Past, Present and the Future of Precision $\sin^2\theta_W$ Measurements

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- Introduction
- Past measurements
- Current Improvement
- Measurement at a Neutrino Factory
- Conclusions

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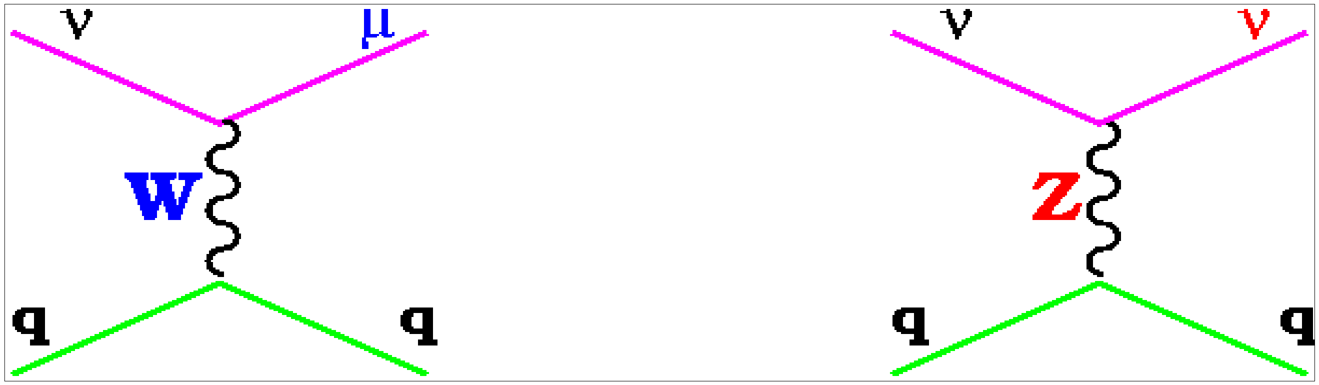
$\sin^2\theta_W$ and ν-N scattering

- 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:

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

- 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 did we measure?



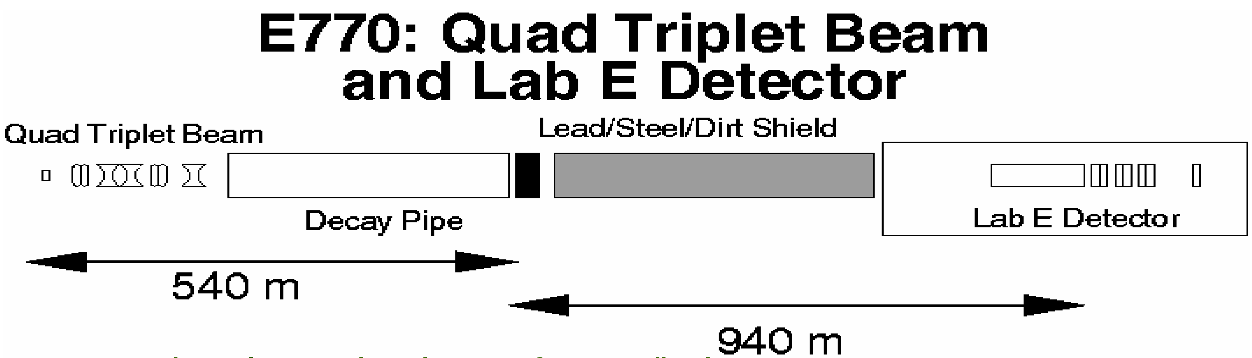
$$coupling \propto I^{(3)}_{weak} \qquad\qquad coupling \propto I^{(3)}_{weak} - Q_{EM}\sin^2 q_W$$

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

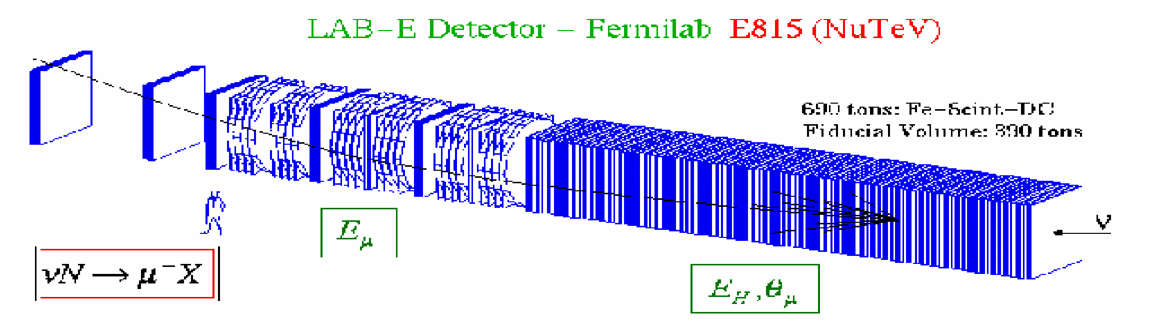
$$R^{n(\bar{n})} = \frac{s^{n(\bar{n})}_{NC}}{s^{n(\bar{n})}_{CC}} = ?^2\left(\frac{1}{2} - \sin^2 ?_W + \frac{5}{9}\sin^4 ?_W\left(1 + \frac{s^{\bar{n}(n)}_{CC}}{s^{n(\bar{n})}_{CC}}\right)\right)$$

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



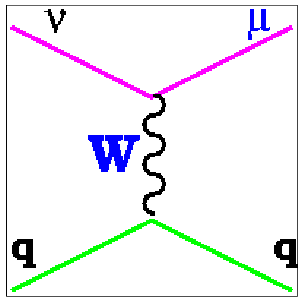
- Conventional neutrino beam from π/k decays
- Focus all signs of π/k for neutrinos and antineutrinos
- Both $\bar{\nu}_\mu$, ν_μ in the beam (NC events are mixed)

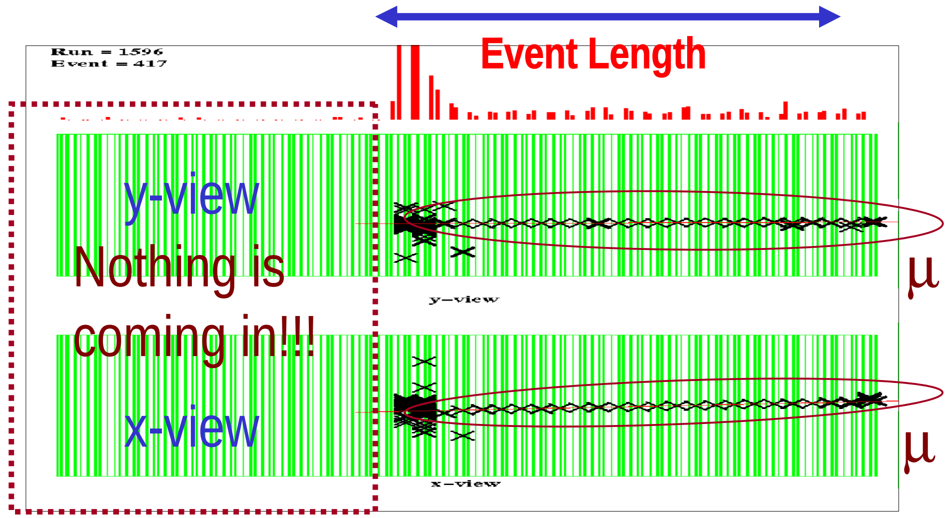


- Very small cross section ➔ Heavy neutrino target
- ν_e are the killers (CC events look the same as NC events)

