Theoretical Interpretations

of the

NuTeV Results

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Based on: hep-ph/0112302 (DFGNS)

Also: hep-ex/0110059, hep-ex/0203004, PRD64(01),112006(NuTeV)
hep-ph/0111385, hep-ph/0202152,hep-ex/0204007 (other theory)

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Outline

- NuTeV measures $\sin^2\theta_W = .2277 \pm .0013 \pm .0009$
  ($SM : 0.2227 \pm .0004,$ LEPEWWG)

  $\Rightarrow \mathcal{NEW\ PHYSICS}$ **??**

- loops?
  - modifications to $Z\bar{\nu}\nu$: $\left\{ \begin{array}{c} Z\bar{\nu}\nu \\ W\bar{\nu}\mu \end{array} \right\}, \left\{ \begin{array}{c} Z\bar{\nu}\nu \\ Z\bar{\mu}\mu \end{array} \right\}$ no, but...
  - oblique no
  - SUSY no

- tree level (four fermion vertices)?
  - leptoquarks euuh, almost
  - Z' a bit better, but ugly

  .....

- "Standard Model systematics" ?:
  - $s - \bar{s}$ momentum asymmetry?
  - LO vs NLO parton distributions?

- summary: no attractive new physics explanation
  SVP NuTeV: NLO analysis
  $s \neq \bar{s}$ pdf (re)fit: BPZ? MRST? CTEQ?

What new physics is needed?

NuTeV measures R^{ν}_{exp} *to small*:

$$R^{\nu}_{exp} = \frac{\text{short events}}{\text{long events}} = \frac{\{\nu_e, \nu_\mu\}N \to \{\nu_e, e, \nu_\mu\}X}{\nu_\mu N \to \mu X}$$

- reduce ν_e flux?

e.g.: $\nu_e \to \nu_s$ oscillations (Giunti and Laveder)
new lepton flavour violating physics in K decays?

$\Rightarrow NO$: NuTeV *measures* ν_e flux

- increase $\sigma(\nu_\mu N \to \mu X)$?

$\Rightarrow NO$: $(\nu_\mu d \to \mu u)$ constrained by $(\pi \to \mu\bar{\nu})$

★ must *reduce* $\sigma(\nu_\mu N \to \nu_\mu X)$

$\Rightarrow$ new physics that interferes negatively
with the SM

modify Z couplings?

NuTeV can be explained by lower ($\sim -0.6\%$) $Z\nu_\mu\bar{\nu}_\mu$ coupling, (re: $-(0.53 \pm 0.28)\%$ deviation in Γ_Z^{inv}).
Models:

- modify the ν couplings: $(Z\bar{\nu}\nu), (W\bar{\nu}\mu)$
  e.g.: SM neutrinos mix with heavy ν_R (extra dim or not)

$$T : \nu_{flav} \to \nu_{light} \text{ NOT unitary}$$
$$\Rightarrow g_{Z\bar{\nu}\nu} = g_{SM}(1 - \epsilon_{\mu\mu})$$
$$g_{W\bar{\nu}\mu} = g_{SM}(1 - \epsilon_{\mu\mu}/2)$$ ...conflicts with $\mu \to e\nu\bar{\nu}$.

- modify the Z couplings $(Z\bar{\nu}\nu), (Z\bar{\mu}\mu)$:
  - fit SM data for $g_{Z\bar{f}f}$, generation universal (...plot)
  - generation non-universal? (Ma and Roy)
    ...but $\frac{Z \to \bar{e}e}{Z \to \bar{\mu}\mu} = 1.0009 \pm 0.003$

