Status of the NuTeV Electroweak Anomaly

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for the NuTeV Collaboration

"From 0 to Z^0"

12 May 2004, FNAL

NuTeV Collaboration

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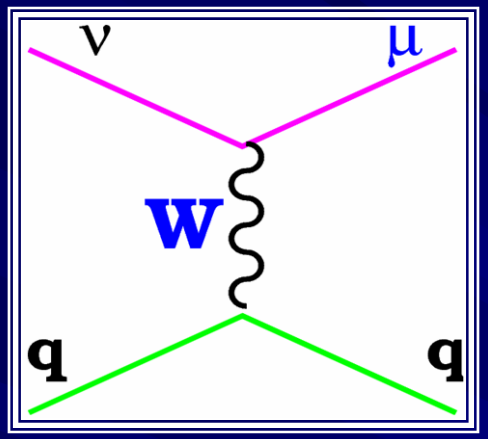
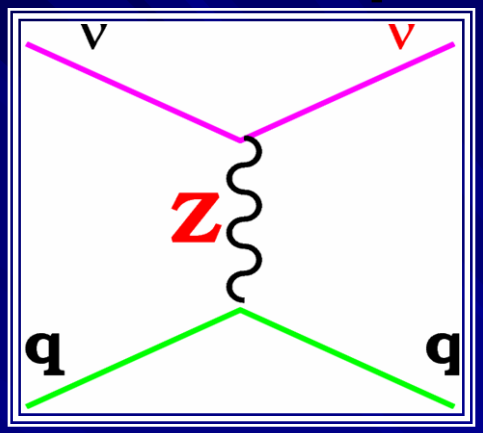
Cincinnati[1], Columbia[2], Fermilab[3], Kansas State[4], Northwestern[5], Oregon[6], Pittsburgh[7], Rochester[8]

Measurement Technique

Charged-Current (CC)



$$\text{Coupling} \propto J^{(3)}_{weak}$$



Neutral-Current (NC)

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

- Measure ν *NC/CC* ratio to extract ratio of weak couplings
  - ratio is experimentally and theoretically robust
  - can extract $\sin^2\theta_W$. NuTeV measurement often quoted this way.
- With neutrino and anti-neutrino beams, can form

Paschos - Wolfenstein Relation

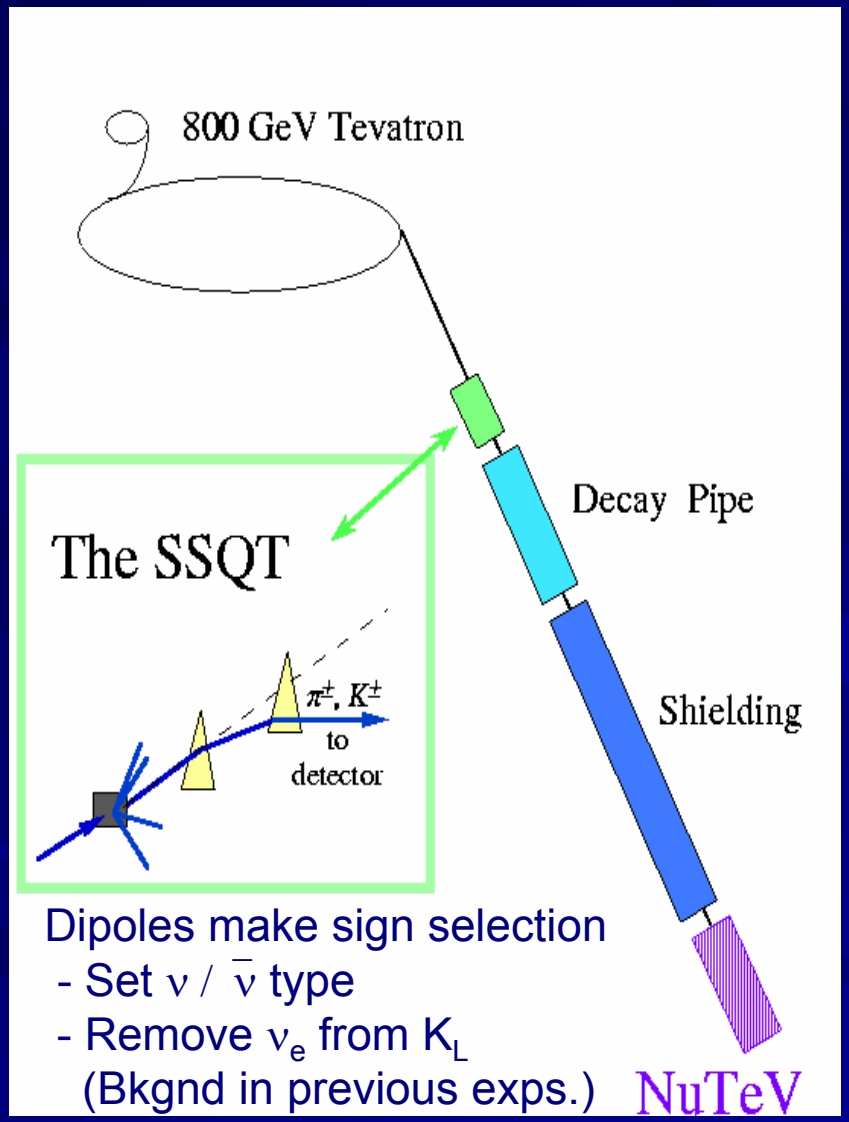
$$R^- = \frac{\sigma^{\nu}_{NC} - \sigma^{\bar{\nu}}_{NC}}{\sigma^{\nu}_{CC} - \sigma^{\bar{\nu}}_{CC}} = \rho^2 \left(\tfrac{1}{2} - \sin^2 \theta_W \right) = g_L^2 - g_R^2$$

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

$$\sigma\left(\nu_\mu q_{sea}\right) - \sigma\left(\bar{\nu}_\mu \bar{q}_{sea}\right) = 0$$

$\Rightarrow$ Only valence quarks contribute

NuTeV Sign-Selected Beamline



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

Paschos - Wolfenstein Relation

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

- Beam identifies neutral currents as 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 à la NuTeV

