Neutral Naturalness

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UC Santa Barbara

Dark Interactions 2016 @ BNL


Dark
Interactions
?
BSM
Motivation

Dark Interactions

~~$SU(3)_c \times SU(2)_L \times U(1)_Y$~~

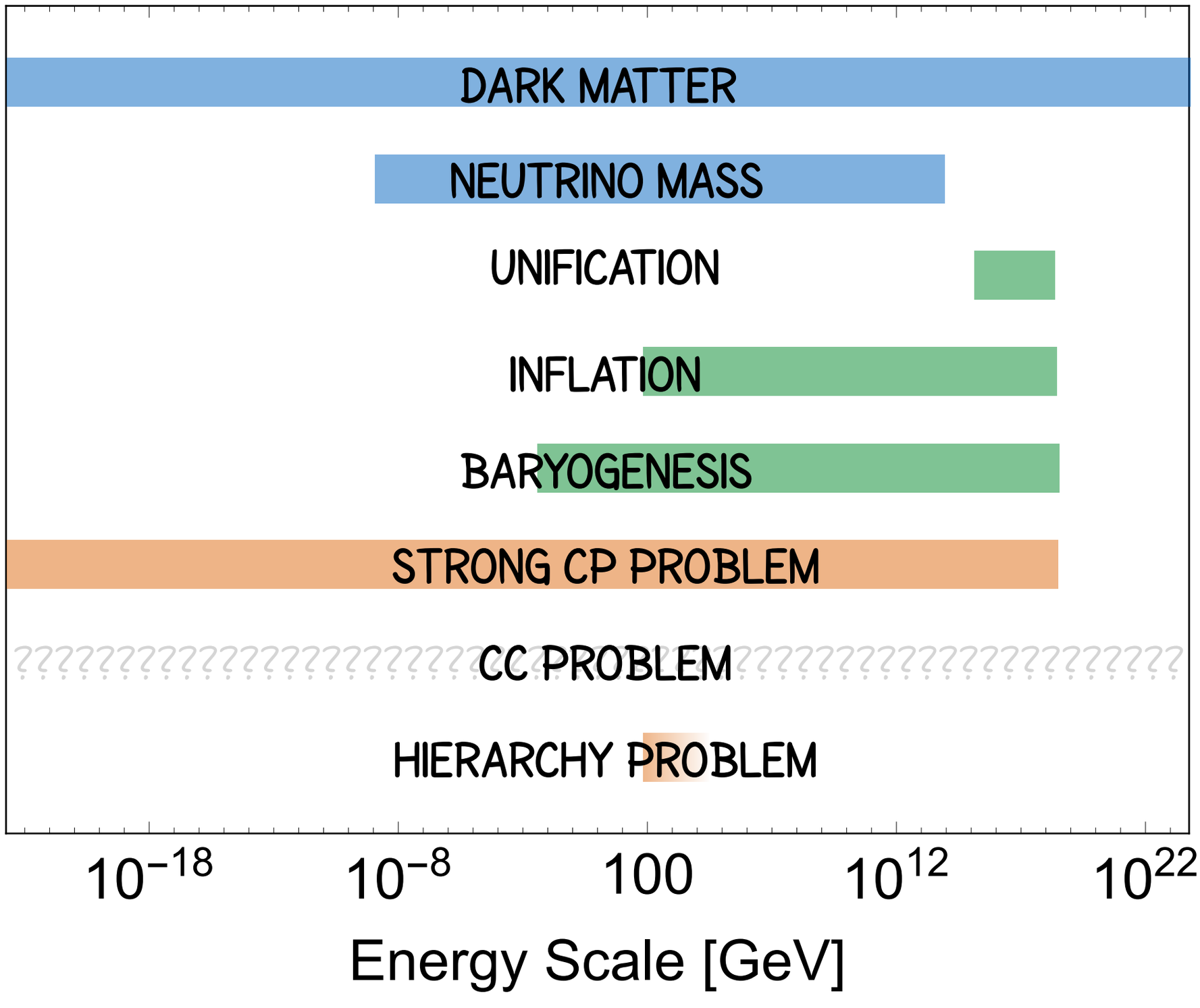
Higgs portal $\lambda|H|^2\mathcal{O}_\phi \sim \left(\frac{E}{\Lambda}\right)^{-1 \text{ or } 0}$

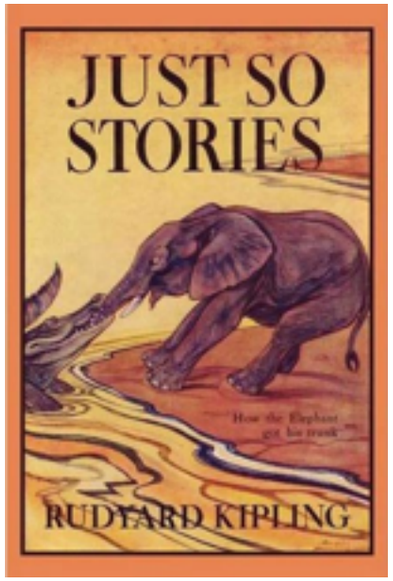
Hypercharge portal $\epsilon F^{\mu\nu}F'_{\mu\nu} \sim \left(\frac{E}{\Lambda}\right)^{0}$

Neutrino portal $y(LH)\mathcal{O}_\psi \sim \left(\frac{E}{\Lambda}\right)^{0 \text{ or } 1}$

Kitchen sink portal $\frac{1}{\Lambda^2}\bar{\Psi}\Psi\bar{\psi}\psi \sim \left(\frac{E}{\Lambda}\right)^{2 \text{ or more}}$

BSM Motivation





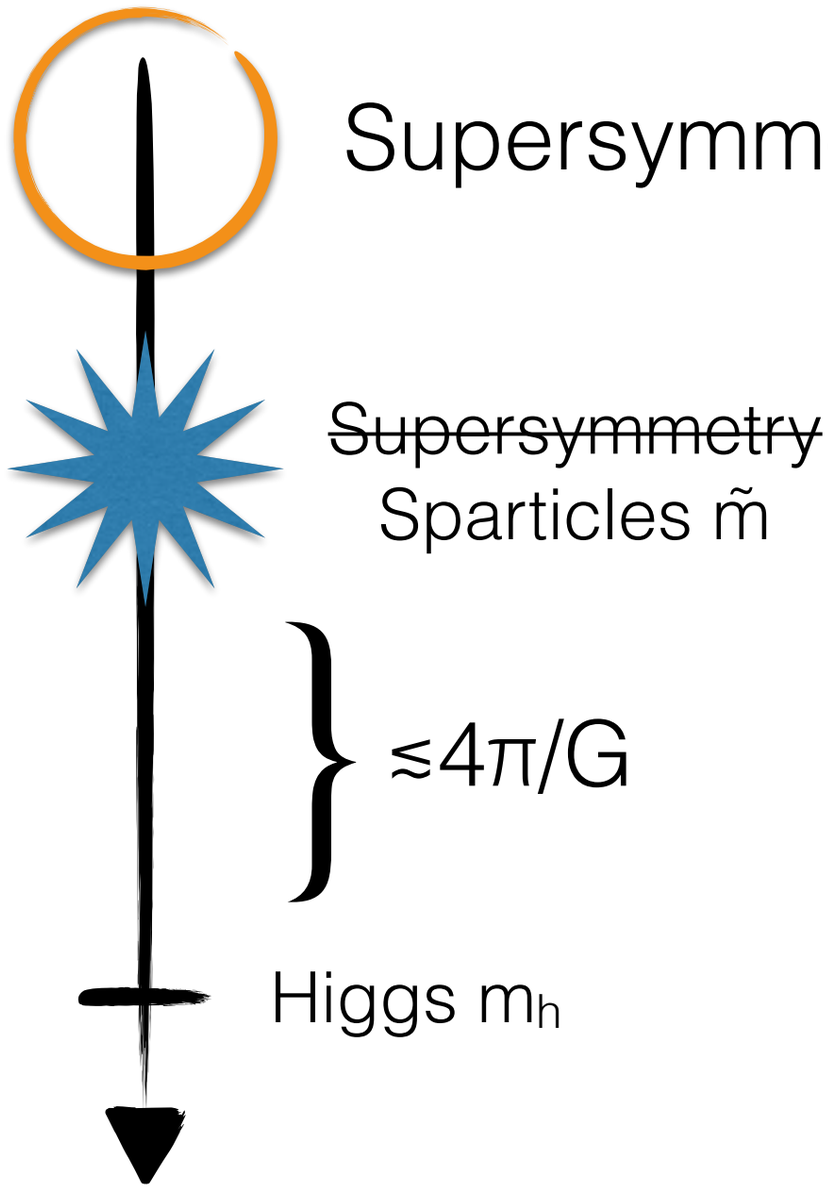
Natural vs. unnatural

Hierarchy problem is more than a "just-so story,"
it's a question of symmetries (or the lack thereof)

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 $m^2\lvert H\rvert^2$	None	$\delta m \propto \Lambda$ **Unnatural!**

