Pondering the NuTeV anomaly

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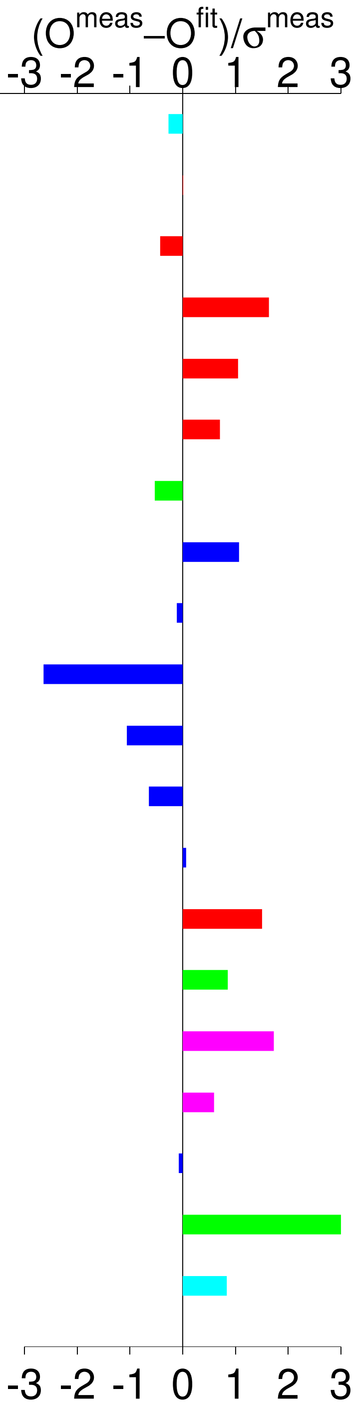
- The context
- The NuTeV electroweak result and its problems
- A catalogue of possible new physics explanations
- Summary

In collaboration with Davidson, Forte, Rius, Strumia

The global SM fit

Winter 2002

	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-.27
m_Z [GeV]	91.1875 ± 0.0021	.01
Γ_Z [GeV]	2.4952 ± 0.0023	-.42
σ^0_{had} [nb]	41.540 ± 0.037	1.63
R_l	20.767 ± 0.025	1.05
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.70
$A_l(P_\tau)$	0.1465 ± 0.0033	-.53
R_b	0.21646 ± 0.00065	1.06
R_c	0.1719 ± 0.0031	-.11
$A^{0,b}_{fb}$	0.0994 ± 0.0017	-2.64
$A^{0,c}_{fb}$	0.0707 ± 0.0034	-1.05
A_b	0.922 ± 0.020	-.64
A_c	0.670 ± 0.026	.06
A_l(SLD)	0.1513 ± 0.0021	1.50
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	.86
m_W [GeV]	80.451 ± 0.033	1.73
Γ_W [GeV]	2.134 ± 0.069	.59
m_t [GeV]	174.3 ± 5.1	-.08
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	3.00
$Q_W(Cs)$	-72.39 ± 0.59	.84



$$\boxed{M_H = 85(81)\ \text{GeV},\ M_H < 196\ \text{GeV at 95\% CL}}$$

χ^2/d.o.f.=28.8/15 (19.6/14) $\Rightarrow$ prob=1.7(14)%.

Some anomalies are more anomalous than others...

observable	date	relevance	papers	problem	status
R_b, R_c	~1995	3.6,2.5σ	100+	exp	solved
A_{LR} vs A^b_{FB}	1995$\longrightarrow$	3-3.5σ	< 10	?	standing
High Q^2 Hera	`hep-ex/9702015`	?	280	exp	solved
A_{PV}	1997	$\sim 3\sigma$	150	th	solved ?
ε'/ε	1998	?	100+	th	solved?
a_μ	`hep-ex/0102017`	2.6σ	340	th	solved?
NuTeV dimuons	`hep-ex/0104037`	many σ	5	?	standing
$\ell\gamma \not{E}_T$(CDF)	`hep-ex/0110015`	$\sim 3\sigma$	2	?	standing
NuTeV $\sin^2\theta_W$	`hep-ex/0110059`	3σ	23	?	standing
$\nu 02\beta$	`hep-ph/0201231`	2-3σ	40	not existing	solved

A^b_{FB} and the SM fit

The SM fit to M_H is NOT satisfactory!

Using only the most important data (M_W,Γ_ℓ, all asymmetries, R_b) but NOT NuTeV: $M_H = 90$ GeV, $M_H < 195$ GeV (95% CL) χ^2/dof=14.1/4, $\boxed{\text{prob=0.7\%}}$