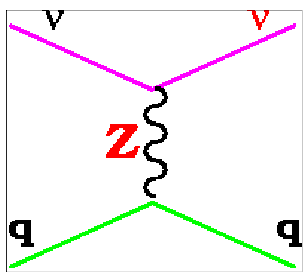
How Do We Separate Events?

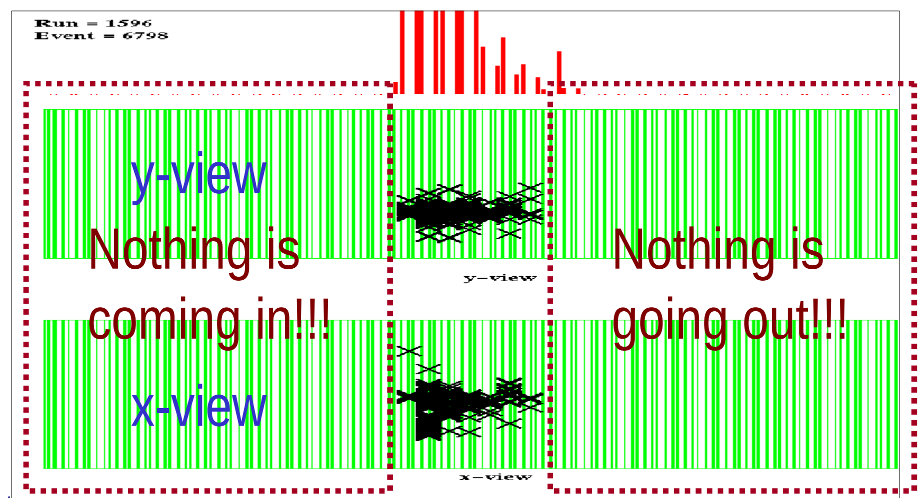
Charged Current Events





Neutral Current Events

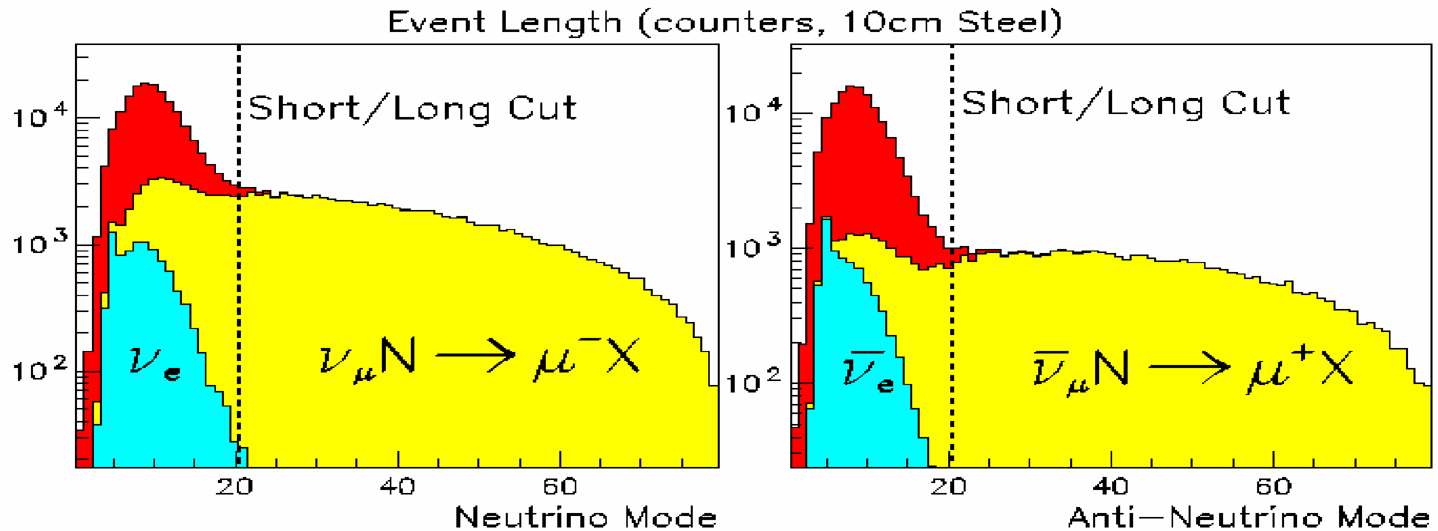




Event Length

Define an Experimental Length variable

➔Distinguishes CC from NC experimentally in statistical manner



Compare experimentally measured ratio

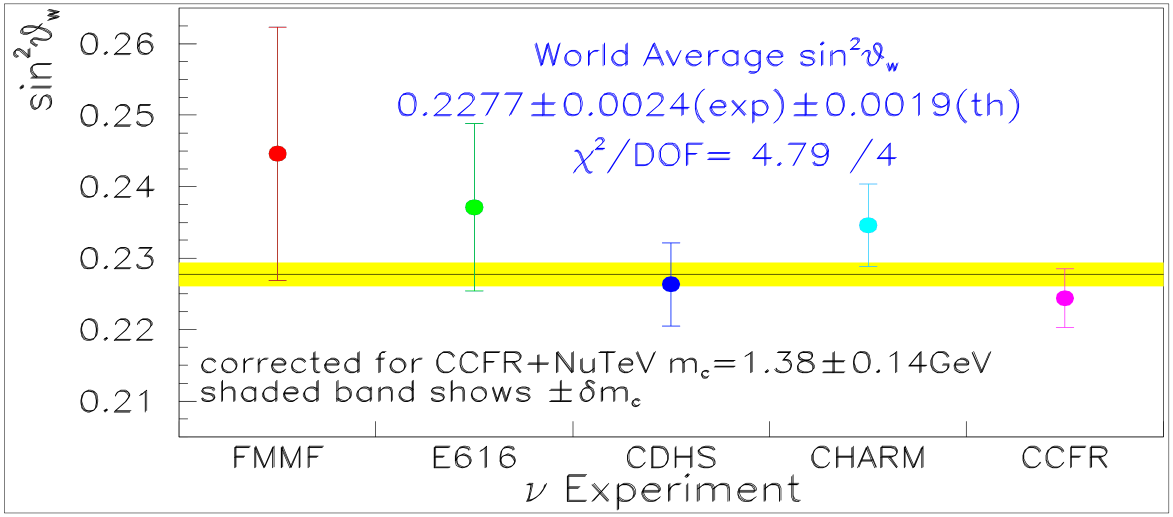
$$R_{Exp} = \frac{N_{Short}}{N_{Long}} = \frac{L < L_{Cut}}{L > L_{Cut}} = \frac{N_{NC\ Candidates}}{N_{CC\ Candidates}}$$

