# Twin Higgs & Its Cousins

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MC4BSM 2015

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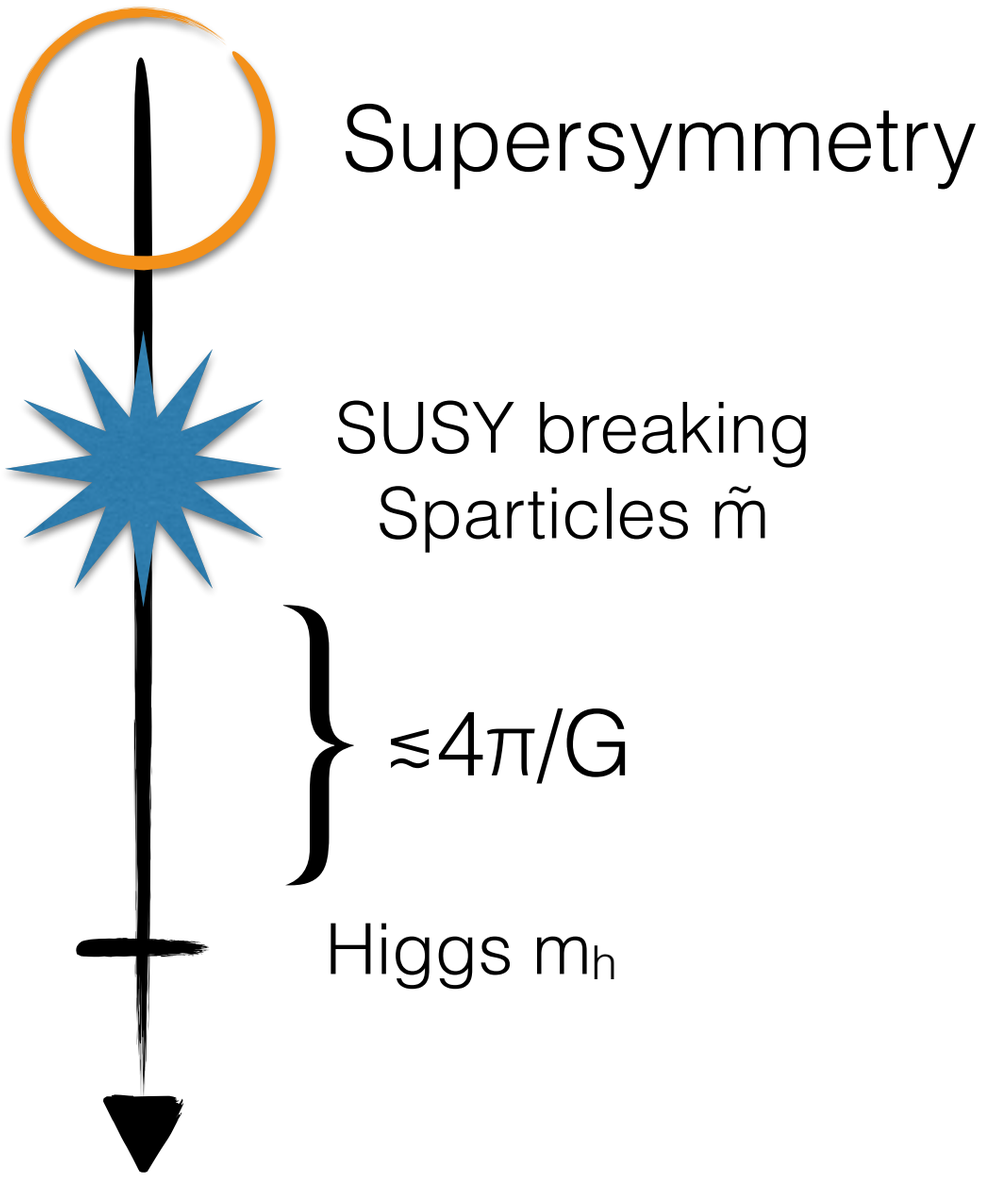
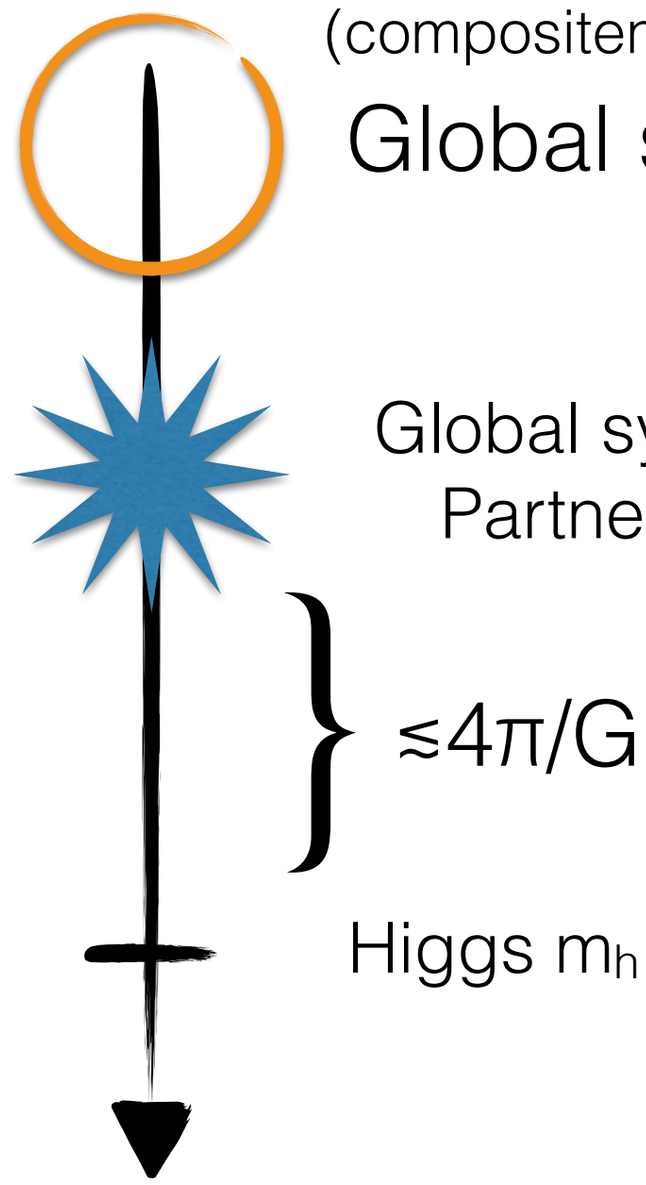
- At the very least, as far as we know a theory of quantum gravity should give physical thresholds around the string scale.
- An apparently elementary Higgs makes the hierarchy problem as pressing as ever!

# Hierarchy Solutions



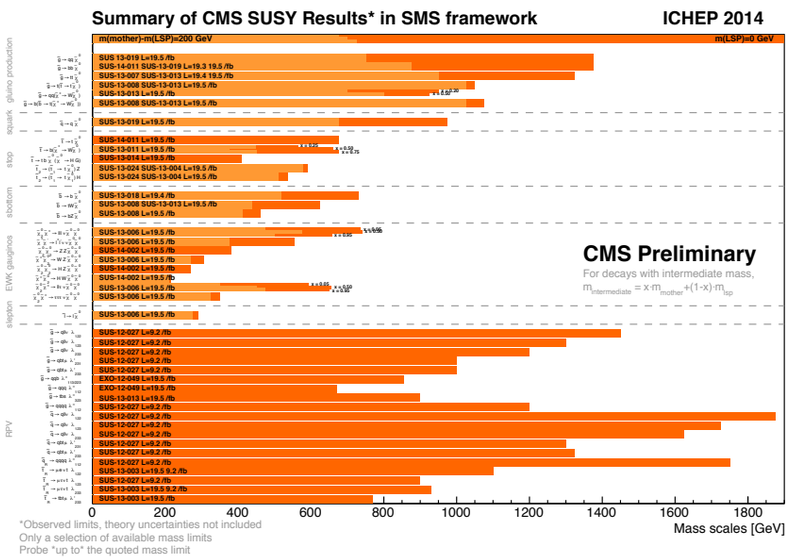



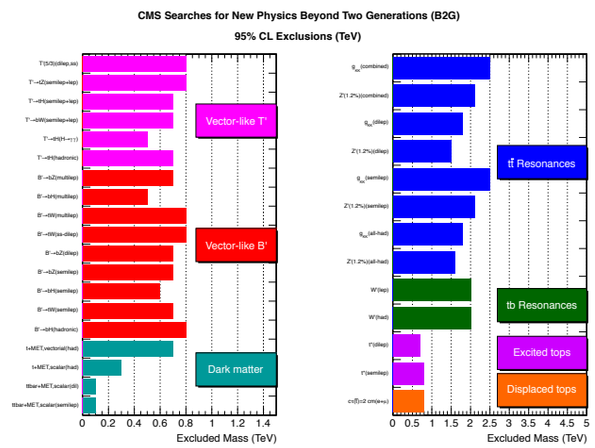

Continuous symmetries → partner states w/ SM quantum #s

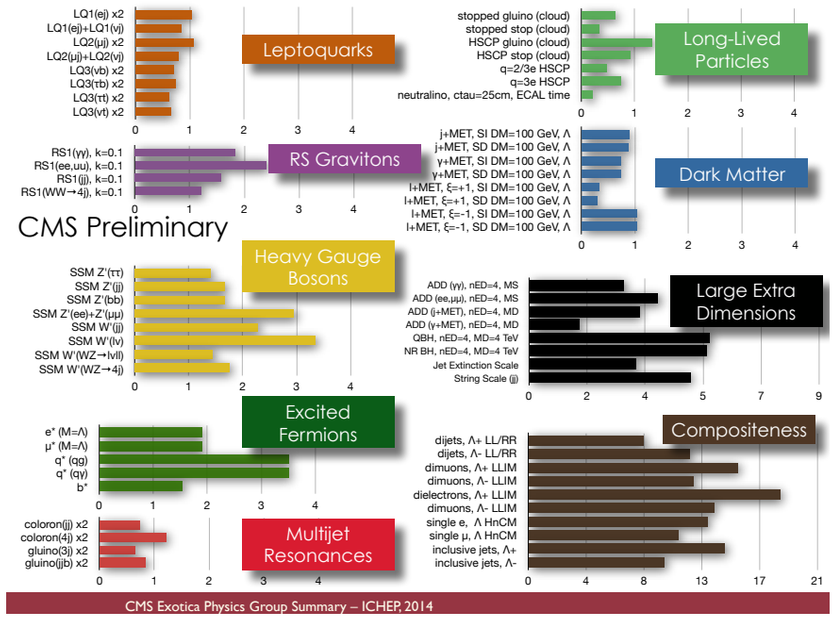
$$m_h^2 \sim \frac{3y_t^2}{4\pi^2}\tilde{m}^2 \log(\Lambda^2/\tilde{m}^2)$$

