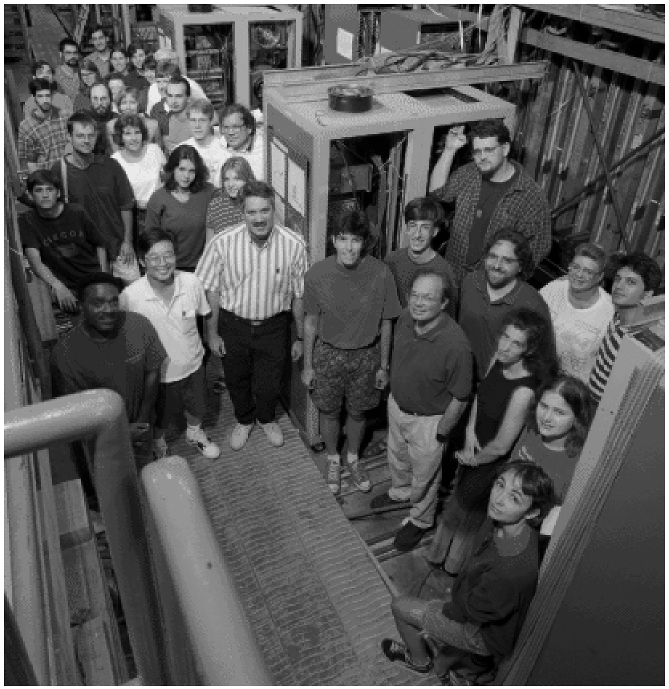
NuTeV: Hints of New Physics or the Dregs of QCD?

Kevin McFarland
University of Rochester
for the NuTeV Collaboration

NUINT02
Foggy Irvine, California
13 December 2002

NuTeV Collaboration



G. P. Zeller[5], T. Adams[4], A. Alton[4], S. Avvakumov[8], L. de Barbaro[5], P. de Barbaro[8], R. H. Bernstein[3], A. Bodek[8], T. Bolton[4], J. Brau[6], D. Buchholz[5], H. Budd[8], L. Bugel[3], J. Conrad[2], R. B. Drucker[6], B. T. Fleming[2], R. Frey[6], J.A. Formaggio[2], J. Goldman[4], M. Goncharov[4], D. A. Harris[8], R. A. Johnson[1], J. H. Kim[2], S. Koutsoliotas[2], M. J. Lamm[3], W. Marsh[3], D. Mason[6], J. McDonald[7], K. S. McFarland[8,3], C. McNulty[2], D. Naples[7], P. Nienaber[3], A. Romosan[2], W. K. Sakumoto[8], H. Schellman[5], M. H. Shaevitz[2], P. Spentzouris[2], E. G. Stern[2], N. Suwonjandee[1], M. Tzanov[7], M. Vakili[1], A. Vaitaitis[2], U. K. Yang[8], J. Yu[3], and E. D. Zimmerman[2]

Cincinnati[1], Columbia[2], Fermilab[3], Kansas State[4], Northwestern[5], Oregon[6], Pittsburgh[7], Rochester[8]

Electroweak Theory

- Standard Model
  - Charged Current mediated by $W^{\pm}$ with (V-A)
    Neutral Current mediated by Z^0 with couplings below
  - One parameter to measure!
    - Weak / electromagnetic mixing parameter $\mathbf{\sin^2\theta_W}$
      (Related to weak/EM coupling ratio $\boldsymbol{g' = g \tan\theta_W}$)

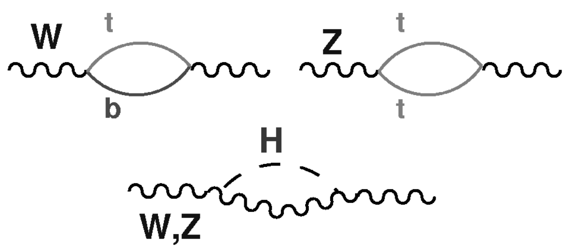
Z Couplings	g_L	g_R
ν_e , ν_μ , ν_τ	$1/2$	0
e , μ , τ	$-1/2 + \sin^2\theta_W$	$\sin^2\theta_W$
u , c , t	$1/2 - 2/3\ \sin^2\theta_W$	$-\ 2/3\ \sin^2\theta_W$
d , s , b	$-1/2 + 1/3\ \sin^2\theta_W$	$1/3\ \sin^2\theta_W$

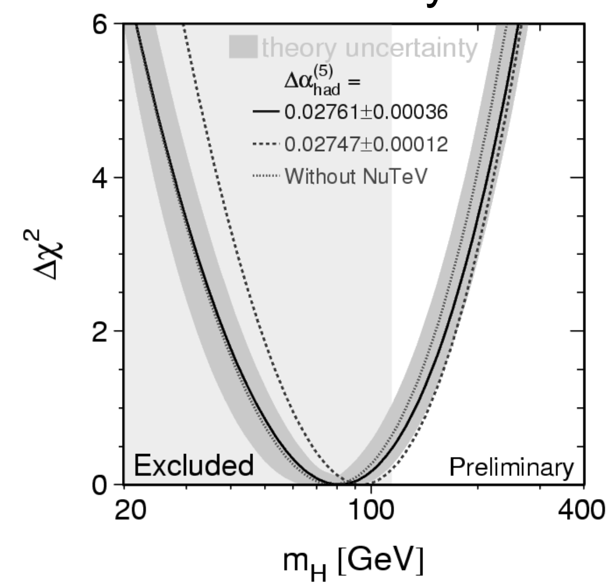
- Neutrinos are special in SM
  - Only have left-handed weak interactions

Current Era of Precision EW Measurements

- Precision parameters define the SM:
  - $\alpha_{EM}^{-1} = 137.03599959(40)$ 45ppb (200ppm@M_Z)
  - $G_\mu = 1.16637(1)\times10^{-5}$ GeV^{-2} 10ppm
  - $M_Z = 91.1871(21)$ 23ppm

- Comparisons test the SM and probe for new physics
  - Sensitivity allows observation of quantum corrections to theory!

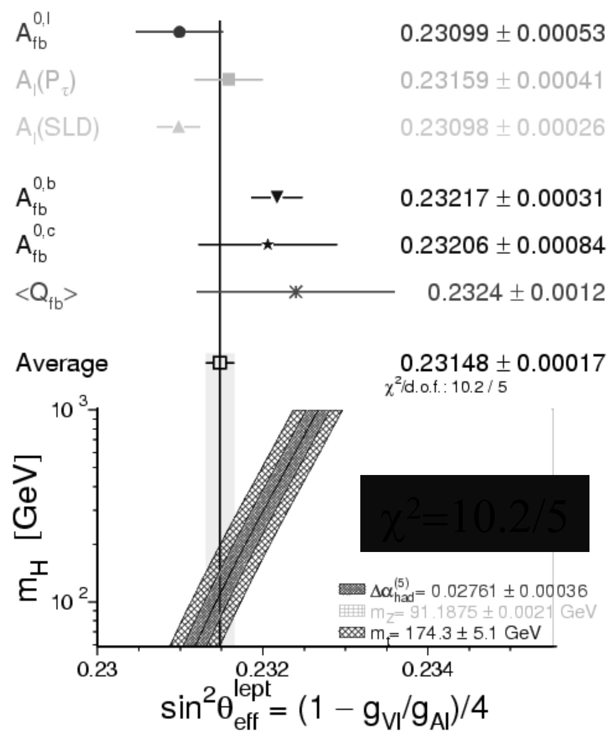




- Radiative corrections are large and sensitive to M_{top} and M_{Higgs}
  - *M_{Higgs} constrained in SM to be less than 196 GeV at 95%CL*

Are There Cracks?

