

# Twin Higgs Theories

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Precision electroweak data are in excellent agreement with the Standard Model with a Higgs mass less than 200 GeV.

In particular, the cutoff for non-renormalizable operators that contribute to precision electroweak observables must be greater than about 5 TeV. More specifically, the scale  $\Lambda$  appearing in operators such as  $\frac{\bar{D}^2 H^\dagger D^2 H}{\Lambda^2}$  and  $\frac{|H^\dagger D_\mu H|^2}{\Lambda^2}$ , which we expect to arise from integrating out new physics, is constrained to be greater than 5 TeV. Naively, this suggests that the scale of new physics must be greater than 5 TeV.

The problem is that radiative corrections from scales of order 5 TeV naturally generate a Higgs mass much larger than 200 GeV. This is called the 'LEP Paradox' or 'Little Hierarchy Problem'.

**The LEP paradox leaves us with three distinct possibilities.**

- **There is no new physics which stabilizes the weak scale below 5 TeV. In this case the Higgs mass is simply fine-tuned at the 2% level or worse.**
- **There is new physics below 5 TeV which stabilizes the weak scale, and which contributes significantly to precision electroweak observables. Consistency with precision electroweak data is a consequence of accidental cancellations between different contributions. In this case the agreement of the Standard Model with the data is merely a coincidence.**
- **There is new physics below 5 TeV which stabilizes the weak scale, but does not contribute significantly to precision electroweak observables.**

**A complete solution of the LEP paradox must fall into the last category. An example is supersymmetry with R-parity.**

**Twin Higgs theories are realizations of the Higgs as a pseudo-Goldstone boson that address the LEP paradox. They are similar in spirit to little Higgs theories but the underlying mechanism is different.**

**In any model where the Higgs is a pseudo-Goldstone boson the challenge is to explain why the Higgs remains light even though the top Yukawa coupling, gauge couplings and Higgs self-couplings necessarily break any global symmetry with order one strength.**

## **Twin Higgs Mechanism**

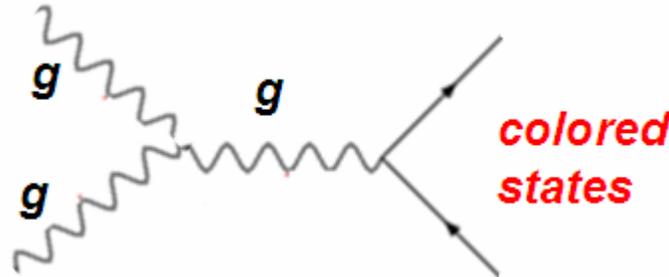
**The theory possesses a discrete symmetry which guarantees that any dimensionful terms in the Higgs potential respect a larger global symmetry. The Standard Model Higgs emerges as the pseudo-Goldstone boson associated with the breaking of this global symmetry.**

**This suffices to ensure the absence of one-loop quadratically divergent contributions to the Higgs mass parameter.**

**A striking feature of twin Higgs theories is that there is no need for new particles charged under Standard Model gauge groups!**

## **Conventional Wisdom**

**A solution to the LEP paradox requires new colored states with mass much less than 5 TeV to cancel the top loop. The discovery of these states at the LHC is likely to be straightforward, and will guide us to an understanding of electroweak symmetry breaking.**



**The conventional wisdom holds for supersymmetry, where the top loop is cancelled by stops, and for little Higgs theories, where the top loop is cancelled by vector-like quarks. However, the twin Higgs is an explicit counterexample! The states which cancel the top loop need not be charged under Standard Model color. A challenge for the LHC!**

How is the twin Higgs mechanism implemented? Consider a scalar field  $H$  which transforms as a fundamental under a global  $U(4)$  symmetry. The potential for  $H$  takes the form

$$V(H) = -m^2|H|^2 + \lambda|H|^4$$



$$|\langle H \rangle|^2 = \frac{m^2}{2\lambda} \equiv f^2$$

The  $U(4)$  symmetry is broken to  $U(3)$ , giving rise to 7 Goldstone bosons. The theory possesses an accidental  $O(8)$  symmetry, which is broken to  $O(7)$ , and the 7 Goldstones can also be thought of as arising from this breaking pattern.

Now gauge an  $SU(2)_A \times SU(2)_B$  subgroup of the global  $U(4)$ .

