WIN02: January 24, 2002

Beautiful Mirrors and Electroweak Precision Measurements

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1. Introduction
2. $\sin^2\theta_W$, m_H and the forward-backward b-asymmetry.
3. Beautiful Mirrors
4. Fit to the Precision Electroweak Data
5. Unification of Couplings and Proton Decay
6. Collider Physics

Based on work done with D. Choudhury and T. Tait,

hep-ph/0109097, Phys. Rev. D, in press

Introduction

The Standard Model provides an excellent fit to the precision electroweak observables, with a notable exception:

$$A_{FB}^b = 0.0990 \pm 0.0017; \quad A_{FB}^b(SM) = 0.1039,$$

A 2.9 σ discrepancy. On the other hand, a related quantity measured at SLC, A_b agrees within 1σ !

$$A_{FB}^b = \frac{3}{4} A_b A_e$$

Also,

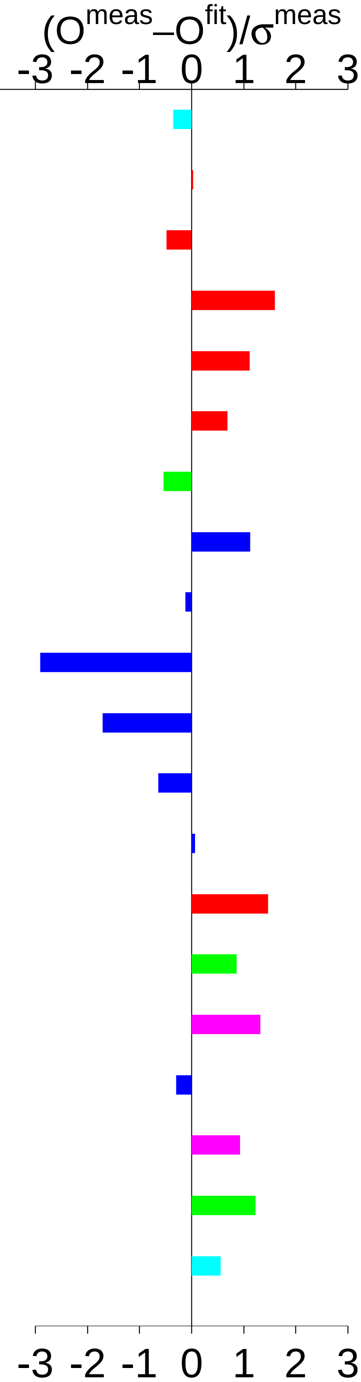
$$R_b = 0.21646 \pm 0.00065; \quad R_b(SM) = 0.2157$$

