The NuTeV Anomaly:
A hint of New Physics?
or Train Wreck of the Mundane?

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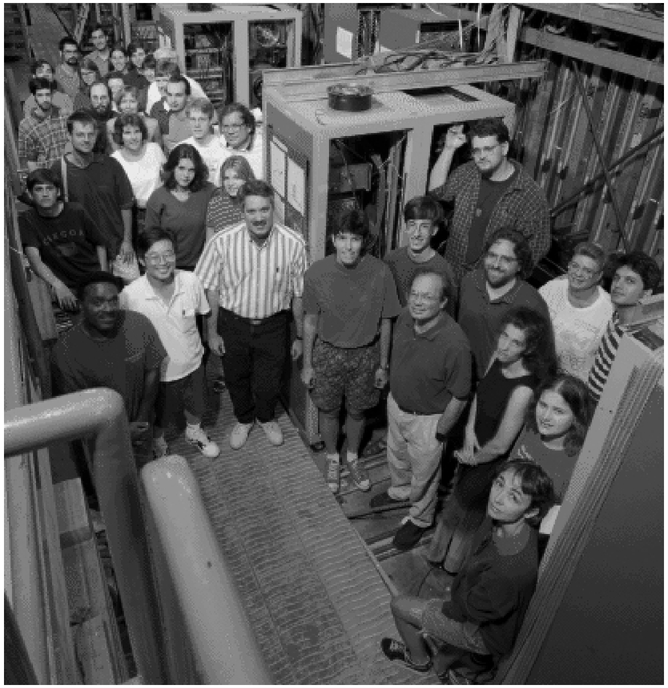
DESY-Zeuthen
Workshop on Precision EW Measurements
28 February 2003

NuTeV Collaboration



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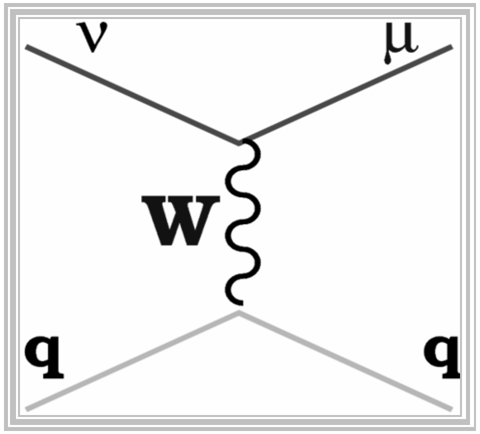
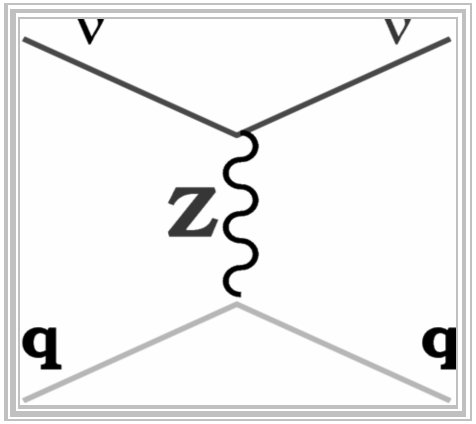
Measurement Technique

Charged-Current (CC)



Neutral-Current (NC)



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

Llewellyn Smith Relation:

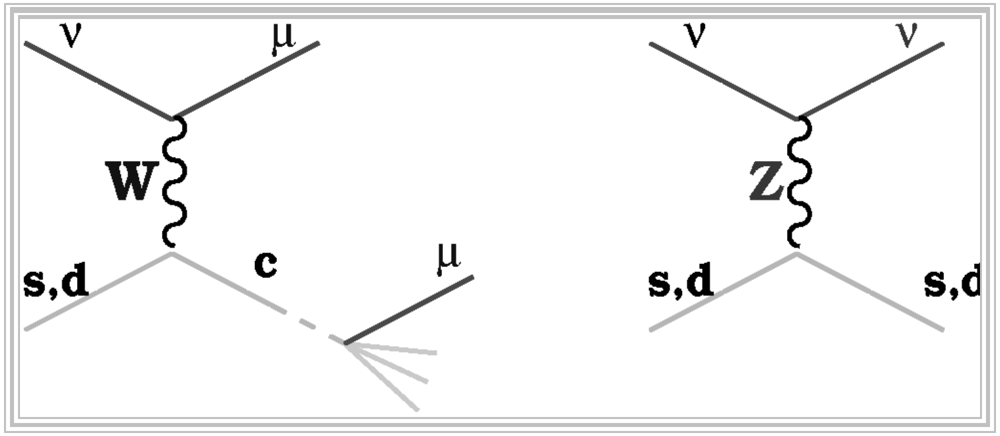
$$R^{\nu(\bar{\nu})} = \frac{\sigma_{NC}^{\nu(\bar{\nu})}}{\sigma_{CC}^{\nu(\bar{\nu})}} = \rho^2\left(\frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W\left(1+\frac{\sigma_{CC}^{\bar{\nu}(\nu)}}{\sigma_{CC}^{\nu(\bar{\nu})}}\right)\right) = g_L^2 + \frac{\sigma_{CC}^{\bar{\nu}(\nu)}}{\sigma_{CC}^{\nu(\bar{\nu})}}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

- *NC/CC* ratio easiest to measure experimentally but ...
  - Many SF dependencies and systematic uncertainties cancel, **BUT**
  - Must correct for up-down quark difference in target, EW radiative corrections, heavy quark effects, non-QPM parts of the cross-section, etc.
    - Here is where QCD and QED enter *(constrained by data where available)*

Charm Mass Effects

Charged-Current Production of Charm

Neutral-Current

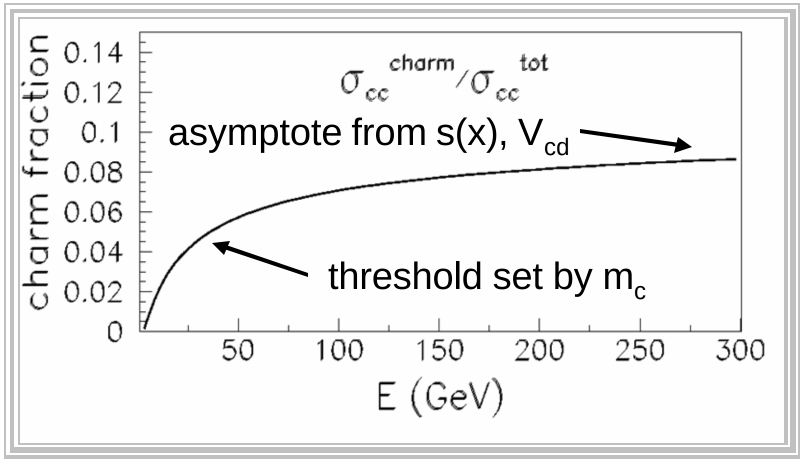


- CC is suppressed due to final state c-quark

  ⇒ Need to know s-quark sea and m_c
  - Modeled with leading-order slow-rescaling

    $$x = Q^2 / 2M\nu \;\rightarrow\; x = \left(Q^2 + m_c^2\right) / 2M\nu$$
  - Measured by NuTeV/CCFR using dimuon events ($\nu N \rightarrow \mu\, cX \rightarrow \mu\mu X$)

    (NuTeV+CCFR: M. Goncharov et al., Phys. Rev. D64: 112006,2001 and D. Mason presentation at ICHEP '02. CCFR: A.O. Bazarko et al., Z.Phys.C65:189-198,1995.)



asymptote from s(x), V_{cd}

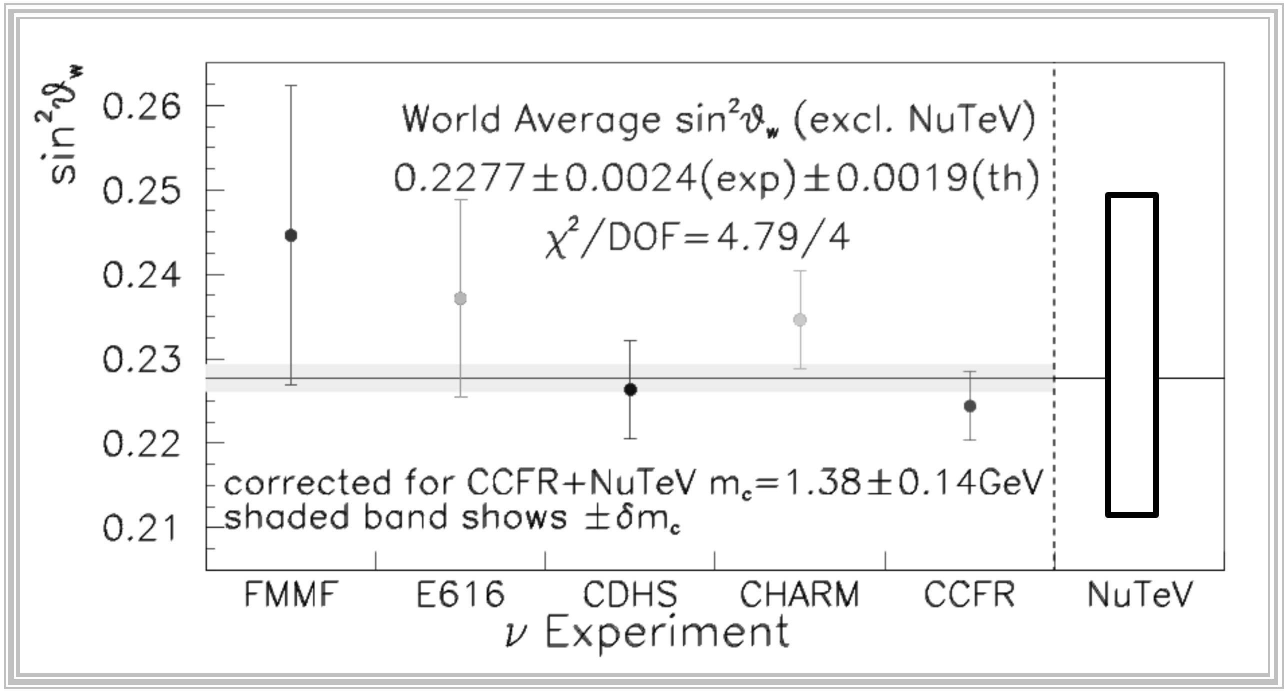
threshold set by m_c

Before NuTeV…

- νN experiments had hit a brick wall in precision
  - ⇒ 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

$$R^{-} = \frac{\sigma^{\nu}_{NC} - \sigma^{\bar{\nu}}_{NC}}{\sigma^{\nu}_{CC} - \sigma^{\bar{\nu}}_{CC}} = \rho^{2}\left(\tfrac{1}{2} - \sin^{2}\theta_{W}\right) = g_{L}^{2} - g_{R}^{2}$$

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

$\sigma\left(\nu_{\mu} d_{sea}\right) - \sigma\left(\bar{\nu}_{\mu} \bar{d}_{sea}\right) = 0 \;\Rightarrow\;$ Only $d_{valence}$ contribute

$\sigma\left(\nu_{\mu} \bar{u}_{sea}\right) - \sigma\left(\bar{\nu}_{\mu} u_{sea}\right) = 0 \;\Rightarrow\;$ Only $u_{valence}$ contribute

$\sigma\left(\nu_{\mu} s_{sea}\right) - \sigma\left(\bar{\nu}_{\mu} \bar{s}_{sea}\right) = 0 \;\Rightarrow\;$ No *strange – sea* contribution $\left(\text{Assuming } xs(x) = x\bar{s}(x)\right)$

