PHYS 5326 – Lecture #5

Monday, Feb. 12, 2007
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1. ILC News from Beijing
2. Interpretation of $\sin^2\theta_W$
3. $\sin^2\theta_W$ link to Higgs

ILC RDR from Beijing

- Global Design Effort (GDE) headed by Barry Barish of CalTech completed a Reference Design Report (RDR)
  - Worldwide group working on ILC machine design
  - Defines the baseline design of the ILC and provides the cost estimate for an ILC
- Baseline design parameters
  - CMS Energy: 200 – 500GeV scannable
  - Total length: 31km
  - Luminosity: $\mathcal{L} = 2\times10^{34}cm^{-2}s^{-1}$
  - Single interaction region two detector in push-pull mode

ILC RDR from Beijing

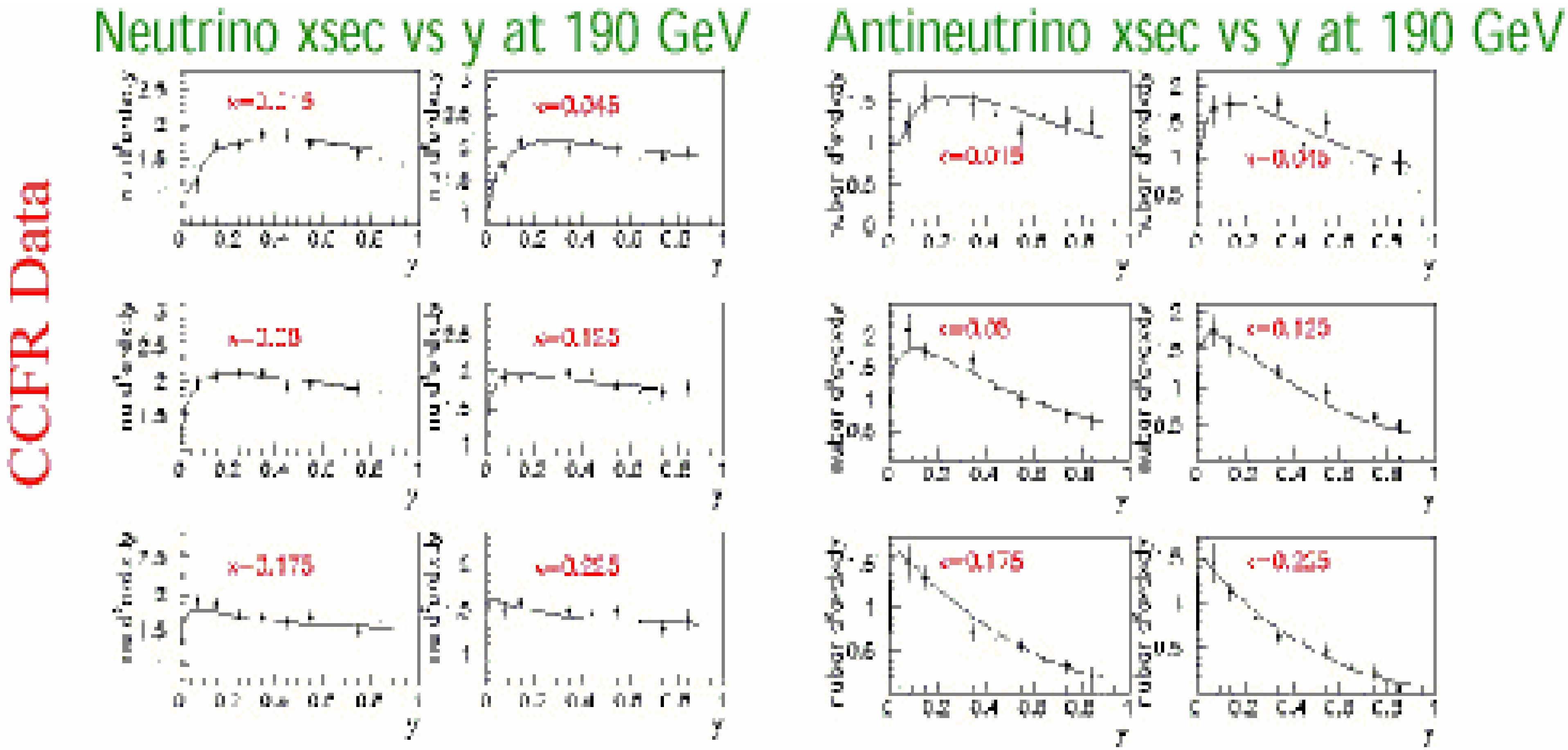
- Baseline cost estimate
  - ILC Value units to provide cost in universally understandable price
    - Lowest reasonable price for required quality
  - Shared cost: $4.87B
  - Site specific cost: $1.78B
    - This is the cost for tunneling, foundation, geological issues, etc
  - Labor cost: 13,000 Man-years
  - Not included in the cost estimate
    - Engineering design, preparation cost for R&D
    - Detectors and associated R&D
    - Contingencies for risks
    - Escalation (inflation)

ILC RDR from Beijing

- The next steps
  - Engineering design report by 2010
    - Should include complete design of the machine except for the site specific portion of it
    - Refined cost estimate
  - Accept expression of interest (EOI) for hosting the ILC from countries from now till 2011
  - Site selection process begins shortly as EOI's collected
  - Construction of the machine begins 2011 or so
- Detector R&D and selection should complete by 2010 – 2011 time scale