Possible solutions

1. Systematics errors.
2. Statistical fluctuation.
3. New Physics.

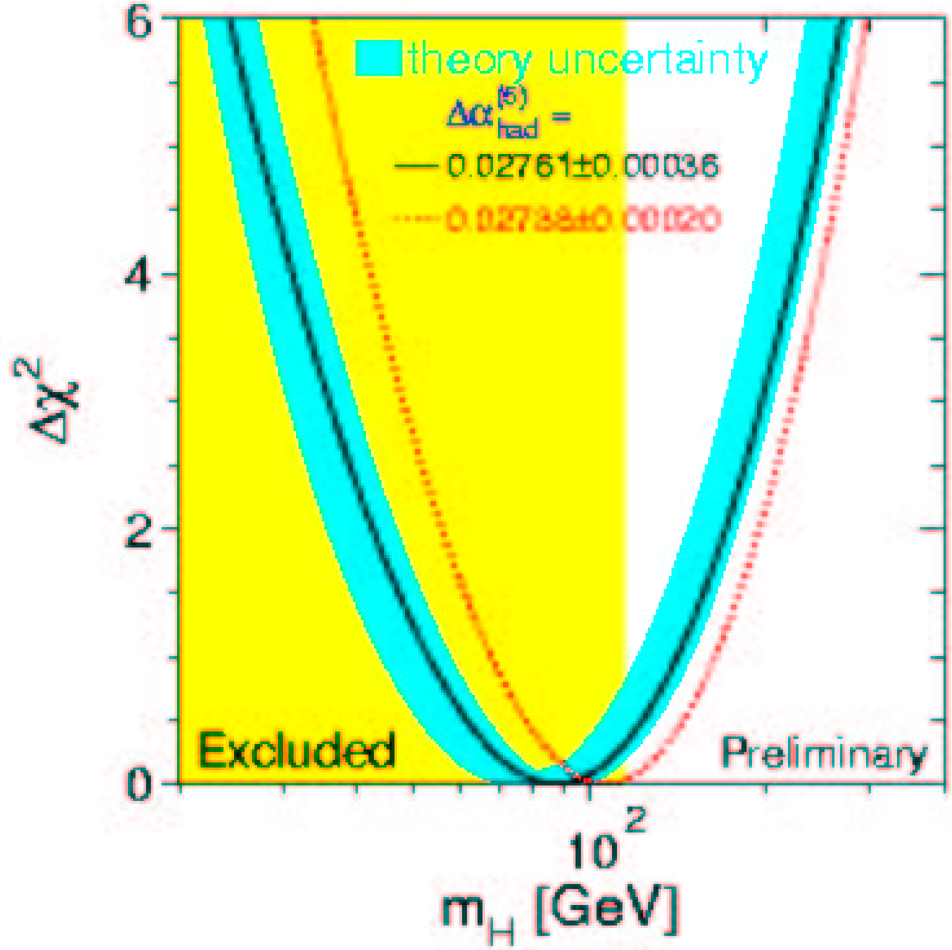
Summer 2001

	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-.35
m_Z [GeV]	91.1875 ± 0.0021	.03
Γ_Z [GeV]	2.4952 ± 0.0023	-.48
σ^0_{had} [nb]	41.540 ± 0.037	1.60
R_l	20.767 ± 0.025	1.11
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.69
$A_l(P_\tau)$	0.1465 ± 0.0033	-.54
R_b	0.21646 ± 0.00065	1.12
R_c	0.1719 ± 0.0031	-.12
$A^{0,b}_{fb}$	0.0990 ± 0.0017	-2.90
$A^{0,c}_{fb}$	0.0685 ± 0.0034	-1.71
A_b	0.922 ± 0.020	-.64
A_c	0.670 ± 0.026	.06
A_l(SLD)	0.1513 ± 0.0021	1.47
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	.86
$m_W^{(LEP)}$ [GeV]	80.450 ± 0.039	1.32
m_t [GeV]	174.3 ± 5.1	-.30
$m_W^{(TEV)}$ [GeV]	80.454 ± 0.060	.93
$\sin^2\theta_W(\nu N)$	0.2255 ± 0.0021	1.22
$Q_W(Cs)$	-72.50 ± 0.70	.56



Precision EW Data: Fit to the Higgs Mass

From the LEPEWWG, www.cern.ch/LEPEWWG:



The Problem

What happens if we ignore the hadronic asymmetries,

$$\sin^2 \theta_W^{\rm eff}\Big|_{\rm hadronic} = 0.2324 \pm 0.00029$$

and consider only

$$\sin^2 \theta_W^{\rm eff}\Big|_{\rm leptonic} = 0.23114 \pm 0.0002\,?$$

The EW-fit value of m_H is already below the direct lower bound. Now it is pushed to lower values ($m_H \simeq 50$ GeV).

['Lose-lose for the SM !', M.S. Chanowitz, hep-ph/010402]

Altarelli *et al.*, hep-ph/0106029 :

Assume A_{FB}^b wrong! Invoke new physics to push up $\sin^2 \theta_W^{\rm eff}\Big|_{\rm leptonic}$ and thus m_H. This can be achieved within the MSSM,

$\tilde{\nu}$'s : 55–80 GeV, $\tilde{e}$'s $\gtrsim$ 95 GeV,

and maybe light charginos as well.

Bottom quark couplings

The effective $Zb\bar{b}$ vertex :

$$\mathcal{L}_{Zb\bar{b}} = \frac{-e}{s_W c_W} Z_\mu \bar{b} \gamma^\mu \left[\bar{g}_L^b P_L + \bar{g}_R^b P_R \right] b$$

where $s_W \equiv \sin\theta_W$, $c_W \equiv \cos\theta_W$.

At LEP:

$$R_b \equiv \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to \text{hadrons})} \simeq \frac{(\bar{g}_L^b)^2 + (\bar{g}_R^b)^2}{\sum_q [(\bar{g}_L^q)^2 + (\bar{g}_R^q)^2]}$$

$$A_b \simeq \frac{(\bar{g}_L^b)^2 - (\bar{g}_R^b)^2}{(\bar{g}_L^b)^2 + (\bar{g}_R^b)^2}$$

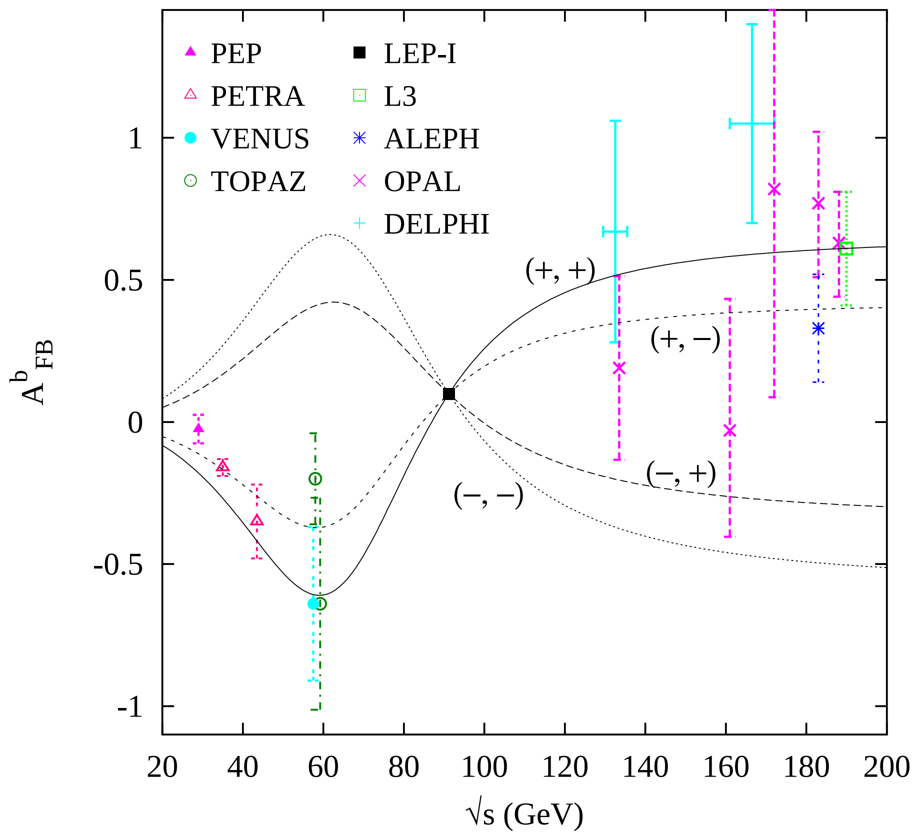
$$A_\ell \simeq \frac{(g_L^\ell)^2 - (g_R^\ell)^2}{(g_L^\ell)^2 + (g_R^\ell)^2}.$$