- 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) beamline

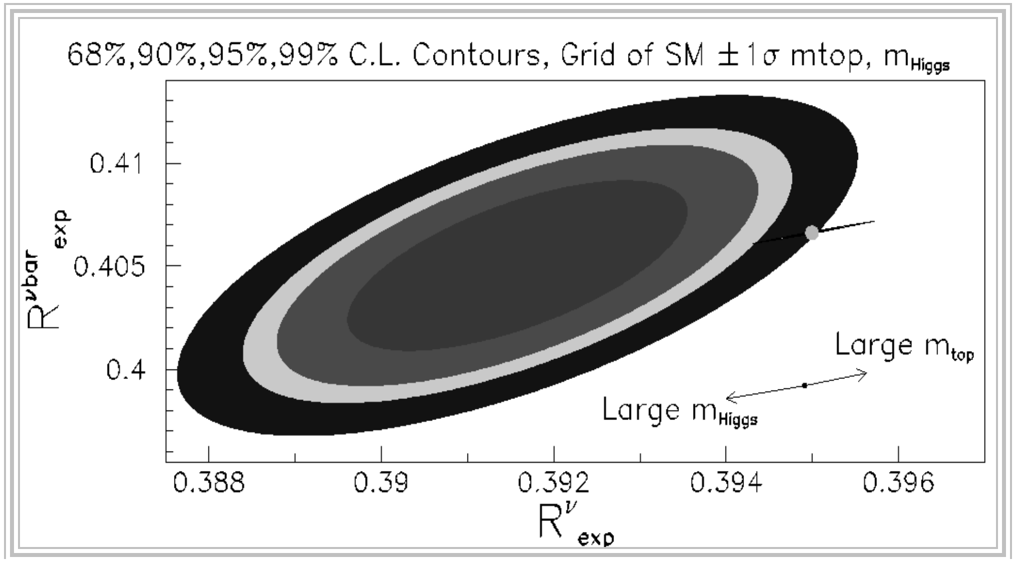
– Realized ν in ν mode 3×10^{-4}, ν in $\bar{\nu}$ mode 4×10^{-3}, 1.6% ν_e $\bar{\nu}_e$

Paschos-Wolfenstein à la NuTeV

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

$$\frac{dR^{\nu}_{\exp}}{d\sin^2\theta_W} \text{ large} \qquad \frac{dR^{\bar{\nu}}_{\exp}}{d\sin^2\theta_W} \text{ small}$$

$$R^{\nu}_{\exp} \rightarrow \sin^2\theta_W \qquad R^{\bar{\nu}}_{\exp} \rightarrow \text{systematics (i.e. } m_c\text{)}$$

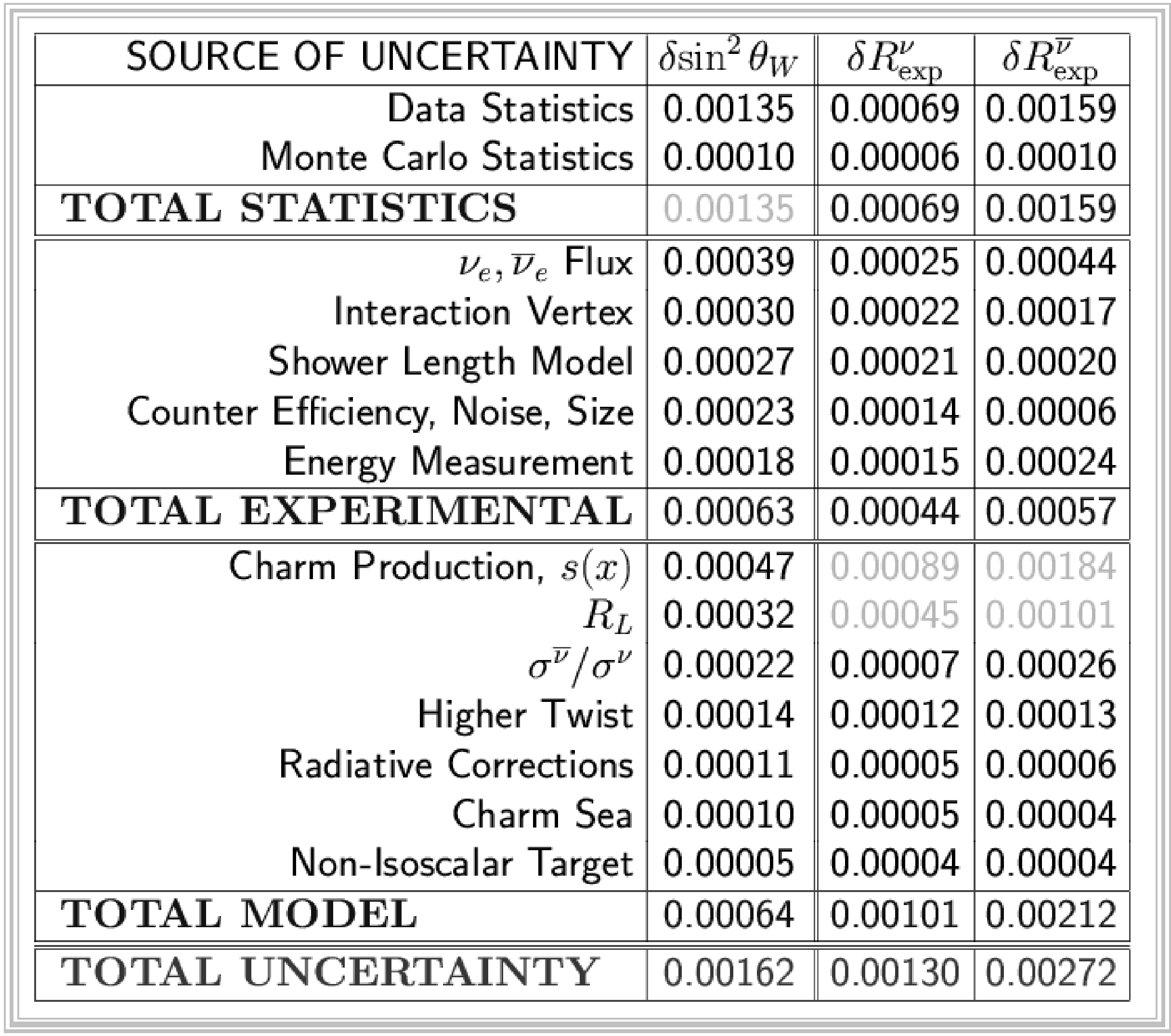


$$\sin^2\theta_W^{(on-shell)} = 0.2227 \pm 0.0013(stat.) \pm 0.0009(syst.)$$

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

Uncertainties in Measurement

- sin^2q_W error statistically dominated *(R^- technique)*
- R^n uncertainty dominated by theory model

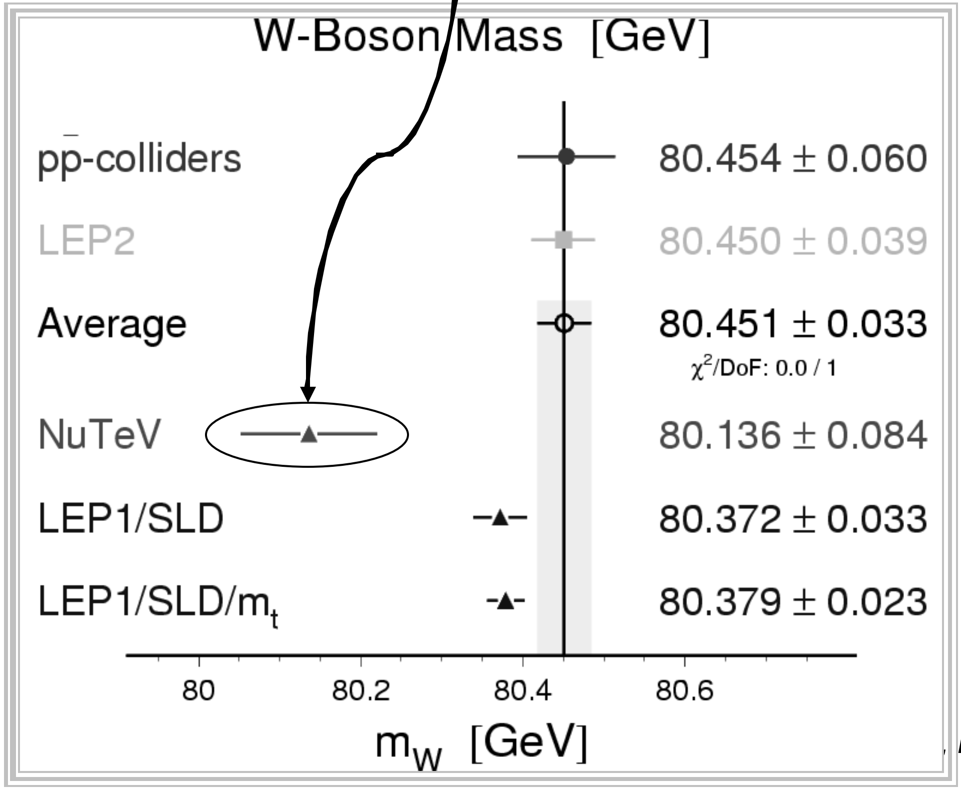


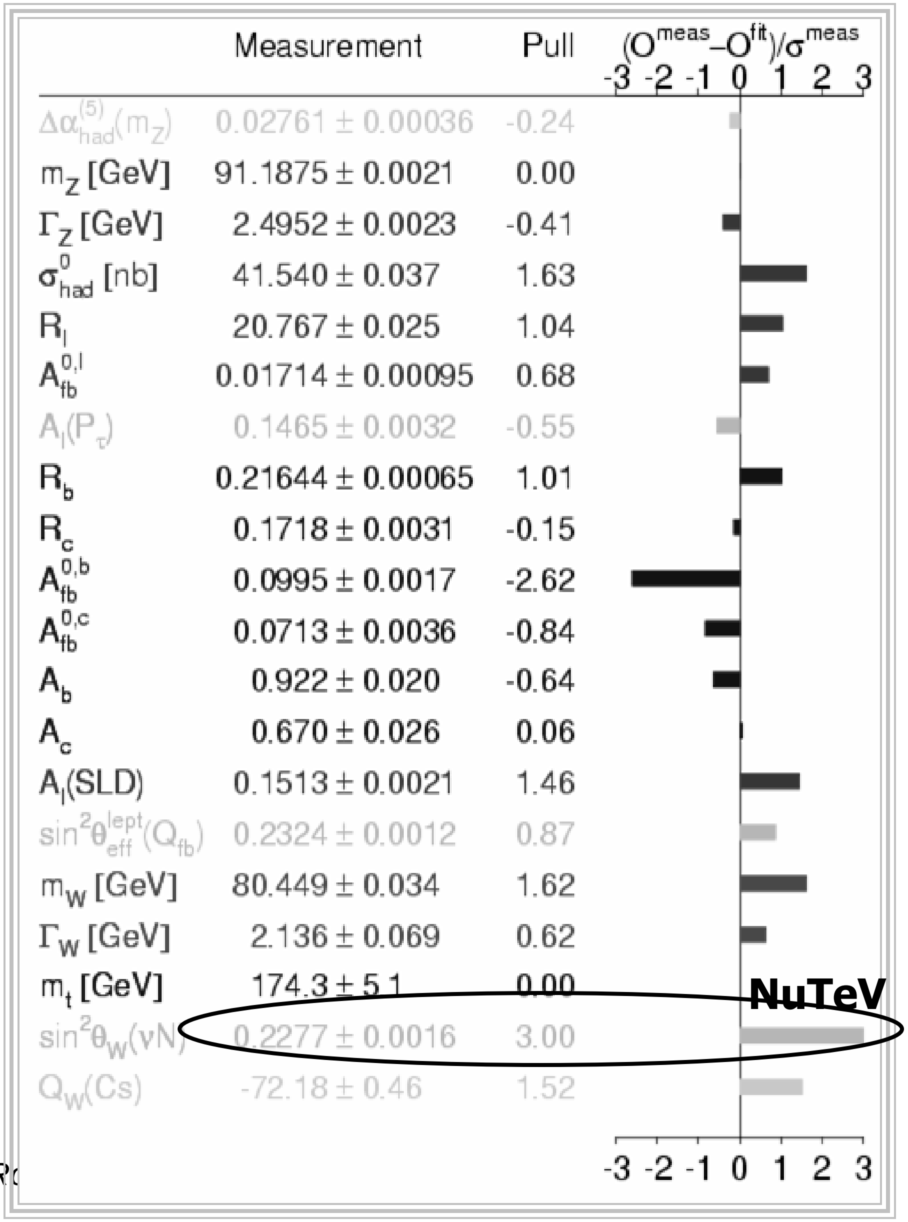
SOURCE OF UNCERTAINTY	$\delta\sin^2\theta_W$	$\delta R^{\nu}_{\mathrm{exp}}$	$\delta R^{\overline{\nu}}_{\mathrm{exp}}$
Data Statistics	0.00135	0.00069	0.00159
Monte Carlo Statistics	0.00010	0.00006	0.00010
TOTAL STATISTICS	0.00135	0.00069	0.00159
$\nu_e, \overline{\nu}_e$ Flux	0.00039	0.00025	0.00044
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

$$M_W = 80.136 \pm 0.084\ \text{GeV}$$

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





	Measurement	Pull
$\Delta\alpha_{had}^{(5)}(m_Z)$	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_{had}^0 [nb]	41.540 ± 0.037	1.63
R_l	20.767 ± 0.025	1.04
$A_{fb}^{0,l}$	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
$A_{fb}^{0,b}$	0.0995 ± 0.0017	-2.62
$A_{fb}^{0,c}$	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
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	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

So what has NuTeV found?