- Most precise data suggests a light Higgs except hadronic asymmetries, notably A_{FB}^b
- Global fit has large χ^2=23/15 (9%)
  - A_{FB}^b is off about 3σ
- Γ_{inv} also off by $\sim 2\sigma$
  - $N_\nu = 2.9841 \pm 0.0083$



Summer 2001

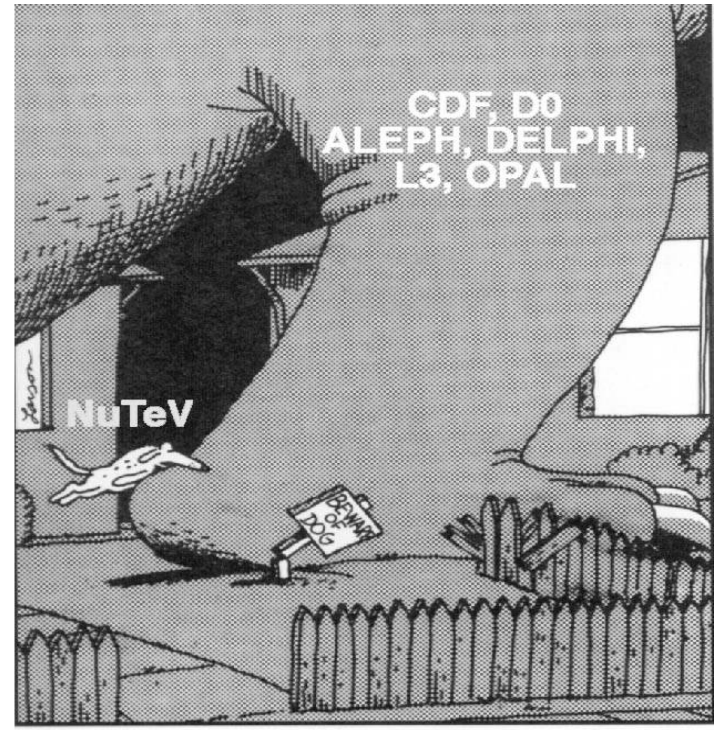
	Measurement	Pull
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	-.35
m_Z [GeV]	91.1875 ± 0.0021	.03
Γ_Z [GeV]	2.4952 ± 0.0023	-.48
σ_{had}^0 [nb]	41.540 ± 0.037	1.60
R_l	20.767 ± 0.025	1.11
$A_{fb}^{0,l}$	0.01714 ± 0.00095	.69
$A_l(P_\tau)$	0.1465 ± 0.0033	-.54
R_b	0.21646 ± 0.00065	1.12
R_c	0.1719 ± 0.0031	-.12
$A_{fb}^{0,b}$	0.0990 ± 0.0017	-2.90
$A_{fb}^{0,c}$	0.0685 ± 0.0034	-1.71
A_b	0.922 ± 0.020	-.64
A_c	0.670 ± 0.026	.06
A_l(SLD)	0.1513 ± 0.0021	1.47
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	.86
$m_W^{(LEP)}$ [GeV]	80.450 ± 0.039	1.32
m_t [GeV]	174.3 ± 5.1	-.30
$m_W^{(TEV)}$ [GeV]	80.454 ± 0.060	.93
$\sin^2\theta_W(\nu N)$	0.2255 ± 0.0021	1.22
Q_W(Cs)	-72.50 ± 0.70	.56

$(O^{meas}-O^{fit})/\sigma^{meas}$: -3 -2 -1 0 1 2 3

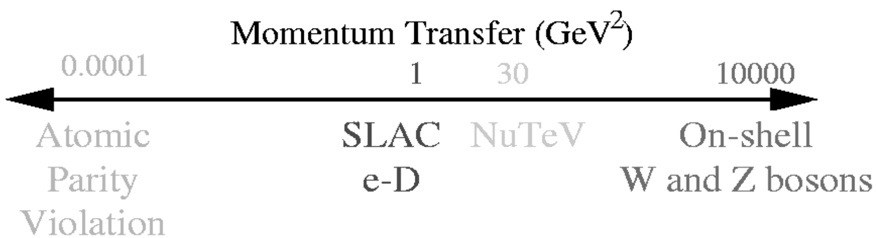
Other oddities:
- g-2 at BNL (2.6σ)
- Atomic Parity Violation ($0 - 2.2\sigma$)
- $|V_{ud}|$ ($2.3 - 3.0\sigma$)

Why NuTeV?

- Precision comparable to collider measurements of M_W
- Sensitive to different new physics
  - Different radiative corrections
- Measurement off the Z pole
  - Exchange is not guaranteed to be a Z
- Measures neutrino neutral current coupling
  - LEP 1 invisible line width is only other precise ν measurement
- Sensitive to light quark (u,d) couplings
  - Overlap with APV, Tevatron Z production
- Tests universality of EW theory over large range of momentum scales

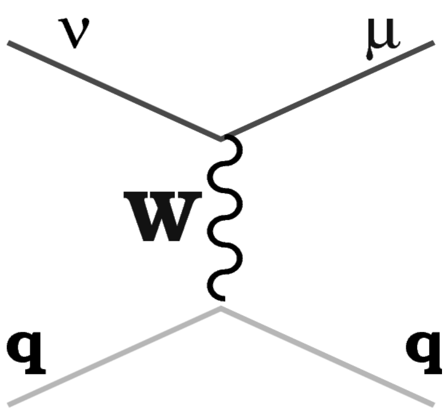


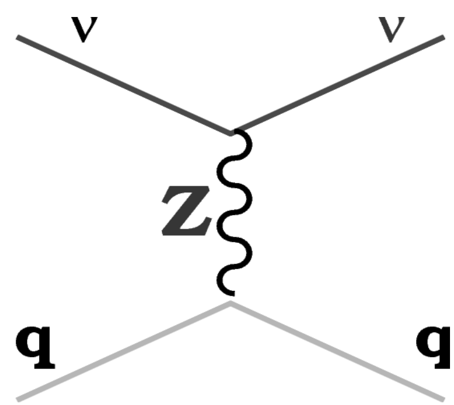
Toby vs. Godzilla



Measurement Technique

Charged-Current (CC)





Neutral-Current (NC)

- For an isoscalar target composed of u,d quarks:

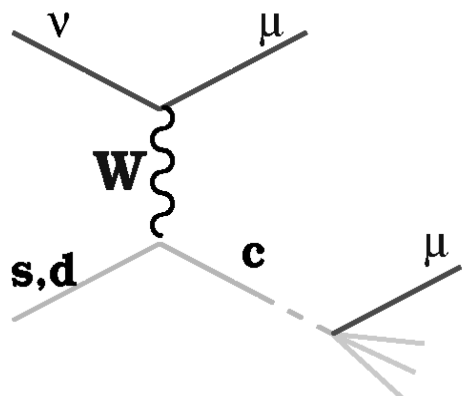
Llewellyn Smith Relation:

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

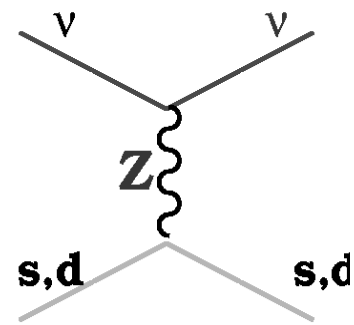
- *NC/CC* ratio easiest to measure experimentally but ...
  - Need to correct for non-isoscalar target, radiative corrections, heavy quark effects, higher twists
  - Many SF dependencies and systematic uncertainties cancel

Charm Mass Effects

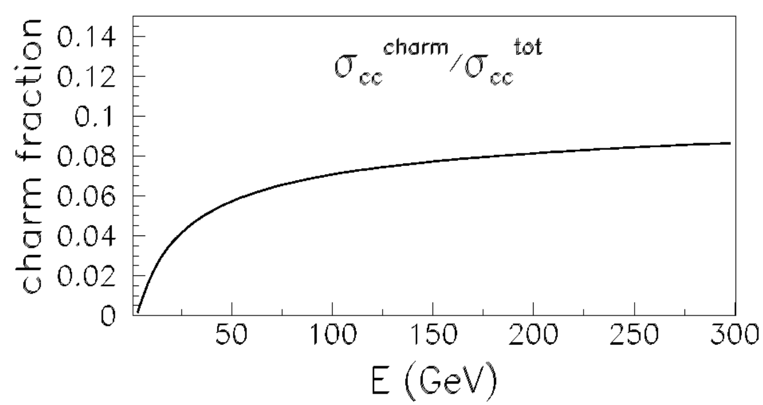
Charged-Current Production of Charm



Neutral-Current



- CC is suppressed due to final state c-quark
  $\Rightarrow$ Need to know s-quark sea and m_c
  – Modeled with leading-order slow-rescaling
  – Measured by NuTeV/CCFR using dimuon events ($\nu N \rightarrow \mu\, cX \rightarrow \mu\mu X$)
    (NuTeV: M. Goncharov et al., Phys. Rev. D64: 112006,2001 and CCFR: A.O. Bazarko et al., Z.Phys.C65:189-198,1995)

