# Electroweak Physics at NuTeV

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**Outline**

1. Precision EW Measurements with Neutrinos
2. Measuring $\sin^2\theta_W$ with Neutrinos
3. NuTeV Experiment
4. Analysis and Preliminary Result
5. Interpretation Within the Standard Model
6. Beyond the SM: Extra Z Bosons, $\nu$ Oscillations
7. Conclusions

# NuTeV Collaboration

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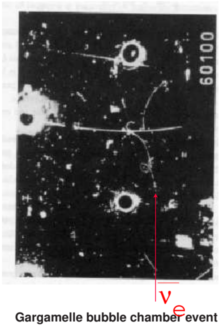
# Weak Neutral Current Experiments
# Proving Ground for the SM

## Discovery of Weak Neutral Current




Gargamelle bubble chamber event

$\overline{\nu}_\mu + e^- \rightarrow \overline{\nu}_\mu + e^-$

Summer 1973
$\nu_\mu N \rightarrow \nu_\mu X$
Gargamelle, CERN
Successful pred. of EW theory

## First Generation of Experiments

SLAC e-D
APV

Experiments in late 1970's
Typically of 10% precision
Basic structure of SM correct
Key input to SM Mw,Mz

## Second Generation of Experiments

CCFR, CDHS
CHARM, CHARM II
UA1,UA2,PETRA,APV

Experiments in late 1980's
Typically of 1-5% precision
Radiative corrs important
First useful limits on Mtop

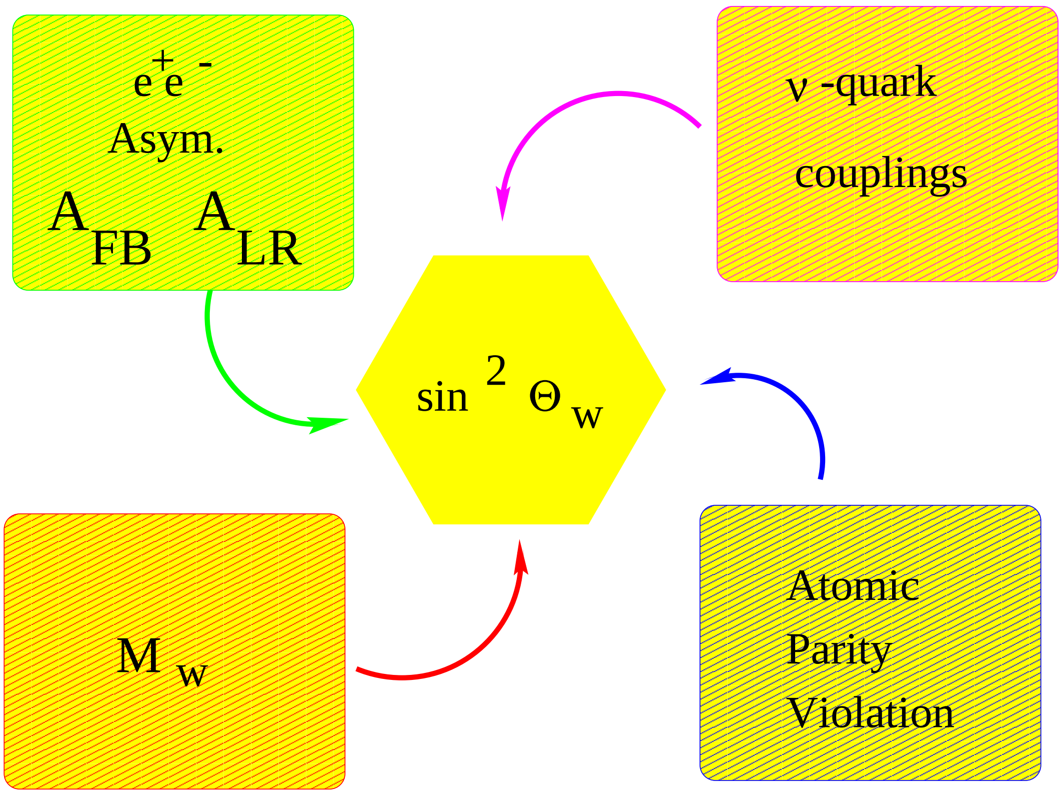
## Third Generation of Experiments

NuTeV, DØ, CDF
LEP I, SLD
LEP II,APV

Typically $\leq$1% precision
Test internal consistency of SM
Constrain Higgs boson mass
Search for new physics

# Physical Observables

What are some physical quantities that we can measure to high precision?



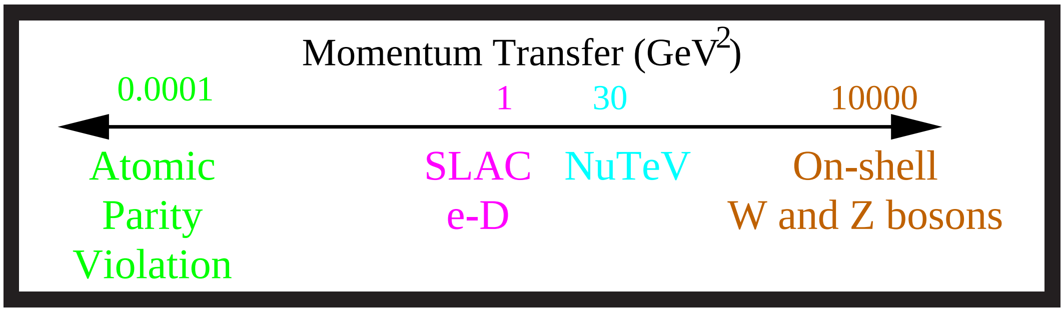

$\Rightarrow \sin^2\theta_W$ can be determined from Z pole observables, $M_W$ and from a variety of NC processes spanning a very wide $Q^2$ range...

# Why study Electroweak Physics in $\nu N$?

## *Within the Standard Model...*

- $\nu N$ measurement of $M_W$ comparable to direct measurements


- Probe electroweak physics at spacelike momentum transfers:

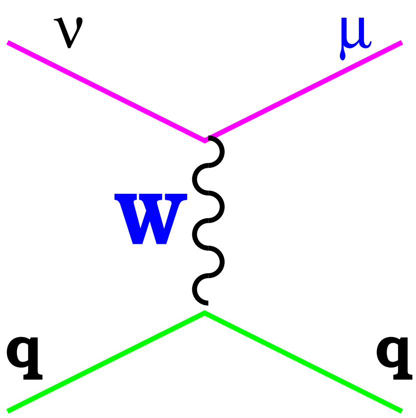


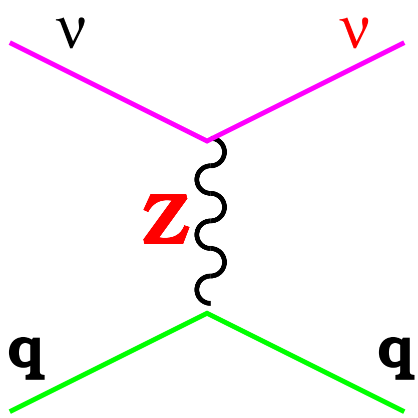

- Measure light quark couplings
- Sensitive to different radiative corrections

## *Outside the Standard Model...*

- New vector bosons, compositeness, leptoquarks, $\nu$ oscillations

# $\sin^2\theta_W$ in Neutrino Scattering




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

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For an isoscalar target composed of only u,d quarks at tree level:

<u>Llewellyn Smith Relation (CCFR):</u>

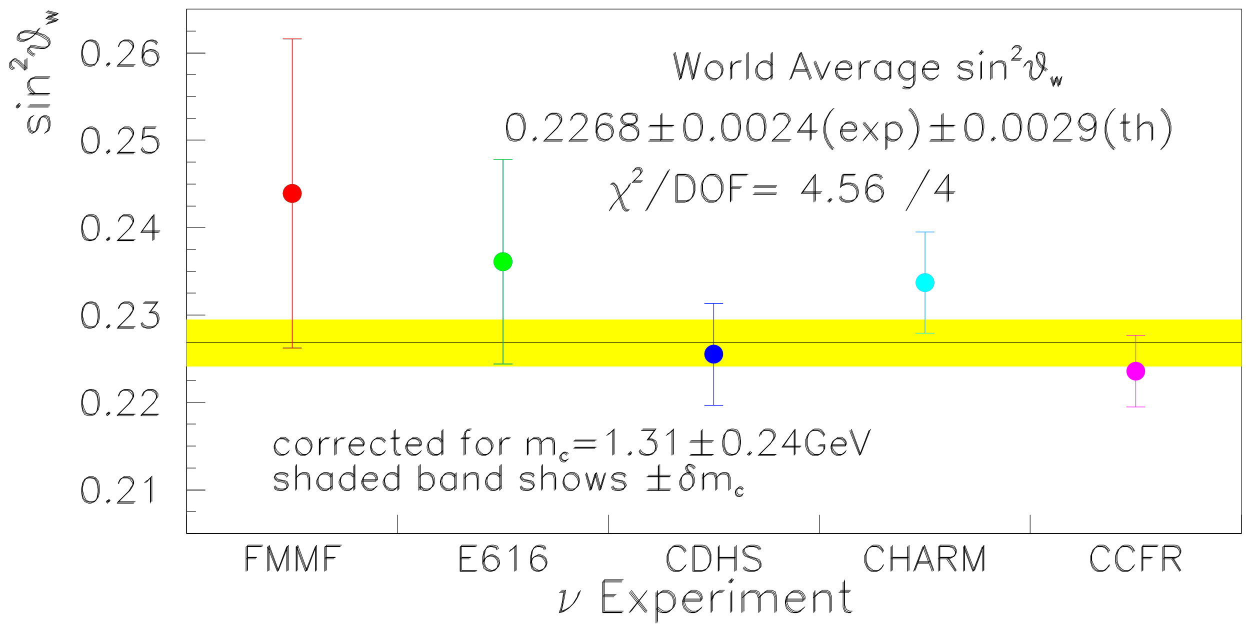
$$R_{\nu(\overline{\nu})} = \frac{\sigma_{NC}^{\nu(\overline{\nu})}}{\sigma_{CC}^{\nu(\overline{\nu})}} = \left(\frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W\left(1 + \frac{\sigma_{CC}^{\overline{\nu}(\nu)}}{\sigma_{CC}^{\nu(\overline{\nu})}}\right)\right)$$

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

# $\nu$ Experiments Before NuTeV

$$\sin^2\theta_W^{\mathrm{on-shell}} \equiv 1 - \frac{{M_W}^2}{{M_Z}^2} = 0.2268 \pm 0.0037$$

$$\Rightarrow M_W = 80.18 \pm 0.190 GeV$$



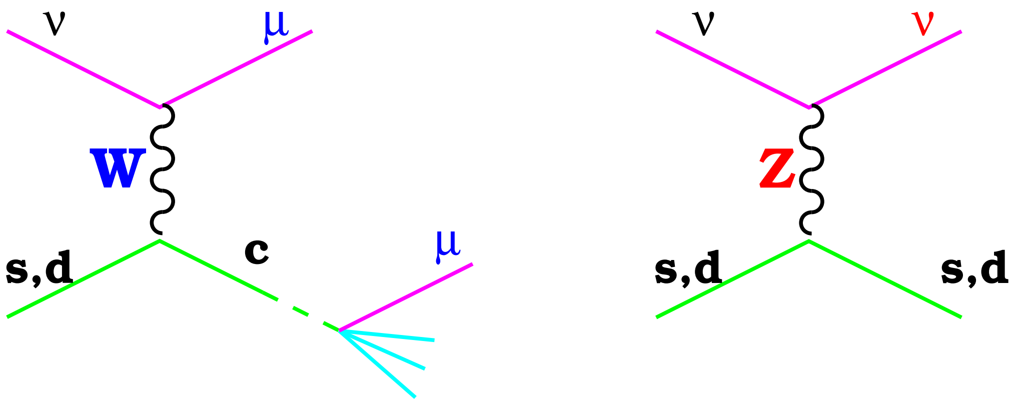

All other experiments are corrected to
CCFR & CDHS average $m_c$ and to large $M_{\mathrm{top}}$ ($M_{\mathrm{top}} > M_W$)