Hierarchy Solutions

Extend the SM with a symmetry acting on the Higgs

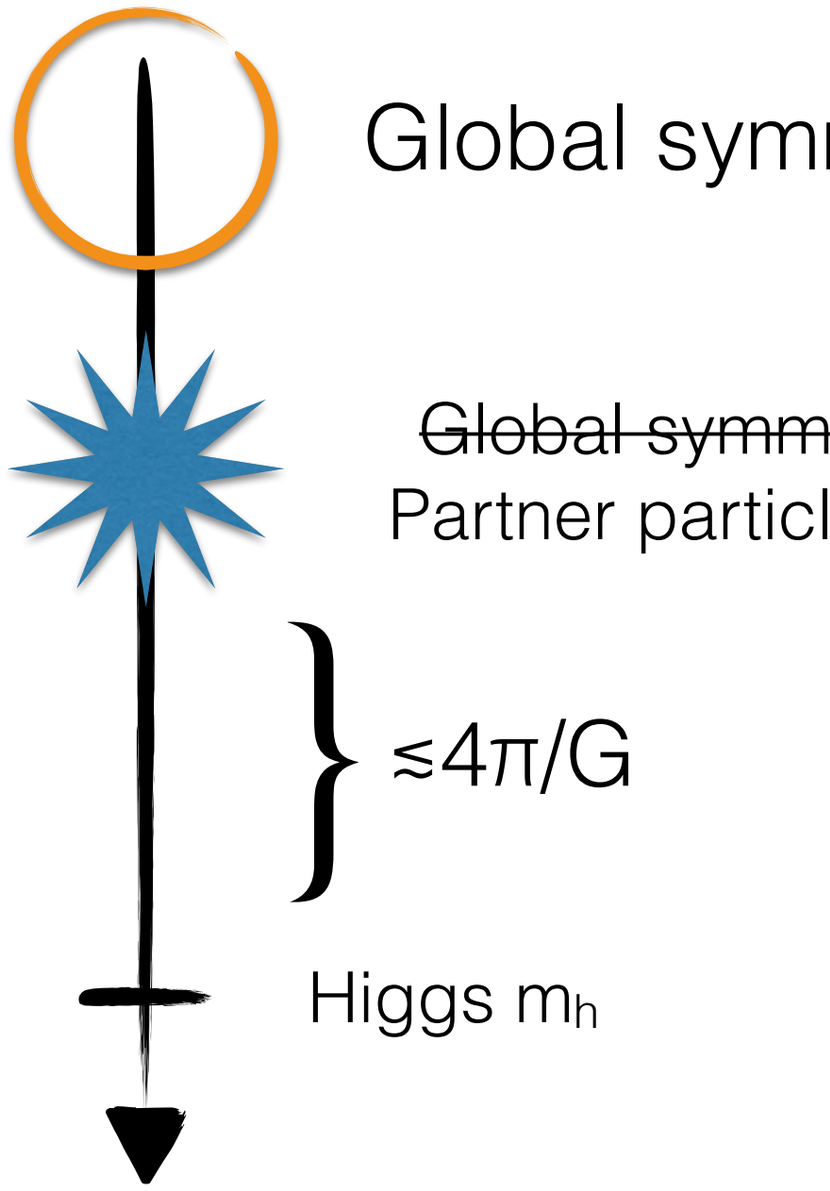


Supersymmetry

~~Supersymmetry~~
Sparticles m̃

≲4π/G

Higgs m_h



Global symmetry

~~Global symmetry~~
Partner particles m̃

≲4π/G

Higgs m_h

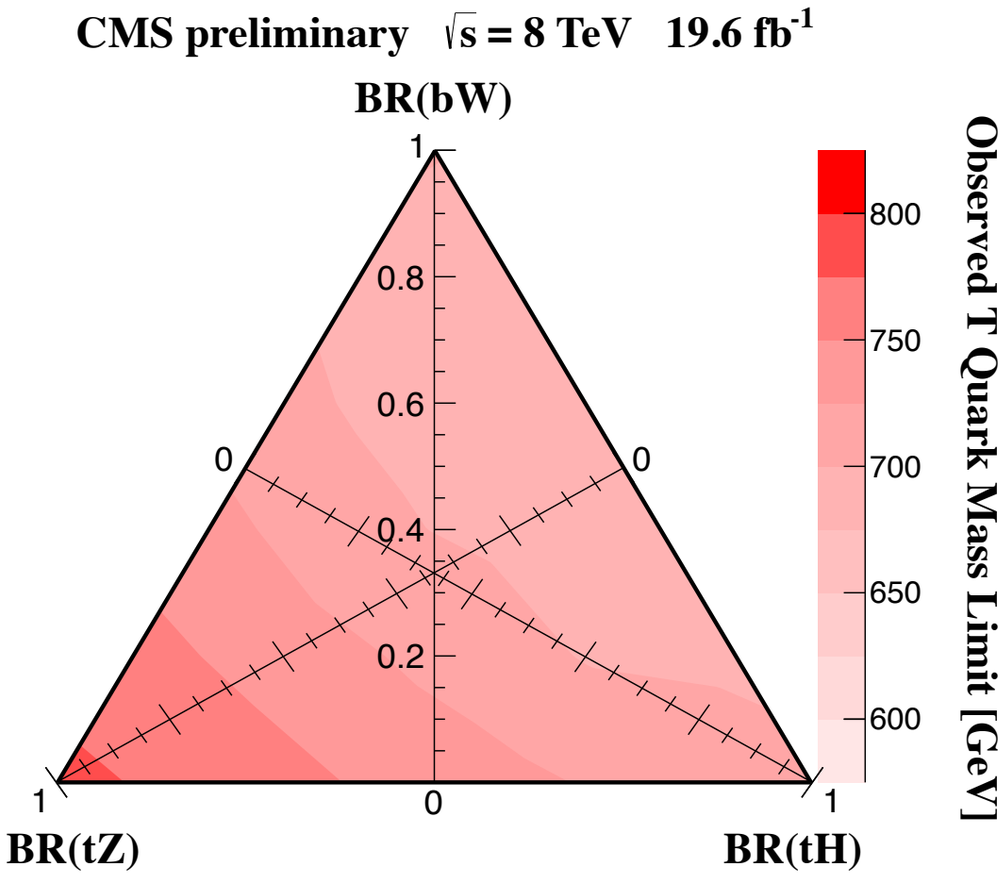
Two spectra

Simple game for LHC: look for colored partners.

Missing top partner problem

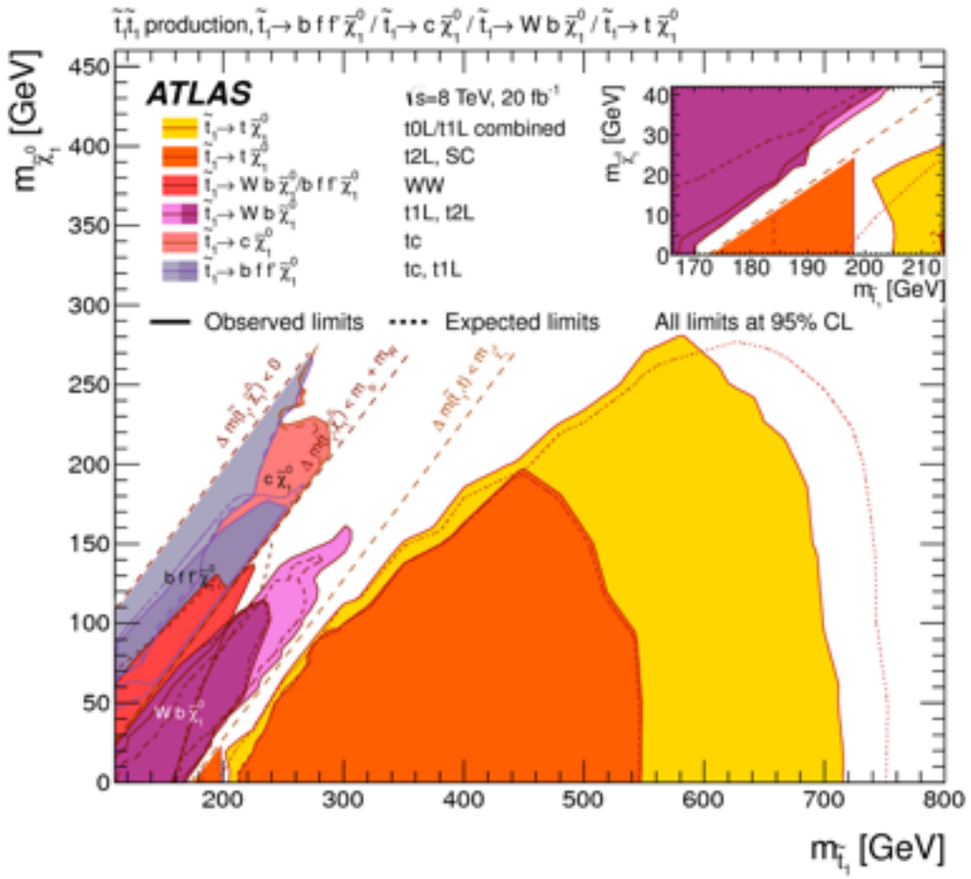
LHC searches driven by top partners

Global Symmetry



CMS B2G-12-015

Supersymmetry

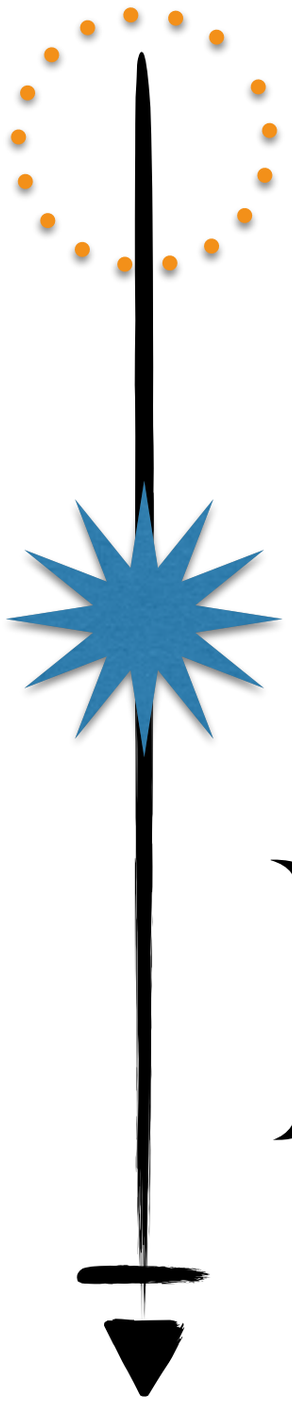


Problem 1: nothing yet (~0.1-10% tuning).

Problem 2: not much new to do.

But: is this all there is?

Discrete symmetries



Discrete symmetry

~~Discrete symmetry~~
Neutral partners $\tilde{m}$

$\lesssim 4\pi/G$

Higgs m_h

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"

Discrete symmetries imply rich dark sector

Hierarchy problem fixes scales near weak scale & requires portals.

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: λ≫1 NLSM; λ≲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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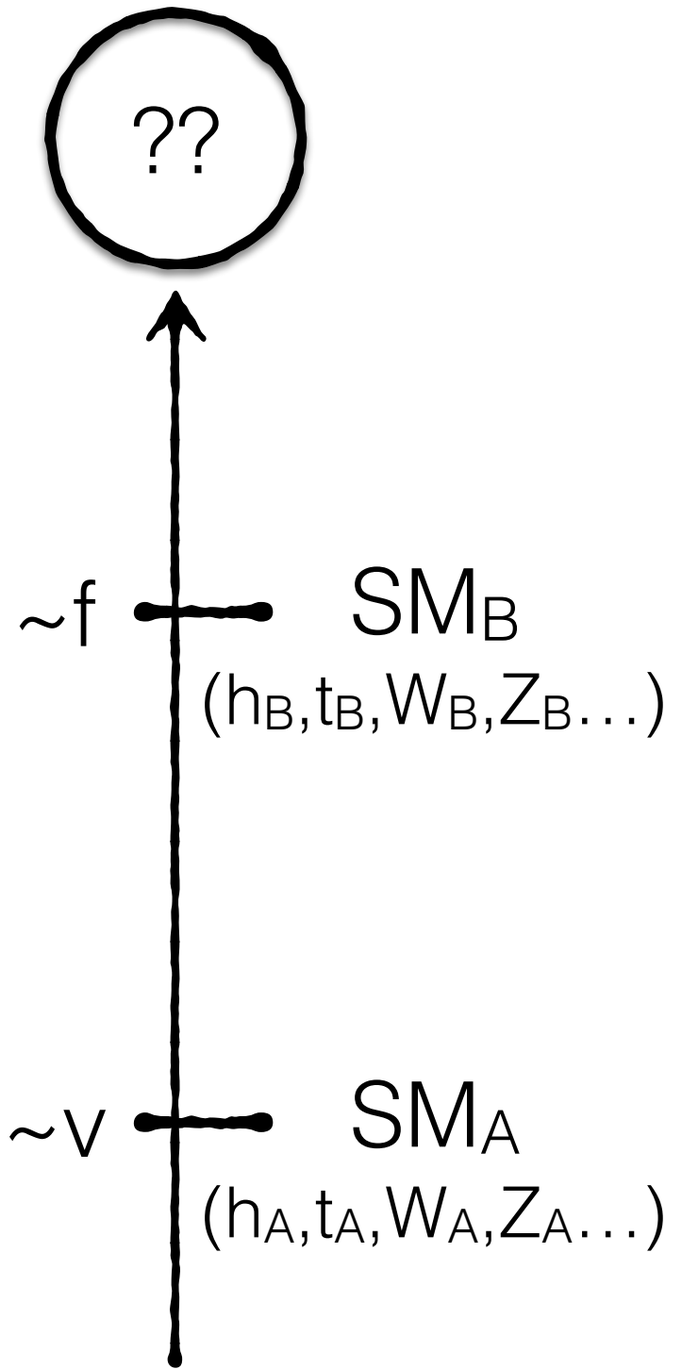
The Twin Higgs