Totally natural: $\tilde{m} \lesssim 200\,\mathrm{GeV}$

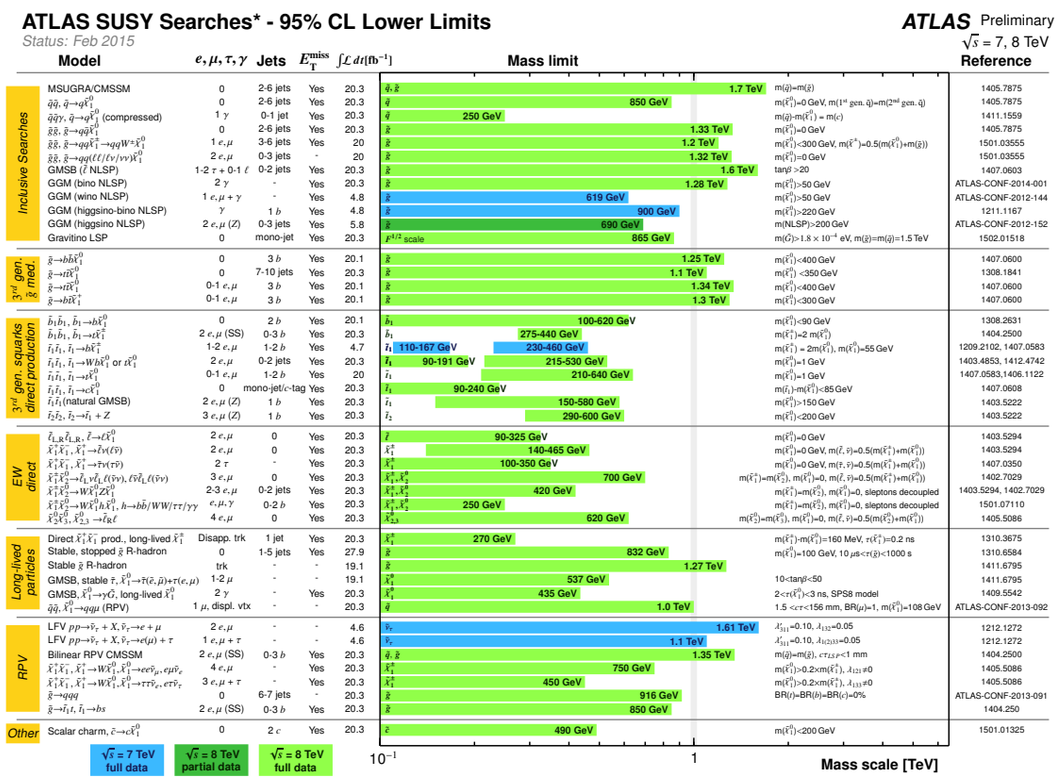
# A physics driver

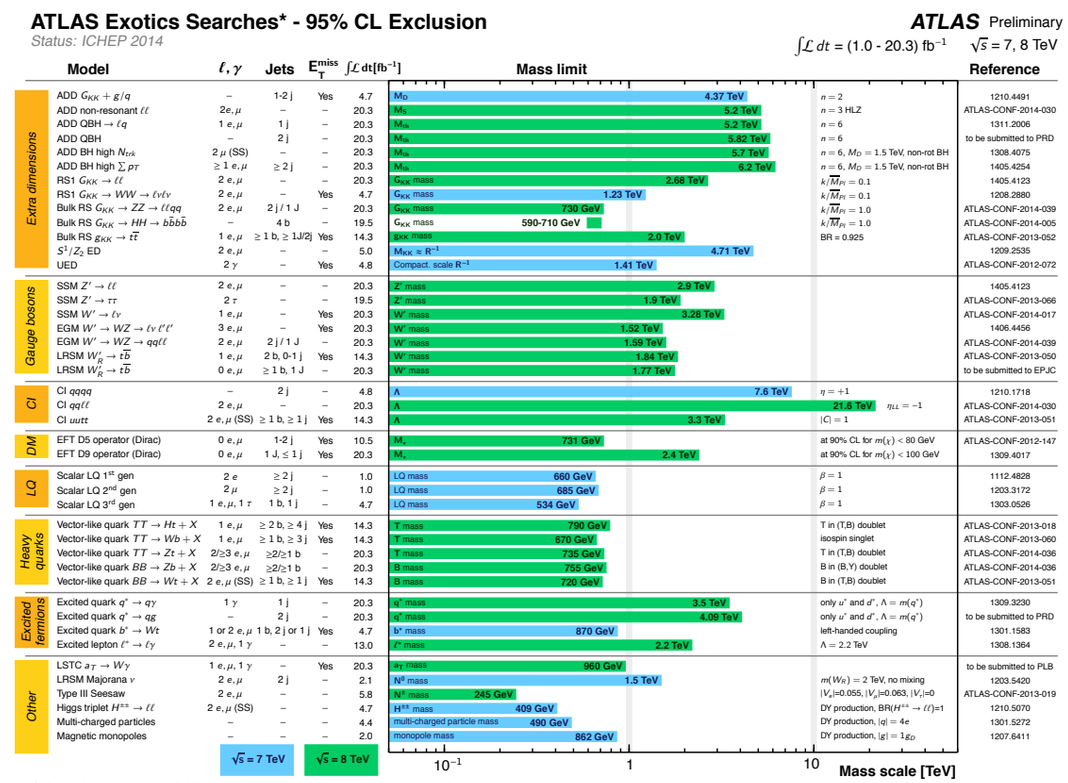



# 170 of these 226 channels tied to naturalness



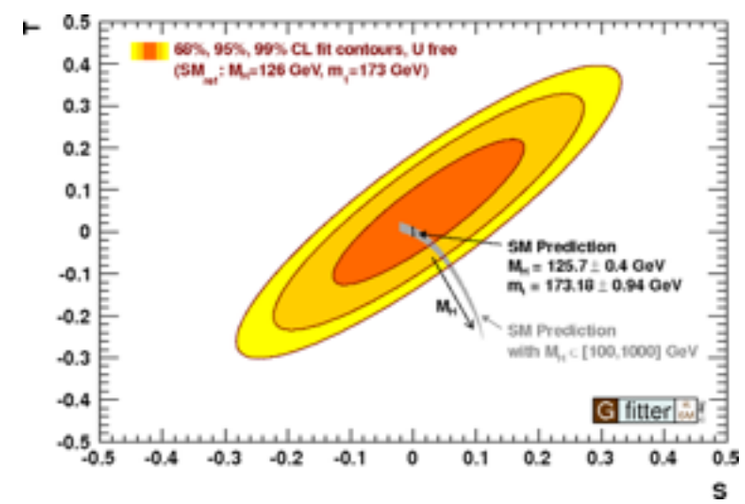



# Testing naturalness

Practically speaking, we only have experimental access to physics up to ~5-10 TeV (modulo flavor).

- Precision Electroweak: SM-like electroweak sector up to ~5 TeV.

- LHC reach: No s-channel heavy resonances below ~3 TeV.



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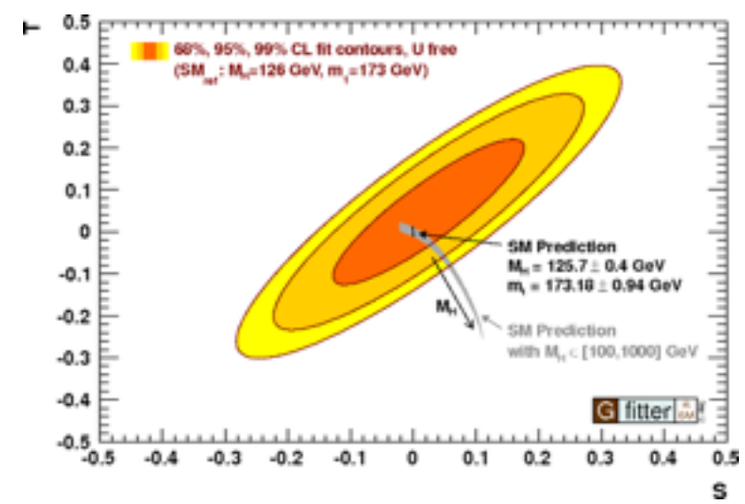

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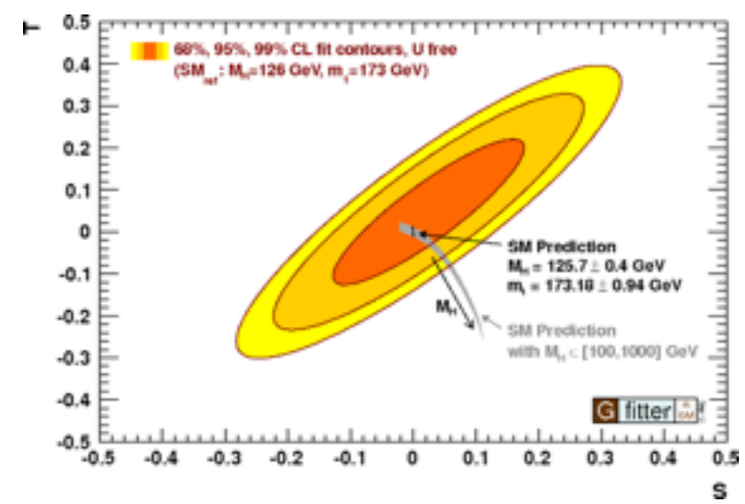

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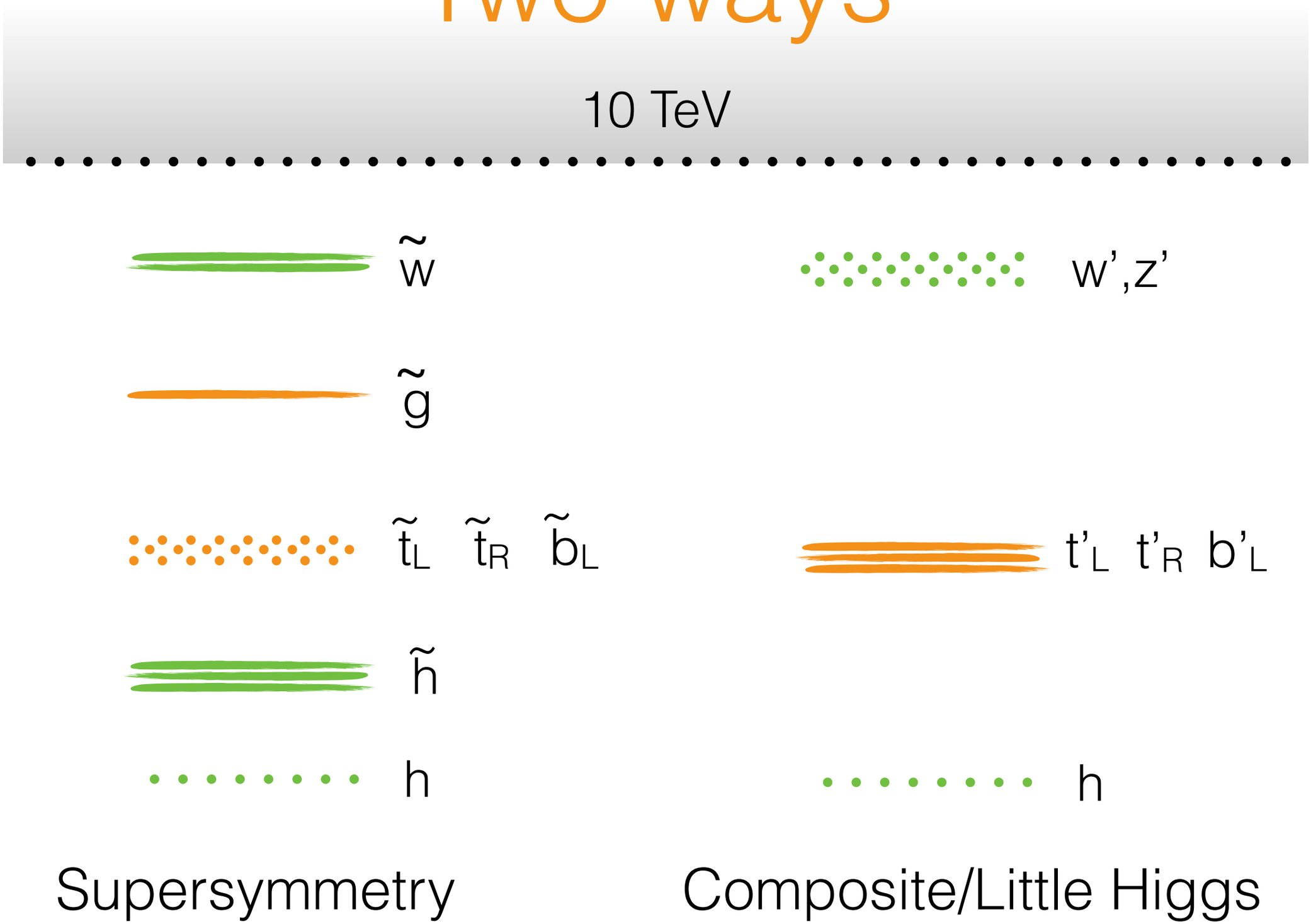
Conservative philosophy: Identify minimal extension for weak scale to be natural up to cutoff at 5-10 TeV.