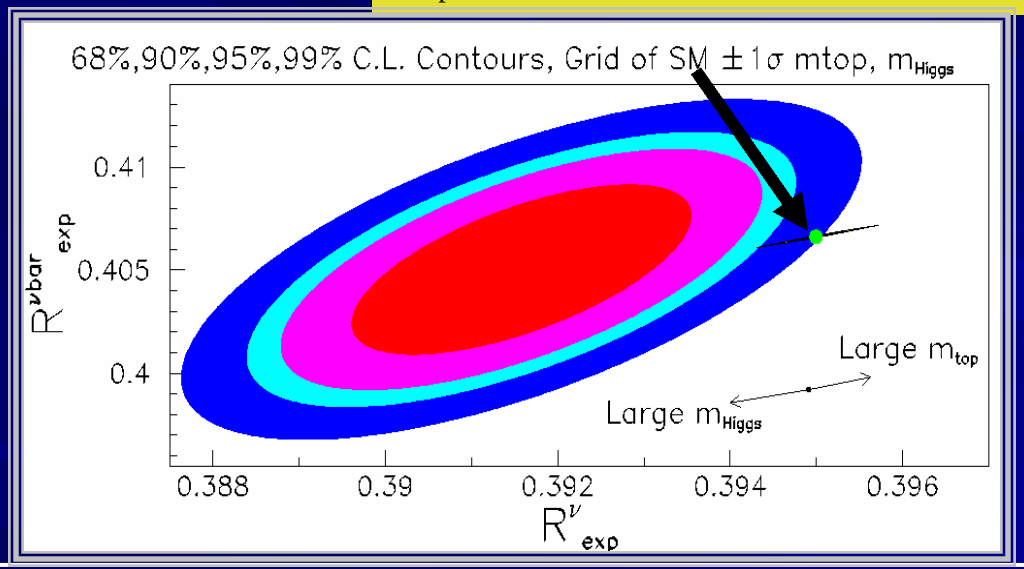
$$R^{\nu(\bar{\nu})} = \frac{\sigma_{NC}^{\nu(\bar{\nu})}}{\sigma_{CC}^{\nu(\bar{\nu})}} = \rho_0^2 \left(\frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W \left(1 + \frac{\sigma_{CC}^{\bar{\nu}(\nu)}}{\sigma_{CC}^{\nu(\bar{\nu})}}\right) \right)$$

$$\frac{dR_{\exp}^{\nu}}{d\sin^2\theta_W} \text{ large}$$

$$R_{\exp}^{\nu} \rightarrow \sin^2\theta_W$$

$$\frac{dR_{\exp}^{\bar{\nu}}}{d\sin^2\theta_W} \text{ small}$$

$$R_{\exp}^{\bar{\nu}} \rightarrow \text{systematics (i.e. } m_c\text{)}$$



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

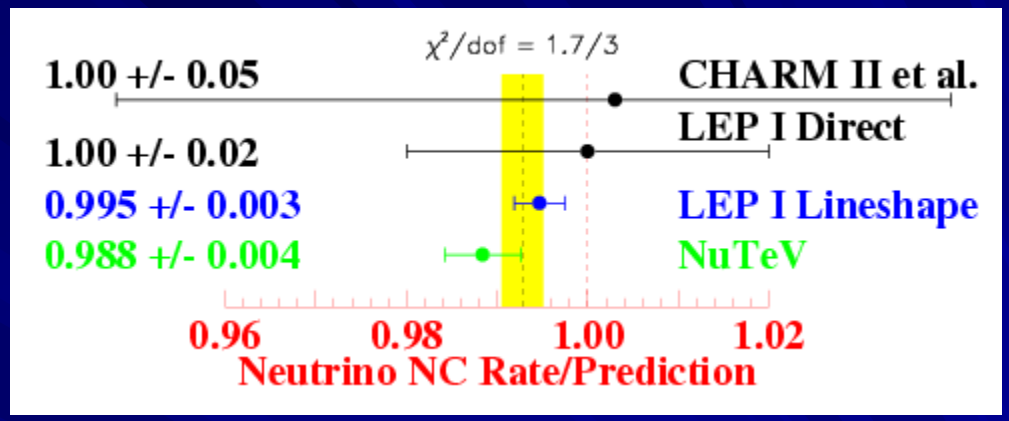
- NuTeV result:
  - Statistics dominate uncertainty
- Standard model fit (LEPEWWG):
  - **0.2227 ± 0.00037, a** 3σ discrepancy

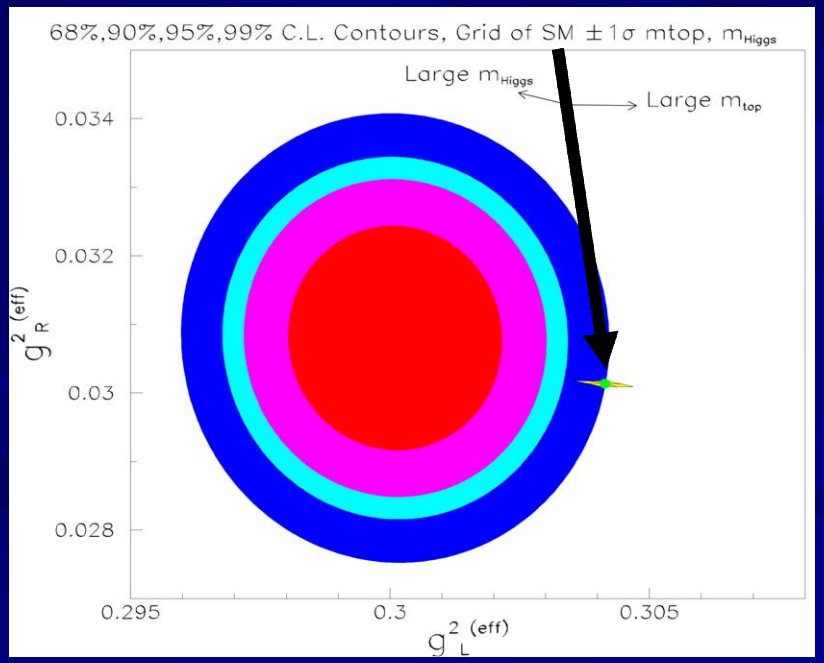
$$R_{\exp}^{\nu} = 0.3916 \pm 0.0013 \quad (SM: 0.3950) \quad \Leftarrow 3\sigma \text{ difference}$$

$$R_{\exp}^{\bar{\nu}} = 0.4050 \pm 0.0027 \quad (SM: 0.4066) \quad \Leftarrow \text{Good agreement}$$

Interpretations Beyond $\sin^2\theta_W$

- Result can also be in terms of the neutral current couplings of neutrinos
  - NuTeV rate measures $\rho^\nu\rho^q$
  - Γ_{inv} measures $(\rho^\nu)^2$