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

$SM_A \times SM_B \times Z_2$



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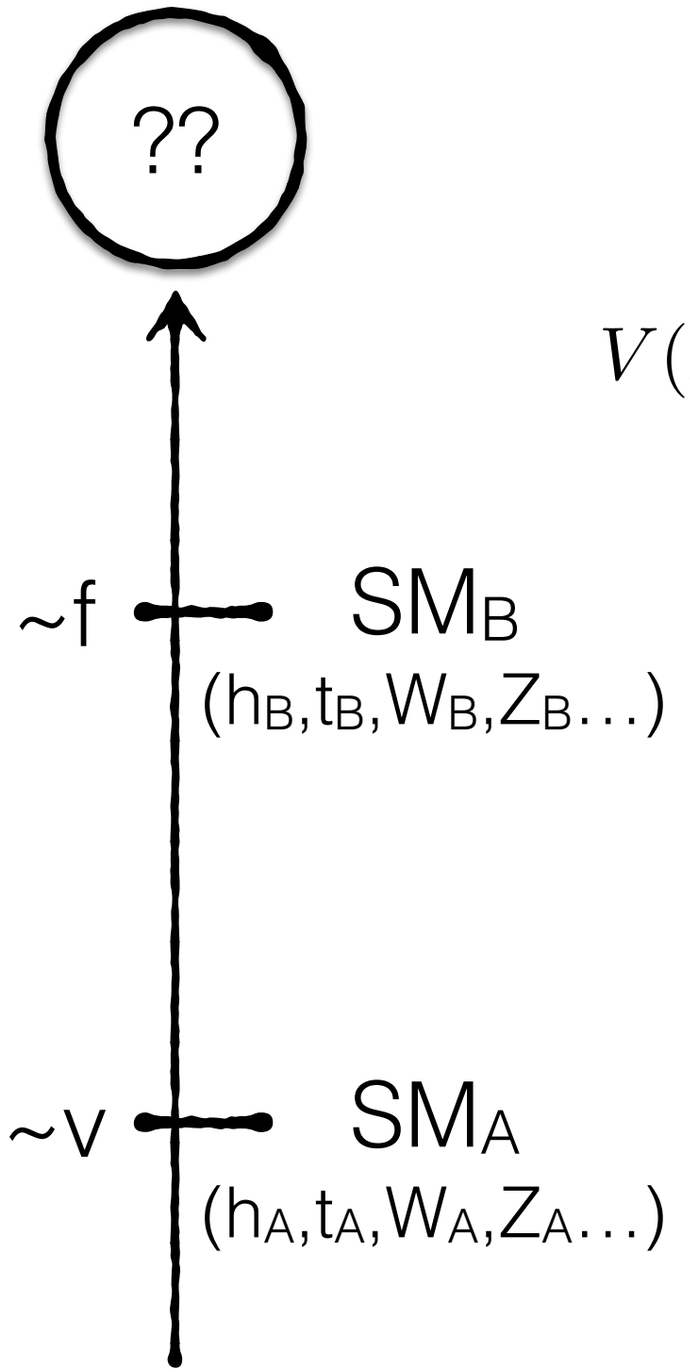
$SM_A \times SM_B \times Z_2$

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



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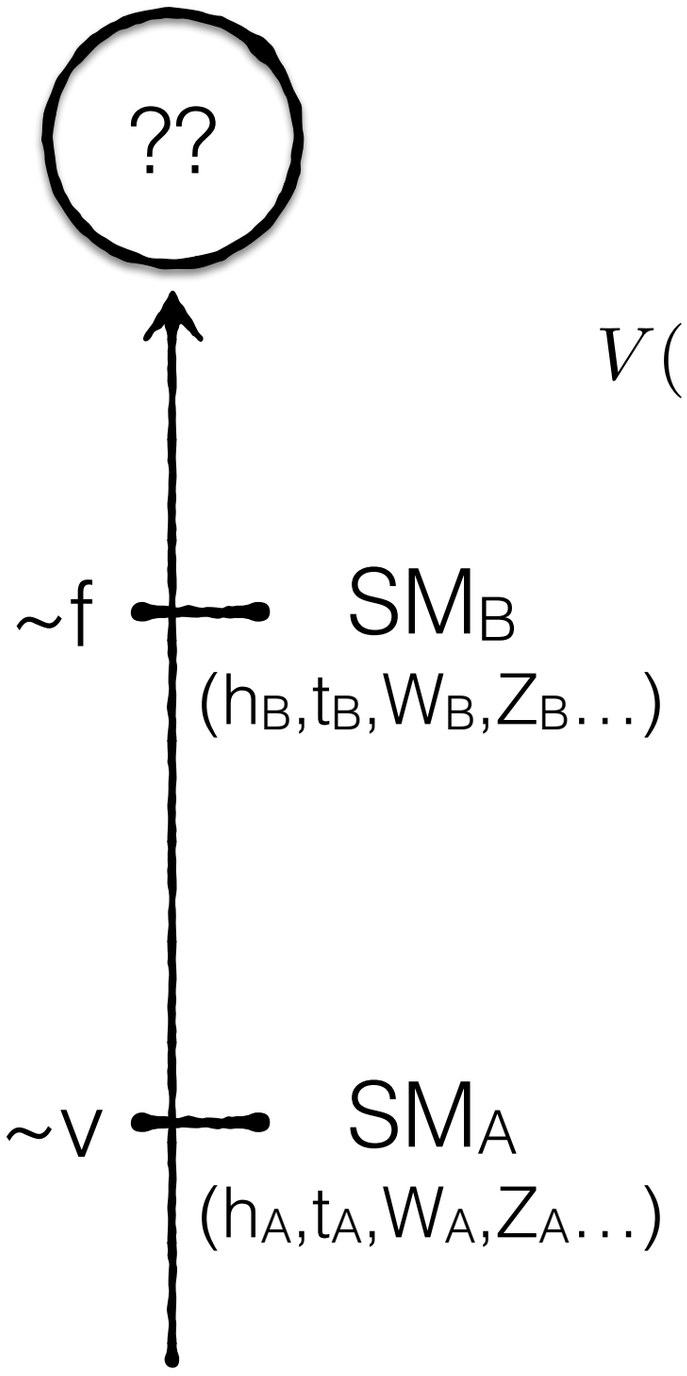

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$$|\langle H_A\rangle|^2 + |\langle H_B\rangle|^2 = f^2$$

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

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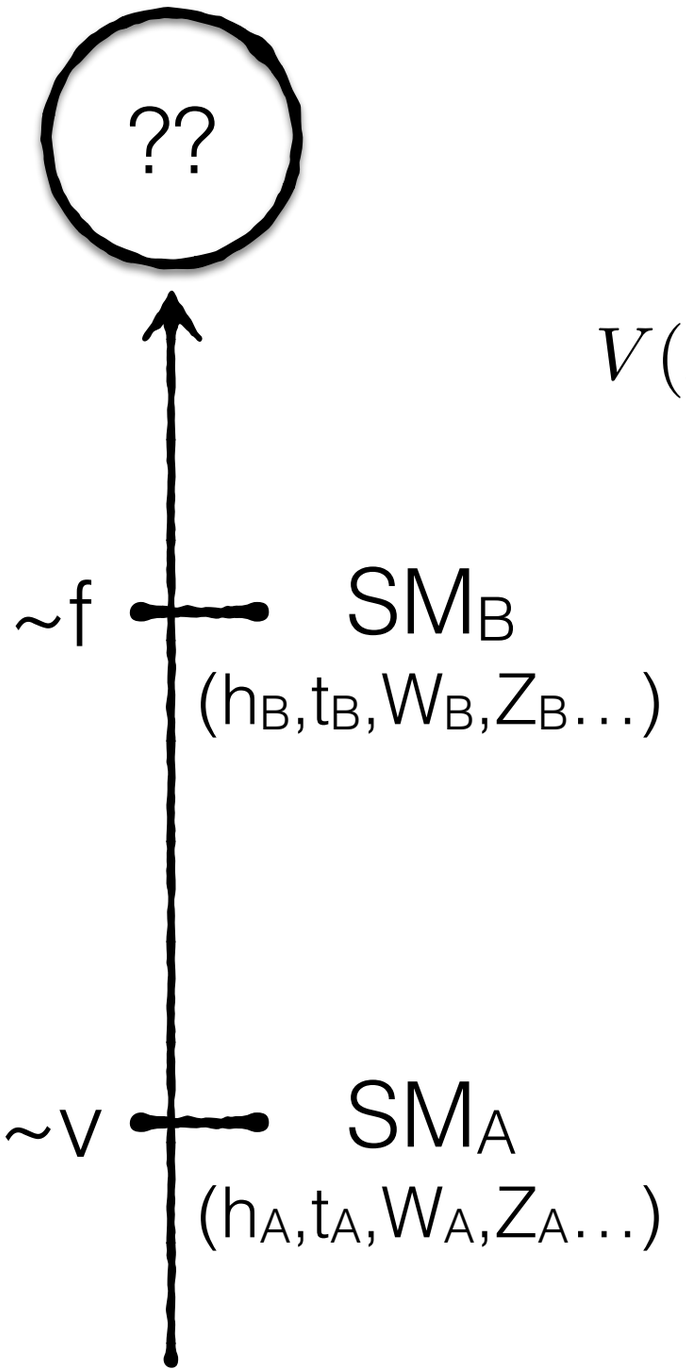

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Gives a radial mode, a goldstone mode,
and **eaten goldstones.**

$v \ll f$ for SM-like Higgs to be the goldstone,
but tuning is O(v/f)

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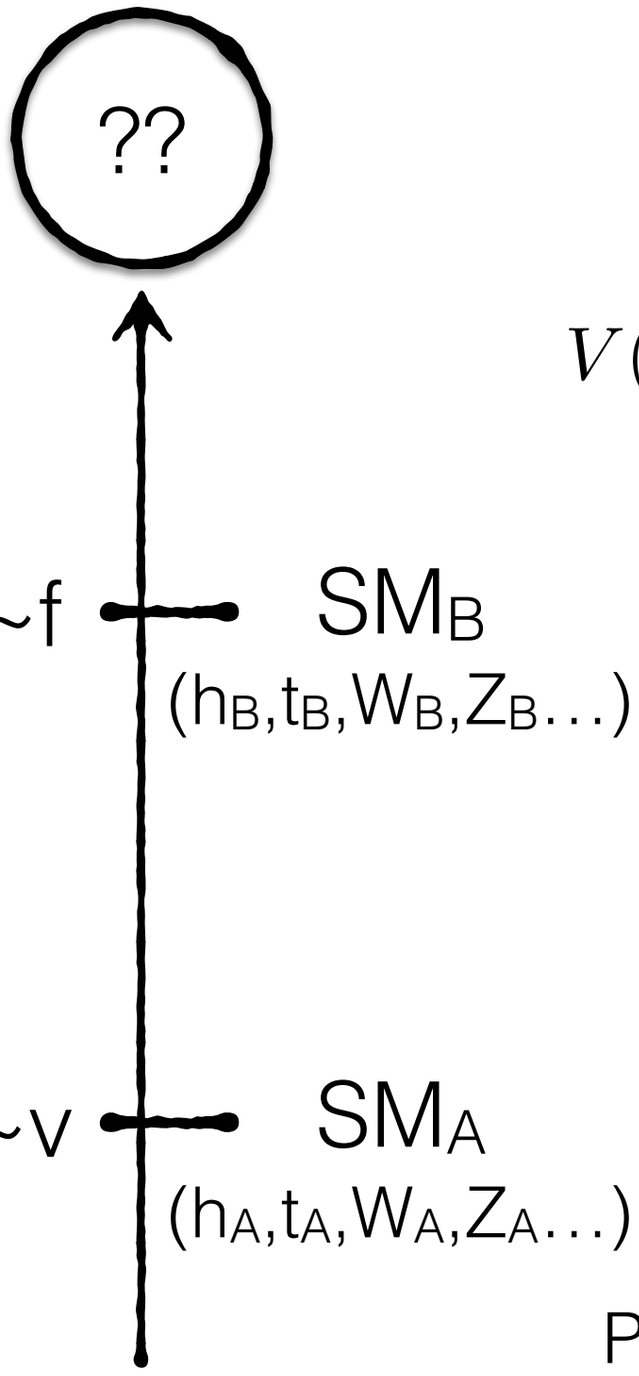