# Two ways

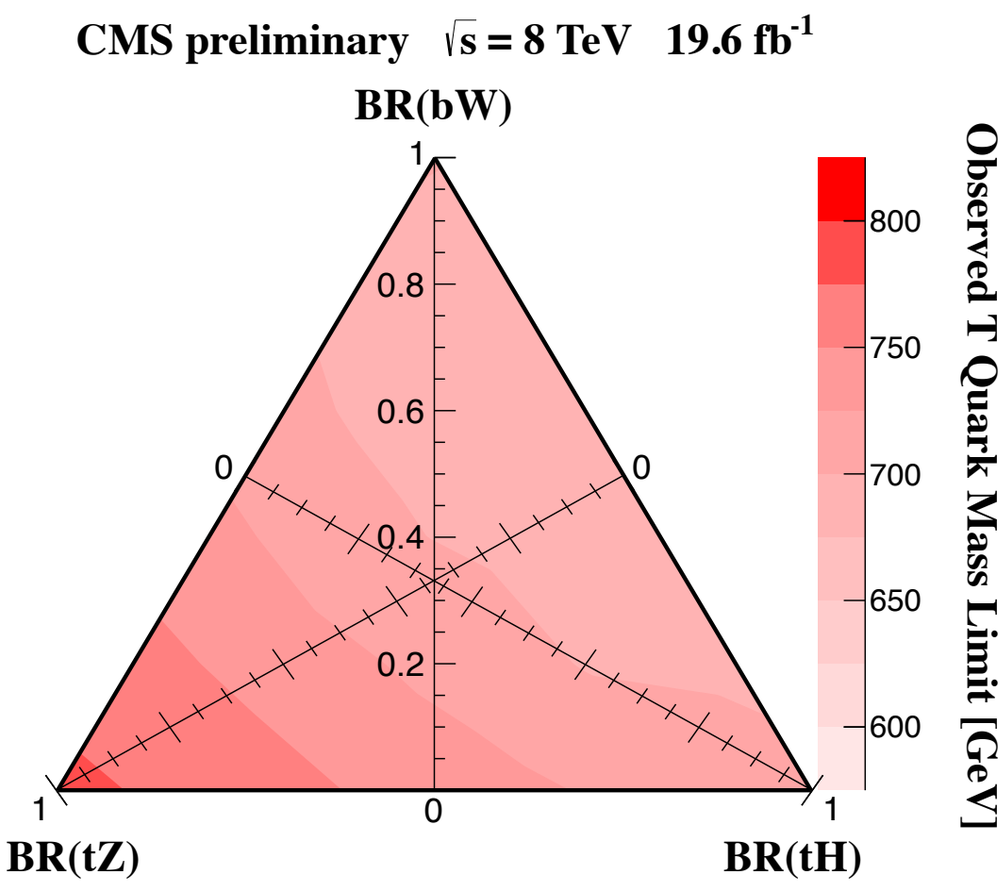



*Simple game for LHC: look for colored partners.*

# Missing top partner problem

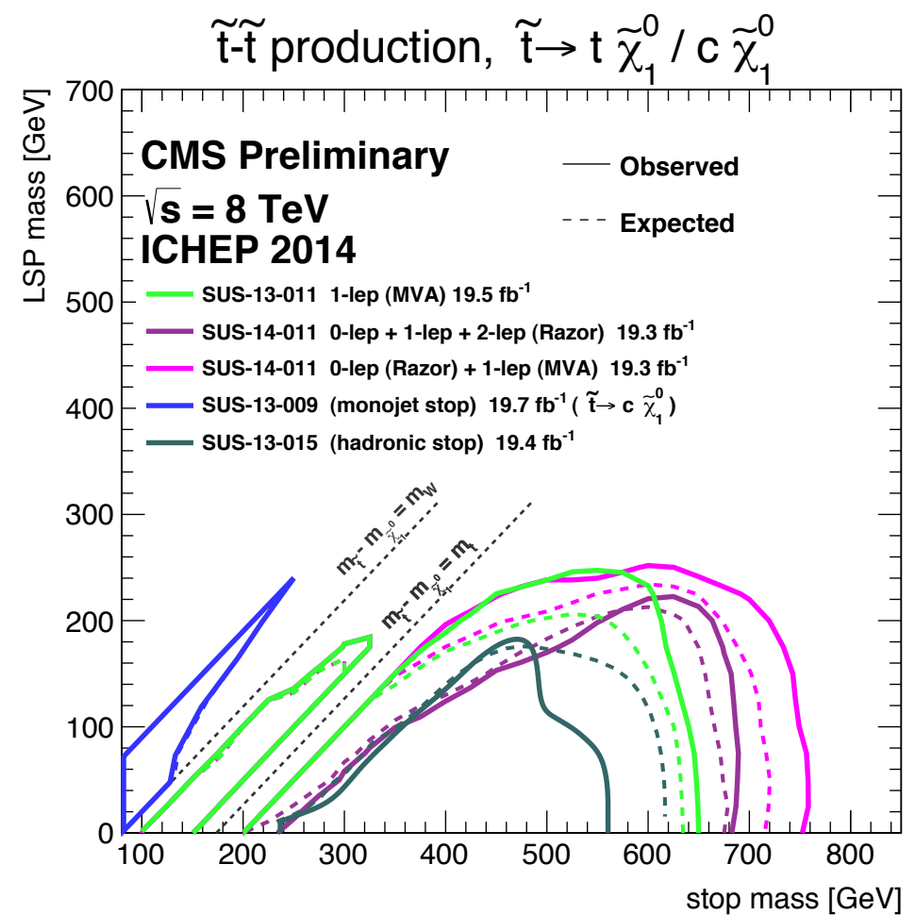
LHC searches driven by top partners

## Global Symmetry




CMS B2G-12-015

## Supersymmetry




Problem 1: nothing yet.

Problem 2: not much new to do.

# But: is this all there is?

*Maybe we've spent too much time under our favorite lamp-posts.*

(Even if you do not find naturalness compelling, its role as a signature/search generator begs for further exploration)

# What about...

**The Twin Higgs**

[Z. Chacko, H.-S. Goh, R. Harnik '05]

electroweak constraints are satisfied by construction. These models demonstrate that, contrary to the conventional wisdom, stabilizing the weak scale does not require new light particles charged under the Standard Model gauge groups.

Symmetry is $SM_A \times SM_B \times Z_2$

# The Twin Higgs

Consider a scalar H transforming as a fundamental under a global SU(4):

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

Potential leads to spontaneous symmetry breaking,

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

$SU(4) \to SU(3)$ yields seven goldstone bosons.



UV: $\lambda \gg 1$ NLSM; $\lambda \lesssim 1$ LSM

# The Twin Higgs

Now gauge $SU(2)_A \times SU(2)_B \subset SU(4)$, w/ $H = \begin{pmatrix} H_A \\ H_B \end{pmatrix}$

Us Twins

Then 6 goldstones are eaten, leaving one behind.

Explicitly breaks the SU(4); expect radiative corrections.

$$V(H) \supset \frac{9}{64\pi^2}\left(g_A^2\Lambda^2|H_A|^2 + g_B^2\Lambda^2|H_B|^2\right)$$

But these become SU(4) symmetric if $g_A = g_B$ from a $Z_2$

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Full theory: extend $Z_2$ to all SM matter and couplings.

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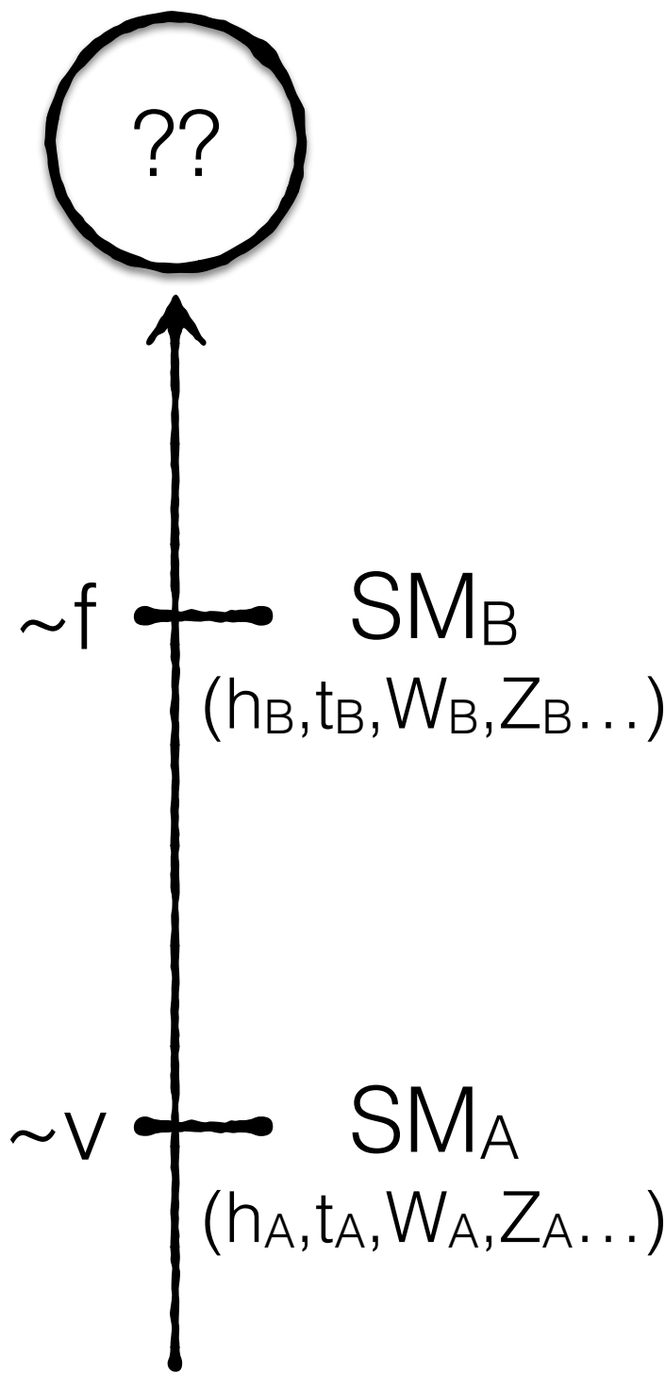

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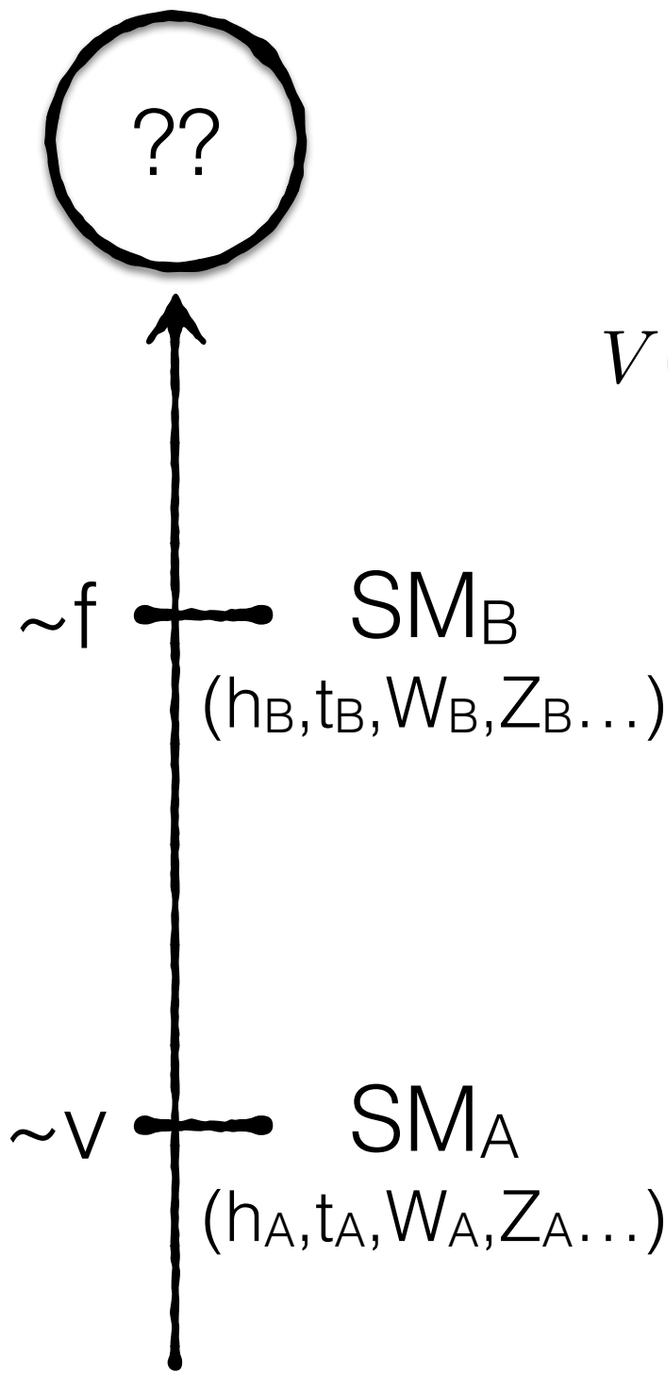


