Title: Signals of Neutral Naturalness

Date: Apr 12, 2016 01:00 PM

URL: http://pirsa.org/16040061

Abstract: <p>I explain the hierarchy problem of the standard model of particle physics, and discuss some of the ideas which have been put forward to resolve it. I then show that a specific class of theories, built around a framework known as neutral naturalness, can help address this problem while remaining consistent with all current experimental tests. I explain that while certain theories in this class give rise to striking signals, others are extremely difficult to test, and require a detailed study of the properties of the Higgs boson. I consider the implications of these results for the Large Hadron Collider, and for future experimental programs.</p>

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

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

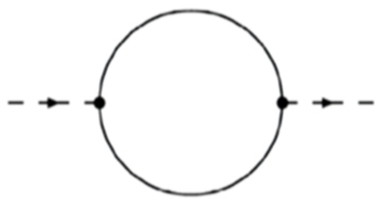
and for the mass of the physical Higgs

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

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

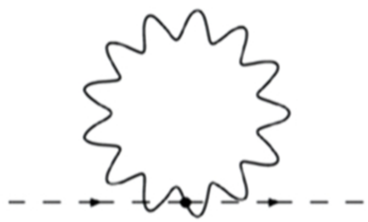
is the radiative correction to the mass squared parameter.

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



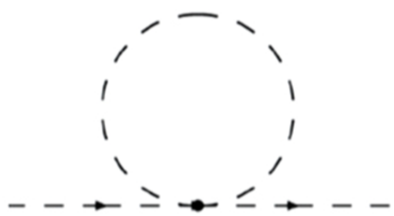
$$= \frac{3y_t^2}{8\pi^2}\Lambda^2$$

Fine Tuning < 10% for Λ > 1.5 TeV.



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

Fine Tuning < 10% for Λ > 4 TeV.



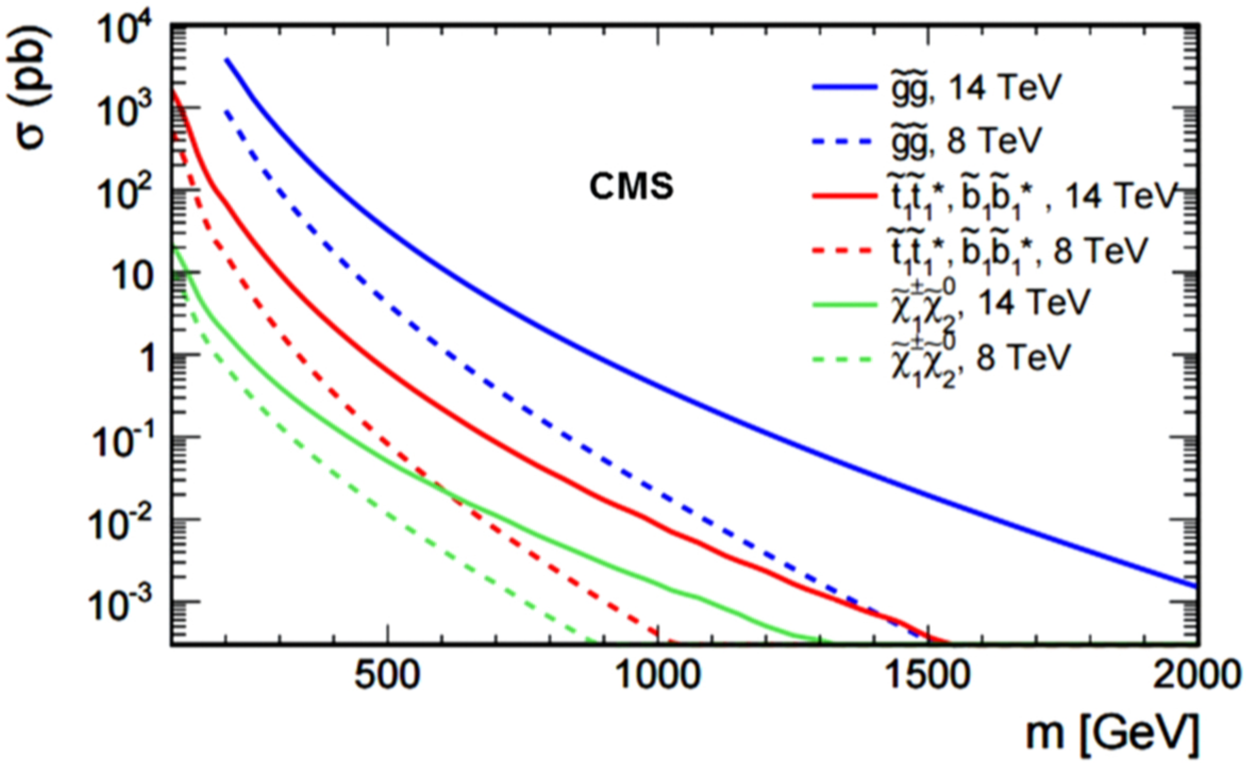
$$= \frac{3\lambda}{8\pi^2}\Lambda^2$$

Fine tuning < 10% for Λ > 3 TeV.

The new particles, the `top partners' 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 top partners would also be colored.

If the top partners are colored, discovery at the LHC is much easier.



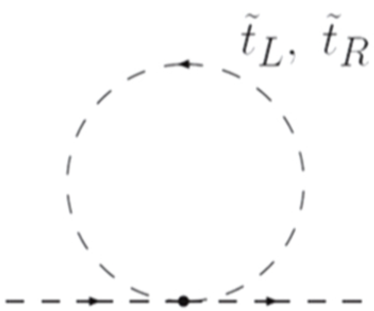
However, in general the top partners need not be colored! This can happen in scenarios where the top and the top partners are related only by a discrete symmetry.

ZC, Goh & Harnik (2005)

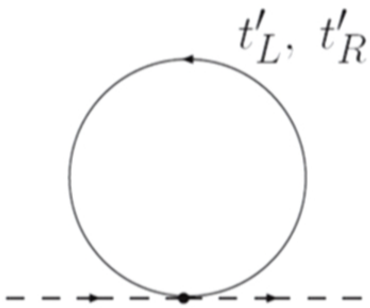
Mirror Twin Higgs and Folded Supersymmetry are the first known examples.

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.

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.

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

Consider the SM 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.

