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

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- Introduction
- Past measurements
- Current Improvements
- What's so new about the results?
- Conclusions

NuTeV Collaboration

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Electroweak Threory

- Standard Model unifies Weak and EM to SU(2)xU(1) gauge theory
  - Weak neutral current interaction
  - Measured physical parameters related to mixing parameters for the couplings

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

- Neutrinos in this picture are unique because they only interact through left-handed weak interactions → Probe weak sector only
  - Less complication in some measurements, such as proton structure

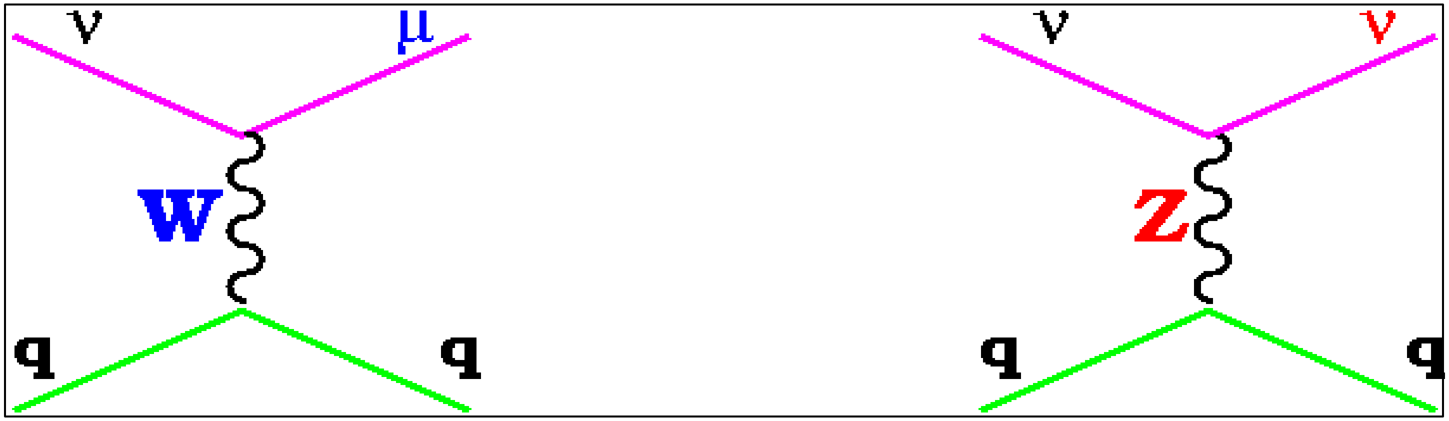
sin^{2}q$_W$ and n-N scattering

- In the electroweak sector of the Standard Model, it is not known *a priori* what the mixture of electrically neutral electomagnetic and weak mediator is➔ This fractional mixture is given by the mixing angle
- Within the on-shell renormalization scheme, sin$^2\theta_W$ is:

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

- Provides independent measurement of M$_W$ & information to pin down M$_{Higgs}$
- Comparable size of uncertainty to direct measurements
- Measures light quark couplings ➔ Sensitive to other types (anomalous) of couplings
- In other words, sensitive to physics beyond SM ➔ New vector bosons, compositeness,ν-oscillations, etc

How do we measure?



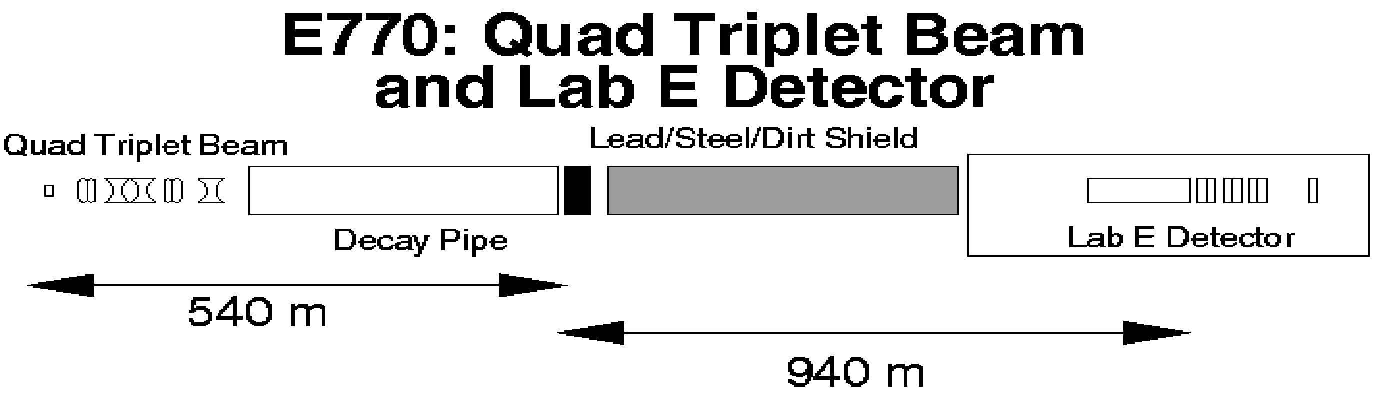
$$coupling \propto I^{(3)}_{weak} \qquad\qquad coupling \propto I^{(3)}_{weak} - Q_{EM}\sin^2\theta_W$$

- Cross section ratios between NC and CC proportional to $\sin^2\theta_W$
- Llewellyn Smith Formula:

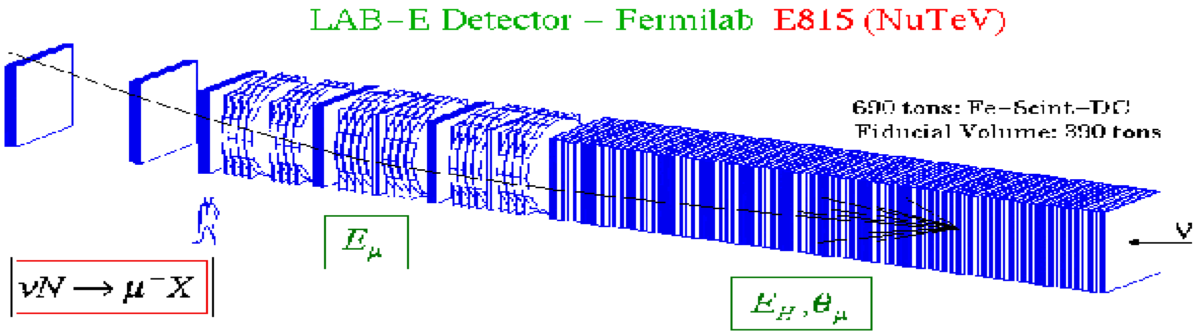
$$R^{\nu(\bar{\nu})} = \frac{\sigma^{\nu(\bar{\nu})}_{NC}}{\sigma^{\nu(\bar{\nu})}_{CC}} = \rho^2\left(\frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W\left(1 + \frac{\sigma^{\bar{\nu}(\nu)}_{CC}}{\sigma^{\nu(\bar{\nu})}_{CC}}\right)\right)$$

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

Previous Experiment



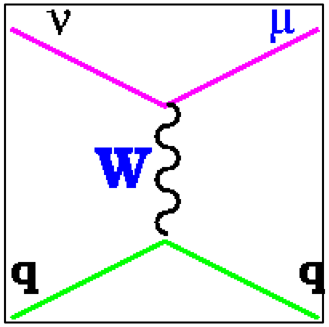
- Conventional neutrino beam from π/k decays
- Focus all signs of π/k for neutrinos and antineutrinos
- Only ν_μ in the beam (NC events are mixed)

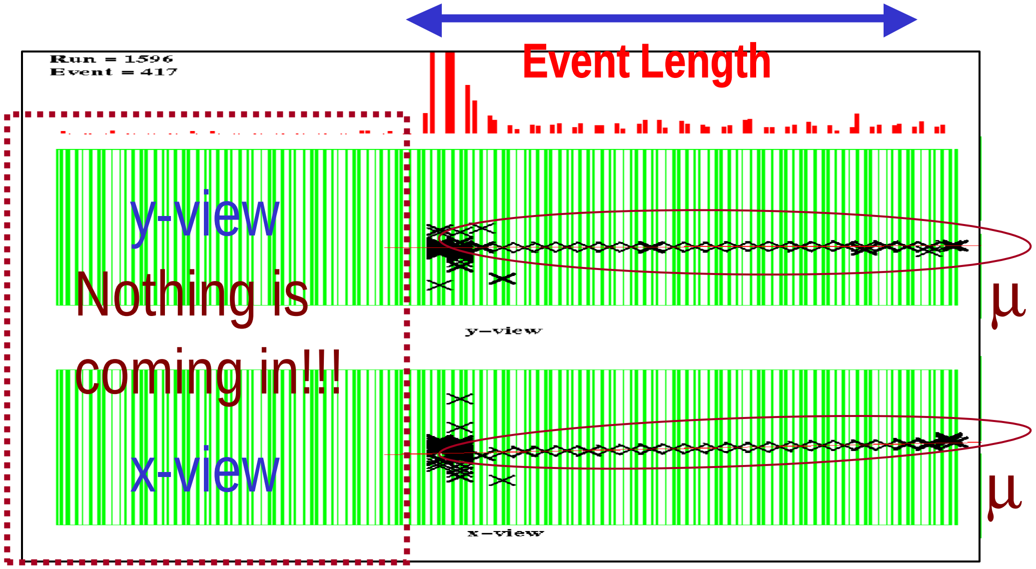


- Very small cross section ➔ Heavy neutrino target
- ν_e are the killers (CC events look the same as NC events)

How Do We Separate Events?

