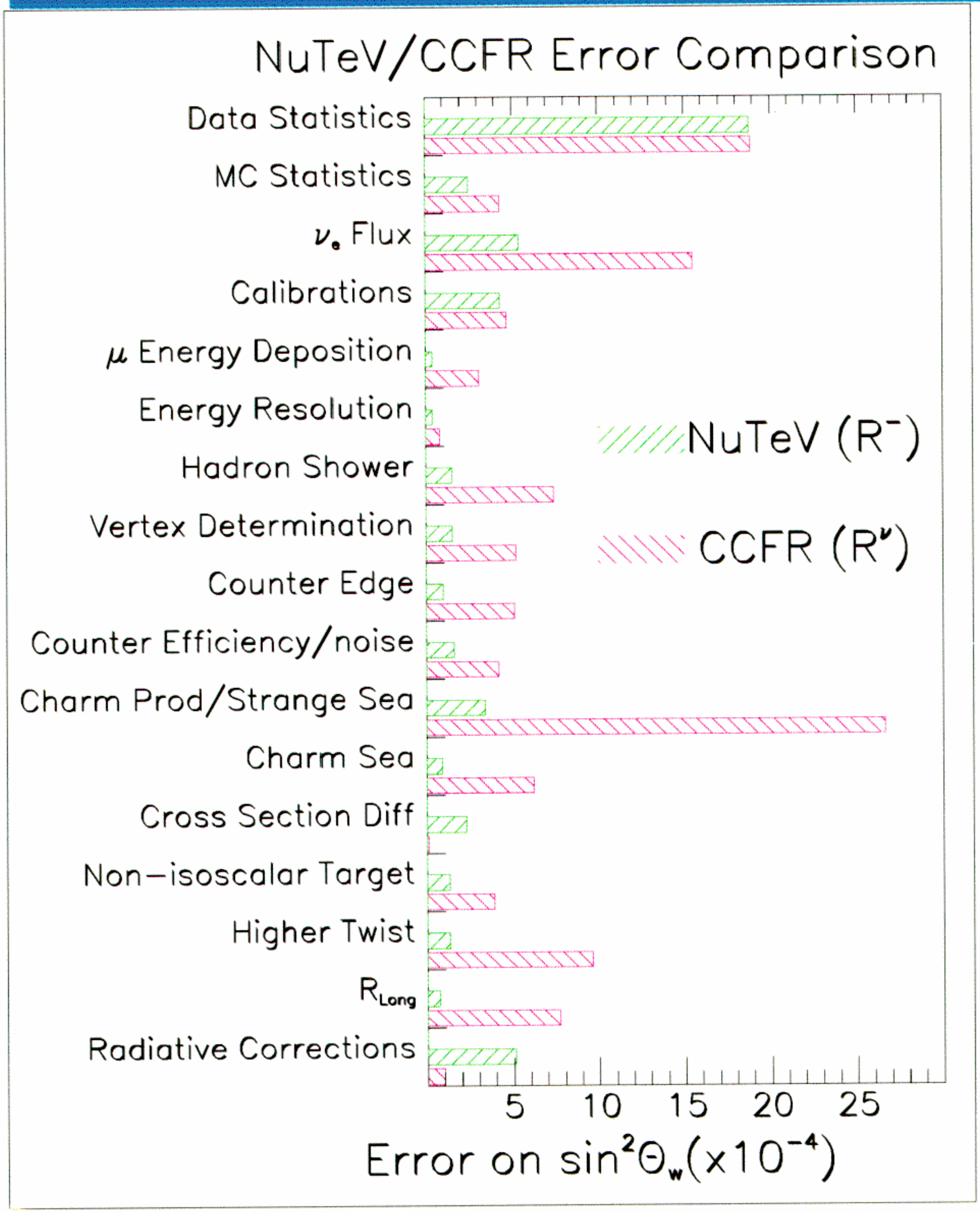
SOURCE OF UNCERTAINTY		$\delta \sin^2 \theta_W$
Statistics:	Data	0.00188
	Monte Carlo	0.00028
TOTAL STATISTICS		0.00190
$\nu_e/\overline{\nu}_e$ *Flux:*	$K^{\pm}$ (1.1%)	0.00024
	Other sources of ν_e's	0.00048
Energy Measurement:	Calibrations (0.5%)	0.00043
	Muon Energy Deposition (3%)	0.00004
	Energy Resolution	0.00004
Event Length:	Hadron Shower	0.00015
	Longitudinal Vertex Determination	0.00015
	Counter Edge Location	0.00010
	Counter Efficiency and Noise	0.00016
TOTAL EXP. SYST.		0.00075
Sea Quarks:	Strange Sea	0.00034
	V_{cd}	0.00004
	Charm Sea	0.00009
	Charm Mass	0.00009
Other $\nu/\overline{\nu}$ Cross-Section Differences:	$\sigma^{\nu}/\sigma^{\overline{\nu}}$	0.00023
	Non-Isoscalar Target	0.00013
	Radiative Corrections	0.00051
Non-QPM Cross-Section:	Higher Twist	0.00013
	Longitudinal Structure Function	0.00007
TOTAL PHYSICS MODEL		0.00070
TOTAL UNCERTAINTY		0.0022