- The cause of NuTeV’s anomaly is highly unclear
  - Beyond SM effects explaining NuTeV are *strained*
    - It’s not SUSY loops or RPV SUSY
    - Hard to fit with leptoquarks
    - “Singular” Z’ is possible
    - Heavy-light ν + more miracles
  - So we turn to mundane explanations
    - I’ll argue none of these are outstanding candidates either
- c.f. $(g-2)_\mu$. “Everyone knows” it is SUSY but result is theoretically shaky.
  - Opposite problem: too many explanations!

S. Davidson et al. hep-ph/0112302

W. Loinaz et al, hep-ph/0210193

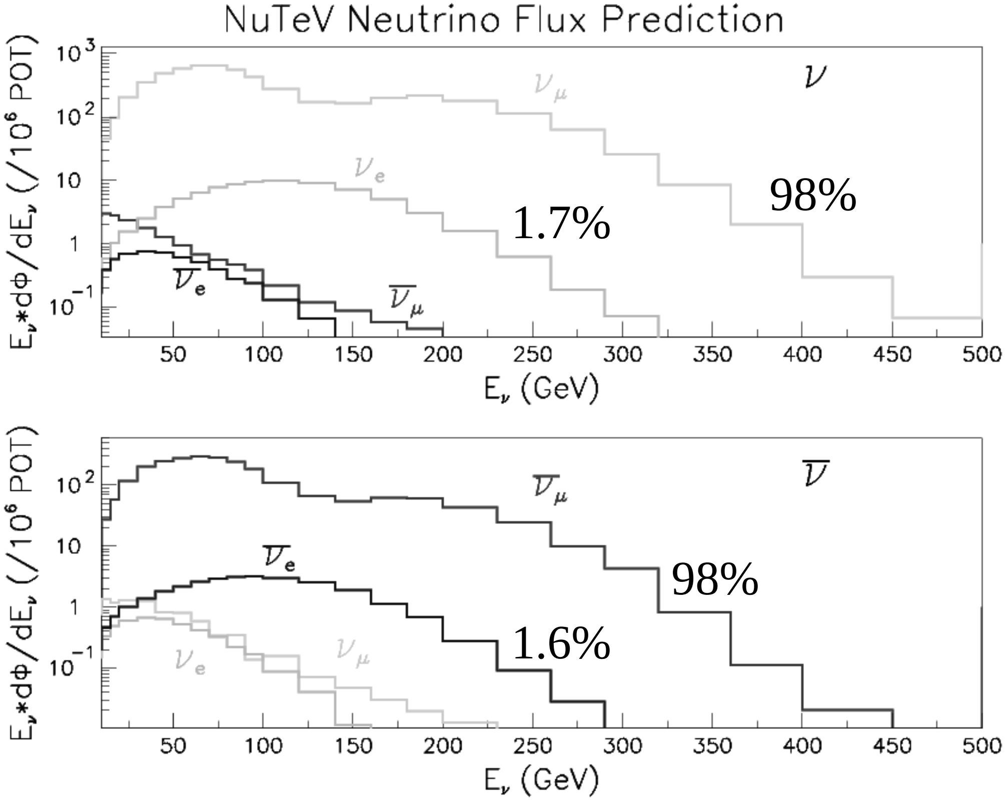
A. Kurlov et al, hep-ph/0301208

Experimental Concerns

1. Electron Neutrino Background
2. Why no others are evident

Electron Neutrino Background

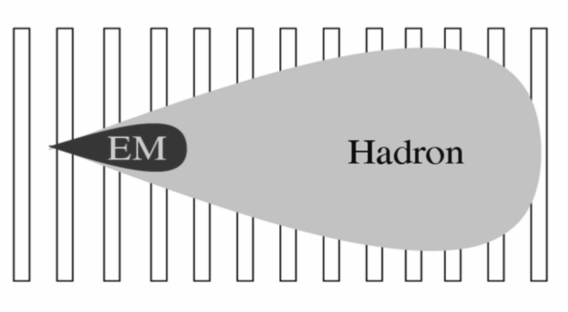
- Approximately 5% of NC candidates are ν_e CC events
  (It would take a 20% overestimate of ν_e to move NuTeV to SM)
  - Main ν_e source is $K^\pm$ decay (93% / 70% of total in ν / $\bar{\nu}$ beams)
  - Others include K_L's (4%/18%) and Charm (2%/9%)
  - Main uncertainty is $K^\pm_{e3}$ branching ratio (known to 1.4%) !
  - Unless BNL-E865 is correct. They claim $K^\pm_{e3}$ BR is 6% higher than PDG, fixing V_{us} problem but exacerbating NuTeV
- Also have direct ν_e measurement.



Direct Measurments of ν_e Flux

1. ν_μ^{CC} (wrong-sign) events in anti-neutrino beam constrain charm and K_L production

2. Shower shape analysis can statistically pick out ν events (E_ν > 80 GeV)
   - Most precise at highest energies
   - Good agreement in peak flux region ($80 < E_\nu < 180$ GeV)



$$N_{meas} / N_{MC} : 1.05 \pm 0.03\ (n_e)$$
$$1.01 \pm 0.04\ (\bar{n}_e)$$

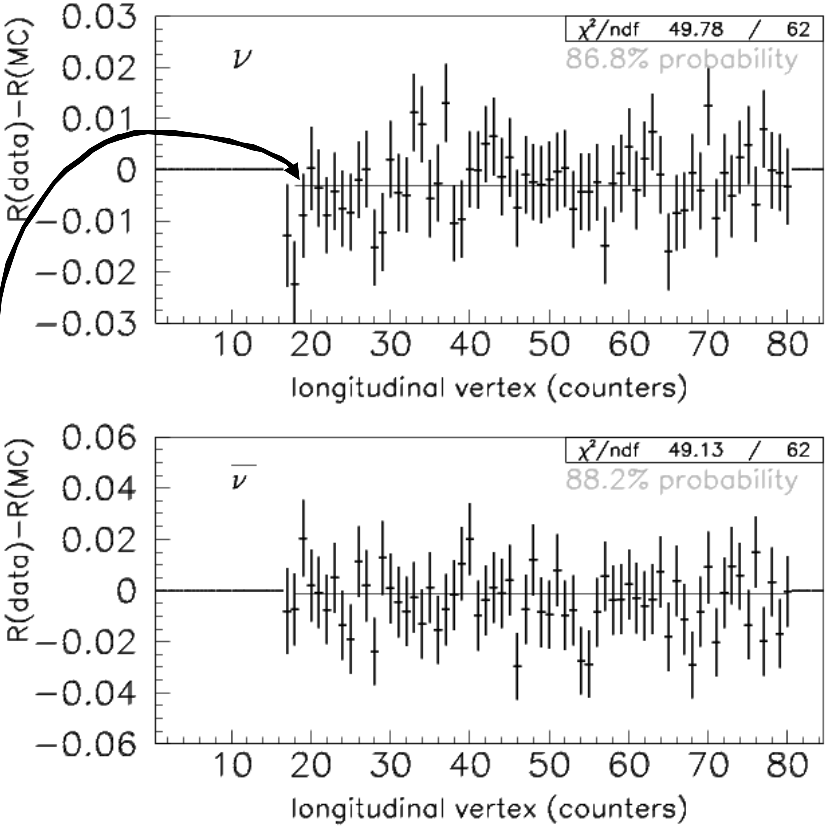
   - Poor agreement with simulation on high energy tail (expected from inability to measure high E ν_μ^{CC}, smearing)
     - Remove events from analysis with E_ν > 180 GeV. Concern?

Why We (NuTeV) Believe the Experimental Analysis: “Stability Tests”

Verify systematic uncertainties with data to Monte Carlo comparisons as a function of exp. variables.

- Longitudinal Vertex: checks detector uniformity

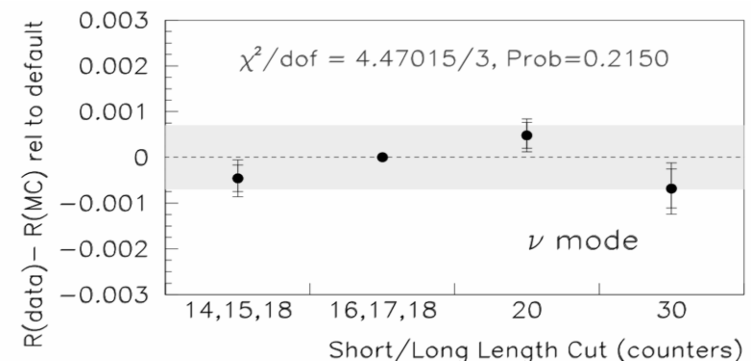
Note: Shift from zero is *because* NuTeV result differs from Standard Model

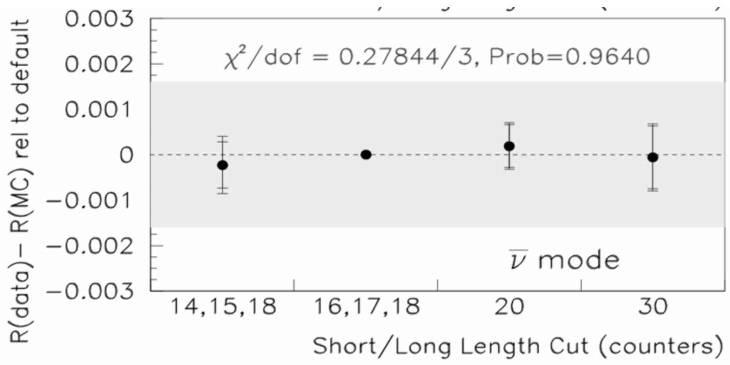


Stability Tests (cont'd)

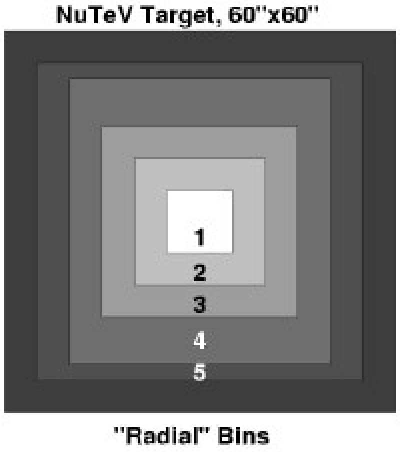
- R_{exp} vs. length cut: Check NC ↔ CC separation syst.
  - "16,17,18" L_{cut} is default: tighten ↔ loosen selection

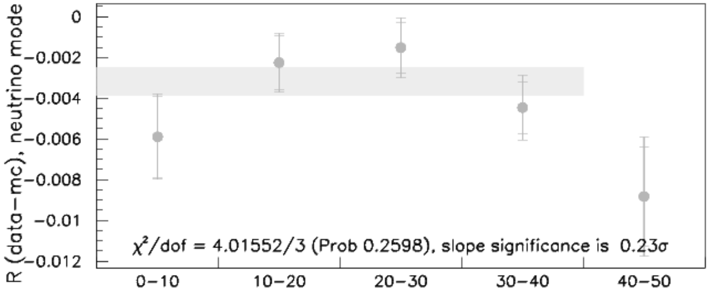
Yellow band is stat error

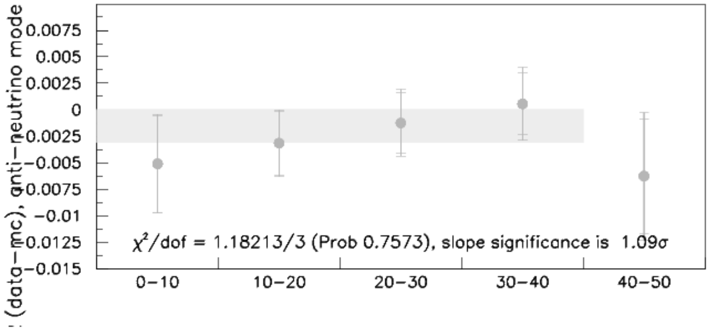




- R_{exp} vs. radial bin: Check corrections for ν_e and short CC which change with radius.