Charged Current Events





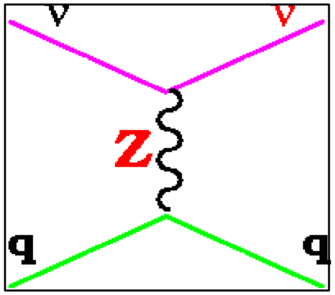
Event Length

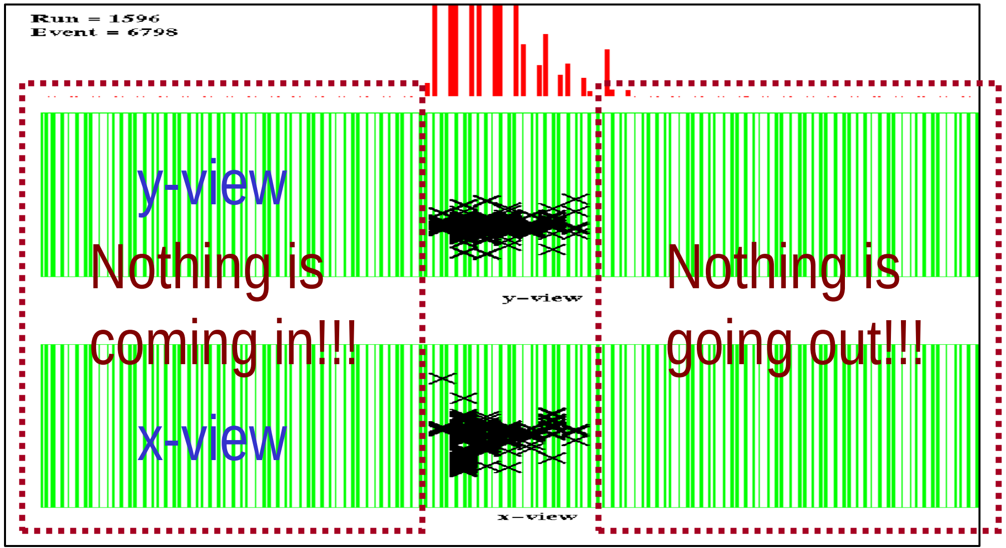
y-view

Nothing is coming in!!!

x-view

Neutral Current Events





y-view

Nothing is coming in!!!

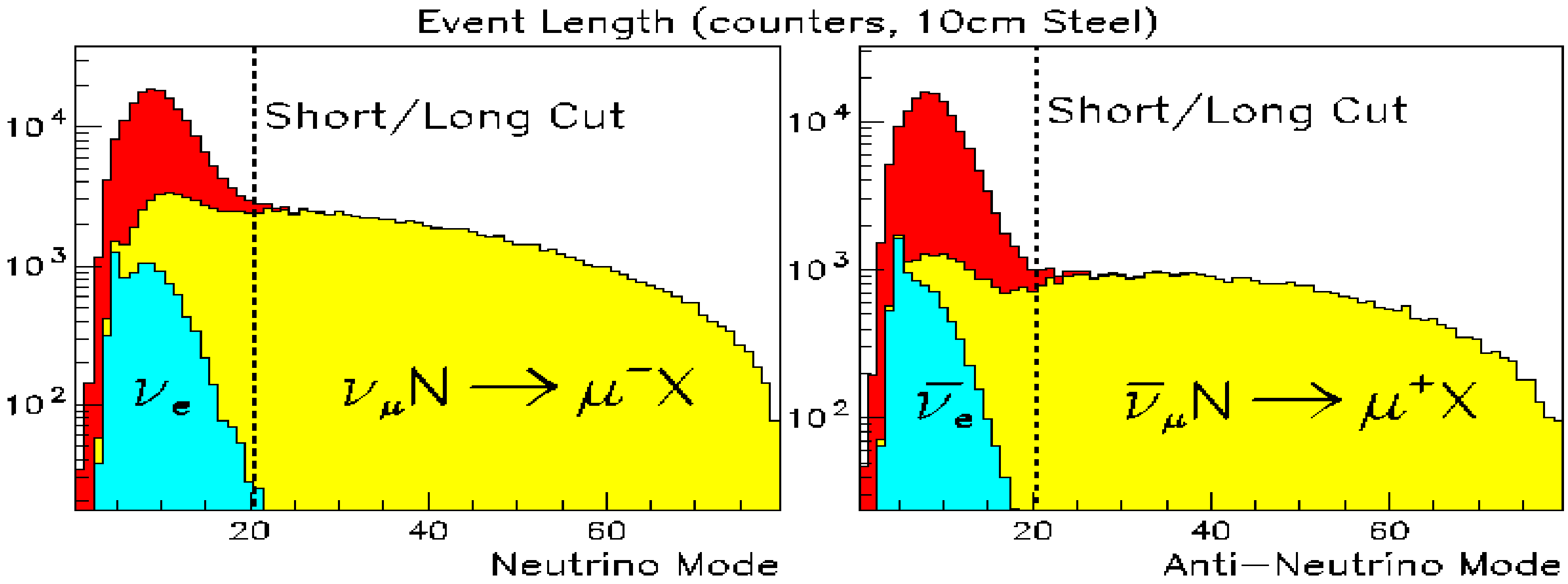
x-view

Nothing is going out!!!

Event Length

Define an Experimental Length variable

➔Distinguishes CC from NC experimentally in statistical manner



Compare experimentally measured ratio

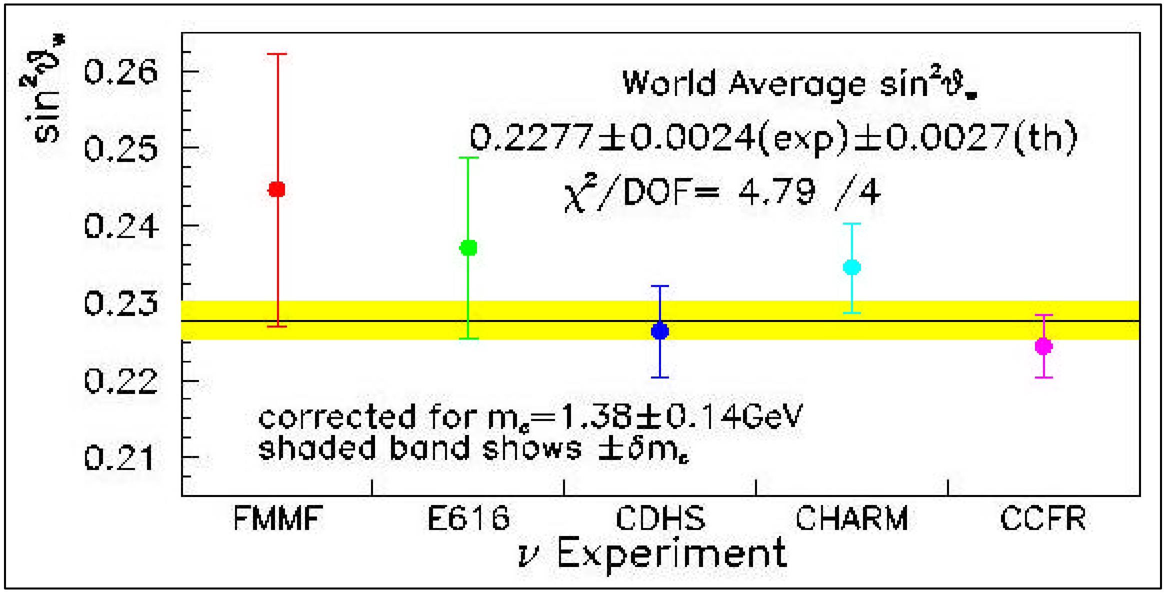
$$R_{Exp} = \frac{N_{Short}}{N_{Long}} = \frac{L < L_{Cut}}{L > L_{Cut}} = \frac{N_{NC\ \ Candidates}}{N_{CC\ \ Candidates}}$$

to theoretical prediction of R^{ν}

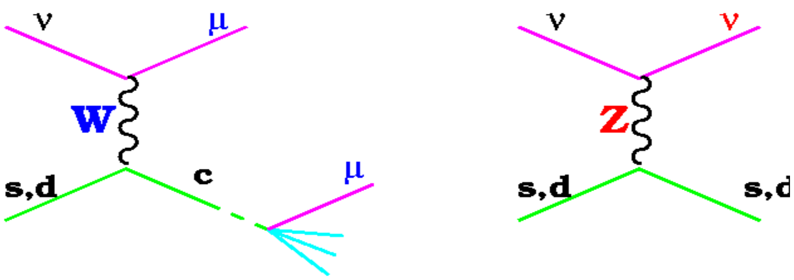
Past Experimental Results

$$\sin^2?_W^{\text{On-Shell}} = 1 - \frac{M_W}{M_Z} = 0.2277 \pm 0.0036$$

$$\Rightarrow M_W^{\text{On-Shell}} = 80.14 \pm 0.19\,\text{GeV}/c^2$$



- Significant correlated error from CC production of charm quark (m_c) modeled by slow rescaling, in addition to ν_e error