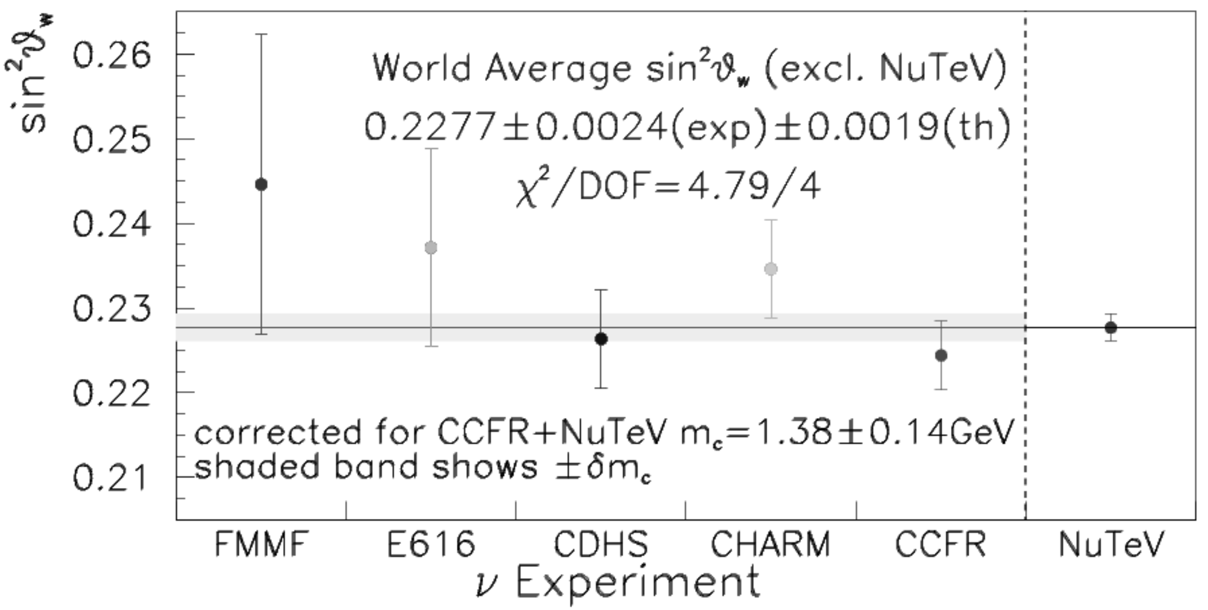


Before NuTeV…

- νN experiments had hit a brick wall in precision
  - $\Rightarrow$ Due to systematic uncertainties (i.e. m_c ....)

$$\sin^2\theta_W^{on-shell} = 1 - \frac{M_W^2}{M_Z^2} = 0.2277 \pm 0.0036$$

$$\Rightarrow M_W = 80.14 \pm 0.19\ GeV$$



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

NuTeV's Technique

Cross section differences remove sea quark contributions

⇒ Reduce uncertainties from charm production and sea

Paschos - Wolfenstein Relation

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

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

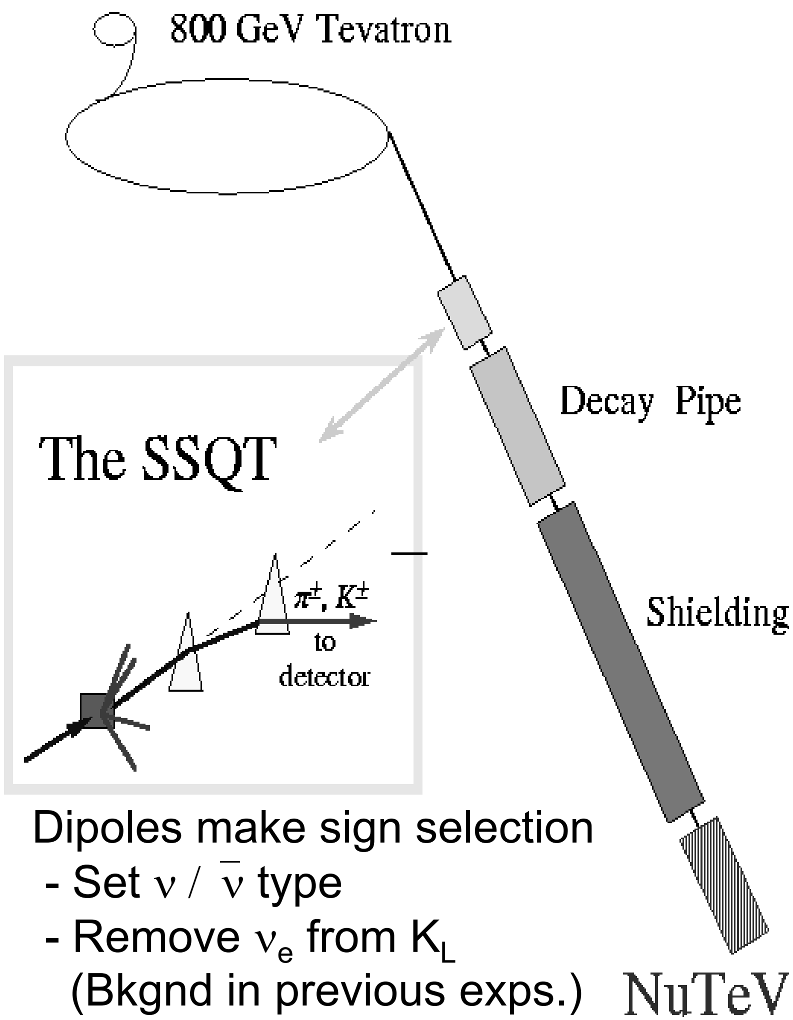
$\left(\text{Assuming } xs(x) = x\bar{s}(x) \right)$

- R^{-} manifestly insensitive to sea quarks
  - Charm and strange sea error negligible
  - Charm production uncertainty small
    - d_V quarks only: Cabbibo suppressed and at high-x

- *But* R^{-} requires separate ν and $\bar{\nu}$ beams

  ⇒ NuTeV SSQT (Sign-selected Quad Train)

NuTeV Sign-Selected Beamline

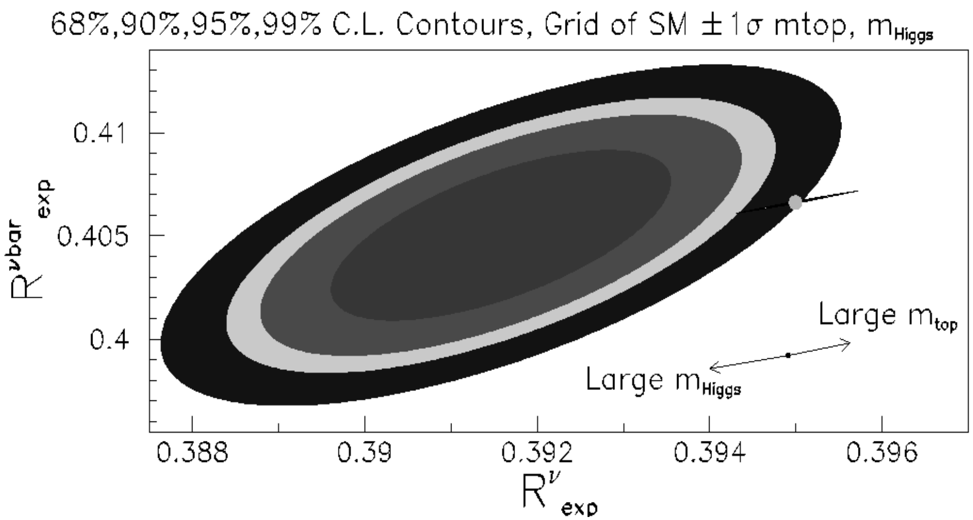


Dipoles make sign selection
- Set ν / $\bar{\nu}$ type
- Remove ν_e from K_L (Bkgnd in previous exps.)

