Uncolored Top Partners, a 125 GeV Higgs and the Limits on Naturalness

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Introduction

The Nobel Prize in Physics 2013

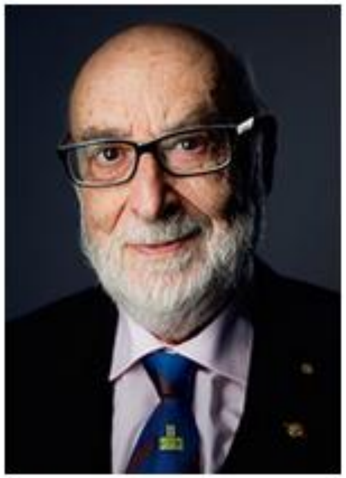


Photo: A. Mahmoud

François Englert

Prize share: 1/2

Photo: A. Mahmoud

Peter W. Higgs

Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

Theories in which electroweak symmetry is broken by a scalar Higgs suffer from a fine-tuning problem. Let us understand the issue in greater detail.

The Higgs potential in the Standard Model takes the following form.

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

Minimizing this potential we find for the electroweak VEV

$$v^2 = m^2/2\lambda$$

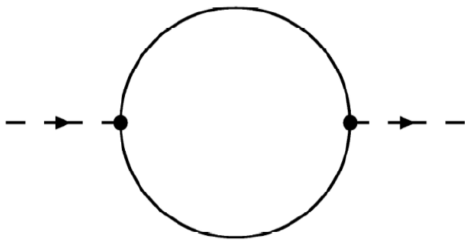
and for the mass of the physical Higgs

$$m_H^2 = 4\lambda v^2 = 2m^2$$

We can estimate the fine-tuning as $\delta m^2/m^2$ where δm^2

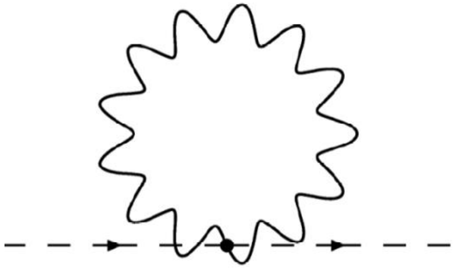
is the radiative correction to the mass squared parameter.

For a physical Higgs mass of 125 GeV, the precision electroweak upper bound, we can estimate the fine-tuning from the top, gauge and Higgs self couplings.



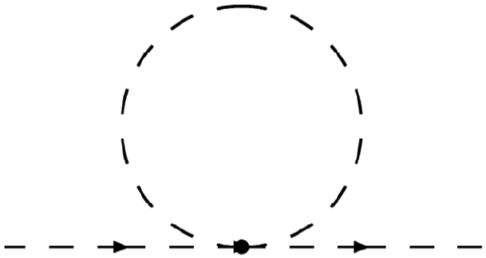
$$= \frac{3y_t^2}{8\pi^2}\Lambda^2$$

Fine Tuning < 10% for Λ > 1.5 TeV.



$$= \frac{9g^2}{64\pi^2}\Lambda^2$$

Fine Tuning < 10% for Λ > 4 TeV.

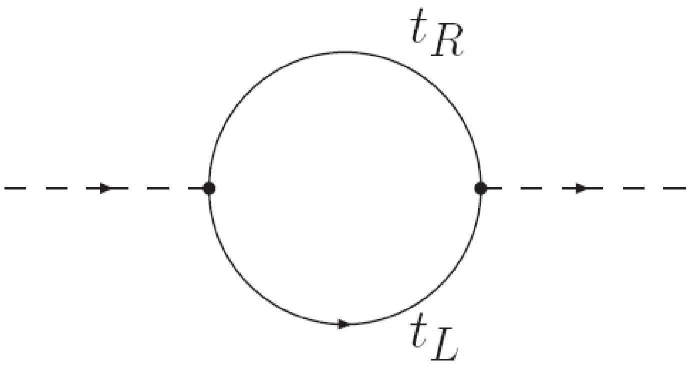


$$= \frac{3\lambda}{8\pi^2}\Lambda^2$$

Fine tuning < 10% for Λ > 3 TeV.

We see that unless the Standard Model is severely fine-tuned, we should expect new physics at or close to a TeV.