The ellipse and the hyperbola representing the solution spaces intersect at *four* points :

$$(\bar{g}_L^b, \bar{g}_R^b) \approx (\pm 0.992\, g_L^b(SM), \pm 1.26\, g_R^b(SM))\,,$$

Information about the b-couplings

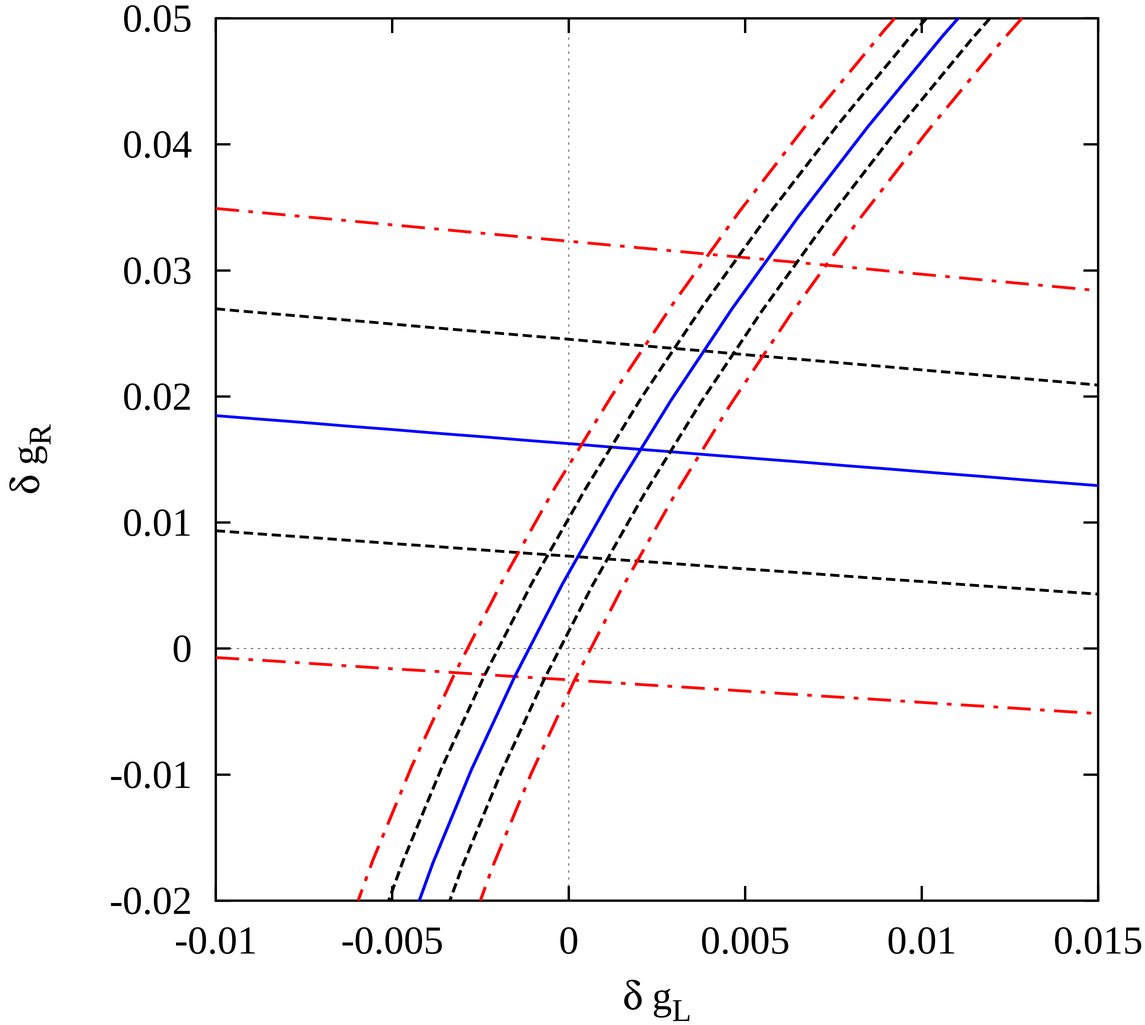
No experiment performed at the Z-peak can reduce the degeneracy any further. Off Z-peak : γ-mediated diagram becomes important.



$\bar{g}_L^b \approx -g_L^b(SM)$: disallowed.

