$\sin^2\theta_W$ from Neutrino Scattering at NuTeV

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Experimental Anomalies
Confront the Standard Model
Università Roma Tre/INFN Sezione Roma III
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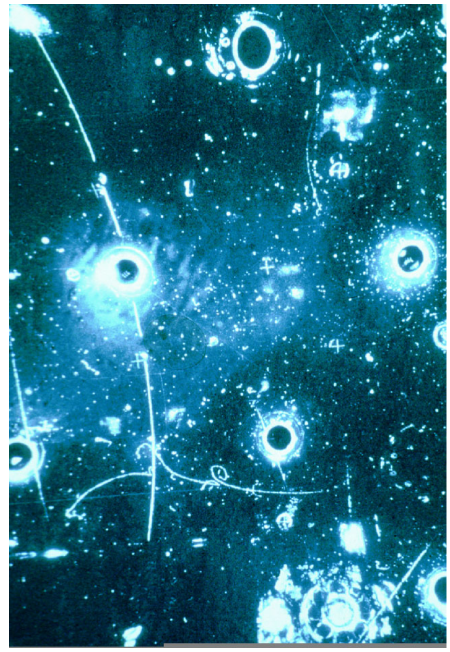
Outline

1. Why Study Electroweak Physics with Neutrinos?
2. The NuTeV Experiment
   - Key Elements of the Analysis
   - NuTeV's Surprising Results
   - Interpretation
3. Conclusions

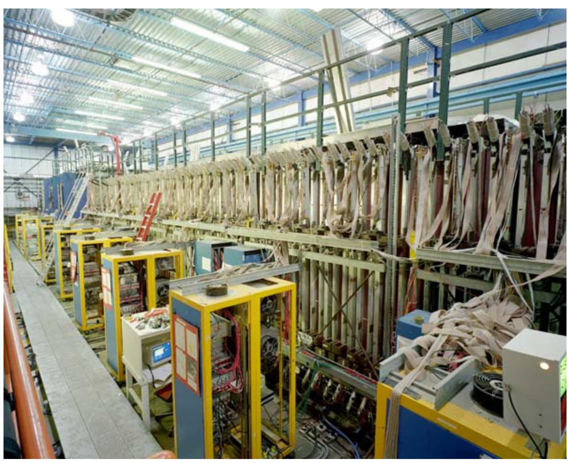
The Role of NuTeV

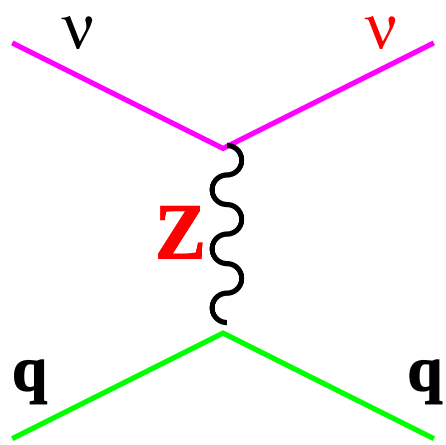


Neutrino scattering played a key historical role in electroweak unification

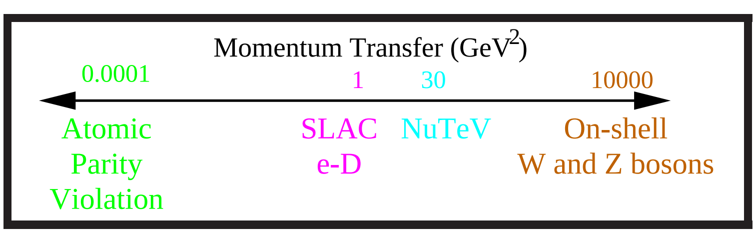
- Discovery of Neutral Current (Gargamelle, FNAL-E1A)
- First determimation of high-energy parameter in EW theory
  $\sin^2\theta_W \sim 0.2 \Rightarrow \frac{M_W}{M_Z} \sim 0.9$

. . . but why continue to study when we make copious on-shell W and Z bosons at colliders?



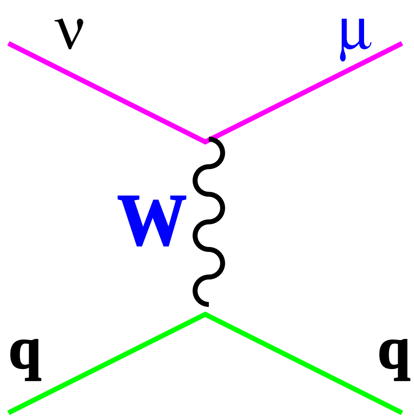


- Testing in a wide range of processes and momentum scales ensures universality of the electroweak theory

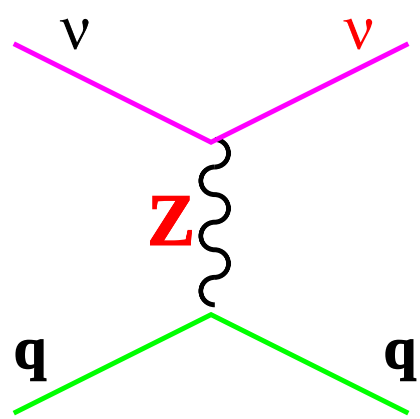


- NuTeV is sensitive to different processes
  - ↪ Measurement is off the Z pole (contributions besides Z?)
  - ↪ Measure neutral current neutrino couplings
    - ⋆ LEP I invisible line width is only other precise measurement

Methodology



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



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

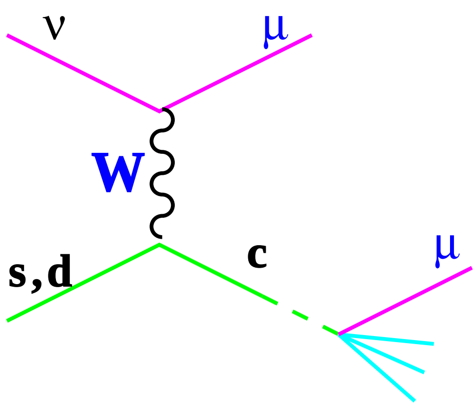
Isoscalar target composed of only u,d quarks at tree level:

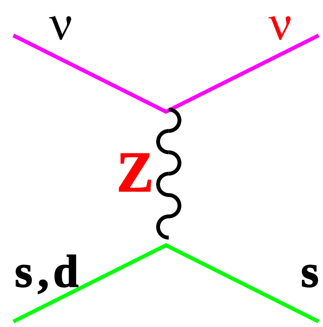
Llewellyn Smith Relation:

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

- R^{ν}, $R^{\overline{\nu}}$ easy to measure experimentally
- Cross-section ratios reduce effects of
  - ↪ Experimental systematics, ν flux
  - ↪ Parton distribution functions (PDFs)
- To extract $\sin^2\theta_W$ from the measured ratio:
  - ↪ isovector target ($2Z \neq A$)
  - ↪ heavy quark seas (and kinematic suppression)
  - ↪ radiative corrections, higher twist, R_L

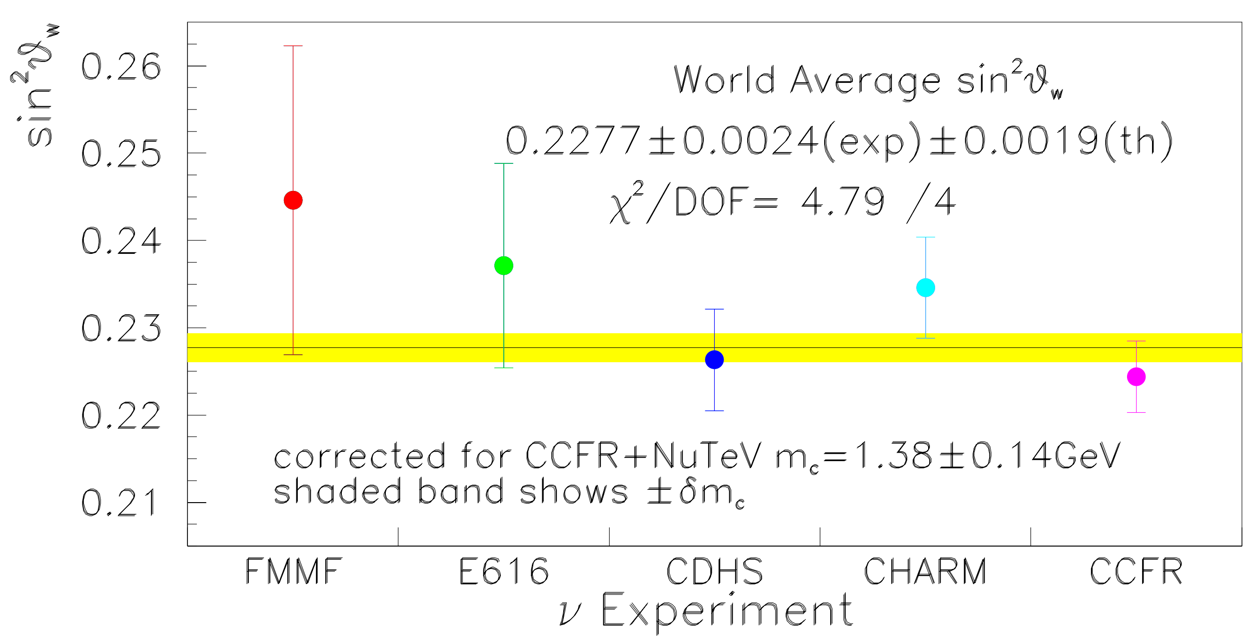
Heavy Quark Effects





- Suppression of CC cross section for interactions with massive charm quark in final state
- Model: leading-order slow-rescaling ($x \longrightarrow \xi = \frac{Q^2+m_c^2}{2M\nu}$)
- Parameters measured by NuTeV/CCFR in dimuon events