As we saw, the biggest contribution to the Higgs mass in the Standard Model is from the top loop, and this is therefore the leading source of fine-tuning.

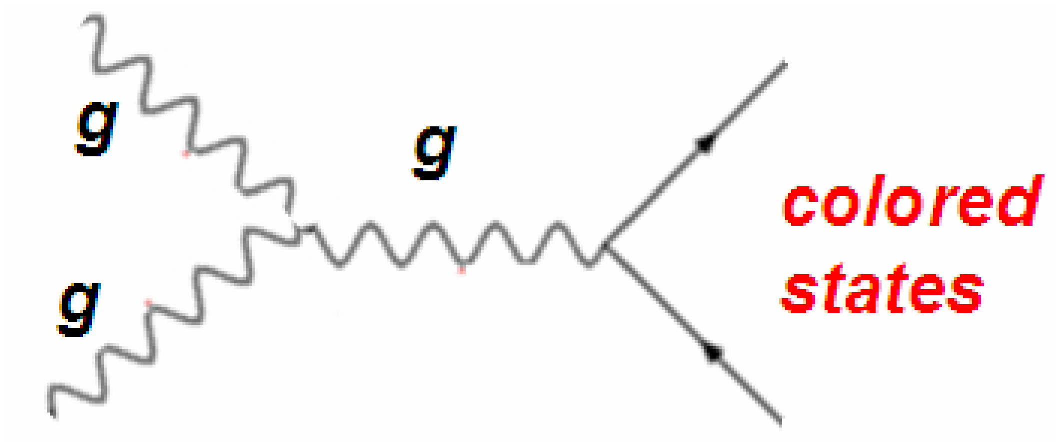


$$\sim \frac{3\lambda_t^2}{8\pi^2}\,\Lambda^2$$

Naturalness requires new particles below a TeV or so to cancel this.

The new particles must be related to the top quark by a symmetry for the cancellation to work. Since top quark is colored, naively one would expect that the new states, the `top partners', would also be colored.

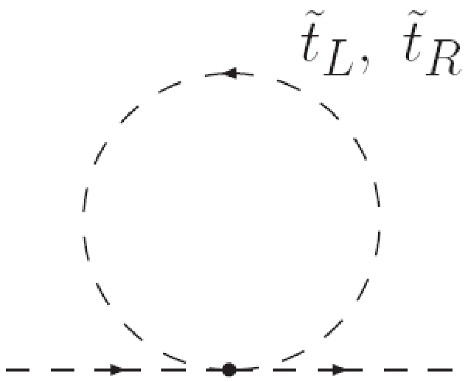
If the top partners are colored, the odds are good that the LHC will find them. If not, it is not clear that the LHC will find the new physics associated with naturalness.

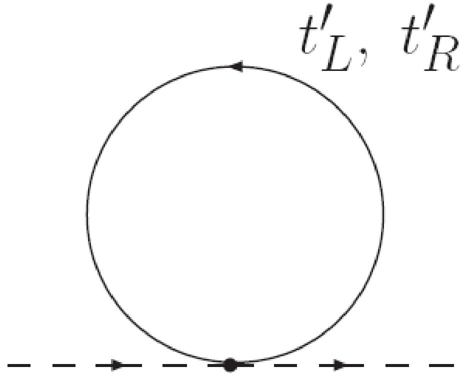


However, in general the top partners need not be colored. This is characteristic of scenarios where the top and the top partners are related only by a discrete symmetry. The Mirror Twin Higgs and Folded Supersymmetry are examples of such a scenario.

Let us understand this.

In general, there are two classes of diagrams that have been found which can cancel the top loop. These two classes correspond to generalizations of the following diagrams.





SUSY cancellation with the third generation (scalar) squarks in loop

Little Higgs cancellation with (fermionic) top partners in loop

In SUSY the scalar quarks are charged under Standard Model color. Why?

Consider a SUSY rotation.

$$q_\alpha \longrightarrow \tilde{q}_\alpha$$

same gauge index

SUSY commutes with the gauge interactions. If top quark is colored, its scalar superpartner is also colored. This is an immediate consequence of SUSY.

In little Higgs theories the fermionic top partners are charged under color. Why?

