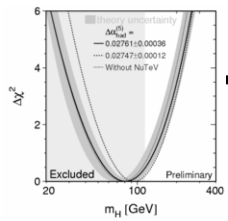
The NuTeV Anomaly:
A hint of New Physics? or
Train Wreck of the Mundane?



Kevin McFarland
University of Rochester

WIN03, Lake Geneva, WI
8 October 2003

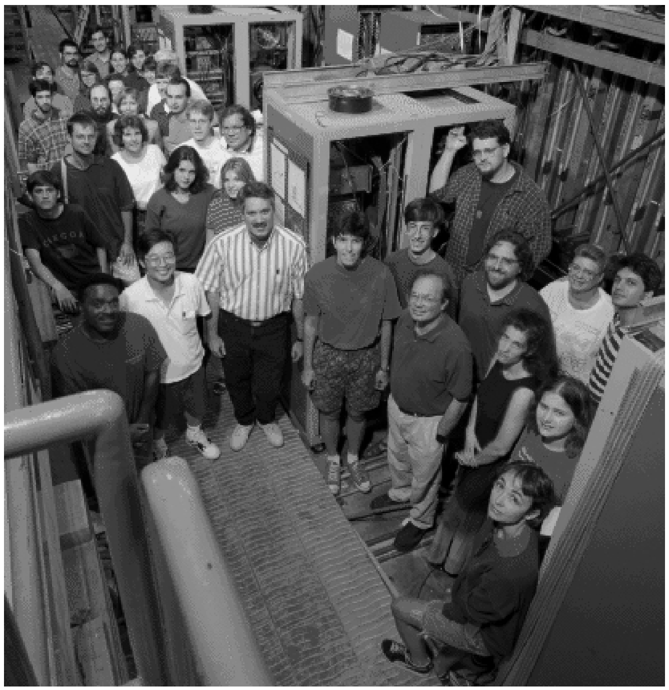
Introduction to NuTeV $\sin^2\theta_W$

To Follow:

(1) three talks on QCD-related uncertainties

(2) I return with a summary of these and other issues

NuTeV Collaboration

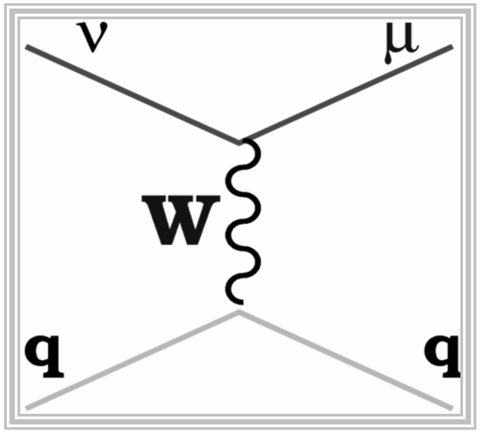


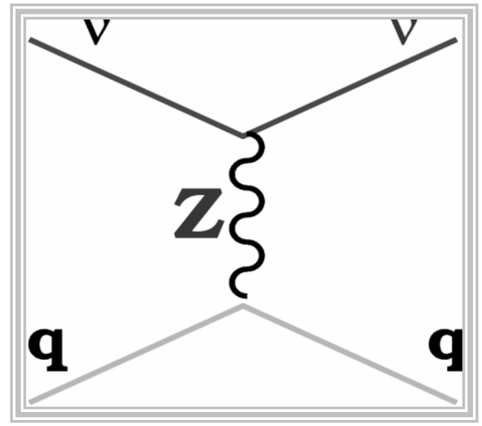
G. P. Zeller[5], T. Adams[4], A. Alton[4],
S. Avvakumov[8], L. de Barbaro[5], P. de Barbaro[8],
R. H. Bernstein[3], A. Bodek[8], T. Bolton[4], J. Brau[6],
D. Buchholz[5], H. Budd[8], L. Bugel[3], J. Conrad[2],
R. B. Drucker[6], B. T. Fleming[2], R. Frey[6],
J.A. Formaggio[2], J. Goldman[4], M. Goncharov[4],
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]

Measurement Technique

Charged-Current (CC)





Neutral-Current (NC)

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

Llewellyn Smith Relation:

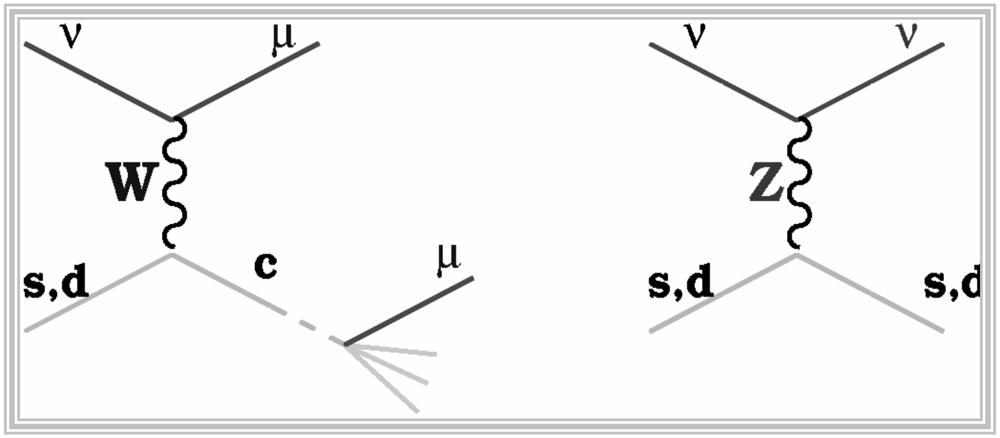
$$R^{\nu(\bar{\nu})} = \frac{\sigma_{NC}^{\nu(\bar{\nu})}}{\sigma_{CC}^{\nu(\bar{\nu})}} = \rho^2 \left(\frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W \left(1 + \frac{\sigma_{CC}^{\bar{\nu}(\nu)}}{\sigma_{CC}^{\nu(\bar{\nu})}}\right) \right) = g_L^2 + \frac{\sigma_{CC}^{\bar{\nu}(\nu)}}{\sigma_{CC}^{\nu(\bar{\nu})}}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

- *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

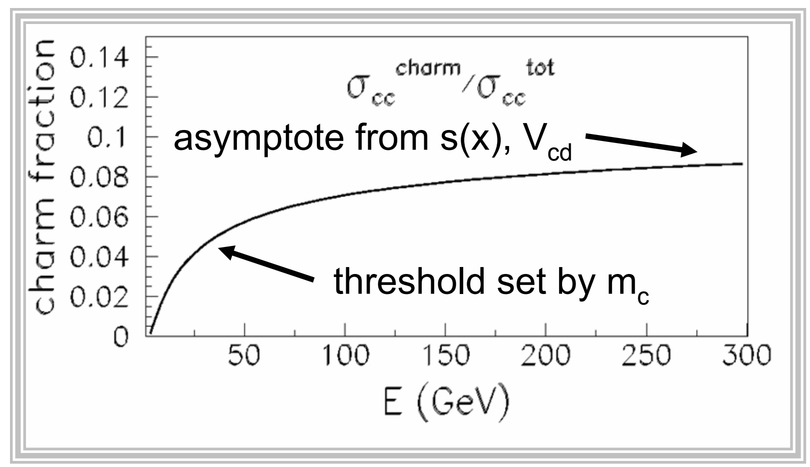
  $\Rightarrow$ Need to know s-quark sea and m_c

  – Modeled with leading-order slow-rescaling

$$x = Q^2/2M\nu \rightarrow \xi = (Q^2 + m_c^2)/2M\nu$$

  – Measured by NuTeV/CCFR using dimuon events ($\nu N \rightarrow \mu\, cX \rightarrow \mu\mu X$)

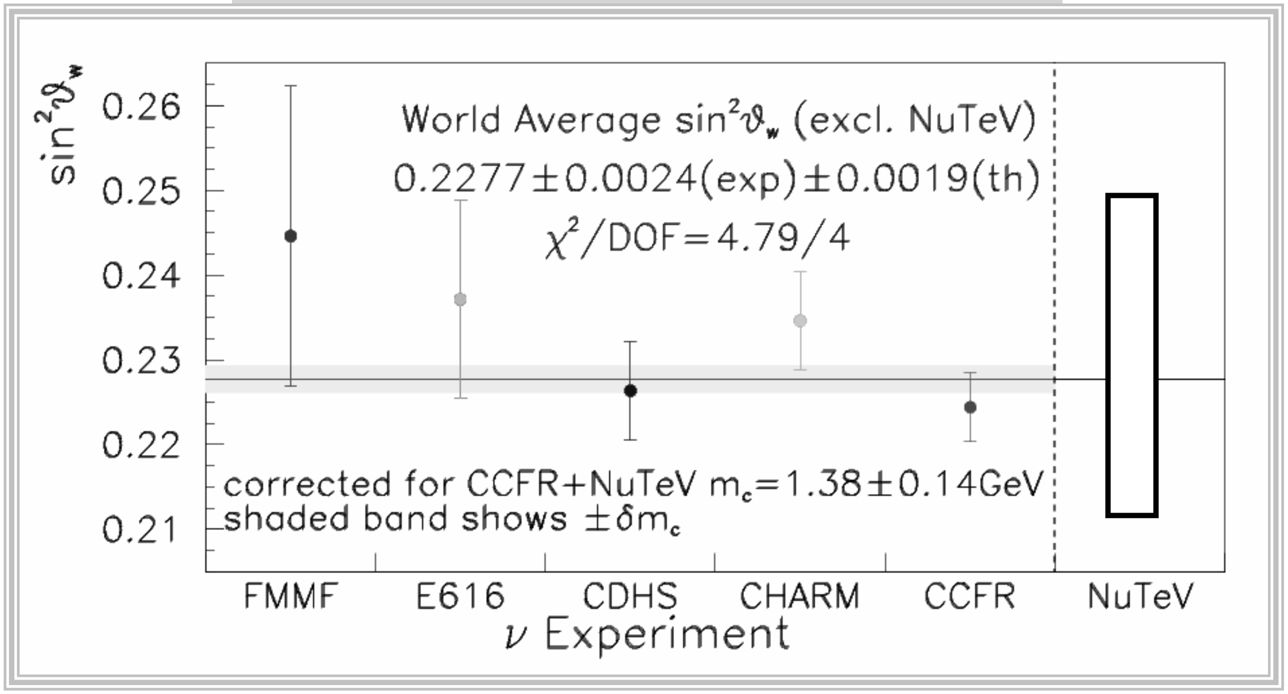
  (NuTeV+CCFR: M. Goncharov et al., Phys. Rev. D64: 112006,2001 and D. Mason presentation at ICHEP '02. CCFR: A.O. Bazarko et al., Z.Phys.C65:189-198,1995.)



Before NuTeV m_c was Limit

- 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

$\Rightarrow$ Reduce uncertainties from charm production and sea

Paschos - Wolfenstein Relation

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

$$g_{L,R}^2 = u_{L,R}^2 + d_{L,R}^2$$

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

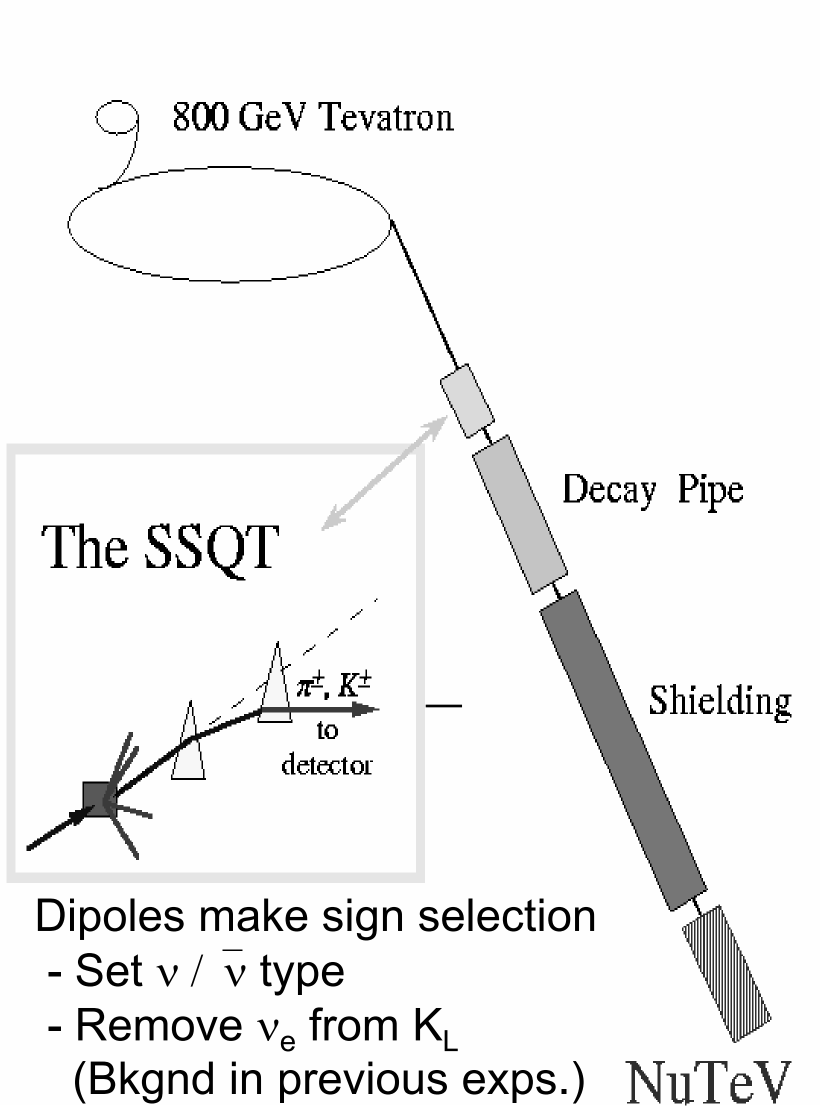
$$\sigma(\nu_\mu \bar{u}_{sea}) - \sigma(\bar{\nu}_\mu u_{sea}) = 0 \quad \Rightarrow \quad \text{Only } u_{valence} \text{ contribute}$$

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

- 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

  $\Rightarrow$ 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 $\bar{\nu}_e$

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

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

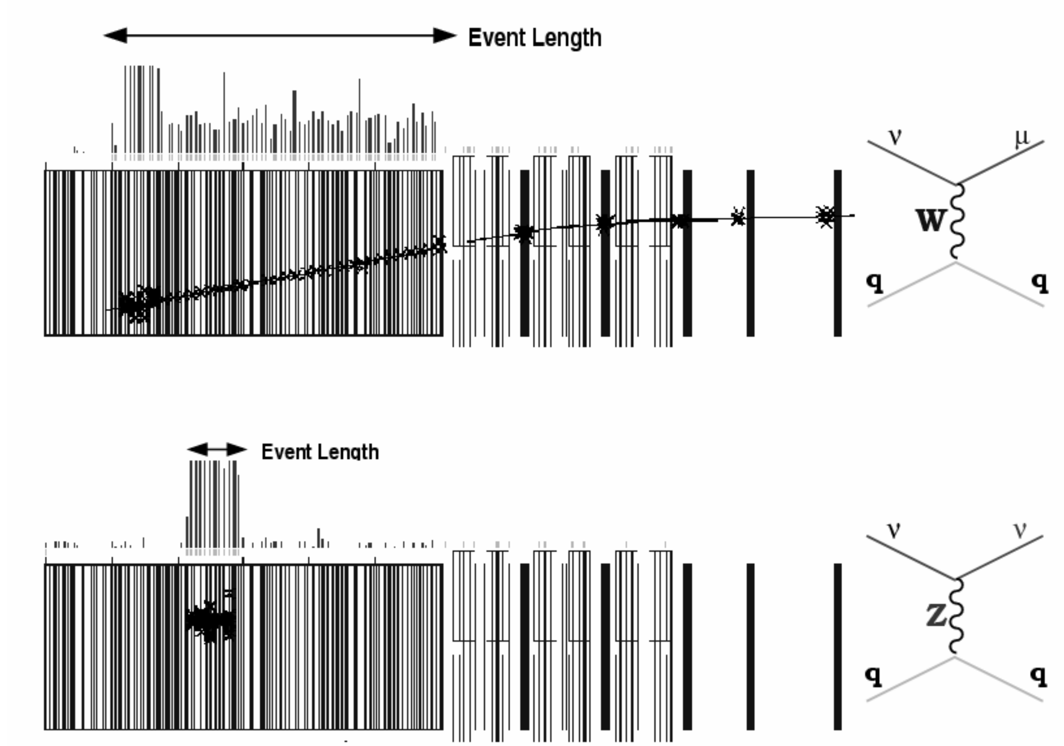
- Beam identifies neutral currents as ν or $\bar{\nu}$ ($\bar{\nu}$ in ν mode 3×10^{-4}, ν in $\bar{\nu}$ mode 4×10^{-3})
- Beam only has $\sim1.6\%$ electron neutrinos
  - $\Rightarrow$ Important background for isolating true NC event

Neutral Current / Charged Current Event Separation

- Separate NC and CC events statistically based on the “event length” defined in terms of # counters traversed
  - n.b., electron neutrinos will be NC candidates

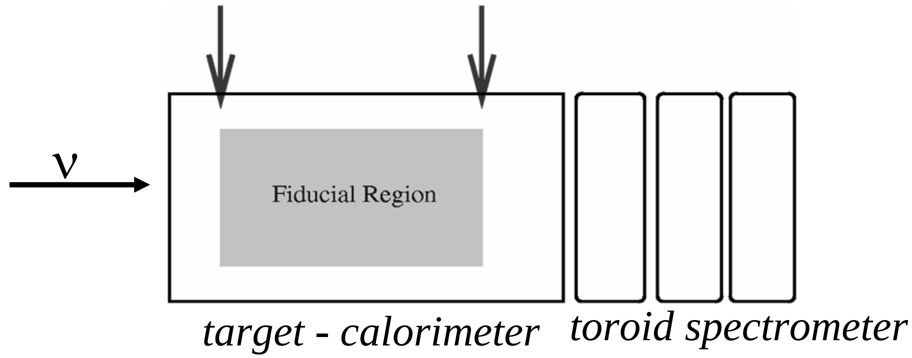
$$R_{\exp} = \frac{\text{SHORT events}}{\text{LONG events}} = \frac{L \leq L_{cut}}{L > L_{cut}} = \frac{\text{NC Candidates}}{\text{CC Candidates}}$$

(measure in ν and $\bar{\nu}$ beams)



