Strongly Interacting Symmetry Breaking Sector and Top Physics

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If we do not find a Higgs either

- it is too heavy.
- it does not exist (but some alternative physics should be there)

We need a predictive approach to deal with the Symmetry Breaking Sector (SBS) up to LHC energies, which should be

- Systematic: to obtain all observables with an organized procedure to calculate quantum corrections in a model independent way.
- Consistent: Finite results. $SU(2)_L \times U(1)_Y$ gauge invariant, unitary ...

This is achieved with the Electroweak Effective Chiral Lagrangian (EChL) formalism.

The EChL is written in terms of the standard fields, $W^{\pm}, Z^0, \gamma \ldots$ as well as

- 3 Goldstone Bosons, because $W^{\pm}, Z^0$ massive. They drive the spontaneous $SU(2)_L \times U(1)_Y \longrightarrow U(1)_{EM}$ breaking.
- a breaking scale $v \simeq 246$ GeV.

FOUR MAIN IDEAS

1. If there is no Higgs or other light resonances:

$$\Downarrow$$

SBS at low energy = Goldstone Boson Dynamics

2. Chiral Symmetry Breaking determines low-energy dynamics.

$$\Downarrow$$

Universal Low Energy Theorems
(like Current Algebra in QCD)

$$t(s,t,u) \simeq \frac{s}{A_I}$$

3. SBS interactions become STRONG around 1 TeV.

4. Intuitively: Gauge bosons $\simeq$ Longitudinal gauge bosons
Equivalence Theorem (ET):

$$T(V_L, V_L, ..., \Phi) = T(\omega, \omega, ..., \Phi) + \mathcal{O}\left(\frac{M}{\sqrt{s}}\right)$$

- We expect an enhancement of V_L's
- With longitudinal gauge bosons we test the SBS

The Electroweak SBS Effective Chiral Lagrangian

(Appelquist, Bernard, Longhitano)

The 3 GB's can be parametrized in an $SU(2)$ matrix:

$$U = \exp\left(\frac{i\omega^a\sigma^a}{v}\right)$$

Since we only know the light modes of the SBS, its lagrangian is a low-energy (derivative) expansion. The dimension 2 term

$$\mathcal{L}^{(2)} = \frac{v^2}{4}\mathrm{tr} D_\mu U D^\mu U^\dagger$$

yields the Low Energy Theorems ($A(s) = s/v2$), in addition we have

$$\begin{aligned}
\mathcal{L}'^{(2)} &= a_0 \frac{g'^2 v^2}{4}[\mathrm{tr}(TV_\nu)]^2 \\
\mathcal{L}^{(4)} &= a_1 \frac{igg'}{2} B_{\mu\nu}\mathrm{tr}(TF^{\mu\nu}) + a_2 \frac{ig'}{2} B_{\mu\nu}\mathrm{tr}(T[V^\mu, V^\nu]) \\
&+ a_3 g\,\mathrm{tr}(F_{\mu\nu}[V^\mu, V^\nu]) + a_4[\mathrm{tr}(V_\mu V_\nu)]^2 \\
&+ a_5[\mathrm{tr}(V_\mu V^\mu)]^2 + a_6\mathrm{tr}(V_\mu V_\nu)\mathrm{tr}(TV^\mu)\mathrm{tr}(TV^\nu) \\
&+ a_7\mathrm{tr}(V_\mu V^\mu)[\mathrm{tr}(TV^\nu)]^2 + a_8\frac{g^2}{4}[\mathrm{tr}(TF_{\mu\nu})]^2 \\
&+ a_9\frac{g}{2}\mathrm{tr}(TF_{\mu\nu})\mathrm{tr}(T[V^\mu, V^\nu]) + a_{10}[\mathrm{tr}(TV_\mu)\mathrm{tr}(TV_\nu)]^2 \\
&+ g a_{11}\epsilon^{\mu\nu\rho\sigma}\mathrm{tr}\,(TV_\mu)\,\mathrm{tr}\,(TV_\nu F_{\rho\sigma}) \\
&+ \text{e.o.m. terms} + \text{non-CP terms}
\end{aligned}$$

$$T = U\tau^3 U^\dagger \quad ; \quad V_\mu = (D_\mu U)\, U^\dagger$$

Present Bounds

Two point functions

We have

$$S = 16\pi\left[-a_1(\mu) + \text{EChL loops}(\mu)\right]$$
$$T = \frac{8\pi}{c_W^2}\left[a_0(\mu) + \text{EChL loops}(\mu)\right]$$
$$U = 16\pi\left[a_8(\mu) + \text{EChL loops}(\mu)\right]$$