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

No useful limits on the Higgs could be set

# Heavy Quark Effects: Charged Current Production of Charm

Charm mass error comes from uncertainty in modeling the mass threshold of charm production cross section:




- Suppression of CC cross section for interactions with massive charm quark in final state
- Modeled by leading-order slow-rescaling

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

- Parameters of model measured by CCFR in dimuon events (i.e. $\nu q \rightarrow \mu^- c, \;\; c \rightarrow \mu^+ X$) (S. Rabinowitz)

$\kappa =$ level of s sea $= \frac{2s}{\bar{u}+\bar{d}} = 0.37 \pm 0.05$

$\alpha =$ shape of s sea $= 2.50 \pm 0.70$

$V_{cd} = 0.209 \pm 0.012$

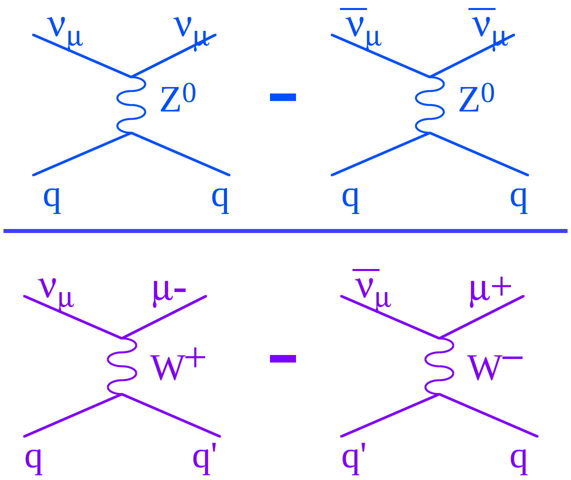
$m_c^{eff} = 1.31 \pm 0.24$ GeV

# NuTeV's Technique: A Better Method

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

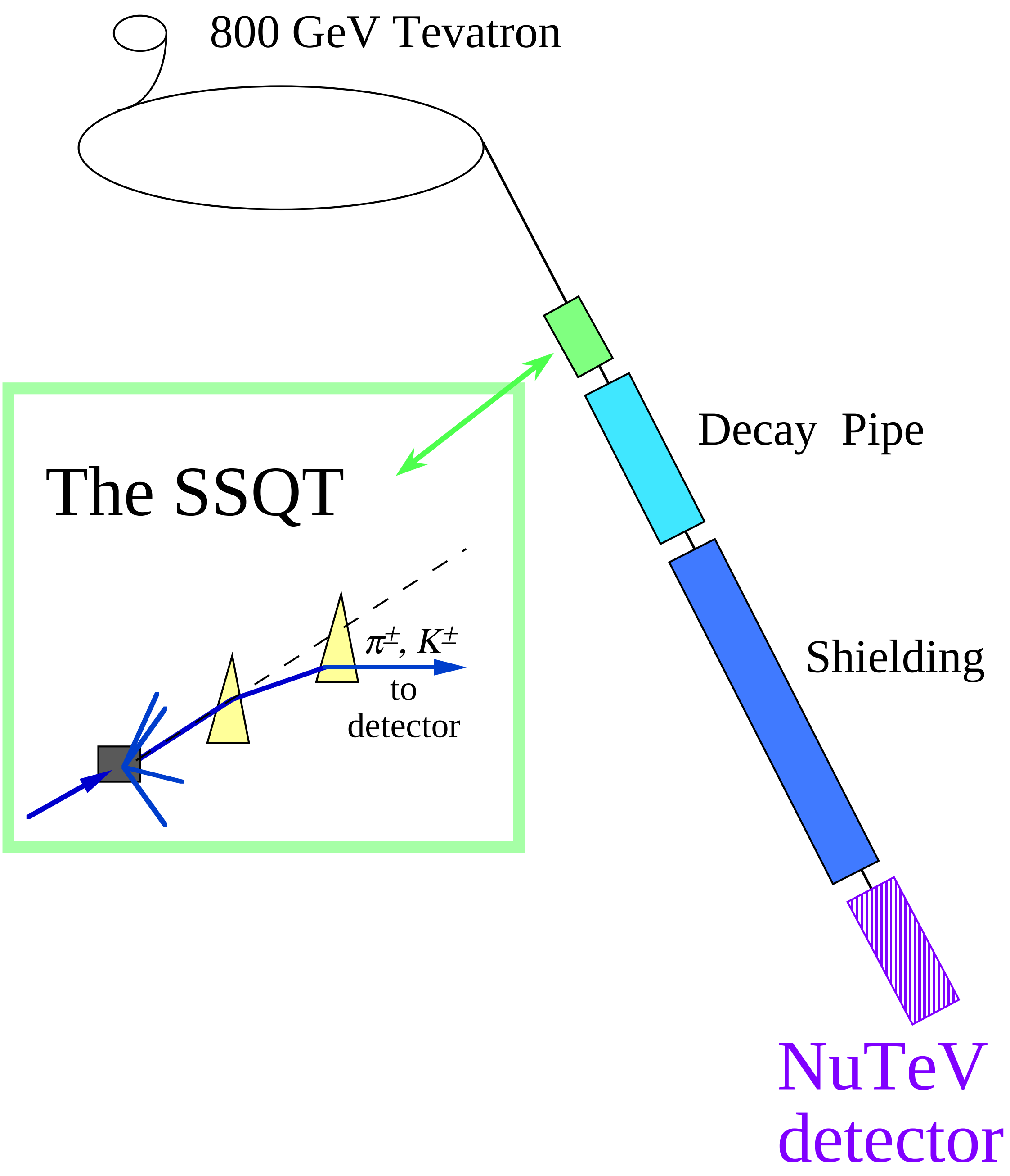
## Paschos-Wolfenstein Relation:

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




- $R^-$ Manifestly insensitive to sea quarks
  $\Rightarrow$ Charm production error from $d_V$ quarks only
  (Cabbibo suppressed and at large x)
  $\Rightarrow$ Charm, strange sea errors negligible
- Requires Separate $\nu$ and $\overline{\nu}$ Beams $\Rightarrow$ NuTeV SSQT

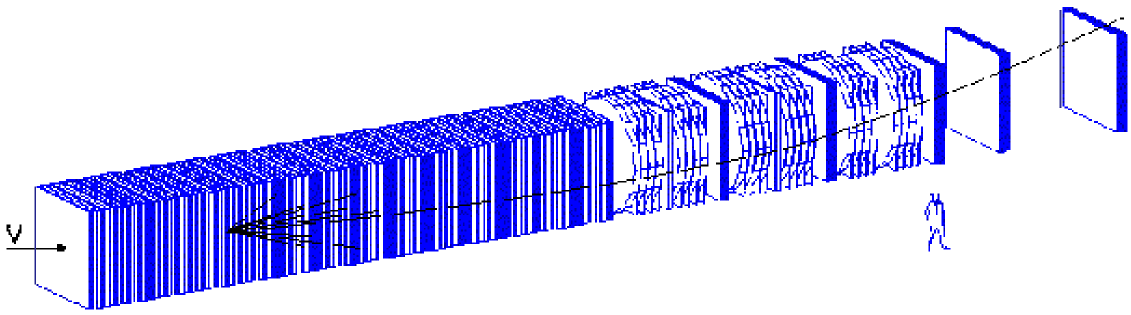
# NuTeV Beamline




- Resulting beam is almost purely $\nu$ or $\overline{\nu}$:
  ($\overline{\nu}$ in $\nu$ mode $< 1\text{x}10^{-3}$, $\nu$ in $\overline{\nu}$ mode $< 2\text{x}10^{-3}$)
- Beam is $\sim$1.8% electron neutrinos

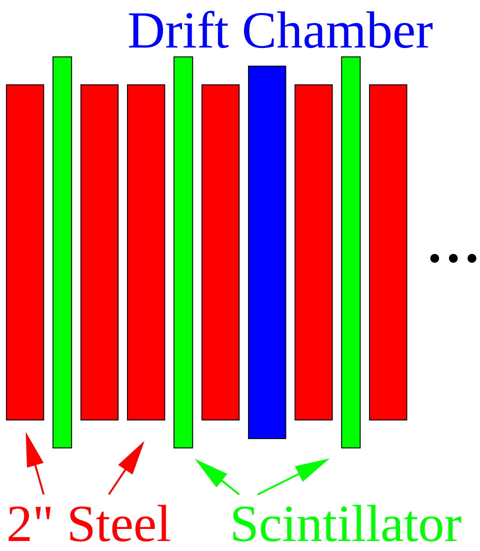
# $\nu$N Deep Inelastic Scattering at NuTeV

Lab E Detector - Fermilab E815(NuTeV)
690 tons: Fe-Scint-DC



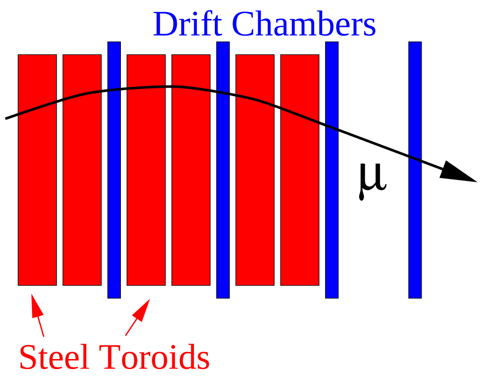

Target/Calorimeter:

- 168 Fe plates (3m $\times$ 3m $\times$ 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:

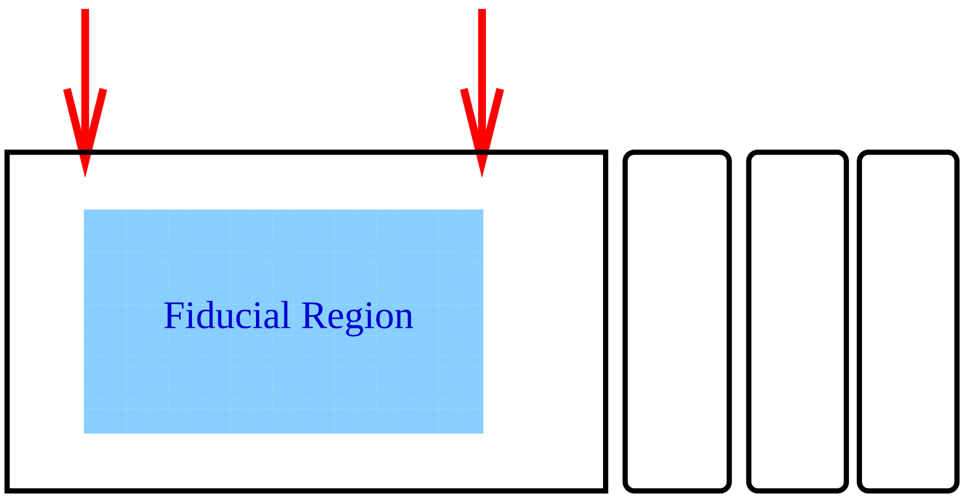
- 15kG field ($P_T = 2.4\,GeV/c$)



