Neutral naturalness of the weak scale

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SUSY 2015

Higgs & Hierarchy Problem

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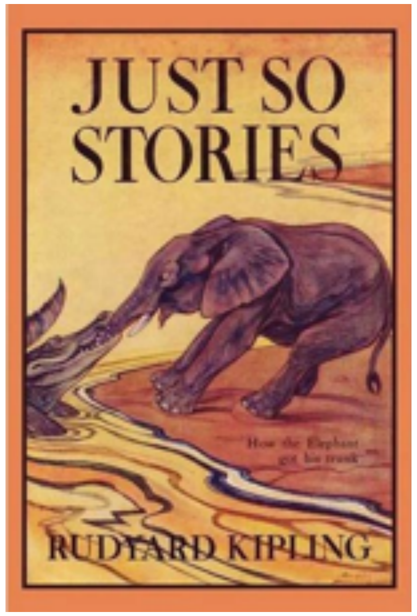
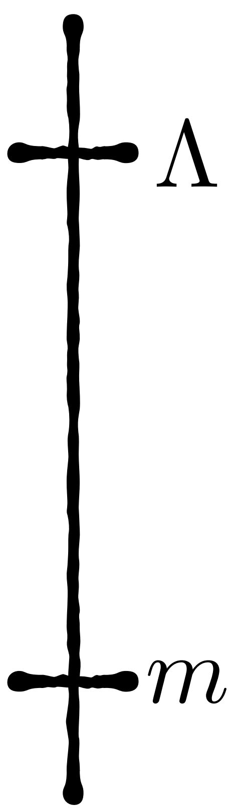
- At the very least, as far as we know a theory of quantum gravity should give physical thresholds around the string scale.

- An apparently elementary Higgs makes the hierarchy problem as pressing as ever.



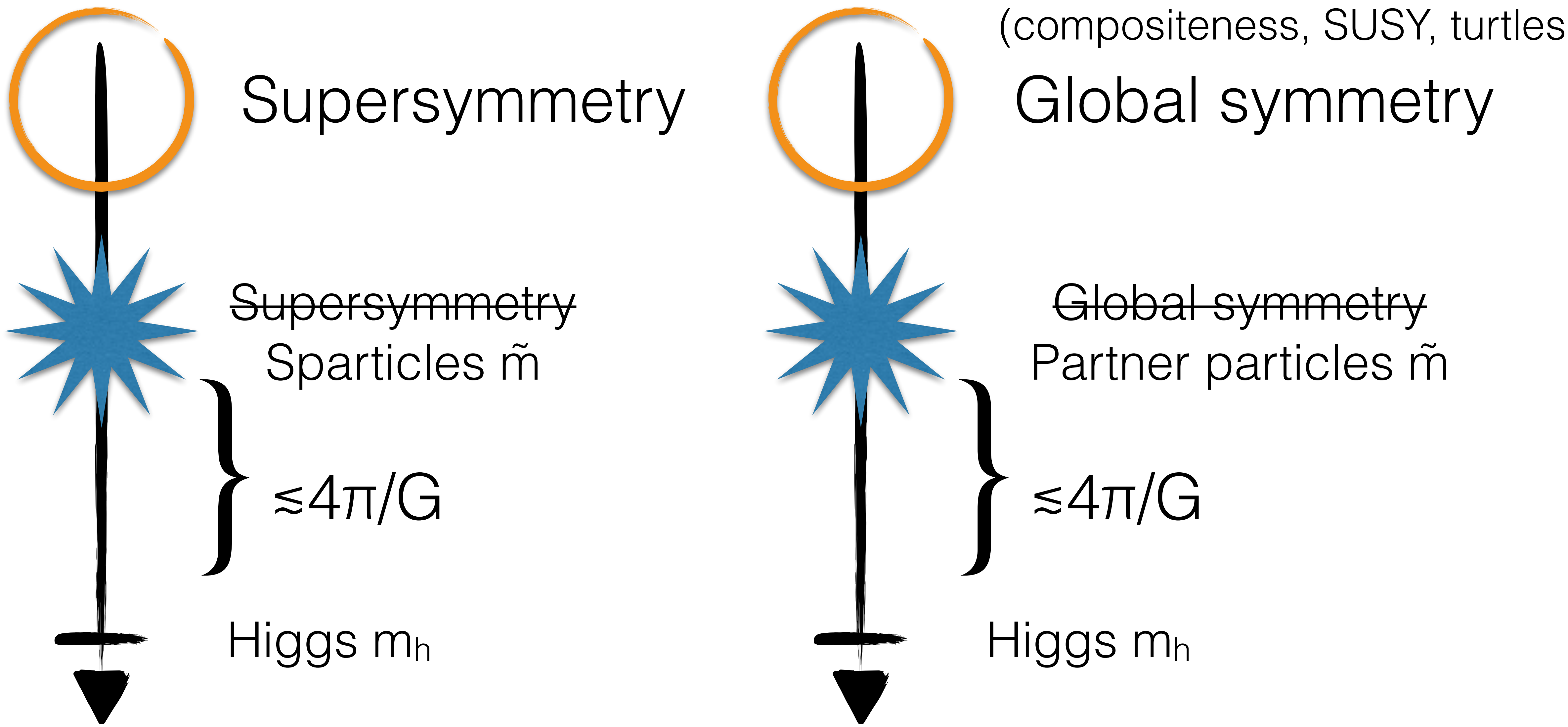
Natural vs. unnatural

Hierarchy problem is not a "just-so story"



Field	Symmetry as $m \to 0$	Implication
Spin-1/2 $m\Psi\bar{\Psi}$	$\Psi \to e^{i\alpha\gamma_5}\Psi$ (chiral symmetry)	$\delta m \propto m$ **Natural!**
Spin-1 $m^2 A_\mu A^\mu$	$A_\mu \to A_\mu + \partial_\mu \alpha$ (gauge invariance)	$\delta m \propto m$ **Natural!**
Spin-0 $m^2\|H\|^2$	None	$\delta m \propto \Lambda$ **Unnatural!**

Hierarchy Solutions

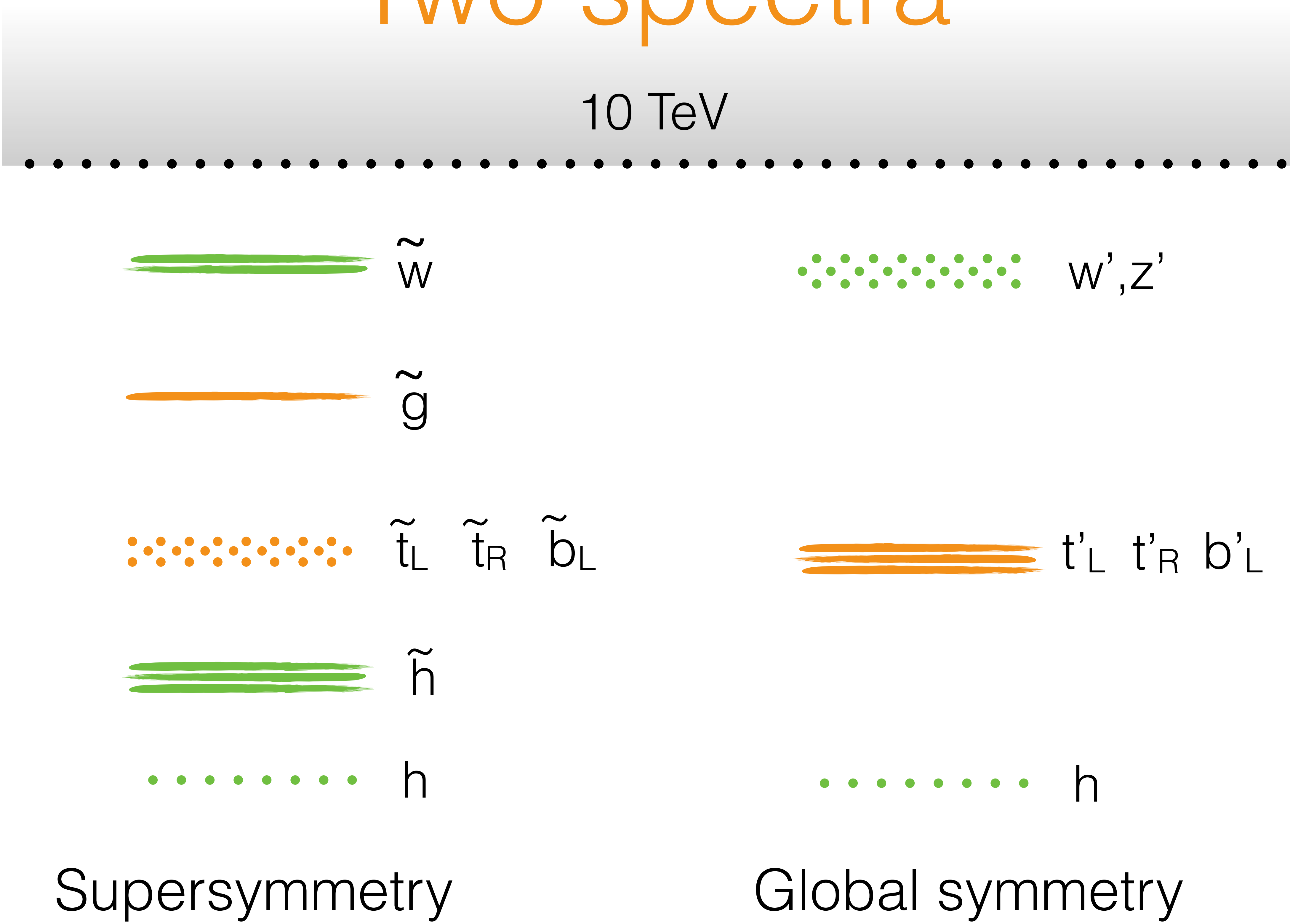


Continuous symmetries commuting w/ SM
→ partner states w/ SM quantum numbers

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

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

Two spectra

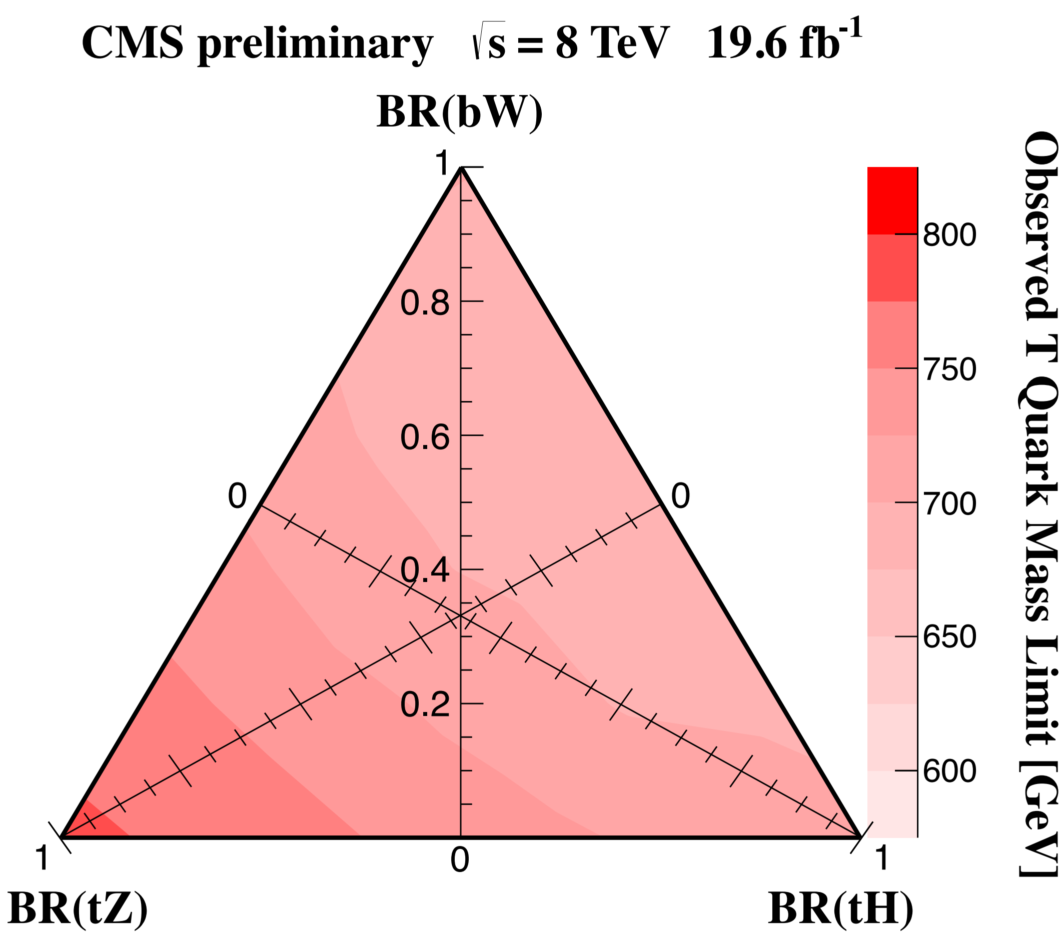


Simple game for LHC: look for colored partners.

