NuTeV

νN & $\bar{\nu} N$
Deep Inelastic Scattering

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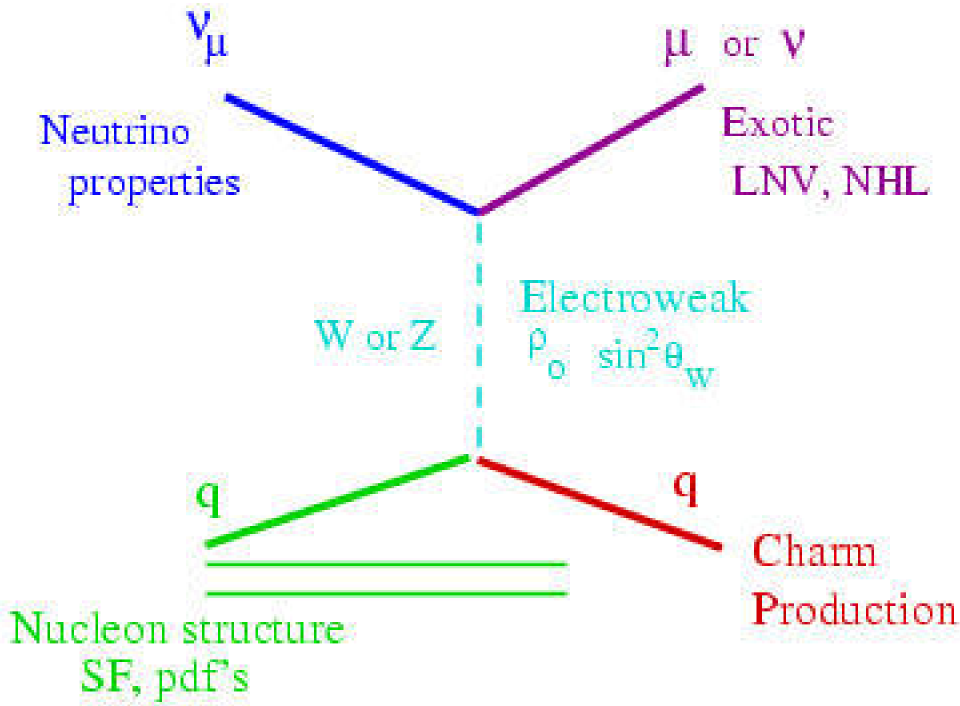

Neutrino Deep Inelastic Scattering

Outline

1. NuTeV Experiment
2. Results *featuring our unique Sign-Selected Beam.*
   - High-purity lepton tag
     - ↪ Charged-Current Charm Production
     - ↪ Neutral-Current Charm Production
     - ↪ Search for Lepton Number Violation
   - Allows new method for extracting $\sin^2\theta_W$.
     - ↪ Precision Electroweak Results
3. Future and Conclusions

The NuTeV Collaboration

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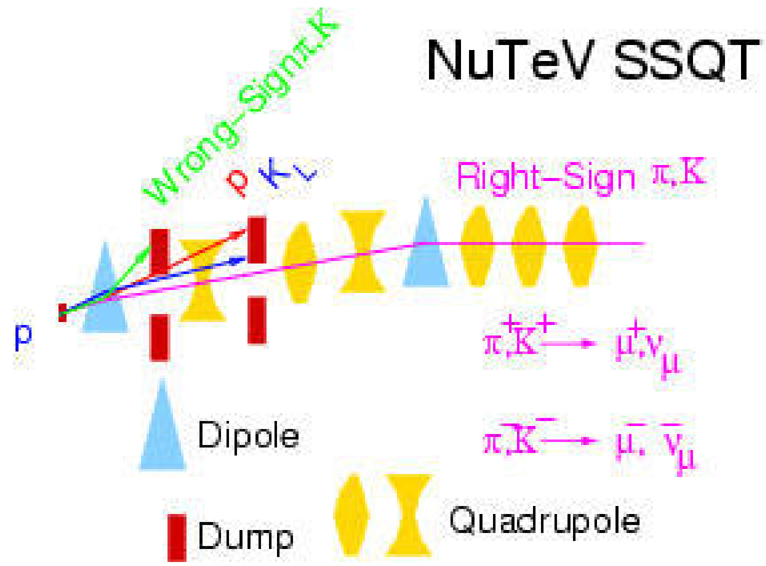
NuTeV's Sign-Selected Beam

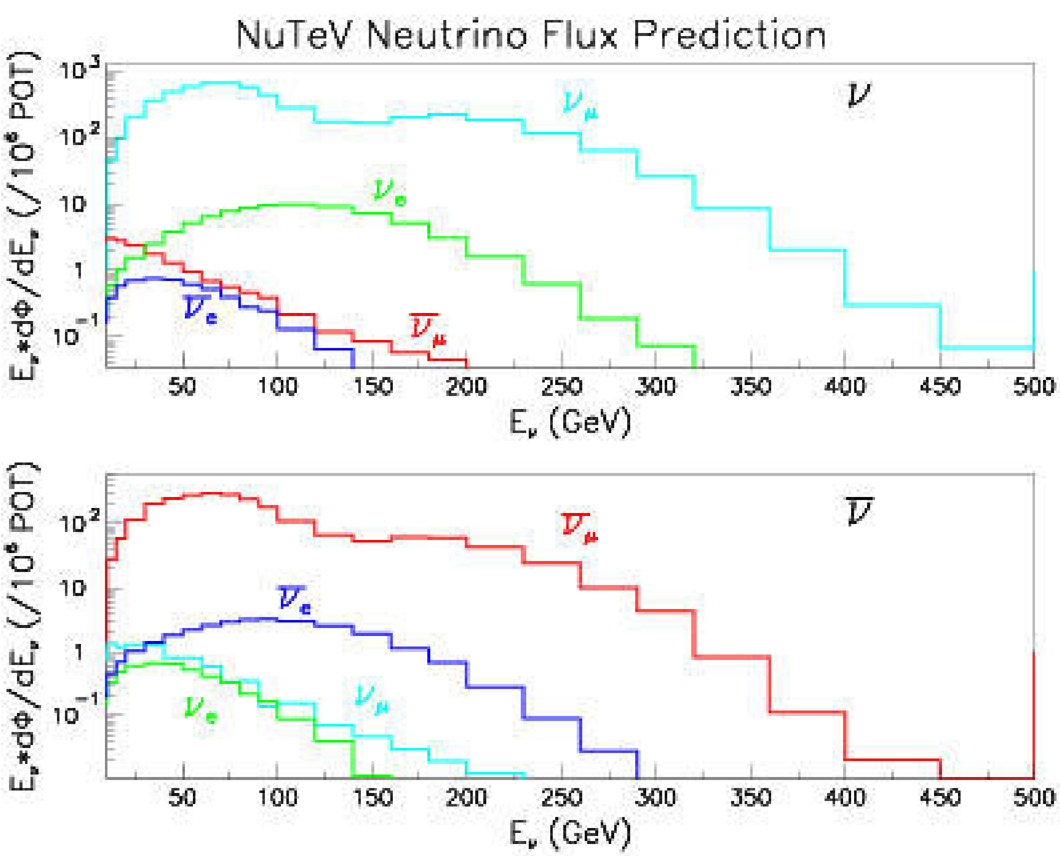


- Dipoles select sign.

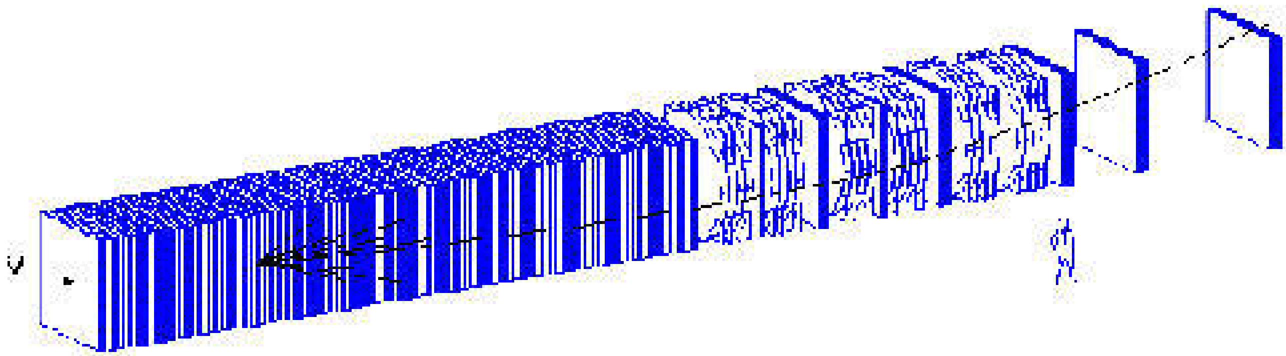
Beam is purely ν or $\overline{\nu}$:
ν mode 3×10^{-4} $\overline{\nu}$
$\overline{\nu}$ mode 4×10^{-3} ν.

- Bend reduces ν_e from K_L.

$\sim$1.6% ν_e fraction better understood.



The NuTeV Detector



690 tons: Fe-Scint-DC

Target Calorimeter

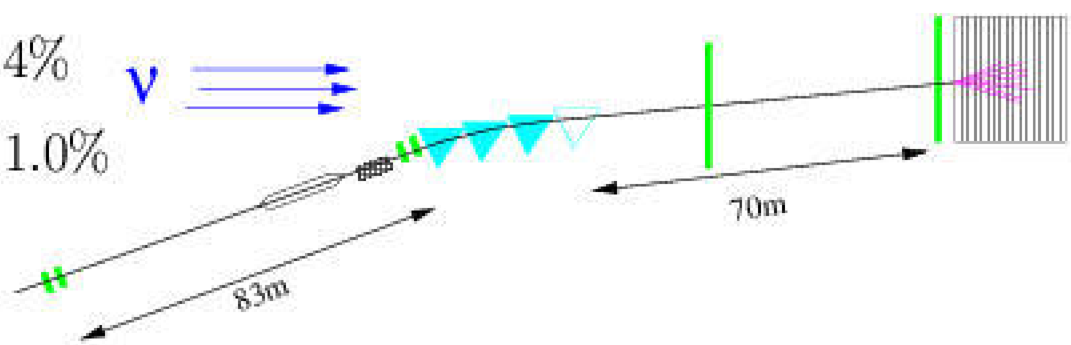
- Steel/Scintillator (10 cm), $\delta E/E \sim 0.86/\sqrt(E)$
- Tracking chambers (every 20 cm Fe)

Toroid Spectrometer

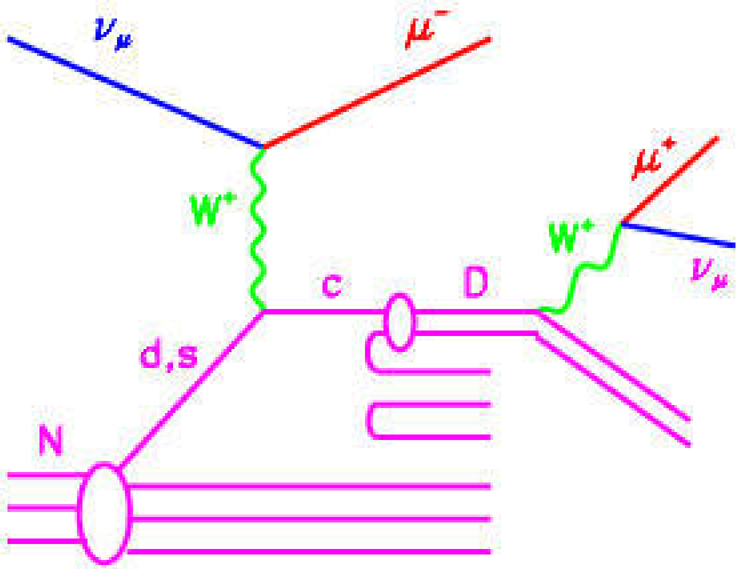
- $B_\phi \sim 15$ kG, $P_T = 2.4$ GeV/c.
- $\delta P/P \sim 11\%$.
- Always focussing for primary muon.