Eventually we will identify  $SU(2)_A$  with  $SU(2)_L$  of the Standard Model, while  $SU(2)_B$  will correspond to a 'twin'  $SU(2)$ .

Under the gauge symmetry,

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix}$$

where  $H_A$  will eventually be identified with the Standard Model Higgs, while  $H_B$  is its 'twin partner'.

Now the Higgs potential receives radiative corrections from gauge fields

$$\Delta V(H) = \frac{9g_A^2\Lambda^2}{64\pi^2} H_A^\dagger H_A + \frac{9g_B^2\Lambda^2}{64\pi^2} H_B^\dagger H_B$$

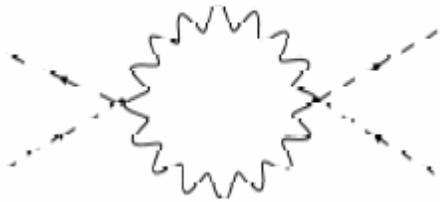
Impose a  $Z_2$  'twin' symmetry under which  $A \leftrightarrow B$ . Then  $g_A = g_B = g$ . Then the radiative corrections take the form

$$\Delta V = \frac{9g^2\Lambda^2}{64\pi^2} (H_A^\dagger H_A + H_B^\dagger H_B)$$

This is U(4) invariant and cannot give a mass to the Goldstones!

As a consequence of the discrete twin symmetry, the quadratic terms in the Higgs potential respect a global symmetry. Even though the gauge interactions constitute a hard breaking of the global symmetry the Goldstones are prevented from acquiring a quadratically divergent mass.

However, logarithmically divergent terms are radiatively generated which are not U(4) invariant and contribute a mass to the pseudo-Goldstones.



$$\Delta V = \kappa(|H_A|^4 + |H_B|^4)$$

$$\kappa \sim \frac{g^4}{16\pi^2} \log \frac{\Lambda^2}{f^2}$$

The resulting mass for the pseudo-Goldstones is of order

$$m_h \sim \sqrt{\kappa} f \sim \frac{g^2 f}{4\pi}$$

In the strong coupling limit,  $\Lambda \sim 4\pi f$  so that

$$m_h \sim \frac{g^2}{16\pi^2} \Lambda$$

Then for  $\Lambda$  of order 5 TeV,  $m_h$  is weak scale size.

Now the flat direction has been lifted, we must determine the vacuum alignment. If we minimize

$$V = -m^2 |H|^2 + \lambda |H|^4 + \kappa (|H_A|^4 + |H_B|^4)$$

we find

$$|\langle H_A \rangle|^2 = |\langle H_B \rangle|^2 = \frac{f^2}{2}$$

Therefore, although the mass  $m_h$  of the pseudo-Goldstone is small compared to  $f$ , the electroweak VEV is not. Also, the pseudo-Goldstone is an equal mixture of the Standard Model Higgs and the twin Higgs.

In the limit of strong coupling, for

$$|\langle H_A \rangle| = 174 \text{ GeV}$$

$$\Lambda \sim 4\pi f = 4\pi\sqrt{2} \langle H_A \rangle \approx 3 \text{ TeV}$$

We would like to create a (mild) hierarchy between  $f$  and the electroweak VEV that would allow the cutoff  $\Lambda$  to be higher than 3 TeV, and allow the pseudo-Goldstone to be more like a Standard Model Higgs.

How does one create a hierarchy between  $f$  and  $\langle H_A \rangle$ ?

Two distinct possibilities.

- Add a term to the Higgs potential which **softly** breaks twin symmetry

$$V_{\text{soft}}(H) = \mu^2 H_A^\dagger H_A$$

(Z.C., Goh and Harnik)  
(Barbieri, Gregoire and Hall)

Such a term does not reintroduce quadratic divergences. Values of  $\mu$  much less than  $\Lambda$  are technically natural.

This approach allows the generation of this hierarchy at the expense of mild fine-tuning.

- Extend the model by adding an extra Higgs doublet for both the Standard Model and the twin sector. It is then possible to generate a tree-level quartic term for the pseudo-Goldstone without a corresponding mass term, which allows for a more natural generation of this hierarchy.