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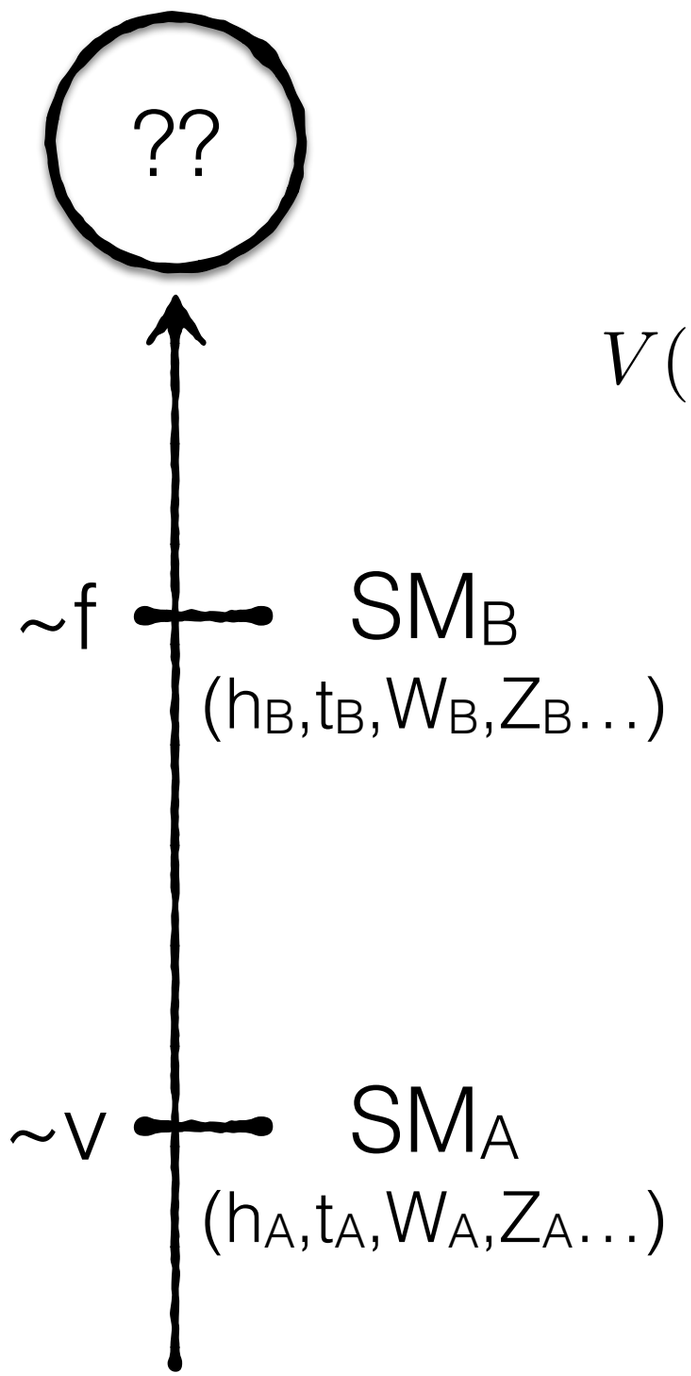


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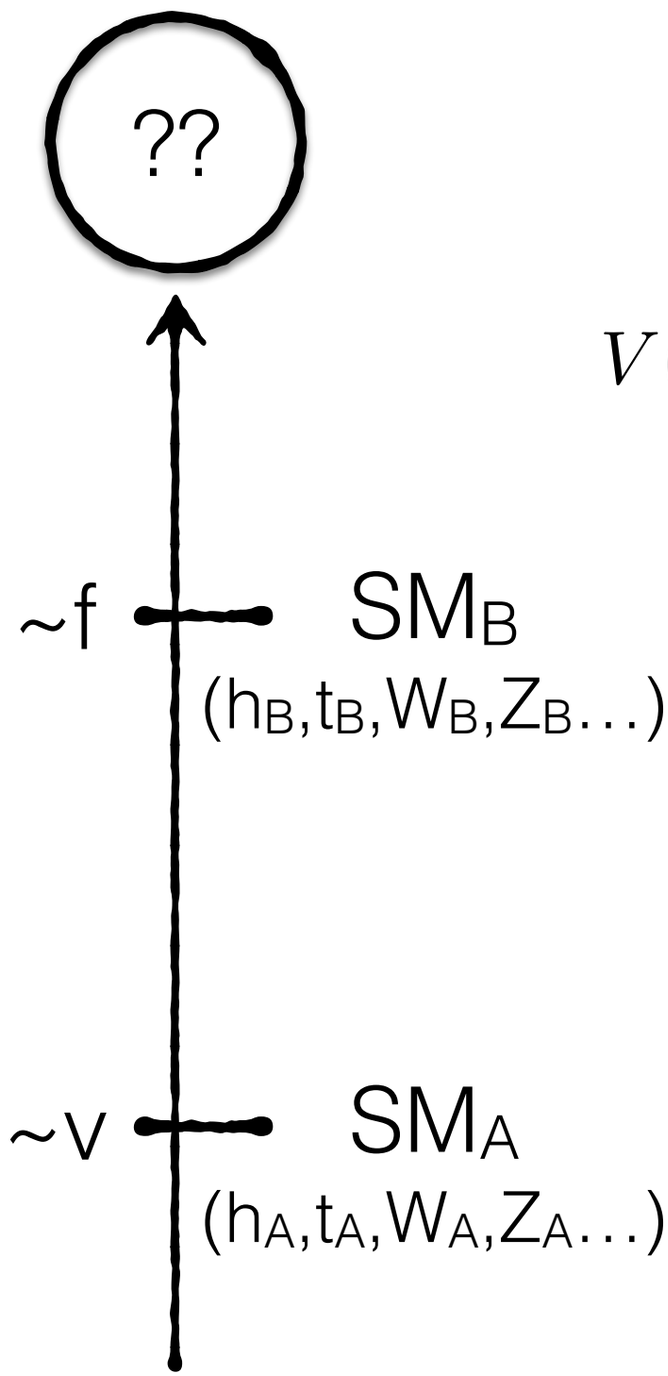


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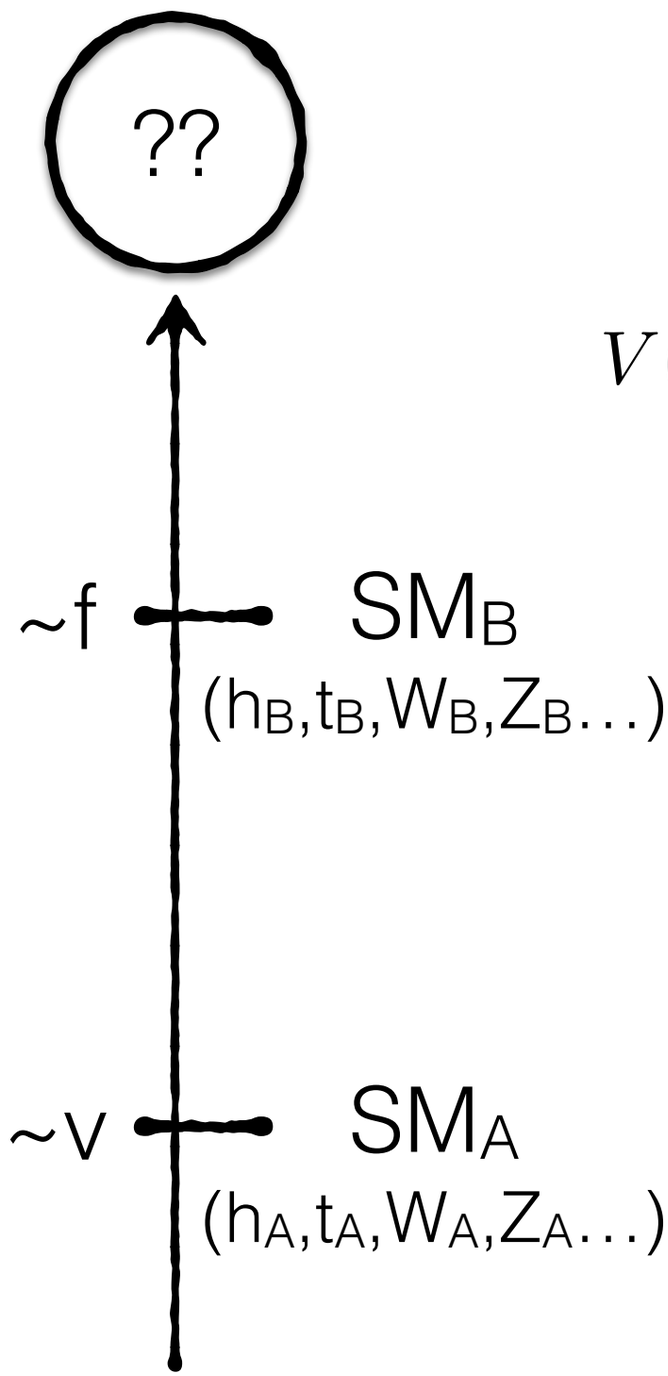


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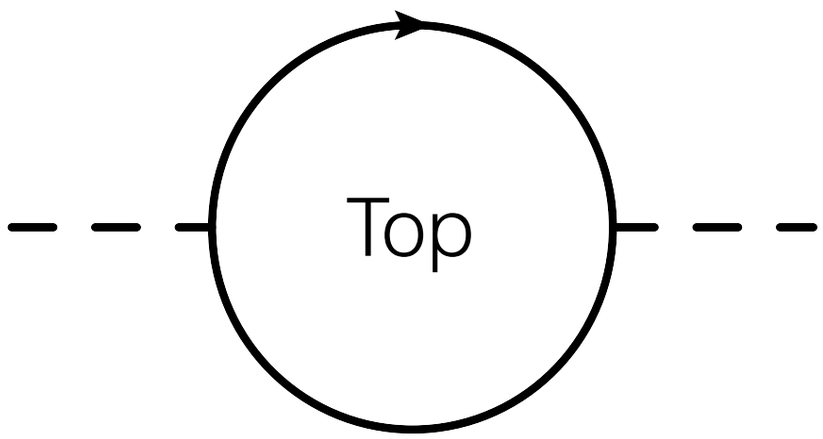
Primary coupling between $SM_A$ and
$SM_B$ is via Higgs portal

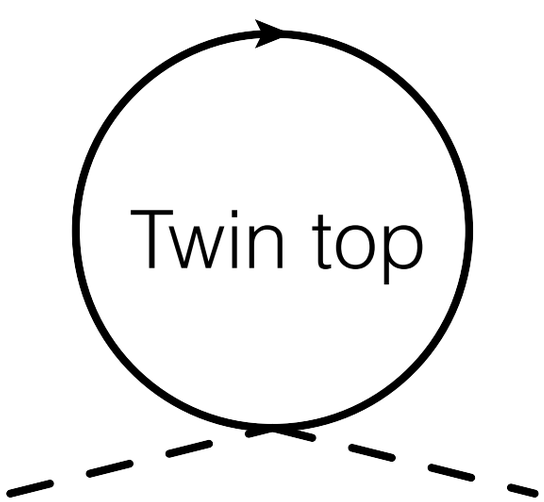
# The Twin Top




The top partner acts as expected from global symmetry protection, *but is not charged under QCD.*

$$\mathcal{L} \supset -y_t H_A Q_3^A \bar{u}_3^A - y_t H_B Q_3^B \bar{u}_3^B$$

$$h + \ldots \qquad\qquad f - \frac{h^2}{2f} + \ldots$$




No direct limit on top partner.

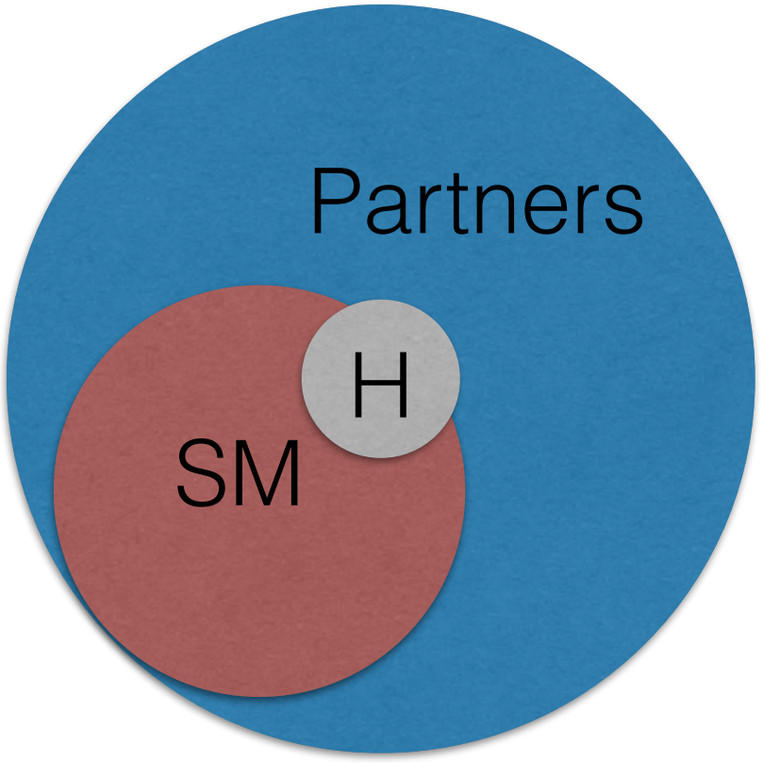
# Twin Higgs Slogan

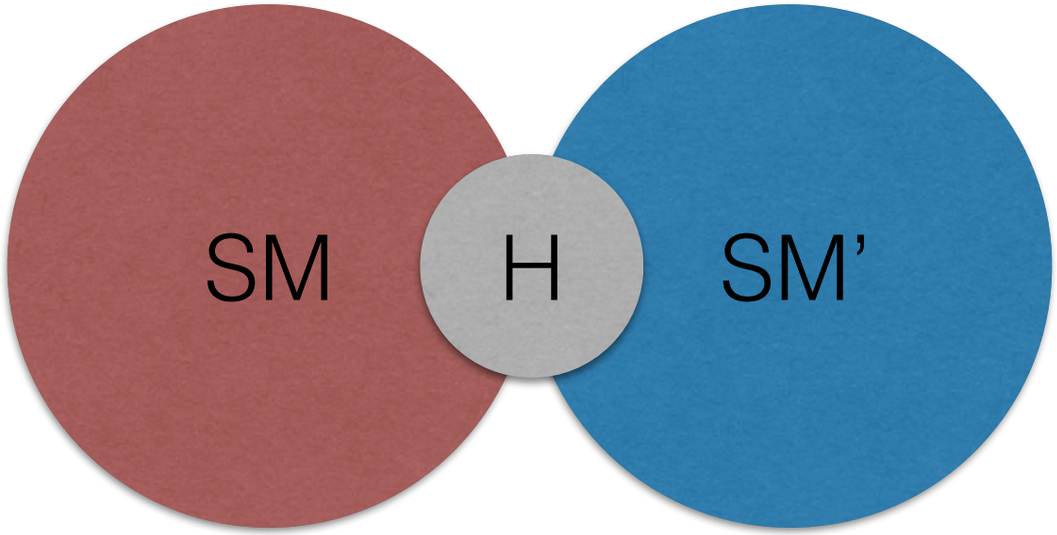
"Higgs is pseudo-goldstone of the accidental global symmetry of the quadratic action obeying a discrete symmetry"*

*plus a symmetric quartic.