  (M. Goncharov *et al.*, Phys. Rev. **D64**, 112006 (2001))
- Limits precision of previous νN measurements...



$$\sin^2\theta_W{}^{on-shell} \equiv 1 - \frac{M_W{}^2}{M_Z{}^2} = 0.2277 \pm 0.0031$$

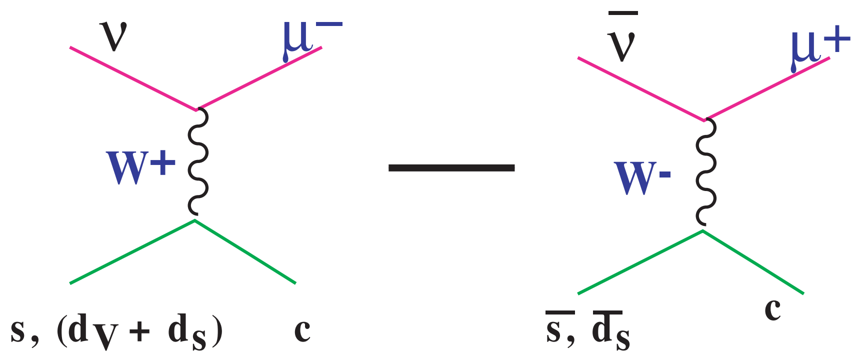
$$\Rightarrow M_W = 80.14 \pm 0.16 \text{ GeV}$$

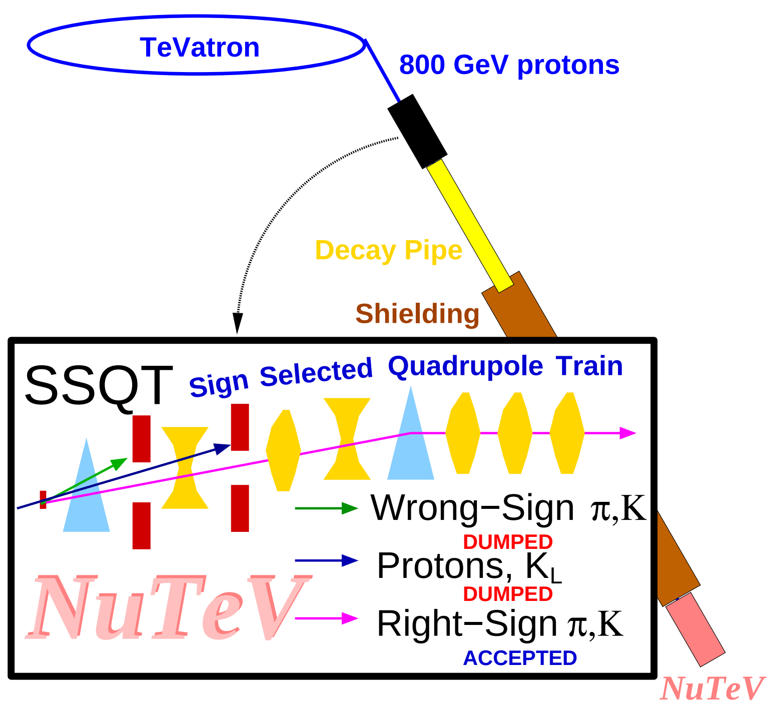
NuTeV's Approach

Large charm production errors $\Rightarrow$ need technique insensitive to sea

<u>Paschos-Wolfenstein Relation:</u>

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





- R^- is manifestly insensitive to sea quarks
  - ↪ Charm and strange sea errors are negligible ...
    (Most of charm from s(x) scattering)
  - ↪ Massive charm production enters from d_V quarks only ...
    (Cabbibo suppressed and at high x)
- Separate ν, $\overline{\nu}$ beams
  $\Rightarrow$ NuTeV SSQT

The $\sin^2\theta_W$ Fit

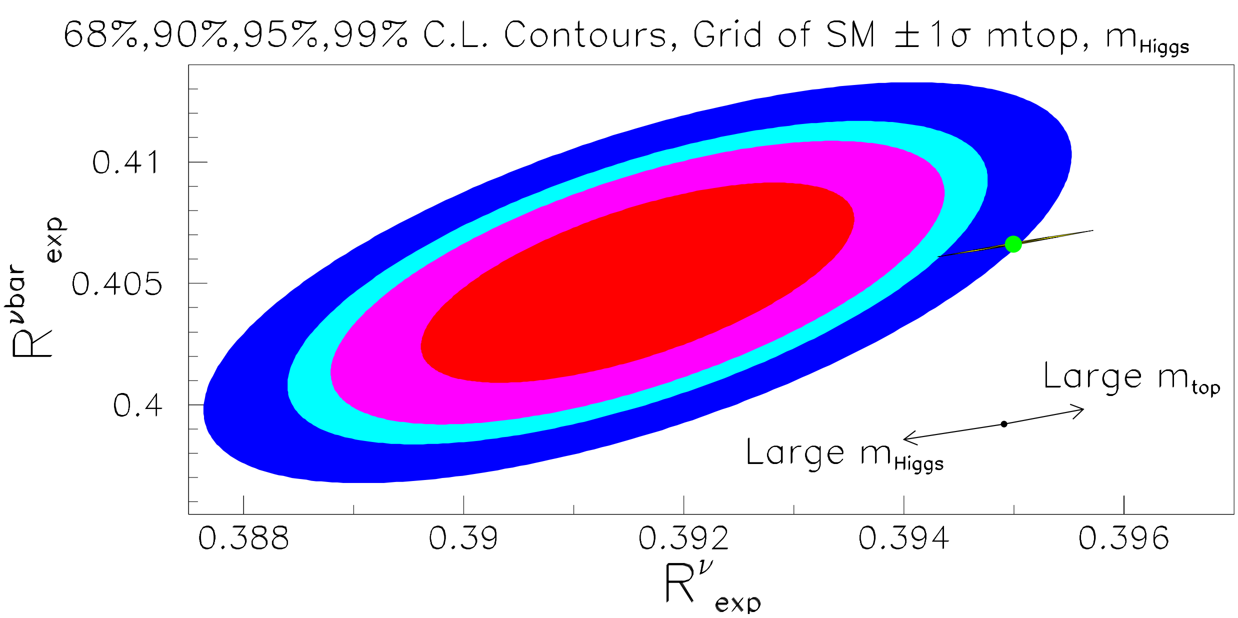
(Llewellyn-Smith)