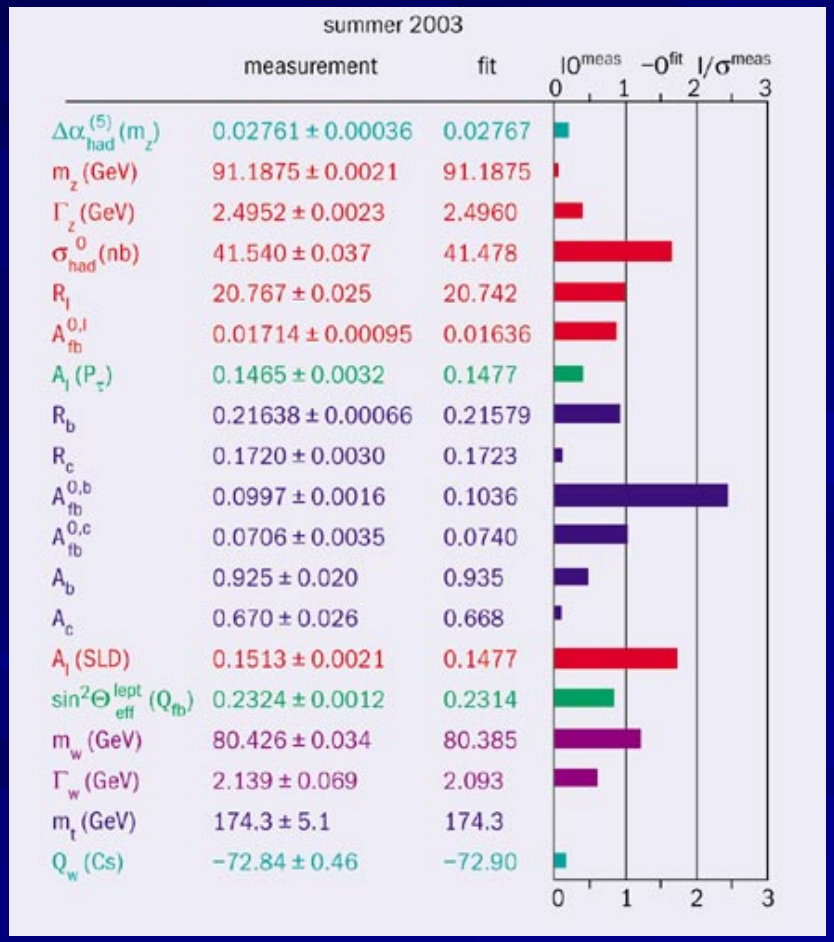
- Model-independent form: effective νq couplings

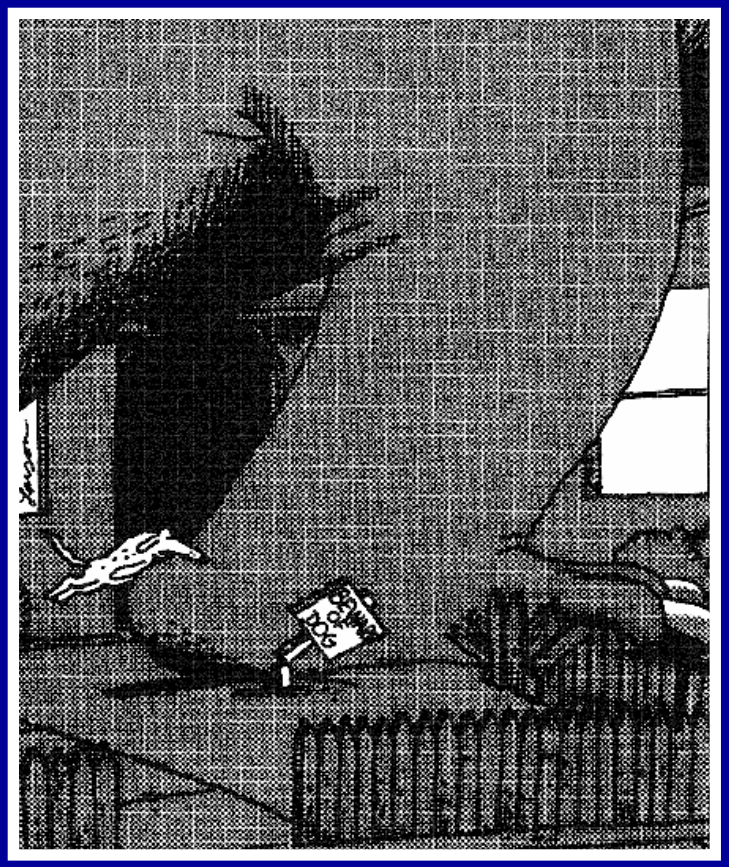
$$\left(g^{\text{eff}}_{\{L,R\}}\right)^2 \equiv \left(\varepsilon^{u,\,\text{eff}}_{\{L,R\}}\right)^2 + \left(\varepsilon^{d,\,\text{eff}}_{\{L,R\}}\right)^2$$

  - Left handed shift: loop level
    - or P-violating tree level
  - Right-handed shift
    - tree level
  - n.b., R^- constrains g_L^2-g_R^2 (more robust)

NuTeV in the Global Context of Precision Electroweak Measurements?

CERN Courier, May 2004





Toby vs. Godzilla

Global Fit courtesy G. Larson

How does Your Speaker Interpret NuTeV?

- 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
    - "Designer" Z' is possible
    - Heavy-light ν mixing + more miracles
  - So the community focuses on mundane explanations
    - mostly novel QCD effects.
    - I will summarize and argue that none of these are outstanding candidates either
- c.f. $(g\text{-}2)_\mu$. "Everyone knows" it is SUSY but result is theoretically shaky due to e^+e^- and τ differences in HVP.
  - g-2 has the opposite problem: too many explanations!

S. Davidson et al. hep-ph/0112302

Li & Ma, Takeuchi et al

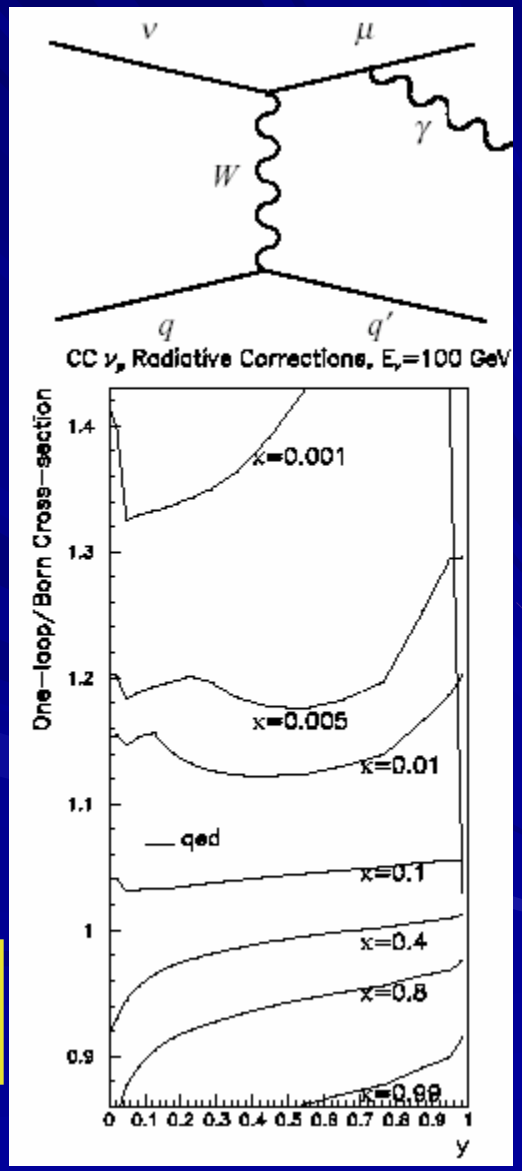
Electroweak Radiative Corrections

Are they a concern?