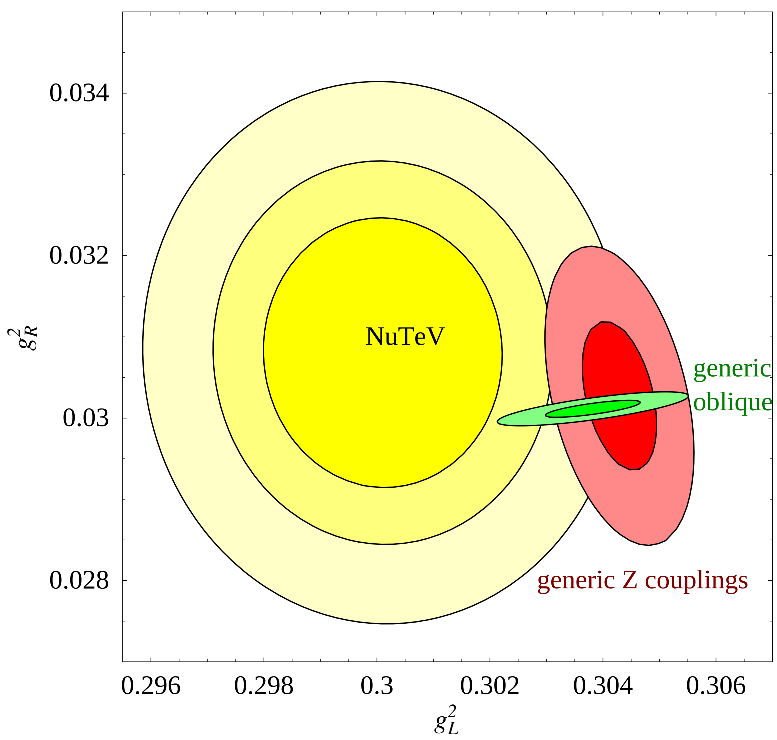
oblique corrections?

If $\Lambda_{NEW} \gg M_Z$, new physics coupled to the vector bosons can be parameterized in a *model independent* way by oblique parameters : $\epsilon_1, \epsilon_2, \epsilon_3 \approx S, T, U$.

$$\frac{\delta g_L^2}{g_L^2} = 2.8\,\delta\epsilon_1 - 1.1\,\delta\epsilon_3 \; ; \qquad \frac{\delta g_R^2}{g_R^2} = -0.9\,\delta\epsilon_1 + 3.7\,\delta\epsilon_3$$

- fit EW precision data for $\epsilon_{1,2,3}$ (...plot)

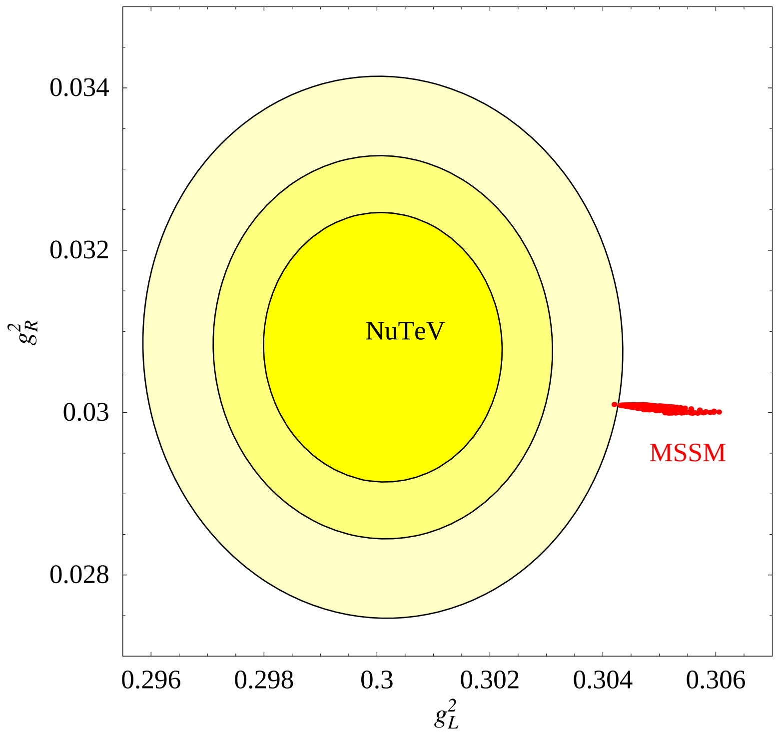
modified Z couplings, and oblique



MSSM

- SUSY oblique ? no

- motivated by LEP: leptonic — $m_h \sim 40$ GeV
  direct search — $m_h > 115$ GeV
  hadronic — $m_h \sim 500$ GeV
  $\Rightarrow$ light $\tilde{\nu}$ and $\chi^{\pm}$, heavy $\tilde{q}$



tree level ($\sim$ four fermion vertices)

