Uncolored Top Partners

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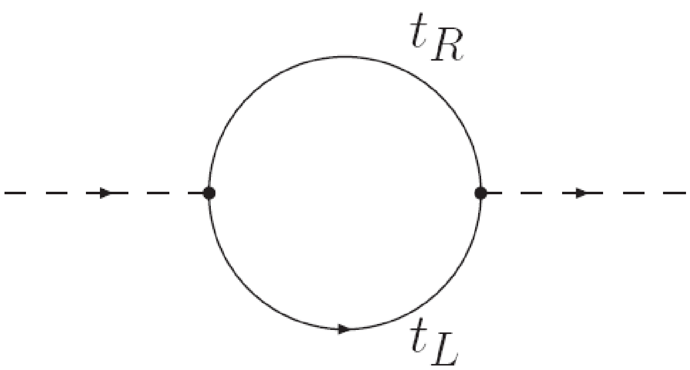
Introduction

Theories in which electroweak symmetry is broken by a scalar Higgs suffer from a fine-tuning problem, the `hierarchy problem'.

The problem arises because the Higgs mass parameter receives quantum corrections from high scales.

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.

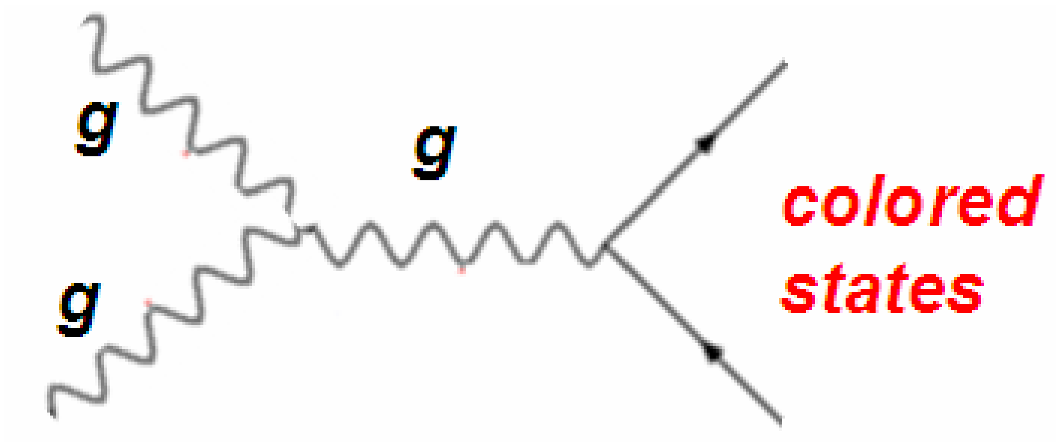


$$\sim \frac{3\lambda_t{}^2}{8\pi^2}\,\Lambda^2$$

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.

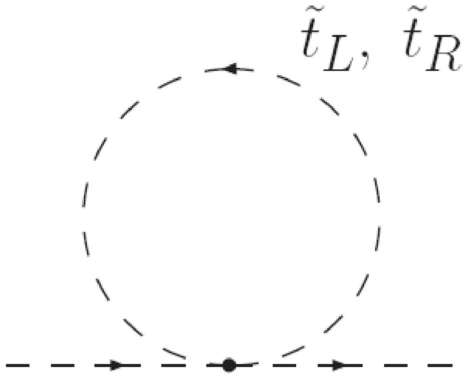
If the top partners are colored, the odds are good that the LHC will find them. If not, it is not clear that the LHC will find the new physics associated with naturalness.

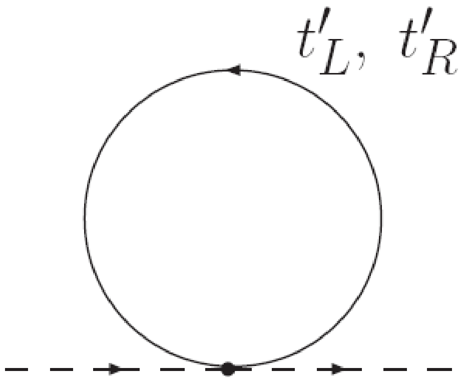


<u>However, in general the top partners need not be colored.</u> This is characteristic of scenarios where the top partners are related to the top quark only by a discrete symmetry. The Mirror Twin Higgs, Folded Supersymmetry and Quirky Little Higgs are examples of such theories.

