

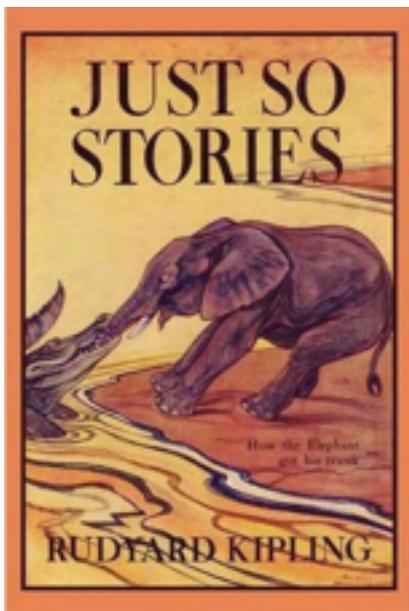
Naturalness in the Dark

Nathaniel Craig
UC Santa Barbara



CoSMS Workshop on Naturalness





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 $m \rightarrow 0$ Implication

Spin-1/2

$$m\Psi\bar{\Psi}$$

$$\Psi \rightarrow e^{i\alpha\gamma_5} \Psi$$

(chiral symmetry)

$$\delta m \propto m$$

Natural!

Spin-1

$$m^2 A_\mu A^\mu$$

$$A_\mu \rightarrow A_\mu + \partial_\mu \alpha$$

(gauge invariance)

$$\delta m \propto m$$

Natural!

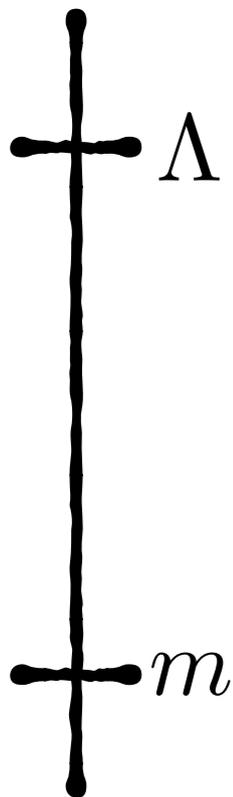
Spin-0

$$m^2 |H|^2$$

None

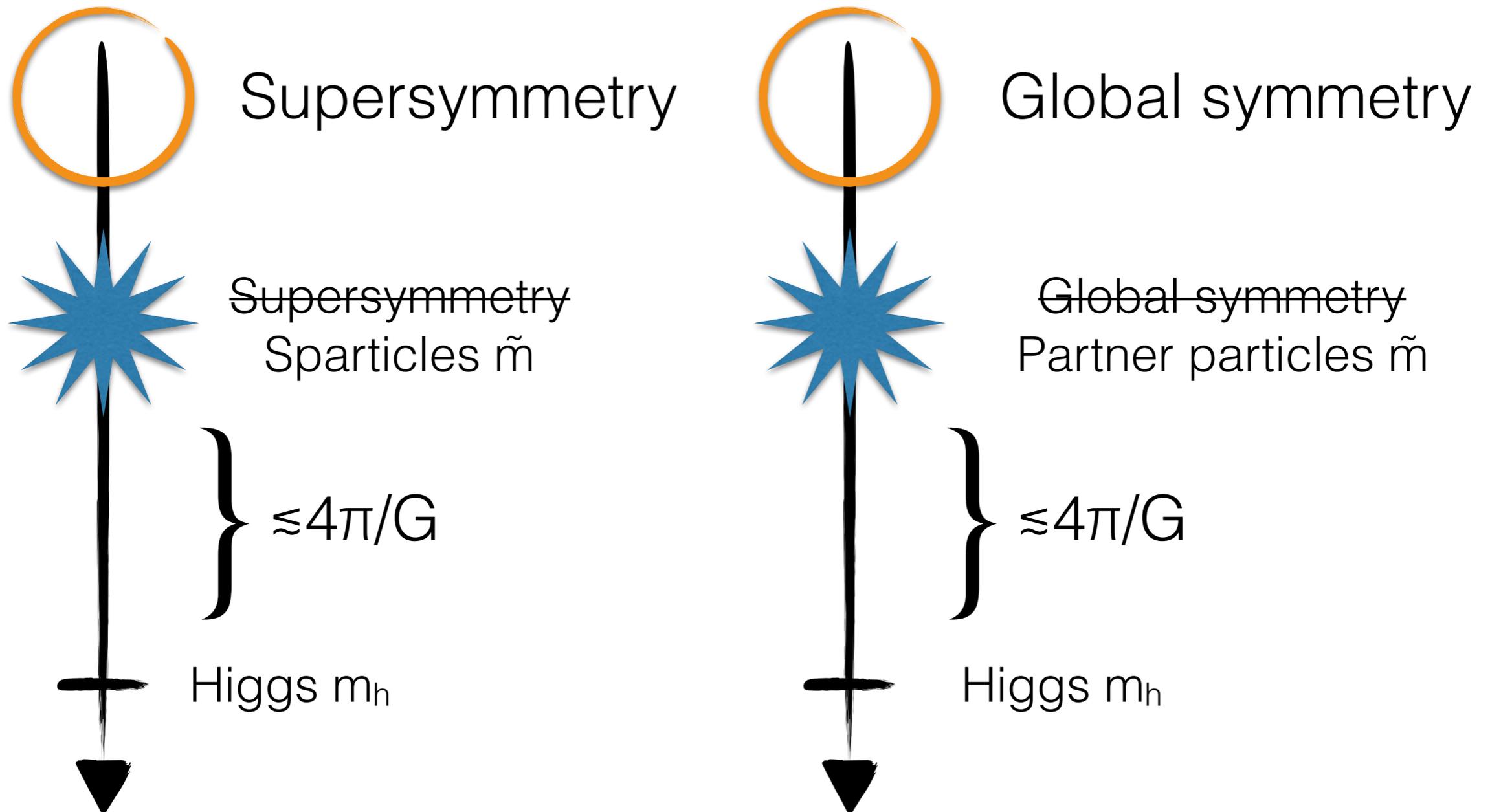
$$\delta m \propto \Lambda$$

Unnatural!



Hierarchy Solutions

Extend the SM with a symmetry acting on the Higgs



Two spectra

5 TeV



Supersymmetry

Global symmetry

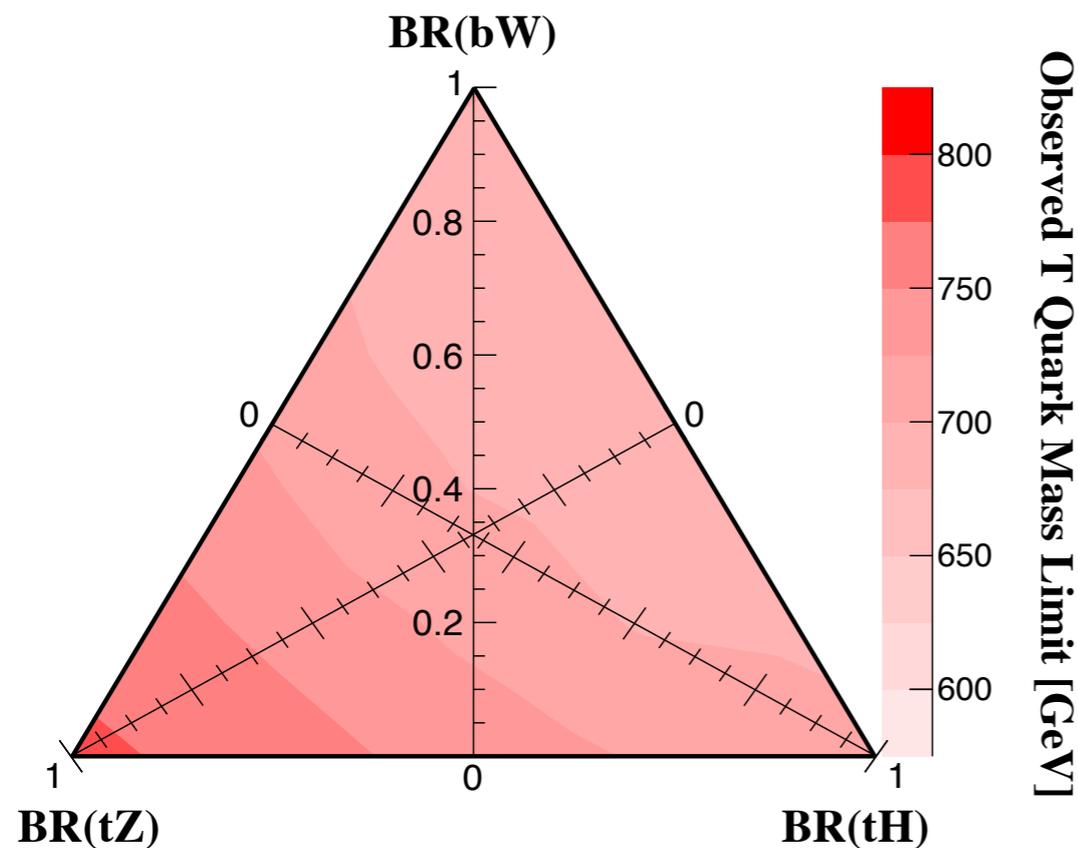
Simple game for LHC: look for colored partners.

Missing top partner problem

LHC searches driven by top partners

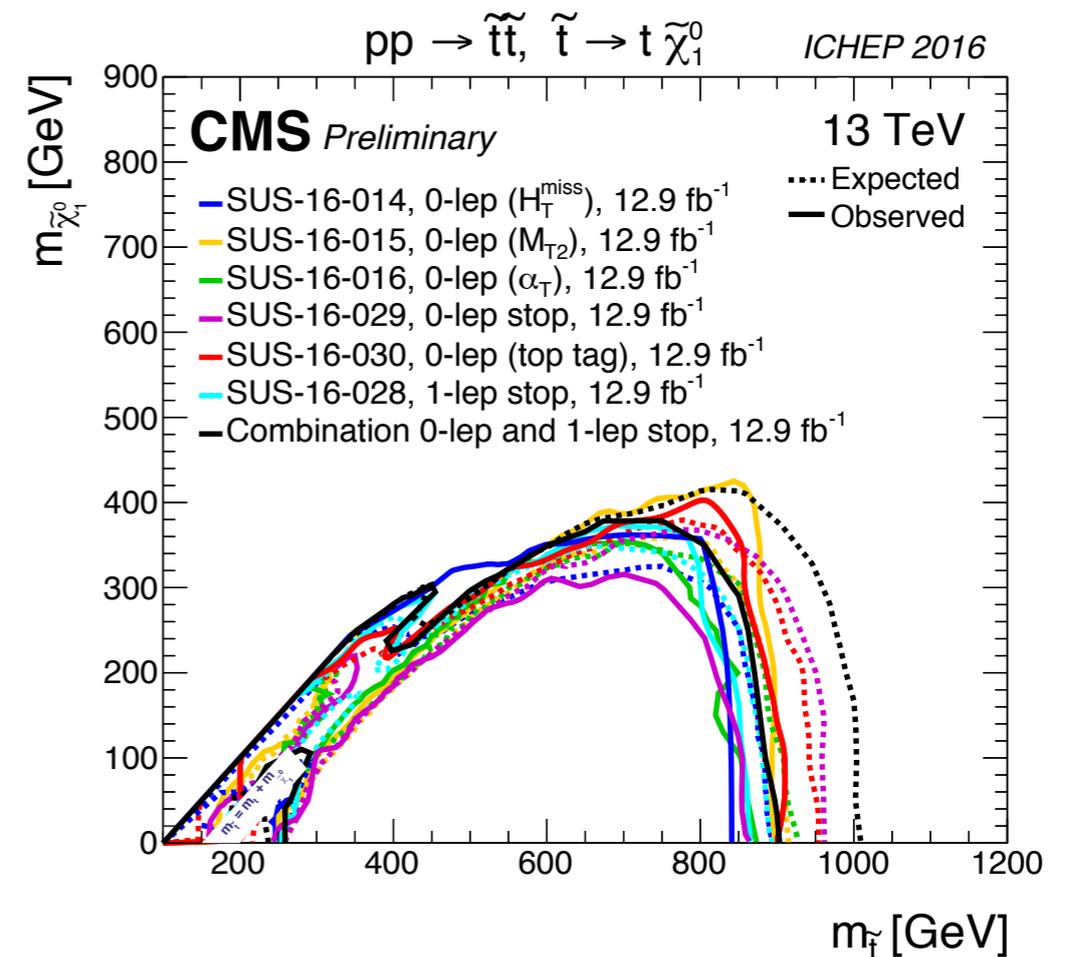
Global Symmetry

CMS preliminary $\sqrt{s} = 8 \text{ TeV}$ 19.6 fb^{-1}



CMS B2G-12-015

Supersymmetry



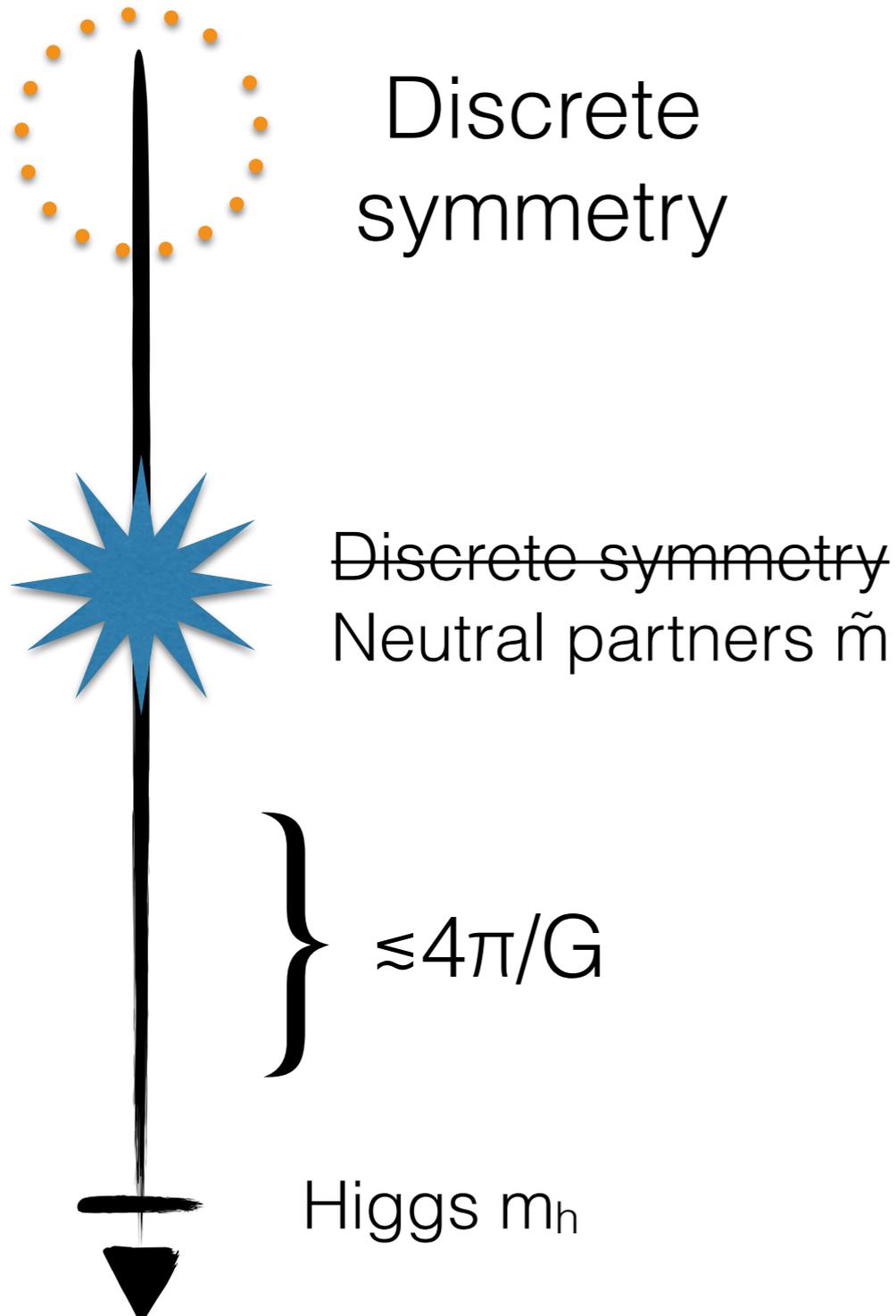
Problem 1: nothing yet ($\sim 0.1-10\%$ tuning).

Problem 2: not much new to do.

But: is this all there is?



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”

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,

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

$SU(4) \rightarrow SU(3)$

yields seven goldstone bosons.

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.