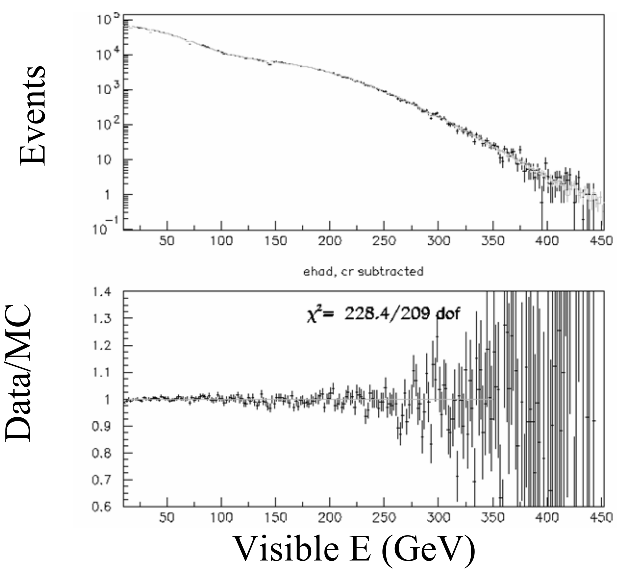
NuTeV Data Sample

- Event selections:
  - –Require energy in calorimeter
    $E_{visible} > 20$ GeV
  - –Require Event Vertex
    within fiducial volume

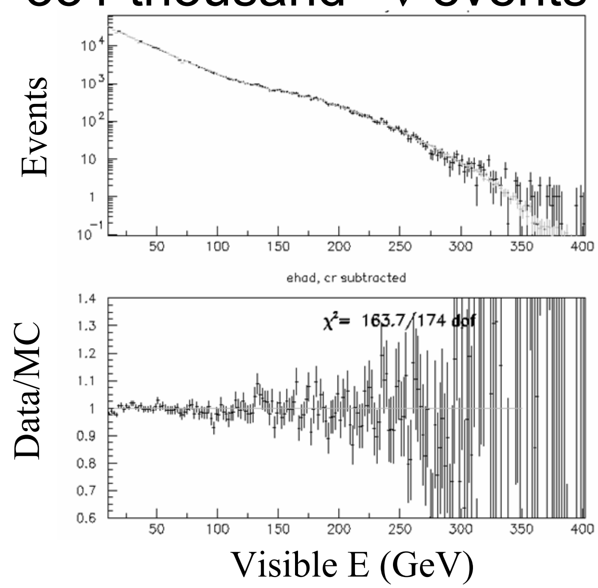


- Data with these cuts:

1.62 million ν events



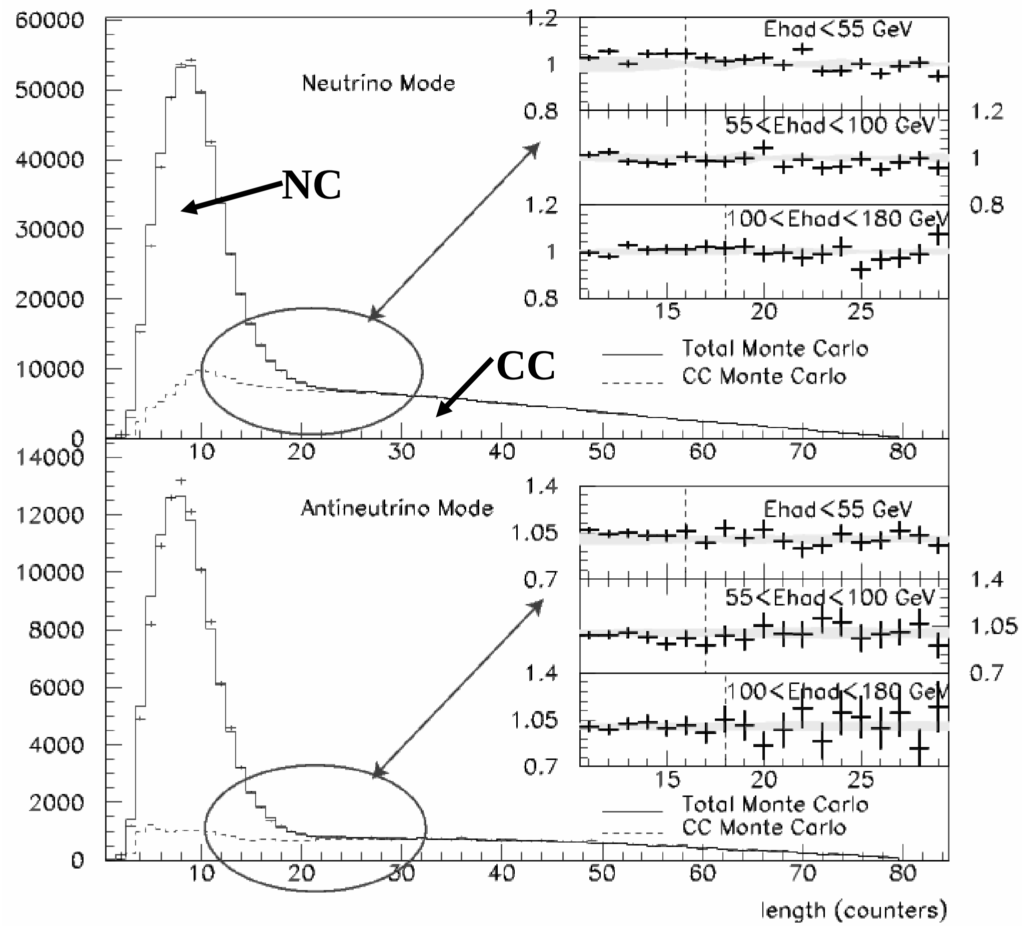
351 thousand $\bar{\nu}$ events



Determine R_{exp}:

Event Length Distribution Neutrinos

Event Length Distribution Antineutrinos



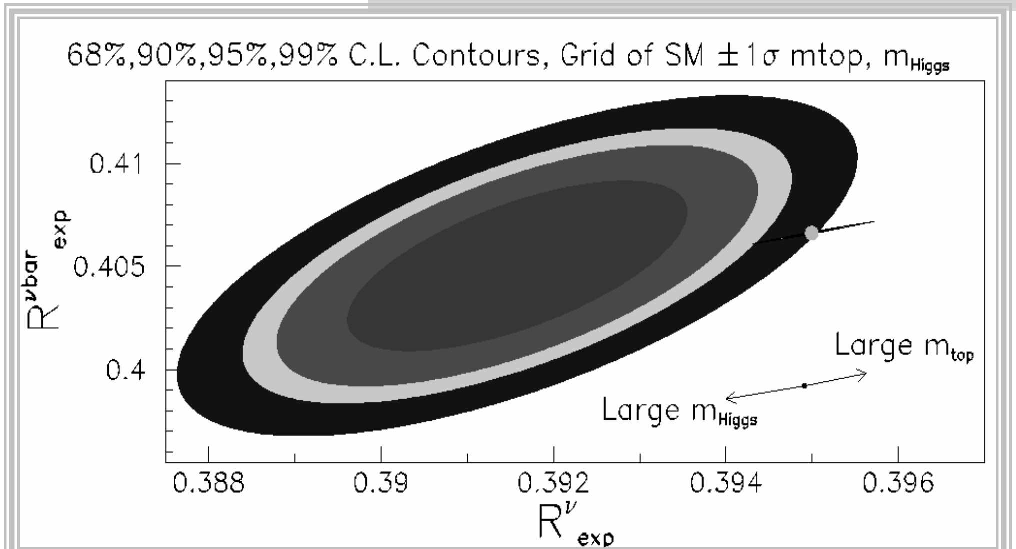
	Short (NC) Events	Long (CC) Events	R_{exp}=Short/Long
Neutrino	457K	1167K	**0.3916** ± 0.0007
Antineutrino	101K	250K	**0.4050**± 0.0016

Paschos-Wolfenstein à la NuTeV

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

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

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



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

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

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

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

Measurement Uncertainties

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

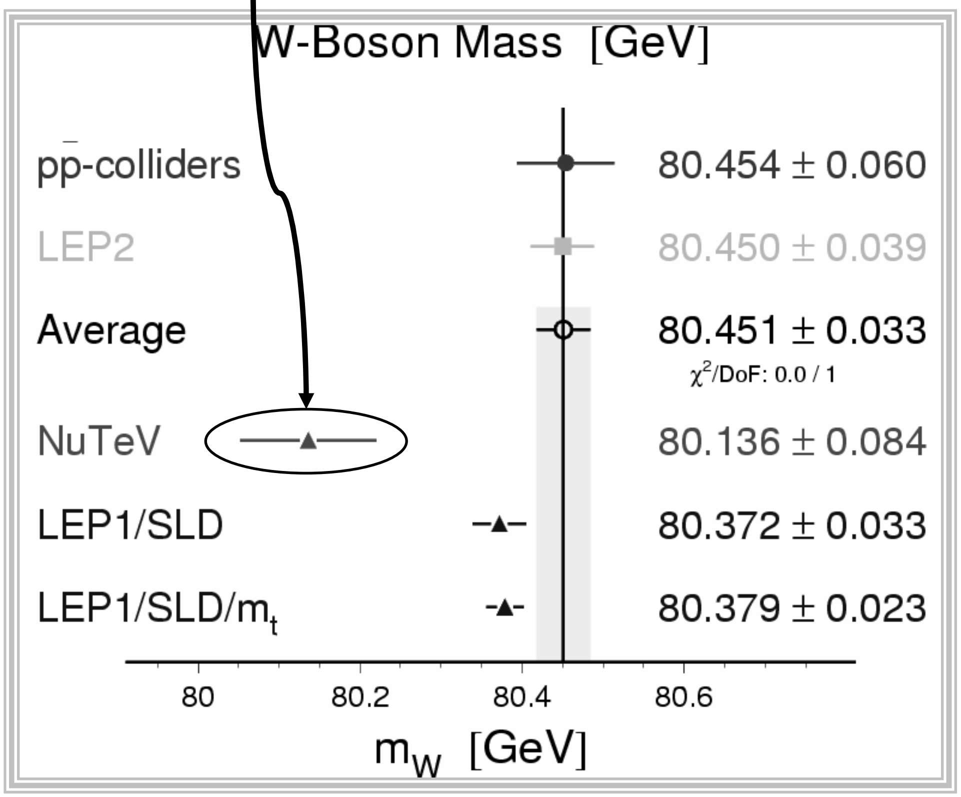
SOURCE OF UNCERTAINTY	$\delta\sin^2\theta_W$	$\delta R^{\nu}_{\rm exp}$	$\delta R^{\overline{\nu}}_{\rm exp}$
Data Statistics	0.00135	0.00069	0.00159
Monte Carlo Statistics	0.00010	0.00006	0.00010
TOTAL STATISTICS	0.00135	0.00069	0.00159
$\nu_e, \overline{\nu}_e$ Flux	0.00039	0.00025	0.00044
Interaction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

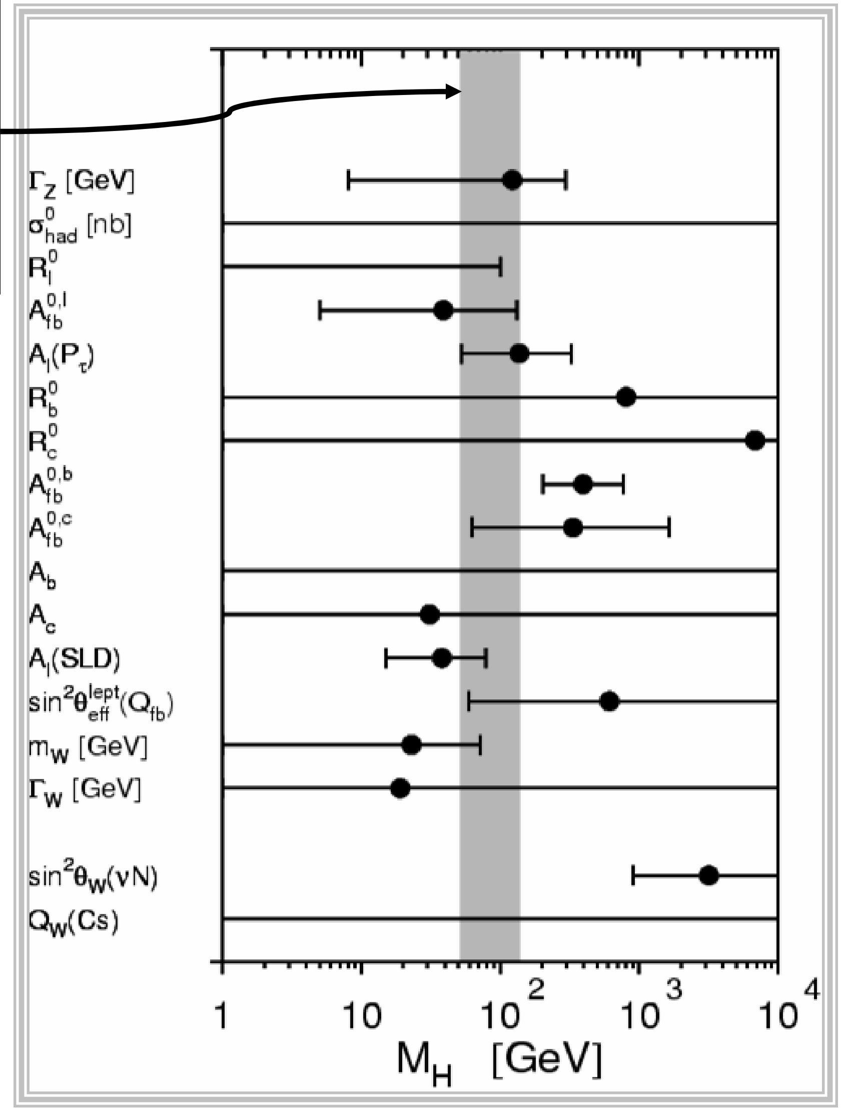
Compared to Other Measurements

M_W = 80.136 ± 0.084 GeV

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

Given other inputs to SM, what Higgs Mass is implied?





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 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

Interpreting NuTeV $\sin^2\theta_W$

Report from the NuTeV collaboration

Kevin McFarland
University of Rochester

WIN03, Lake Geneva, WI
8 October 2003

New Physics?

A brief comment on the possibilities.

New Physics Summary

- 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

S. Davidson et al. hep-ph/0112302

Li & Ma, Takeuchi et al

  - So the community focuses on mundane explanations
    - I would 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!

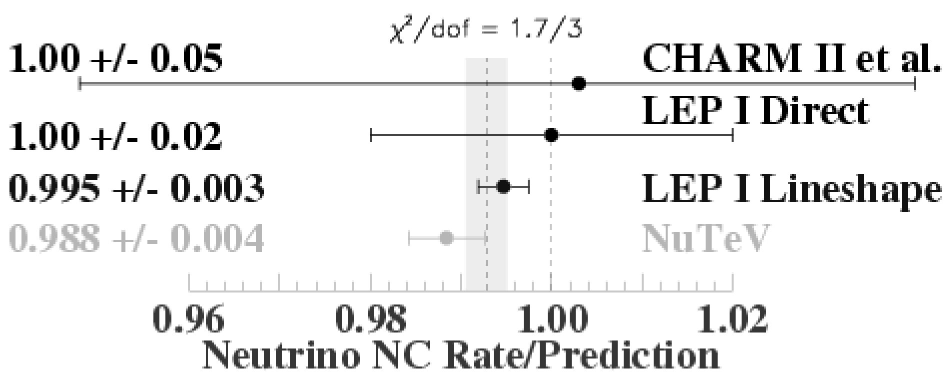
Corroborating Evidence and Impact of Future Results

Is there other evidence of BSM physics
or Mundane Physics?

What can we learn in the future?

Is NuTeV Result Confirmed? Are there corroborating data?

- In short, nothing definite.
- It is consistent with previous νN measurements, but even combined, these are low precision.
- Other tests of neutrino neutral current also consistent, but not high precision…



- An interesting hint?
- Model building around this is a challenge.

S. Davidson et al. hep-ph/0112302

W. Loinaz et al, hep-ph/0210193

X. Li and E. Ma, hep-ph/0212029

Future Data and Interpretation

- 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-P906 $\pi^\pm$p, $\pi^\pm$d Drell-Yan can directly probe this
  - Re-analysis of old ν bubble-chamber data? νp vs. νn

Future Data (cont'd)

- Other precision EW data with quarks or neutrinos
  - e-Baryon scattering is undergoing a re-emergence!
    - QWEAK at JLab (ep)
    - DISParity at SLAC (eD) to redo Prescott experiment
    - 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)
      - Same systematic concerns
      - Maybe worth doing if there were a 1 TeV ν beam at LHC.
    - ν-e scattering would be a great measurement, but it's tough
      - Cross-section is down by factor of a few 10^3
      - Normalization?

Bigi et al, hep-ph/0106177

Future Data (cont'd)

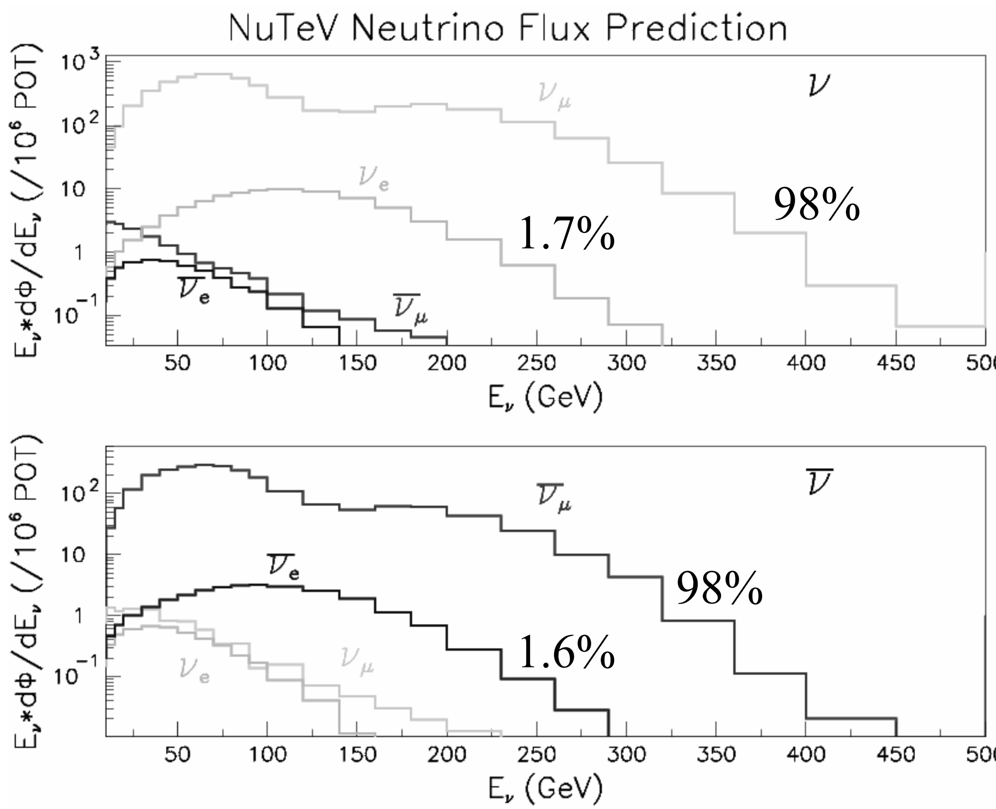
- Always the possibility of a future discovery impacting the NuTeV interpretation
  - LHC or TeVatron finds a Z'
  - Giga-Z confirms and strengthens small deficit in invisible width
  - …

Electron Neutrino Background Under Control?