Consider top Yukawa coupling,

$$\lambda_t \, (3,2)_{\mathsf{Q}}(1,2)_{\mathsf{H}}(\overline{3},1)_{\mathsf{U}}$$

where Q and U are third generation quark and anti-quark, and H is the Higgs. The brackets indicate quantum numbers under SU(3) and SU(2).

If we extend the SU(2) symmetry to an SU(3) symmetry this becomes

$$\lambda_t (3,3)_{\hat{\mathsf{Q}}}(1,\overline{3})_{\hat{\mathsf{H}}}(\overline{3},1)_{\mathsf{U}}$$

When this SU(3) symmetry is broken down to SU(2) the Higgs field H becomes the Goldstone boson associated with the breaking of the symmetry.

When this structure is embedded into a little Higgs theory, the extra state in $\hat{Q}$ becomes the top partner. Notice that it is necessarily charged under color.

However, in a twin Higgs model, the top Yukawa interaction takes the form

Higgs — Twin Higgs

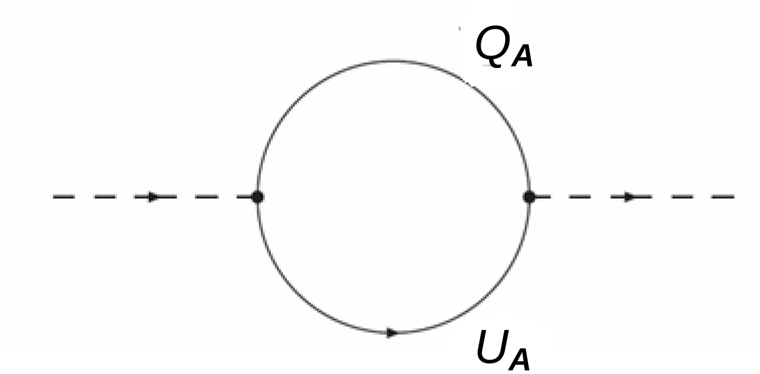
$$\lambda_t \, Q_A H_A U_A + \lambda_t \, Q_B H_B U_B$$

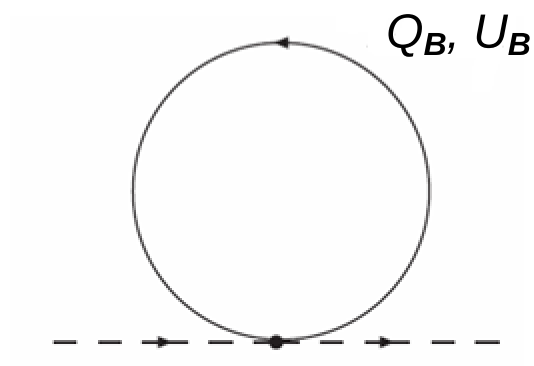
Standard Model Quarks — Twin Quarks

The top Yukawa need not respect any global symmetry at all, simply a discrete A ⟶ B exchange symmetry. As a consequence, in general the twin Higgs and twin quarks need not carry any Standard Model quantum numbers.

Only the Higgs sector of the theory has an enhanced global symmetry. The Standard Model Higgs emerges as the Goldstone boson associated with the breaking of this global symmetry. This is sufficient to ensure the cancellation of quadratic divergences from the top Yukawa coupling.

The cancellation of the top loop takes pace through a diagram of exactly the same form as in the (simplest) little Higgs case. The major difference is that the fermions running in the loop, the top partners, are now the twin quarks, which need not be charged under SM color.



