

NEW PHYSICS AT THE LHC

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- Large Hierarchy Collider, Little Hierarchy Collider or Last Huge Collider?
- The top quark sector in Little Higgs models
- *A minimal* model
- LHC Physics

R. Barceló, M. Masip, M. Moreno-Torres, to appear in NPB

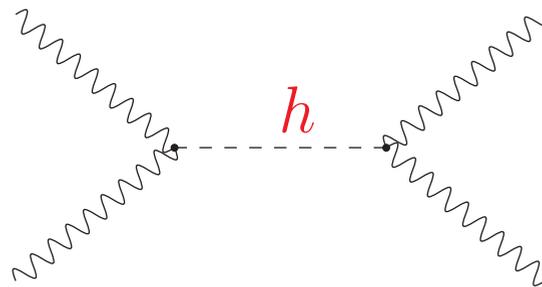
R. Barceló, M. Masip, in preparation

Fermilab, August 2007

The LHC has been built to measure the mass of the Higgs and to find the mechanism that explains that value

1. The Higgs *must* be there:

- It breaks the EW symmetry. $\langle h^0 \rangle = v/\sqrt{2} = 174 \text{ GeV} + 3 \text{ GBs}$
- It *unitarizes* the $WW \rightarrow WW$ c.s. **If Higgsless, then $\Lambda \approx 1.7 \text{ TeV}$**



- It is *difficult* to accommodate Technicolor or X-dims below such a low cutoff. **There should be a Higgs at the reach of the LHC.**

2. Suppose that the SM Higgs is discovered at the LHC. The mass parameter $-m^2 = \lambda v^2 \approx (100 \text{ GeV})^2$ in the Higgs potential is not *natural*, and the LHC will unveil the mechanism that *explains* it (will solve the *hierarchy problem*).

- The SM is an **effective theory** (it does not include gravity) valid below a cutoff Λ .
- Since it is **renormalizable**, we don't know what the value of Λ is. **Hints:**
 - (a) Neutrino masses introduce a scale $\Lambda_\nu \approx 10^{14} \text{ GeV}$:

$$-\mathcal{L}_\nu = \frac{1}{2\Lambda_\nu} H^\dagger H^\dagger LL + \text{h.c.}$$

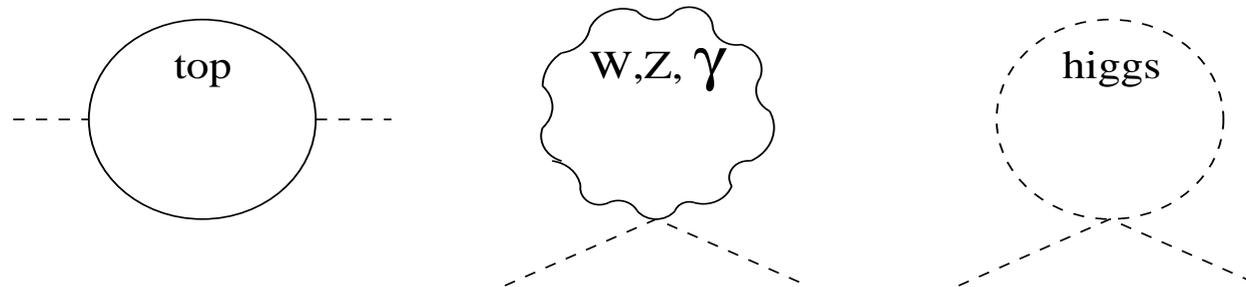
- (b) Dark matter suggests a scale $M_\chi \leq 1 \text{ TeV}$.
- (c) Cosmology indicates a vacuum energy density $\Lambda_{DE} \approx (10^{-3} \text{ eV})^4$.
- (d) The unification of the gauge coup. points to a scale $M_X \approx 10^{16} \text{ GeV}$.

(e) Gravity introduces the Planck scale, $M_P = G_N^{-1/2} \approx 10^{19} \text{ GeV}$.

(a)–(d): the SM must be *completed* (e): the SM must be *changed*

3. Since $-m^2 \approx (100 \text{ GeV})^2$, what is the *expected* value of the cutoff Λ ?

- The tree level value $-m_0^2$ is defined by the *complete* theory above Λ .
- The one-loop value $-m^2$ includes then the corrections



$$m^2 = m_0^2 - \frac{3}{8\pi^2} y_t^2 \Lambda^2 + \frac{9}{64\pi^2} g^2 \Lambda^2 + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

- If $\Lambda \approx M_P$, then $m^2 = O(10^{34}) + O(10^{34}) \approx -10^4 \text{ GeV}^2$

- If $\Lambda \approx 2 \text{ TeV}$, then $m^2 = O(10^5) + O(10^5) \approx -10^4 \text{ GeV}^2$

If there is a dynamical reason for m^2 to take such an *unnatural* value, it must be effective at 1 TeV and should manifest at the LHC.