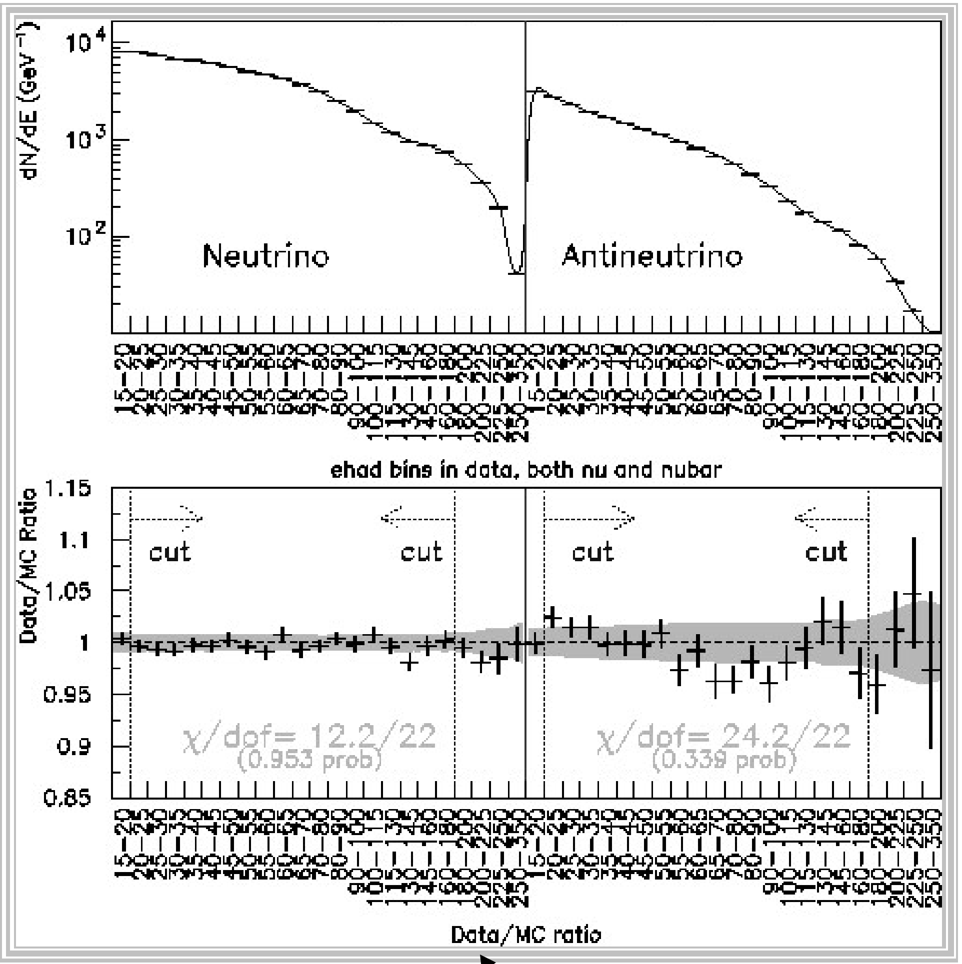




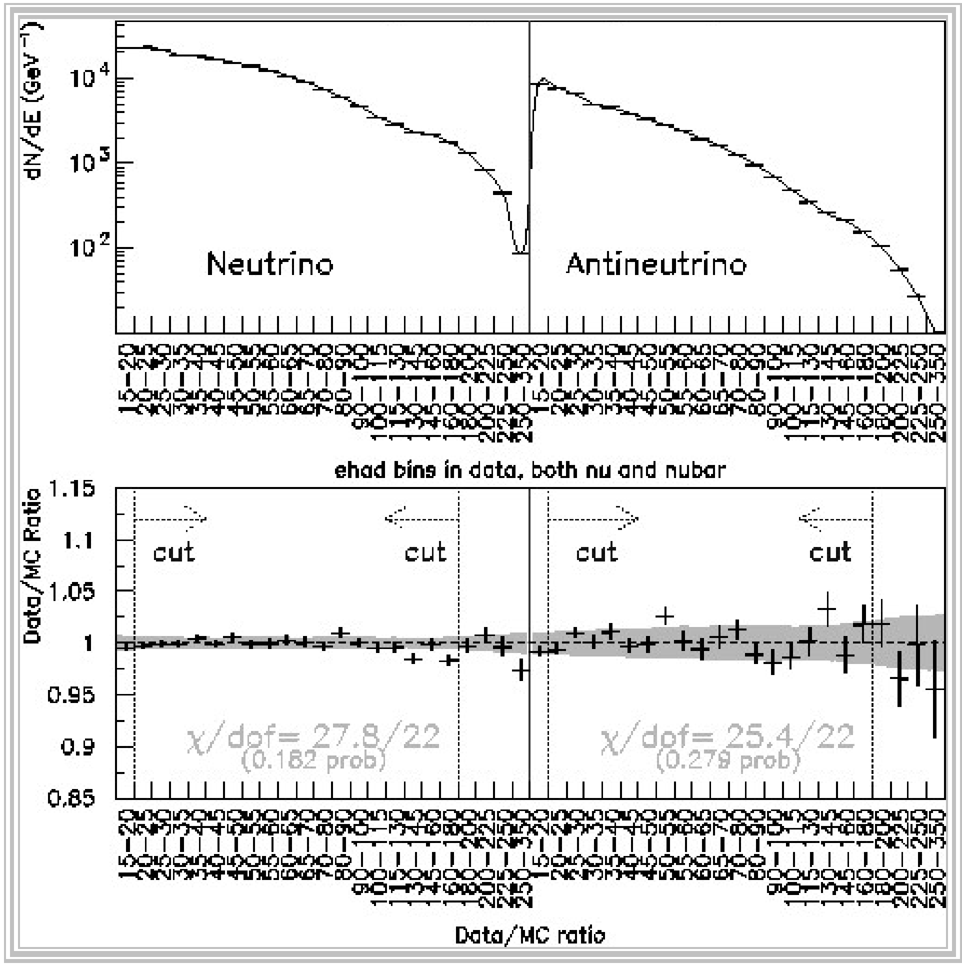


Distributions vs. E_{had}

NC Candidates vs. visible Energy



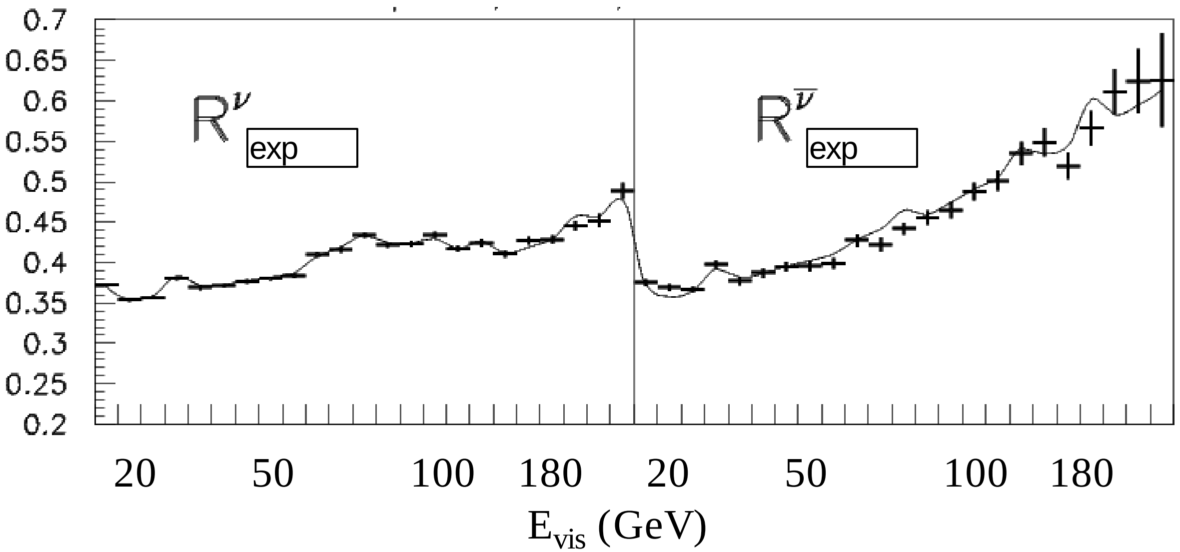
CC Candidates vs. visible Energy

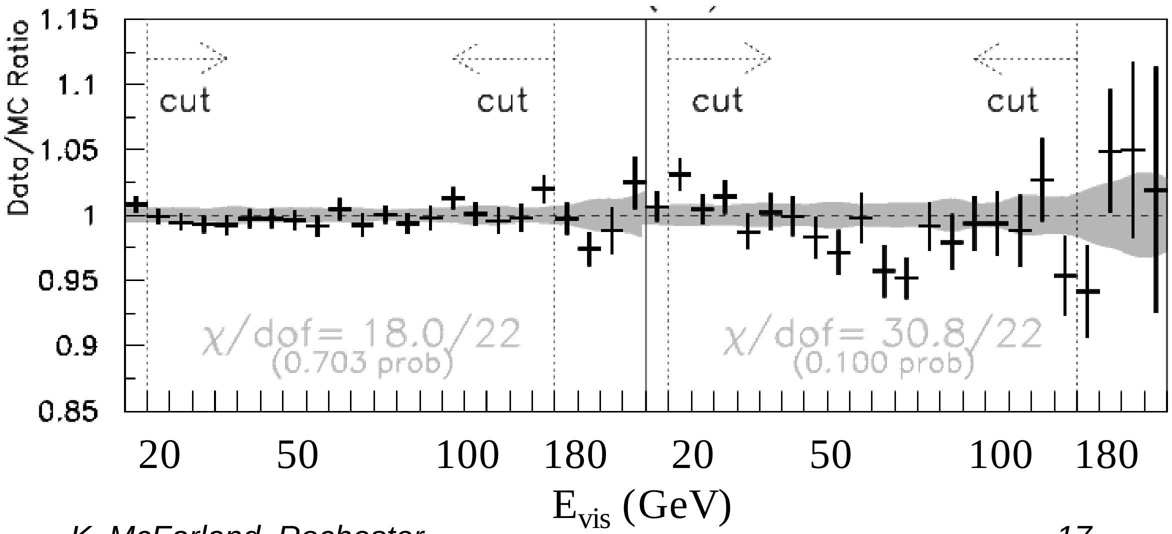


Systematic error bands

Stability Test: R_{exp} vs. Energy

- Modeling of NC/CC Ratio vs. visible energy checks
  - – backgrounds
  - – cross-section model
  - – detector effects
- Bottom line: no obvious causes for concern





Cross-Section Model Concerns

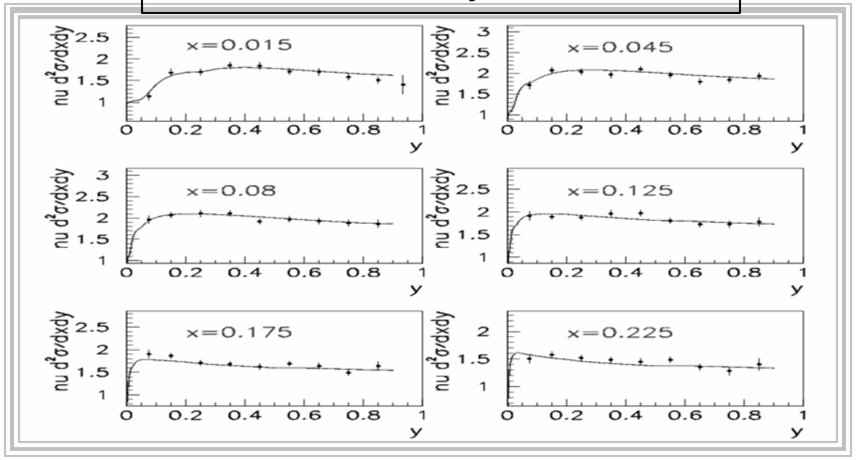
1. "Enhanced LO" vs NLO QCD
2. EM Radiative Corrections

Enhanced LO Cross-Section

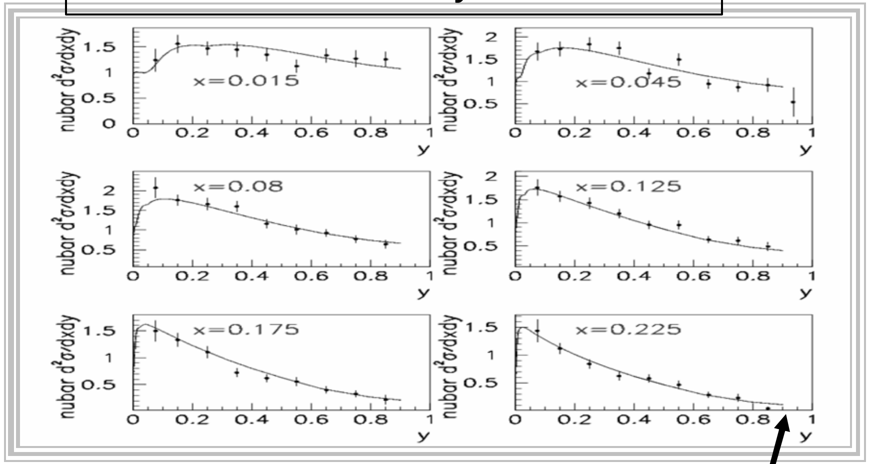
- “Enhanced” means: include R_L and higher twist terms
- PDFs extracted from CCFR data exploiting symmetries:
  - Isospin symmetry: $u^p=d^n$, $d^p=u^u$, and $s(x) = \bar{s}(x)$
- Data-driven: uncertainties come from measurements