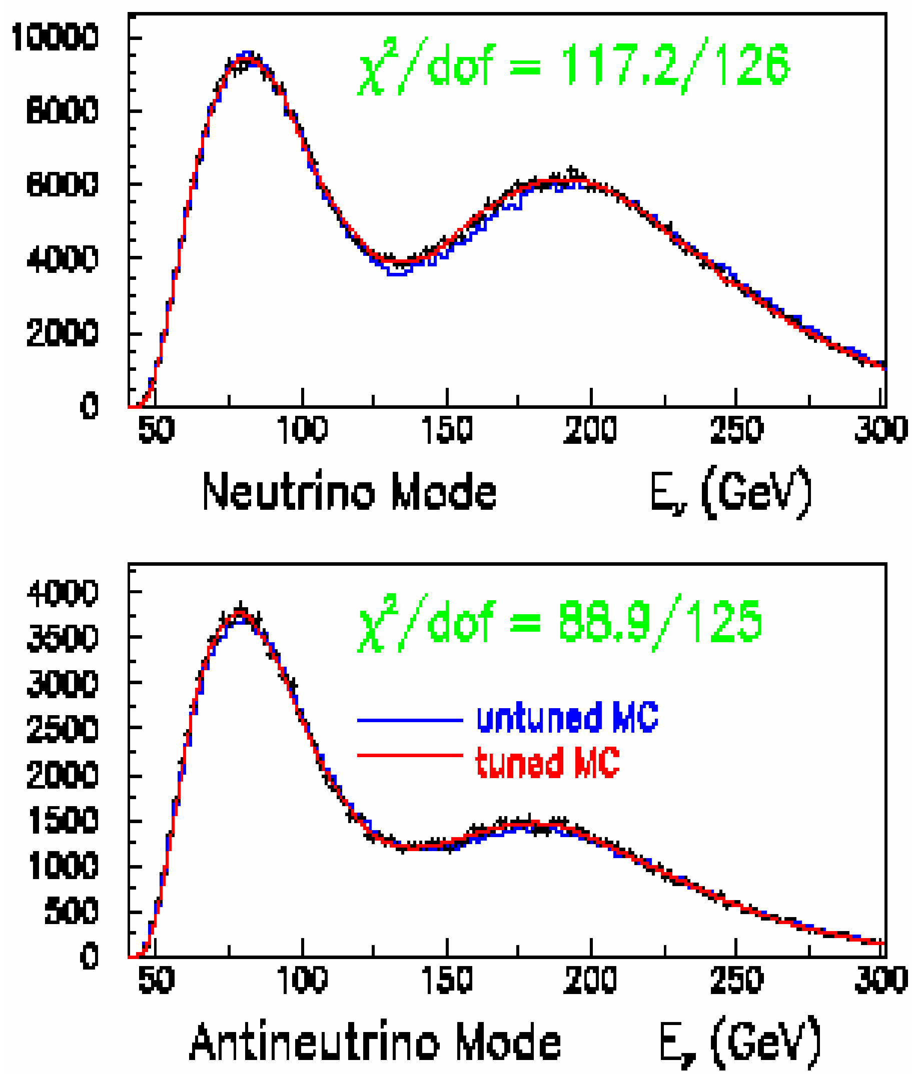
MC to Relate R_{ν}^{exp} to R^{ν} and $\sin^2\theta_W$

- Parton Distribution Model
  - Correct for details of PDF model ➔ Used CCFR data for PDF
    - To minimize systematic effects
  - Model cross over from short ν_{μ} CC events



MC to Relate R_ν^{exp} to R^ν and $\sin^2\theta_W$

- Neutrino Fluxes
  - $\nu_\mu, \nu_e, \bar{\nu}_\mu, \bar{\nu}_e$ in the two running modes
  - ν_e CC events always look short
- Shower length modeling
  - Correct for short events that look long
- Detector response vs energy, position, and time
  - Continuous testbeam running minimizes systematics



$\sin^2\theta_W$ Fit to R_ν^{exp} and $R_{\bar{\nu}}^{exp}$

- Thanks to the separate beam ➔ Measure R^ν's separately
- Use MC to simultaneously fit $\mathbf{R}_\nu^{\mathbf{exp}}$ and $\mathbf{R}_{\bar{\nu}}^{\mathbf{exp}}$ to $\sin^2\theta_W$ and m_c, and $\sin^2\theta_W$ and ρ

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

- R^ν Sensitive to $\sin^2\theta_W$ while $R^{\bar{\nu}}$ isn't

$\Rightarrow R^\nu$ is used to extract $\sin^2\theta_W$ and $R^{\bar{\nu}}$ to control systematics

$\Rightarrow$Why???

$\sin^2\theta_W$ Fit to R_ν^{exp} and $R_{\bar{\nu}}^{exp}$

- Single parameter fit, using SM values for EW parameters (ρ_0=1)

$$\boxed{\sin^2\theta_W = 0.2277 \pm 0.0013\,(\text{stat}) \pm 0.0009\,(\text{syst})}$$

$$m_c = 1.32 \pm 0.09\,(\text{stat}) \pm 0.06\,(\text{syst}) \Rightarrow m_c = 1.38 \pm 0.14\ \text{GeV/c}^2 \text{ as input}$$

- Two parameter fit for $\sin^2\theta_W$ and ρ_0 yields

$$\sin^2\theta_W = 0.2265 \pm 0.0031$$

$$\rho_0 = 0.9983 \pm 0.040$$

Syst. Error dominated since we cannot take advantage of sea quark cancellation

NuTeV $\sin^2\theta_W$ Uncertainties

Source of Uncertainty	$\delta \sin^2\theta_W$
Statistical	**0.00135**
ν_e flux	0.00039
Event Length	0.00046
Energy Measurements	0.00018
Total Experimental Systematics	**0.00063**
CC Charm production, sea quarks	0.00047
Higher Twist	0.00014
Non-isoscalar target	0.00005
$\sigma^{\bar{\nu}} / \sigma^{\nu}$	0.00022
RadiativeCorrection	0.00011
R_L	0.00032
Total Physics Model Systmatics	**0.00064**
Total Systematic Uncertainty	**0.00162**
ΔM_W (GeV/c^2)	**0.08**