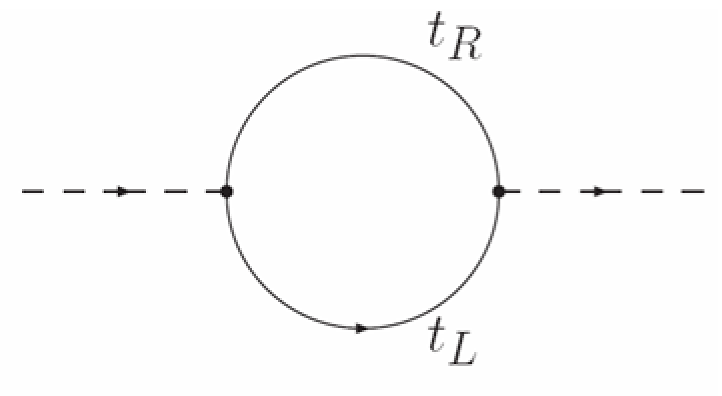


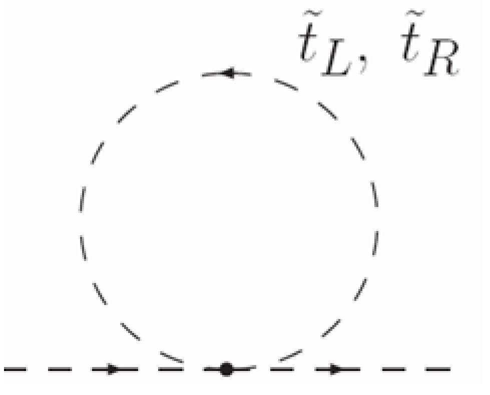
The crucial point to appreciate is that in this cancellation, color is simply a multiplicative factor of 3 with no further significance! What really matters is that the vertices in the two diagrams be related in a specific way by symmetry.

In folded supersymmetric theories, at low energies the Lagrangian for the top sector has the same form as in supersymmetric theories. However, now the scalars are charged under a hidden color group, not SM color.

$$[\ \lambda_t\, h_u\, q_\alpha\, u_\alpha\ +\ \text{h.c.}\ ]\ +$$
$$\lambda_t^2\ |\tilde{q}_\beta h_u|^2 + \lambda_t^2\ |\tilde{u}_\beta|^2\ |h_u|^2$$

The cancellation of quadratic divergences occurs through diagrams of exactly the same form as in the conventional supersymmetric case.





The scalars do however carry charge under the SM electroweak groups.

In scenarios with colorless top partners, their direct discovery at the LHC may be very challenging, or even impossible.

However, because of the large couplings of the top partners to the Higgs, the Higgs production cross section and decay rates are affected.

Therefore, a detailed study of Higgs phenomenology may be the most efficient way to probe scenarios with colorless top partners.

In this talk, I focus on the Mirror Twin Higgs and Folded Supersymmetry, and consider the phenomenology associated with the Higgs in these scenarios. I discuss the current and future bounds on the top partners in these models, and the implications for naturalness.

The Mirror Twin Higgs Model

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

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

$$\Downarrow$$

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

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 $SU(2)_A$ X $SU(2)_B$ 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

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

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

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

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.

Let us focus on 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

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

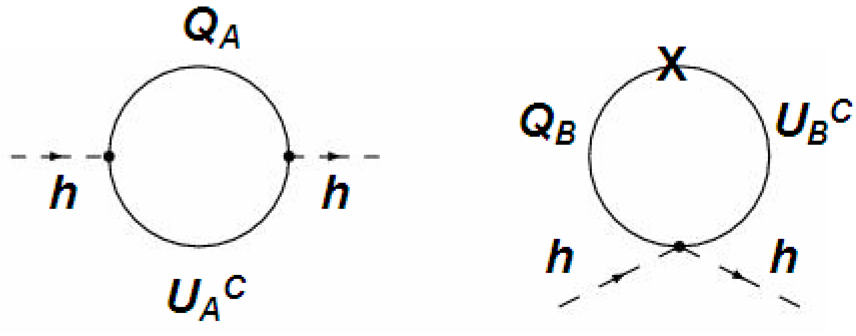
is the Standard Model Higgs field.

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 Λ consistent with the global O(8) symmetry.

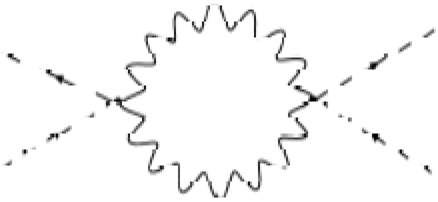
Let us now understand the cancellation of quadratic divergences in the non-linear model.

$$
\begin{aligned}
L_{top} &= y\, H_A\, Q_A\, U_A^c + y\, H_B\, Q_B\, U_B^c \\
&\rightarrow y\, h\, Q_A\, U_A^c + \; y \left(f - \frac{|h|^2}{2f} \right) \, Q_B\, U_B^c
\end{aligned}
$$



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.