The NuTeV Experiment

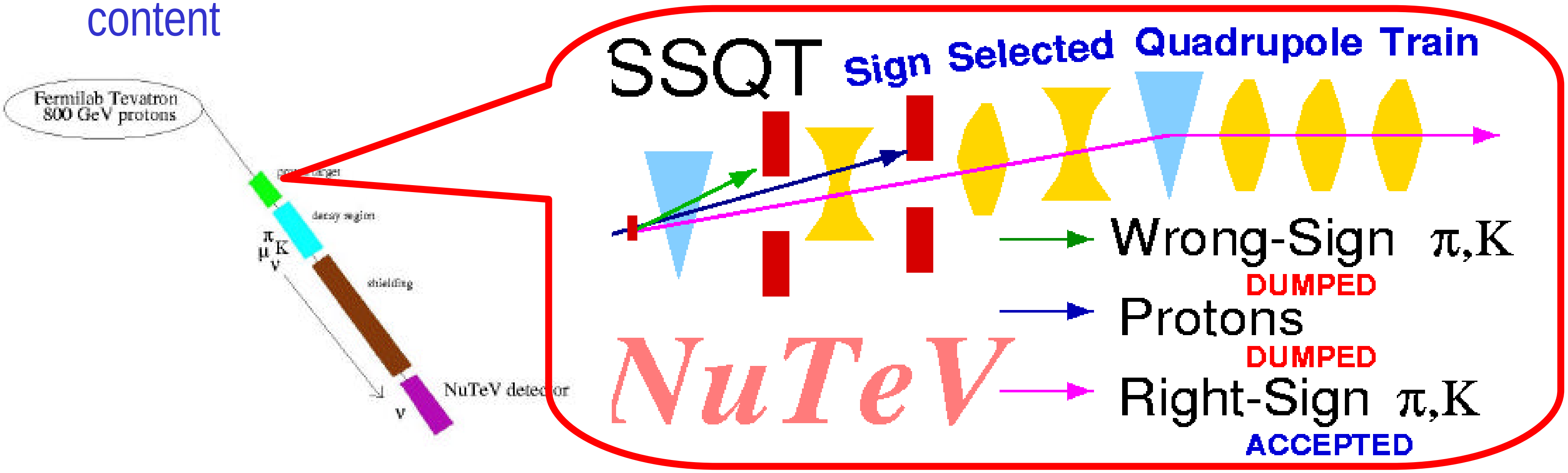
- Suggestion by Paschos-Wolfenstein formula by separating ν and $\bar{\nu}$ beams:

$$R^{-}=\frac{\sigma^{\nu}_{NC}-\sigma^{\bar{\nu}}_{NC}}{\sigma^{\nu}_{CC}-\sigma^{\bar{\nu}}_{CC}}=?^{2}\left(\frac{1}{2}-\sin^{2}?_{W}\right)=\frac{R^{\nu}-R^{\bar{\nu}}}{1-r}$$

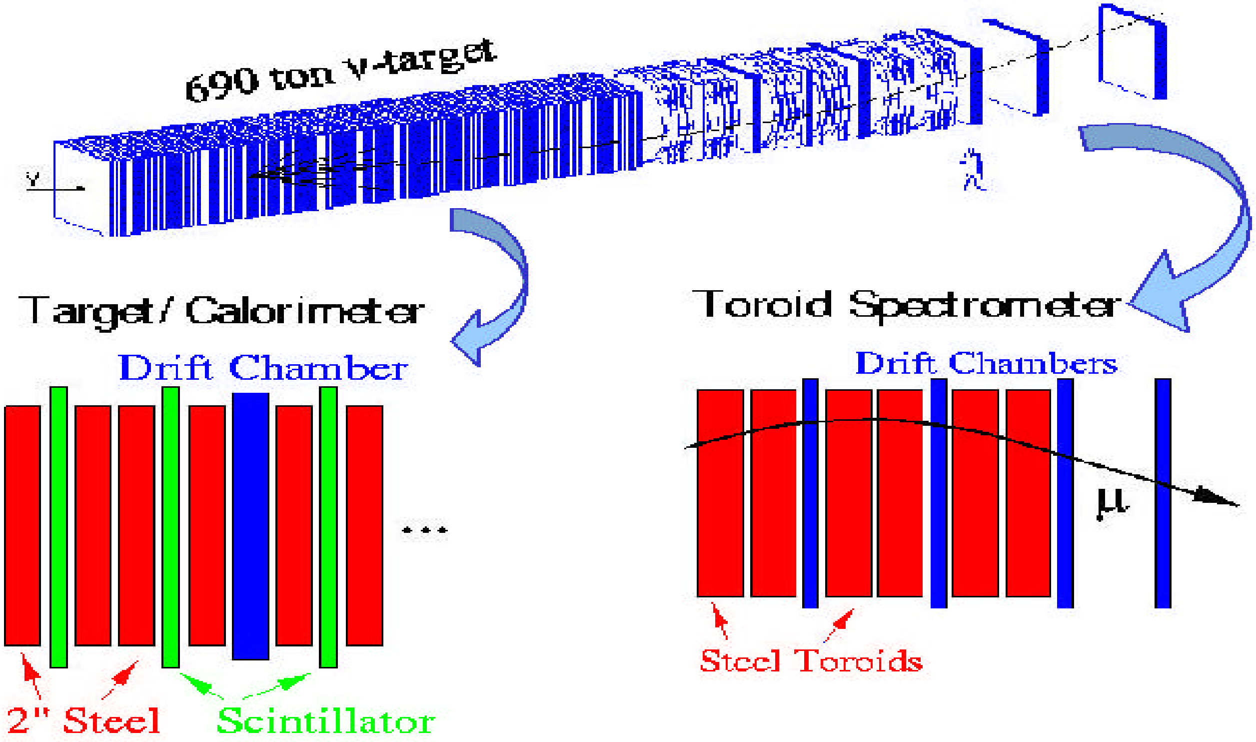
➔ Reduce charm CC production error by subtracting sea quark contributions

  - ➔Only valence u, d, and s contributes while sea quark contributions cancel out
  - ➔Massive quark production through Cabbio suppressed d_v quarks only

- Smarter beamline ➔ Removes all neutral secondaries to eliminate ν_e content



The NuTeV Detector



- Calorimeter
  - 168 FE plates & 690tons
  - 84 Liquid Scintillator
  - 42 Drift chambers interspersed

- Solid Iron Toroid
  - Measures Muon momentum $\Delta p/p \sim 10\%$

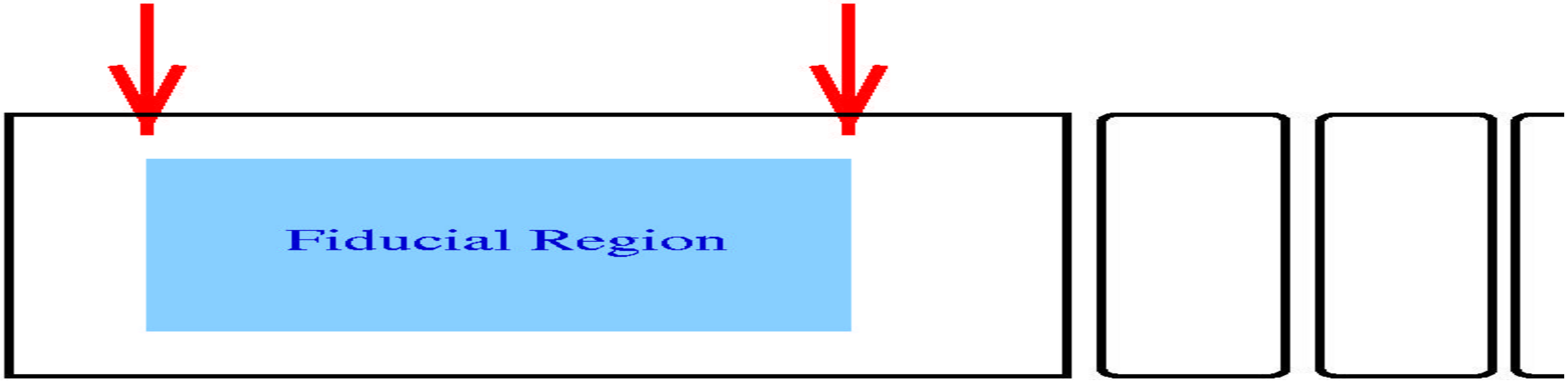
Continuous test beam for in-situ calibration

The NuTeV Detector

A picture from 1998. The detector has been dismantled to make room for other experiments, such as DØ

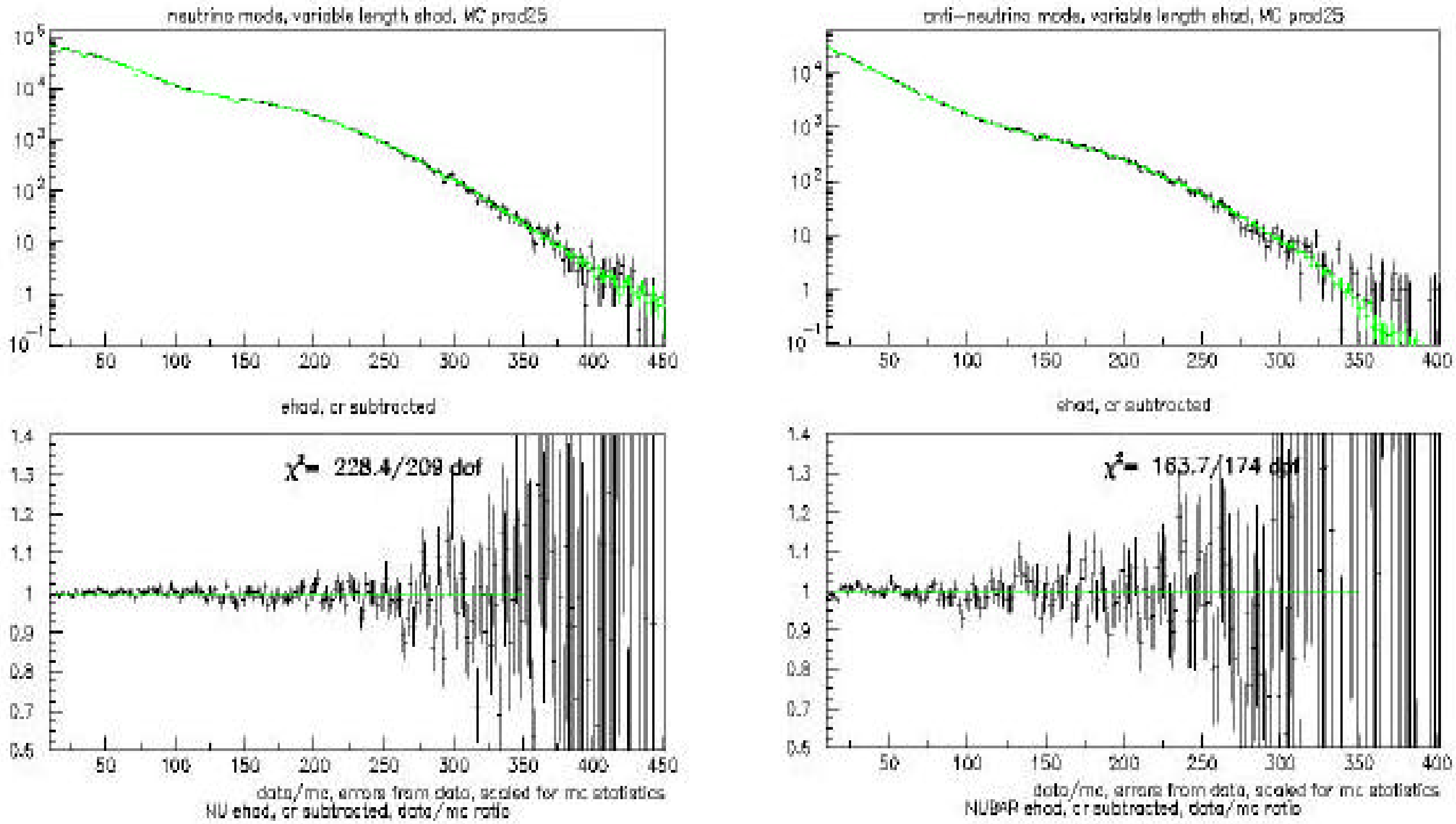
NuTeV Event Selection

- $E_{had} > 20$GeV
  - 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 containment
  - Further reduce ν_e contamination
- Longitudinal vertex, Z_{vert}, cut
  - To ensure neutrino induced interaction
  - Better discriminate CC and NC



