Precision electroweak measurements: a theorist point of view

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$M_H < 193$ GeV at 95% CL

χ^2/d.o.f.=29.7/15

probability=1.3%.

Two $\sim 3\sigma$ *anomalies*

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M_H fit independent of NuTeV

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m_Z [GeV]	91.1875 ± 0.0021	0.00
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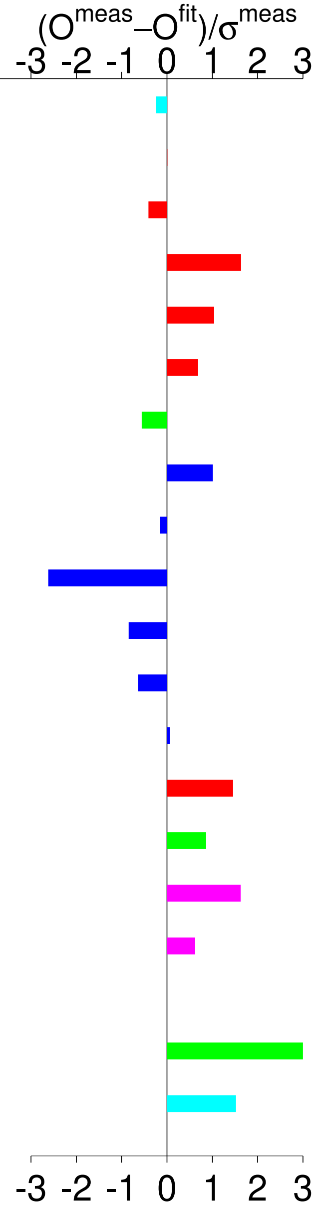
σ^0_{had} [nb]	41.540 ± 0.037	1.63
R_l	20.767 ± 0.025	1.04
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.68
$A_l(P_\tau)$	0.1465 ± 0.0032	-0.55
R_b	0.21644 ± 0.00065	1.01
R_c	0.1718 ± 0.0031	-0.15
$A^{0,b}_{fb}$	0.0995 ± 0.0017	-2.62
$A^{0,c}_{fb}$	0.0713 ± 0.0036	-0.84
A_b	0.922 ± 0.020	-0.64
A_c	0.670 ± 0.026	0.06
A_l(SLD)	0.1513 ± 0.0021	1.46
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.87
m_W [GeV]	80.449 ± 0.034	1.62
Γ_W [GeV]	2.136 ± 0.069	0.62
m_t [GeV]	174.3 ± 5.1	0.00
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	3.00
Q_W(Cs)	-72.18 ± 0.46	1.52



THE NUTEV ELECTROWEAK RESULT

NuTeV measures ratios of NC/CC cross sections in νN DIS. Ideally

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

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

$$r \equiv \frac{\sigma(\bar\nu\mathcal{N} \to \bar\mu X)}{\sigma(\nu\mathcal{N} \to \mu X)}$$

$R_{\nu,\bar\nu}^{exp}$ differ from above because of ν_e contamination, cuts, NC/CC misID, 2nd gen quarks, non isoscalar target, QCD-EW corrections... MonteCarlo relates $R_{\nu,\bar\nu}^{exp}$ to $R_{\nu,\bar\nu}$.

Most uncertainties and $O(\alpha_s)$ effects drop from Paschos-Wolfenstein relation

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

Since $\frac{\partial R_\nu}{\partial s_W^2} \gg \frac{\partial R_{\bar\nu}}{\partial s_W^2}$, NuTeV fit $R_{\nu,\bar\nu}^{exp}$ for $\sin^2\theta_{\rm W}, m_c$ or $g_{L,R}^2$ at LO in QCD

NuTeV relies heavily on MC. In first approx corresponds to a measurement of R_{PW}

NuTeV result is expressed as a test on the on-shell $s_W^2 \equiv 1 - M_W^2/M_Z^2$:

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

Global fit $s_W^2 = 0.2226 \pm 0.0004 \Rightarrow 3\sigma$!

QED-EW treatment not perfect, but expect only small effects

$\star$ Can PDFs uncertainties be responsible for the discrepancy?
Unlikely if you use STANDARD sets of PDFs (see later), thanks to the cancellations in R_{PW}.