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

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

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

$$m_h^2 \sim \left(\frac{g^2}{16\pi^2}\right)^2 \Lambda^2$$

Then for Λ 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 Λ 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 the VEV of H_A ?

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

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

Such a term does not reintroduce quadratic divergences. Values of μ much less than Λ are technically natural.

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

How much is the residual tuning in this model?

$$m_h^2|_{\rm top} = -\frac{3y^2}{8\pi^2} m_T^2 \log\left(\frac{\Lambda^2}{m_T^2}\right)$$

For $m_T \sim y f$ of order 500 GeV, $\Lambda \sim 4\pi f$ of order 5 TeV, the tuning is only of order 1 part in 5.

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 lead 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.

Let us consider the Mirror Twin Higgs model in more detail.

This theory predicts an entire light mirror Standard Model at low energies. This mirror world is invisible to us because nothing transforms under the Standard Model gauge groups! (Lee & Yang)

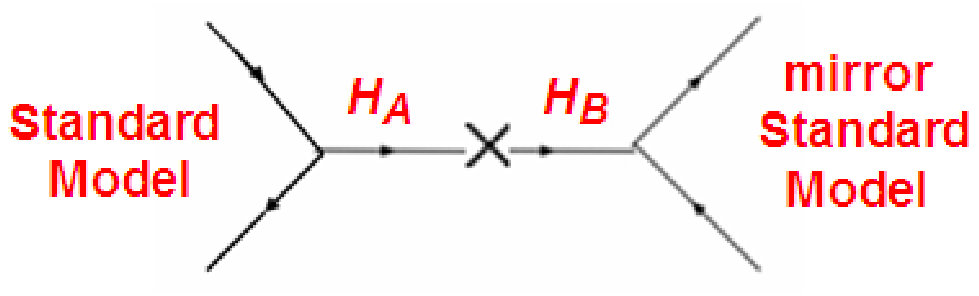
Gauge invariance allows only two renormalizable couplings between the Standard Model and the mirror Standard Model. (Foot, Lew & Volkas)

$|H_A|^2 |H_B|^2$ → part of U(4) invariant Higgs quartic

$(F_{\mu\nu})^A (F^{\mu\nu})^B$ → photon-mirror photon mixing

The quartic coupling between the Standard Model Higgs and the twin Higgs is necessarily part of the theory. Photon-mirror photon mixing is very tightly constrained. We set it to zero (not radiatively generated till high loop order.)

The most severe constraint arises from the interaction $|H_A|^2\ |H_B|^2$, which is part of the U(4) symmetric quartic. This leads to mixing between the Standard Model Higgs and the twin Higgs once the Higgs fields get VEVs.



This interaction keeps the mirror sector in thermal equilibrium with the Standard Model until temperatures of order a 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.

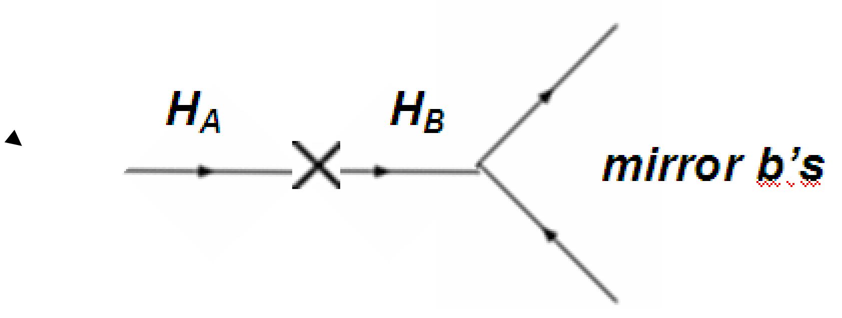
What are some of the possibilities?

- 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. (Ignatiev & Volkas)

- The QCD phase transition in the Standard Model generates considerable entropy, much more than the QCD phase transition in the mirror sector.