A. Dobado, D. Espriu and M.J. Herrero

Using PDG 1998

$$\Delta S = -0.26 \pm 0.14$$
$$\Delta T = -0.11 \pm 0.16$$
$$\Delta U = 0.26 \pm 0.24$$

for $M_H = 300\,\text{GeV}$ and $m_t = 175 \pm 5\,\text{GeV}$ at 1 σ, we get

$$a_1(1\text{TeV}) = (6.8 \pm 2.8) \times 10^{-3}$$
$$a_0(1\text{TeV}) = (4.3 \pm 4.9) \times 10^{-3}$$
$$a_8(1\text{TeV}) = (4.9 \pm 4.7) \times 10^{-3}$$

Other studies agree within errors. Dawson , Valencia and Alan,Dawson,Szalapski

The Matter Sector

- The presence of strongly interacting physics has consequences in the matter sector of the standard model
- We must extend the EChL to the matter sector
- We write the most general set of operators up to a given dimensionality
- Some operators are universal while others depend on the underlying theory

$\boxed{d=3}$

$$\mathcal{L}_Y = -v\bar{q}_L U(y + \tau_3 y_3) q_R + \text{H.C.}$$

$\boxed{d=4}$

$$\mathcal{L}_4^1 = i\delta_1 \bar{q}_L U \gamma^\mu D_\mu U^\dagger q_L$$

$$\mathcal{L}_4^2 = i\delta_2 \bar{q}_R U^\dagger \gamma^\mu D_\mu U q_R$$

$$\mathcal{L}_4^3 = i\delta_3 \bar{q}_L \gamma^\mu D_\mu U \tau_3 U^\dagger q_L + \text{H.C.}$$

$$\mathcal{L}_4^4 = i\delta_4 \bar{q}_L U \tau_3 U^\dagger \gamma^\mu D_\mu U \tau_3 U^\dagger q_L$$

$$\mathcal{L}_4^5 = i\delta_5 \bar{q}_R \tau_3 U^\dagger \gamma^\mu D_\mu U q_R + \text{H.C.}$$

$$\mathcal{L}_4^6 = i\delta_6 \bar{q}_R \tau_3 U^\dagger \gamma^\mu D_\mu U \tau_3 q_R$$

[Appelquist, Bowick, Cohler and Hauser]

- The $d = 4$ operators carry non-universal information relevant at scales $q^2 \leq \Lambda_{SB}^2$. They involve both V_L and V_T

$d = 5$ **operators contributing to the** $Zb\bar{b}$ **vertex**

$$\mathcal{L}_5^7 = \bar{q}_L\sigma^{\mu\nu}D^\dagger{}_{[\mu}(D_{\nu]}U)q_R - \bar{q}_L\sigma^{\mu\nu}(D_{[\nu}U)D_{\mu]}q_R + \mathrm{H.C.}$$

$$\mathcal{L}_5^8 = \bar{q}_L\sigma^{\mu\nu}D^\dagger{}_{[\mu}(D_{\nu]}U)\tau^3 q_R - \bar{q}_L\sigma^{\mu\nu}(D_{[\nu}U)\tau^3 D_{\mu]}q_R + \mathrm{H.C.}$$

$$\mathcal{L}_5^9 = \bar{q}_L\sigma^{\mu\nu}D^\dagger{}_{[\mu}U\tau^3U^\dagger(D_{\nu]}U)q_R - \bar{q}_L\sigma^{\mu\nu}U\tau^3U^\dagger(D_{[\nu}U)D_{\mu]}q_R + \mathrm{H.C.}$$

$$\mathcal{L}_5^{10} = \bar{q}_L\sigma^{\mu\nu}D^\dagger{}_{[\mu}U\tau^3U^\dagger(D_{\nu]}U)\tau^3 q_R - \bar{q}_L\sigma^{\mu\nu}U\tau^3U^\dagger(D_{[\nu}U)\tau^3 D_{\mu]}q_R + \mathrm{H.C.}$$

$$\mathcal{L}_5^{11} = \bar{q}_L U D^2 q_R + \mathrm{H.C.}$$

$$\mathcal{L}_5^{12} = \bar{q}_L(D^\dagger)^2 U q_R + \mathrm{H.C.}$$

$$\mathcal{L}_5^{13} = \bar{q}_L(D^2U)q_R + \mathrm{H.C.}$$

$$\mathcal{L}_5^{14} = \bar{q}_L U\tau^3 D^2 q_R + \mathrm{H.C.}$$

$$\mathcal{L}_5^{15} = \bar{q}_L(D^\dagger)^2 U\tau^3 q_R + \mathrm{H.C.}$$

$$\mathcal{L}_5^{16} = \bar{q}_L(D^2U)\tau^3 q_R + \mathrm{H.C.}$$

$$\mathcal{L}_5^{17} = \bar{q}_L U\tau^3U^\dagger(D^2U)q_R + \mathrm{H.C.}$$

$$\mathcal{L}_5^{18} = \bar{q}_L D^\dagger_\mu U\tau^3U^\dagger(D^\mu U)q_R - \bar{q}_L U\tau^3U^\dagger(D^\mu U)D_\mu q_R + \mathrm{H.C.}$$

$$\mathcal{L}_5^{19} = \bar{q}_L U\tau^3U^\dagger(D^2U)\tau^3 q_R + \mathrm{H.C.}$$

$$\mathcal{L}_5^{20} = \bar{q}_L D^\dagger_\mu U\tau^3U^\dagger(D^\mu U)\tau^3 q_R - \bar{q}_L U\tau^3U^\dagger(D^\mu U)\tau^3 D_\mu q_R + \mathrm{H.C.}$$