$\star$ Are Next-to-Leading QCD corrections necessary?
Not in R_{PW}, but any CC/NC or $\nu/\bar{\nu}$ asymmetry (cuts, spectra, sensitivity) spoils delicate cancellations. NuTeV seems to differ enough from R_{PW}. A consistent NLO analysis would simplify several other issues

$\ggg$ NuTeV ANALYSIS NEEDS TO BE UPGRADED TO NLO $\lll$

The strange sea asymmetry

$s(x) \neq \bar{s}(x)$ leads to a violation of the PW relation (Davidson *et al.* hep-ph/0112302):

$$R_{PW} = \frac{1}{2} - s_W^2 + 1.3\,(\Delta u - \Delta d - \Delta s)$$

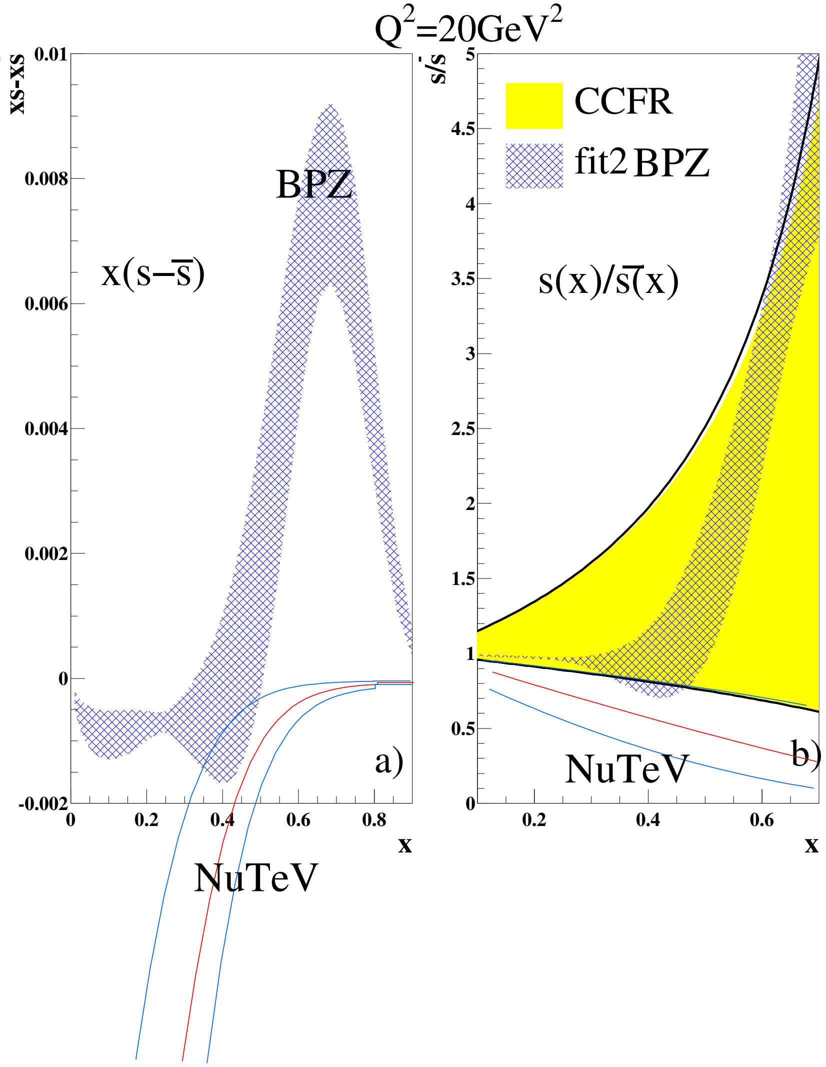
where Δq is the asymmetry in the momentum carried, $\int_0^1 x\,[q(x) - \bar{q}(x)]\,dx$

- $s \neq \bar{s}$ of the sign needed to explain NuTeV can be induced non-perturbatively ($intrinsic\ strange$) Brodsky et al., Signal, Thomas
- $s(x)$ mainly constrained by νN DIS. 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, but agrees well with positivity constraints. BPZ best fit $\boxed{\Delta s \approx 0.002}$ with $\Delta\chi^2 = -25$ (two dof more) can explain a fraction of discrepancy and agrees with theory estimates

The strange sea asymmetry (II)

NuTeV fits from dimuons $\Delta s = -0.0027 \pm 0.0013$ (hep-ex/0102049,hep-ex/0203004)
which would increase the anomaly.

This estimate has various problems
parametrization, LO fit depending on underlying PDF and not global, theory error much larger than statistical:
fitting dimuons events is not enough



Bottom line:

We know very little on the strange sea.