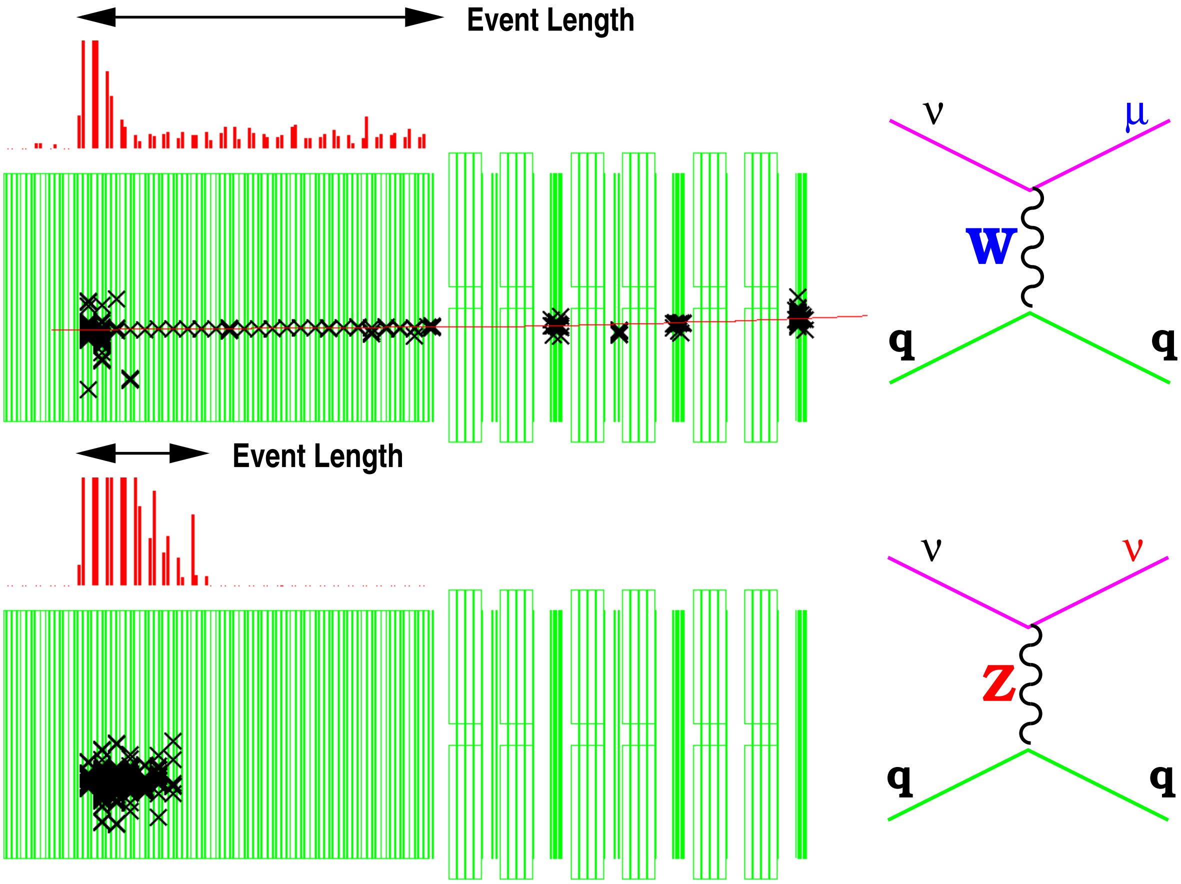
# Event Selection

## 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



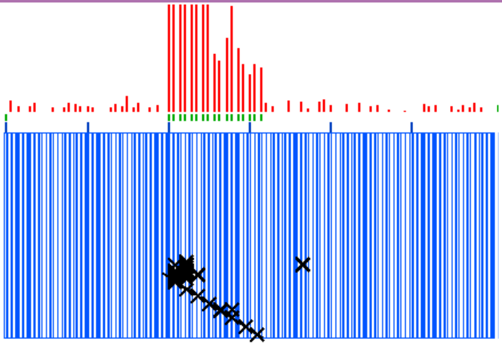
# Neutral Current/Charged Current Event Separation

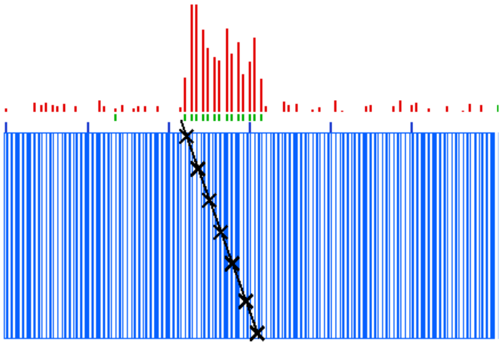



Statistical separation of NC and CC events simply based on "event length" (longitudinal E deposition).

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

# It's Not Just a Counting Experiment: Event Contamination and Backgrounds

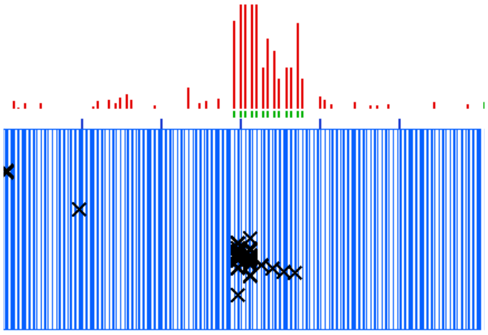




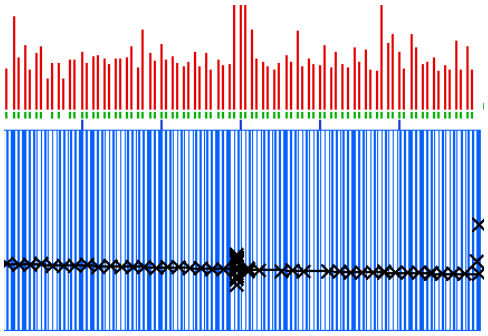
- SHORT $\nu_\mu$ CC's (20%)
  muons that exit, range out
- SHORT $\nu_e$ CC's (5%)
  $\nu_e N \to eX$
- Cosmic rays (0.8%)

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

- LONG $\nu_\mu$ NC's (0.3%)
  punch-through effects



- Hard $\mu$ brem (0.2%)
  deepmu events

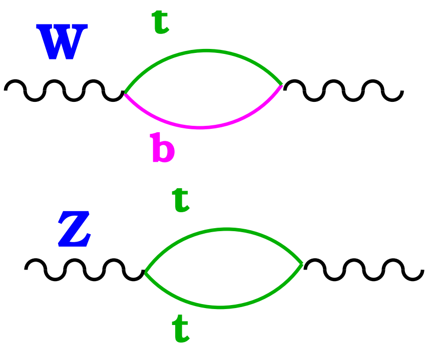


# Experimental Technique

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

Measured ratio can be related to $\sin^2\theta_W$ using a detailed Monte Carlo which must include:

→ **CROSS SECTION MODEL**




- Radiative corrections

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

- Target isovector effects (6% neutron excess)
- CCFR LO parton dist functions
- Isovector corrections

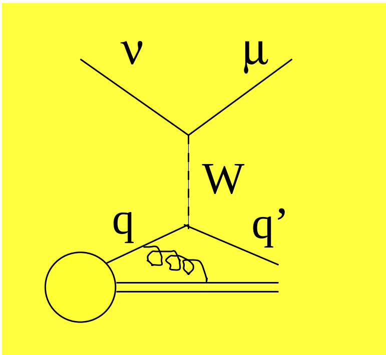
  NMC data (Un-Ki Yang,SLAC); NUSEA Data

- Heavy quark corrections
- Longitudinal structure function

  $R_L$ from Whitlow fit

- Higher twist ($\sim \frac{1}{Q^2}$)

  Vector-axial-vector dominance model(Pumplin)



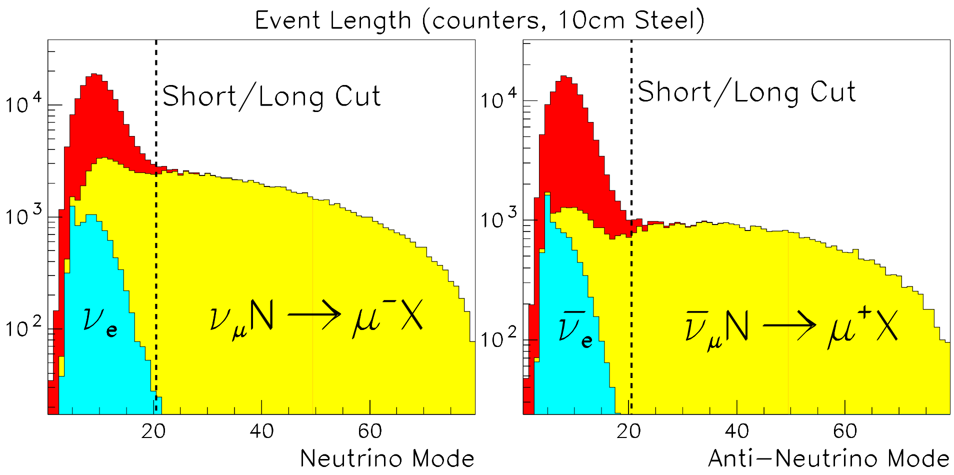

→ **NEUTRINO FLUX** ⟹

→ **DETECTOR RESPONSE** ⟹

# NuTeV Neutrino Flux

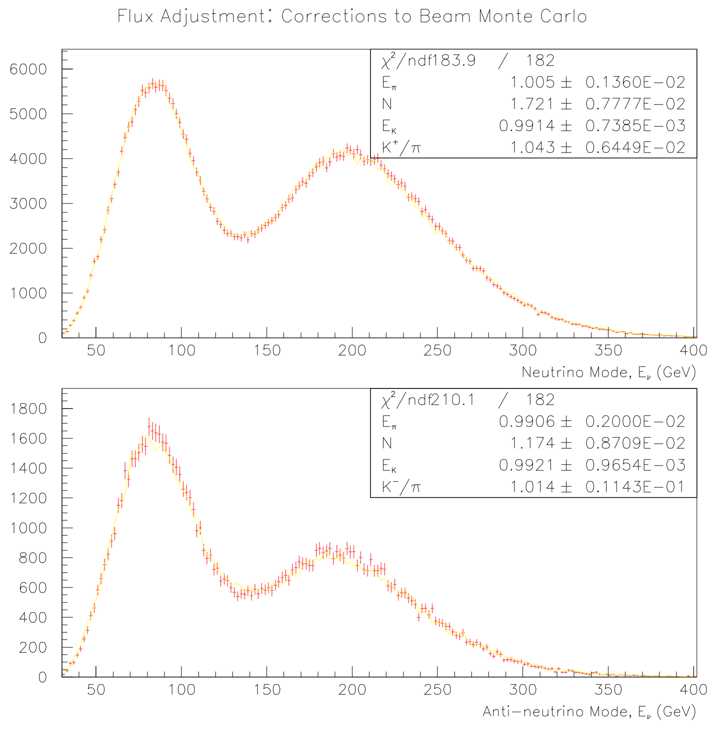
## NuTeV uses a detailed $\nu$ beam Monte Carlo

- Need to predict $\nu_e$ and $\overline{\nu}_e$ background to $\nu_\mu/\overline{\nu}_\mu$ beam
- Precise alignment of SSQT from optical survey and beam tests