- Beam is almost pure ν or $\bar{\nu}$ ($\bar{\nu}$ in ν mode 3×10^{-4}, ν in $\bar{\nu}$ mode 4×10^{-3})
- Beam only has ~1.6% electron neutrinos
  - $\Rightarrow$ Important background for isolating true NC event

Paschos-Wolfenstein Another Way

$$R^{\nu(\bar{\nu})} = \frac{\sigma_{NC}^{\nu(\bar{\nu})}}{\sigma_{CC}^{\nu(\bar{\nu})}} = \rho_0^2 \left(\frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W (1 + \frac{\sigma_{CC}^{\bar{\nu}(\nu)}}{\sigma_{CC}^{\nu(\bar{\nu})}}) \right)$$



- NuTeV result:
  - Statistics dominate uncertainty
- Standard model fit (LEPEWWG):
  - **0.2227** ± **0.00037, a** 3σ discrepancy

Uncertainties in Measurement

- $\sin^2\theta_W$ error statistically dominated *(R^- technique)*
- R^ν uncertainty dominated by theory model

SOURCE OF UNCERTAINTY	$\delta\sin^2\theta_W$	$\delta R^{\nu}_{\text{exp}}$	$\delta R^{\overline{\nu}}_{\text{exp}}$
Data Statistics	0.00135	0.00069	0.00159
Monte Carlo Statistics	0.00010	0.00006	0.00010
TOTAL STATISTICS	0.00135	0.00069	0.00159
$\nu_e, \overline{\nu}_e$ Flux	0.00039	0.00025	0.00044
Interaction Vertex	0.00030	0.00022	0.00017
Shower Length Model	0.00027	0.00021	0.00020
Counter Efficiency, Noise, Size	0.00023	0.00014	0.00006
Energy Measurement	0.00018	0.00015	0.00024
TOTAL EXPERIMENTAL	0.00063	0.00044	0.00057
Charm Production, $s(x)$	0.00047	0.00089	0.00184
R_L	0.00032	0.00045	0.00101
$\sigma^{\overline{\nu}}/\sigma^{\nu}$	0.00022	0.00007	0.00026
Higher Twist	0.00014	0.00012	0.00013
Radiative Corrections	0.00011	0.00005	0.00006
Charm Sea	0.00010	0.00005	0.00004
Non-Isoscalar Target	0.00005	0.00004	0.00004
TOTAL MODEL	0.00064	0.00101	0.00212
TOTAL UNCERTAINTY	0.00162	0.00130	0.00272

Compared to Other Measurements

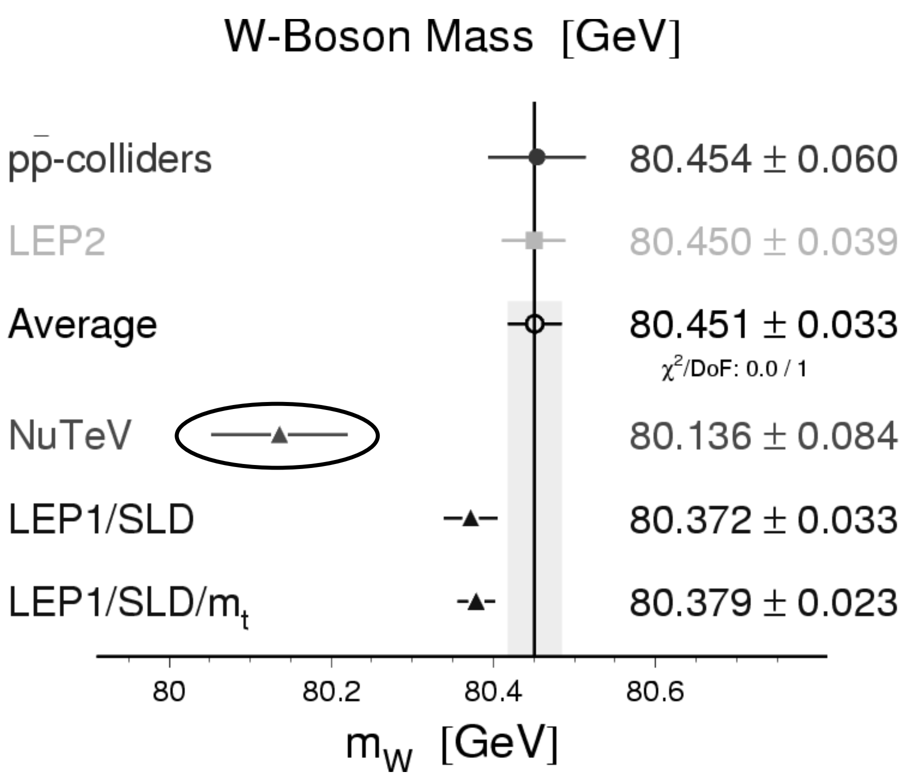
$M_W = 80.136 \pm 0.084$ GeV

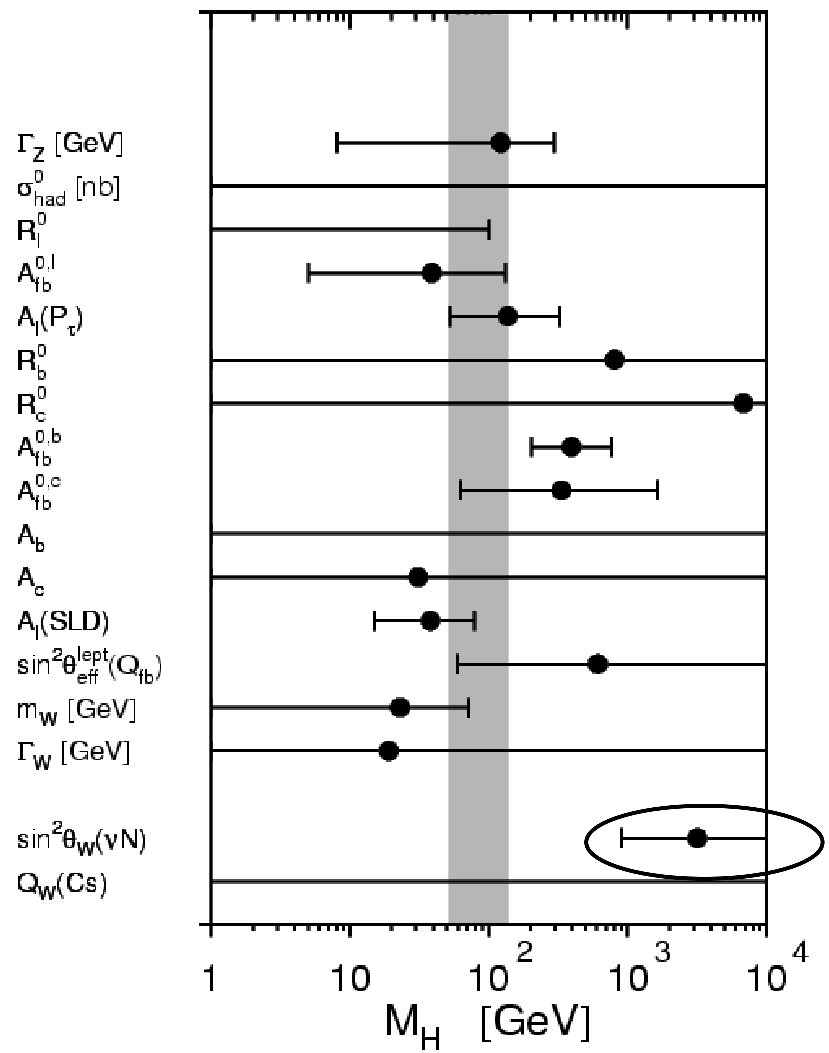
from $\sin^2 \theta_W^{(on-shell)} \equiv 1 - \frac{M_W^2}{M_Z^2}$