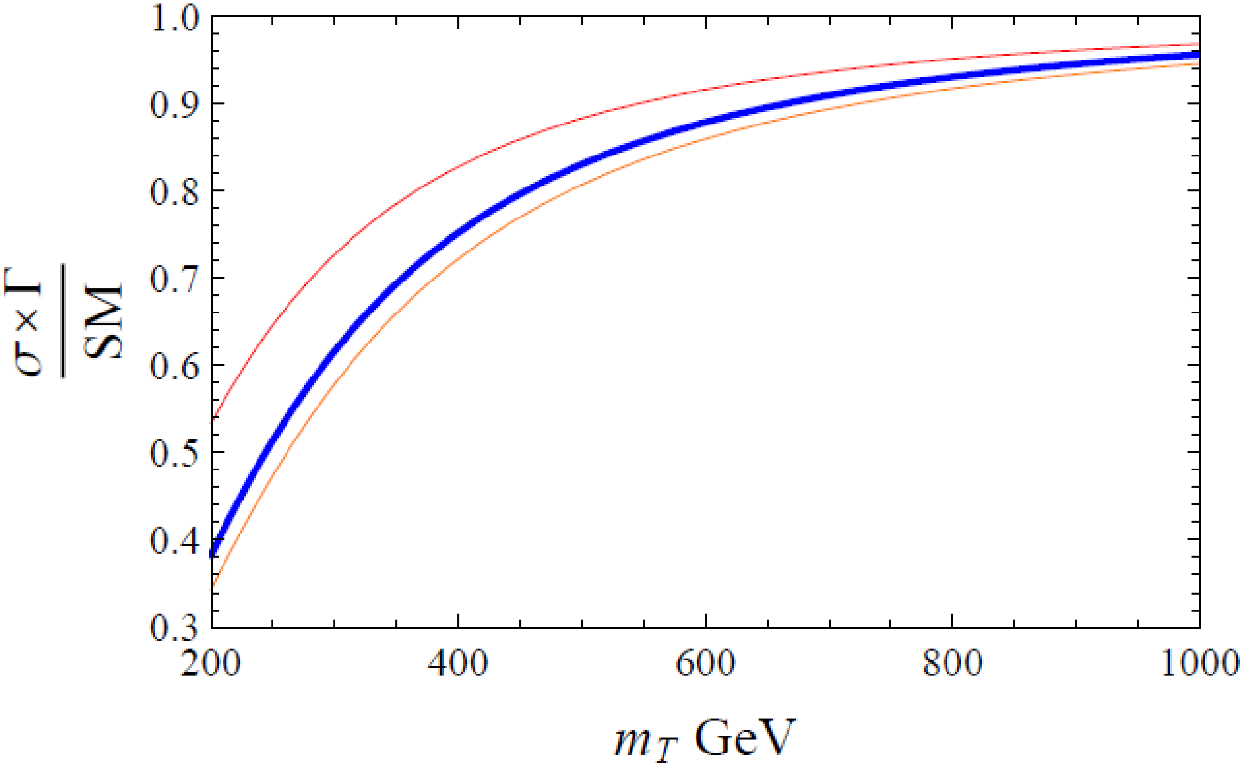
How can this class of models be tested at colliders? Challenging, because in general the new states are not charged under the Standard Model gauge groups. The Standard Model communicates with the mirror world only through the Higgs.

After electroweak symmetry breaking the SM Higgs and twin Higgs mix . Then the Higgs production cross section is suppressed by the cosine of the mixing angle. In addition, the Higgs can now decay into invisible hidden sector states.



Both effects contribute to a uniform suppression of the Higgs events into all SM final states. At the same time, invisible Higgs decays can be directly searched for. In the minimal Mirror Twin Higgs model, with only soft breaking of parity, a single mixing angle controls both these rates. There is a prediction!

At present, the bound on invisible decays of the Higgs assuming the SM production rate stands at about 20%. Looking at the graph, this corresponds to a limit on the top partner mass of about 500 GeV. The bound on tuning is only at the level of 1 part in 5.