1. How it is measured
2. The recent BNL-E865 Measurement

Electron Neutrino Background

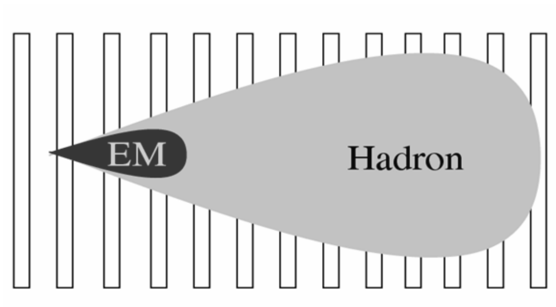
- Approximately 5% of NC candidates are ν_e CC events
  (It would take a 20% overestimate of ν_e to move NuTeV to SM)
  - Main ν_e source is $K^{\pm}$ decay (93% / 70% of total in ν / $\bar{\nu}$ beams)
  - Others include K_L's (4%/18%) and Charm (2%/9%)
  - Main uncertainty is $K^{\pm}_{e3}$ branching 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 by +0.7σ
- 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_ν <180 GeV)



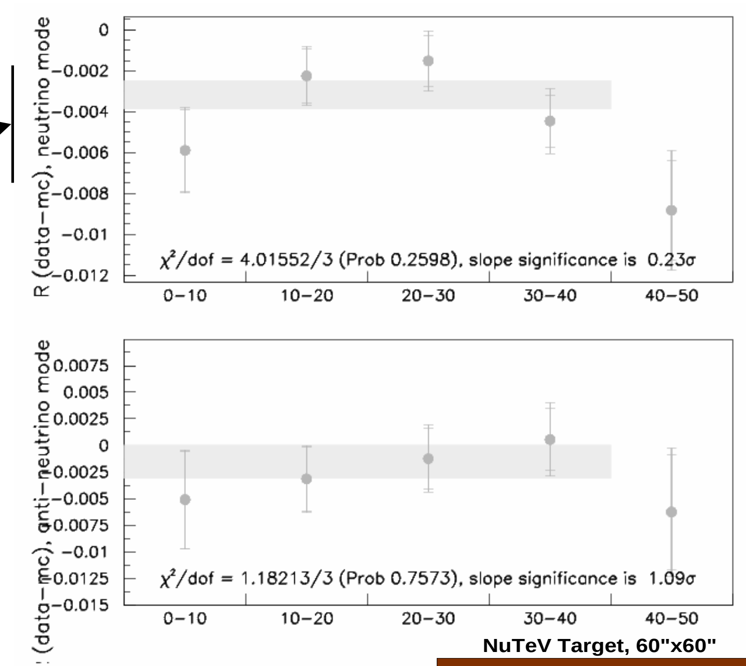
$$N_{meas} / N_{MC} : 1.05 \pm 0.03 \ (\nu_e)$$
$$1.01 \pm 0.04 \ (\bar{\nu}_e)$$

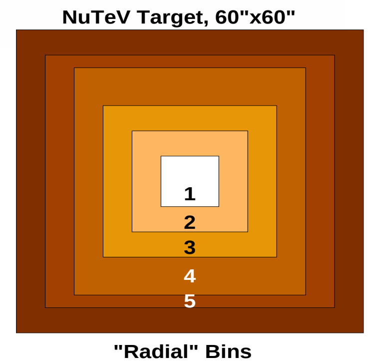
   - Poor agreement with simulation on high energy tail (expected from inability to measure high E ν_μ^{CC}, smearing)
     - Remove events from analysis with E_ν > 180 GeV. Concern?

Feel-Good Checks of ν_e

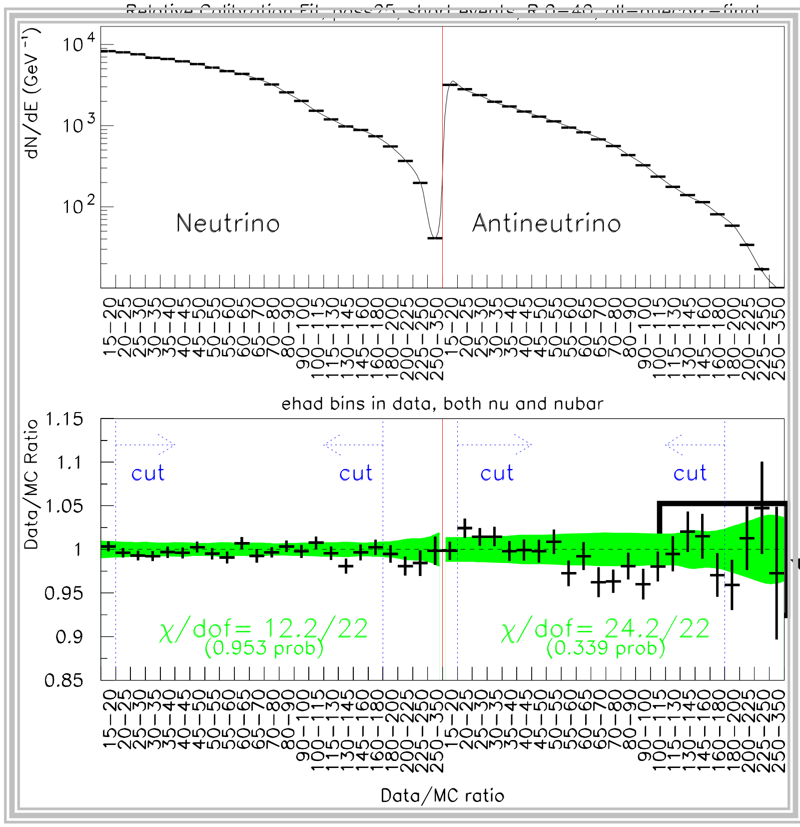
- R_{exp} vs. radial bin
  Electron neutrino background much higher near edge of detector.

Statistical error bands





NC Candidates vs. visible Energy



- R_{exp} vs. visible energy
  Electron neutrino background dominant at high visible energy

Systematic error bands

Stability Checks

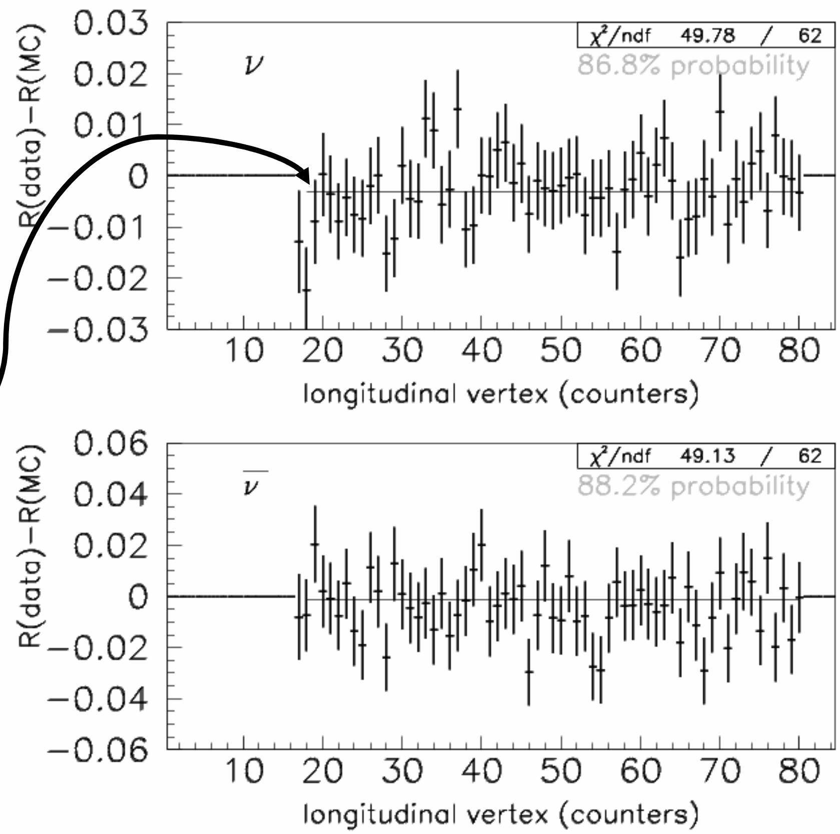
Is NuTeV Result robust if data is sub-divided to highlight different kinematic regions, backgrounds?

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

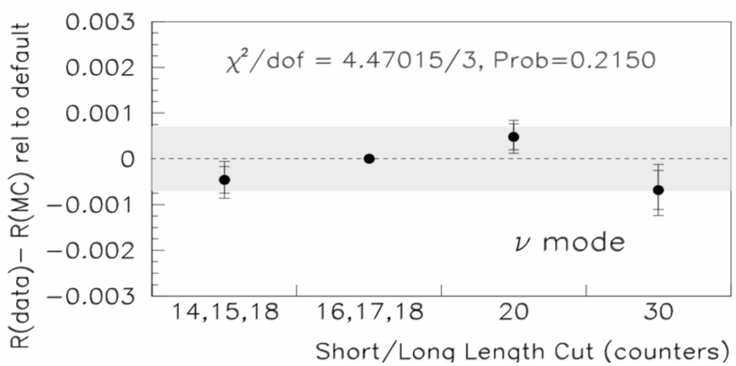
Note: Shift from zero is *because* NuTeV result differs from Standard Model

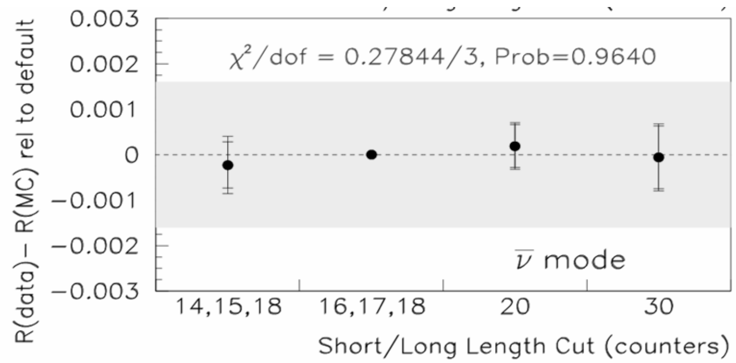


Stability Tests (cont'd)

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

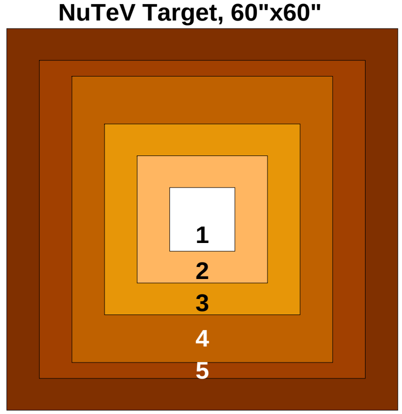
Yellow band is stat error



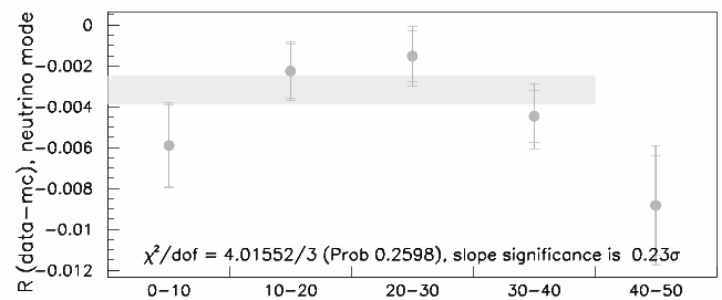


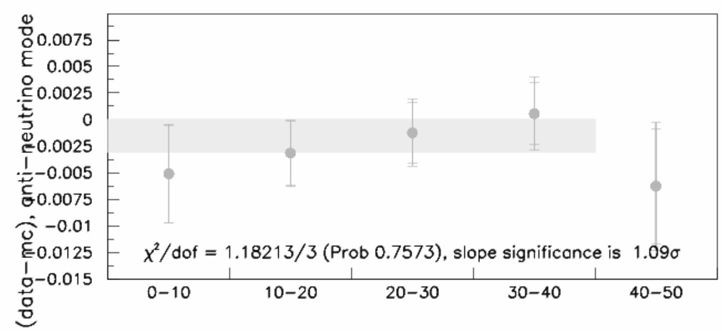
- R_{exp} vs. radial bin: Check corrections for ν_e and short CC which change with radius.

NuTeV Target, 60"x60"