CCFR Data

Neutrino xsec vs y at 190 GeV



Antineutrino xsec vs y at 190 GeV



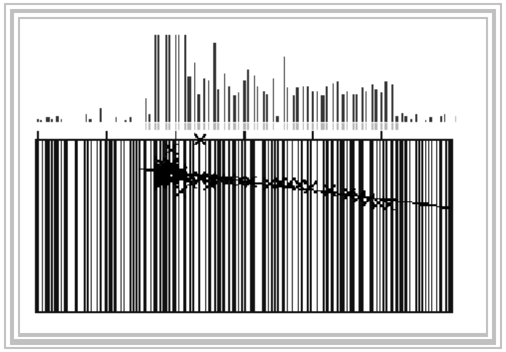
- LO quark-parton model tuned to agree with data:
  - Heavy quark production suppression and strange sea (CCFR/NuTeV $\nu N \rightarrow \mu^+\mu^- X$ data)
  - R_L , F_2 higher twist (from fits to SLAC, BCDMS)
  - d/u constraints from NMC, NUSEA(E866) data
  - Charm sea from EMC F_2^{cc}

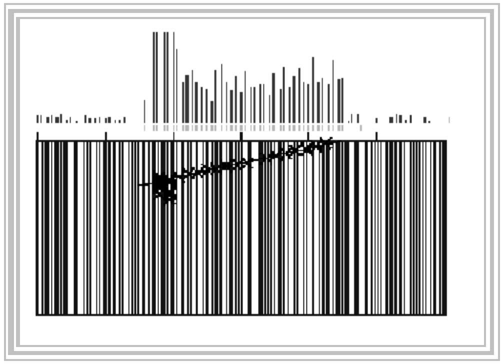
high y events are background to the neutral current sample

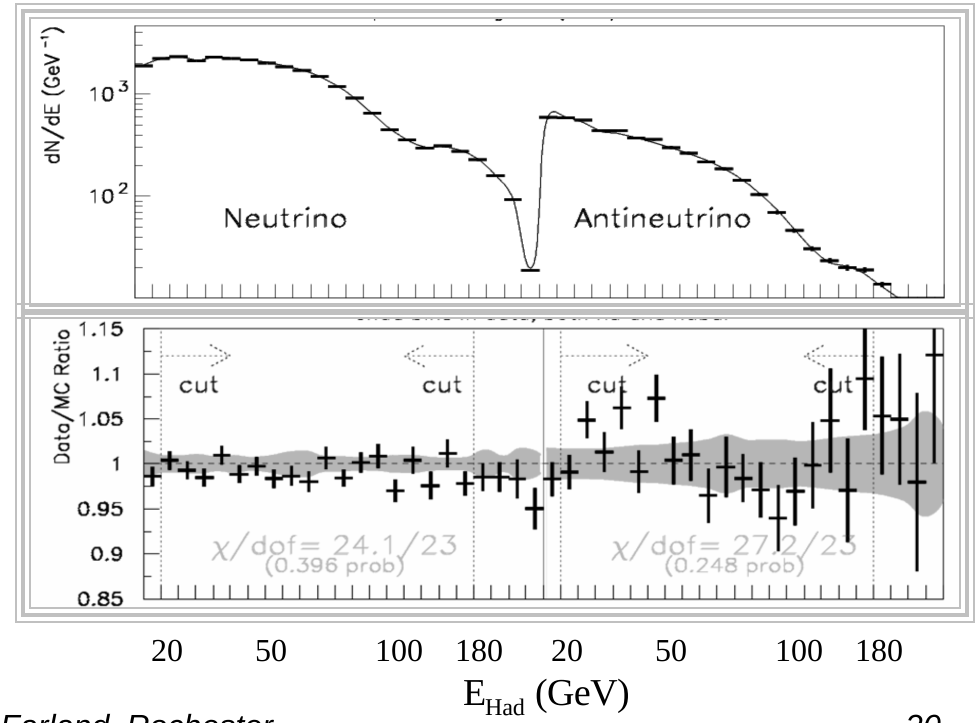
Model is fit directly to this data; uncertainties come from data.

Charged-Current Control Sample

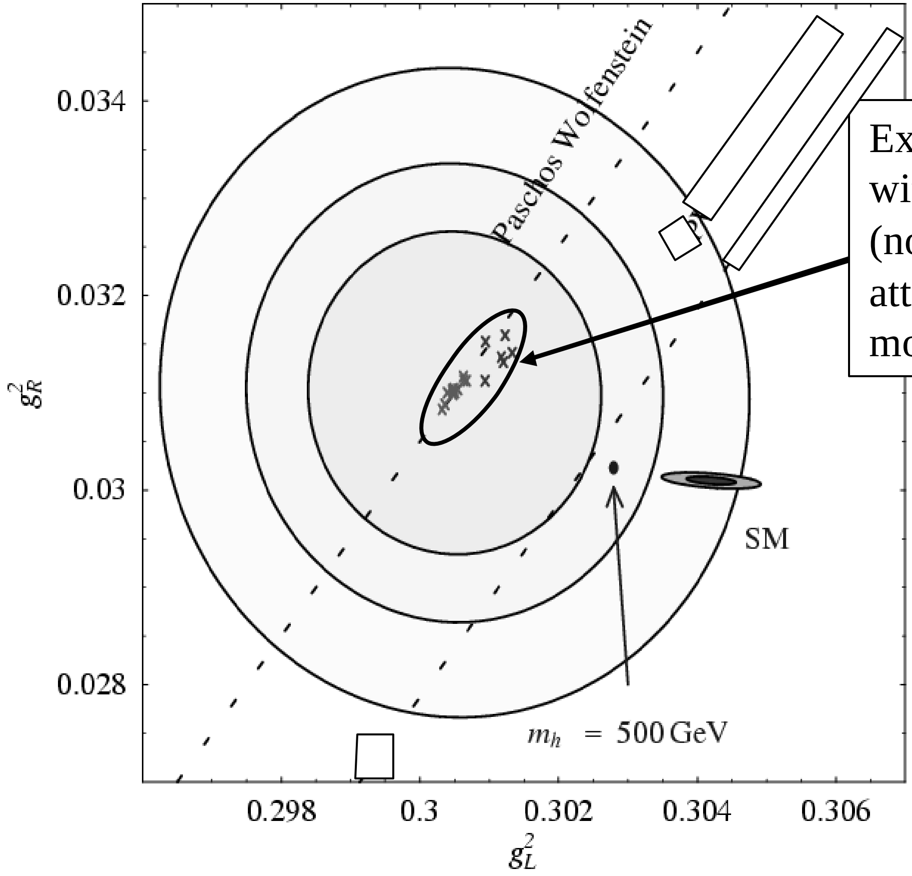
- Medium length events, clearly CC but with similar kinematics to NC candidates from CC events, check modeling
- Excellent agreement with prediction







PDF changes have little effect



Extreme variations with LO/NLO PDF Sets (no NLO m_c effects). No attempt to make cross-section model + PDFs fit ν data!

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

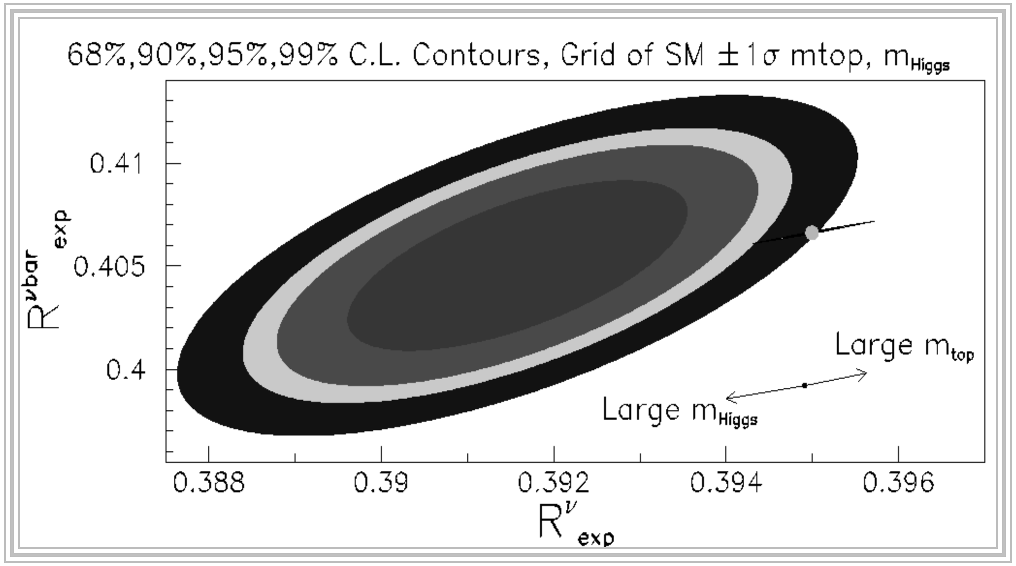
- Illustrates (relative) independence of R^- from (most) PDF details, even s(x) !
- But this does not prove NLO effects are small
- Also, this is R^-, not the full NuTeV analysis.

How is NuTeV's Analysis Different from R^- ?

- Backgrounds (excluding ν_e background)
  - Taken from data. Only increase statistical errors.
- Cross-talk (including ν_e background)
  - Dilute statistical significance of the result $\Rightarrow \left|\frac{\partial \sin^2 q_W}{\partial ?}\right| < \left|\frac{\partial R^-}{\partial ?}\right|$
  - In the case of ν_μ^{CC}, cross-talk occurs for particular kinematics
    - High y, large θ_μ
- Different NC, CC acceptance
  - Very small effects from muon (energy, vertex). Likely negligible?
- Use of external dimuon constraint on charm suppression ("m_c") reduces role of anti-neutrino data
  - Sensitive to charm model
  - And to non-QPM cross-section, e.g. R_L

How is NuTeV's Analysis Different from R^-? (cont'd)

- But if the latter were a problem, we should see a big difference when extracting $\sin^2\theta_W$ without constraint…
- See very small difference if charm mass constraint dropped.
  - This is equivalent to saying that $R^{\bar{\nu}}$ is in agreement with expectations.



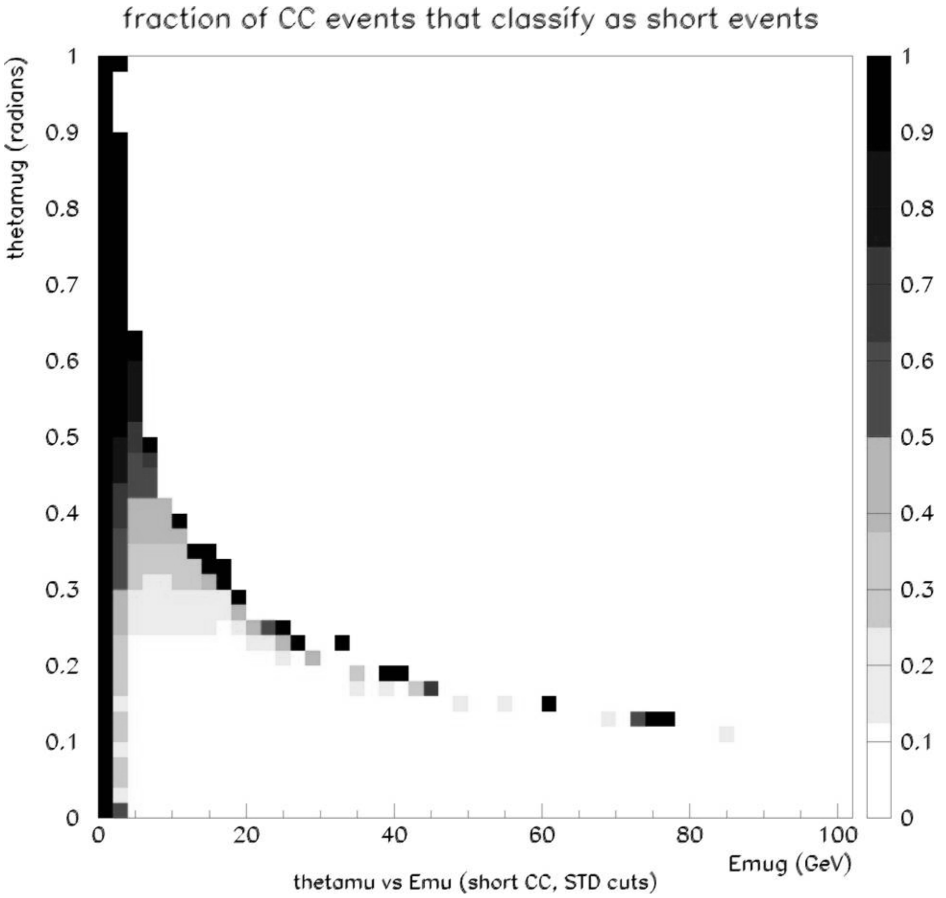
$$\sin^2 q_W^{(on-shell)} = 0.2274 \pm 0.0014(stat.) \pm 0.0008(syst.)$$