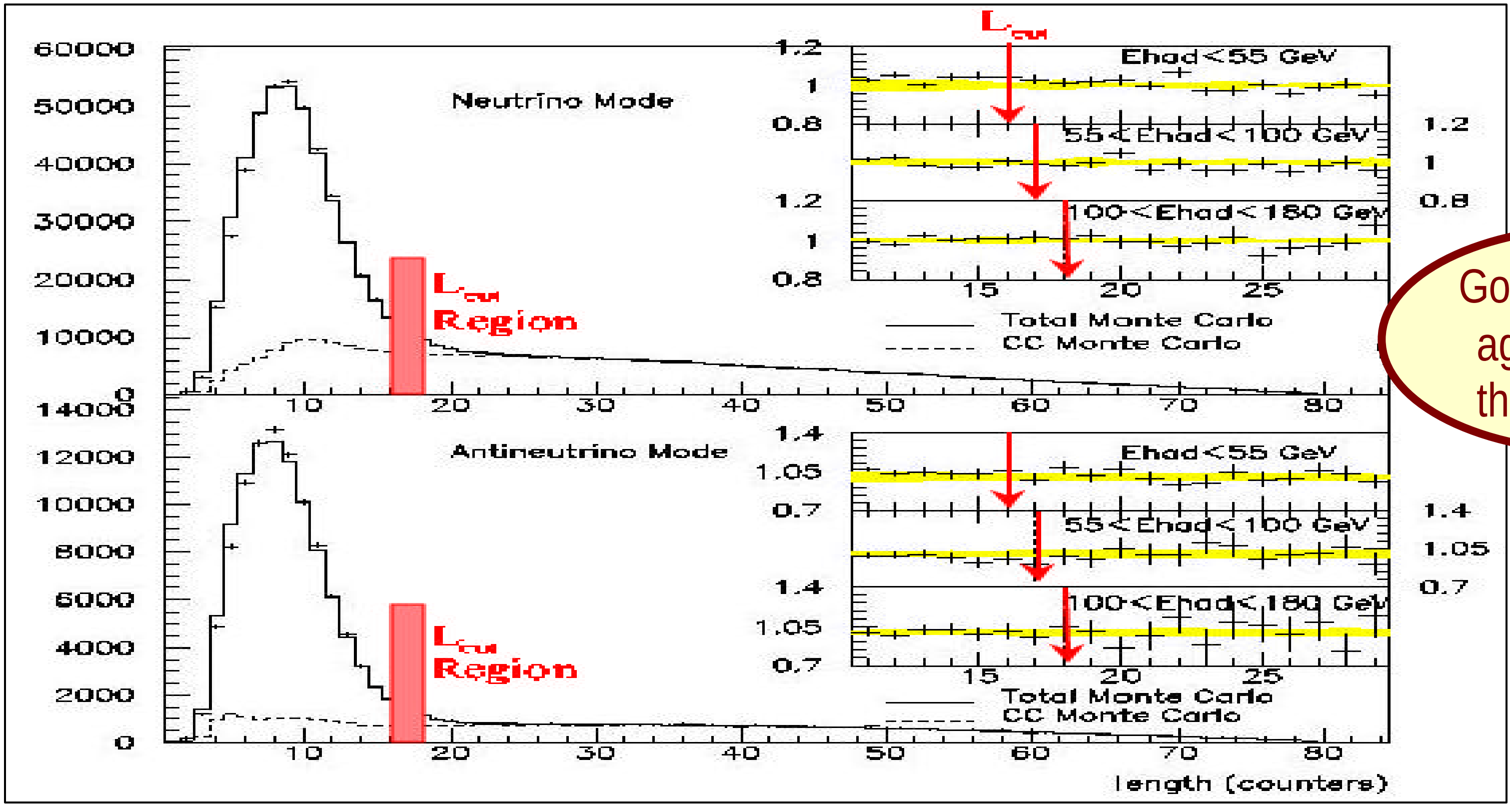
Events and Flux After Selection

Remaining number of events: 1.62M ν & 350k $\bar{\nu}$



NuTeV Event Length Distributions

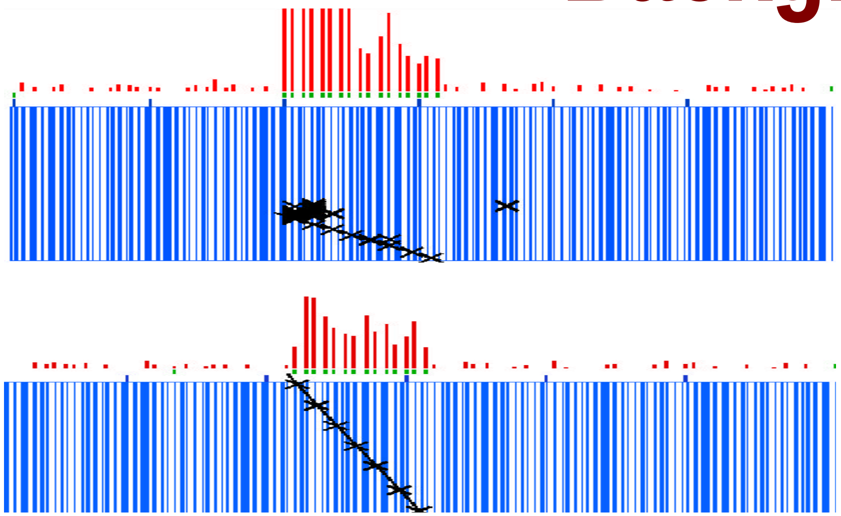
Energy Dependent Length cut implemented to improve statistics and reduce systematic uncertainties.



Good Data-MC agreement in the cut region

Mode	N_{short}	N_{long}	$R_\nu = N_{short}/N_{Long}$
n	457k	1167k	**0.3916 ± 0.0007(stat)**
$\bar{n}$	101k	250k	**0.4050 ± 0.0016(stat)**