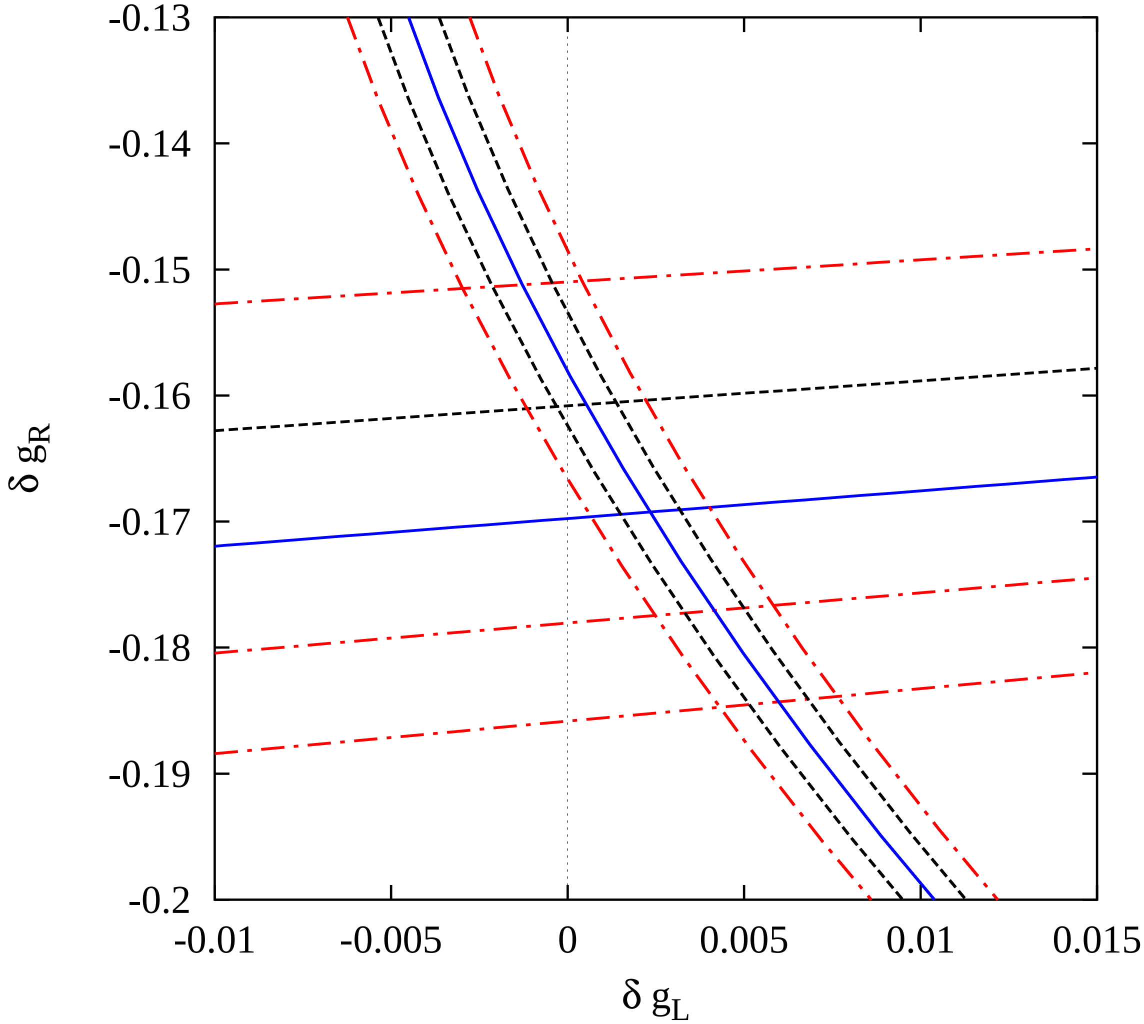
$\bar{g}_R^b \approx \pm 1.26\ g_R^b(SM)$: High-energy data inconclusive. However, measurements at LEP, 2 GeV away from Z-peak show preference towards equal sign (sign reversal is 2 σ away). Low-energy data, instead, prefers sign reversal!!

Resolution of the A_{FB}^b anomaly



Where we have chosen

$$\frac{\delta g_R}{g_R} > 0$$



where we have chosen

$$\frac{\delta g_R}{g_R} < 0$$

Since $g_R \simeq 0.077$ and $g_L \simeq 0.42$,

$$|\delta g_R/g_R| \gg |\delta g_L/g_L|$$

Beautiful Mirrors

Suppose there exists a charge $-1/3$ quark that mixes with b but not with d, s.

Mass matrix :

$$\mathcal{L}_{m_b} = -\sum_{ij} \bar{b}'_{iL} M_{ij} b'_{jR} + \text{h.c.}, \quad M \equiv \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}$$

b'_1 : ordinary b-quark.
b'_2 : exotic b-quark.

Mixing matrices for the left- and right-handed quarks : diagonalization matrices for $MM^\dagger$ and $M^\dagger M$ respectively.
$\Longrightarrow$ physical states $b_{1,2}$

Note : b'_2 need not have same $SU(2) \otimes U(1)_Y$ quantum numbers.
$\Longrightarrow$ non-trivial structure for gauge currents.