- There are (at least) three possibilities

1. **SUSY below 1 TeV.** The discovery of squarks, sleptons, higgsinos and gauginos at the LHC would take the cutoff of the SM+SUSY up to M_X or M_P . **LHC = Large Hierarchy Collider.** Favorite possibility (hundreds of PhD dissertations during the past 30 years).

However...

Bounds from Flavour Physics ($b \rightarrow s\gamma, \mu \rightarrow e\gamma$), CP violation (**electric dipole moments**) and other precision EW observables imply a 1% fine-tuning or SUSY particles above $\approx 5 \text{ TeV} \rightarrow$ Little Hierarchy Problem and SUSY beyond the reach of the LHC!

2. **Little Higgs below 1 TeV.** Bottom–top approach. The objective of these models would be just to rise the cutoff of the SM+LH from 1 TeV to 10 TeV, where a more *fundamental* mechanism (SUSY) would take the cutoff up to the Planck scale.

LH ideas provide a simple mechanism that cancels SM one-loop quadratic corrections to m^2

They are *less ambitious* than SUSY, but could be more compatible with precision observables: do *not* require a 1% fine tuning (they solve the little hierarchy problem). **LHC = Little Hierarchy Collider.**

3. **Just the SM Higgs below 1 TeV.** If no dynamical mechanism explaining the value of m^2 is found at the LHC, this parameter may take different values in different regions of the universe (multiverse).

If there are over 10^{30} of these regions, we may expect one of them (the

universe we see) with such an odd value. The *Hierarchy Problem* is actually two problems:

- Why $v^2 = \frac{-m^2}{\lambda} \approx 10^{-36} M_P^2$?
- Why $v \approx 0.1 \frac{\Lambda_{QCD}}{y_{u,d}}$?