Excluding or diluting the hadronic asymmetries, a consistent picture emerges,

$$\boxed{M_H = 40 \text{ GeV}, \; M_H < 106 \text{ GeV (95\% CL)}}$$

$$\chi^2/\text{dof}=2.2/3, \text{ prob}=70\%$$

with a paradox: Chanowitz; Altarelli,Caravaglios,PG,Giudice,Ridolfi

LEP: $M_H > 113.5$ GeV

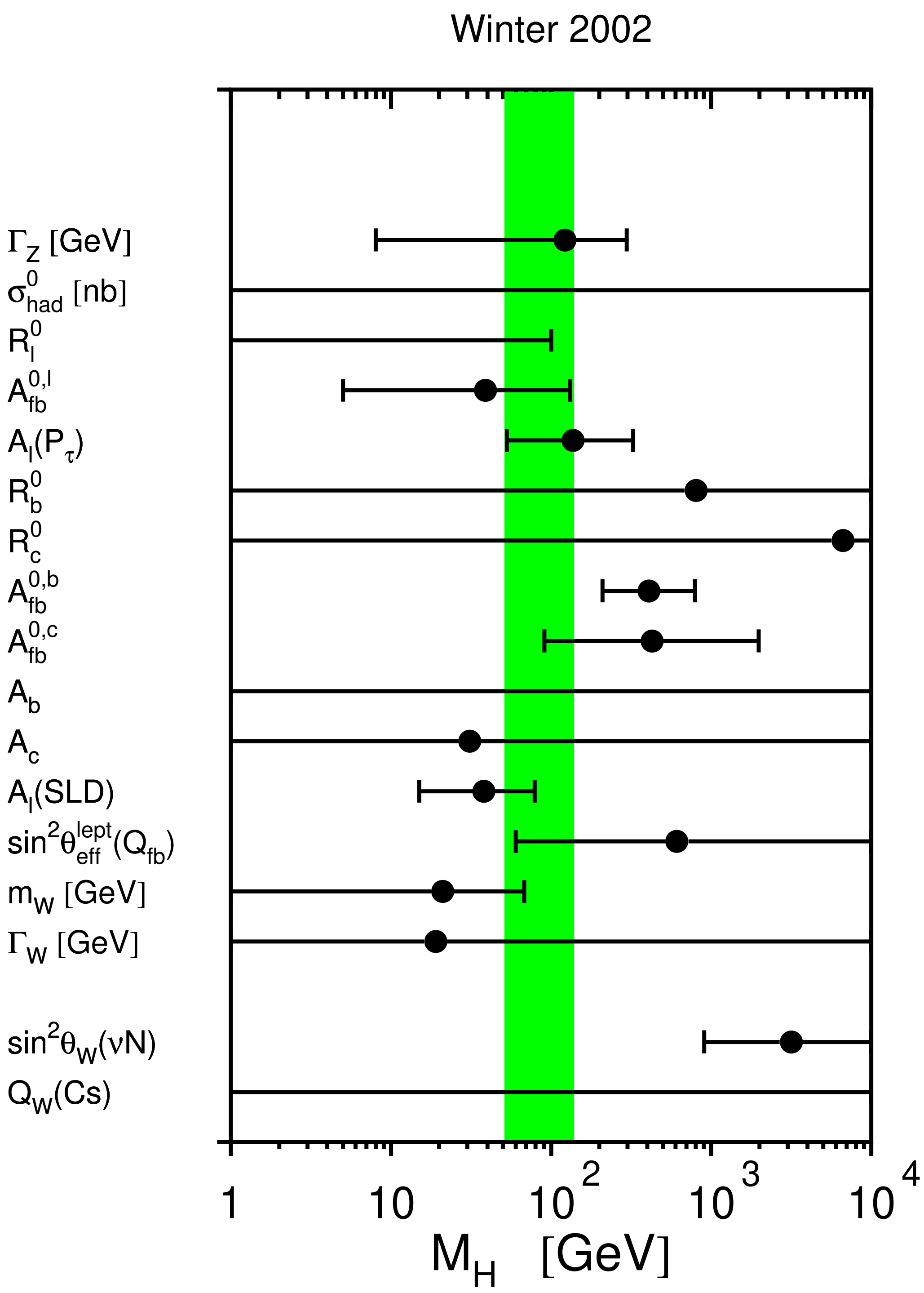
Why hasn't the Higgs been found?

There is some sensitivity to the choice of $\alpha(M_Z)$:

Ref.	$\Delta\alpha_h$	m_H	$m_H^{\max}$ 95% c.l.
BP01	0.02761(36)	40 GeV	106 GeV
MOR00	0.02738(20)	50 GeV	121 GeV
J01	0.027896(395)	33 GeV	89 GeV
Jeucl01	0.027730(209)	39 GeV	96 GeV
DH98	0.02763(16)	41 GeV	102 GeV
TY01	0.02747(12)	48 GeV	113 GeV

More important M_t: shifting M_t by 1σ up $\Rightarrow M_H < 150$ GeV

Higgs dependence of various observables



THE NUTEV ELECTROWEAK RESULT

Historically, νN DIS was crucial in establishing the SM

NuTeV measures ratios of NC/CC cross sections

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

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

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

The experimental $R^{exp}_{\nu,\bar\nu}$ differ from above because of

- 1.6% ν_e contamination of ν_μ beam
- cuts, NC/CC misidentification
- 2nd generation quarks, non isoscalarity of target
- QCD, EW corrections

Monte Carlo relates $R^{exp}_{\nu,\bar\nu}$ to $R_{\nu,\bar\nu}$. Most uncertainties drop in the Paschos-Wolfenstein relation

$$R_{\rm PW} \equiv \frac{R_\nu - rR_{\bar\nu}}{1-r} = \frac{\sigma(\nu\mathcal{N} \to \nu X) - \sigma(\bar\nu\mathcal{N} \to \bar\nu X)}{\sigma(\nu\mathcal{N} \to \ell X) - \sigma(\bar\nu\mathcal{N} \to \bar\ell X)} = \frac{1}{2} - \sin^2\theta_{\rm W},$$

Since $\frac{\partial R_\nu}{\partial s_W^2} \gg \frac{\partial R_{\bar\nu}}{\partial s_W^2}$, NuTeV fit $R^{exp}_{\nu,\bar\nu}$ for $\sin^2\theta_{\rm W}$ and m_c at Leading Order in QCD (with some improvements)