(Z.C., Nomura, Papucci and Perez)

**The discrete symmetry must now be extended to all the interactions of the Standard Model. The simplest possibility is to identify the discrete symmetry with parity. This has led to two distinct classes of models.**

- **Mirror Symmetric Twin Higgs Models**

**There is a mirror copy of the Standard Model, with exactly the same field content and interactions. The parity symmetry interchanges every Standard Model field with the corresponding field in the mirror Standard Model. Although the mirror fields are light they have not been observed because they carry no charge under the Standard Model gauge groups.**

- **Left-Right Symmetric Twin Higgs Models**

**The Standard Model gauge symmetry is extended to left-right symmetry. Parity symmetry now interchanges the left-handed Standard Model fields with the corresponding right-handed fields.**

**There may be other possibilities waiting to be explored!**

Let us study the mirror symmetric model in more detail. We are interested in the case where the symmetry breaking pattern is realized non-linearly. This will enable us to show that the low-energy behaviour is universal, and is independent of any specific ultra-violet completion.

We parametrize the field  $H$  as

$$H = e^{iT^a \frac{h^a}{f}} \begin{pmatrix} 0 \\ 0 \\ 0 \\ f \end{pmatrix}$$

where

$$h = \begin{pmatrix} h^1 \\ h^2 \end{pmatrix}$$

is the Standard Model Higgs field.

The cut-off

$$\Lambda \leq 4\pi f$$

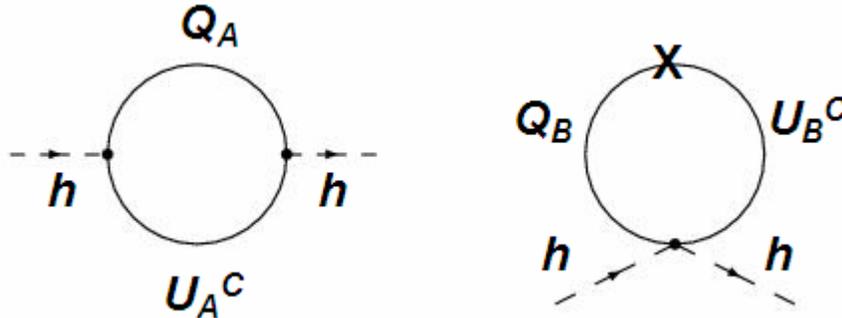
where upper bound is at strong coupling.

In general the theory will contain arbitrary non-renormalizable operators suppressed by  $\Lambda$  consistent with  $O(8)$  symmetry.

Let us now understand the cancellation of quadratic divergences in the non-linear model.

$$L_{top} = y H_A Q_A U_A^c + y H_B Q_B U_B^c$$

$$\rightarrow y h Q_A U_A^c + y \left( f - \frac{|h|^2}{2f} \right) Q_B U_B^c$$



The quadratic divergences of these two diagrams cancel exactly! The cancellation takes exactly the same form as in little Higgs theories. The states which cancel top loop need not be colored! Cancellation of gauge loops also takes same form as in little Higgs.



Now that quadratic divergences have been eliminated, the leading terms in the Higgs potential are at most logarithmically divergent.

By computing the effective potential for the pseudo-Goldstone field we can estimate the fine-tuning. For the minimal model,

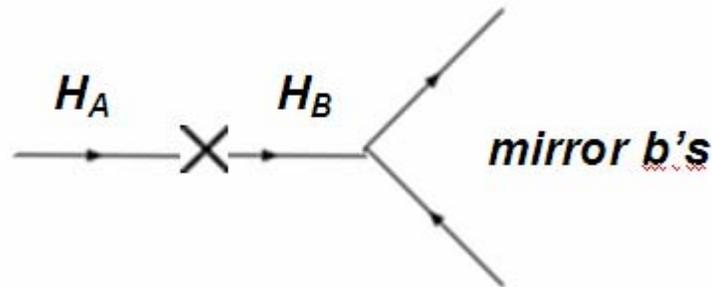
- for  $f = 800$  GeV and  $\Lambda \sim 4 \pi f = 10$  TeV, we find that the Higgs mass is of order 166 GeV and fine-tuning about 11% (1 in 9);

- for  $f = 500$  GeV and  $\Lambda \sim 4 \pi f = 6$  TeV, we find that the Higgs mass is of order 153 GeV and fine-tuning about 31% (1 in 3).