$$m_p = 0.93827 \text{ GeV}$$

$$m_n = 0.93956 \text{ GeV}$$

$$m_p^{QCD} = m_n^{QCD}$$

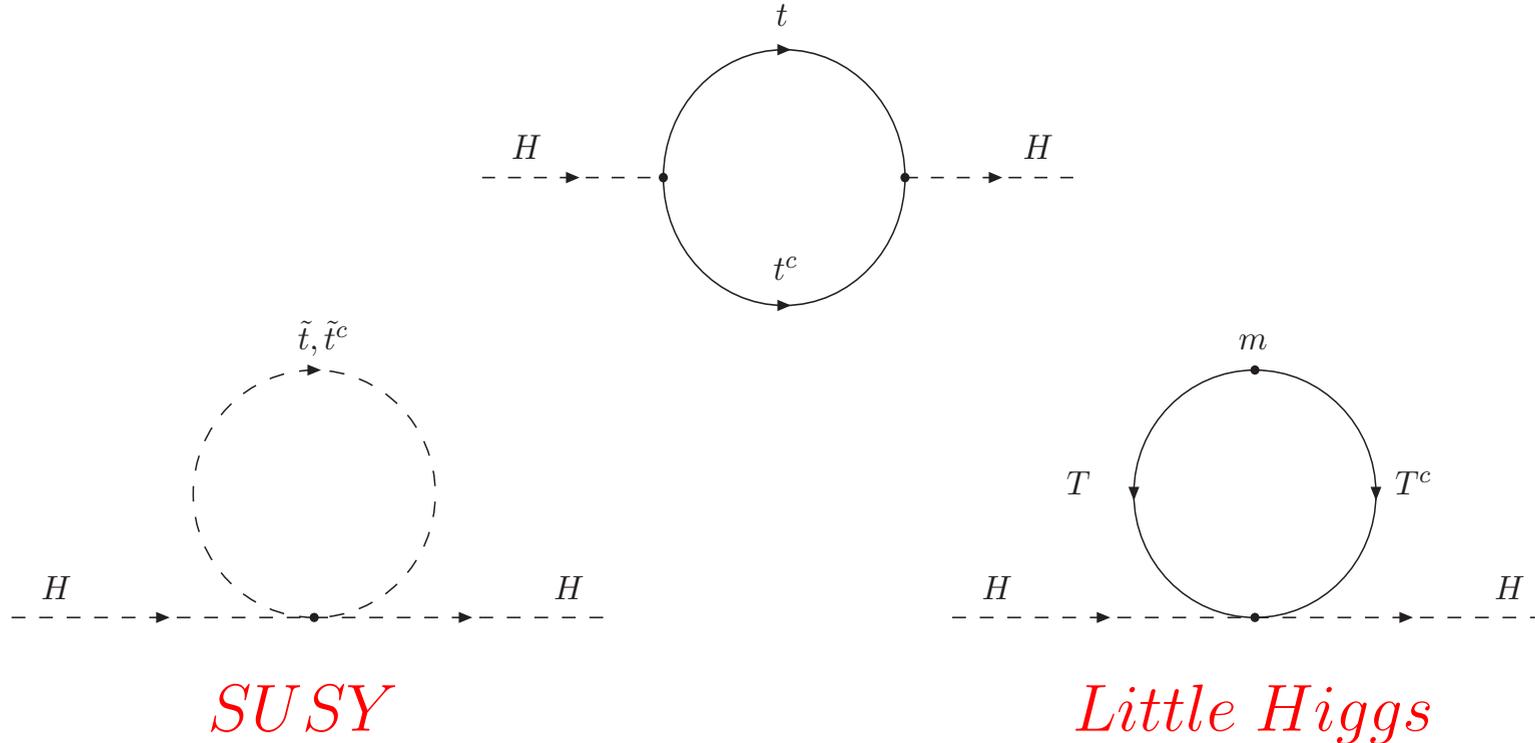
$$m_p^{uud} < m_n^{udd}$$

$$m_p^{EM} > m_n^{EM}$$

- For fixed Λ_{QCD} and $y_{u,d}$: If v **decreases** $m^{qqq} \approx 0$ and $m_p > m_n$, p decays into n . If v **increases** m_n^{udd} grows, $m_n - m_p$ becomes larger than the nuclear binding energy. n unstable inside a nucleus.
- If $v = \sqrt{-m^2/\lambda}$ were a factor of 3 larger or smaller there would be **NO ATOMS**. We shouldn't expect much new physics below the GUT/Planck scale just because it is not *necessary*. **LHC = Last Huge Collider**.

Can the SM be *natural* and compatible with observation?

Little Higgs provides for a mechanism to cancel quadratic corrections to m^2

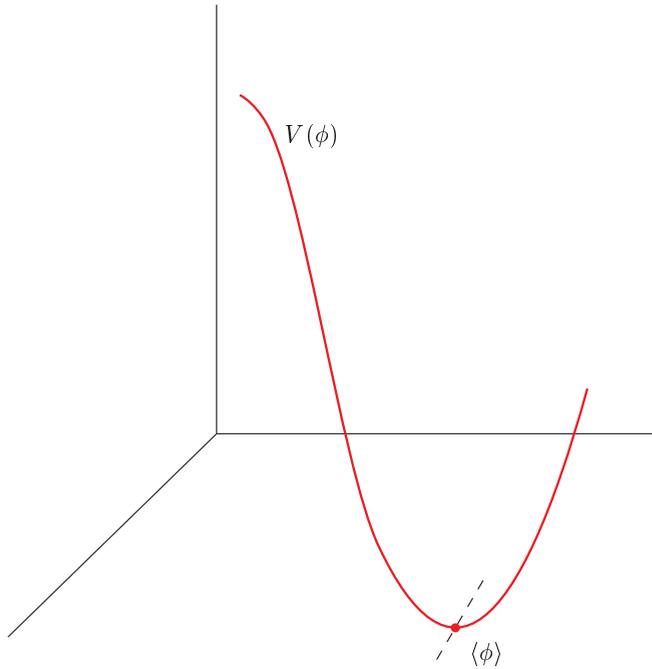


- Vectorlike T quark of mass m_T :

$$-\mathcal{L}_t \supset y_t H^\dagger Q t^c + m_T T T^c - \frac{y_t^2}{2m_T} H^\dagger H T T^c + \text{h.c.}$$