Dominant uncertainty

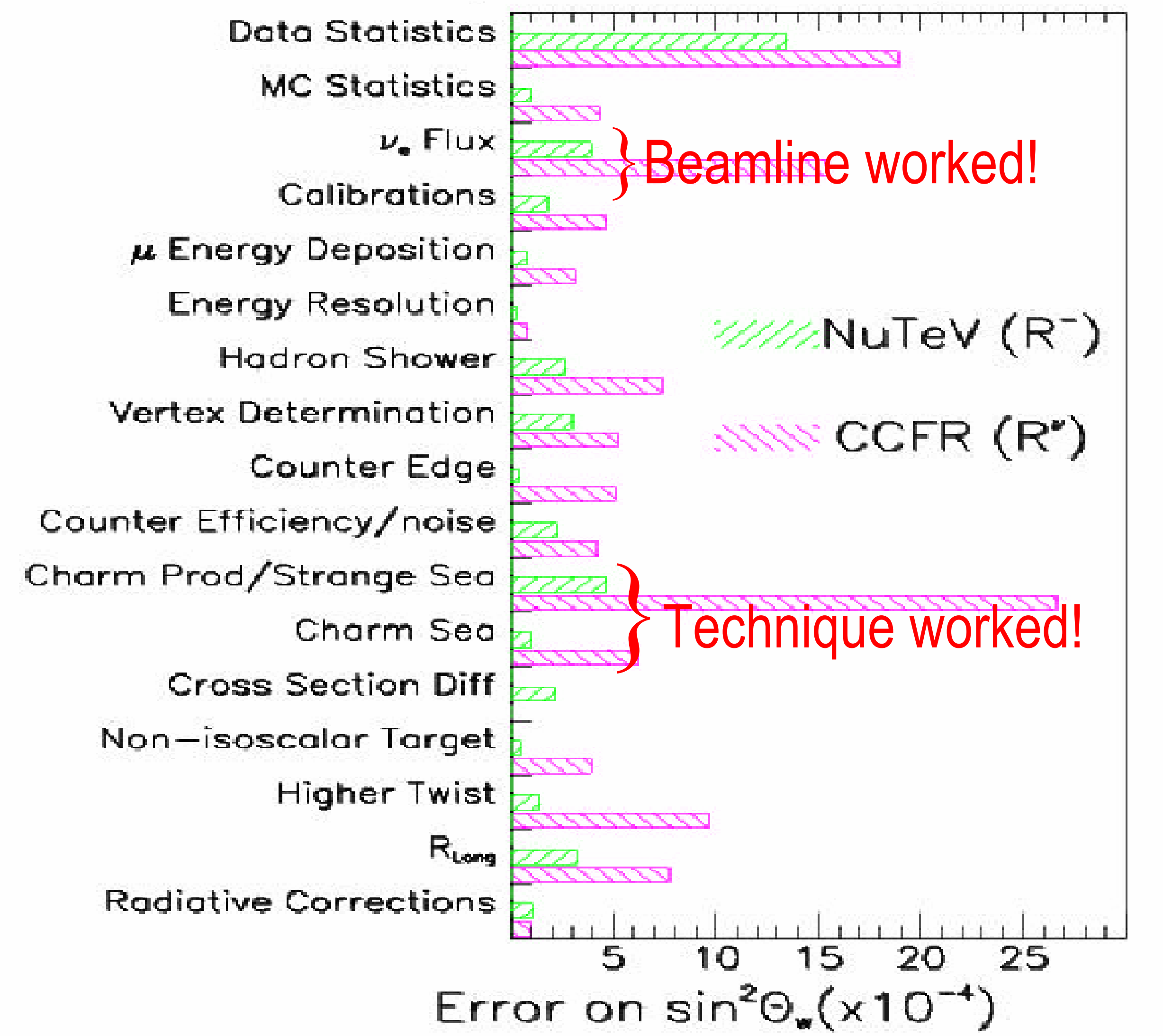
1-Loop Electroweak Radiative Corrections based on Bardin, Dokuchaeva **JINR-E2-86-2 60 (1986)**

$$\delta\sin^2\theta_W^{(On-shell)} = -0.00022 \times \left(\frac{M_t^2 - (175\,GeV)^2}{(50\,GeV)^2}\right) + 0.00032 \times \ln\left(\frac{M_H}{150\,GeV}\right)$$

