Twin Higgs Theories

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Introduction

The Twin Higgs framework is a promising approach to the naturalness problem of the Standard Model (SM). ZC, Goh & Harnik (2005)

In Mirror Twin Higgs models, the SM is extended to include a complete mirror ("twin") copy of the SM, with its own particle content and gauge groups.

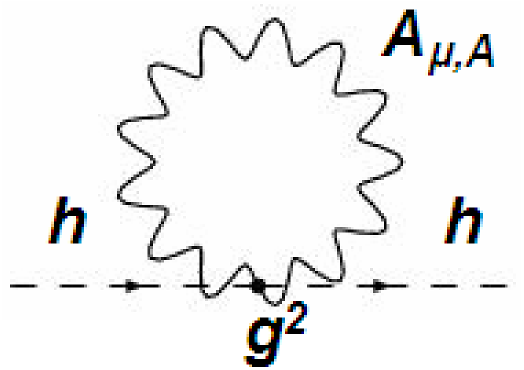
The SM and its twin counterpart are related by a discrete Z_2 "twin" symmetry.

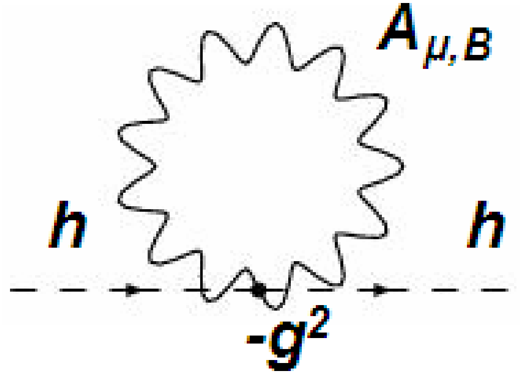
$$\mathrm{SM}_A \xleftrightarrow{\;Z_2\;} \mathrm{SM}_B$$

The mirror particles are completely neutral under the SM strong, weak and electromagnetic forces. Only feel gravity.

The Higgs emerges as the pseudo-Goldstone boson of an approximate global symmetry. Its mass is protected against one loop radiative corrections by a combination of the global symmetry and the discrete Z_2 twin symmetry.

In Mirror Twin Higgs models, the one loop quadratic divergences that contribute to the Higgs mass are cancelled by twin sector states that carry no charge under the SM gauge groups.





Discovery of these mirror states at LHC is therefore difficult.

A possible explanation of the null LHC results.

Twin Higgs models stabilize the hierarchy up to the precision electroweak scale, 5-10 TeV. Above this scale a UV completion, such as supersymmetry or composite Higgs, is required.

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

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

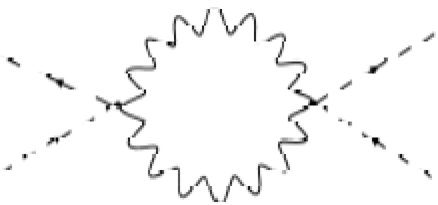
Impose a Z_2 `twin' symmetry under which A ⇔ B, so that $g_A = g_B = g$.
Then the radiative corrections take the form,

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

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.

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

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

If the global symmetry is broken by strong dynamics, as in composite Higgs,

$\Lambda \sim 4\pi f$ so that $m_h^2 \sim \left(\frac{g^2}{16\pi^2}\right)^2 \Lambda^2$

Then for Λ of order 5 TeV, the Higgs mass is naturally of order the weak scale.

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.

We would like to create a (mild) hierarchy between f and the electroweak VEV that would allow the pseudo-Goldstone to have the couplings similar to a SM Higgs, and accommodate a higher compositeness scale, $\Lambda \sim 4\pi f$.

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

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

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, of order 1 part in 4 for 500 GeV top partners.

Hard breaking of the twin symmetry would allow even lower tuning.