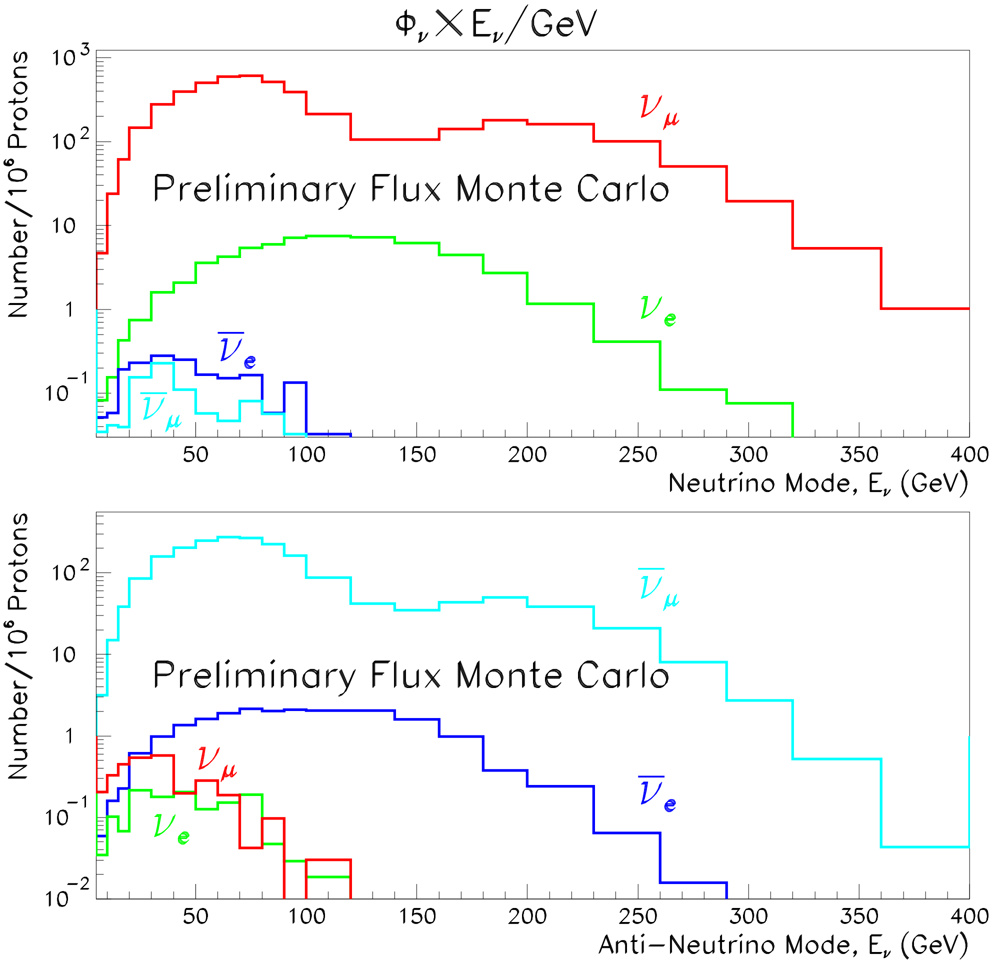



## Tuning of Beam Monte Carlo

- Can extract $\nu_\mu$ flux from a broad spectrum of CC events
- Tune the MC prediction to match the observed $\nu_\mu$ spectrum
- Reflects small uncertainties in SSQT alignment and large production uncertainties
- Procedure is robust at 0.5% level



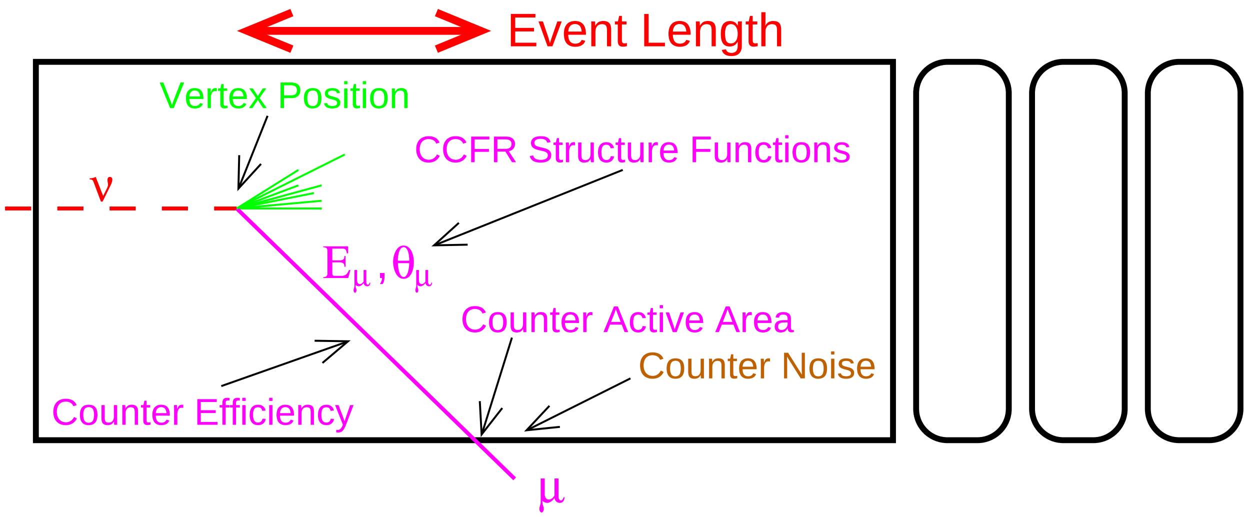
# *PRELIMINARY* NuTeV $\nu_e$ Flux




## Sources of Neutrinos and Event Fractions

| Source | $\nu$ Mode | $\overline{\nu}$ Mode |
|---|---|---|
| $\pi^{\pm}_{\mu 2}$ | 0.786 | 0.856 |
| $K^{\pm}_{\mu 2,\mu 3}$ | 0.201 | 0.133 |
| $K^{\pm}_{e3}$ | $0.0124 \pm 0.00015$ | $0.0081 \pm 0.00012$ |
| $K_{Le3}$ | $0.00047 \pm 0.00009$ | $0.00153 \pm 0.00030$ |
| $\mu \to \nu_e$ | $0.00020 \pm 0.00002$ | $0.00096 \pm 0.00010$ |
| Charm Meson$\to \nu_e$ | $0.00021 \pm 0.00004$ | $0.00069 \pm 0.00012$ |
| $\Lambda_c \to \nu_e$ | $0.00007 \pm 0.00004$ | $0.00022 \pm 0.0001$ |

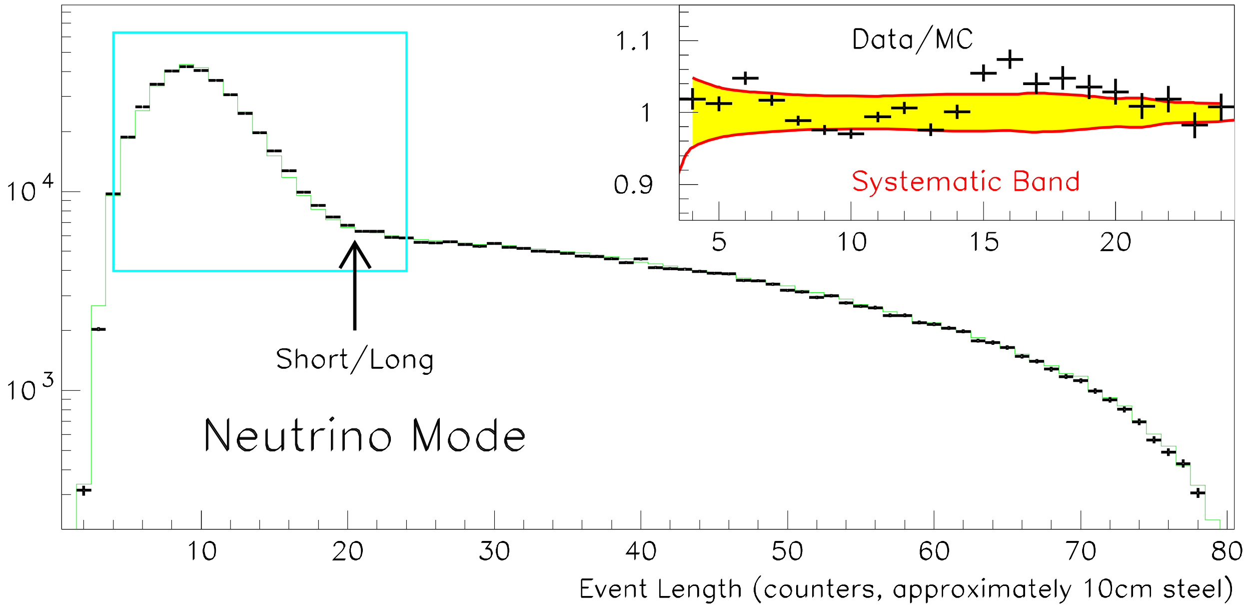
# Detector Effects

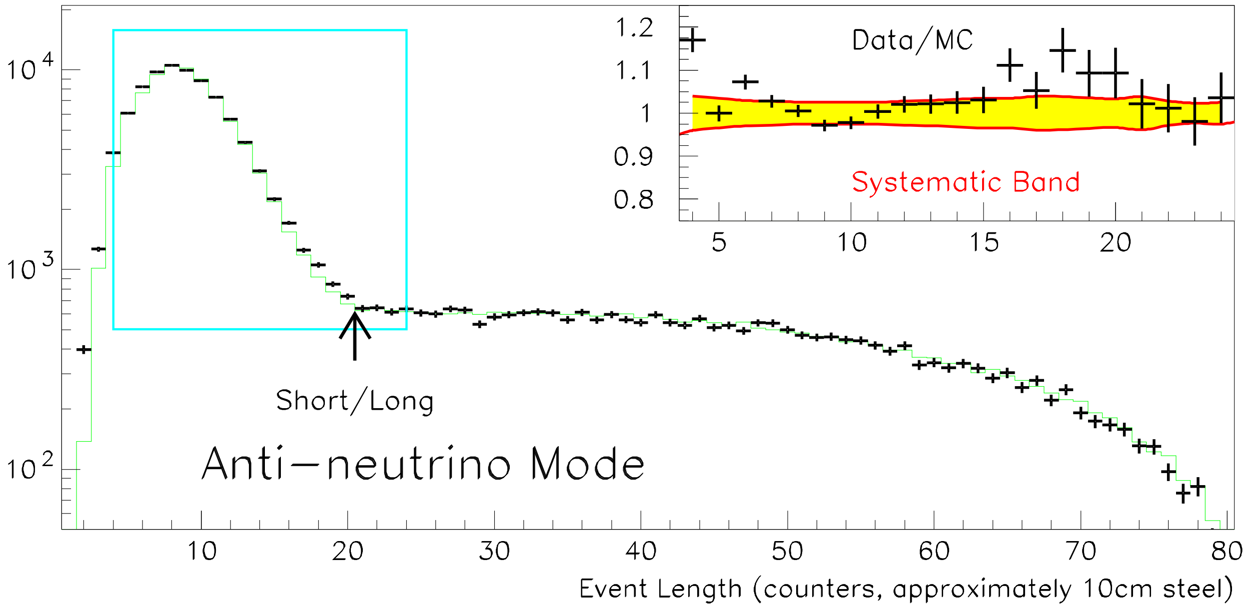



Other sources of experimental uncertainties were kept small through extensive modeling based on $\nu$ and test beam data:

| Effect | Size($\delta\sin^2\theta_W$) | How We Measure |
|---|---|---|
| Longitudinal Vertex Position | 0.001/inch | $\mu^+\mu^-$ events |
| Transverse Vertex Position | 0.001 | monte carlo |
| Counter Noise | 0.00035 | testbeam $\mu$'s |
| Counter Efficiency | 0.0002 | $\nu$ events |
| Counter Active Area | 0.0025/inch | $\mu$'s from $\nu$'s, tb |
| Hadron Shower Length | 0.0015/cntr | tb $\pi$'s, $K$'s |
| Energy Scale | 0.001/1% | testbeam |
| Muon Energy Deposit | 0.004 | $\nu$ and $\mu$ data |