$$\mathrm{SM}_A \times \mathrm{SM}_B \times Z_2$$

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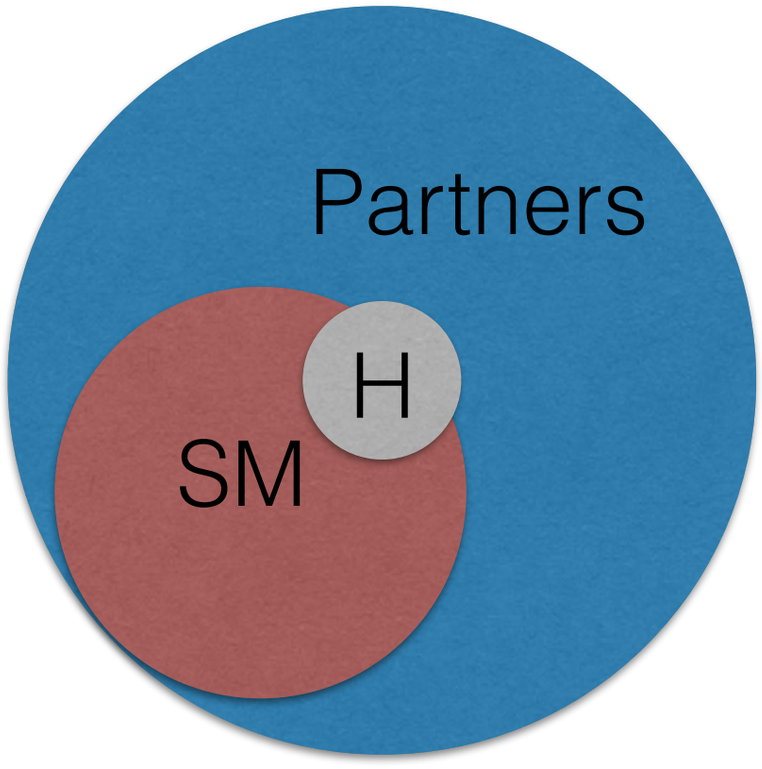
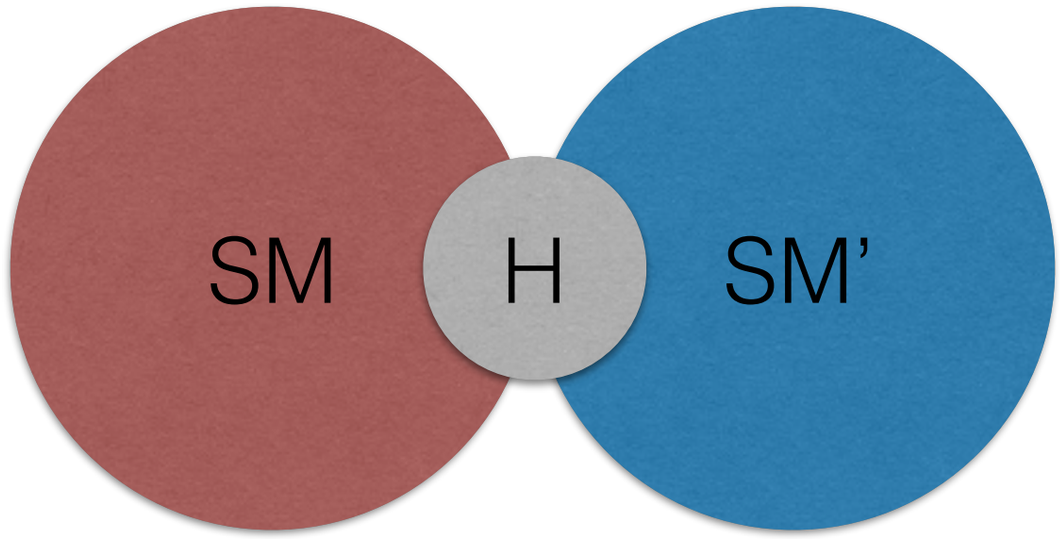
v ≪ f for SM-like Higgs to be the goldstone,
but tuning is O(v/f)

Primary coupling between SM_A and SM_B via Higgs portal

The big picture

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

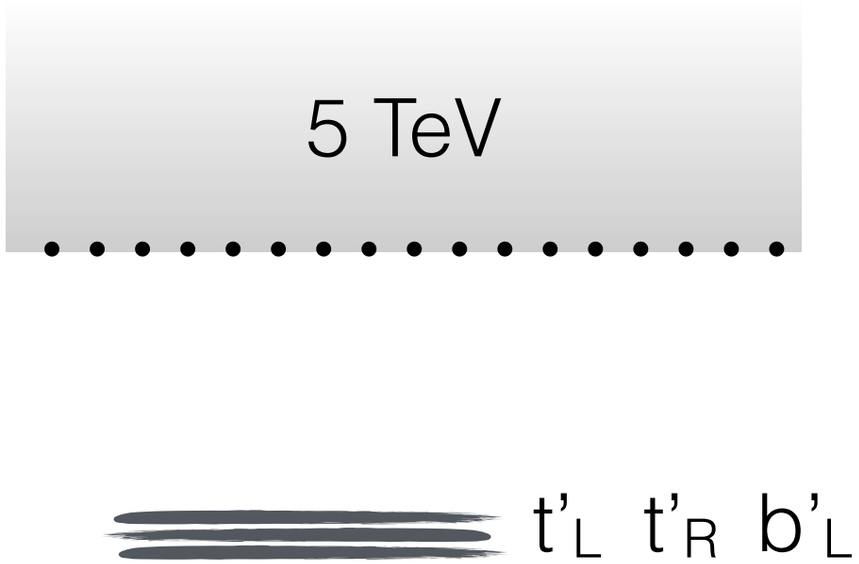




Protect Higgs w/ a hidden sector mirroring the SM. Partners have no SM charges. Must have Higgs portal.

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

The space of theories



Simplest theory: exact mirror copy of SM

[Chacko, Goh, Harnik '05]

But this is more than you need, and mirror 1st, 2nd gens lead to cosmological problems

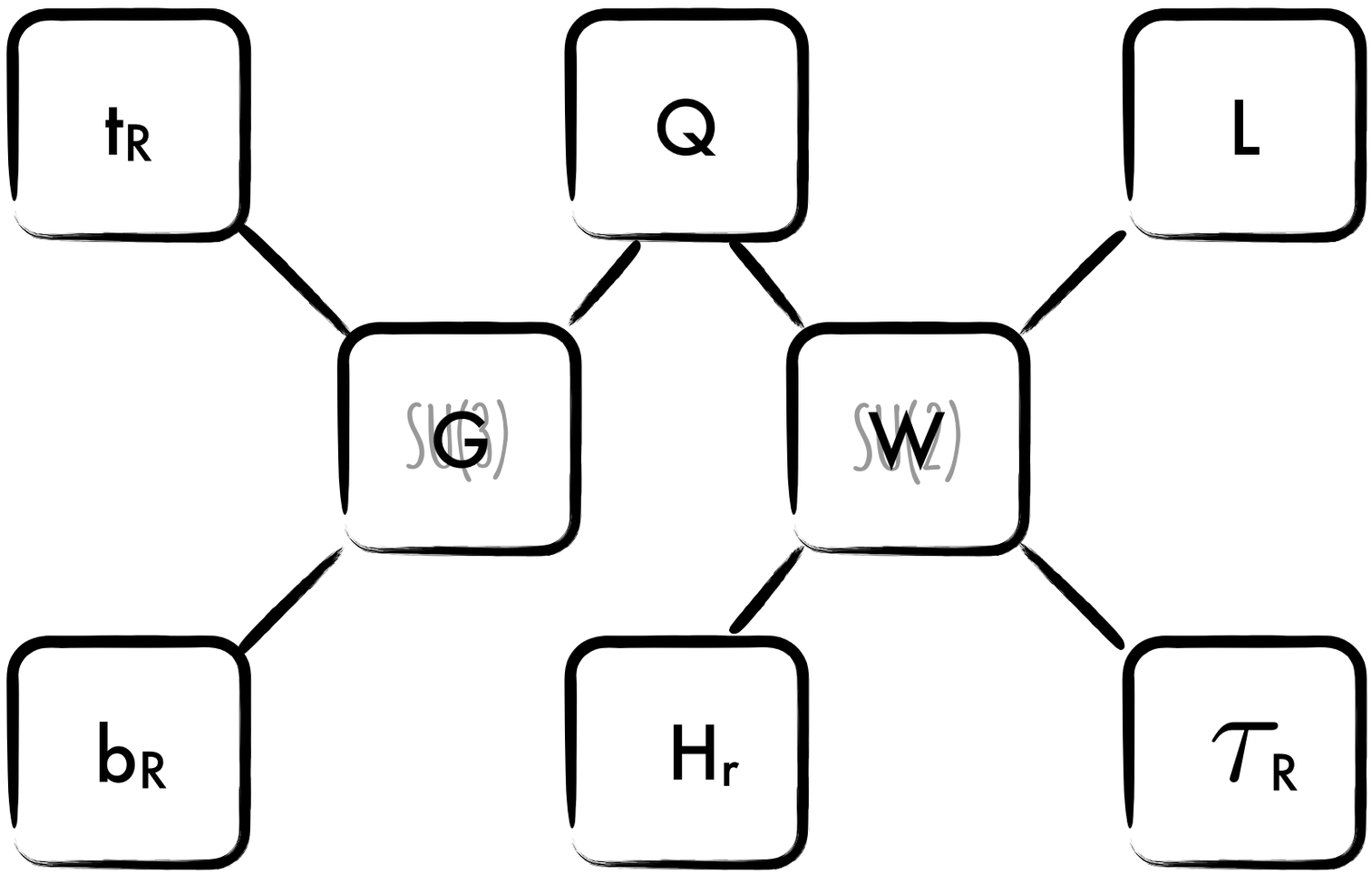
Many more options where symmetry is approximate, e.g. a good symmetry for heaviest SM particles.

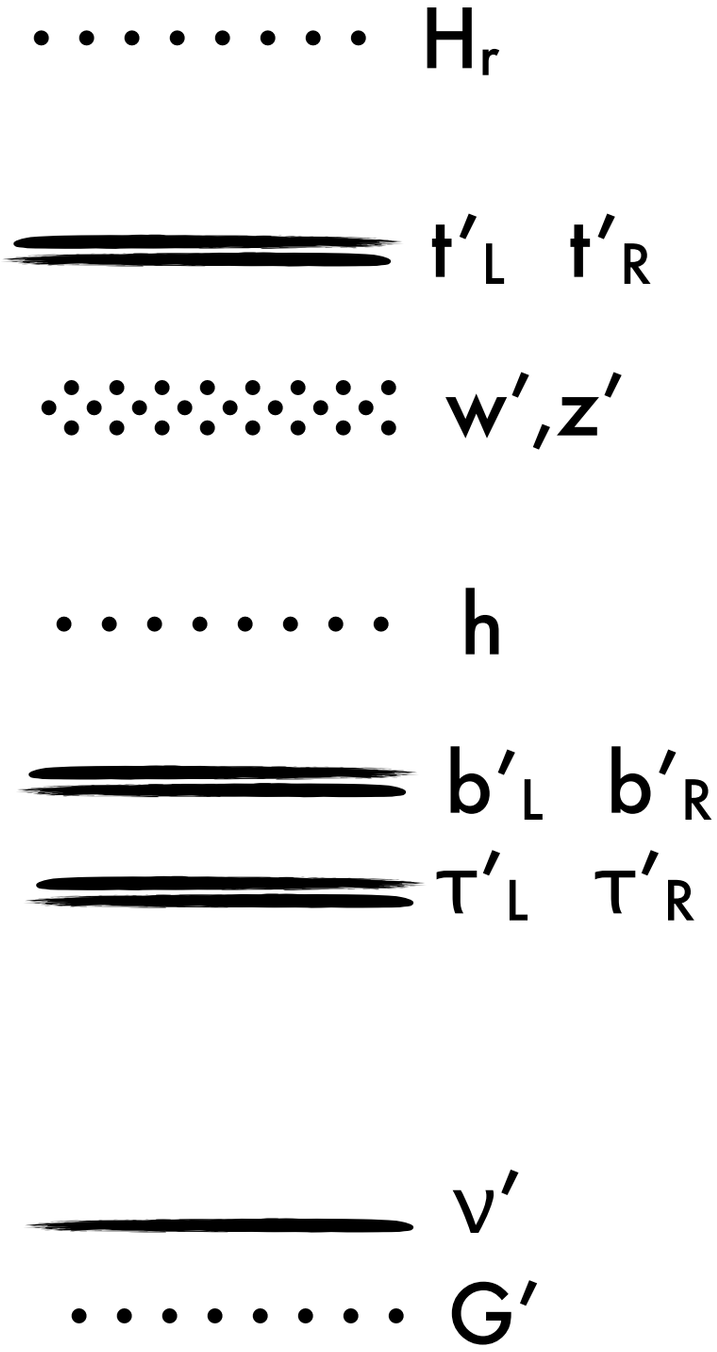
[NC, Knapen, Longhi '14; Geller, Telem '14; NC, Katz, Strassler, Sundrum '15; Barbieri, Greco, Rattazzi, Wulzer '15; Low, Tesi, Wang '15, NC, Knapen, Longhi, Strassler '16]

[NC, Katz, Strassler, Sundrum '15]

The minimal model

Just Z_2 partner states for the third generation.