to theoretical prediction of R^ν

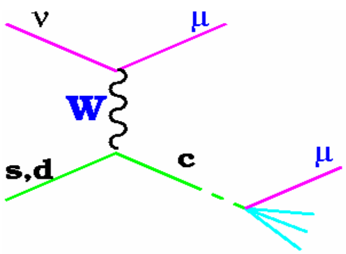
Past Experimental Results

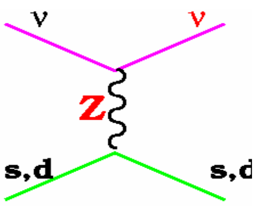
$$\sin^2 ?_W^{On-Shell} = 1 - \frac{M_W}{M_Z} = 0.2277 \pm 0.0031$$

$$\Rightarrow M_W^{On-Shell} = 80.14 \pm 0.16 \mathrm{GeV/c}^2$$



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



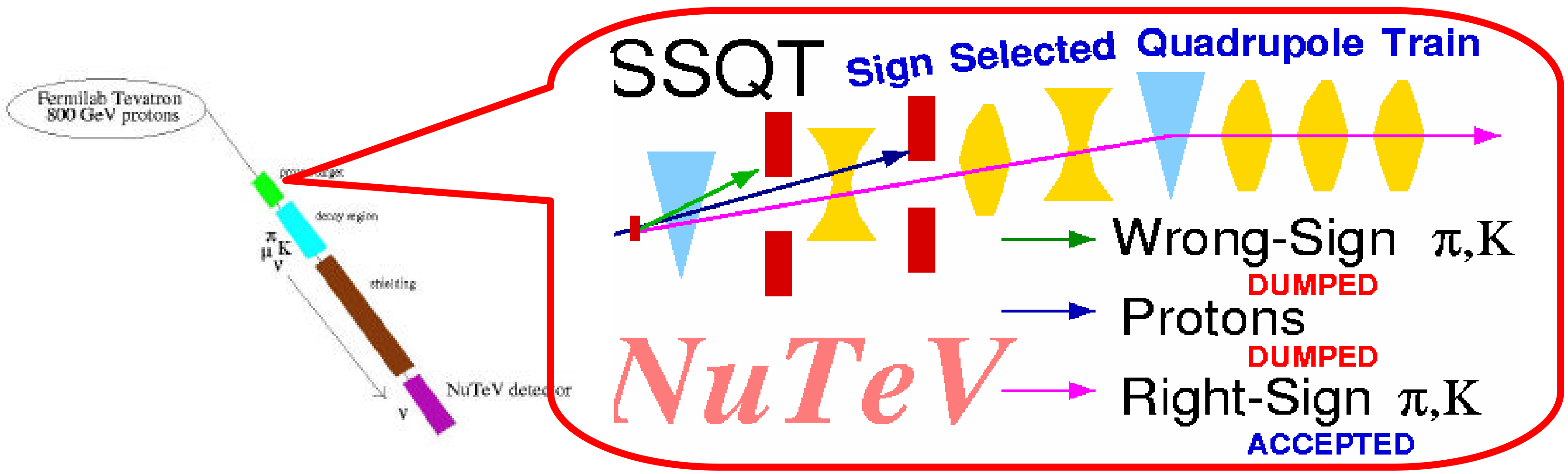


The NuTeV Experiment

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

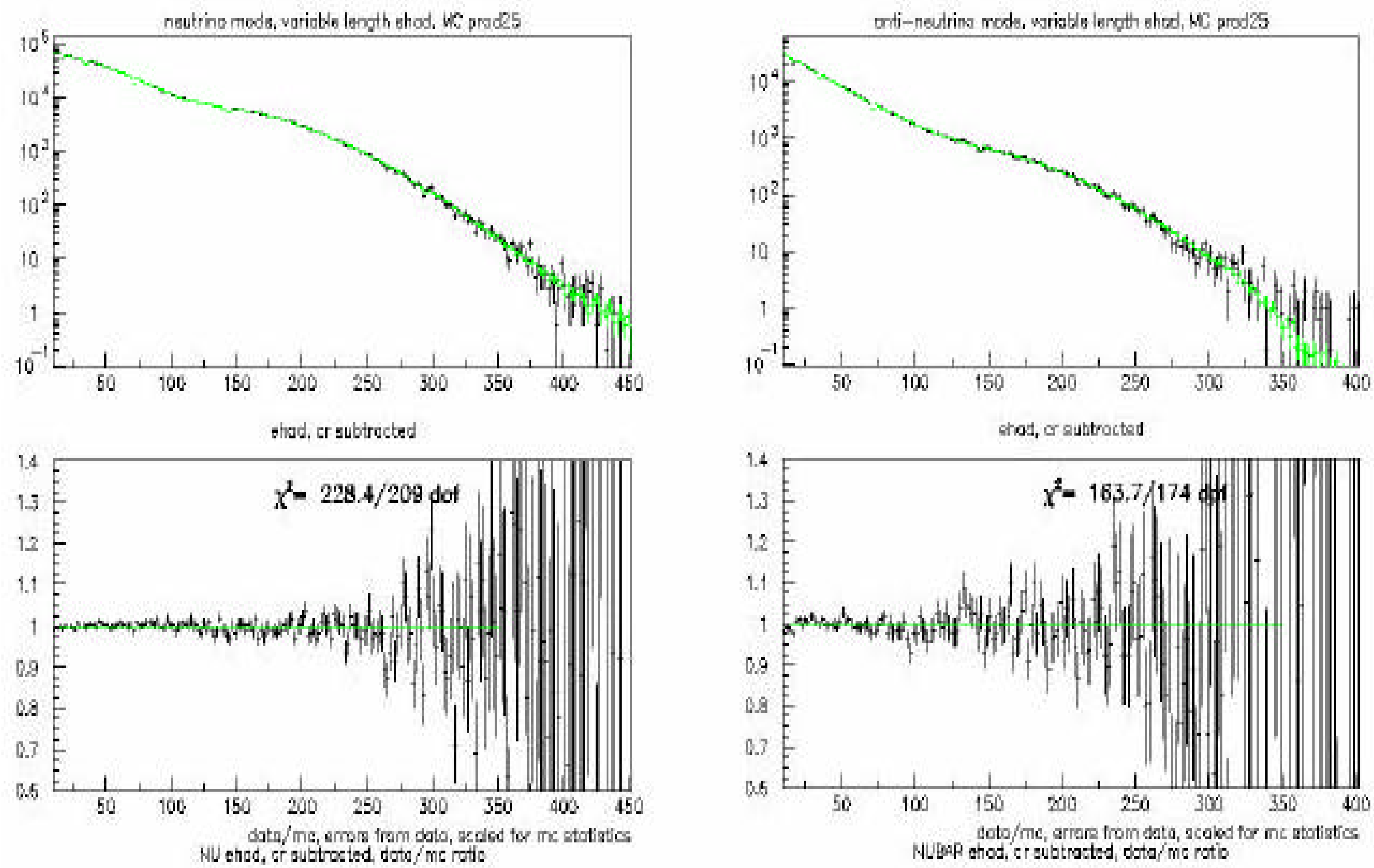
$$R^{-} = \frac{\sigma^{\nu}_{NC} - \sigma^{\bar{\nu}}_{NC}}{\sigma^{\nu}_{CC} - \sigma^{\bar{\nu}}_{CC}} = \rho^2\left(\frac{1}{2} - \sin^2\theta_W\right) = \frac{R^{\nu} - R^{\bar{\nu}}}{1 - r}$$

