

A Totally Different Angle on Neutrinos:

The Weak Mixing Angle

$$\sin^2 \theta_w$$

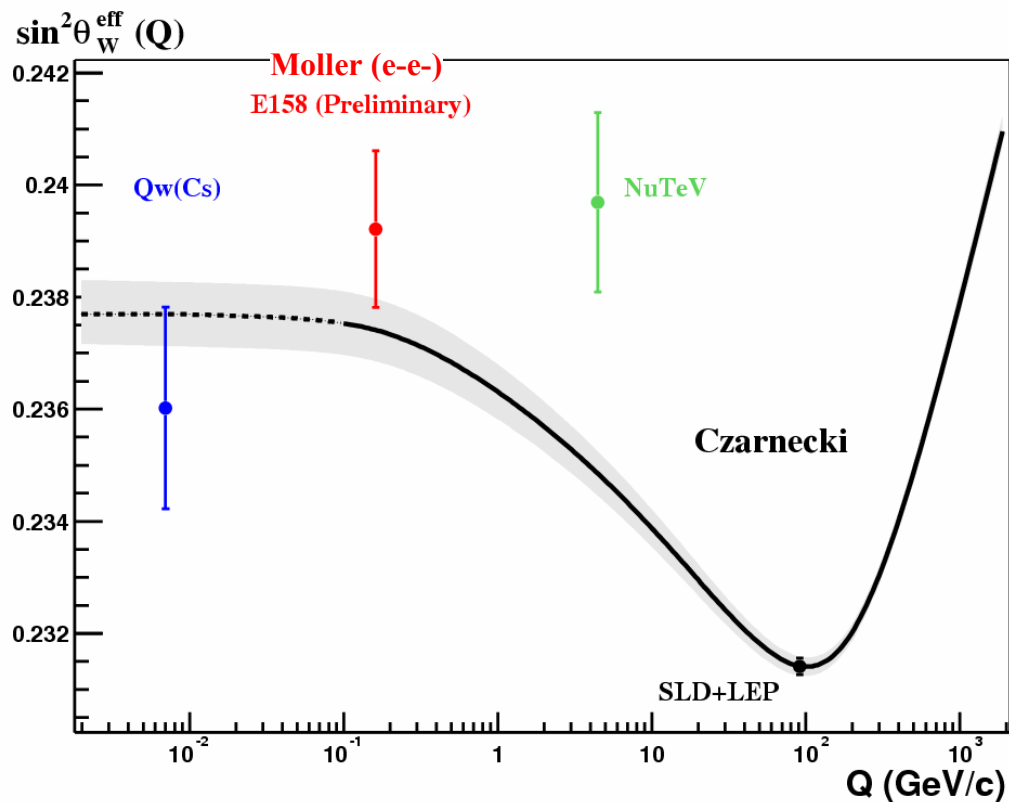
- Fundamental parameter describing the γ/Z mixing
- Precision measurements are sensitive to New Physics

“The NuTeV Anomaly”

Mike Shaevitz
Columbia University

The NuTeV Anomaly

Three standard deviation deviation from the Standard Model prediction at low Q^2 (off the Z pole)



- **Introduction to Electroweak Measurements**
- **NuTeV Experiment and Technique**
- **Explanation of the NuTeV Anomaly (Old Physics? and/or New Physics?)**
- **Future Prospects**

Standard Model Electroweak Theory

- Standard Model
 - Charged Current (CC) mediated by W^\pm with (V-A)
 - Neutral Current (NC) mediated by Z^0 with couplings below
 - One parameter to measure!
 - Weak / electromagnetic mixing parameter $\sin^2\theta_W$

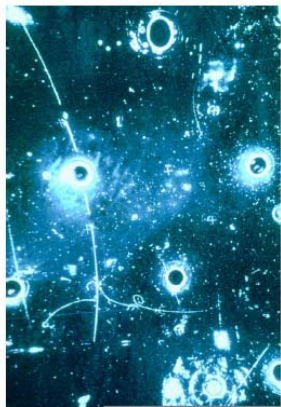
<i>Z Couplings</i>	g_L	g_R
ν_e, ν_μ, ν_τ	1/2	0
e, μ, τ	$-1/2 + \sin^2\theta_W$	$\sin^2\theta_W$
u, c, t	$1/2 - 2/3 \sin^2\theta_W$	$-2/3 \sin^2\theta_W$
d, s, b	$-1/2 + 1/3 \sin^2\theta_W$	$1/3 \sin^2\theta_W$

- Neutrinos are special in SM
 - Only have left-handed weak interactions
 - $\Rightarrow W^\pm$ and Z boson exchange

History of EW Measurements

Gargamelle

- **Discovery of the Weak Neutral Current (1973 CERN)**



Gargamelle HPWF CIT-F

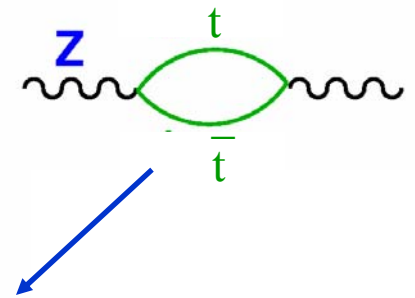
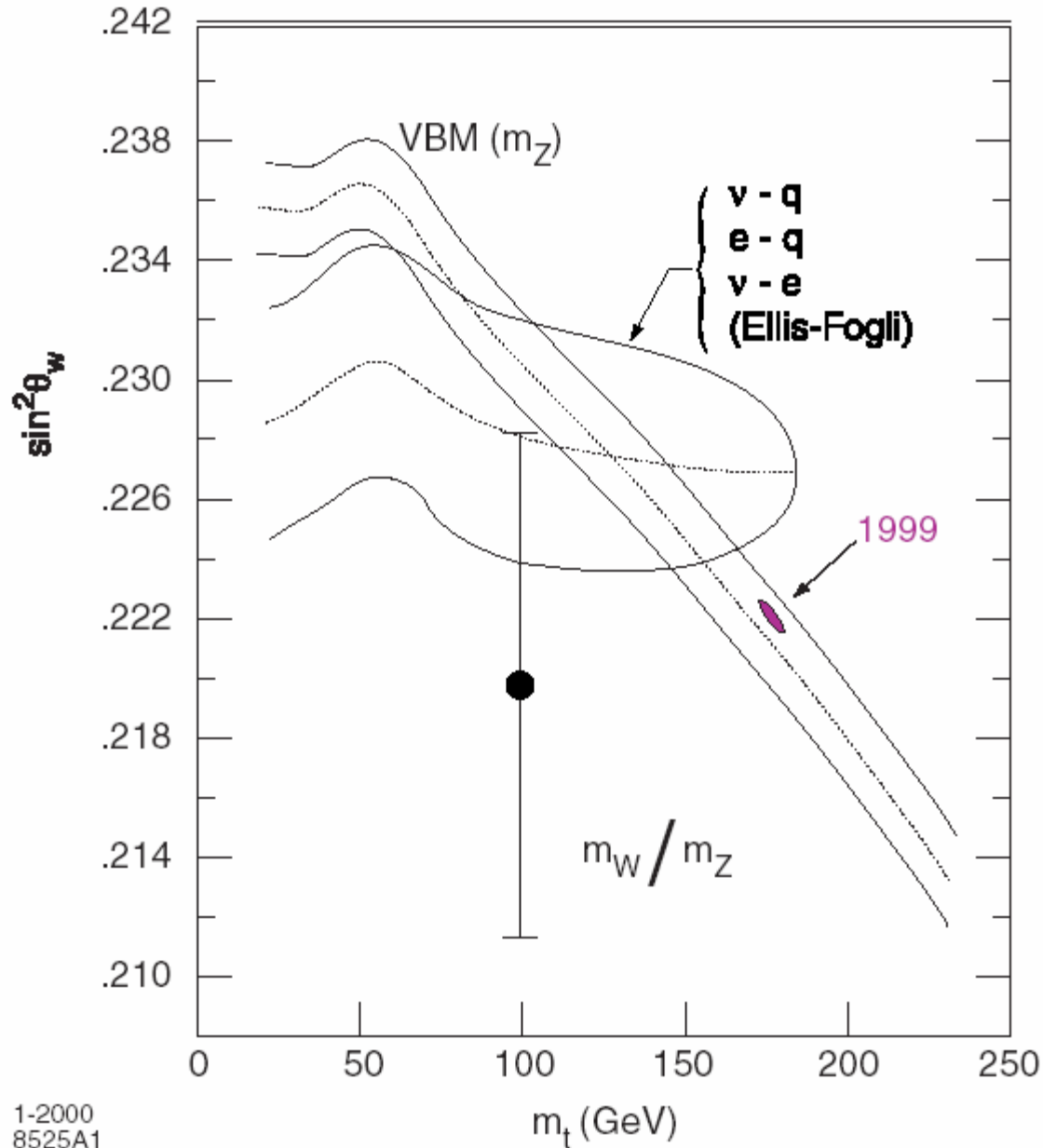
- **First Generation EW Experiments (late 1970's)**
 - Precision at the 10% level
 - Tested basic structure of SM $\Rightarrow M_W, M_Z$

CCFR, CDHS, CHARM, CHARM II UA1 , UA2 , Petra , Tristan , APV, SLAC eD

- **Second Generation EW Experiments (late 1980's)**
 - **Discovery of W,Z boson in 1982-83**
 - Precision at the 1-5% level
 - Radiative corrections become important
 - First limits on the M_{top}