M_{higgs} Term

M_t Term

NuTeV vs CCFR Uncertainty Comparisons



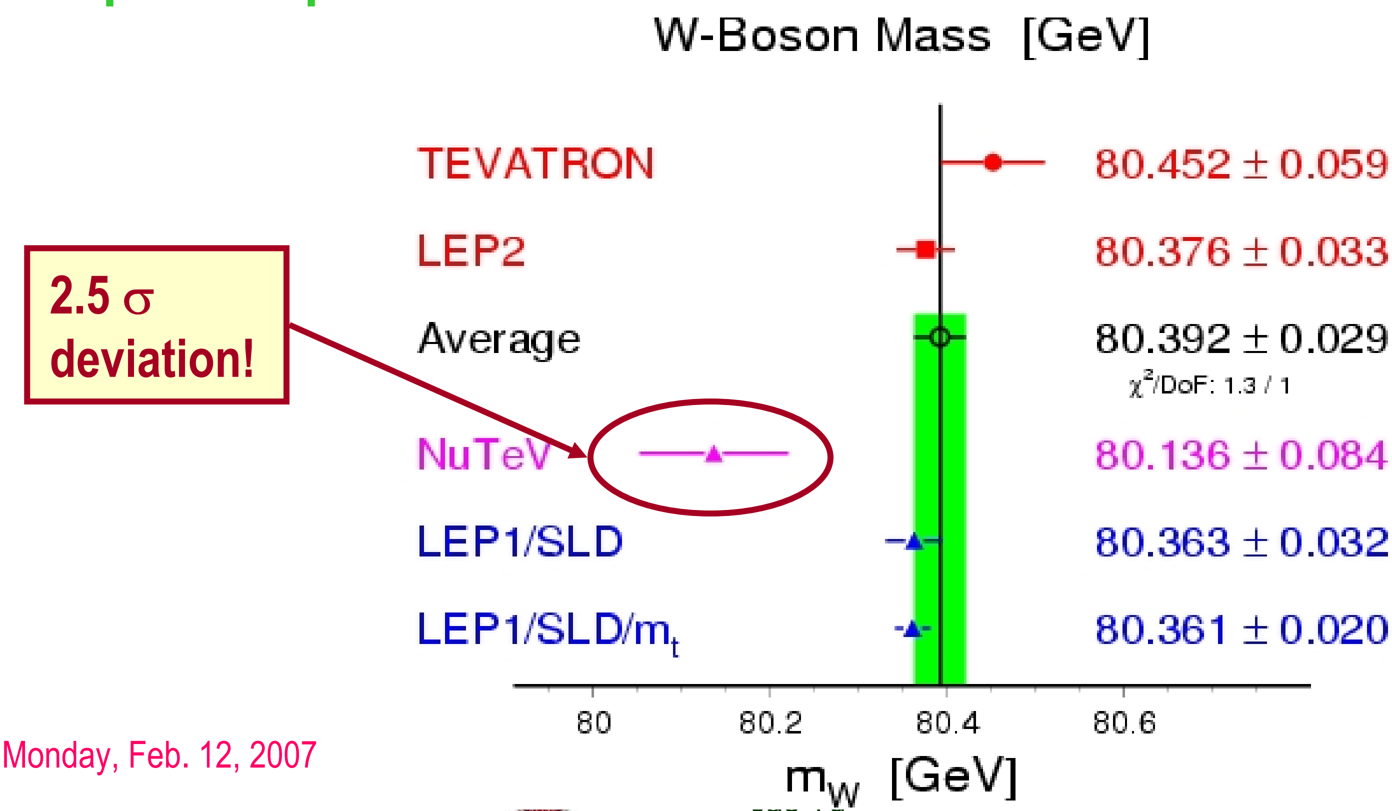
Comparison of New $\sin^2\theta_W$

$$\sin^2\theta_W^{On-Shell} = 0.2277 \pm 0.0013\,(stat) \pm 0.0009\,(syst)$$

$$\sin^2\theta_W^{On-shell} = 1 - \frac{M_W^2}{M_Z^2}$$

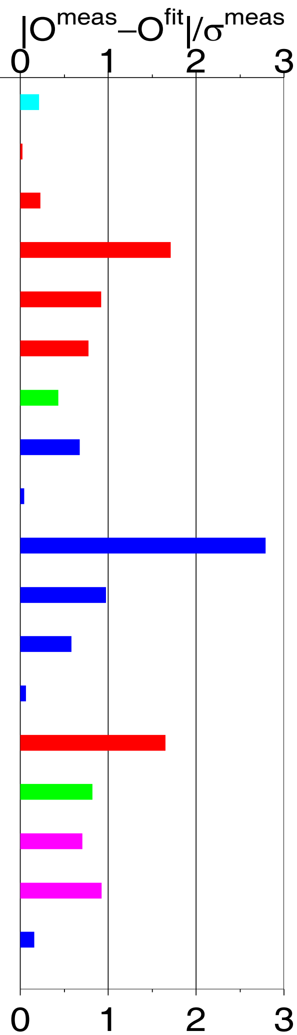
$$\Rightarrow M_W^{On-Shell} = 80.14 \pm 0.08\ GeV/c^2$$

Comparable precision but value smaller than other measurements



SM Global Fits with New Results

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02766
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ^0_{had} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01640
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479
R_b	0.21629 ± 0.00066	0.21585
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0741
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1479
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.392 ± 0.029	80.371
Γ_W [GeV]	2.147 ± 0.060	2.091
m_t [GeV]	171.4 ± 2.1	171.7