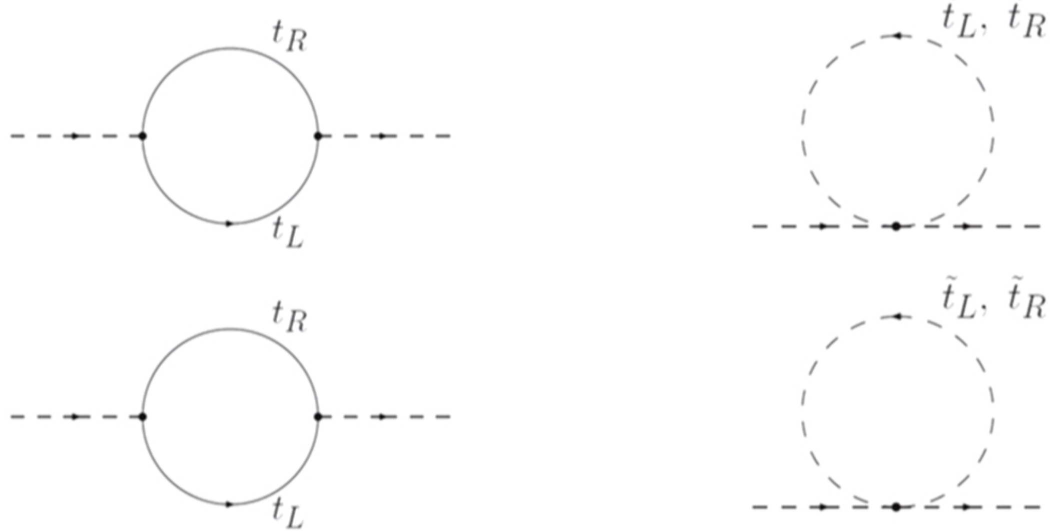
The global symmetries protecting Higgs mass commute with color.

A toy example of uncolored top partners.

- 2 copies of the top quark, A and B
- A carries charge under QCD, B under a hidden QCD.
- There is an interchange symmetry $A \to B$, QCD $\to$ QCD'.
- Supersymmetrize.

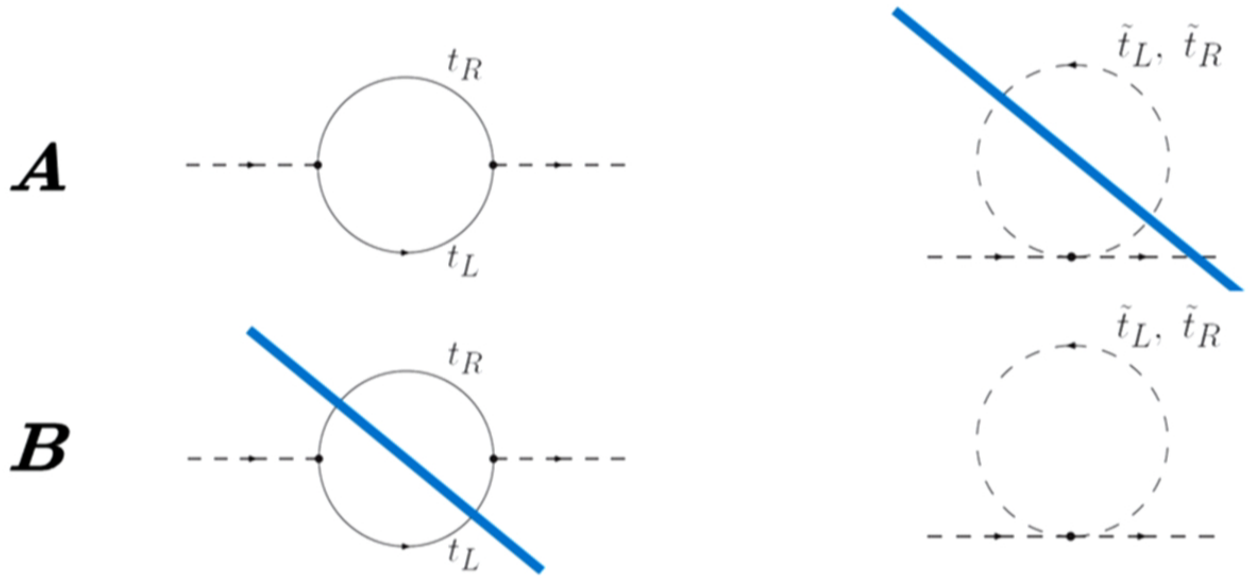
$\boldsymbol{A}$

$\boldsymbol{B}$



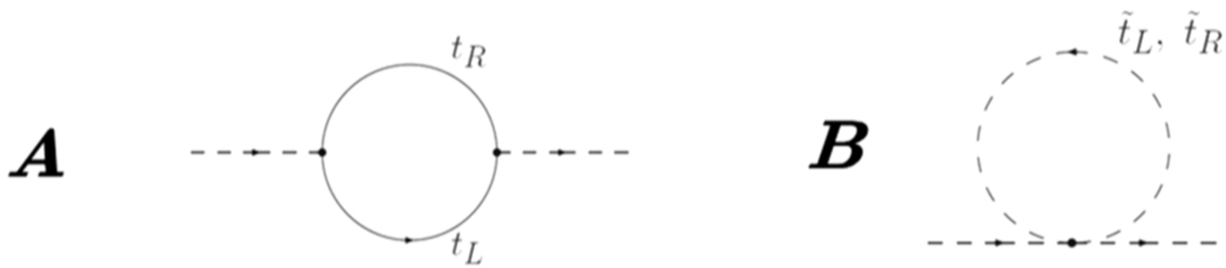
Self energy contributions cancel because of supersymmetry.

(Orbifold) project out scalars from A and fermions from B.

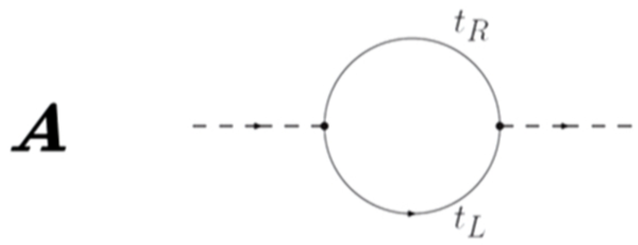


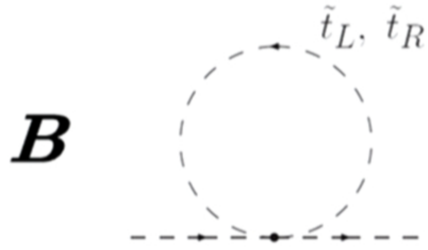
The cancellation still goes through because of <u>Folded Supersymmetry</u>.