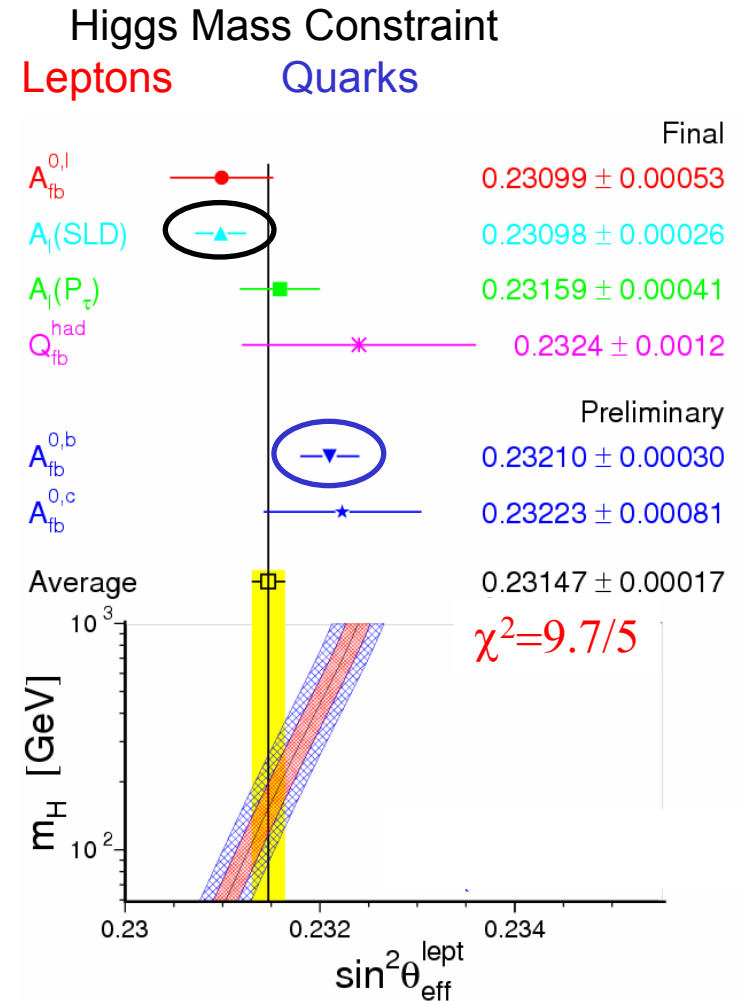
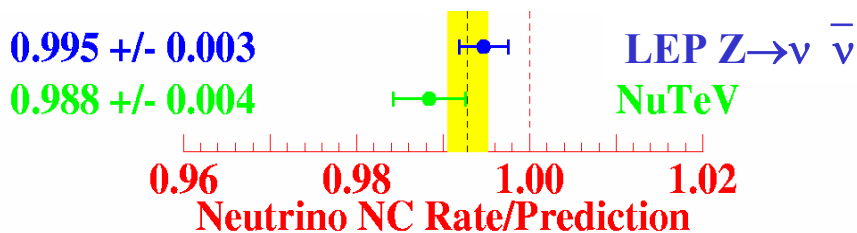
NuTeV, D0, CDF, LEP1 SLD LEP2, APV , SLAC-E158

- **Current Generation Experiments**
 - Precision below 1% level
 - Discovery of the top quark
 - **Constrain M_{Higgs}**
 \Rightarrow Predict light Higgs boson (and possibly SUSY)
 - **Use consistency to search for new physics !**



There are some other indications of cracks.

- Quark and Lepton measurements don't agree
 - All data suggest a light Higgs except A_{FB}^b
 - Global fit without NuTeV is good
 $\chi^2=15/13$ (31%)
 - But disagreement
 - A_{FB}^b = Forward-back asymmetry for b-quarks is off about 3σ in opposite direction from A_1 = Left-right asymmetry for electrons
- Number of neutrinos from invisible width off $2\sigma \Rightarrow 2.985 \pm 0.008$
 - May indicate reduced coupling of neutrinos to the Z-boson

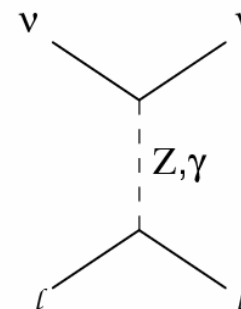


Neutrino Electroweak Measurements

- Standard model defined by Collider measurements (LEP/SLD/CDF/D0)
 - Not very precise on neutrino couplings
 - Only probe the theory at large (i.e. $Q^2=M_Z^2$)

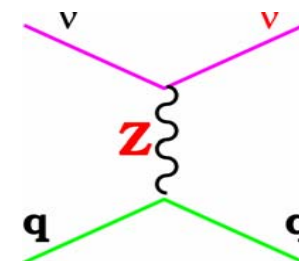
- Neutrino - lepton scattering

- Clean probe of neutrino weak coupling at low Q^2
- Very small cross section makes measurements difficult
- Examples:
 - Inverse beta decay $\nu_\mu e^- \rightarrow \mu^- \nu_e$
 - Neutrino electron elastic scattering $\nu e^- \rightarrow \nu e^-$



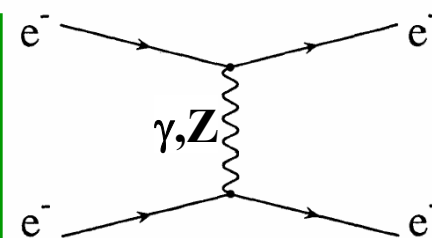
- Neutrino - quark (nucleon) scattering

- Pure weak process at low to moderate Q^2
- High statistics but complications due to quark distribution modeling
- Examples:
 - Elastic and quasi-elastic scattering: $\nu_\mu p \rightarrow \nu_\mu p$ and $\nu_\mu n \rightarrow \mu^- p$
 - Deep inelastic scattering (DIS) NC & CC : $\nu_\mu N \rightarrow \nu_\mu X$ and $\nu_\mu N \rightarrow \mu^- X$



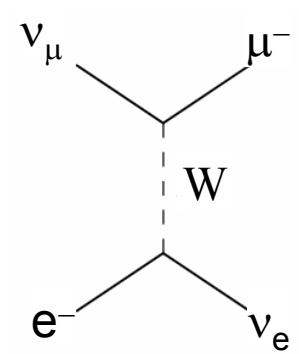
Also, charged lepton parity violating measurements at Low Q^2 :

- Sensitive to charged lepton couplings at low Q^2
- Use polarization to pick out parity violating weak part (Q_{Weak})
- Examples: Moller (e^-e^-), ep elastic, atomic parity violation

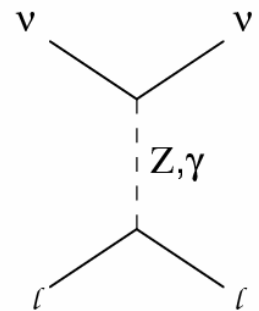


Neutrino – Lepton Scattering

- Inverse muon decay (NuTeV, CHARM II) $\nu_\mu e^- \rightarrow \mu^- \nu_e$
 - CHARM II: Check for anomalous couplings
 $\sigma = (16.5 \pm 0.9) \times 10^{-42} \text{ cm}^2/\text{GeV}$ (SM: 17.2×10^{-42})
 \Rightarrow Constrains scalar coupling: $|g_{LL}^S| < 0.475$ at 90% CL
 - NuTeV: Search for lepton number violation
 $\sigma(\nu_\mu e^- \rightarrow \mu^- \nu_e) / \sigma(\nu_\mu e^- \rightarrow \mu^- \nu_e) < \sim 1\%$ at 90% CL

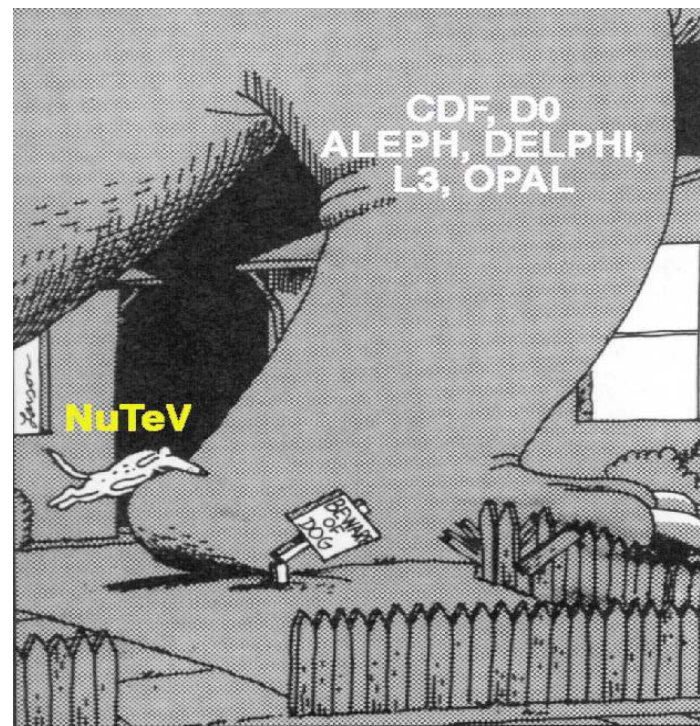


- Neutrino – electron elastic scattering $\nu_\mu e^- \rightarrow \nu_\mu e^-$
 - CHARM II: Agreement with Standard Model but large errors
 - $\sin^2\theta_W = 0.2324 \pm 0.0083$
 - $g_V = -0.035 \pm 0.017$ (SM: -0.0398)
 - $g_A = -0.503 \pm 0.017$ (SM: -0.5065)
 - Neutrino magnetic moment limits (γ exchange)
 - Electron neutrino: Reactor exps, $\mu_\nu < 1 \times 10^{-10} \mu_B$ at 90% CL
 - Muon neutrino: LSND exp, $\mu_\nu < 6.8 \times 10^{-10} \mu_B$ at 90% CL
 - Standard model prediction: $\mu_\nu = 3.2 \times 10^{-19} \mu_B \times m_\nu/eV$