# *PRELIMINARY* NuTeV Event Length Distributions




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

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

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

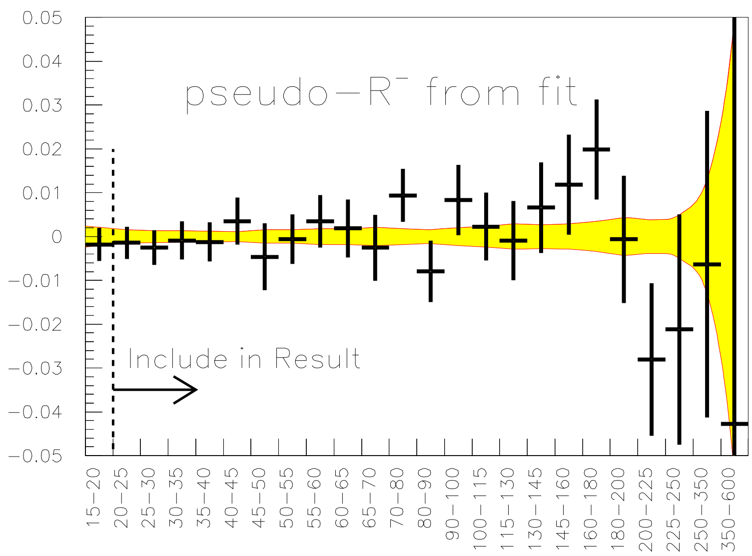
where $R^{\nu,\overline{\nu}} = \sigma^{\nu,\overline{\nu}}_{NC}/\sigma^{\nu,\overline{\nu}}_{CC}$, and $r = \sigma^{\overline{\nu}}_{CC}/\sigma^{\nu}_{CC}$.

NuTeV's approach: Since we have separate $\nu, \overline{\nu}$ samples, we can measure any linear combination of $R^{\nu}, R^{\overline{\nu}}$:

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

- x is chosen to minimize charm production sensitivity (largest cross section uncertainty); sea effects approx cancel in this prescription
- Monte Carlo used to find x and $\tilde{R^-}$ dependence on $\sin^2\theta_W$
- $x \approx 0.514$, $d(\tilde{R^-})/d\sin^2\theta_W \approx -0.636$

$\Delta\tilde{R^-}$
(data-MC)




$\chi^2$/dof is 12/22

shower energy (GeV)

# *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 $\nu_e$'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 |

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## 1-Loop Electroweak Radiative Corrections

Calculation from Bardin, Dokuchaeva JINR-E2-86-2 60 (1986)

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

# NuTeV vs CCFR

## Reduction of dominant systematic errors:

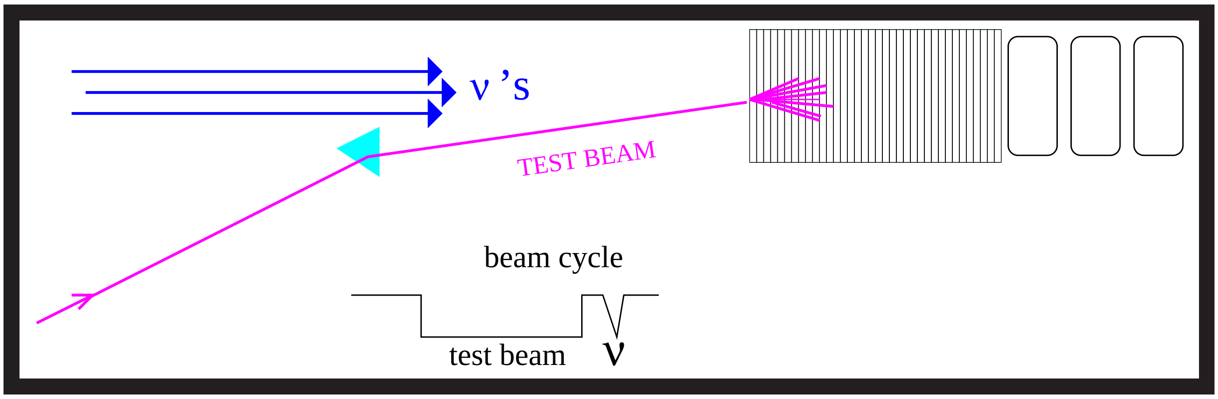
- Charm production → $R^-$ technique
- Electron neutrino contamination → SSQT
  (20% uncertainty in $K_L$ production)

## Beamline is different:

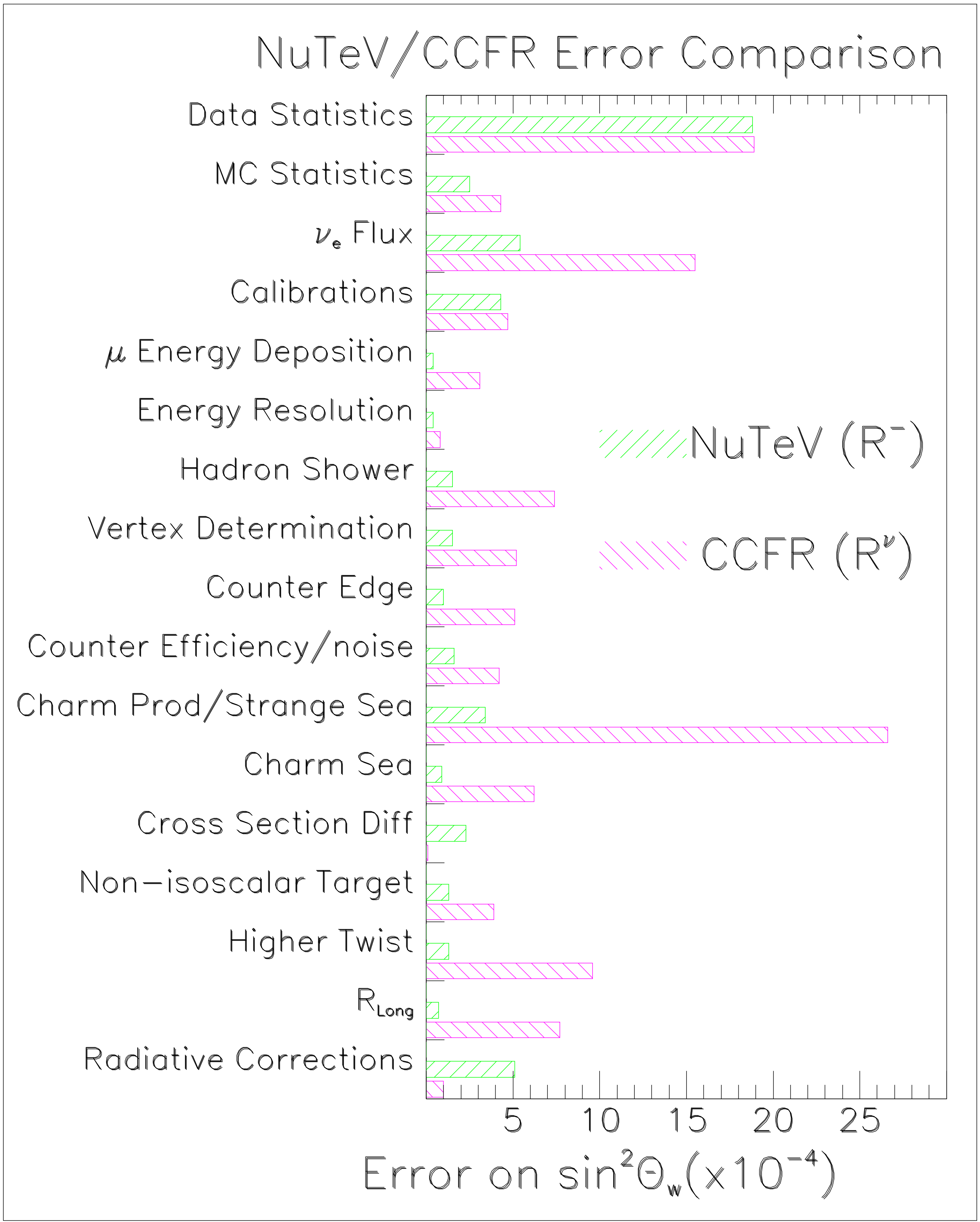
| Beam | $\nu_\mu/\overline{\nu}_\mu$ | Analyzed Neutri nos | $\langle E_\nu \rangle$ | $\nu_e$,$\overline{\nu}_e$ |
|---|---|---|---|---|
| CCFR QT | simultaneous | 0.81M (mixed) | 160 GeV | 2.3% |
| NuTeV SSQT | separate | 1.305M ($\nu$), 0.299M ($\overline{\nu}$) | 125 GeV | 1.8% |

## Calibration using testbeam hadrons and muons:

- CCFR twice
- NuTeV continuous



# *PRELIMINARY* NuTeV and CCFR Uncertainties



# *PRELIMINARY* NuTeV $\sin^2\theta_W$

NuTeV measures:

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

- Measurement is limited by statistics.
- Currently the most precise $\nu N$ measurement of the weak mixing angle.
- Based on a total collected sample of 1.3x10$^6$ $\nu$ events, 0.3x10$^6$ $\overline{\nu}$ events
- First measurement of the Paschos-Wolfenstein ratio.