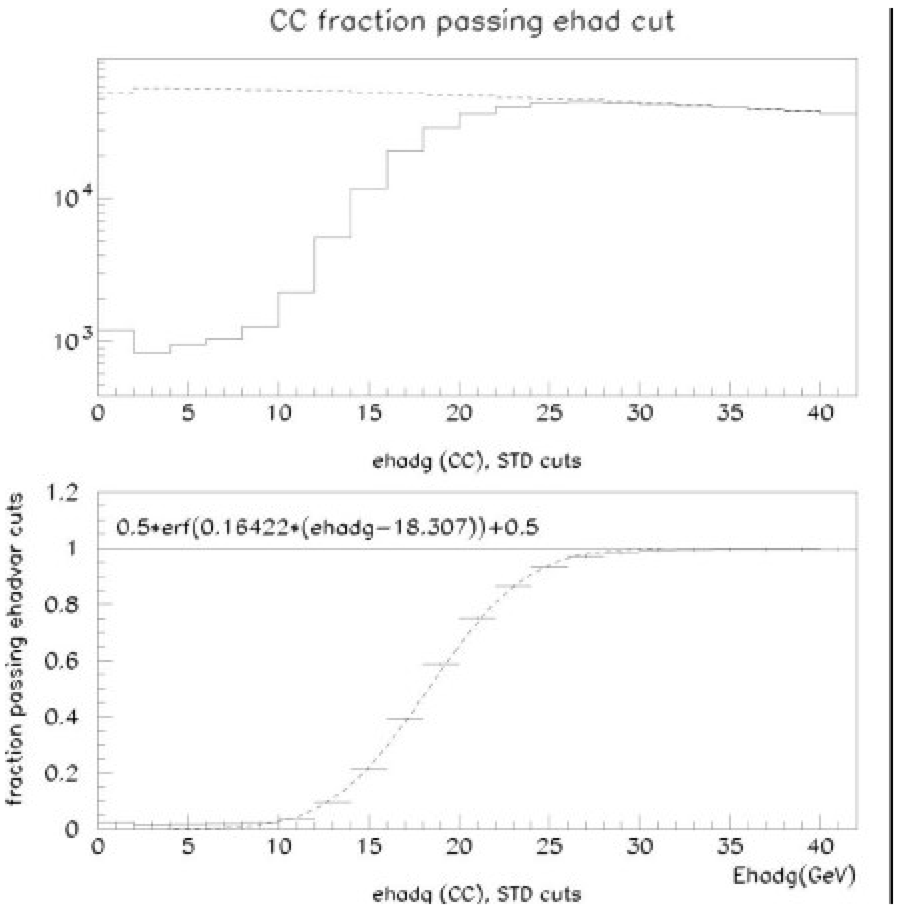
- Statistical and experimental systematics increase Model errors, of course, decrease…

NLO QCD Effects

- NLO corrections to R^- are small
  - – Not the case for R^{ν} and $R^{\bar{\nu}}$ separately…
- So where are the worries?
  - – Charm production (concern is tempered by previous argument)
  - – Kinematic regions where CC events fake NC
    - High y, large θ_μ
  - – NC/CC acceptance difference
- We are actively working to “parameterize” this effect so that independent authors can check LO-NLO differences
  - – Should resolve the issue?

NLO QCD Effects (cont'd)

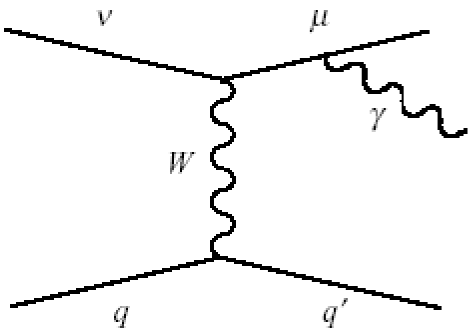




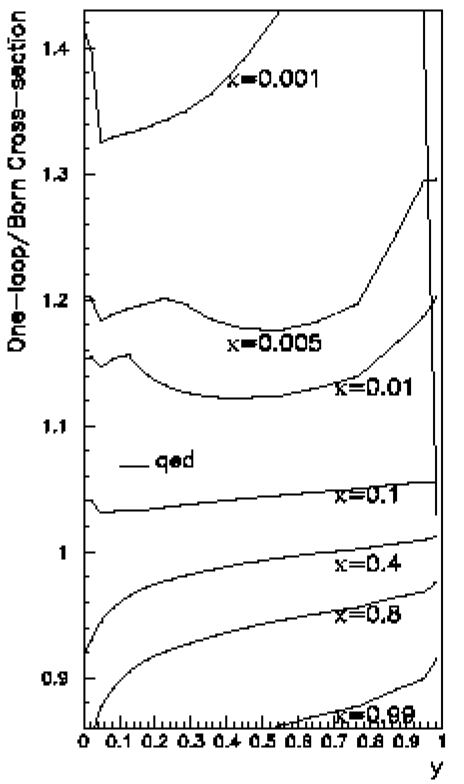
EW Radiative Corrections

- I see no serious reason to believe effective coupling calculations are inadequate. Comments?
- EM radiative corrections are large
  - Bremsstrahlung from final state lepton in CC is a big correction.
    - Not present in NC; promotes CC events to higher y
    - $\{\delta R^{\nu}, \delta R^{\bar{\nu}}, \delta\sin^2\theta_W\} \sim$ $\{+.0074, +.0109, -.0030\}$
  - These should be checked. How to proceed?

D. Yu. Bardin and V. A. Dokuchaeva, JINR-E2-86-260, (1986)



CC ν_μ Radiative Corrections, E_ν=100 GeV



Symmetry Violations in QCD

1. Isospin Violation
2. Strange Strange Sea
3. Nuclear Effects

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
- To get a rough idea of first two effects, can calculate them for R^-

$$
\begin{aligned}
R^- &\approx \Delta_u^2 + \Delta_d^2 \\
&\quad - dN\left(\frac{U_v - D_v}{U_v + D_v}\right)\left(3\Delta_u^2 + \Delta_d^2\right) \\
&\quad - \frac{1}{2}\left(\frac{dU_v - dD_v}{U_v + D_v}\right)\left(3\Delta_u^2 + \Delta_d^2\right) \\
&\quad + \left(\frac{dS}{U_v + D_v}\right)\left(2\Delta_d^2 - (3\Delta_u^2 + \Delta_d^2)e_c\right)
\end{aligned}
$$

$$
\begin{aligned}
\text{where } dN &= \frac{(N-Z)}{A} \\
U_v &= \int x(u_v^p + d_v^p)dx, \text{ etc.} \\
dU_v &= \int x(u_v^p - d_v^n)dx, \text{ etc.} \\
\Delta_{u,d}^2 &= \left(e_L^{u,d}\right)^2 - \left(e_R^{u,d}\right)^2 \\
dS &= \int x(s - \bar{s})dx \\
e_c &= \text{ kinematic charm CC suppression}
\end{aligned}
$$

Symmetry Violating QCD Effects

- Violations could arise from:

1. A ≠ 2Z due to neutron excess (corrected for in NuTeV)

2. Isospin violating PDF's, $u_p(x)$ ¹ $d_n(x)$
   (Sather; Rodinov, Thomas and Londergan; Cao and Signal)
   - Changes d/u of target ⇒ mean NC couplings and CC rates

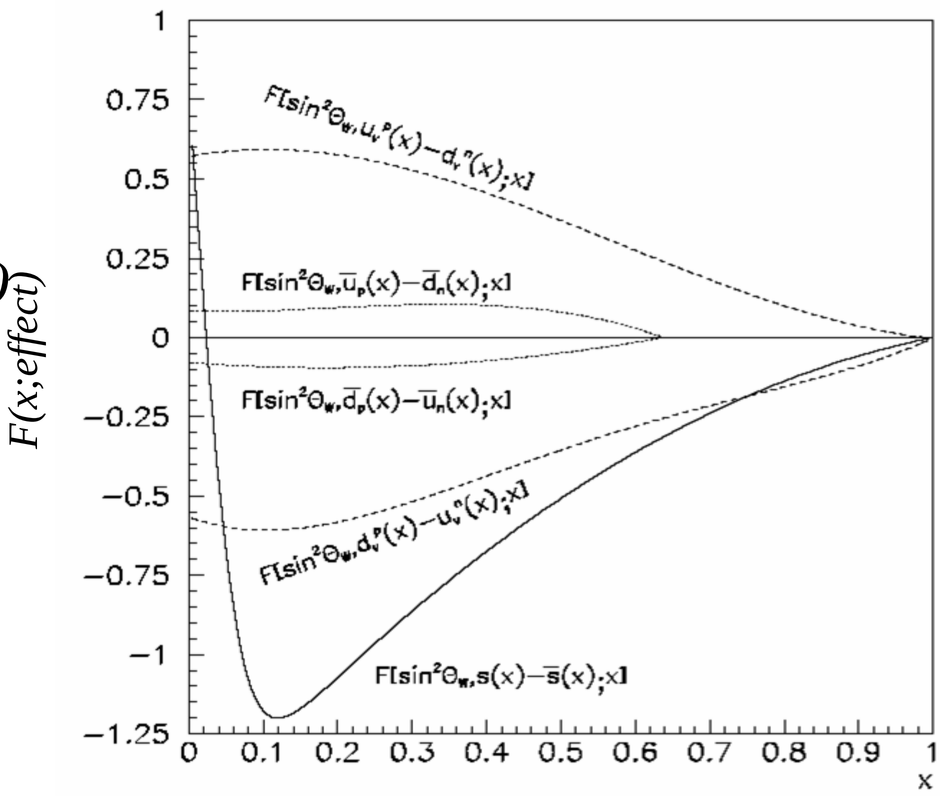
3. Asymmetric heavy-quark sea, s(x) ? $\bar{s}(x)$
   (Signal and Thomas; Burkhardt and Warr; Brodsky and Ma)
   - Strange sea doesn't cancel in R^-

4. Mechanisms for different nuclear effects in NC/CC
   (Thomas and Miller; Kumano; Schmidt et al; Kulagin)
   - Affects R^ν, $R^{\bar{\nu}}$ directly

Detailed Examination of Symmetry Violation Effects

"On the Effects of Asymmetric Strange Seas and Isospin-Violating Parton Distribution Functions on sin^2q_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



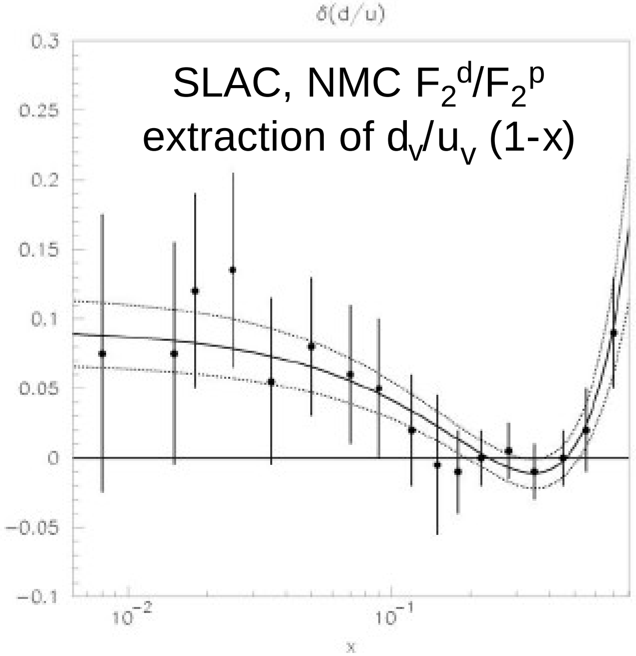
Conclusions:

- require a ~5% minority (d^p ¹ u^n) valence quark isospin violation
- or a ~30% momentum difference between strange and anti-strange seas

Neutron excess correction

- Neutron excess of target is well-known
  - primary *a priori* uncertainty, chemical composition of steel, resolved by assay

    $\delta N = 0.00574 \pm 0.00002$
  - correction for U_v-D_v is large, -0.0080 in $\sin^2\theta_W$
    - but it is well-constrained by existing data



SLAC, NMC F_2^d/F_2^p extraction of d_v/u_v (1-x)

- N.B., PRL uncertainty is too small, ±*0.0003 is new estimate*
  - *Thanks to S. Kulagin and S. Alekhin for catching our mistake!*

Isopin Violation

- Isospin symmetry violation: u^p ¹ d^n and d^p ¹ u^n
- Bag models offer a useful framework for estimating effect
  - NuTeV has used full “Bag Model” calculation *(Rodionov, Thomas, Londergan, MPL A9 1799)* and obtained

    $\Rightarrow \Delta\sin^2\theta_W = -0.0001$ *(G.P. Zeller et al., Phys.Rev.D65:111103,2002)*
  - But Londergan and Thomas recently suggested the effect is actually -0.0017 in magnitude. What is going on? Not surprisingly, it’s a complex story.