Need new physics which induces effective operator:

$$\epsilon \; 2\sqrt{2}G_F(\bar{\nu}_\mu\gamma^\alpha\nu_\mu)(\bar{q}_1\gamma_\alpha q_1) \qquad q_1 = \{u, d\}, \;\; \epsilon \simeq .01$$

leptoquarks ? ??

vector or scalar bosons that couple to a lepton and quark

SU(2) triplets and singlets induce

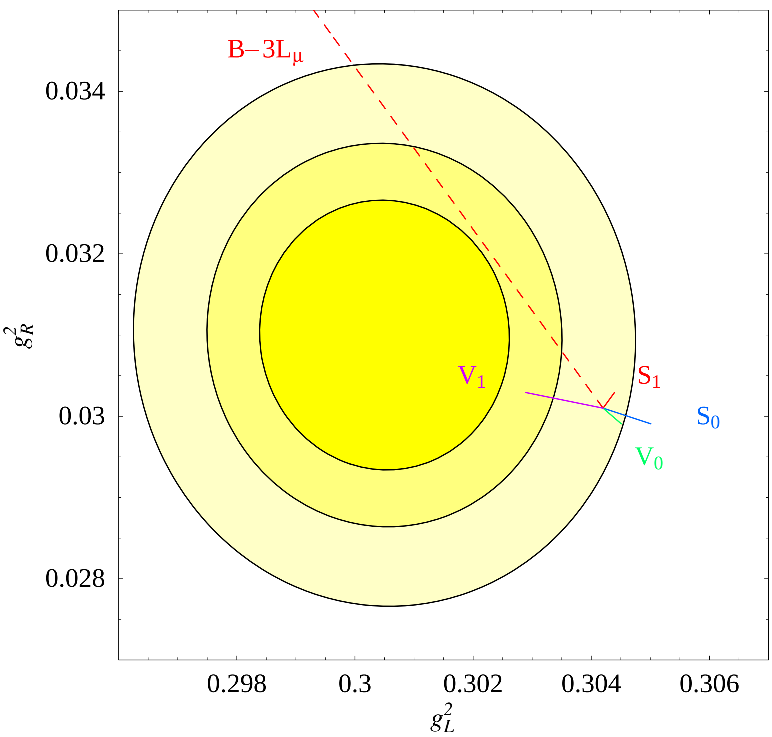
1. either
$$-|\lambda_{\mu q}|^2(\bar{\nu}_\mu\gamma^\alpha\nu_\mu)(\bar{q}\gamma_\alpha q)$$
$\mathcal{WRONG\ SIGN}$! (decreases $\sin^2\theta_W$ wrt the SM)

2. or also the operator $(\bar{\mu}\gamma^\alpha\nu_m u)(\bar{u}\gamma_\alpha d)$, which is constrained by $\pi \to \mu\nu$ to have coeff $\epsilon < .002$.

loophole: split the masses of SU(2) triplet leptoquarks... can (probably) explain NuTeV without conflict with other data. (should be seen at Tevatron/LHC)

• RPV SUSY contains SU(2) doublet and singlet "leptoquarks", so cannot explain NuTeV

leptoquarks and Z'_{B-3L_μ} ?



Unmixed Z' ?

A new Z' can

1. contribute to oblique parameters by mixing with the Z
2. change the Z couplings by mixing with the Z
3. induce 4-fermion operators $\propto Q_q Q_\nu (\bar{\nu}_\mu \gamma^\alpha \nu_\mu)(\bar{q}\gamma_\alpha q)$

$$\Rightarrow \textit{unmixed } Z'$$

A model: (...but also contributes to g_R^2)

- no $U'(1) * U_Y^2(1)$ anomalies
- Z' interacts with 2nd (1st) generation leptons (quarks)

$$\Rightarrow B - 3L_\mu$$

(but ?? m_ν ??)