Bottom-quark weak neutral Current :

Third component of the isospin : $t_{3L(R)}$

$$J^3_\mu \quad (b) \quad = \frac{e}{s_W c_W} \sum_{ij} \bar{b}_i \gamma_\mu (L_{ij} P_L + R_{ij} P_R) b_j \ ,$$

$$L \quad \equiv \quad \begin{pmatrix} t_{3L} s_L^2 - \frac{1}{2} c_L^2 & -\left(t_{3L} + \frac{1}{2}\right) s_L c_L \\ -\left(t_{3L} + \frac{1}{2}\right) s_L c_L & t_{3L} c_L^2 - \frac{1}{2} s_L^2 \end{pmatrix}$$

$$R \quad \equiv \quad \begin{pmatrix} t_{3R} s_R^2 & -t_{3R} s_R c_R \\ -t_{3R} s_R c_R & t_{3R} c_R^2 \end{pmatrix}$$

- Flavour changing neutral currents
- $\delta g^b_L = \left(t_{3L} + \frac{1}{2}\right) s_L^2 \ , \qquad \delta g^b_R = t_{3R} s_R^2 \ ,$
- Right handed component of the exotic cannot be a $SU(2)_L$ singlet.

Possible Quark Represenations

In principle, b'_L and b'_R : any (and inequivalent) representation.

- Anomaly cancellation: vector-like assignment most economic choice.
- Also vector-like fermions $\Longrightarrow$ relatively small contribution to the oblique electroweak parameter S.
- Nonzero mass terms connecting ordinary b with exotic necessary.
- Demand: electroweak symmetry breaking only through $SU(2)$ doublet Higgs boson $\Longrightarrow$ Choice for the exotic limited to a $SU(2)$ singlet and two varieties each of $SU(2)$ doublets and triplets.
- $t_{3R} \neq 0$ eliminates the singlet and one of the triplets as source for δg_R^b.

Choices : $\Psi_{L,R} = (3, 2, 1/6)$, $(3, 2, -5/6)$ and $(3, 3, 2/3)$.

Standard Mirrors

$$\Psi^T_{L,R} = (\chi, \omega) \equiv (3, 2, 1/6)$$

Most general Yukawa and mass term :

$$\begin{aligned}\mathcal{L} \supset \quad & - \quad \left(y_1 \overline{Q'_L} + y_2 \overline{\Psi_L}\right) b'_R \phi - \left(x_1 \overline{Q'_L} + x_2 \overline{\Psi'_L}\right) t'_R \tilde{\phi} \\ & - \quad M_1 \overline{\Psi'_L} \Psi'_R + h.c.,\end{aligned}$$

Ψ'_L and Q'_L have same quantum numbers : $\Longrightarrow \overline{Q'_L} \Psi_R$ can be trivially rotated away. In the basis (b', ω'), we then have a mass matrix of the form

$$M_b = \begin{pmatrix} Y_1 & 0 \\ Y_2 & M_1 \end{pmatrix} , \quad Y_i \equiv y_i \langle \phi \rangle$$

and an analogous one for the top.

Assume that the mass matrices are real.

$Y_1 \ll Y_2 < M_1$

$$\begin{aligned} m_b &\approx Y_1 / \sqrt{1 + \frac{Y_2^2}{M_1^2}}, & \tan \theta^b_R &\approx \frac{-Y_2}{M_1} \\ m_\omega &\approx \left(M_1^2 + Y_2^2\right)^{1/2}, & \tan \theta^b_L &\approx \frac{-Y_1 Y_2}{M_1^2 + Y_2^2}. \end{aligned}$$

- $\omega'_L \equiv b'_L$ and $\chi'_L \equiv t'_L$
  $\Longrightarrow$ gauge current in L-sector unmodified.

- FCNC's in both b_R and t_R sectors.

- $\delta g^b_R < 0$, (but $g^b_R(SM) > 0$)
  Large negative correction that takes us to the second allowed region in the parameter space. For example,

$$Y_2 \approx 0.7\, M_1 \quad \Longrightarrow \quad \delta g^b_R = \frac{-s^2_R}{2} \approx -0.165$$

  results in 1σ agreement for both A^b_{FB} R_b.

- Right-handed charged currents!
  $b \to s\gamma$ measurement requires $s^b_R s^t_R < 0.02$.
  Larios, Perez and Yuan ' 99

  Since the y's and x's are independent, could set $x_2 = 0$. $\Longrightarrow$ No mixing in top-sector and x_1 is the usual top Yukawa coupling.

- Tevatron limits on exotic quarks : $M_1 \gtrsim 200\ \mathrm{GeV}$.

Standard Mirrors : The fit

- Large mixing in the b-sector: Large corrections to parameters S, T and U. For $Y_2 \approx 0.7\, M_1$:
  $\Delta T(M_1 = 200\,\mathrm{GeV}) = 0.35$,
  $\Delta T(M_1 = 250\,\mathrm{GeV}) = 0.54$
  $\Delta S \simeq 0.1$ and increases very slowly with M_1 ΔU small.
- Data $\Longrightarrow$ non-zero δg_L^b as well.
  Also large ΔT and g_R^b tend to increase Γ_{had} and Γ_{tot}.
- Solution: Introduce a $SU(2)$-singlet quark as well

$$\xi'_{R,L} \equiv (3, 1, -1/3)$$

  Mass matrix modified. In the (b', ω', ξ') basis,

$$M_b = \begin{pmatrix} Y_1 & 0 & Y_3 \\ Y_2 & M_1 & 0 \\ 0 & 0 & M_2 \end{pmatrix}, \quad Y_i \equiv y_i \langle \phi \rangle$$

  $(M_b)_{31}$: could be trivially rotated away. $(M_b)_{23}$ and $(M_b)_{32}$: minor effects if small.