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 $\widehat{Q}$ 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

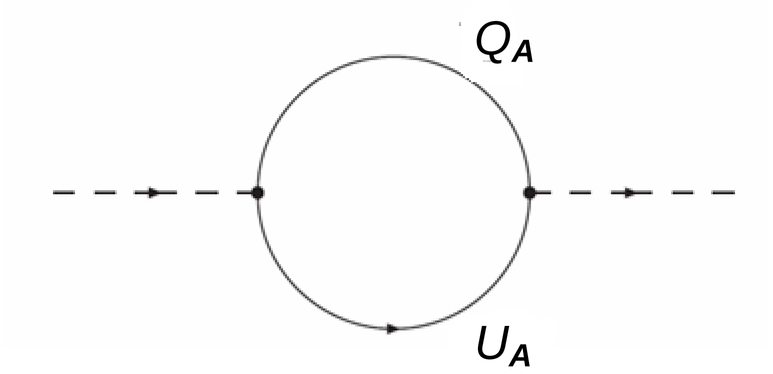
$$\lambda_t\, Q_A H_A U_A + \lambda_t\, Q_B H_B U_B$$

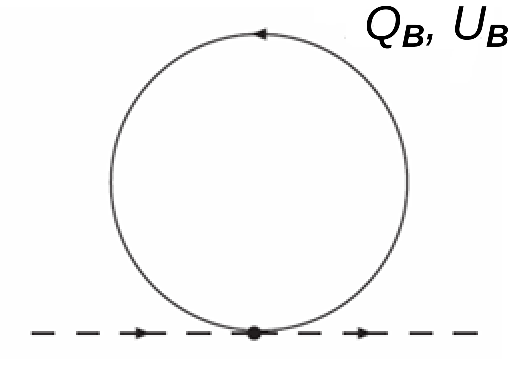
Standard Model Quarks — Twin Quarks

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.



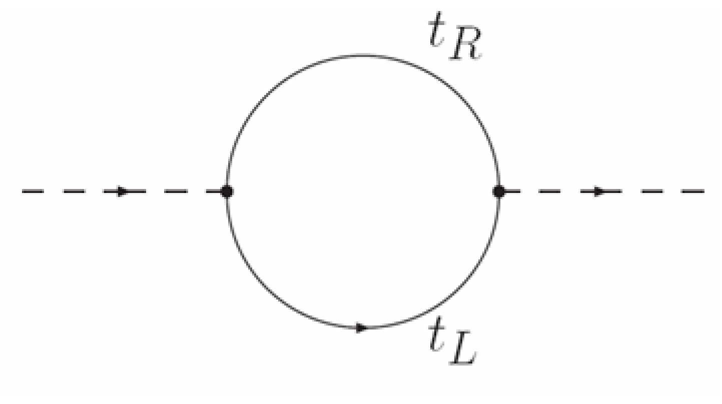


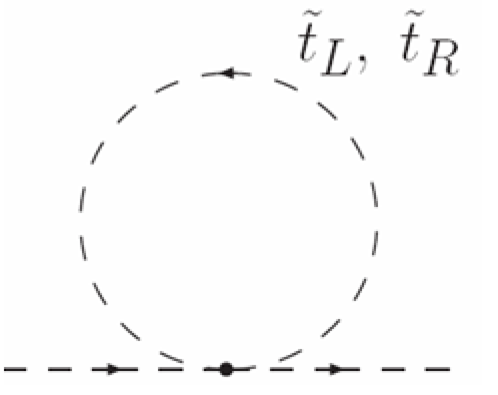
The crucial point to appreciate is that in this cancellation, color is simply a multiplicative factor of 3 with no further significance! What really matters is that the vertices in the two diagrams be related in a specific way by symmetry.

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.

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

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, 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

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

Impose a Z_2 `twin' symmetry under which A ←→ B. Then $g_A = g_B = g$, so that 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.

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 largely universal, and that the cancellation is not limited to a 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

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

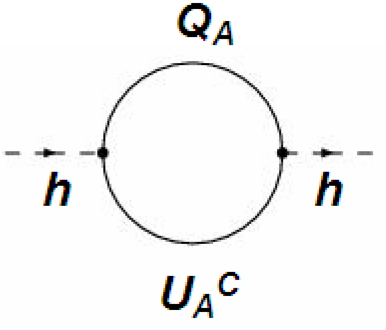
is the Standard Model Higgs field.