Missing top partner problem

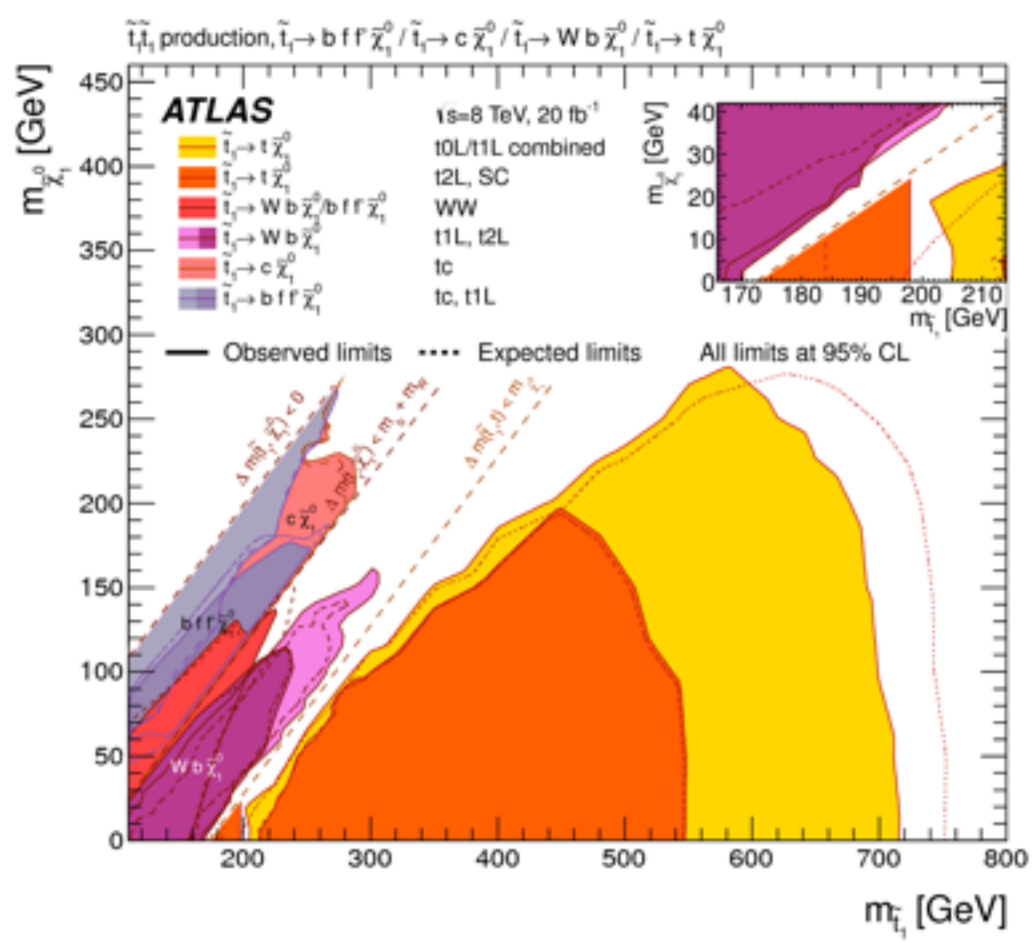
LHC searches driven by top partners

Global Symmetry



CMS B2G-12-015

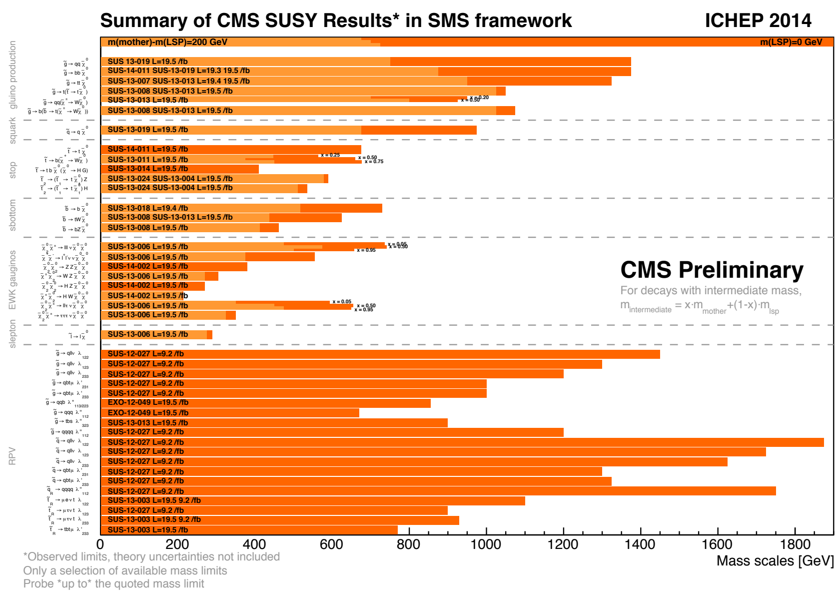
Supersymmetry

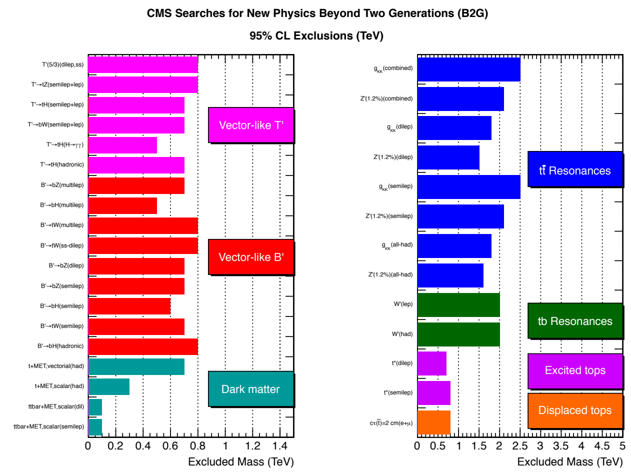


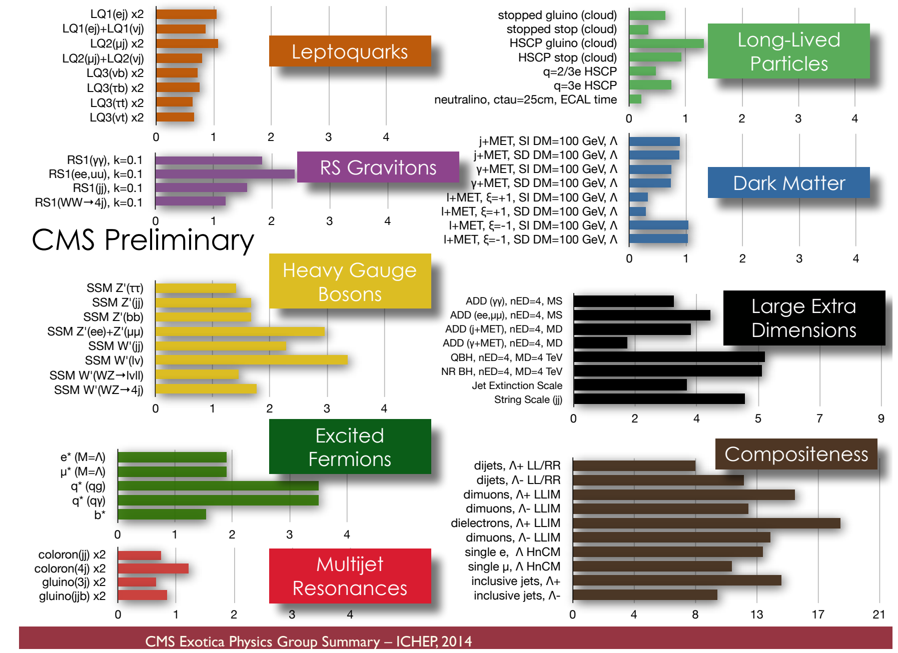
Problem 1: nothing yet (~10% tuning).

Problem 2: not much new to do.

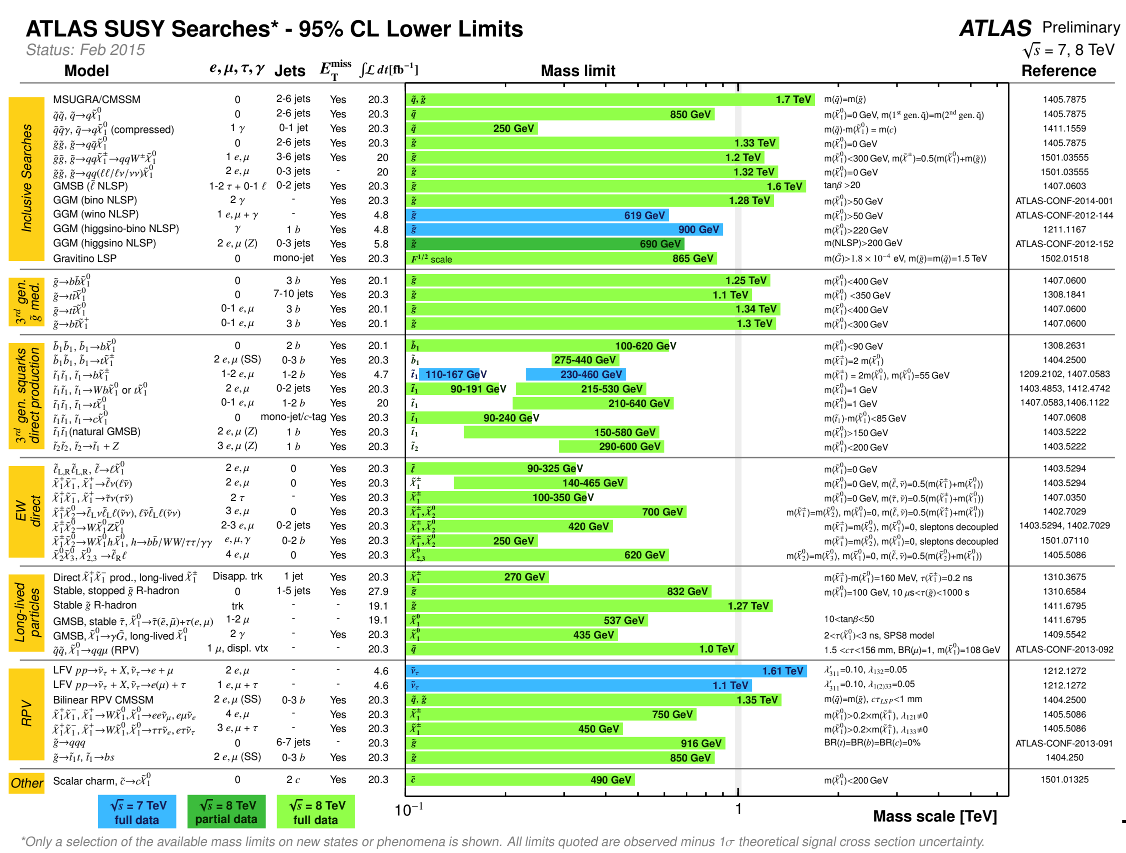
More generally...

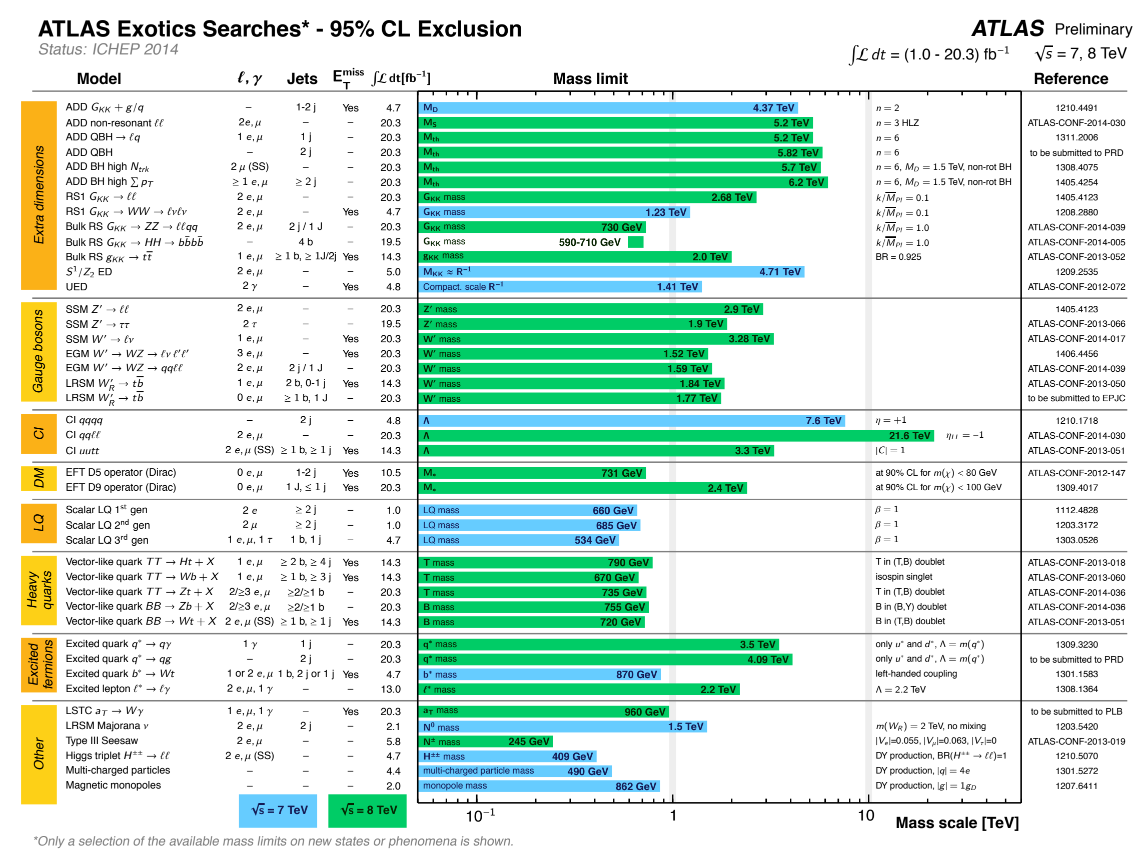






Only limits so far.