Continuous Test Beam

- Calorimeter to 0.4%
- Spectrometer to 1.0%

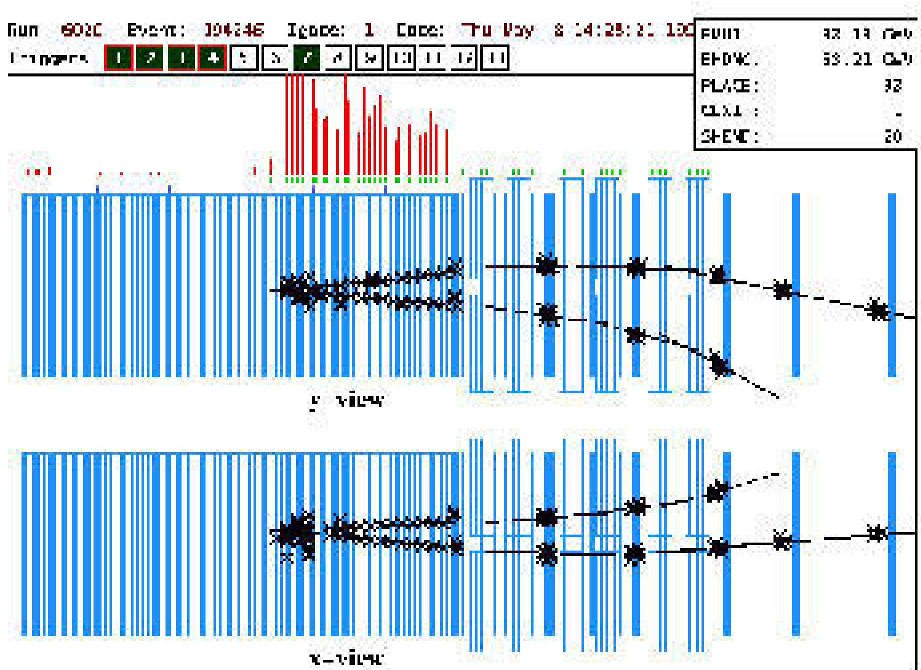


Charged-Current Charm Production



- Coarse-grained detector observes $c \to \mu^+ X$. Signature: dimuon event.
- Sign-Selected beam $\to$ Tags lead muon

Scattering off $d(\bar{d})$ is Cabibbo suppressed $|V_{cd}|^2 \sim 0.05$,
$\to$ strange sea is important. 50% ν, 90% $\bar{\nu}$



Leading Order Charm Production

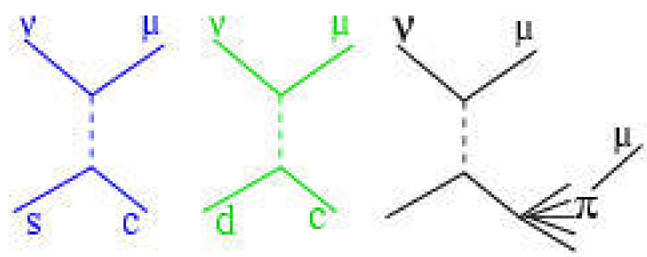
Technique: Extract parameters for charm production within a Specific model → Leading order slow-rescaling.

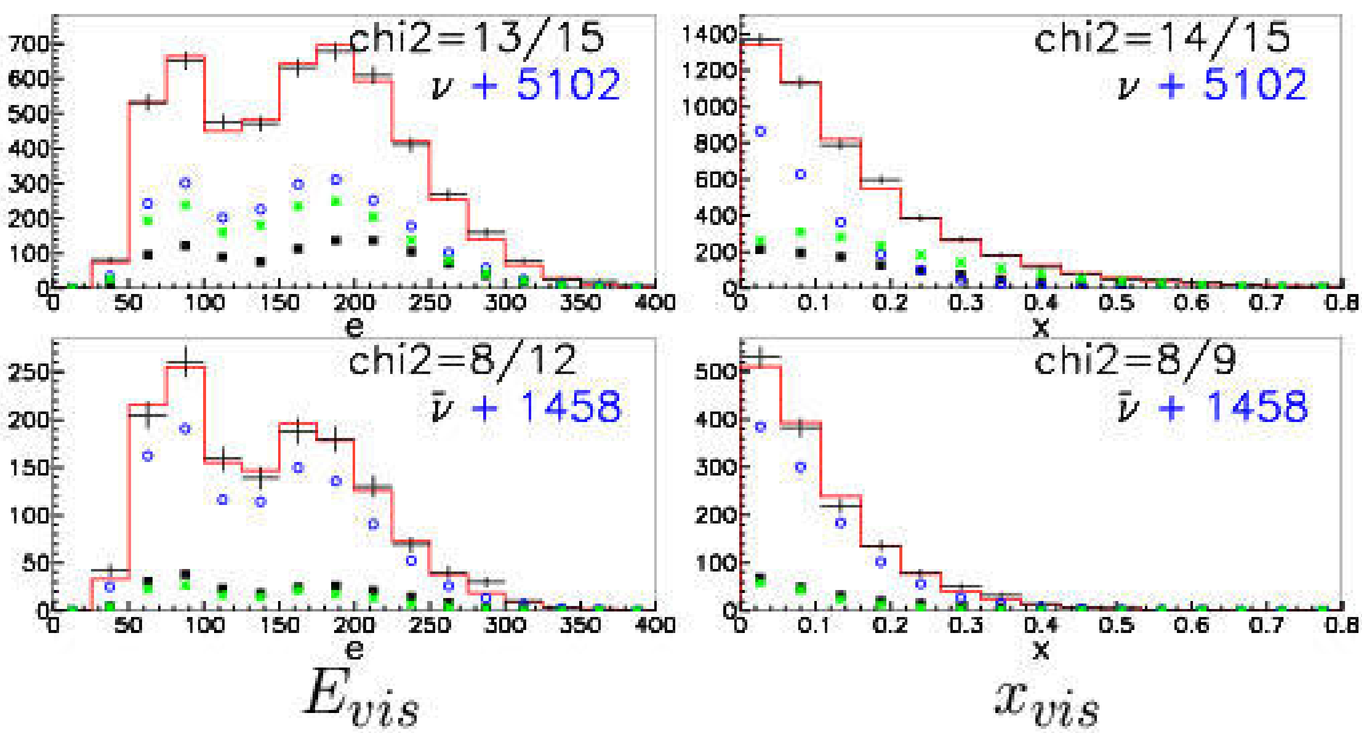
$$\frac{d^3\sigma(\nu_\mu N \to \mu^- \mu^+ X)}{d\xi\, dy\, dz} = \frac{d^2\sigma(\nu_\mu N \to cX)}{d\xi\, dy}\, D(z)\, B_c(c \to \mu^+ X),$$

$$\frac{d^2\sigma(\nu_\mu N \to cX)}{d\xi\, dy} \propto \left(1 - \frac{m_c^2}{2ME_\nu \xi}\right) \left[\frac{[u(\xi,Q^2) + d(\xi,Q^2)]}{2} |V_{cd}|^2 + (s(\xi,Q^2)\, |V_{cs}|^2 \right]$$

- $s(\xi, Q^2)$ strange sea → *Low* x
- m_c charm quark mass → *Low* E

$$x = \frac{Q^2}{2M\nu} \longrightarrow \xi = \frac{Q^2 + m_c^2}{2M\nu}$$

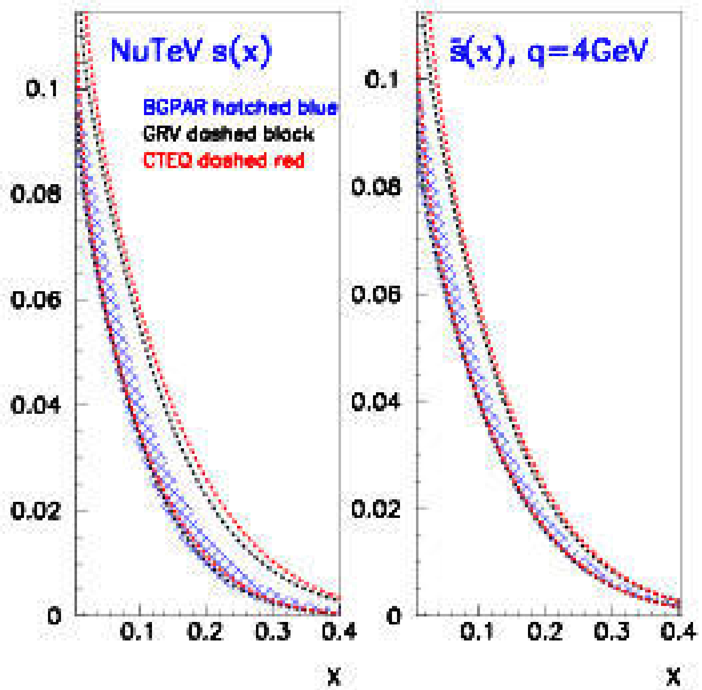




NuTeV Strange Sea

$$s = \kappa \left(\frac{\overline{d} + \overline{u}}{2} \right) (1 - x)^{\alpha}$$

	κ	α
ν	0.38 ± 0.08	-2.07 ± 0.96
$\overline{\nu}$	0.39 ± 0.06	-2.42 ± 0.45



LO Strange Sea ~40% of light quark seas.

Strange Anti-strange sea asymmetry *small*

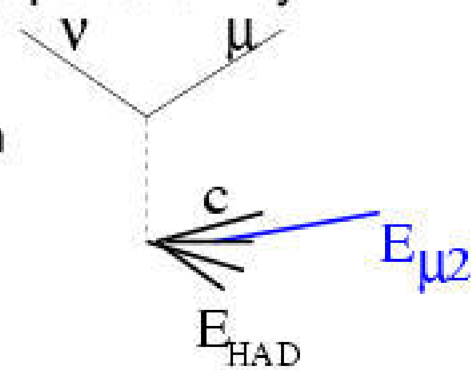
$$\int x\,(s - \overline{s})\,dx = -0.0027 \pm 0.0013$$

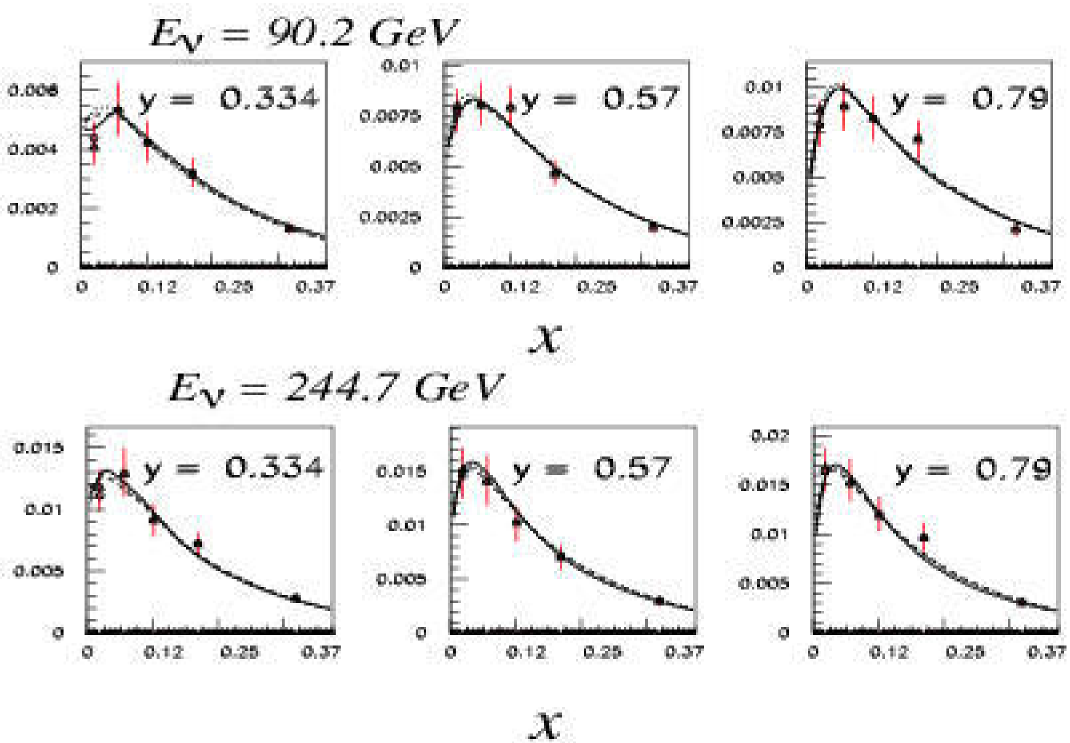
- Other model parameters: $m_c = 1.33 \pm 0.19$ GeV, $\epsilon = 2.07 \pm 0.31$ (Collins-Spiller), $B_c(c \to \mu^+ X) = 11.40 \pm 1.08$.
- Results consistent with previous LO extractions. (CDHS,CCFR,CHARMII,NOMAD)
- Model dependent results difficult to use in global fits.

Dimuon Cross Section

New Method: Present data in model independent way.

- Measure $\left(\frac{d\sigma}{dxdy}\right)_{dimuon}$ Differential Cross section for dimuon production with $E_{\mu 2} > 5\ GeV$
  → *Forward dimuon cross section.*





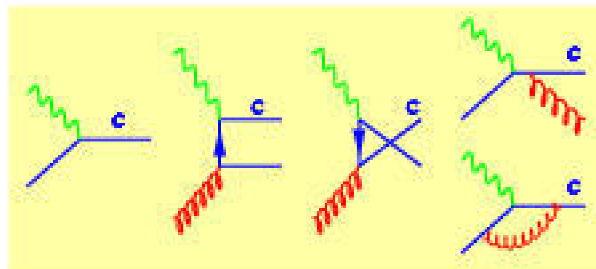
- Three LO fits (CTEQ,GRV,BGPAR) all describe the data well.

Test other models → Apply fragmentation, decay, count fraction of dimuon events with $E_{\mu 2} > 5$ GeV.