1. For the cancelation to be effective, $m_T \approx 500 \text{ GeV}$
2. The T quark gets its mass through the VEV $f \approx m_T/y_t$ of a $SU(2)_L$ singlet. **The Higgs field will have a singlet component $\approx m_t/m_T$.**
3. Other ingredients of the model, namely, extra gauge bosons and scalar fields, are not essential **(they could decouple)**. Actually, if these ingredients are present at 500 GeV they introduce large corrections to EW precision observables **(they should decouple!)**
4. Two types of LH models: based on a simple group **($SU(5)$, *littlest model*)** or a product group **($SU(3) \times SU(3)$, *simplest model*)**
5. $SU(5)$ models can incorporate a discrete symmetry **(T-parity)** that avoids mixing and tree level exchange of exotic particles.
6. **Minimal realization of the $SU(3) \times SU(3)$ LH model.**

Little Higgs



$$SU(3)_1 \times SU(3)_2$$

(8+8 generators)

$$\phi_1 \rightarrow \exp(-i\theta_1^\alpha T^\alpha) \phi_1 \quad (3, 1)$$

$$\phi_2 \rightarrow \exp(-i\theta_2^\alpha T^\alpha) \phi_2 \quad (1, 3)$$

$$\langle \phi_1 \rangle = \begin{pmatrix} 0 \\ 0 \\ f_1 \end{pmatrix} \quad \langle \phi_2 \rangle = \begin{pmatrix} 0 \\ 0 \\ f_2 \end{pmatrix}$$

Higgs: **Pseudo** Goldstone boson of an **approximate** global symmetry broken spontaneously at the TeV.

- Symmetries that leave the vacuum unchanged

$$T^\alpha \sim \begin{pmatrix} \cdot & \cdot & 0 \\ \cdot & \cdot & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad SU(2)_1 \times SU(2)_2$$

3+3 generators

- Symmetries that move the vacuum along a flat direction (GB)

broken symmetries
5+5 generators

LOCAL $SU(3)$

$$\phi_{1(2)} \rightarrow e^{-i \theta^\alpha(x) T^\alpha} \phi_{1(2)}$$

$$SU(3) \times U(1) \rightarrow SU(2)_L \times U(1)_Y$$

$\phi_1 \phi_2 \rightarrow H' \eta'$ eaten + $H \eta$ massless + $\sigma_1 \sigma_2$ massive

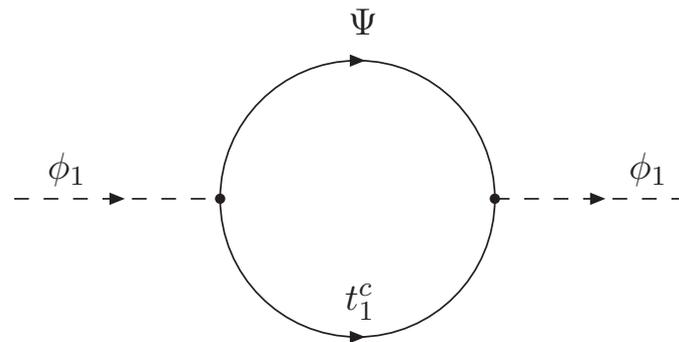
- Gauge and Yukawa interactions break the global symmetries, but do not introduce quadratic corrections to m^2 **collective breaking**.

TOP QUARK SECTOR

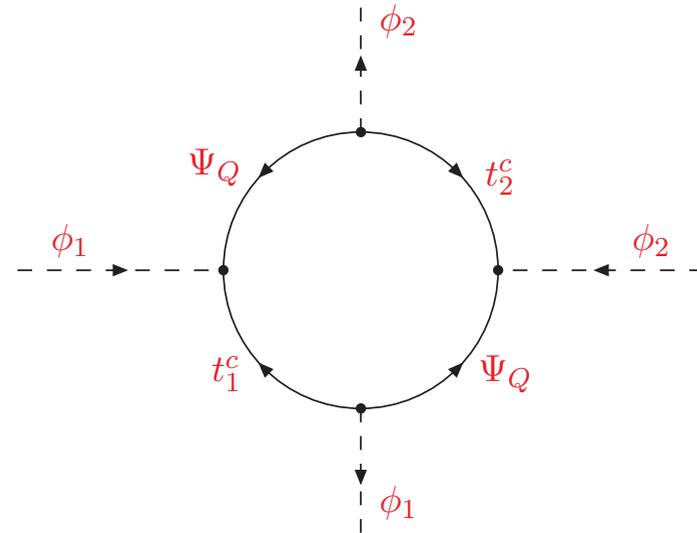
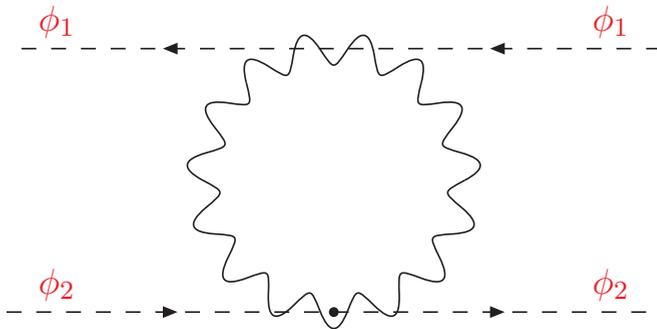
$$Q \equiv \begin{pmatrix} t \\ b \end{pmatrix} t^c \longrightarrow \Psi_Q = \begin{pmatrix} Q \\ T \end{pmatrix} t_1^c t_2^c$$