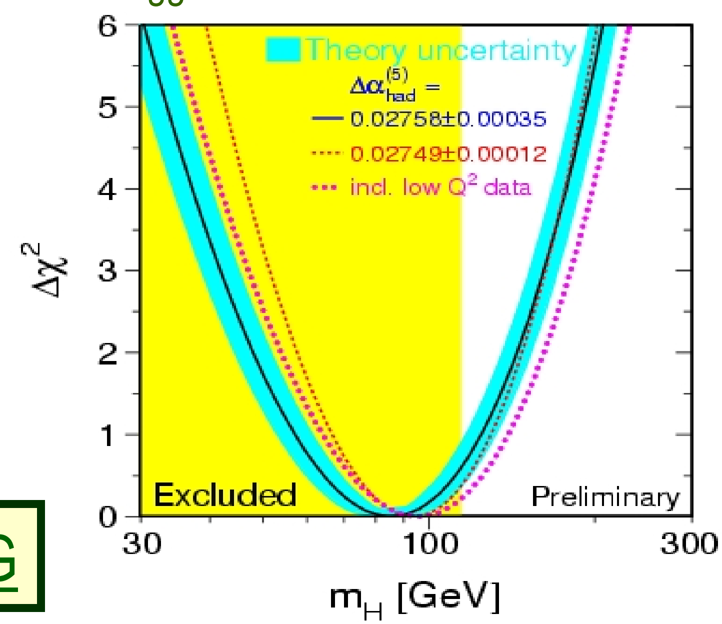
Without NuTeV

χ^2/dof=20.5/14: $\mathcal{P}$=11.4%

With NuTeV

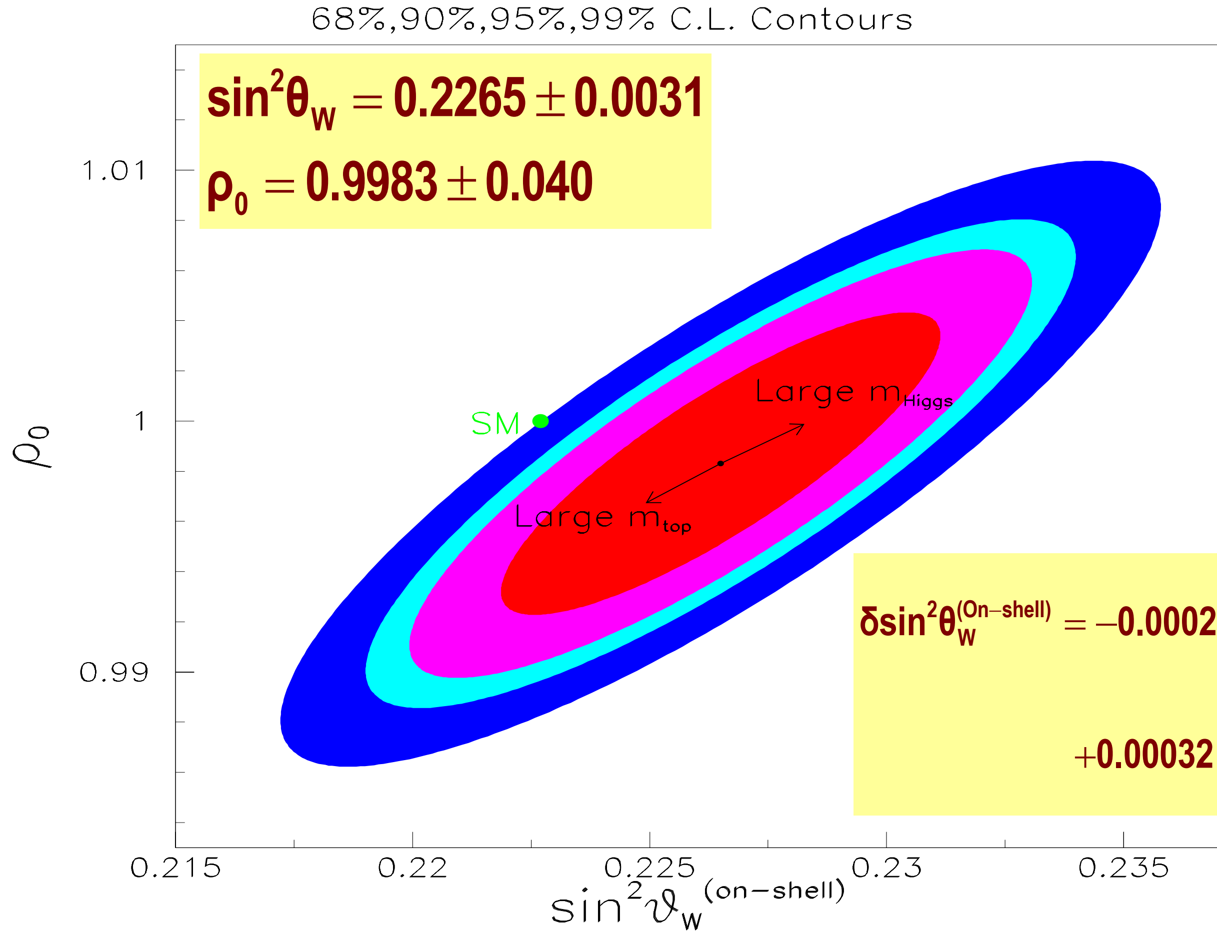
χ^2/dof=29.7/15: $\mathcal{P}$=1.3%

Confidence level in upper M_{higgs} limit weakens slightly.



LEP EWWG: http://www.cern.ch/LEPEWWG

Tree-level Parameters: ρ_0 and $\sin^2\theta_W^{(on\text{-}shell)}$



$$\sin^2\theta_W = 0.2265 \pm 0.0031$$

$$\rho_0 = 0.9983 \pm 0.040$$

$$\delta\sin^2\theta_W^{(On-shell)} = -0.00022 \times \left(\frac{M_t^2 - (175\text{GeV})^2}{(50\text{GeV})^2}\right) + 0.00032 \times \ln\left(\frac{M_H}{150\text{GeV}}\right)$$

- Either $\sin^2\theta_W^{(on\text{-}shell)}$ or ρ_0 could agree with SM but both agreeing simultaneously is unlikely

Model Independent Analysis

- $R^{\nu(\bar{\nu})}$ can be expressed in terms of quark couplings:

$$R^{\nu(\bar{\nu})} \equiv \frac{\sigma\left(\overset{(-)}{\nu} N \to \overset{(-)}{\nu} X\right)}{\sigma\left(\overset{(-)}{\nu} N \to \ell^{-(+)} X\right)} = g_L^2 + r^{(-1)} g_R^2$$

Where $$r \equiv \frac{\sigma\left(\bar{\nu}N \to \ell^{+}X\right)}{\sigma\left(\nu N \to \ell^{-(+)}X\right)} \approx \frac{1}{2}$$

Paschos-Wolfenstein formula can be expressed as

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

Model Independent Analysis

- Performed a fit to quark couplings (and g_L and g_R)
  - For isoscalar target, the νN couplings are

$$g_L^2 = u_L^2 + d_L^2 = \rho_0^2\left(\frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W\right)$$

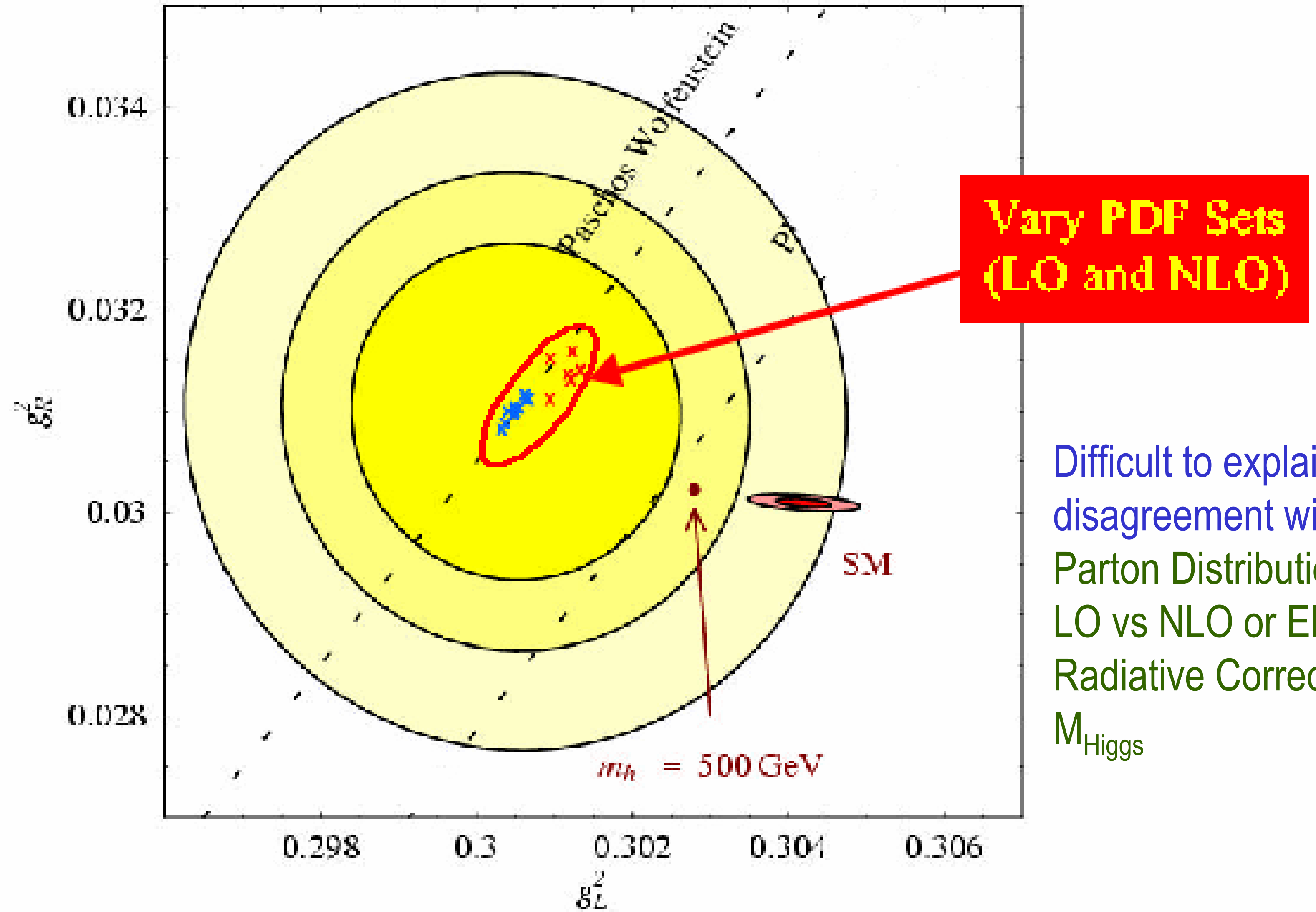
$$g_R^2 = u_R^2 + d_R^2 = \rho_0^2\frac{5}{9}\sin^4\theta_W$$