Goal: encourage use of νN in global PDF fits.

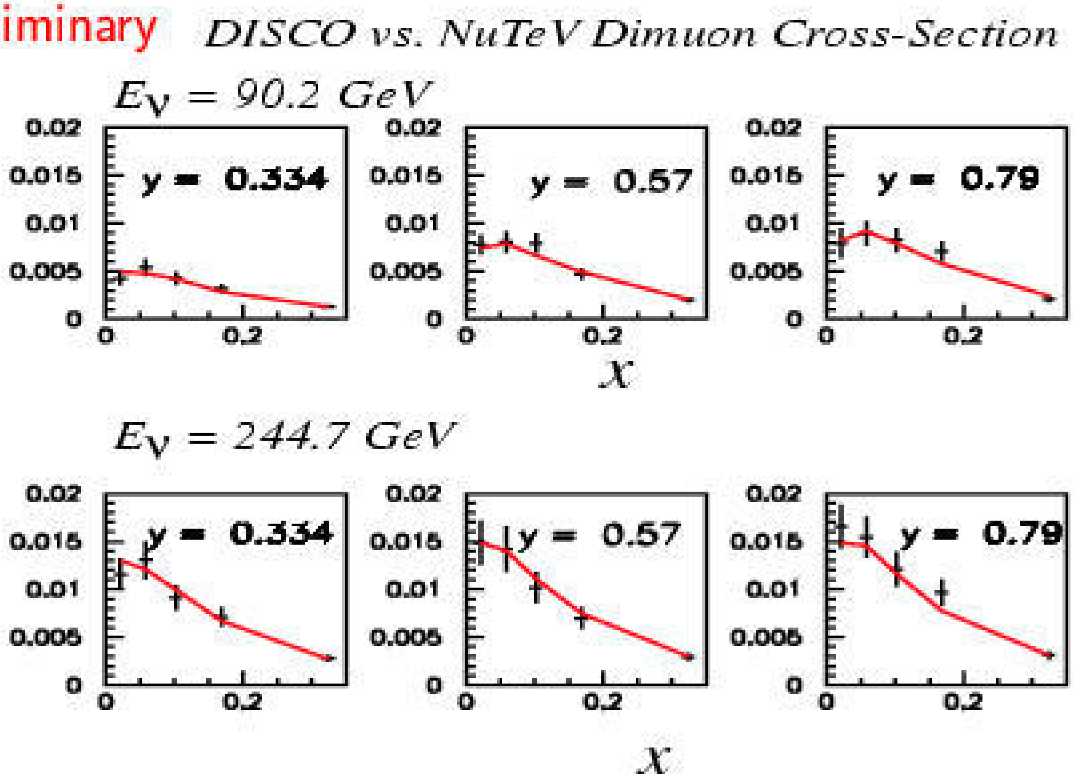
NLO Dimuon Cross Section

- Large LO sea → Gluon initiated diagrams important.
- NLO Cross section does not Factorize



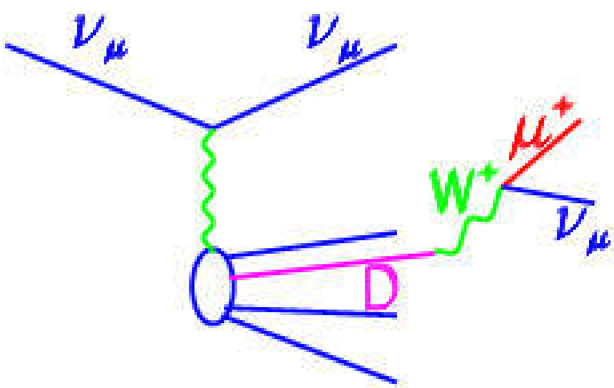
First Model to Test: (S. Kretzer, *et al.*, Phys. Rev. **D65**, 074010 (2002))
Differential dependence includes charm rapidity, η, and z.

Preliminary



- NLO model can describe Forward cross section data with reasonable fit parameters. → NLO acceptance effects on Forward cross section will be small.
- Future: Cross section extraction with NLO model.

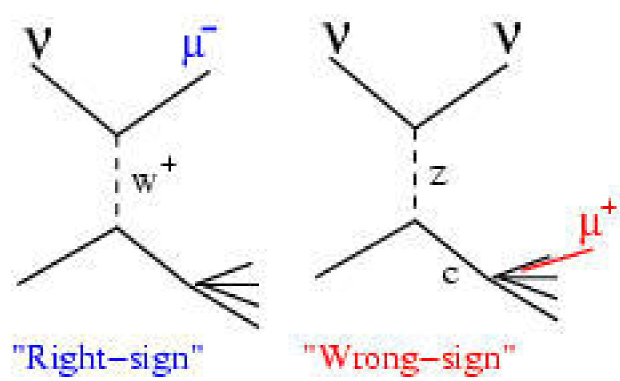
Neutral-Current Charm Production



$\nu_\mu N \to \nu_\mu c\bar{c}X$

- Scattering off the Charm sea
- FCNC $u \to c$

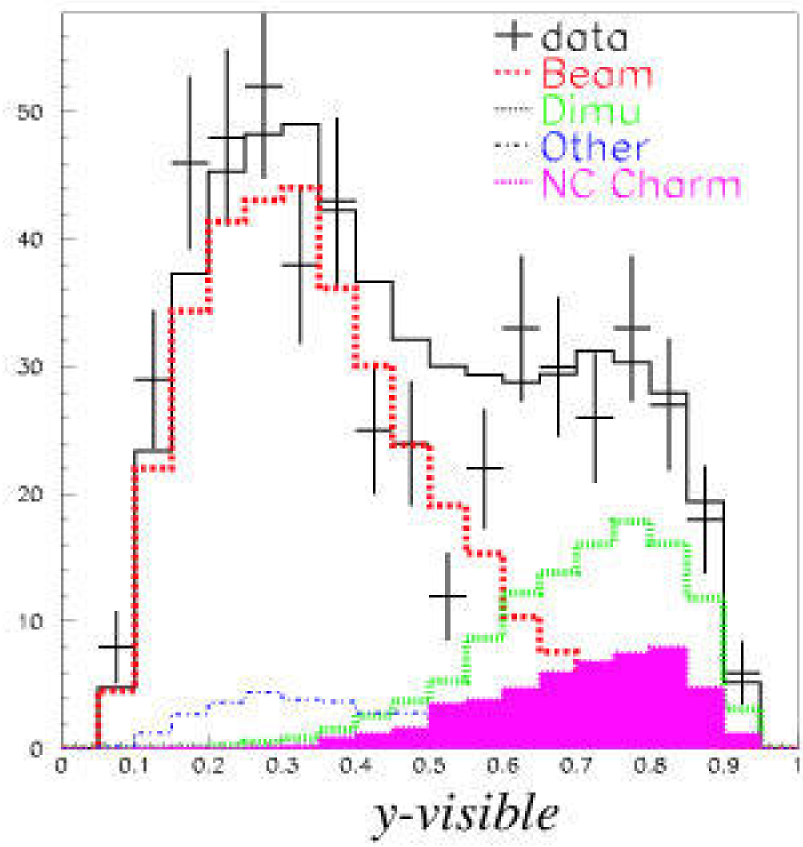
- Single muon final state: Sign-Selected beam $\to$ Tags "Wrong-sign" muon.
- Low beam background.
  ν mode 3×10^{-4} $\overline{\nu}$
  $\overline{\nu}$ mode 4×10^{-3} ν.



NC Charm Production (cont'd)

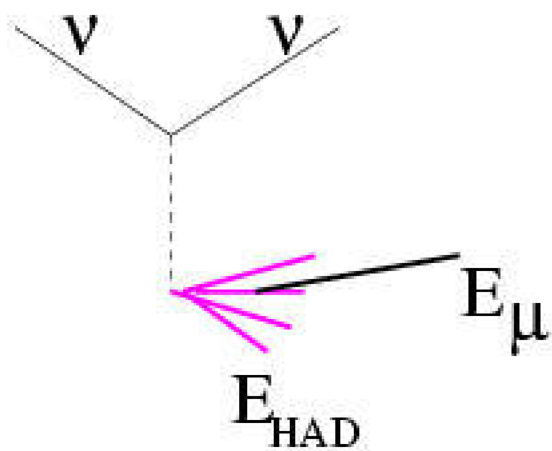
ν mode has higher beam purity. ($12\times$ $\overline{\nu}$ mode)

- Use $\overline{\nu}$ mode "wrong-signs" to tune beam background sources (prompt decays D, K^o).
- ν mode beam background ($\overline{\nu}$'s) are at Low Y_{VIS}



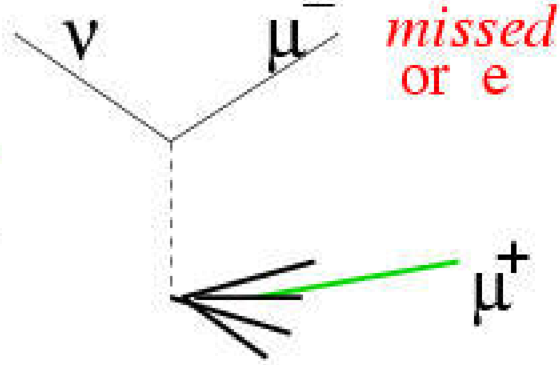
$$Y_{VIS} = \frac{E_{HAD}}{E_{HAD}+E_{\mu}}$$

- Signal at high-Yvis



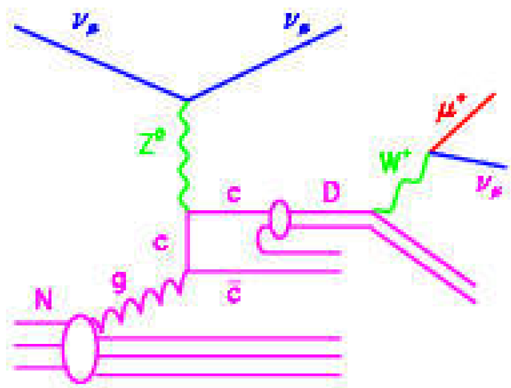
Backgrounds at High-Y_{VIS}

- ν_μ or ν_e CC-charm production. $\rightarrow e$ or undetected μ^-.
- π, K Decays or μ^- Mis-id.



NC Charm Production (cont'd)

- Fit excess for contribution from charm sea (GRV94HO) and $m_c = 1.40^{+0.83}_{-0.36}\ GeV$



$$\sigma(\nu_\mu N \to \nu_\mu c\bar{c}X) = 2.1^{+1.8}_{-1.5} fb$$

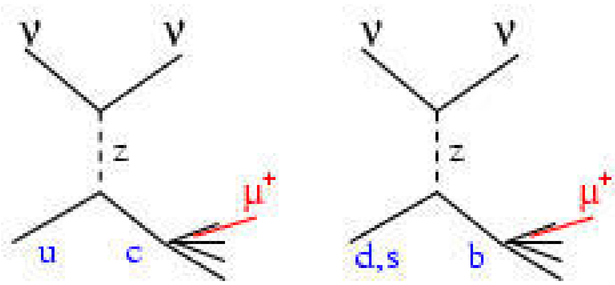
(Average $E_\nu = 154\ GeV$).

$$\frac{\nu_\mu N \to \nu_\mu c\bar{c}X}{\nu_\mu N \to \mu X} \approx 2 \times 10^{-3}$$

- F_2^{charm} for signal consistent with charged-lepton scattering.

Constrain charm sea contribution using other data:

Search for FCNC



- $d, s \to b$ accessible $b \to \mu X$

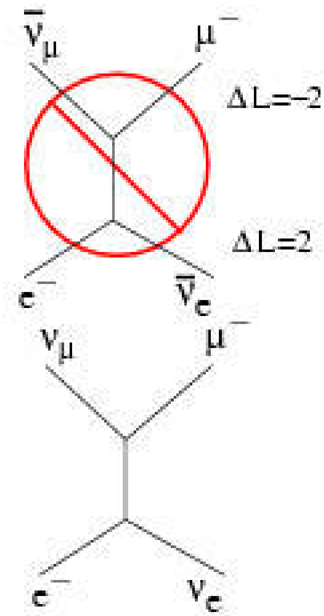
FCNC	90% CL	Decay limits
$u \to c$	3.7×10^{-3}	2.3×10^{-4}
$d \to b$	2.7×10^{-3}	1.6×10^{-3}
$s \to b$	2.9×10^{-2}	2.1×10^{-5}

- Comparable to decay searches for $d \to b$.
- More universal, no dependence on form factors.

Lepton Number Violation

Pure $\overline{\nu}_\mu$ beam allows search for Lepton number violating ($\Delta L = 2$) process: $\overline{\nu}_\mu e^- \rightarrow \mu^- \overline{\nu}_e$

- Allowed in models with multiplicative lepton number conservation, or left-right symmetric models.