Event Contamination and Backgrounds



- **SHORT** n_m **CC's (20%** n, 10% `n**)**

  μ exit and rangeout
- **SHORT** n_e **CC's (5%)**

  ν_eN→eX
- **Cosmic Rays (0.9%)**

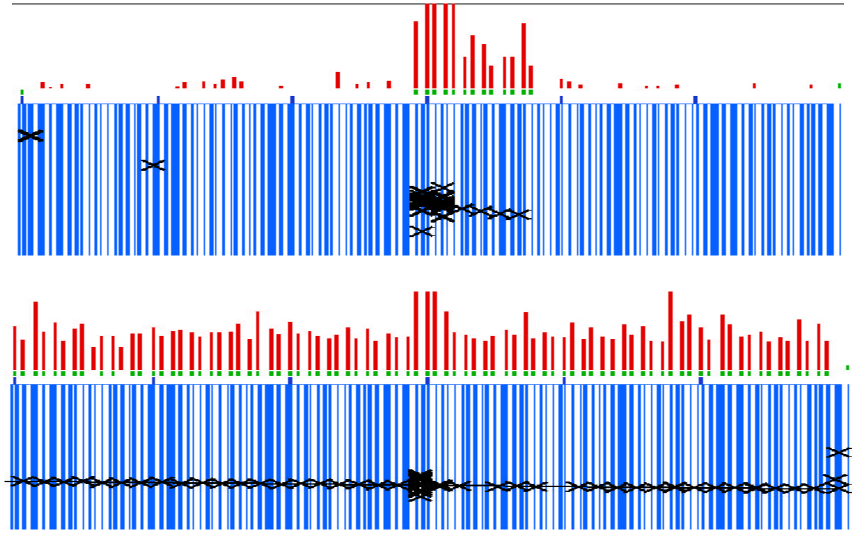
- **LONG** n_m **NC's (0.7%)**

  hadron shower

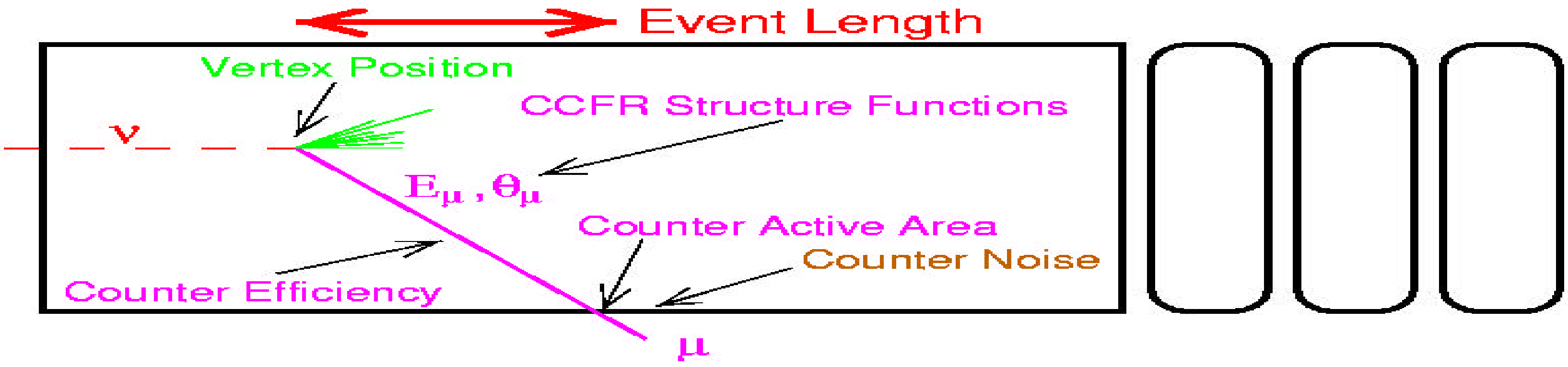
  punch-through effects

- **Hard** m **Brem(0.2%)**

  Deep μ events



Other Detector Effects

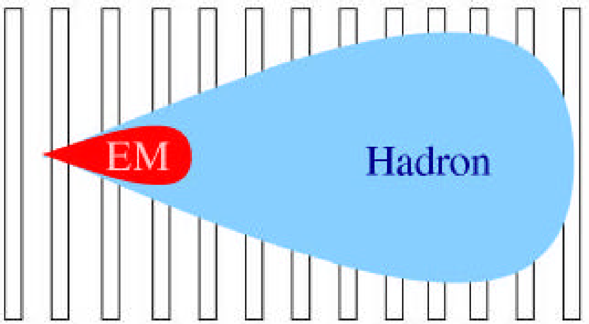


Sources of experimental uncertainties kept small, through modeling using n and TB data

Effect	Size(dsin^{2}q$_W$)	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

Measurements of n_e Flux

- Neutrino events in anti-neutrino running constraint charm and K_L induced production (K_{e3}) in the medium energy range ($80<E_\nu<180$GeV)
- Shower Shape Analysis can provide direct measurement ν_e events, though less precise



N_{meas}/N_{MC}

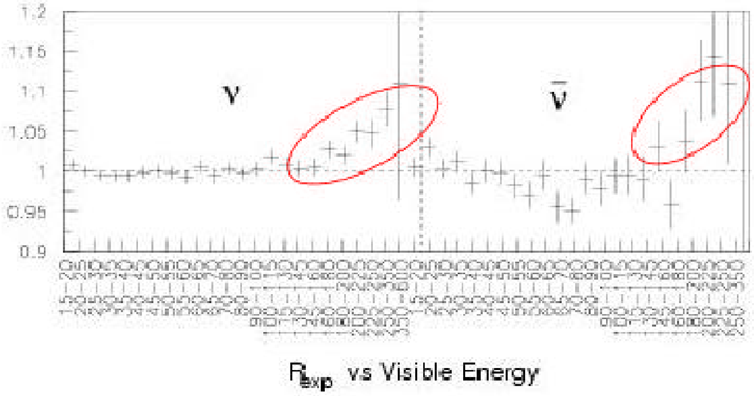
$$1.05 \pm 0.03\ (n_e)$$

$$1.01 \pm 0.04\ (\bar{n}_e)$$

Weighted average used for ν_e ➔ $\delta R_\nu^{exp}\sim 0.0005$

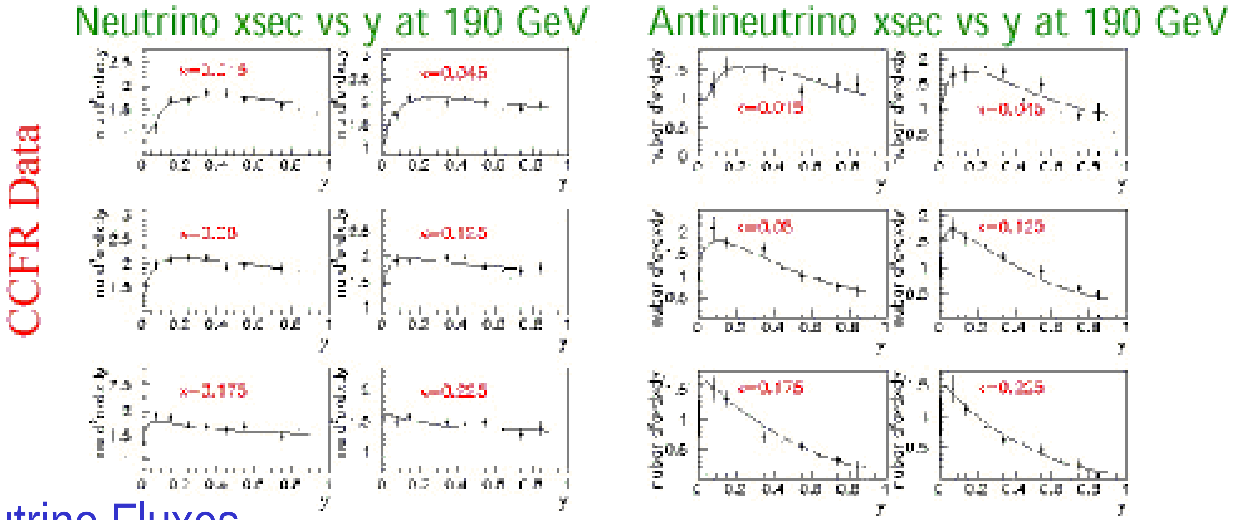
- ν_e from very short events ($E_\nu>180$ GeV)
  - Precise measurement of ν_e flux in the tail region of flux ➔ ~35% more $\bar{\nu}_e$ in $\bar{\nu}$ than predicted
  - Had to require ($E_{had}<180$ GeV) due to ADC saturation

Results in $\sin^2\theta_W$ shifts by +0.002

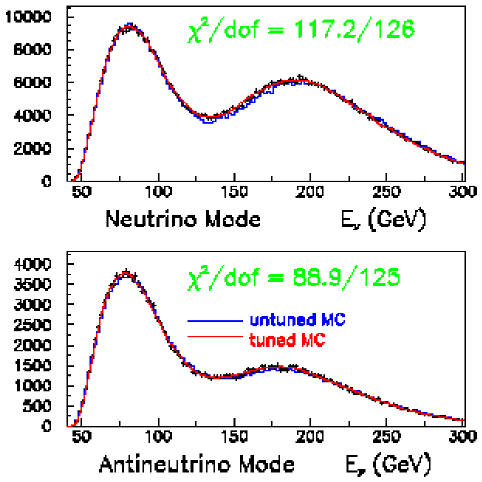


MC to Relate R_n^{exp} to R^n and $\sin^2\theta_W$

- Parton Distribution Model
    - Correct for details of PDF model ➔ Used CCFR data for PDF
    - Model cross over from short ν_μ CC events

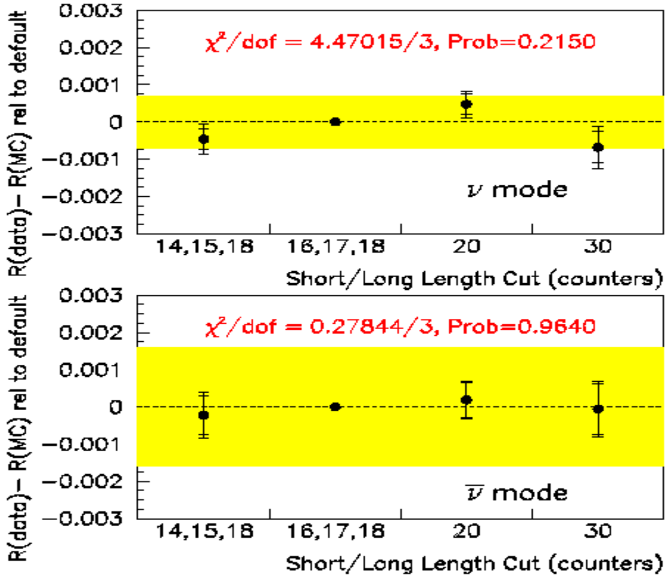


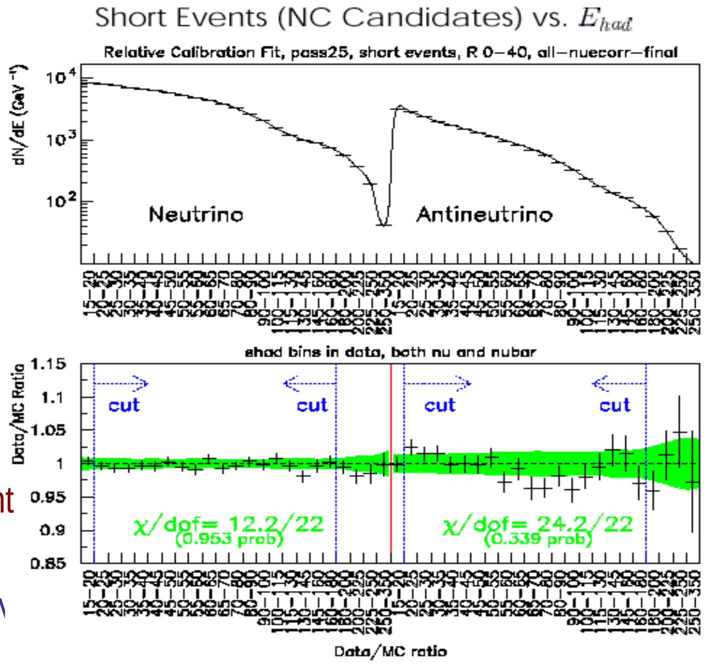
- Neutrino Fluxes
    - $\nu_\mu, \nu_e, \bar{\nu}_\mu, \bar{\nu}_e$ in the two running modes
    - ν_e CC events always look short
- Shower length modeling
    - Correct for short events that look long
- Detector response vs energy, position, and time
    - Continuous testbeam running minimizes systematics



R_n^{exp} Stability Check

- Crucial to verify the R_ν^{exp} comparison to MC is consistent under changes in cuts and event variables
  - Longitudinal vertex ➔ Detector uniformity
  - Length cut ➔ Check CC to NC cross over
  - Transverse vertex ➔ NC background at the detector edge
  - Visible energy (E_{Had})➔Checks detector energy scale and other factors





Green bands represent 1σ uncertainty.