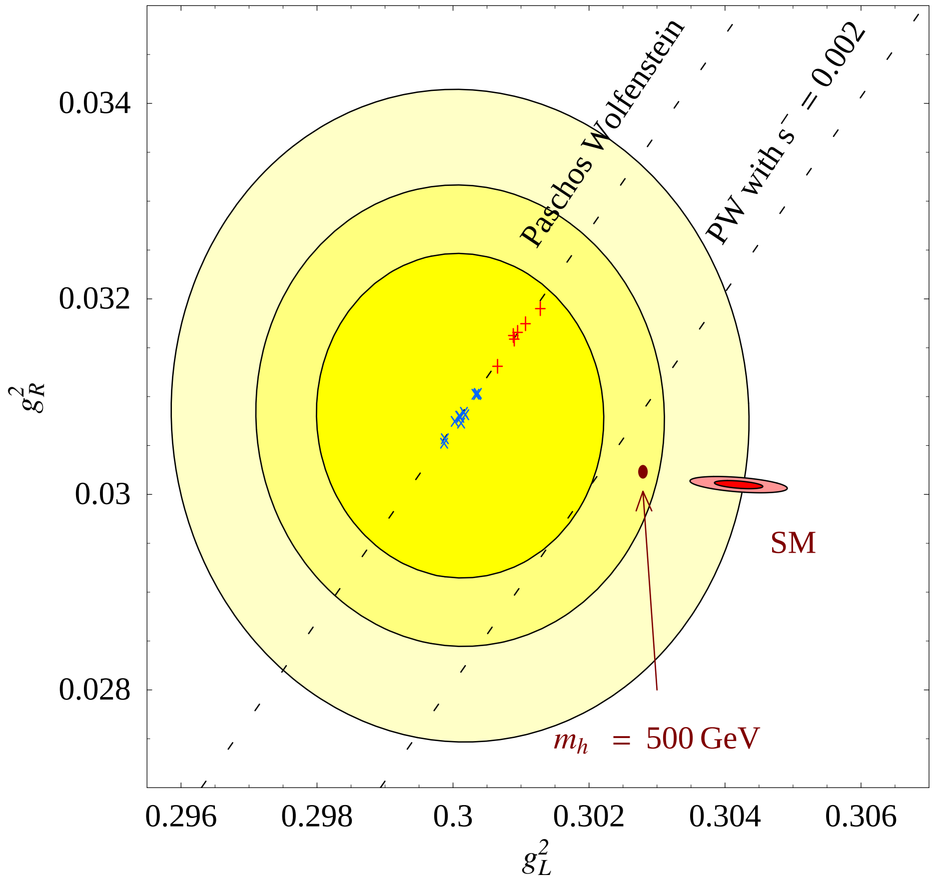
NuTeV relies heavily on MC, but $\approx R_{PW}$ (how well??).

NuTeV result

$s_W^2(\mathrm{NuTeV}) = 0.2276 \pm 0.0013\ (\mathrm{stat}) \pm 0.0006\ (\mathrm{syst}) \pm 0.0006\ (\mathrm{th})$
$-0.00003(M_t/\,\mathrm{GeV} - 175) + 0.00032 \ln(m_h/100\,\mathrm{GeV}).$

$s_W^2 \equiv 1 - M_W^2/M_Z^2$ (on-shell) $\Rightarrow M_W = 80.14 \pm 0.10\mathrm{GeV}$

Global fit $s_W^2 = 0.2226 \pm 0.0004 \Rightarrow 3\sigma$! (even more from direct M_W)



In terms of effective ν-q couplings $R_{PW} = g_L^2 - g_R^2$.

QED treatment not perfect, but we expect only small effects

• Could PDFs be responsible for the discrepancy?

Not in R_{PW}, if you use standard sets of PDFs.

• Are Next-to-Leading QCD corrections necessary?

Not in R_{PW}. Absolutely YES in R_ν, $R_{\bar\nu} \leftrightarrow g_{L,R}^2$

Violation of the Paschos-Wolfenstein relation

$$R_{PW} = \frac{1}{2} - s_W^2 + (1.3 + O(\alpha_s)) \left[u^- - d^- - s^- \right]$$

if no assumptions is made on the parton content of target, with quark/antiquark momentum fractions

$$q^- = \int_0^1 x \left[q(x) - \bar{q}(x) \right] dx$$

R_{PW} is very stable. Violations only occur with *small* isospin violation or $s - \bar{s}$ asymmetry

Isospin violation

A small violation of charge symmetry

$$u^p \neq d^n, \qquad \frac{u_p - d_n}{u_p + d_n} \approx \frac{m_u - m_d}{\Lambda_{QCD}} \approx 1\%$$

would NOT give visible effects elsewhere.

In R_{PW} would lead to $\delta s_W^2 \sim 0.002$

This agrees with a bag model estimate ($\delta s_W^2 < 0$) Sather

other calculations and models predict 10 times smaller effects

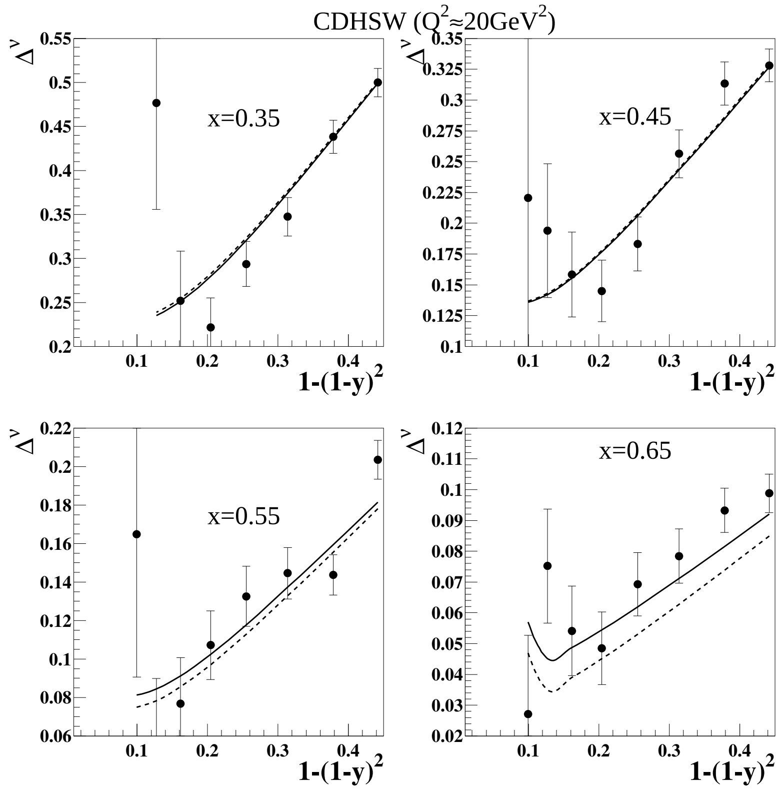
cancellations? Rodionov et al, Signal Cao