- Left-handed mixing angle : $s_L \simeq \dfrac{Y_3}{\sqrt{Y_3^2 + M_2^2}}$,

$$\delta g_L^b = \frac{s_L^2}{2}$$

Hence, s_L (or Y_3) must be relatively small. Main effect of s_L : reduce Γ_b and thus $\Gamma_{\rm had} \Longrightarrow$ should improve fit.
Oblique corrections still dominated by b_R–ω_R mixing.
Precision observables have epsilon dependences:

$$\begin{aligned} \Gamma_Z &\simeq 2.489\,(1 + 1.35\,\epsilon_1 - 0.46\,\epsilon_3 + ...)\ \mathrm{GeV} \\ \sin^2\theta_l^{\rm eff} &\simeq 0.2310\,(1 + 1.88\,\epsilon_3 - 1.45\,\epsilon_1) \\ \frac{m_W^2}{m_Z^2} &\simeq 0.7689\,(1 + 1.43\,\epsilon_1 - \epsilon_2 - 0.86\,\epsilon_3)\,, \end{aligned}$$

$$\begin{aligned} \epsilon_1 &= \alpha T &= 5.6 \times 10^{-3} \\ -\epsilon_2 &= \frac{\alpha U}{4 s_W^2} &= 7.4 \times 10^{-3} \\ \epsilon_3 &= \frac{\alpha S}{4 s_W^2} &= 5.4 \times 10^{-3} \end{aligned}$$

[Numbers for SM with $m_t = 174.3$ GeV and $m_H = 115$ GeV]

Additional dependence on $\alpha(M_Z)$ and $\alpha_s(M_Z)$, $\alpha(M_Z)$: $\Delta\alpha^{(5)}_{\rm had} = 0.02761$, $\alpha_s(M_Z)$: allowed to float around 0.118.

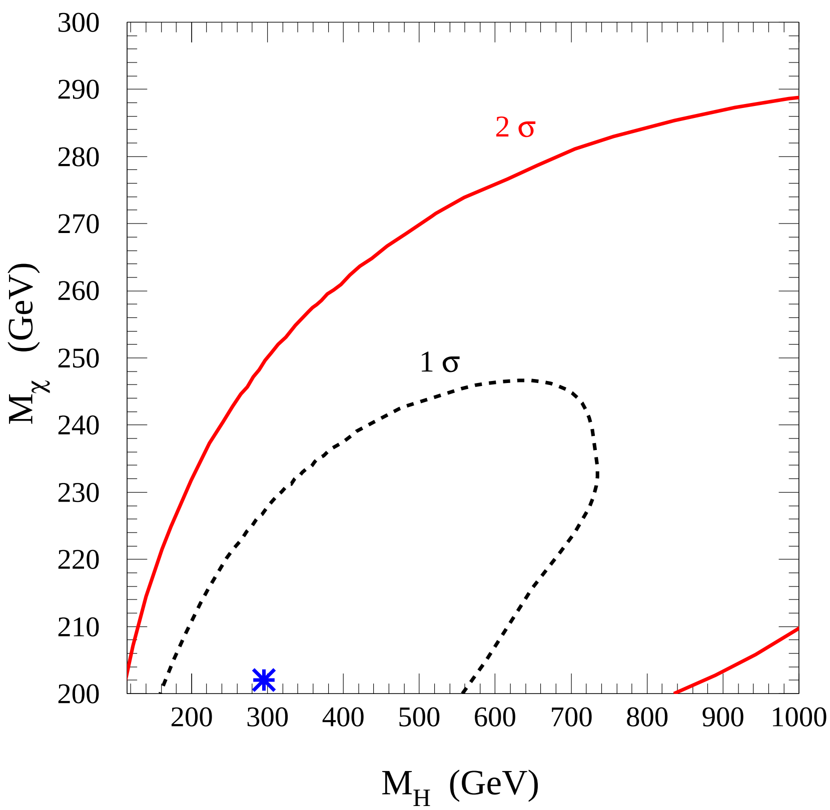
- Extra Quarks: Large positive corrections to $\epsilon_1 \equiv T$
- Heavy Higgs: Large negative corrections to ϵ_1. Positive ϵ_3 correction.
- Correlation between quark and Higgs masses.

Best fit : Standard Mirrors

$$M_1 = 200 \text{ GeV} \qquad Y_2 = 143 \text{ GeV}$$

$$m_H = 295.4 \text{ GeV} \qquad \sin^2 \theta_L^b = 0.00811$$

$$\alpha_s(M_Z) = 0.116$$



Observable	Exp. Value	Best fit	Pull
Γ_Z	2.4952 ± 0.0023	2.49885	-1.59
R_ℓ	20.767 ± 0.025	20.7337	1.33
A_e	0.1465 ± 0.0033	0.14730	-0.24
A_ℓ^{FB}	0.01714 ± 0.00095	0.01627	0.91
σ_h	41.54 ± 0.037	41.482	1.56
R_b	0.21646 ± 0.00065	0.21597	0.76
R_c	0.1719 ± 0.0031	0.17225	-0.11
A_c^{FB}	0.0685 ± 0.0034	0.07375	-1.55
A_b	0.922 ± 0.02	0.9060	0.80
A_c	0.67 ± 0.026	0.6676	0.09
m_W/m_Z	0.778381 ± 0.00064	0.778397	-0.025
A_b^{FB}	0.099 ± 0.0017	0.100091	-0.64
$A_{LR}(SLD)$	0.1513 ± 0.0021	0.147297	1.91
M_t	174.3 ± 5.1	172.667	0.32
$CW(Ces)$	-72.5 ± 0.7	-73.2261	1.04