Burdman, ZC, Goh & Harnik



The cancellation of the top loop takes pace through a diagram of exactly the same form as in supersymmetry. The major difference is that the scalars running in the loop, the top partners, carry no charge under SM color.





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 this scenario, the discrete A → B symmetry that protects the Higgs mass does not commute with SM color.

This class of models protect the weak scale against radiative corrections up to the precision electroweak scale, of order 5 – 10 TeV.

- partial neutral naturalness – top partners carry electroweak charges

  Folded Supersymmetry — Burdman, ZC, Goh and Harnik

  Quirky Little Higgs — Cai, Cheng and Terning

- complete neutral naturalness – top partners neutral under all SM forces

  Mirror Twin Higgs — ZC, Goh & Harnik

  Fraternal Twin Higgs — Craig, Katz, Strassler & Sundrum

Beyond 5 -10 TeV, a UV completion such as compositeness or supersymmetry is required to complete the solution the hierarchy problem.

However, the physics of the UV completion may be inaccessible to the LHC.

To illustrate the twin Higgs mechanism, 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). 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, so that $g_A = g_B = g$.
Then the radiative corrections take the form,

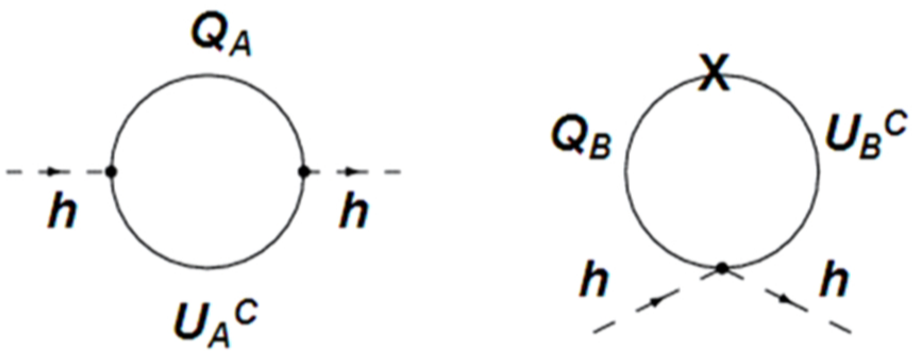
$$\Delta V = \frac{9g^2\Lambda^2}{64\pi^2} (H_A^\dagger H_A + H_B^\dagger H_B)$$

This is U(4) invariant, and can be completely absorbed into the U(4) symmetric mass term. It 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 now understand the cancellation of quadratic divergences in the non-linear model, at one loop. Start with the top Yukawa,

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



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!

Can be generalized to all loop orders using a spurion analysis.

Cancellation of gauge loops also takes same form as in little Higgs.

However, higher dimension terms such as $|H^\dagger D_\mu H|^2$ also contain gauge interactions which can potentially contribute to the Higgs mass at one loop.

Therefore, for strongly coupled UV completions, a more careful analysis is needed to establish this result.

Provided the symmetry breaking pattern is O(8) → O(7), the quadratic divergences from the gauge sector are canceled, even if UV completion is strongly coupled.

ZC, Goh & Harnik

Barbieri, Greco, Rattazzi & Wulzer

The discrete symmetry must be extended to all the interactions of the SM. The simplest possibility is to identify the discrete symmetry with parity.

Mirror 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.

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

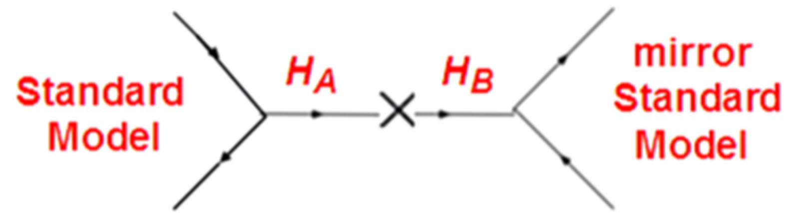
$$(F_{\mu\nu})^A\,(F^{\mu\nu})^B$$ photon-mirror photon mixing

Photon-mirror photon mixing is very tightly constrained. We set it to zero (not radiatively generated till high loop order).

The SM sector communicates with the mirror world only through the Higgs portal. Very difficult to test.

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

After electroweak symmetry breaking the SM Higgs and twin Higgs mix, leading to corrections to Higgs physics.



The tightest constraints on this class of theories come from the cosmological bounds on dark radiation.

The Higgs portal interaction keeps the mirror sector in thermal equilibrium with the SM until temperatures of order a few 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.

Fraternal Twin Higgs Models

Craig, Katz, Strassler & Sundrum

Below 5 TeV, the only light twin states present in the theory are those essential for naturalness or consistency (anomaly cancellation).

- 3rd generation fermions.
- SU(2) gauge bosons (but not hypercharge)
- mirror color gauge bosons

The absence of light mirror states associated with the light quarks means that the lightest hadrons in mirror sector can be glueballs.

These can be accessed through the Higgs portal and can give rise to exotic phenomenology such as displaced vertices.

Cosmological constraints are more easily satisfied. The mirror b and τ are dark matter candidates.

Garcia, Lasenby & March-Russell

Craig & Katz

Signals of Neutral Naturalness

How can these theories be tested at colliders?

- **Precision Higgs studies.**
  Hidden sector must have large couplings to the Higgs. Can affect its properties.

  Mirror and Fraternal Twin Higgs

  Folded Supersymmetry

  Quirky Little Higgs

- **Exotic Higgs decays.**
  Mirror QCD is a characteristic feature of these theories. Higgs can decay to mirror glueballs, which can decay back to SM particles.

  Fraternal Twin Higgs

  Folded Supersymmetry

  Quirky Little Higgs

- **If top partners carry electroweak charge, direct production.**
  Decay products may be SM particles.