# The big picture

Instead of protecting Higgs w/ continuous symmetry extending the SM, so partners have SM charges…




Protect Higgs w/ a hidden sector mirroring the SM. Partners have no SM charges.

# UV Physics

SUSY

~f — $SM_B$

~v — $SM_A$

## The SUSY Twin Higgs

*SUSY protects the linear sigma model*

[Chang, Hall, Weiner '06; NC, Howe '14]

$MSSM_A \times MSSM_B \times Z_2$

Quartic $\lambda$ can be ~1; there is a perturbative radial twin Higgs mode

## The Composite Twin Higgs

*Compositeness for nonlinear sigma model*

[Geller, Telem '14; Barbieri, Greco, Rattazzi, Wulzer '15; Low, Tesi, Wang '15]

No perturbative radial twin Higgs mode; only fermionic partner states are light

Strong

~f — $SM_B$

~v — $SM_A$

# The General Framework

"The twin Higgs is an example of ???"

NC, S. Knapen & P. Longhi [PRL 114, 061803 & 1411.7393/JHEP]

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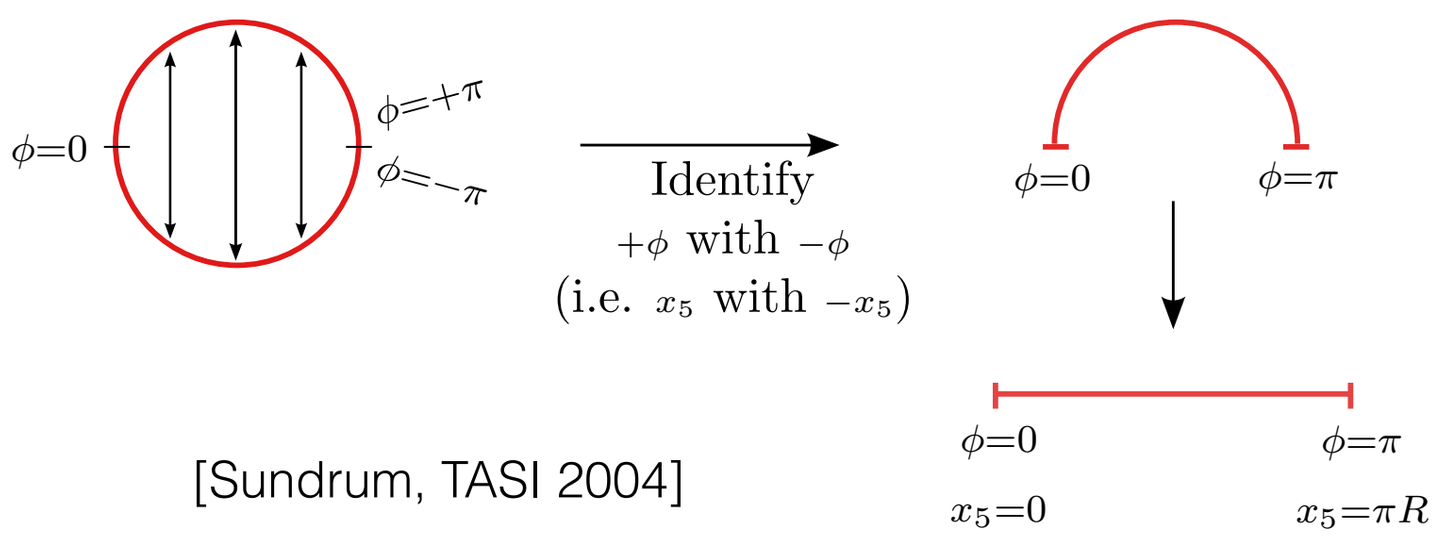


[Sundrum, TASI 2004]

Familiar tool in string theory & field theory (realistic string compactifications, orbifold GUTs, 5D SUSY theories, etc.)

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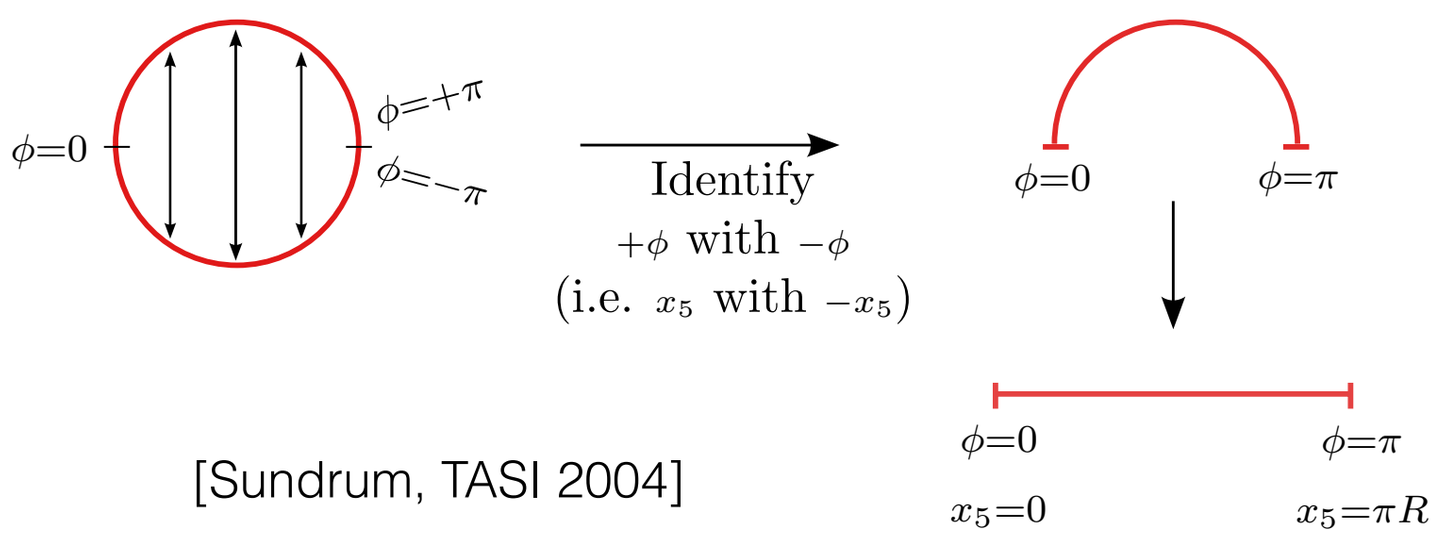


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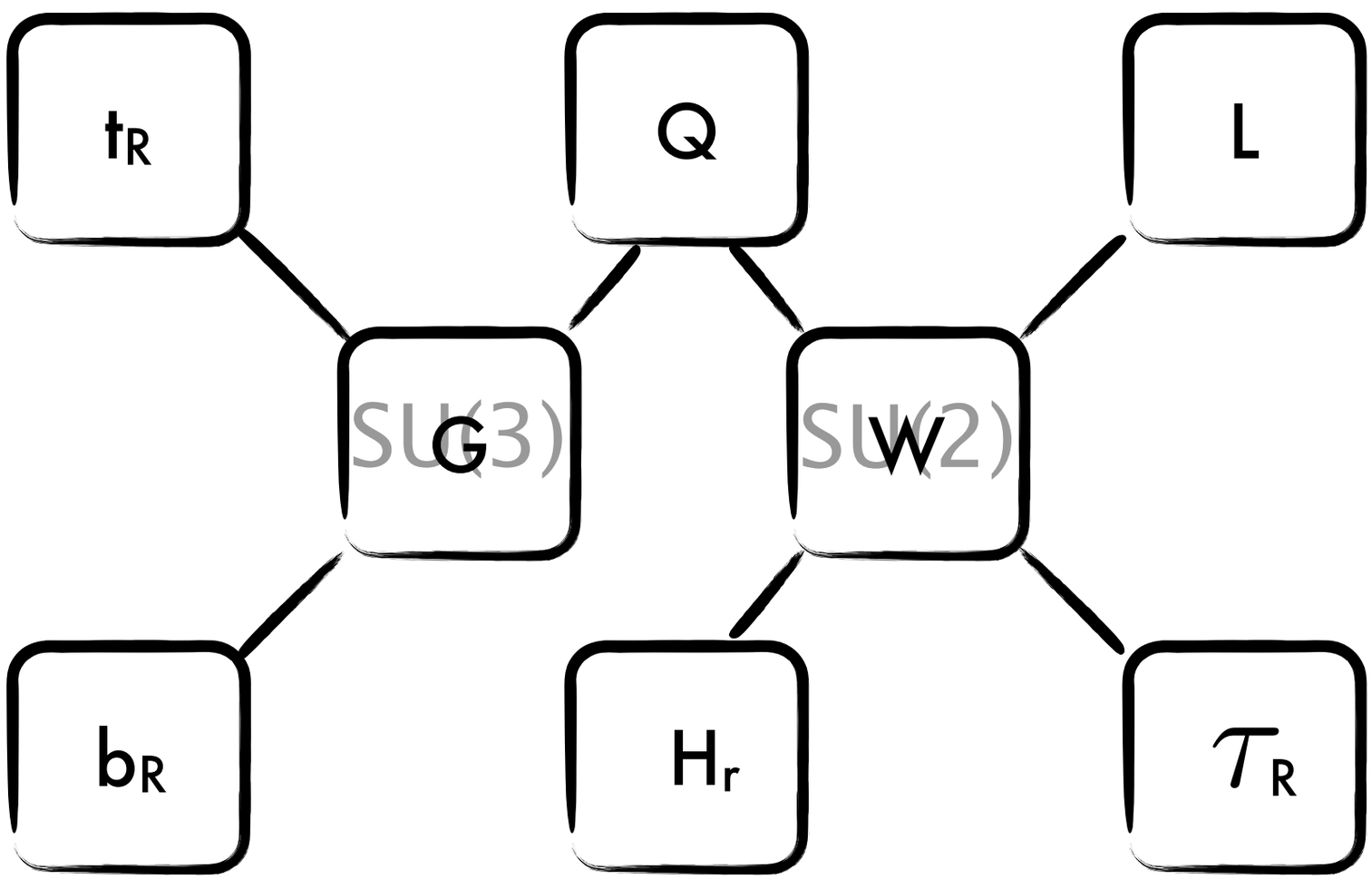
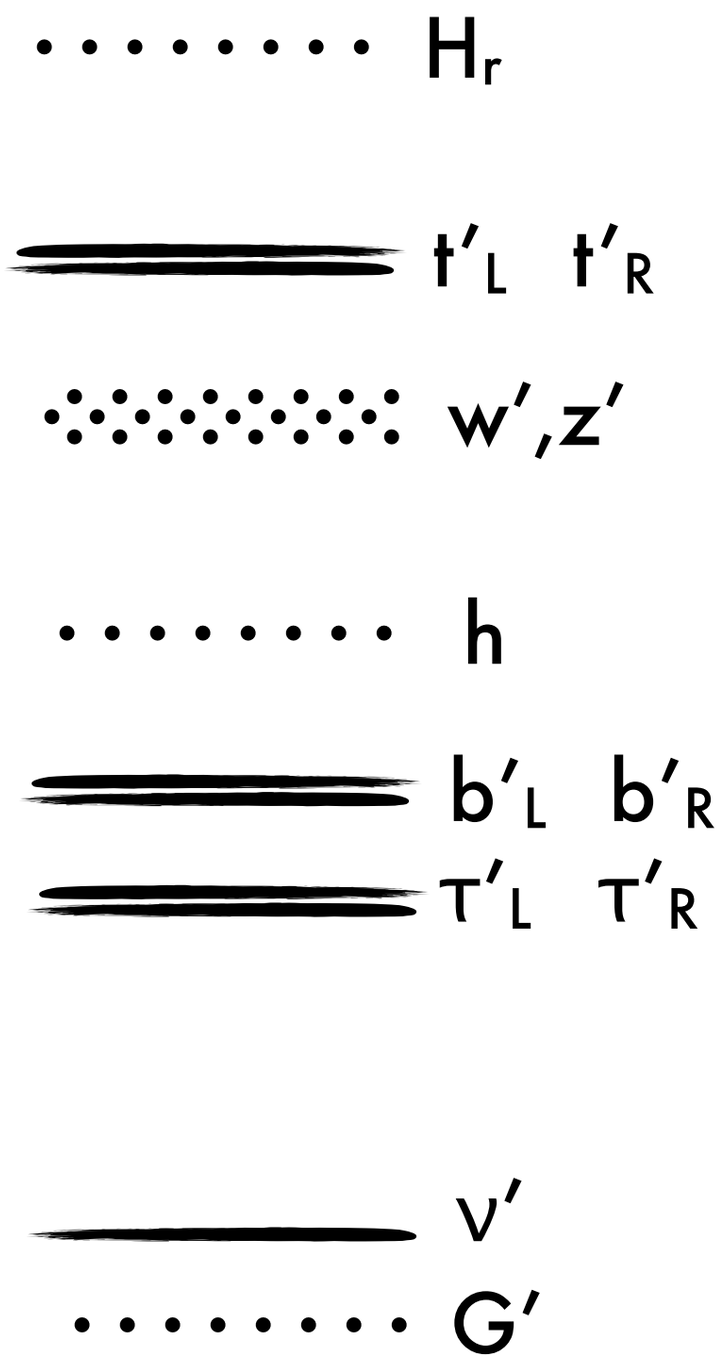
*Punchline: Many models of the twin kind, where Z2 or larger symmetries may be exact or approximate.*