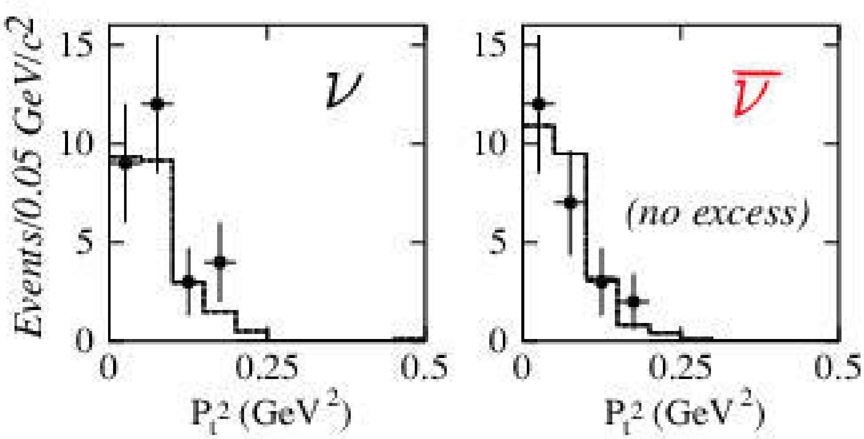


Compare with SM allowed process $\nu_\mu e^- \rightarrow \mu^- \nu_e$ (IMD) measured in ν mode.

Events with:

- No hadronic energy $E_{Had} < 3GeV$
- Kinematic limit $P_T^2(\mu) < 2m_e E_\nu$

- Signal : Wrong signs in $\overline{\nu}$ mode. Background is from beam impurities $\nu_\mu e^- \rightarrow \mu^- \nu_e$ and $\overline{\nu}_e e^- \rightarrow \mu^- \overline{\nu}_\mu$
- ν mode measures IMD rate $\sigma = 13.8 \pm 1.2 \pm 1.4 \times 10^{-42}$ cm^2/GeV.



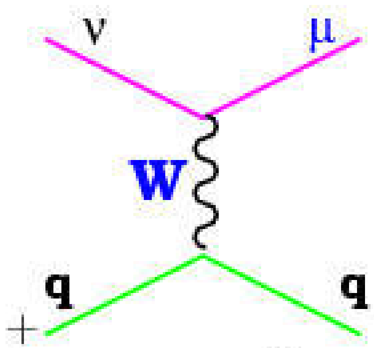
$$\frac{\overline{\nu}_\mu e^- \rightarrow \mu^- \overline{\nu}_e}{\nu_\mu e^- \rightarrow \mu^- \nu_e}$$

< 0.6% (Scalar)

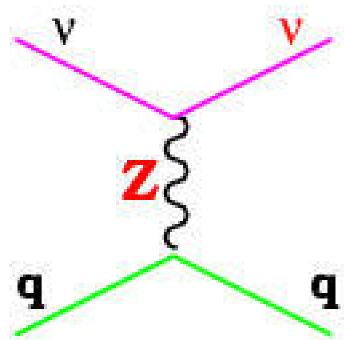
< 1.7% (V-A)

$\Rightarrow 3\times$ improvement

Electroweak Physics with ν's



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



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

With a neutrino beam...

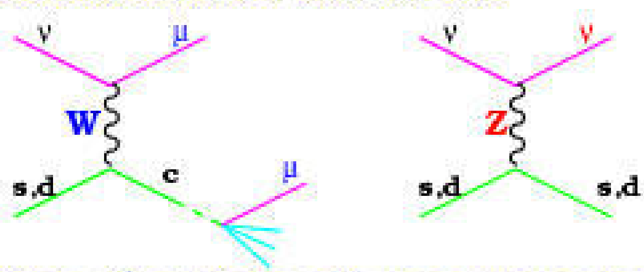
Llewellyn Smith Relation:

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

$\rightarrow$ Many systematic uncertainties, sensitivity to neutrino flux, and SF dependence cancel in the ratio.

Heavy Quark Effects are the major theoretical uncertainty:

- Suppresses CC cross section but not NC.



- Limited precision of previous νN measurements of $\sin^2\theta_W$ ...

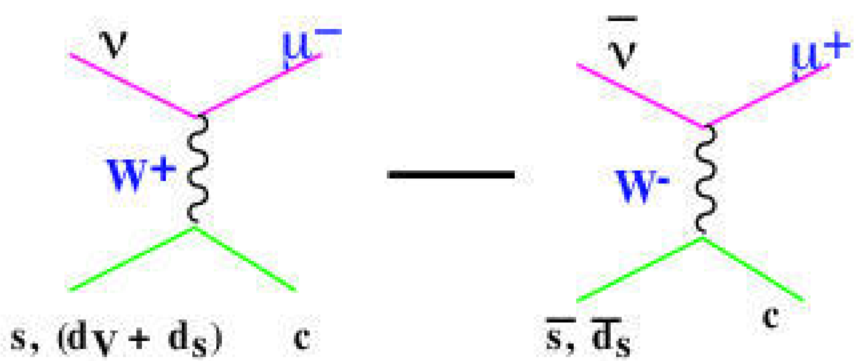
Electroweak Physics with ν's & $\overline{\nu}$'s

With separate ν, $\overline{\nu}$ beams:

<u>Paschos-Wolfenstein Relation:</u>

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

- R^- is insensitive to sea quarks



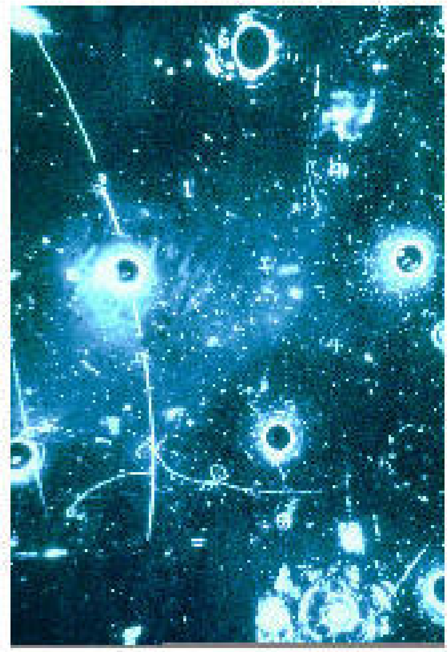
- Strange sea errors negligible
- Massive charm production enters from d_V quarks only (Cabbibo suppressed and at high x)

NuTeV's measurement is 2× more precise than CCFR.

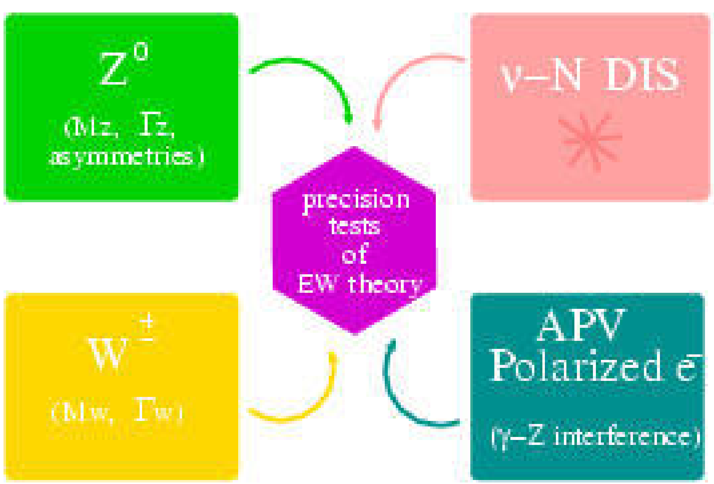
The Role of NuTeV

Neutrino scattering played a key historical role in electroweak unification

- Discovery of Neutral Current (Gargamelle, FNAL-E1A)
- First determination of high-energy parameter $\sin^2\theta_W \sim 0.2 \Rightarrow \frac{M_W}{M_Z} \sim 0.9$



. . . but why continue to study when we make copious on-shell W and Z bosons at colliders?

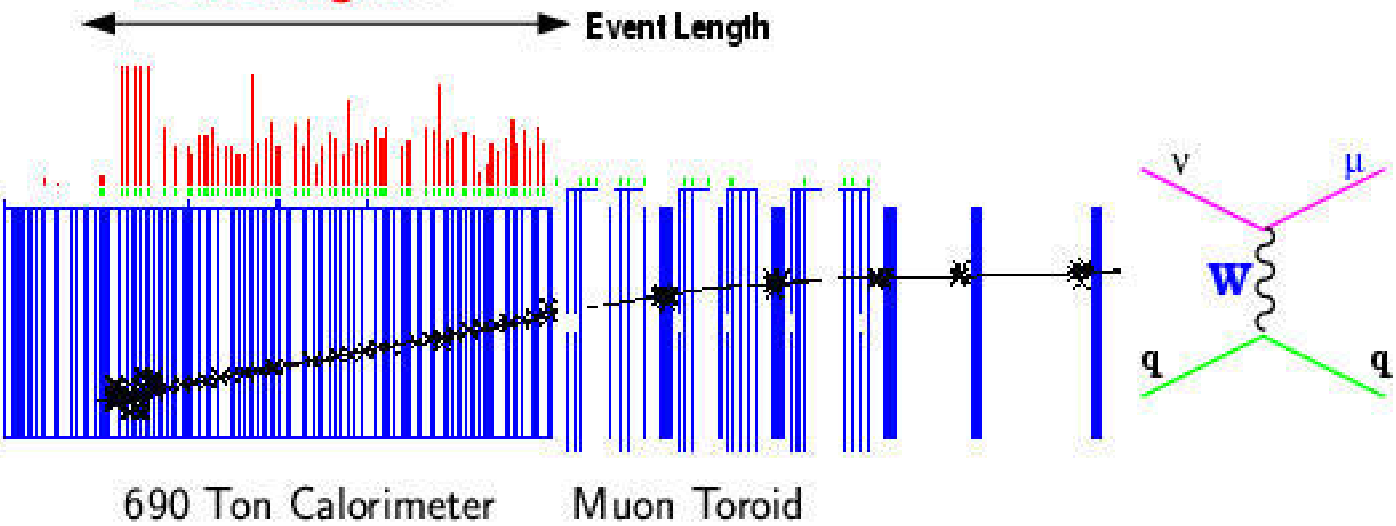


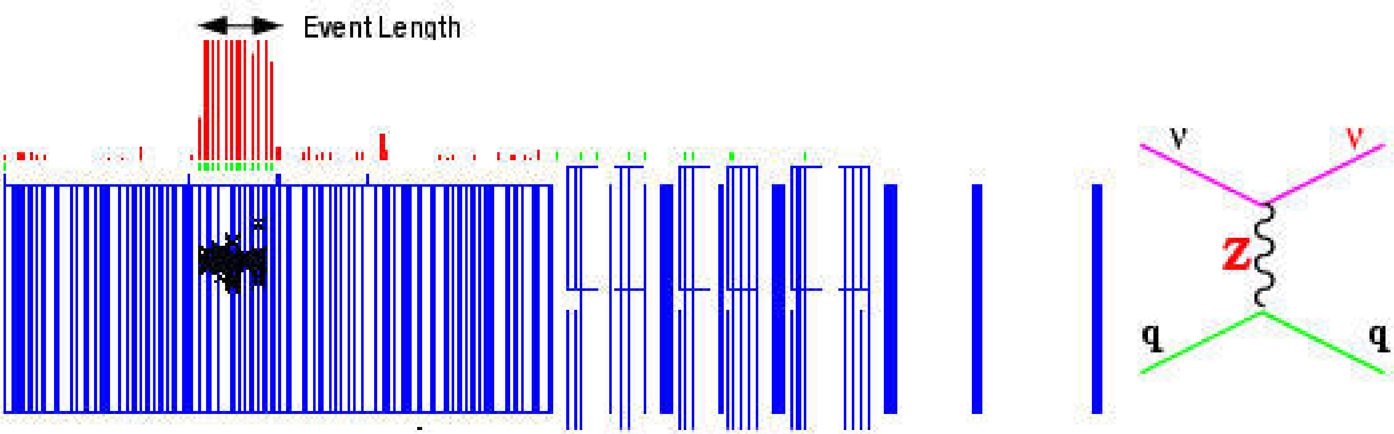
- NuTeV is precise: M_W comparable to collider precision.
- NuTeV is sensitive to different new physics.
- Measurement is off Z pole (contributions besides Z?)
- Measure NC neutrino couplings

- Testing in a wide range of processes and momentum scales ensures universality of the electroweak theory.