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

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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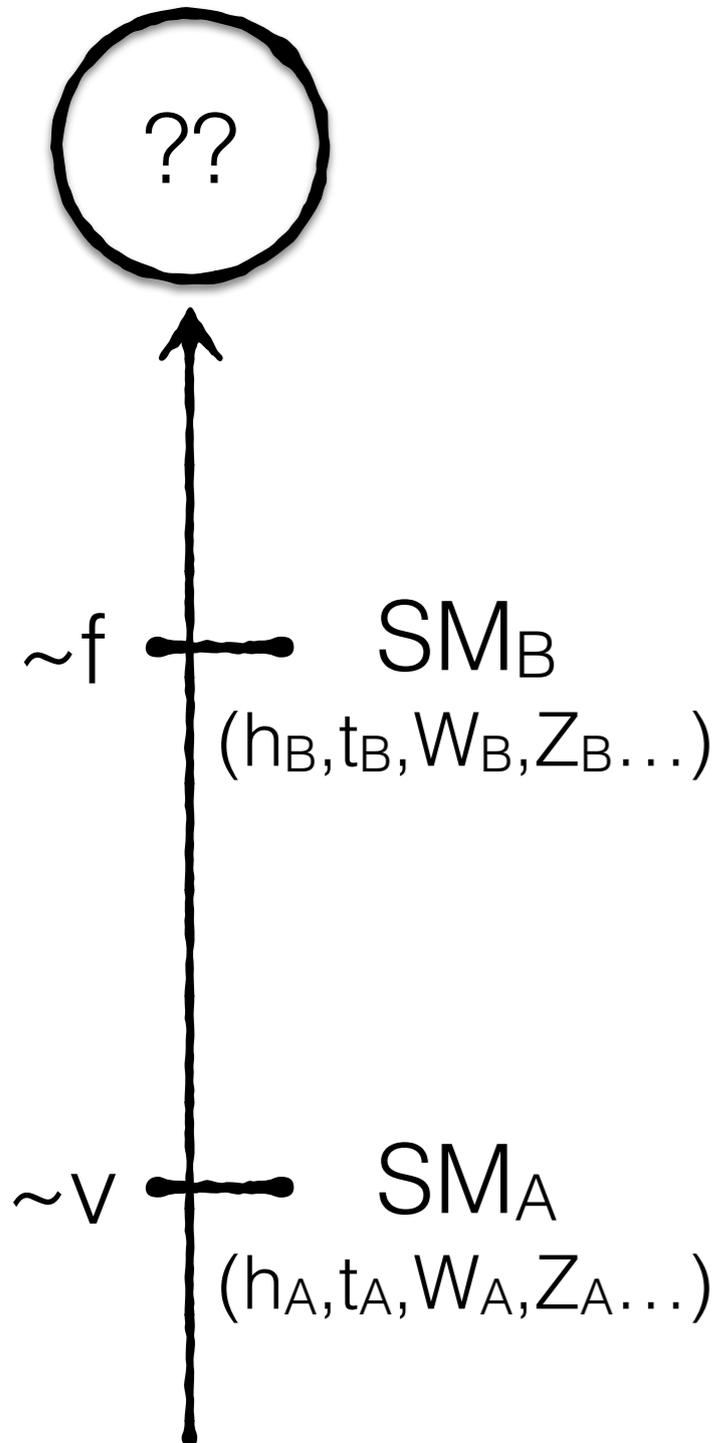
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The Twin Higgs

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



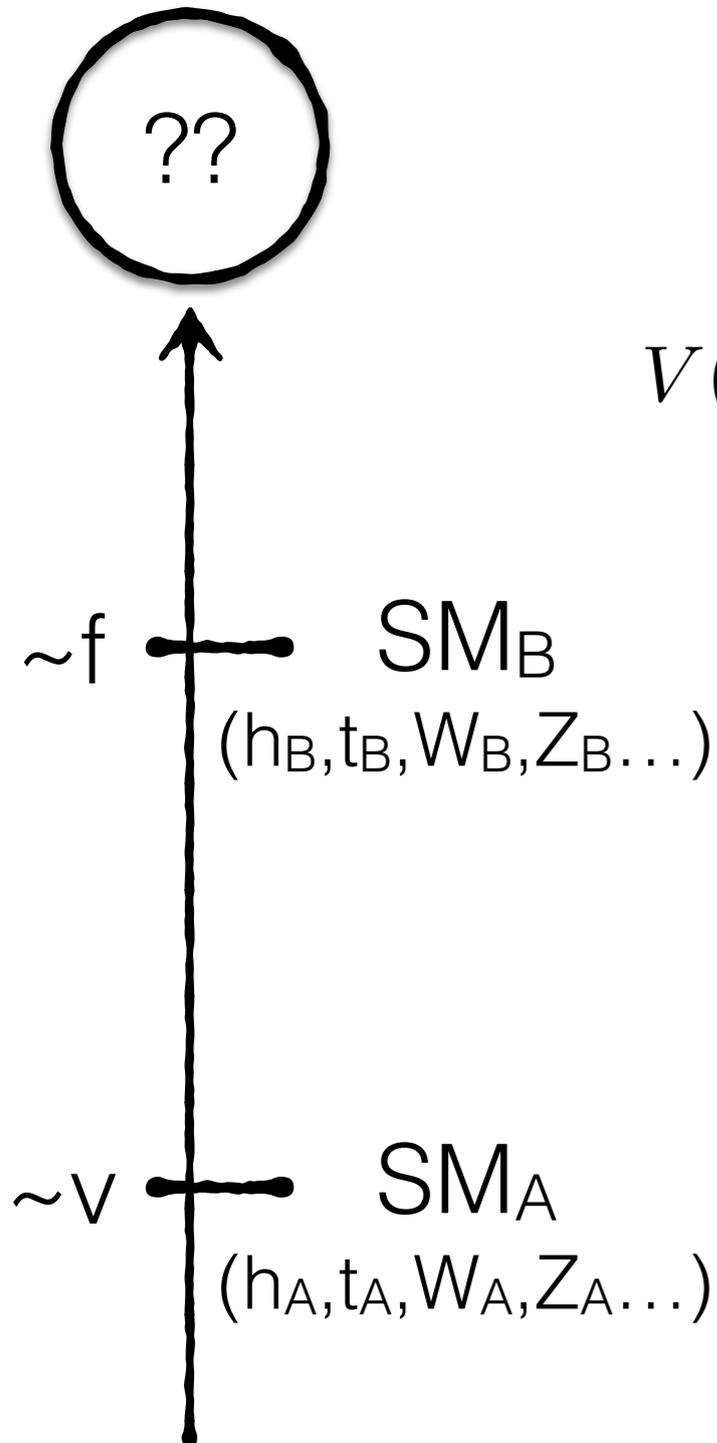
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$$V(H) \supset \frac{\Lambda^2}{16\pi^2} \left(-6y_t^2 + \frac{9}{4}g^2 + \dots \right) (|H_A|^2 + |H_B|^2)$$



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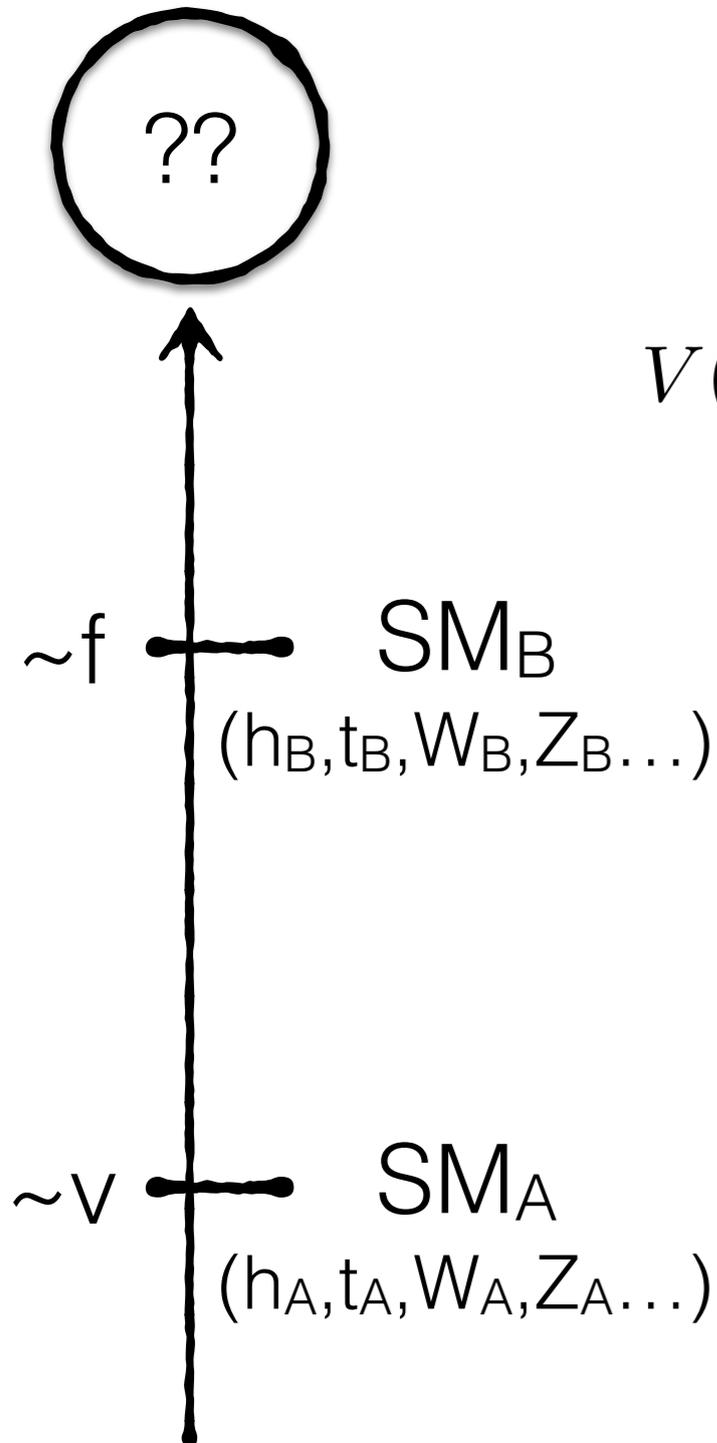
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Breaks “quadratic” $SU(4)$, higgses EWK_A & EWK_B



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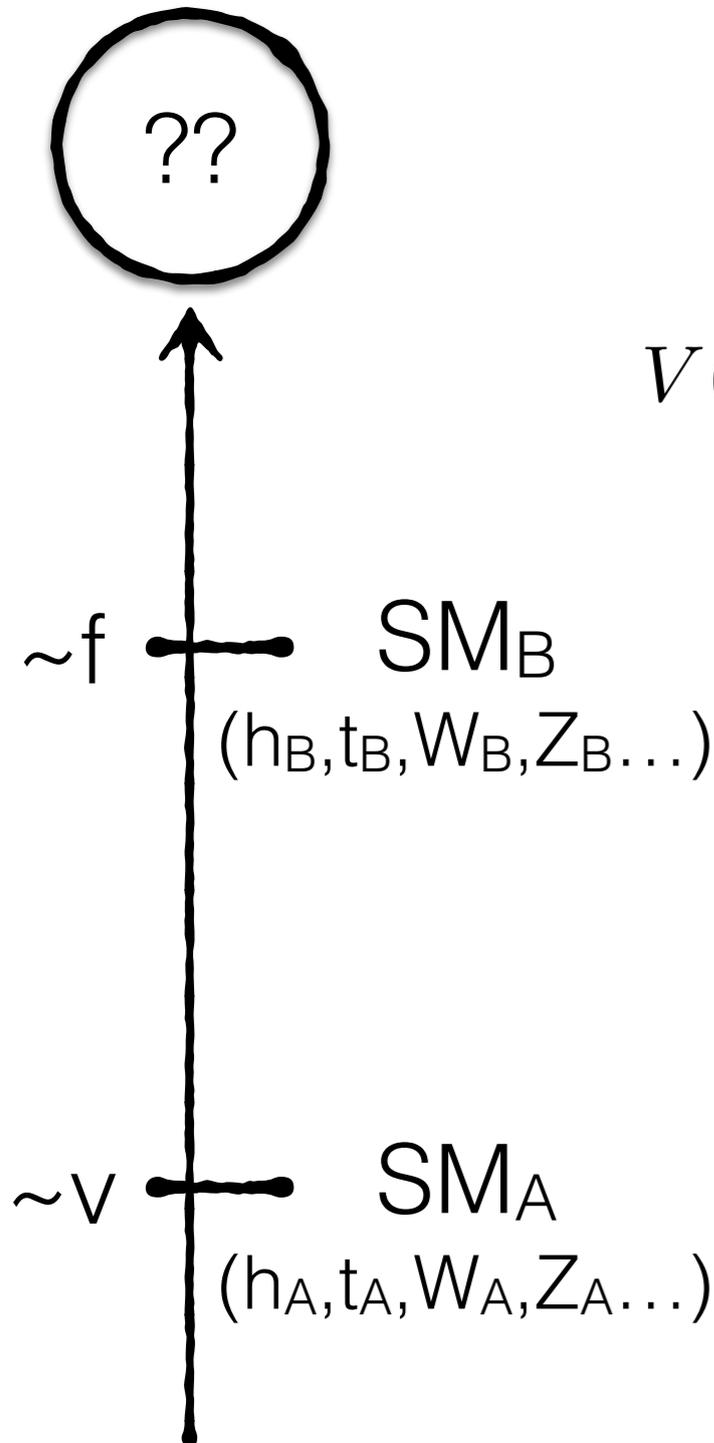
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Gives a **radial mode**, a **goldstone mode**,
and eaten goldstones.

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



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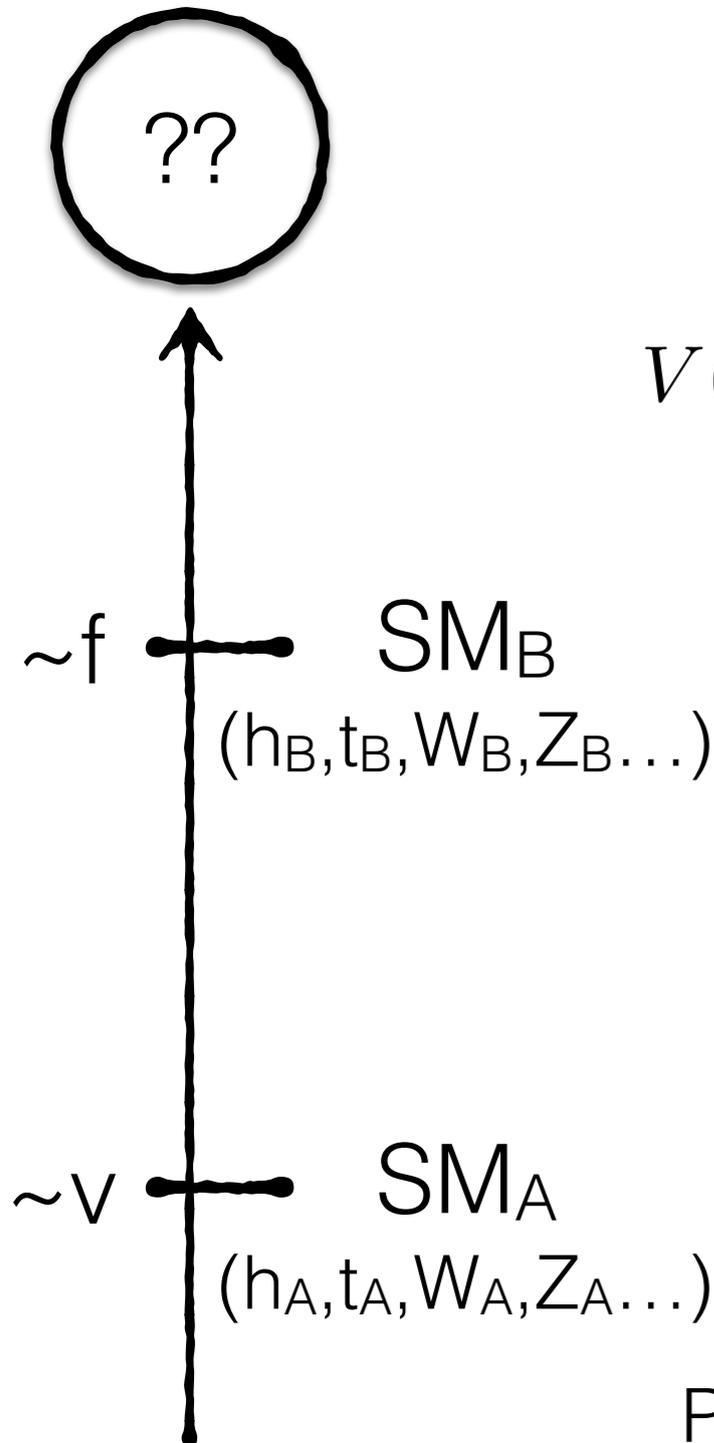
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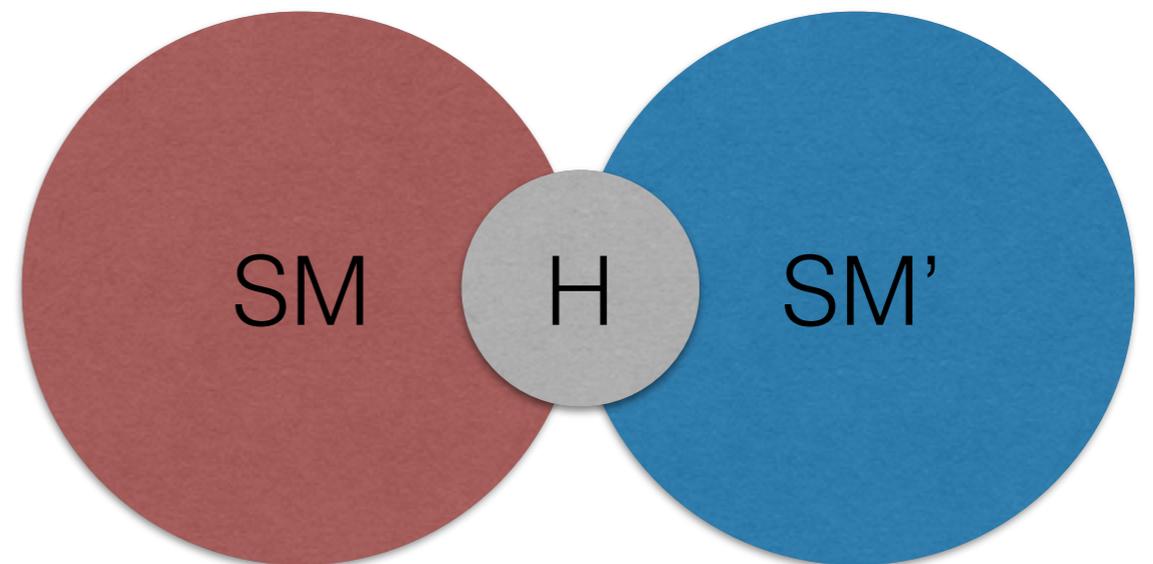
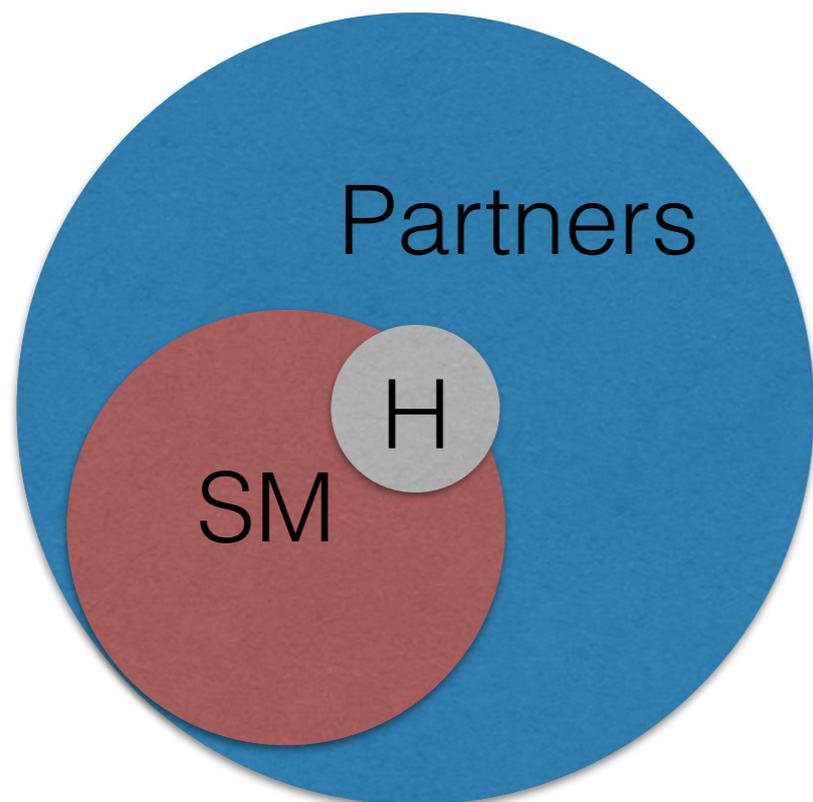
$v \ll f$ for *SM-like Higgs to be the goldstone*,
but tuning is $O(v/f)$

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:
naturalness in the dark.