(independent of quantum corrections)

Precision comparable to collider measurements but value is much smaller

Each electroweak measurement also indicates a range of Higgs masses

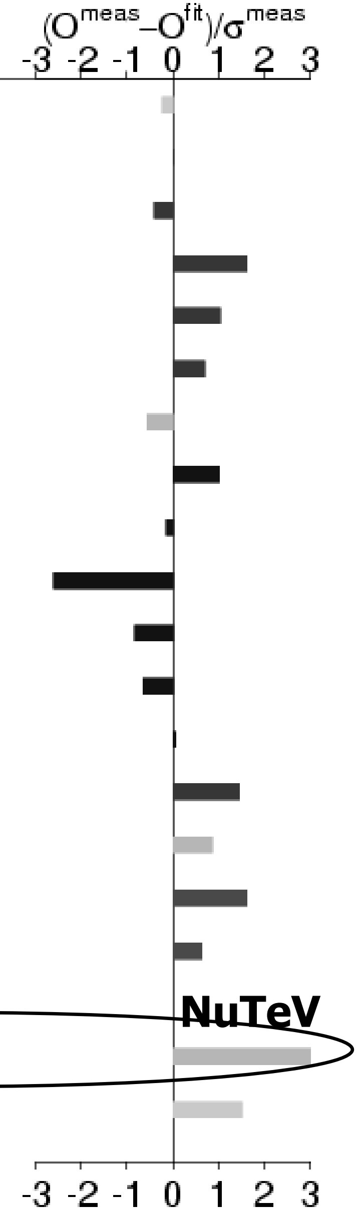




SM Fit with NuTeV $\sin^2\theta_W$

- Without NuTeV:
  - χ^2/dof = 19.6/14, probability of 14%
- With NuTeV:
  - χ^2/dof = 28.8/15, probability of 1.7%
- Upper m_{Higgs} limit only weakens slightly

	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



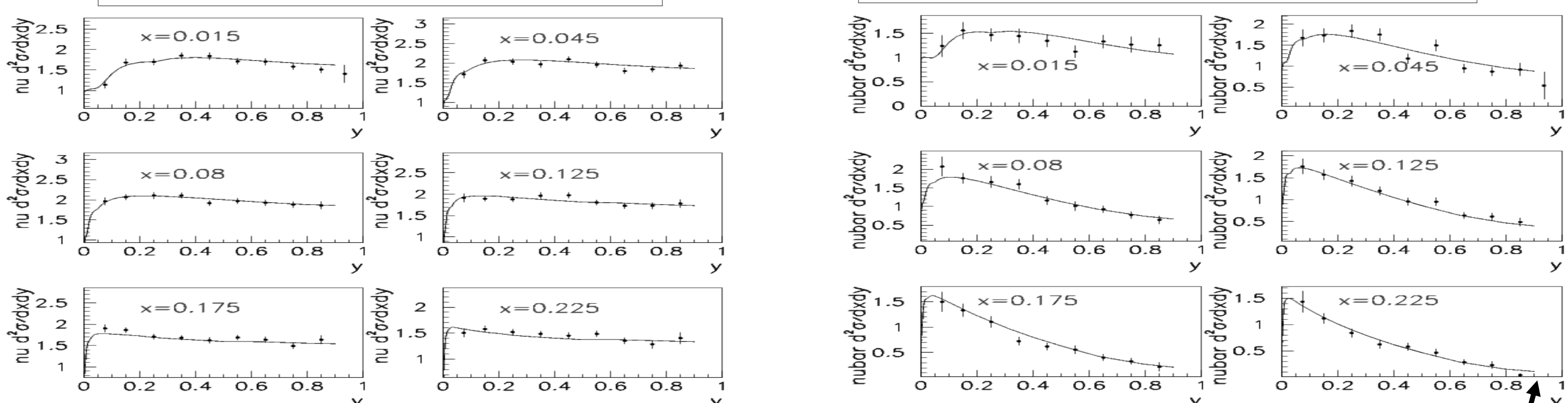
Enhanced LO Cross-Section

- "Enhanced" means: include R_L and higher twist terms
- PDFs extracted from CCFR data exploiting symmetries:
  - Isospin symmetry: $u^p=d^n$, $d^p=u^u$, and strange = anti-strange
- Data-driven: uncertainties come from measurements

CCFR Data

Neutrino xsec vs y at 190 GeV

Antineutrino xsec vs y at 190 GeV



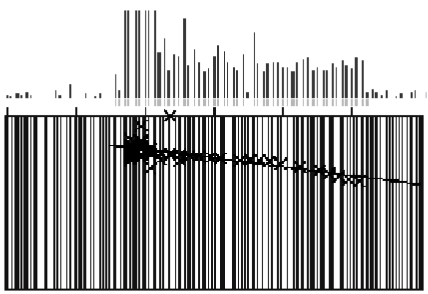
- LO quark-parton model tuned to agree with data:
  - Heavy quark production suppression and strange sea (CCFR/NuTeV $\nu N \to \mu^+\mu^- X$ data)
  - R_L , F_2 higher twist (from fits to SLAC, BCDMS)
  - d/u constraints from NMC, NUSEA(E866) data
  - Charm sea from EMC F_2^{cc}

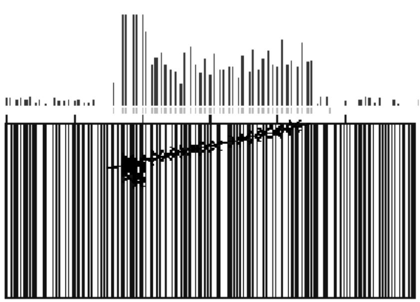
high y events are background to the neutral current sample

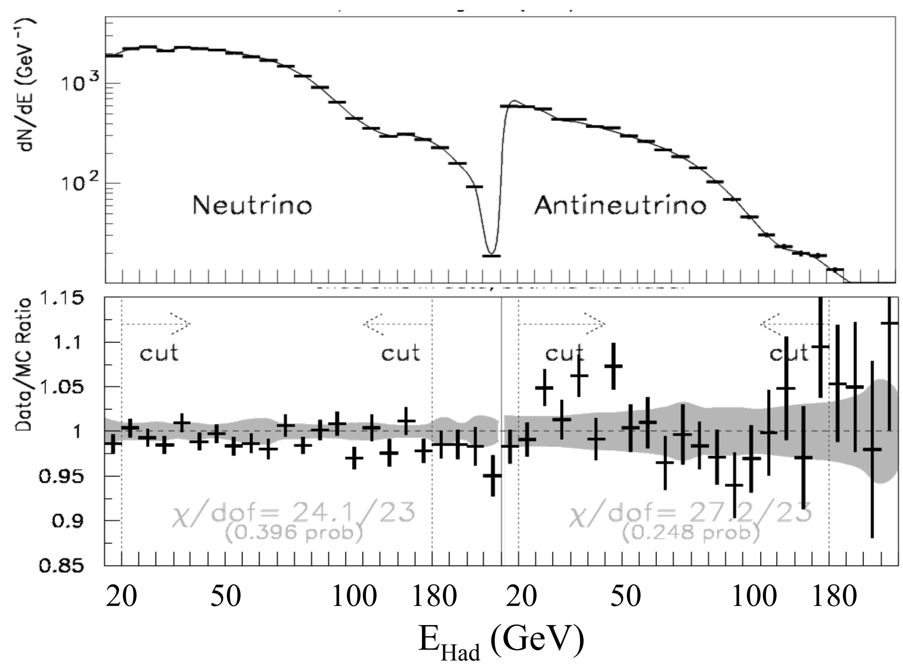
This "tuning" of model is crucial for the analysis