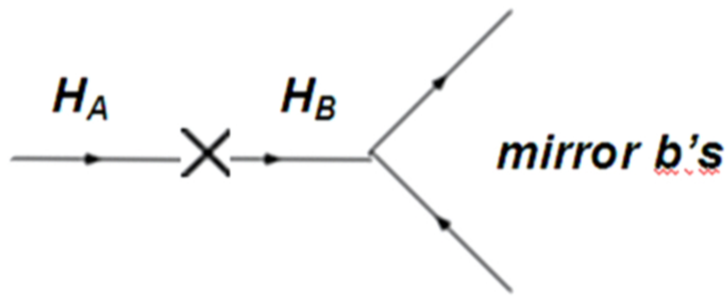
  Folded Supersymmetry

  Quirky Little Higgs

Precision Higgs Studies (Burdman, ZC, Harnik, de Lima & Verhaaren)

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.**

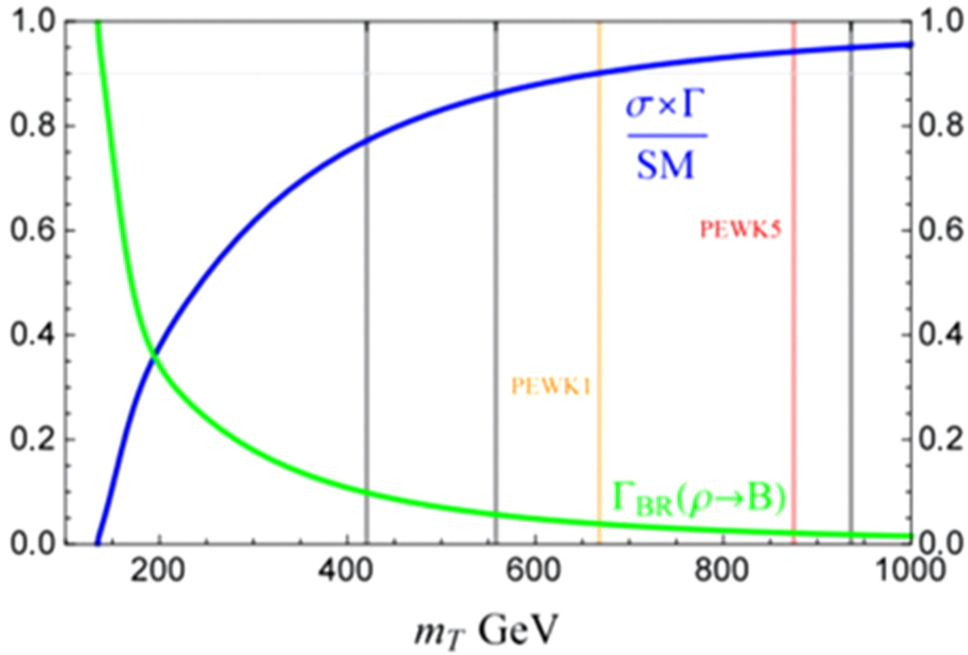


Both effects contribute to a uniform suppression of the Higgs events into all SM final states.

At the same time, invisible Higgs decays can be directly searched for.

In the 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 cross section is known to be within 20% of the standard model prediction. Mirror Top must be heavier than about 500 GeV.



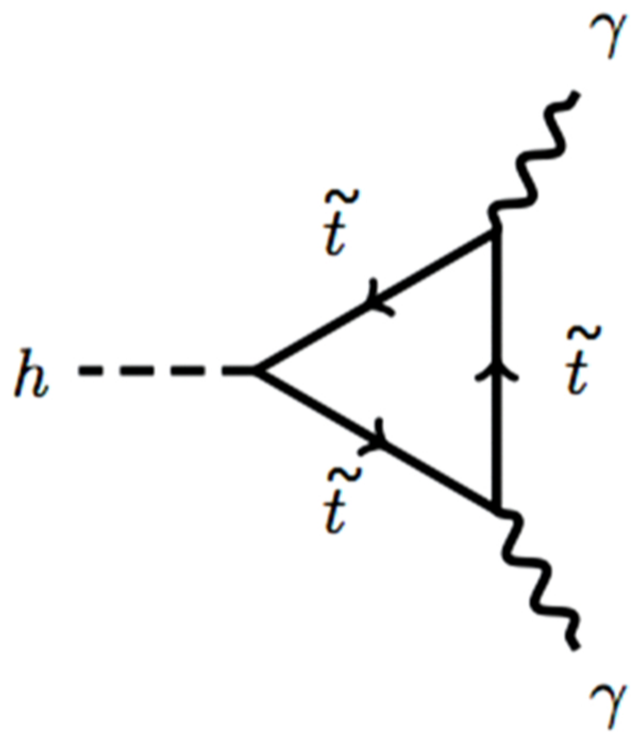
Limit expected to improve only to about 10%.

The LHC will not be able to conclusively disfavor naturalness!

A linear collider (`Higgs Factory') may be needed to exclude this theory.

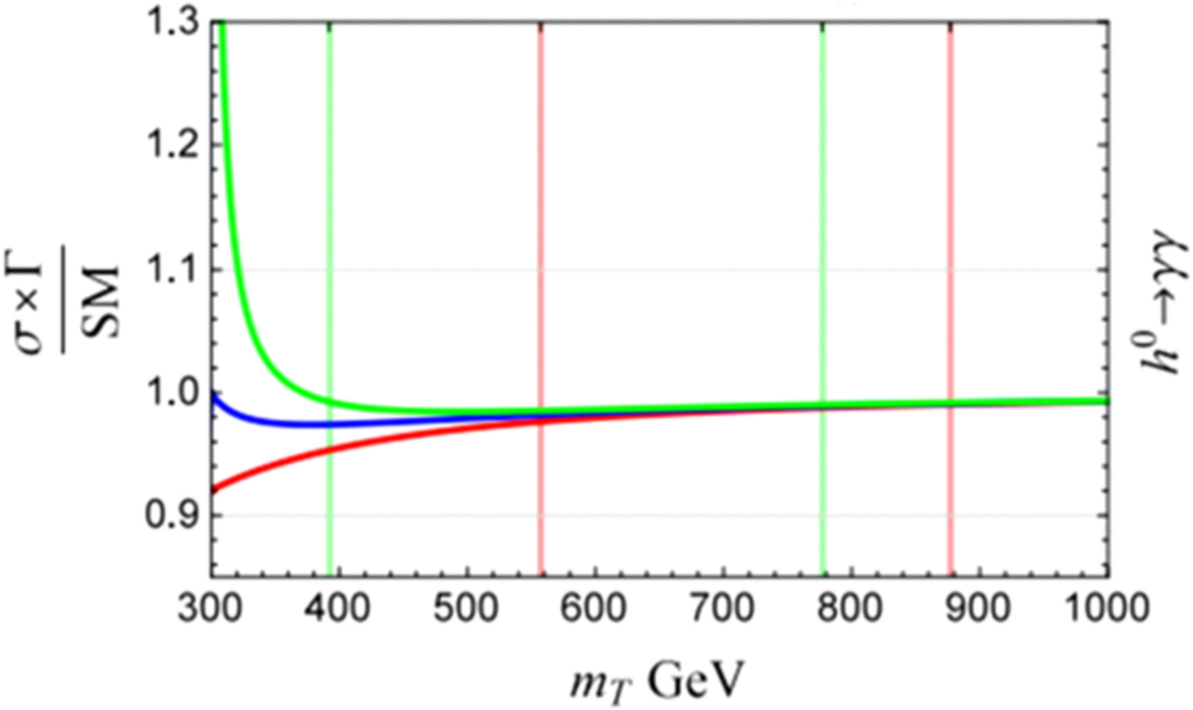
In Folded Supersymmetry, Higgs production is largely unchanged.