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

UV Physics

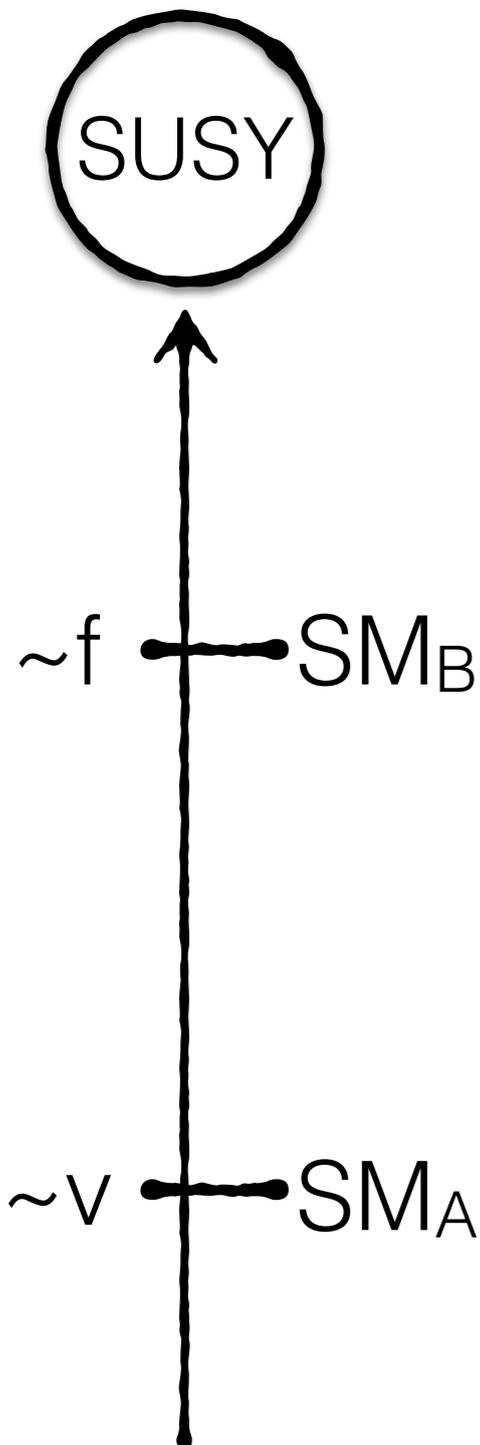
The SUSY Twin Higgs

SUSY protects the linear sigma model

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

$$\text{MSSM}_A \times \text{MSSM}_B \times Z_2$$

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

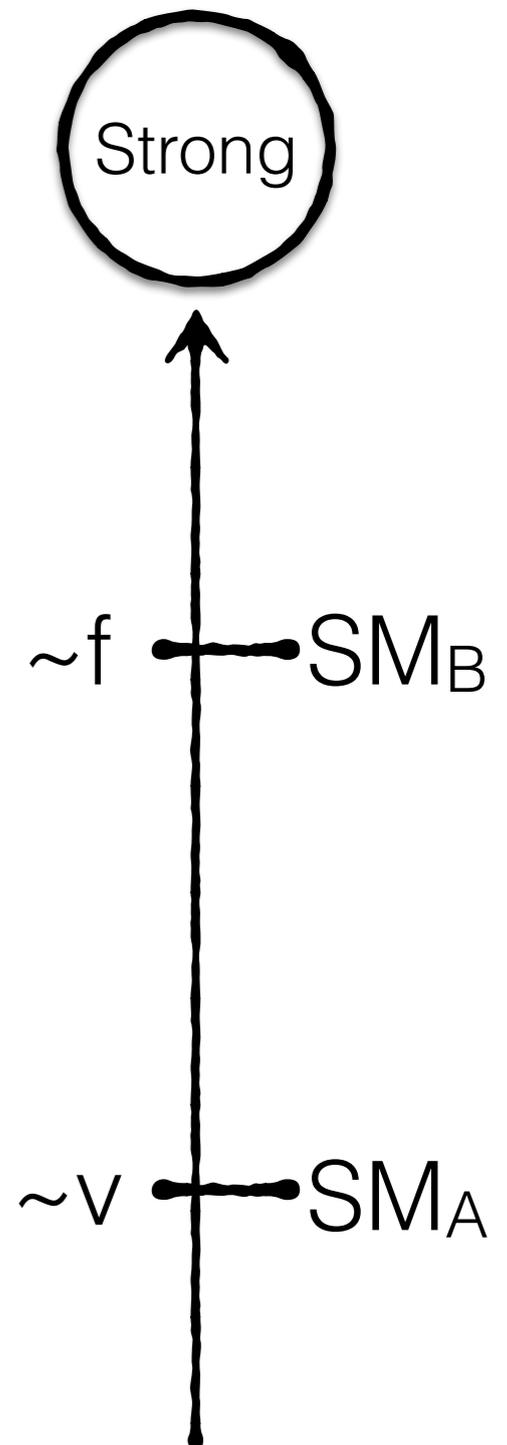


The Composite Twin Higgs

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 ???”

[NC, S. Knapen & P. Longhi '14]

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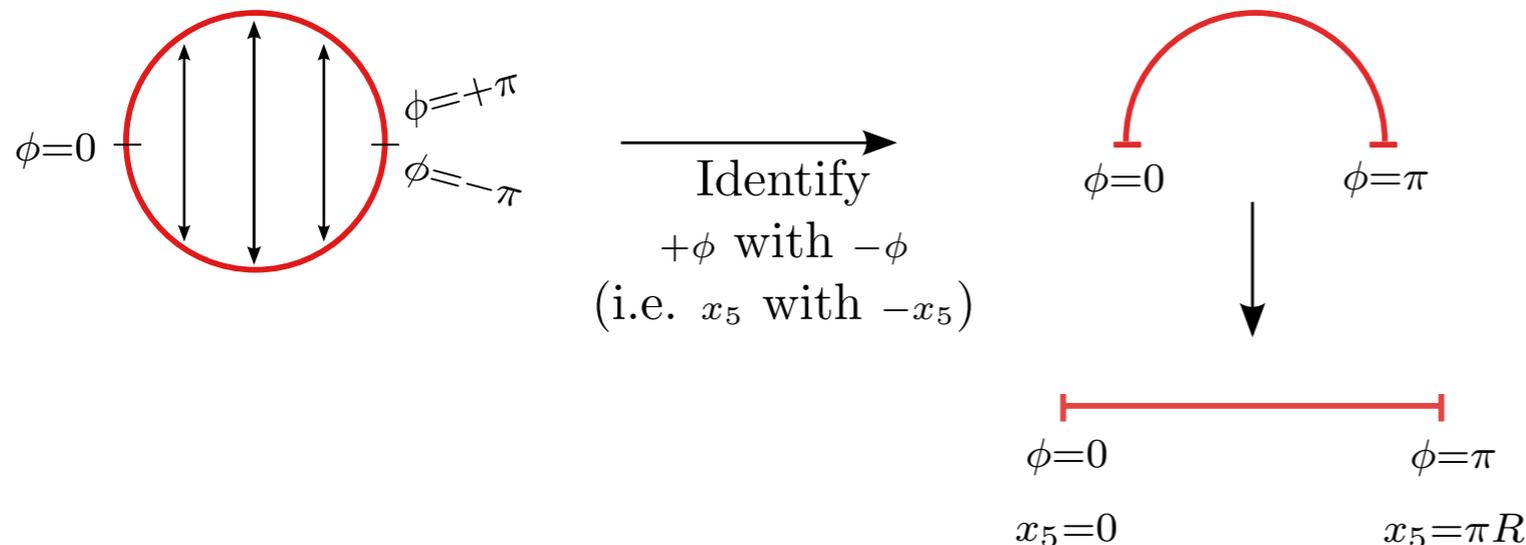
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Familiar tool in string theory & field theory (realistic string compactifications, orbifold GUTs, 5D SUSY theories, etc.)

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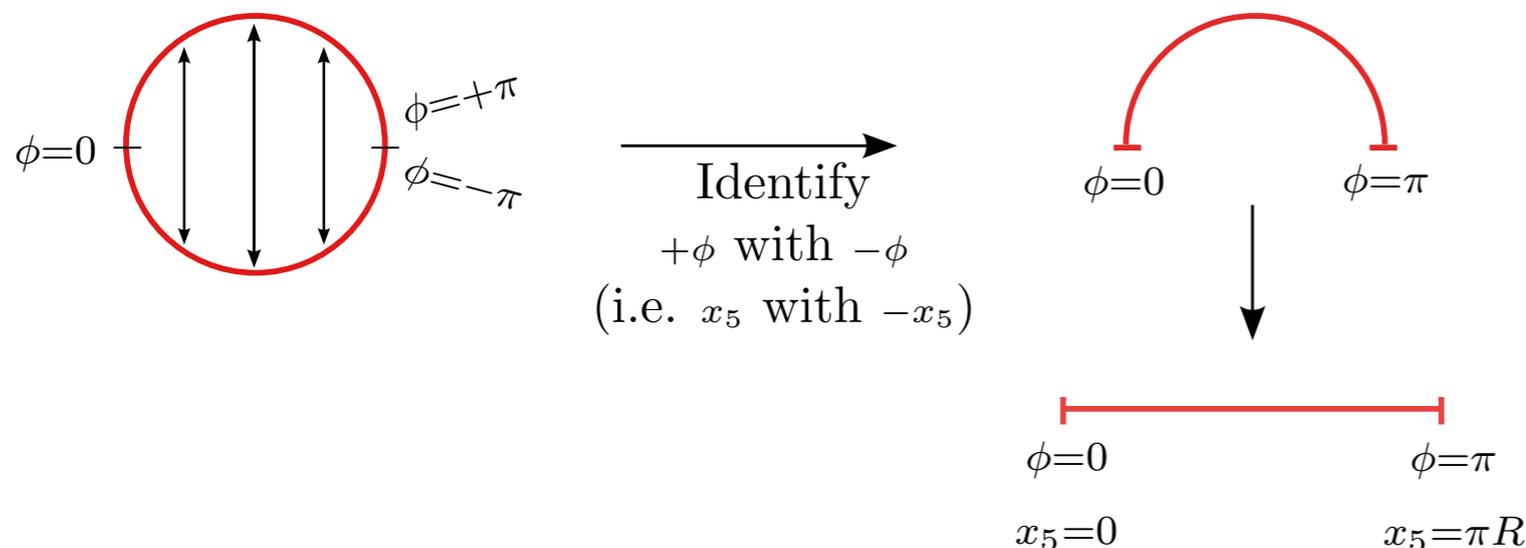
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Punchline: Many models of the twin kind, where Z_2 or larger symmetries may be exact or approximate.

Models of neutral naturalness



~~=====~~ t'_L t'_R b'_L

•••••••••• w', z'

•••••••• h

•••••••• g'

Simplest theory: exact mirror copy of SM

[Chacko, Goh, Harnik '05]

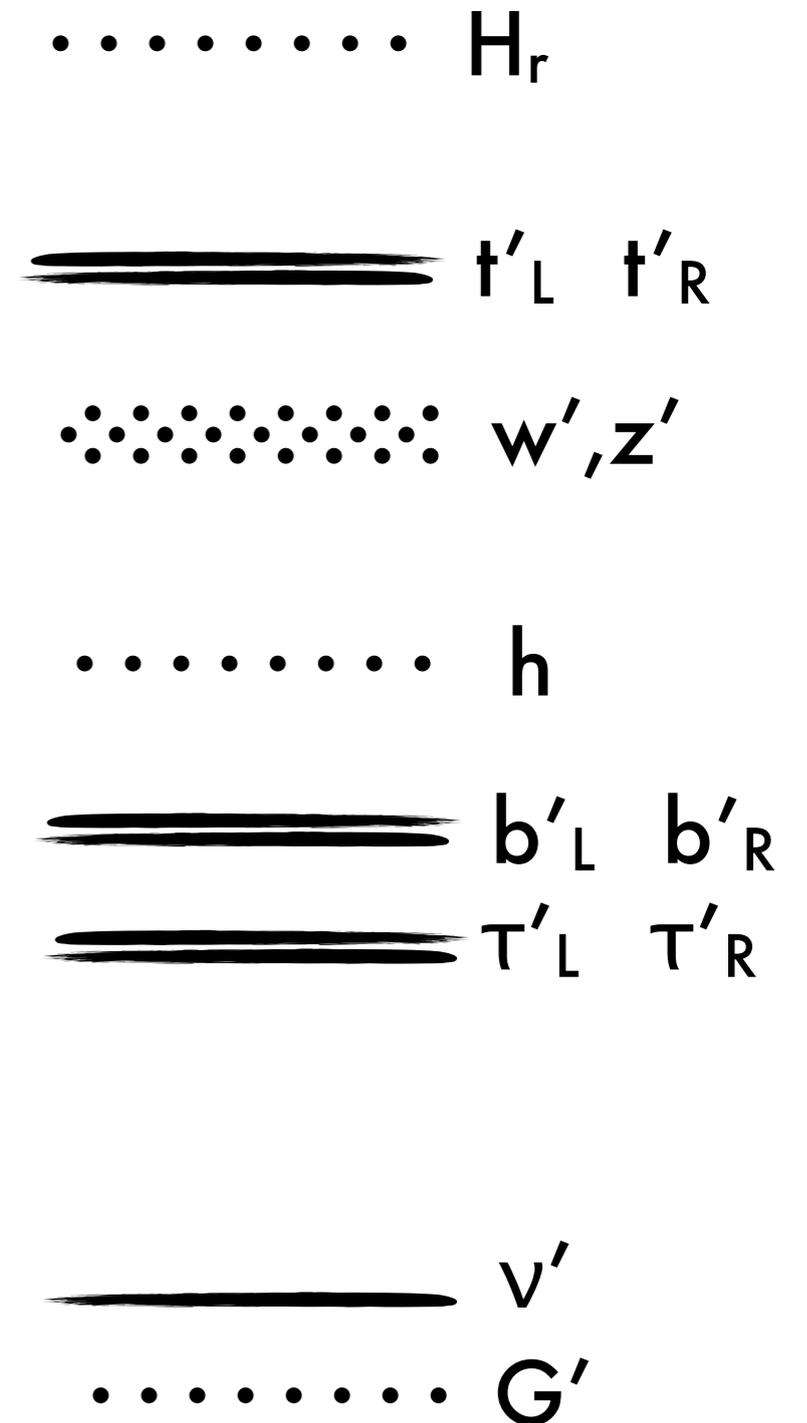
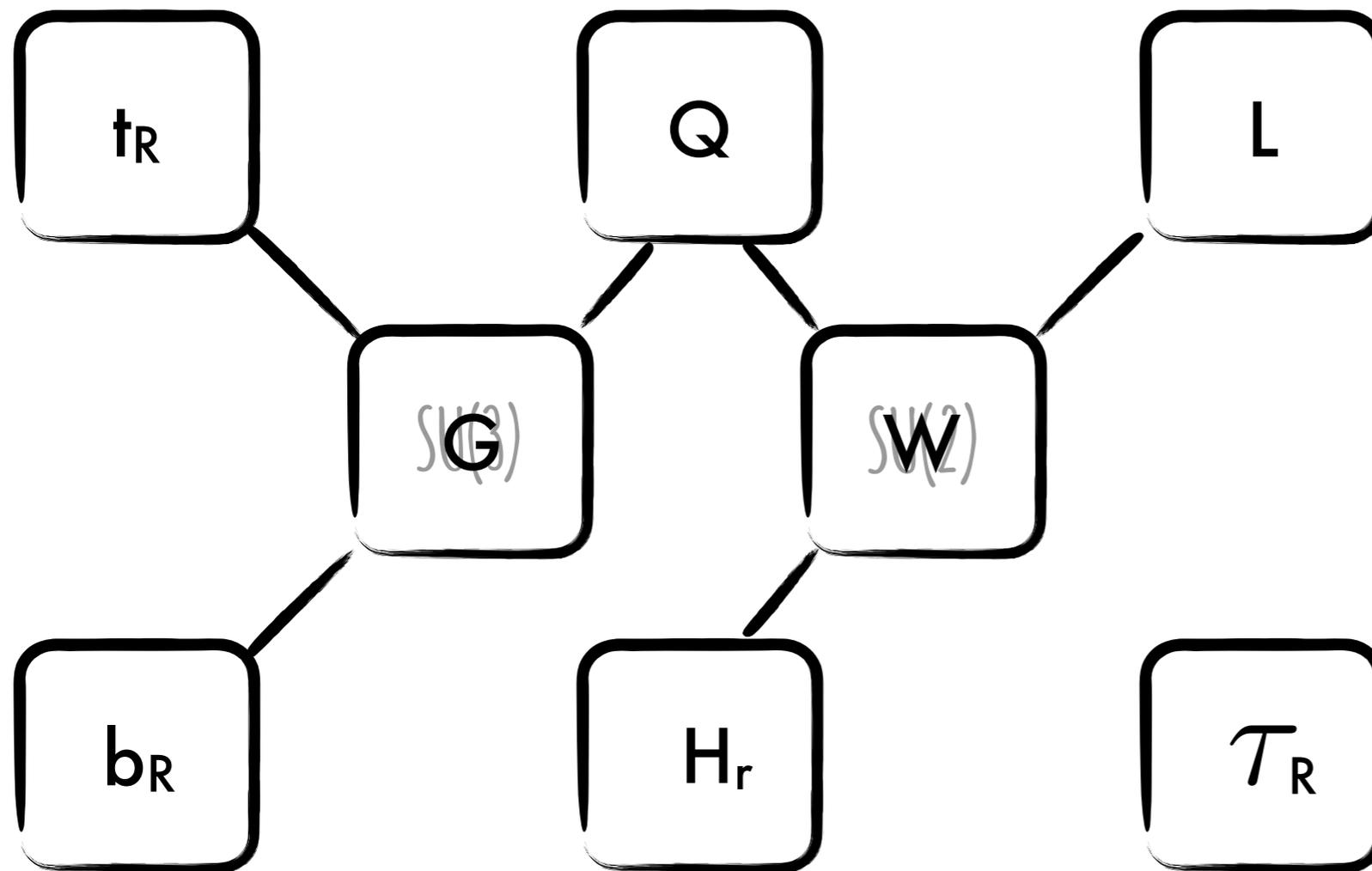
But this is more than you need, and mirror 1st, 2nd gens lead to cosmological problems

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]

The minimal model

Just Z_2 partner states for the third generation.