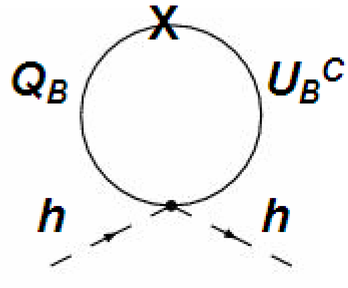
The cut-off $\Lambda \leq 4\pi f$ where upper bound is at strong coupling.

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

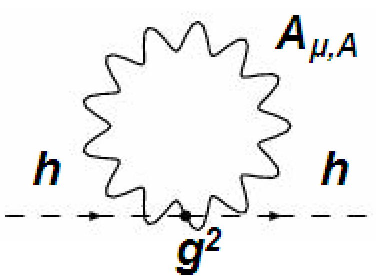
Let us now understand the cancellation of quadratic divergences in the non-linear model.

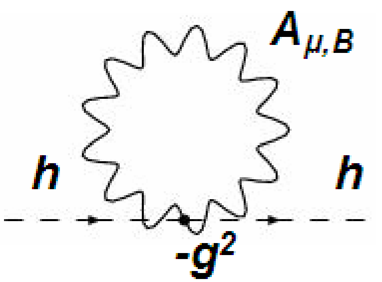
$$
\begin{aligned}
L_{top} &= y\, H_A\, Q_A\, U_A^c + y\, H_B\, Q_B\, U_B^c \\
&\to y\, h\, Q_A\, U_A^c + \; y \left(f - \frac{|h|^2}{2f} \right) Q_B\, U_B^c
\end{aligned}
$$



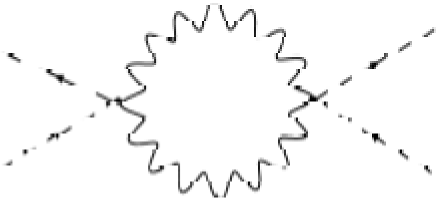


The quadratic divergences of these two diagrams cancel exactly! The cancellation takes exactly the same form as in little Higgs theories. The states which cancel top loop need not be colored! Cancellation of gauge loops also takes same form as in little Higgs.





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



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

Then for Λ of order 5 TeV, m_h is weak scale size.

However, the pseudo-Goldstone is an equal mixture of H_A and H_B, which is disfavored by experiment. To avoid this problem, add a term to the Higgs potential which softly breaks the discrete symmetry.

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

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

This approach also allows the generation of a hierarchy between v and f, but at the expense of mild fine-tuning.

The discrete symmetry must now be extended to all the interactions of the Standard Model. The simplest possibility is to identify this symmetry with parity, which may be realized as mirror symmetry or left-right symmetry.

- **Mirror Symmetric Twin Higgs Model**

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.

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)**

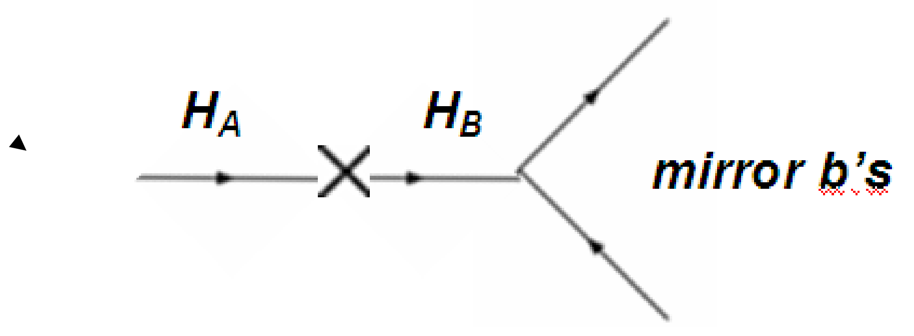
There are potential cosmological problems associated with these mirror states, but it is possible to resolve them.

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 .