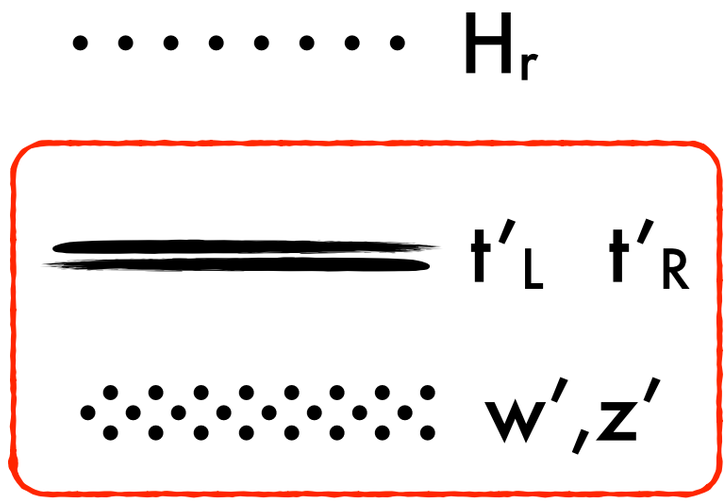


The "Fraternal" Twin Higgs

See also: Vector-like Twin Higgs [NC, Knapen, Longhi, Strassler '16]

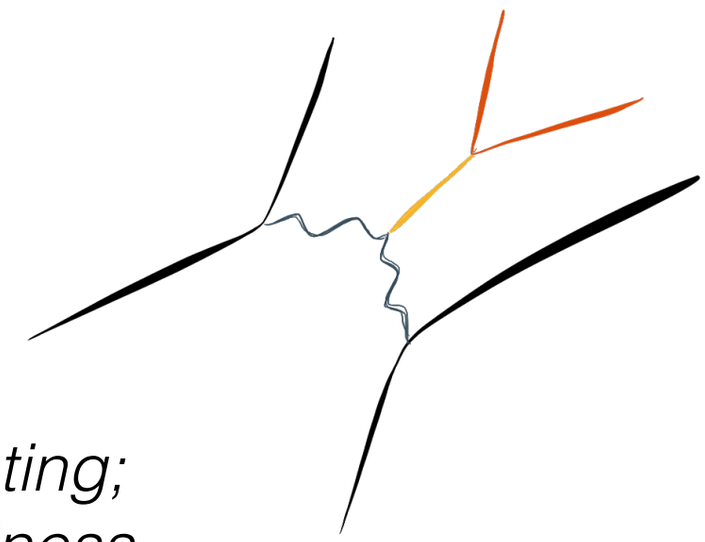
What to look for?

[Mixing leads to O(v/f)^2 changes in Higgs couplings; current O(20%) precision not constraining.]

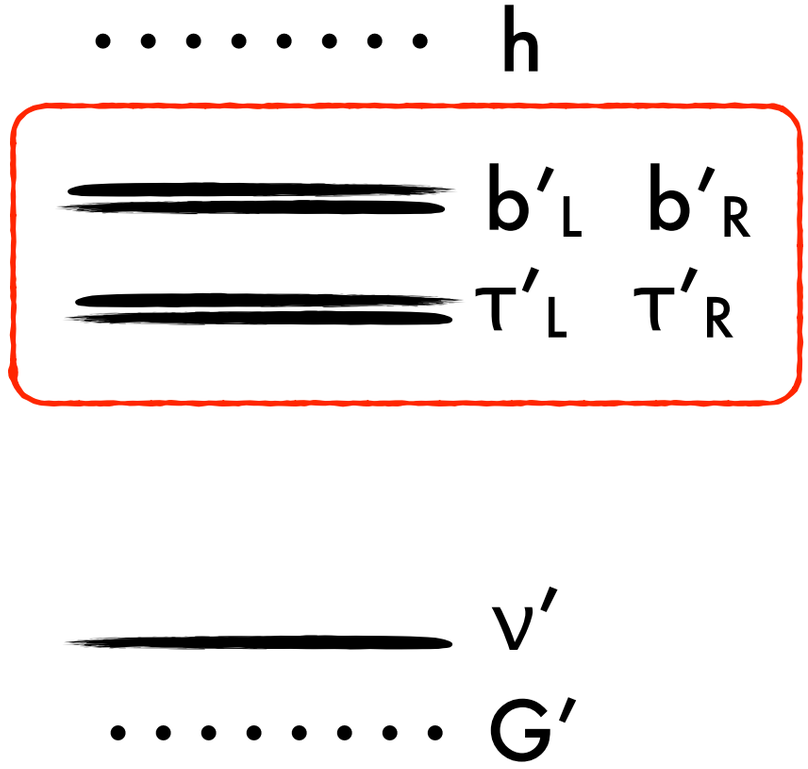


- Partner states are SM neutral, couple only to the Higgs. Lighter than $m_h/2$: modest invisible BR (or more).

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

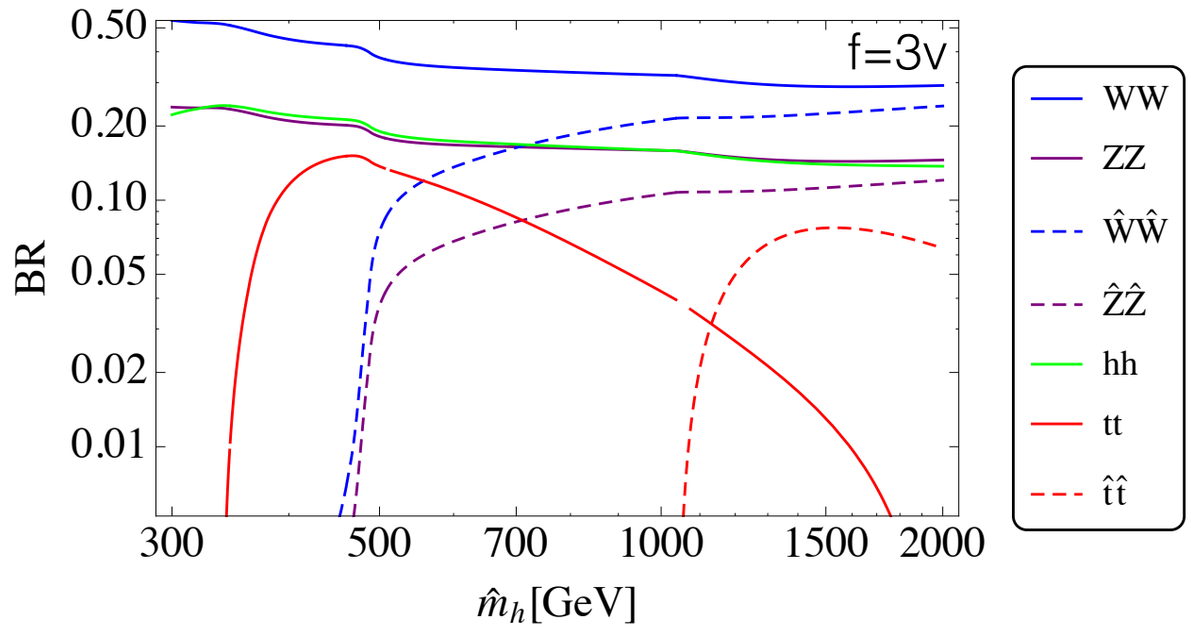


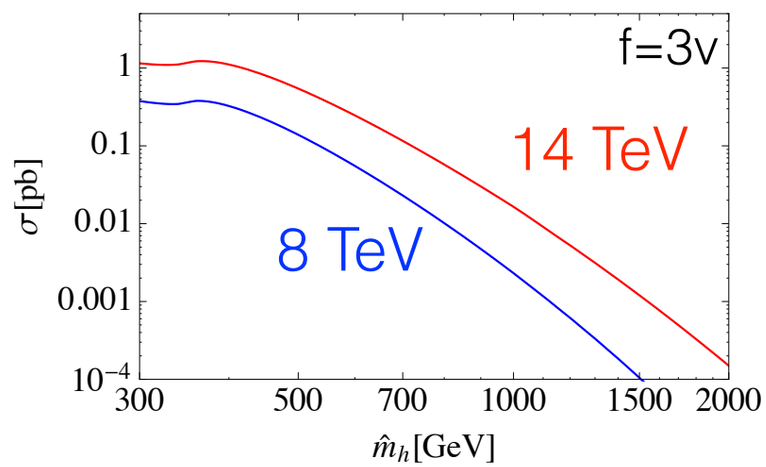
Hard but very interesting; directly probe naturalness



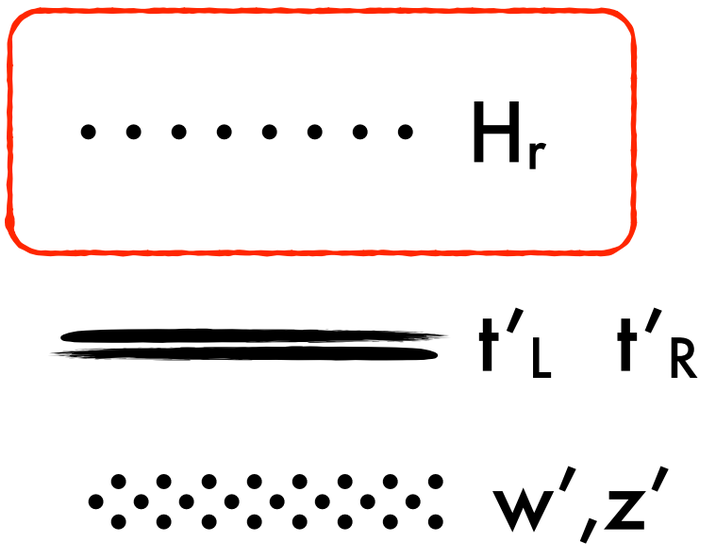
What to look for?