  - From two parameter fit to $\mathbf{R}_\nu^{\mathbf{exp}}$ and $\mathbf{R}_{\bar{\nu}}^{\mathbf{exp}}$

$g_L^2 = 0.3005 \pm 0.0014$ (SM: 0.3042 ← -2.6σ deviation)

$g_R^2 = 0.0310 \pm 0.0011$ (SM: 0.0301 ← Agreement)

Model Independent Analysis



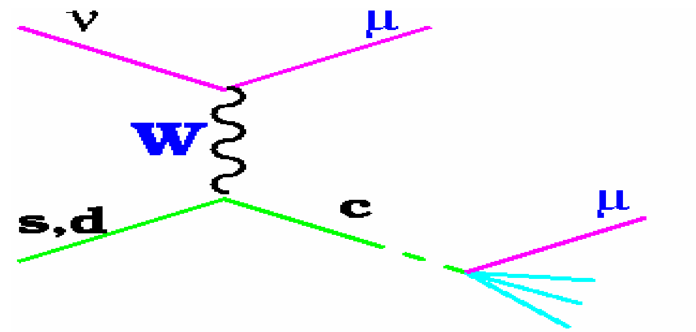
Difficult to explain the disagreement with SM by: Parton Distribution Function or LO vs NLO or Electroweak Radiative Correction: large M_{Higgs}

What is the discrepancy due to (Old Physics)?

- R^- technique is sensitive to q vs $\bar{q}$ differences and NLO effect
  - Difference in valence quark and anti-quark momentum fraction
- Isospin symmetry assumption might not be entirely correct
  - Expect violation about 1%
    - $\rightarrow$NuTeV reduces this effect by using the ratio of ν and $\bar{\nu}$ cross sections
    - $\rightarrow$Reducing dependence by a factor of 3

What is the discrepancy due to (Old Physics)?

- s vs $\bar{s}$ quark asymmetry
  - s and $\bar{s}$ needs to be the same but the momentum could differ
    - A value of $\Delta s = xs - x\bar{s}$ ~+0.002 could shift $\sin^2\theta_W$ by -0.0026, explaining ½ the discrepancy (S. Davison, et. al., hep-ph/0112302)
    - NuTeV di-μ measurement shows that Δs~-0.0027+/-0.0013



Use opposite sign di-μ events to measure s and $\bar{s}$.

What is the discrepancy due to (Old Physics)?

- NLO and PDF effects
  - PDF, m_c, Higher Twist effect, etc, are small changes
- Heavy vs light target PDF effect (Kovalenko et al., hep-ph/0207158)
  - Using PDF from light target on Iron target could make up the difference ➔ NuTeV result uses PDF extracted from CCFR (the same target)

$\nu_e \rightarrow \nu_s$ Oscillations with Large M_ν

- LSND result implicate a large Δm^2 (~10 — 100eV^2) solution for ν_e oscillation ➔MiniBooNe at FNAL is running to put the nail on the coffin
- How would this affect NuTeV $\sin^2\theta_W$?

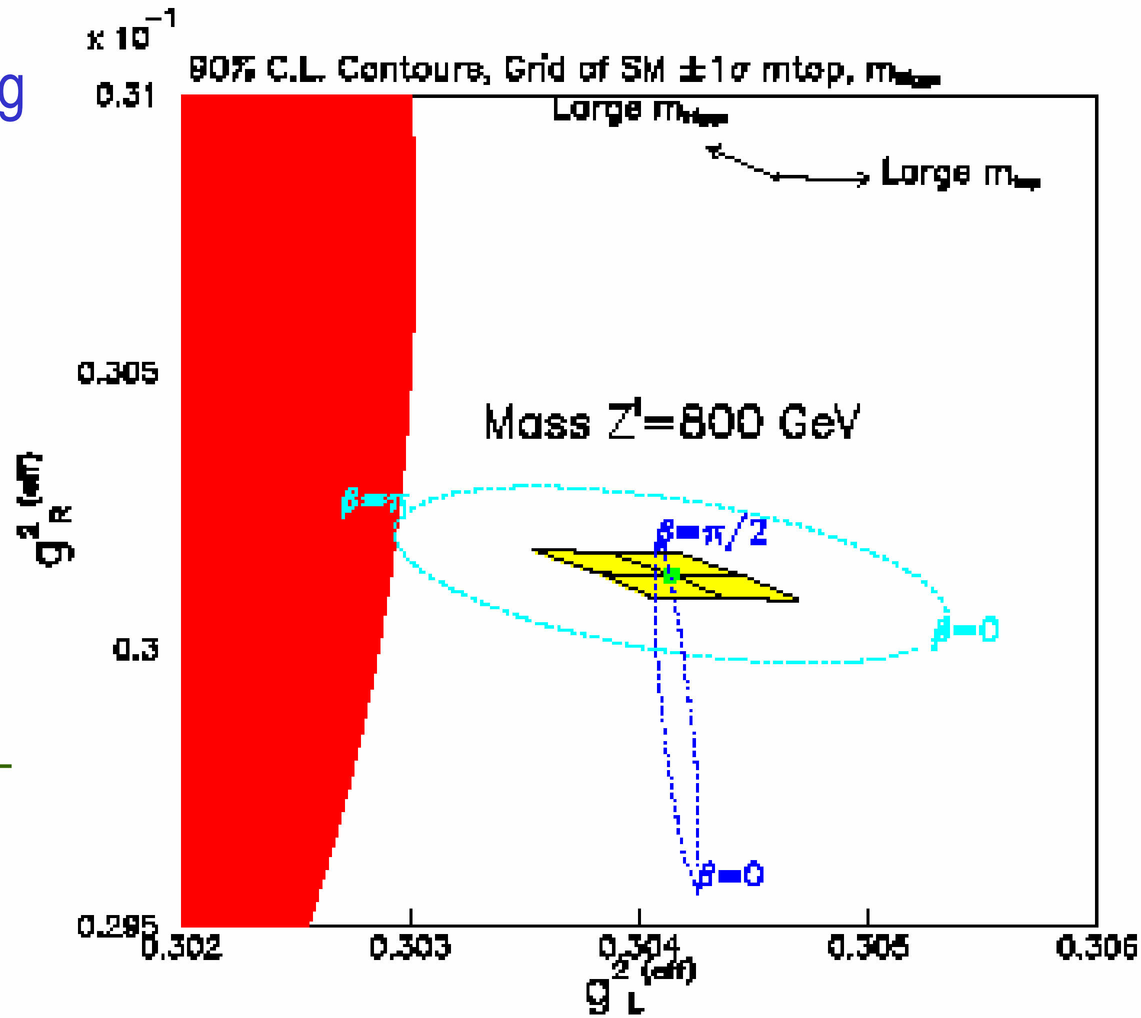
$$\sin^2\theta_W = \frac{1}{2} - \frac{R^\nu - rR^{\bar{\nu}}}{1-r} \quad \text{and} \quad R^\nu = \frac{N^\nu_{Short} - N^{MC}_{\nu_e}}{N^\nu_{Long}}$$