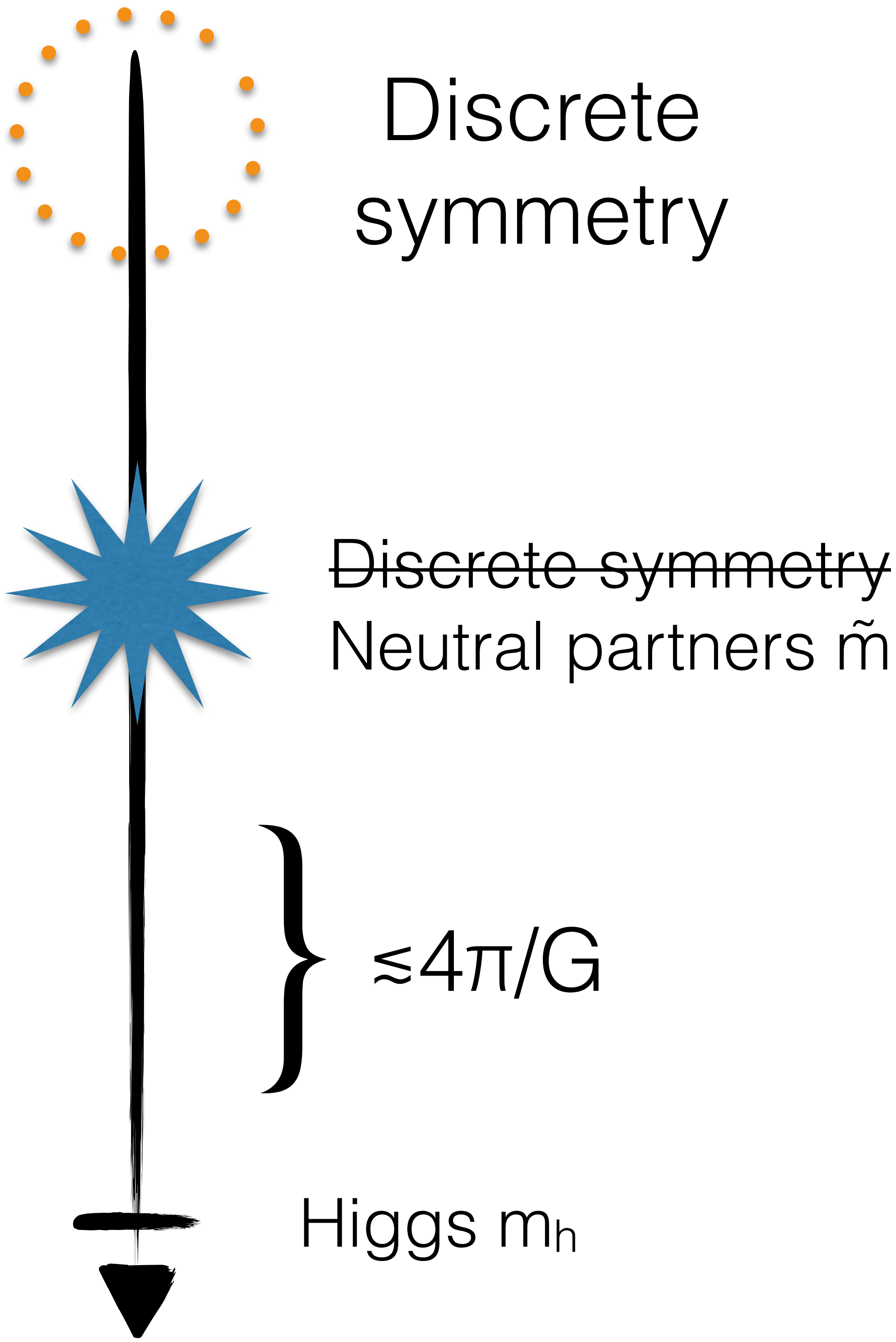


But: is this all there is?

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)

Discrete symmetries



Symmetry-based approaches to hierarchy problem employ *continuous symmetries.*

Leads to partner states w/ SM quantum numbers.

Discrete symmetries can also serve to protect the Higgs.

Leads to partner states w/ non-SM quantum numbers.

"Neutral naturalness"

Neutral naturalness

Partner quantum #s	Global *tree-level Higgs couplings*	SUSY *loop-level Higgs couplings*
QCD x EWK	CHM, Little Higgs	MSSM
Neutral x EWK	Quirky Little Higgs	Folded SUSY
Neutral x Neutral	Twin Higgs	????

Proof of principle

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

Quadratic potential has accidental SU(4) symmetry.

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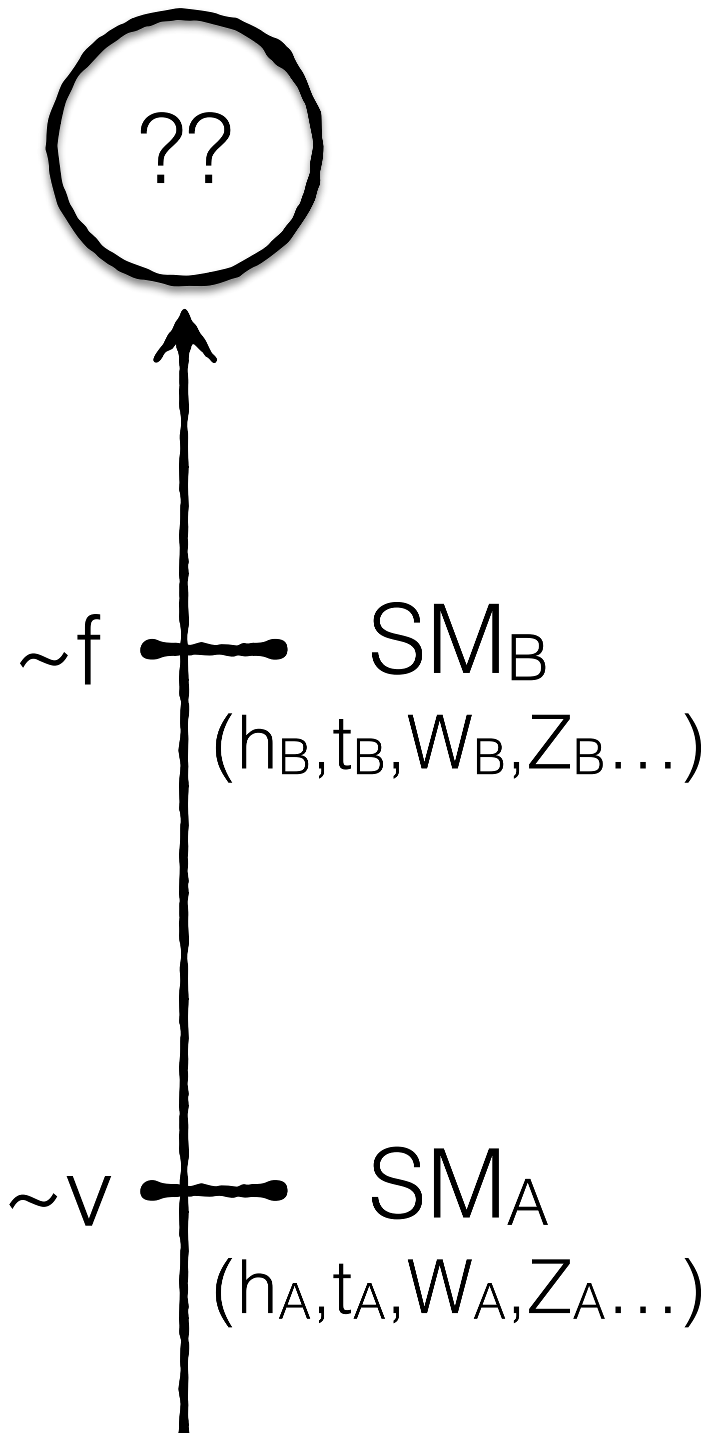
Full theory: extend Z_2 to all SM matter and couplings.

$SM_A \times SM_B \times Z_2$



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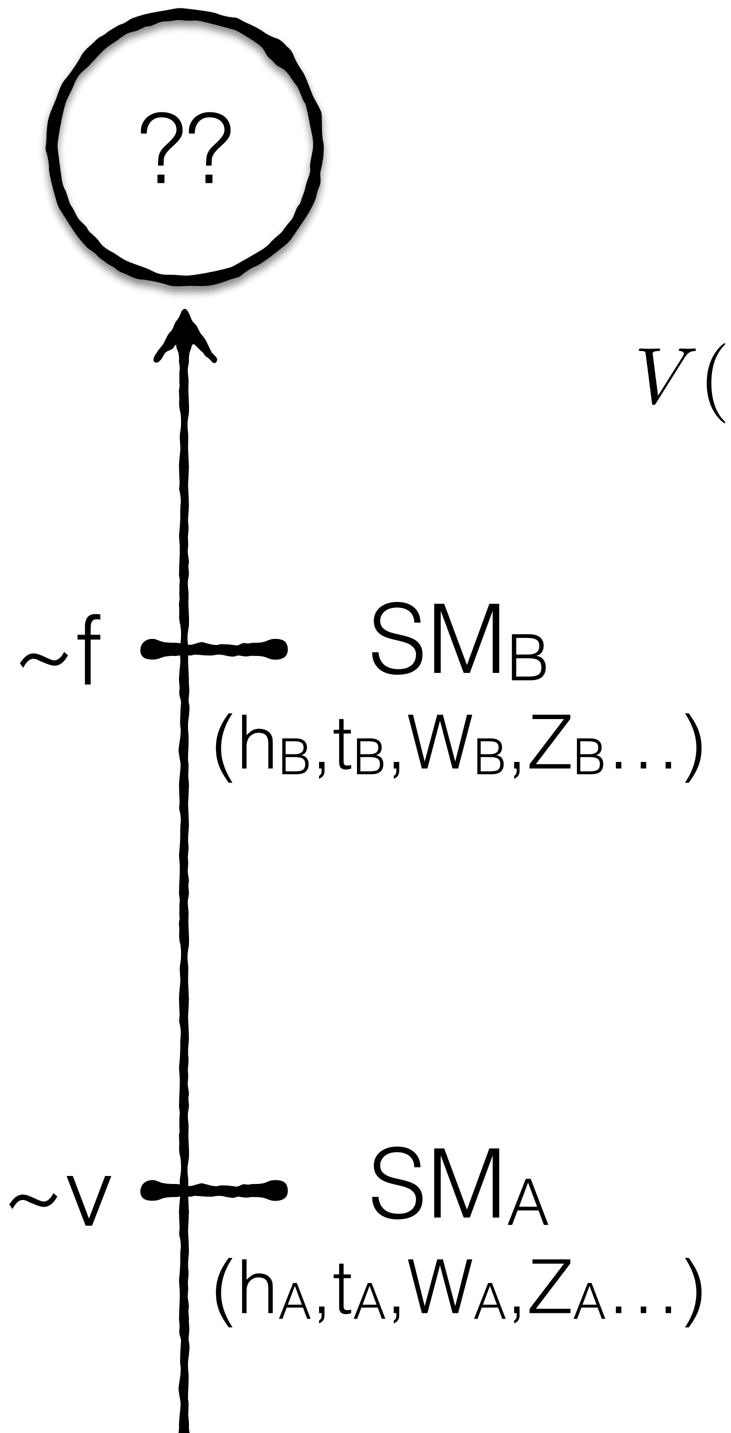
$$V(H) \supset \frac{\Lambda^2}{16\pi^2}\left(-6y_t^2 + \frac{9}{4}g^2 + \ldots\right)\left(|H_A|^2 + |H_B|^2\right)$$



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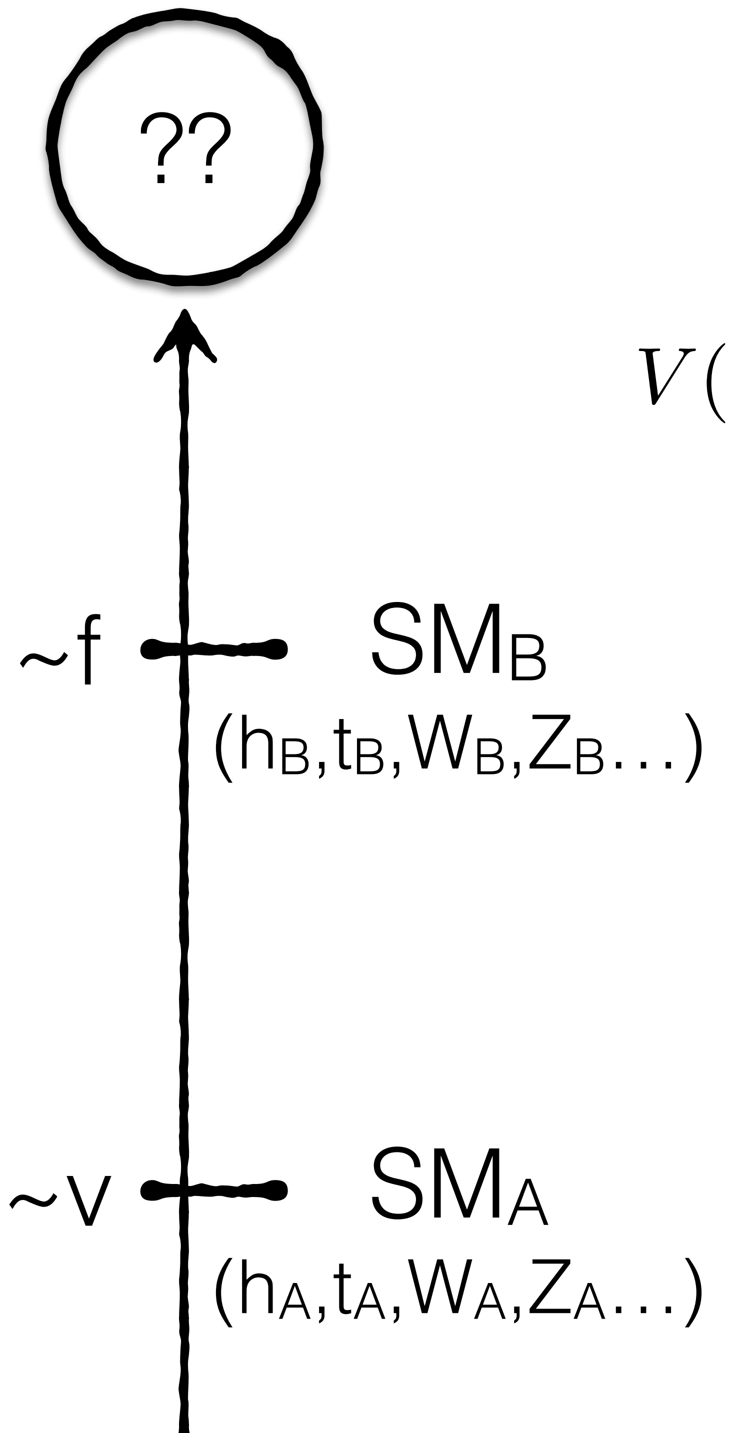

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$$|\langle H_A \rangle|^2 + |\langle H_B \rangle|^2 = f^2$$