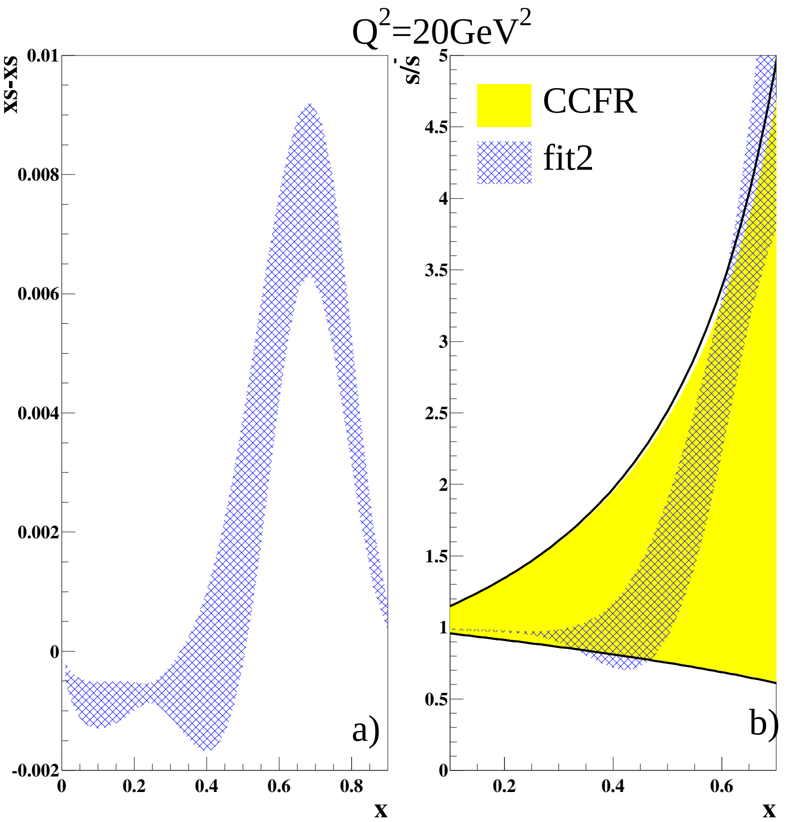
A strange sea asymmetry

- $s(x)$ is mainly constrained by νN DIS.
- *Standard* PDFs (MRST, CTEQ) use $s = \bar{s} = \frac{\bar{u}+\bar{d}}{4}$
- Barone et al. (BPZ, 1999) reanalysed at NLO all νN DIS together with ℓN and Drell-Yan data. $\Rightarrow$ Higher sensitivity to strange sea than standard fits
- BPZ $s(x)$ is larger than usual at high-x, mostly due to CDHSW data. This is in contrast to NuTeV dimuon results, not included in BPZ
- Allowing $s \neq \bar{s}$ leads to $\Delta\chi^2 = -25$ with 2 more parmts. Best fit gives $\boxed{s^- = 0.002 \pm 0.002}$ could explain $\sim 50\%$ of discrepancy.
- NO other exp is sensitive to effects of this kind!
- $s \neq \bar{s}$ of same sign can be induced non-perturbatively (*intrinsic strange*) by higher Fock states $p \leftrightarrow \Lambda K^+$ fluctuations $\Rightarrow$ $\bar{s}$ has smaller x

Brodsky et al., Signal, Thomas

BPZ strange sea fit

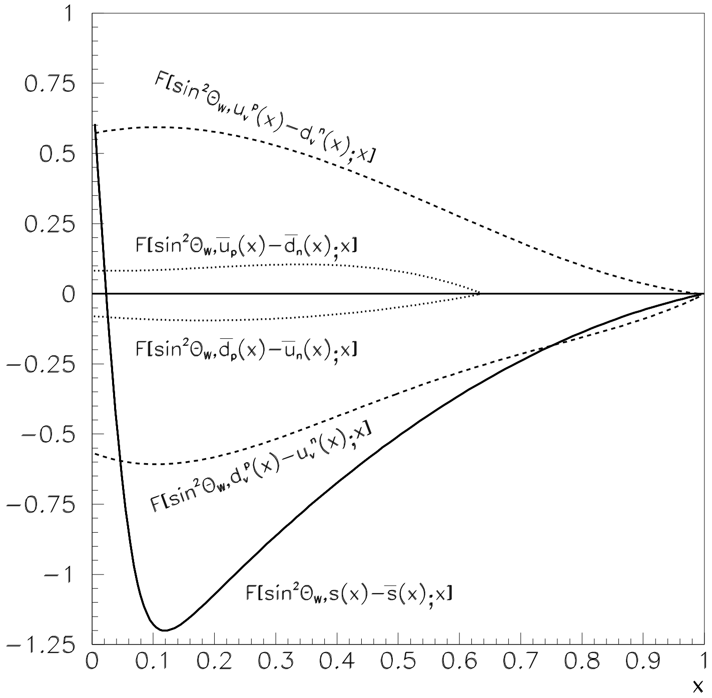




NuTeV reply (hep-ex/0203004)

(1) cuts, charm threshold effects, no R_{PW} dilute the effect of $s/\bar{s}$ and isospin asymmetry by a factor 0.5 or less

we include cuts on R_{PW} and find less dilution but cannot simulate NuTeV!



(2) NuTeV fits from dimuons $\boxed{s^- = -0.0027 \pm 0.0013}$

OPPOSITE SIGN!