$\gg\gg$ A GLOBAL NLO FIT INCLUDING ALL DATA IS NEEDED $\ll\ll$

Before that effect of Δs on s^2_W is UNCLEAR

Isospin violation - Nuclear effects

Isospin violating PDFs also violate the PW relation $R_{PW} = \frac{1}{2} - s_W^2 + 1.3(\Delta u - \Delta d)$

$$u_p(x) \neq d_n(x), \qquad \frac{u_p - d_n}{u_p + d_n} \approx \frac{m_u - m_d}{\Lambda_{QCD}} \approx 1\%$$

Such small violation of charge symmetry would NOT give visible effects elsewhere and could explain a fraction of the anomaly

A bag model estimate (Sather) implies $\delta s_W^2 = -0.002$, others (Rodionov et al, Signal Cao) predict 10 times smaller effects, but with subtle cancellations

NUCLEAR EFFECTS look very UNLIKELY to explain NuTeV

- Nuclear Shadowing different in NC/CC (Miller & Thomas, hep-ex/0204007) VMD model, wrong sign
- More detailed analysis (Kovalenko *et al.* hep-ph/0207158) nuclear rescaling model that explains EMC data but NuTeV fits self-consistently its PDFs

New Physics vs NuTeV

NuTeV requires a $\sim 1\%$ (tree level) effect. Very difficult to build realistic models that satisfy all exp constraints. See Davidson *et al.*, hep-ph/0112302 for overview

- $\star$ NO Supersymmetry, with or without R parity
- $\star$ NO Models inducing only oblique corrections
- $\star$ NO (in general) anomalous Z coupling
  including models with ν_R mixing like Babu-Pati, hep-ph/0203029
- $\star$ YES Contact interactions $(-0.024 \pm 0.009)\, 2\sqrt{2} G_F\, [\bar{L_2}\gamma_\mu L_2][\bar{Q_1}\gamma_\mu Q_1]$
- $\star$ Maybe... Leptoquarks but only with split SU(2) triplet
- $\star$ YES unmixed Z' light or heavy, for ex. narrow superweak abelian $B - 3L_\mu\ Z'$, $2 \lesssim M_{Z'} \lesssim 10$GeV, Davidson *et al.*, less successful $L_\mu - L_\tau$, Ma & Roy hep-ph/0111385

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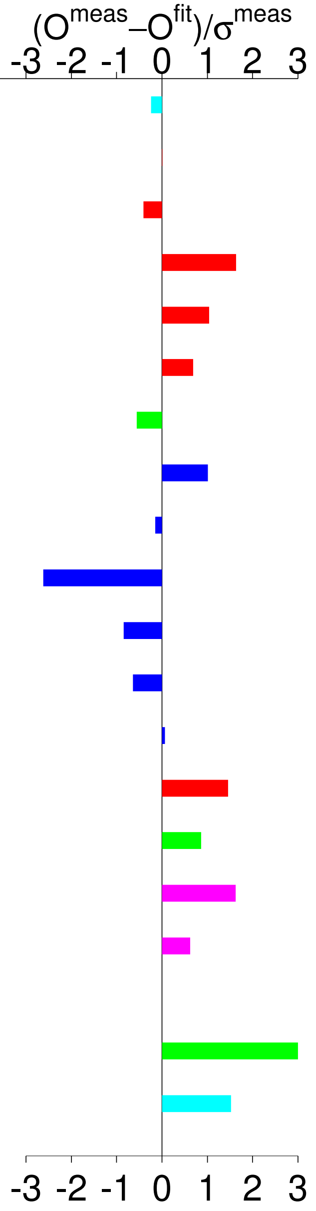