NC/CC Event Separation

Statistical separation of NC and CC events based solely on "event length":



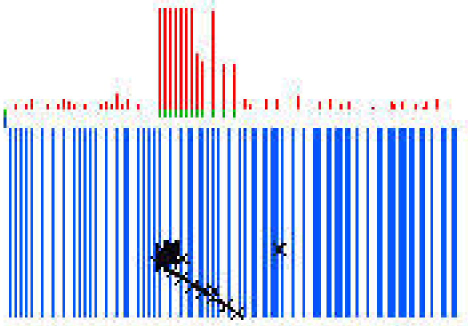


$$R_{\rm exp} = \frac{\text{SHORT events}}{\text{LONG events}} = \frac{\text{L < Lcut}}{\text{L > Lcut}} = \frac{\text{NC candidates}}{\text{CC candidates}}$$

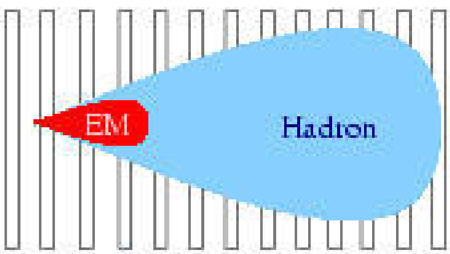
	Short (NC-Like)	Long (CC-Like)	$R_{\rm exp} \equiv \frac{Short}{Long}$
ν	457K	1167K	$0.3916 \pm 0.0007(\rm stat)$
$\overline{\nu}$	101K	250K	$0.4050 \pm 0.0016(\rm stat)$

CC↔NC Contaminations

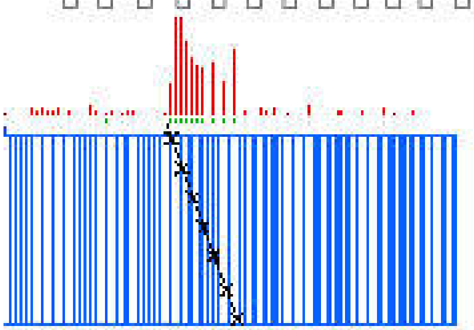
"Short" Sample Contamination



- SHORT ν_μ CC's (20% ν, 10% $\overline{\nu}$)
  muons exit, range out (high y)



- SHORT ν_e CC's (5%)
  $\nu_e N \rightarrow eX$



- Cosmic Rays (0.9%,4.7%)

"Long" Sample Contamination

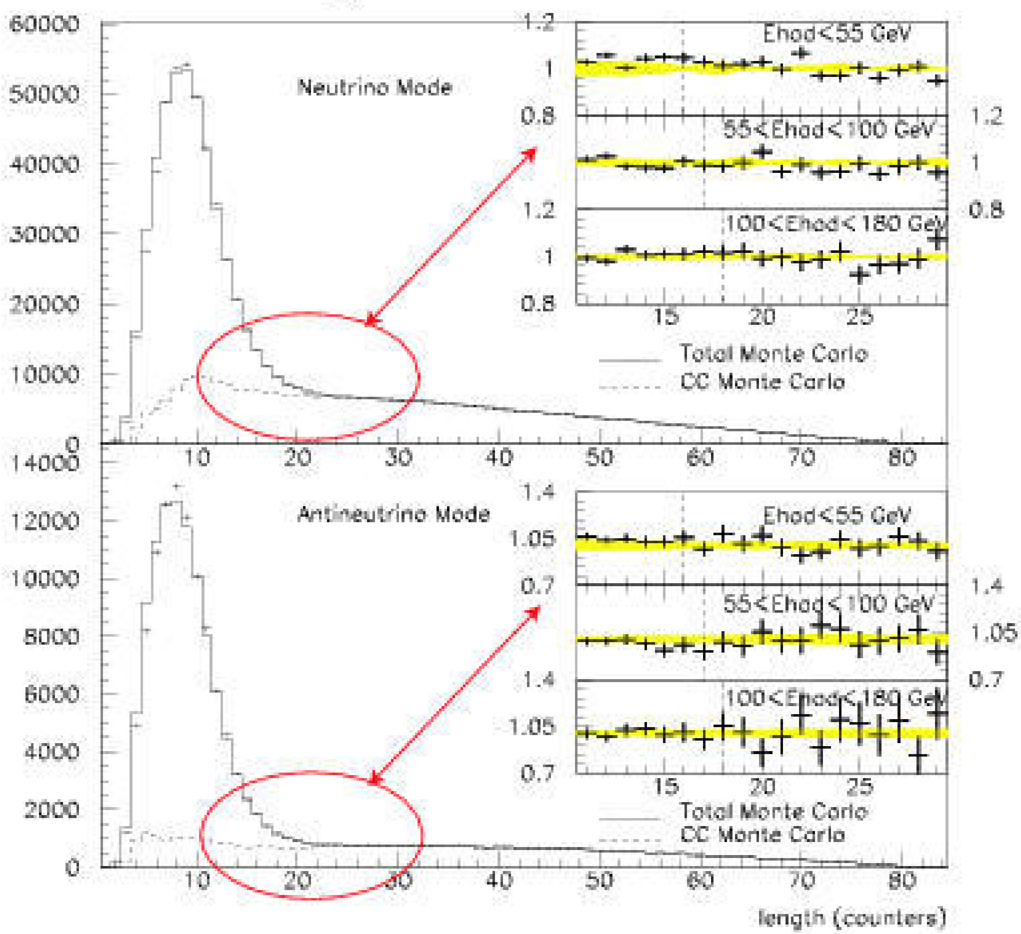
- LONG ν_μ NC's (0.7%)
  punch-through effects

Experimental Technique

Relate R_{exp} to R^{ν} and $R^{\overline{\nu}}$ $(\sin^2\theta_W) \rightarrow$

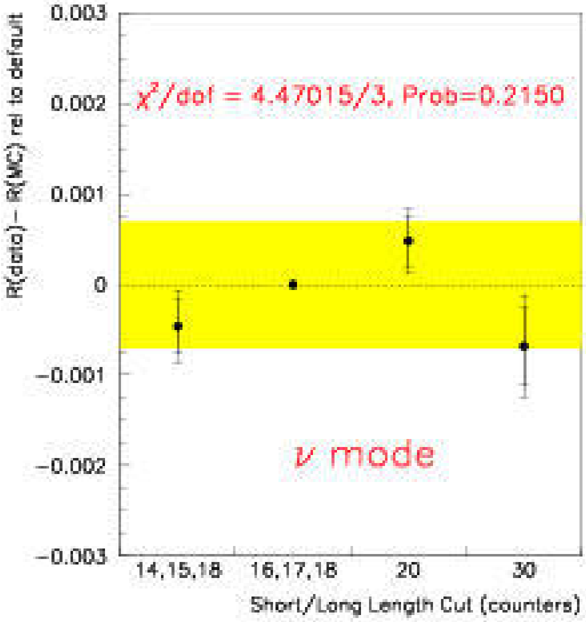
- <u>CROSS SECTION MODEL</u> LO PDFs (CCFR) tuned to data: (Higher twist, R_L, heavy quark corrections, $\overline{d}/\overline{u} \neq 1$).
- <u>DETECTOR RESPONSE</u> Tuned with Test beam and ν data.
- <u>NEUTRINO FLUX</u> (ν_μ and ν_e) using beam simulation tuned to ν_μ(CC) spectrum.

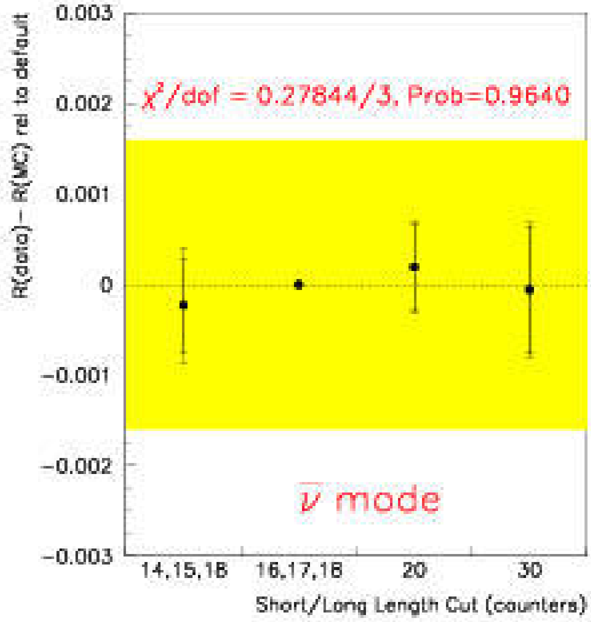
Event Length Data vs. Monte Carlo



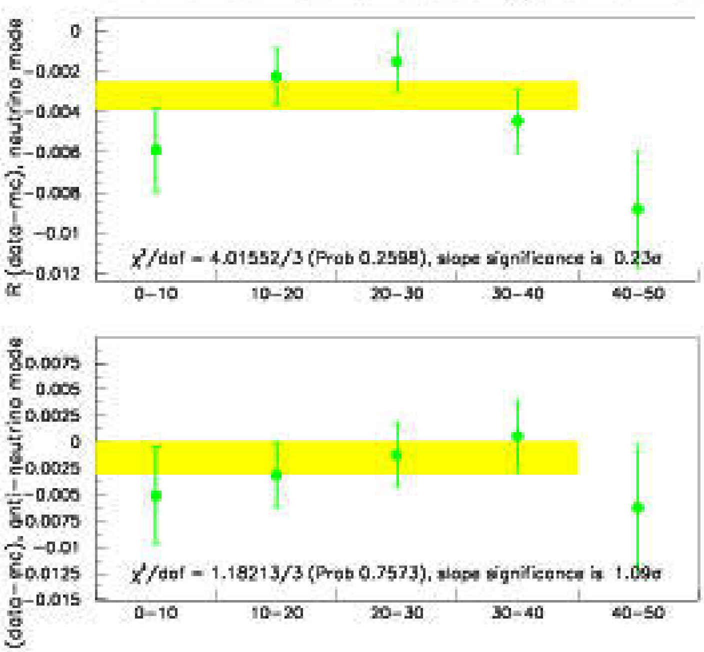
Stability of $R_{\rm exp}$

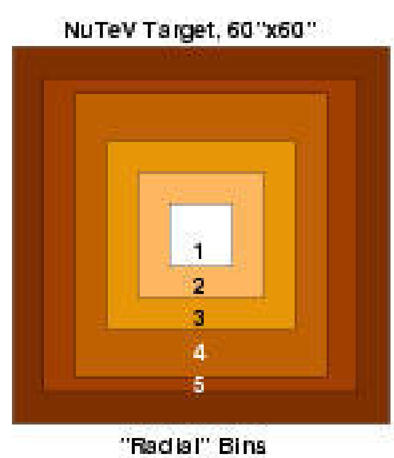
- R vs. Length Cut: Checks NC $\leftrightarrow$ CC separation
  "16,17,18" L_{cut} is default: tighten$\leftrightarrow$loosen selection
  (uncertainties are on *difference*)





- R vs. "radial bin": Checks electron neutrino and short CC events
  More Short sample background near edge

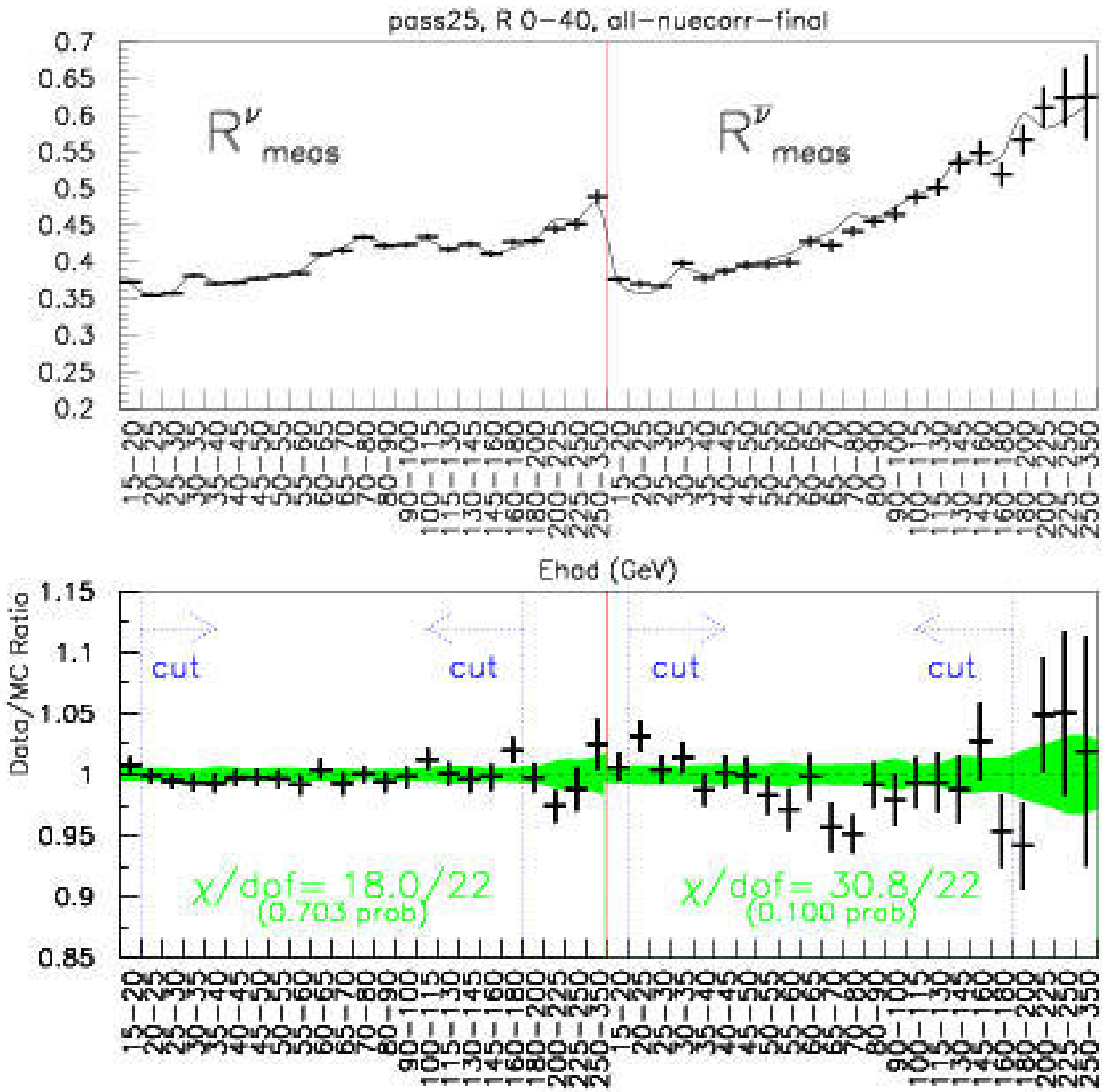




Stability of $R_{\rm exp}$

$R_{\rm exp}$ vs. $E_{\rm had}$: Checks stability of final measurement over full kinematic range

Checks almost everything - backgrounds, flux, detector modeling, cross section model, ...