– NuTeV use

$$s(x) = k\left(\frac{\bar{u}(x) + \bar{d}(x)}{2}\right)(1-x)^{\alpha} \qquad \frac{s(x)}{\bar{s}(x)} = \frac{k}{\bar{k}}(1-x)^{\alpha-\bar{\alpha}}$$

which artificially relates low x and high x and have $\int (s - \bar{s})dx \neq 0$! and too large asymmetry at low x

– NuTeV fits $s, \bar{s}$ using their LO PDF fit, obtained for $s = \bar{s}$, as a basis, cut and paste PDFs, no global fit, large NLO effects

– NuTeV has very few high x events

NuTeV dimuons should be included in a (BPZ-like) NLO fit in order to draw a conclusion on the asymmetry

Use of Paschos-Wolfenstein is only approximate (cuts, different ν and $\bar{\nu}$ spectra, r is not directly measured...)

$\Rightarrow$ Cancellations of NLO effects certainly disrupted

It is very difficult to quantify these effects from outside. Much safer to upgrade the analysis at NLO.

As an illustration, $\boxed{\text{NLO Effect on } R_\nu}$ (all second moments):

$$R_\nu = \frac{g_L^2\left(u+\frac{\bar{u}}{3}\right)+g_R^2\left(\bar{u}+\frac{u}{3}\right)+\left(g_L^2+g_R^2\right)C_g\otimes g}{u+\frac{\bar{u}}{3}+C_g\otimes g}$$

$O(15\%)$ enhancement of numerator and denominator
BUT $\frac{\delta R_\nu}{R_\nu}\gtrsim O(1\%)$ only. If NuTeV extracted s_W^2 from R_ν alone, this would more than explain the NuTeV anomaly.
Still, R_ν has more importance in the NuTeV analysis.
Moreover, cuts disrupt these cancellations!

Other effects proposed to explain NuTeV:

- Nuclear Shadowing — Miller and Thomas

  BUT VMD contributions can be large at low x and Q^2

  very small effect if any

- Neutrino oscillations

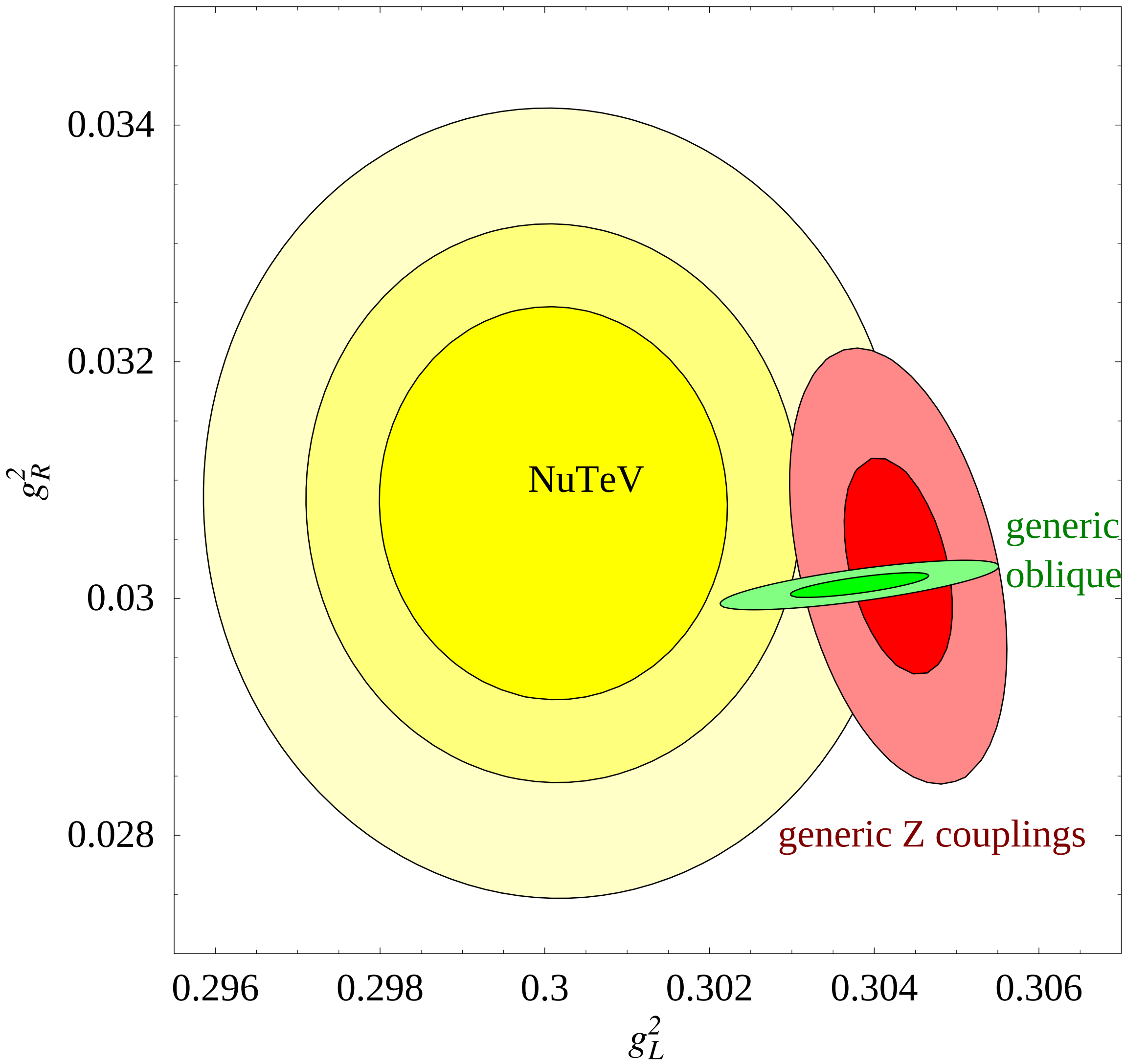
  NO, they could explain result only with large $\nu_e-\nu_s$ but NuTeV measures ν_e spectrum to a few percent