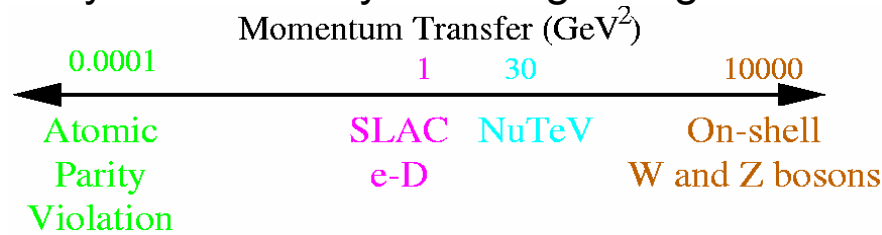


NuTeV Adds Another Precision Arena using DIS ν

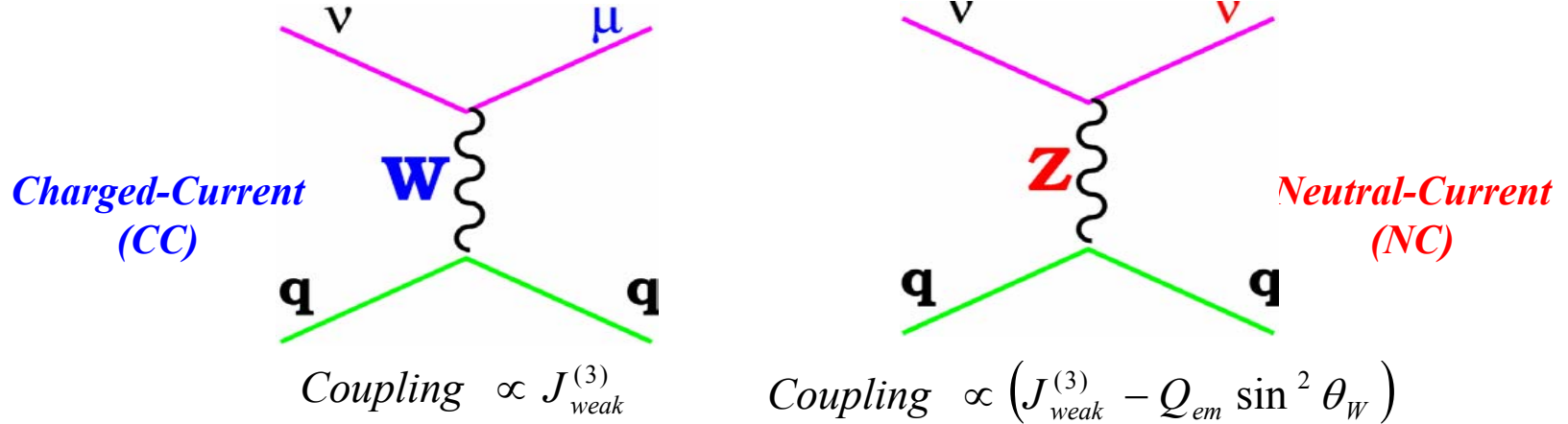
- **Precision** comparable to collider measurements of M_W
- Sensitive to different **new physics**
 - Different radiative corrections
- Measurement **off the Z pole**
 - Exchange is not guaranteed to be a Z
- Measures **neutrino neutral current** coupling
 - LEP 1 invisible line width is only other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



Toby vs. Godzilla

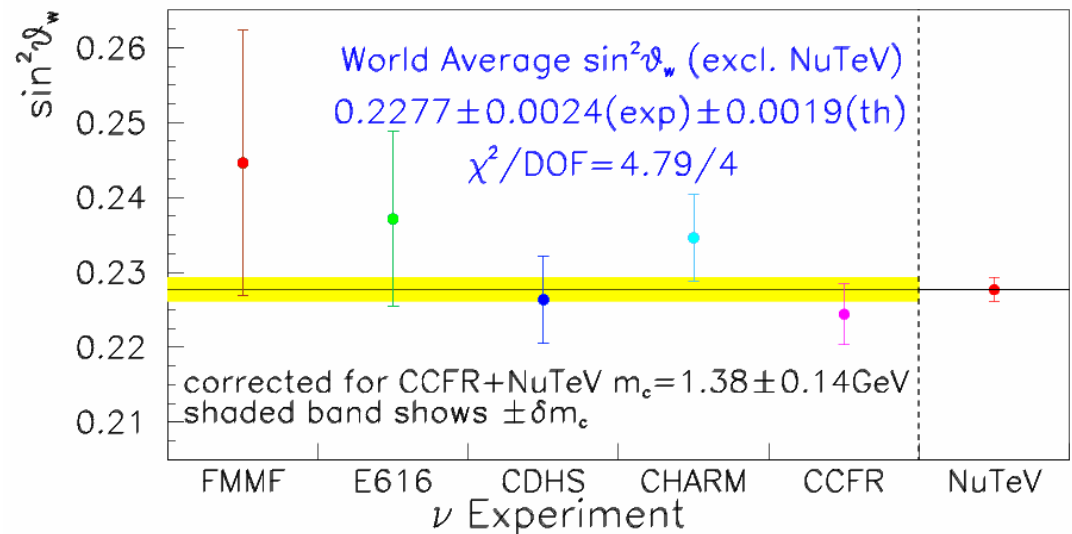


EW Measurements using Neutrino DIS



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

- Before NuTeV, νN exp's had hit a brick wall in precision
 \Rightarrow Due to systematic uncertainties (mainly CC charm quark production)



NuTeV's Technique to Reduce Systematics

Cross section differences remove sea quark contributions
 \Rightarrow Reduce uncertainties from charm production and sea

Paschos - Wolfenstein Relation

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

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

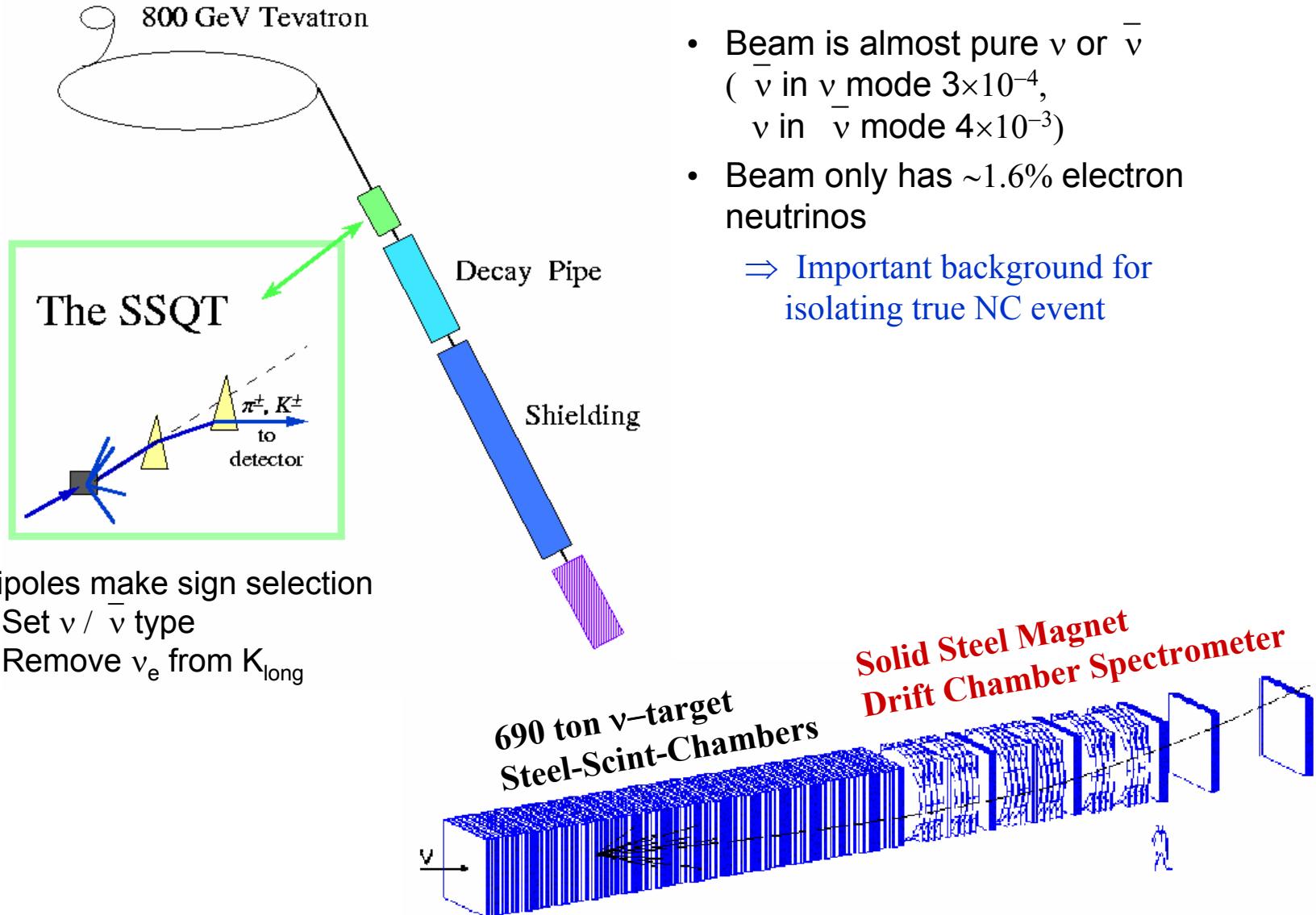
$$\sigma(\nu_{\mu} d_{sea}) - \sigma(\bar{\nu}_{\mu} \bar{d}_{sea}) = 0 \Rightarrow \text{Only } d_{valence} \text{ contribute}$$