Mirror Twin Higgs

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

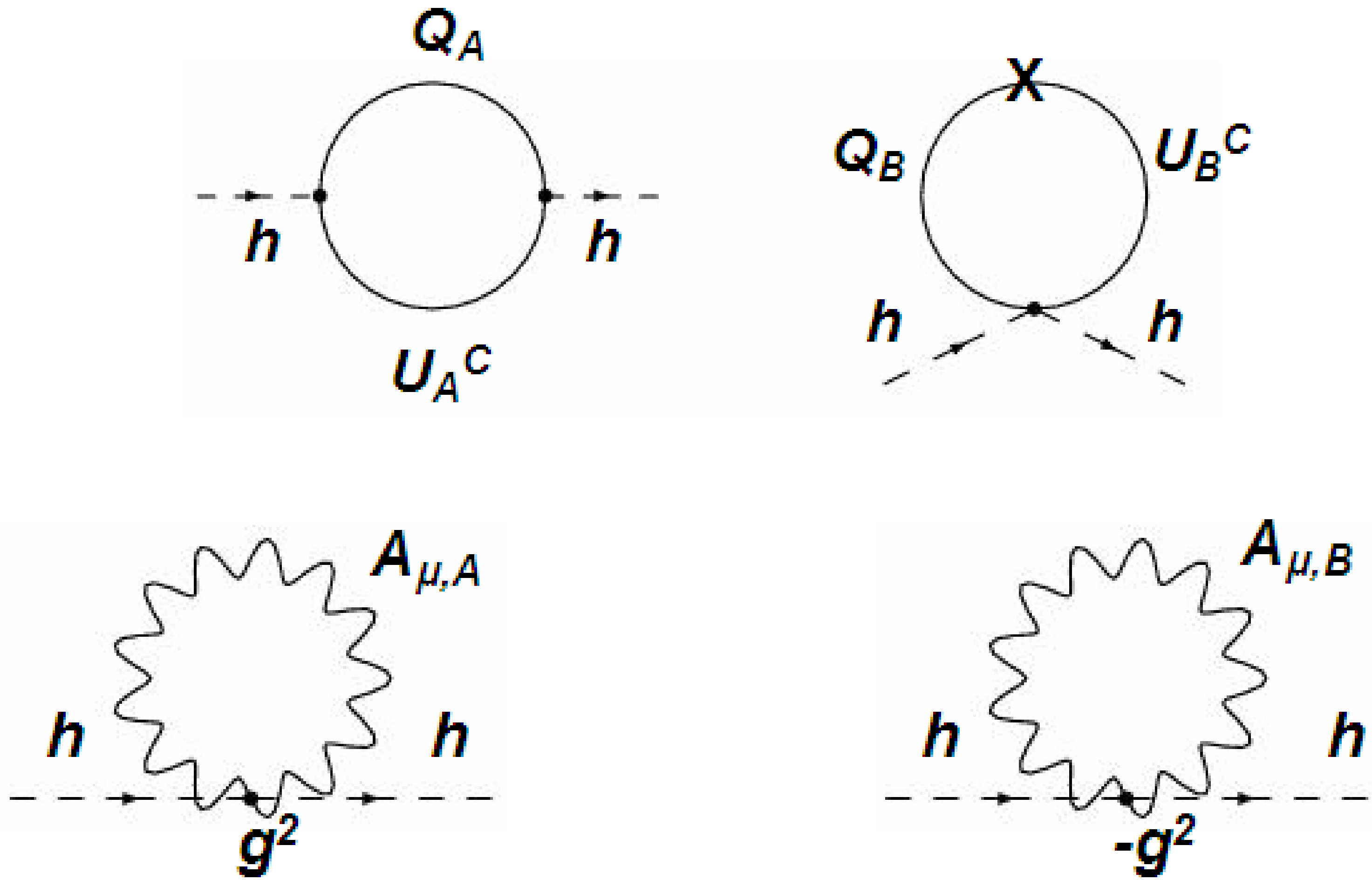
Mirror Symmetric Twin Higgs Models

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

The couplings of the fermions and gauge bosons respect only the discrete Z_2 A ←→ B twin interchange symmetry, not the larger global symmetry!

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

The mirror particles are responsible for cancelling the Higgs self-energy.