New Physics: Oblique Corrections

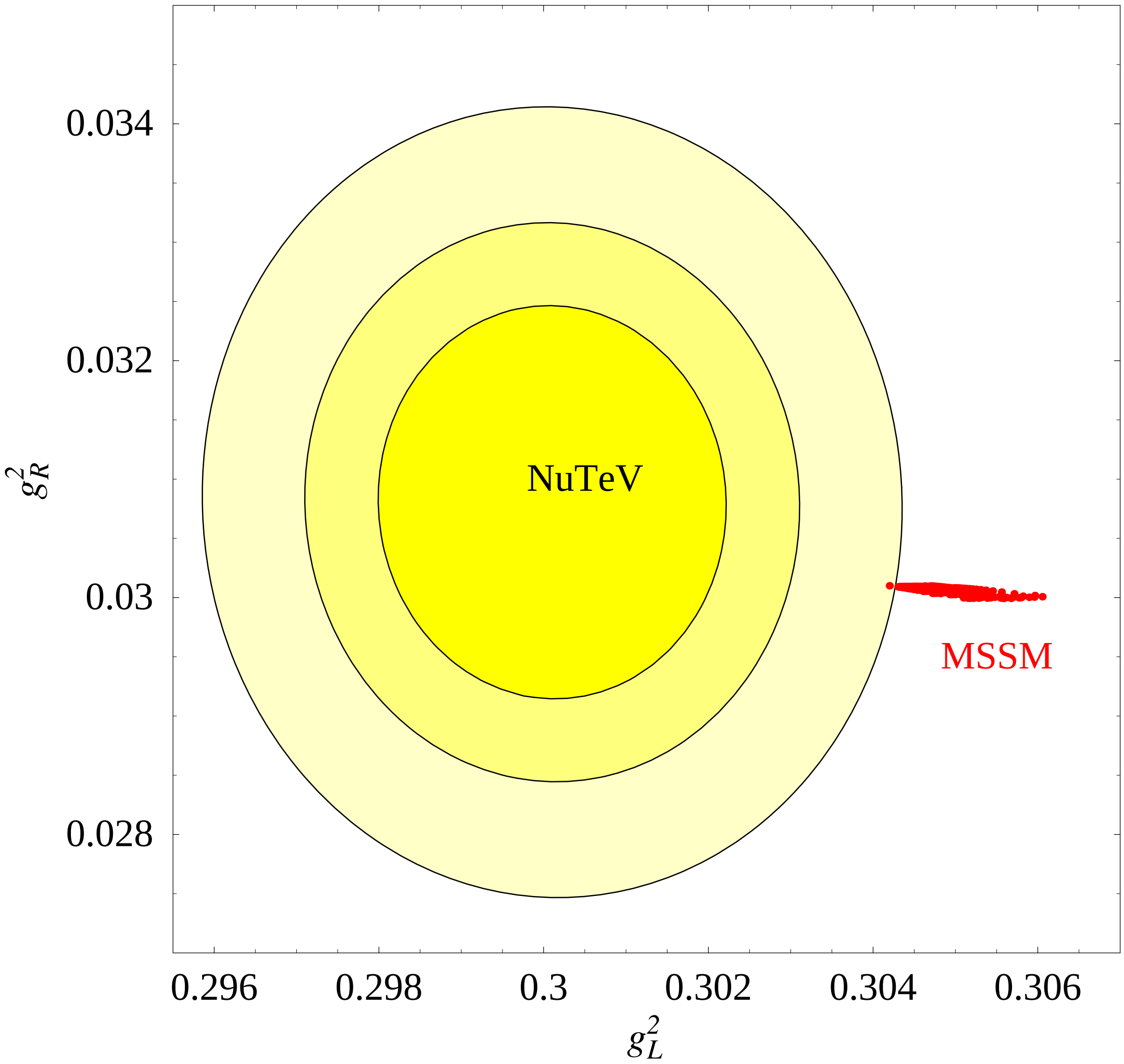
If $\Lambda_{NEW} \gg M_Z$ and new physics couples dominantly to the vector bosons it can be parameterized in a model independent way by three (*oblique*) parameters $\epsilon_1, \epsilon_2, \epsilon_3 \approx S, T, U$.

Altarelli et al., Peskin Takeuchi,...

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



New Physics: Supersymmetry



In general susy corrections have the wrong sign, especially if you don't want to destroy agreement somewhere else.

New Physics: Anomalous Z^0 Couplings

NuTeV can be explained by lower ($\sim -0.6\%$) $Z\nu\bar{\nu}$ coupling, also favored by $-(0.53 \pm 0.28)\%$ deviation in Γ_Z^{inv}. However, realistic models alter either

- the charged current couplings of ν

  e.g.: SM neutrinos mix with heavy ν_R (extra dim or not)

  $$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \epsilon_{ij}\ 2\sqrt{2}G_F(H^\dagger \bar{L}_i)i\partial\!\!\!/(HL_j),$$

  $\epsilon_{\mu\mu} \lesssim 2\text{-}3 \times 10^{-3}$ while NuTeV needs 1.2%.

- other Z couplings

  e.g.: extra U(1) Z' mixing with Z. Model indep fit to SU(2) invariant and universal Z couplings shows only marginal improvement. Dropping SU(2) requirement improves fit. Non universal couplings less constrained $L_\mu - L_\tau$, Ma & Roy; ESSM-$SO(10)$, Babu & Pati

New Physics: Contact Interactions

Non-renormalizable ops parameterize effects of heavy dof

Vector ops $(\bar{\nu}_\mu\gamma^\alpha\nu_\mu)(\bar{q}_r\gamma_\alpha P_L q_s)$ (and possibly tensor) can explain NuTeV without conflict with LEP, Tevatron, R_π or rare decays.