Other constraints:

1. colliders: $m'_Z < 10$ GeV, or $m'_Z > 600$ GeV
2. $(g-2)_\mu \Rightarrow m'_Z > 2$ GeV

$$\Rightarrow m'_Z > 600 \text{ GeV}, \; g' \sim 1$$

$$\Rightarrow 2\text{GeV} < m'_Z < 10 \text{ GeV}, \; g' \simeq .001 \; (!)$$

could produce cosmic rays above the GZK cutoff via " Z' bursts" : $E_\nu m_\nu \sim m_{Z'}^2$
for $E_\nu \sim 10^{10}$ eV, $m_\nu \sim \sqrt{\Delta m_{atm}^2}$, and $M_{Z'} \sim 3$ GeV

BACK TO THE STANDARD MODEL...

NuTeV measures:

$$R^{\nu}_{exp} = \frac{\text{short events}}{\text{long events}} = \frac{\{\nu_e, \nu_\mu\}N \to \{\nu_e, e, \nu_\mu\}X}{\nu_\mu N \to \mu X}$$

want to extract :

where $r \equiv \frac{\sigma(\bar{\nu}\mathcal{N} \to \bar{\mu}X)}{\sigma(\nu\mathcal{N} \to \mu X)} \simeq \frac{3\bar{q}+q}{3q+\bar{q}}$

$$R_\nu \equiv \frac{\sigma(\nu\mathcal{N} \to \nu X)}{\sigma(\nu\mathcal{N} \to \mu X)} = g_L^2 + r g_R^2$$

$$R_{\bar{\nu}} \equiv \frac{\sigma(\bar{\nu}\mathcal{N} \to \bar{\nu} X)}{\sigma(\bar{\nu}\mathcal{N} \to \bar{\mu} X)} = g_L^2 + \frac{1}{r} g_R^2,$$

$$g_L^2 = \frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W, \quad g_R^2 = \frac{5}{9}\sin^4\theta_W$$

then NuTeV fits for $\sin^2\theta_W, m_c$.

...need to include effects of:

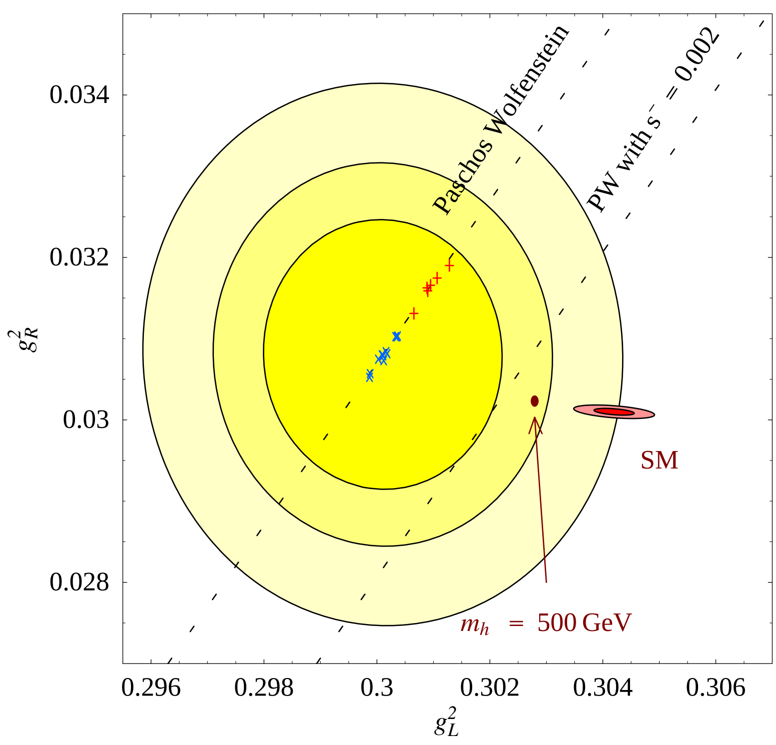
1. 1.6% ν_e contamination of ν_μ beam
2. cuts, NC/CC misidentification (...Monte Carlo...)
3. EW corrections, QCD
4. 2nd generation quarks, non isoscalarity of target