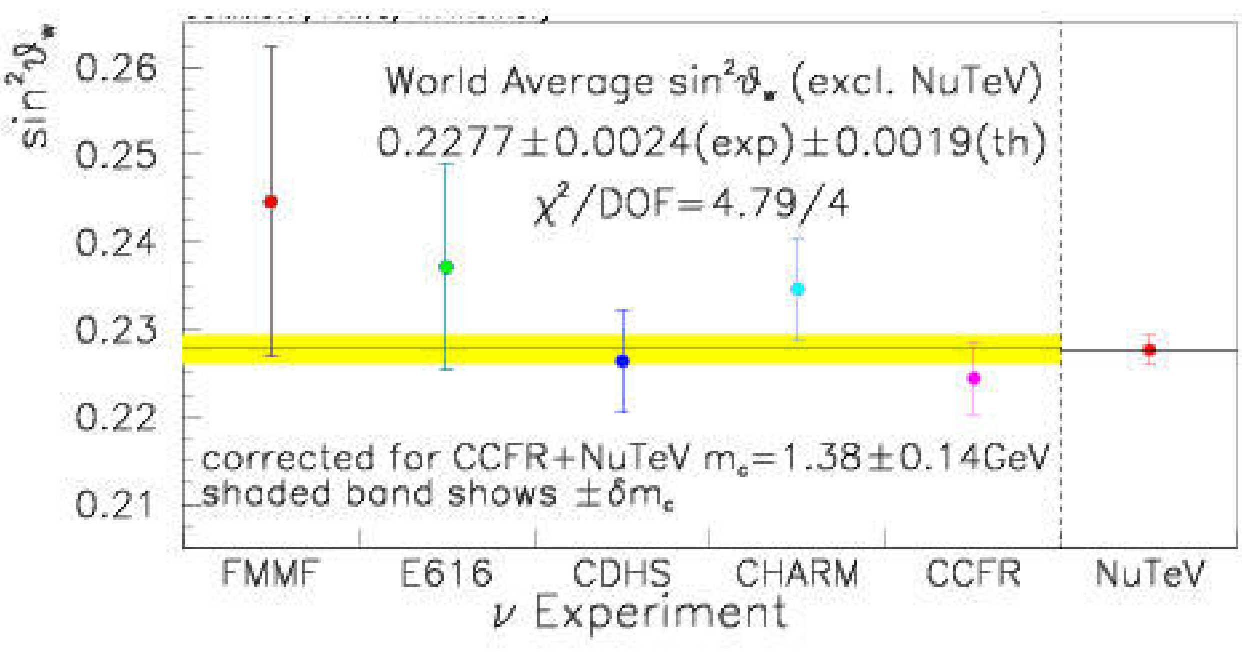


(Green band is $\pm 1\sigma$ systematic uncertainty)

The Result

$$\sin^2\theta_W^{(\text{on-shell})} = 0.2277 \pm 0.0013\,(\text{stat}) \pm 0.0009\,(\text{syst}) - 0.00022 \cdot \left(\frac{M_{\text{top}}^2 - (175\,\text{GeV})^2}{(50\,\text{GeV})^2}\right) + 0.00032 \cdot \ln\left(\frac{M_{\text{Higgs}}}{150\,\text{GeV}}\right)$$

$\rightarrow$ Good agreement with previous νN:
$\sin^2\theta_W = 0.2277 \pm 0.0036$



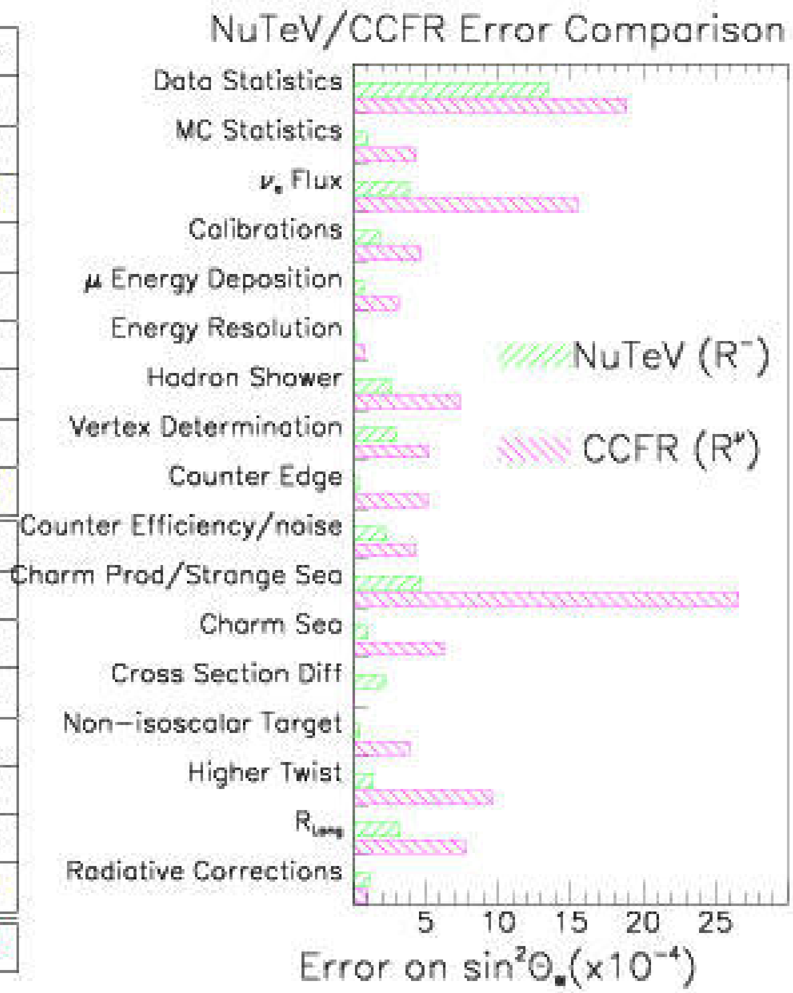
(All other experiments are corrected to NuTeV/CCFR m_c and to large M_{top} ($M_{\text{top}} > M_W$))

- Standard Model fit (LEPEWWG): 0.2227 ± 0.0004

A discrepancy of 3σ ...

Uncertainties

SOURCE OF UNCERTAINTY	$\delta\sin^2\theta_W$
Data Statistics	0.00135
Monte Carlo Statistics	0.00010
TOTAL STATISTICS	0.00135
$\nu_e, \overline{\nu}_e$ Flux	0.00039
Interaction Vertex	0.00030
Shower Length Model	0.00027
Counter Efficiency, Noise, Size	0.00023
Energy Measurement	0.00018
TOTAL EXPERIMENTAL	0.00063
Charm Production, $s(x)$	0.00047
R_L	0.00032
$\sigma^{\overline{\nu}}/\sigma^{\nu}$	0.00022
Higher Twist	0.00014
Radiative Corrections	0.00011
Charm Sea	0.00010
Non-Isoscalar Target	0.00005
TOTAL MODEL	0.00064
TOTAL UNCERTAINTY	0.00162

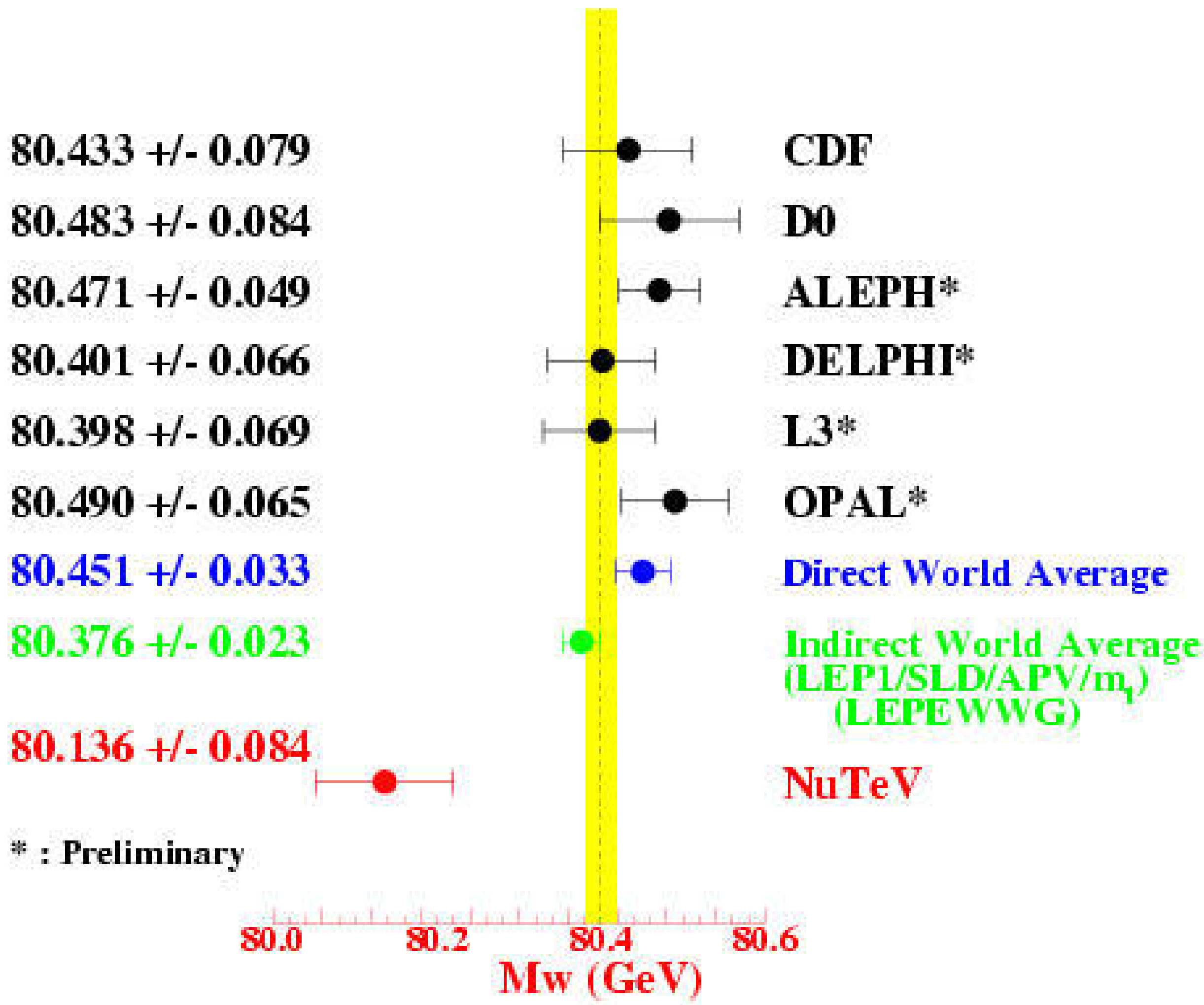


Why is NuTeV so much more precise than CCFR?