But Higgs decay rate into two photons receives corrections.



Since the top partners carry electroweak charges, there are now new diagrams with the top partners in the loop.

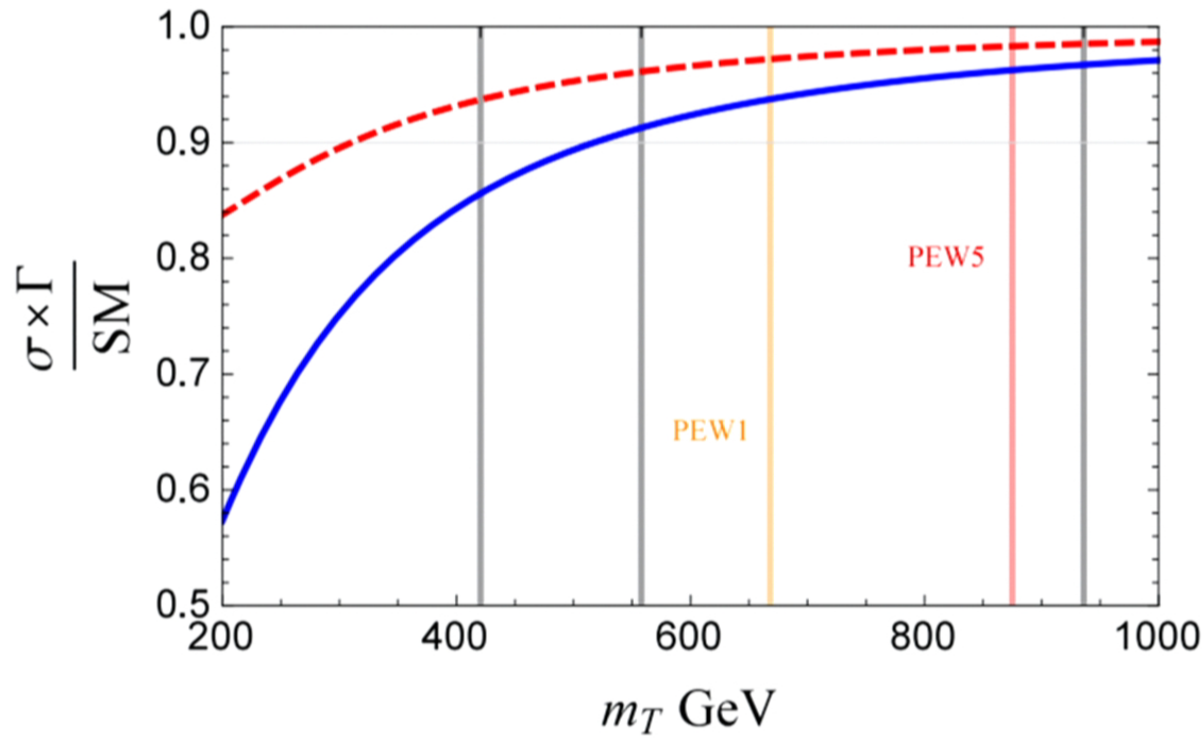
The current LHC limits from this are weak. Not expected to improve much.



Precision electroweak measurements at a future lepton collider would be able to better constrain this scenario. **Fan, Reece & Wang**

In Quirky Little Higgs, there is a net reduction in Higgs events compared to the SM, but also a correction to the decay rate of Higgs to two photons.

At present, the overall Higgs rate (in blue) gives the stronger bound.

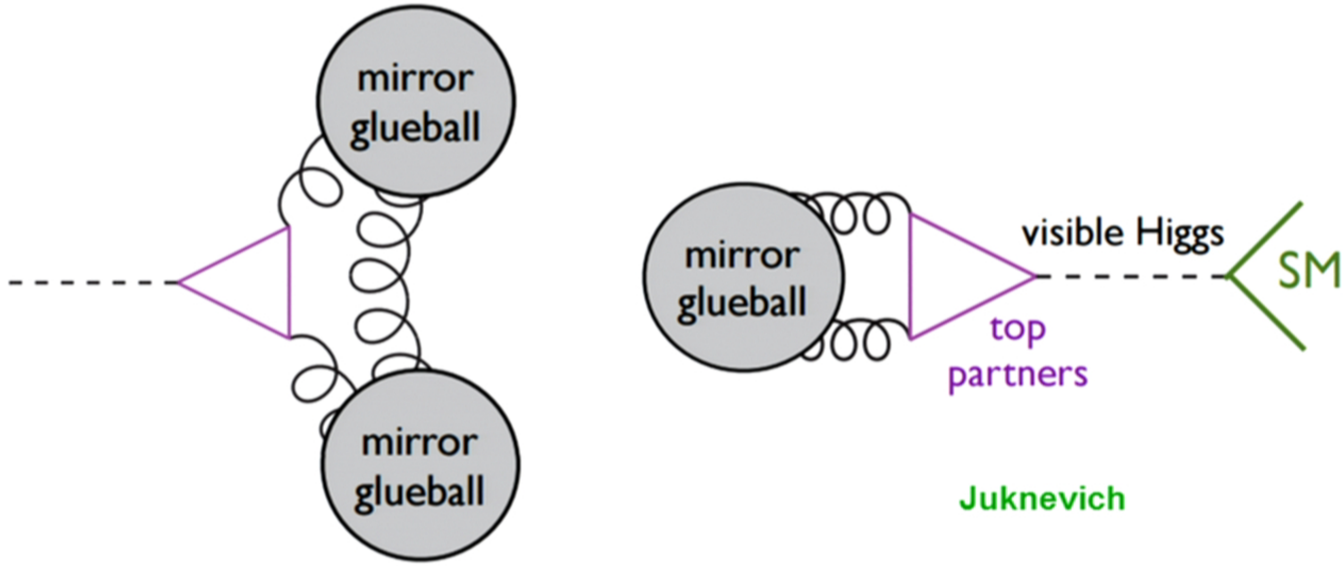


Bound on the top partner mass is of order 350 GeV. Will not improve much.