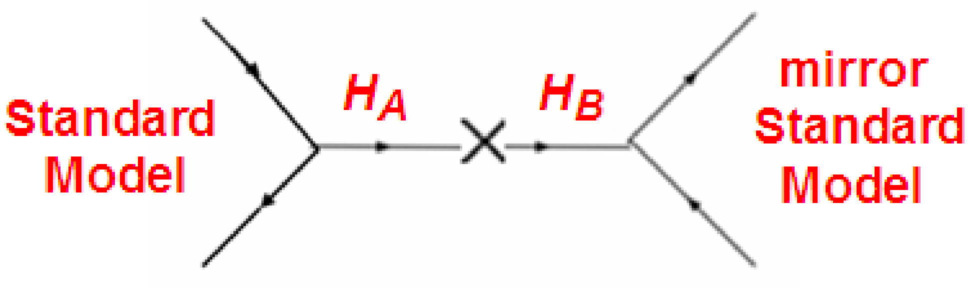
The mirror particles are completely neutral under the standard model strong, weak and electromagnetic forces. Challenging for the LHC.

The SM and twin SM primarily interact through the Higgs portal.

$$|H_A|^2 |H_B|^2$$

This interaction is needed for cancellation of quadratic divergences.

After electroweak symmetry breaking, SM Higgs and twin Higgs mix.



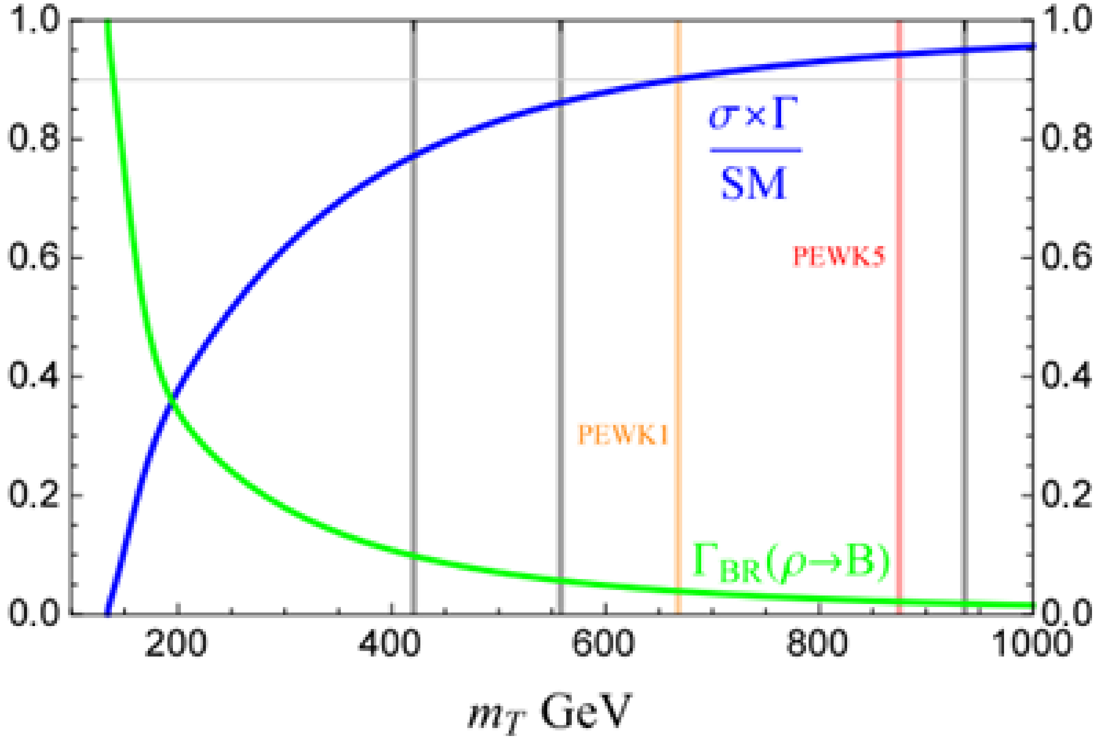
- Higgs couplings to SM states are suppressed by the mixing.
- The mixing allows the Higgs to decay invisibly to twin states.