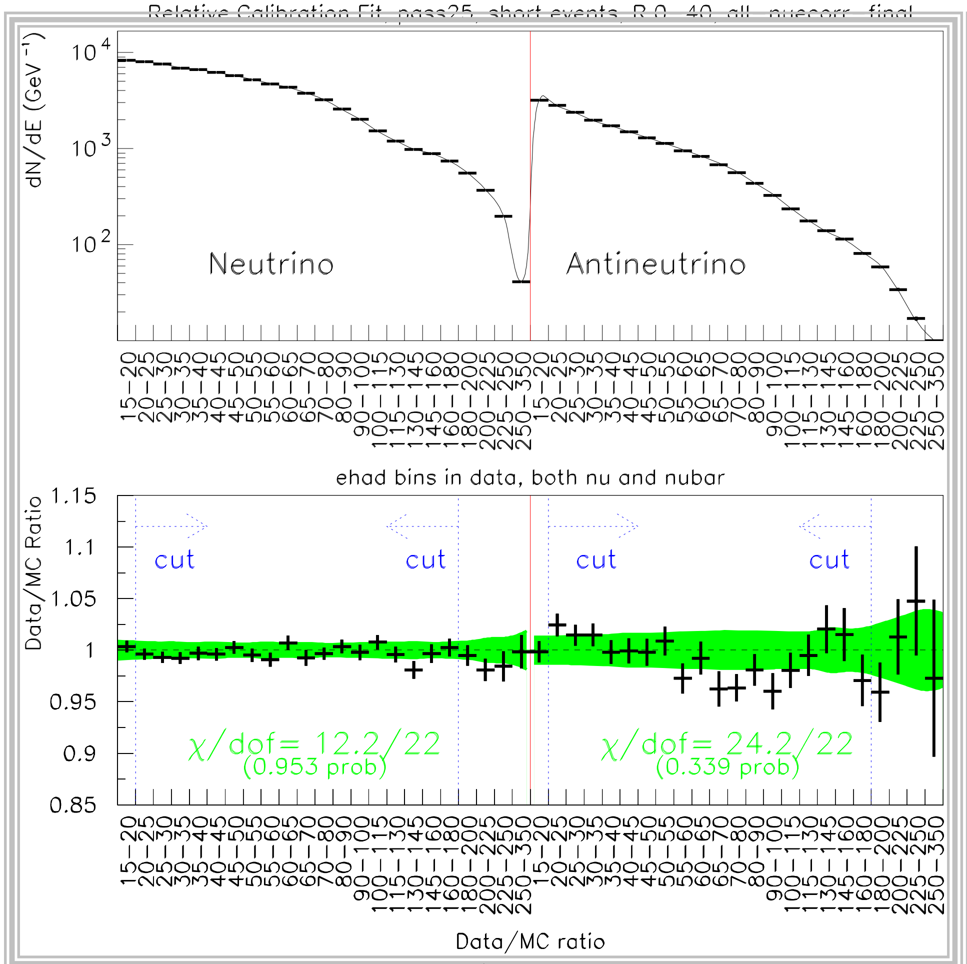
"Radial" Bins



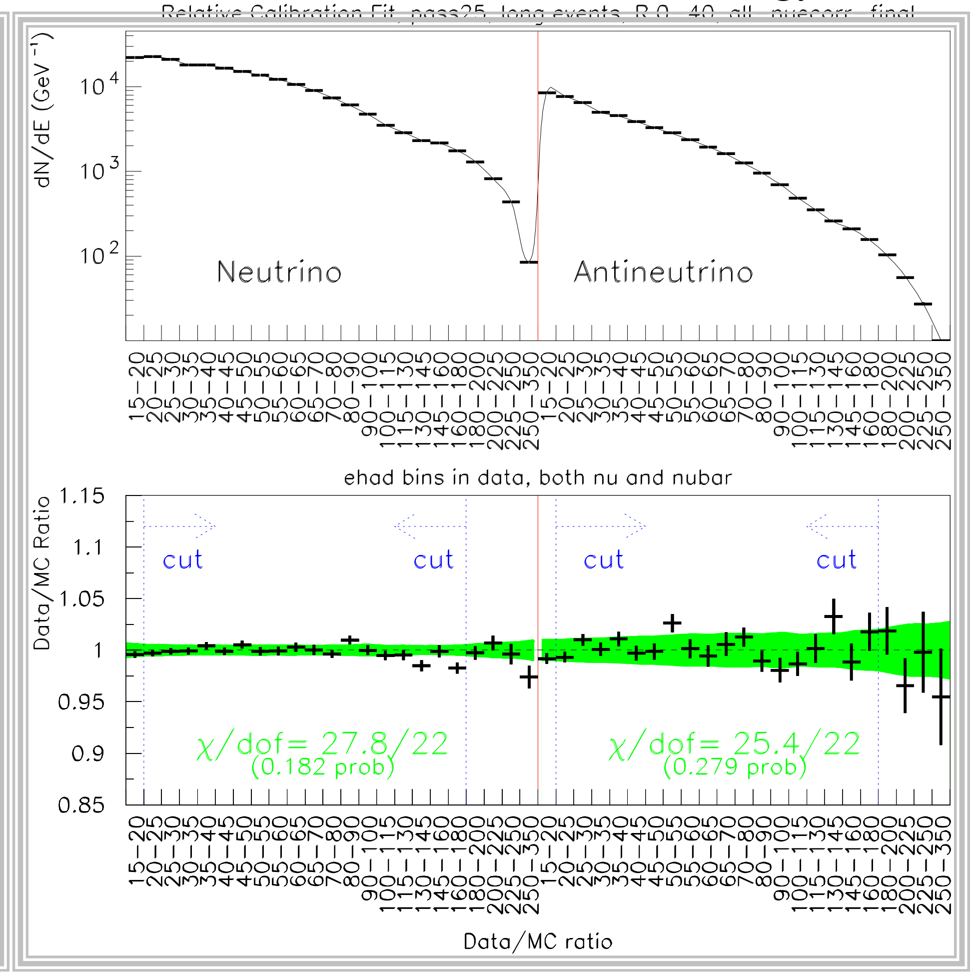


Distributions vs. E_{had}

NC Candidates vs. visible Energy



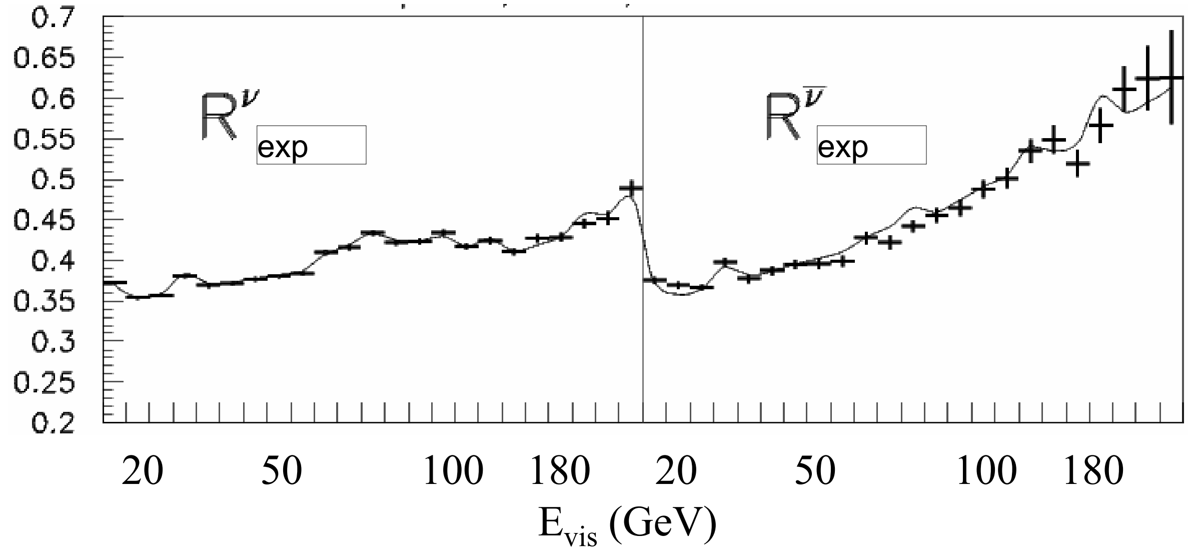
CC Candidates vs. visible Energy



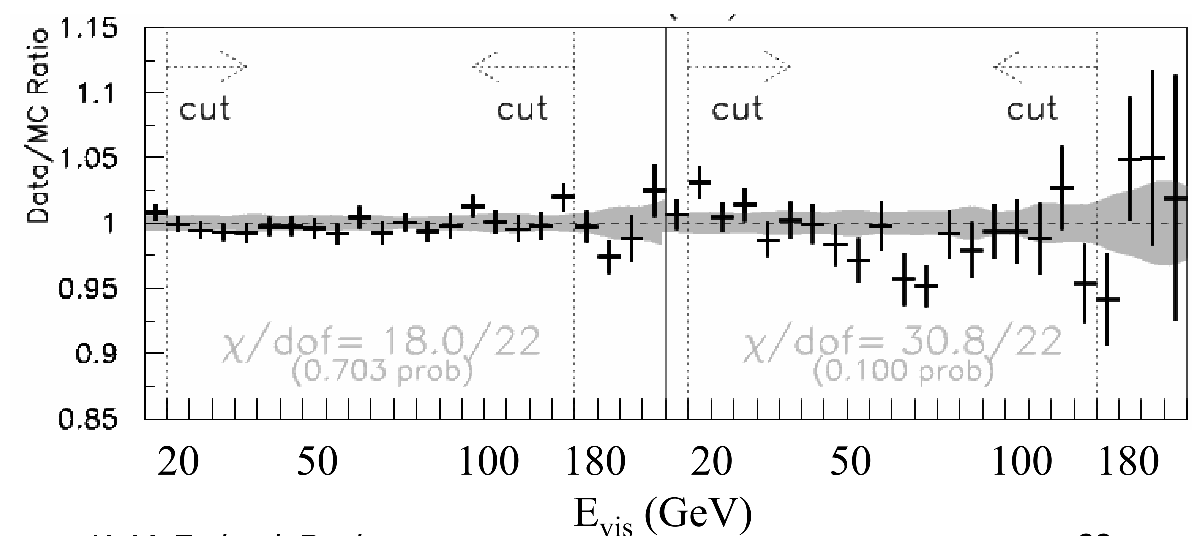
Systematic error bands

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



LO Cross-Section Model

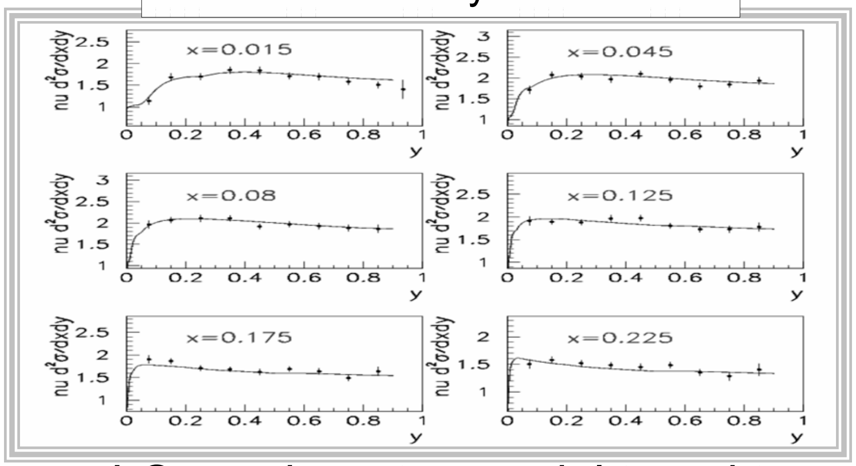
1. How does the model work?
   How is it used?
2. NLO Corrections

Enhanced LO Cross-Section

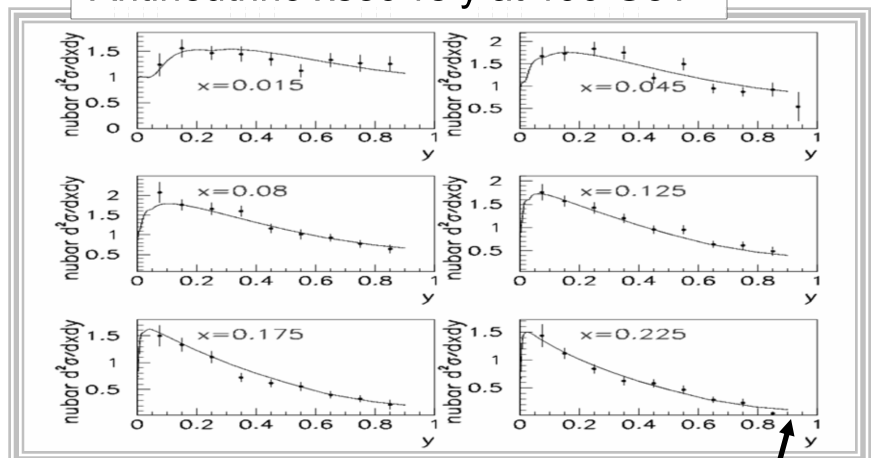
- "Enhanced" means: include R_L and higher twist terms
- PDFs extracted from CCFR data exploiting symmetries:
  - Isospin symmetry: $u^p = d^n$, $d^p = u^u$, and $s(x) = \bar{s}(x)$
- Data-driven: uncertainties come from measurements

CCFR Data

Neutrino xsec vs y at 190 GeV



Antineutrino xsec vs y at 190 GeV



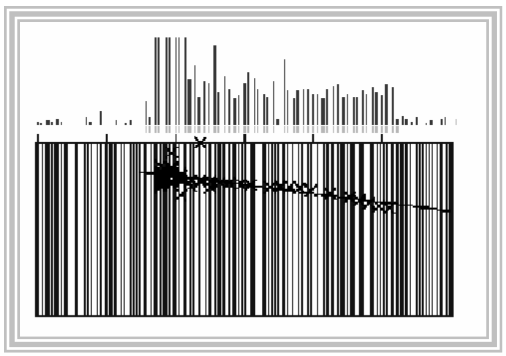
high y events are background to the neutral current sample

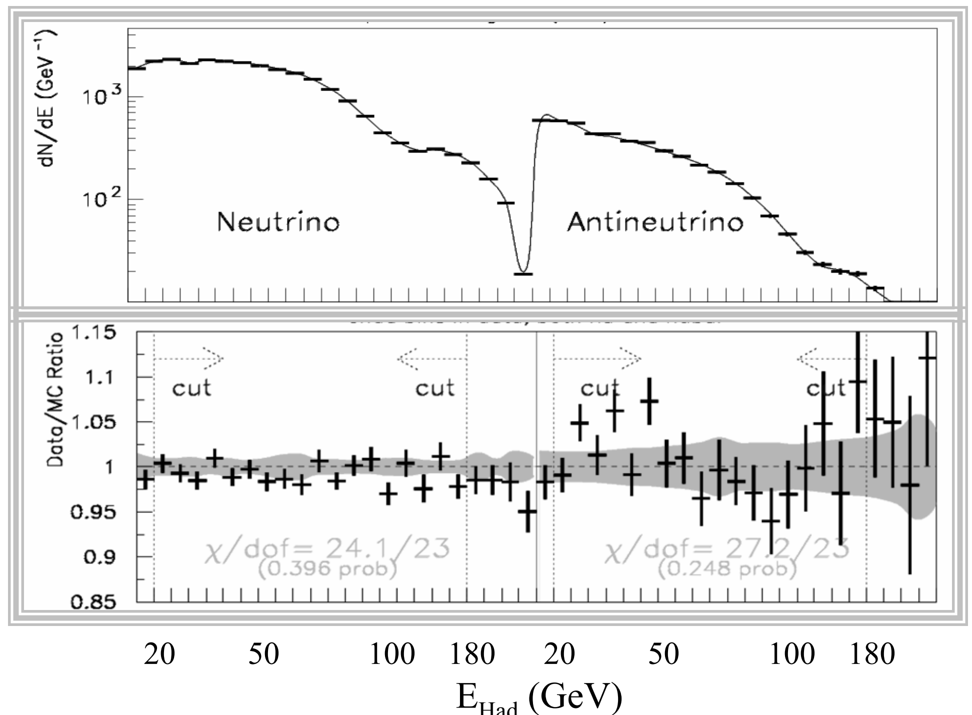
- LO quark-parton model tuned to agree with data:
  - Heavy quark production suppression and strange sea (CCFR/NuTeV $\nu N \rightarrow \mu^+ \mu^- X$ data)
  - R_L , F_2 higher twist (from fits to SLAC, BCDMS)
  - d/u constraints from NMC, NUSEA(E866) data
  - Charm sea from EMC F_2^{cc}

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

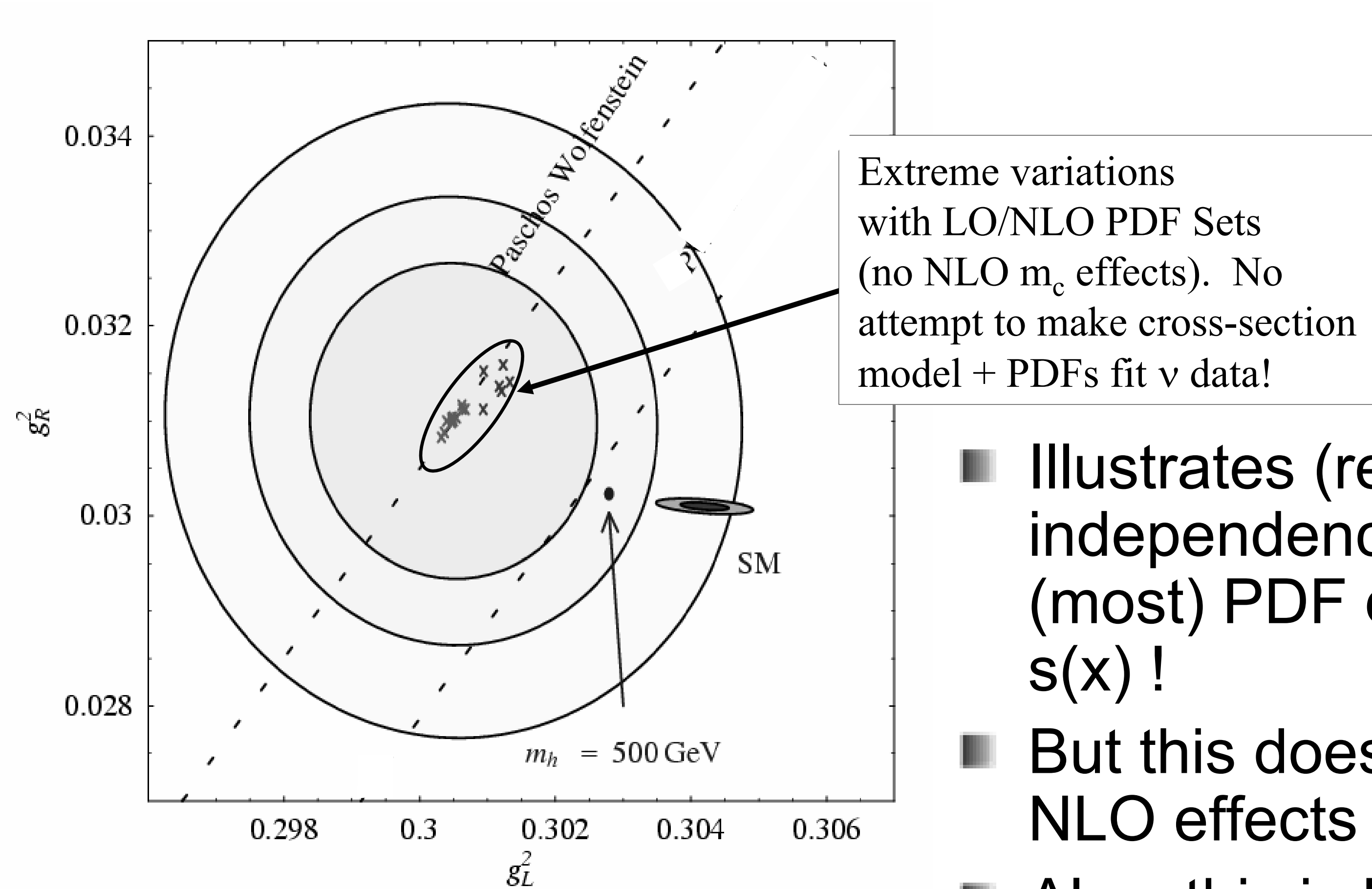
Charged-Current Control Sample

- 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



(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 R^- Changed in NLO QCD?

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

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

$$C^i = \text{ NLO coefficient fcns. in SF } F_i$$

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

(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
  – however, again, NuTeV does not measure precisely R^-

Numerical Evaluation of NLO QCD Effects

	Davidson et al	McFarland-Moch (I)	McFarland-Moch (II)	Kretzer-Reno	Dobrescu-Ellis
NuTeV PDFs		√	√		√
Gluon, Sea contributions (cancel in R^-)				√	√
Experimental Cuts			√		
Realistic Treatment of Target Mass, Heavy Flavor				√	
δNLO	N/A	-0.0003	-0.0003	-0.0004	+0.0015

Final Word on NLO QCD Effects

- None of these analyses
  - account for fitting CCFR CC cross-sections and dimuon data at same order
  - check background predictions at NLO
- Full NLO Analysis
  - Ellis and Dobrescu have written a generator
    - invaluable assistance! thank you!
    - too slow by 1-2 orders of magnitude to use. Working to improve.
    - need additions to associated evolution code for strange sea
  - Work in progress…

NuTeV's Use of Neutrino and Anti-Neutrino Data

What's the difference between NuTeV and R^- ?