$$\mathcal{L}_t = \lambda_1 \phi_1^\dagger \Psi_Q t_1^c + \lambda_2 \phi_2^\dagger \Psi_Q t_2^c + \text{h.c.}$$

- Top quark interactions involving only ϕ_1 or only ϕ_2 do not break the global symmetry: redefine $m_1^2 \phi_1^\dagger \phi_1$, $m_2^2 \phi_2^\dagger \phi_2$ but do not contribute to $m^2 H^\dagger H$

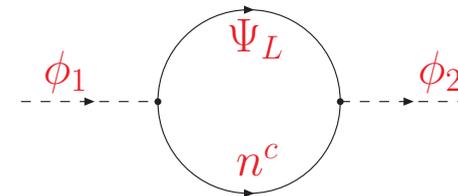


- **Top quark** and **gauge fields** introduce at one loop only logarithmic divergent corrections in the Higgs potential:



- **Light fermions** and/or **massive neutrinos** may (or may not) introduce one-loop quadratic divergencies: $(\nu \ e) \rightarrow \Psi_L = (\nu \ e \ N) \ n^c$

$$\mathcal{L} = \lambda'_1 \phi_1^\dagger \Psi_L n^c + \lambda'_2 \phi_2^\dagger \Psi_L n^c$$



$$V_{eff} = \alpha_1 (\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1) + \alpha_2 (\phi_1^\dagger T^\alpha \phi_2)(\phi_2^\dagger T^\alpha \phi_1) + m_{12}^2 \phi_1^\dagger \phi_2 + \text{h.c.}$$

A minimal model

- $\langle \phi_1^T \rangle = (0 \ 0 \ f_1)$ $\langle \phi_2^T \rangle = (0 \ 0 \ f_2)$
- Extra gauge bosons mass $M_X \approx g f$, where $f \equiv \sqrt{f_1^2 + f_2^2}$. T quark mass $m_T = \sqrt{\lambda_1^2 f_1^2 + \lambda_2^2 f_2^2}$

If $f_1 \ll f_2$ and $\lambda_2 \ll \lambda_1 \approx 1$ then $m_T \ll f$

- Non-linear realization of the GBs (complex doublet $(h^0 \ h^-)$ and CP-odd singlet η):

$$\begin{aligned} \phi_1 &= e^{+i \frac{f_2}{f_1} \Theta} \langle \phi_1 \rangle \\ \phi_2 &= e^{-i \frac{f_1}{f_2} \Theta} \langle \phi_2 \rangle \end{aligned} \quad \Theta = \frac{1}{f} \begin{pmatrix} \eta/\sqrt{2} & 0 & h^0 \\ 0 & \eta/\sqrt{2} & h^- \\ h^{0\dagger} & h^+ & \eta/\sqrt{2} \end{pmatrix}$$

- The global symmetry is *approximate*. Non-symmetric operators give a VEV and a mass to the Higgs: $\langle h^0 \rangle = u/\sqrt{2}$

- Triplet VEVs and scalars in the unitary gauge (analogous expression for ϕ_2)

$$\langle \phi_1 \rangle = \begin{pmatrix} i f_1 s_1 \\ 0 \\ f_1 c_1 \end{pmatrix} \quad \phi_1 = \exp \left(i \frac{f_2 \eta}{f_1 f \sqrt{2}} \right) \begin{pmatrix} i f_1 \sin \frac{(u+h) f_2}{\sqrt{2} f f_1} \\ 0 \\ f_1 \cos \frac{(u+h) f_2}{\sqrt{2} f f_1} \end{pmatrix}$$