If $\nu_e \rightarrow \nu_s$ with $P_{\nu_e\to\nu_s}$ then $N_{\nu_e} = N^{MC}_{\nu_e} P_{\nu_e\to\nu_e} = N^{MC}_{\nu_e}\left(1\text{-}P_{\nu_e\to\nu_s}\right)$

Thus, MC will subtract more than it is in nature, causing measured R^ν to be smaller and thereby increasing $\sin^2\theta_W$

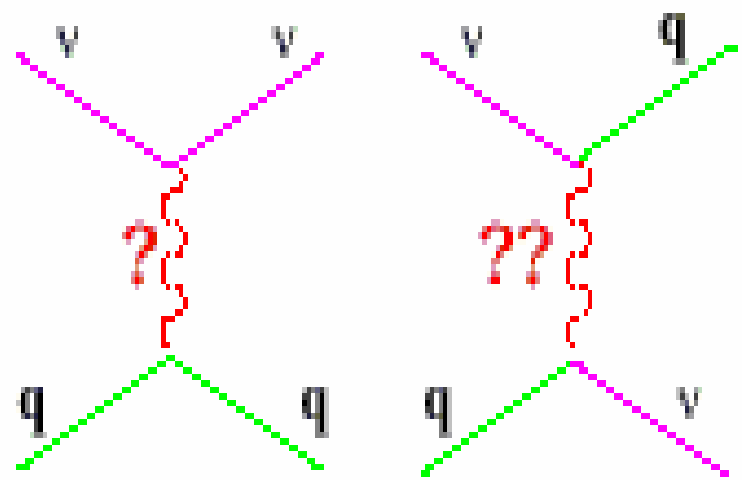
New Physics: Interactions from Extra U(1) – Z'

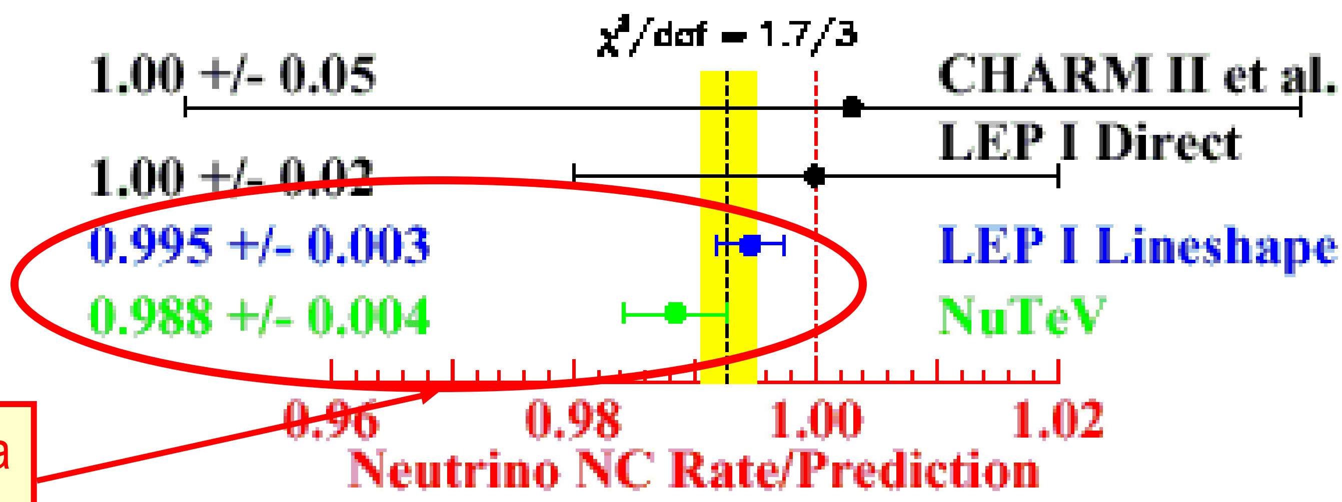
- Extra U(1) gauge group giving rise to interactions mediated by heavy Z' boson ($M_{Z'} >> M_Z$)
- While couplings in these groups are arbitrary, E(6) gauge groups can provide mechanism for extra U(1) interaction via heavy Z'.
- Can give rise to g_R but not g_L which is strongly constrained by precision Z measurement



What other explanations (New Physics)?