Breaks “quadratic” SU(4), higgses EWK_A & EWK_B

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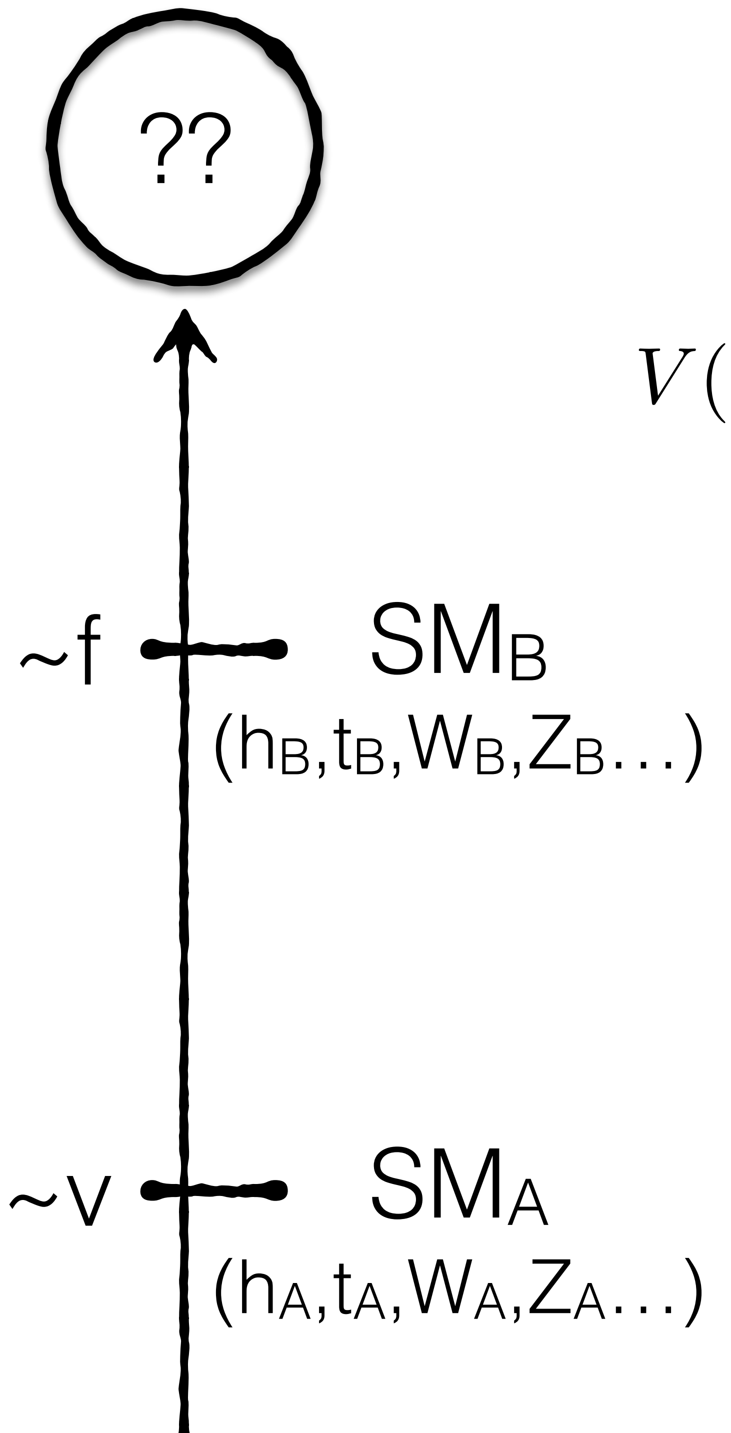

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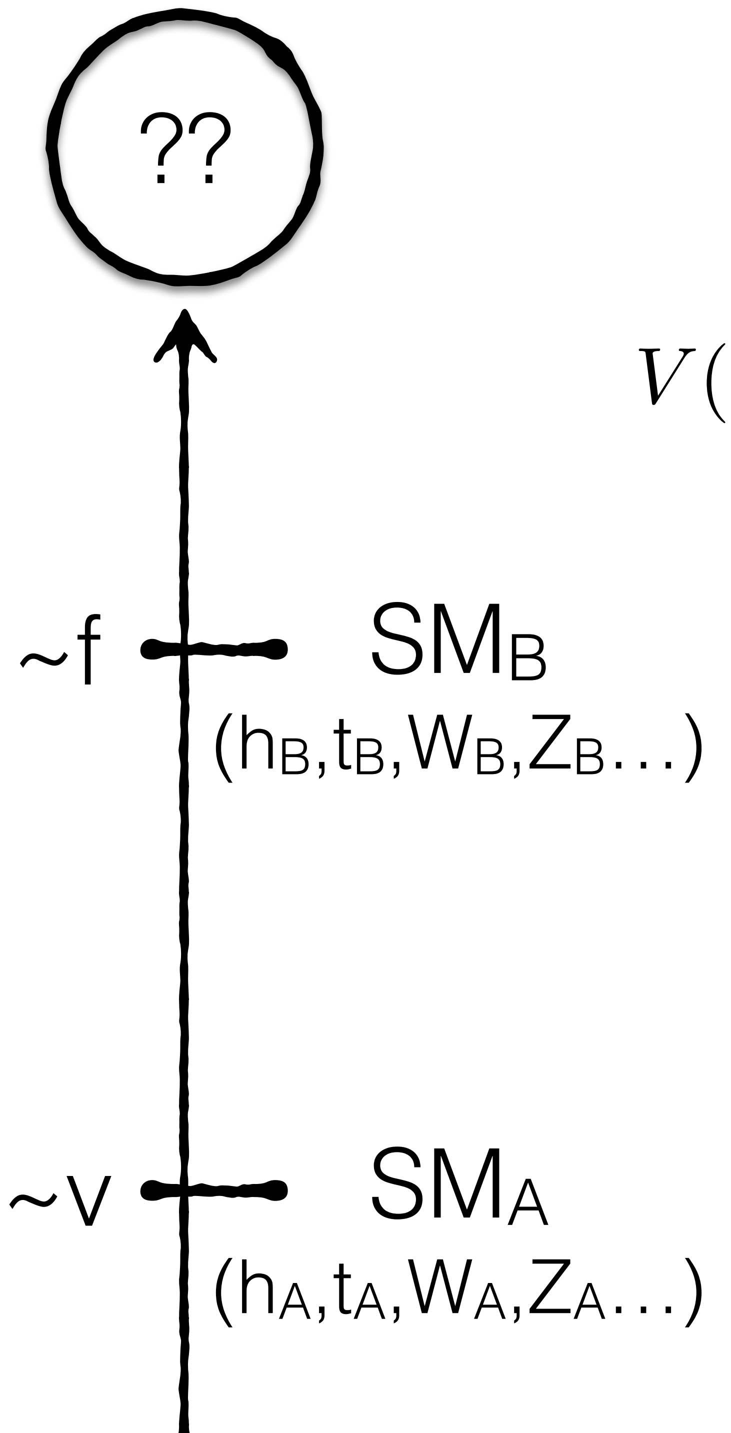

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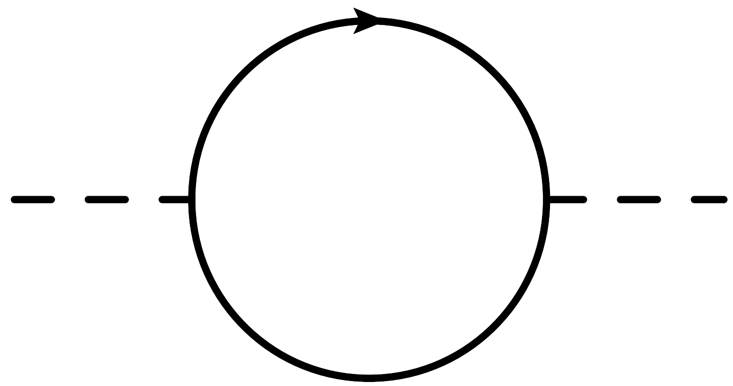
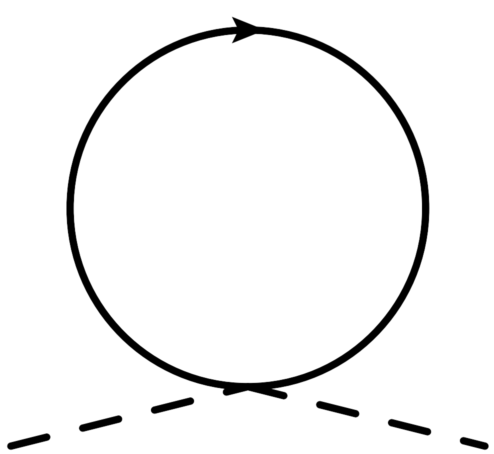
Primary coupling between SM_A and SM_B is via Higgs portal

The Twin Top



Standard Model



Twin top

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

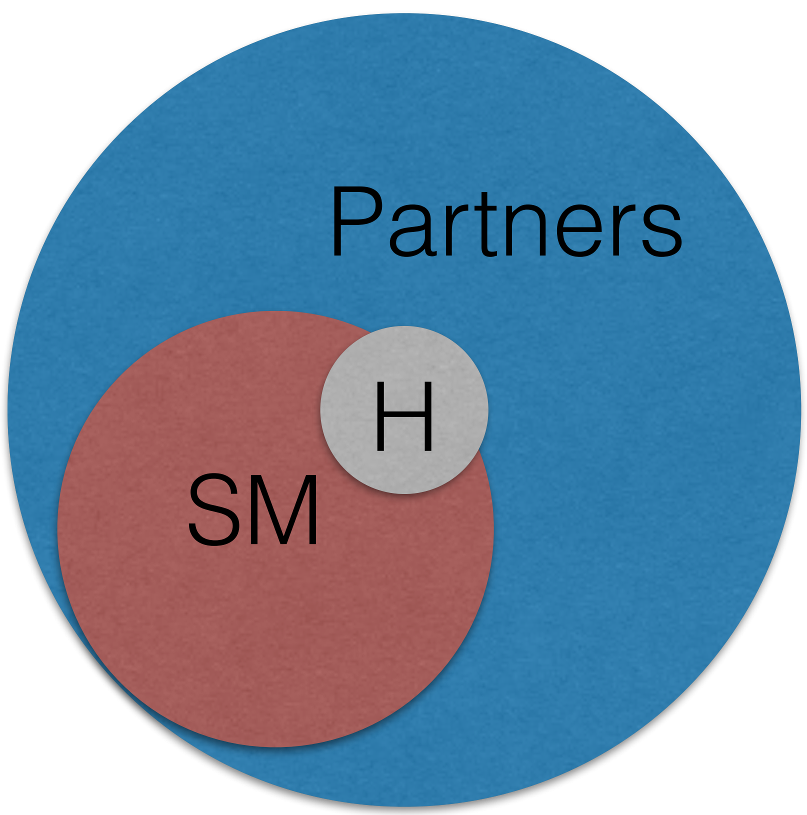
$$\mathcal{L} \supset -y_t H_A Q_3^A \bar{u}_3^A - y_t H_B Q_3^B \bar{u}_3^B$$

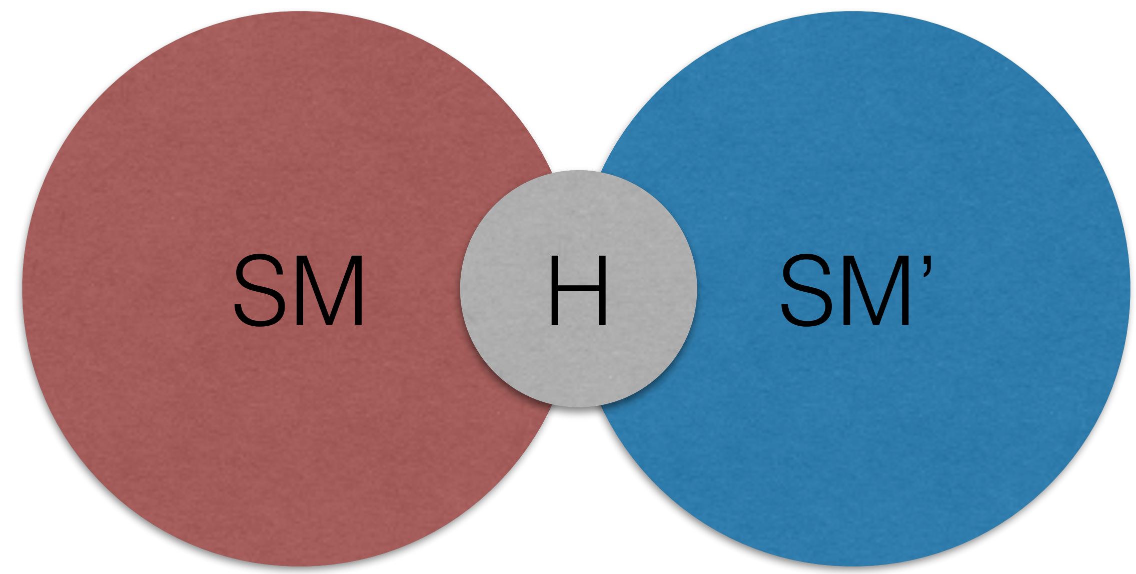
$$H_A \rightarrow h + \ldots \qquad H_B \rightarrow f - \frac{h^2}{2f} + \ldots$$

Symmetry protecting the Higgs takes us into a different SU(3) group. No direct limit on top partners.