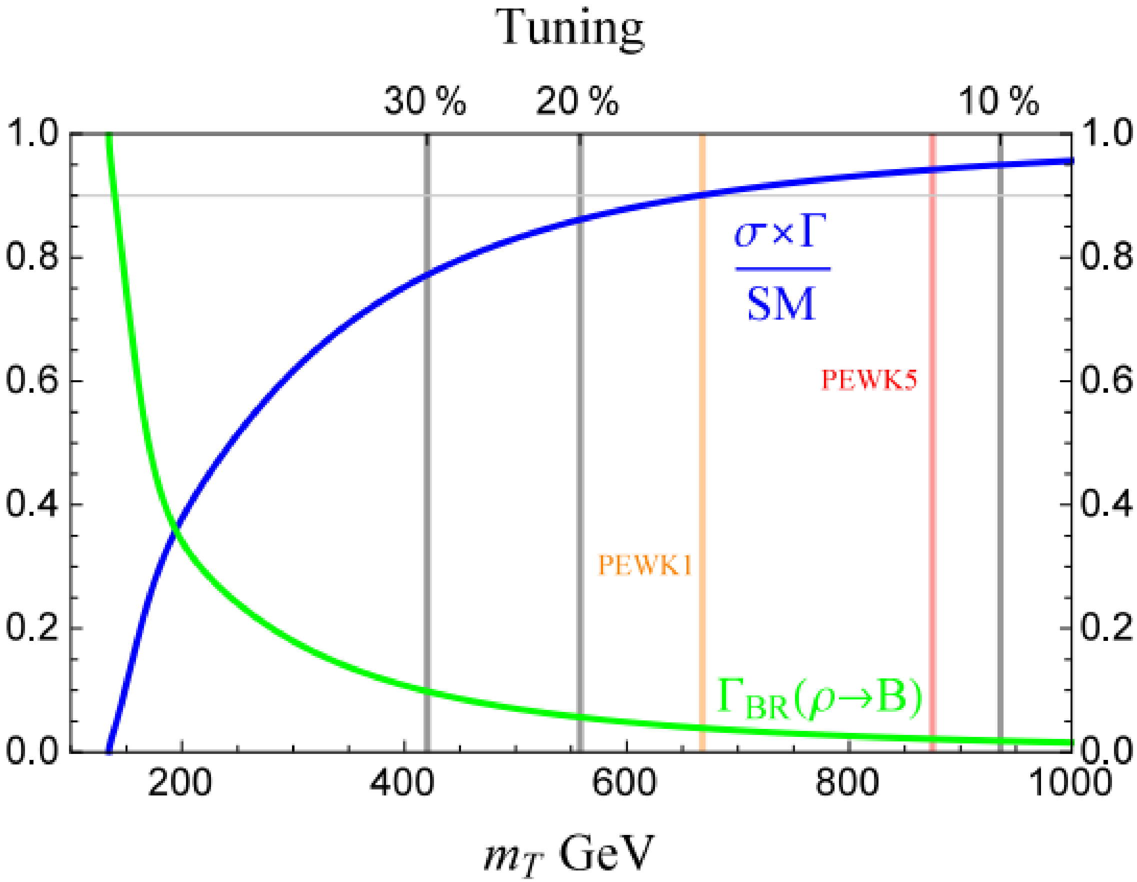
- **Higgs production cross section is suppressed by the mixing angle.**

- **the mixing allows the Higgs to 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 less than 500 GeV. The bound on tuning is only at the level of 1 part in 4.

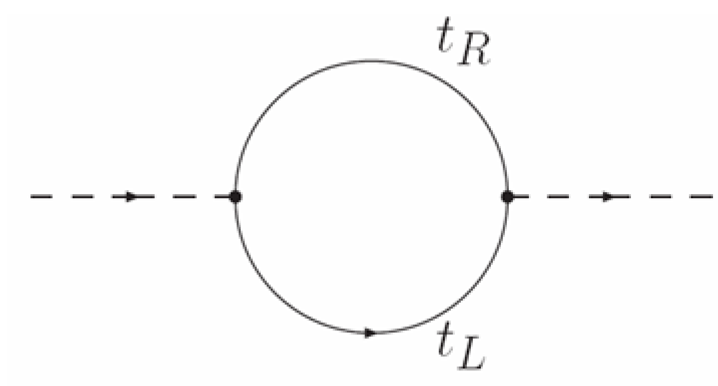


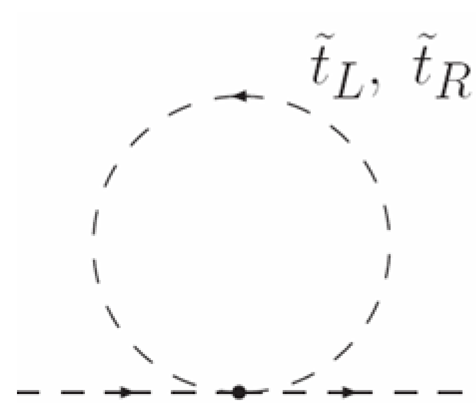
As the indirect (and direct) limits on invisible decays improve, the bound on the top partner will be increased. However, even with 3000 fb^{-1} at 14 TeV the bound on tuning is only expected to be about 1 part in 10.