- Heavy non-SM vector boson exchange: Z', LQ, etc
  - Suppressed $Z\nu\nu$ (invisible) coupling
  - LL coupling enhanced than LR needed for NuTeV





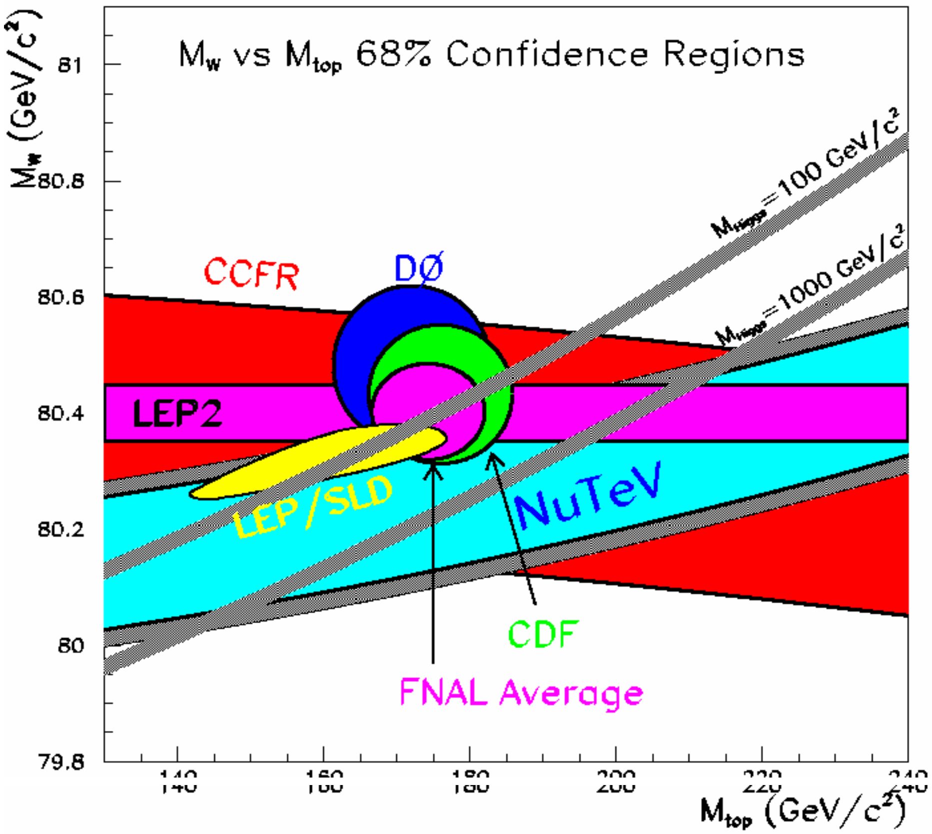
Both precision data are lower than SM

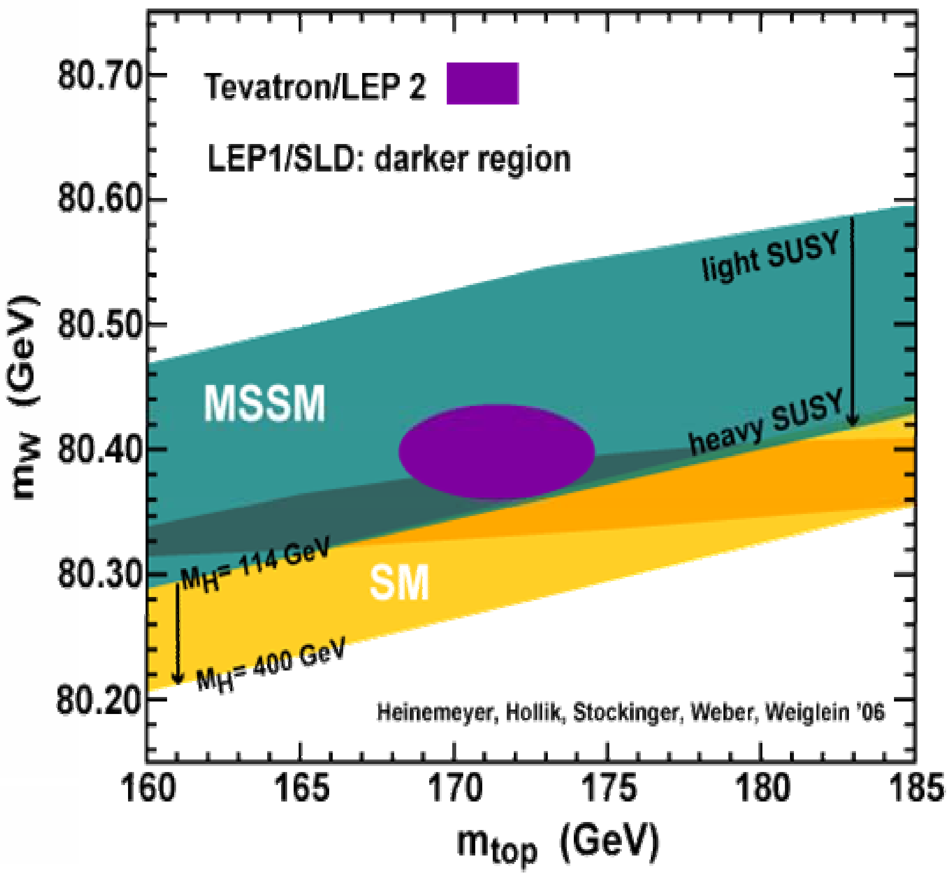
What other explanations (New Physics)?

- Propagator and coupling corrections
  - Small compared to the effect
- MSSM : Loop corrections wrong sign and small for the effect
- Many other attempts in progress but so far nothing seems to explain the NuTeV results
  - Lepto-quarks
  - Contact interactions with LL coupling (NuTeV wants $m_{Z'}$~1.2TeV, CDF/DØ: $m_{Z'}$>700GeV)
  - Almost sequential Z' with opposite coupling to ν

Langacker *et al*, Rev. Mod. Phys. **64** 87; Cho *et al.*, Nucl. Phys. **B531**, 65; Zppenfeld and Cheung, hep-ph/9810277; Davidson et al., hep-ph/0112302

Linking $\sin^2\theta_W$ with Higgs through M_{top} vs M_W





One-loop correction to $\sin^2\theta_W$

$$\delta\sin^2\theta_W^{(On-shell)} = -0.00022\times\left(\frac{M_t^2-(175GeV)^2}{(50GeV)^2}\right)+0.00032\times\ln\left(\frac{M_H}{150GeV}\right)$$

Homework Assignments

- Draw a few additional Feynman diagrams for higher order GSW corrections to ν-N scattering at the same order as those on pg 4 of the previous lecture
  - Due: One week from today, Mon., Feb. 19