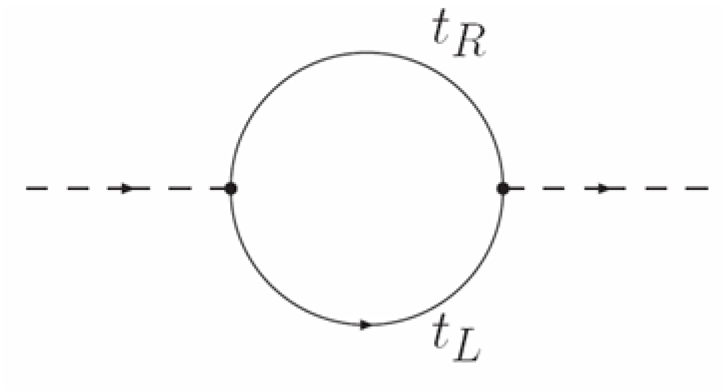


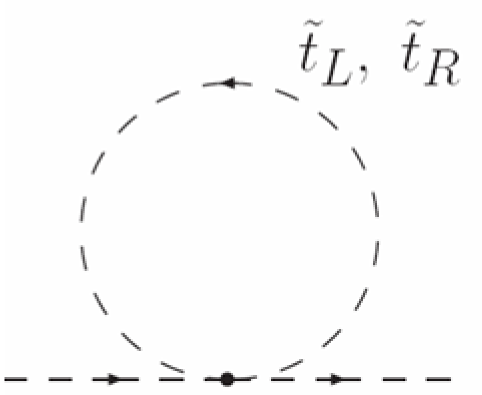
As the indirect (and direct) bounds on invisible decays improve, the bound on the top partner will be increased. However, even with 300 fb^{-1} at 14 TeV the bound on tuning is only expected to be at level of 1 part in 10.

Folded Supersymmetry

In Folded Supersymmetric theories, the cancellation of the one loop quadratic divergences associated with the top Yukawa coupling takes place exactly as in supersymmetric theories, but the top and the its scalar partners, the `F-stops', are charged under different color groups.

$$[\ \lambda_t\ h_u\ q_\alpha\ u_\alpha\ +\ \mathrm{h.c.}\ ]\ \ +$$
$$\lambda_t^2\ |\tilde{q}_\beta h_u|^2 + \lambda_t^2\ |\tilde{u}_\beta|^2\ |h_u|^2$$





The SM quarks are charged under the SM color group, labelled SU(3)$_A$, while the F-stops are charged under SU(3)$_B$.

This scenario can be realized in a 5D supersymmetric construction, with the extra dimension compactified on S^1/Z_2. Choose 1/R ~ 5 TeV.

A combination of boundary conditions and discrete symmetries ensures that the spectrum of light states includes the SM particles, the scalar F-spartners and the up- and down-type Higgs bosons.

The gauginos are projected out by the boundary conditions and are not part of the low energy spectrum below the compactification scale.

The electroweak quantum numbers of the light scalar F-spartners are the same as those of the corresponding SM fermions.

We can estimate the contribution to the finetuning from the top sector for a 125 GeV Higgs mass.

$$m_h^2\big|_{\text{top}} = -\frac{3y^2}{8\pi^2}\tilde{m}_t^2 \log\left(\frac{\Lambda^2}{\tilde{m}_t^2}\right)$$

Taking the cutoff to be 5 TeV, the precision electroweak scale, we can estimate the fine tuning to be 1 part in 5 for an F-stop mass of 500 GeV.

The fine tuning worsens to 1 part in 10 for an F-stop mass of 750 GeV.

To determine the effects of the top partners on Higgs physics, we focus on the limit when one Higgs doublet is much lighter than the other.