Paschos-Wolfenstein at NuTeV

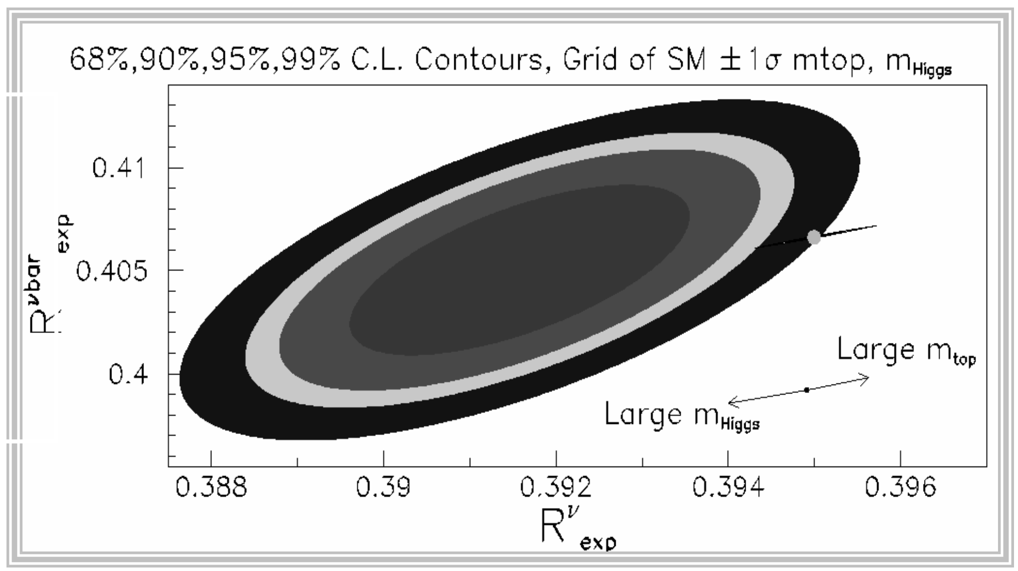
$$R^{\nu(\bar{\nu})} = \frac{\sigma_{NC}^{\nu(\bar{\nu})}}{\sigma_{CC}^{\nu(\bar{\nu})}} = \rho_0^2 \left(\frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W \left(1 + \frac{\sigma_{CC}^{\bar{\nu}(\nu)}}{\sigma_{CC}^{\nu(\bar{\nu})}}\right) \right)$$

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

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

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

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

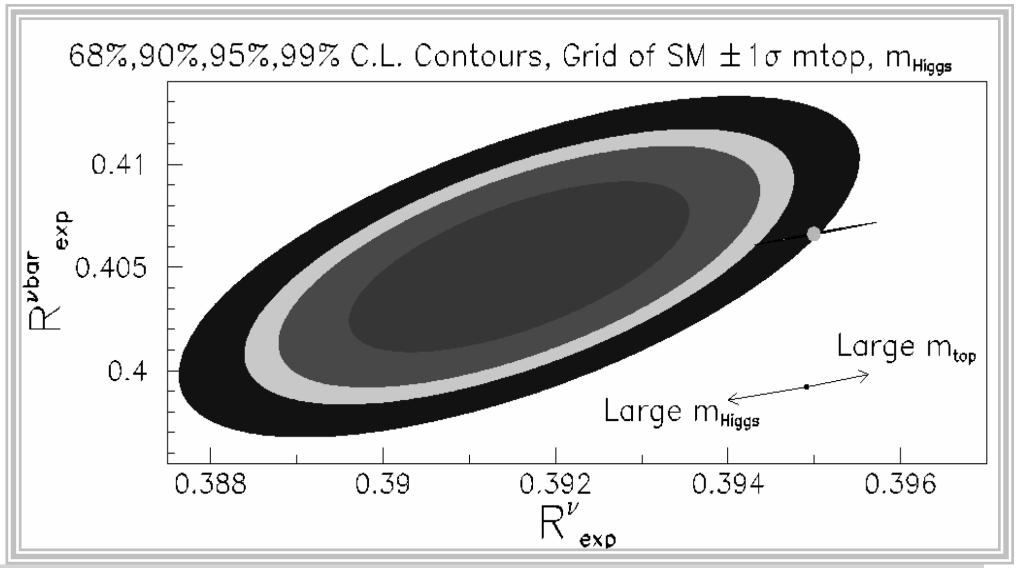


How is NuTeV's Analysis Different from R^-? (Details)

- Backgrounds (cosmic rays, non-neutrino events)
  - Taken from data. Only increase statistical errors.
- Cross-talk (including ν_e background)
  - Dilute statistical significance of the result $\Rightarrow \left|\frac{\partial \sin^2\theta_W}{\partial ?}\right| < \left|\frac{\partial R^-}{\partial ?}\right|$
  - 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)

- If this charm mass constrained fit were the 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.



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

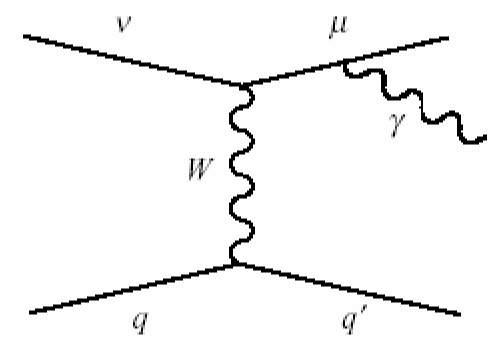
- Statistical and experimental systematics increase Model errors, of course, decrease…

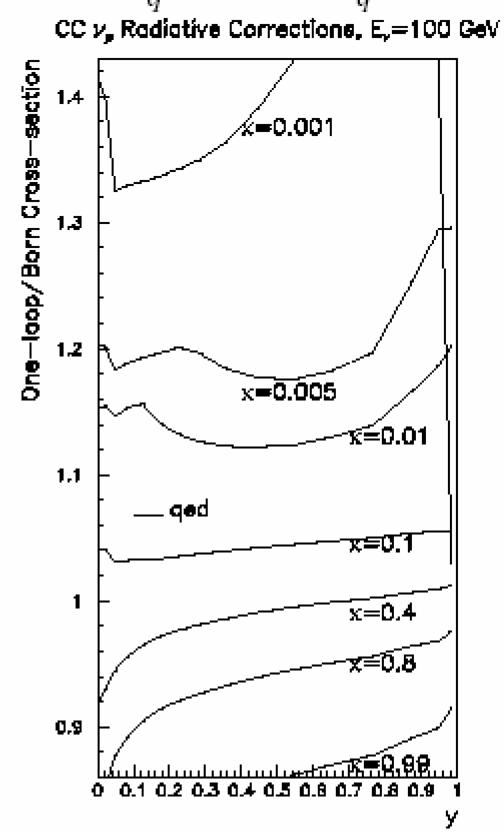
Electroweak Radiative Corrections

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. (Baur, Dittmaier, Hollik)





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

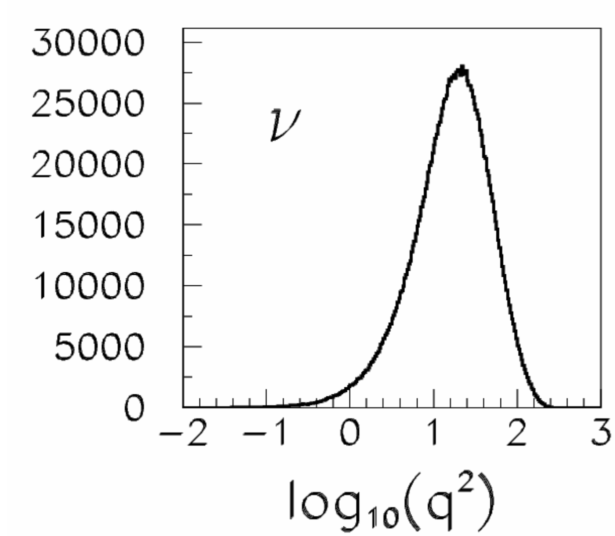
Dividing NuTeV Data into Regions in Q^2

What can we check to mitigate concerns about low Q^2 data?

Low Q^2 Contributions to NuTeV Analysis

- Bulk of NuTeV data is high Q^2, but some data with Q^2<1 GeV^2 is in analysis
  – visible energy cut limits this to very low x since $Q^2 = 2M\nu x$
    - sea region, common to ν and anti-ν

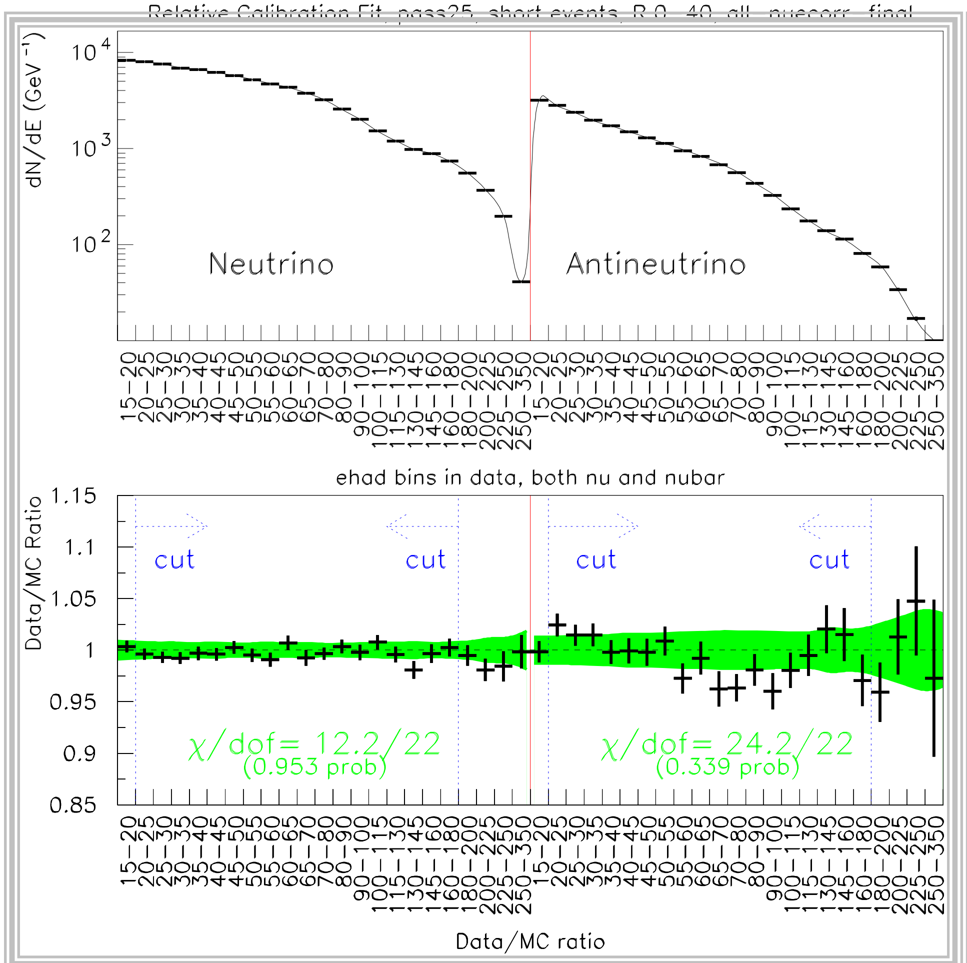
$$\langle Q^2 \rangle = \begin{matrix} 25\,\mathrm{GeV}^2 & \nu \\ 16\,\mathrm{GeV}^2 & \bar{\nu} \end{matrix}$$



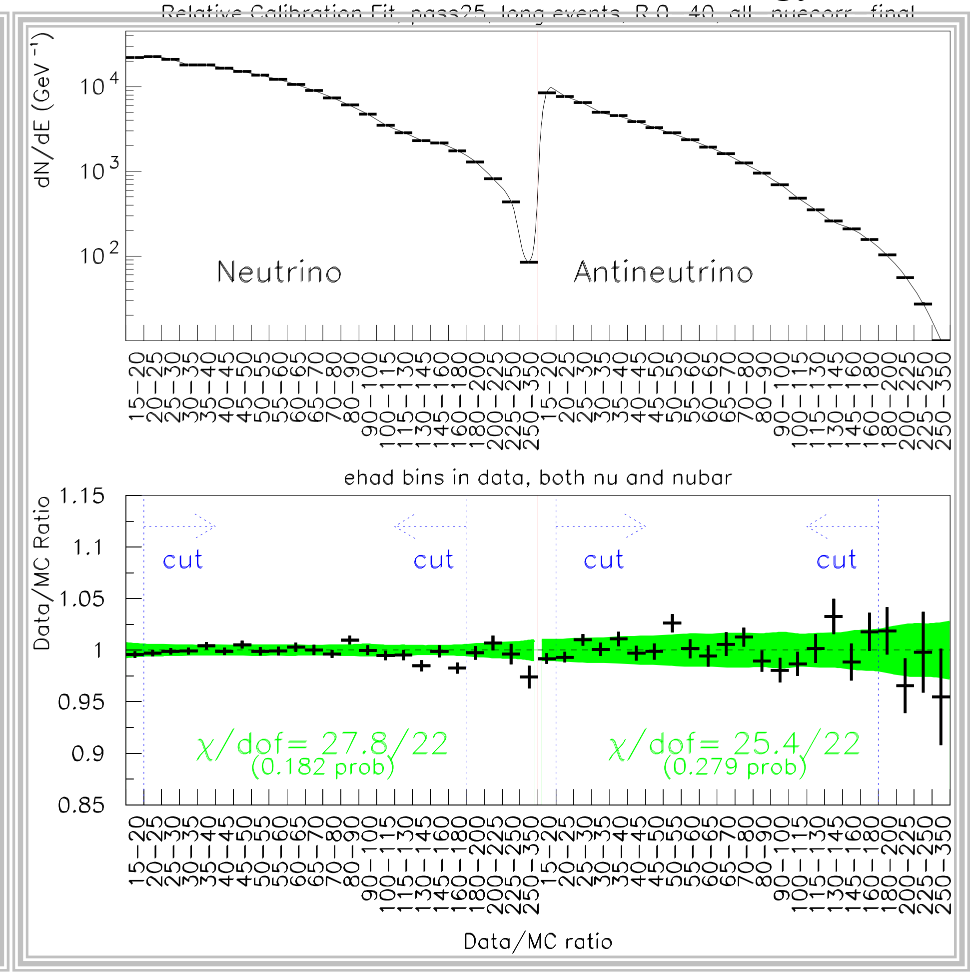
- Unfortunately, for neutral currents, we don't reconstruct Q^2
- However, $E_{visible}$ and Q^2 are correlated by q(x)

Distributions vs. $E_{visible}$

NC Candidates vs. visible Energy



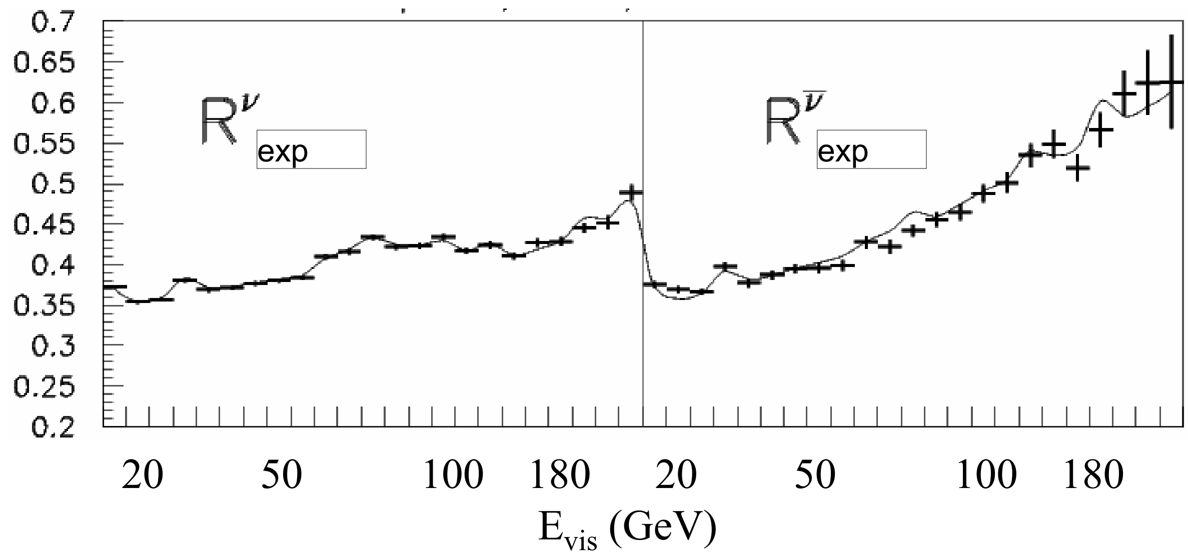
CC Candidates vs. visible Energy

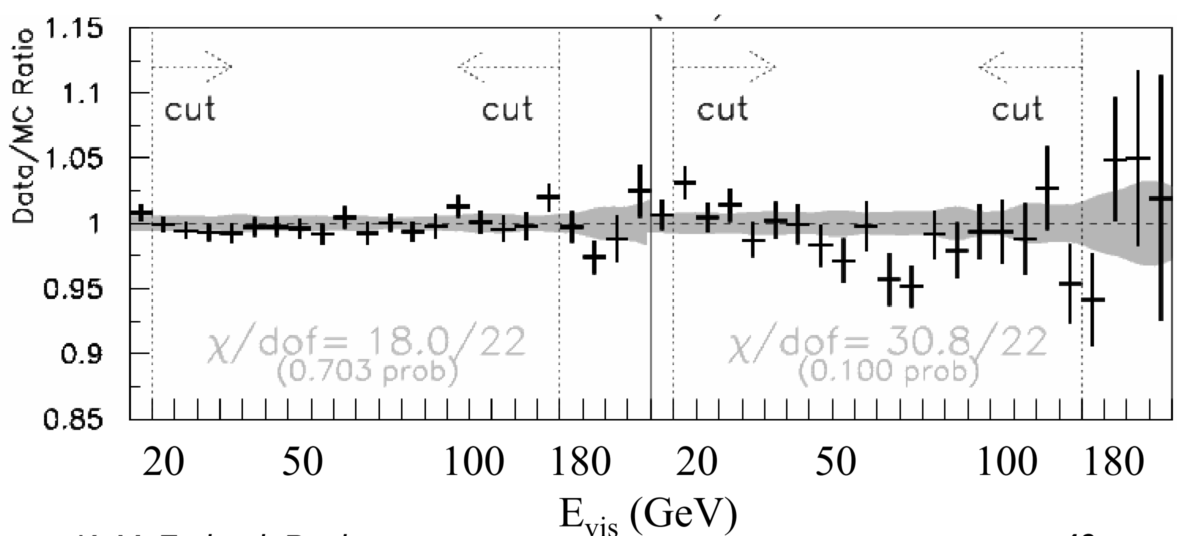


Systematic error bands

R_{exp} vs. Energy

- **A Q^2 dependence would show up as a trend in this graph**
- Bottom line: no obvious causes for concern





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^-

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

where

$$
\begin{aligned}
\delta N &= \frac{(N-Z)}{A} \\
U_v &= \int x(u_v^p + d_v^p)dx, \text{ etc.} \\
\delta U_v &= \int x(u_v^p - d_v^n)dx, \text{ etc.} \\
\Delta_{u,d}^2 &= \left(\varepsilon_L^{u,d} \right)^2 - \left(\varepsilon_R^{u,d} \right)^2 \\
\delta S &= \int x(s - \bar{s})dx \\
\varepsilon_c &= \text{ kinematic charm CC suppression}
\end{aligned}
$$