1-Loop Electroweak Radiative Corrections

Calculation from Bardin, Dokuchaeva JINR-E2-86-260 (1986)

$$\delta \sin^2 \theta_W^{(\mathrm{on-shell})} = -0.00142 \times \left(\frac{{M_{\mathrm{top}}}^2 - (175\ \mathrm{GeV})^2)}{(100\ \mathrm{GeV})^2} \right)$$
$$+0.00048 \times \log_e \left(\frac{M_{\mathrm{Higgs}}}{150\ \mathrm{GeV}} \right).$$

PRELIMINARY NuTeV and CCFR Uncertainties



PRELIMINARY NuTeV $\sin^2\theta_W$

NuTeV measures:

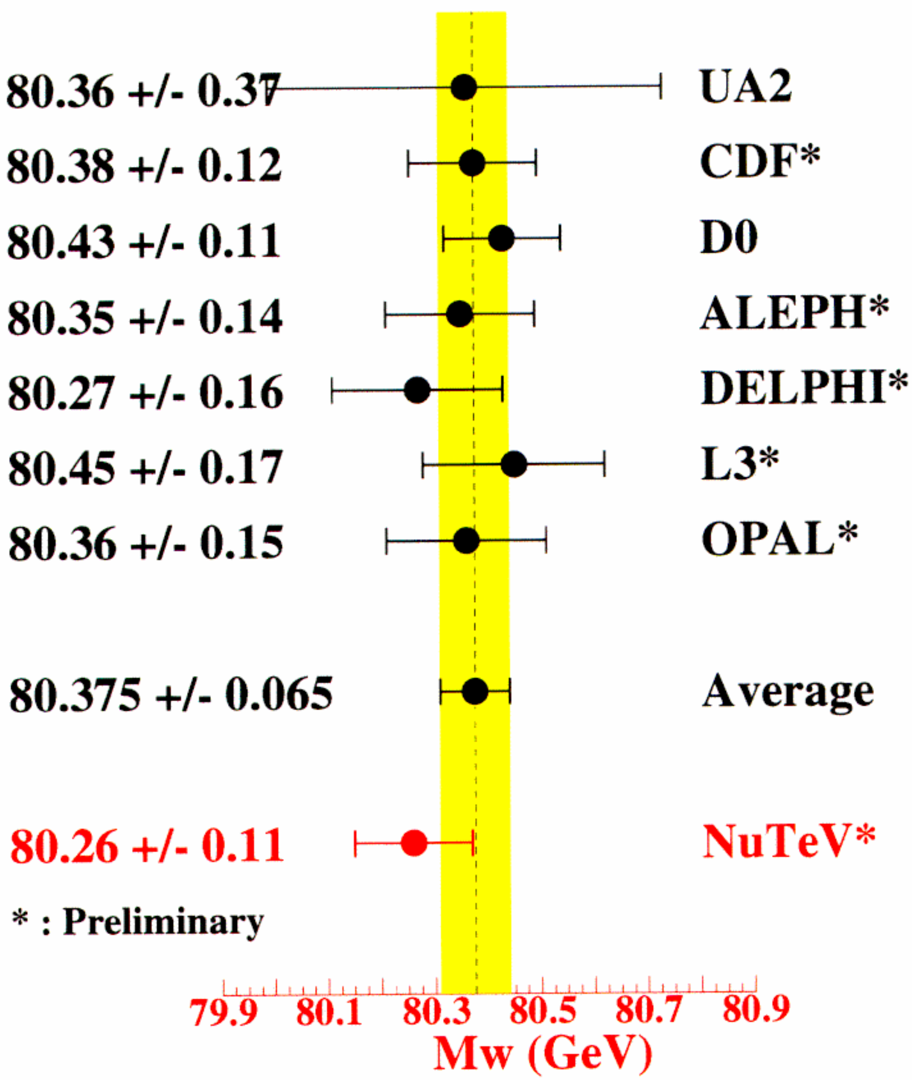
$$\sin^2\theta_W{}^{(\text{on-shell})} =$$
$$0.2253 \pm 0.0019(\text{stat}) \pm 0.0010(\text{syst})$$