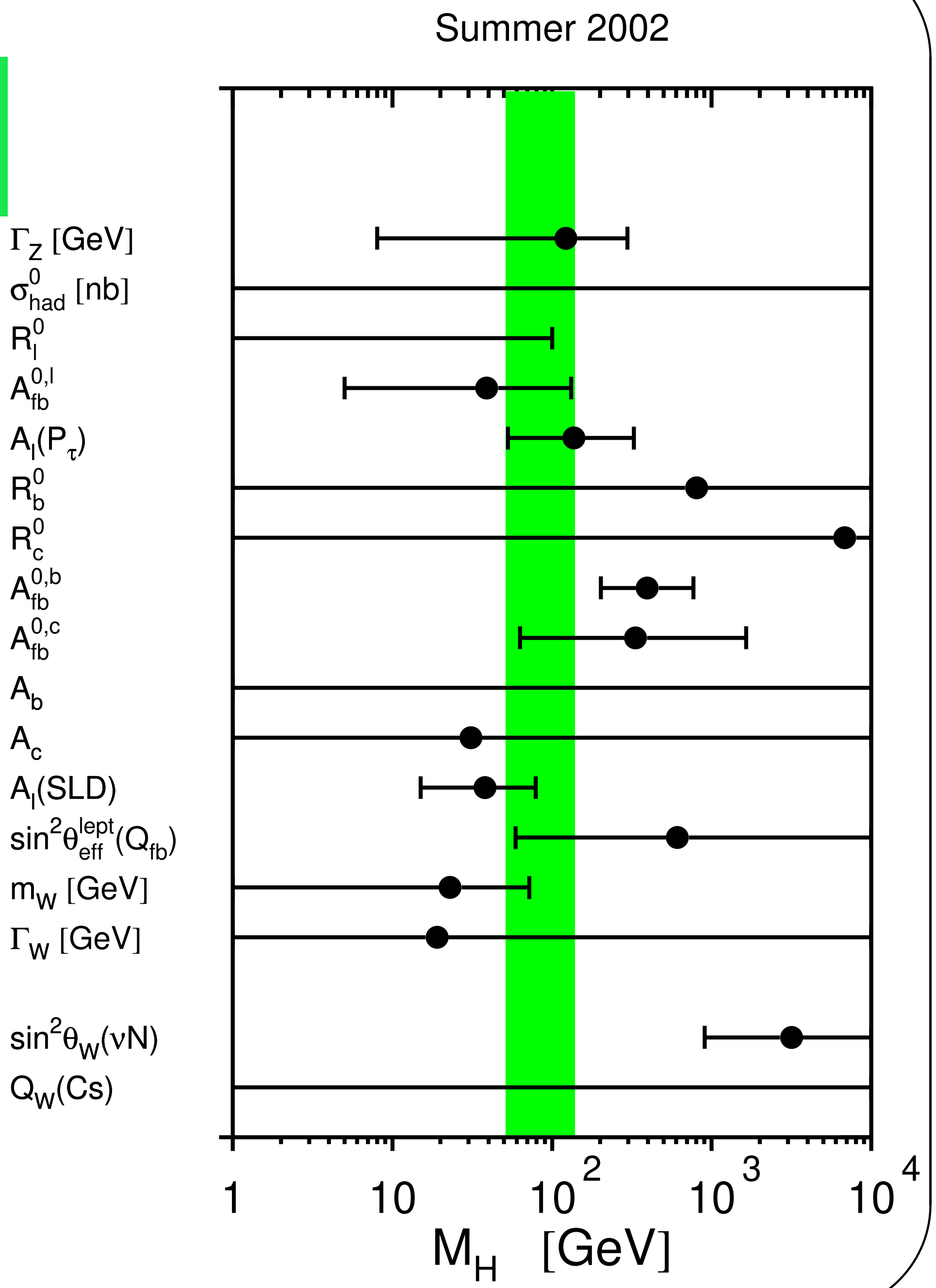
The SM fit to M_H is not satisfactory

Only a subset of observables are really SENSITIVE to M_H (and M_t)

Using only M_W,M_t,Γ_ℓ, the asymmetries, R_b (NOT NuTeV):