Present Bounds on δ_i

• The $d=4$ effective coefficients contribute to the effective couplings of $W^{\pm}$, Z (but not of γ

$\boxed{\bar{q}Zq}$

$$\hat{g}_V^f = I_f^3(\delta_1 - \delta_4 - \delta_2 - \delta_6) - \delta_3 - \delta_5$$

$$\hat{g}_A^f = I_f^3(\delta_1 - \delta_4 + \delta_2 + \delta_6) - \delta_3 + \delta_5$$

$\boxed{\bar{t}W^+b}$

$$\hat{g}_R = \delta_2 - \delta_6$$

$$\hat{g}_L = -\delta_1 - \delta_4$$

[Bagan, Espriu and Manzano]

• The effective couplings are expected to be sizeable only for the third generation (for almost any model one may think of)

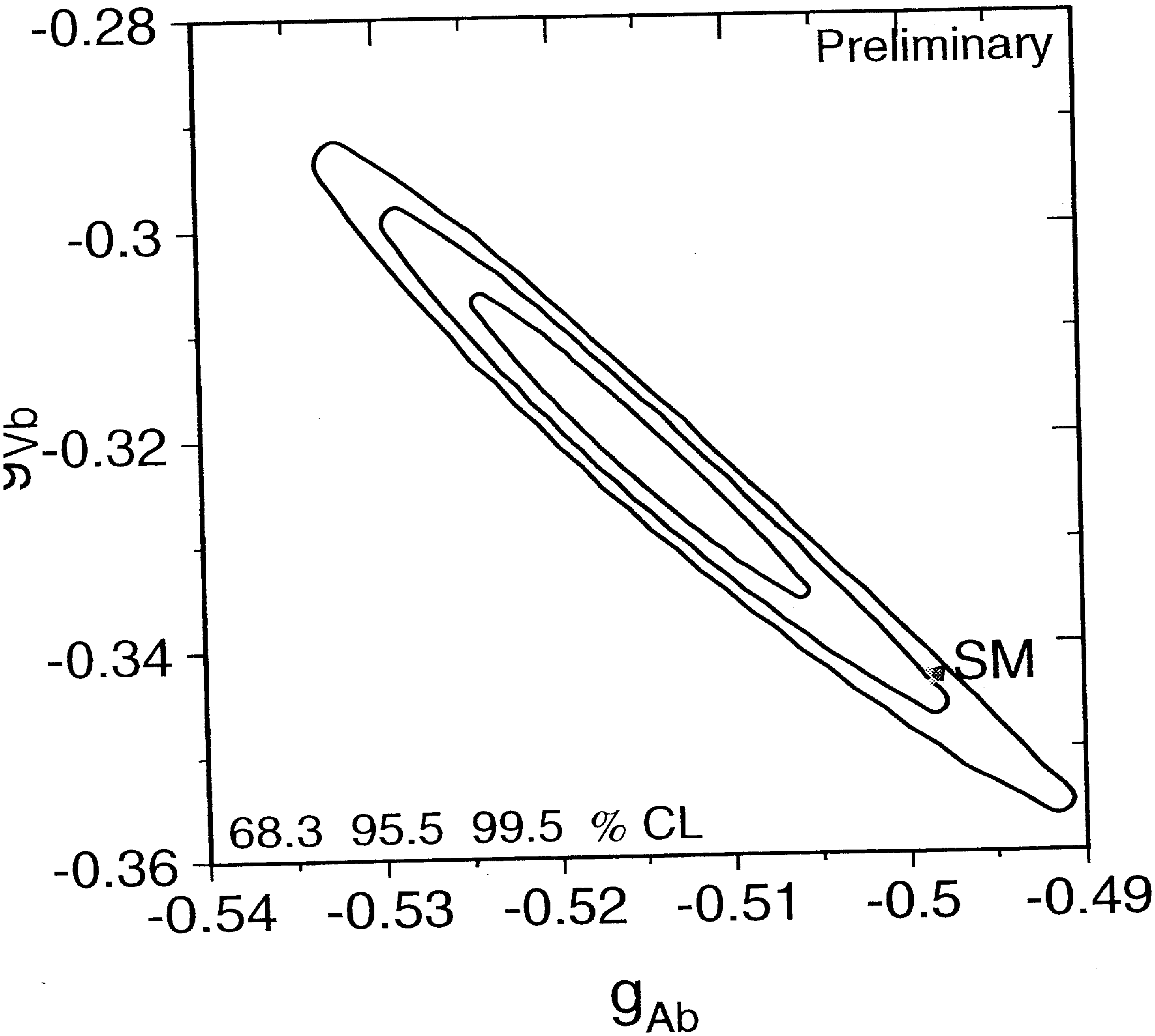
$$\boxed{g_V^b = -0.3195 \pm 0.0096, \qquad g_A^b = -0.5163 \pm 0.0061}$$

[Moriond 99]

• Only 2 particular combinations can be determined at present. Top physics is essential!!!