- Low $m_T \rightarrow$ low $f_1 \rightarrow$ large $s_1 \equiv \sin \frac{u f_2}{\sqrt{2} f f_1} \approx \sin \frac{u}{\sqrt{2} f_1}$

$$s_1 = 0 \quad f_2 \gg f_1 \gg 174 \text{ GeV}$$

$$s_1 = 1 \quad f_2 \gg f_1 = 174 \text{ GeV}$$

$$\phi_1 \approx e^{\frac{i\eta}{\sqrt{2}f_1}} \begin{pmatrix} i h / \sqrt{2} \\ 0 \\ f_1 - h^2 / 4 f_1 \end{pmatrix}$$

$$\phi_1 \approx e^{\frac{i\eta}{\sqrt{2}f_1}} \begin{pmatrix} i f_1 - i h^2 / 4 f_1 \\ 0 \\ -h / \sqrt{2} \end{pmatrix}$$

- The top-quark sector includes a vectorlike T quark: m_T , tT mixing V_{Tb}

$$-\mathcal{L}_t \supset m_t tt^c + m_T V_{Tb} tT^c + m_T TT^c + \text{h.c.}$$

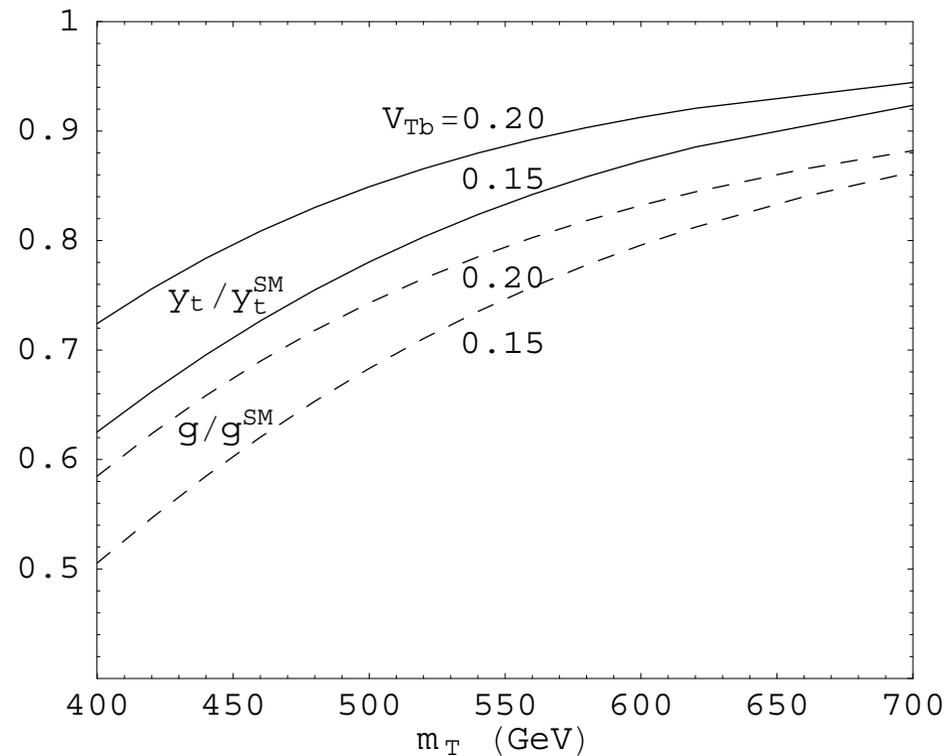
- T quark coupling to the W boson and flavor-changing interactions with the Z boson proportional to V_{Tb}

- The top-quark Yukawa coupling is *not* $\sqrt{2}m_t/v$, it is reduced because $h = c_1 h_d + s_1 h_s$ and also affected by the tT mixing:

$$\frac{y_t}{y_t^{SM}} \approx c_1 + s_1 V_{Tb} .$$

- Same type of suppression in the coupling of the higgs to the gauge bosons:

$$\frac{g}{g^{SM}} \approx c_1$$



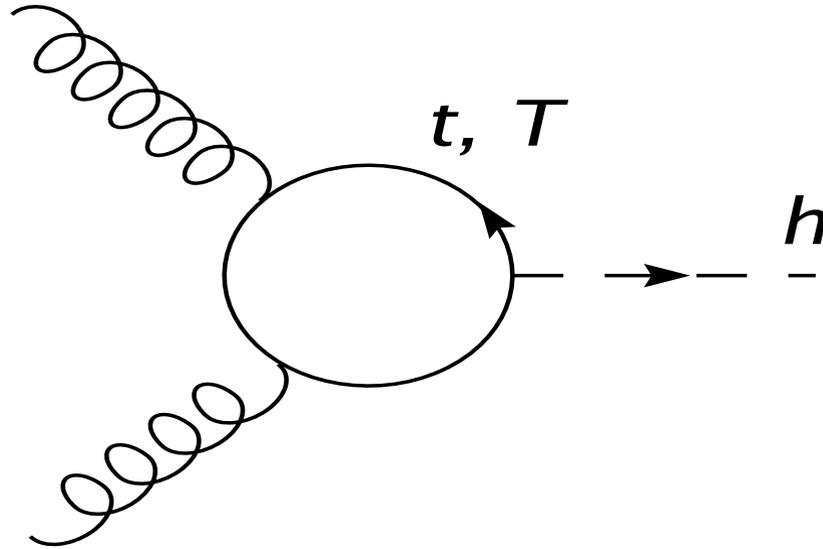
Implications on EW precision measurements

- The massive gauge bosons mix with the standard bosons and introduce four-fermion operators (shift in the Z mass, corrections in atomic parity violation experiments and LEP II data) $f \approx f_2 \geq 3 \text{ TeV}$

- The effects on EW precision observables due to the singlet component of the Higgs field are negligible. The Yukawa coupling of the top with the neutral Higgs is here smaller than in the SM, but it is the coupling with the *would be* GBs eaten by the W and Z bosons what determines the top-quark radiative corrections, and these are not affected by the presence of singlets.
- The mixing of the top with the vectorlike T quark reduces its coupling with the W boson (affects its radiative corrections to the Zbb vertex, measured in $R_b = \Gamma(Z \rightarrow b\bar{b})/\Gamma(Z \rightarrow \text{hadrons})$ and forward-backward asymmetries) It also affects the oblique parameters S , T , and U (vacuum polarization diagrams). These corrections vanish if $m_T = m_t$, and for large m_T imply $V_{Tb} \leq 0.2$

Implications on Higgs physics at the LHC

- Suppression of the $gg \rightarrow h$ cross section.

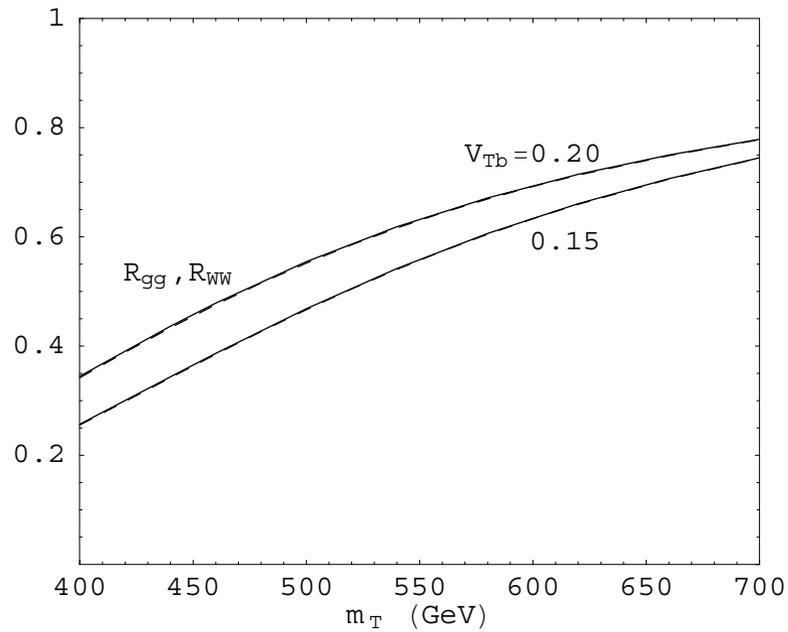
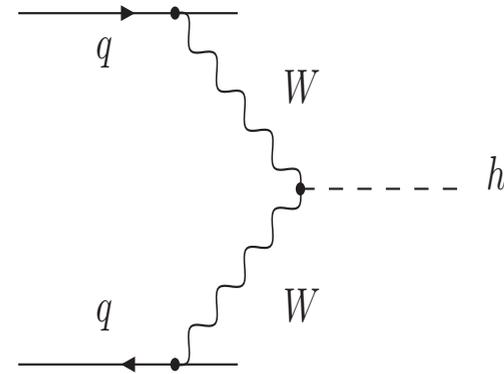
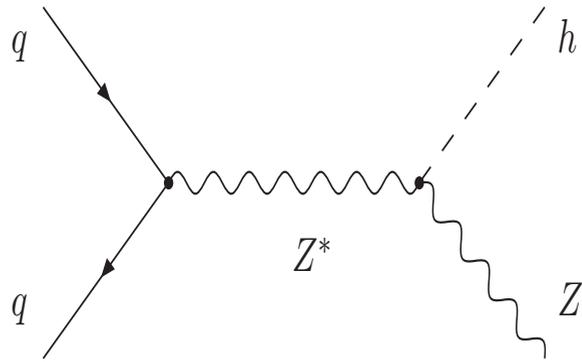