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 so they pass energy cut.
    - $\{\delta R^{\nu}, \delta R^{\bar{\nu}}, \delta \sin^2\theta_W\} \approx$ $\{+.0074, +.0109, -.0030\}$
  - These should be checked. (Diener-Dittmaier-Hollik, Baur-Wackeroth)

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



Status of New Calculations

- Diener-Dittmaier-Hollik have completed a calculation

K. Diener, S. Dittmaier, W. Hollik hep-ph/0310364
K. Diener hep-ph/0311122

  - major new feature over Bardin and Dokuchaeva is improved treatment of initial state mass singularities
  - they calculate δR^{ν} only for E_{had}>10 GeV, so not directly comparable

calculation	$\delta\sin^2\theta_W$ (R^{ν})
Bardin&D.	-.0114
DDH, $\sin^2\theta_W$, MSbar	-.0130
DDH, α, MSbar	-.0132
DDH, $\sin^2\theta_W$, BD	-.0138
DDH, α, BD	-.0139

- Conclusions:
  - may not agree with BD
  - input parameter and scheme dependence small but not negligible. New systematic.
  - Dear DDH, please send code! ☺ Best wishes, NuTeV
- Baur and Wackeroth calculation in progress

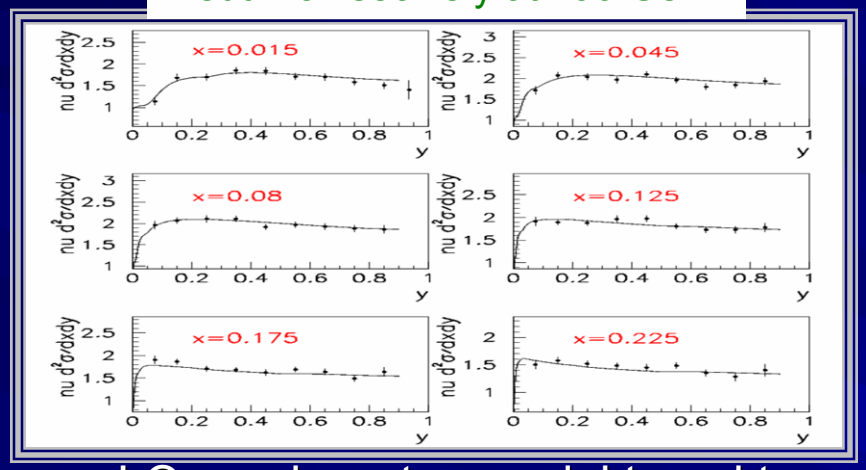
LO Cross-Section Model

1. How does the model work? How is it used?
2. NLO Corrections

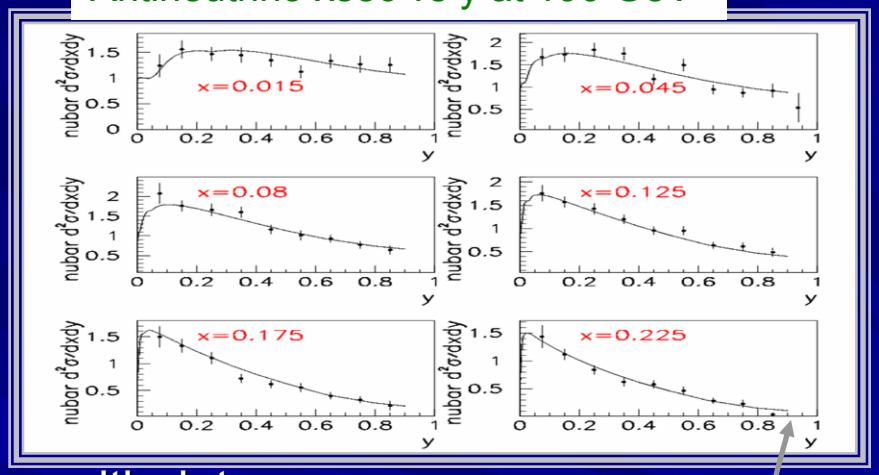
Enhanced LO Cross-Section

- "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

Neutrino xsec vs y at 190 GeV



Antineutrino xsec vs y at 190 GeV



CCFR Data

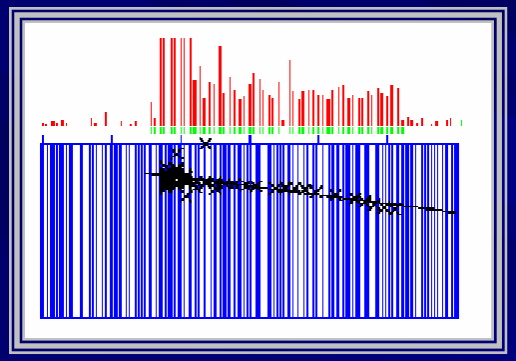
- LO quark-parton model tuned to agree with data:
  - Heavy quark production suppression and strange sea (CCFR/NuTeV $\nu N \rightarrow \mu^+\mu^- X$ data)
  - R_L , F_2 higher twist (from fits to SLAC, BCDMS)
  - d/u constraints from NMC, NUSEA(E866) data
  - Charm sea from EMC F_2^{cc}

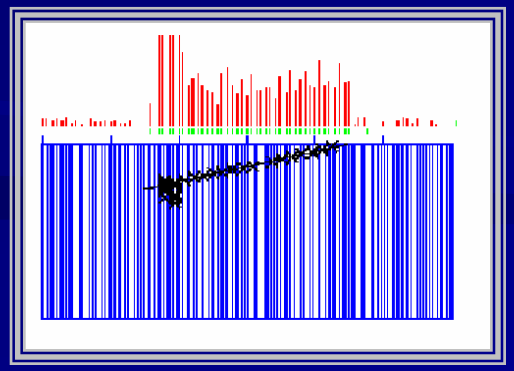
high y events are background to the neutral current sample