The big picture

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

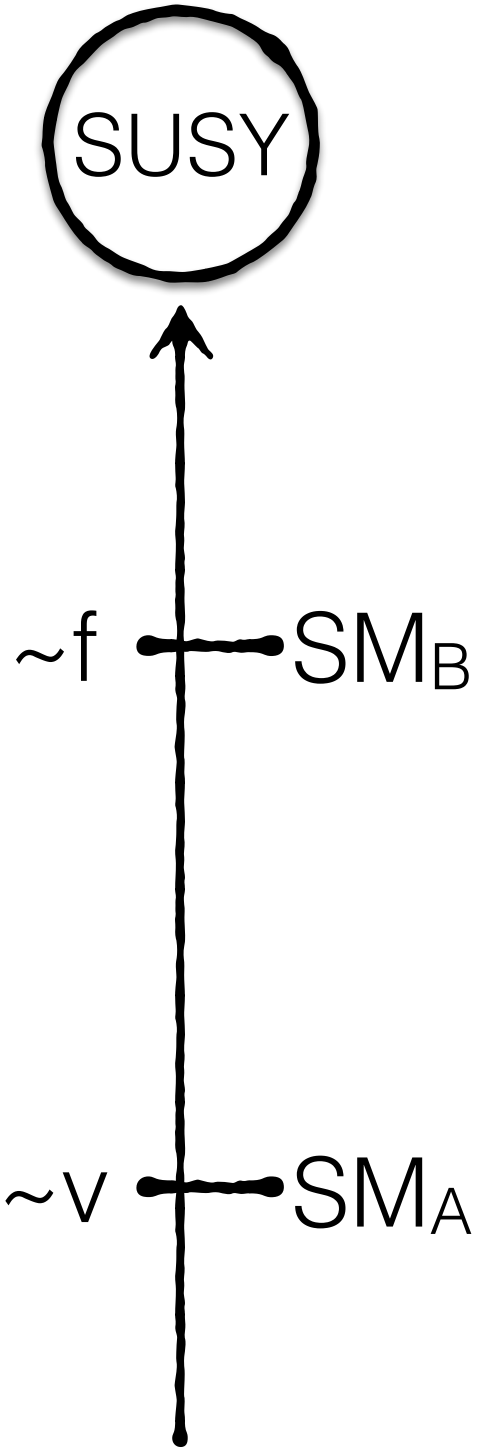




Protect Higgs w/ a hidden sector mirroring the SM. Partners have no SM charges.

“Higgs is pseudo-goldstone of the accidental global symmetry of the quadratic action obeying a discrete symmetry”

UV Physics



The SUSY Twin Higgs

SUSY protects the linear sigma model

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

$MSSM_A \times MSSM_B \times Z_2$

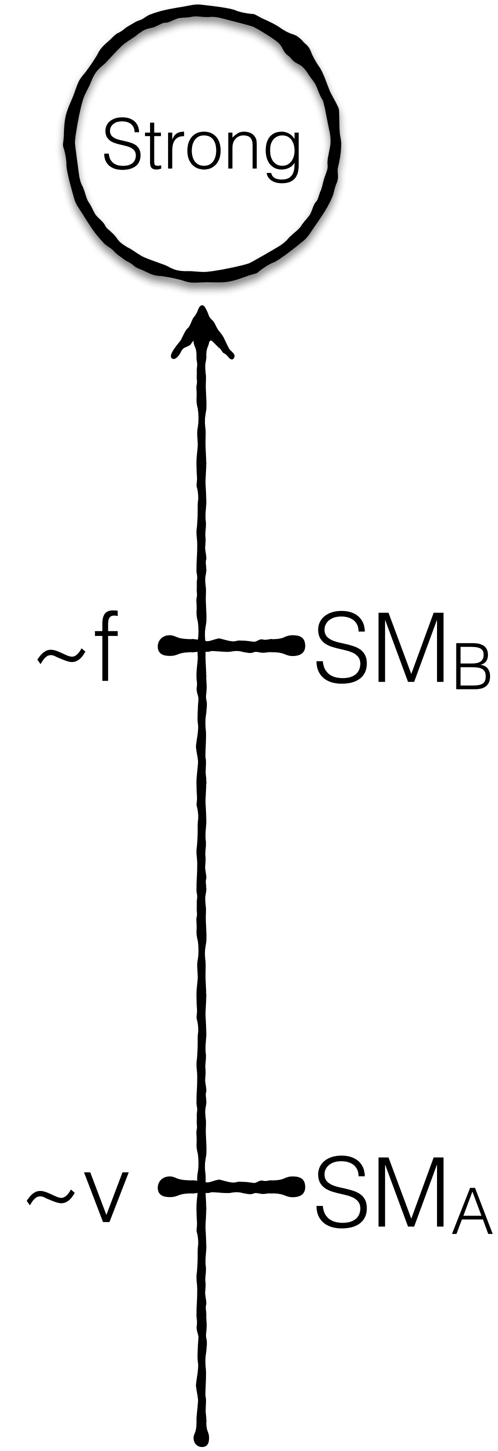
Quartic λ can be ~1; there is a perturbative radial twin Higgs mode

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



The General Framework

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

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(Quotient space of manifold modded out by a discrete group)

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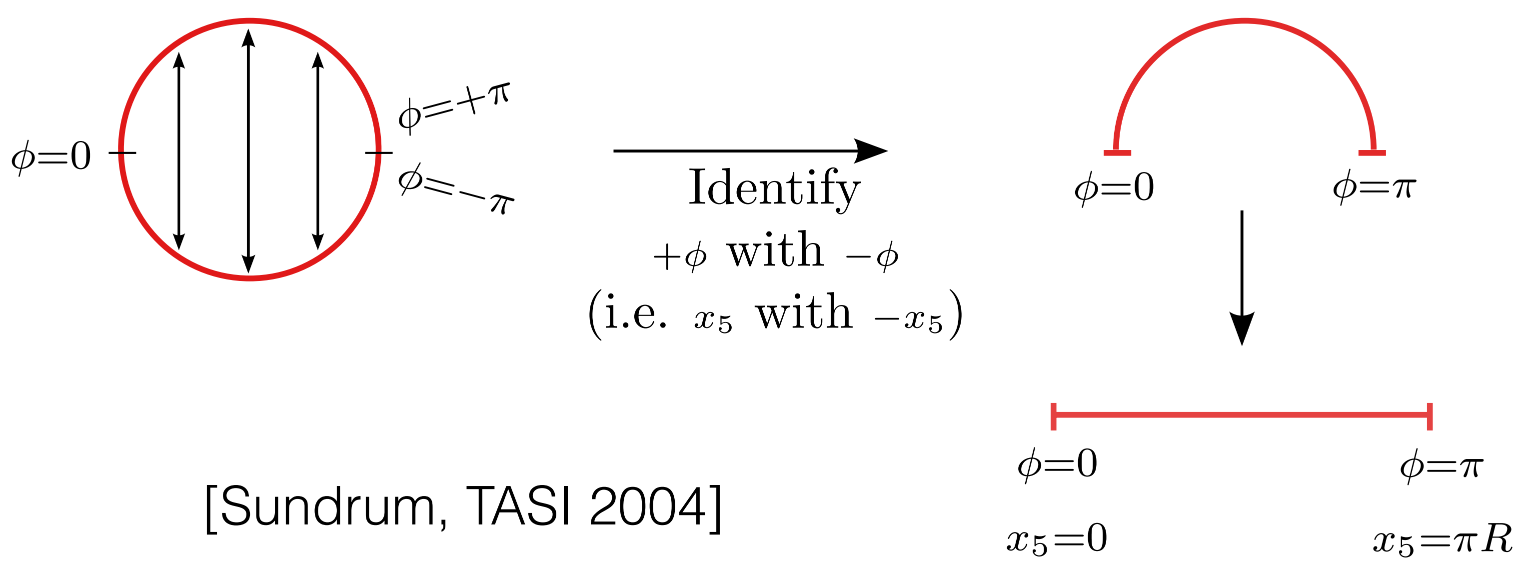

[Sundrum, TASI 2004]

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

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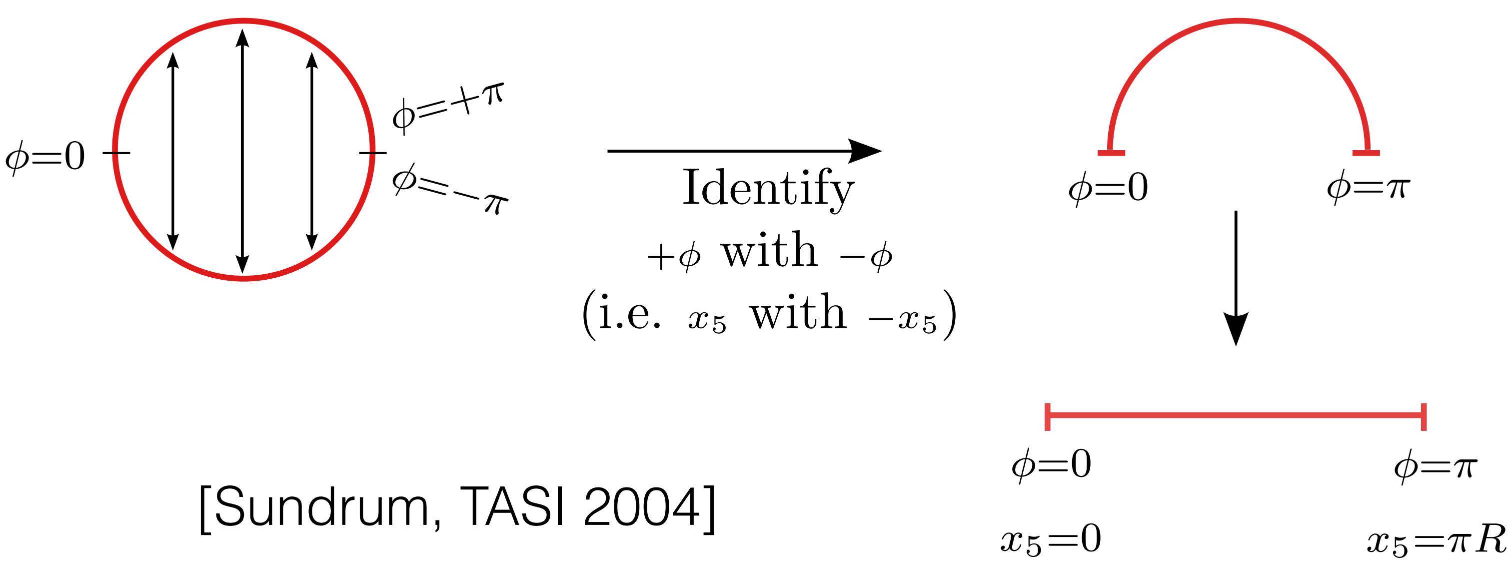

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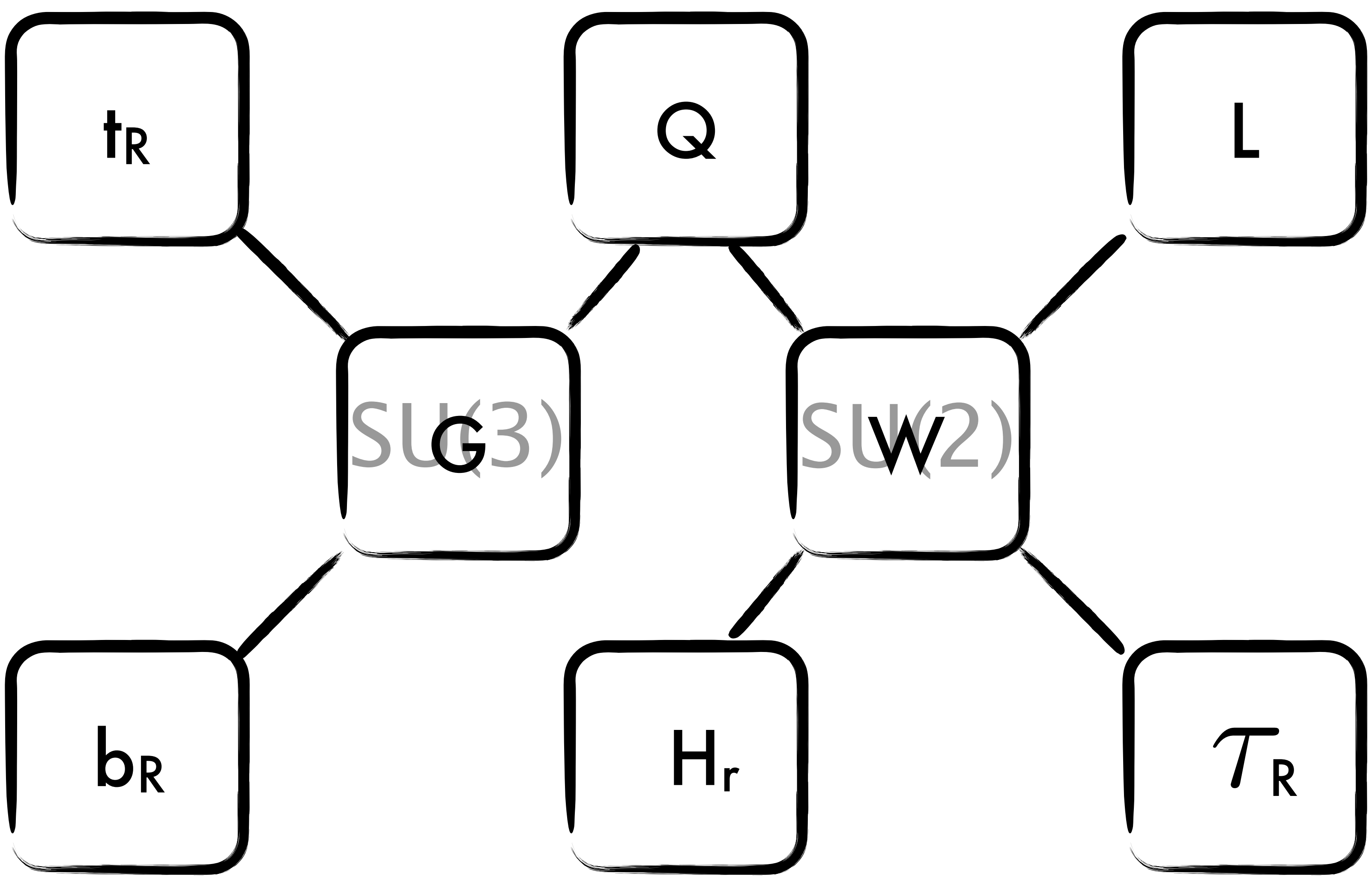
Familiar tool in string theory & field theory (realistic string compactifications, orbifold GUTs, 5D SUSY theories, etc.)