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



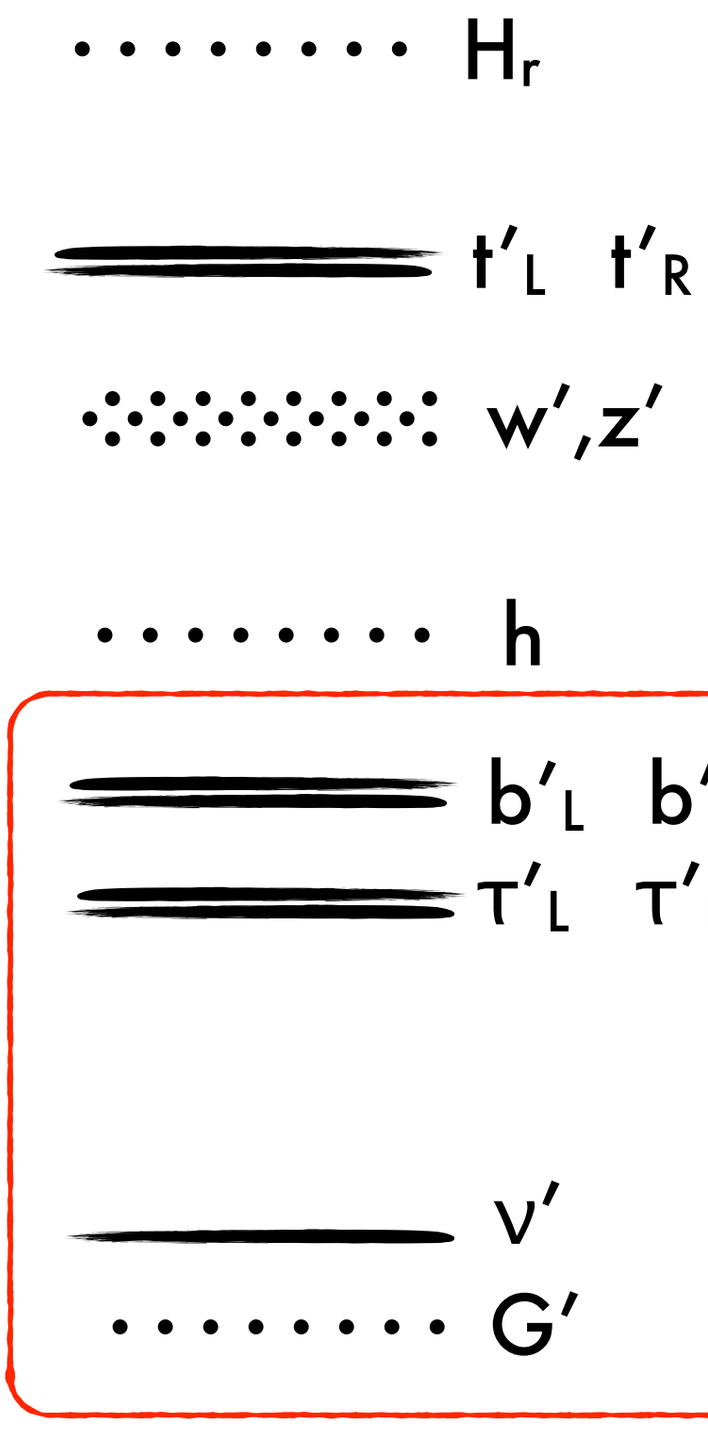


Current searches not constraining; very interesting for 13/14 TeV LHC



What to look for?

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



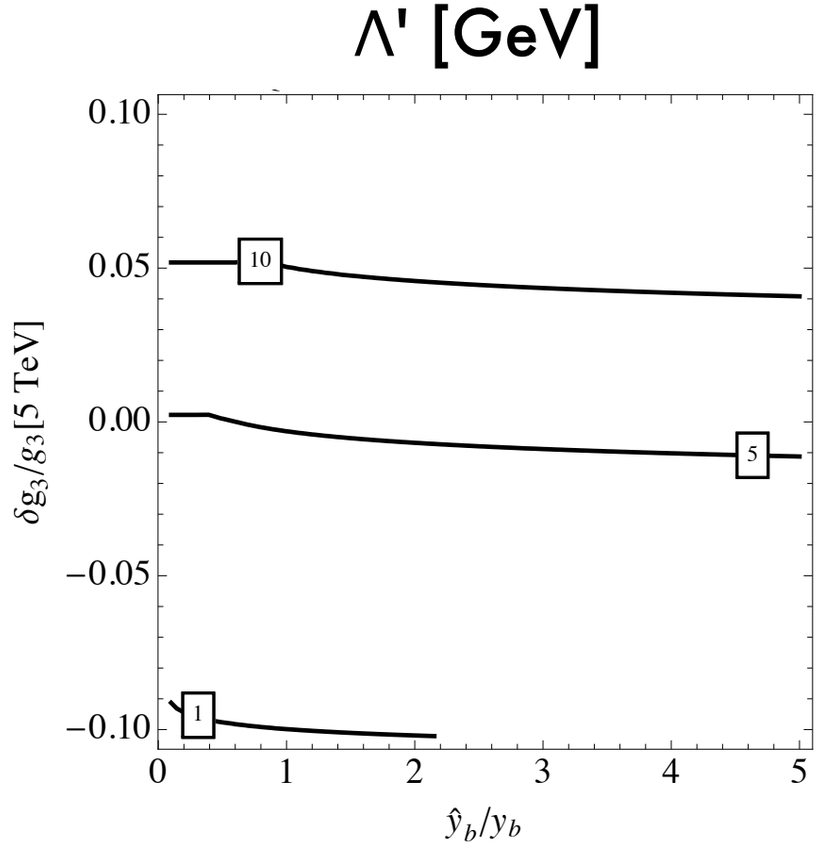
- Light colored fermions in the hidden sector: form light hadrons. Look for invisible decays of the Higgs.
- Light neutrinos in the hidden sector can mix with SM: look for neutrino portal.
- Light U(1) in the hidden sector: massless or massive, can kinetically mix, look for hidden photon phenomena.
- 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:

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

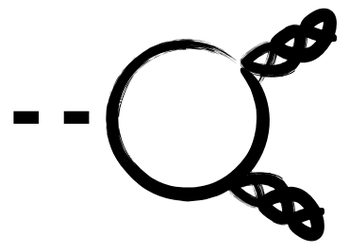
Glueballs are special: mix with SM via dim-6 operator

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

Portal for production… $gg \to h \to 0^{++} + 0^{++} + \ldots$

…and decay: $0^{++} \to h^* \to f\bar{f}$

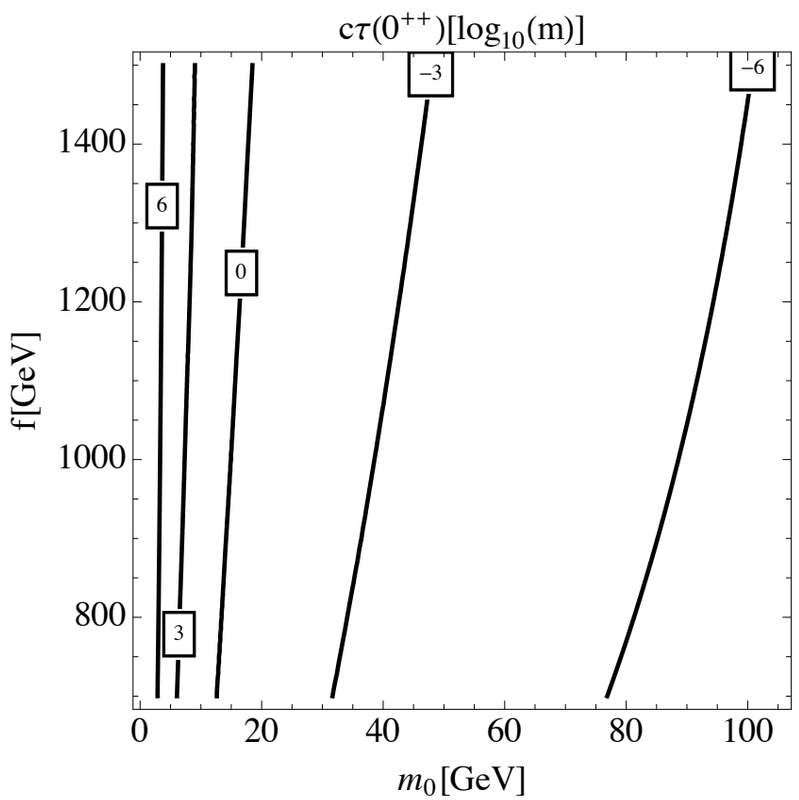
Displaced decays @ LHC



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

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



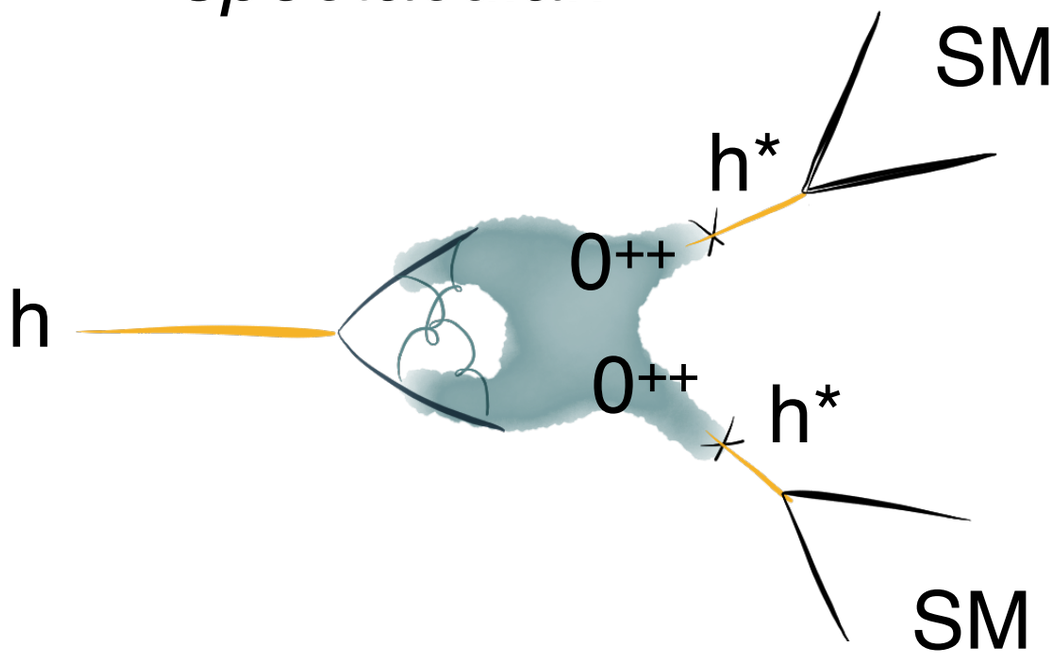
Intriguing lifetime!