# The minimal model

[NC, A. Katz, M. Strassler, & R. Sundrum '15]

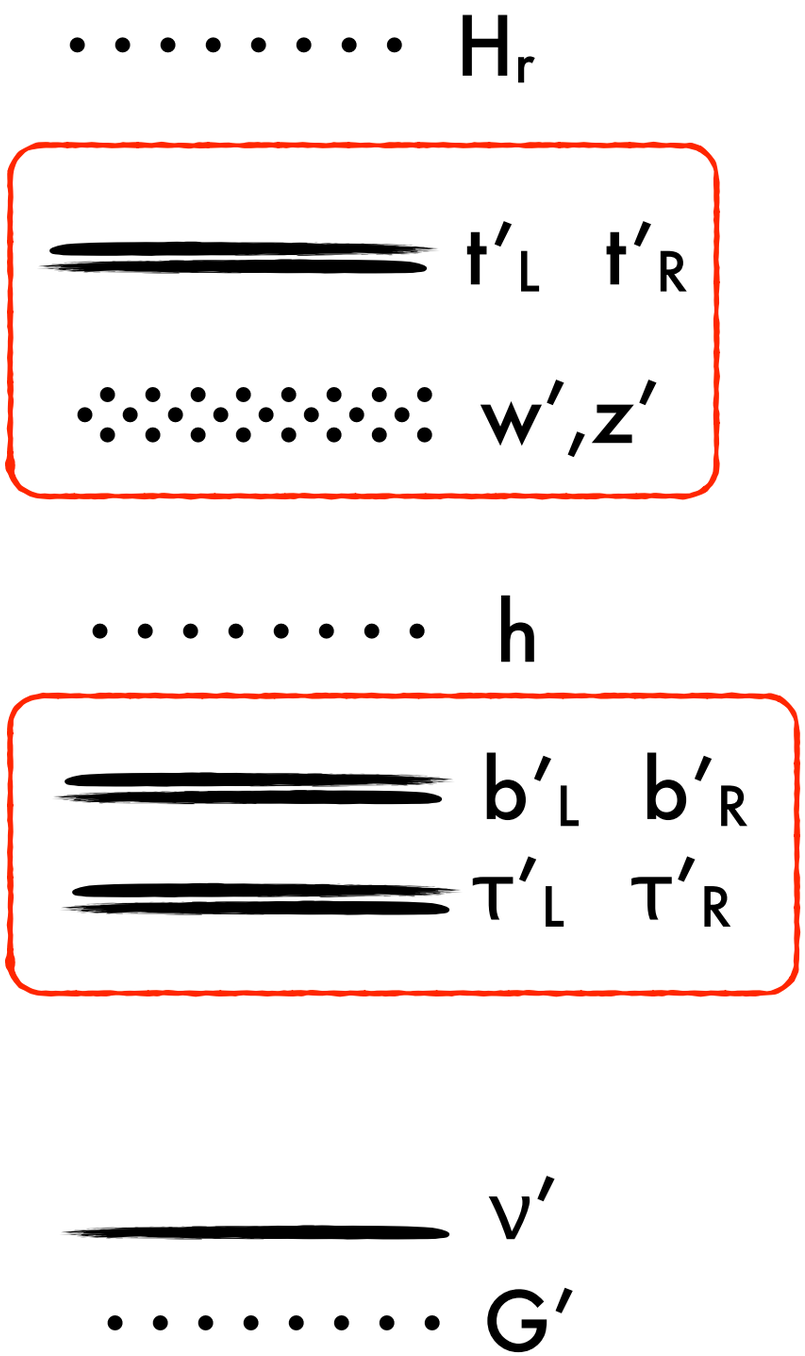
Just $Z_2$ partner states for the third generation.



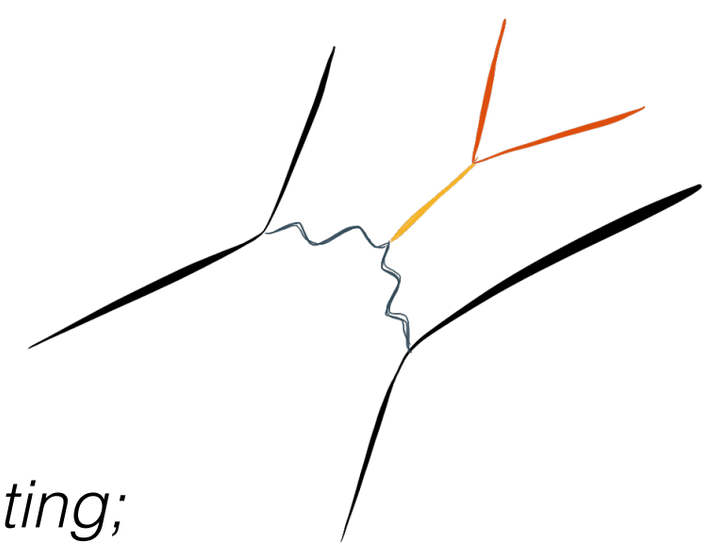
# What to look for?

[SM-like Higgs misaligned from *v* by an amount *v/f (usual story for a pNGB Higgs)*. Leads to O(*v/f*)$^2$ changes in Higgs couplings; current O(20%) precision not constraining.]




- Partner states are SM neutral, couple only to the Higgs. Lighter than $m_h/2$: modest invisible BR (or more).

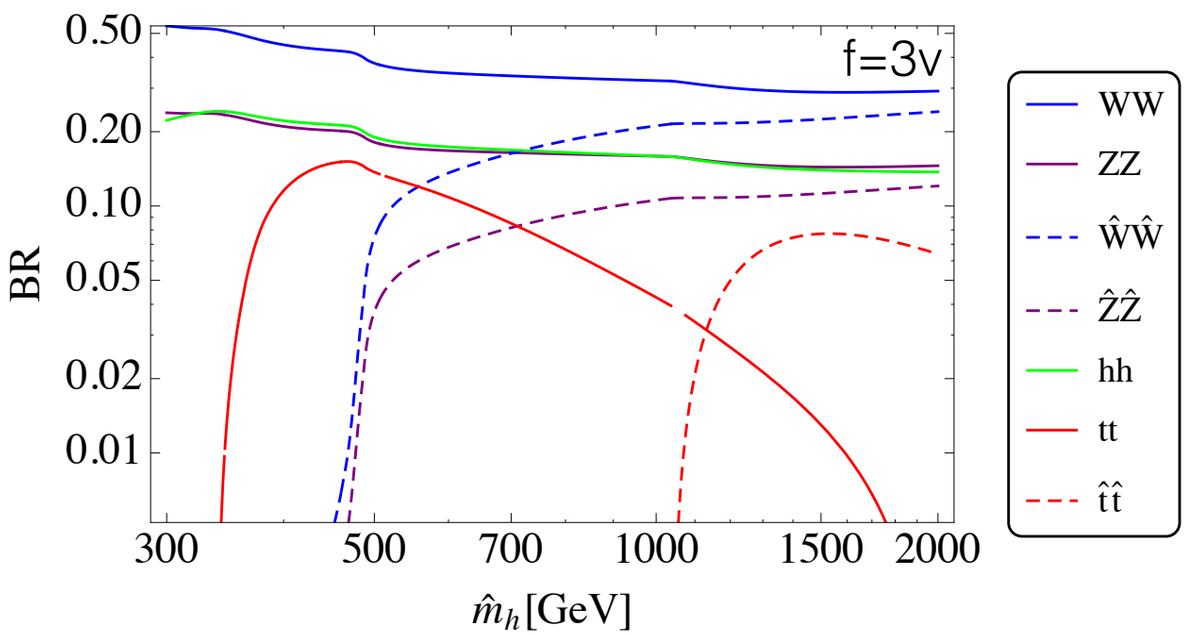
- Heavier than $m_h/2$: produce through an off-shell Higgs.

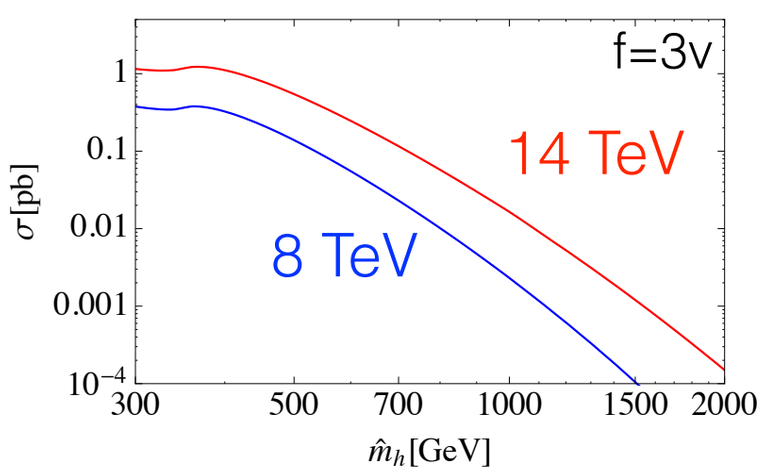


*Hard but very interesting; directly probe naturalness*

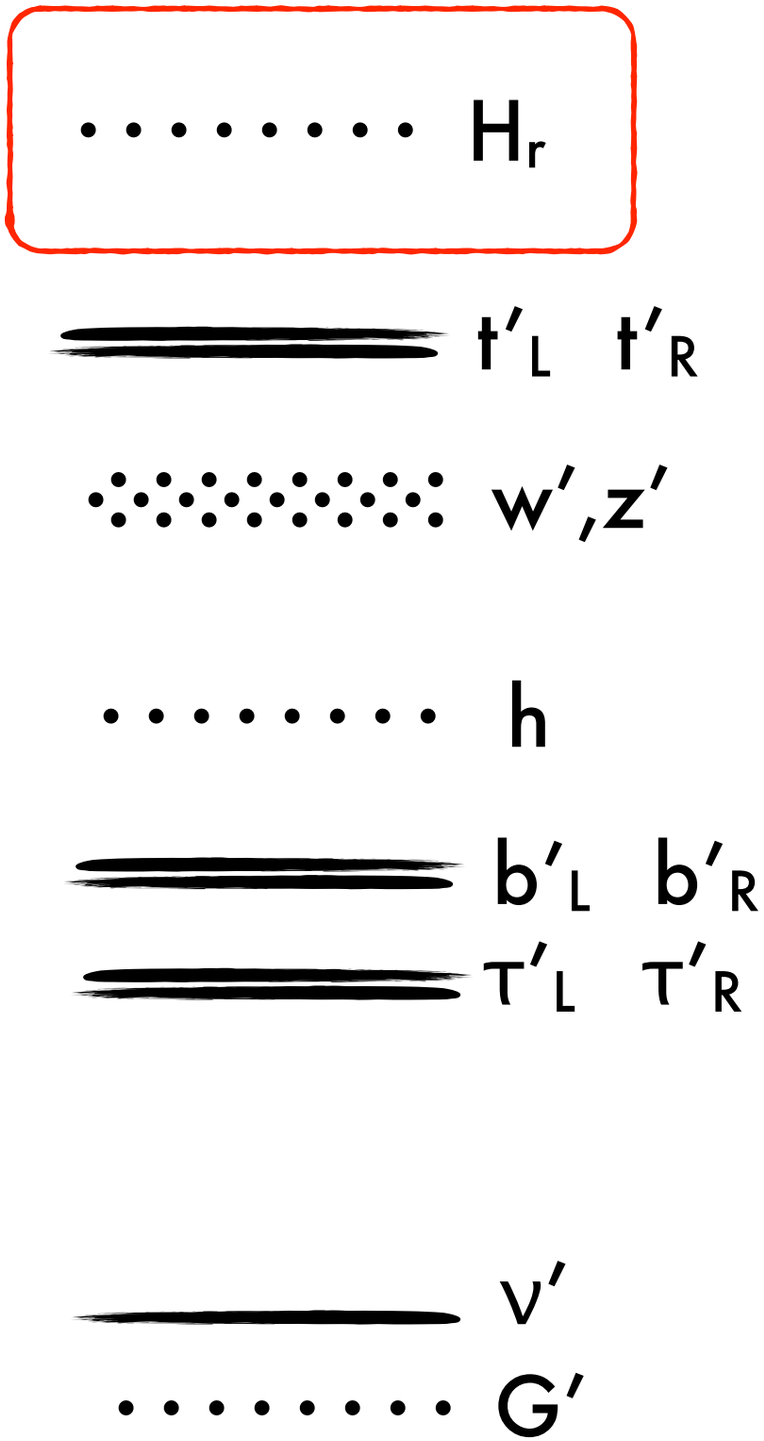
# What to look for?