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

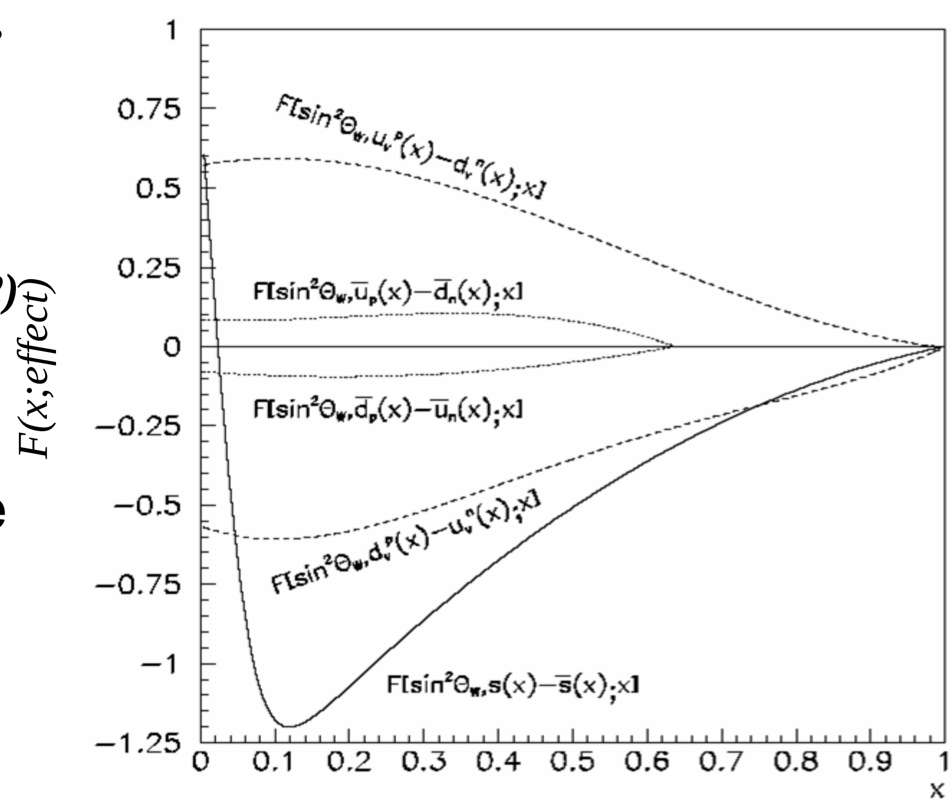
3. Asymmetric heavy-quark sea, $s(x) \neq \bar{s}(x)$
   (Signal and Thomas; Burkhardt and Warr; Brodsky and Ma)
   – Strange sea doesn't cancel in R^{-}

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

Detailed Examination of Symmetry Violation Effects

"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

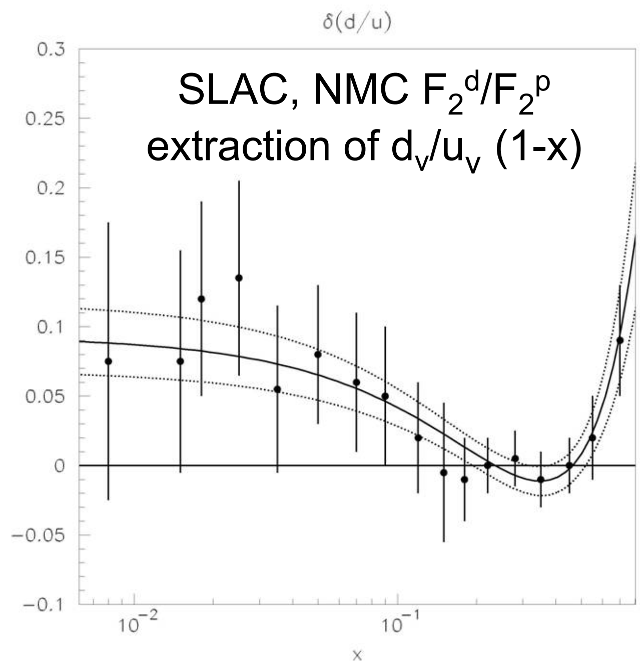
The NuTeV Neutron Excess

How it is evaluated

Neutron excess correction

- Neutron excess of target is well-known
  - primary *a priori* uncertainty, chemical composition of steel, resolved by assay. (N.B, not just steel… lots of H_2O, CH_n)

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



NMC Gottfried Sum Rule Data
NUSEA pp, pd Drell-Yan

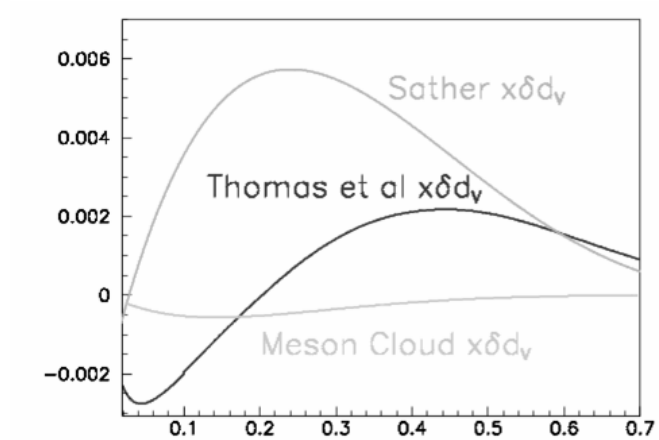
- N.B., PRL uncertainty is too small, ±*0.0003 is new estimate*
  - *Thanks to S. Kulagin and S. Alekhin for catching our mistake!*

Isospin Violation in PDFs

1. Impact on NuTeV
2. Experimental Constraints
3. Models

Isospin Violation in PDFs

- Isospin symmetry violation: $u^p \neq d^n$ and $d^p \neq u^n$
  (called "charge symmetry violation" in nuclear physics literature)
  - Three models shown:
    bag model ("Sather et al"),
    bag model w/ smearing ("Thomas et al"),
    meson cloud model ("Cao et al")
  - Not clear how much information is contained in these models…
    more on this later



- What is needed to explain the NuTeV data?
  - e.g., a 5% excess of momentum carried by d_p over that of u_n
  - what is "back of the envelope" effect?
    - terms of order
      $(m_d-m_u)/m_p$~0.5%,
      $(m_n-m_p)/m_p$~0.1%
  - ***Do global PDF fits allow enough isospin violation to explain NuTeV?***

What Can Global Fits Say?

- Unfortunately, not a lot.
- Conclusion of MRST study:
  - even with very restrictive functional form, constraint is almost non-existent.
  - could accommodate enough isospin to explain NuTeV.
  - could accommodate zero or isospin violation in the opposite direction
- Need more data

Martin et al, hep-ph/0308087

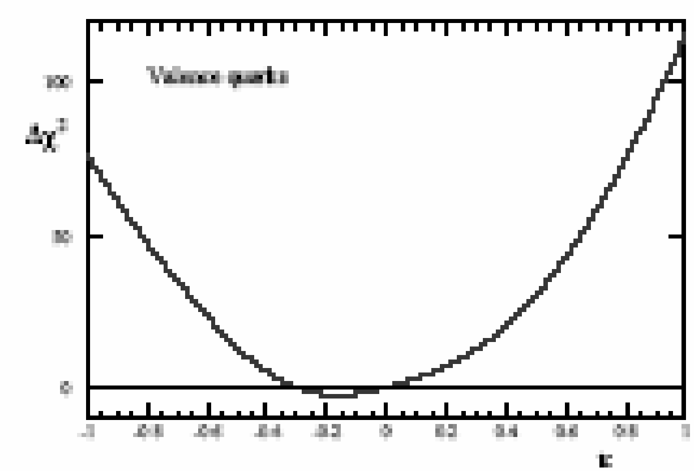


Figure 6. $\Delta\chi^2$ against the isospin violating parameter κ.

Isopin Violation

- 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…

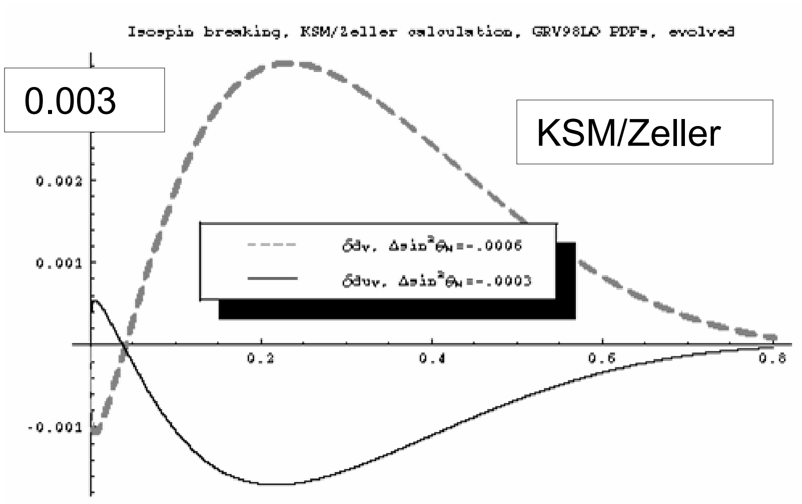
- Londergan and Thomas
  - revived analytic technique of Sather (PLB 274, 433) in hep-ph/0301147
    - analytic relation applied to phenomenological PDFs at bag scale

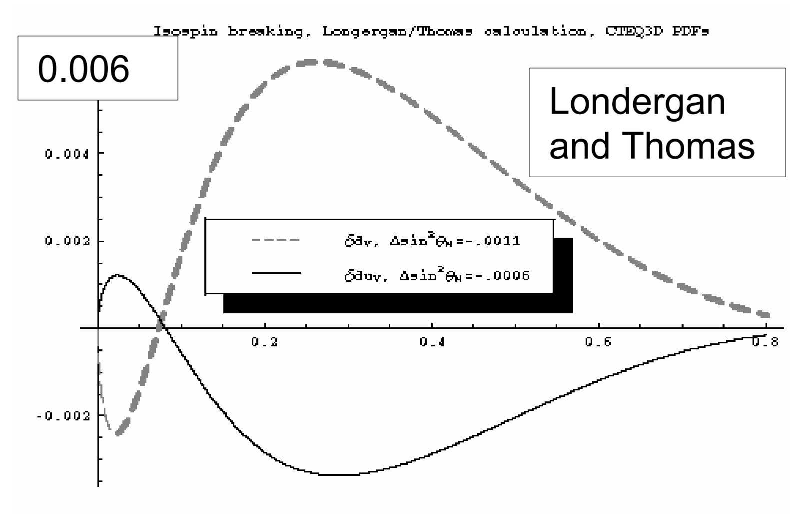
$$\delta d_v(x) = -\frac{1}{M_N}\left[(\delta M_N)\frac{d[xd_v(x)]}{dx} + (\delta m_q)\frac{d[d_v(x)]}{dx}\right]$$

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

  - L&T took NLO PDFs (CTEQ3D) at Q^2 of 2.56 GeV^2, didn't evolve it up in Q^2 but have shown this is OK.
  - neglects "diquark smearing"

Isospin Violation (cont'd)

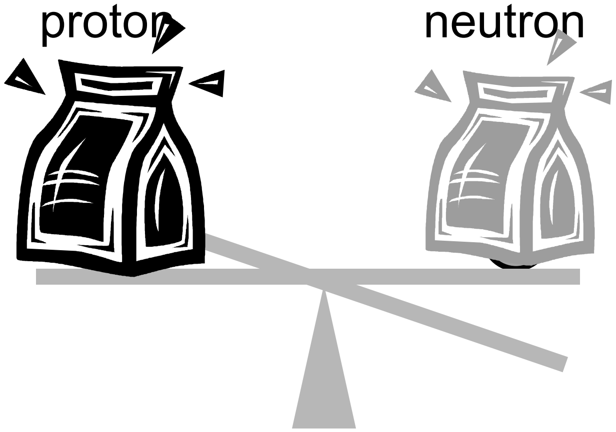




- Compare analytic calculations calculations:
  - KSM/Sam Zeller analytic analysis (Sather technique) agrees roughly with NuTeV published *ad hoc* result (without "diquark smearing")
    - δd_v effect on $\sin^2\theta_W$ is 0.0005 (PRD65:111103,2002) → 0.0006
  - Londergan & Thomas (hep-ph/0301147) show 0.0009 for same quantity
    - effect of different input PDFs? has not been resolved.

Isospin Violation (cont'd)

- Diquark what? Huh?
  - Analytic Sather relationship uses the idea that a DIS process removes one quark from the "bag", leaving a remnant behind, to measure $u_n(x)$ $d_p(x)$
  - Isospin violation arises from
    - difference in initial state energy (mass) between proton and neutron
    - difference in final state energy "diquark mass" (dominant effect)



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

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

Isospin Violation (cont'd)

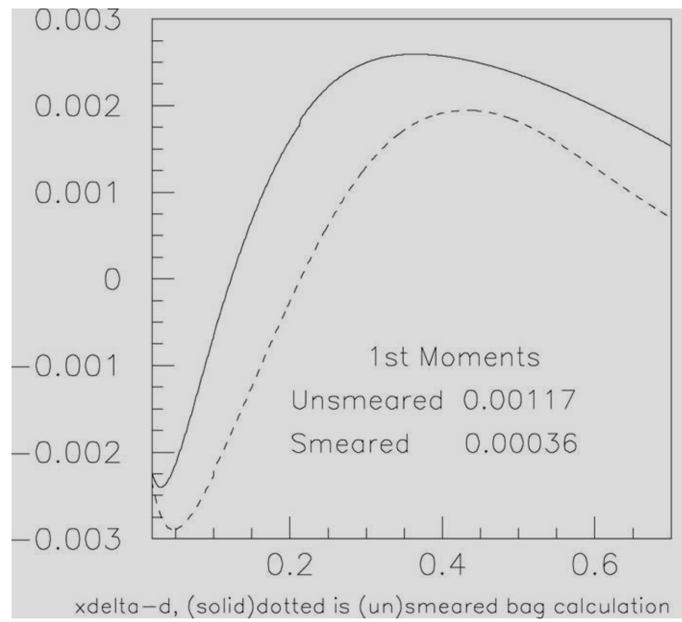
- What is "diquark smearing"?
  - Idea that energy of diquark in final state struck nucleon is not a delta-function but has some width

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

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

would modify these dominant terms

  - In Rodionov et al calculation with NuTeV approximate technique, smearing wipes out effect. Is it right?
  - Model appears to be highly sensitive to this level of detail.
  - This is a concern if relying on models.



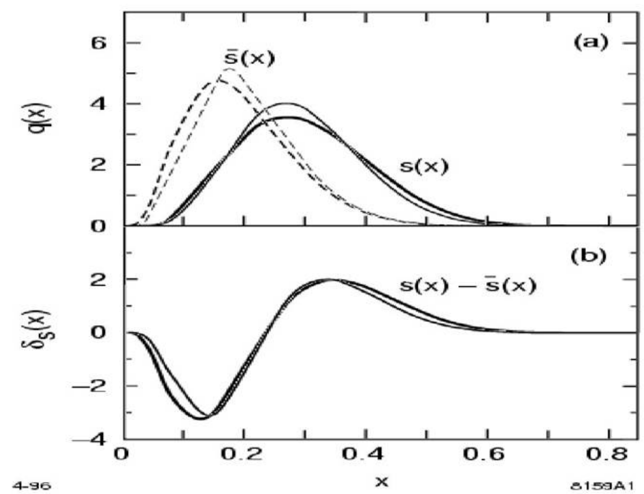
Asymmetric Strange Sea

1. How it is measured at NuTeV
2. Outside Analyses
3. 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)
- 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



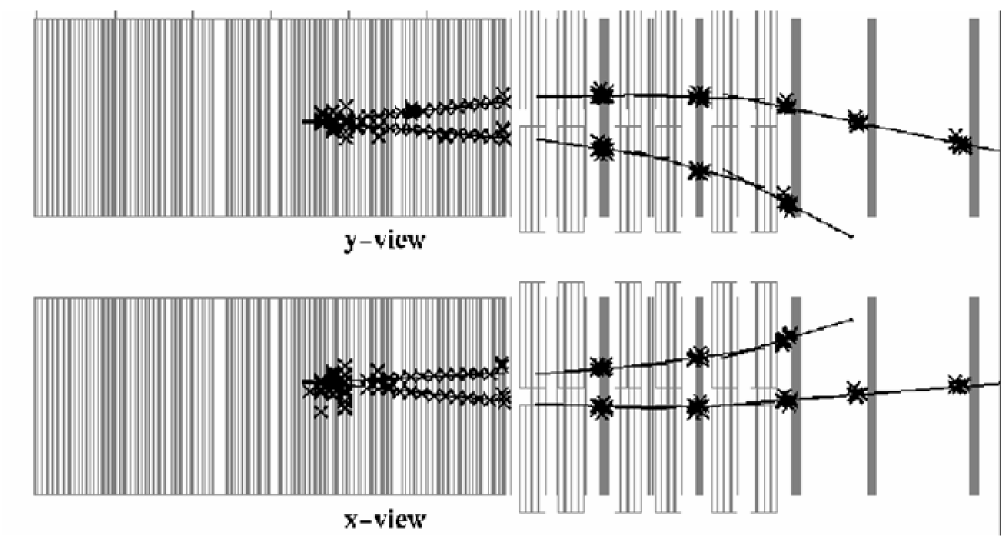
How Does NuTeV Measure This?