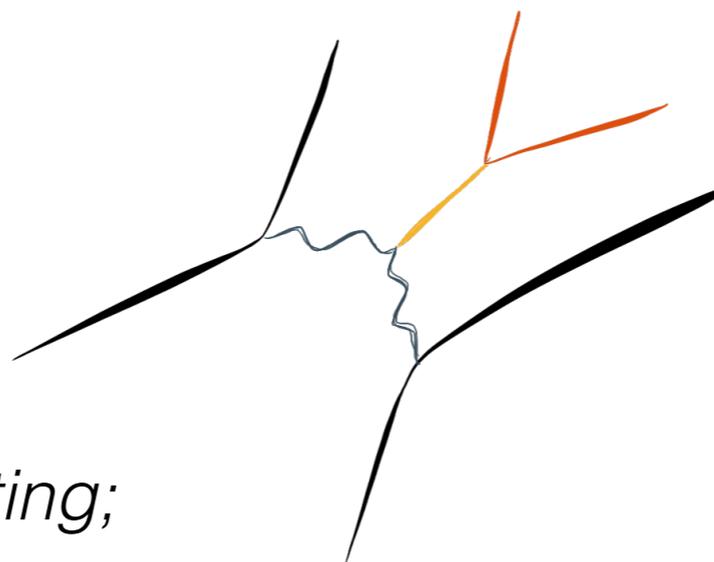


The “Fraternal” Twin Higgs

What to look for?

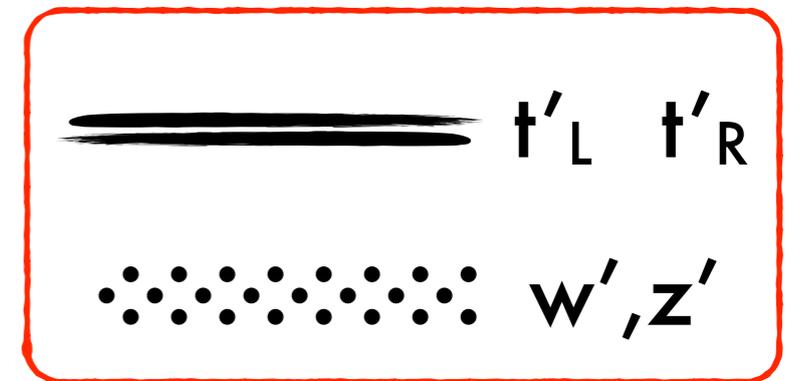
[Mixing leads to $O(v/f)^2$ changes in Higgs couplings; current $O(20\%)$ precision not constraining.]

- 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.

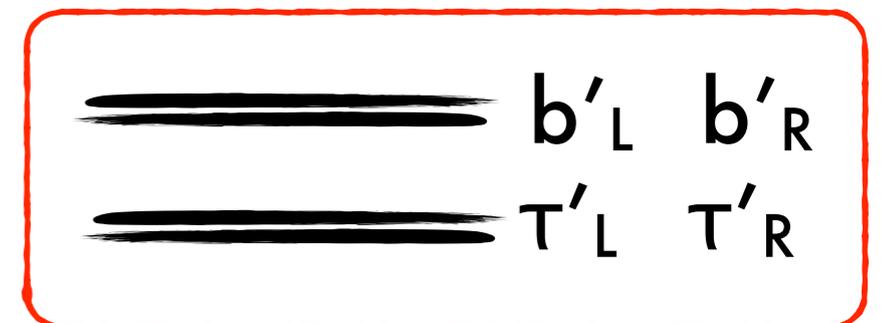


*Hard but very interesting;
directly probe naturalness*

..... H_r



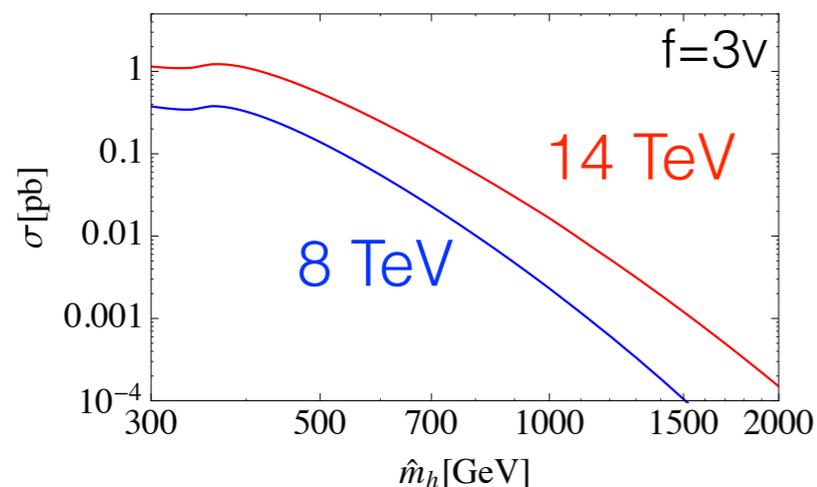
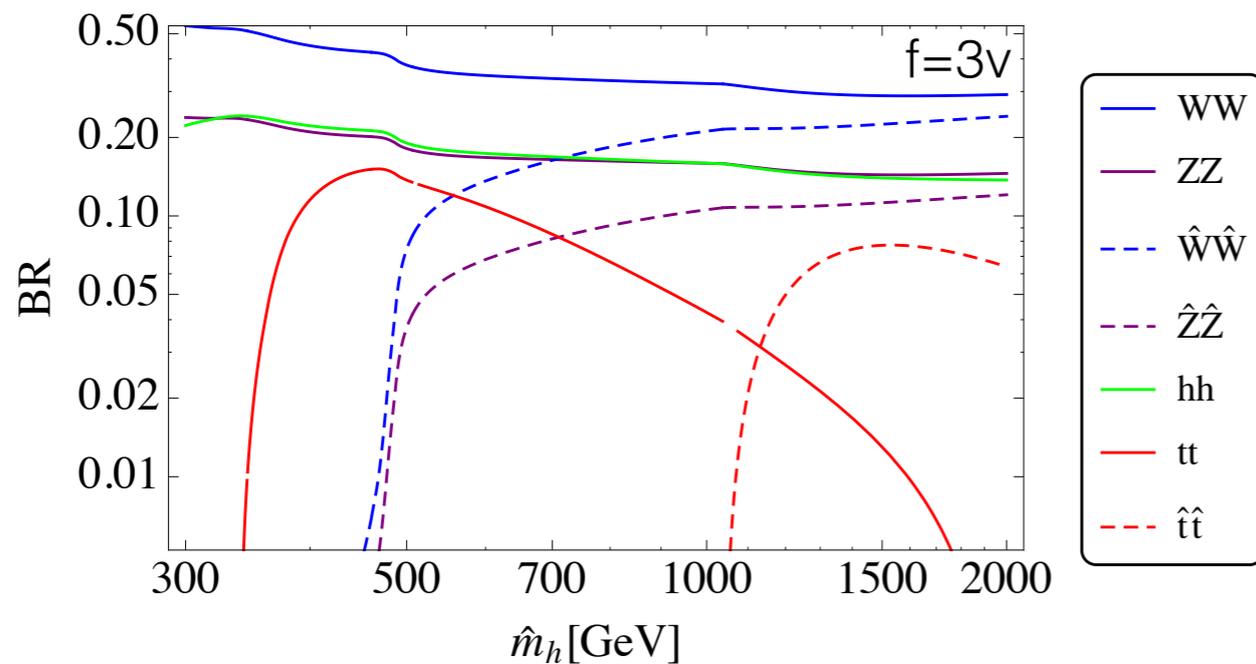
..... h



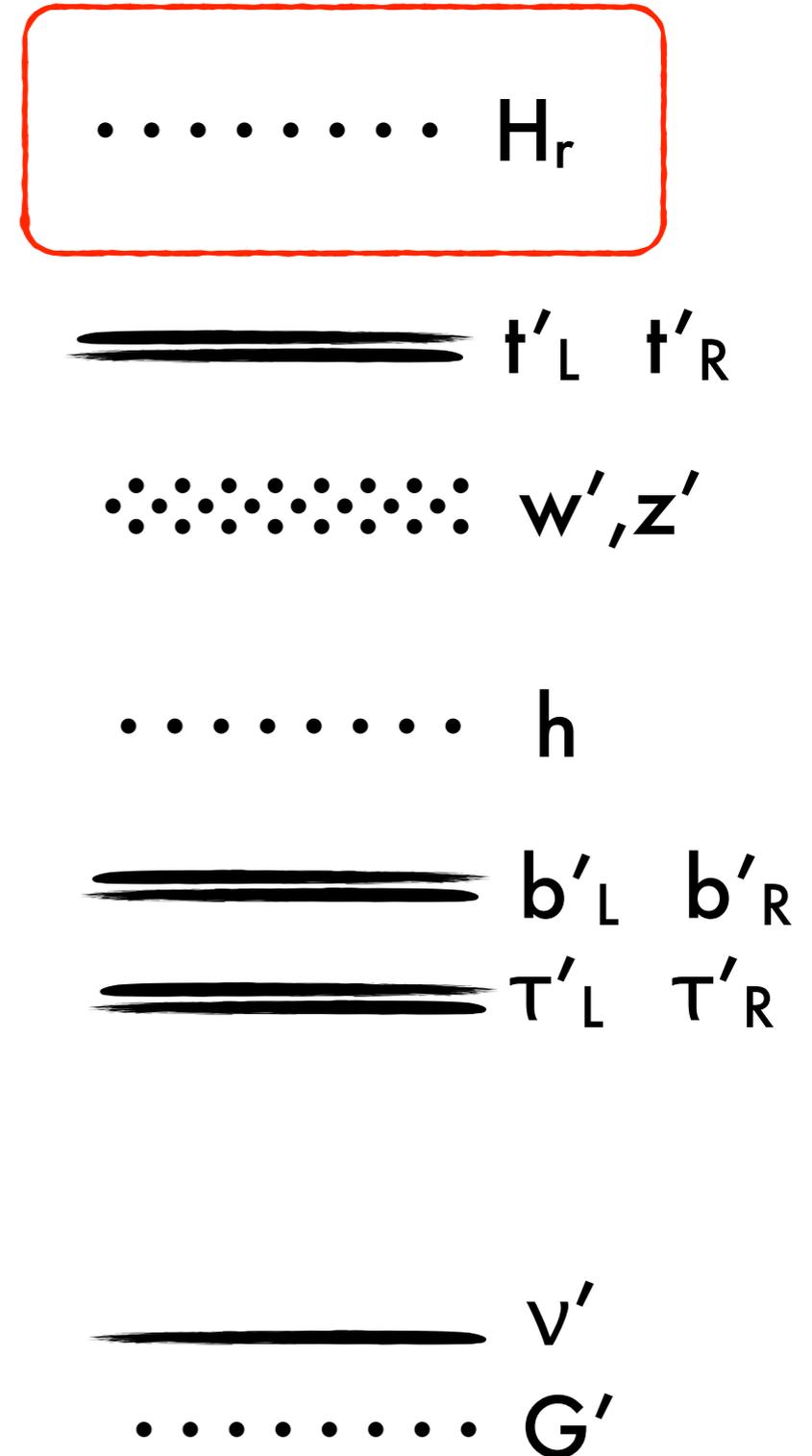
v'
..... G'

What to look for?

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



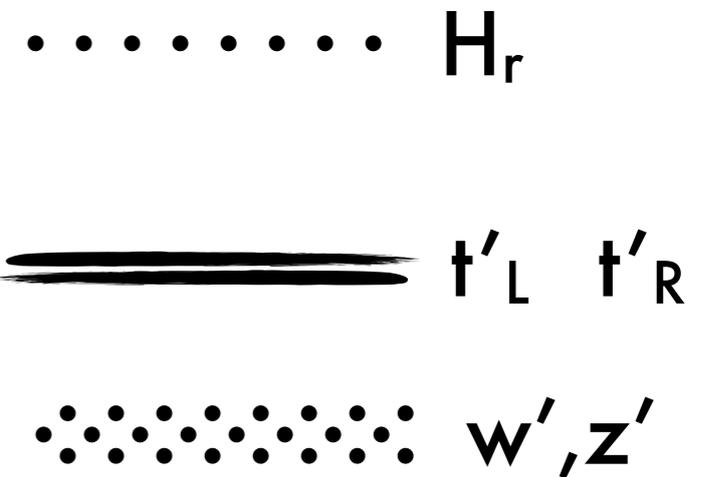
Current searches not constraining; very interesting for 13/14 TeV LHC



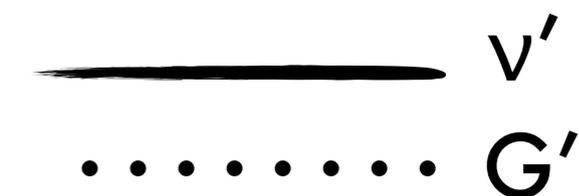
What to look for?

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...



..... h



Twin QCD

Coupling related to QCD by twin symmetry.

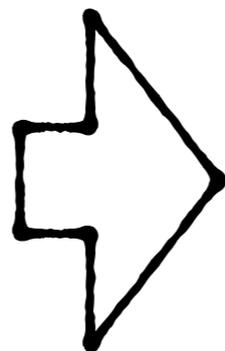
Must be present to keep top yukawas in twin sector(s) related to SM top yukawa.

Confinement within ~order of magnitude of QCD

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

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

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

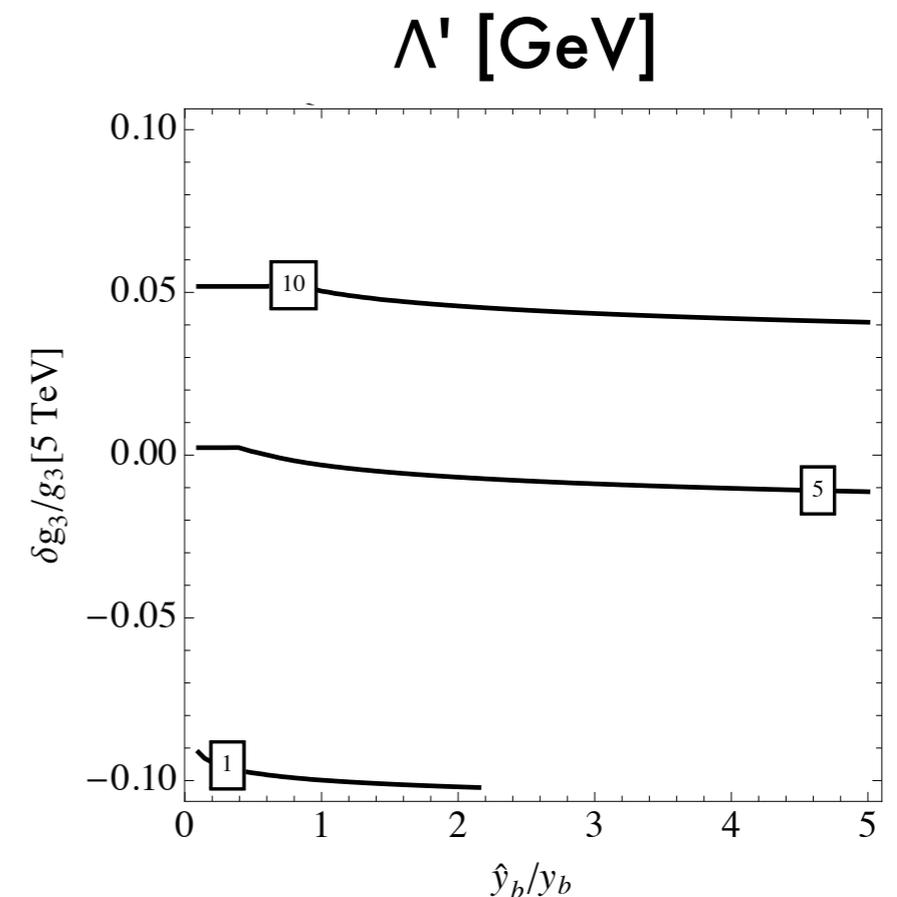


Portal for production...

$$gg \rightarrow h \rightarrow 0^{++} + 0^{++} + \dots$$

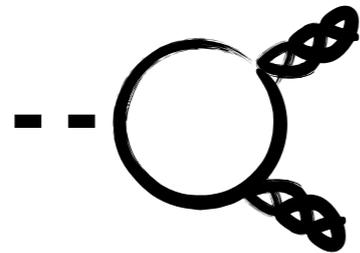
...and decay:

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



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

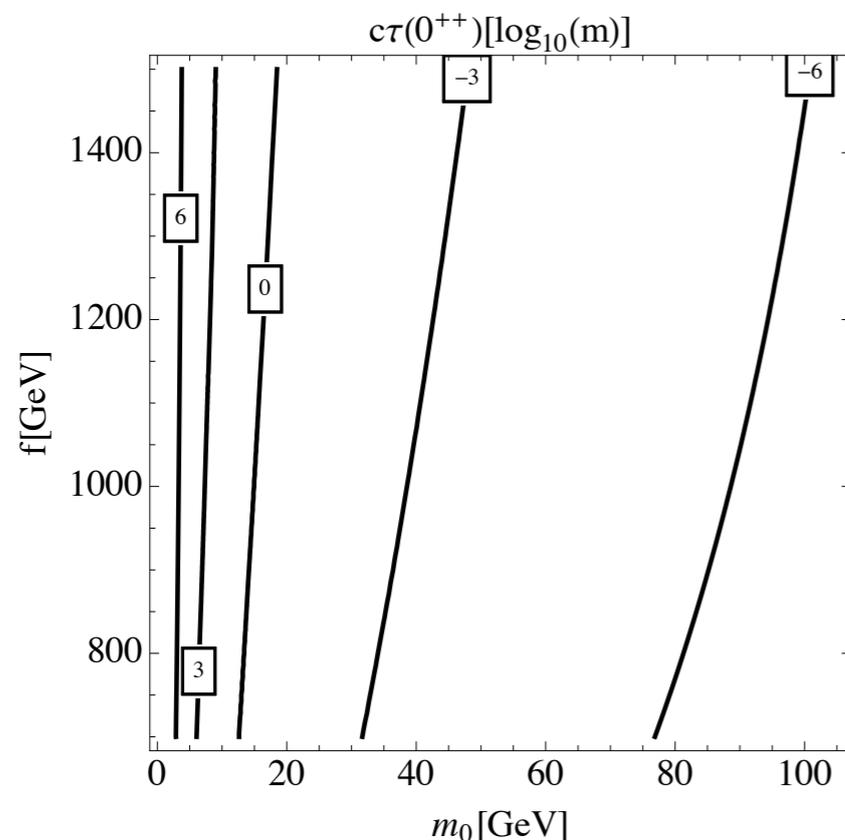
Displaced decays @ LHC



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

$$\mathcal{L} \supset -\frac{\alpha'_3}{6\pi} \frac{v}{f} \frac{h}{f} G'_{\mu\nu}{}^a G'^{\mu\nu}{}_a \rightsquigarrow 0^{++} \rightarrow h^* \rightarrow \dots$$



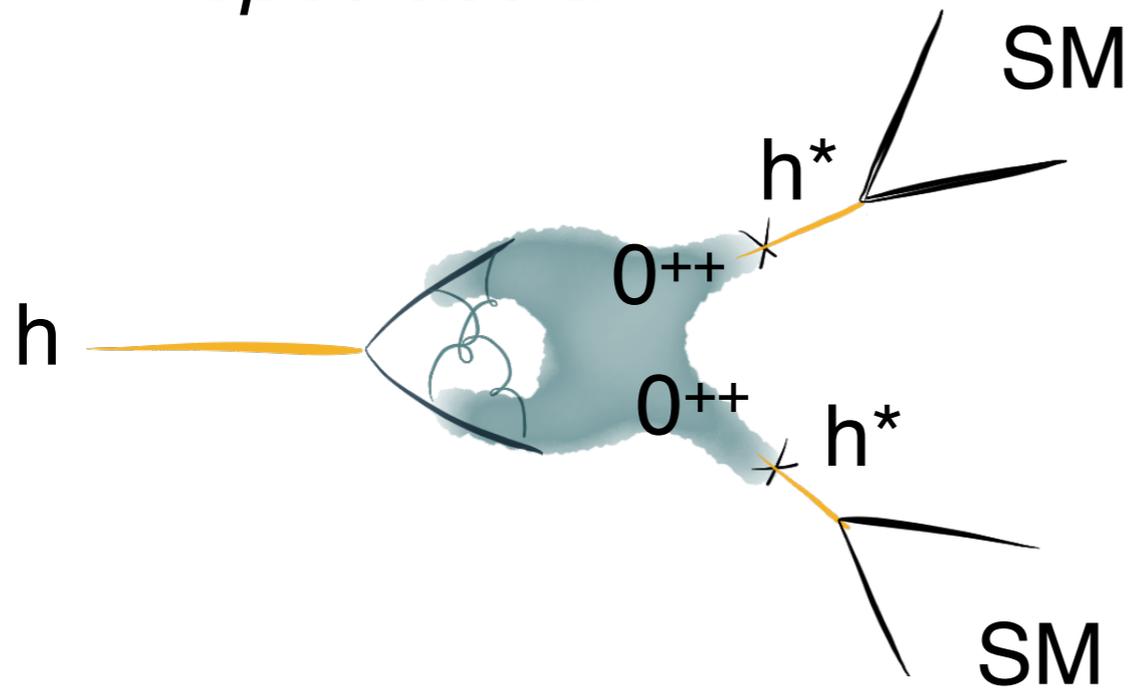
Intriguing lifetime!

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

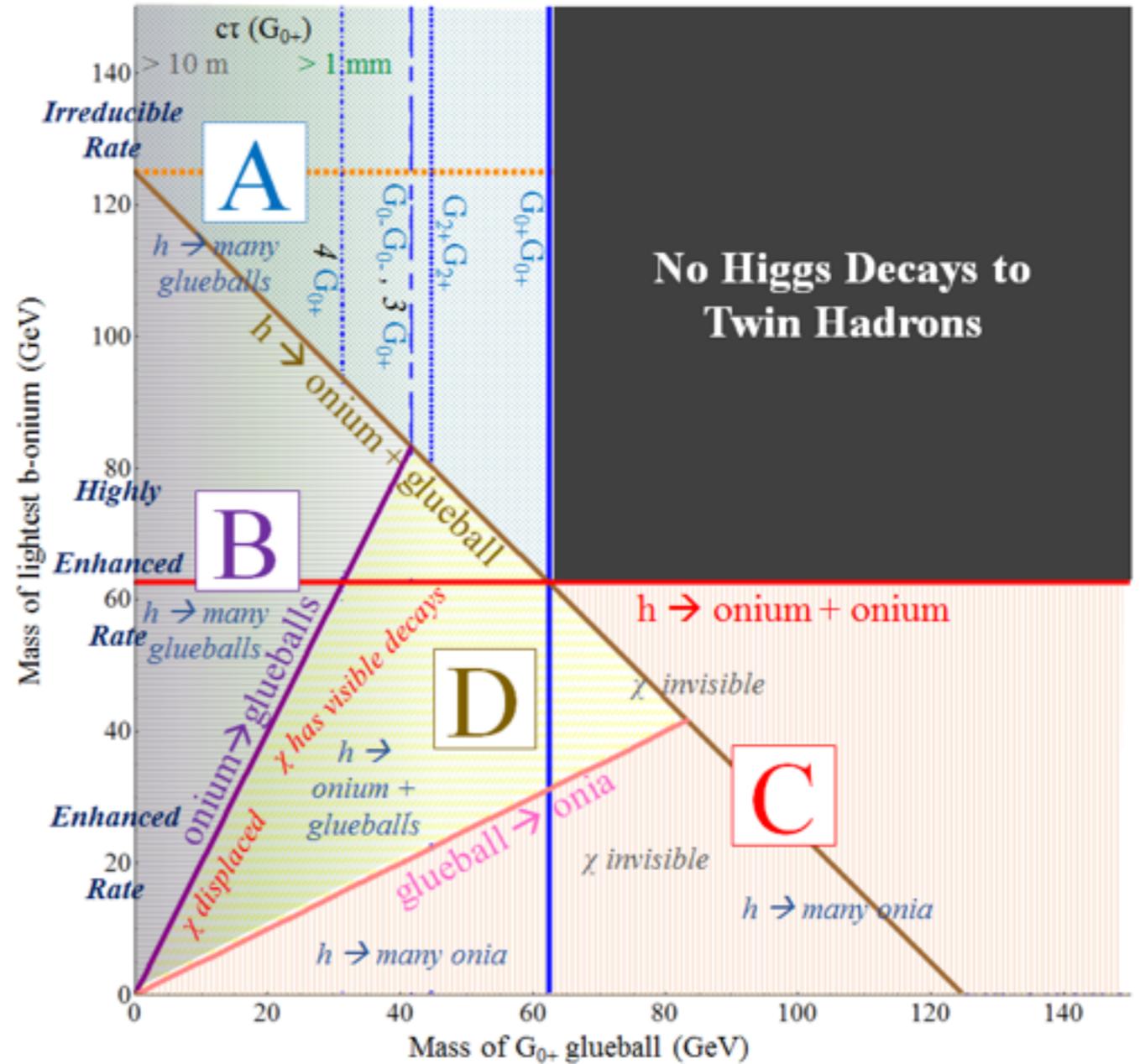
Strong dependence (7th power) on glueball mass → decays scan rapidly over LHC length scales.

Displaced decays

Rates small, signals spectacular.



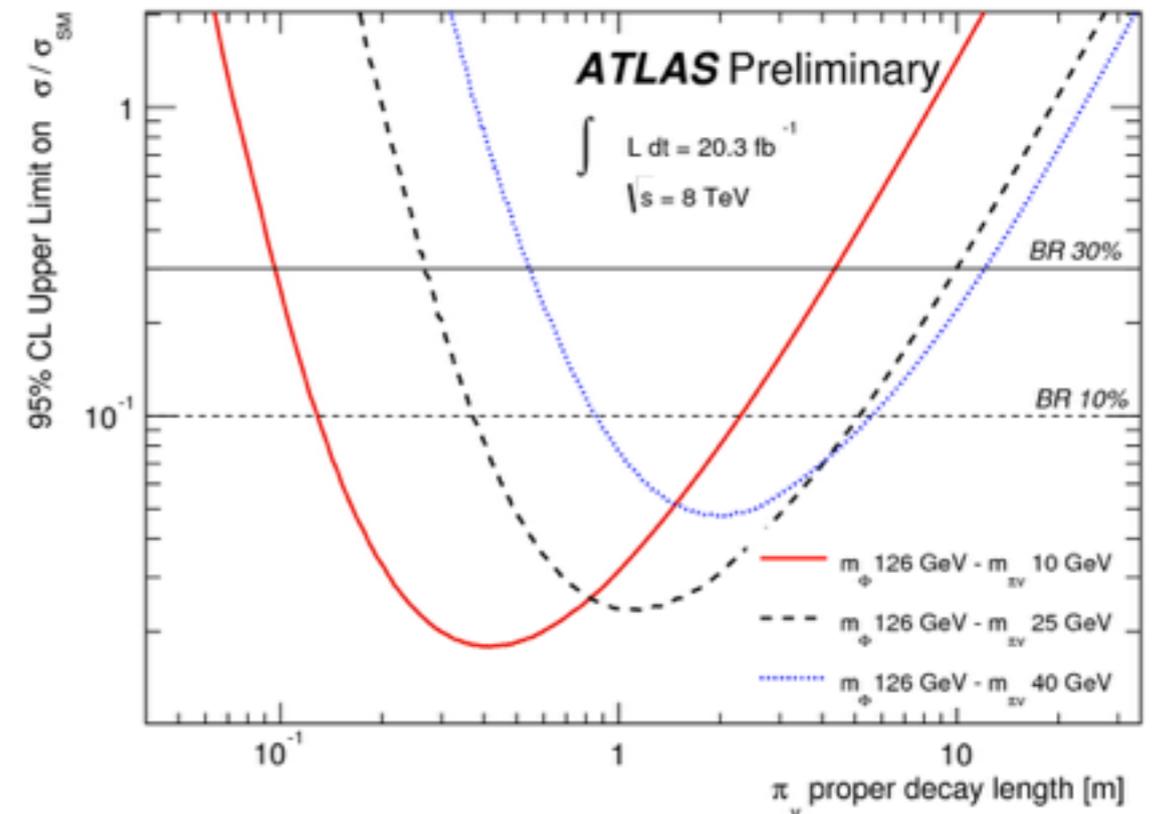
Simplest case: decay into 0^{++} pairs
But wide variety of signals across parameter space.



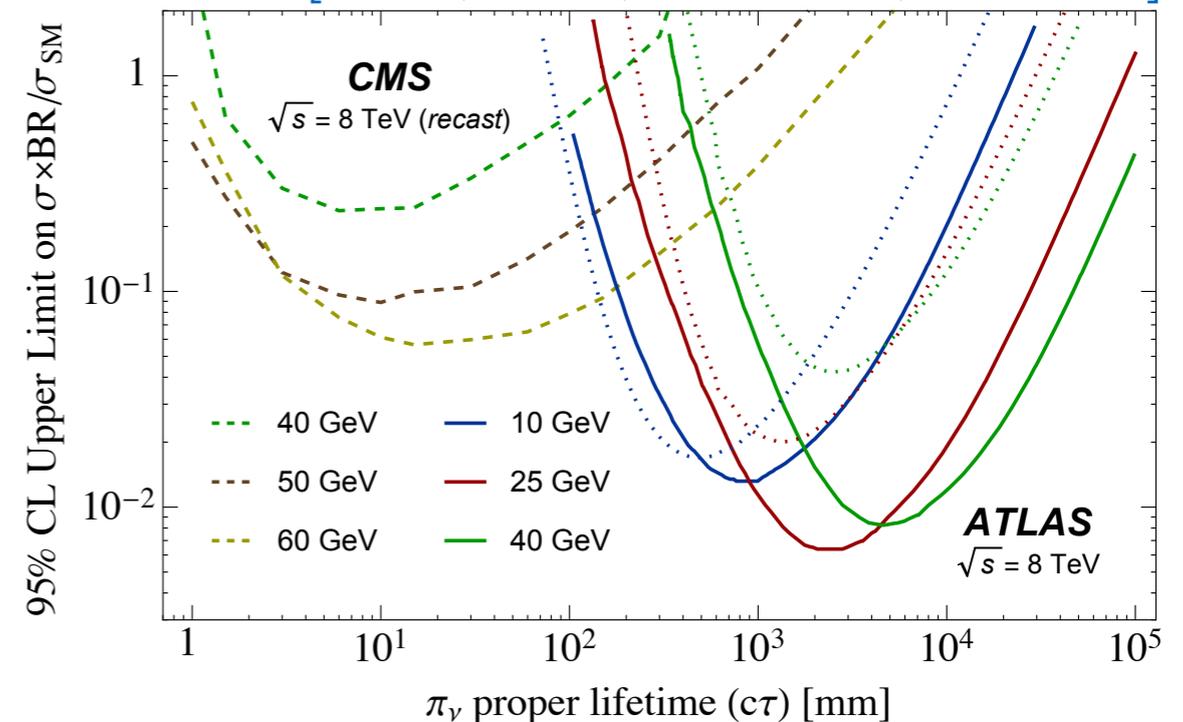
Not yet strongly constrained @ LHC

Existing searches

- ATLAS: HCAL/ECAL & muon chamber searches powerful, sensitive to displaced Higgs decay.
- CMS: use inner tracker, sensitivity to short decay lengths. Reliant on vertexing, trigger thresholds too high for Higgs decay.
- Signal: displaced decays of SM Higgs with $BR \sim 10^{-4} - 10^{-1}$ ($\sigma \cdot BR > 2 \text{ fb}$ @ Run 1).
- Reinterpretation away from benchmarks challenging [Cui, Shuve '14; Liu, Tweedie '15; Curtin, Verhaaren '15; Csaki, Kuflik, Lombardo, Slone '15]



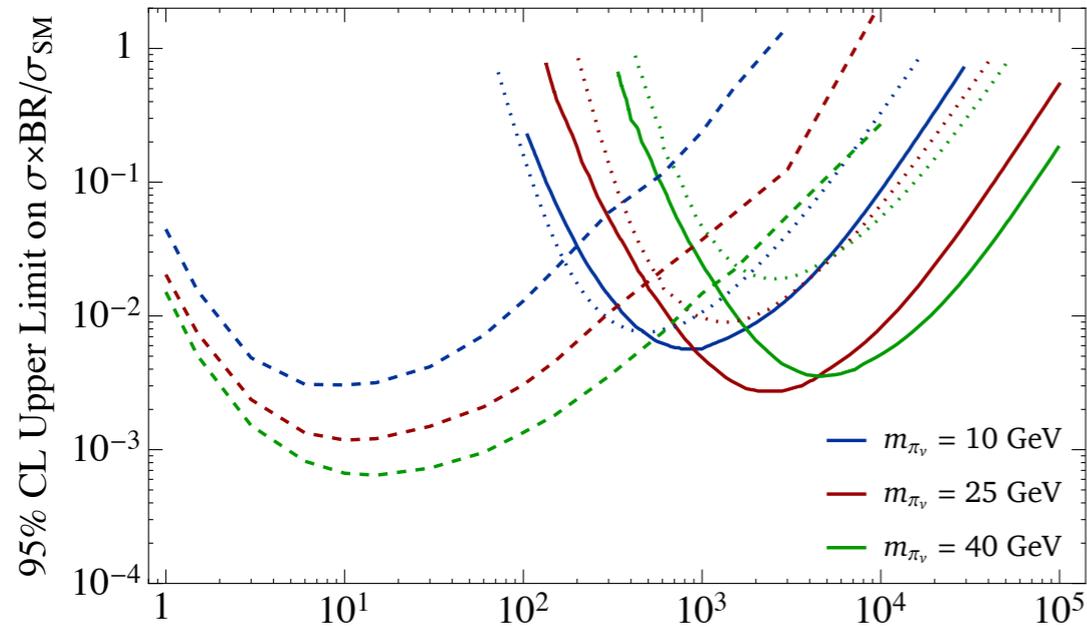
[Csaki, Kuflik, Lombardo, Slone '15]



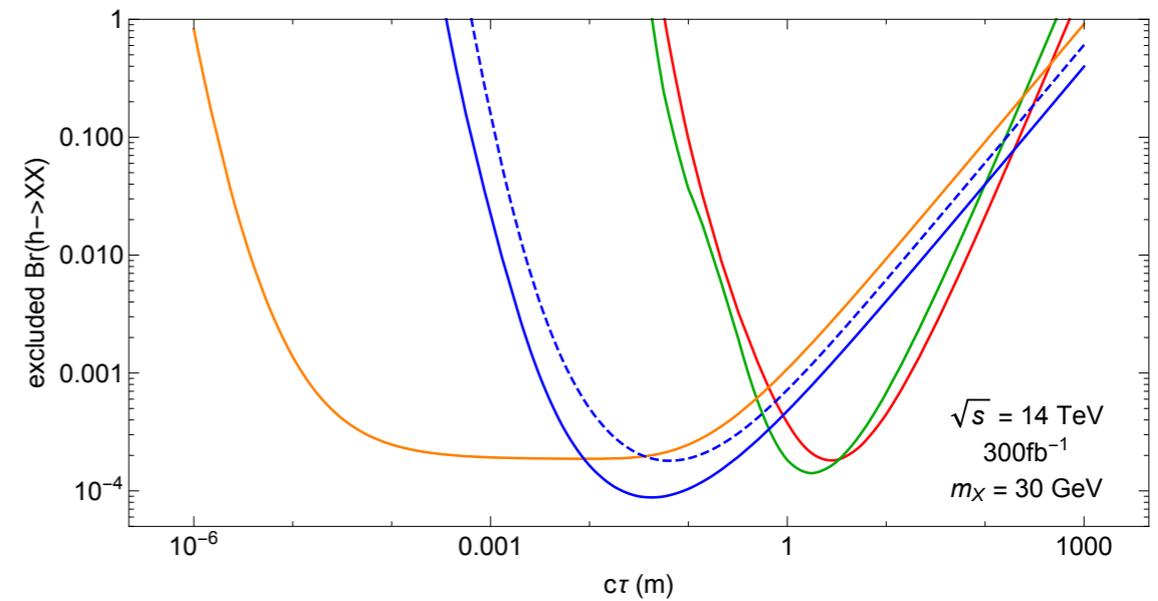
Run 2 and beyond

[Csaki, Kuflik, Lombardo, Slone '15]