• δ_1 and δ_2 parametrize custodially preserving physics, the rest are custodially breaking.

• Nothing is known at present on the coefficients of the $d=5$ operators.


Preliminary
SM
68.3 95.5 99.5 % CL
-0.28
-0.3
-0.32
-0.34
-0.36
g_{Vb}
-0.54
-0.53
-0.52
-0.51
-0.5
-0.49
g_{Ab}

The δ_i in the Minimal Standard Model

- Determined via matching conditions
- On-shell scheme.

$$\delta_1(\mu) = -\frac{y_t^2+y_b^2}{16\pi^2}\frac{1}{4}\left(\frac{5}{2} - \log\frac{M_H^2}{\mu^2}\right)$$

$$\delta_2(\mu) = -\frac{(y_t+y_b)^2}{16\pi^2}\frac{1}{8}\left(\frac{5}{2} - \log\frac{M_H^2}{\mu^2}\right)$$

$$\delta_3(\mu) = \frac{y_t^2-y_b^2}{16\pi^2}\frac{1}{8}\left(\frac{5}{2} - \log\frac{M_H^2}{\mu^2}\right)$$

$$\delta_4 = 0$$

$$\delta_5 = -\delta_3$$

$$\delta_6(\mu) = \frac{(y_t-y_b)^2}{16\pi^2}\frac{1}{8}\left(\frac{5}{2} - \log\frac{M_H^2}{\mu^2}\right)$$

[Dittmaier, Grosse-Knetter; Bagan, Espriu]

- For comparison

$$a_1(\mu) = \frac{1}{16\pi^2}\frac{1}{24}\left(\frac{5}{6} - \log\frac{M_H^2}{\mu^2}\right)$$

- The δ_i contain the non-decoupling effects in the matter sector of the SM

The δ_i in Dynamical Symmetry Breaking

- Theories without light scalars ($>$ 100 GeV) and a large scale (e.g. ETC) can be parametrized in terms of four-fermion operators

- Very general analysis

- Effects are potentially very big for third generation, small for the second (10^{-3}) and negligible for the first (10^{-5})

- Vertex corrections cannot be considered 'universal'

$L^2 = (\bar{Q}_L\gamma_\mu Q_L)(\bar{q}_L\gamma^\mu q_L)$	
$R^2 = (\bar{Q}_R\gamma_\mu Q_R)(\bar{q}_R\gamma^\mu q_R)$	$R_3R = (\bar{Q}_R\gamma_\mu\tau^3 Q_R)(\bar{q}_R\gamma^\mu q_R)$
	$RR_3 = (\bar{Q}_R\gamma_\mu Q_R)(\bar{q}_R\gamma^\mu\tau^3 q_R)$
	$R_3^2 = (\bar{Q}_R\gamma_\mu\tau^3 Q_R)(\bar{q}_R\gamma^\mu\tau^3 q_R)$
$RL = (\bar{Q}_R\gamma_\mu Q_R)(\bar{q}_L\gamma^\mu q_L)$	$R_3L = (\bar{Q}_R\gamma_\mu\tau^3 Q_R)(\bar{q}_L\gamma^\mu q_L)$
$LR = (\bar{Q}_L\gamma_\mu Q_L)(\bar{q}_R\gamma^\mu q_R)$	$LR_3 = (\bar{Q}_L\gamma_\mu Q_L)(\bar{q}_R\gamma^\mu\tau^3 q_R)$
$rl = (\bar{Q}_R\gamma_\mu\vec{\lambda}Q_R)\cdot(\bar{q}_L\gamma^\mu\vec{\lambda}q_L)$	$r_3l = (\bar{Q}_R\gamma_\mu\vec{\lambda}\tau^3 Q_R)\cdot(\bar{q}_L\gamma^\mu\vec{\lambda}q_L)$
$lr = (\bar{Q}_L\gamma_\mu\vec{\lambda}Q_L)\cdot(\bar{q}_R\gamma^\mu\vec{\lambda}q_R)$	$lr_3 = (\bar{Q}_L\gamma_\mu\vec{\lambda}Q_L)\cdot(\bar{q}_R\gamma^\mu\vec{\lambda}\tau^3 q_R)$
$l^2 = (\bar{Q}_L\gamma_\mu\vec{\lambda}Q_L)\cdot(\bar{q}_L\gamma^\mu\vec{\lambda}q_L)$	
$r^2 = (\bar{Q}_R\gamma_\mu\vec{\lambda}Q_R)\cdot(\bar{q}_R\gamma^\mu\vec{\lambda}q_R)$	$r_3r = (\bar{Q}_R\gamma_\mu\vec{\lambda}\tau^3 Q_R)\cdot(\bar{q}_R\gamma^\mu\vec{\lambda}q_R)$
	$rr_3 = (\bar{Q}_R\gamma_\mu\vec{\lambda}Q_R)\cdot(\bar{q}_R\gamma^\mu\vec{\lambda}\tau^3 q_R)$
	$r_3^2 = (\bar{Q}_R\gamma_\mu\vec{\lambda}\tau^3 Q_R)\cdot(\bar{q}_R\gamma^\mu\vec{\lambda}\tau^3 q_R)$
$\vec{L}^2 = (\bar{Q}_L\gamma_\mu\vec{\tau}Q_L)\cdot(\bar{q}_L\gamma^\mu\vec{\tau}q_L)$	
$\vec{R}^2 = (\bar{Q}_R\gamma_\mu\vec{\tau}Q_R)\cdot(\bar{q}_R\gamma^\mu\vec{\tau}q_R)$	
$\vec{l}^2 = (\bar{Q}_L\gamma_\mu\vec{\lambda}\vec{\tau}Q_L)\cdot(\bar{q}_L\gamma^\mu\vec{\lambda}\vec{\tau}q_L)$	
$\vec{r}^2 = (\bar{Q}_R\gamma_\mu\vec{\lambda}\vec{\tau}Q_R)\cdot(\bar{q}_R\gamma^\mu\vec{\lambda}\vec{\tau}q_R)$	