Low values of  $f$  are allowed because precision electroweak constraints are weak  no particles charged under Standard Model gauge groups. Custodial SU(2) is a natural consequence of O(8) symmetry.

How can mirror symmetric twin Higgs models be tested at colliders? Challenging, because in general the new states are not charged under the Standard Model gauge groups. The Standard Model communicates with the mirror world only through the Higgs.

One possibility is to look for invisible decays of the Standard Model Higgs into mirror states. We expect this to occur between 5% and 50% of the time, depending on the value of  $f$ , **provided the decay of the Higgs to  $W^+ W^-$  is kinematically forbidden**. If this decay channel is open, an understanding of electroweak symmetry breaking may not be possible at the LHC.



## What are the experimental constraints on the mirror model?

The most severe constraint comes from cosmology, from the requirement that the mirror states not contribute significantly to the energy density of the universe at the time of Big Bang Nucleosynthesis (BBN).

The interaction  $|H_A|^2 |H_B|^2$ , which is part of the U(4) symmetric quartic, ensures that the mirror sector is in thermal equilibrium with the Standard Model until temperatures of order 5 GeV. We require that between this temperature and 5 MeV, when the weak interactions decouple, some entropy is added to the Standard Model sector, but not to the mirror sector.

## What are some of the possibilities?

- A brief epoch of late inflation, followed by reheating. The reheating temperature is between 5 GeV and 5 MeV, with our sector reheated more efficiently than the mirror sector.
- The QCD phase transition in the Standard Model generates considerable entropy, much more than the QCD phase transition in the mirror sector.

Let us take a brief look at the left-right symmetric twin Higgs model. The gauge group is now

$$\mathbf{SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}}$$

The field  $H$  which breaks the  $U(4)$  symmetry now consists of an  $SU(2)_L$  doublet and an  $SU(2)_R$  doublet.

$$H = \begin{pmatrix} H_L \\ H_R \end{pmatrix}$$

Parity symmetry guarantees that  $g_L = g_R$ , and also that the Yukawa couplings of  $H_L$  are equal to those of  $H_R$ . Then the dimensionful terms in the potential for  $H$  will again be  $U(4)$  invariant.

The VEV of  $H_R$  breaks  $SU(2)_R \times U(1)_{B-L}$  to  $U(1)_Y$ . The field  $H_L$ , which corresponds to the Standard Model Higgs emerges as the pseudo-Goldstone of the broken  $U(4)$  symmetry.

The Standard Model fermions have the quantum numbers below under  $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} = [2, 1, 1/2], \quad L_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = [2, 1, -1],$$

$$Q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix} = [1, 2, 1/3], \quad L_R = \begin{pmatrix} \nu_R \\ e_R \end{pmatrix} = [1, 2, -1],$$

The light fermions acquire masses through non-renormalizable operators. Since the top Yukawa is order one, we introduce additional fermions.