- R^- method reduces charm error
- Few K_L in beam $\Rightarrow$ ν_e reduced

Comparison to Direct M_W

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

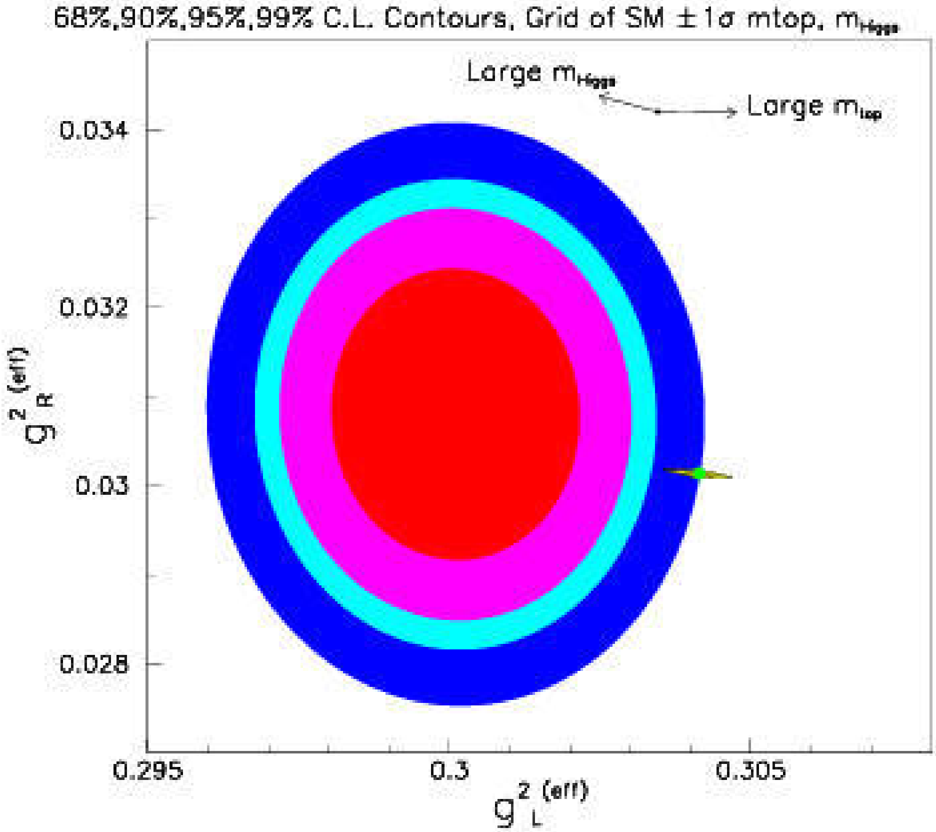


- Precision comparable to a single direct measurement.

Quark Couplings: $(g_L^{\rm eff})^2$ and $(g_R^{\rm eff})^2$

Two Parameter Fit: R^{ν}_{exp}, $R^{\overline{\nu}}_{exp} \leftrightarrow (g_L^{\rm eff})^2$,$(g_R^{\rm eff})^2$

(Radiative corrections modify $g^2_{L,R} \rightarrow (g^{\rm eff}_{L,R})^2$)



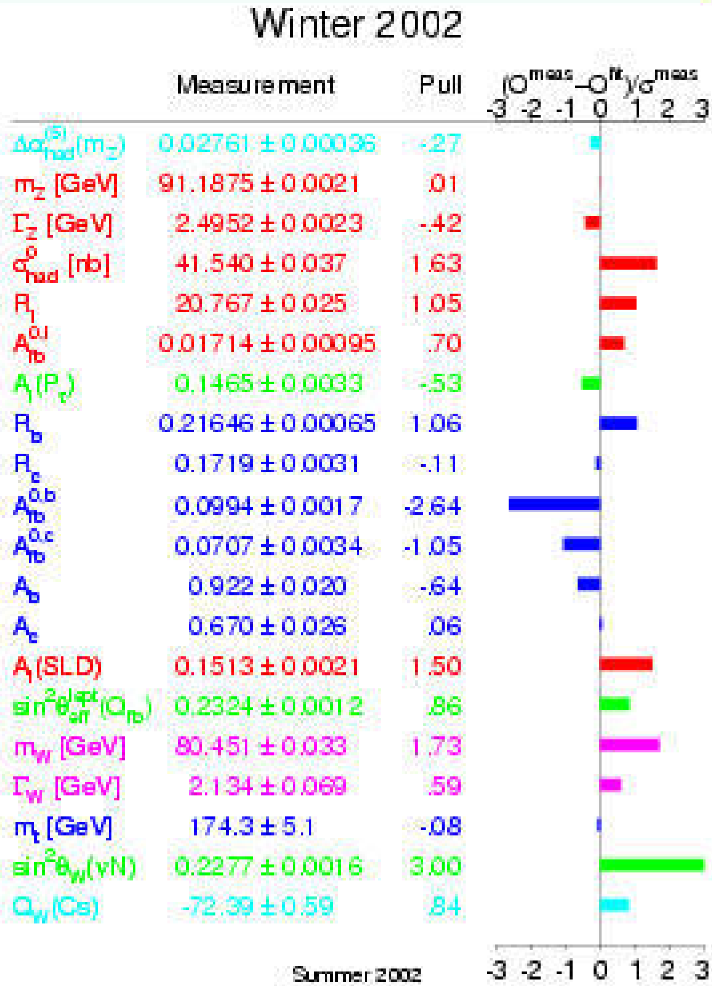
$g_L^2 \equiv u_L^2 + d_L^2$
$g_R^2 \equiv u_R^2 + d_R^2$

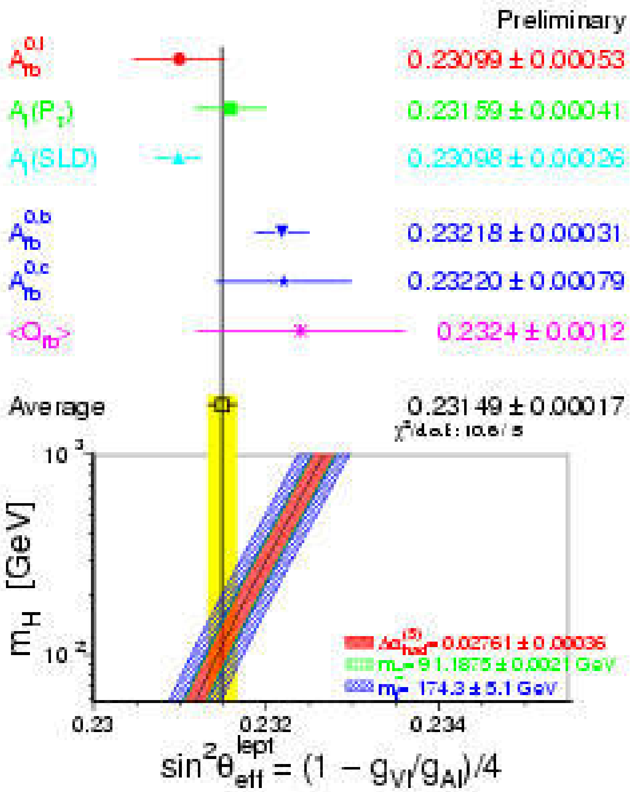
NuTeV measures:
$(g_L^{\rm eff})^2 = 0.3001 \pm 0.0014$ (SM 0.3042) $\Leftarrow 3\sigma$ difference.
$(g_R^{\rm eff})^2 = 0.0308 \pm 0.0011$ (SM: 0.0301) $\Leftarrow$ Good agreement.

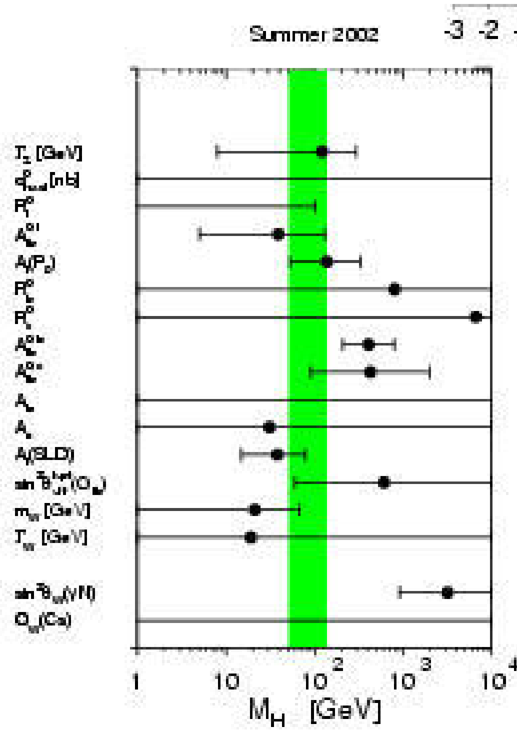
- Assuming predicted ν coupling, $(g_L^{\rm eff})^2$ appears low

How Healthy is the EW Fit?

- Global fit has a χ^2 of $\chi^2/\mathrm{dof} = 19.6/14$ (probability of 14%)
- Two most precise measurements of $\sin^2\theta_W$ at Z pole differ by 3σ
- Data suggest light Higgs except $A_{FB}^{0,b}$
- Adding NuTeV: $\chi^2/\mathrm{dof} = 28.8/15$ (probability of 1.7%)







Interpretation Summary

Symmetry violating PDFs

- $d^P \neq u^N \Rightarrow d$'s in proton carry ~5% more momentum than u's in neutron ($< Q^2 >= 15\ GeV^2$).

  ↪ Can Global PDF fits accomodate this ?

- $s(x) \neq \overline{s}(x) \Rightarrow s$ quarks carry ~30% more momentum than $\overline{s}$.

  ↪ NuTeV dimuon data disfavors this interpretation.

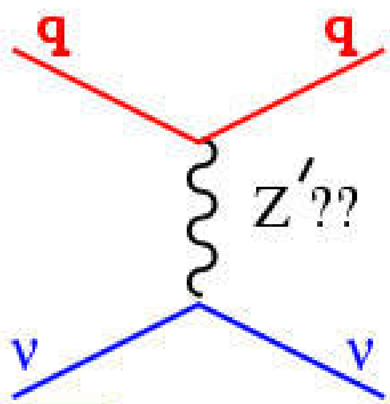
Something here besides the Z?

✓ "Almost sequential" $Z'_{\rm SM} = 1.2^{+0.3}_{-0.2}$ TeV

- CDF/D0 limits: $M_{Z'_{\rm SM}} \gtrsim 700$ GeV

✗ E(6) Z' cannot accommodate entire discrepancy.

- Needs $Z - Z'$ Mixing. ($< \times 10^{-3}$ LEP/SLD).

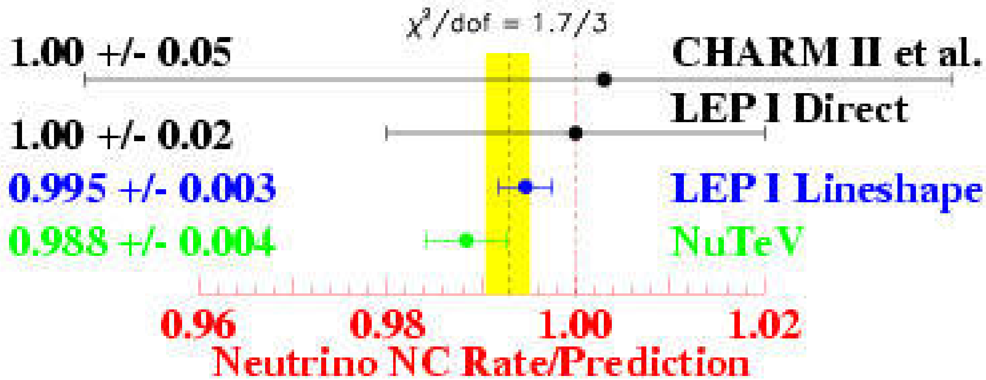


Weaker Neutrino NC ?

Fit NuTeV for deviation in $\nu \& \overline{\nu}$ NC rate.

$\rho_0^2 = 0.9884 \pm 0.0026({\rm stat}) \pm 0.0032({\rm syst})$

$\Rightarrow$ ~1% low (3σ below SM Value)



$N_\nu = 3\frac{\Gamma_{\rm exp}(Z\rightarrow\nu\overline{\nu})}{\Gamma_{\rm SM}(Z\rightarrow\nu\overline{\nu})}$

$= 3(0.9947 \pm 0.0028)$

$\Rightarrow 1.9\sigma$ Low.

Symmetry Violating PDFs

R^- is sensitive to asymmetries in parton distributions:

- Assumes total u and d momenta are equal in the target. (we correct for 5.67% neutron excess in our target).
- Assumes momentum symmetry for strange sea, $s(x) = \overline{s}(x)$.

Isospin Symmetry Violation

- All PDF fits performed assuming quark distributions in proton are related to those in the neutron by isospin symmetry, but $m_n \neq m_p$ $\Rightarrow u^P \neq d^N, d^P \neq u^N$, Isospin violating PDFs needed ?
- Calculated in non-perturbative models. ($\delta \sin^2\theta_W$ shifts are *small*).

Bag Model	Meson Cloud Model
$\delta\sin^2\theta_W = -0.0001$	$\delta\sin^2\theta_W = +0.0002$
(Thomas *et al.*, Mod. Phys. Lett **A9**, 1799)	(Cao & Signal, Phys. Rev. **C62**, 015203.)

- To explain NuTeV $\Rightarrow$ d quarks in proton carry ~5% more momentum than u quarks in neutron ($< Q^2 >= 15\ GeV^2$).
- Global fit to all PDF input data is needed to see if this can be accomodated.