- NuTeV original calculation
  - take Rodionov et al. bag model $(\delta d_V/d_V)(x)$ at high Q^2 and multiply by $d_V(x)$ from data
  - this is not rigorous…

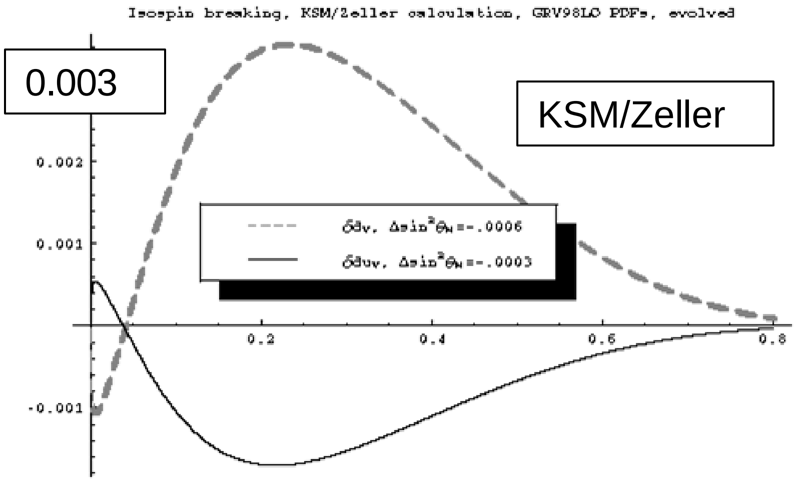
- Londergan and Thomas
  - revived analytic technique of Sather (PLB 274, 433).
    - use analytic relation applied to phenomenological PDFs at bag scale to calculate effect

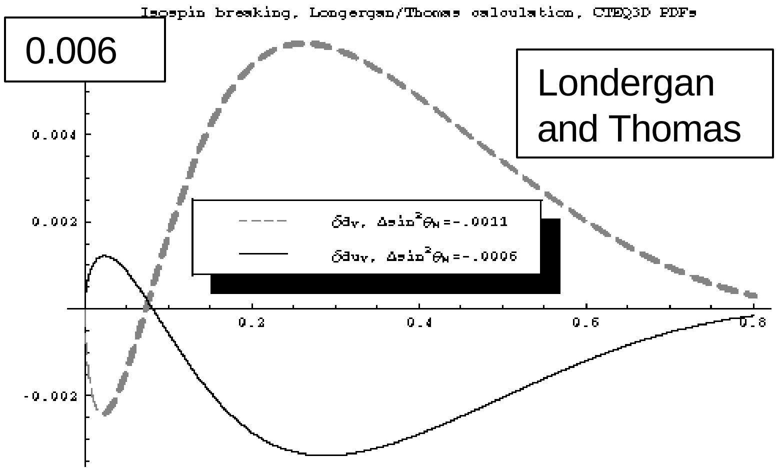
$$d\,d_v(x) = -\frac{1}{M_N}\left[(dM_N)\frac{d[xd_v(x)]}{dx} + (dm_q)\frac{d[d_v(x)]}{dx}\right]$$

$$d\,u_v(x) = \frac{1}{M_N}\left[(dM_N)\frac{d[xu_v(x)]}{dx} - (dM_N)\frac{d[u_v(x)]}{dx}\right]$$

    - evolve up to expt. scale
  - L&T took NLO PDFs (CTEQ3D) at Q^2 of 2.56 GeV^2 and didn’t evolve it up
  - neglects “diquark smearing”

Isospin Violation (cont'd)





- Compare analytic calculations calculations:
  - KSM/Sam Zeller analytic agrees roughly with NuTeV *ad hoc* approximate technique without "diquark smearing"
    - (δd_v effect is 0.0005 ? 0.0006)
  - New Londergan and Thomas calculation appears in error

Isospin Violation (cont'd)

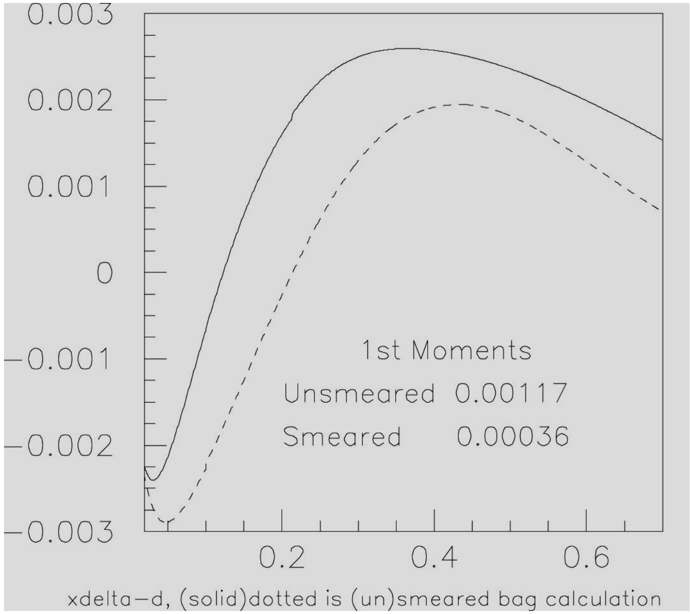
- What is "diquark smearing"?
  - Idea that energy of diquark in struck nucleon is not a delta-function but has some width

$$d\,d_v(x) = -\frac{1}{M_N}\left[(dM_N)\frac{d[xd_v(x)]}{dx} + (dm_q)\frac{d[d_v(x)]}{dx}\right]$$

$$d\,u_v(x) = \frac{1}{M_N}\left[(dM_N)\frac{d[xu_v(x)]}{dx} - (dM_N)\frac{d[u_v(x)]}{dx}\right]$$

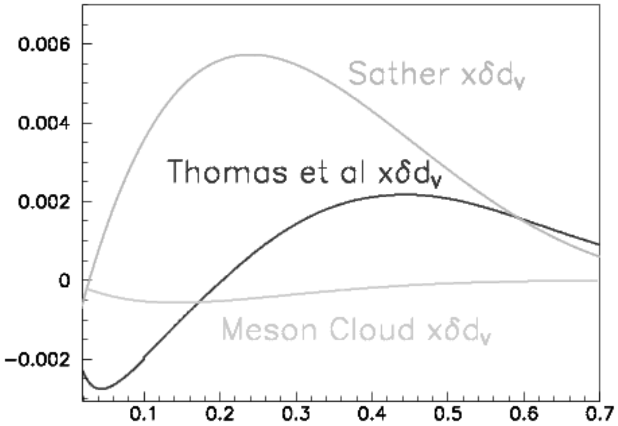
would modify these dominant terms

  - In Rodionov et al calculation with NuTeV approximate technique, smearing wipes out effect. Is it right?
    - working to find analytic analog for this calculation. May not be possible or unambiguous.



Isopin Violation (cont'd)

- Isospin symmetry violation: $u^p \neq d^n$ and $d^p \neq u^n$
  - Another model "Meson Cloud Model": *(Cao et al., Phys Rev C62 015203)*
    $\Rightarrow \Delta\sin^2\theta_W = +0.0002$
  - Not clear how much information is contained in these models…
  - 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

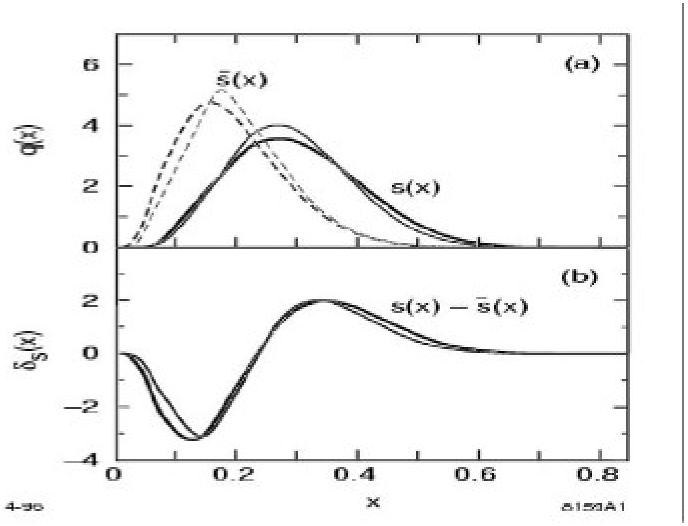
Model calculations predict an order of magnitude smaller change in minority quark dist

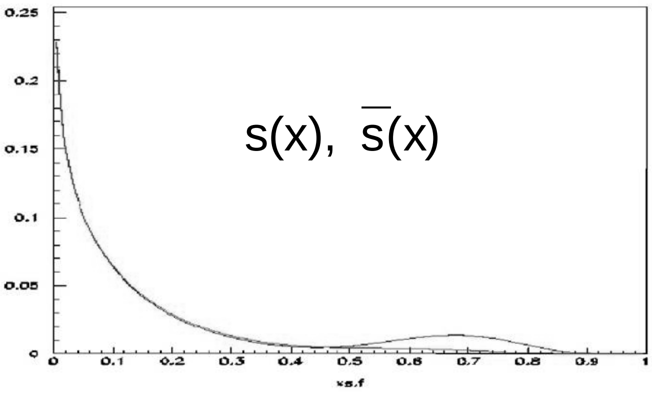
  - ***Can global PDF fits accommodate a large enough isospin violation to explain NuTeV?***

A Very Strange Asymmetry

- Non-perturbative QCD effects could generate a strange vs. antistrange momentum asymmetry in the nucleon
  - decreasing at higher Q^2

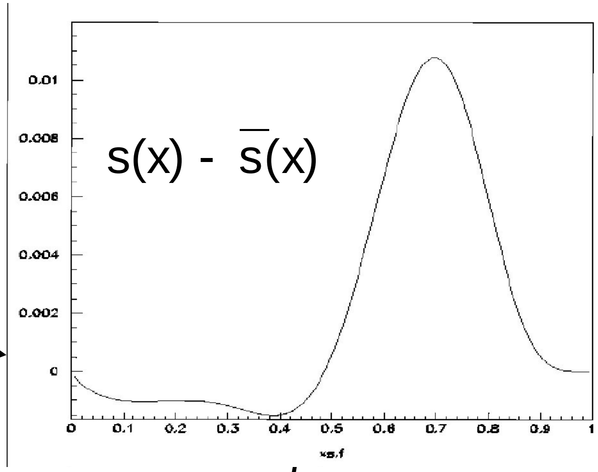
Brodsky and Ma, Phys. Let. B392





s(x), $\bar{s}$(x)

Barone et al,
hep-ph/9907912

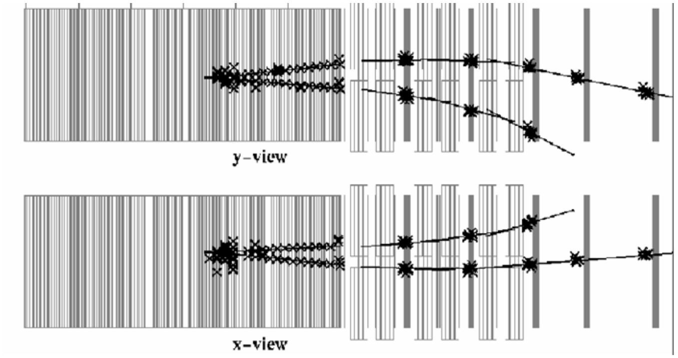


s(x) - $\bar{s}$(x)