- Result is twice as precise as best previous νN measurement (CCFR)
- This is a preliminary result and we are continuing to work on the analysis.

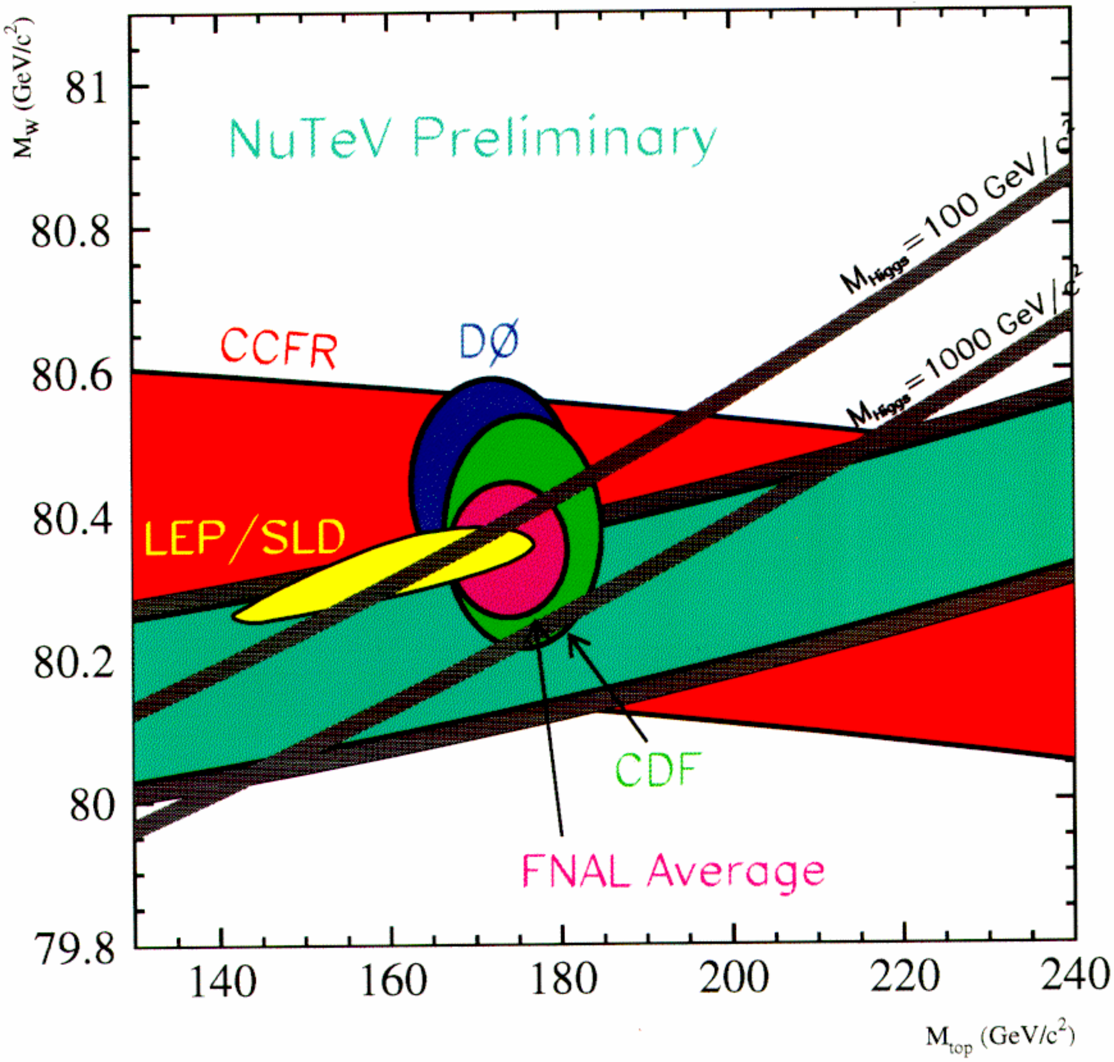
M_W

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

NuTeV *Preliminary*: $M_W = 80.26 \pm 0.11$ GeV



Fermilab M_{top} vs. M_W



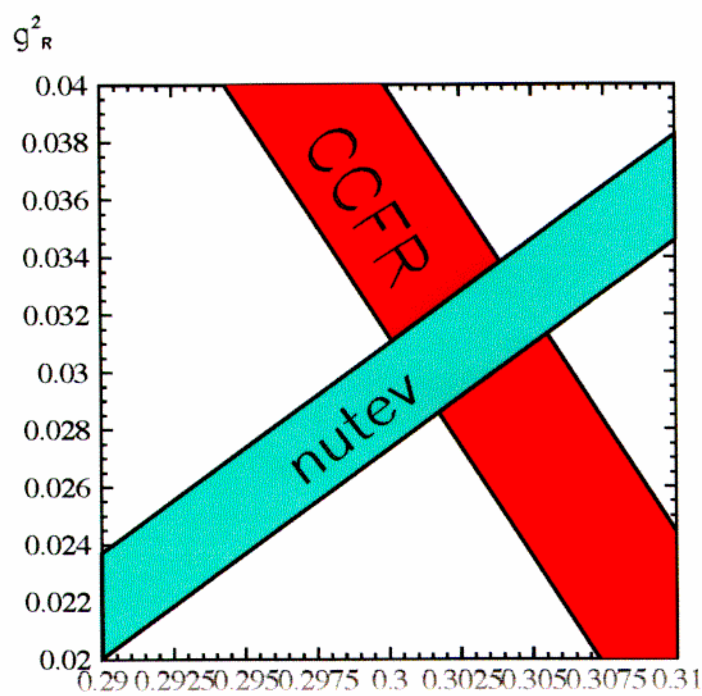
Model Independent Couplings

R^- expressed in terms of quark couplings

$$R^- = \frac{\sigma^{\nu}_{NC} - \sigma^{\overline{\nu}}_{NC}}{\sigma^{\nu}_{CC} - \sigma^{\overline{\nu}}_{CC}}$$
$$= \left(\frac{1}{2} - \sin^2\theta_W\right)$$
$$= u_L^2 + d_L^2 - u_R^2 - d_R^2$$

Couplings measured by NuTeV pseudo-R^-

$$0.4530 - \sin^2\theta_W =$$
$$0.2277 \pm 0.0022 \quad =$$
$$0.8587 u_L^2 + 0.8828 d_L^2 - 1.1657 u_R^2 - 1.2288 d_R^2$$



Conclusions

NuTeV Has Completed its Data-Taking Successfully

- 3×10^{18} 800 GeV Protons, June 1996-August 1997
- Preliminary results on Neutrino Oscillations, Neutral Heavy Leptons, Tridents ($\nu\gamma$ scattering)
- Expect results soon on Charm Production, Wrong-sign Muon
- A little later... Structure Functions and α_S

NuTeV Has Measured $\sin^2\theta_W$ from νN Scattering

$$\sin^2\theta_W{}^{(\text{on-shell})} = 0.2253 \pm 0.0019(\text{stat}) \pm 0.0010(\text{syst})$$

- NuTeV $\Rightarrow$ $M_W = 80.26 \pm 0.11$ GeV$/c^2$
  c.f.: Direct Average $M_W = 80.375 \pm 0.065$ GeV$/c^2$

Near Future for This Result

- Modest improvements in $\delta\sin^2\theta_W$
- Full NLO cross-section model; NuTeV charm production data
- Model-independent νq couplings
- Explore implications for new physics (Extra Z Bosons, Compositeness, Leptoquarks)