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

$\frac{dR^{\nu}_{exp}}{d\sin^2\theta_W}$ large

$\frac{dR^{\overline{\nu}}_{exp}}{d\sin^2\theta_W}$ small

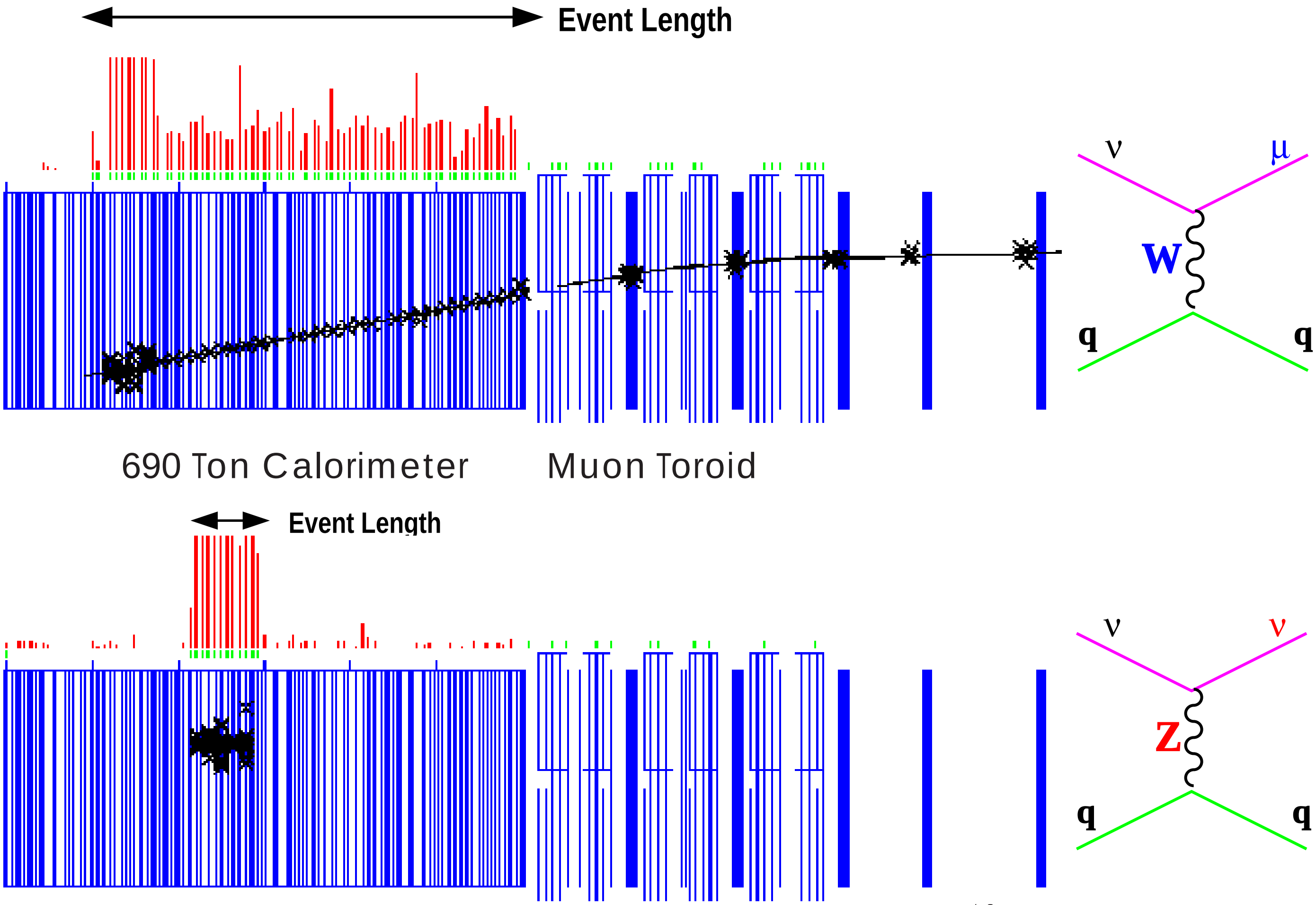
$R^{\overline{\nu}}_{exp}$ "measures" systematic effects, independent of $\sin^2\theta_W$



R^{ν}_{exp} and $R^{\overline{\nu}}_{exp}$ measured to a precision of 0.3%, 0.65%, respectively

(common systematics lead to correlated uncertainty)

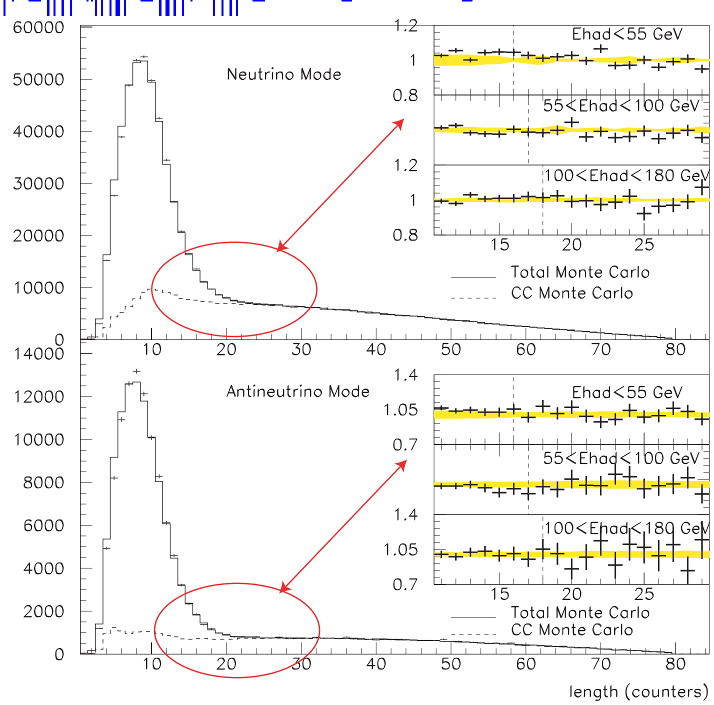
Neutral Current/Charged Current Event Separation



Separate by simple **length cut**

$$R_{exp} = \frac{SHORT\ events}{LONG\ events} = \frac{L \leq Lcut}{L > Lcut} = \frac{NC\ candidates}{CC\ candidates}$$

in ν and $\overline{\nu}$ beams (1.62 and 0.35 million events)



Summary of Corrections to R_{exp}

Corrections Applied to Data

Effect	δR^{ν}_{exp}	$\delta R^{\overline{\nu}}_{exp}$	Control
Cosmic Ray Background	–0.0036	–0.019	†
Beam μ Background	+0.0008	+0.0012	†
Vertex Efficiency	+0.0008	+0.0010	†

Effects in Monte Carlo that relate $R^{\overset{(-)}{\nu}}$ to $R^{\overset{(-)}{\nu}}_{exp}$

Effect	δR^{ν}_{exp}	$\delta R^{\overline{\nu}}_{exp}$	Control
Short CC Background	–0.068	–0.026	†, √
nu nubar Electron Neutrinos	–0.021	–0.024	♮, √
Long NC	+0.0028	+0.0029	†, √
Counter Noise	+0.0044	+0.0016	†
Heavy m_c	–0.0052	–0.0117	†, ♣
R_L	–0.0026	–0.0092	†, ♣
EM Radiative Correction	+0.0074	+0.0109	
Weak Radiative Correction	–0.0005	-0.0058	
d/u	–0.00023	–0.00023	†
Higher Twist	–0.00012	–0.00013	†

Recall: R^{ν}_{exp} and $R^{\overline{\nu}}_{exp}$ measured to a precision of 0.0013 and 0.0027, respectively

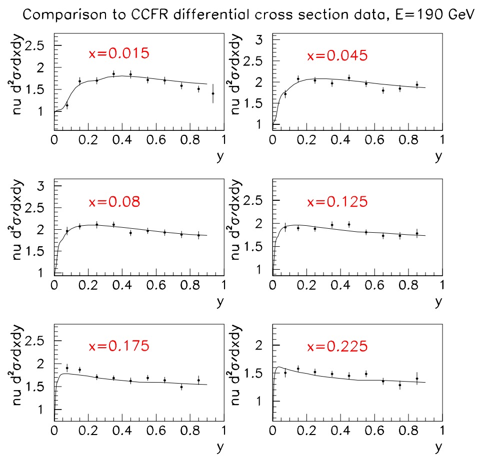
Key to coping techniques

- †: Determined from data
- √: Checked with data
- ♮: Independent Simulation
- ♣: R^{-} technique

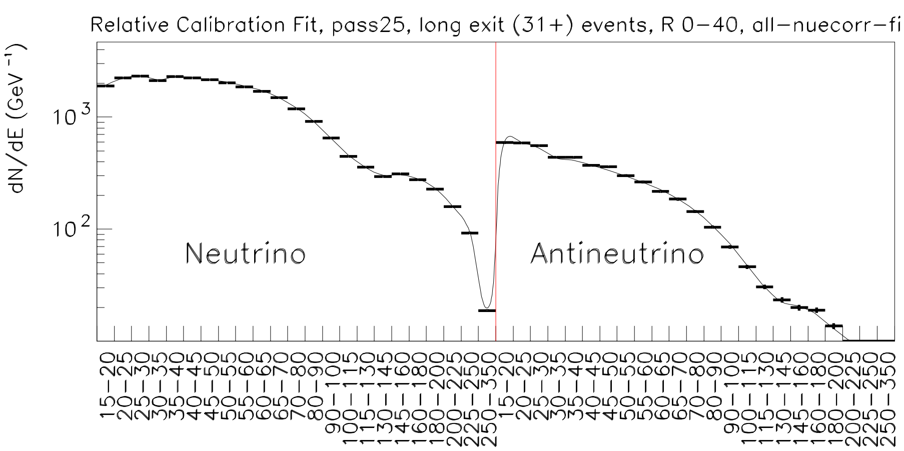
ν_μ Charged-Current Background

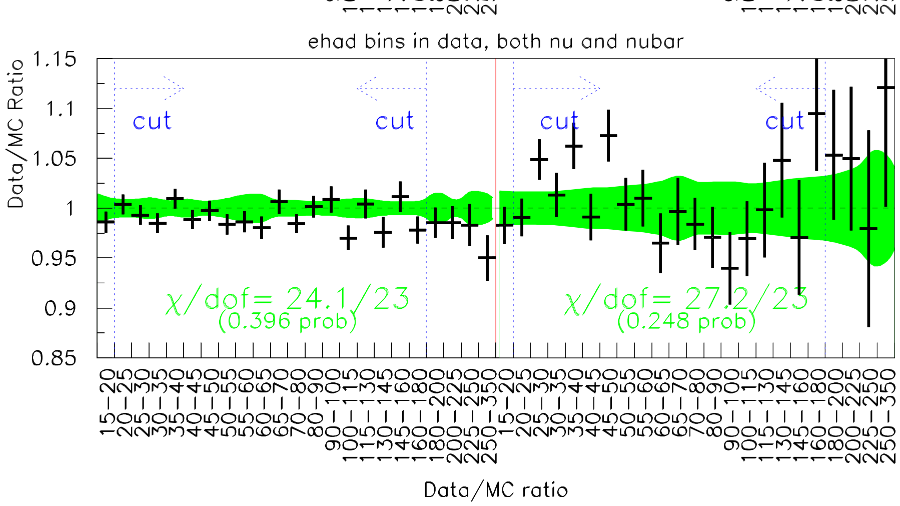
- High y charged-current is background to NC sample
  - $\overset{(-)}{\nu}$ NC & CC quark model cross-section