$\sin^2\theta_W$ Fit to R_ν^{exp} and $R_{\bar\nu}^{exp}$

- Thanks to the separate beam ➔ Measure R^ν's separately
- Use MC to simultaneously fit R_ν^{exp} and $R_{\bar\nu}^{exp}$ to $\sin^2\theta_W$ and m_c, and $\sin^2\theta_W$ and ρ

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

- R^ν Sensitive to $\sin^2\theta_W$ while $R^{\bar\nu}$ isn't, so R^ν is used to extract $\sin^2\theta_W$ and $R^{\bar\nu}$ to control systematics
- Single parameter fit, using SM values for EW parameters ($\rho_0=1$)

$$\sin^2\theta_W = 0.2277 \pm 0.0013\ (\mathrm{stat}) \pm 0.0009\ (\mathrm{syst})$$

$$m_c = 1.32 \pm 0.09\,(\mathrm{stat}) \pm 0.06\,(\mathrm{syst})\ \mathrm{w/}\ m_c = 1.38 \pm 0.14\ \mathrm{GeV/c^2}\ \mathrm{as\ input}$$

- Two parameter fit for $\sin^2\theta_W$ and ρ_0 yields

$$\sin^2\theta_W = 0.2265 \pm 0.0031$$

$$\rho_0 = 0.9983 \pm 0.040$$

Syst. Error dominated since we cannot take advantage of sea quark cancellation

NuTeV $\sin^2\theta_W$ Uncertainties

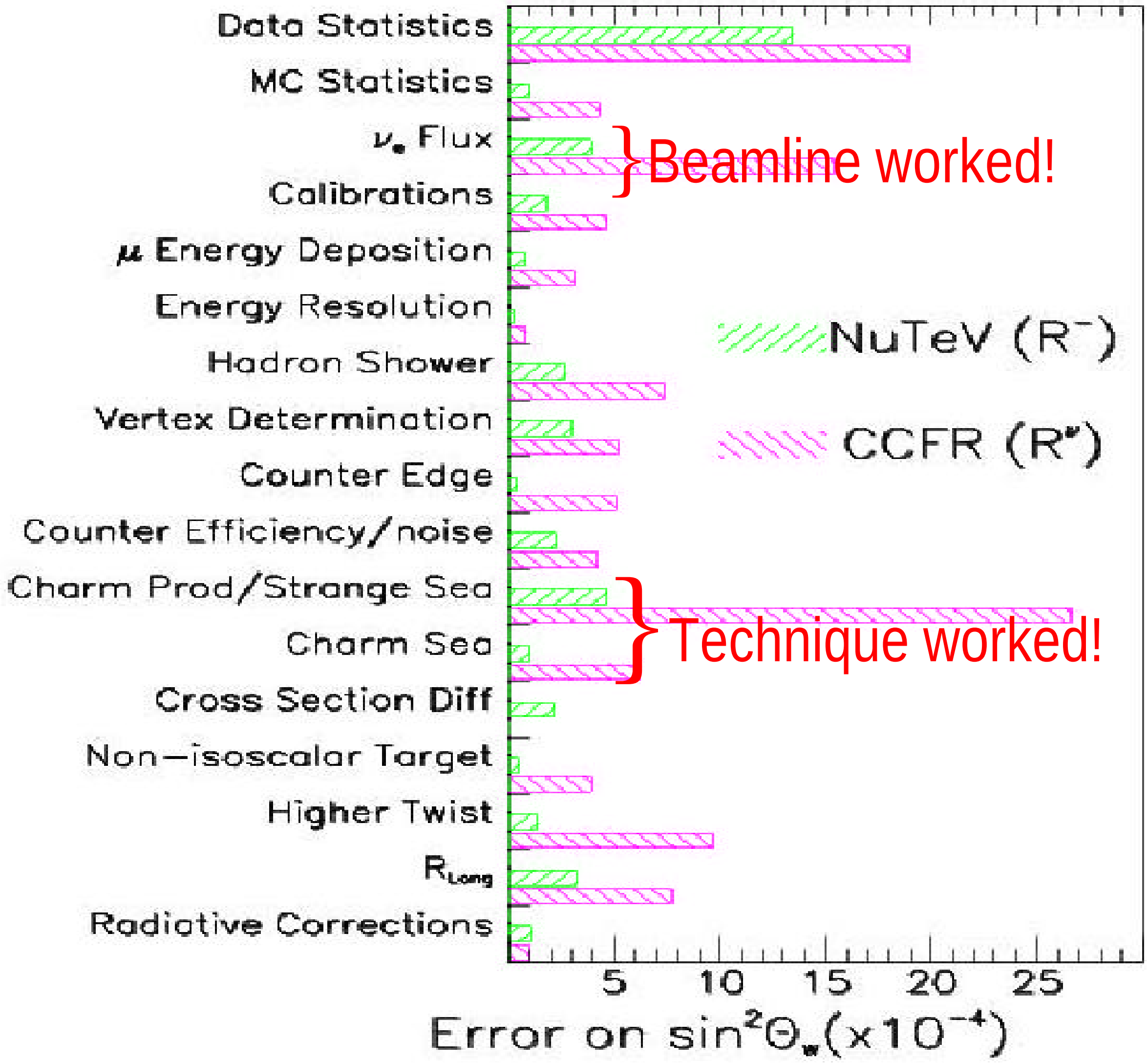
Source of Uncertainty	$\delta \sin^2\theta_W$
Statistical	**0.00135**
ν_e flux	0.00039
Event Length	0.00046
Energy Measurements	0.00018
Total Experimental Systematics	**0.00063**
CC Charm production, sea quarks	0.00047
Higher Twist	0.00014
Non-isoscalar target	0.00005
$s^{\bar{\nu}}/s^{\nu}$	0.00022
RadiativeCorrection	0.00011
R_L	0.00032
Total Physics Model Systmatics	**0.00064**
Total Systematic Uncertainty	**0.00162**
ΔM_W (GeV/c^2)	**0.08**

Dominant uncertainty

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

$$d\sin^2\theta_W^{(On-shell)} = -0.00022 \times \left(\frac{M_t^2 - (175\,GeV)^2}{(50\,GeV)^2} \right) + 0.00032 \times \ln\left(\frac{M_H}{150\,GeV} \right)$$

NuTeV vs CCFR Uncertainty Comparisons



}Beamline worked!

}Technique worked!