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

$$\sigma(\nu_{\mu} s_{sea}) - \sigma(\bar{\nu}_{\mu} \bar{s}_{sea}) = 0 \Rightarrow \text{No } strange\text{-}sea \text{ contribution}$$

- R^- manifestly insensitive to sea quarks
 - Charm and strange sea error negligible (If $x s(x) = x \bar{s}(x)$)
 - Charm production small since only enters from d_V quarks only which is Cabbibo suppressed and at high-x
- But R^- requires separate ν and $\bar{\nu}$ beams so needed to develop a high-intensity separated beam
 - \Rightarrow NuTeV SSQT (Sign-selected Quad Train)

NuTeV Experimental Setup



- Beam is almost pure ν or $\bar{\nu}$
($\bar{\nu}$ in ν mode 3×10^{-4} ,
 ν in $\bar{\nu}$ mode 4×10^{-3})
- Beam only has $\sim 1.6\%$ electron neutrinos

\Rightarrow Important background for isolating true NC event

NuTeV Collaboration

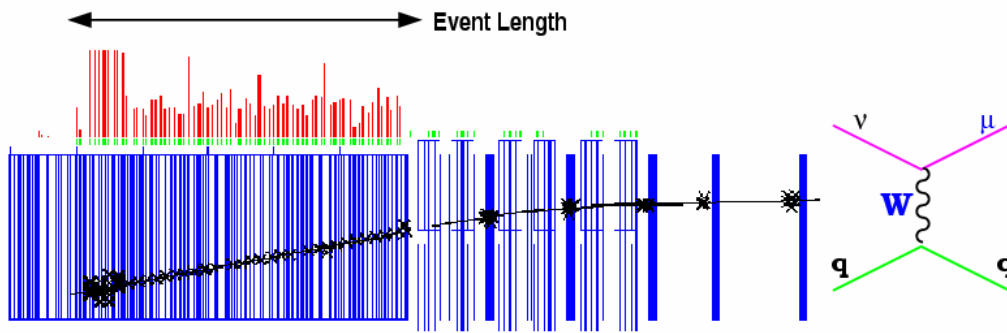


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 (Co-spokepersons: R.Bernstein, M.Shaevitz)

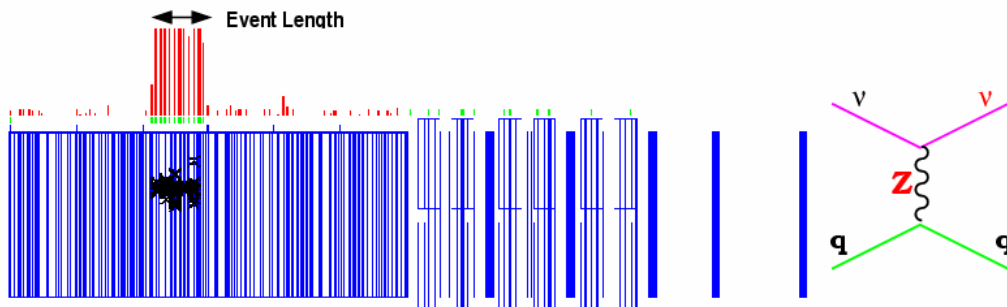
Neutral Current / Charged Current Event Separation

- Separate NC and CC events statistically based on the “event length” defined in terms of # counters traversed



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

(measure this ratio in both ν and $\bar{\nu}$ modes)



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

Use Detailed Monte Carlo to relate R_{exp} to R^ν and $\sin^2 \theta_W$

- Quark Distribution Model
 - Needed for including the NC and CC couplings
 - Needed to model the event cross sections (i.e. sets the amount short CC events)
- Neutrino fluxes ($\nu_\mu, \nu_e, \bar{\nu}_\mu, \bar{\nu}_e$)
 - Combined with cross sections to predict event numbers
 - Allows correction for electron neutrino CC events always look short NC events
- Shower Length Modeling
 - Needed to correct for NC short events that look long like CC events
- Detector response vs energy, position, and time
 - Test beam running throughout experiment crucial

Top Five Largest Corrections

Source	δR_{exp}^ν	$\delta R_{exp}^{\bar{\nu}}$	Comments
Short CC Background	-0.068	-0.026	Check medium length events
Electron Neutrinos	-0.021	-0.024	Direct check from data
EM Radiative Correction	+0.0074	+0.0109	Well understood
Heavy m_c	-0.0052	-0.0117	R^- technique
Cosmic-ray Background	-0.0036	-0.019	Direct from data
Compare to statistical error	± 0.0013	± 0.0027	

*Analysis uses **data** directly to set and check the Monte Carlo simulation*

Result

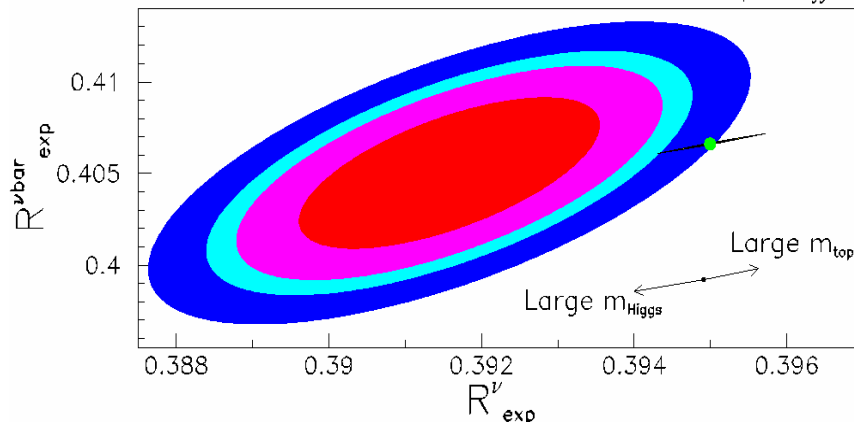
$$\sin^2 \theta_W^{(on-shell)} = 0.2277 \pm 0.0013 (stat.) \pm 0.0009 (syst.)$$

$$= 0.2277 \pm 0.0016$$

Phys.Rev.Lett. 88,91802 (2002)

- NuTeV result:
 - Error is statistics dominated
 - Is $\times 2.3$ more precise than previous νN experiments where $\sin^2 \theta_W = 0.2277 \pm 0.0036$ and syst. dominated
- Standard model fit (LEP-EWWG): **0.2227 ± 0.00037**
A 3σ discrepancy

68%,90%,95%,99% C.L. Contours, Grid of SM $\pm 1\sigma$ m_{top} , m_{Higgs}



$$R^{\nu} = \frac{\sigma_{NC}^{\nu}}{\sigma_{CC}^{\nu}} \quad \text{and} \quad R^{\bar{\nu}} = \frac{\sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^{\bar{\nu}}}$$

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

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

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

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

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

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

SOURCE OF UNCERTAINTY	$\delta \sin^2 \theta_W$	$\delta R_{\text{exp}}^\nu$	$\delta R_{\text{exp}}^{\bar{\nu}}$
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
$\nu_e, \bar{\nu}_e$ 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
$\sigma^{\bar{\nu}}/\sigma^\nu$	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

What we worried about as experimentalists

What has been criticized by others

- **Criticisms not about the measurement details but about the theory uncertainties:**
 - Quark model uncertainties
 - Because result doesn't fit into expected types of new physics

Result from Fit to R^ν and $R^{\bar{\nu}}$

- Separating ν and $\bar{\nu}$ measurements :

$$R_{\text{exp}}^\nu = 0.3916 \pm 0.0013 \quad R_{\text{exp}}^{\bar{\nu}} = 0.4050 \pm 0.0027$$

$$(SM : 0.3950) \quad \Leftarrow 3\sigma \text{ difference} \quad (SM : 0.4066) \quad \Leftarrow \text{Good agreement}$$

Discrepancy is neutrinos not antineutrinos

- In terms of left and right-handed couplings:

$$g_L^2 = u_L^2 + d_L^2 = 0.30005 \pm 0.00137 \quad g_R^2 = u_R^2 + d_R^2 = 0.0308 \pm 0.0011$$

$$(SM : 0.3042) \quad \Leftarrow 2.6\sigma \text{ difference} \quad (SM : 0.0301) \quad \Leftarrow \text{agreement}$$