➔ Reduce charm CC production error by subtracting sea quark contributions
  - ➔ Only valence u, d, and s contribute while sea quark contributions cancel out
  - ➔ Massive quark production through Cabbio suppressed d_v quarks only
- Smarter beamline
  - Separate ν and $\bar{\nu}$ beam
  - Removes all neutral secondaries to eliminate ν_e content



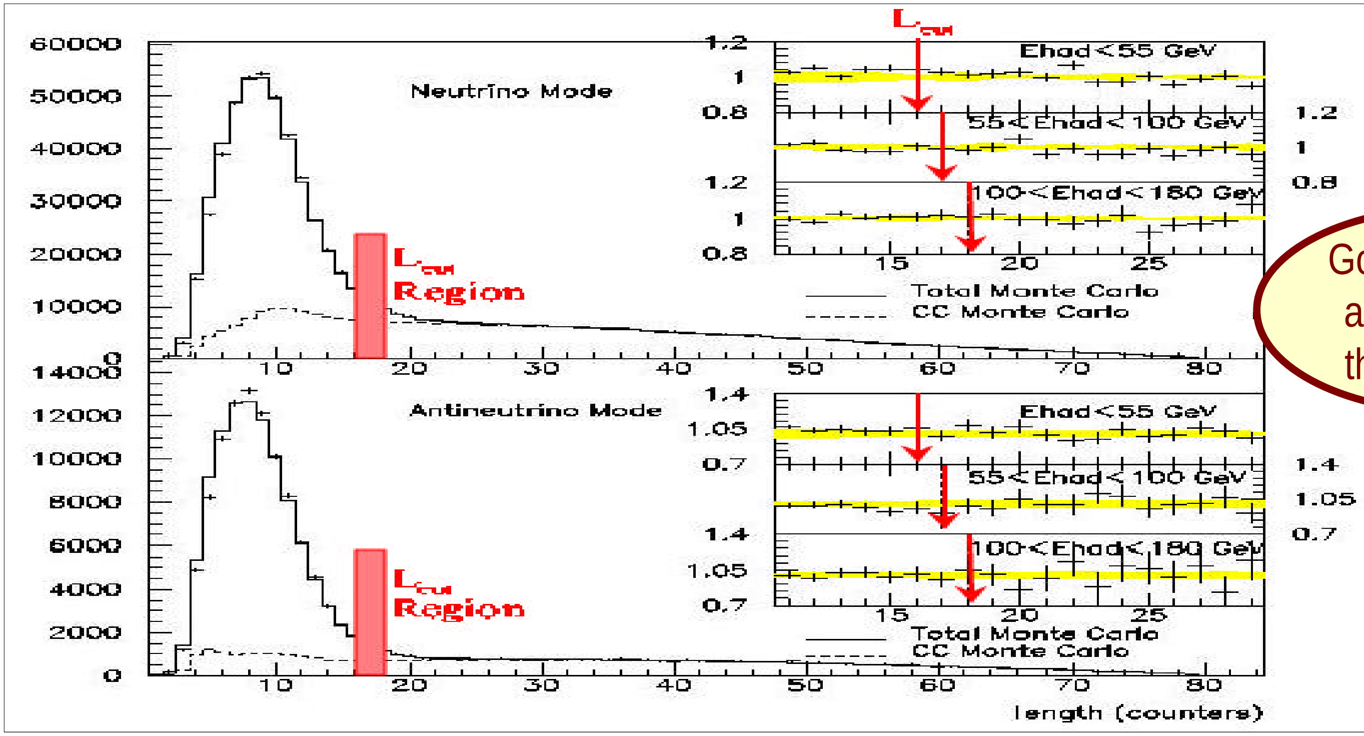
Events and E_{Had} After Event Selection

Events passing cuts: 1.62M ν & 350k $\bar{\nu}$ (<Eν>~100GeV)



NuTeV Event Length Distributions

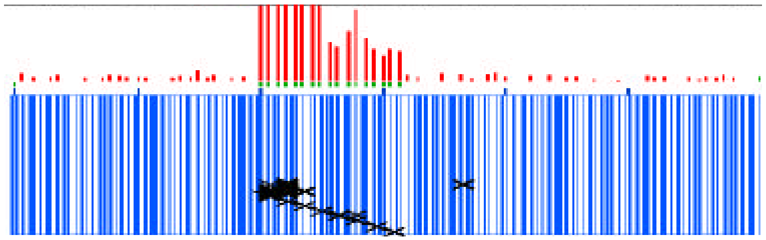
Energy Dependent Length cut implemented to improve statistics and reduce systematic uncertainties.