$$T_L = [1, 1, 4/3], \quad T_R = [1, 1, 4/3],$$

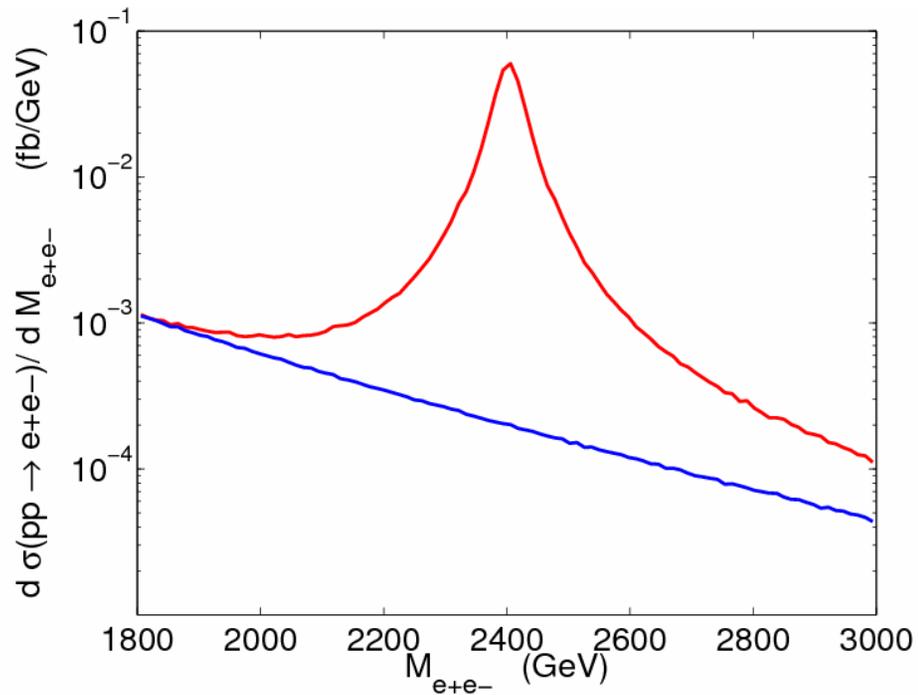
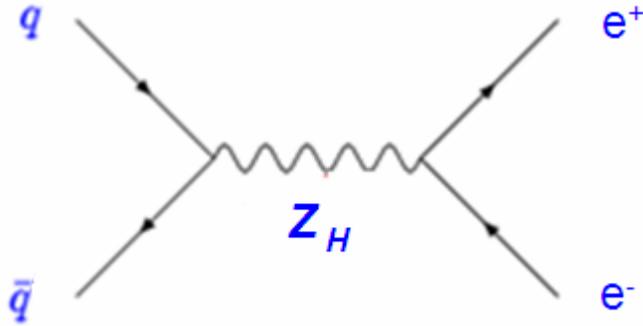
A left-right symmetric top Yukawa coupling then emerges from

$$y \bar{Q}_R H_R^\dagger T_L + y \bar{Q}_L H_L^\dagger T_R + \text{h.c.}$$

The Higgs sector must also be extended to avoid experimental constraints. Among the predictions of this theory are  $SU(2)_R$  gauge bosons, vector-like quarks and a natural dark matter candidate. Promising for the LHC!

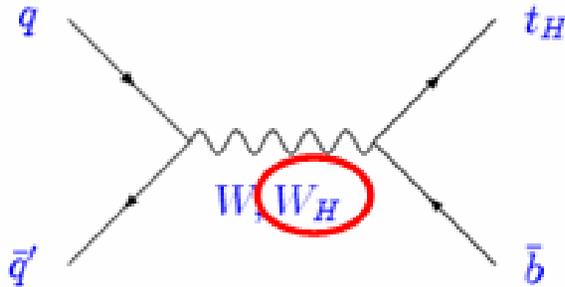
The heavy  $Z'$  can be observed through the Drell-Yan process.

(Goh & Su)

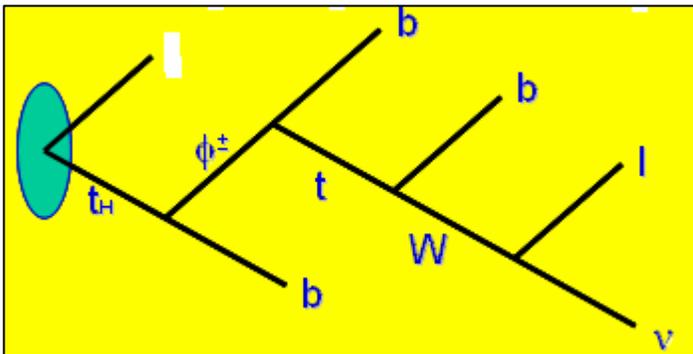


The top partners can also be produced.

(Goh and Su)



In large regions of parameter space the top partners decay to three b jets, a lepton and missing energy. It may be possible to reconstruct these events.



# Conclusions

- **Twin Higgs theories are a novel way of realizing the Higgs as a pseudo-Goldstone and stabilizing the weak scale without large corrections to precision electroweak observables.**
- **Existing models are based on parity symmetry, realized either as mirror symmetry or as left-right symmetry. The two cases have completely different phenomenology.**
- **These theories show that cancelling quadratic divergences to the Higgs mass parameter does not require new particles charged under the Standard Model gauge groups.**
- **Naturalness does NOT imply that new physics will be easy to see at the LHC. Even if the LHC does not find new physics naturalness will not have been disproven.**
- **The next step is to find ultra-violet completions for these models. Supersymmetric ultra-violet completions have been found.**  
**(Chang, Hall & Weiner; Falkowski, Pokorski & Schmaltz)**