Run II Projections, $\sqrt{s} = 13 \text{ TeV}$, 20 fb^{-1}



[Curtin, Verhaaren '15]

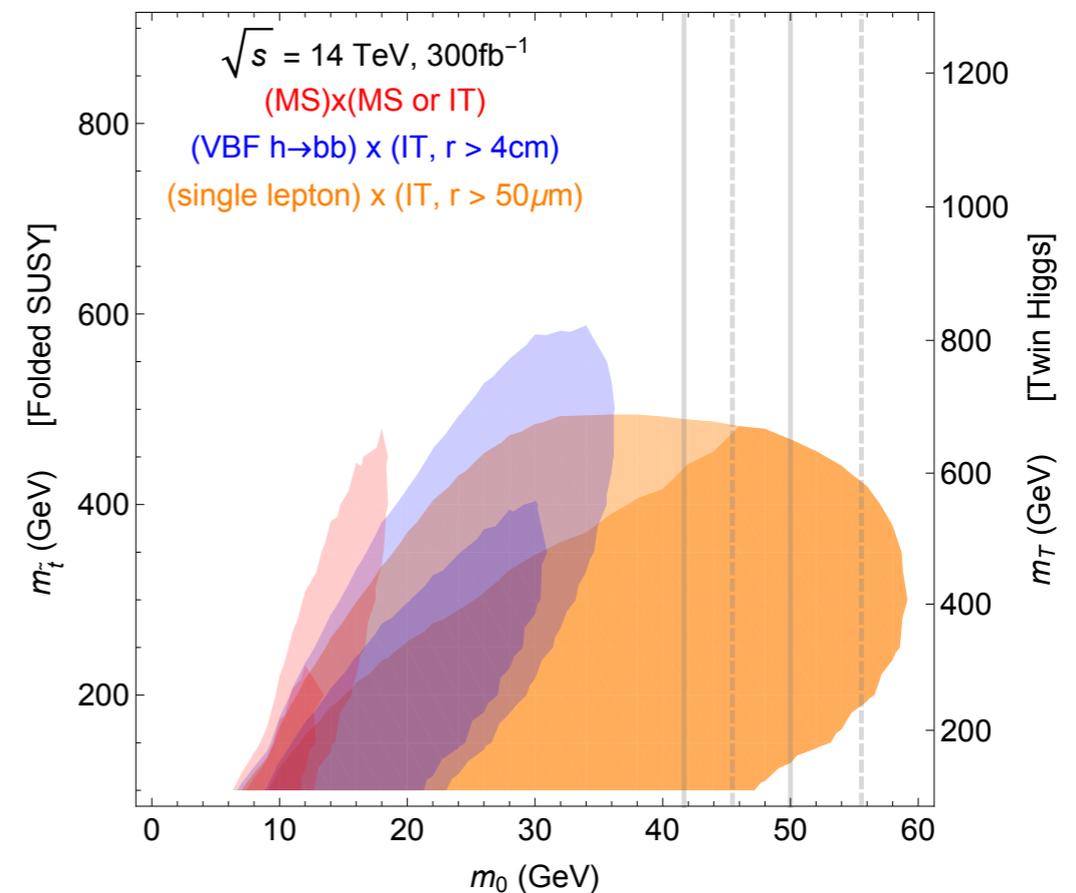


MATHUSLA

John-Paul Chou
David Curtin
Henry Lubatti

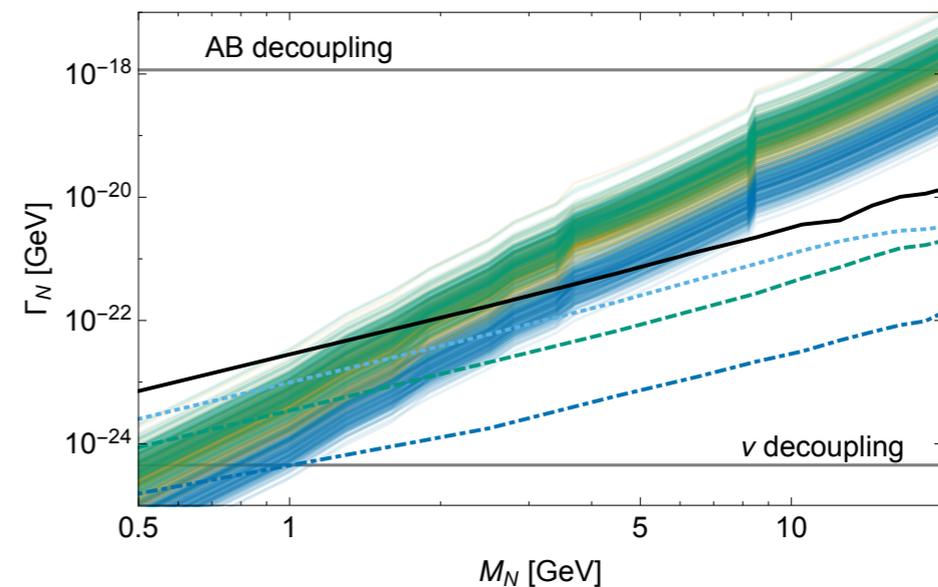
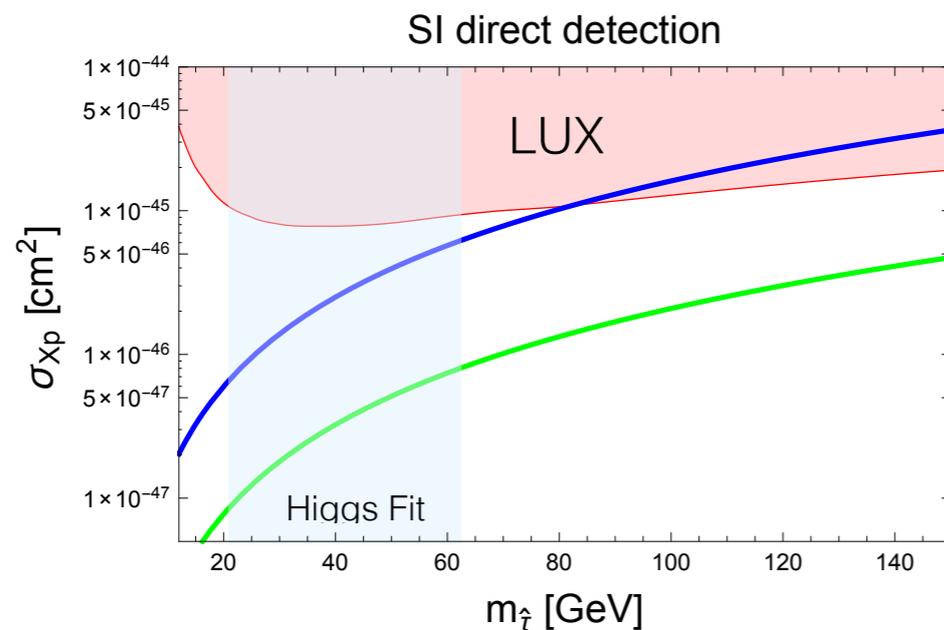
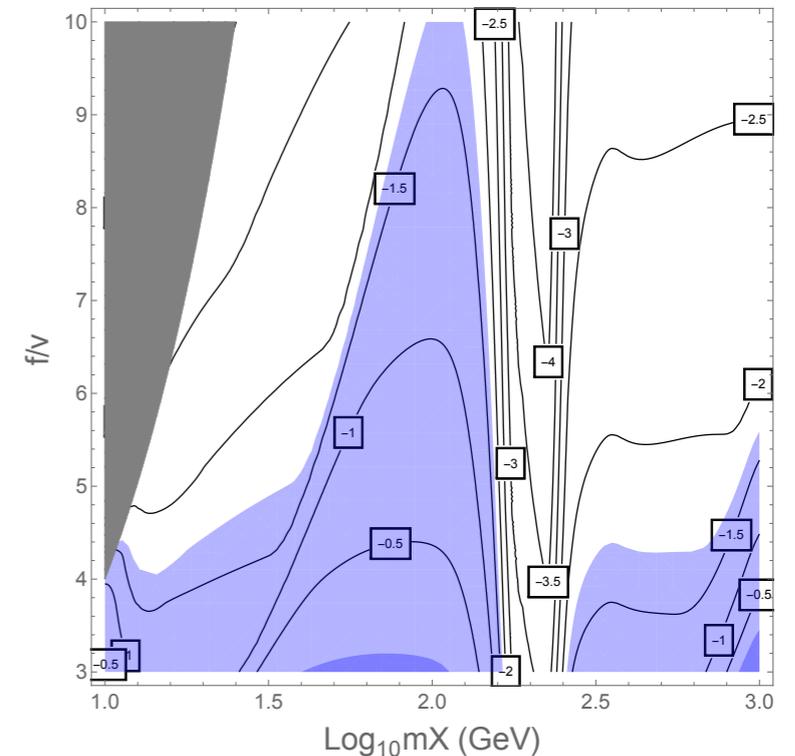
MAssive Timing Hodoscope for Ultra-Stable Neutral Particles

Methuselah (Hebrew: מתושלח / מתושלח, Modern *Metušélah* / *Metušálah* Tiberian *Meṭúšélah* / *Meṭúšálah*; "Man of the dart/spear", or alternatively "his death shall bring judgment"^[1]) is the man reported to have lived the longest at the age of 969 in the Hebrew Bible.^[2]



Cosmic directions

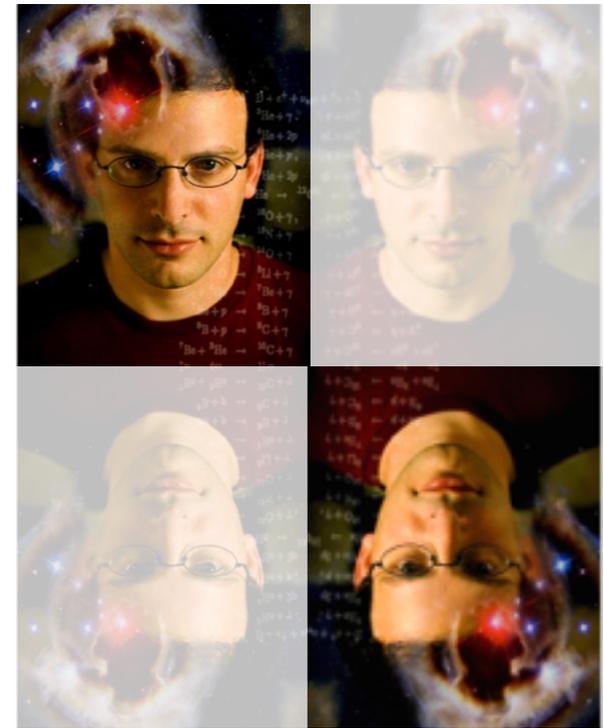
- Dark matter: many possible DM candidates for WIMP or asymmetric DM, within reach of next-gen direct detection. [NC, A. Katz '15, I. Garcia Garcia, R. Lasenby, J. March-Russell '15; M. Farina '15]
- Many models predict dark radiation; consistent cosmologies give dark radiation within reach of CMB-S4. [NC, S. Koren, T. Trott '16]
- Neutrino portal to SM gives additional novel cosmological and terrestrial signatures. [Z. Chacko, NC, P. Fox, R. Harnik '16]



A SUSY variation

Folded Supersymmetry

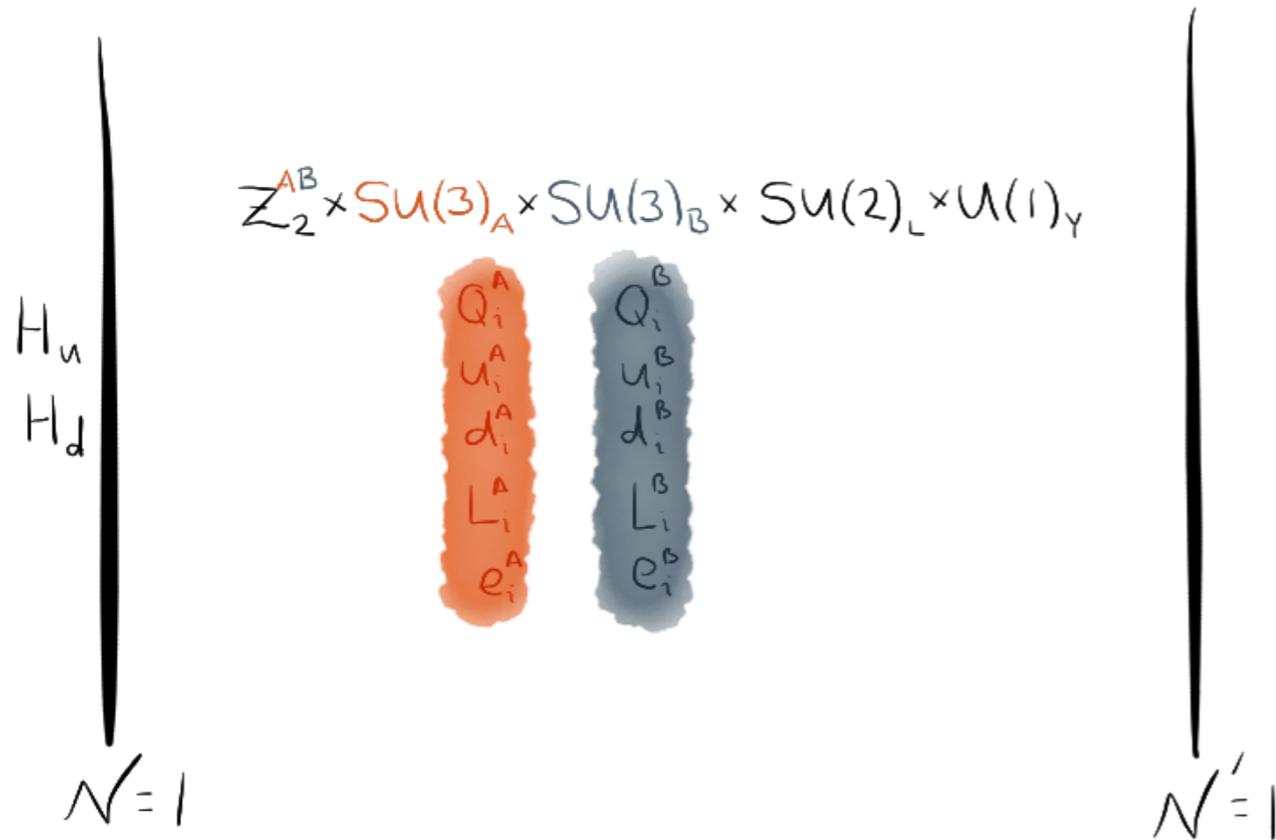
[G. Burdman, Z. Chacko, R. Harnik '06]



'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 around the correspondence that exists in the large N limit between the correlation functions of

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.

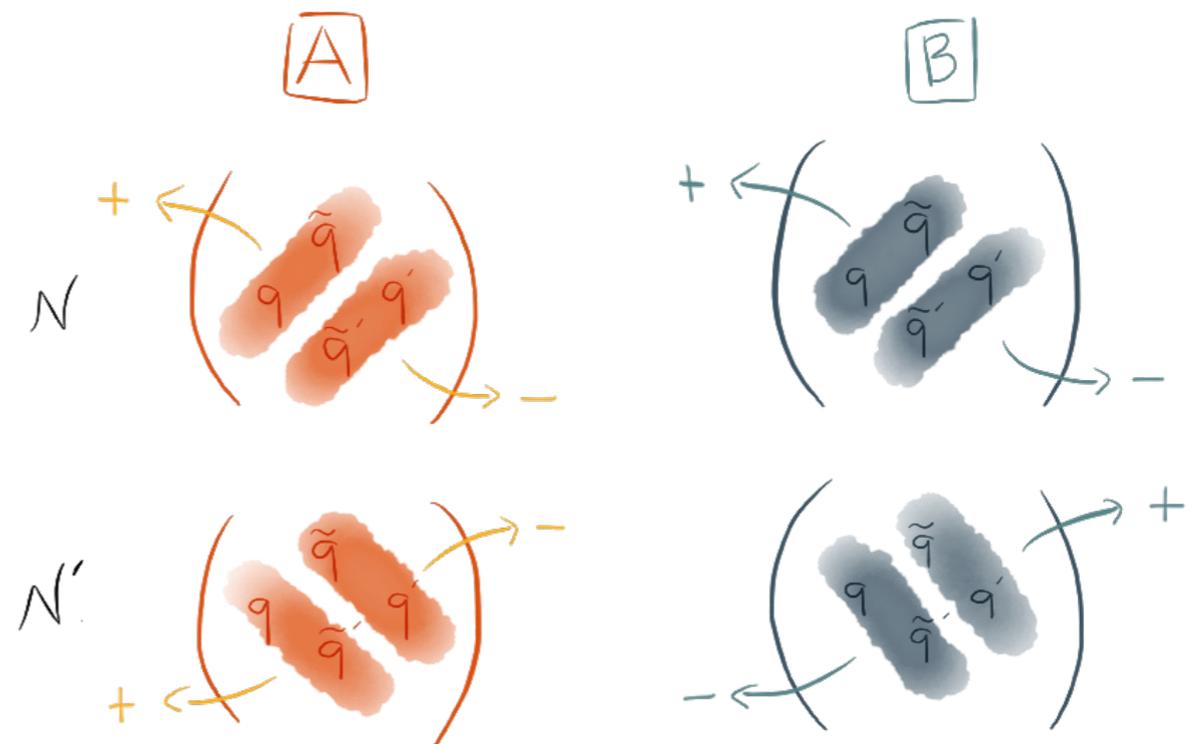
Reduce symmetries & SUSY at the boundaries