$M_H^{fit} = 90$ GeV, $M_H^{95\%} < 195$ GeV

χ^2/dof=13/4, $\boxed{\text{prob=0.9\%}}$



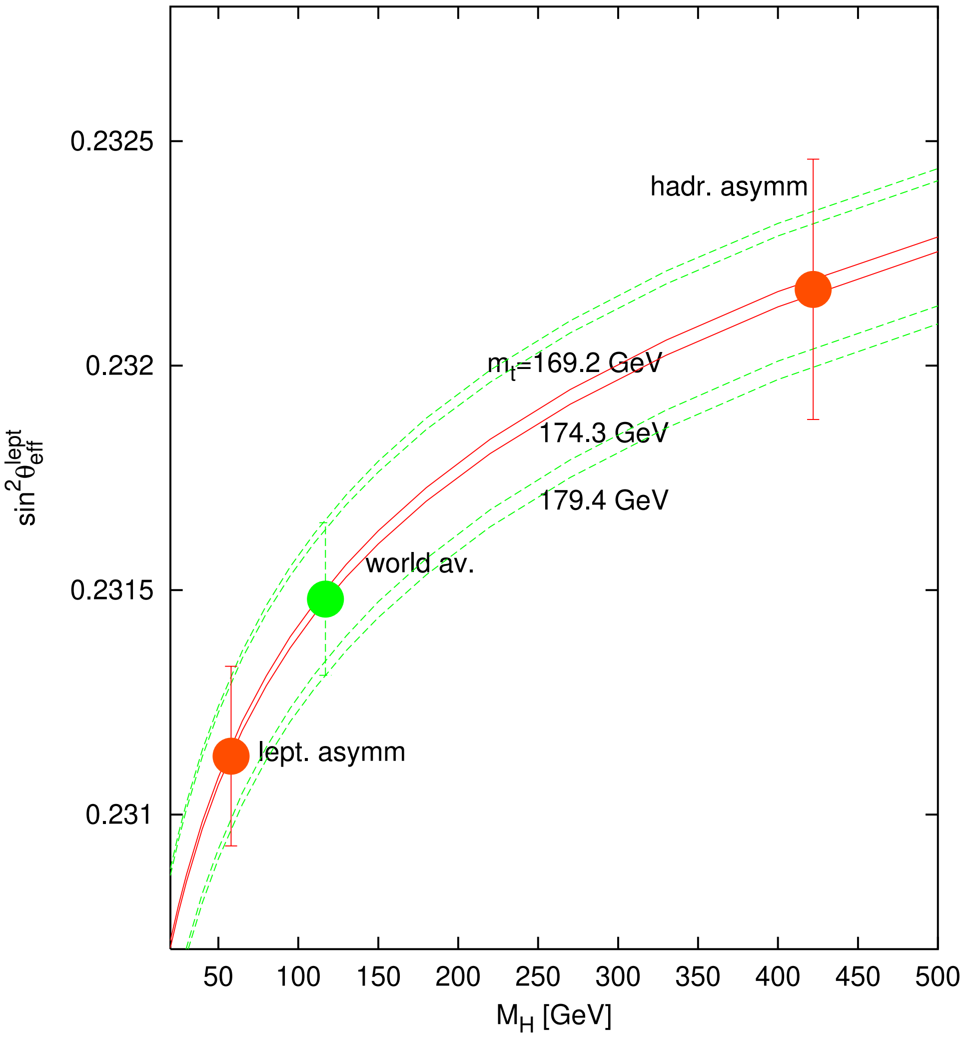
Another unwelcome anomaly

Root of the problem is the 3σ discrepancy between the L-R asymmetries of SLD ($very\ light\ Higgs$, like M_W) and the FB b asymmetries of LEP ($heavy\ Higgs$)

In the SM leptonic and hadronic asymmetries measure the SAME quantity, $\sin^2\theta^{lept}_{eff}$

leptonic asymmetries are mutually consistent and M_W pushes for a light Higgs too.
Hadronic ones dominated by b:
NEW PHYSICS in the b couplings?