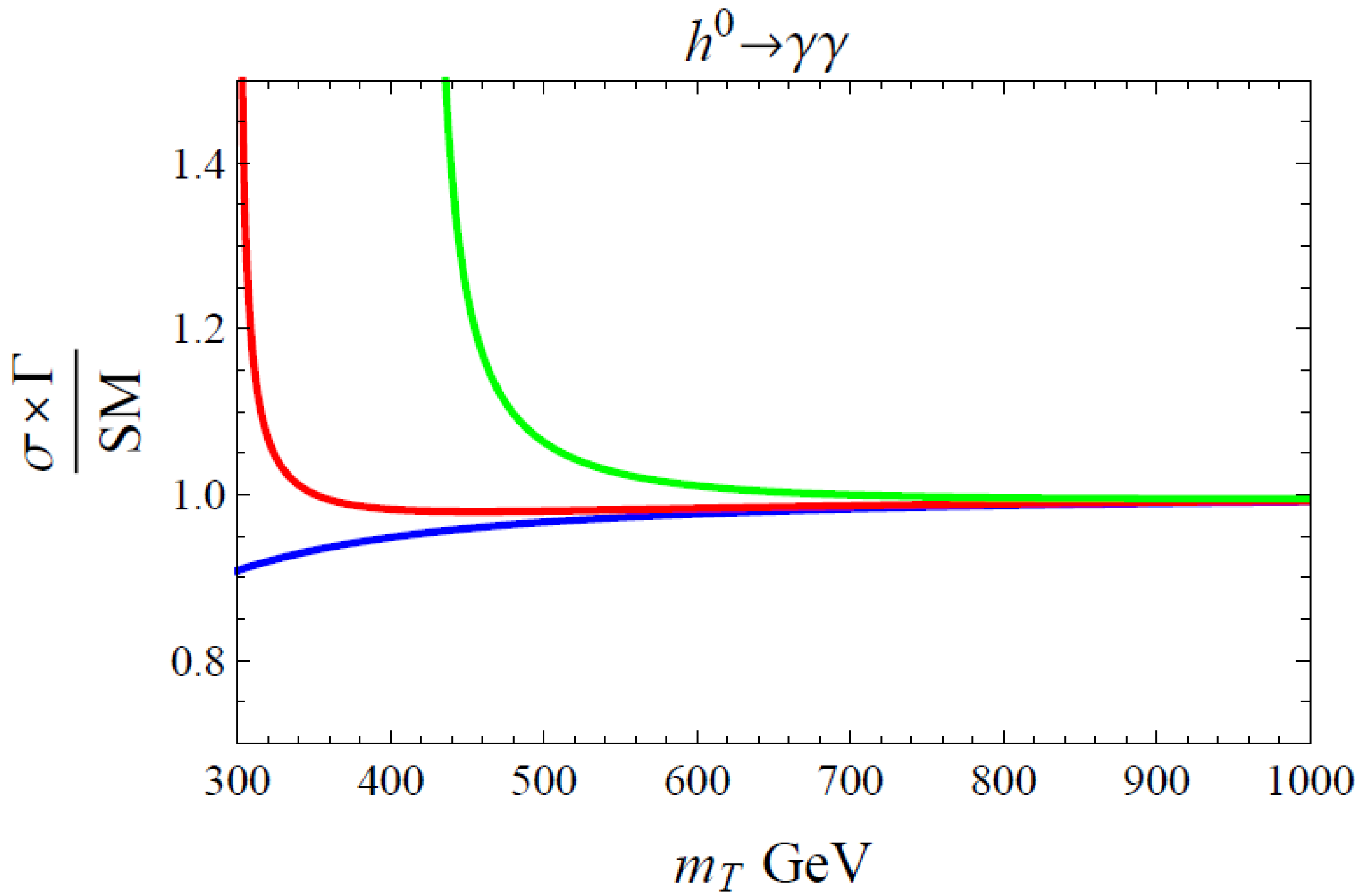
In this limit, the tree level coupling of the light Higgs to fermions and gauge bosons is exactly the same as in the SM.

However, at one loop these couplings receive corrections from the Higgs coupling to top partners. These corrections are significant for Higgs couplings to photon, because this only arises at one loop in the SM.

The Higgs coupling to gluons remains unchanged since F-partners are uncolored.

The Higgs production cross section in gluon fusion, associated production and vector boson fusion is largely unchanged from SM.

The rate to two photons can be used to constrain this scenario.



At present the constraints on F-stops are not significant except for large A terms. The bound may improve to about 400 GeV with 300 fb^{-1} of data. But then the bound from direct production of F-spartners will be stronger.

Conclusions

In scenarios with colorless top partners, their direct discovery at the LHC may be very challenging, or even impossible.

However, because of the large couplings of the top partners to the Higgs, the Higgs production cross section and decay rates are affected.

Therefore, a detailed study of Higgs phenomenology may be the most efficient way to probe scenarios with colorless top partners.

In the Mirror Twin Higgs, this can be used to bound the top partner mass, and set a limit on naturalness.

In Folded Supersymmetry, the direct bound on the F-spartner masses is expected to be stronger than the limits from Higgs physics.