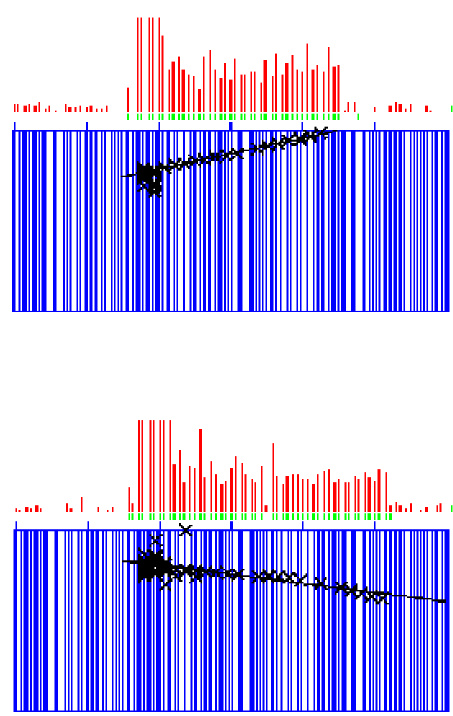
    $\hookrightarrow$ R_L term added to F_2, xF_3 to describe $g \to q\overline{q}$
  - PDFs extracted from CCFR σ_{CC}
  - Other data determines $s(x)$, d/u, R_L, higher twist, $F_2^{c\bar{c}}$



- Data-driven: uncertainties come from measurements





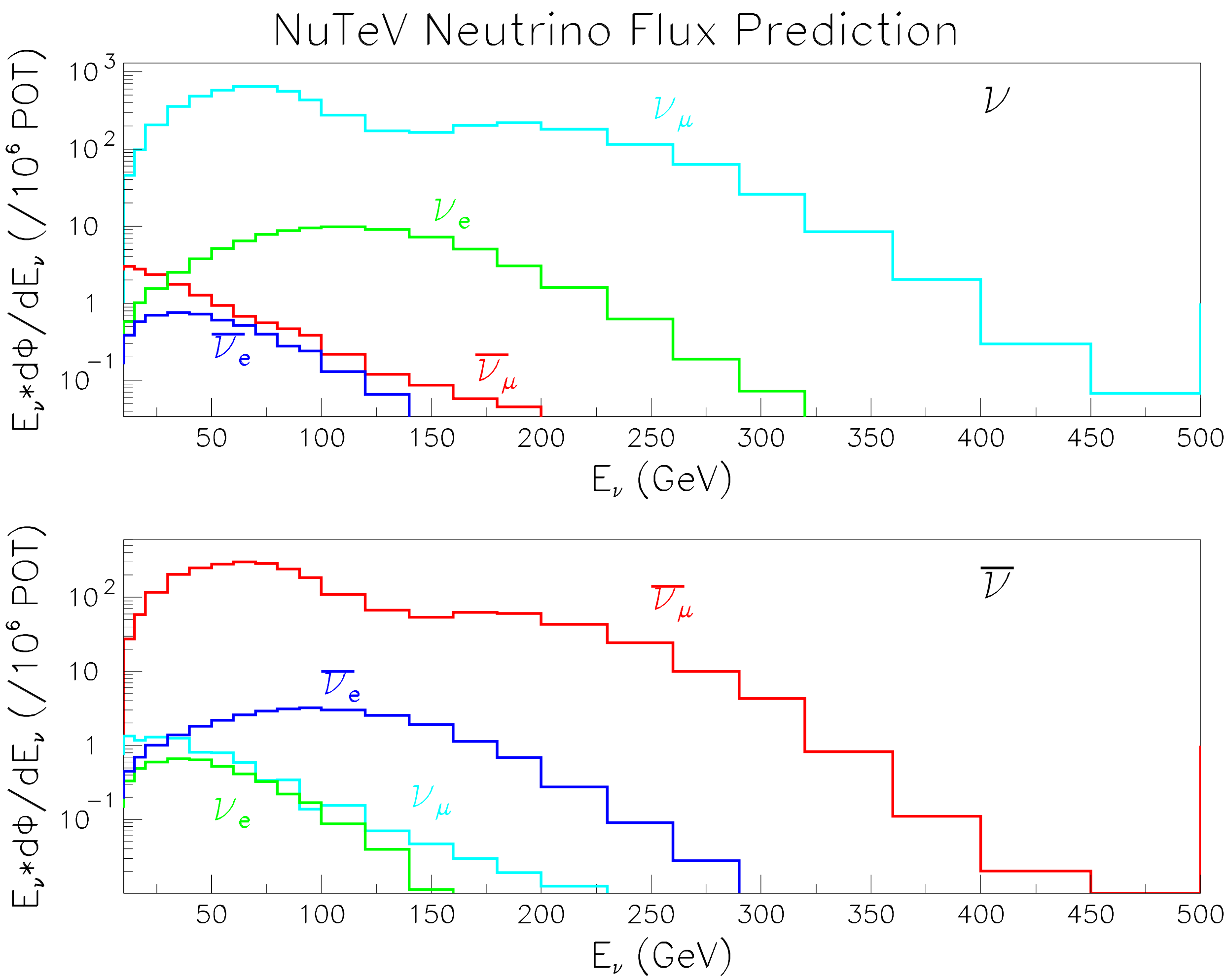


- Check by looking at "long exit" CC events which start in the detector center and stop before toroid

Electron Neutrinos

Approximately 5% of all short events are ν_e CC.

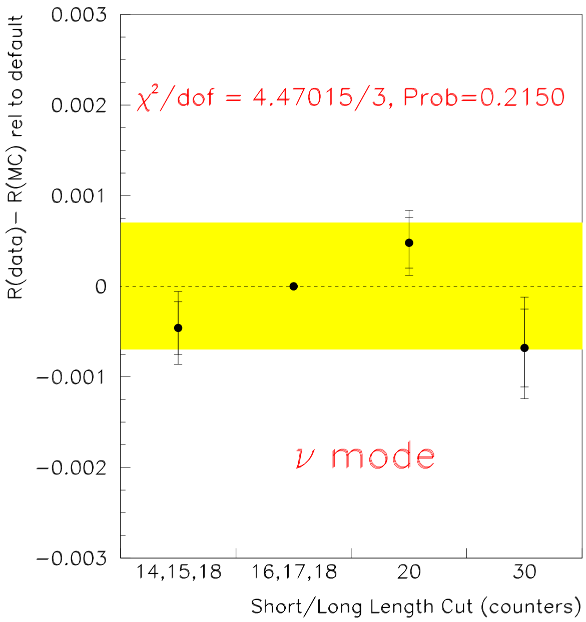
$\Rightarrow$ *It would take a 20% mistake in ν_e to move $\sin^2\theta_W$ to SM value*

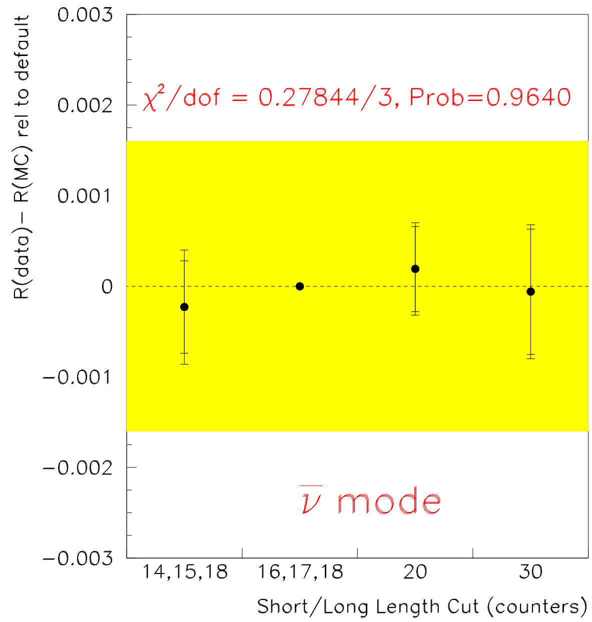


- Excess of ν_e over $\overline{\nu}_e$ in ν beam is due to K^+_{e3} decay
  - ↪ Vast majority of $\nu_e/\overline{\nu}_e$ in $\nu/\overline{\nu}$ beams
  - ↪ K_L and charm decay, which make both ν_e and $\overline{\nu}_e$, are small
- $K^\pm_{e3}$ decay is very well understood
  - ↪ $K^\pm$ production. . . *is constrained by ν_μ and $\overline{\nu}_\mu$ flux*
  - ↪ Use predicted flux (few % shifts from production data), *except* high energy tail ($E_\nu > 180$ GeV direct measurement)
- Have (less precise) direct measurements of ν_e and $\overline{\nu}_e$
  - ↪ N_{meas}/N_{pred}: 1.05 ± 0.03 (ν_e), 1.01 ± 0.04 ($\overline{\nu}_e$) ($80 < E_\nu < 180$ GeV)