Charged-Current Control Sample

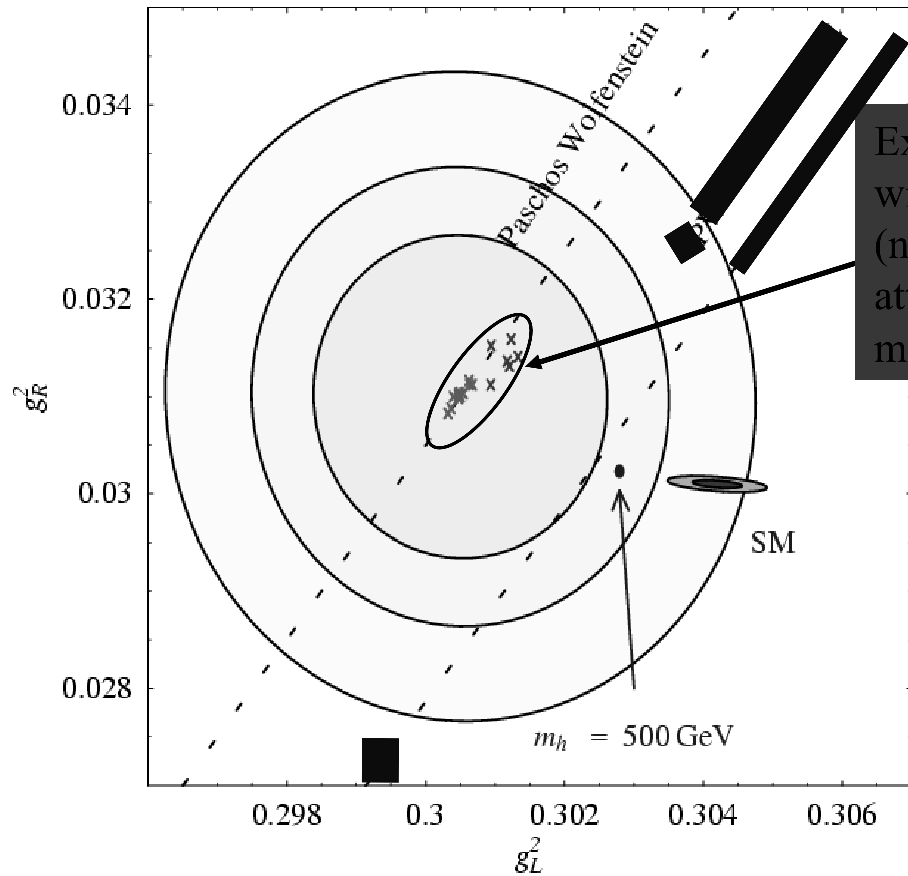
- Medium length events (L>30 cntrs) check modeling and simulation of Short charged-currents sample
  - –Similar kinematics and hadronic energy distribution to CC events that appear as NC background







Wow is R⁻ Robust!



(S.Davidson et al. hep-ph/0112302)

- Difficult to explain discrepancy with SM using:
  - Parton distributions or LO vs NLO or
  - Electroweak radiative corrections: heavy m_{Higgs}

Does NuTeV need to do a NLO Analysis?

- Hard to argue it is a bad idea…
- But it doesn’t necessarily solve anything
  - After all α_s is large. Otherwise LO would be fine. Why NLO instead of NNLO?
  - LO analysis fits data the relevant data well. May work less well at NLO?
- What would improve?
  - Concerns about $y \rightarrow 1$ σ_{CC} limit at NLO
  - Heavy flavor production model
  - Less *ad hoc* description of R_L
- Barring human cloning, outlook isn’t good
  - NLO effects above should be investigated

Symmetry Violating QCD Effects

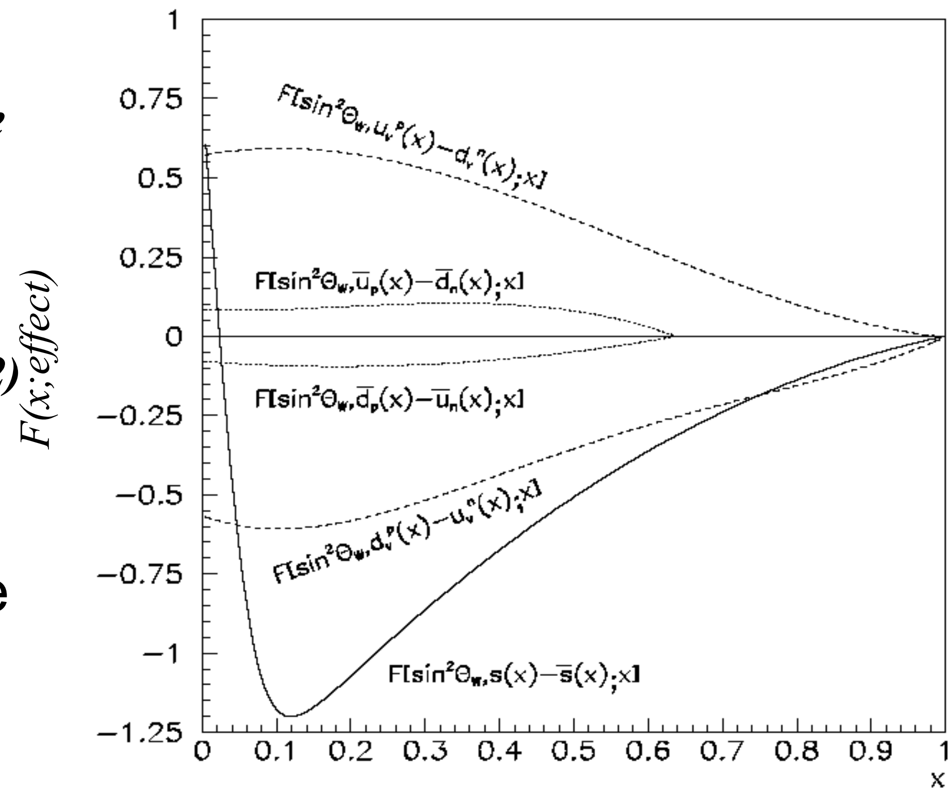
- Paschos-Wolfenstein R^- assumptions:
  - Assumes total u and d momenta equal in target
  - Assumes sea momentum symmetry, $s = \bar{s}$ and $c = \bar{c}$
  - Assumes nuclear effects common in W/Z exchange
- Violations of these symmetries can arise from
  1. $A \neq 2Z$ due to neutron excess (corrected for in NuTeV)
  2. Isospin violating PDF's, $u_p(x) \neq d_n(x)$

Detailed Examination of Symmetry Violation Effects

New since NUINT01:

"On the Effects of Asymmetric Strange Seas and Isospin-Violating Parton Distribution Functions on $\sin^2\theta_W$ Measured in the NuTeV Experiment"
(G.P. Zeller et al., Phys.Rev.D65:111103,2002)

- Parameterize the shifts from various asymmetries for the NuTeV $\sin^2\theta_W$ analysis technique



Conclusions:

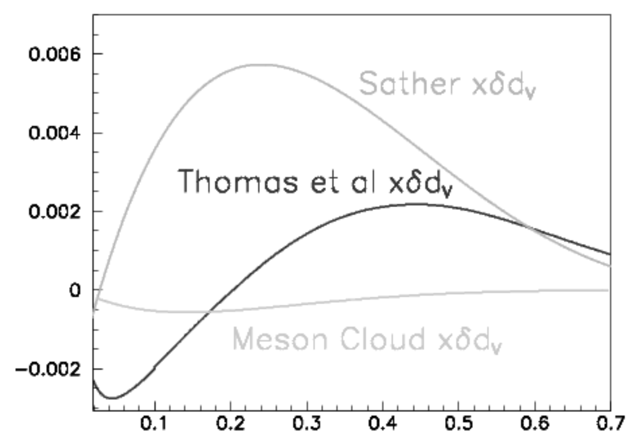
- require a ~5% minority ($d^p \neq u^n$) valence quark isospin violation
- or a ~30% momentum difference between strange and anti-strange seas

Models for Isopin Violation

- Isospin symmetry violation: $u^p \neq d^n$ and $d^p \neq u^n$
  - Full “Bag Model” calculation: *(Rodionov, Thomas, Londergan, MPL A9 1799)*

    $\Rightarrow \Delta\sin^2\theta_W = -0.0001$
    - Violation is x dependent; opposite sign at large and small x
    - Largest contribution from $m_d - m_u \sim 4$ MeV and $m_{dd} - m_{uu}$
  - “Meson Cloud Model”: *(Cao et al., PhysRev C62 015203)*

    $\Rightarrow \Delta\sin^2\theta_W = +0.0002$
  - What is needed to explain the NuTeV data?