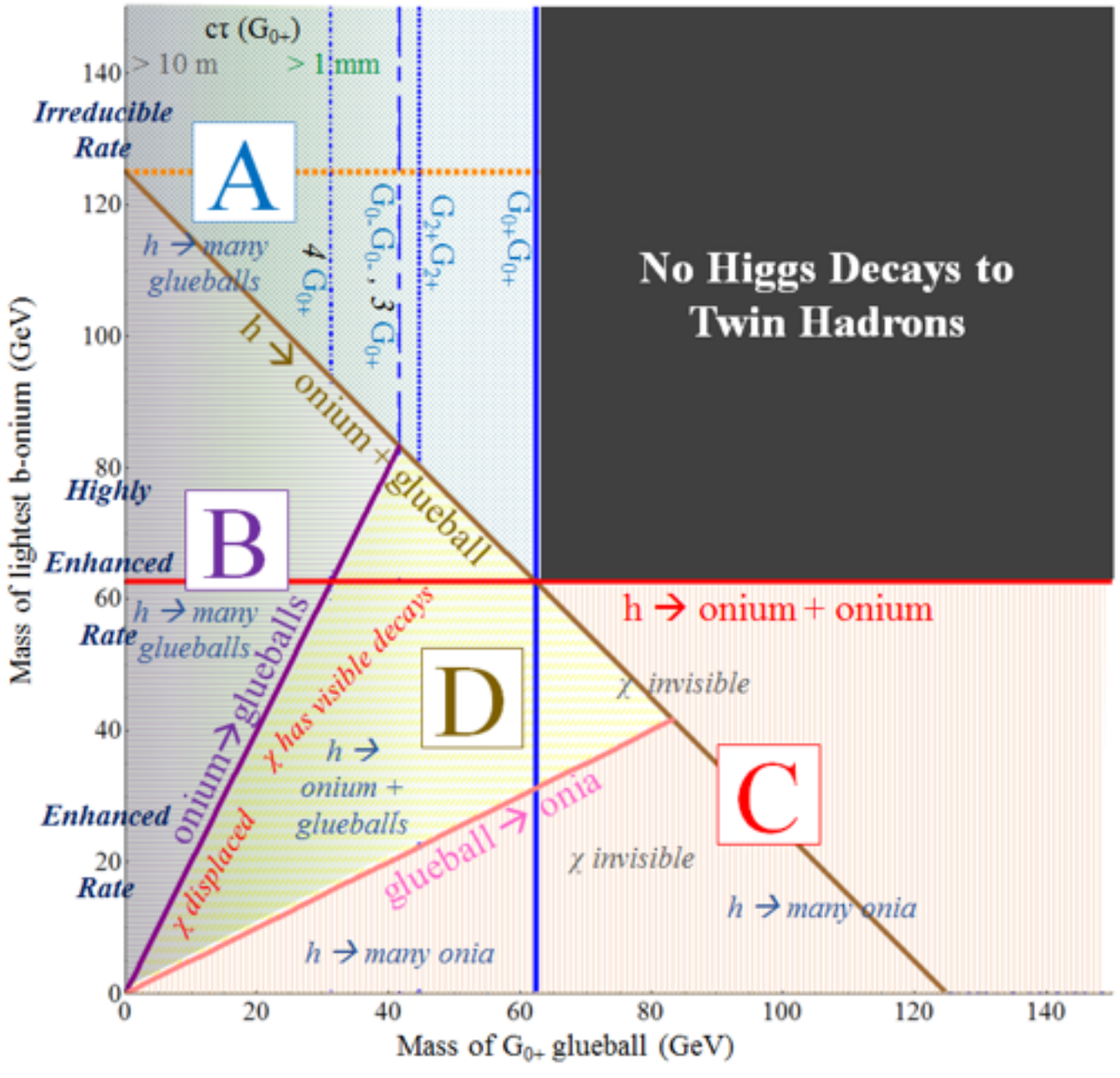
$$c\tau \approx 18\ \mathrm{m} \times \left(\frac{10\ \mathrm{GeV}}{m_0}\right)^7 \left(\frac{f}{500\ \mathrm{GeV}}\right)^4$$

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

Displaced decays

Rates small, signals spectacular.





Simplest case: decay into 0^{++} pairs
But wide variety of signals across parameter space.

Not yet strongly constrained @ LHC

Dark interactions of neutral naturalness

New sectors neutral under the SM, with mass scales comparable to SM

✓ Higgs portal $\lambda|H|^2\mathcal{O}_\phi$ $\sim \left(\frac{E}{\Lambda}\right)^{-1 \text{ or } 0}$

Higgs portal required by naturalness

✓ Hypercharge portal $\epsilon F^{\mu\nu}F'_{\mu\nu}$ $\sim \left(\frac{E}{\Lambda}\right)^{0}$

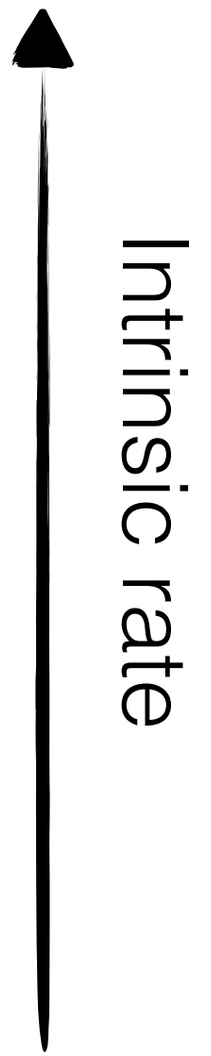
New U(1) in many cases, kinetic mixing from UV

✓ Neutrino portal $y(LH)\mathcal{O}_\psi$ $\sim \left(\frac{E}{\Lambda}\right)^{0 \text{ or } 1}$

Sterile neutrinos in many cases

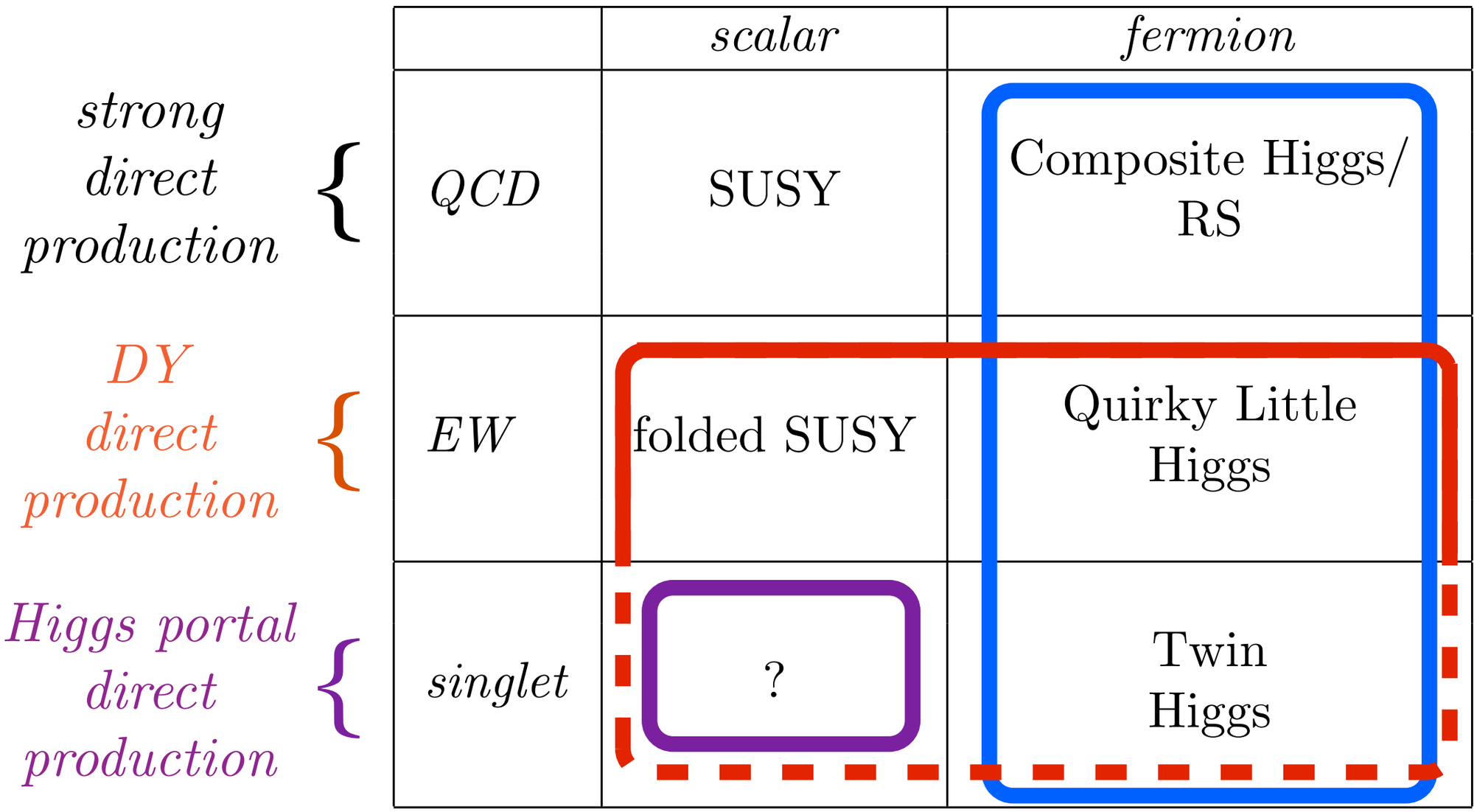
✓ Kitchen sink portal $\frac{1}{\Lambda^2}\bar{\Psi}\Psi\bar{\psi}\psi$ $\sim \left(\frac{E}{\Lambda}\right)^{2 \text{ or more}}$

Additional portals can arise from UV completions



Horizons of neutral naturalness

[Curtin, Verhaaren '15]



Pandora's box

- In all of these theories, naturalness lies in hidden sectors connected via the Higgs portal and possibly other portals.

A motivated realization of rich dark sectors with SM-like scales:

- Hidden valley [Strassler, Zurek '06] phenomenology @ LHC *with a preferred scale & couplings.*
- Dark matter candidates (WIMP, SIMP, asymmetric).
- Additional sterile neutrino species.

We've only scratched the surface of experimental signals & tests…

Thank you!

Bonus slides

NC, A. Katz [arXiv:1505.07113/JCAP]

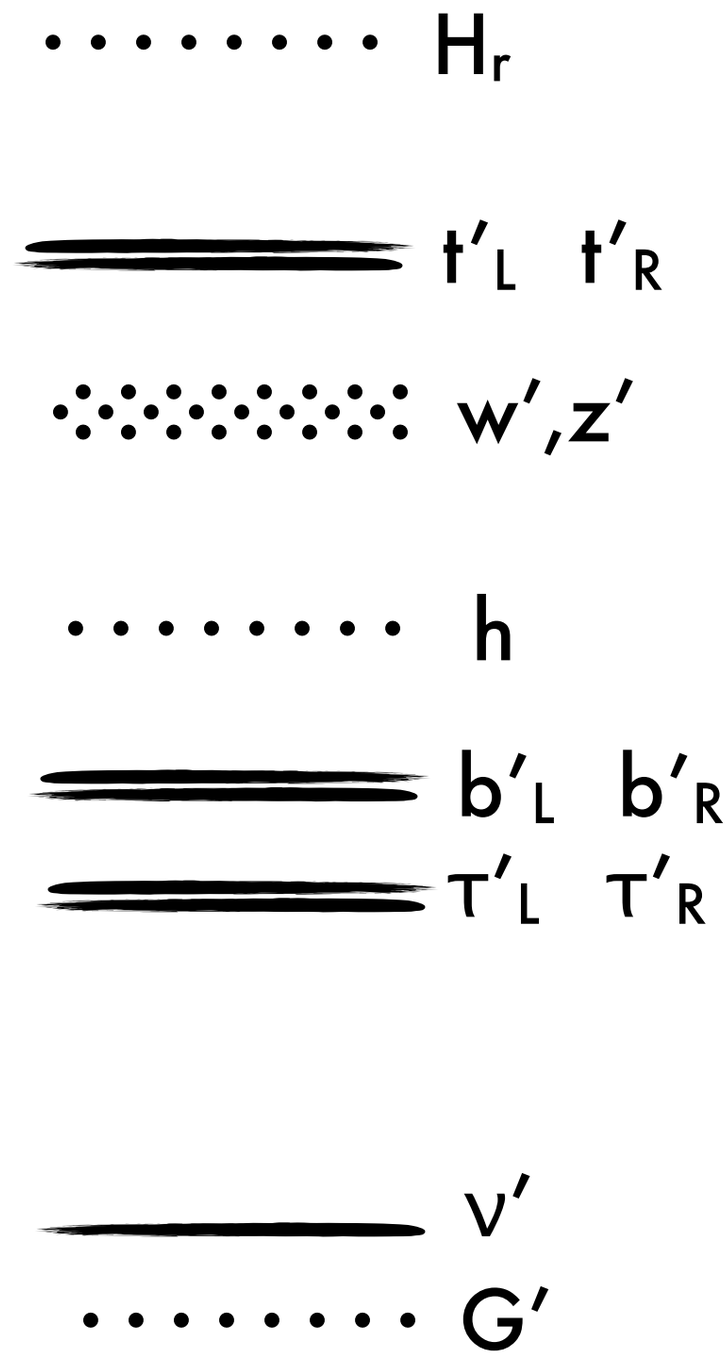
Dark matter

Long history of dark matter candidates from solutions to hierarchy problem!