Top-less Mirror Quark Doublets

$\Psi^T_{L,R} = (\omega, \chi) \equiv (3, 2, -5/6), \qquad \xi^T_{L,R} \equiv (3, 1, -1/3)$

Mass matrix [basis (b', ω', ξ')] similar to the earlier one.

$$M_b = \begin{pmatrix} Y_1 & 0 & Y_L \\ Y_R & M_1 & 0 \\ 0 & 0 & M_2 \end{pmatrix}, \quad Y_i \equiv y_i \langle \phi \rangle$$

$(M_b)_{12}$: prevented by gauge inv, $(M_b)_{31}$: can be rotated away, $(M_b)_{23}$ and $(M_b)_{32}$: minor effects

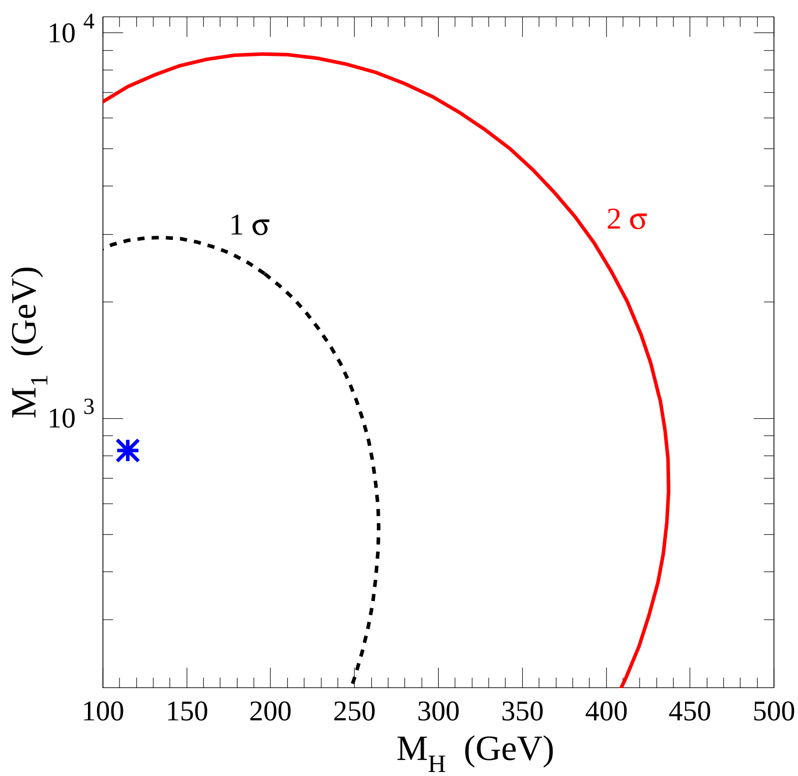
$$s_L \simeq \frac{Y_L}{\sqrt{Y_L^2 + M_2^2}} \qquad s_R \simeq \frac{Y_R}{\sqrt{Y_R^2 + M_1^2}}$$

$$\delta g_L^b = \frac{s_L^2}{2} \qquad \delta g_R^b = +\frac{s_R^2}{2}$$

- Positive $\delta g_R^b \Longrightarrow$ small s_R.
- EW symmetry breaking terms $\ll$ gauge inv masses. $\Longrightarrow$ Small corrections to S, T, U
- But, larger corrections needed for m_H to be in the experimentally allowed range: Heavy exotics (doublets) while light Higgs.

Best fit : Top-less Mirrors

$$M_1 = 825 \text{ GeV} \qquad Y_R = 160 \text{ GeV}$$
$$m_H = 115 \text{ GeV} \qquad Y_L = 15 \text{ GeV}$$
$$\alpha_s(M_Z) = 0.116 \qquad M_t = 176.04 GeV$$



Observable	Exp. Value	Best fit	Pull
Γ_Z	2.4952 ± 0.0023	2.4971	-0.88
R_ℓ	20.767 ± 0.025	20.7443	0.63
A_e	0.1465 ± 0.0033	0.1487	-0.61
A_ℓ^{FB}	0.01714 ± 0.00095	0.01658	0.59
σ_h	41.54 ± 0.037	41.482	1.56
R_b	0.21646 ± 0.00065	0.21613	0.50
R_c	0.1719 ± 0.0031	0.17225	-0.11
A_c^{FB}	0.0685 ± 0.0034	0.07451	-1.7
A_b	0.922 ± 0.02	0.9003	1.0
A_c	0.67 ± 0.026	0.6682	0.07
m_W/m_Z	0.778381 ± 0.00064	0.7778	0.92
A_b^{FB}	0.099 ± 0.0017	0.1004	-0.82
$A_{LR}(SLD)$	0.1513 ± 0.0021	0.148685	1.24
M_t	174.3 ± 5.1	176.046	-0.34
$CW(Ces)$	-72.5 ± 0.7	-73.1872	0.98

Collider Signatures

Shall concentrate on Tevatron:

Run I : Exotic b heavier than 199 GeV

$\chi \to b + W^+$ (Usual t' search) : Should be found

If ω light enough, $\omega \to b + Z$

Standard Mirrors

68.0% C.L. : $M_\chi \lesssim 245$ GeV, $M_\omega \lesssim 300$ GeV

99.5% C.L. : $M_\chi \lesssim 300$ GeV, $M_\omega \lesssim 370$ GeV

Run II with 1 fb^{-1} : $m_Q \lesssim 320$ GeV $\Longrightarrow$ larger than top sample in Run I

LC: $e^+ + e^- \to \bar{b} + \omega\ (b + \bar{\omega}) \to b + \bar{b} + Z$ LC may even measure s_R.