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

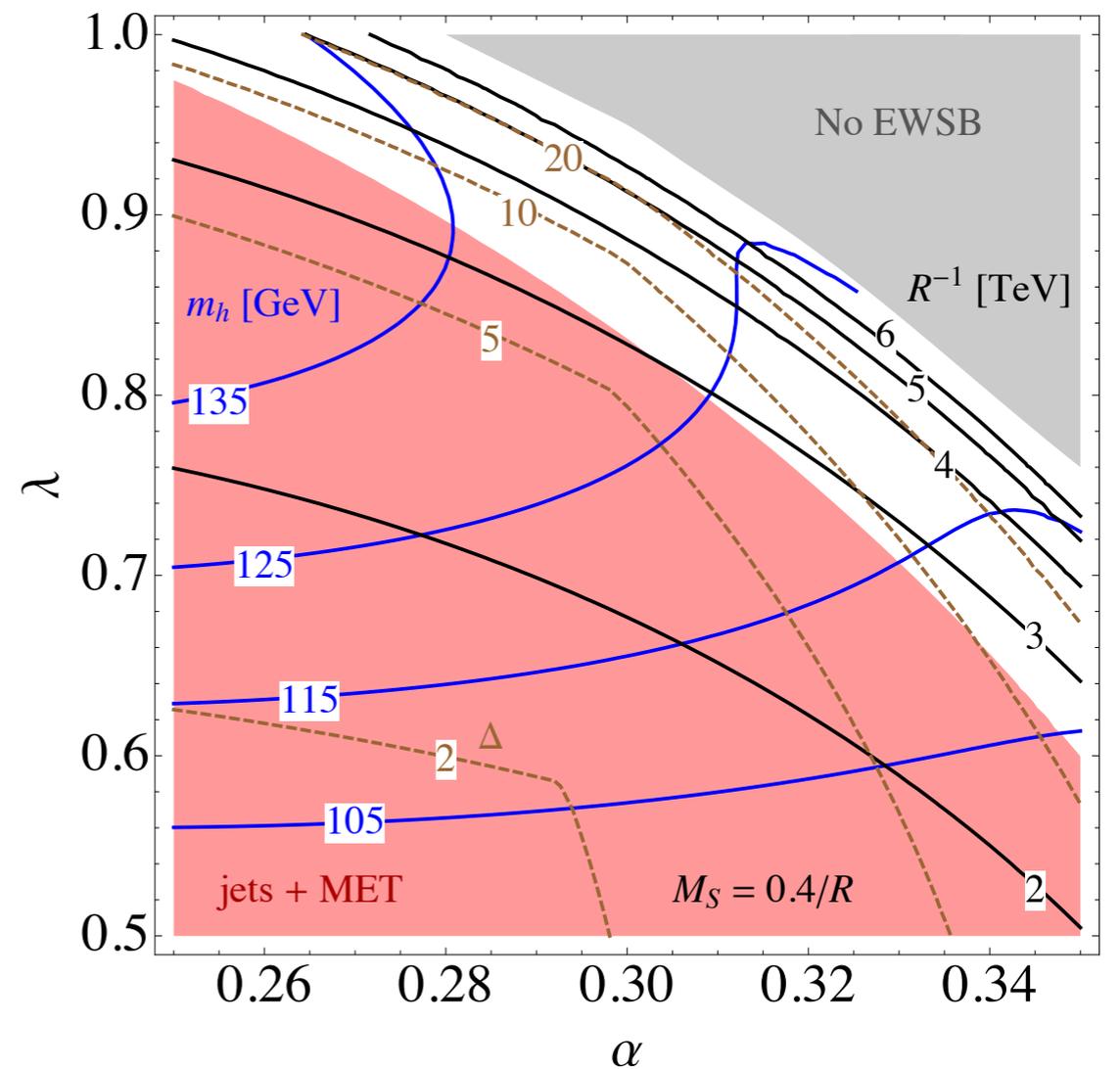
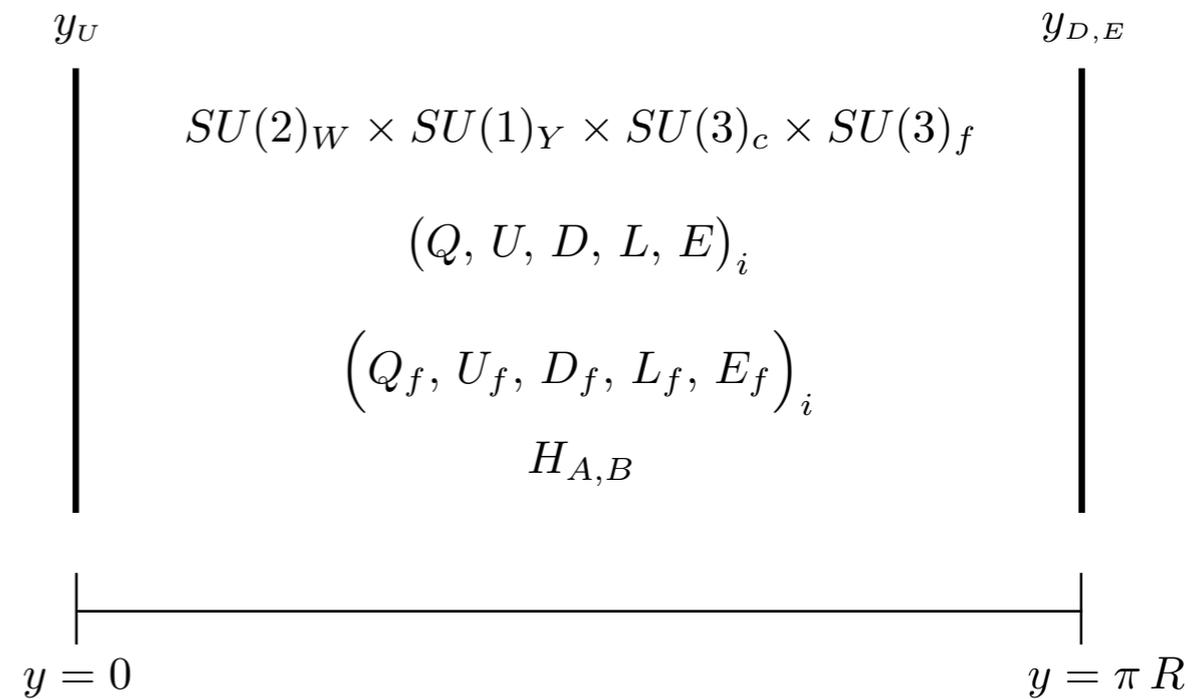
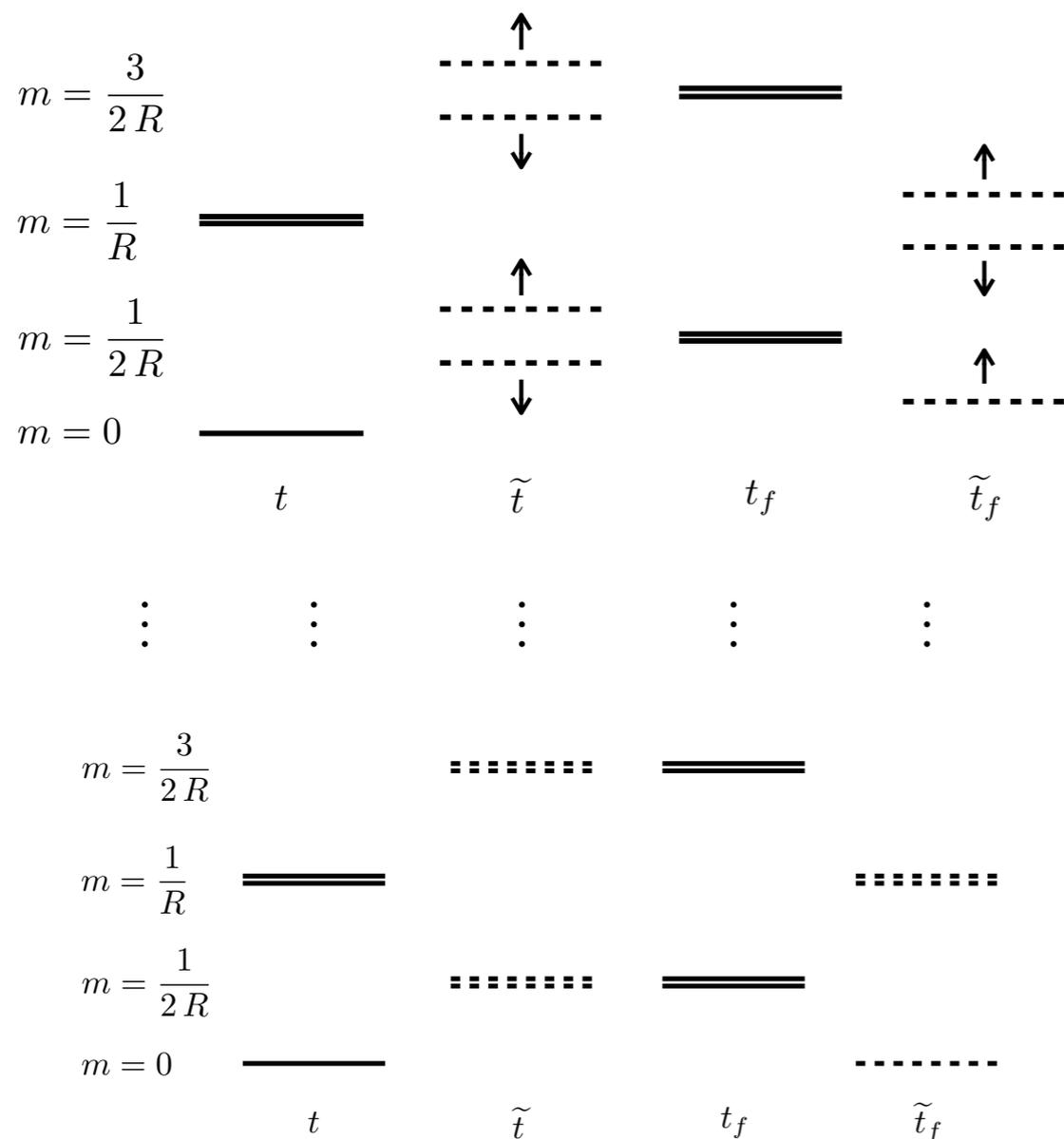
Many possible variations using the tools of 5D SUSY model-building.

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

“Realistic” model

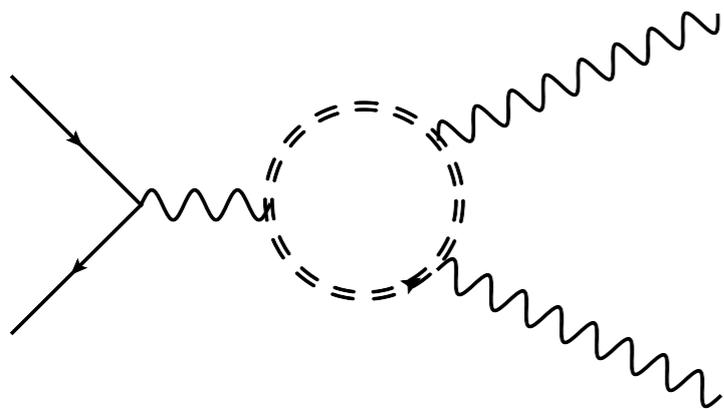
[Cohen, NC, Lou, Pinner '15]

Partial SS twist for viable EWSB
 Signals of heavy SUSY + f-sfermions
 Tuning is \sim best in class

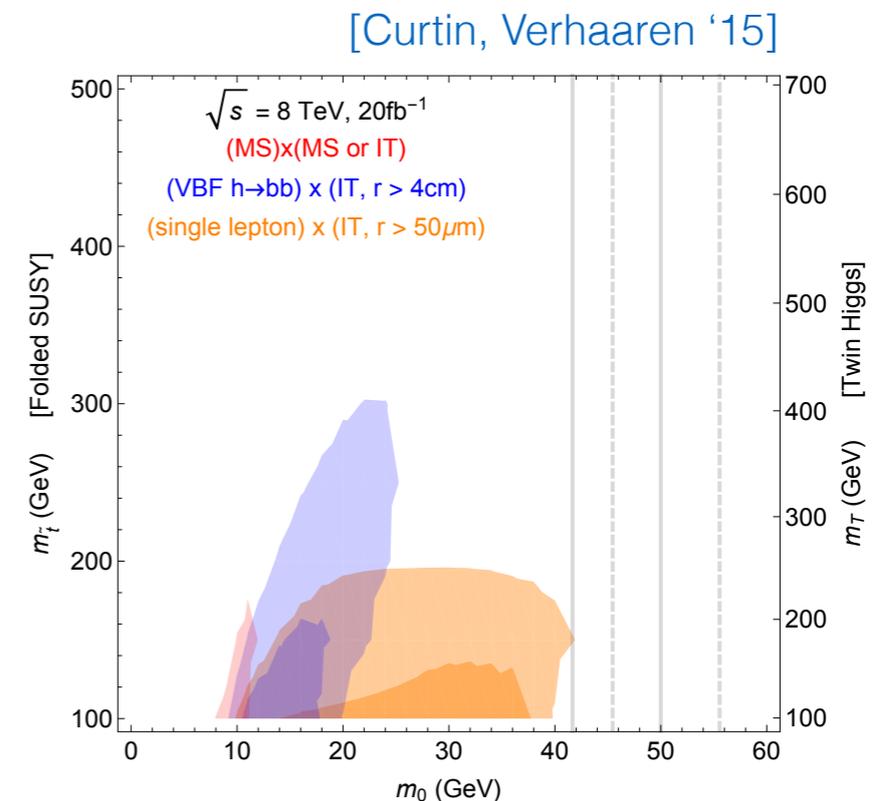
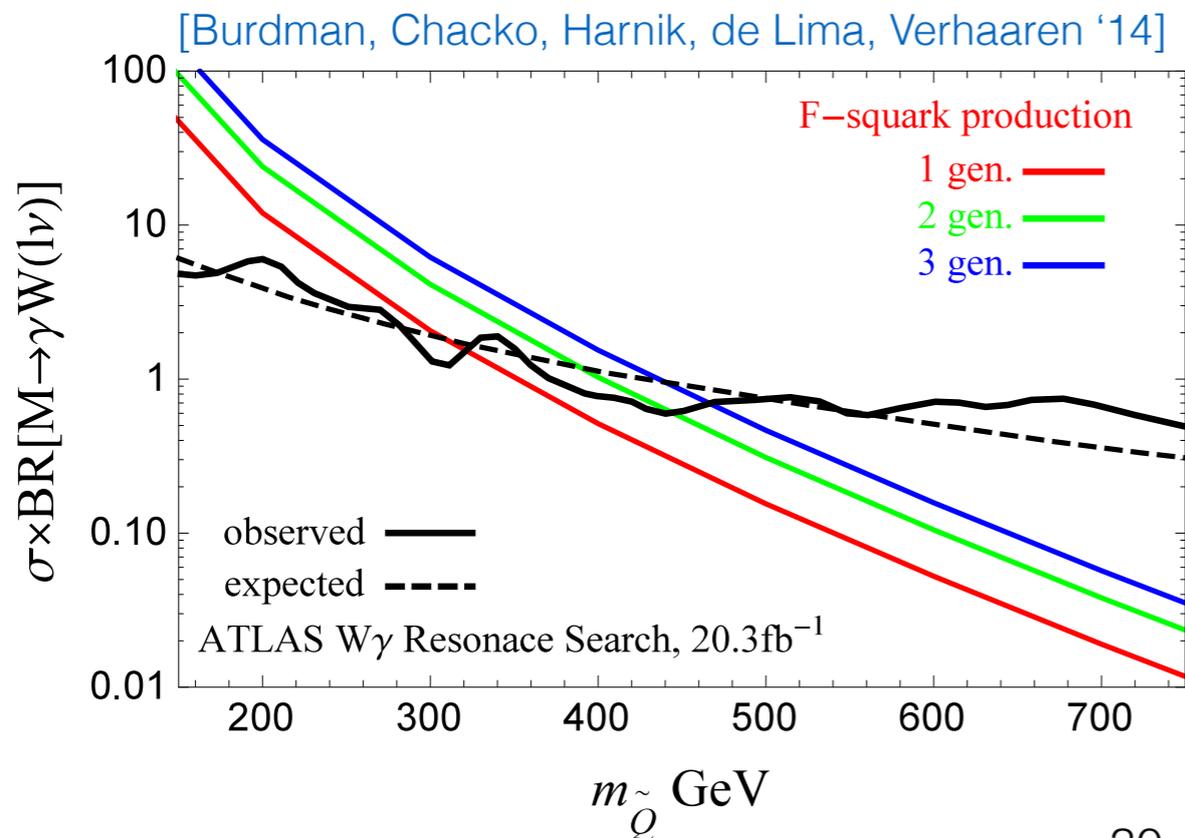


Colorless Signals

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. [Curtin, Verhaaren '15]
- Produced via a W , annihilate back into the SM to shed their charge.
- (Also leave their mark indirectly, correcting Higgs decays to photons.)



Future of neutral naturalness

[Curtin, Verhaaren '15]

		<i>scalar</i>	<i>fermion</i>
<i>strong direct production</i> {	<i>QCD</i>	SUSY	Composite Higgs/ RS
<i>DY direct production</i> {	<i>EW</i>	folded SUSY	Quirky Little Higgs
<i>Higgs portal direct production</i> {	<i>singlet</i>	?	Twin Higgs

Mirror Glueballs

Higgs portal observables

Higgs coupling shifts

~ tuning

Pandora's box

- In all of these theories, naturalness lies in hidden sectors connected via the Higgs portal



A realization of rich hidden sectors with SM-like scales:

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

Thank you!