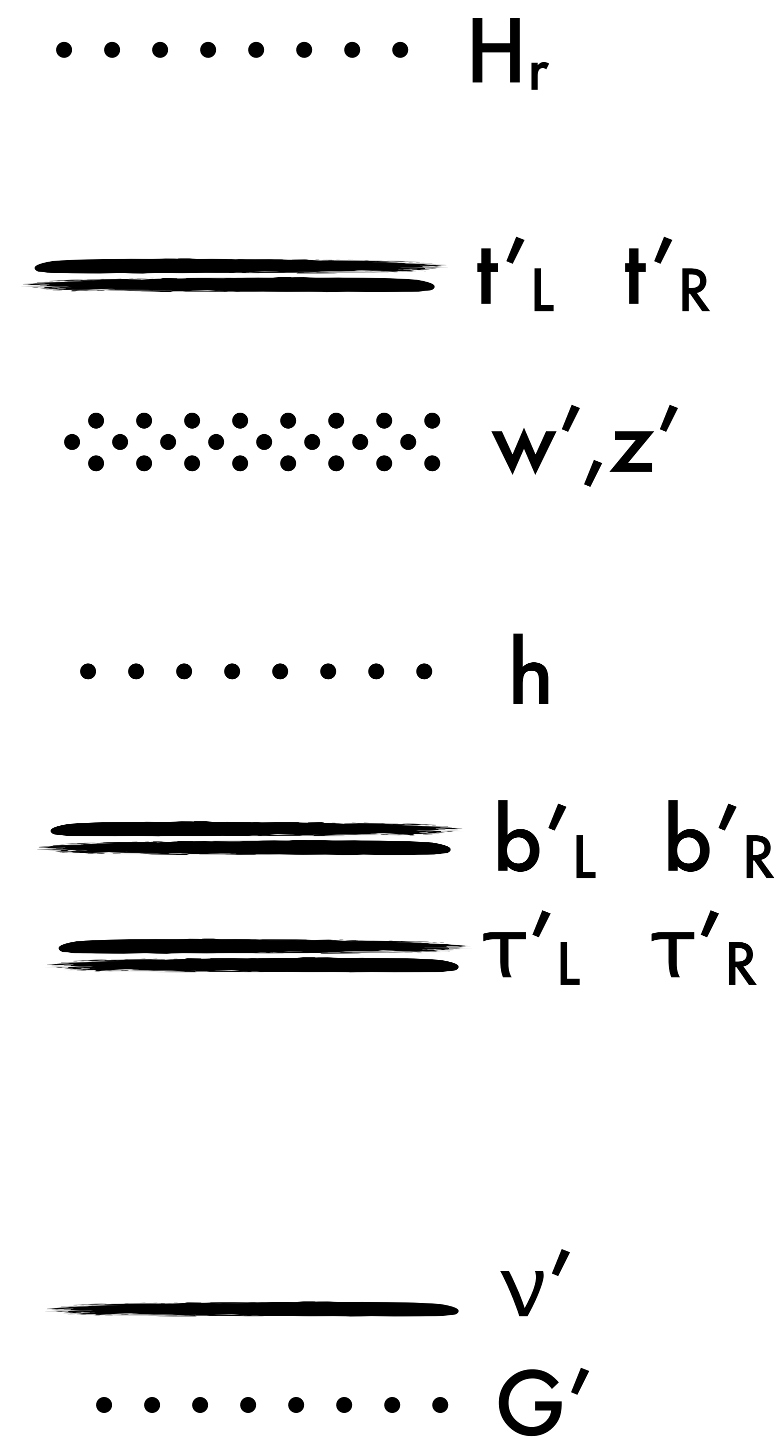
Punchline: Many models of the twin kind, where Z_2 or larger symmetries may be exact or approximate.

The minimal model

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

Just Z_2 partner states for the third generation, *a la* “natural SUSY”.

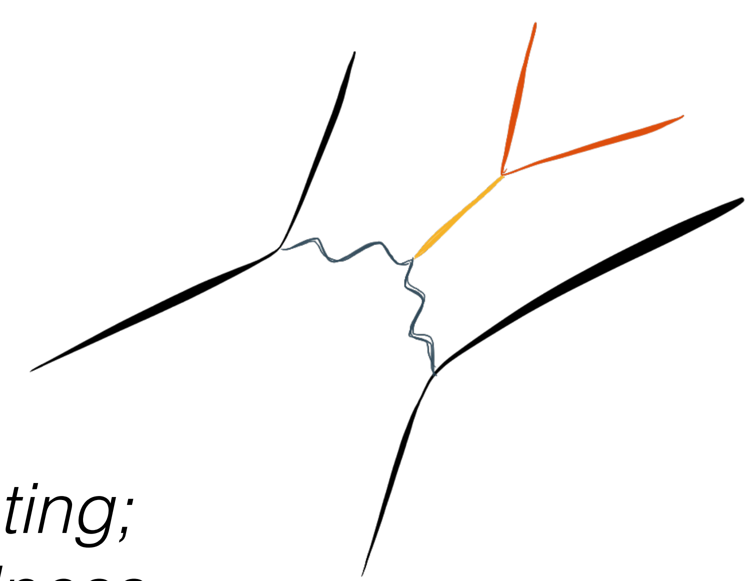




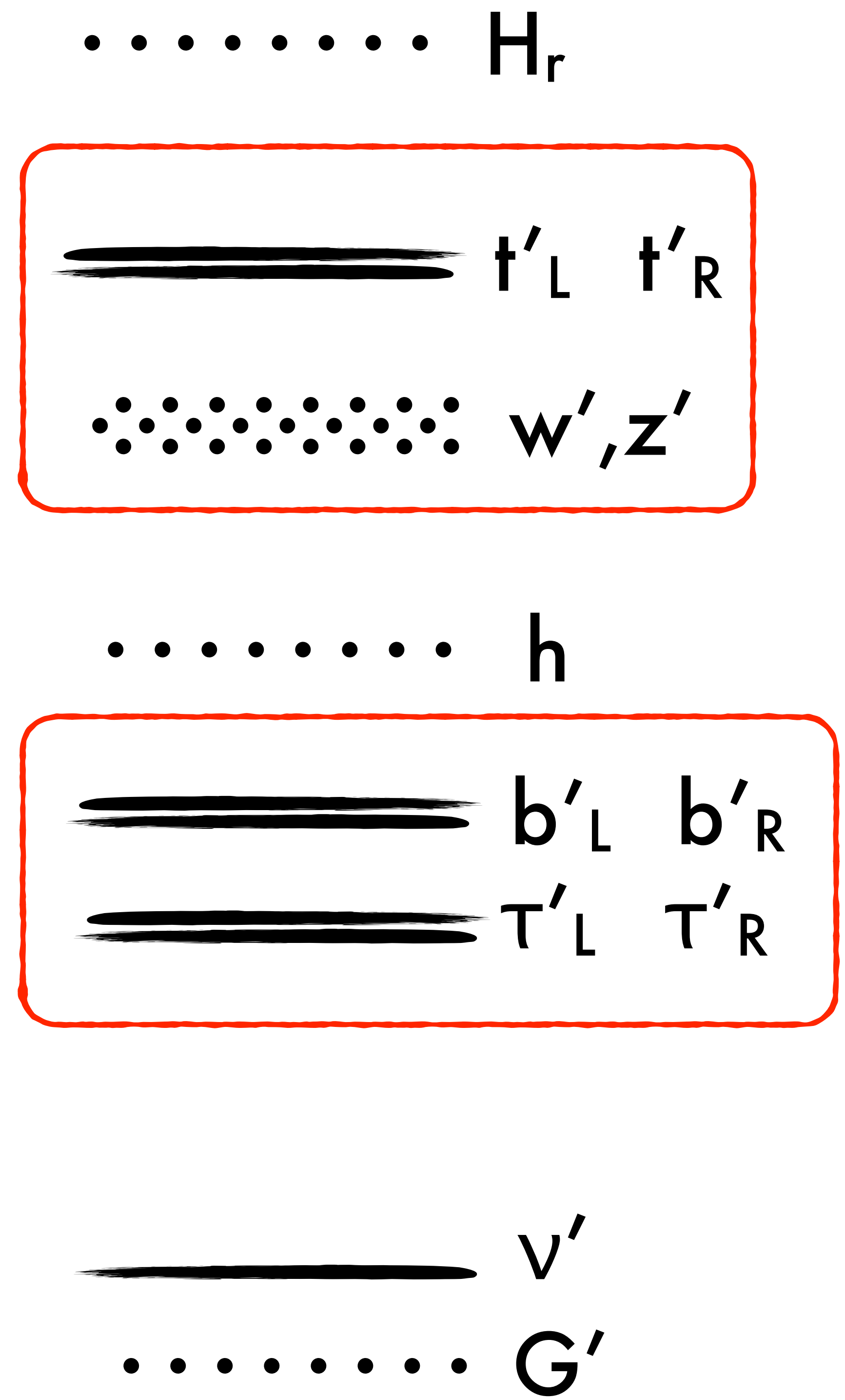
What to look for?

[Mixing 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.

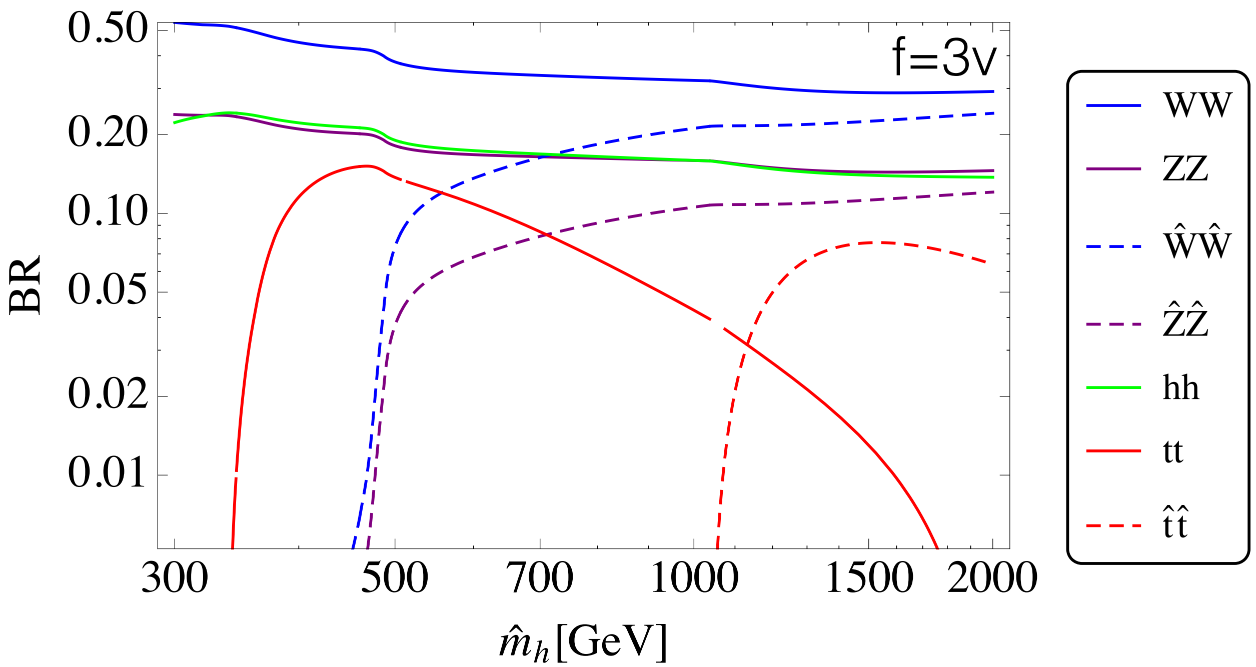


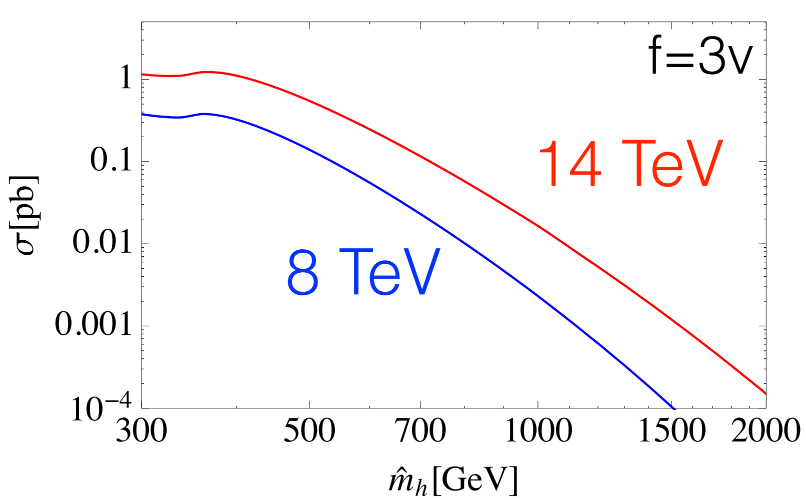
Hard but very interesting; directly probe naturalness