$y_t < y_t^{SM}$ + destructive interference from the T contribution

In the limit of $m_h \ll m_t, m_T$

$$R_{gg} \equiv \frac{\sigma(gg \rightarrow h)}{\sigma^{SM}(gg \rightarrow h)} \approx \left(\frac{y_t}{y_t^{SM}} + \frac{y_T v}{m_T} \right)^2 \approx c_1^2$$

- Suppression of the $q\bar{q} \rightarrow Wh$ and $WW \rightarrow h$ cross section. $g < g^{SM}$



$$R_{WW} \equiv \frac{\sigma(WW \rightarrow h)}{\sigma^{SM}(WW \rightarrow h)} \approx c_1^2$$

- New Higgs production channels through T -quark decay

A T quark of mass below 600 GeV will be copiously produced at the LHC

T decays into Wb , Zt , ht , and ηt (BRs approx. indep. of V_{Tb} !)

$$\Gamma(T \rightarrow Wb) \approx \frac{\alpha}{16s_W^2} V_{Tb}^2 \frac{m_T^3}{M_W^2}$$

$$\Gamma(T \rightarrow Zt) \approx \frac{1}{2} \Gamma(T \rightarrow Wb)$$

$$\Gamma(T \rightarrow ht) \approx \frac{1}{2} \left(c_1^2 + \frac{s_1^2}{t_\alpha^2} \right) \Gamma(T \rightarrow Wb)$$

$$\Gamma(T \rightarrow \eta t) \approx \frac{1}{2} \left(s_1^2 + \frac{c_1^2}{t_\alpha^2} \right) \Gamma(T \rightarrow Wb)$$

$T\bar{T} \rightarrow W^+ b \bar{t} h \rightarrow W^+ b W^- \bar{b} h$, $T\bar{T} \rightarrow h t h \bar{t} \rightarrow W^+ b W^- \bar{b} h h$

give a very high statistical significance for the Higgs discovery at the LHC.

Is this model more *natural* than the SM?

- The light higgs h is not a pure doublet: it unitarizes the elastic WW only *partially*. The unitarity cutoff goes from 1.7 TeV (Higgsless SM) to $1.7/s_1$ TeV.
- Where is the *other* component of the higgs doublet? It is not a GB, it gets mass at f_1 . Therefore, it could be found with masses of up to $1.7/s_1$ TeV.
- The T quark cancels corrections to the EW scale $\langle h \rangle$. However, the scale $f_1 \approx (174 \text{ GeV})/s_1$ is *unprotected*. The *natural* cutoff of the SM is just increased by a factor of $1/s_1$. The optimal value $s_1 \approx 0.5$ GeV defines a model with a cutoff at ≈ 5 TeV.
- The higgs production rate at LEP decreases by a factor of c_1^2 , so the $m_h > 114$ GeV bound may weaken if s_1 (i.e., the singlet component in h) is large. The decay modes $h \rightarrow \eta\eta$ and $h \rightarrow \eta b\bar{b}$ may also affect these bounds.

Summary

- The SM is a great effective theory with a cutoff at ≈ 2 TeV.
- SUSY (or X-dim) could take the cutoff up to the Planck scale. However, if SUSY is below 1 TeV it introduces a 1% fine tuning in precision observables.
- We have presented a Little Higgs model that could rise the naive cutoff up to 5 TeV, scale where SUSY (or X-dim) would manifest. LHC = Little Hierarchy Collider.
- The signature of the model would be a light (500 GeV) T quark and a Higgs with anomalous Yukawa and gauge couplings. The usual higgs production channels at the LHC decrease; new production channels through T quark decay may dominate.
- What are we going to find at the LHC? Just enough to plan for a bigger collider...