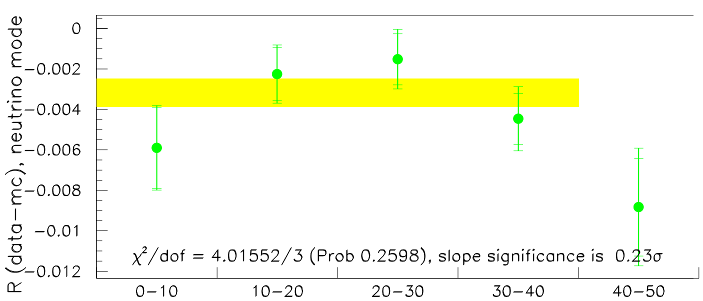
Stability of R_{exp} (cont'd)

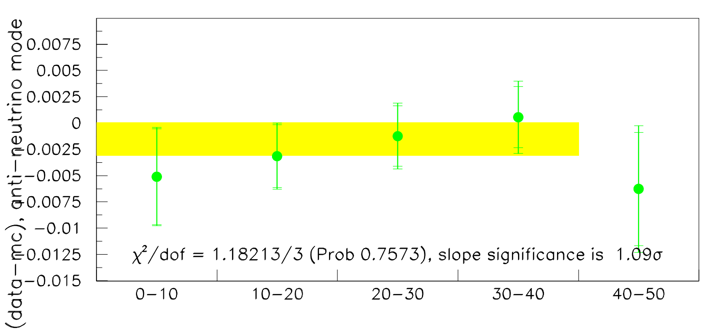
- R vs. length cut: Checks NC $\leftrightarrow$ CC separation
  "16,17,18" L_{cut} is default: tighten$\leftrightarrow$loosen selection



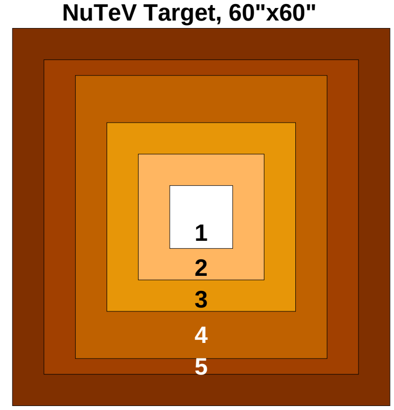


- R vs. "radial bin": Checks electron neutrino and short CC events
  More NC background near edge





NuTeV Target, 60"x60"

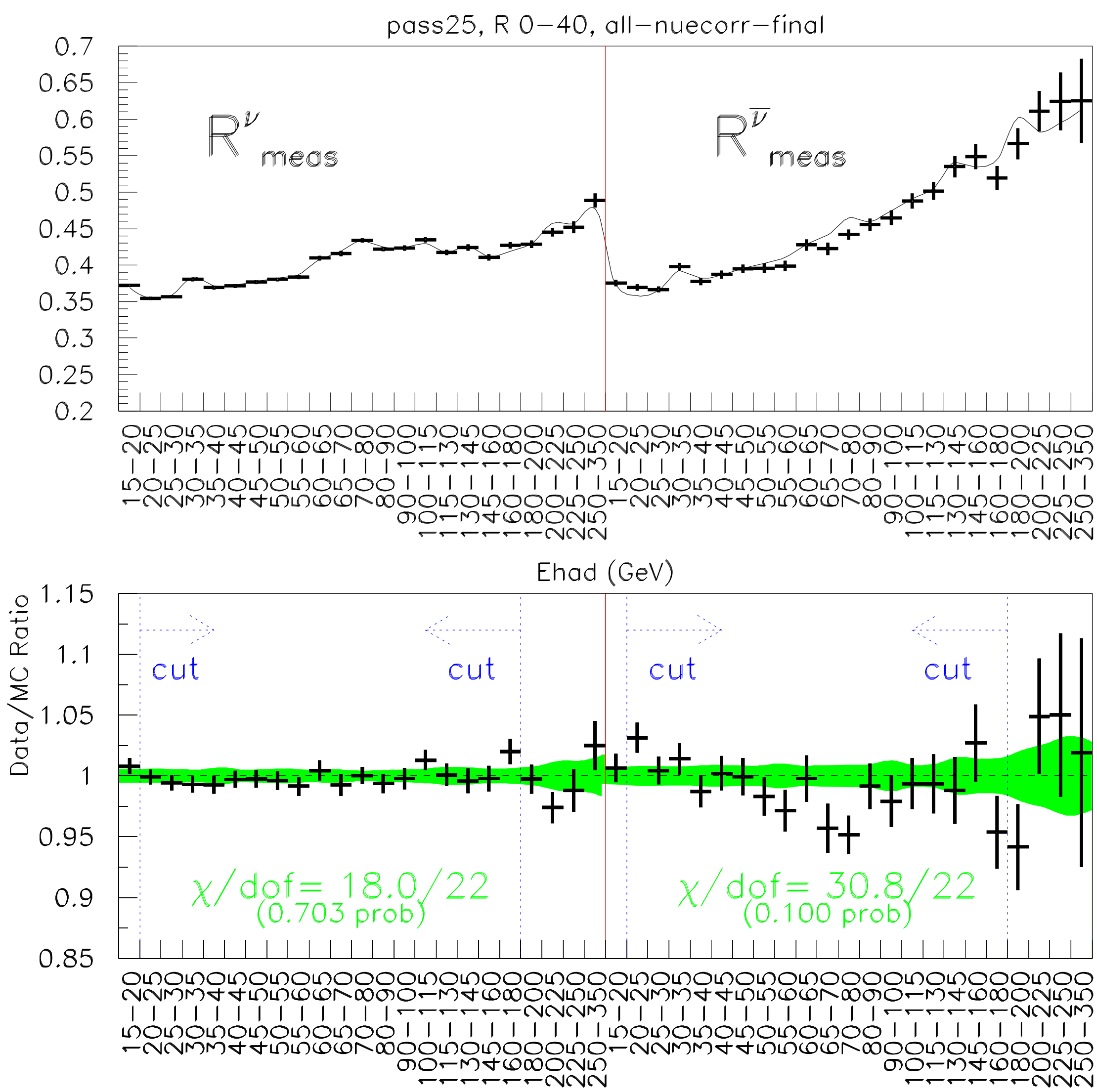


"Radial" Bins

Stability of R_{exp} (cont'd)

R_{exp} vs. E_{had}: Checks stability of final measurement over full kinematic range

Checks almost everything - backgrounds, flux, detector modeling, cross section model, ...



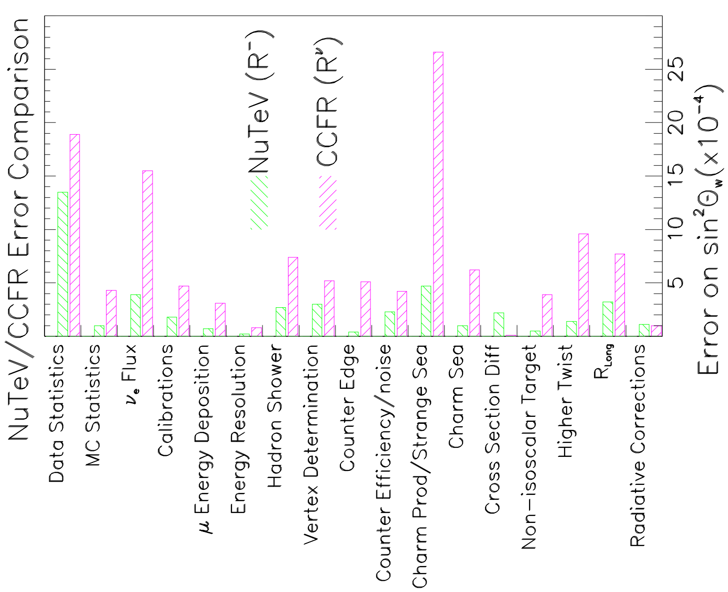
(Green band is $\pm 1\sigma$ systematic uncertainty)

The Result

$$\sin^2\theta_W^{(on-shell)} = 0.2277 \pm 0.0013\,(stat) \pm 0.0009\,(syst)$$
$$- 0.00022 \cdot \left(\frac{M_{top}^2 - (175\,GeV)^2}{(50\,GeV)^2}\right)$$
$$+ 0.00032 \cdot \ln\left(\frac{M_{Higgs}}{150\,GeV}\right)$$

- In good agreement with previous νN: $\sin^2\theta_W$ = 0.2277 $\pm$ 0.0031
- Standard Model fit (LEPEWWG): 0.2227 ± 0.00037

SOURCE OF UNCERTAINTY	$\delta\sin^2\theta_W$	δR^{ν}_{exp}	$\delta R^{\overline{\nu}}_{exp}$
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



In the end, why is NuTeV so much more precise than CCFR?