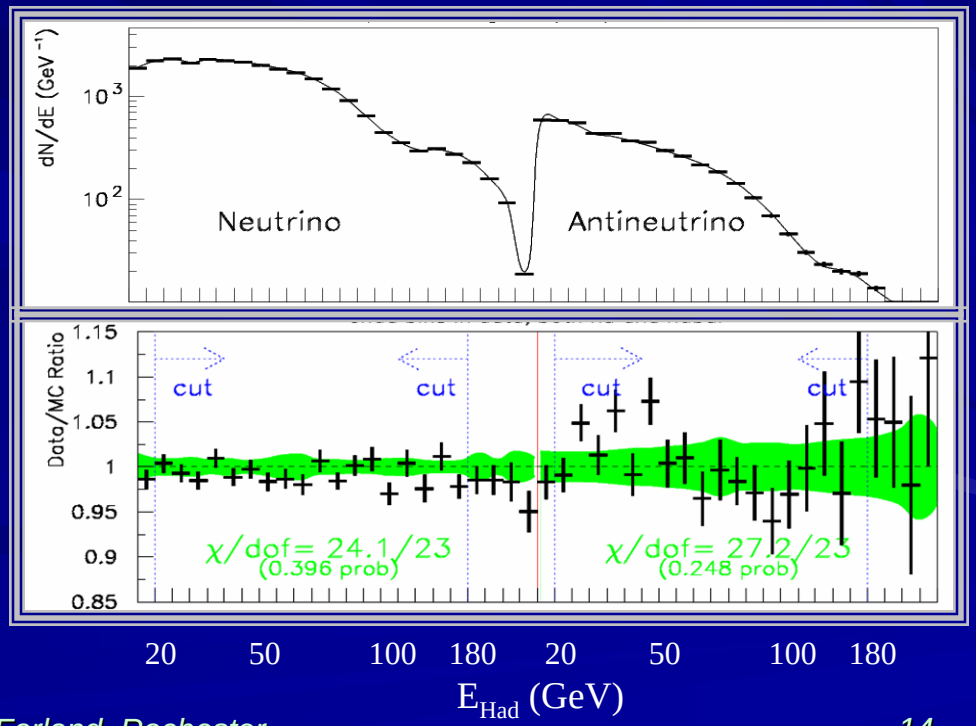
Model is fit directly to this data; uncertainties come from data.

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







NLO QCD Corrections to R^- ?

$$R^- \approx \Delta_u^2 + \Delta_d^2 + \frac{1}{2}\left(\frac{U^- - D^- + C^- - S^-}{U^- + D^-}\right)\left[\left(3\Delta_u^2 + \Delta_d^2\right) + \frac{\alpha_S}{2\pi}\left(\Delta_u^2 + \Delta_d^2\right)\left(\frac{C^1}{4} + \frac{3C^2}{4} - C^3\right)\right]$$

where $U^- = \int x(u - \bar{u})dx$ in target, etc.

$C^i =$ NLO coefficient fcns. in SF F_i

$$\Delta_{u,d}^2 = \left(\varepsilon_L^{u,d}\right)^2 - \left(\varepsilon_R^{u,d}\right)^2$$

(S.Davidson et al. hep-ph/0112302, K. McFarland and S. Moch hep-ph/0306052, S. Kretzer and M-H. Reno unpublished, B. Dobrescu and K. Ellis to appear)

- So NLO terms only enter multiplied by isovector valence quark distributions
  - for NuTeV this is a numerically negligible correction
  - n.b., NuTeV does not measure precisely R^-

Evaluation of NLO QCD Effects

	Davidson et al	McFarland-Moch (I)	McFarland-Moch (II)	Kretzer-Reno	Dobrescu-Ellis
NuTeV PDFs		√	√		√
Include NuTeV PDF Fits		implicitly	explicitly	implicitly	***no***
Gluon, Sea contributions (cancel in R^-)				√	√
Experimental Cuts			√		
Treatment of Target Mass, Heavy Flavor				√	
δNLO	N/A	-0.0003	-0.0003	-0.0004	***+0.0015***

- NuTeV full NLO analysis in progress
  - Ellis and Dobrescu contributed generator code. Thank you! ☺

QCD Symmetry Violations in R^-

What symmetry violations can affect the result?

1. $u \neq d$ in target (neutron excess)
2. asymmetric heavy seas
3. process dependent 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^-

$$R^- \approx \Delta_u^2 + \Delta_d^2 - \delta N \left(\frac{U_v - D_v}{U_v + D_v} \right) \left(3\Delta_u^2 + \Delta_d^2 \right) - \frac{1}{2} \left(\frac{\delta U_v - \delta D_v}{U_v + D_v} \right) \left(3\Delta_u^2 + \Delta_d^2 \right) + \left(\frac{\delta S}{U_v + D_v} \right) \left(2\Delta_d^2 - (3\Delta_u^2 + \Delta_d^2)\varepsilon_c \right)$$

where $\delta N = \frac{(N - Z)}{A}$

$$U_v = \int x(u_v^p + d_v^p)dx, \text{ etc.}$$

$$\delta U_v = \int x(u_v^p - d_v^n)dx, \text{ etc.}$$

$$\Delta_{u,d}^2 = \left(\varepsilon_L^{u,d}\right)^2 - \left(\varepsilon_R^{u,d}\right)^2$$

$$\delta S = \int x(s - \bar{s})dx$$

$\varepsilon_c =$ kinematic charm CC suppression

Symmetry Violating QCD Effects

- Violations could arise from *(ref. for theory motivation)*
  1. $A \neq 2Z$ due to neutron excess (corrected for in NuTeV)
  2. Isospin violating PDF's, $u_p(x) \neq d_n(x)$
     (Sather; Rodinov, Thomas and Londergan; Cao and Signal)
     – Changes d/u of target $\Rightarrow$ mean NC couplings and CC rates
  3. Asymmetric heavy-quark sea, $s(x) \neq \bar{s}(x)$
     (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
- How big must these violations be to explain NuTeV?
  – require a ~5% minority ($d^p \neq u^n$) valence quark isospin violation
  – or a ~30% momentum difference between strange and anti-strange seas

(G.P. Zeller et al., Phys.Rev.D65:111103,2002)

Asymmetric Strange Sea

1. Why it might be so
2. How it is measured at NuTeV
3. The CTEQ L-P Conjecture
4. Impact on NuTeV $\sin^2\theta_W$

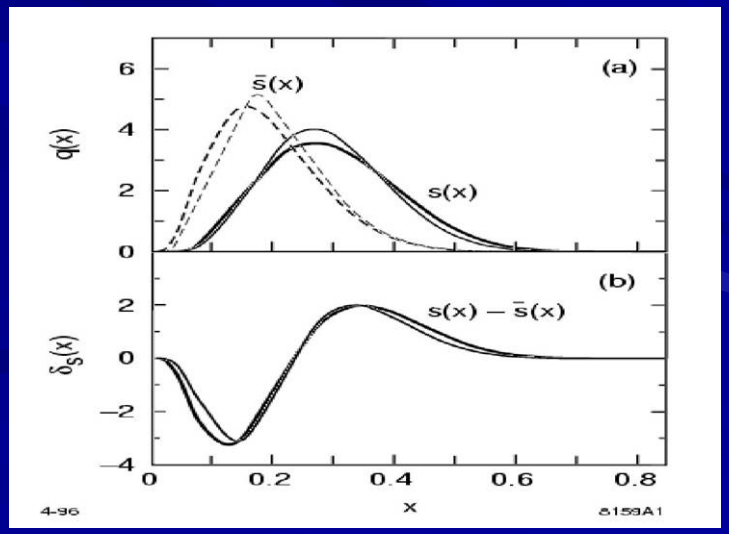
A Very Strange Asymmetry

- Paschos-Wolfenstein relation assumes that strange sea is symmetric, i.e., no "valence" strange distribution
  - if there were on, this would be a big deal since it is an isovector component of the PDFs (charm sea is heavily suppressed)