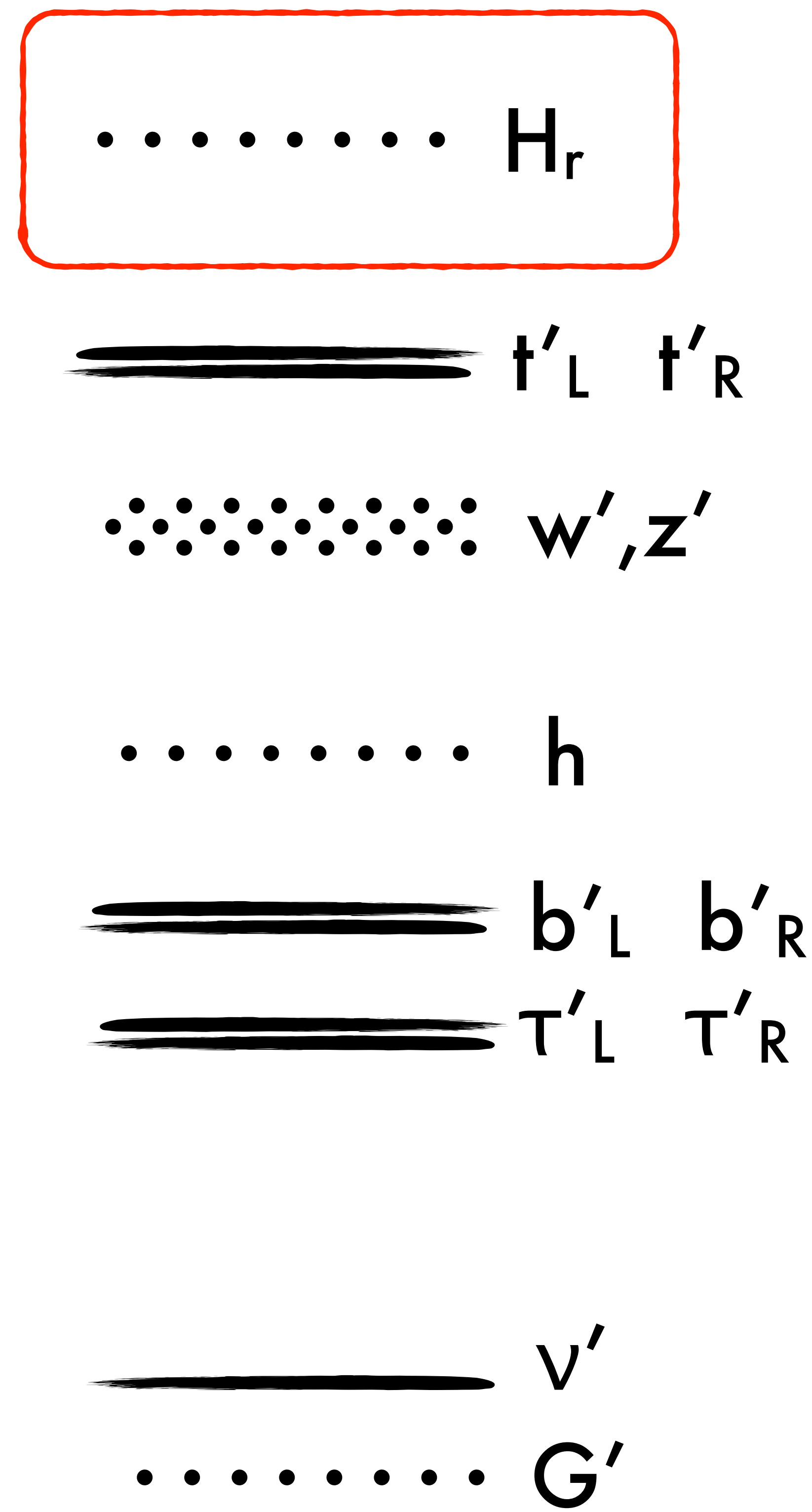
What to look for?

- Heavy radial mode may be visible in perturbative completion (e.g. SUSY). Looks like singlet mixing w/ invisible decays.





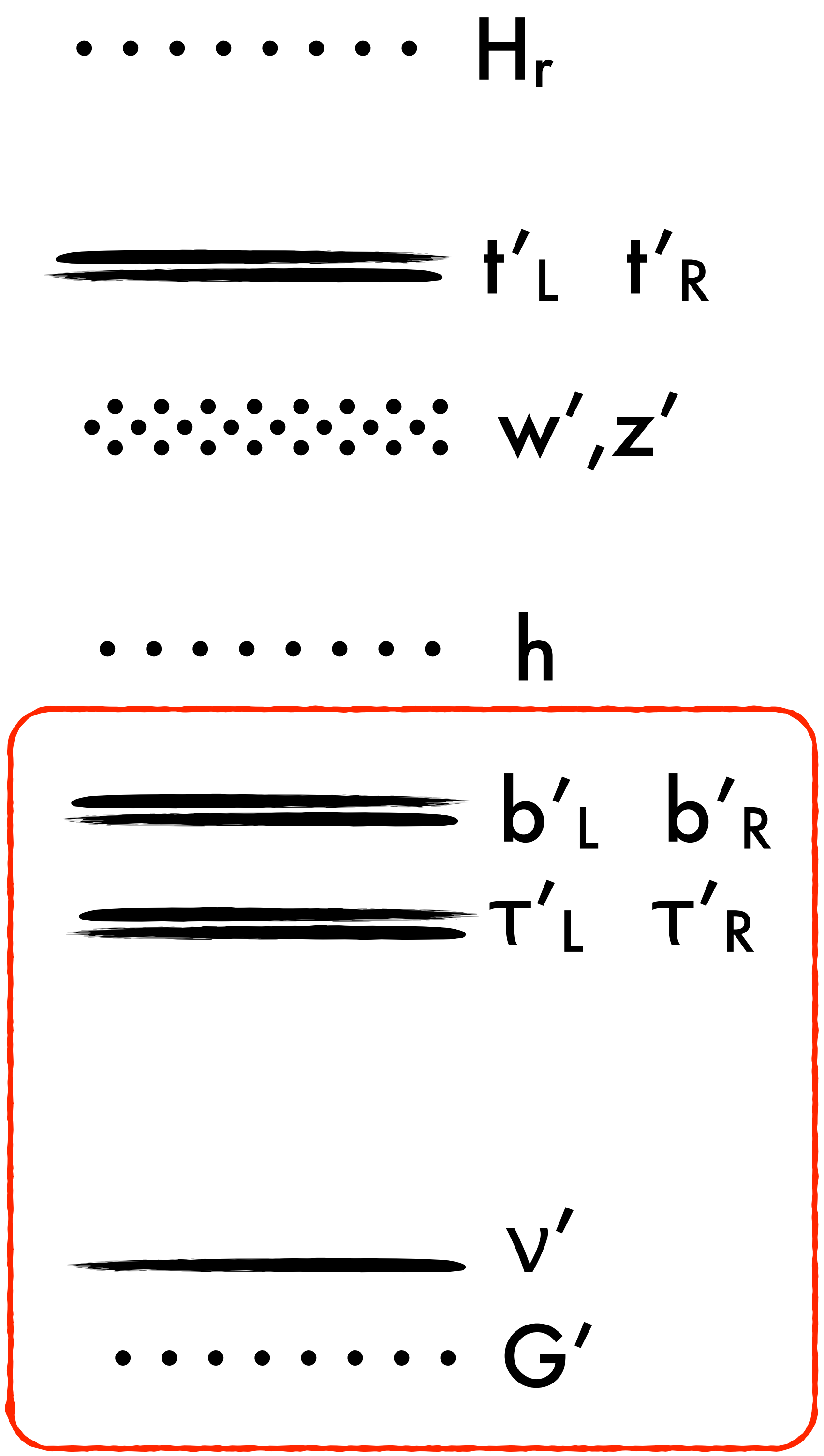
Current searches not constraining; very interesting for 13/14 TeV LHC



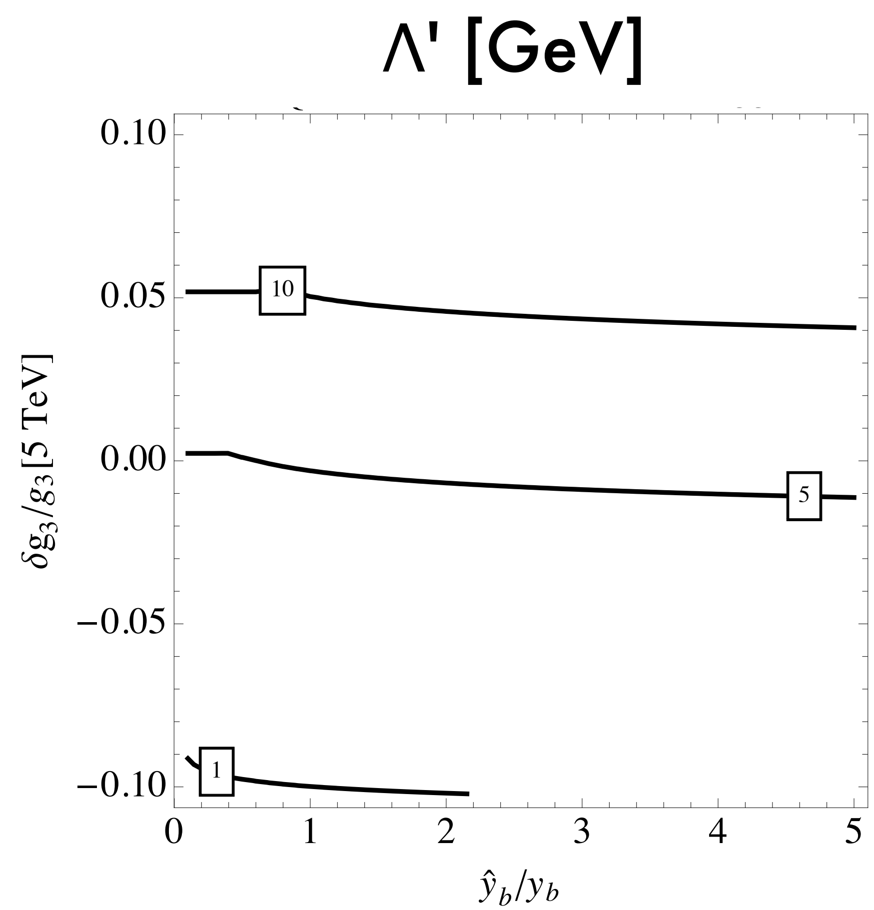
What to look for?

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



Coupling related to QCD by twin symmetry.

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

Confinement within ~order of magnitude of QCD

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

$$\mathcal{L} \supset -\frac{\alpha_3'}{6\pi}\frac{v}{f}\frac{h}{f}G'^{\,a}_{\mu\nu}G'^{\,\mu\nu}_{a}$$

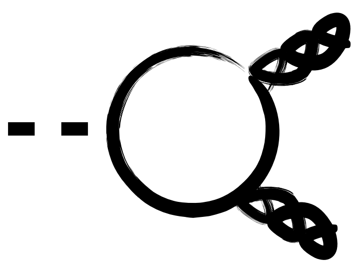
Portal for production…

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

…and decay:

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

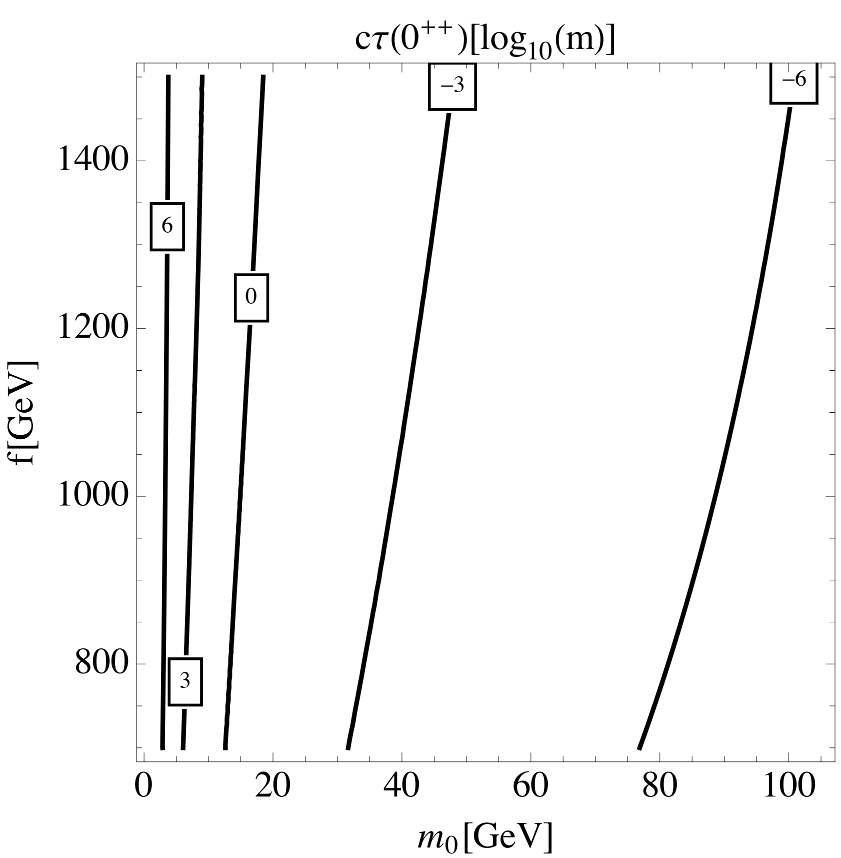
Displaced decays @ LHC



Glueballs produced through decays of Higgs into twin sector, BR ~ 0.1%-10%

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.