Singlet (mass not dertermined well) :

$\xi \to b + Z, \qquad \omega + Z\ \ [\text{nonzero}\ (M_b)_{23}]$

LHC should be able to see all new quarks !

More on Collider Signatures

In the Top-less model, the χ-quark signatures will be similar to that of the top quark, but decaying to a wrong sign W,

$$\chi \to \ b \ + \ W^-$$

The ω and χ signatures similar to the Standard Mirror case.

FCNC somewhat suppressed. Due to the larger masses, only LHC is certain to find the new quarks.

Higgs phenomenology:

In Standard Mirror case, if $m_H > m_\omega + m_b$, new decay channel opens. If $m_H > 2\omega$, two more channels open, with

$$\frac{BR(H \to \omega\bar{\omega})}{BR(H \to \omega\bar{b})} \simeq \tan^2\theta_R$$

These will suppress the $H \to ZZ$ Branching Ratio.

In the Top-less scenario, Higgs carries standard phenomenology.

Unification of Couplings: Standard Mirrors

In SM (for $n_H = 1$), $\alpha_s(\mu)$ and $\alpha_2(\mu)$ meet at $\sim 10^{17}$ GeV.

But $\alpha_1(\mu)$ crosses them at a much lower scale. We do not assume supersymmetry though. How to protect light masses? Perhaps invoke extra gauge symmetry:

Top-color, Top-flavor, Bottom-color, Compositeness

Shall do only a one-loop analysis. Will not take threshold effects into account. beta-function coefficients:

$$
\begin{aligned}
b_3 &= -11 + \frac{4}{3}n_g + 2 \\
b_2 &= \frac{-22}{3} + \frac{4}{3}n_g + \frac{n_H}{6} + 2 \\
b_1 &= \frac{4}{3}n_g + \frac{n_H}{10} + \frac{2}{5}
\end{aligned}
$$

where n_g is number of generations and n_H is number of Higgs doublets.

Since $\delta b_1 < \delta b_2 = \delta b_3 \Longrightarrow \alpha_1$ crosses the others much later.

	Average M_{GUT}	Discrepancy
$n_H = 1$	5×10^{16} GeV	3%
$n_H = 2$	2×10^{16} GeV	1%
$n_H = 3$	1×10^{16} GeV	3%

Small differences.

Threshold effects? m_{Pl} suppressed operators?

Good feature: No dimension five operators leading to proton decay.

Large M_{GUT} : dim-6 operators well suppressed.

However, heavy Higgs $\Longrightarrow$ Landau pole well below M_{GUT}.

Give up ?

Unification of Couplings : Top-less Beauties.

Higgs is light $\Longrightarrow$ No Landau-pole problem.

beta-function coefficients:

$$\begin{aligned} b_3 &= -11 + \frac{4}{3} n_g + 2 \\ b_2 &= \frac{-22}{3} + \frac{4}{3} n_g + \frac{n_H}{6} + 2 \\ b_1 &= \frac{4}{3} n_g + \frac{n_H}{10} + \frac{18}{5} \end{aligned}$$

$\delta b_1 > \delta b_2 = \delta b_3 \Longrightarrow \alpha_1$ crosses the others much earlier.

Unification problem worsened.

Note: doublets $\subset \mathbf{24}$,   singlets $\subset \mathbf{5} + \bar{\mathbf{5}}$ of $SU(5)$.

(Everything in adjoint of $SU(6) \subset E_6$)

Complete the representations

(“ Gluino”, “ Wino”, “ Bino”) and “ Higgsino”

and we are back at the SM situation.

Unification of Couplings: Hybrid Model

- Complete **24** of fermions at the weak scale, together with the standard mirror doublet and singlet quarks. (All these fields are contained in the adjoint of E_6.)

- b-quark mixes mainly with the top-less doublet (and singlet).

- Higgs tends to be light $\Longrightarrow$ No Landau-pole problem.

- Standard doublet: light but virtually no mixing with b.

- Unification of Couplings OK ! Not affected by complete representations.

  "Gaugino"-like fields: "Gluino": Unless new fields added, very long lived or even stable.

  "Wino", "Bino" : could mix with leptons $\Longrightarrow$ either a discrete symmetry (" R-Parity") or very small Yukawa's.

- Introduction of new Higgs doublet (slepton): correct coannihilation rate for "Bino" as a Dark Matter candidate.

Conclusions

- A_{FB}^{b} creates a problem in the otherwise perfect SM fit to the precision electroweak data.
- Solution: Either we ignore it $\rightarrow$ New physics preferred, or, if we take it into account, new exotic quarks can improve dramatically the fit.
- Standard Beautiful Mirror Quarks: Improve the fit, implying light quarks and a relatively heavy Higgs.
- Top-less Beautiful Mirror Quarks: Improve dramatically the fit, implying a light Higgs, with SM properties, and heavy quarks.
- Exciting New phenomenology at near future Colliders !
- Unification of Couplings at high scales with no proton decay achievable within the Beautiful Mirror Framework !
- Open Problem : Electroweak Symmetry Breaking.