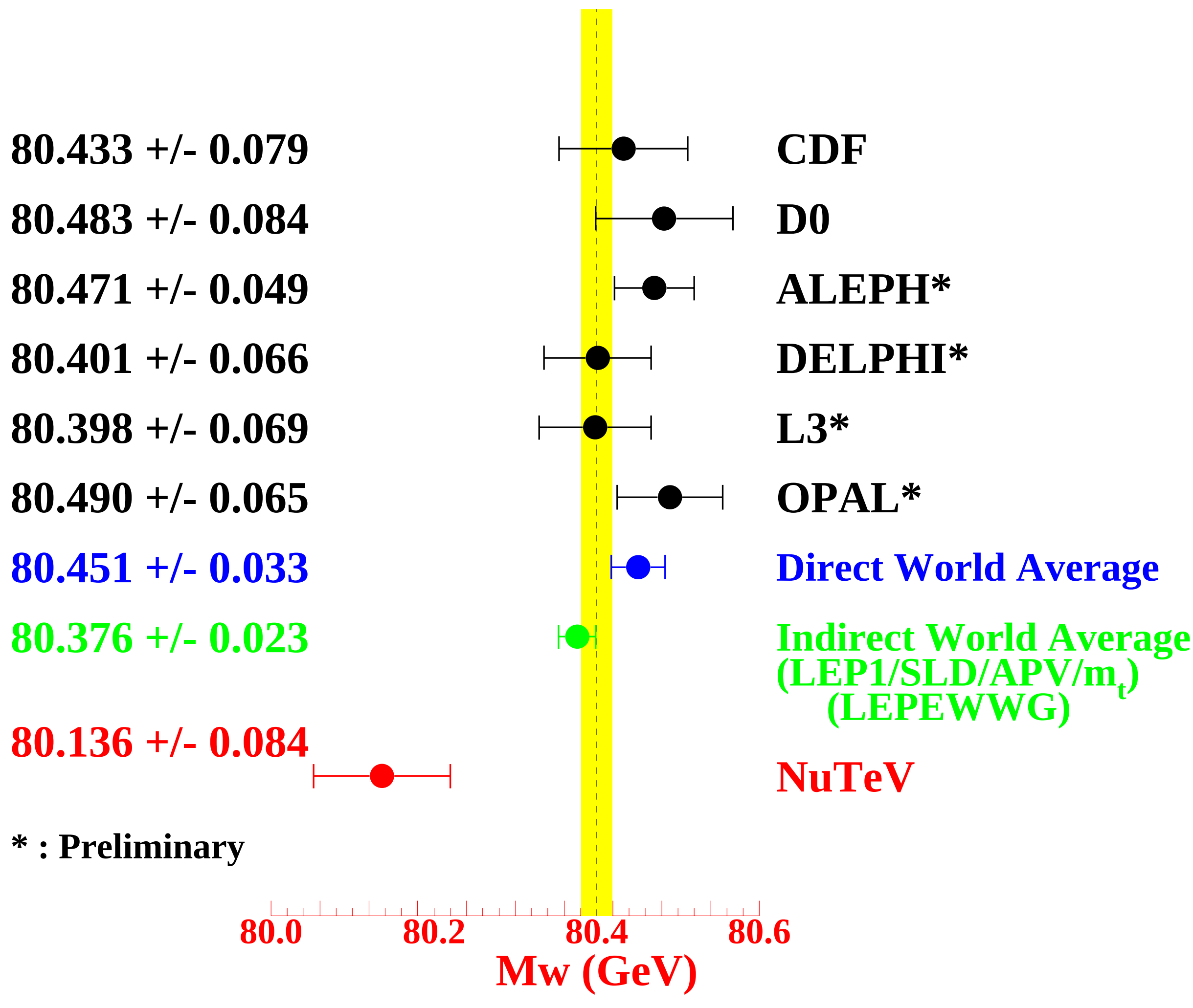
- R^- method makes charm production error small
- Few K_L because of beam $\Rightarrow \nu_e$ greatly reduced

Comparison to Direct M_W

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

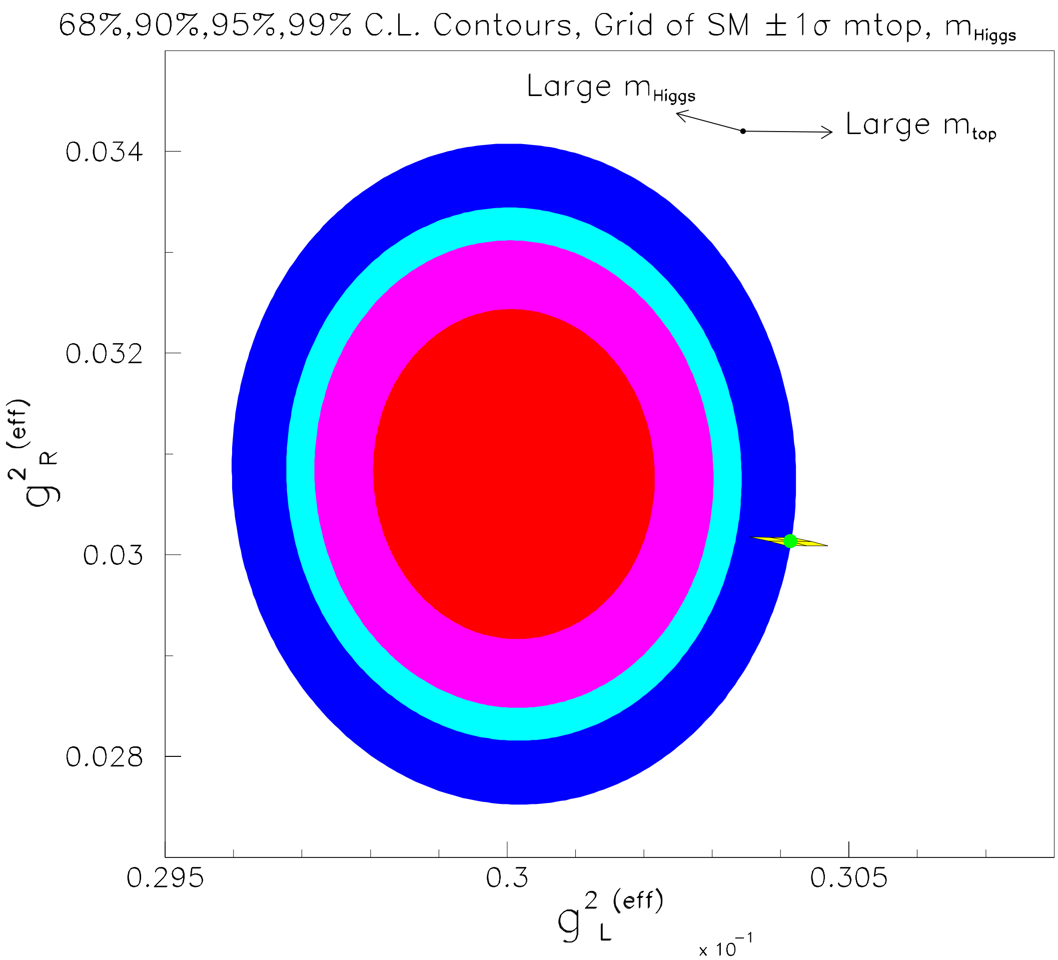
Given the precise measurement of the Z mass from LEP...

...can express NuTeV $\sin^2\theta_W$ as an equivalent M_W



- In standard electroweak theory, NuTeV precision is comparable to a single direct measurement of M_W
- More inconsistent with direct M_W than other data

Quark Couplings: $(g_L^{eff})^2$ and $(g_R^{eff})^2$



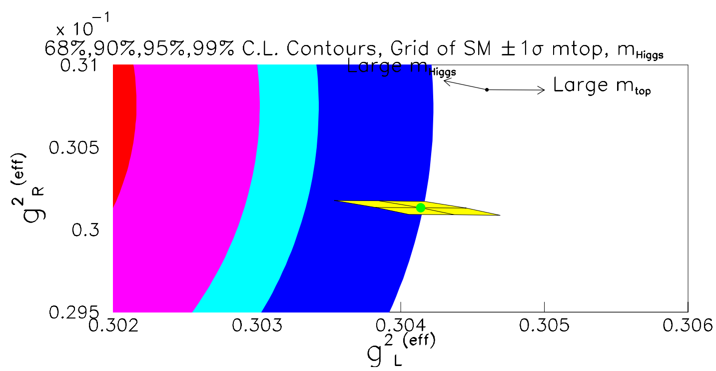
2 parameter fit to R^ν, $R^{\overline{\nu}}$:

$$R^\nu = g_L^2 + r\, g_R^2$$
$$R^{\overline{\nu}} = g_L^2 + \frac{1}{r}\, g_R^2$$

$$g_L^2 \equiv u_L^2 + d_L^2$$
$$g_R^2 \equiv u_R^2 + d_R^2$$

NuTeV measures:

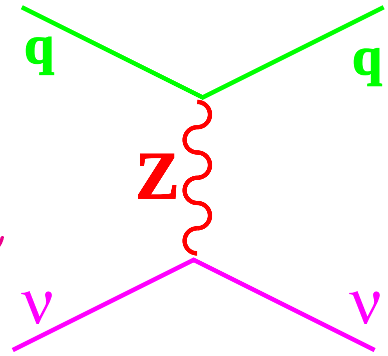
$$(g_L^{eff})^2 = 0.3001 \pm 0.0014$$
$$(g_R^{eff})^2 = 0.0308 \pm 0.0011$$
$$\rho_{corr} = -0.02$$



- Assuming predicted ν coupling, $(g_L^{eff})^2$ appears low

Interpretations

- Symmetry violations in QCD
- New Interactions
- Neutral current coupling of ν



Symmetry Violating QCD Effects

Paschos-Wolfenstein, $R^- = \frac{1}{2} - \sin^2\theta_W$

- **Assumes total u and d momenta equal in target**
- **Assumes sea momentum symmetry, $s = \overline{s}$ and $c = \overline{c}$**
- **Assumes nuclear effects common in W/Z exchange**

Violations of these symmetries can arise from

1. **$A \neq 2Z$, e.g., high Z neutron excess** *(CORRECTED)*
   - ***Changes d/u of target $\Rightarrow$ mean NC coupling***
   - ***Large correction, $\sim .008$, known precisely from material survey, chemical assay of target***
2. **Isospin violating PDFs, e.g., $u_p(x) \neq d_n(x)$**
   - ***Changes d/u of target $\Rightarrow$ mean NC coupling***

   (Sather; Rodinov, Thomas and Londergan; Cao and Signal)
3. **Asymmetric heavy seas, e.g., $s(x) \neq \overline{s}(x)$**
   - ***Strange sea doesn't cancel in R^-***

   (Signal and Thomas; Burkhardt and Warr; Brodsky and Ma)
4. **Nuclear Effects Different for NC/CC**
   - ***Changes R^ν, $R^{\overline{\nu}}$ directly***
   - ***Shadowing region (low x), EMC region (high x)***

   (Thomas and Miller; Schmitt et al; Kumano)

Symmetry Violation in the Nucleon

Strange-Antistrange Sea Asymmetry

- If $S-\overline{S}\sim +0.0020$, $\Longrightarrow\ \delta\sin^2\theta_W = -0.0026\ (m_c=0)$

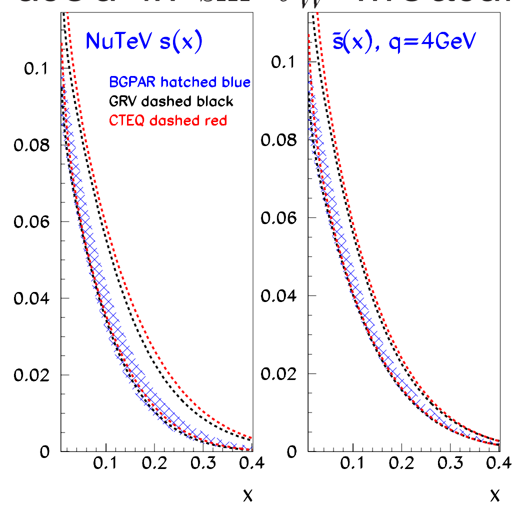
  (S. Davidson *et al.* ,hep-ph/0112302)

- Significant overestime of effect on $\sin^2\theta_W$

- But NuTeV dimuon data measures s, $\overline{s}$ separately in cross-section model used in $\sin^2\theta_W$ measurement

$$S-\overline{S} = -0.0027\pm0.0013$$
$$\Longrightarrow\ \delta\sin^2\theta_W \sim +0.0020\pm0.0009$$

Then $\sin^2\theta_W = 0.2297\pm0.0019$
(3.7σ above SM)



Isospin symmetry violations

- Small nucleon isospin is established; $m_n\neq m_p$
- *LARGE* isospin violation needed to explain NuTeV,

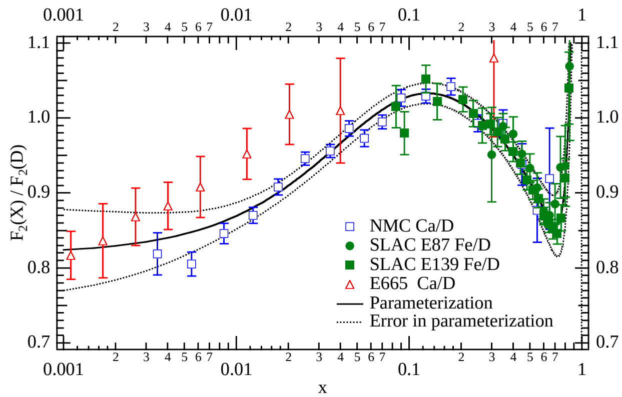
$$\int[d_p(x)-u_n(x)]/\int[d_p(x)+u_n(x)]\sim 5\%$$

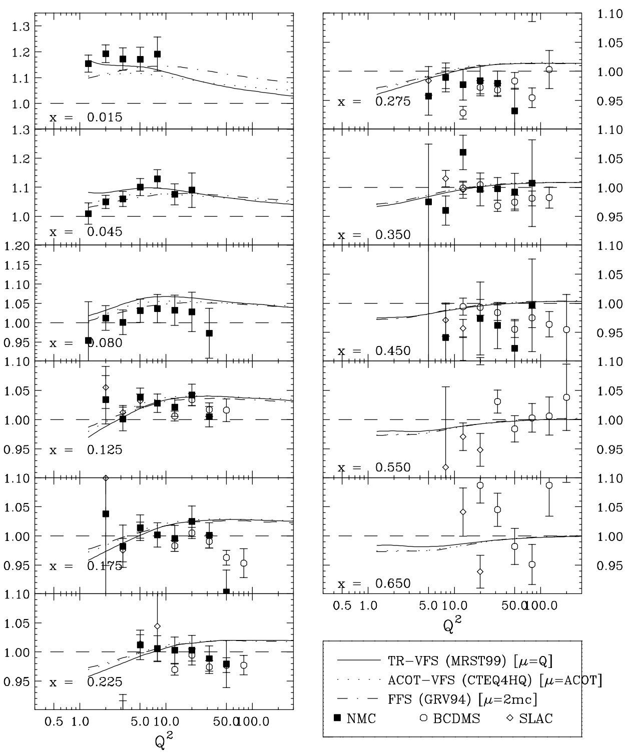
Bag model	Meson Cloud model
Thomas *et al.* , Mod. Phys. Lett**A9**, 1799.	Cao & Signal, Phys. Rev. **C62**, 015203.
↪ $\delta\sin^2\theta_W^{(on-shell)} = -0.0001$	↪ $\delta\sin^2\theta_W^{(on-shell)} = +0.0002$
↪ ~ 0.0004 shifts at high, low x cancel	

- Are models trustworthy? Can global fits accomodate large isospin violation to explain NuTeV?

Process-Dependent Nuclear Effects

- Nuclear effects on PDFs are large
- NuTeV analysis uses only PDFs on iron

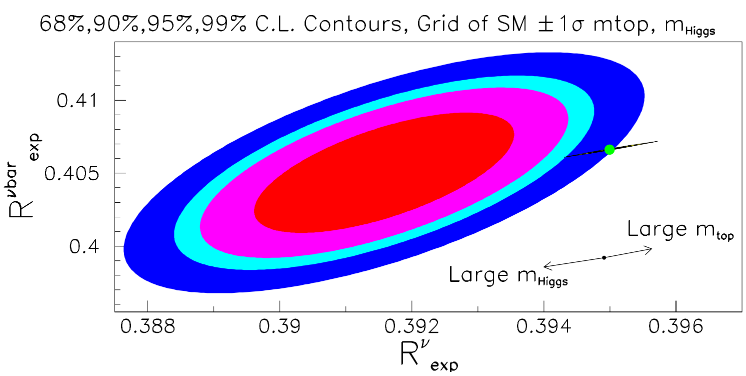




- Why believe these effects are process independent?
- Models: e.g., Pomeron description of high Q^2 shadowing
  - $\hookrightarrow$ NMC High Q^2 data shows predicted $\log Q^2$ behavior
- $F_2^{\nu\ CC}/F_2^{\ell}$ supports picture
- No independent test of ν NC

Process-Dependent Nuclear Effects (continued)

- VMD predicts nuclear shadowing different for W, Z
  (G. Miller and A. Thomas, hep-ex/0204007)
  - ↪ No evidence for predicted $1/Q^2$ behavior in NuTeV kinematic region $x > 0.01$ (NMC)
  - ↪ Effect would **increase** R^ν, $R^{\overline{\nu}}$
  - ↪ Low $x \Rightarrow$ effect cancels in R^-

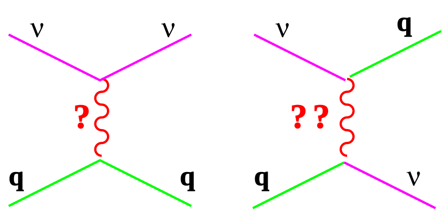


Interesting idea, but...
inconsistent with NuTeV

Also on the market...