Exotic Higgs Decays

In Folded Supersymmetry, Fraternal Twin Higgs and Quirky Little Higgs, mirror QCD has no light quarks, only gluons. The lightest hadrons are glueballs.

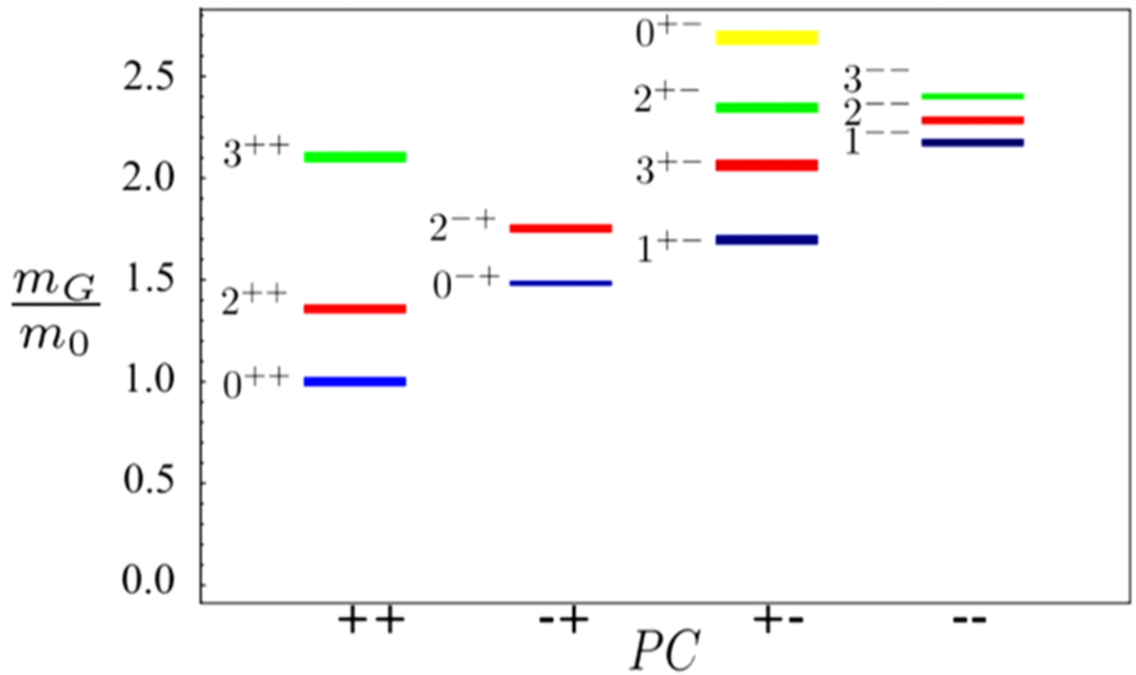
The Higgs can decay into two mirror gluons, resulting in glueballs.



Juknevich

The 0^{++} glueballs mix with the Higgs, and can therefore decay back to SM particles.

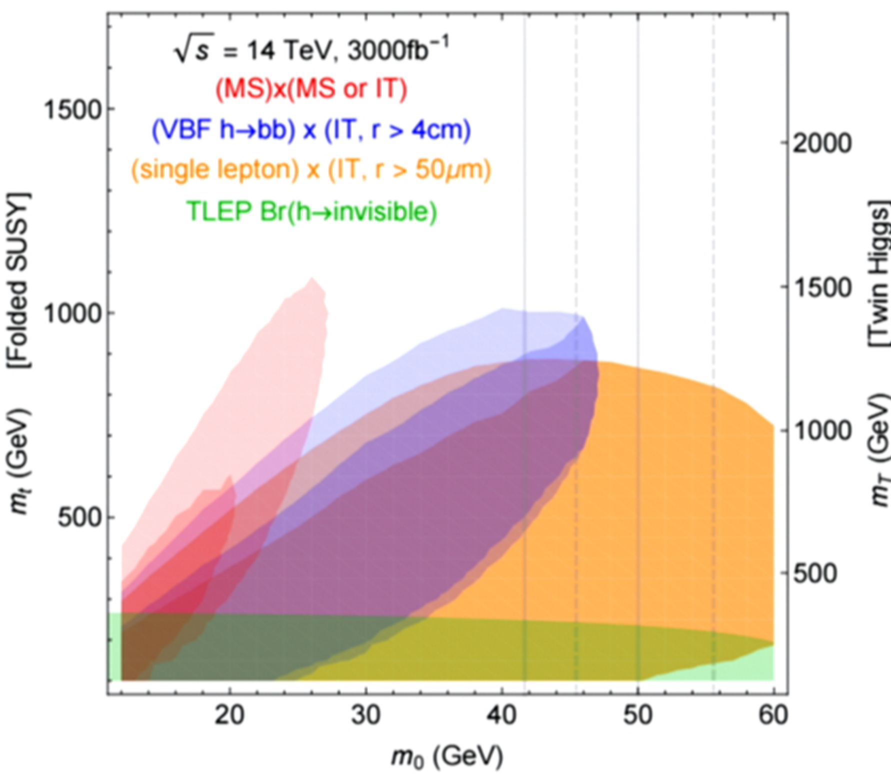
The spectrum of glueball states, and some of the relevant matrix elements are known from lattice studies. Allows an estimate of the glueball lifetime.



For most of the parameter range of interest, the decays of the 0^{++} glueballs are slow on collider time scales, resulting in displaced vertices.

Craig, Katz, Strassler & Sundrum

The LHC can use exotic Higgs decays to place useful limits on this scenario.



Curtin & Verhaaren

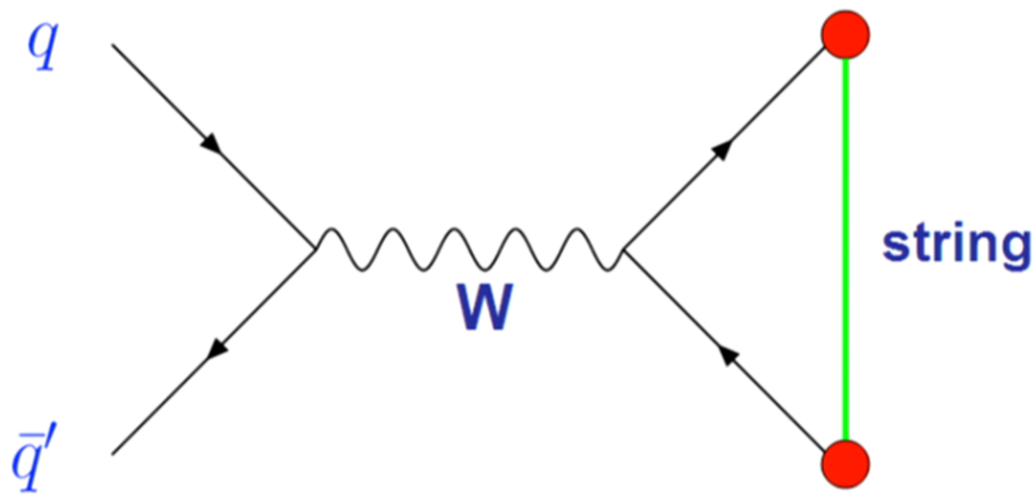
Csaki, Kuflik, Lomardo & Slone

In some cases, this may be the most effective probe of neutral naturalness.