[Bagan, Espriu, Manzano]

Oblique Corrections to g_A, g_V

$$\bar{g}^f_V = a_0[I^3_f + 2Q_f(2c^2_W - s^2_W)] + 2a_1 Q_f g^2 s^2_W + 2a_8 Q_f g^2 c^2_W$$

$$\bar{g}^f_A = a_0 I^3_f$$

- Recall that

$$g^{f\,X} = g^{f\,SM} + \bar{g}^f(a^X_i - a^{SM}_i) + \hat{g}^f(\delta^X_i - \delta^{SM}_i)$$

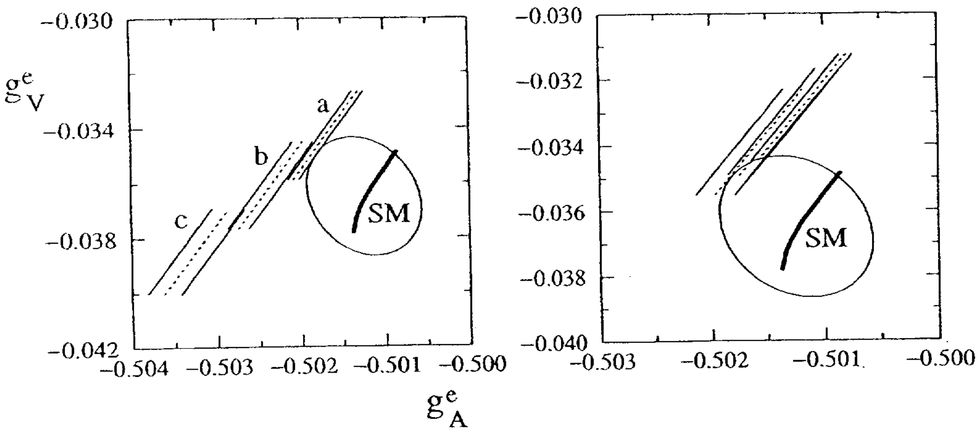


Figure 7: Oblique and vertex corrections for the electron effective couplings. The elipse indicate the 1-σ experimental region. Three values of the effective mass m_2 are considered: 250 (a), 350 (b) and 450 GeV (c), and two splittings: 10% (right) and 20% (left). The dotted lines correspond to including the oblique corrections only. The coefficients of the four-fermion operators vary in the range [-2,2] and this spans the region between the two solid lines. The Standard Model prediction (thick solid line) is shown for $m_t = 175.6$ GeV and $70 \leq M_H \leq 1500$ GeV.