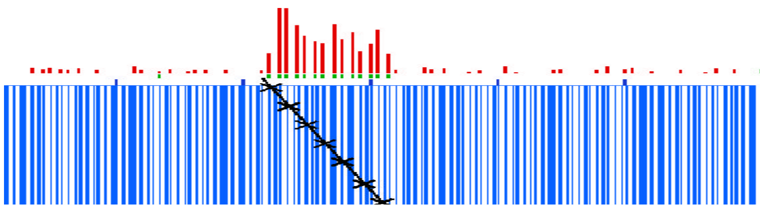


Good Data-MC agreement in the cut region

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)**

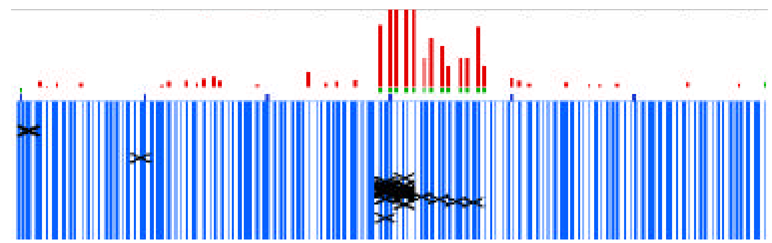
Event Contamination and Backgrounds



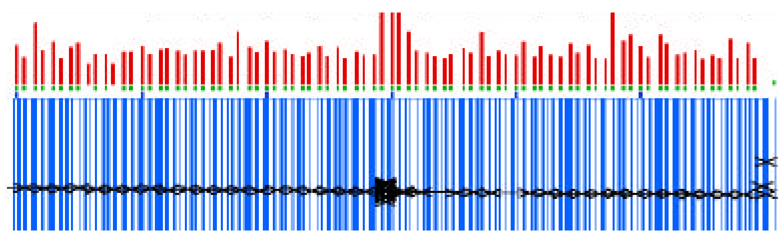


•**SHORT n_m CC's (20% n, 10% `n)**
μ exit and rangeout
•**SHORT n_e CC's (5%)**
$\nu_e N \rightarrow eX$
•**Cosmic Rays (0.9%)**

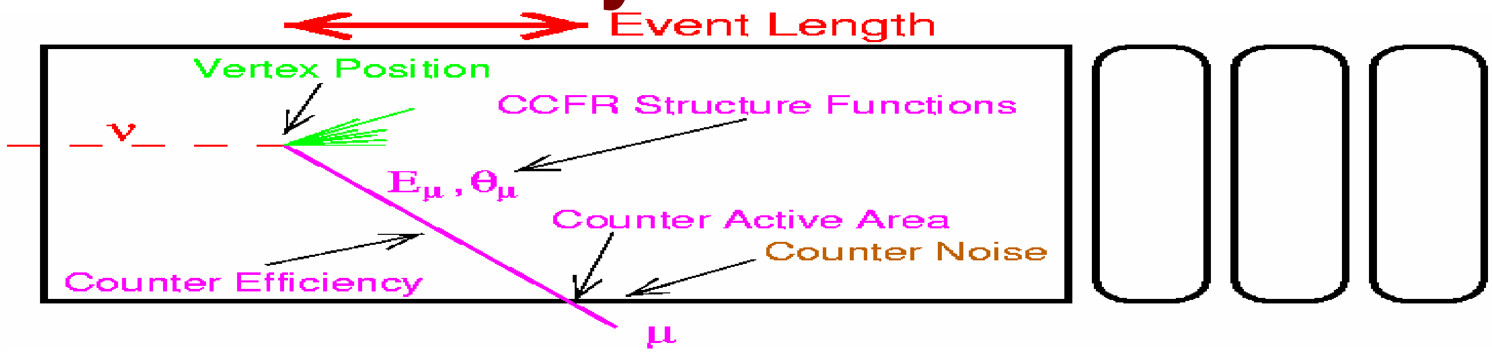
•**LONG n_m NC's (0.7%)**
hadron shower
punch-through effects



•**Hard m Brem(0.2%)**
Deep μ events



Other Systematic Effects

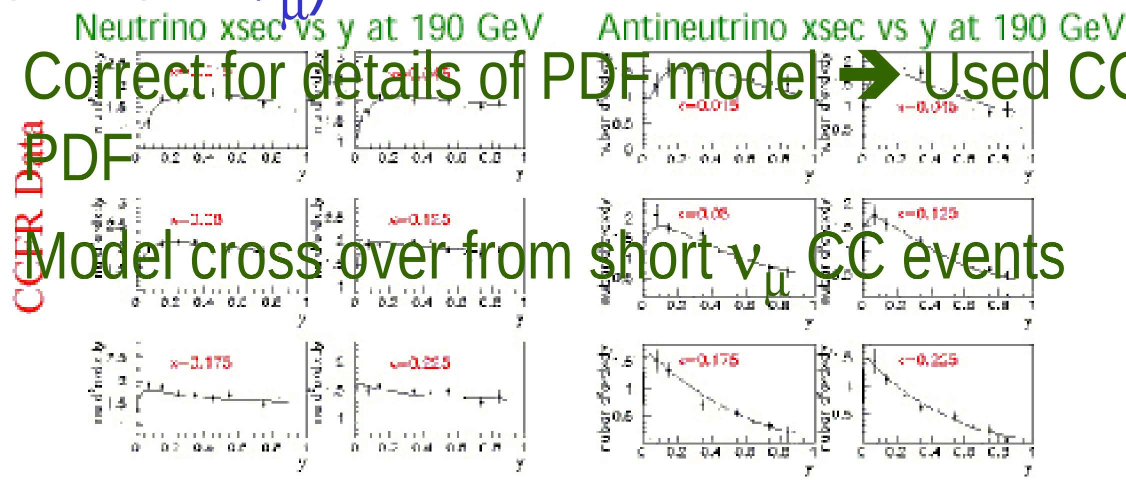


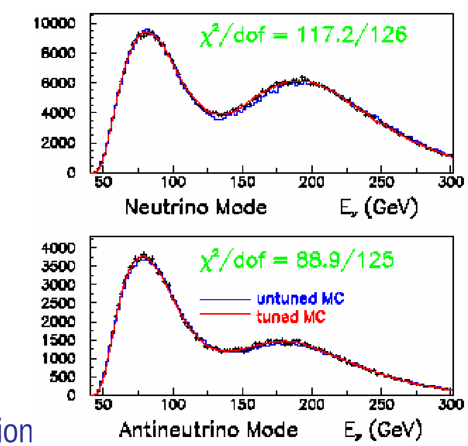
Sources of experimental uncertainties kept small, through modeling using n and TB data