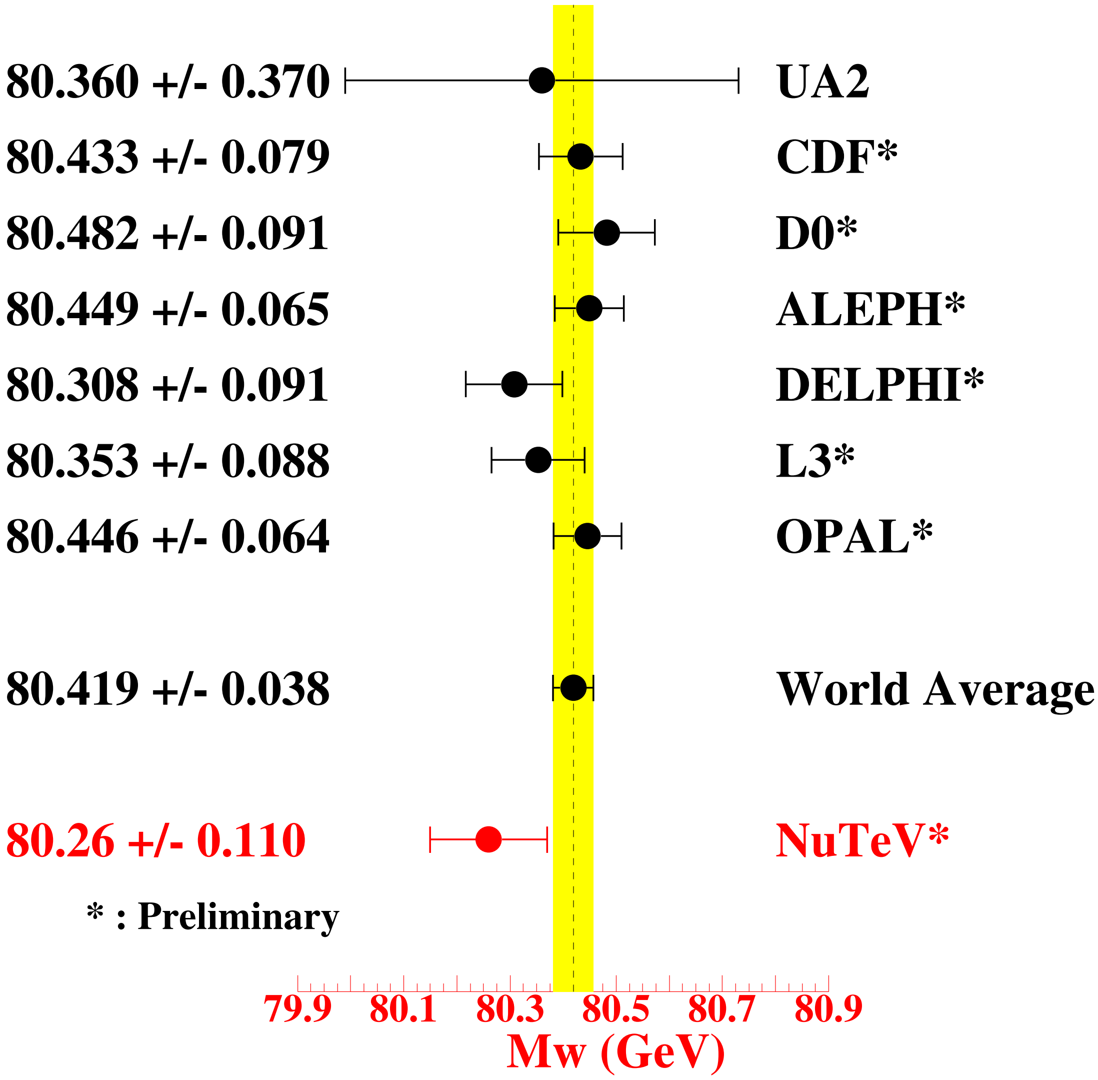
- Experiment and technique yield a precision that is comparable to collider measurements...

# Comparison to Direct $M_W$

Given the precise measurement of the Z mass from LEP...

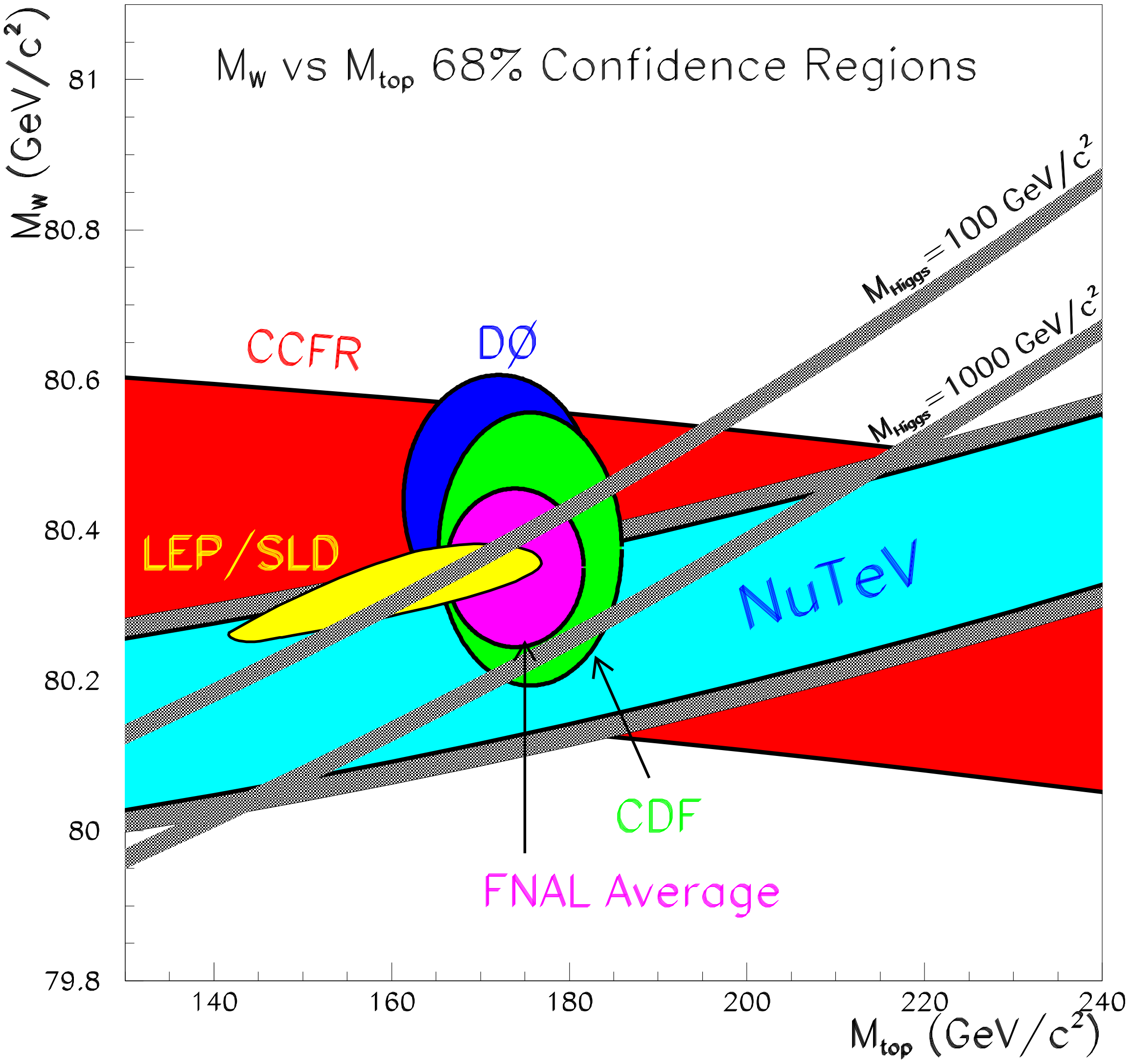
$$\boxed{\sin^2\theta_W^{(\text{on-shell})} \equiv 1 - \frac{{M_W}^2}{{M_Z}^2}}$$

⇒ NuTeV results provides precise determination of the W mass at energies far below W production threshold



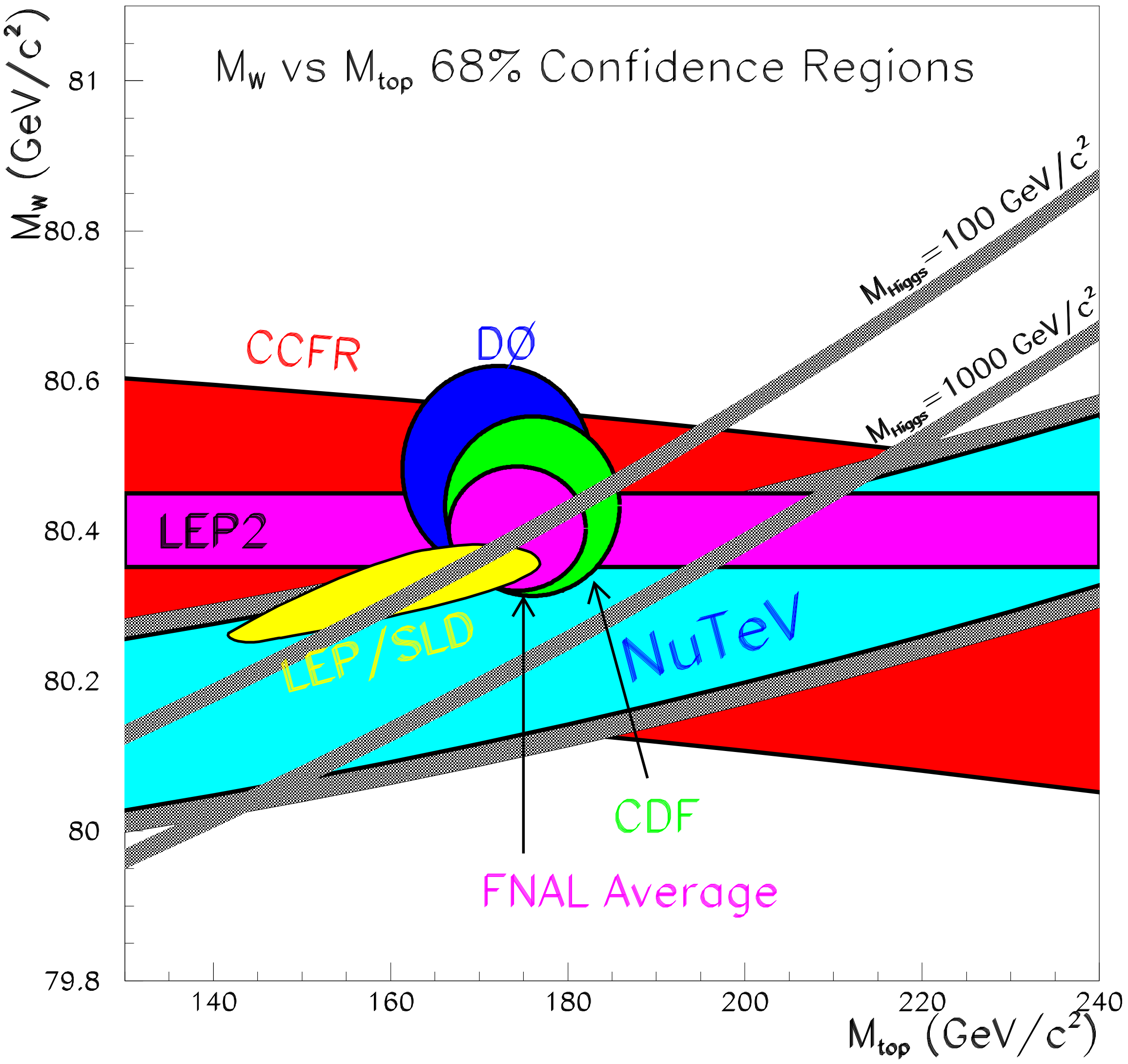
# $M_{\rm top}$ vs. $M_W$

About a year and a half ago...



# $M_{\rm top}$ vs. $M_W$

Current situation...