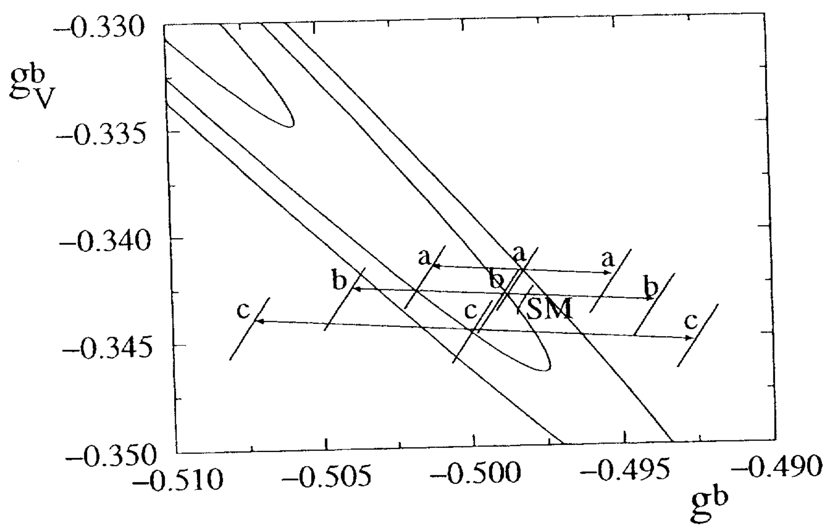
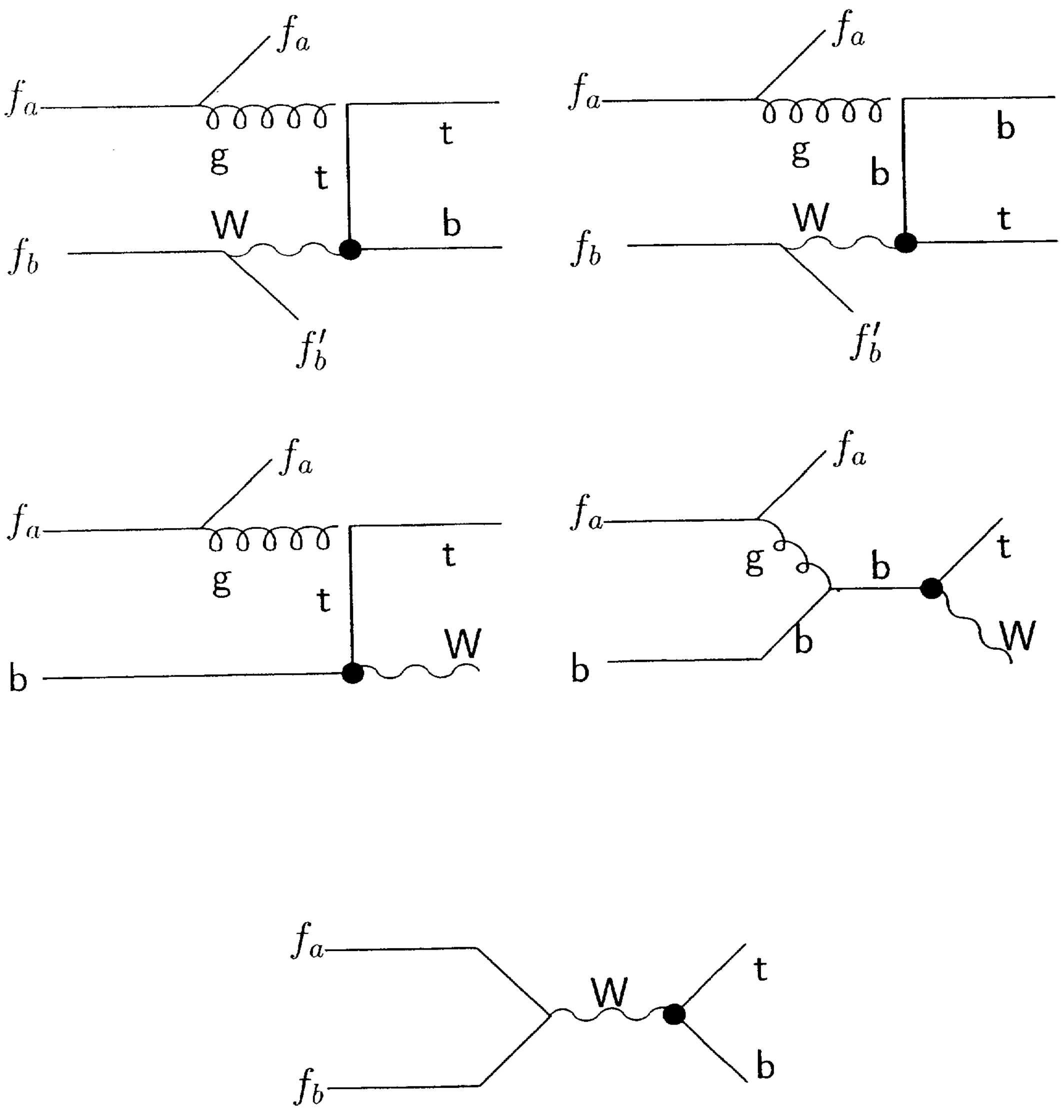