$\delta d_v \equiv d_v^p - u_v^n$

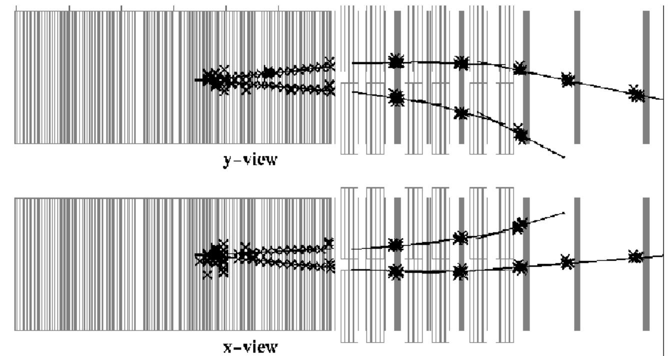
Need d_v quarks in proton to carry $\sim 5\%$ more momentum than u_v quarks in neutron

Model calculations predict an order of magnitude smaller change in minority quark dist

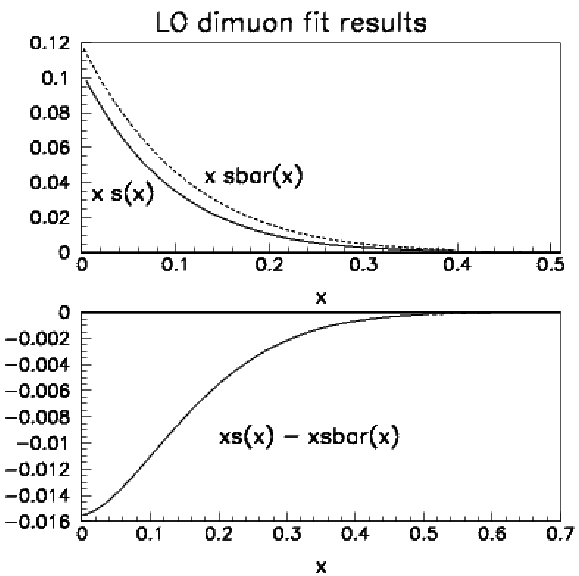
  - ***Can global PDF fits accommodate a large enough isospin violation to explain NuTeV?*** $\Leftarrow$ ***CTEQ, MRS investigating***

Strange / Anti-strange Asymmetry

- Non-perturbative QCD effects can generate a strange vs. anti-strange momentum asymmetry
  - Fits to NuTeV and CCFR ν and $\bar{\nu}$ dimuon data can measure this asymmetry: $\nu\, s \rightarrow \mu\, c \rightarrow \mu\mu X$
  - NuTeV separate ν and $\bar{\nu}$ beams important for reliable separation of s and $\bar{s}$ distributions



(NuTeV: M. Goncharov et al.and CCFR: A.O. Bazarko et al.)



↪ Same σ model as $\sin^2\theta_W$

$$\int x\,(s-\bar{s})\,dx \sim -0.0027 \pm 0.0013$$
$$\Longrightarrow \delta\sin^2\theta_W \sim +0.0020 \pm 0.0009$$

↪ Weakly prefers 10% asymmetry

↪ Increases discrepancy with SM to 3.7σ significance:

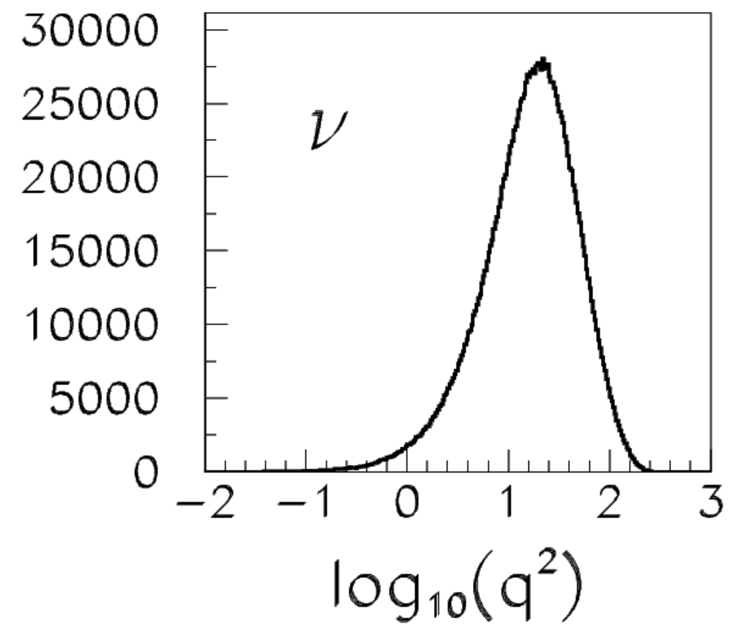
$$\sin^2\theta_W = 0.2297 \pm 0.0019$$

- To explain NuTeV discrepancy would require 30% asymmetry in the opposite direction!

Nuclear Effects

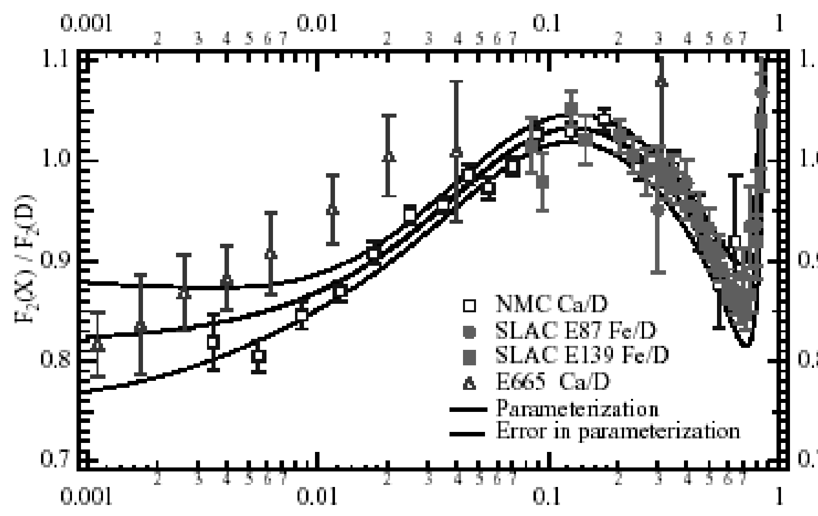
$$\langle Q^2 \rangle = \begin{matrix} 25\,\mathrm{GeV}^2 & \nu \\ 16\,\mathrm{GeV}^2 & \bar{\nu} \end{matrix}$$

- Use NuTeV CC data to fit parton distributions
  - PDFs that enter are already on iron
  - Need to worry about nuclear effects that could be different for W and Z exchange?