There is a theoretically clean ratio:

$$R_{\mathrm{PW}} \equiv \frac{R_\nu - r R_{\bar{\nu}}}{1-r} = \frac{1}{2} - \sin^2\theta_{\mathrm{W}} + \ldots$$

where we theorists can study effects of 3. and 4.
($\Leftrightarrow$ what is " + ..."?)

NuTeV $\rightarrow g_L^2, g_R^2 \leftarrow$ SM



x MRST

+ CTEQ

partons— $s_W^2 \pm 1\%$ in DIS?

$$R_{PW} = \frac{d\sigma(\nu N \to \nu X) - d\sigma(\bar\nu N \to \bar\nu X)}{d\sigma(\nu N \to \mu N X) - d\sigma(\bar\nu N \to \bar\mu X)}$$
$$= \frac{1}{2} - \sin^2\theta_W$$
$$+ \Big[(u^- - d^-) + (c^- - s^-)\Big] \{1.3 + \mathcal{O}(\alpha_s) NLO\}$$

$$q^- \equiv \int_0^1 dx x (q(x) - \bar q(x))$$

NuTeV assumes $u^n(x) = d^p(x)$ (isospin),

$$\frac{u^- - d^-}{u^- + d^-} \sim \frac{m_u + m_d}{\Lambda} \sim .01, \quad \Rightarrow \Delta s_W^2 \simeq .002$$

and that $s(x) = \bar s(x)$:

$$\text{if } s^- \sim .002 \Rightarrow \sin^2\theta_W|_{NuTeV} \simeq \sin^2\theta_W|_{SM} + \sigma$$

...pdfs, LO, NLO...??
use of R_{PW} is a theoretical simplification (...cuts, different ν and $\bar\nu$ spectra, r not measured...), so cancellations among pdfs, NLO effects are disrupted.

How big are NLO corrections? Difficult to quantify from outside— better to upgrade analysis to NLO...

a momentum asym in the strange sea?

BPZ fit parton distribution functions at NLO, *allowing* $s(x) \neq \bar{s}(x)$

- all available ν DIS cross-section data (BEBC,CDHS, CDHSW), EW corrections included, also μ DIS and Drell-Yan
- best fit ($\Delta\chi^2 = -25$) gives $s^- \sim .002$, due to CDHSW at $x \sim .65$ (see figures)

NuTeV hep-ex/0102049: LO fit to CCFR/NuTeV dimuon data, allowing $s(x) \neq \bar{s}(x)$

- restrictive functional form for $s(x)$ and $\bar{s}(x)$: (not allow $s(x) > \bar{u}(x) + \bar{d}(x)$ at $x > .5$, net strangeness in the nucleon, significant NLO effects)
- few events at $x > .5$... $\Rightarrow$ inconsistent with CDHSW?
- find $s^- = -.0027 \pm 0.0013$ ... *opposite* sign!

$\Rightarrow$ information about $s(x)$, and $\bar{s}(x)$, not reliable for s^-.

NuTeV hep-ex/0203004 reply:

1. the $\sin^2\theta_W$ discrepancy cannot be explained with the s^- distribution they extract (their $s^- < 0$).
2. cuts, charm threshhold, and they do not measure R_{PW}, $\Rightarrow \Delta s_W^2 \sim -1.3 s^-/2$

1. $\Rightarrow$ an NLO global fit to all the ν DIS cross-section data is needed...BPZ? MRST?

2...if not measuring R_{PW}, then pdfs do *not* cancel, and can NuTeV measure $\sin^2\theta_W \pm 1\%$ at LO?

BPZ strange sea fit