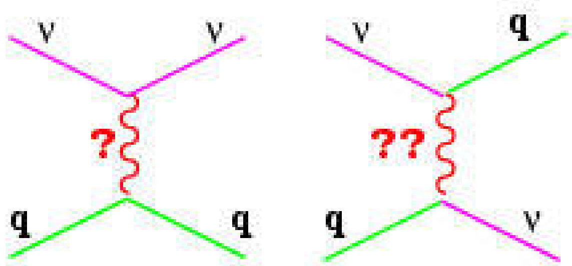
Asymmetric heavy quark seas, $s(x) \neq \overline{s}(x)$

- To explain NuTeV $\Rightarrow \int x\,(s-\overline{s})\,dx = 0.007 \rightarrow \frac{S-\overline{S}}{S+\overline{S}} \sim 30\%$.
- Using the NuTeV dimuon data: $\int x\,(s-\overline{s})\,dx = -0.0027 \pm 0.0013$

$$\Longrightarrow \delta\sin^2\theta_W \sim +0.0020 \pm 0.0009$$

Then $\sin^2\theta_W = 0.2297 \pm 0.0019$ (3.7σ above SM)

New Tree Level Physics?



- Z' , LQ, etc.
- $Z - Z'$ mixing and Z' exchange.
- NuTeV needs effect on g_L^2 not g_R^2.

- $E(6)$ Z' accounts for NuTeV??

$$(Z' \equiv Z_\chi cos\beta + Z_\psi sin\beta)$$

(Cho *et al.*, Nucl. Phys. B531, 65.

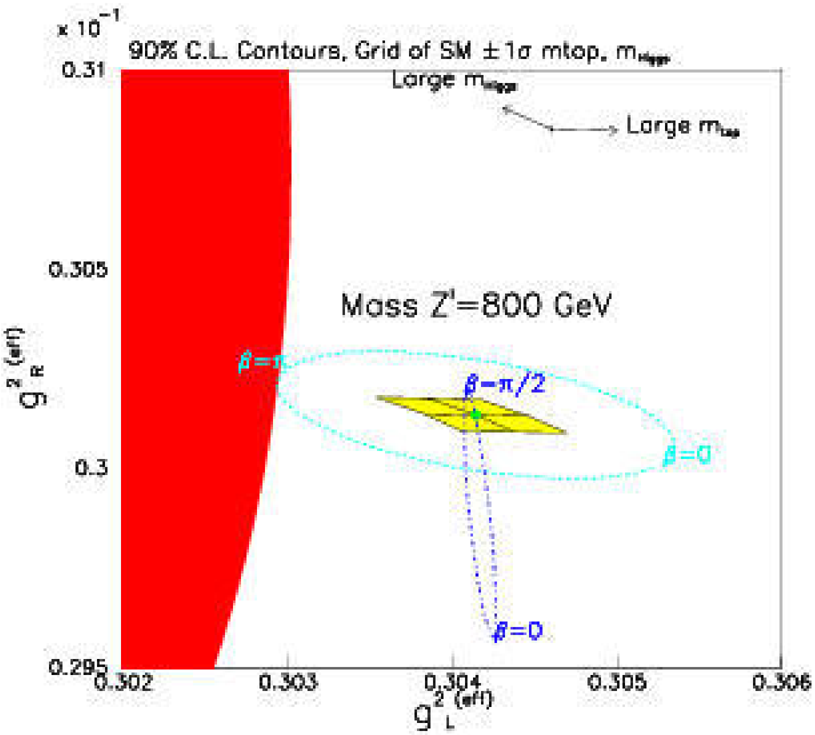
Zeppenfeld and Cheung, hep-ph/9810277.
Langacker *et al.*, Rev. Mod. Phys. 64 87.)

↪ Unmixed E(6) Z' shifts g_R^2

↪ Need $Z - Z'$ Mixing.
(here 3×10^{-3})

↪ Mixing $< \times 10^{-3}$ LEP/SLD.

- E(6) Z' cannot accommodate entire NuTeV discrepancy



- "Almost sequential" $Z'_{\rm SM}$ with opposite coupling to ν

↪ NuTeV preferred mass range: $1.2^{+0.3}_{-0.2}$ TeV

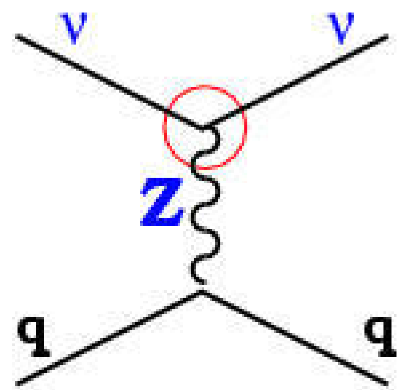
↪ CDF/D0 limits: $M_{Z'_{\rm SM}} \gtrsim 700$ GeV

Are Neutrinos Different ?

Use SM $\sin^2\theta_W$ and Fit NuTeV for deviation in $\nu\&\overline{\nu}$ NC rate.

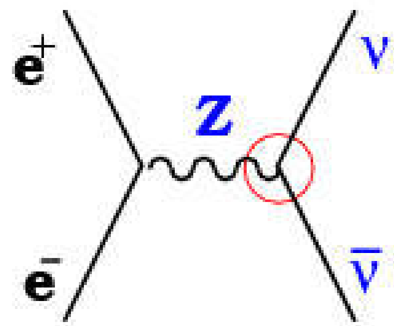
$\rho_0^2 = 0.9884 \pm 0.0026(\text{stat}) \pm 0.0032(\text{syst})$

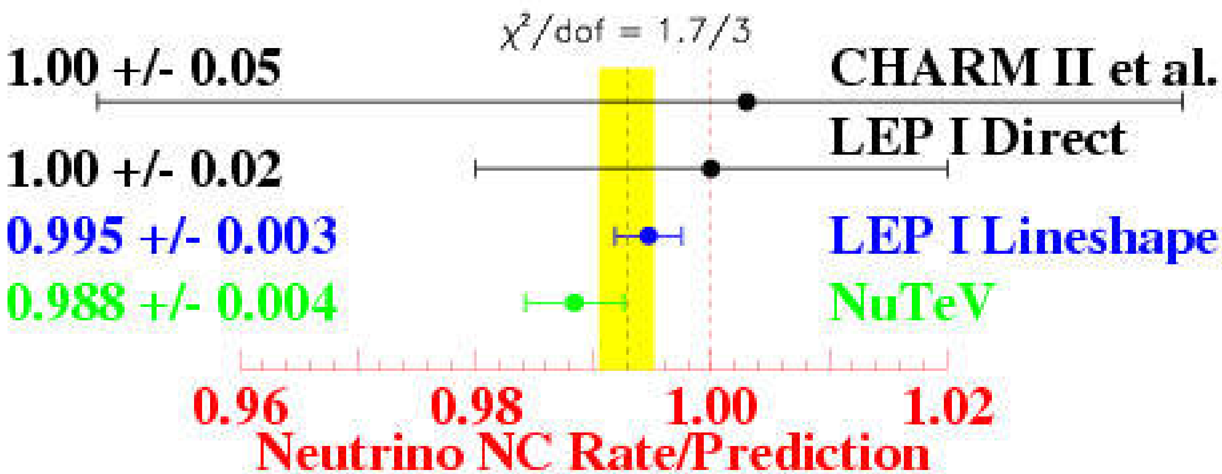
(3σ below SM Value)
$\Rightarrow$ ~1% weaker νZ coupling.



LEP I measures Z lineshape and decay partial widths to infer the "number of neutrinos" $N_\nu = 3\frac{\Gamma_{\text{exp}}(Z\to\nu\overline{\nu})}{\Gamma_{\text{SM}}(Z\to\nu\overline{\nu})}$
$= 3 \times (0.9947 \pm 0.0028)$

$\Rightarrow 1.9\sigma$ Low



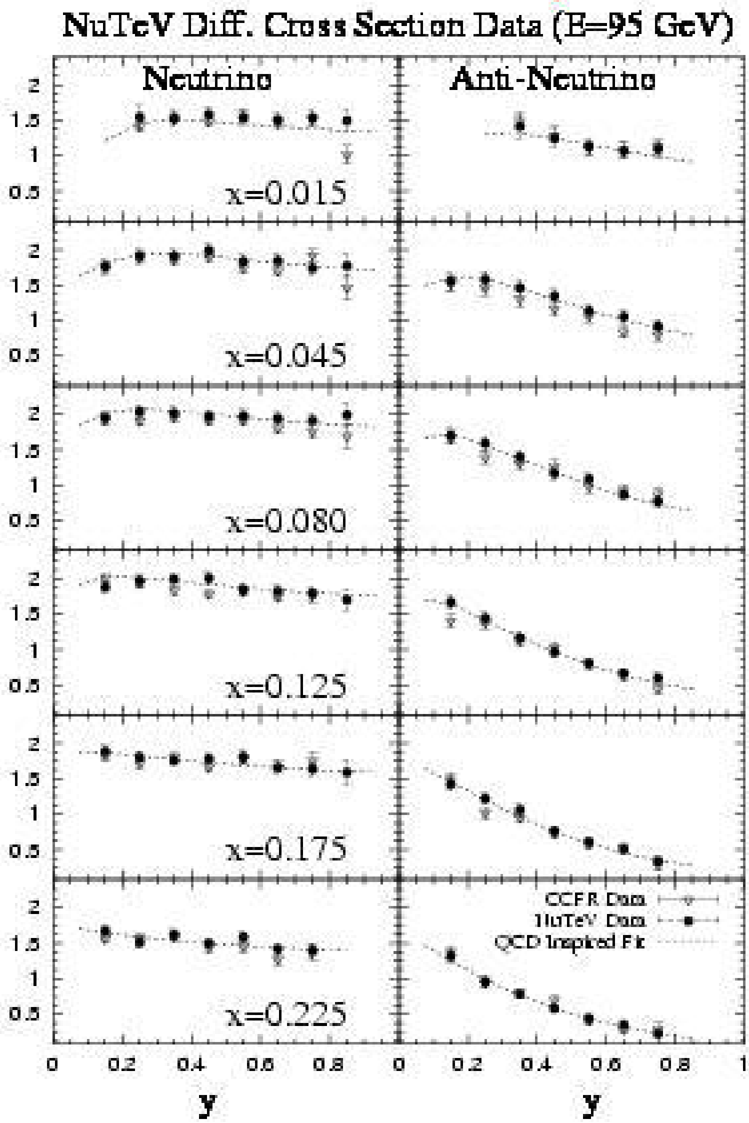


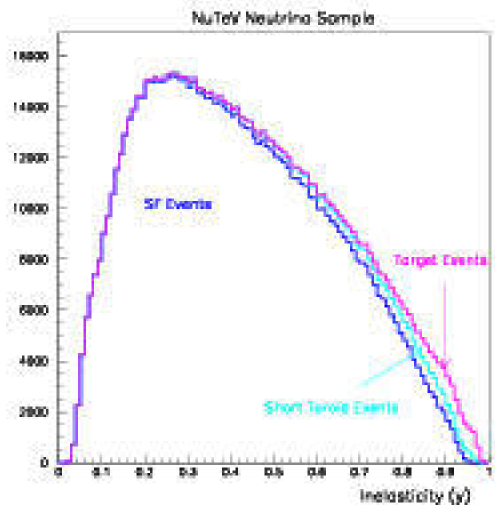
In this interpretation, NuTeV confirms and strengthens LEP I indications of "weaker" neutrino neutral current.

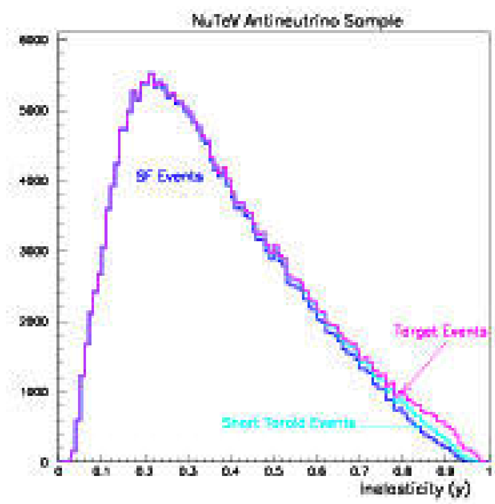
Future: NuTeV Cross Section

- Measurement of Charged-Current Differential Cross sections (ν and $\overline{\nu}$) and Structure Functions.
- Sign selected beam allows low energy muon data.
  High $y = E_{HAD}/E_{\nu}$.

NuTeV Preliminary







New Samples:

1. Target μ
2. Short Toroid μ

Conclusions

Charm production

- LO Model extraction.
- NEW Model independent cross section extracted.
- Observation of NC charm.

Searches

- LNV
- FCNC

Electroweak

- The SM predicts 0.2227 ± 0.0004, but we measure:

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

- NuTeV data prefers lower effective left-handed coupling
- Pending confirmation, refutation, or alternative explanations, it's a puzzle.

Future

- NLO charm production
- NuTeV Structure Functions