Limits may eventually be comparable to bounds on colored top partners.

Direct Production

Top (and bottom) partners that carry electroweak charges can be pair produced at the LHC.



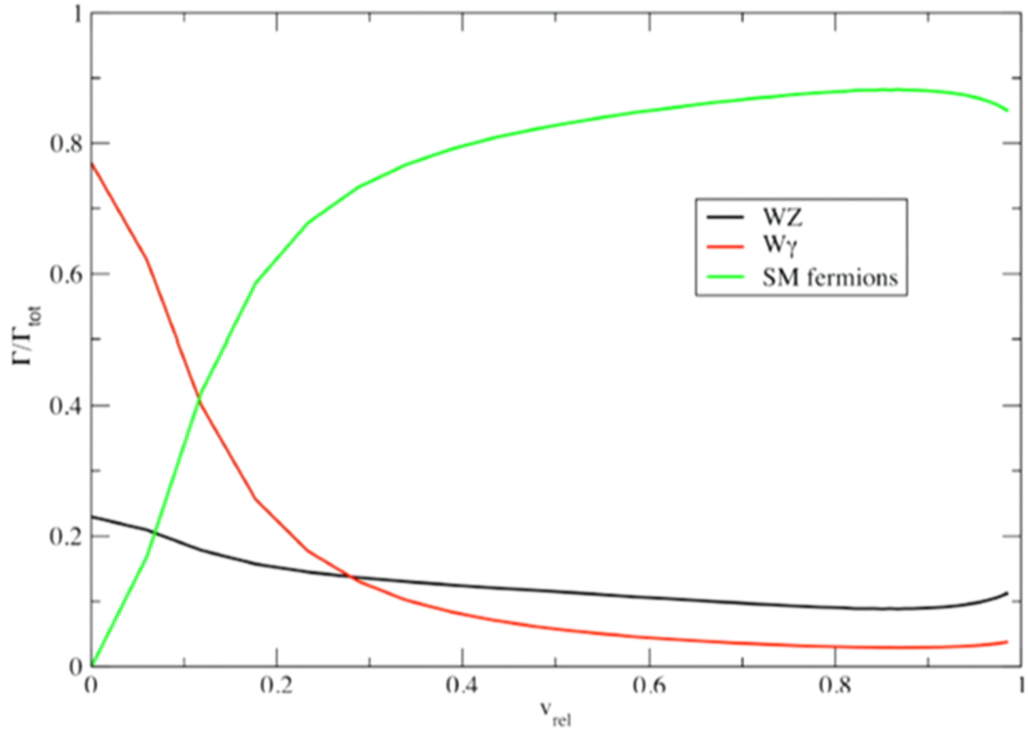
Their hidden color charge prevents them from decaying to SM particles.

Instead they can form a “quirky” bound state that de-excites through the emission of photons and hidden glueballs.

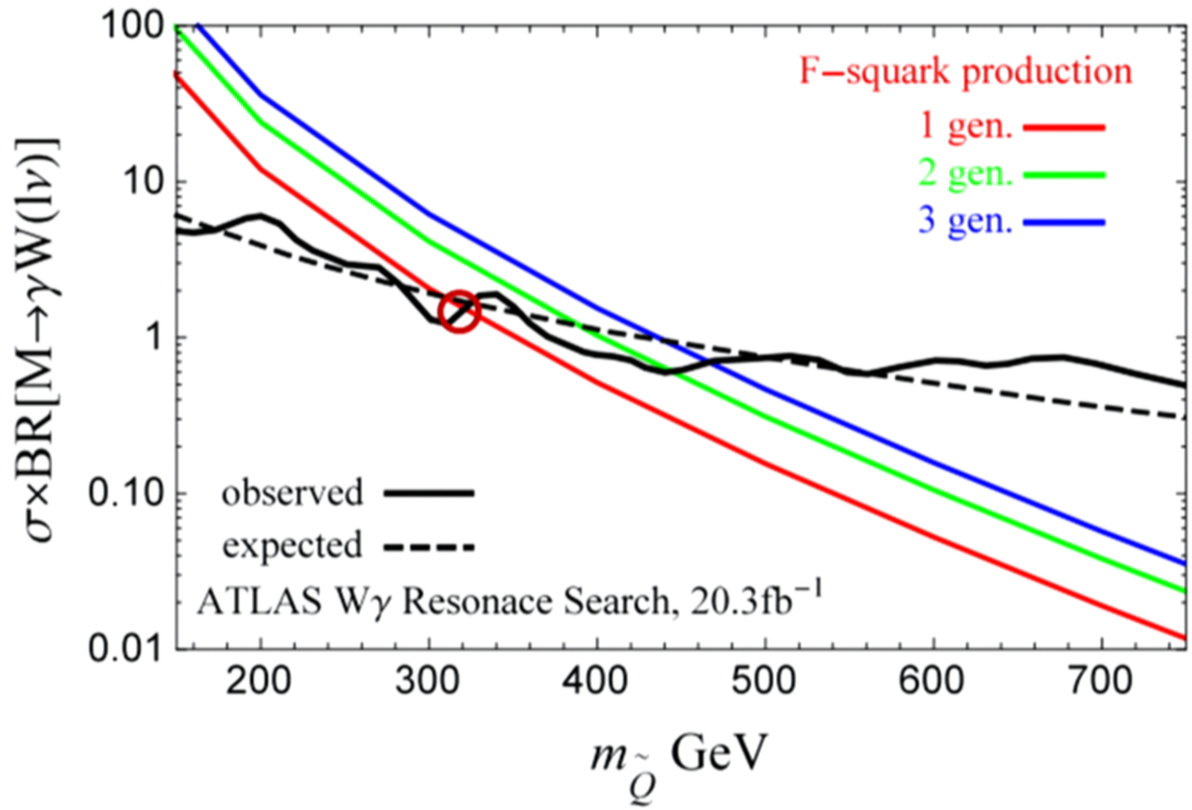
Eventually these particles pair-annihillate, resulting in final states that can potentially be detected.