- The heavy radial mode may be visible, especially for a perturbative completion (e.g. SUSY). Looks like singlet-doublet mixing w/ invisible decays.




*Current searches not constraining; very interesting for 13/14 TeV LHC*



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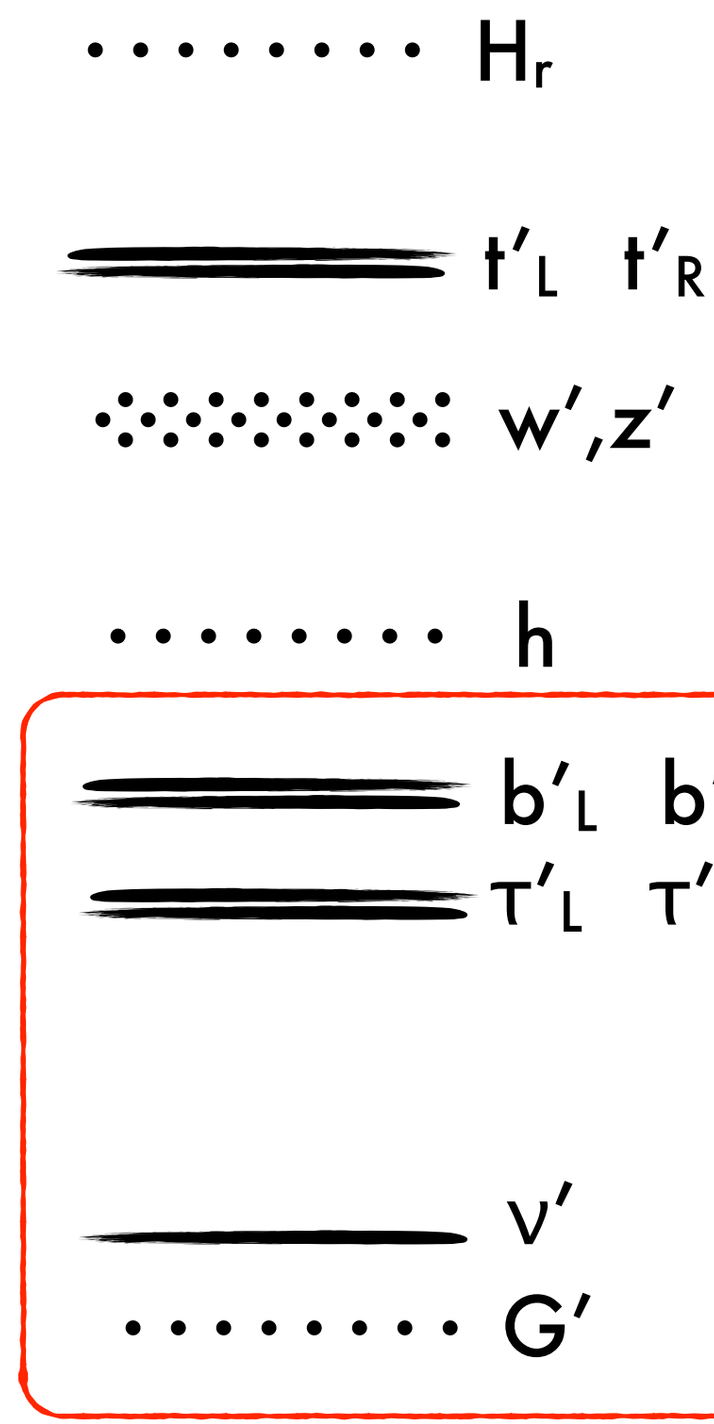
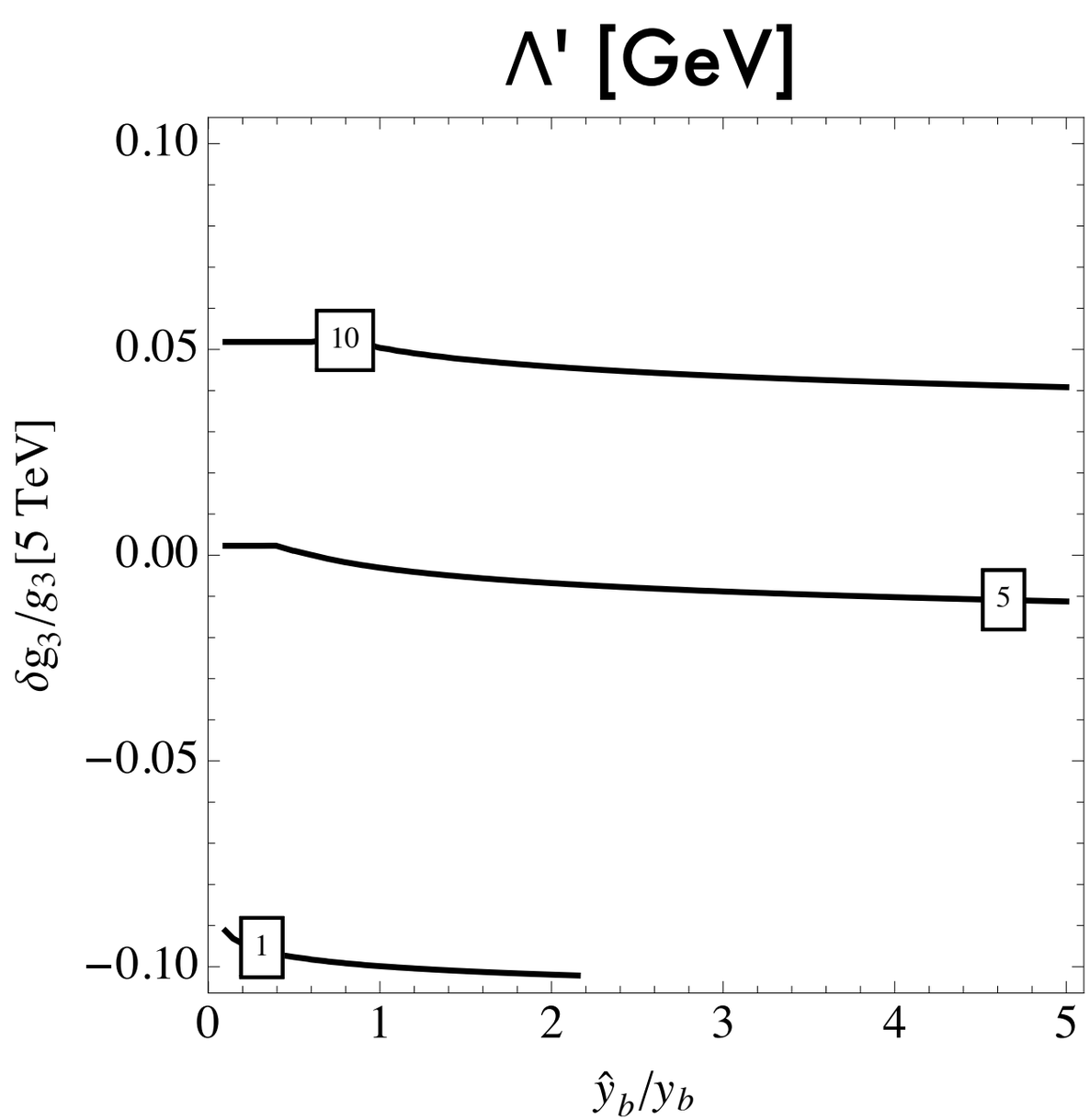
Decays into the hidden sector may come back to the Standard Model on interesting scales.




- Light fermions in the hidden sector: form light hadrons. Look for invisible decays of the Higgs.
- Light U(1) in the hidden sector: look for hidden photon phenomena.
- Light glueballs in the hidden sector…

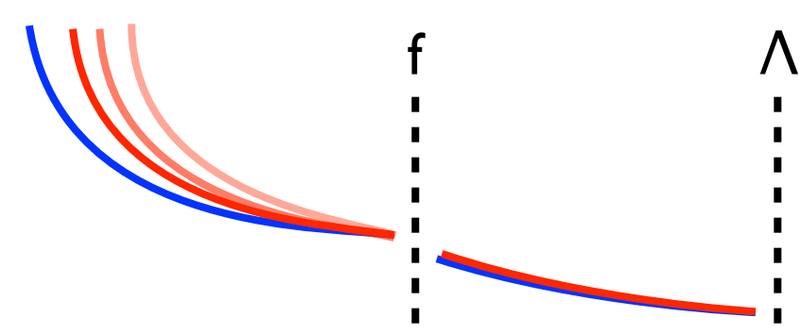
# Twin QCD

Gauge coupling related to QCD by twin symmetry.




*Must be present to keep top yukawas in twin sector(s) related to SM top yukawa.*

Runs differently in downstairs theory due to fewer & heavier fermions; confines at higher scale than QCD.



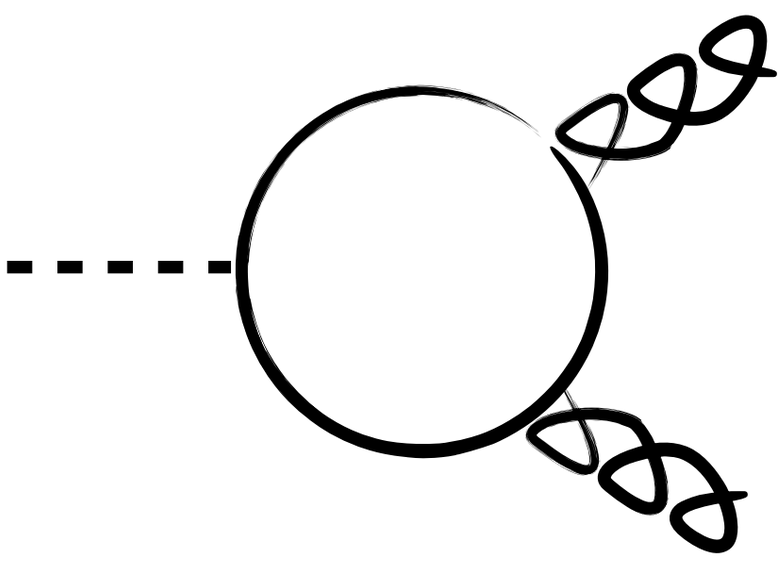
# Twin Glueballs

If no light fermions, glueballs of twin QCD at bottom of the spectrum.

$$m_{0++} \sim 7\Lambda'_{QCD}$$

Glueballs are special: mix with SM via dim-6 operator

$$\mathcal{L} \supset -\frac{\alpha'_3}{6\pi}\frac{v}{f}\frac{h}{f}G'^{a}_{\mu\nu}G'^{\mu\nu}_{a}$$