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.

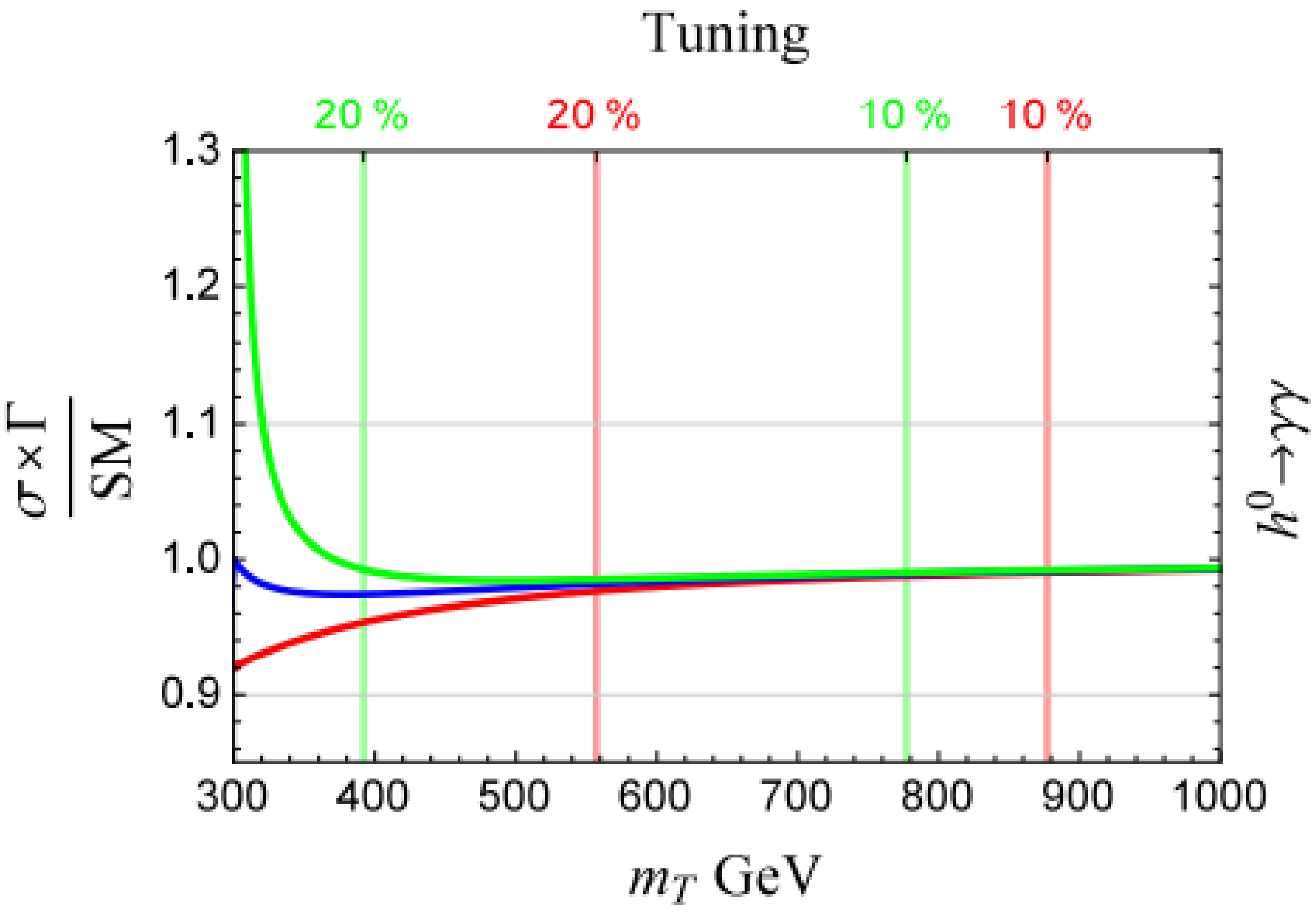
$$[\ \lambda_t\ h_u\ q_\alpha\ u_\alpha\ +\ \mathrm{h.c.}\ ]\ \ +$$
$$\lambda_t^2\ |\tilde{q}_\beta h_u|^2 + \lambda_t^2\ |\tilde{u}_\beta|^2\ |h_u|^2$$