In terms of $SU(2)_L$ ops there is only one possibility,

$$(-0.024 \pm 0.009)\, 2\sqrt{2}G_F\, [\bar{L}\gamma_\mu L][\bar{Q}\gamma_\mu Q]$$

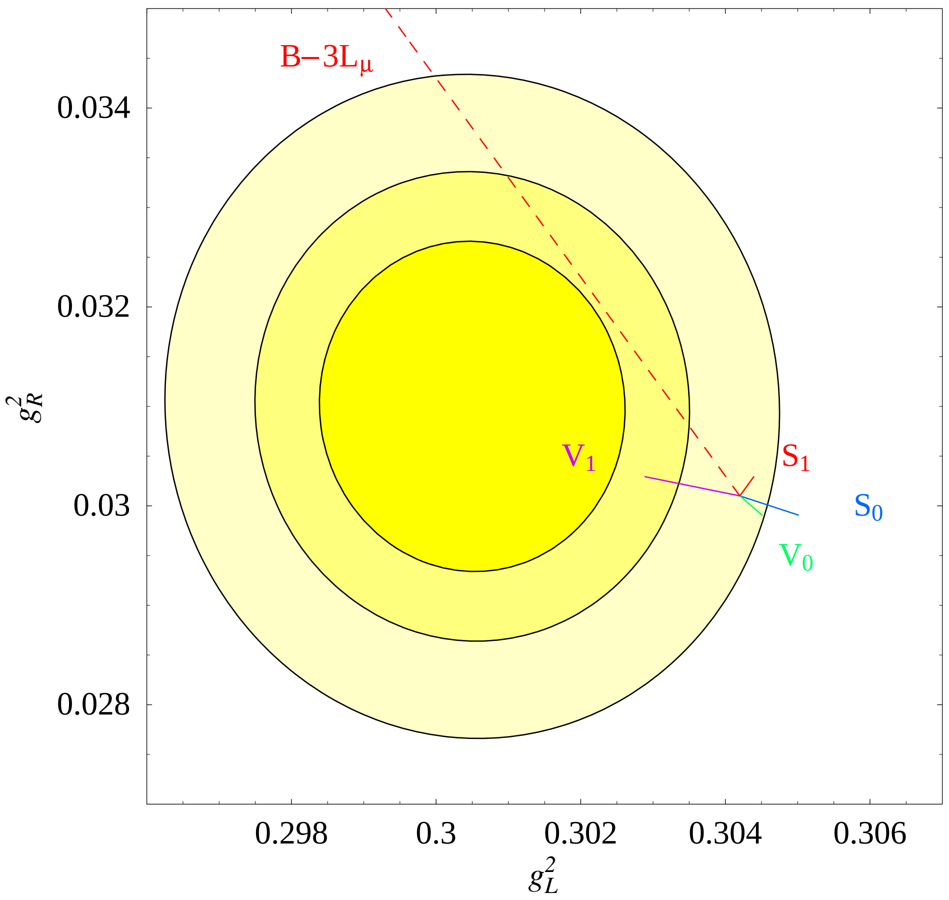
can be realized by exchange of leptoquarks ($M \gtrsim 200$ GeV) or Z', even lighter than 10 GeV

New Physics: Leptoquarks

LQ = scalar or vector bosons coupled to L and Q.
Occur for ex. in SUSY without R parity (squarks).

$$\lambda_{S_0} Q L S_0 + \lambda_{S_1} Q \tau^a L S_1^a + \lambda_{V_0} \bar{Q} \gamma_\mu L V_{0\mu} + \lambda_{V_1} \bar{Q} \gamma_\mu \tau^a L V_{1\mu}^a$$

They all also give rise to $\mathcal{O}'_{LQ} = [\bar{L}\gamma_\mu \tau^a L][\bar{Q}\gamma_\mu \tau^a Q]$ whose CC component overcontribute to $\pi \to \mu \bar{\nu}_\mu$



Way out: split the triplet LQ, then vector and scalar LQ can explain NuTeV.

R-parity violating SUSY can give only $SU(2)_L$ singlet and doublet $\tilde{Q}$, which cannot explain NuTeV.

New Physics: unmixed extra U(1) Z'

Sign of Z' contribution to $[\bar{L}\gamma_\mu L][\bar{Q}\gamma_\mu Q]$ depends on U(1) charges. Require

- quark, lepton mass terms U(1) invariant
- only couplings to second generation (LEP2 constrains first gen)
- absence of anomalies

then $B - 3L_\mu$ is the simplest option. Gninenko, Krasnikov

NuTeV needs $\sqrt{M_{Z'}^2 + 20\mathrm{GeV}^2} \approx g_{Z'} 3$ TeV

LEP & Tevatron imply $M_{Z'} \gtrsim 600$ GeV and $\lesssim 10$ GeV

a_μ combined with NuTeV places a strong constraint

$$M_{Z'} \gtrsim 2\mathrm{GeV}$$

A narrow superweakly coupled light Z' escapes all exp bounds.

It can be a source of Z' bursts, which could generate cosmic rays above the GZK cutoff more easily than Z bursts.

Asymmetries at the Z^0 resonance

$$\sim \quad \frac{g}{\cos\theta_W}\gamma^\mu \left[g_V^f + g_A^f\gamma_5\right] \qquad \text{at tree level}$$

$$\sim \quad \frac{g^R}{2\cos\theta_W^R}\bar{\rho}_f \ \gamma^\mu \left[1-\gamma_5 - 4|Q_f|\kappa_R^f(M_Z^2)\ \sin^2\theta_W^R\right]$$

and we can identify $\sin^2\theta_{eff}^f = \mathrm{Re}\ \kappa_R^f(M_Z^2)\ \sin^2\theta_W^R$

- Asymmetries measure $\frac{g_V^f}{g_A^f} \Rightarrow \sin^2\theta_{eff}^f$
- Γ_Z^f measure $(g_A^f)^2 + (g_V^f)^2 \Rightarrow \bar{\rho}_f \approx 1 + \Delta\rho(0) + \ldots$