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

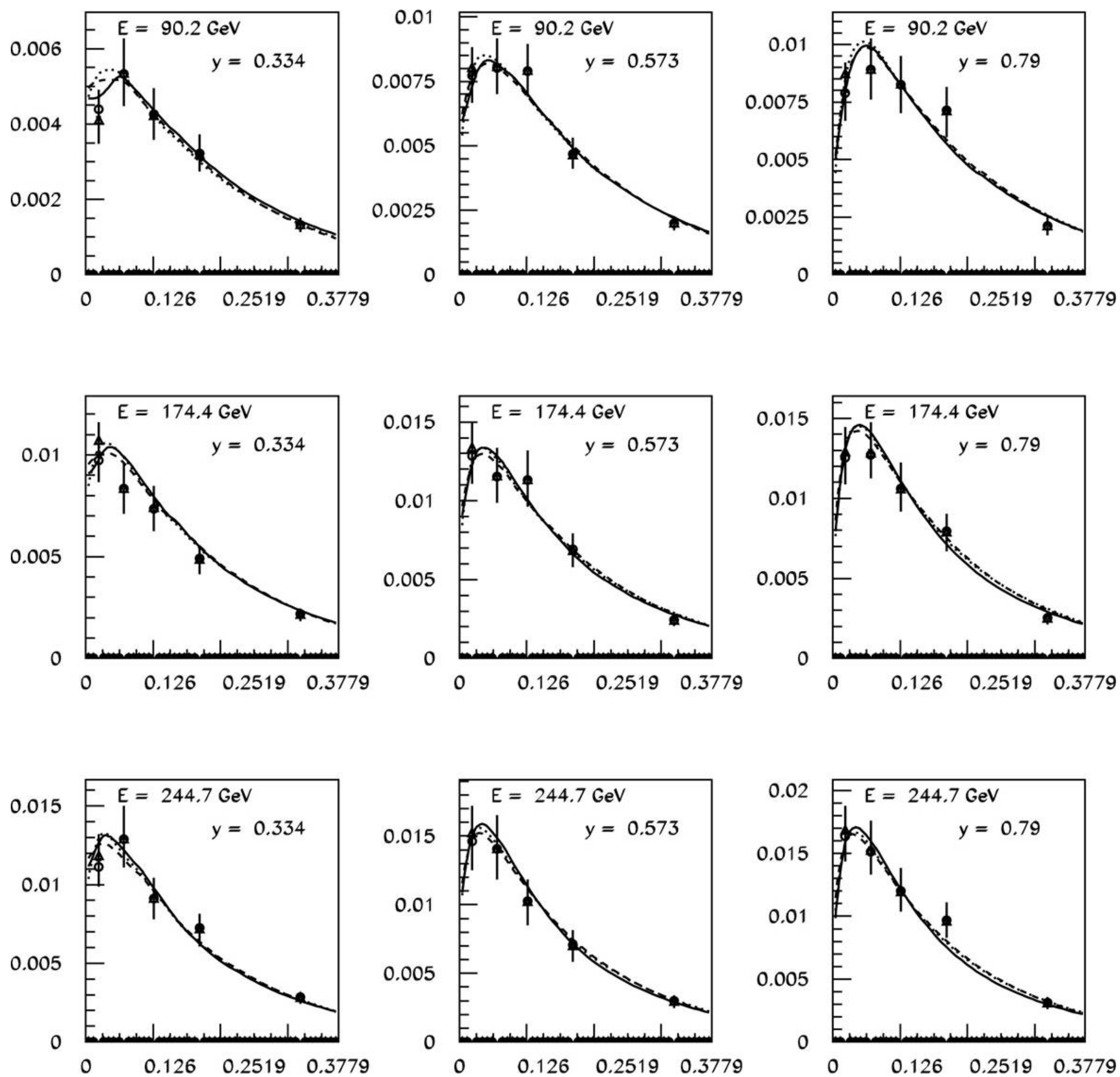
- $\mu^{\pm}$ from semi-leptonic charm decay

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

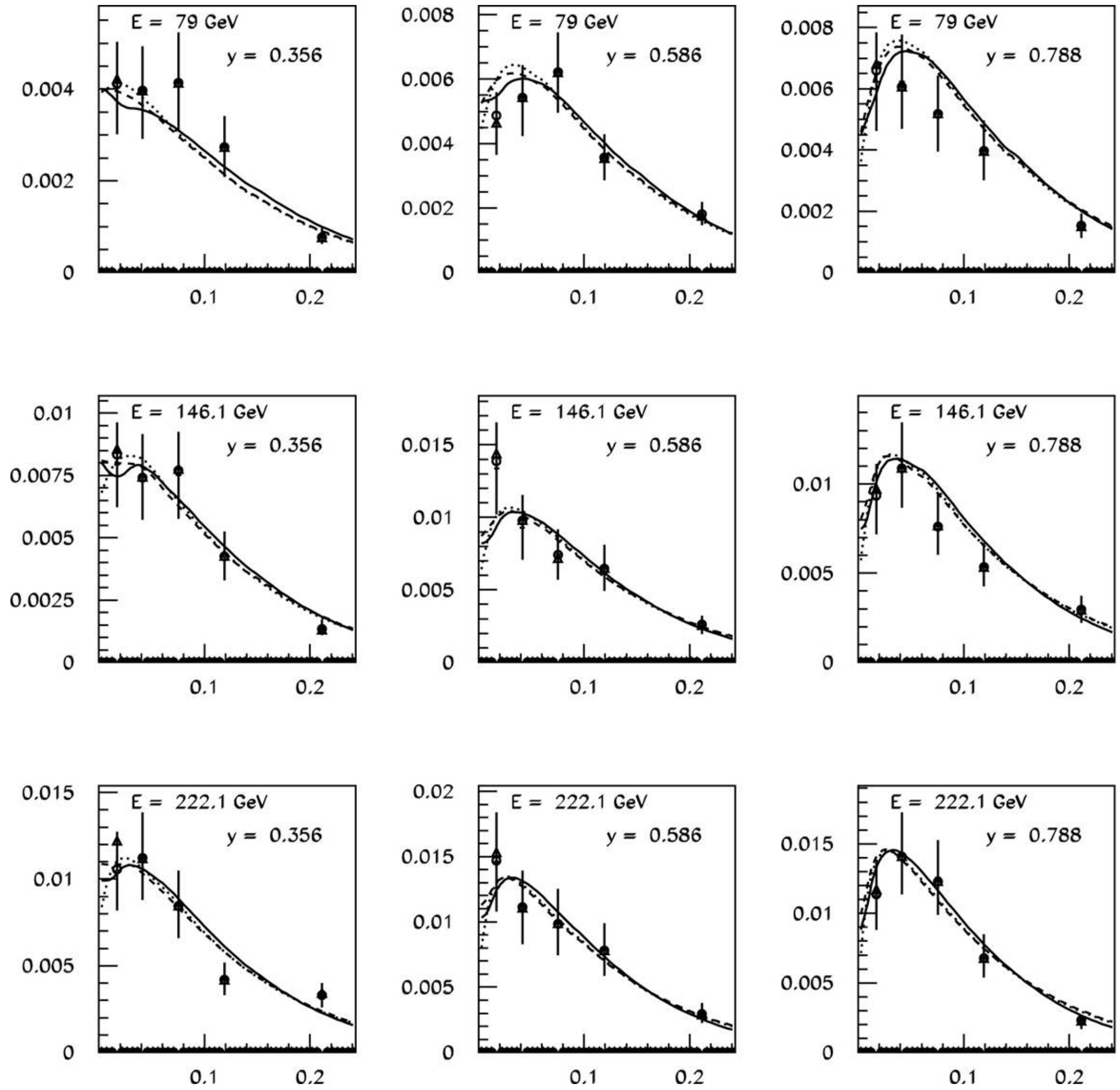
- Fits to NuTeV and CCFR ν and $\bar{\nu}$ dimuon data can measure the strange and antistrange seas separately
  - NuTeV separate ν and $\bar{\nu}$ beams important for reliable separation of s and $\bar{\text{s}}$



Neutrino Dimuon Cross-Sections

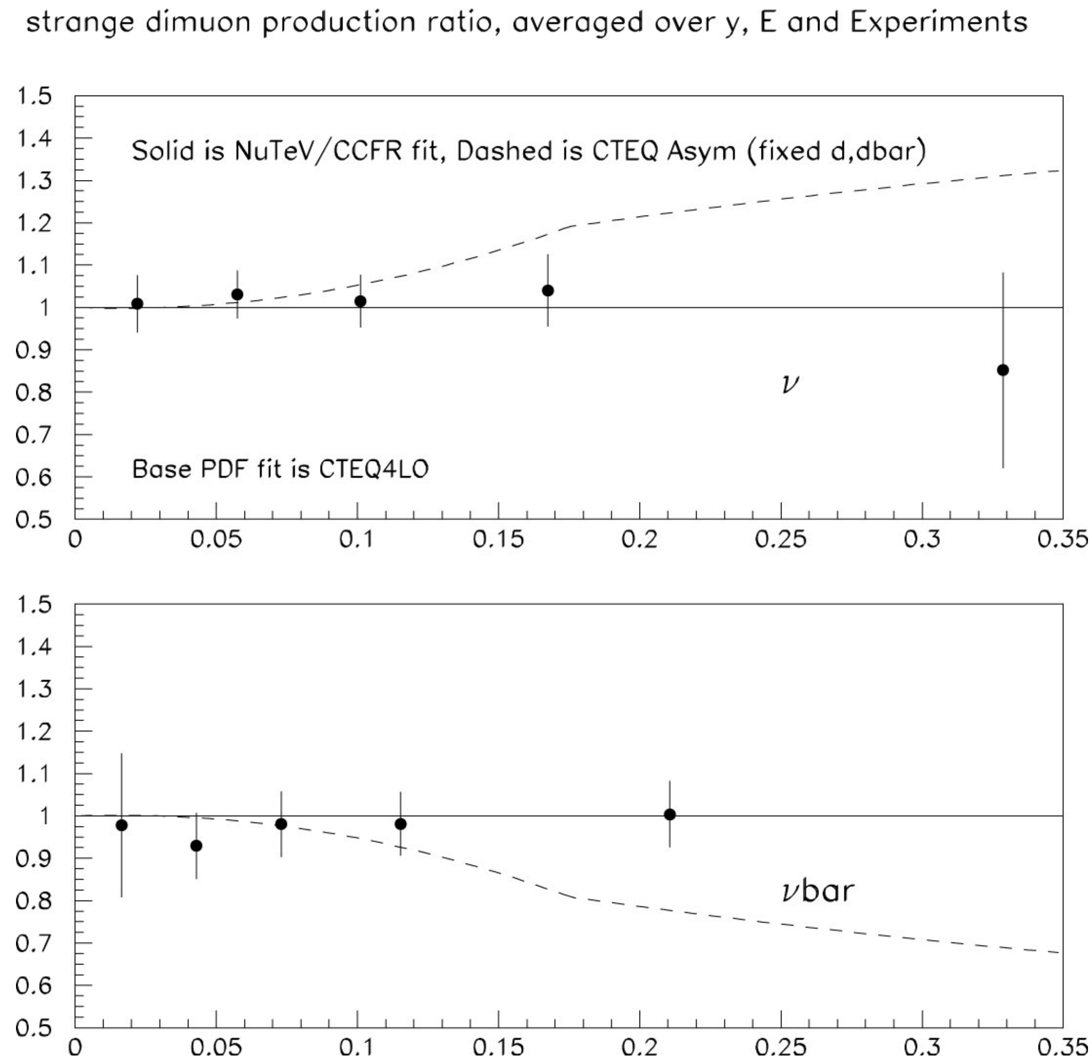


Antineutrino Dimuon Cross-Sections



Any asymmetry in Dimuons?

- Collapse the data in E, y as function of x
- Solid line assumes symmetric sea
- Independent of parameterization, no significant asymmetry



Preliminary NLO Analysis of NuTeV Dimuon Data

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

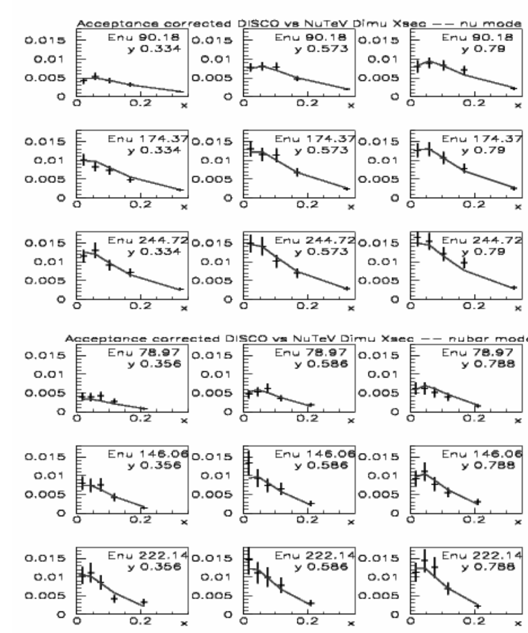
$$\overline{s}(x) = \overline{\kappa} \frac{\overline{u}(x) + \overline{d}(x)}{2}(1-x)^{\overline{\alpha}}$$

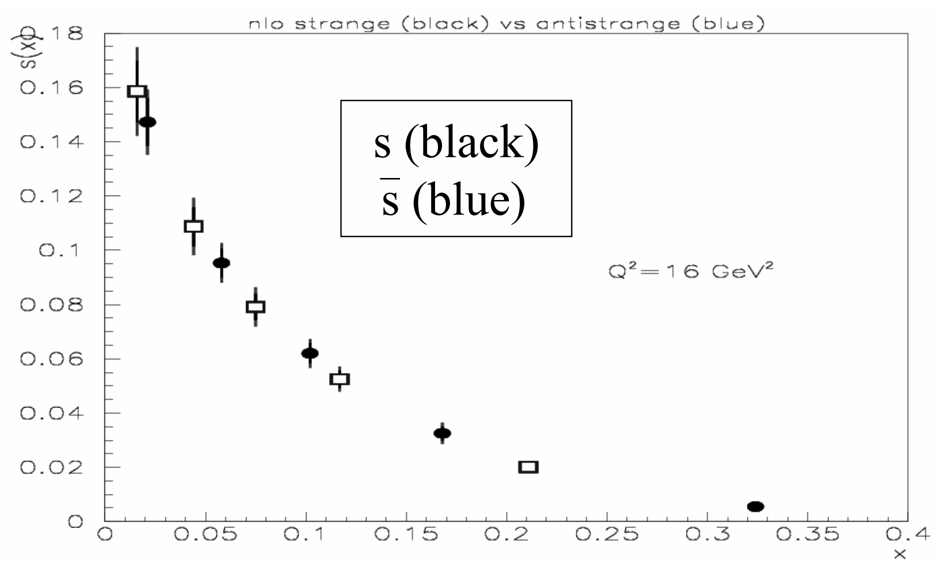
Dave Mason et al.(NuTeV Collab.), ICHEP02 Proceedings

Table 1
Results from the preliminary 6 parameter fit to the NuTeV dimuon cross section tables

parameter	result	± stat.	± syst.
m_c	1.46	± 0.24	± 0.07
κ	0.516	± 0.033	± 0.031
$\overline{\kappa}$	0.511	± 0.038	± 0.040
α	0.73	± 0.47	± 0.52
$\overline{\alpha}$	0.92	± 0.43	± 0.06
ϵ	0.203	± 0.13	± 0.04
χ^2/NDF	36.2/38		

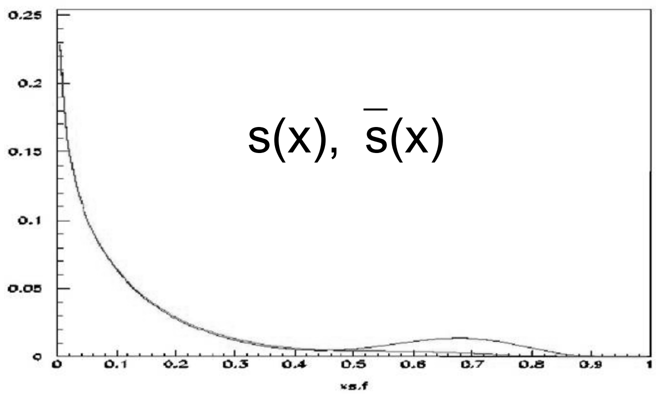
s = $\overline{\textbf{s}}$





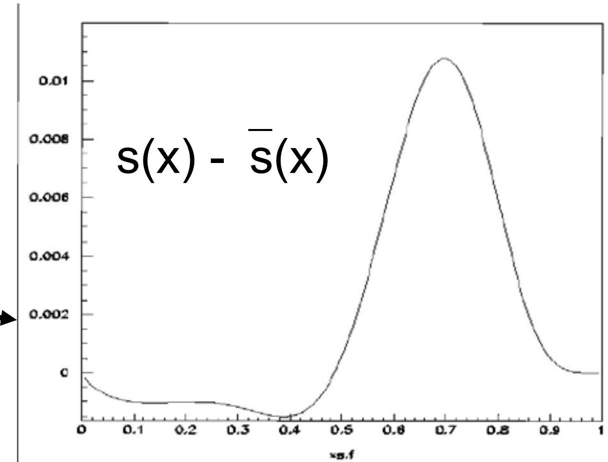
N.b., Parameterized strange sea shape is used as an approximation

“Inclusive” Measurements, A Prehistory



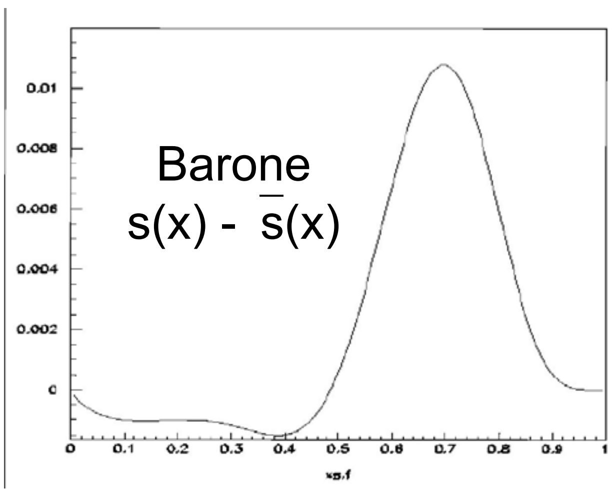
- Can try to do this by comparing inclusive reactions across processes

Barone et al,
hep-ph/9907912



- 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…

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



- The Barone $s - \bar{s}$ would increase by 5% the total ν dimuon cross-section, all at x>0.5
  – 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. *This should, in my opinion, serve as a cautionary tale when extracting s and $\bar{s}$ from global fits. Comments?*

Recent Results (pre-CTEQ)

- Dimuon fits to CCFR/NuTeV data
  - Goncharov et al [NuTeV] LO"+" QCD
    Zero asymmetry (CTEQ, GRV d-quark PDFs)
    or *Small asymmetry, -(9±5)%* $\int xs(x) < \int x\bar{s}(x)$
    (NuTeV internal LO+ d-quark PDFs on iron)
  - Mason et al [NuTeV] NLO [ICHEP02]
  - *Zero asymmetry* (CTEQ, GRV d-quark PDFs)
- Update of Inclusive data fits
  - Portheault et al [BPZ update] NLO
    Zero asymmetry [DIS03]