QCD systematics in A^b_{FB} are well studied

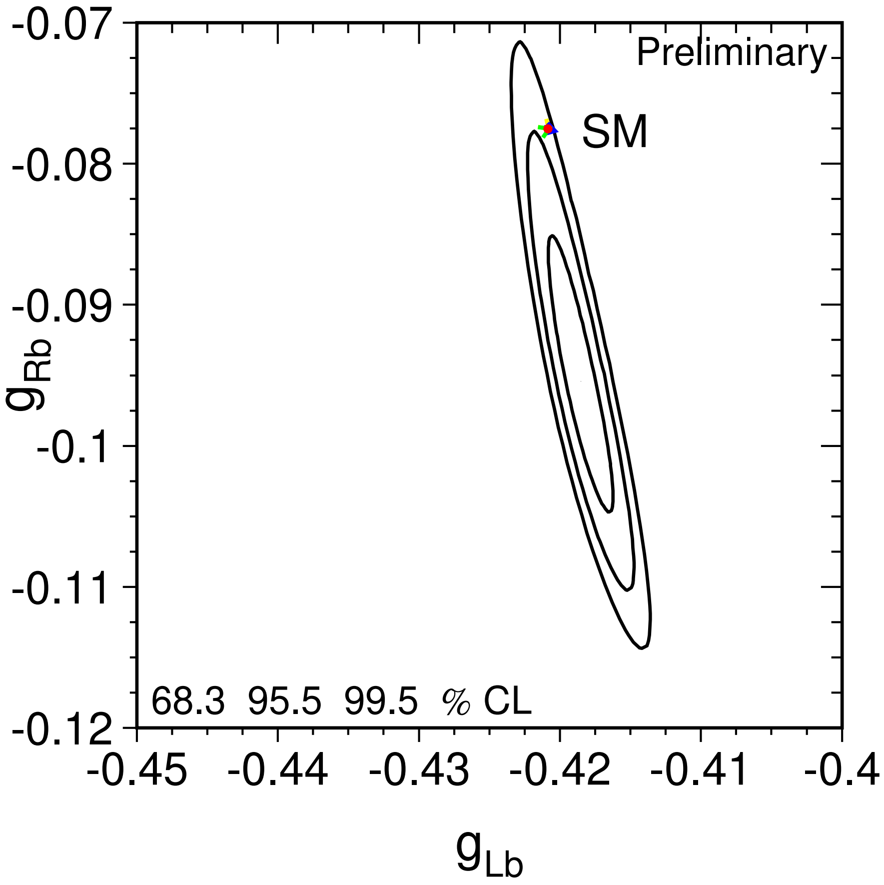


New Physics in the b couplings?

$\star$ A_{LR}^{FB} of SLD agree with SM

$\star$ fixing lept coupling, A_{FB}^{b} implies 30% correction to b vertex $\Rightarrow$ needs tree level physics

$\star$ R_b agrees with SM, $|\delta g_R^b| \gg |\delta g_L^b|$



EXOTIC SCENARIOS that shift b_R coupling:

- Mirror Vector-like fermions mixing with b quark Choudhury *et al.* hep-ph/0109097
- L-R models that single out the third generation He, Valencia hep-ph/0203036

Too light a Higgs

First option: dilute all asymmetries according to PDG, only χ^2 changes

Ferroglia *et al.* hep-ph/0203224, DeBoer & Sander

Diluting the hadronic asymmetries, a consistent picture emerges

$M_H^{fit} = 40$ GeV prob=75%, $\boxed{M_H^{95\%} < 109 \text{ GeV}}$ but $\boxed{\text{LEP: } M_H > 114 \text{ GeV}}$

Why hasn't the Higgs been found?

Chanowitz hep-ph/0207123; Altarelli *et al.* hep-ph/0106029

NB: small sensitivity to $\alpha(M_Z)$: most unfavorable $M_H^{95\%} \sim 120$ GeV. Theoretical error cannot shift up $M_H^{95\%}$ more than 20 GeV

Freitas *et al.* hep-ph/0202131, PG

The paradox dissolves if $M_t \gtrsim 180$ GeV

Combined probability of global fit and of $M_H > 114$GeV is the same with/without $A_{FB}^b \sim 0.003/0.025$ (with/without NuTeV)

Chanowitz, hep-ph/0207123

New physics simulating a light Higgs

Excluding A_{FB}^b and NuTeV from global fit the quality of the fit improves considerably, but M_H^{fit} becomes very small

Finding New Physics that simulates a very light Higgs is much easier than fixing the two anomalies!

- oblique corrections: in general requires $S < 0 (T > 0)$ or $\epsilon_{2,3} < 0$
- A non-degenerate unmixed 4th generation with $m_N \approx 50$ GeV
  Novikov et al. hep-ph/0205321, 0111028
- More interestingly, the MSSM offers:
  - rapid decoupling (strongly constrained by direct searches)
  - M_W always higher than in SM, $\sin^2\theta_{eff}^{lept}$ lower than in SM

  A plausible MSSM scenario involves light $\tilde{\nu}, \tilde{\ell}$ and possibly charginos, heavy squarks, at $\tan\beta \gtrsim 5$, and is testable at Tevatron Altarelli *et al.* hep-ph/0106029

  Other susy scenario: EMSSM, Babu & Pati, hep-ph/0203029

CONCLUSIONS

- NuTeV aims at precision measurements in a complex hadronic environment. Theoretical systematics not fully under control or untested include a small strange/antistrange asymmetry and isospin violation. The analysis should be upgraded to NLO.
- 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 FB asymmetries, which represents another (even more) puzzling anomaly.
- Both anomalies require new tree level effects. No susy. Proposed new physics explanations for both NuTeV and A^b_{FB}, when viable, are ad-hoc and exotic.
- removing the anomalies from the SM fit leads to inconsistency with the direct lower bound on M_H. Some solution of this problem will be tested at Tevatron
- A clear-cut, compelling case for New Physics has yet to be made but SM is definitely under strain

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