Superabundance of candidates in twin scenarios; many stabilization symmetries (lepton #, baryon #, global EM).

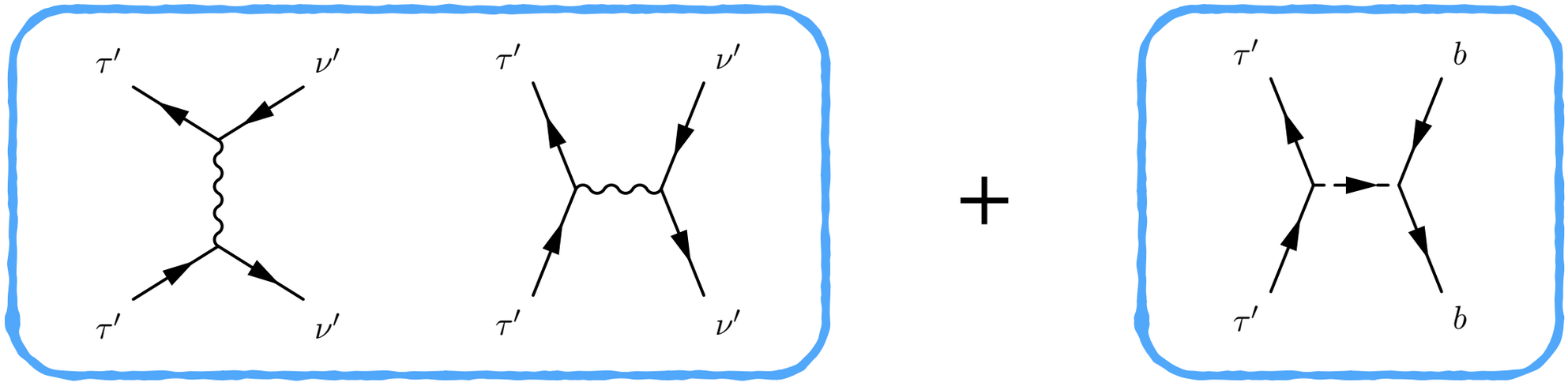
Various mechanisms for symmetric or asymmetric abundance.

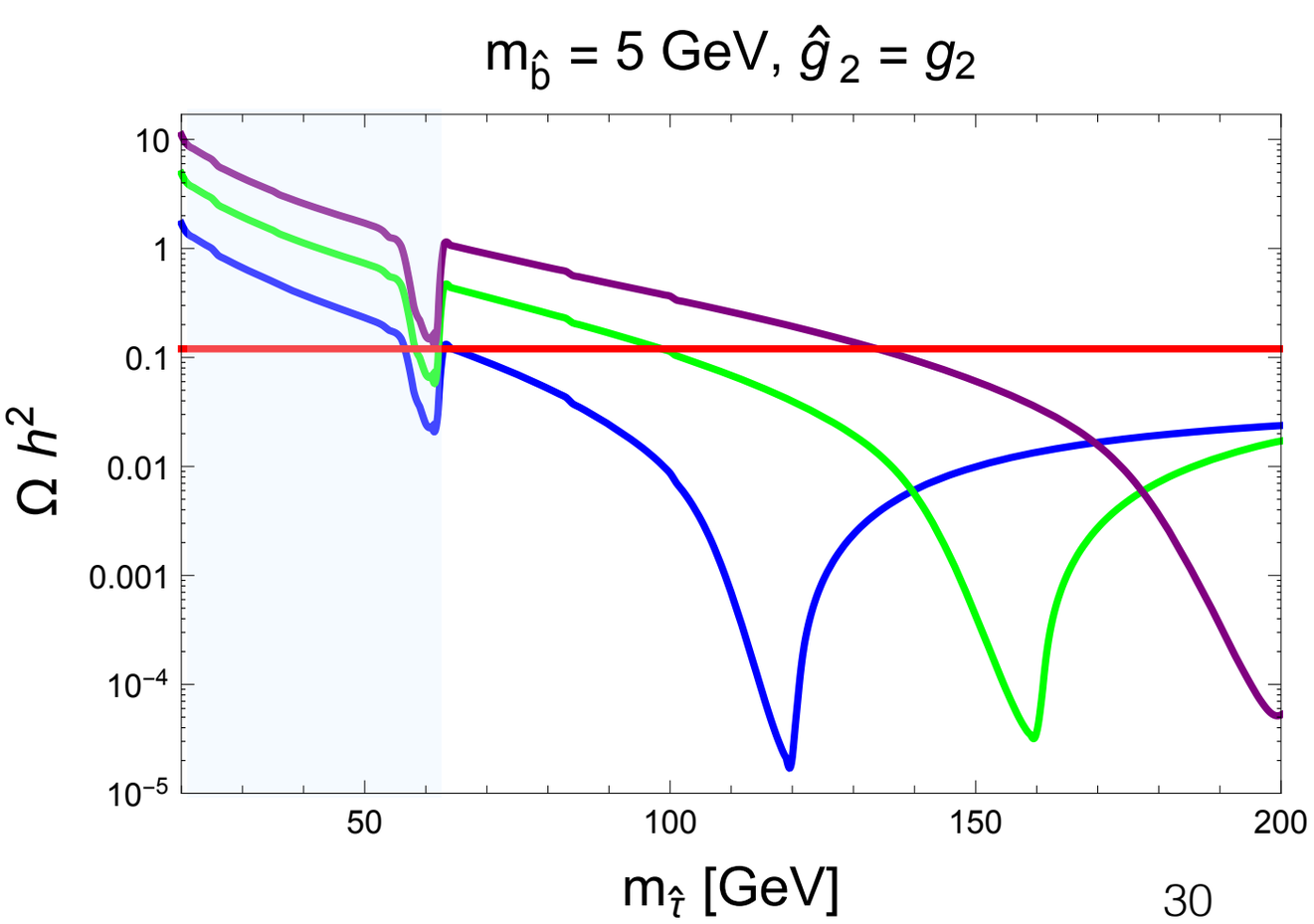
Simplest case: no light twin U(1); DM candidate is twin tau.



See also: [I. Garcia Garcia, R. Lasenby, J. March-Russell '15; M. Farina '15]

Fraternal WIMP miracle





$f = 3v$

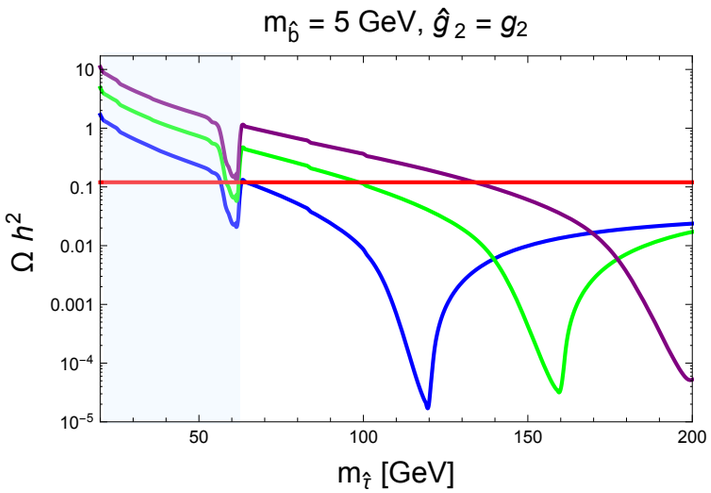
$f = 4v$

$f = 5v$

Viable thermal population, annihilating via twin W', Z'

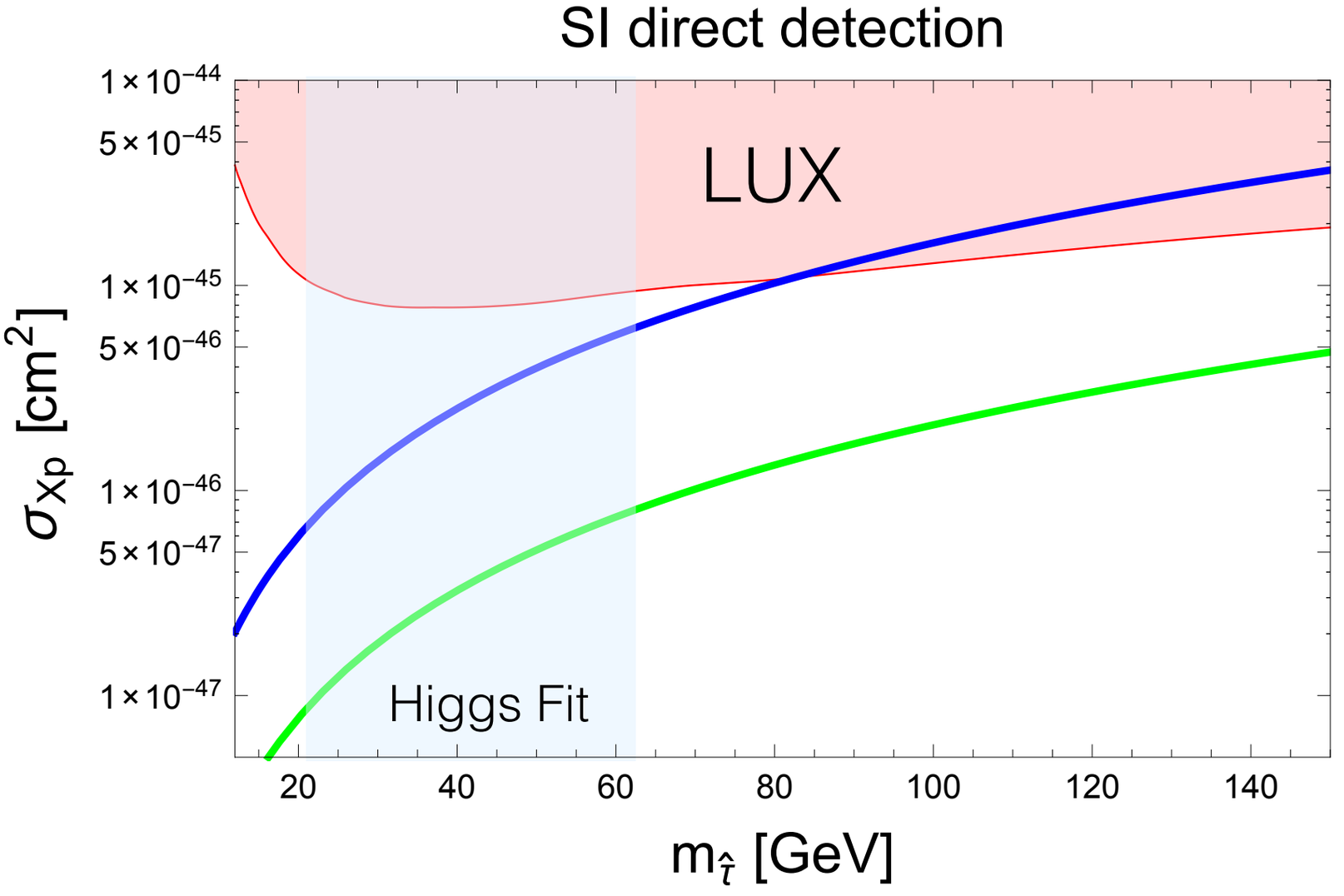
(Twin neutrino contribution to N_{eff} safe if no light twin fermions)

Direct detection



$f = 3v$

$f = 5v$



Natural parameter space right on the edge of direct detection

Many interesting variations — light U(1), multiple hidden sectors, etc.