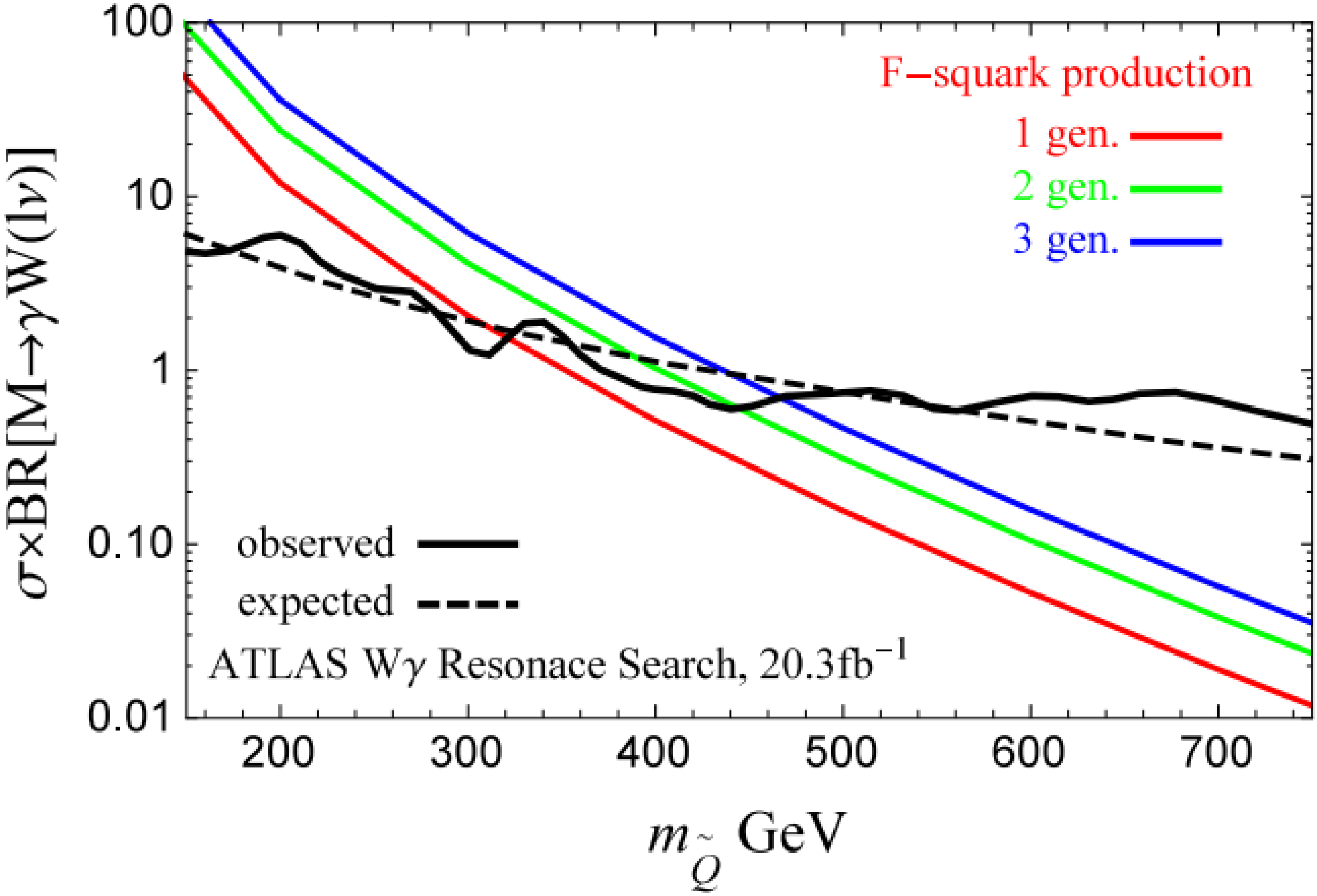
In this scenario, the F-stops carry electroweak quantum numbers.

The Higgs production cross section is unchanged, but the decay 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 500 GeV with 3000 fb^{-1} of data.

A scalar top and bottom partner can be produced through an off-shell W. They pair annihilate back into W + γ. A resonance in this channel!



In general the limits on top partners from direct production are stronger than the indirect limits from Higgs decay to two photons.

Conclusions

It is possible to cancel the top loop with uncolored top partners!

The direct discovery of uncolored top partners 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 at the LHC.

In the Mirror Twin Higgs, this can be used to bound the top partner mass, and set limits on naturalness (currently 25%, and eventually improving to 10%). The LHC will only be able to mildly disfavor naturalness.

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