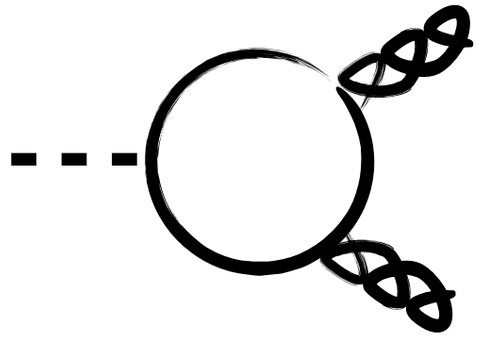


portal for production

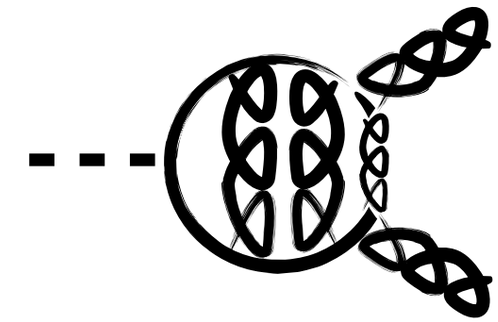
$$gg \to h \to 0^{++} + 0^{++} + \ldots$$

portal for decay

$$0^{++} \to h^* \to f\bar{f}$$



# Into the dark



**Irreducible:**

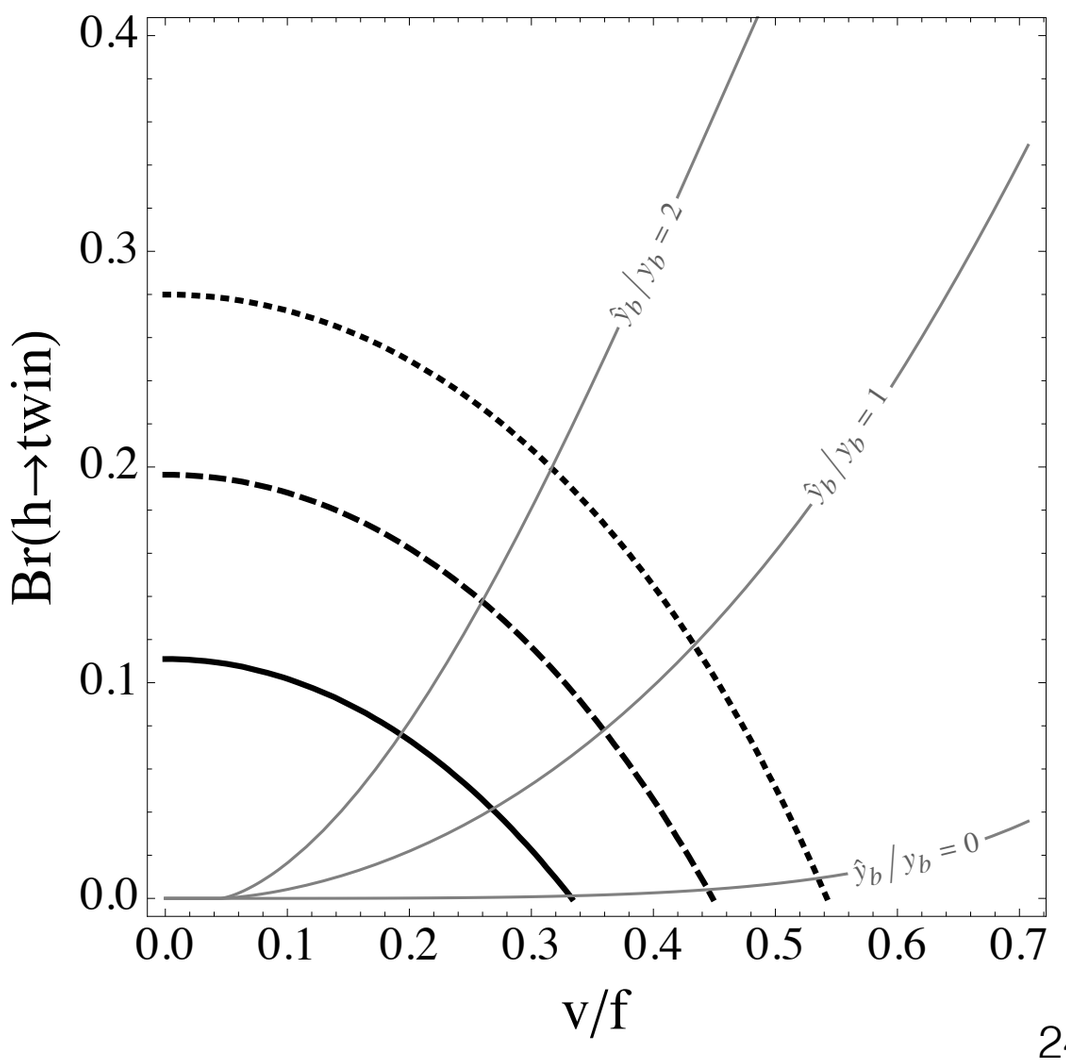
$$h \to g'g' \to \ldots$$

Perturbative rate a good guide for small $m_0$, continuum of states near $m_h$

**Reducible:**

$$h \to b'b' \to \ldots$$

Large corrections to perturbative rate, few bottomonium states below $m_h$



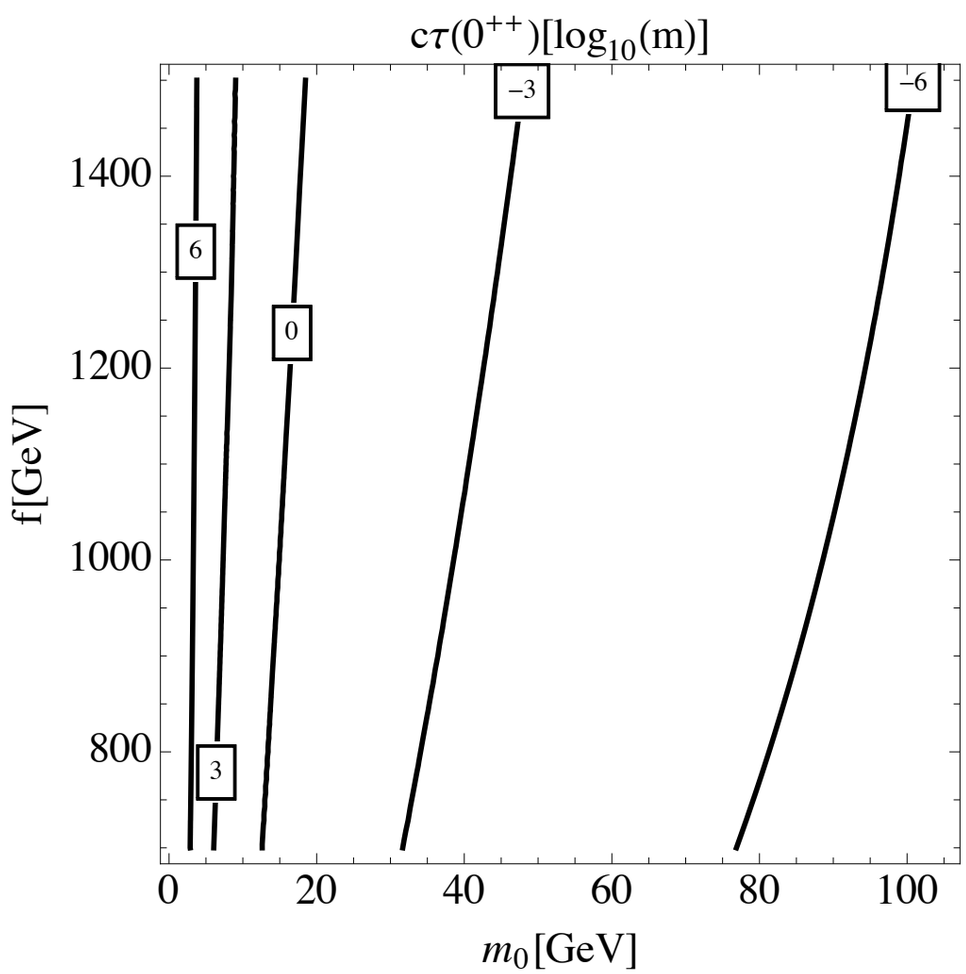

**Irreducible** through the orbifold top coupling. **Reducible** through the orbifold bottom coupling, sensitive to yukawa & bottomonium spectrum; also constrained by Higgs couplings.

Irreducible contribution gives BR ~ $10^{-3}$

# Out of the dark

Glueballs decay back to the SM through an off-shell SM higgs

$$\mathcal{L} \supset -\frac{\alpha_3'}{6\pi}\frac{v}{f}\frac{h}{f}G'^{a}_{\mu\nu}G'^{\mu\nu}_{a} \rightsquigarrow 0^{++} \to h^* \to \dots$$

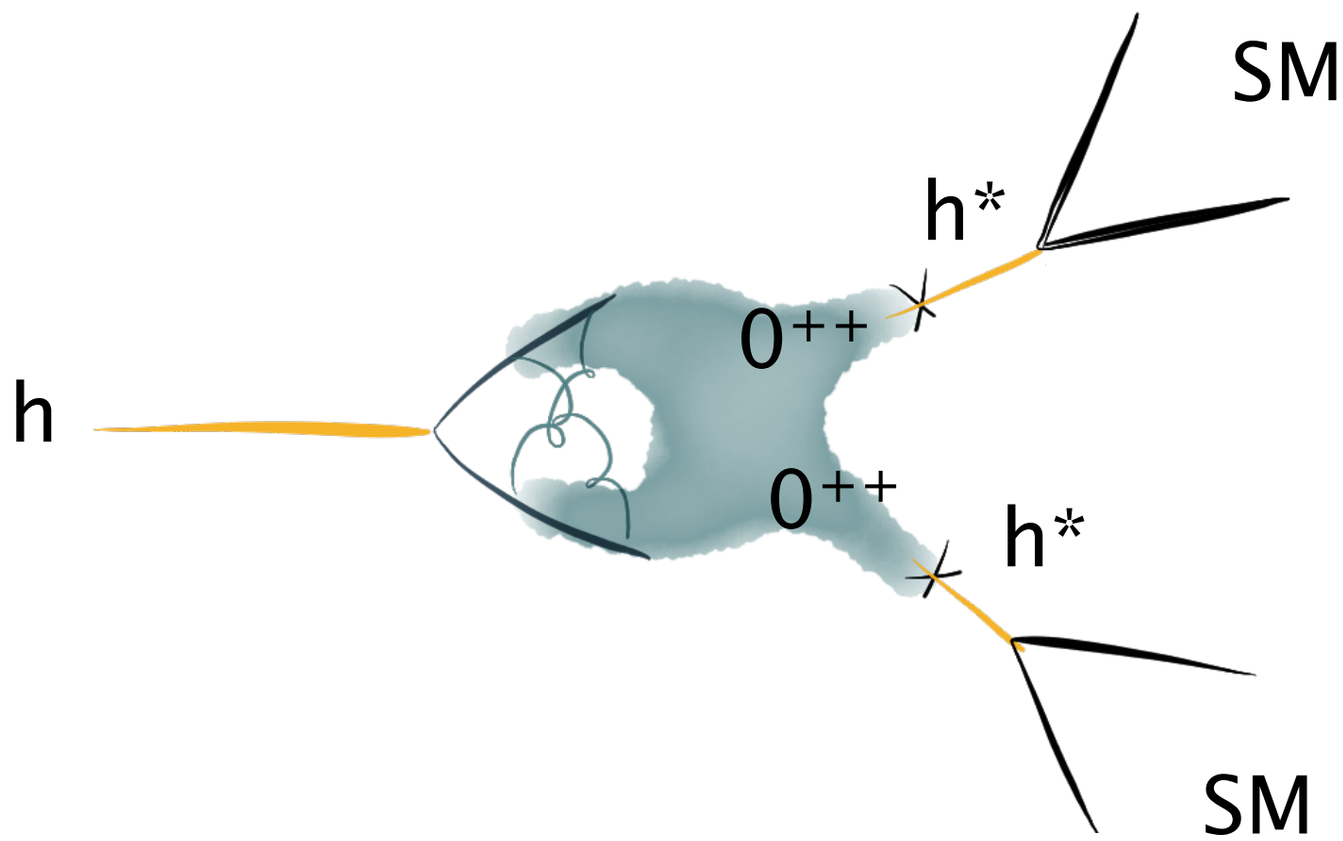



Intriguing lifetime!

$$c\tau \approx 18\ \mathrm{m}\ \times \left(\frac{10\ \mathrm{GeV}}{m_0}\right)^7 \left(\frac{f}{500\ \mathrm{GeV}}\right)^4$$

Strong dependence (7th power) on glueball mass → decays scan rapidly over LHC length scales.

# Displaced decays




*Rates small, signals spectacular. Best possible handle.*

# Pandora's box

- In the Twin Higgs and its cousins, naturalness lies in hidden sectors connected via the Higgs portal

A realization of rich hidden sectors with SM-like scales, new signs of naturalness:

- On- or off-shell Higgs portal to invisible states
- Heavy radial Higgs mode(s)
- Glueballs with displaced decays, hidden valley phenomenology.

*Much to explore, much to simulate!*