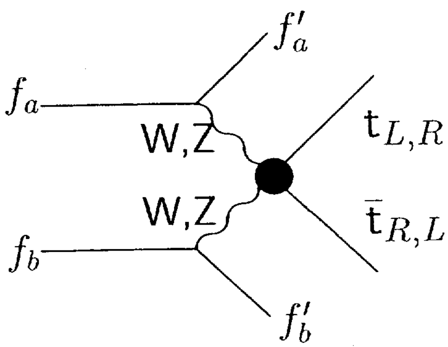
Figure 8: Bottom effective couplings compared to the SM prediction for $m_t = 175.6$ as a function of the Higgs mass (in the range [70,1500] GeV). The elipses indicate 1, 2, and 3-σ experimental regions. The dynamically generated masses are 250 (a), 350 (b) and 400 GeV (c) and we show a 20% splitting between the masses in the heavy doublet. The degenerate case does not present quantitative differencies if we consider the experimental errors. The central lines correspond to including only the oblique corrections. When we include the vertex corrections (depending on the size of the four-fermion coefficients) we predict the regions between lines indicated by the arrows. The four-fermion coefficients in this case take values in the range [-0.1,0.1].

Anomalous single top production

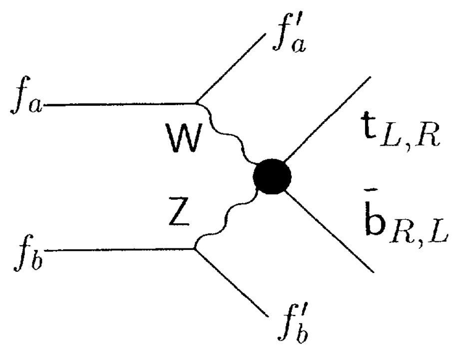


Top from VV fusion

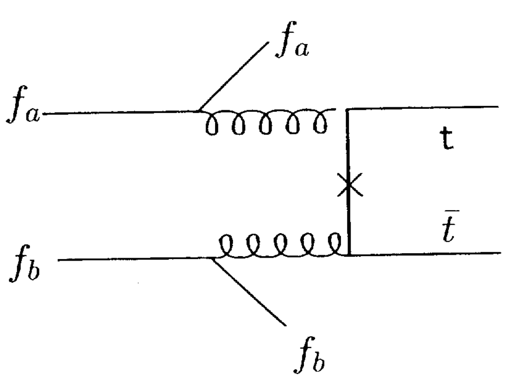
$t\bar{t}$ from fusion (d=3,5)

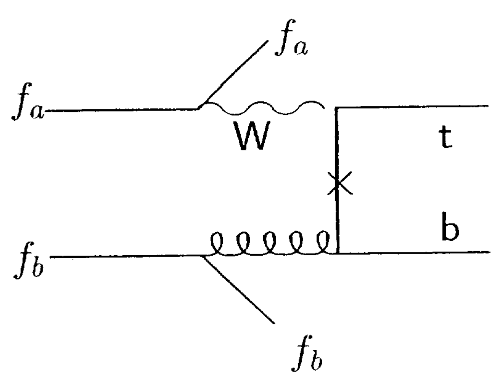


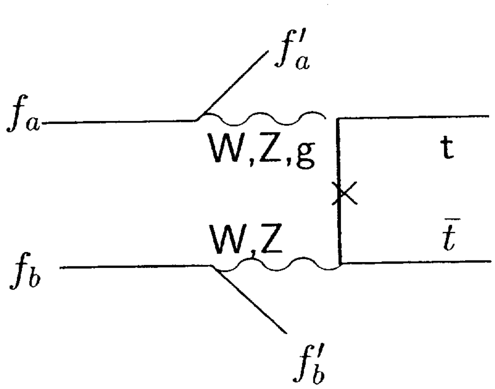
$t\,\bar{b}$ from fusion (d=3,5)

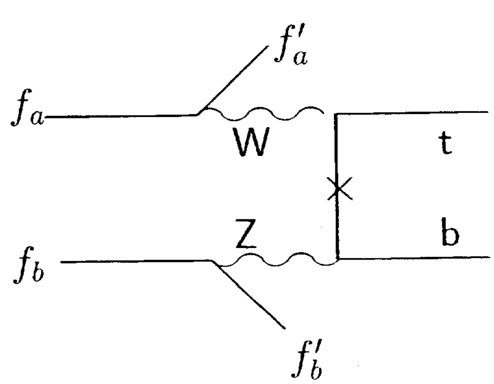


Backgrounds









LHC Prospects with the EChL (Matter Sector)

- Very clear (universal) predictions at the leading order ($d = 3$ operator) for $V_L V_L$ fusion (dominant)
- Final $\bar{q}q$ state in opposite chiralities. Useful to disentangle from background.