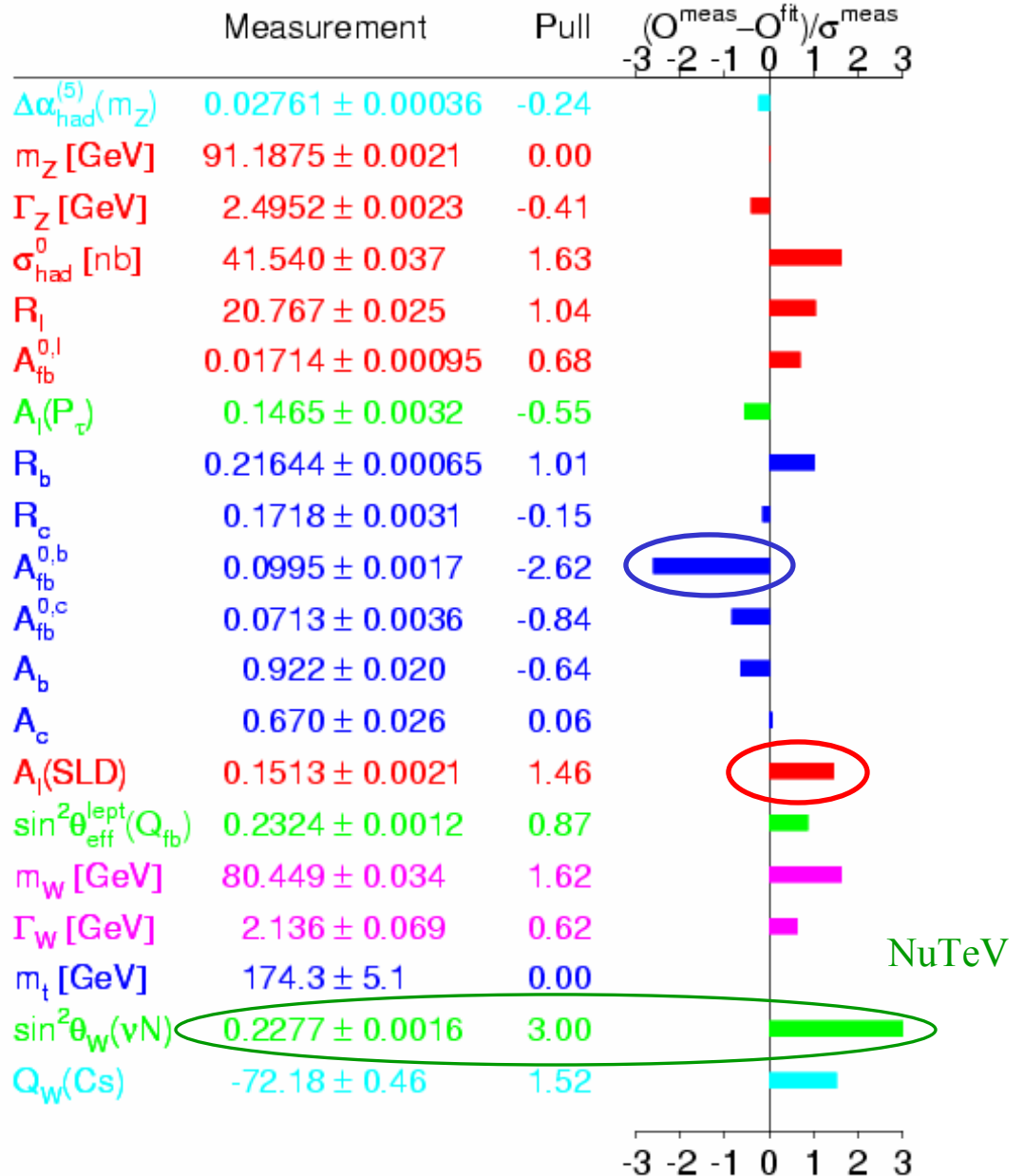
Discrepancy is left-handed coupling to u and d quarks

- Or in terms of the NC to CC $\nu/\bar{\nu}$ coupling strength (1 - parameter fit)
 $\rightarrow \rho_0^2 = 0.9884 \pm 0.0026(\text{stat.}) \pm 0.0032(\text{syst.}) \quad (SM : \rho = 1.0)$

ν NC coupling is too small $\Leftarrow 2.8\sigma$ difference

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

- With NuTeV:
 - $\chi^2/\text{dof} = 25/15$,
probability of 4%
- Without NuTeV:
 - $\chi^2/\text{dof} = 15/13$,
probability of 31%
- Upper m_{Higgs} limit only
weakens slightly



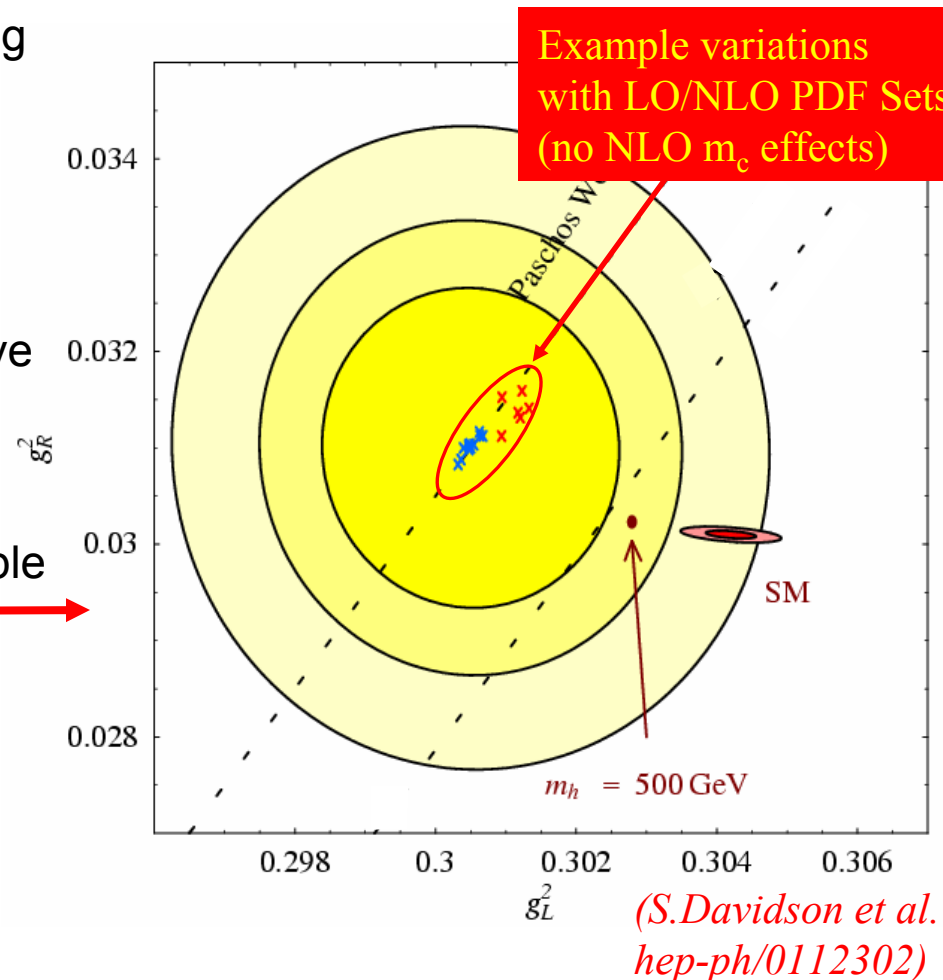
Possible Interpretations

- Changes in Standard Model Fits
 - Changes in quark distributions sets
 - Cross section models: Leading Order (LO) vs Next to Leading Order (NLO)
 - Changes in standard model radiative corrections
- “Old Physics” Interpretations: QCD
 - Violations of “isospin” symmetry
 - Strange vs anti-strange quark asymmetry
 - Shadowing and other nuclear effects
- Physics Beyond the Standard Model
 - Neutrino Properties
 - Special couplings to new particles
 - Mixing and oscillation Effects
 - “New Particle” Interpretations
 - New Z' or lepto-quark exchanges
 - New particle loop corrections
 - Mixtures of new physics



Can Quark Distributions or LO vs NLO Analysis Be a Problem?

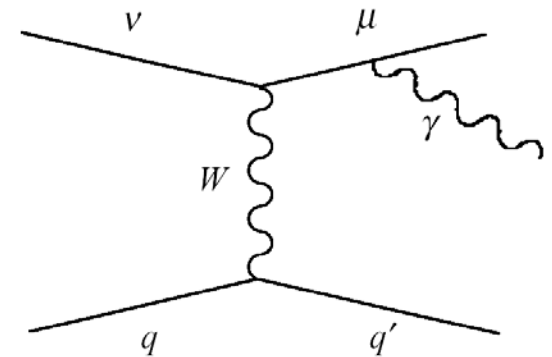
- NuTeV analysis uses an enhanced Leading Order (LO) formalism that implements:
 - Constraints from both CC 1μ and 2μ data
 - Uses external measurements for R_{Long} , d/u , charm sea, higher twist
- NLO estimates from idealized analyses give small changes
 $\delta\sin^2\theta_W = -0.0004$ to $+0.0015$
- Quark distribution variations are not sizeable for the idealized analyses →
- To test possible NLO effects, we are developing a full NLO ν event generator
 - Full NLO evolution with gluons
 - Include heavy charm at NLO
 - Many new NLO calculations are becoming available ↘



K. McFarland and S. Moch, hep-ph/0306052
B. Dobrescu and K. Ellis, Phys. Rev. D69, 114014 (2004)
S. Kretzer et al., Phys. Rev. Lett. 93, 041802 (2004)

Are the Standard Model Radiative Corrections Uncertain?

- EM radiative corrections are large
 - Bremsstrahlung from the final state lepton in CC events is the largest correction
 - Straightforward to calculate
 - Currently using the only available code from Bardin and Dokuchaeva (JINR-E2-86-260,1986)
 - Adding correction shifts $\delta\sin^2\theta_W = -0.0030$
- New calculations becoming available
 - Diener-Dittmaier-Hollik (hep-ph/0310364, hep-ph/0311122)
 - Improved treatment of initial state mass singularities
 - Point out additional uncertainties: input parameter, scheme dependence
 - Scaling their estimates $\Rightarrow \delta\sin^2\theta_W = -0.0036$ (would reduce value by $1/3 \sigma$)
- We are implementing Diener et al. code (and others) into NuTeV analysis
 - Only way to determine the quantitative effects of different corrections.