- Results are in reasonable agreement with each other ⇒ quantitative success of SM
- Global fit indicates preference for light Higgs...
  - ▷ central value $M_{\rm Higgs} = 98 \pm^{57}_{38}$ GeV
  - ▷ $M_{\rm Higgs} \leq 235$ (95% CL)

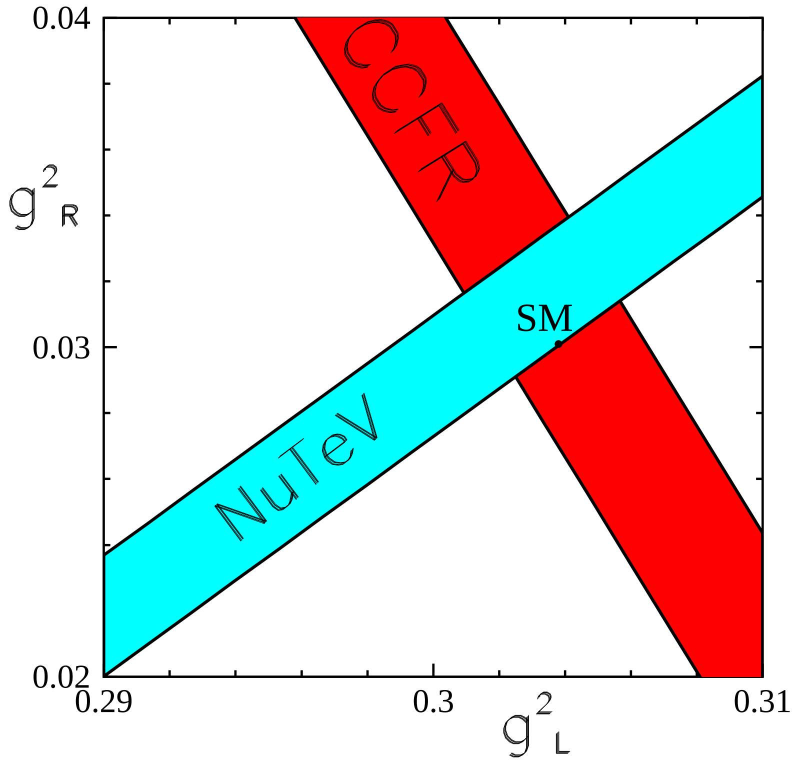
# Model Independent Fit

$R^-$ can be expressed in terms of L and R handed q couplings:

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

To facilitate comparisons with extensions to the SM, what NuTeV measures ($\tilde{R}^-$) can also be used to extract a constraint on the couplings of quarks to the $Z^0$:

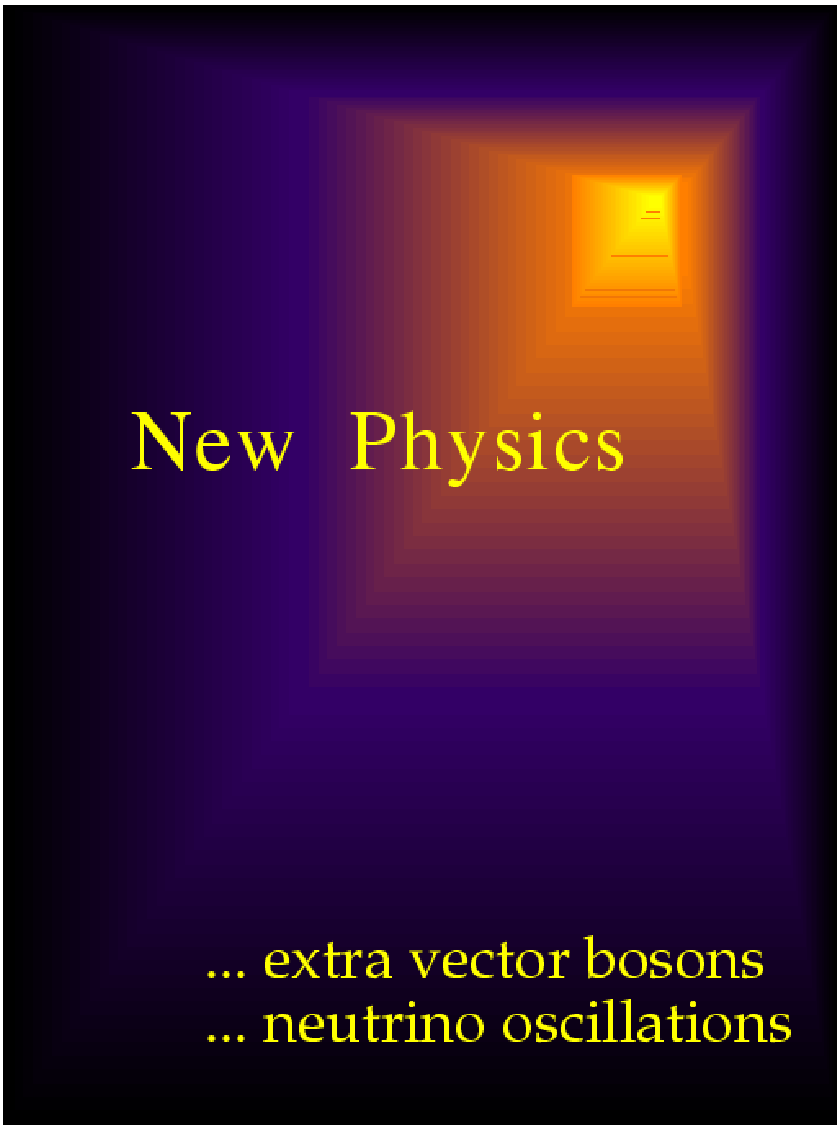
$$0.4530 - \sin^2\theta_W =$$
$$0.2277 \pm 0.0022 \quad =$$
$$0.8587u_L^2 + 0.8828d_L^2 - 1.1657u_R^2 - 1.2288d_R^2$$




$$g^2_{L,R} = u^2_{L,R} + d^2_{L,R}$$

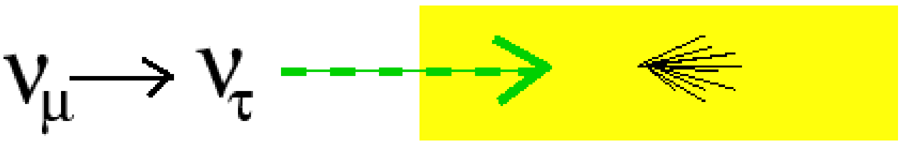
## Beyond the Standard Model

Although the SM agrees well with current electroweak experiments it is important to examine the consequences of ....



# Neutrino Oscillations: Searching for $\nu_\mu \to \nu_\tau$

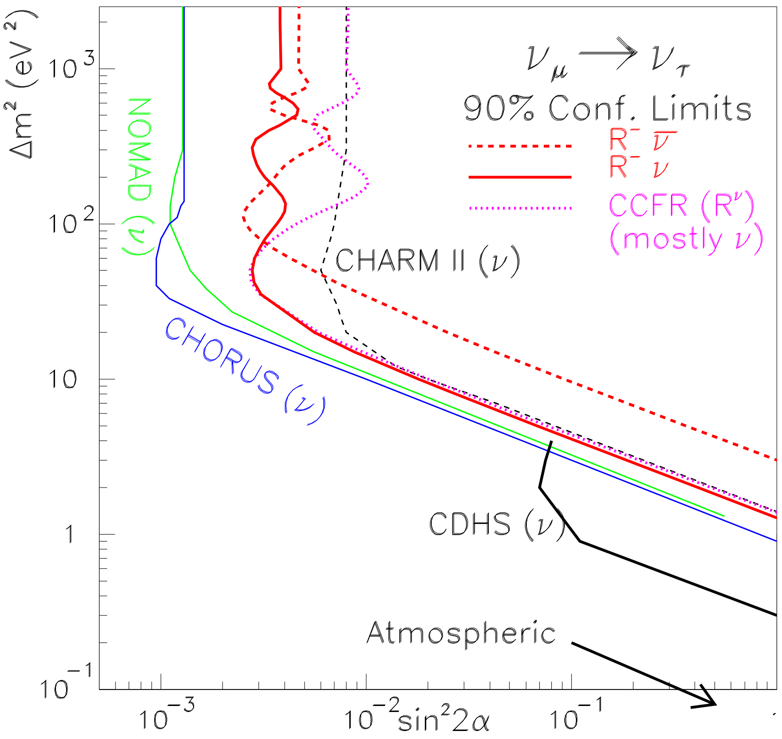
Effect on our $\sin^2\theta_W$ measurement is an observed excess of short events...




- The CC interaction produces a $\tau$.
  For most decay modes, this is lost in the shower
- CC $\nu_\tau$ events will be misidentified as NC $\nu_\mu$ events!
- Changes overall level of and shape of NC/CC ratio

$\Rightarrow$ Look for $E$-dependent variations to $R^-$

- The first limit on $\bar{\nu}_\mu \to \bar{\nu}_\tau$
- An important proof of principle for future $\nu$ osc experiments (MINOS)



# New Physics: Extra Z Bosons

Any new physics contribution to NC processes:

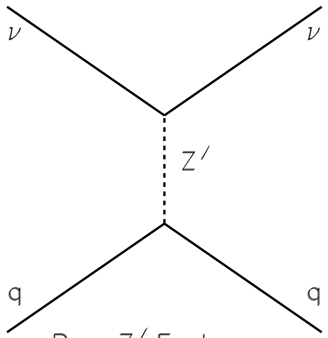
$$M^{ff'}_{\alpha\beta}(q^2) = M^{ff'}_{\alpha\beta}(q^2)_{SM} + \eta^{ff'}_{\alpha\beta}(q^2)$$

Presence of new interactions leads to shift in q couplings:
(Langacker, et al. Rev Mod Phys <u>64</u>,(1992))

$$q_\beta = q_\beta^{SM'} + \delta q_\beta$$

$$q_\beta = q_\beta^{SM'} + \eta^{\nu q}_{L\beta}$$

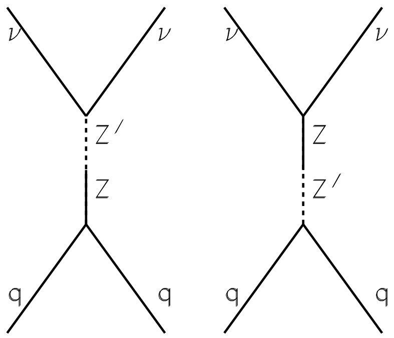
where q=u,d and $\beta$=L,R



Pure Z′ Exchange

If the new physics is the result of an extra neutral vector boson:

$$\delta q_\beta = \frac{g_E^2 Q_E^{Z'\,\nu} Q_E^{Z'\,q}}{2\sqrt{2} G_F M_{Z'}^2}$$ Low E data



Z − Z′ Interference

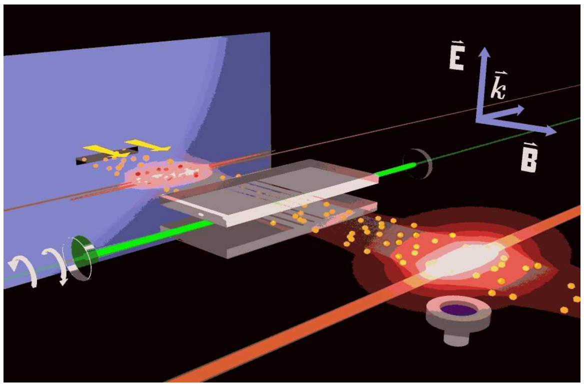
$$\tan^2\theta = \frac{M_0^2 - M_Z^2}{M_{Z'}^2 - M_0^2}$$ Z pole data

Consider constraints on extra Z bosons in $E_6$ models:

$$Z' = Z_\chi cos\beta + Z_\psi sin\beta$$

# Beyond the SM: Extra Z Bosons Motivation

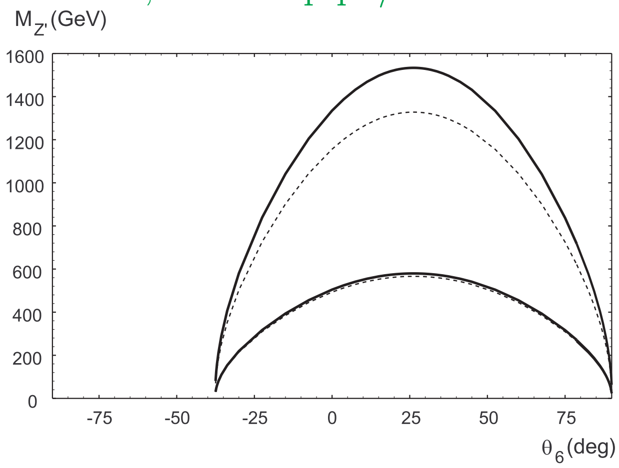
- Many GUT and string models → Z′
- Recent APV measurement (JILA/Boulder;Ce):
  Bennett,S.C. and Wieman,C.E. PRL 82, 2482-2487 (1999)