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

MC to Relate R_ν^{exp} to R^ν and $\sin^2\theta_W$

- Parton Distribution Model ($<Q^2>$ ~ 25 GeV^2 for ν_μ, 16 GeV^2 for $\bar{\nu}_\mu$)
  - Correct for details of PDF model ➔ Used CCFR data for PDF
  - Model cross over from short ν_μ CC events





sin^{2}q$_W$ Fit to R_n^{exp} and $R_{`n}^{exp}$

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

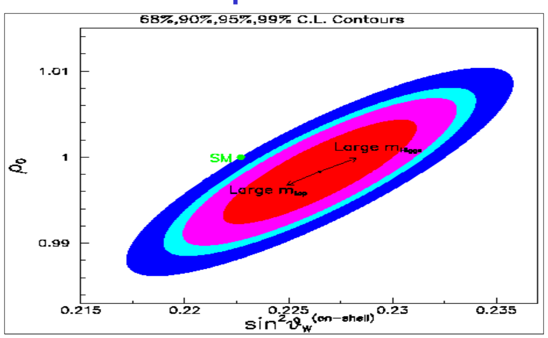
$$R^{n(\bar{n})} = \frac{s^{n(\bar{n})}_{NC}}{s^{n(\bar{n})}_{CC}} = ?^2\left(\frac{1}{2} - \sin^2 ?_W + \frac{5}{9}\sin^4 ?_W\left(1 + \frac{s^{\bar{n}(n)}_{CC}}{s^{n(\bar{n})}_{CC}}\right)\right)$$

- 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 (ρ_0=1)

$$\sin^2 ?_W = 0.2277 \pm 0.0013\ (stat) \pm 0.0009\ (syst)$$

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

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



$$\sin^2 ?_W = 0.2265 \pm 0.0031$$

$$?_0 = 0.9979 \pm 0.041$$

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

NuTeV $\sin^2\theta_W$ Uncertainties

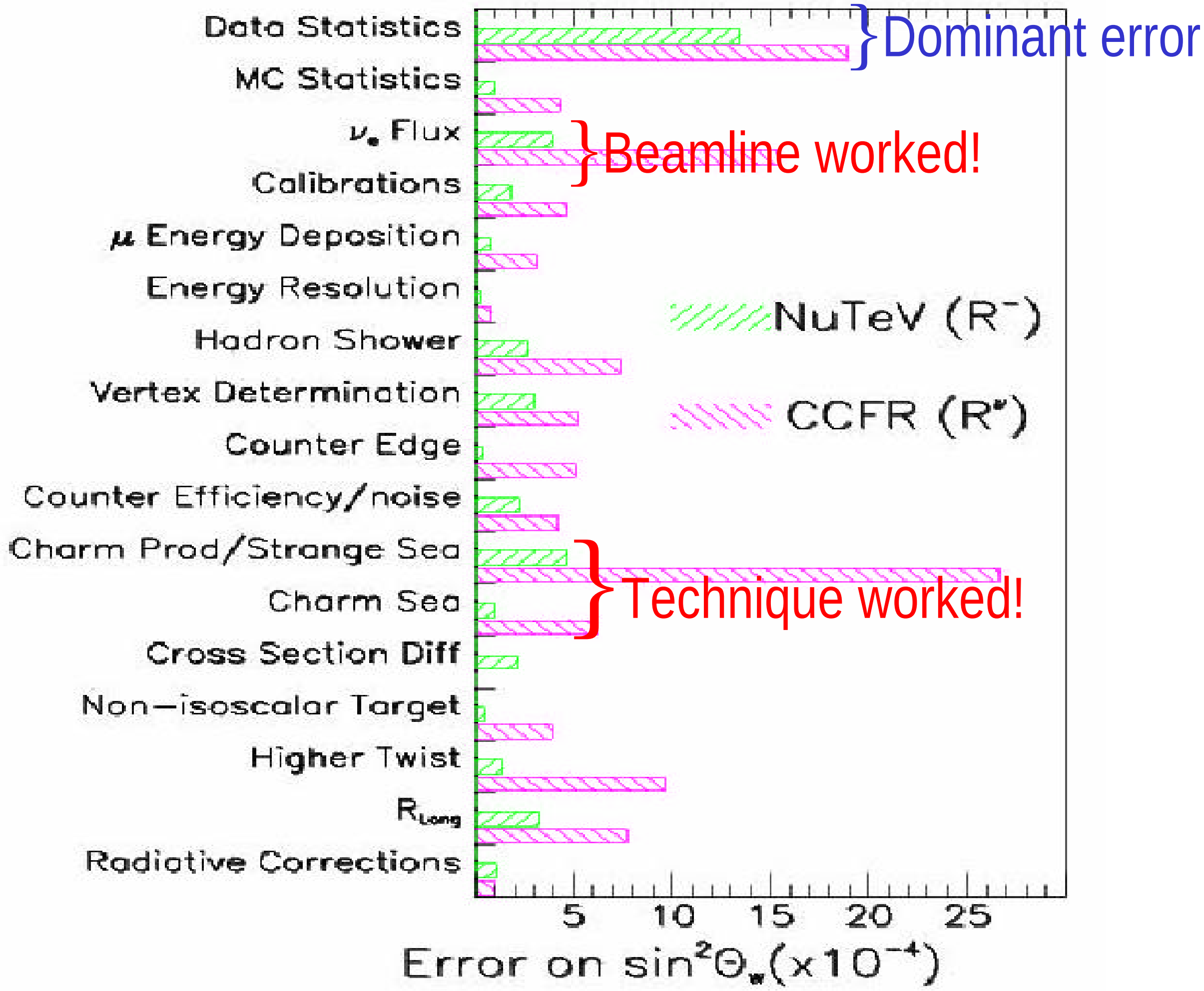
Source of Uncertainty	$\delta \sin^2\theta_W$
Statistical	**0.00135**
ν_e flux	0.00039
Event Vertex	0.00030
Length (Other effects)	0.00027 (23)
Total Experimental Systematics	**0.00063**
CC Charm production, sea quarks	0.00047
R_L	0.00032
$s^{\bar{\nu}} / s^{\nu}$	0.00022
Higher Twist	0.00014
RadiativeCorrection	0.00011
Non-isoscalar target	0.00005
Total Physics Model Systmatics	**0.00064**
Total 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)**