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 - ✗ Changes in quark distributions sets
 - ✗ Cross section models: LO vs NLO
 - ✗ Changes in standard model radiative corrections
- “Old Physics” Interpretations: QCD
 - Violations of “isospin” symmetry
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Symmetry Violating QCD Effects

$$R^- = \frac{\sigma_{NC}^{\nu} - \sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^{\nu} - \sigma_{CC}^{\bar{\nu}}} = \frac{1}{2} + \sin^2 \theta_W$$

- Paschos-Wolfenstein Relation Assumptions:
 - Assumes isospin symmetry, $u_p(x) \neq d_n(x)$
 - Assumes sea momentum symmetry, $s = \bar{s}$ and $c = \bar{c}$
 - Assumes nuclear effects common in W/Z exchange

⇒ Violations of these symmetries are possible but constrained

Bottom Line: R^- technique is very robust

Isospin Symmetry Violation

- Isospin symmetry violation: $u^p \neq d^n$ and $d^p \neq u^n$
 \Rightarrow Could come about from $m_u \neq m_d$ or wave function differences
- What is needed to explain the NuTeV data?
 - Need d_v quarks in proton to carry $\sim 5\%$ more momentum than u_v neutron
 \Rightarrow Model calculations are not very predictive
 \Rightarrow Typically predict from 0 to 1.5%

- Full “Bag Model” calculations:

- *G.P. Zeller et al., Phys. Rev. D65, 111103, 2002*
- *J.T. Londergan, A.W. Thomas, hep-ph/0407247*
 $\Rightarrow \Delta \sin^2 \theta_W = 0.0$ to -0.0017 (0 to -1σ)

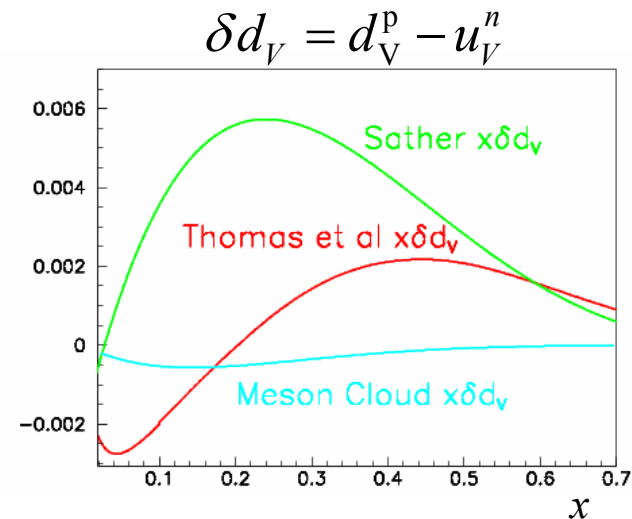
- “Meson Cloud Model”:

- (*Cao et al., PhysRev C62 015203*)
 $\Rightarrow \Delta \sin^2 \theta_W = +0.0002$ ($\sim 0 \sigma$)

- Global quark distribution fits also are not very predictive

- Best fit from MRST would lower NuTeV value by 1σ
(Martin et al., Eur. Phys. J. C35, 325, 2004, hep-ph/0308087)

\Rightarrow *Conclusion: Need more data to constrain these type of effects*



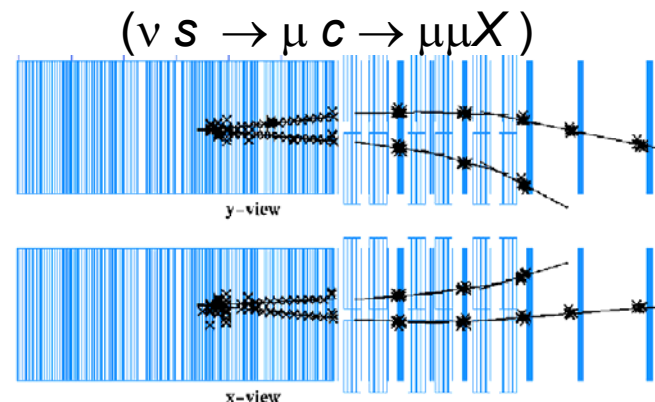
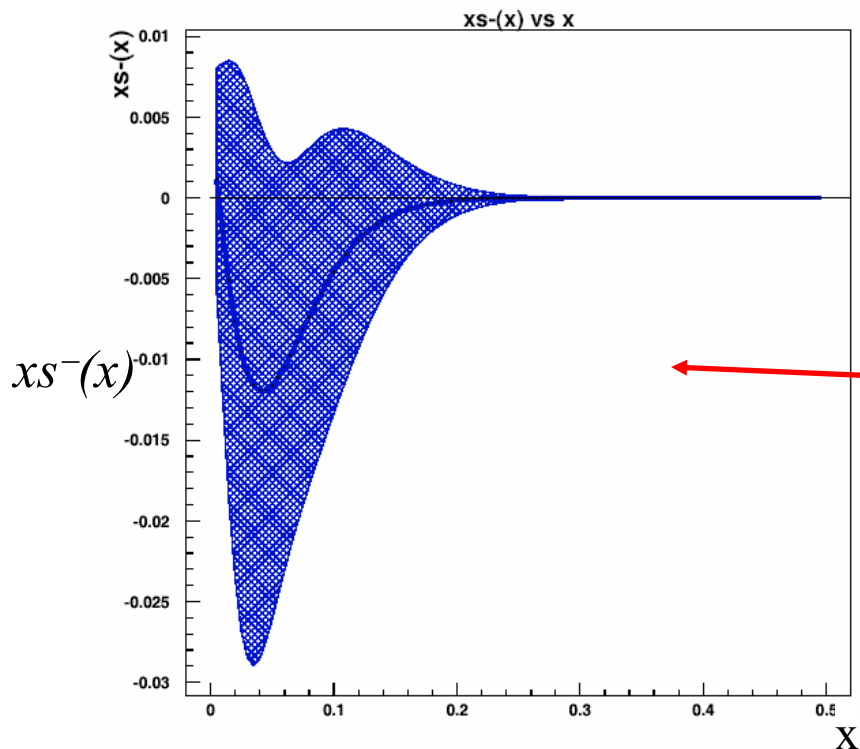
$s(x)$ vs $\bar{s}(x)$ Asymmetry

- Non-perturbative QCD effects can generate a strange vs. anti-strange momentum asymmetry

- Only available data is NuTeV and CCFR

- ν and $\bar{\nu}$ dimuon data

- Fits to this data can measure the s vs. \bar{s} asymmetry.



NLO fits to ν and $\bar{\nu}$ dimuon data:

$$\text{Measures } \Rightarrow s^- = \frac{s - \bar{s}}{2}$$


Give

$$\int xs^-(x) dx = -0.0009 \pm 0.0014$$

To explain NuTeV $\sin^2 \theta_W$ would require +0.0060

Work of D.Mason et al. (NuTeV grad student)
(In collaboration with Amundson, Kretzer, Olness, Tung)

Nuclear Effects

- Need to worry about nuclear effects that could be different for W and Z exchange?
- Most nuclear effects are only large at small Q^2 and would effect W and Z the same
 - NuTeV is at relatively high Q^2 
 - NuTeV $\sin^2\theta_W$ shows no effect with increasing the E_{had} cut (which increases the sampled Q^2)
 - Quark distribution measurements show no $1/Q^2$ dependence in the NuTeV kinematic region
- Proposals with enhanced nuclear effects.
 - Vector meson dominance models could have differences for W and Z exchange
(*Miller and Thomas, hep-ex/0204007; also our rebuttal, G.P. Zeller et al. hep-ex/0207052*)
 - Mainly effect sea quarks at low x and cancel in R^-
 \Rightarrow Would increase both R^{ν} and $R^{\bar{\nu}}$

Conclusion:

These nuclear effects will change R^{ν} and $R^{\bar{\nu}}$ more than R^-

Making their deviation with the SM much more significant

\Rightarrow Hard to explain NuTeV discrepancy with nuclear effects

Possible Interpretations

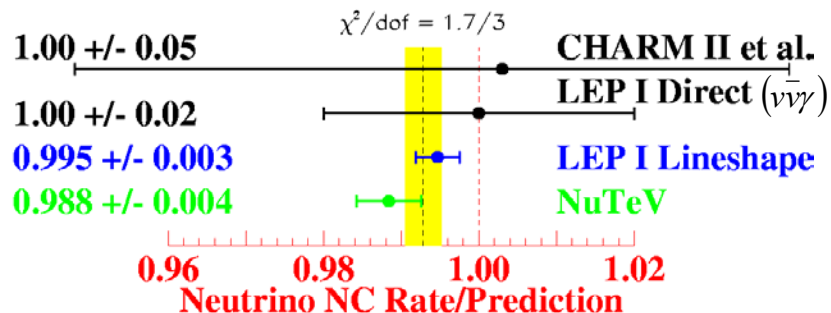
- Changes in Standard Model Fits
 - ✗ Changes in quark distributions sets
 - ✗ Cross section models: LO vs NLO
 - ✗ Changes in standard model radiative corrections
- “Old Physics” Interpretations: QCD
 - ? Violations of “isospin” symmetry
 - ✗ Strange vs anti-strange quark asymmetry
 - ✗ Shadowing and other nuclear effects
- Physics Beyond the Standard Model
 - Neutrino Properties
 - Special couplings to new particles
 - Mixing and oscillation Effects
 - “New Particle” Interpretations
 - New Z' or lepto-quark exchanges
 - New particle loop corrections
 - Mixtures of new physics