High Energy Physics at the Sensitivity Frontier

Coordinators: Nathaniel Craig, Rouven Essig, and Kathryn Zurek

Scientific Advisors: Peter Graham and Michael Romalis

DATES

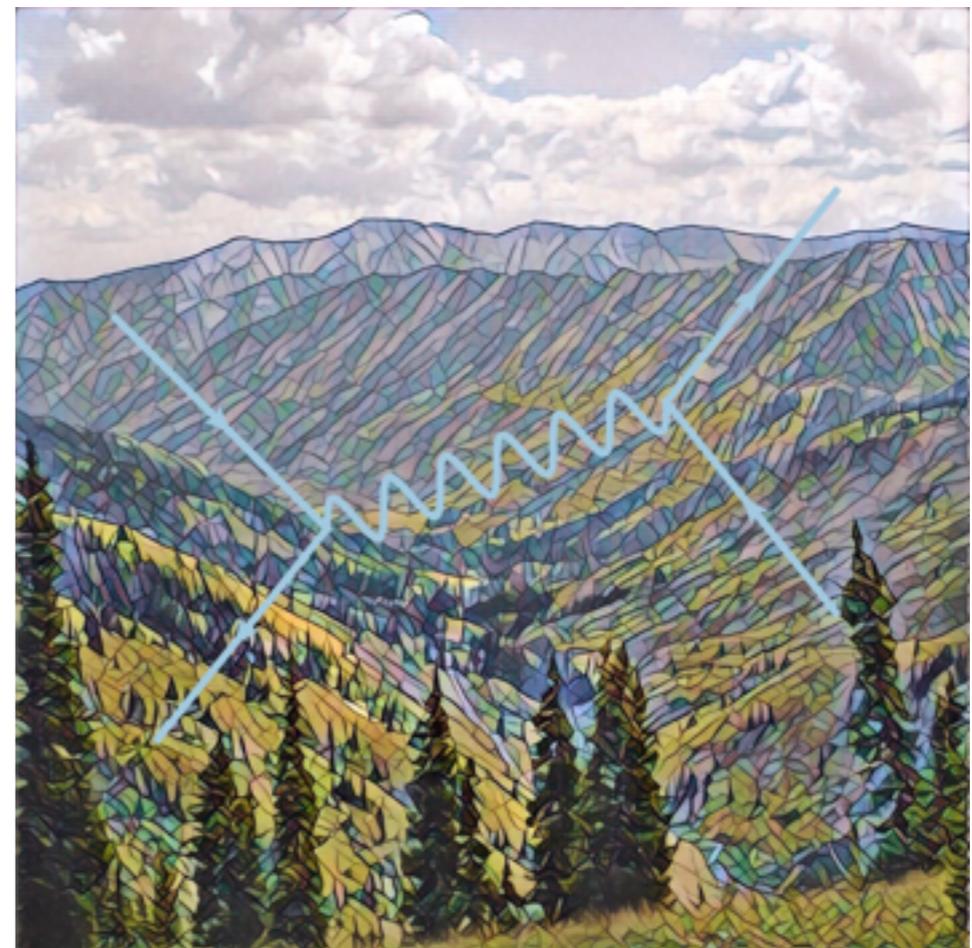
Mar 26, 2018 - May 25, 2018

INFORMATION

[Apply](#)

Application deadline is:

Dec 4, 2016.



Bonus slides

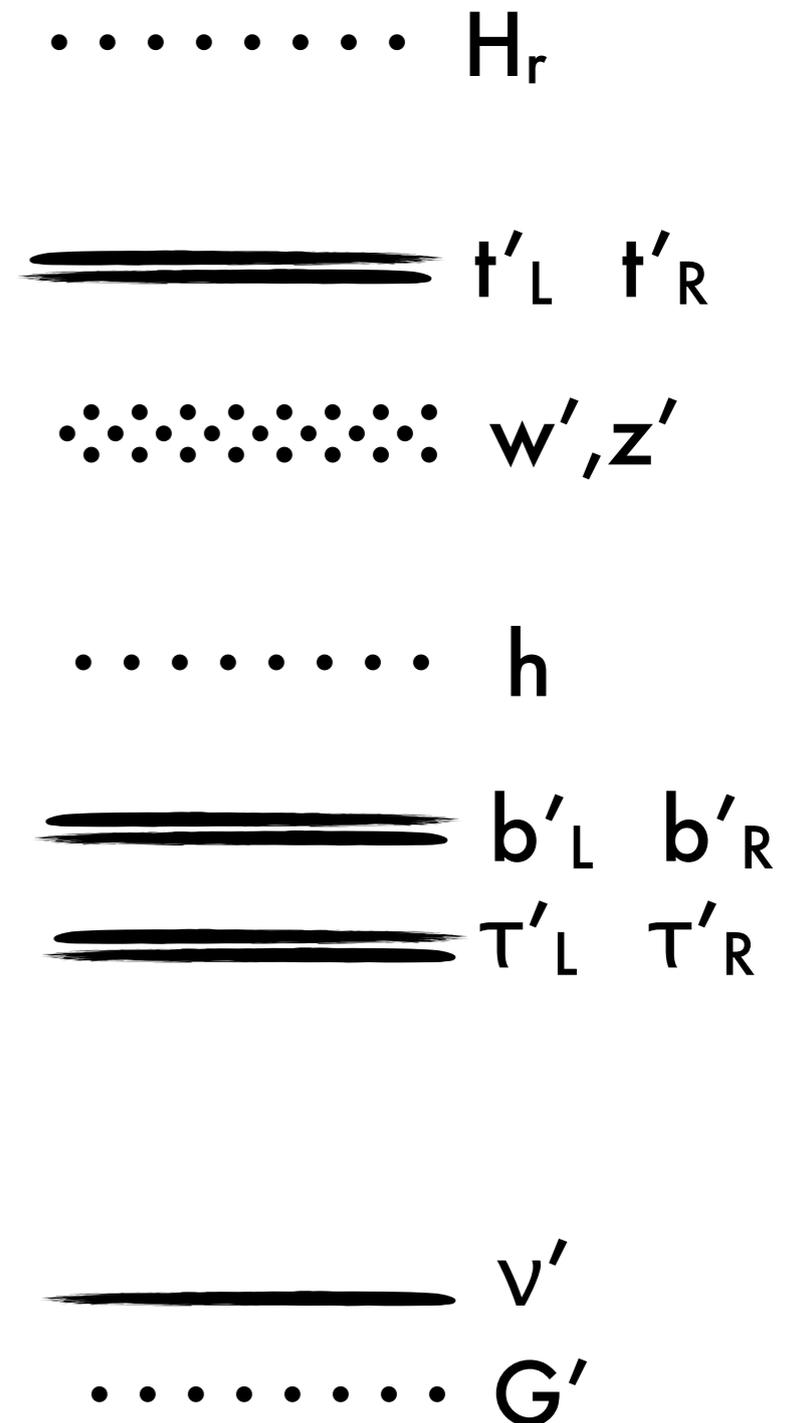
Dark matter

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

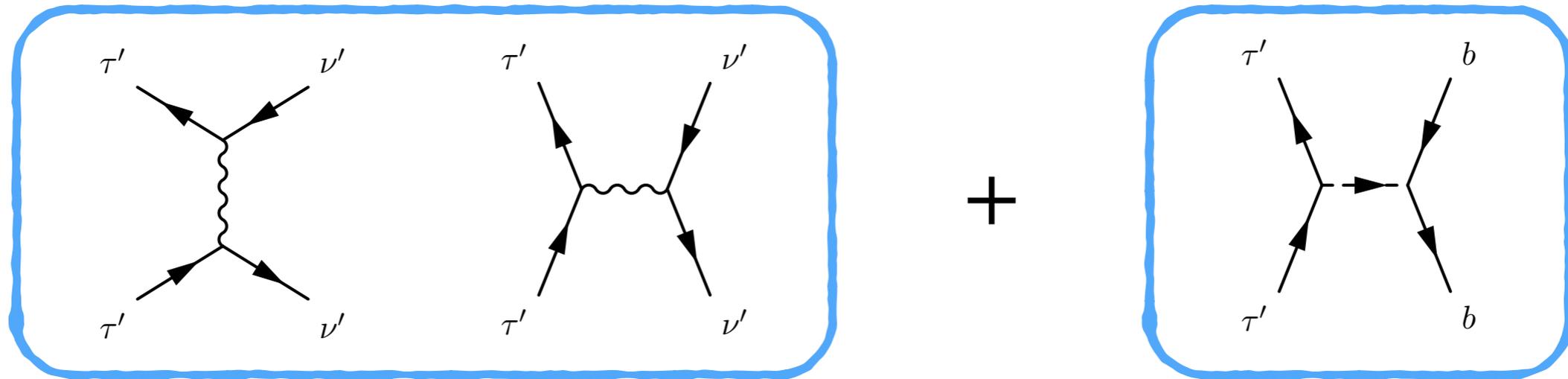
Superabundance of candidates in twin
scenarios; many stabilization symmetries
(lepton #, baryon #, global EM).

Various mechanisms for symmetric or
asymmetric abundance.

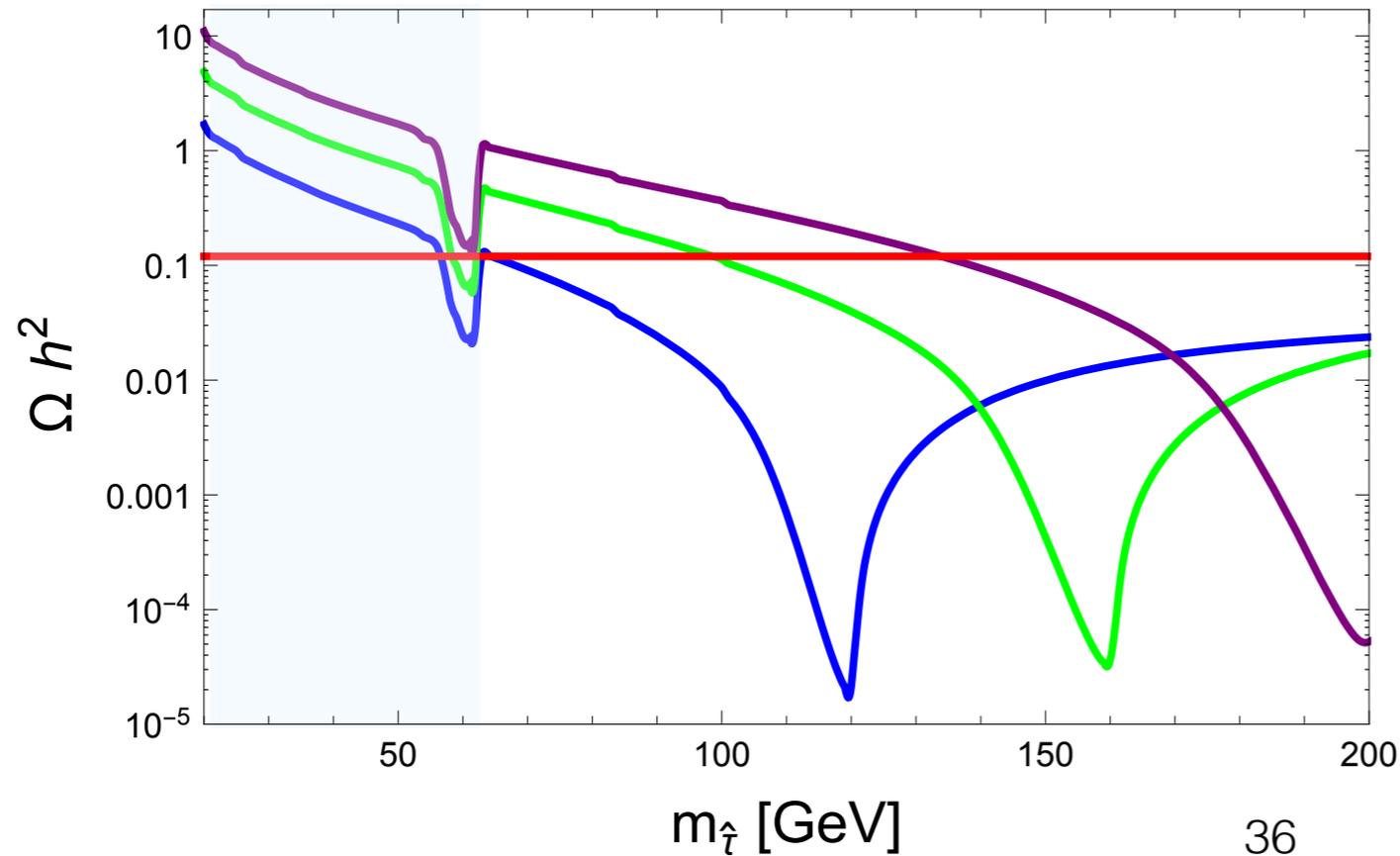
*Simplest case: no light twin $U(1)$;
DM candidate is twin tau.*



Fraternal WIMP miracle



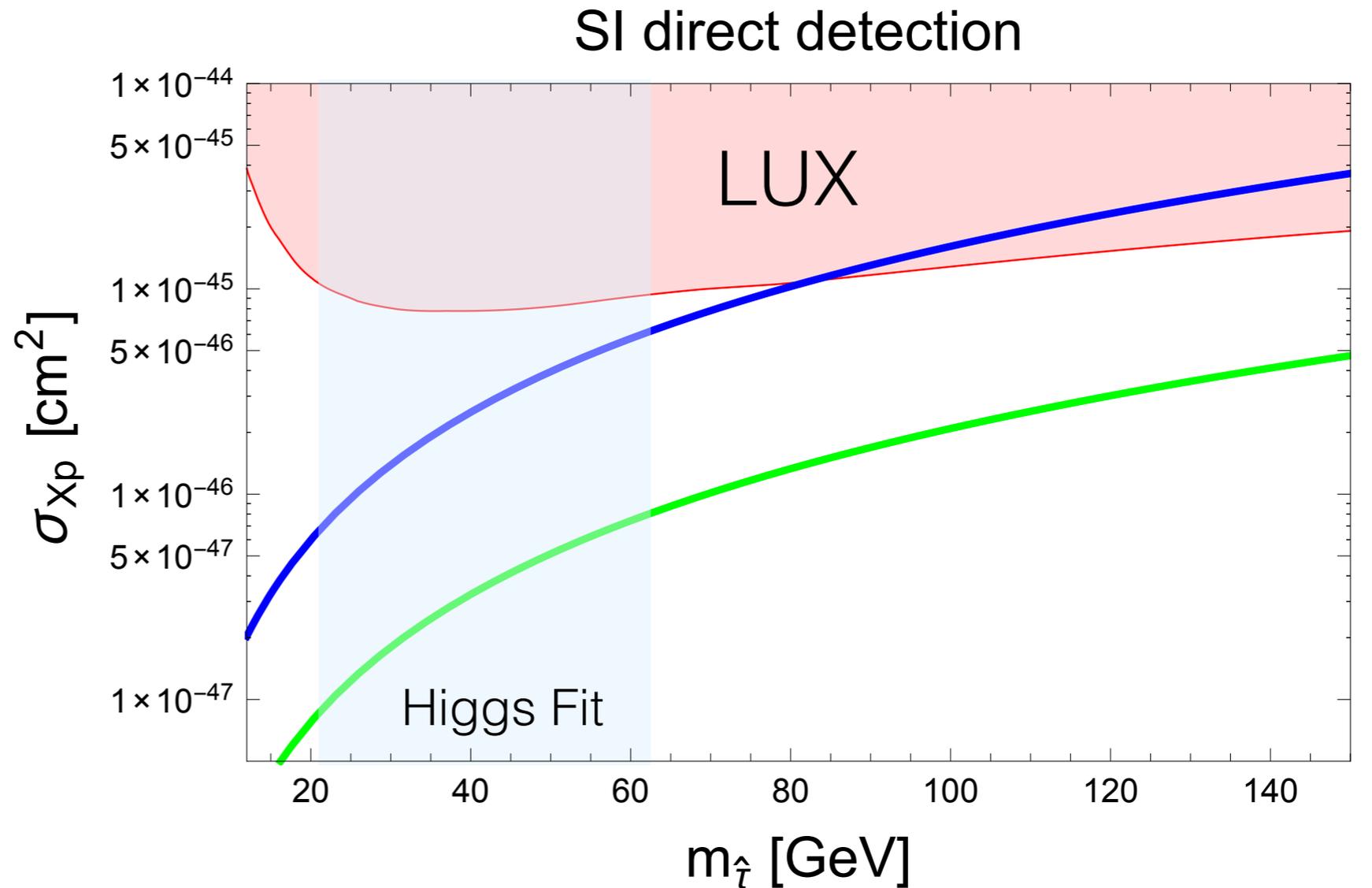
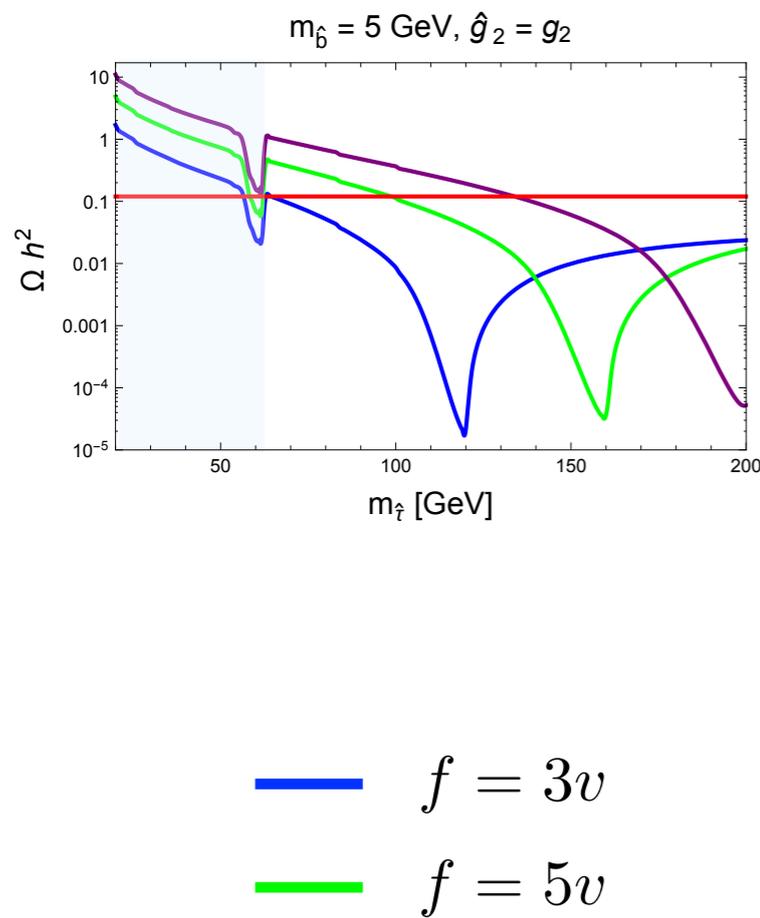
$m_{\hat{g}} = 5 \text{ GeV}, \hat{g}_2 = g_2$



- $f = 3v$
 - $f = 4v$
 - $f = 5v$
- Viable thermal population, annihilating via twin W', Z'

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

Direct detection



Natural parameter space right on the edge of direct detection

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