G.P. Zeller et al., Phys.Rev.D65:111103,2002)

- 30% more momentum in strange than anti-strange seas would be enough to make NuTeV agree with SM
- Why might one think that the strange and anti-strange seas would be different?
- 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



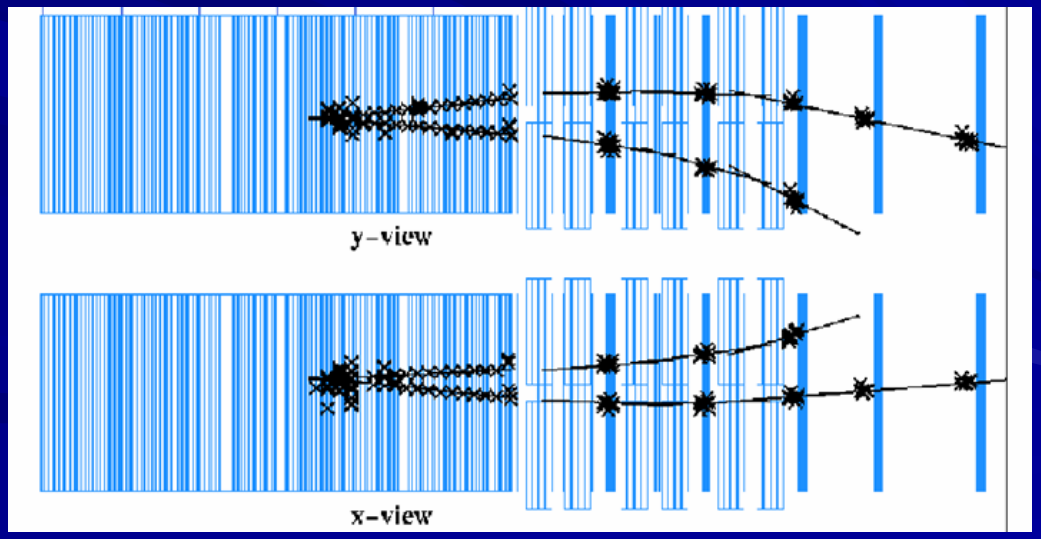
How Does NuTeV Measure This?

$$\overset{(-)}{\nu}_{\mu} N \rightarrow \mu^{\mp} \mu^{\pm} X$$

- $\mu^{\pm}$ from semi-leptonic charm decay

$$\nu \text{ beam: } s, d \text{ (Cabbibo supp.)} \rightarrow c$$
$$\bar{\nu} \text{ beam: } \bar{s}, \bar{d} \text{ (Cabbibo supp.)} \rightarrow \bar{c}$$

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

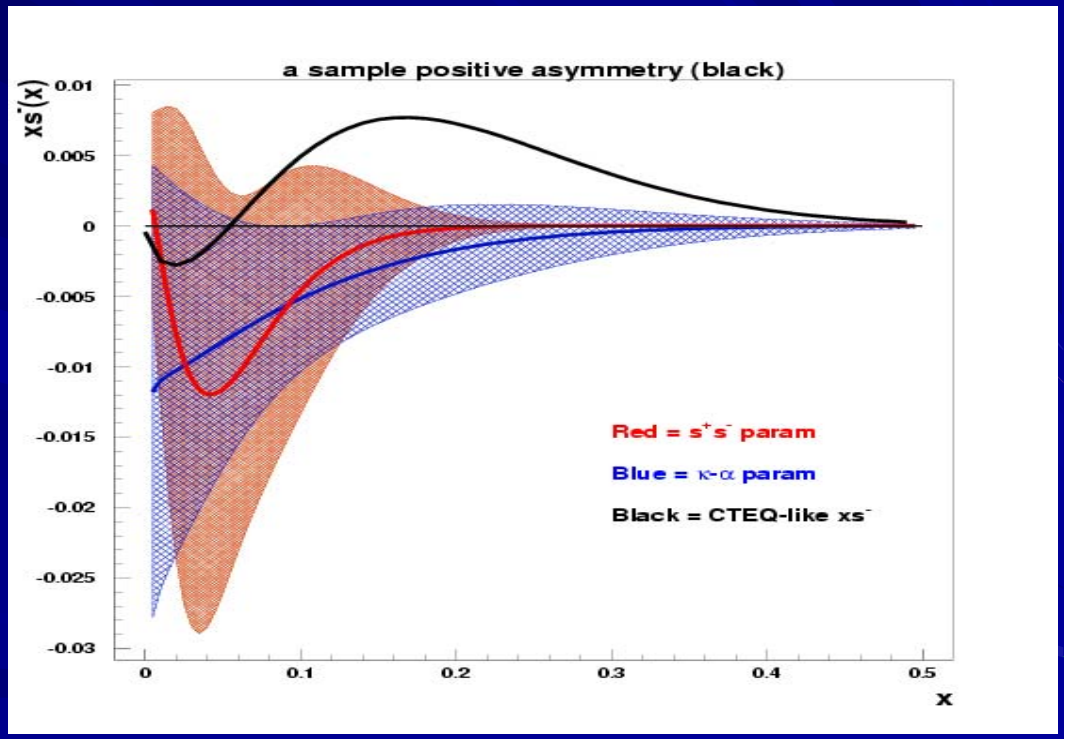


The CTEQ Lepton-Photon Conjecture

- The CTEQ (Olness, Tung *et alia*) NLO/LO fit
  Small LO asymmetry, ~+10%
  (CTEQ NLO d-quark PDFs)
  $$\int xs(x) > \int x\bar{s}(x)$$
  - inconsistency with zero not claimed
  - could explain at least part of NuTeV anomaly
    - *approximately one out of the three sigma*
  - uses inclusive data and NuTeV/CCFR dimuons
    - claim is that dimuons are dominant constraint
- NuTeV analyses show zero or negative asymmetry
  - CTEQ pointed out mistakes in NuTeV evolution, concerns about strangeness not being conserved outside of measured region
  - *They are good points; do they matter?*

Updated NuTeV NLO Analysis

- Have incorporated CTEQ strange "valence" evolution and CTEQ parameterizations
  - thanks esp. to Amundson, Kretzer, Olness & Tung
- NuTeV analysis is consistent with zero, slightly negative
  - NuTeV: - (5-10)%
  - c.f. CTEQ-like result of +10% in black curve
  - χ^2 NuTeV is 37/37
  - χ^2 CTEQ is 55/40
- CTEQ LP Conjecture inconsistent with this analysis