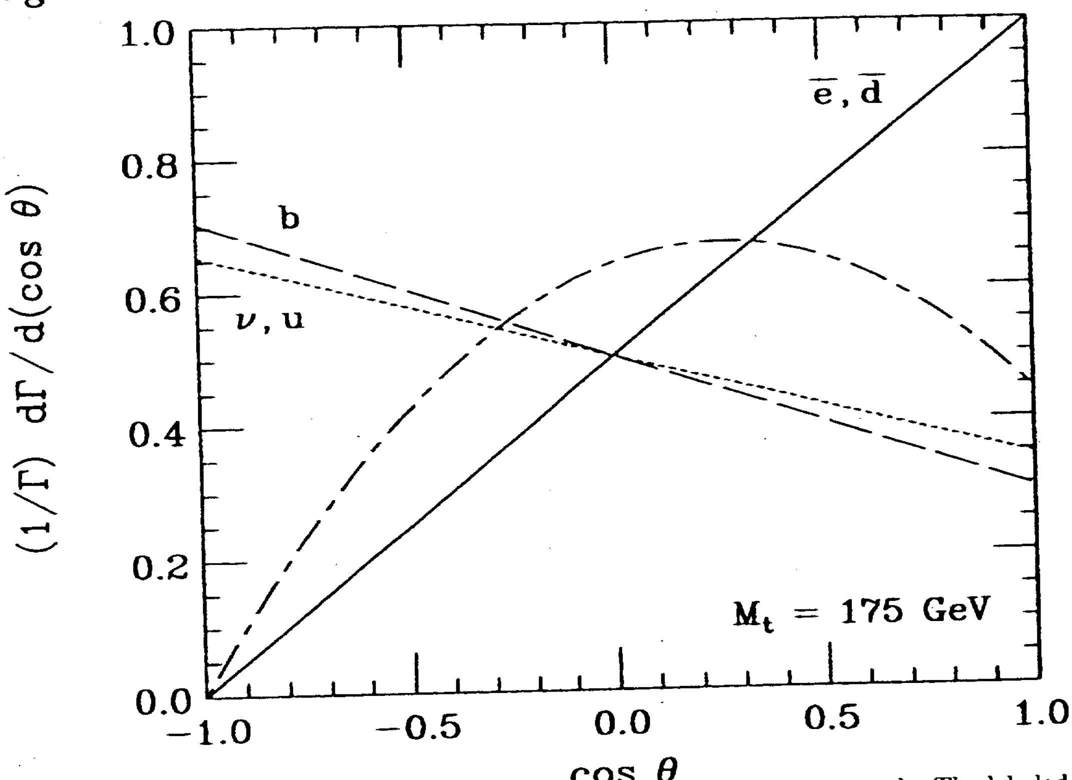


Figure 4: Angular correlations in the decay of a 175 GeV spin-up top quark. The labeled lines are the angle between the spin axis and the particle in the rest frame of the top quark. The unlabeled dot-dash line is the angle between the b quark and the positron (or d-type quark) in the rest frame of the W-boson.

[Parke]

- Non-universal ($d = 5$ operators) are subleading: $\rightarrow (1 + \lambda \frac{E^2}{16\pi^2 v^2})$
- Is is claimed that precision for λ can be as high as 1 % (?)

[Larios, Yuan]

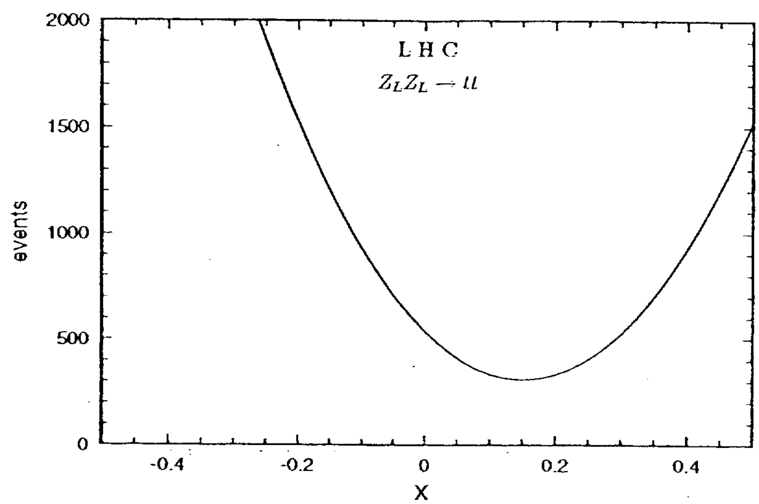


Figure 6: Number of events at the LHC for $Z_L Z_L$ fusion. The variable X is defined in Eq. (83).

Conclusions

- The EChL provides an appropriate formalism to study in a model independent way a strongly interacting SBS

- Provides a sytematic and consistent approach

- Very rich phenomenology can be described by the $d = 4$ operators in the EChL. Some info on top form factors should be available soon from the Tevatron. LHC will improve our knowledge considerably on them.

- Extension to several families (including CP odd) of considerable interest

- $V_L V_L$ fusion dominated by universal term (still, predictions are considerably different from those with theories with a light Higgs). It is claimed that precision on non-universal $d = 5$ operators can be as large as 1 %

- We intend to explore these issues in detail