- EMC effect is absent in ν charged-current? (Schmitt *et al*)
  - ↪ Would explain NuTeV $\sin^2\theta_W$
  - ↪ But would violate $F_2^{\nu\ CC}/F_2^{\ell}$ agreement
- Data-driven "nuclear PDF" fit, allowing for flavor-dependent nuclear effects (Kumano)
  - ↪ Small effect on NuTeV analysis

New Tree Level Physics?

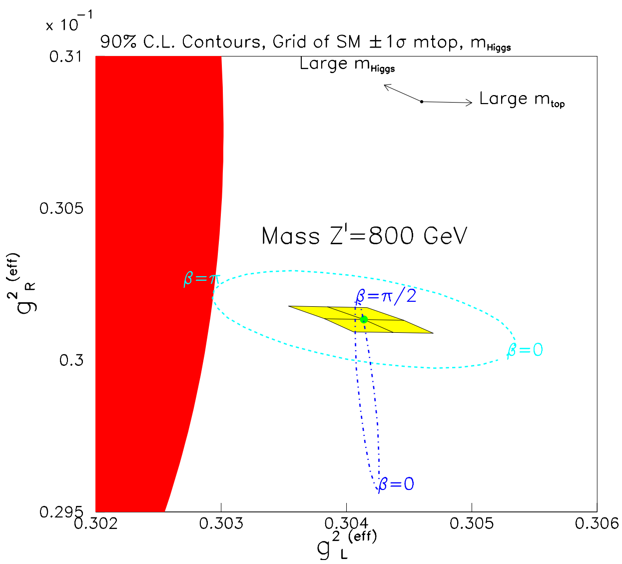


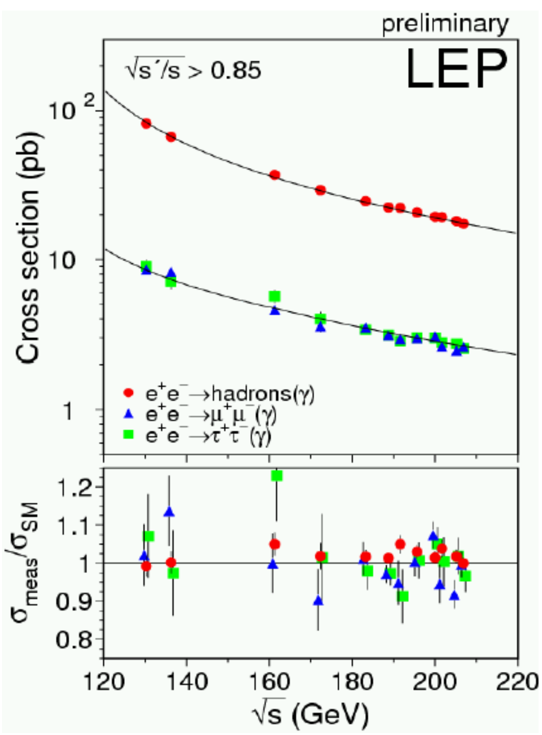
- "Natural" interpretation of result
- Z', LQ, etc.
- Must enhance LL not LR coupling

- $E(6)$ Z' accounts for NuTeV?
  - ↪ Contact terms shift LR coupling
  - ↪ Mixing (here 3×10^{-3}) to Z severely limited by LEP/SLD

$$(Z' \equiv Z_\chi cos\beta + Z_\psi \sin\beta)$$

(Cho *et al.*, Nucl. Phys. **B531**, 65.
Zeppenfeld and Cheung, hep-ph/9810277.
Langacker *et al.*, Rev. Mod. Phys. **64** 87.)

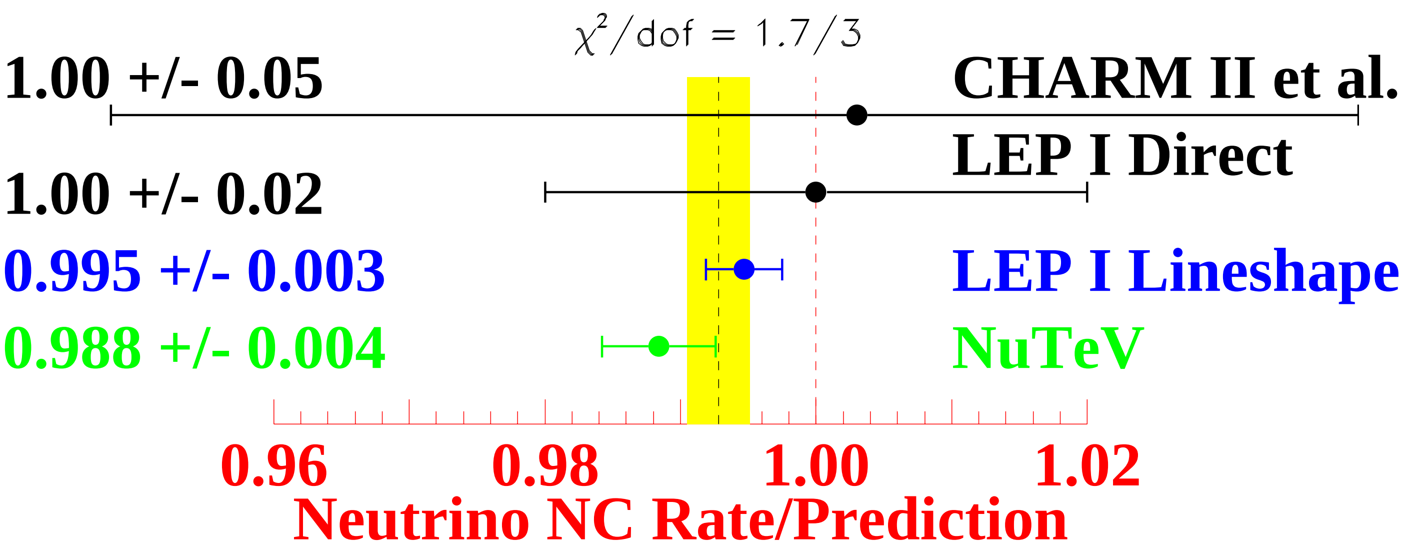




- "Almost sequential" Z' with opposite coupling to ν
  - ↪ NuTeV preferred mass range: $1.2^{+0.3}_{-0.2}$ TeV
  - ↪ CDF/D0 limits: $M_{Z'_{SM}} \gtrsim 700$ GeV. LEP II?
- Contact interaction with LL coupling
  - ↪ $\nu\nu qq$ $\Lambda_{LL} = 4.5 \pm 1$ TeV
  - ↪ Consistent with other ℓ–q data? (Barger,Cheung,Hagiwara,Zeppenfeld)
  - ↪ Depends on:
    - ⋆ Lepton RH couplings
    - ⋆ How seriously one takes 2–3σ discrepancies in this data ("CKM unitarity", $e^+e^- \to q\overline{q}$, APV?)

Neutral Current ν Interactions

- LEP I measures Z lineshape and decay partial widths to infer the "number of neutrinos"
  - ↪ Their result is $N_\nu = 3\frac{\Gamma_{exp}(Z\to\nu\overline{\nu})}{\Gamma_{SM}(Z\to\nu\overline{\nu})} = 3\times(0.9947\pm0.0028)$
  - ↪ LEP I "direct" partial width ($\nu\nu\gamma$) $\Rightarrow N_\nu = 3\times(1.00\pm0.02)$
- $\overset{(-)}{\nu}_\mu e^- \to \overset{(-)}{\nu}_\mu e^-$ scattering (CHARM II *et al.*)
  - ↪ PDG fit: $g_V^2+g_A^2 = 0.259\pm0.014$, cf. 0.258 predicted
- NuTeV can fit for a deviation in $\nu\&\overline{\nu}$ NC rate
  - ↪ $\rho_0^2 = 0.9884\pm0.0026(stat)\pm0.0032(syst)$



- In this interpretation, NuTeV confirms and strengthens LEP I indications of "weaker" neutrino neutral current
  - ↪ NB: This is not a unique or model-independent interpretation!
  - ↪ Theoretically awkward to accomodate without changing $W\ell\nu$ vertex as well
    - ⋆ Latter is possible? (T. Takeuchi, hep-ph/0209109)

Conclusions

Surprise!

- NuTeV measures R^ν, $R^{\overline{\nu}}$ to precisely determine $\sin^2\theta_W$
- NuTeV expects 0.2227 ± 0.0003; measures

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

- Given inconsistency with Standard Model, we present result also in model-independent frameworks
  - ↪ Data prefers lower effective left-handed coupling
- QCD interpretations (isospin violation, process-dependent nuclear effects) possible, but none are "attractive"
  - ↪ So, perhaps we've found something unattractive?
- Neutral-current couplings of neutrinos may be suspect
  - ↪ Only other precise measurement,
    LEP Invisible Z Width,
    also suggests a discrepancy
  - ↪ Consistent with earlier νN measurements
- Pending *confirmation*, *refutation*,
  or *alternative explanations*, it's a puzzle.

Contents