In particular $A_{FB}^f = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f$ and $A_{LR} = \mathcal{A}_e$

$$\mathcal{A}_f = \frac{2g_A^f g_V^f}{(g_A^f)^2+(g_V^f)^2} \Rightarrow \mathcal{A}_e \simeq 0.15 \quad \frac{1}{\mathcal{A}_e}\frac{\partial\mathcal{A}_e}{\partial s_W^2} \simeq -55$$

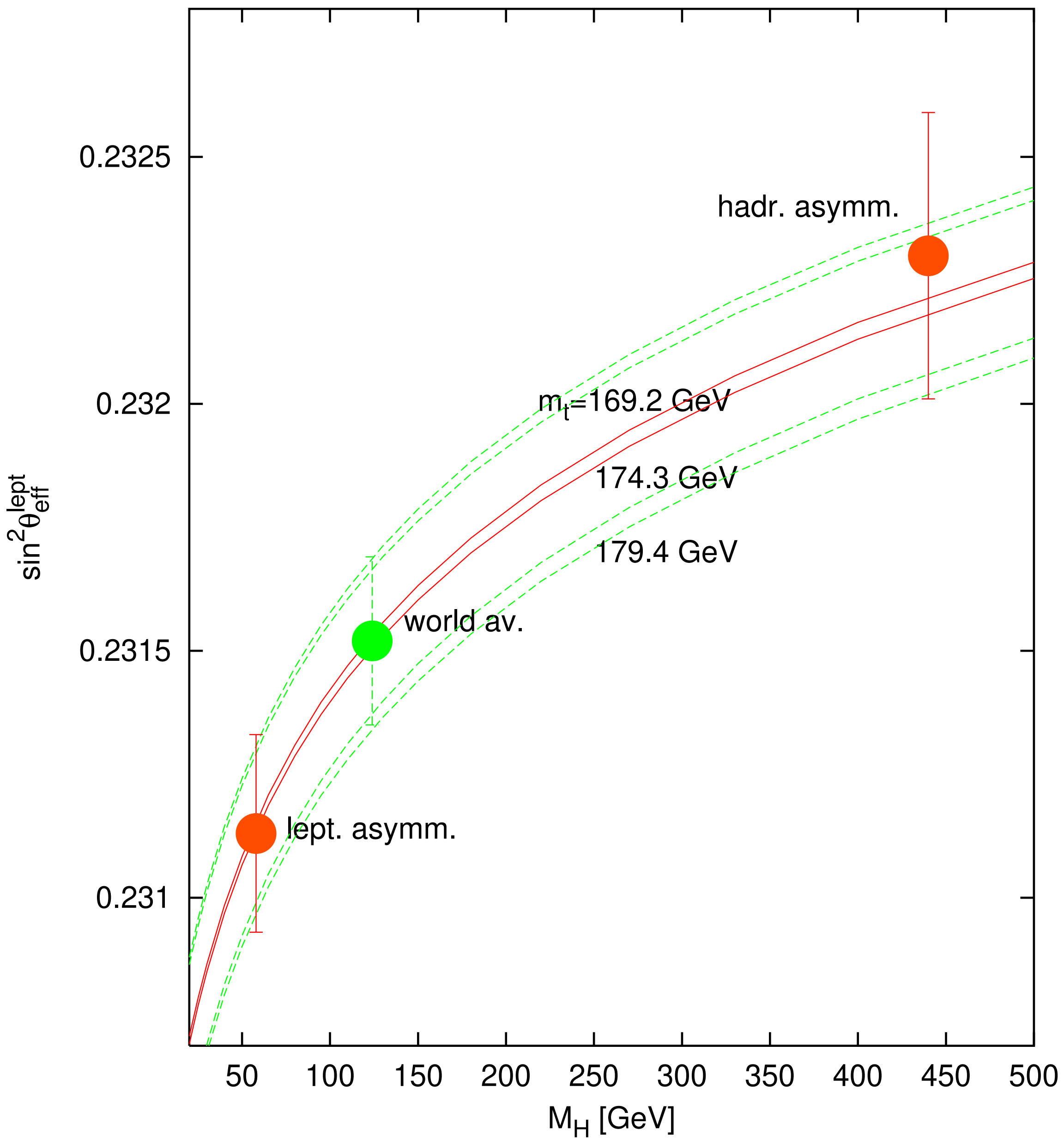
$$\Rightarrow \mathcal{A}_b \simeq 0.935 \quad \frac{1}{\mathcal{A}_b}\frac{\partial\mathcal{A}_b}{\partial s_W^2} \simeq -0.7$$

$\mathcal{A}_e$ is very sensitive to radiative corrections (to $\sin^2\theta_{eff}^{lept}$)

$\mathcal{A}_b$ is very $\boxed{\text{insensitive}}$ to radiative corrections

Best determinations of $\sin^2\theta_{eff}^{lept}$ come from A_{LR} and $A_{FB}^b = \frac{3}{4}\mathcal{A}_e\mathcal{A}_b$

Higgs dependence: the effective leptonic sine



- $\sin^2\theta_{eff}^{lept}$ is 3 (6) times more sensitive to $\ln M_H$ $(\Delta\alpha_h)$ than M_W
- A_{FB}^b inconsistent with other asymmetry measurements and also with M_W and other precision data, as it points to a very heavy Higgs, $M_H \gtrsim 600$ GeV. I will quantify this in a moment.

CONCLUSIONS

- NuTeV aims at precision measurements in a complex hadronic environment. Theoretical systematics which may not be under control and are untested include a small strange/antistrange asymmetry and isospin violation. The analysis should be upgraded to NLO.
- The NuTeV anomaly requires new tree level effects. Viable new physics explanations are ad-hoc and exotic.
- Even without NuTeV, the SM fit to M_H is not good. What we know on M_H depends *crucially* on the measurement of the b forward-backward asymmetries, which represents another (even more) puzzling anomaly.