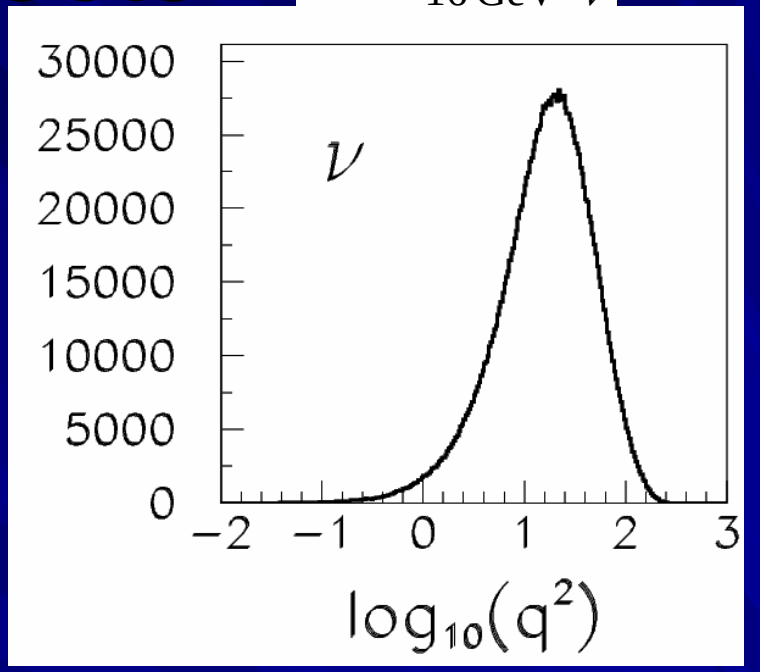
courtesy heroic efforts of D. Mason, P. Spentzouris

Nuclear Effects

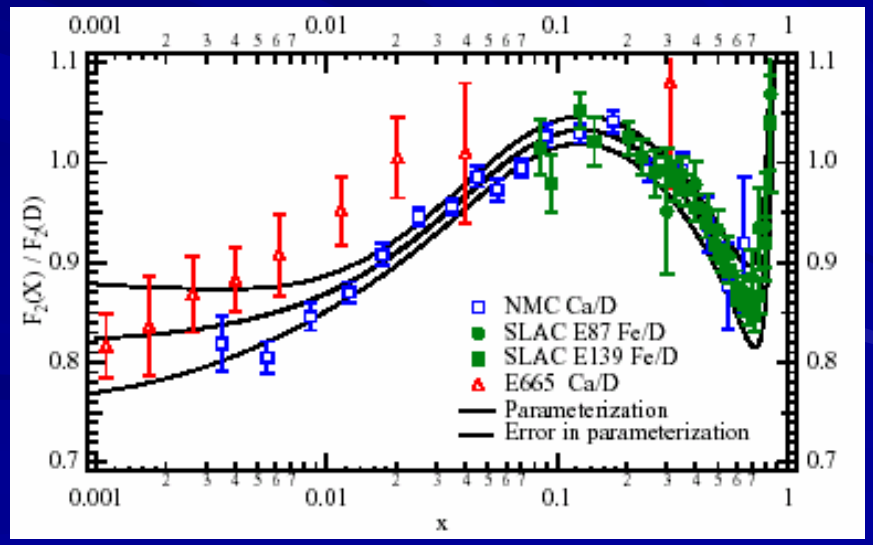
1. Introduction
2. Constraints on Effects

Nuclear Effects

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

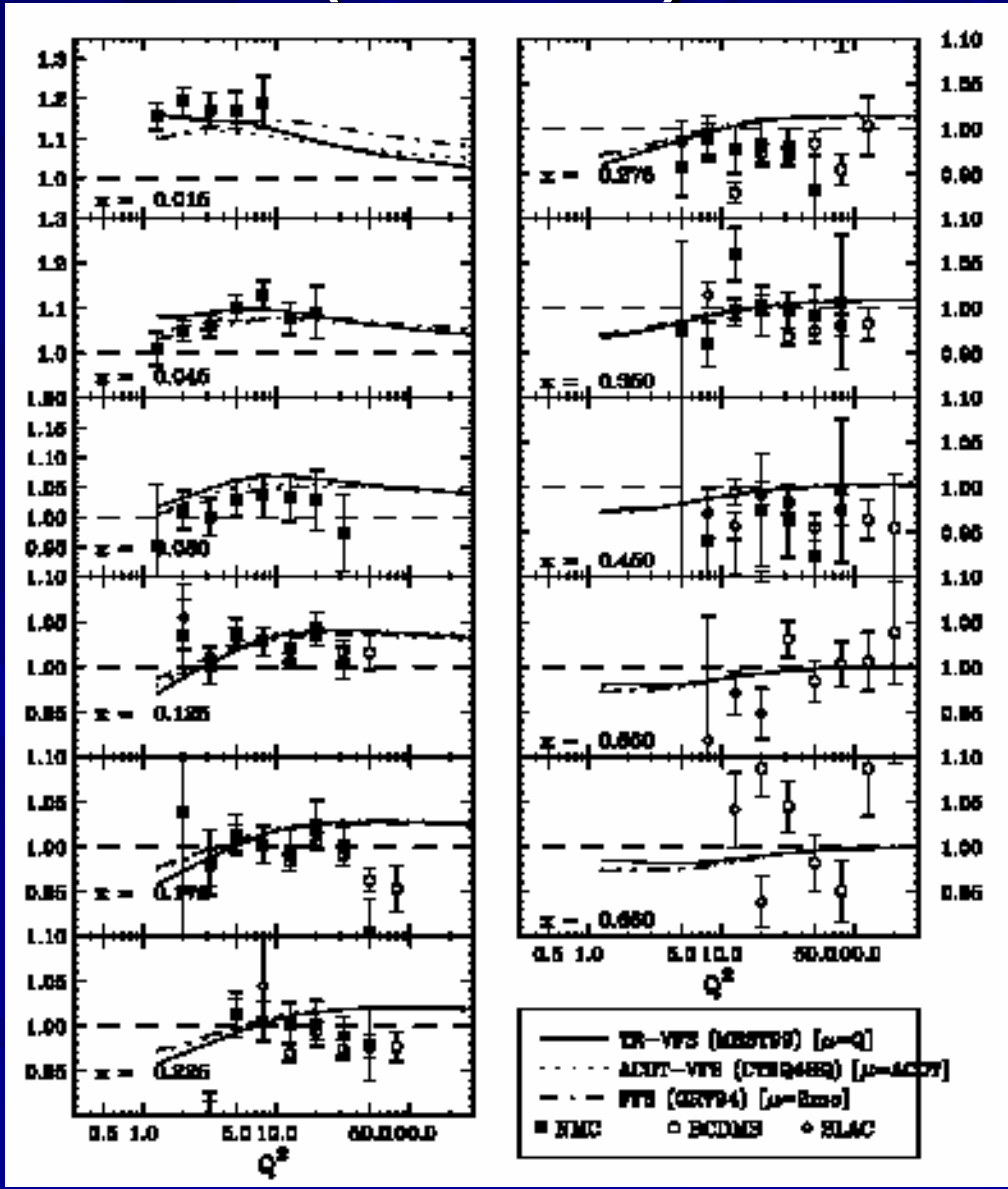


- We use NuTeV CC data to fit parton distributions
  - PDFs that enter are already on iron
  - Need to worry about nuclear effects that could be different for W and Z exchange?
- NuTeV kinematics are high Q^2 valence distributions
  - $\langle E_\nu \rangle \sim 100$ GeV
  - Sea cancels in R^-
- Fermi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