Explanations Involving Neutrino Properties

Reduced Neutrino Coupling

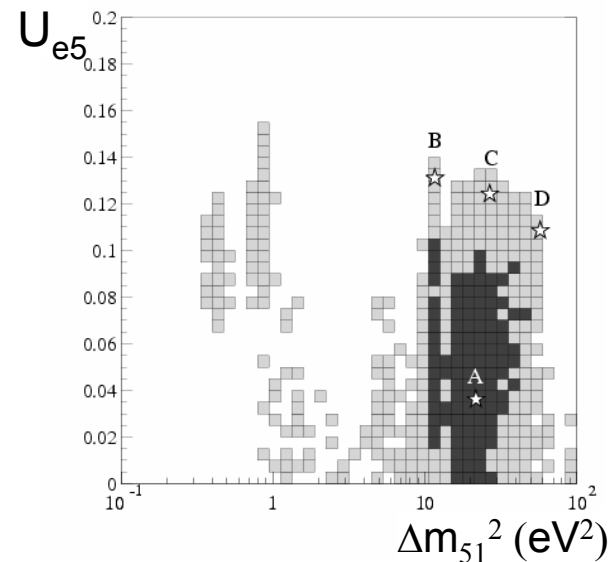
- NuTeV result fit as a change in the $\nu/\bar{\nu}$ coupling
 $\rightarrow \rho_0^2 = 0.9884 \pm 0.0026(\text{stat.}) \pm 0.0032(\text{syst.})$
- LEP 1 measures Z lineshape and partial decay widths to infer the “number of neutrinos”
 $\Rightarrow 3 \times (0.995 \pm 0.003) \Rightarrow 1.9\sigma$ low



\Rightarrow Explain discrepancies by invoking an effectively lower coupling of the neutrino due to some new phenomena (i.e. mixing with heavy or sterile ν 's)

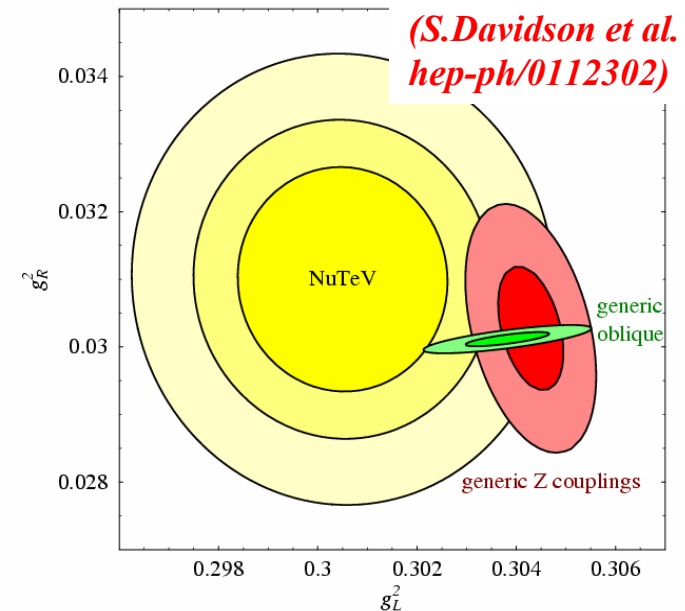
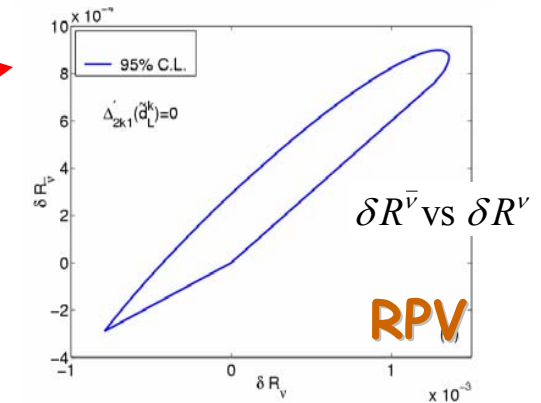
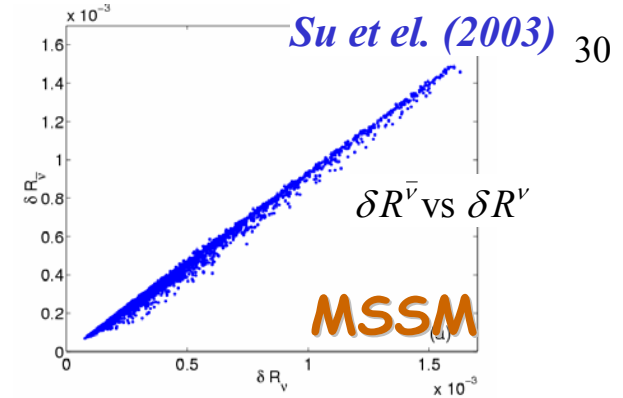
Reduced Background from $\nu_e \rightarrow \nu_s$ Osc.

- Neutrino oscillations to Sterile Neutrinos (Giunti et al. hep-ph/0202152;)
 - $\nu_e \rightarrow \nu_s$ oscillation make real ν_e background subtraction smaller giving NuTeV anomaly
 - Requires high Δm^2 and $\sim 20\%$ mixing
 - Is this consistent with other oscillation limits
 - For (3+1) model inconsistent with Bugey reactor limits
 - Recent work has shown that shift is below $1/3 \sigma$ even for high mass (3+2) models (J.S. Ma et al., in progress)



Possible New Physics Interpretations

- Constraints
 - Z pole measurements (LEP/SLD)
 - Insensitive to effects not directly involving the Z
 - Not too constraining for neutrino couplings
 - Need to change R^ν and not $R^{\bar{\nu}}$ (or change g_L and not g_R)
- SUSY in loop corrections or RPV SUSY at tree level
 - Generally small and in the wrong direction
 - Typically, change both R^ν and $R^{\bar{\nu}}$
 - Maybe extended SUSY models (i.e. *K.S.Babu and J.C.Pati, hep-ph/0203029*)
 - Also, can give LEP ν deficit
 - Will be tested at LHC
- Contact Interactions:
 - Fine tune a Left-handed q-q-lepton-lepton vertex, with strength ~ 0.01 of the weak interaction (~ 5 TeV)
- Leptoquarks:
 - Generally, increase both NC and CC $\Rightarrow g_L$ discrepancy worsens
 - Hard to fit with leptoquark and evade π -decay constraints
- Extra U(1) vector bosons (“ Designer Z' ”) that evades other constraints
 - Examples: Leptophobic, special couplings to 2nd generation, E(6) Z'
 - Could be seen at Tevatron (LHC) with masses up to 1 (5) TeV

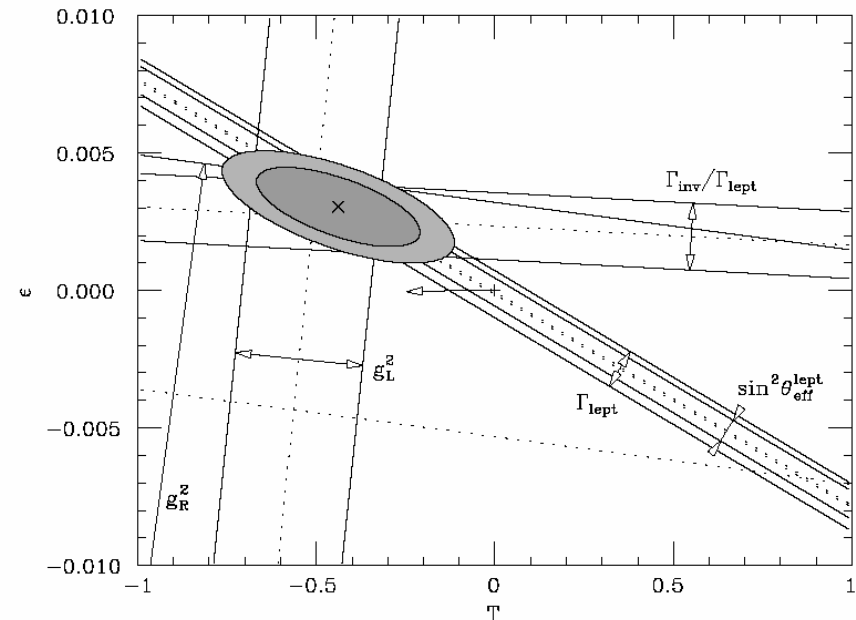


“The NuTeV Anomaly, Neutrino Mixing and a Heavy Higgs”

W. Loinaz, N. Okamura, T. Takeuchi, and L. Wijewardhana

(Phys. Rev. D67, 073012,2003,hep-ph/0210193, also hep-ph/0403306)

- Fit all measurements with a “cocktail model”
 - Neutrino Mixing
 - Heavy Higgs
 - New heavy bound state physics
- Suppression of the $Z\nu\nu$ coupling occur naturally in models which mix the neutrinos with heavy gauge singlet states
 - i.e. $\nu_L = \cos\theta \nu_{\text{light}} + \sin\theta \nu_{\text{heavy}}$
 - $Z\nu\nu$ reduced by $\cos^2\theta = (1-\varepsilon)$
 - But this changes G_F extracted from μ -decay by $(1-\varepsilon)$ and messes up dozens of Z-pole agreements
 - Can fix this if G_F is compensated by a shift in the ρ parameter (T) \Rightarrow allowed with “new physics”
 - Contradicts M_W
 - Need extra U-type new physics
- Can fit all data with
 - Mixed neutrinos: $\theta = 0.055 \pm 0.010$
 - Heavy Higgs: $M_{\text{higgs}} \geq 200 \text{ GeV}$
 - New physics (U-parameter type)
 - \Rightarrow New heavy bound states???