Both effects lead to a reduction in the number of observed Higgs events.

Invisible decays of the Higgs can also be independently searched for.

At present, the Higgs visible event rate is known to be within 20% of the Standard Model prediction. Mirror Top must be heavier than about 500 GeV.

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



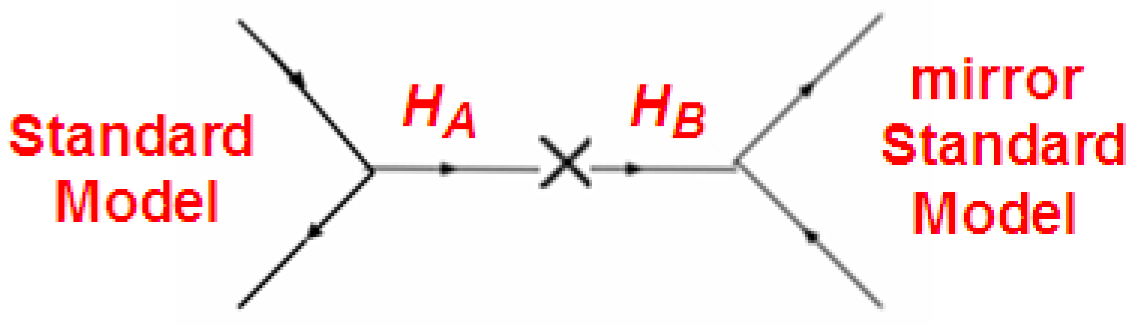
Expected to improve only to about 5 -10%.

The LHC may not be able to conclusively disfavor naturalness!

A lepton collider (`Higgs Factory') would decisively test this theory.

The Higgs portal interaction has implications for cosmology.

Interactions mediated by the Higgs keep the SM and twin sectors in thermal equilibrium until temperatures of order a few GeV.



Then the twin photon and twin neutrinos contribute significantly to the energy density in radiation at the time of BBN and CMB.

Leads to a contribution to effective number of neutrinos $\Delta N_{\rm eff} = 5.7$.

The 2σ bound from CMB on dark radiation is given by $\Delta N_{\rm eff} \lesssim 0.5$.

The simplest Mirror Twin Higgs model is excluded!

Two distinct approaches to this problem have been proposed.

- Introduce hard breaking of Z_2 to alter the decoupling temperature and the number of degrees of freedom in the twin sector at a given temperature.

  Farina; Barbieri, Hall & Harigaya; Csaki, Kuflik & Lombardo

- **Introduce new dynamics that preferentially heats up the SM sector** after the two sectors have decoupled. May not require further Z_2 breaking.

  ZC, Craig, Fox & Harnik; Craig, Koren & Trott

Focus on the second approach, and assume no further breaking of Z_2.

Then the light degrees of freedom at CMB include the twin photon plus the 3 twin neutrinos. In general, $\Delta N_{\rm eff}$ is a free parameter.

If there is a baryon asymmetry in the mirror sector, the bath will also contain twin baryons and electrons.

This scenario leads to characteristic cosmological signals.

ZC, Curtin, Geller & Tsai

- Twin photons and twin neutrinos constitute distinct forms of dark radiation that have different effects on the CMB, and can be distinguished.
    - The twin neutrinos free stream, suppressing inhomegeneities.
    - The twin photons scatter of dark baryons. Do not free stream till late.

Fraction of dark radiation that free streams is fixed by the model. A prediction!

- The twin baryons constitute an acoustic subcomponent of dark matter. Baryon acoustic oscillations in the twin sector lead to a characteristic suppression of large scale structure.

The Twin Higgs only stabilizes the hierarchy up to scales of order 5-10 TeV. Above this, some form of UV completion is needed.