In folded supersymmetry a top and bottom partner can be produced through an off-shell W boson.

They can pair annihilate back into SM final states.

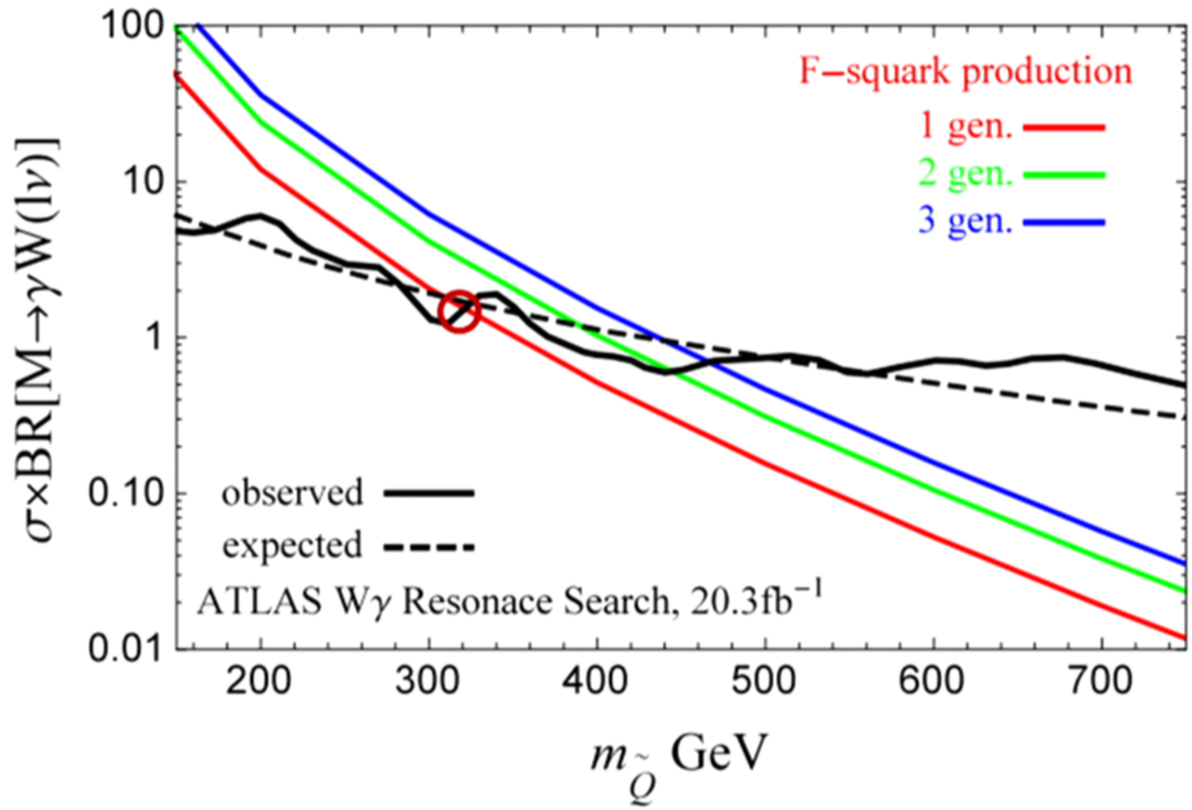


Primary annihilation channel is into W + γ. A resonance in this channel!



At present, the limits are quite weak. Expected to improve significantly.

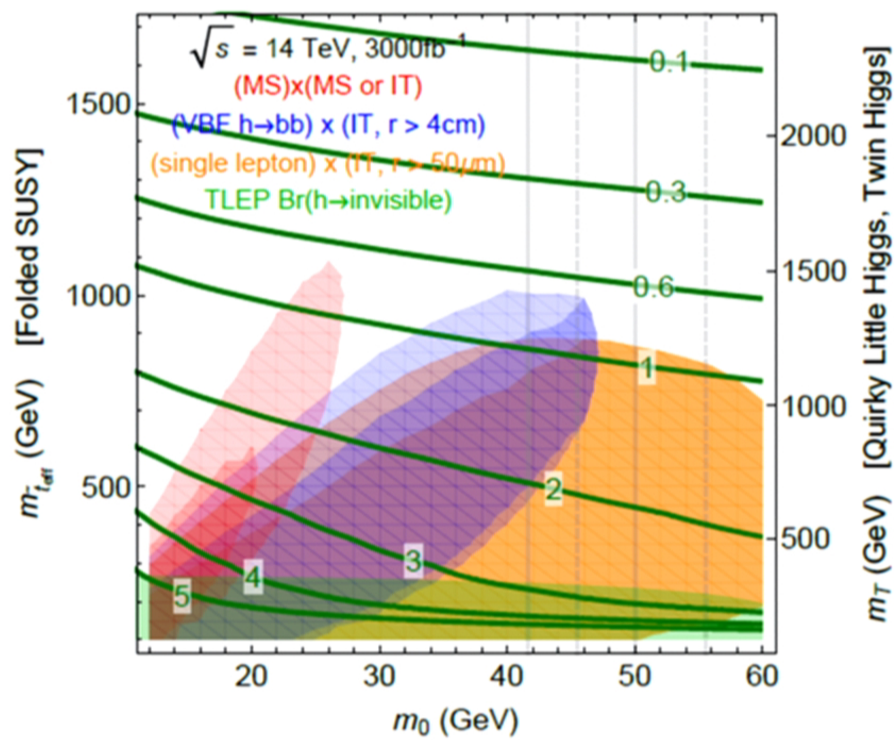
(Burdman, ZC, Harnik, de Lima & Verhaaren)



At present, the limits are quite weak. Expected to improve significantly.

(Burdman, ZC, Harnik, de Lima & Verhaaren)

For the Quirky Little Higgs, direct top partner production leads to the most promising signal in almost all of parameter space!



Curtin, ZC & Verhaaren

For Folded Supersymmetry, this is also the most promising signal in a large part of parameter space.

Solutions to the hierarchy problem based on symmetry may only involve particles that are neutral under some, perhaps even all, of the forces in the standard model.

The experimental signals of such a scenario tend to be very different from conventional solutions to the hierarchy problem. Motivates several new searches involving displaced vertices.

The LHC will probably not be able to conclusively exclude symmetry based solutions to the hierarchy problem.