Possible Interpretations

- Changes in Standard Model Fits
 - ✗ Changes in quark distributions sets
 - ✗ Cross section models: LO vs NLO
 - ✗ Changes in standard model radiative corrections
- “Old Physics” Interpretations: QCD
 - ? Violations of “isospin” symmetry
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 - ? Mixtures of new physics

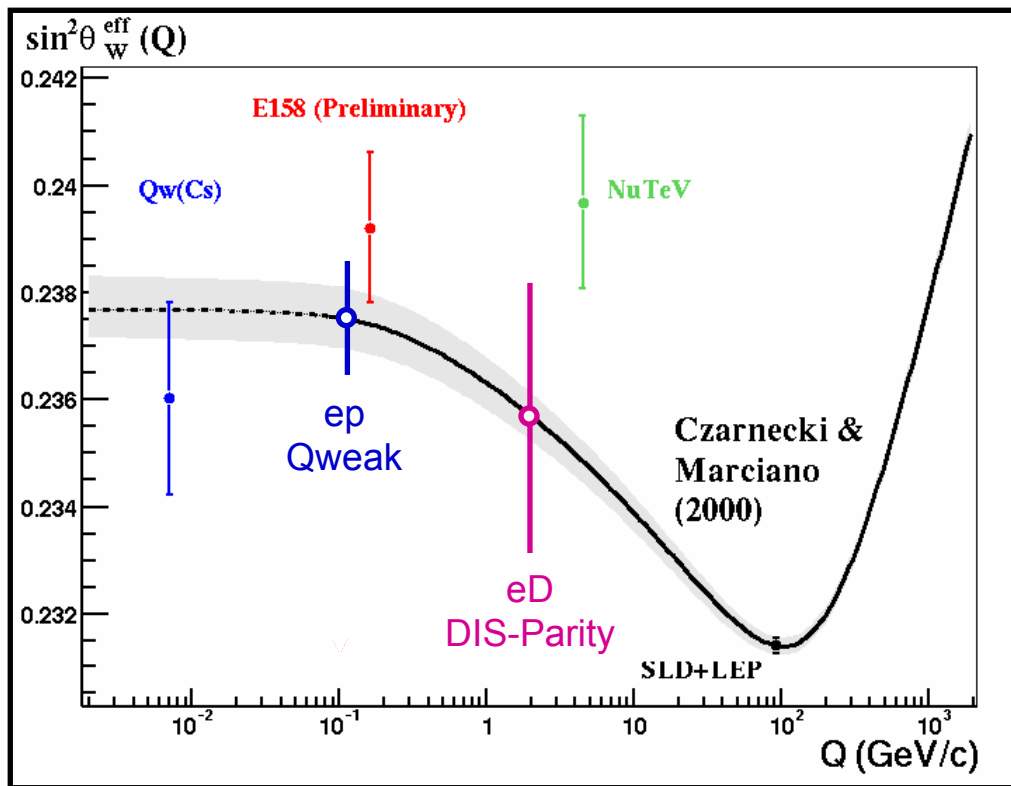
*Need New Experiments
to Explore
Low Q^2 and Neutrinos*

Future Measurements

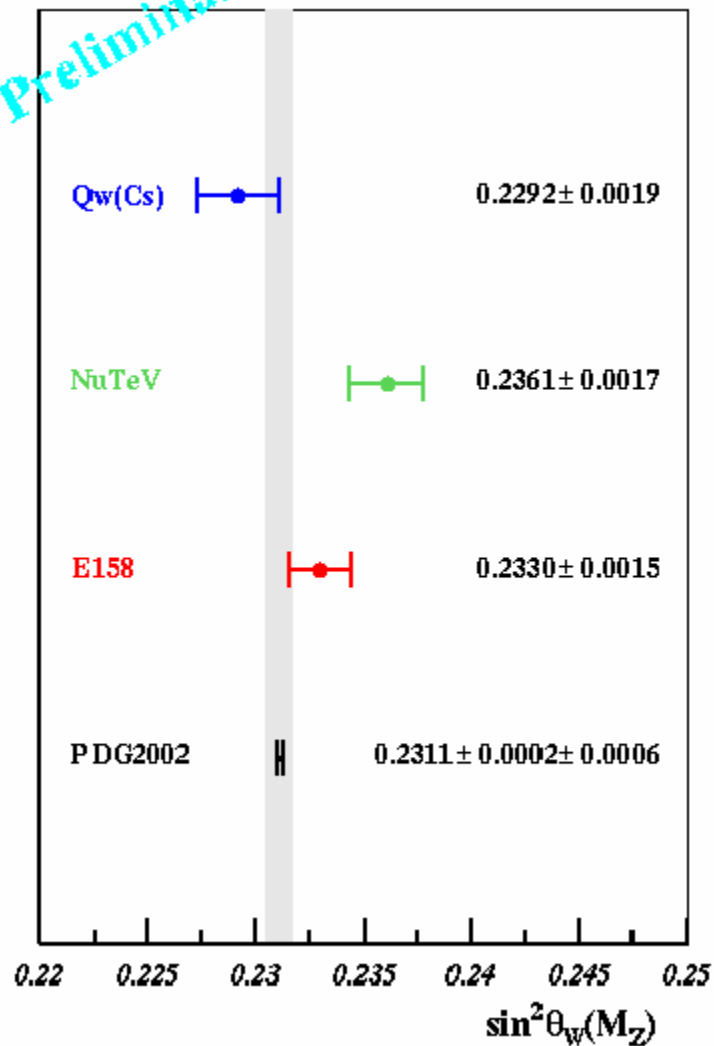
- Unfortunately, the high-energy neutrino beam at Fermilab has been terminated
 - ⇒ Need to rely on other experiments for progress
- Upcoming new measurements:
 - Low Q^2 measurements:
 - SLAC E-158 Pol. Polarized electron-electron scattering
 - JLab QWEAK Polarized elastic ep
 - JLab DIS-Parity Polarized eD

(Test low Q^2 But for e's and not ν 's)
 - High energy measurements:
 - Fermilab Tevatron Run 2 and LHC searches for Z' and leptoquarks

New “Preliminary” Final E-158 Results



Preliminary



From talk by Y. Kolomensky
at the SLAC Summer Institute
(Aug. 6, 2004)

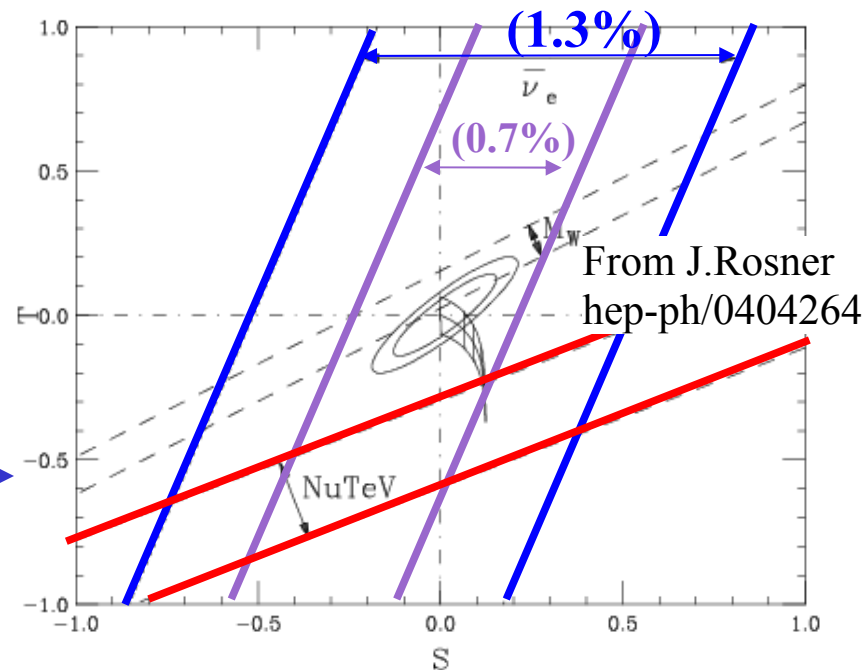
Other ν Measurement Possibilities

- Nomad νN experiment (data taking completed)

- Use R^ν only at $\langle Q^2 \rangle = 15 \text{ GeV}^2$
- Make corrections for quark model effects
 - NNLO QCD model with $1/Q^2$ corrections
 - Use dimuon data to constrain $s(x)$ and m_c
- Difficulties: NC/CC separation, E_ν spectrum
 $\Rightarrow \delta \sin^2 \theta_W = 0.002$

- Reactor $\bar{\nu}_e e^-$ elastic scattering
(Conrad, Link, Shaevitz hep-ex/0403048)

- Combination of W and Z exchange
- Total rate is sensitive to $\sin^2 \theta_W$
- Use $\bar{\nu}_e p \rightarrow e^- n$ for normalization
 \Rightarrow Measure rate to $\sim 1\% \Rightarrow \delta \sin^2 \theta_W = 0.002$



- Dedicated $\nu_\mu e^-$ accelerator experiment (Super CHARM II)

- Required sensitivity $\Rightarrow \times 25$ increase in statistics over CHARM II
- Improved detector: Fine grained (ie LiqAr), larger mass (5 kton)
- Improved beam: higher rep rate/intensity
 $\Rightarrow \delta \sin^2 \theta_W = 0.002$

- NuTeV measurement has the precision to be important for SM electroweak test
Many experimental checks and the R^- technique is robust with respect to systematic uncertainties
- For NuTeV the SM predicts 0.2227 ± 0.0003 but we measure
 $\sin^2 \theta_w^{(on-shell)} = 0.2277 \pm 0.0013(stat.) \pm 0.0009(syst.)$
(Previous neutrino measurements gave 0.2277 ± 0.0036)
- In comparison to the Standard Model
The NuTeV data prefers lower effective left-handed quark couplings
Or neutral current coupling that is $\sim 1.1\%$ smaller than expected
- The discrepancy with the Standard Model could be related to:
Quark model uncertainties but unlikely or only partially
and / or
Possibly new physics that is associated with neutrinos and
interactions with left-handed quarks or neutrino mixing/oscillations

Jan/Feb 2002 CERN Courier article:

*“Is the latest NuTeV result a blip or another neutrino surprise?
Only time will tell.”*