Supersymmetric UV Completions

Chang, Hall & Weiner
Falkowki, Pokorski & Schmaltz
Craig & Howe
Katz, Mariotti, Pokorski, Redigolo & Ziegler
Badziak & Harigaya

The twin partner of the SM Higgs may be accessible at the LHC.

Composite Twin Higgs Models

Geller & Telem
Barbieri, Greco, Rattazzi & Wulzer
Low, Tesi & Wang

These theories predict additional states with mixed SM and twin gauge quantum numbers that may be accessible to the LHC.

Cheng, Jung, Salvioni & Tsai
Cheng, Salvioni & Tsai

Fraternal Twin Higgs

In Fraternal Twin Higgs models, the only light states present in the theory below 5 TeV are those essential for naturalness or consistency (anomaly cancellation).

Craig, Katz, Strassler & Sundrum

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

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

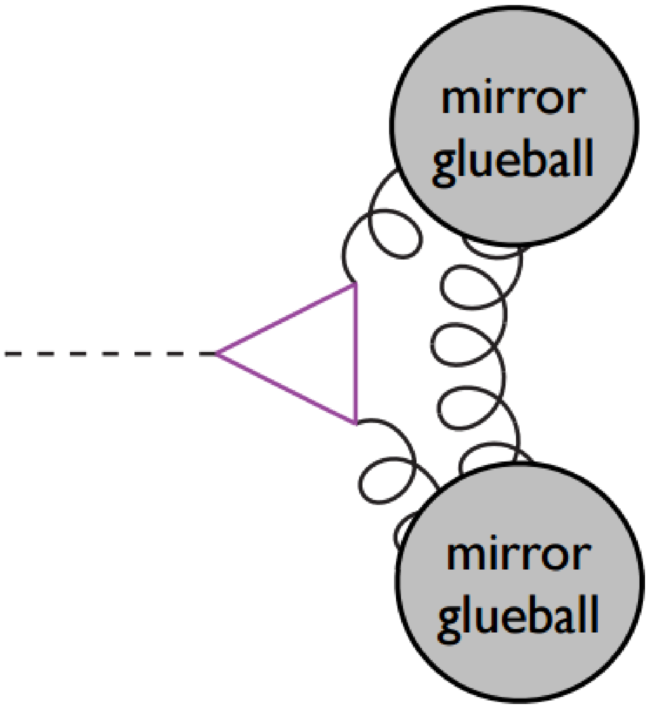
The Fraternal Twin Higgs is free of any cosmological problems associated with $\Delta N_{\rm eff}$.

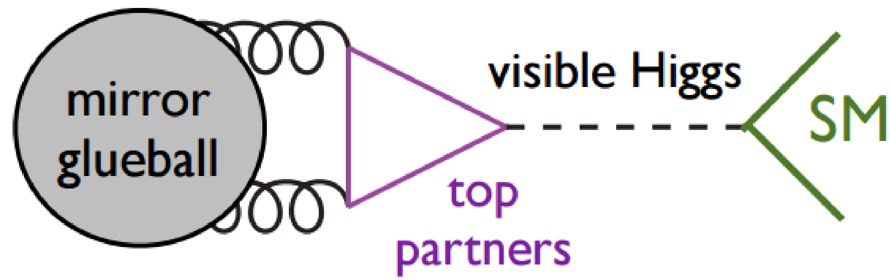
This framework admits several promising dark matter candidates.

Craig & Katz
Garcia Garcia, Lasenby & March-Russell
Freytsis, Knapen, Robinson & Tsai

Exotic Higgs decays are a characteristic signal of the Fraternal Twin Higgs.