A SUSY variation

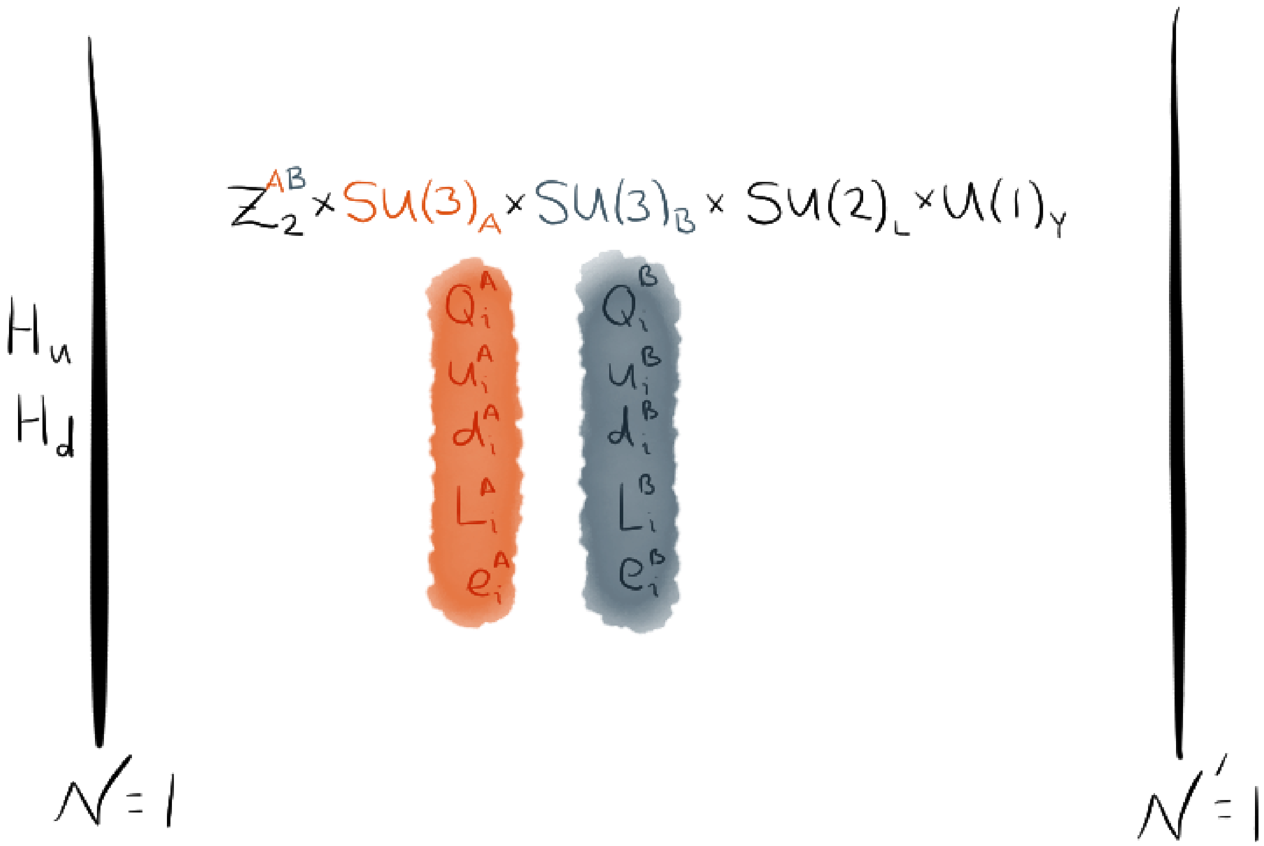
Folded Supersymmetry

[G. Burdman, Z. Chacko, R. Harnik '06]

'folded supersymmetric' theories the one loop quadratic divergences of the Standard Model Higgs field are cancelled by opposite spin partners, but the gauge quantum numbers of these new particles are in general different from those of the conventional superpartners. This class of models is built

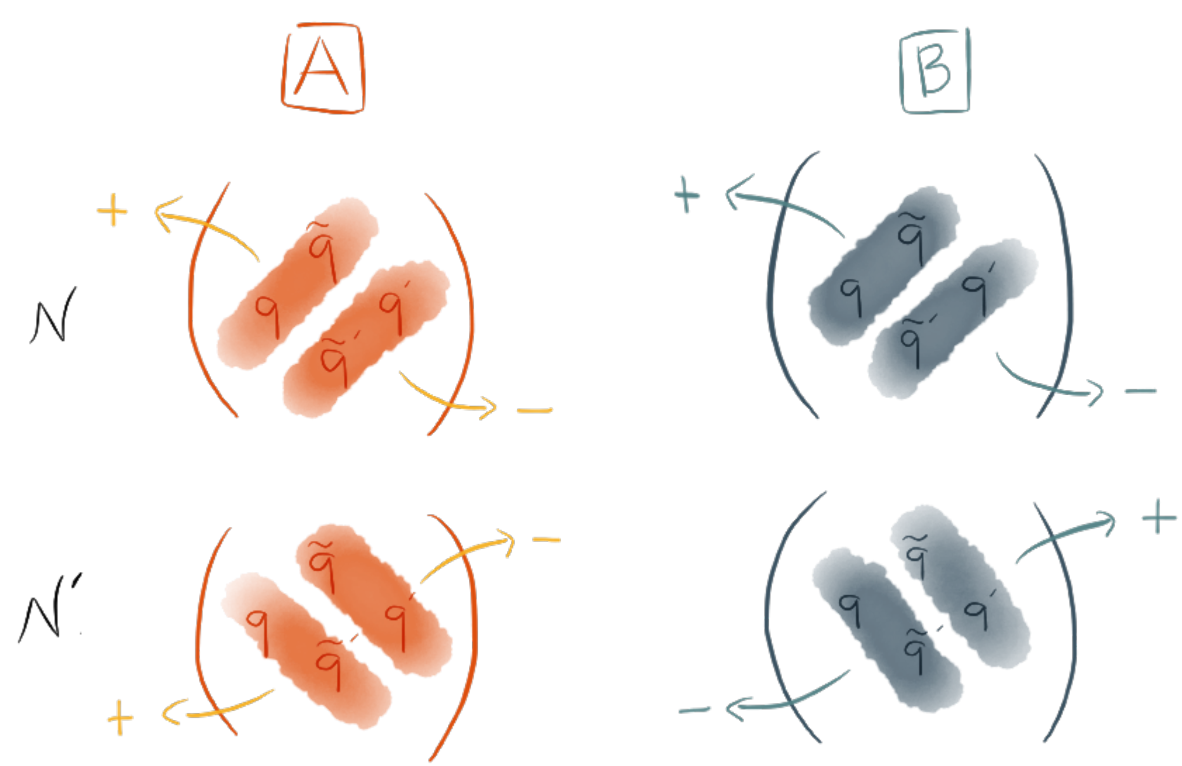
Symmetry is SUSY w/ [$SU(3) \times SU(3)_f \times Z_2$] $\times SU(2) \times U(1)$

SUSY without color



Want a low-energy spectrum with opposite-spin partners; start with a discrete symmetry + 5D SUSY.

Reduce symmetries & SUSY at the boundaries



Can lead to light superpartners with different gauge quantum numbers from SM counterparts.

Folded SUSY

[Burdman, Chacko, Goh, Harnik '06]
[Cohen, NC, Lou, Pinner '15]

Colorless Stops

Zero mode spectrum: SM fermions, folded sfermions

Couplings related by SUSY

$$\mathcal{L} \supset \lambda_t H_u q_3^A u_3^A + \lambda_t^2 |H_u \cdot \tilde{q}_3^B|^2 + \lambda_t^2 |H_u|^2 |\tilde{u}_3^B|^2$$

Normal top quarks

Charged under a hidden SU(3); only carry electroweak SM quantum #'s.

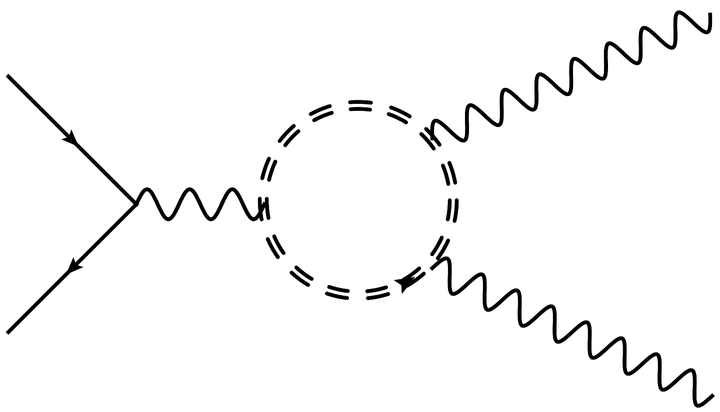
...Plus towers of KK states

Many possible variations using the tools of 5D SUSY model-building.

Higgs potential is finite and calculable, protected by 5D SUSY but with the lightest partner states neutral under QCD.

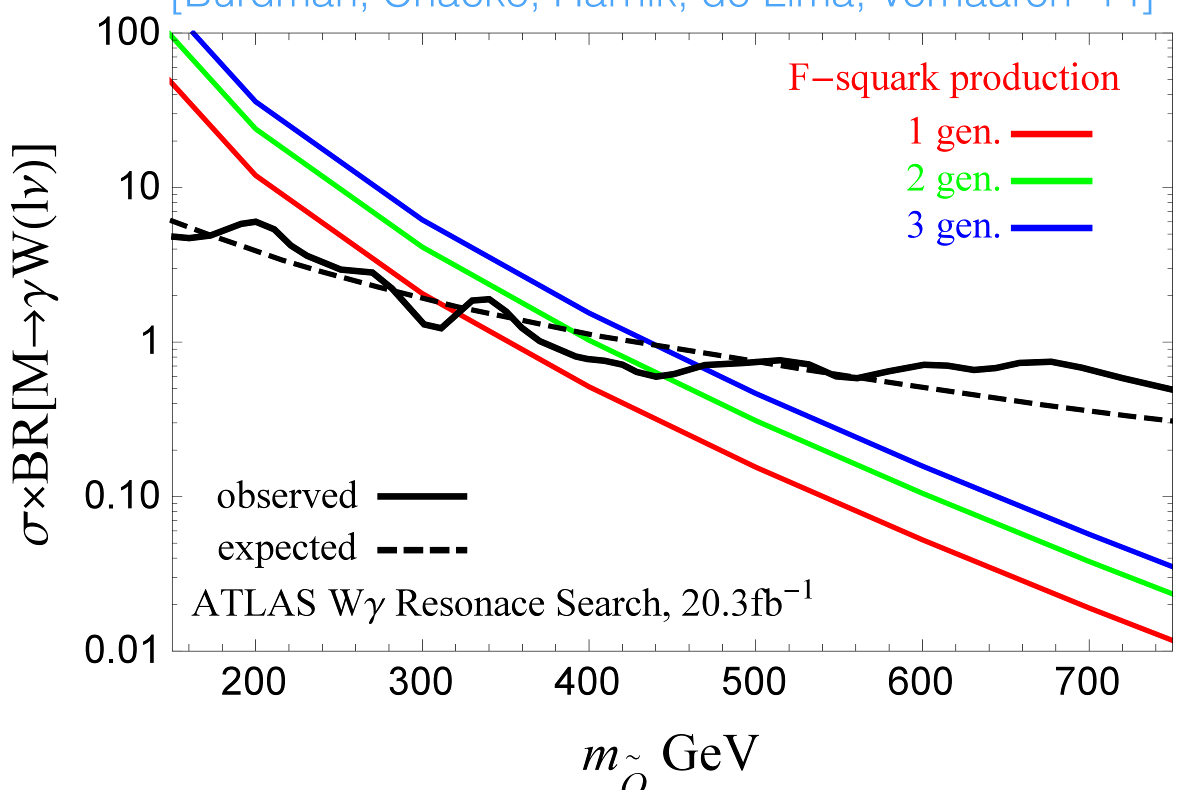
Colorless Signals

F-squarks carry electroweak quantum numbers.

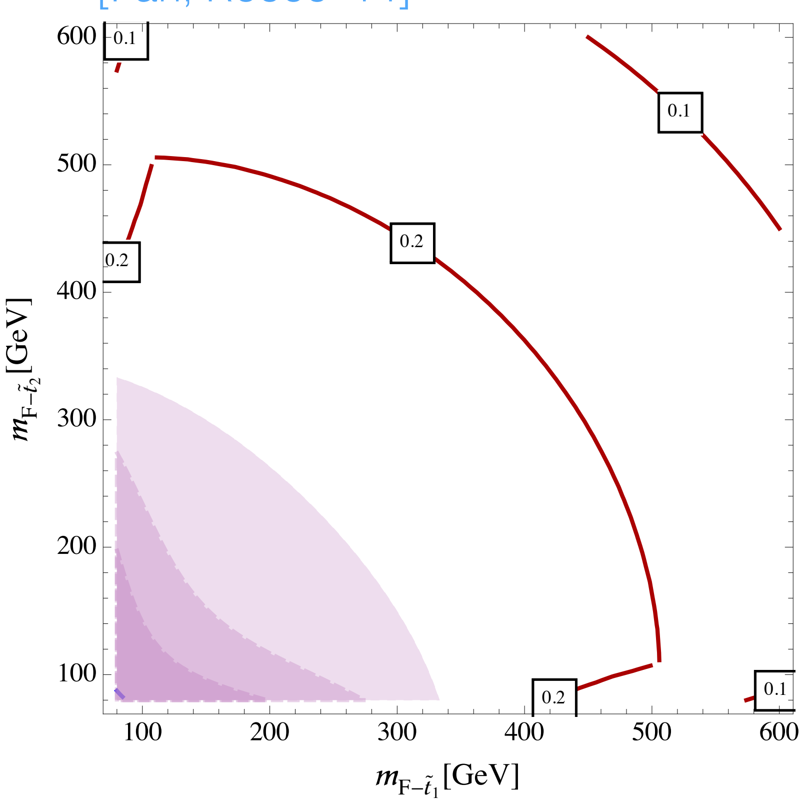


- Produced via a *Z*, annihilate into hidden glueballs, which decay back to SM via Higgs; displaced decays @ LHC length scales.
- Produced via a *W*, annihilate back into the SM to shed their charge.
- Also leave their mark indirectly, correcting Higgs decays to photons.

[Burdman, Chacko, Harnik, de Lima, Verhaaren '14]



[Fan, Reece '14]



Pandora's box

Much progress in recent years; much room to explore

[Chacko, Goh, Harnik '05; Barbieri, Gregoire, Hall '05; Chacko, Nomura, Papucci, Perez '05; Falkowski, Pokorski, Schmaltz '06; Chang, Hall, Weiner '06; Burdman, Chacko, Harnik '06; Foot, Volkas '06; Poland, Thaler '08; Harnik, Wizansky '08; Batra, Chacko '08; NC, Englert, McCullough '13; Chacko, Cui, Hong '13; NC, Howe '13; NC, Knapen, Longhi '14; Geller, Telem '14; Burdman, Chacko, Harnik, Lima, Verhaaren '14; NC, Lou, McCullough, Thalapillil '14; NC, Katz, Strassler, Sundrum '15; Batell, McCullough '15; Barbieri, Greco, Rattazzi, Wulzer '15; Low, Tesi, Wang '15; NC, Katz '15; Garcia Garcia, Lasenby, March-Russell '15; Farina '15; Curtin, Verhaaren '15, Csaki, Kuflik, Lombardo, Slone '15; Kilic, Swaminathan '15; Cohen, NC, Lou, Pinner '15]

See also Friday talks by Curtin, Telem, Verhaaren, Salvioni

A plethora of new naturalness-related signatures @ LHC:

- Higgs invisible width [mirror Twin Higgs]
- Tree-level Higgs coupling deviations [Twin Higgs]
- Loop-level $h\gamma\gamma$, hZZ coupling deviations [folded SUSY]
- Displaced Higgs decays [folded SUSY, fraternal Twin Higgs]
- Heavy higgs with reduced couplings, invisible width [Twin Higgs]
- $W\gamma$, hh, displaced 4b resonances [folded SUSY]

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Thank you!