CTEQ "Lepton-Photon" Result

- Olness, Tung *et alia* [CTEQ] NLO/LO fit

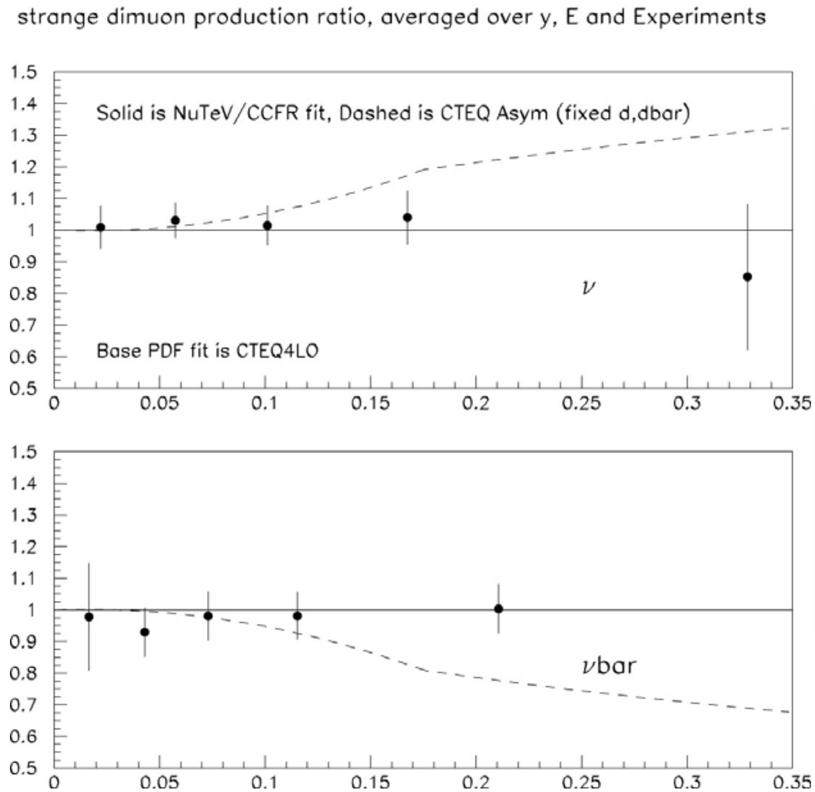
  Small asymmetry, ~+10%

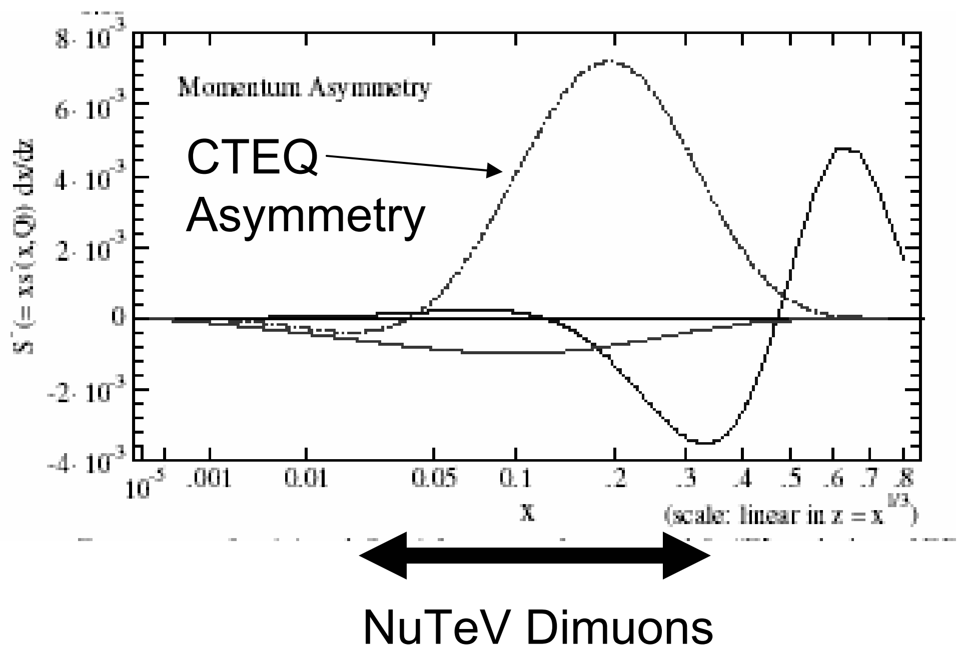
  (CTEQ NLO d-quark PDFs)

  $$\int xs(x) > \int x\bar{s}(x)$$

  – inconsistency with zero not claimed
  – uses inclusive data and dimuons
- Paper speculates about errors in NuTeV analysis
  – Strangeness not conserved at x below charm production threshold
  – Evolution not correct for assumed functional form
  – *They are good points; do they matter?*

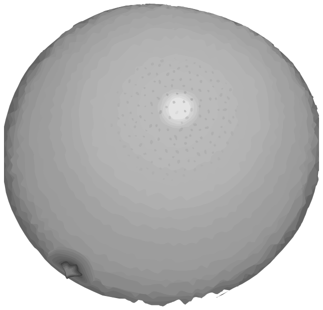
Dimuon Data and Asymmetry





- x region of CTEQ asymmetry is covered by NuTeV dimuon data
  - so it's all a question of interpretation…

What Needs to Be Resolved?



NuTeV

- Functional form does not evolve correctly
  – from Q_0 of 12.6 GeV^2 to range of 4-100 GeV^2
- Strangeness not conserved (low x)
- Not global fit
  – with outside PDFs, d-quark distributions not adjusted for changes in s(x)

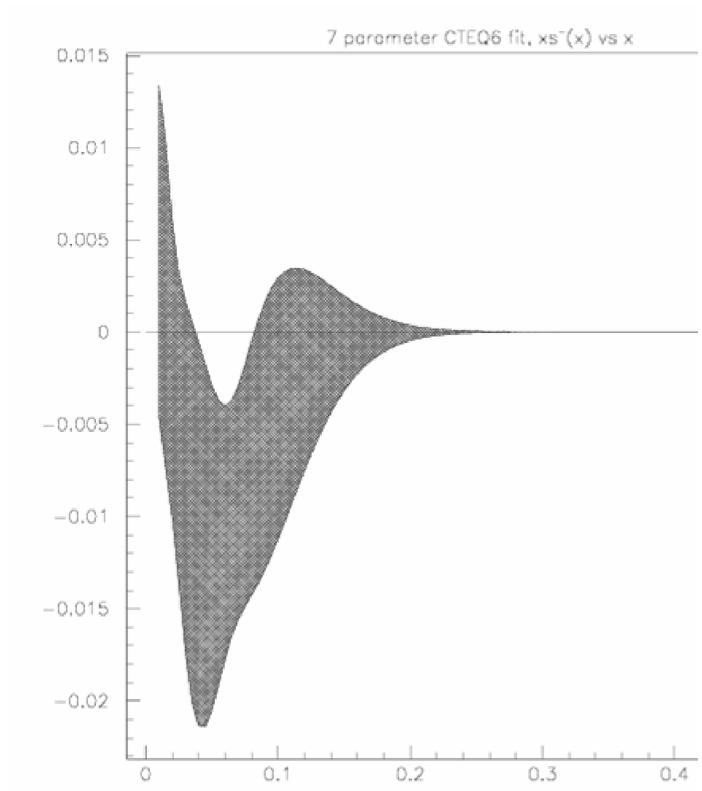
CTEQ

- Inclusive measurements fit to same PDFs with NLO cross-section that go into LO cross-section for dimuons
- Dimuon acceptance mildly inconsistent with data
- m_c used isn't best fit to dimuon data

- Nuclear corrections for proton PDFs handled consistently in two analyses?

Current NuTeV Status

- Have refit at NLO with total strangeness constraint of CTEQ
- See little change in net momentum difference
  - Still precise constraint. Still weakly negative
  - Panagiotis Spentzouris is here and can give details if desired
- Work is ongoing



Summary on Strange Sea

- A 30% excess of strange momentum over anti-strange would explain the NuTeV $\sin^2\theta_W$
- NuTeV analysis is consistent with zero, weakly negative using “all-iron” internal PDFs
  - uncertainty of 5% with assumed functional forms
- CTEQ measurement favors +10%
- We need to sort this out, but it won’t “fix” the NuTeV $\sin^2\theta_W$

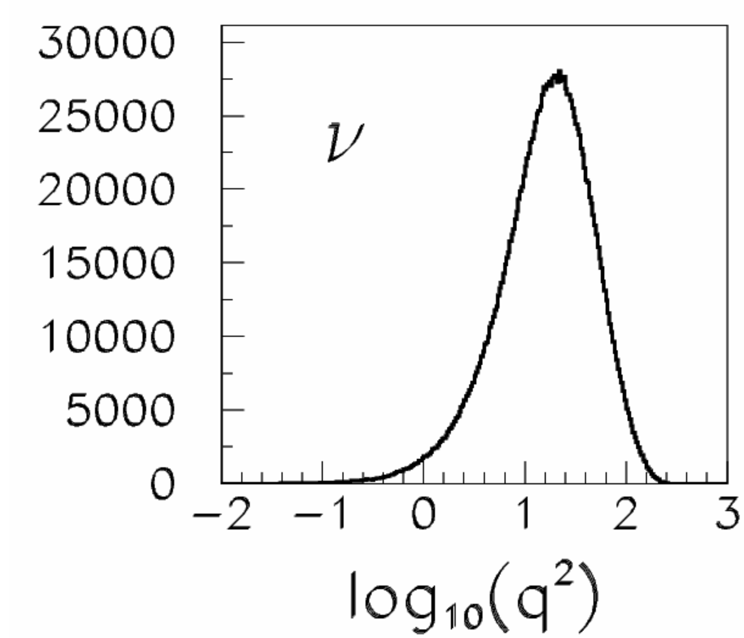
Nuclear Effects

1. Introduction
2. Constraints on Effects

Nuclear Effects

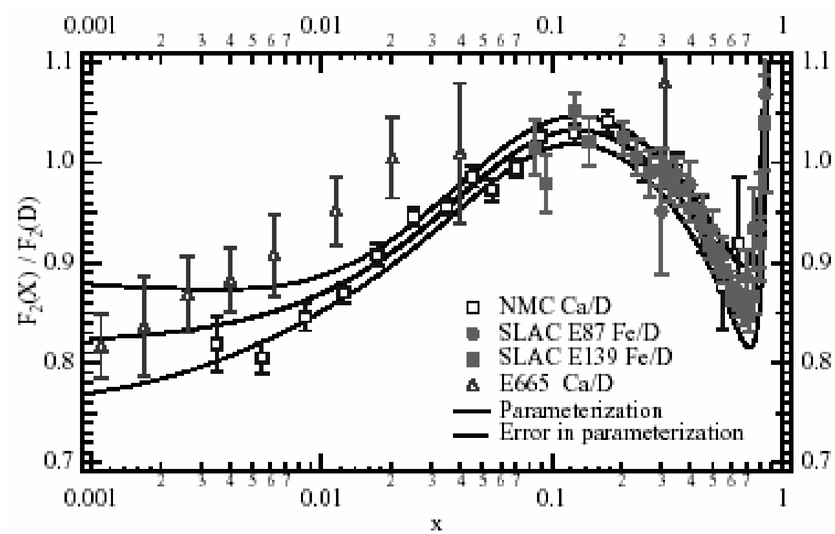
$$\langle Q^2 \rangle = \begin{matrix} 25\,\mathrm{GeV}^2 & \nu \\ 16\,\mathrm{GeV}^2 & \bar{\nu} \end{matrix}$$

- 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?



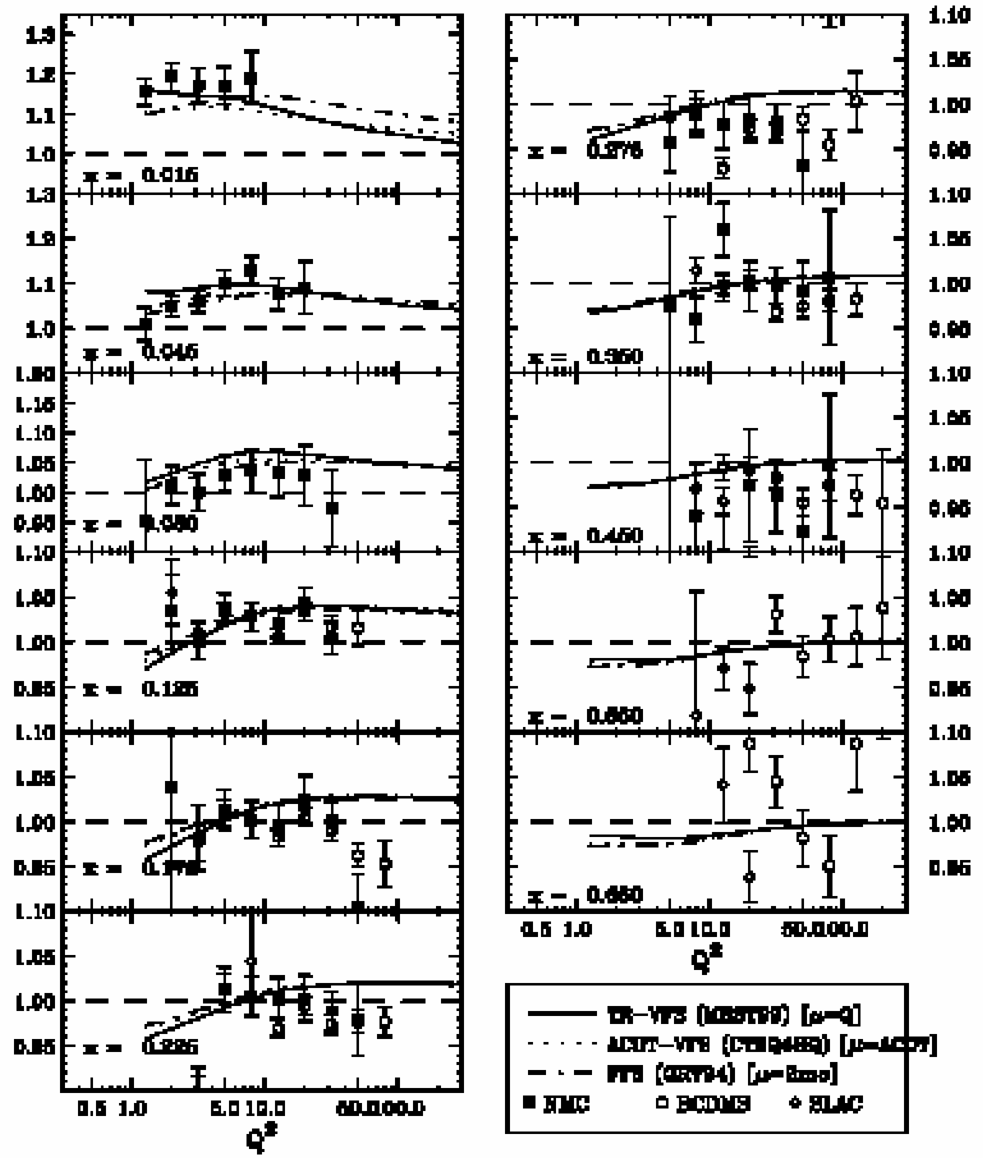
- NuTeV kinematics are high Q^2 valence distributions
  - $<E_\nu> \sim 100$ GeV
  - Sea cancels in R^-

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



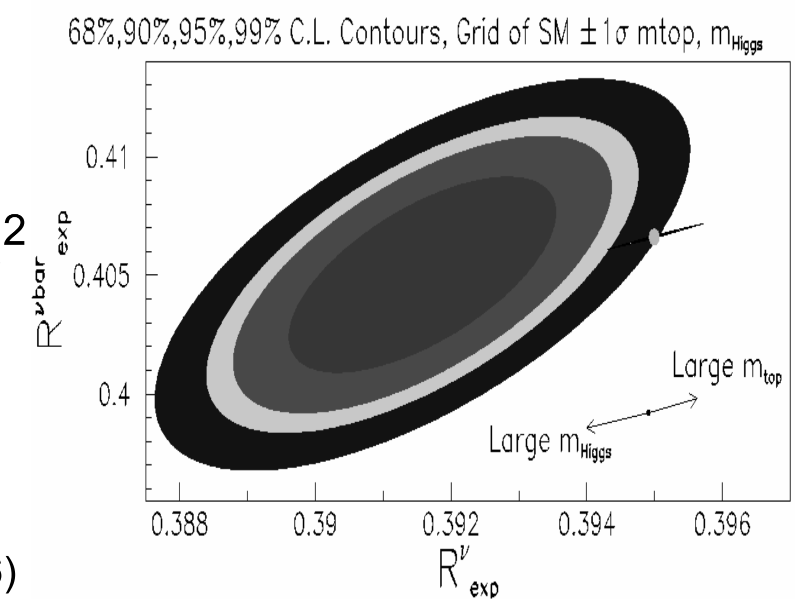
Nuclear Effects (cont'd)

- 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)

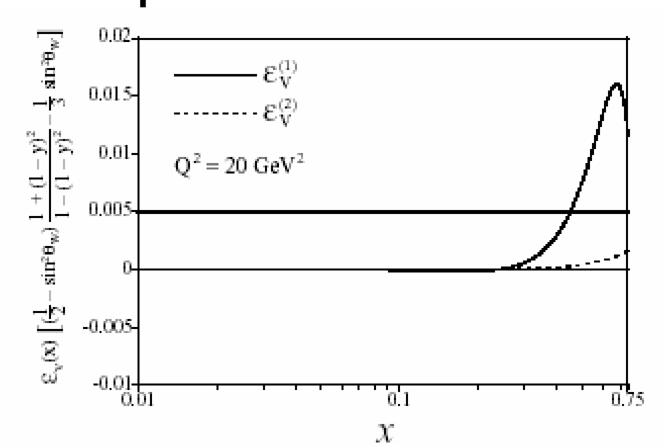
- Shadowing due to VMD would be different EM, NC and CC (Miller and Thomas, hep-ex/0204007)
  - Weak evidence for predicted $1/Q^2$ dependence in the NuTeV kinematic region x > 0.01 (NMC)
  - But lower x, Q^2 data suggests VMD (Melnitchouk and Thomas, hep-ex/0208016)
  - Low-x phenomena like VMD affect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

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

Conclusions

Sound Bites

- Experimental concerns were paramount to us…
  - but they seem to be generating little concern now
  - ν_e backgrounds are slightly underestimated if BNL-E865 is correct about K_{e3} BR. Increases discrepancy by 0.7 sigma

- Isospin violating PDFs
  - guidance from models and data is minimal
  - this could be the explanation if violation larger than one might guess a priori
  - need data! rah rah FNAL-P906!

Sound Bites (cont'd)

- Strange Sea
  - NuTeV dimuon data has the precision to address this
  - NuTeV analysis shows zero or weakly negative asymmetry
  - CTEQ finds positive asymmetry
  - Both CTEQ and NuTeV are working to resolve this

- Nuclear effects
  - data constrains possibilities at high x (EMC region)
  - shadowing region doesn't have the desired effect

Sound Bites (cont'd)

- Electroweak Radiative Corrections
  - No reason to think anything is wrong here, but…
  - Corrections are large. Bremsstrahlung correction relies on one calculations
  - New calculations are in the works
- NLO QCD corrections
  - Calculated to be small (except recent Dobrescu-Ellis which shows an increase in discrepancy of 1 sigma)
  - However, results do show a full NLO analysis would be a prudent step

Sound Bites (cont'd)

- Others
  - deficit of neutrino NC don't appear only at low Q^2 (ν)
  - neutron excess correction under control
    - originally underestimated *uncertainty*;
      its contribution is about 1/10 of total systematic

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. 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

Fish in a barrel,
perturbatively or not,
Those arrows sure sting