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



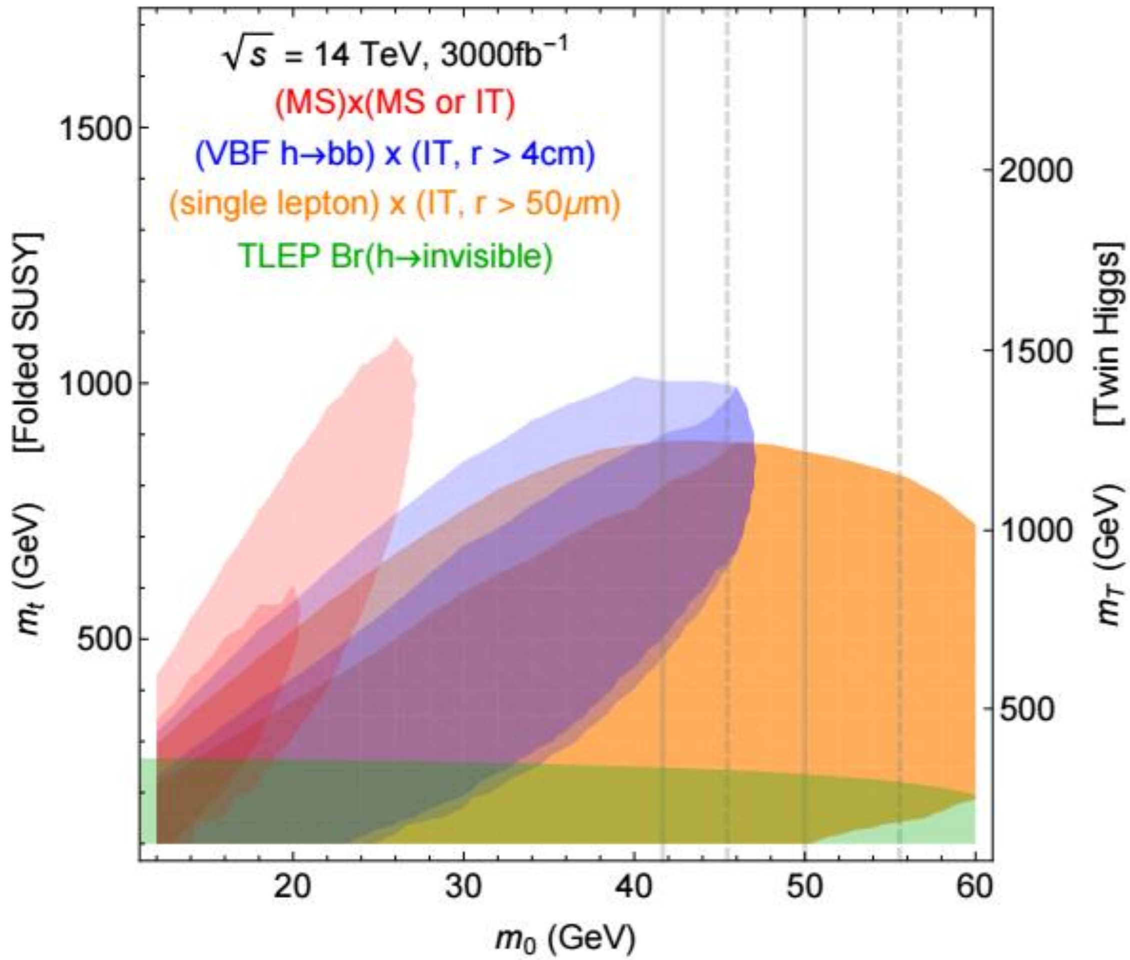


Juknevich

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

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

Conclusions

The Mirror Twin Higgs is the first known example of a theory in which the top loop is canceled by uncolored top partners.

In its original incarnation, the theory predicts an entire light mirror SM at low energies. This mirror world is invisible to us because nothing transforms under the SM gauge groups!

The direct detection of the mirror states at the LHC is very challenging, perhaps even impossible.

However, the Higgs and twin Higgs mix, leading to a suppression of Higgs events. This can be used to set limits on naturalness (currently 25%, and eventually improving to 5 -10%). In this scenario the LHC will only be able to mildly disfavor naturalness.

In fraternal realizations of the Twin Higgs, the low energy spectrum contains (only) the states necessary for naturalness. Lightest twin hadrons can be glueballs, leading to exotic signals involving displaced vertices.

UV completions based on supersymmetry and composite Higgs have been realized. Involve additional states that may be accessible to experiment.