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

Past vs Present Uncertainty Comparisons



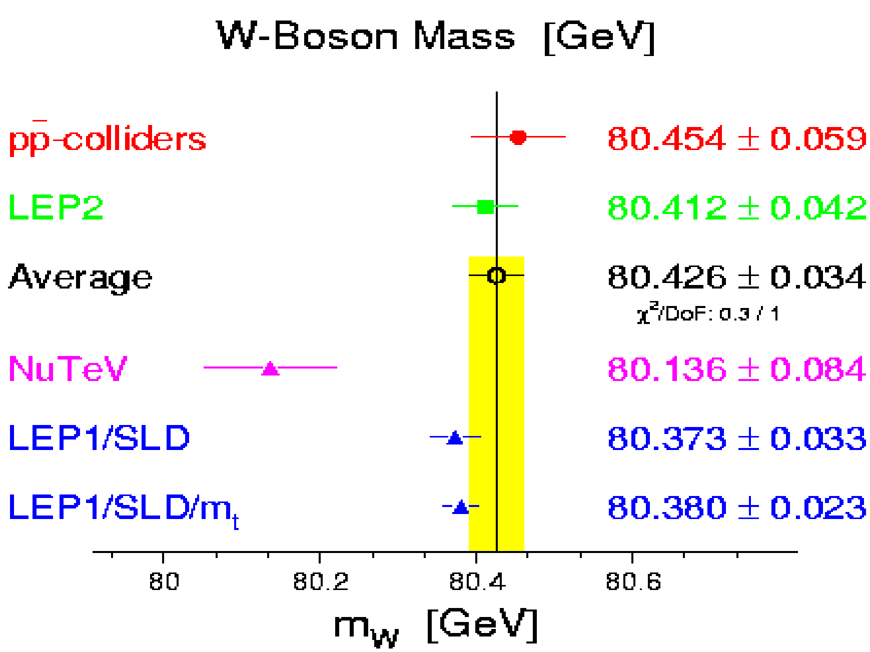
The Present (NuTeV) $\sin^2\theta_W$

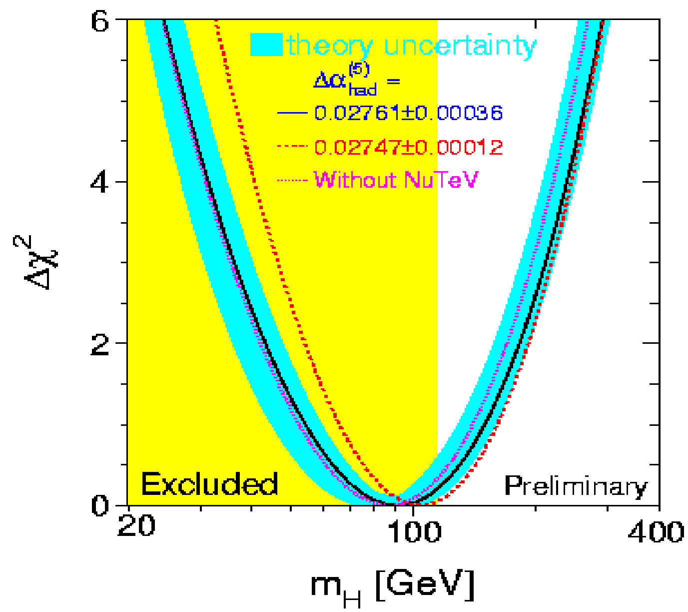
$$\sin^2\theta_W^{On-Shell} = 0.2277 \pm 0.0013\ (stat) \pm 0.0009\ (syst)$$

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

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

Comparable precision but value smaller than other measurements





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

Model Independent Analysis

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

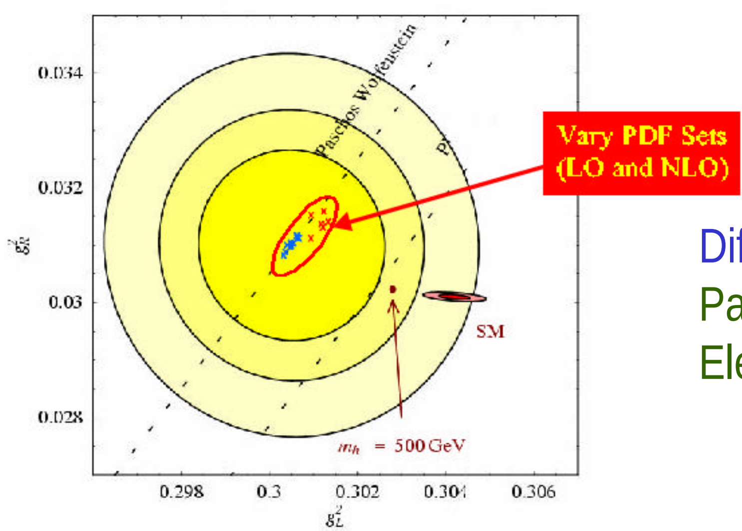
$$g_L^2 = u_L^2 + d_L^2 = ?_0^2\left(\frac{1}{2} + \sin^2 ?_W + \frac{5}{9}\sin^4 ?_W\right)$$

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

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

$$g_L^2 = 0.3001 \pm 0.0014$$ (SM: 0.3042 ← -2.6σ deviation)

$$g_R^2 = 0.0308 \pm 0.0011$$ (SM: 0.0301 ← Agreement)



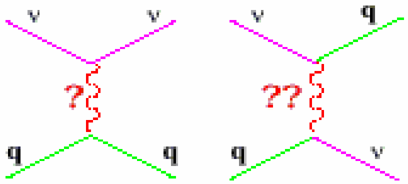
Difficult to explain the disagreement with SM by:
Parton Distribution Function or LO vs NLO or
Electroweak Radiative Correction: large M_{Higgs}

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 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 if +30% asymmetry
    - NuTeV LO di-μ measurement shows $\Delta s = s - \bar{s} \sim -0.0027$
    - NuTeV NLO analysis show no-asymmetry (D. Mason, et al., ICHEP02 proceedings)
- 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

NLO Upgrade of $\sin^2\theta_W$ Analysis

- To address concerns within the community
  - Don't expect to see large effects
    - LO x-sec model describe CC x-sec data well
    - Gambino, et al., (hep-ph/0112302) shown little NLO PDF effect to R-
      σ level shifts to R- small (Davidson, hep-ph/0112302 & Kulagin, hep-ph/0301045)
- To calculate $O(\alpha_s)$ pQCD corrections to the differential X-sec for ν, $\bar{\nu}$ DIS
- NuTeV (Zeller & McFarland) is collaborating with Theorists
  - FNAL Theory group: K. Ellis, B. Dobrescu, W. Gigele
  - DESY: Seven-Olaf Moch
  - others
- Approach based on Altarellu, Ellis & Martinelli, NP B143, 521 (1978)
  - X-sec's written in terms of xF_1, F_2, xF_3
  - pQCD corrections affect $2xF_1$-F_2=F_L & xF_3-F_2
  - F_L effect taken into account via R_L
  - Need α_s correction of xF_3-F_2, because α_s^2 is small (Zijlstra, PLB297, 377, 1992)
- Calculations and Implementation of the correction in progress