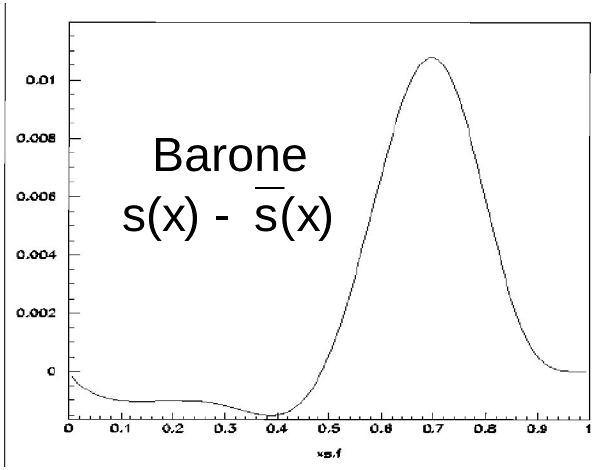
- Barone et al. global PDF fit to NC and CC structure function finds strange excess at very high x
  - not in favored region for models, but…

$$\delta \sin^2\theta_W \approx -0.001$$

Strange / Anti-strange Asymmetry



- Fits to NuTeV and CCFR ν and $\bar{\nu}$ dimuon data can measure the strange and antistrange seas separately ($\nu s \to \mu c$ but $\bar{\nu}\,\bar{s} \to \mu\,\bar{c}$)
  - NuTeV separate ν and $\bar{\nu}$ beams important for reliable separation of s and $\bar{s}$ distributions

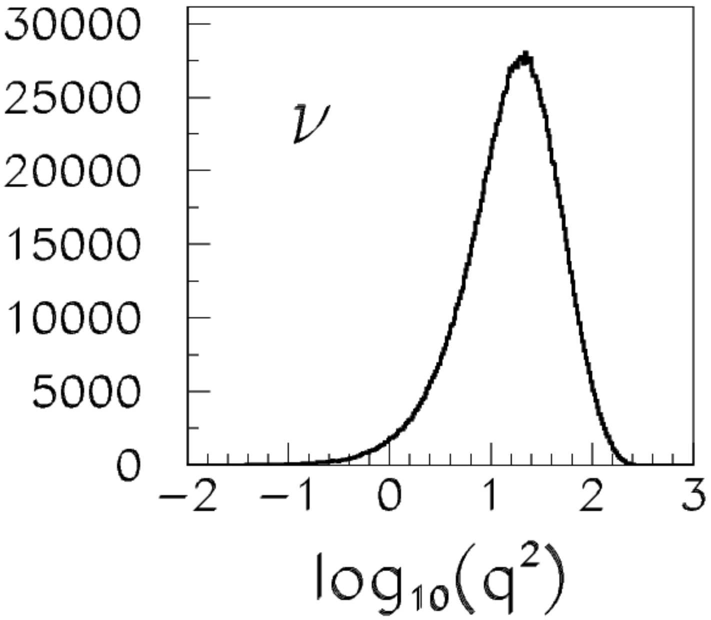


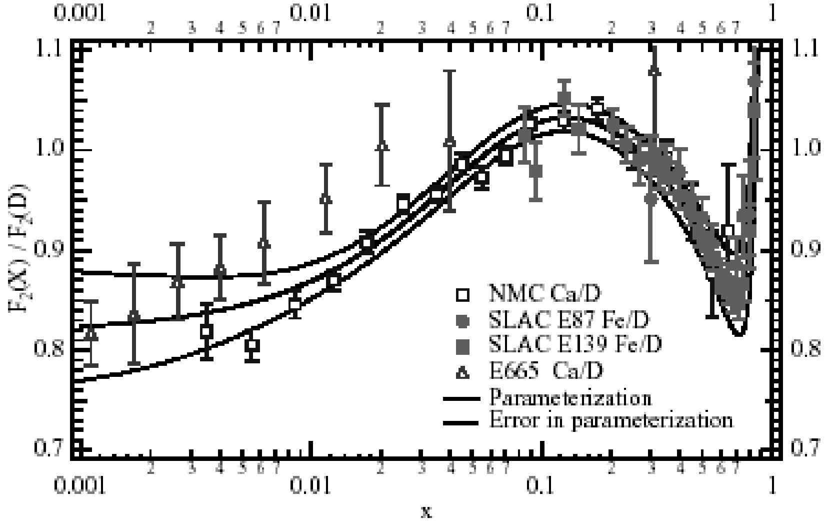
- The Barone s - $\bar{s}$ would cause an excess at x>0.5 that would be 5% of the total neutrino dimuon cross-section
  - NuTeV+CCFR dimuon data limits any such contribution at x>0.5 to 0.2% (0.6%) in the neutrino (antineutrino) dimuon rates at 90% CL
  - End of story
- Can also fit for a general difference between s(x) and $\bar{s}$(x)
  - Done for NuTeV+CCFR in LO and NLO cross-section models
    - Find -9±5% asymmetry at LO. NLO also consistent with no asymmetry
  - N.b., Parameterized strange sea shape is used; therefore this analysis is insensitive to bumps at very high x (already eliminated) or an excess at very low x

Nuclear Effects

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

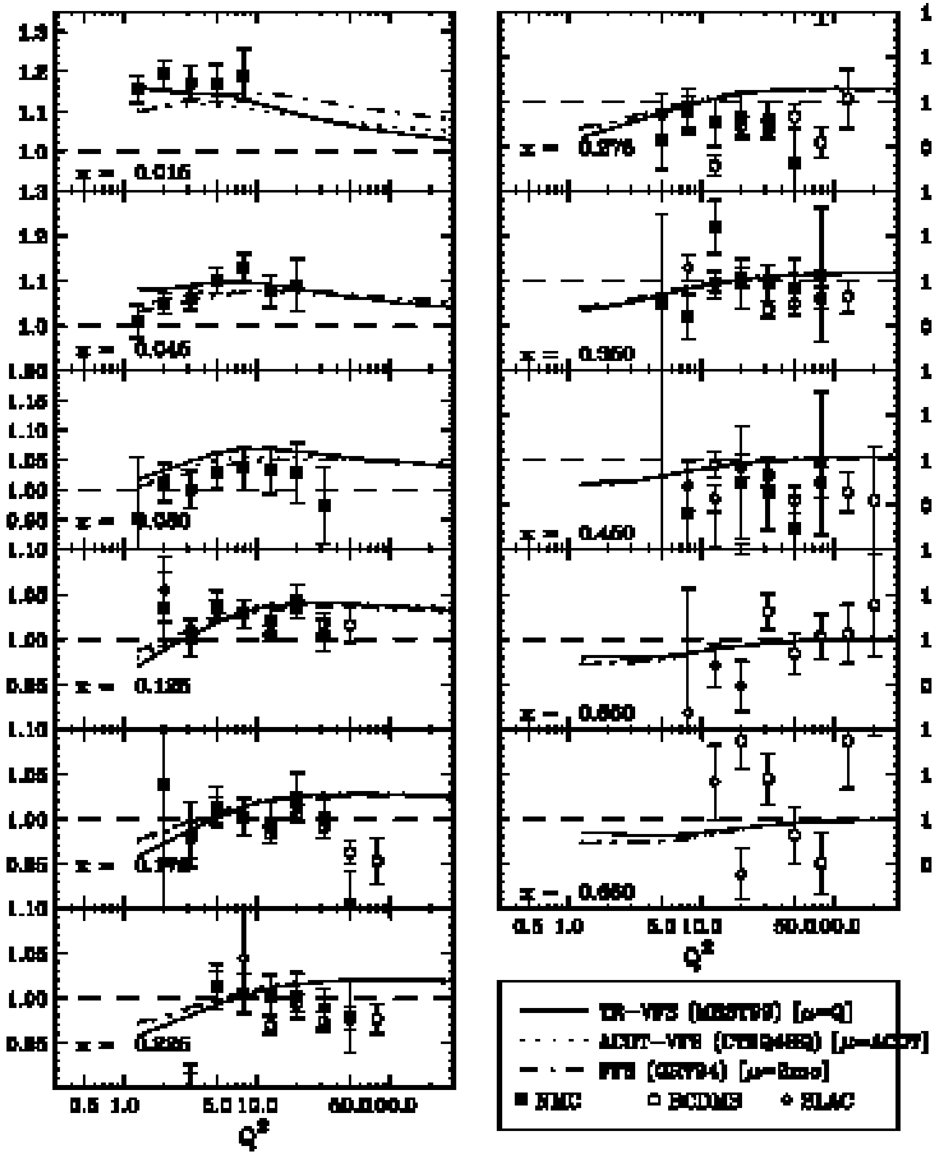
- Use NuTeV CC data to fit parton distributions
  - PDFs that enter are already on iron
  - Need to worry about nuclear effects that could be different for W and Z exchange?
- NuTeV kinematics are high Q^2 valence distributions
  - $\langle E_\nu \rangle \sim 100$ GeV
  - Sea cancels in R^-
- Fermi motion, Pomeron component of shadowing process independent. EMC?





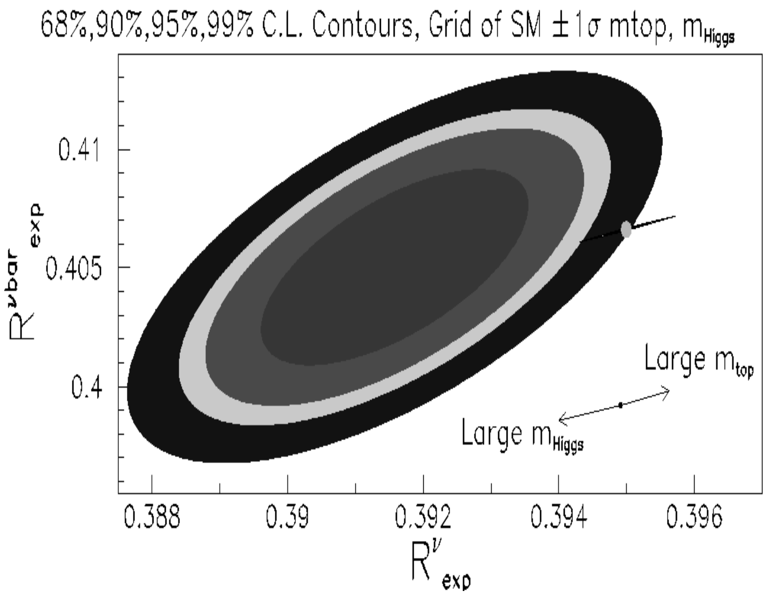
Nuclear Effects (cont'd)

- 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)

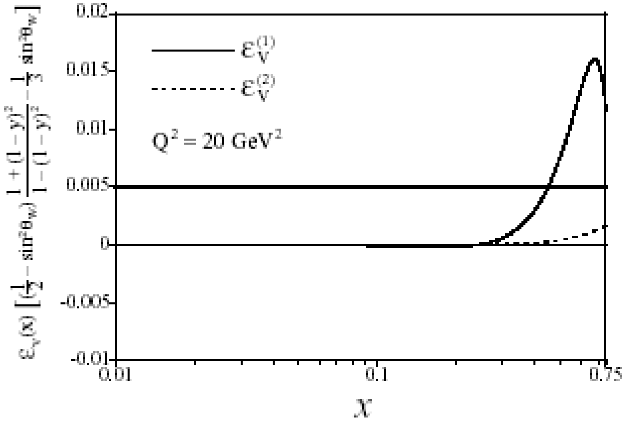
- Shadowing due to VMD would be different EM, NC and CC (Miller and Thomas, hep-ex/0204007)
  - – Weak evidence for predicted $1/Q^2$ dependence in the NuTeV kinematic region $x > 0.01$ (NMC)
  - – But lower x, Q^2 data suggests VMD (Melnitchouk and Thomas, hep-ex/0208016)
  - – Low-x phenomena like 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)
    - 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



  - – Kulagin: Fermi motion, binding effects and shadowing.
    - Concluded all are small effects for NuTeV

Summary

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

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

  – No obvious experimental problems.
  – QCD effects are a possibility
    - But no attractive explanation now exists
      – Very large isospin violation is a possibility…
      – Nuclear effects? Constrained by data.
      – NLO seems unlikely, but…
  – QED corrections large. To check…
  – Beyond SM Physics?
    - Candidate explanations are unattractive, in conflict with other data or require too many miracles…
      – Maybe NuTeV has found something unattractive!

- The result remains an interesting puzzle