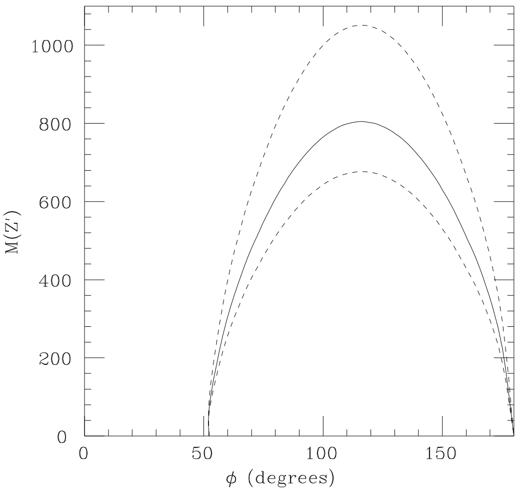



$Q_W = -72.06(28)_{exp}(34)_{theory}$ $\Rightarrow$ 2.5$\sigma$ deviation from SM

Recent analyses have shown this deviation could be explained by the inclusion of a new (unmixed) neutral vector gauge boson $Z'$:

Casalbuoni, et al. hep-ph/0001215




Rosner hep-ph/9907524

w/ a mass above present exp limits ($M_{Z'}$ >600 GeV) for a range $-20^o \leq \beta \leq 70^o$

# Beyond the SM: Extra Z Bosons
# Global Fits to EW data

- Global fits also show some evidence that these fits are preferred: Langacker and Erler, PRL 84, 212-215 (2000)

  SM: $\chi^2 = 41.88/37$ dof $\rightarrow$ $\chi^2 = 35.35/35$ dof

  Fit suggests a TeV scale $Z'$ with small mixing:

$$mZ_\chi = 812 \text{ GeV}$$
$$\sin\theta = (-1.12 \pm 0.80) \times 10^{-3}$$

- In general, our data tends to disfavor these models...
  - ▷ NuTeV result is $1.3\sigma$ above the SM
  - ▷ Assuming Langacker $Z_\chi = 812$GeV with small mixing increases this discrepancy $\rightarrow$ (becomes a $1.5\sigma$ deviation)

- Though have an allowed region of parameter space...

# NuTeV Limits on Extra Z Bosons

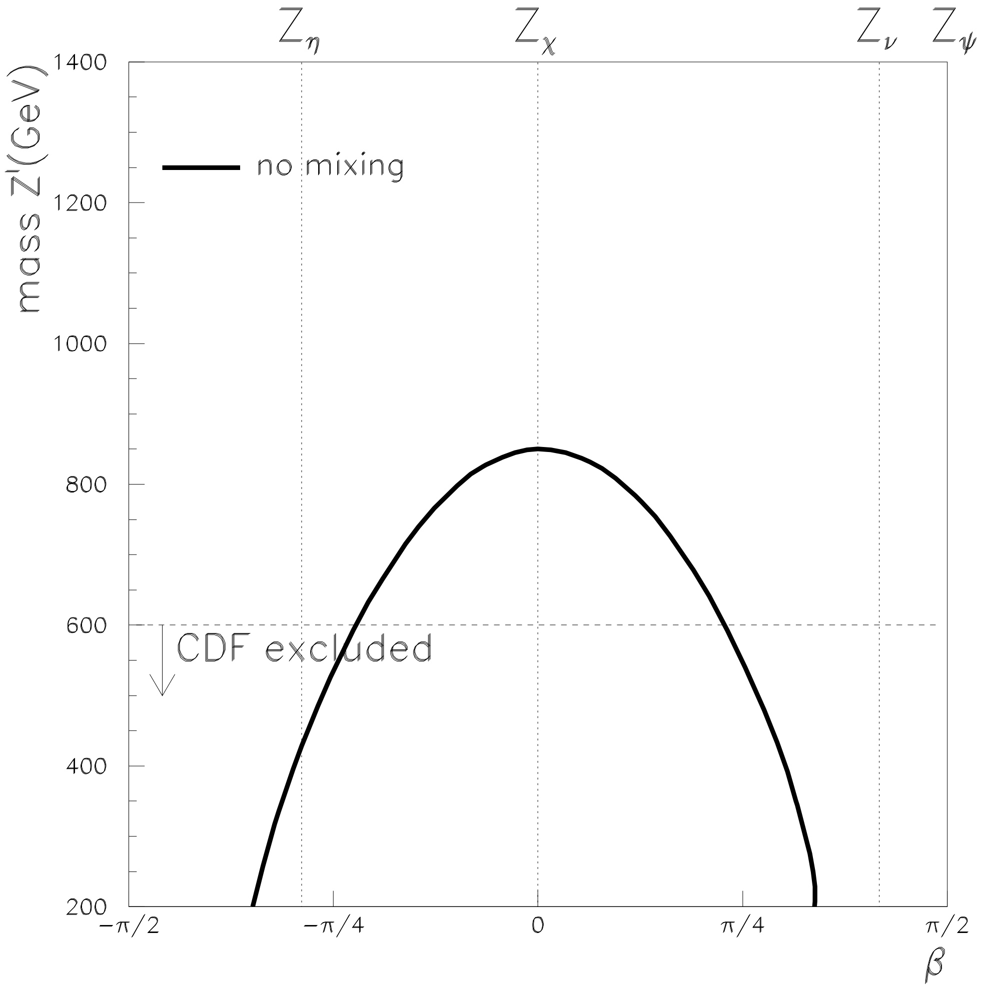
- Our maximum sensitivity is to $Z_\chi$

** <u>ASSUMING NO Z-Z$'$ MIXING</u> **...

$mZ_\chi \geq$ 850 GeV at 95% CL (mixing=0)
$mZ_\eta \geq$ 428 GeV at 95% CL (mixing=0)

<u>95% Confidence Level Lower Mass Limits on $Z'$</u>

$$Z' = Z_\chi cos\beta + Z_\psi sin\beta$$



# NuTeV Limits on Extra Z Bosons

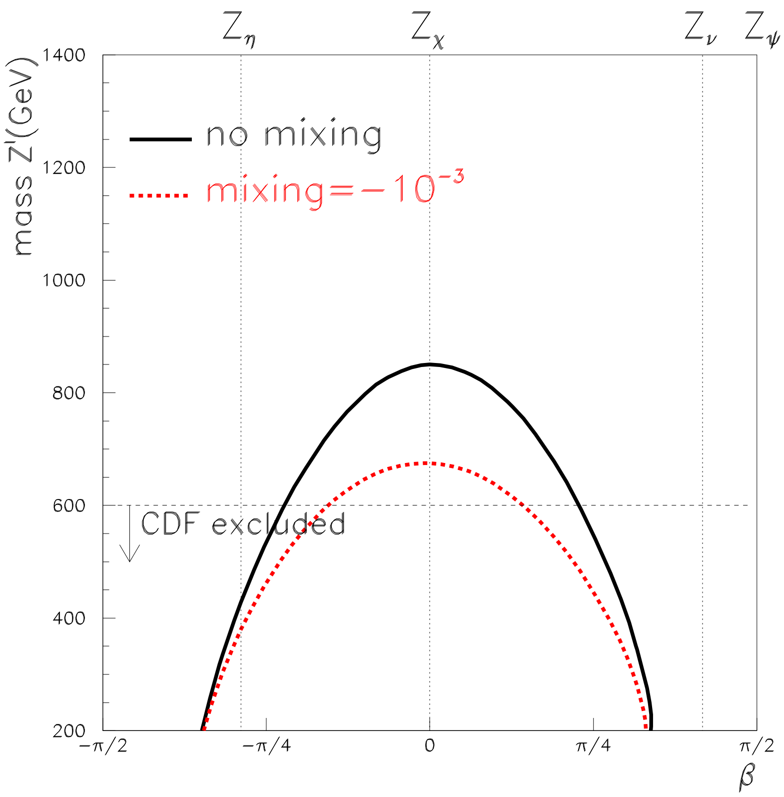
- Allowing mixing weakens limits (but more realistic)...

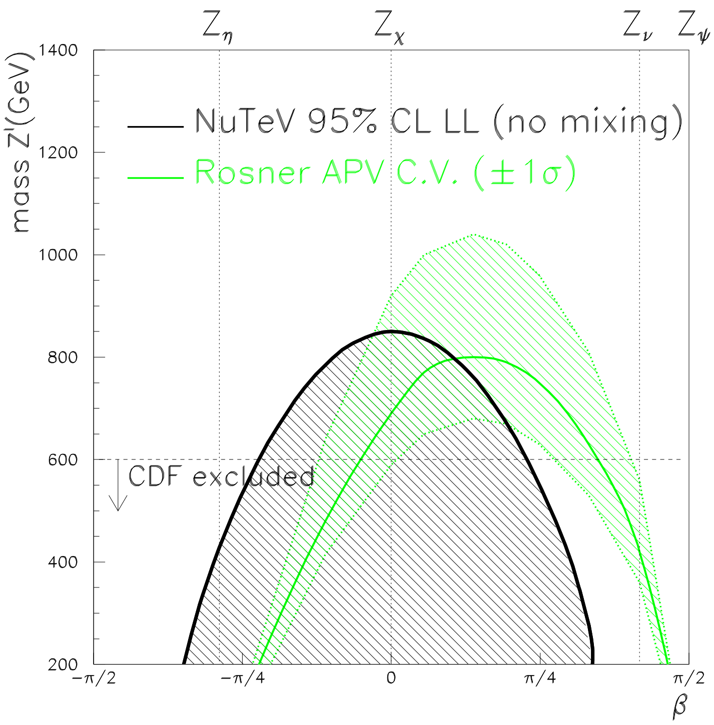
$$mZ_\chi \geq 675 \text{ GeV at 95\% CL} \quad \text{(mixing=-0.001)}$$
$$mZ_\eta \geq 380 \text{ GeV at 95\% CL} \quad \text{(mixing=-0.001)}$$

- Our sensitivity peaks right in the most viable region suggested by APV data

95% Confidence Level Lower Mass Limits on $Z'$

$$Z' = Z_\chi cos\beta + Z_\psi sin\beta$$



# Conclusions

- Within the SM:
  - ▷ NuTeV has measured $\sin^2\theta_W$ from $\nu N$ scattering:

$$\boxed{\begin{array}{c}\sin^2\theta_W{}^{(\mathrm{on-shell})} = \\ 0.2253 \pm 0.0019(\mathrm{stat}) \pm 0.0010(\mathrm{syst})\end{array}}$$

    - ∗ NuTeV $\Rightarrow$ $M_W = 80.26 \pm 0.11\ \mathrm{GeV}/c^2$
      c.f.: World Average $M_W = 80.419 \pm 0.038\ \mathrm{GeV}/c^2$
  - ▷ NuTeV result is consistent with measurements from many different physical processes
  - ▷ Impressive confirmation of the Standard Model across many momentum scales

- Beyond the SM:
  - ▷ Imposes important constraint on new physics
  - ▷ First limit ever on $\bar{\nu}_\mu \to \bar{\nu}_\tau$
  - ▷ Low energy measurement offers complementary information about $Z^{'}$ exchange and interference effects which are suppressed at the Z pole