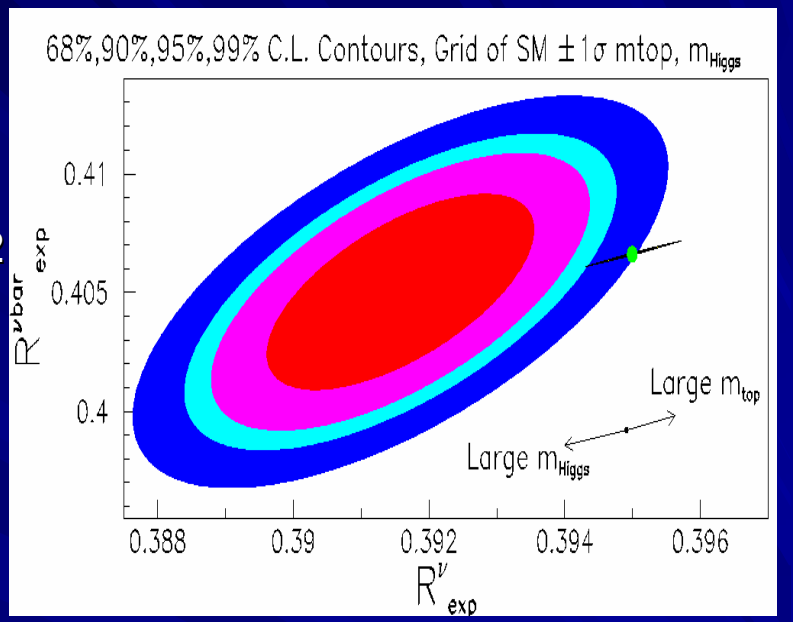
Nuclear Effects (cont'd)

- 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^-



Shadowing effects neutrino and anti-neutrino data in the same way. Systematic controlled by R^- technique.

Isospin Violation

1. What is required and what does data allow?
2. Conclusions

Isospin Violation in PDFs

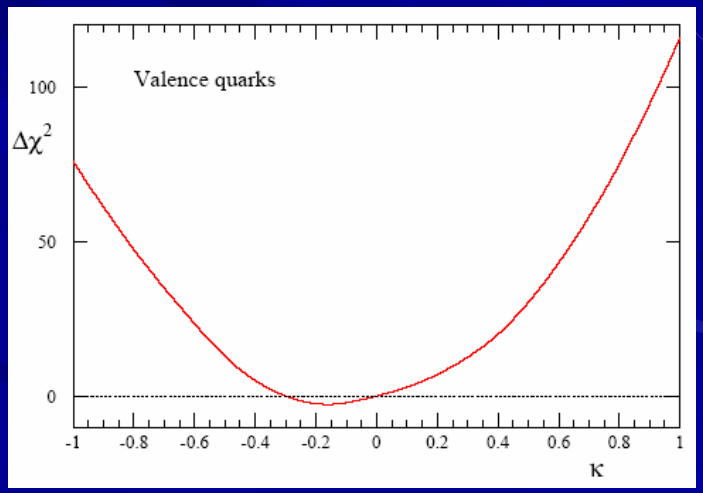
- Naively, effect is ~ $(m_d-m_u)/M_N$=0.5%
  - roughly, a 5% momentum excess of d_v^p over u_v^n quarks would move NuTeV to SM value

G.P. Zeller et al., Phys.Rev.D65:111103,2002)

- Theory offers little guidance
  - full range of bag models predict 0-2% effects

(Rodionov, Thomas, Londergan, MPL A9 1799)

- Little experimental constraint
  - valiant effort by MRST!
  - they conclude zero, negative or positive effect all allowed in fit
    - best fit moves NuTeV toward SM for whatever that is worth!



Martin et al, hep-ph/0308087

This possibility is NOT like the others…

- Note that if there is no constraint, this is a perfectly viable explanation for NuTeV anomaly
  - Size of effect may be "unexpected", but that doesn't mean it is impossible or inconsistent with QCD
- *NuTeV may have found large isospin violation*
- One should pursue all available means of measuring this. More later…
- Is there impact on collider PDFs?
  - e.g., one would question NUSEA, NMC d/u results in light of this since they come from isospin symmetry assumption…

Corroborating Data and Impact of Future Results

Is there other evidence of Mundane Physics that would affect NuTeV?

What can we learn in the future?

PDF and Nuclear Data

- Strange Sea Asymmetry, $u_p \neq d_p$, nuclear effects
  - For the most part, I would argue the data in hand already constrains these possibilities well enough
  - Any continuing debate is over interpretation
  - Caveat: no independent check of Z^0 exchange nuclear effects (by definition). Rely on ν CC and $\ell^\pm$ NC.
- Isospin violation in PDFs, e.g., $u_n \neq d_p$
  - Almost completely unconstrained, even at levels that would appear *a priori* ludicrous. *Martin et al, hep-ph/0308087*
  - FNAL-E906 $\pi^\pm p$, $\pi^\pm d$ Drell-Yan can directly probe this
  - Re-analysis of old ν bubble-chamber data? νp vs. νn

Other Precision EW Data

- e-Baryon scattering is undergoing a re-emergence!
  - QWEAK at JLab (ep), DISParity proposal (eD)
  - These experiments suffer from many of QCD uncertainties that are worries in interpreting NuTeV. Worse because lower Q^2?
- Future neutrino experiments will be very very tough
  - Is there any point to re-measuring this in ν DIS?
    - More statistics would help, but NuTeV systematic floor is 0.0008 (c.f., total NuTeV error of 0.0016)
    - Maybe worth doing if there were a 1 TeV ν beam at LHC.
    - NOMAD is trying this without antineutrinos at low Q^2. *Vaya con dios…*
  - ν-e scattering would be a great measurement, but it's not easy
    - Cross-section is down by factor of a few 10^3
    - Normalization? Hard in conventional or μ-based beams
    - Reactor? Definitely tough; close to NuTeV precision in $\sin^2\theta_W$ looks achievable.

Bigi et al, hep-ph/0106177

Conrad, Link & Shaevitz, hep-ph/0403048

Future Discoveries?

- Always the possibility of a future discovery impacting the NuTeV interpretation
  - LHC or TeVatron finds a Z'
  - Giga-Z confirms and strengthens small deficit in invisible width
  - …

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.
  - "Old physics" 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. Should be checked…
  - Beyond SM Physics?
    - Candidate explanations are unattractive, in conflict with data or require many miracles…
- Either way, perhaps everyone can agree that NuTeV has found something unattractive!