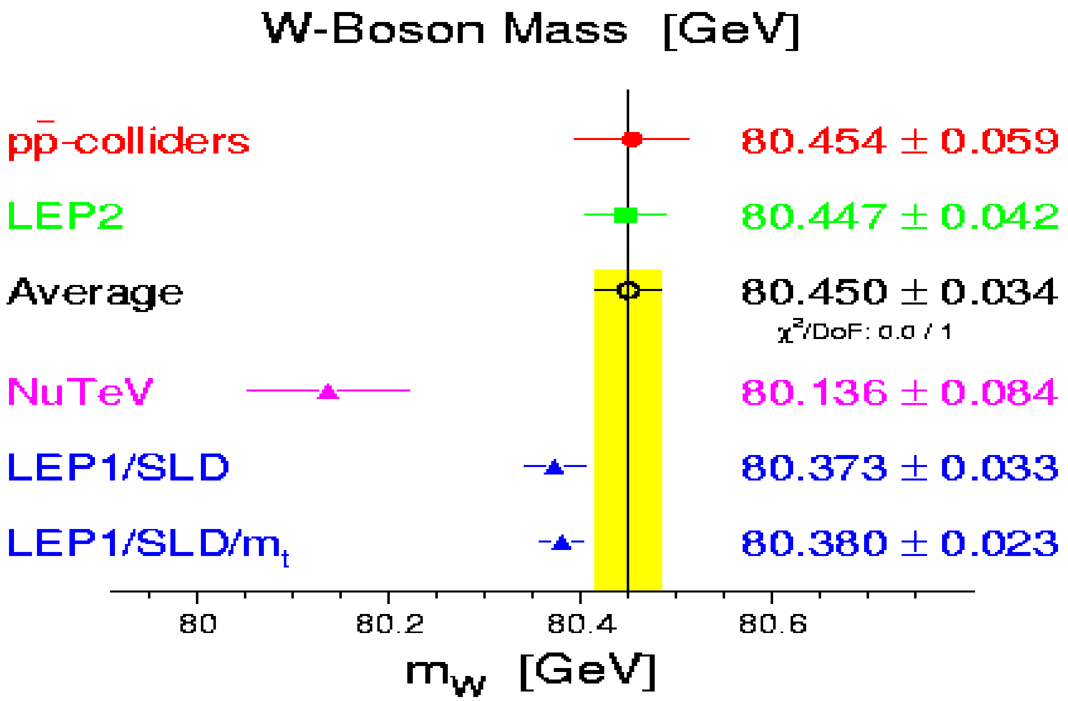
The NuTeV sin^{2}q$_W$

$$\sin^2 ?_W^{On-Shell} = 0.2277 \pm 0.0013 \;(stat) \pm 0.0009 \;(syst)$$

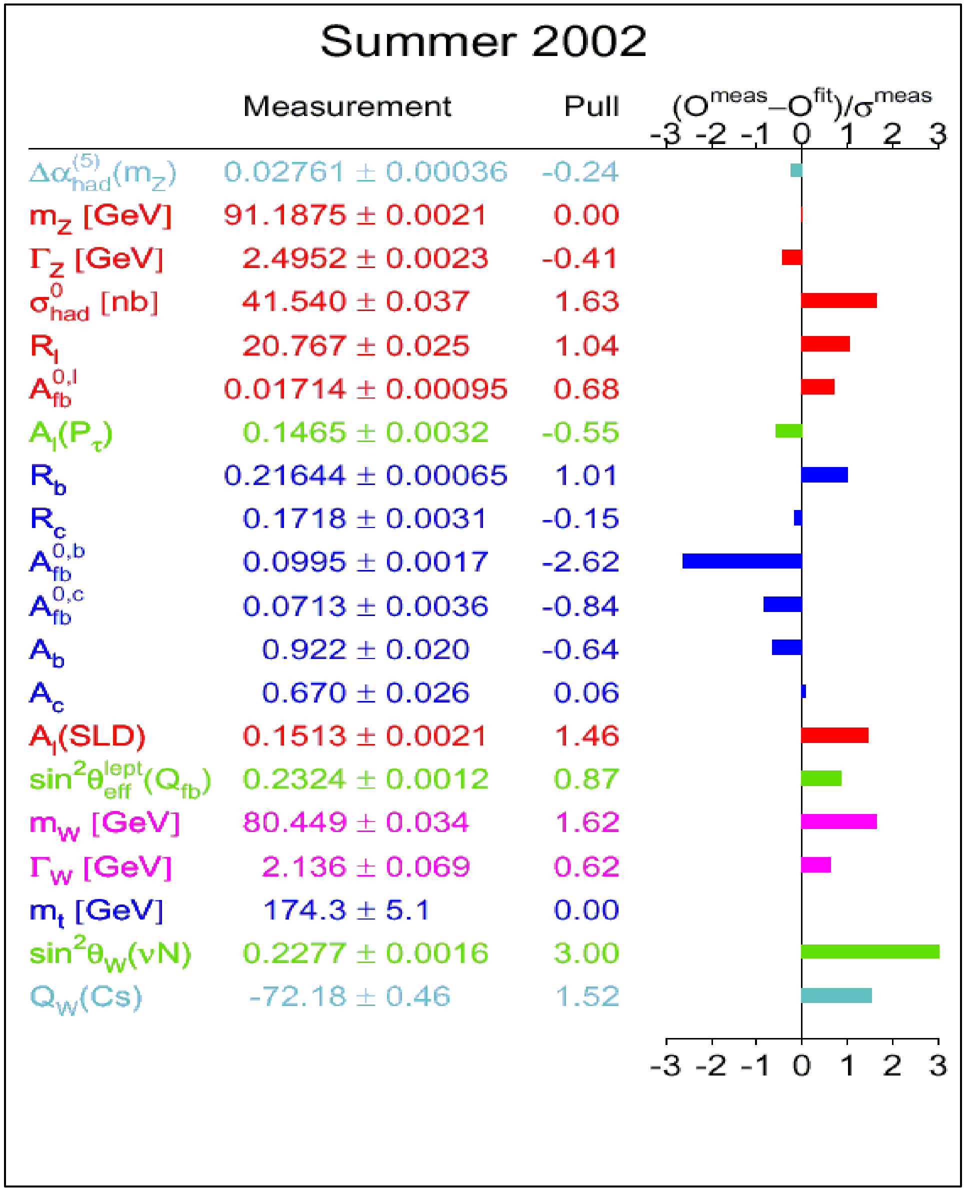
$$\sin^2 ?_W^{On-shell} = 1 - \frac{M_W^2}{M_Z^2}$$

$$\Rightarrow M_W^{On-Shell} = 80.14 \pm 0.08 \;GeV/c^2$$

Comparable precision but value smaller than other measurements



SM Global Fits with NuTeV Result



	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-0.24
m_Z [GeV]	91.1875 ± 0.0021	0.00
Γ_Z [GeV]	2.4952 ± 0.0023	-0.41
σ^0_{had} [nb]	41.540 ± 0.037	1.63
R_l	20.767 ± 0.025	1.04
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.68
$A_l(P_\tau)$	0.1465 ± 0.0032	-0.55
R_b	0.21644 ± 0.00065	1.01
R_c	0.1718 ± 0.0031	-0.15
$A^{0,b}_{fb}$	0.0995 ± 0.0017	-2.62
$A^{0,c}_{fb}$	0.0713 ± 0.0036	-0.84
A_b	0.922 ± 0.020	-0.64
A_c	0.670 ± 0.026	0.06
A_l(SLD)	0.1513 ± 0.0021	1.46
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.87
m_W [GeV]	80.449 ± 0.034	1.62
Γ_W [GeV]	2.136 ± 0.069	0.62
m_t [GeV]	174.3 ± 5.1	0.00
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	3.00
Q_W(Cs)	-72.18 ± 0.46	1.52

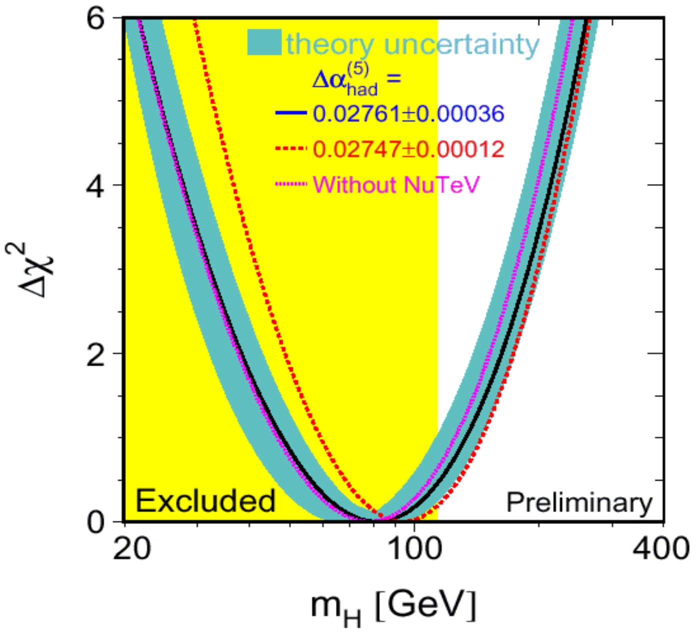
Without NuTeV

χ^2/dof=20.5/14: *P=11.4%*

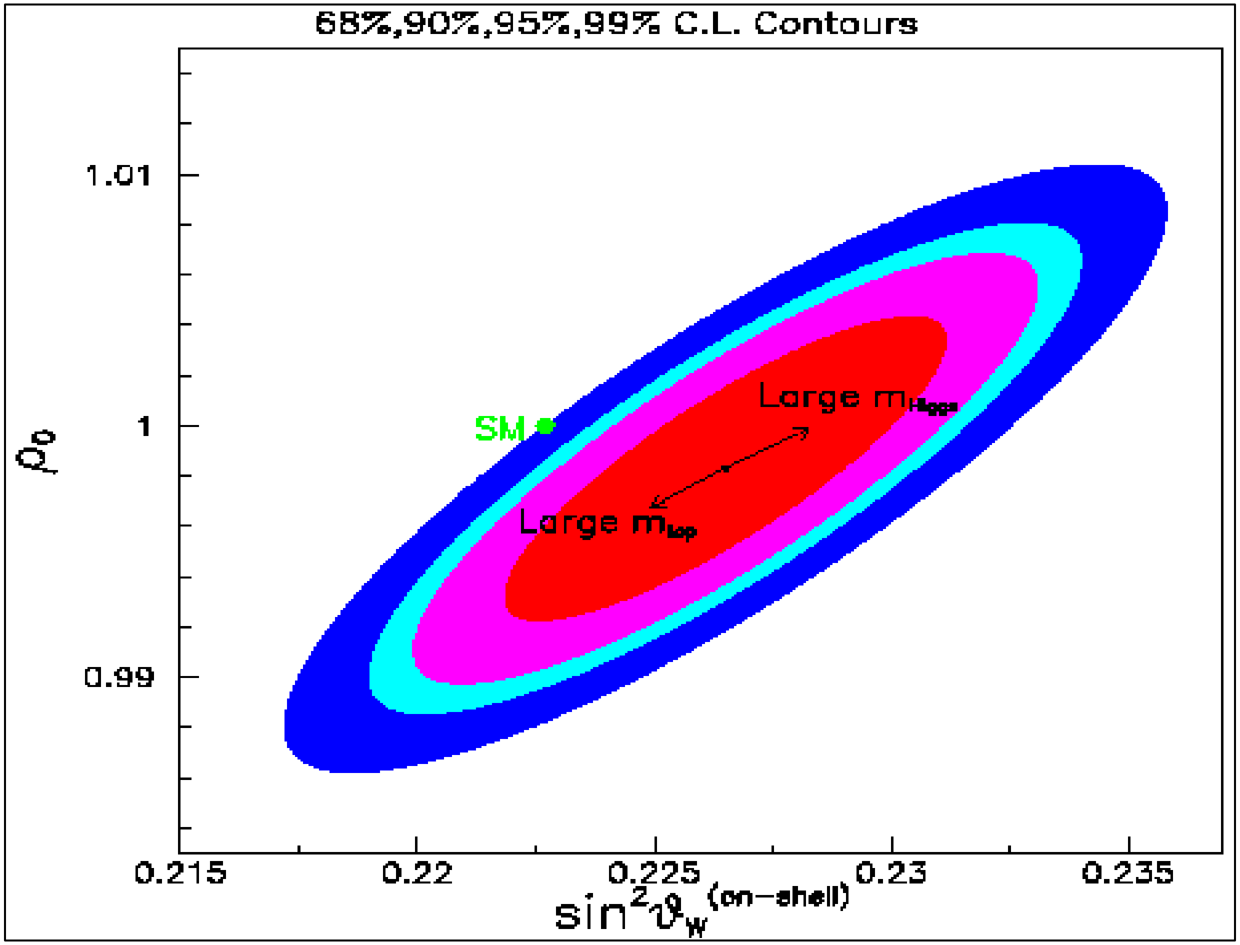
With NuTeV

χ^2/dof=29.7/15: *P=1.3%*

Confidence level in upper M_{higgs} limit weakens slightly.