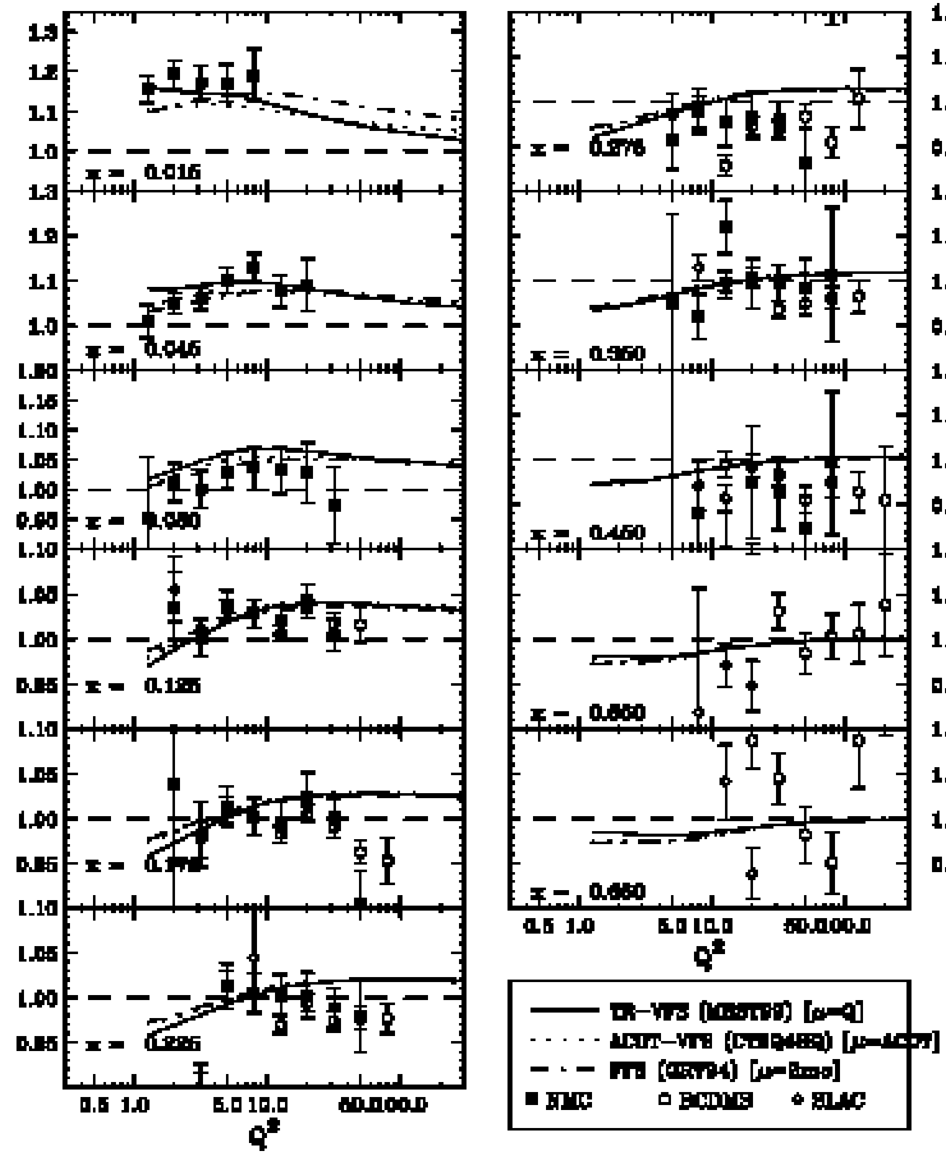
- NuTeV kinematics are high Q^2 valence distributions
  - $<E_\nu> \sim 100$ GeV
  - Sea cancels in R^-

- Fermi motion, Pomeron component of shadowing process independent. EMC?



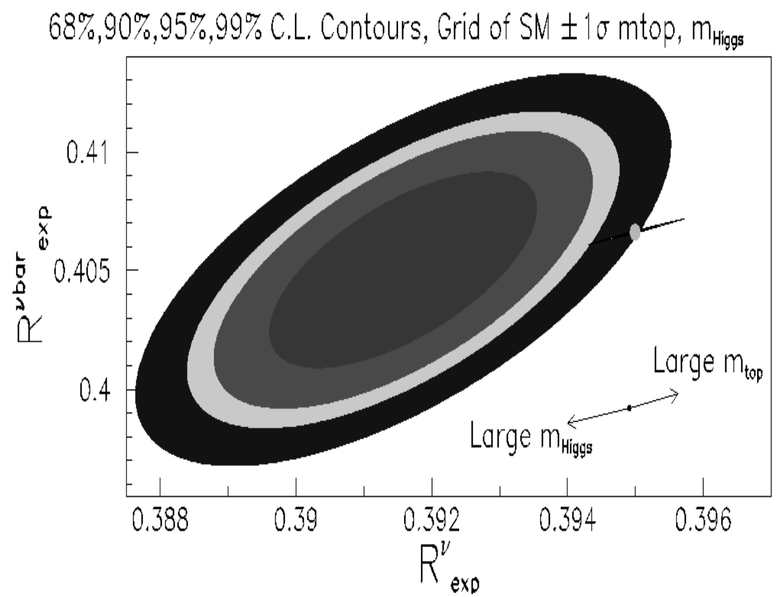
Nuclear Effects (cont'd)

- There is not arbitrary freedom in the data to introduce process dependent nuclear effects
- CC and EM F_2 on iron are in agreement!
- No analogous independent test that EM and NC would have common nuclear effects



Nuclear Effects (cont'd)

- Shadowing due to VMD would be different EM, NC and CC (Miller and Thomas, hep-ex/0204007)
  - No evidence for predicted $1/Q^2$ dependence in the NuTeV kinematic region x > 0.01 (NMC)
  - But low Q^2 data fit want some VMD (Melnitchouk and Thomas, hep-ex/0208016)
  - Low-x phenomena like VMD affect mainly sea quarks and the effect is canceled in R^-
    - Would increase both R^ν and $R^{\bar{\nu}}$
    - This model would make a very large R^ν shift (4.5σ from SM)
    - A much larger effect is needed for R^-

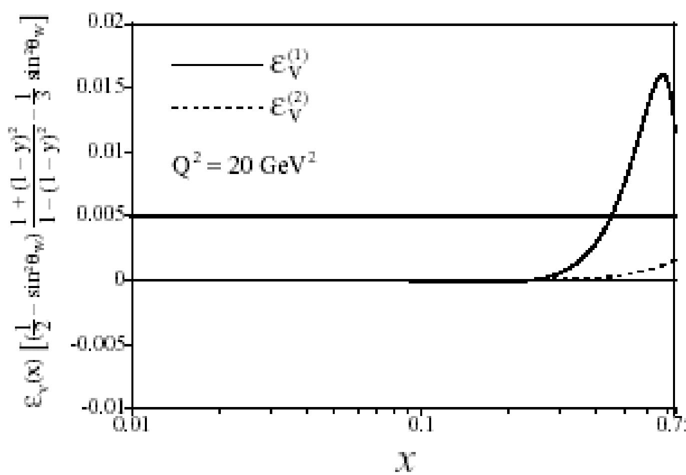


Nuclear Effects (cont'd)

- Other ideas…
  - Schmidt *et al* have proposed that the EMC effect is absent in CC (Kolvaenko, Schmidt, Yang, hep-ph/0207158)
    - An effect of that size would explain NuTeV
    - However, this would **massively violate** the F_2 CC/EM agreement shown previously
  - Kumano: are nuclear effects flavor dependent?

    (Kumano, hep-ph/0209200)
    - separate u and d type contributions
    - fits to data show large effect at

      at high x (physical reason?)
    - low x effect is non-zero, small
      - absence of D-Y anti-shadowing?
    - effect is negligible for NuTeV
      - ν cut suppresses high x
      - very little parton content there



Summary

- For NuTeV the SM predicts 0.2227 ± 0.0003 but we measure

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

(Previous neutrino measurements gave 0.2277 ± 0.0036)

- Origin?
  - QCD effects are a possibility
    - But no attractive explanation now exists
      - Very large isospin violation is still a possibility…
      - Nuclear effects? Possibilities are constrained..
  - Beyond SM Physics?
    - Most candidate explanations are unattractive, or in conflict with other data
  - Maybe NuTeV has found something unattractive!
- The result remains an interesting puzzle