$\sin^2\theta_W$ Measurement at a NuFact

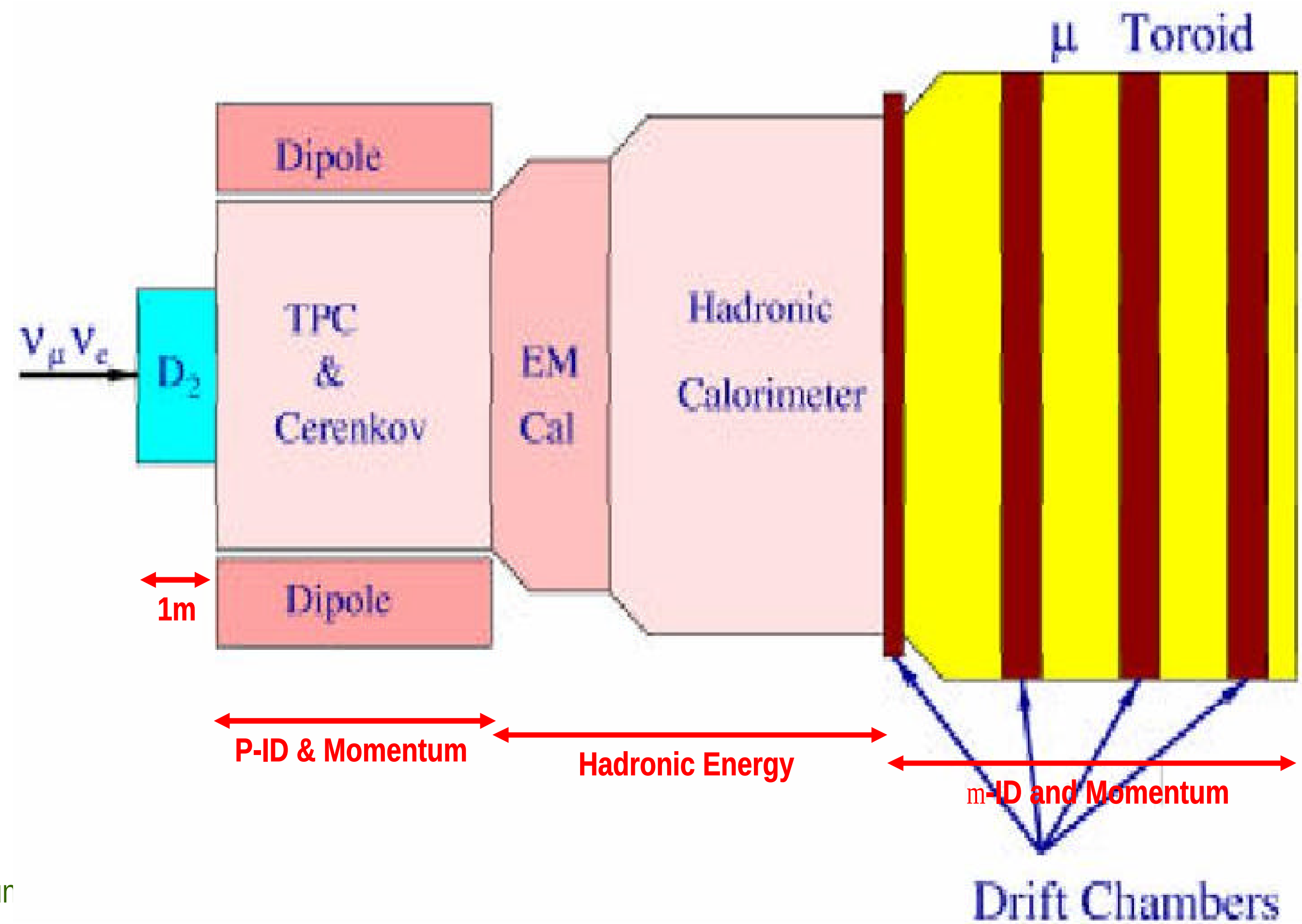
- Neutrinos come from μ decays
  - Good understanding of the beam content and flux
- Better collimated than conventional beam
- Large neutrino flux (10^5~10^6 higher than the current)

But…

- Always two neutrinos simultaneously in the given beam ($\nu_e+\nu_\mu$ or $\nu_\mu+\nu_e$)
  - Traditional heavy target detector will not work
    - Will screw up NC counting due to ν_e CC events
  - Need light target detectors ➔ Can afford to do this
- Might need new techniques for NC to CC ratio
  - Can't distinguish ν_e vs ν_μ induced NC events

A Light Target $\sin^2\theta_W$ Detector at a NuFact

ν_e and ν_μ from muon decays are in the beam at all times
➔Must use light target (D_2) detectors



Expectation at a NuFact

Using a 1m thick D_2 target, one can obtain about 20M ν_μ CC events per year → With the help of good p-id, the stat doubles → Length related uncertainties become irrelevant

Source of Uncertainty	d $\sin^2 q_W$
Statistical	**1.35×10^{-3} → 2.13×10^{-4}**
ν_e flux	3.9×10^{-4} → 0
Event Vertex	3.0×10^{-4} → 3.0×10^{-6}
Energy Measurements	1.80×10^{-4} → 9.00×10^{-5}
Total Experimental Systematics	**6.30×10^{-4} → 9.00×10^{-5}**
CC Charm production, sea quarks	4.70×10^{-4} → 2.40×10^{-4}
Higher Twist	1.40×10^{-4} → 1.40×10^{-4}
Non-isoscalar target correction	5.00×10^{-5} → 0 (D_2 target)
$s^{\bar{n}} / s^{n}$	2.20×10^{-4} → 1.50×10^{-4}
Radiative Correction	1.10×10^{-4} → 1.10×10^{-4}
R_L	3.20×10^{-4} → 9.00×10^{-5}
Total Physics Model Systmatics	**6.40×10^{-4} → 4.6×10^{-4}**
Total Uncertainty	**1.62×10^{-3} → 5.15×10^{-4}**
DM_W (GeV/c^2)	**0.08 → 0.025**

Experimental and Theoretical Issues

Experimental Issues

- Must be able to reverse beam polarity and measure current well
- Detector must be light weight
- Must be able to distinguish primary e, μ, and π
  - Need to control overall p-ID efficiency to be better than 10^{-3}
- High electron detection efficiency
- Good EM and Hadronic shower ID
- Good charged particle momentum measurement
- Good vertex measurement w/ triggering capability at the target

Theoretical Issues

- Better measured charm CC x-sec
- Need to understand radiative correction better
- Better understanding of higher twist effects

Conclusions

- NuTeV has improved $\sin^2\theta_W$

$$\sin^2 ?_W^{On-shell} = 0.2277 \pm 0.0013\ \text{(stat)} \pm 0.0009\ \text{(syst)}$$
$$\Rightarrow M_W^{On-Shell} = 80.14 \pm 0.08 \text{GeV/c}^2$$

  - NuTeV result deviates from SM prediction by about +3σ (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)
  - No single one can explain the discrepancy
- NuTeV working on NLO analysis of $\sin^2\theta_W$
- A Neutrino factory can provide a dramatic improvement in $\sin^2\theta_W$
  - Large neutrino flux (both ν_e and ν_μ)
    - Significant improvement in uncertainties (ΔM_W<25MeV)
  - Light target detector with p-id would be necessary
  - Theoretical improvement will help further improving the measurement