Tree-level Parameters: r_0 and $\sin^2 q_W^{(on\text{-}shell)}$



- Either $\sin^2\theta_W^{(on\text{-}shell)}$ or ρ_0 could agree with SM but both agreeing simultaneously is unlikely

Model Independent Analysis

- Performed the fit to quark couplings (and g_L and g_R)
  - For isoscalar target, the νN couplings are

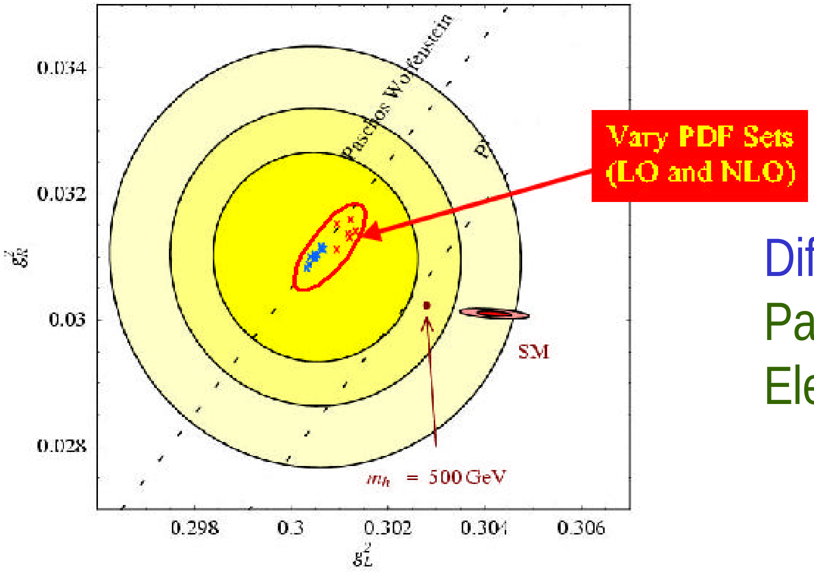
$$g_L^2 = u_L^2 + d_L^2 = ?_0^2\left(\frac{1}{2} + \sin^2 ?_W + \frac{5}{9}\sin^4 ?_W\right)$$

$$g_R^2 = u_R^2 + d_R^2 = ?_0^2\,\frac{5}{9}\sin^4 ?_W$$

  - From two parameter fit to R_{n}^{exp} and $R_{\bar{n}}^{exp}$

$$g_L^2 = 0.3005 \pm 0.0014$$ (SM: 0.3042 ← -2.6σ deviation)

$$g_R^2 = 0.0310 \pm 0.0011$$ (SM: 0.0301 ← Agreement)



Vary PDF Sets (LO and NLO)

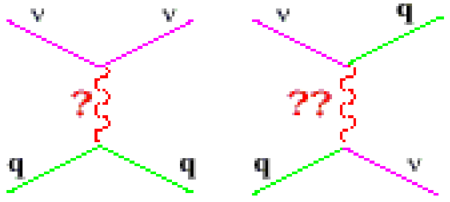
Difficult to explain the disagreement with SM by:
Parton Distribution Function or LO vs NLO or
Electroweak Radiative Correction: large M_{Higgs}

What is the discrepancy due to (Old Physics)?

- R^- technique is sensitive to q vs $\bar{q}$ differences and NLO effect
  - Difference in valence quark and anti-quark momentum fraction
- Isospin spin symmetry assumption might not be entirely correct
  - Expect violation about 1% ➔ NuTeV reduces this effect by using the ratio of ν and $\bar{\nu}$ cross sections ➔ Reducing dependence by a factor of 3
- s vs $\bar{s}$ quark asymmetry
  - s and $\bar{s}$ needs to be the same but the momentum could differ
    - A value of $\Delta s = s - \bar{s} \sim +0.002$ could shift $\sin^2\theta_W$ by -0.0026, explaining ½ the discrepancy (S. Davison, et. al., hep-ph/0112302)
    - NuTeV di-μ measurement shows that $\Delta s << 0.002$
- NLO and PDF effects
  - PDF, m_c, Higher Twist effect, etc, are small changes
- Heavy vs light target PDF effect (Kovalenko et al., hep-ph/0207158)
  - Using PDF from light target on Iron target could make up the difference ➔ NuTeV result uses PDF extracted from CCFR (the same target)

What other explanations (New Physics)?

- Heavy non-SM vector boson exchange: Z’, LQ, etc
  - LL coupling enhanced than LR needed for NuTeV



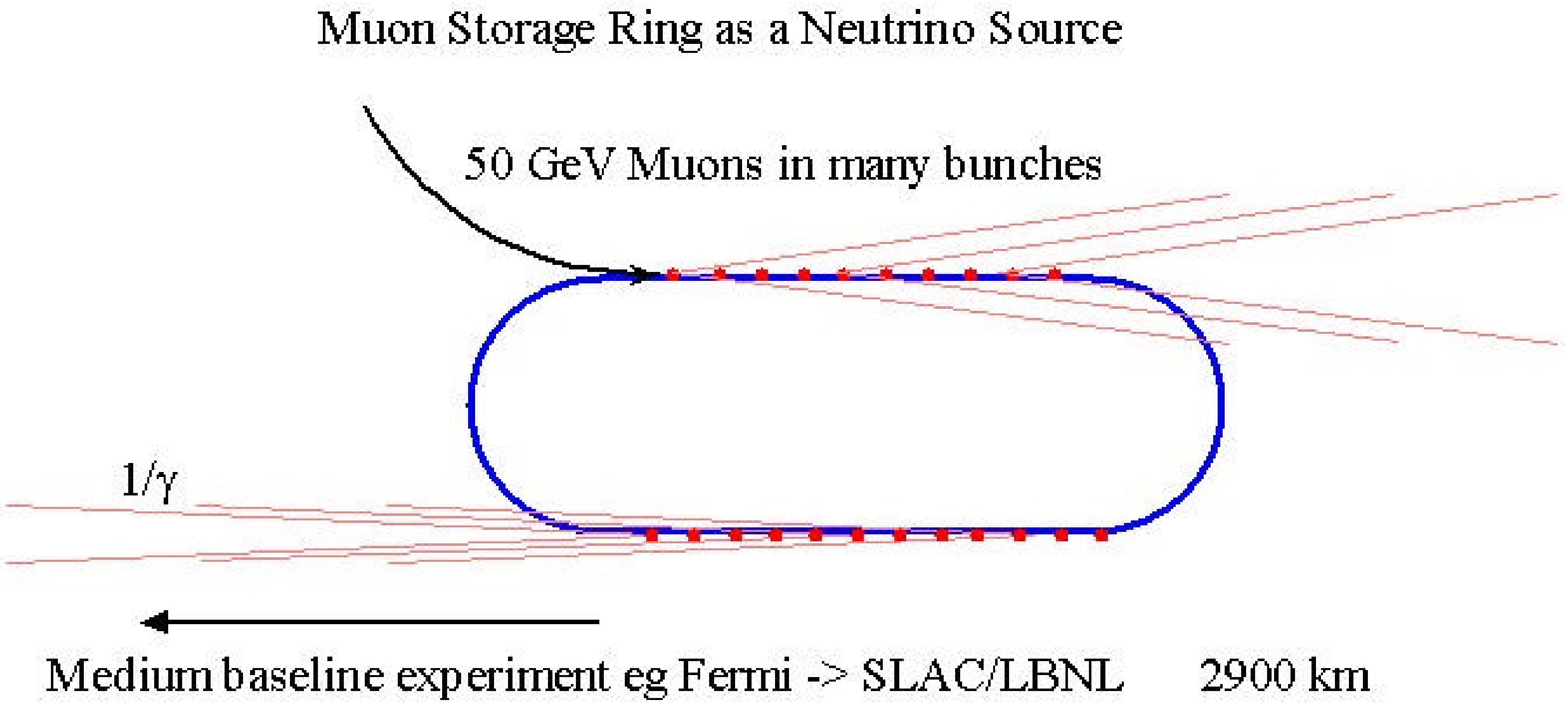
- Propagator and coupling corrections
  - Small compared to the effect
- MSSM : Loop corrections wrong sign and small for the effect
- Gauge boson interactions
  - Allow generic couplings ➔ Extra Z’ bosons???
    - LEP and SLAC results says < 10^{-3}
- Many other attempts in progress but so far nothing seems to explain the NuTeV results
  - Lepto-quarks
  - Contact interactions with LL coupling (NuTeV wants $m_{Z'}$~1.2TeV, CDF/D0: $m_{Z'}$>700GeV)
  - Almost sequential Z’ with opposite coupling to ν

Langacker *et al*, Rev. Mod. Phys. **64** 87; Cho *et al.*, Nucl. Phys. **B531**, 65;
Zppenfeld and Cheung, hep-ph/9810277; Davidson et al., hep-ph/0112302

Future???

Muon storage ring can generate 10^6 times higher flux and well understood, high purity neutrino beam ➔ significant reduction in statistical uncertainty

But ν_e and ν_μ from muon decays are in the beam at all times
➔ Deadly for traditional heavy target detectors



Conclusions

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

$$\sin^2 ?_W^{On-shell} = 0.2277 \pm 0.0013\ (stat) \pm 0.0009\ (syst)$$

$$\Rightarrow M_W^{On-Shell} = 80.14 \pm 0.08 GeV/c^2$$

  - NuTeV result deviates from SM prediction by about $+3\sigma$ **(PRL 88, 091802, 2002)**
  - Interpretations of this result implicates lower left-hand coupling (-2.6σ) but good agreement in right-hand coupling with SM
- NuTeV discrepancy has generated a lot of interest in the community
  - Still could be a large statistical fluctuation (5σ has happened before)
  - Yet, many interpretations are being generated:
    - Some could explain partially but not all
    - Asymmetric s-quark sea
    - Additional mediator, extra U(1) vector bosons, etc
  - No single one can explain the discrepancy ➔ it still is a puzzle…
- Could this be a signature of new physics?
  - No other current experiment is equipped to redo this measurement
  - Muon storage ring seems to provide a promising future…