Naturalness of the electroweak scale?

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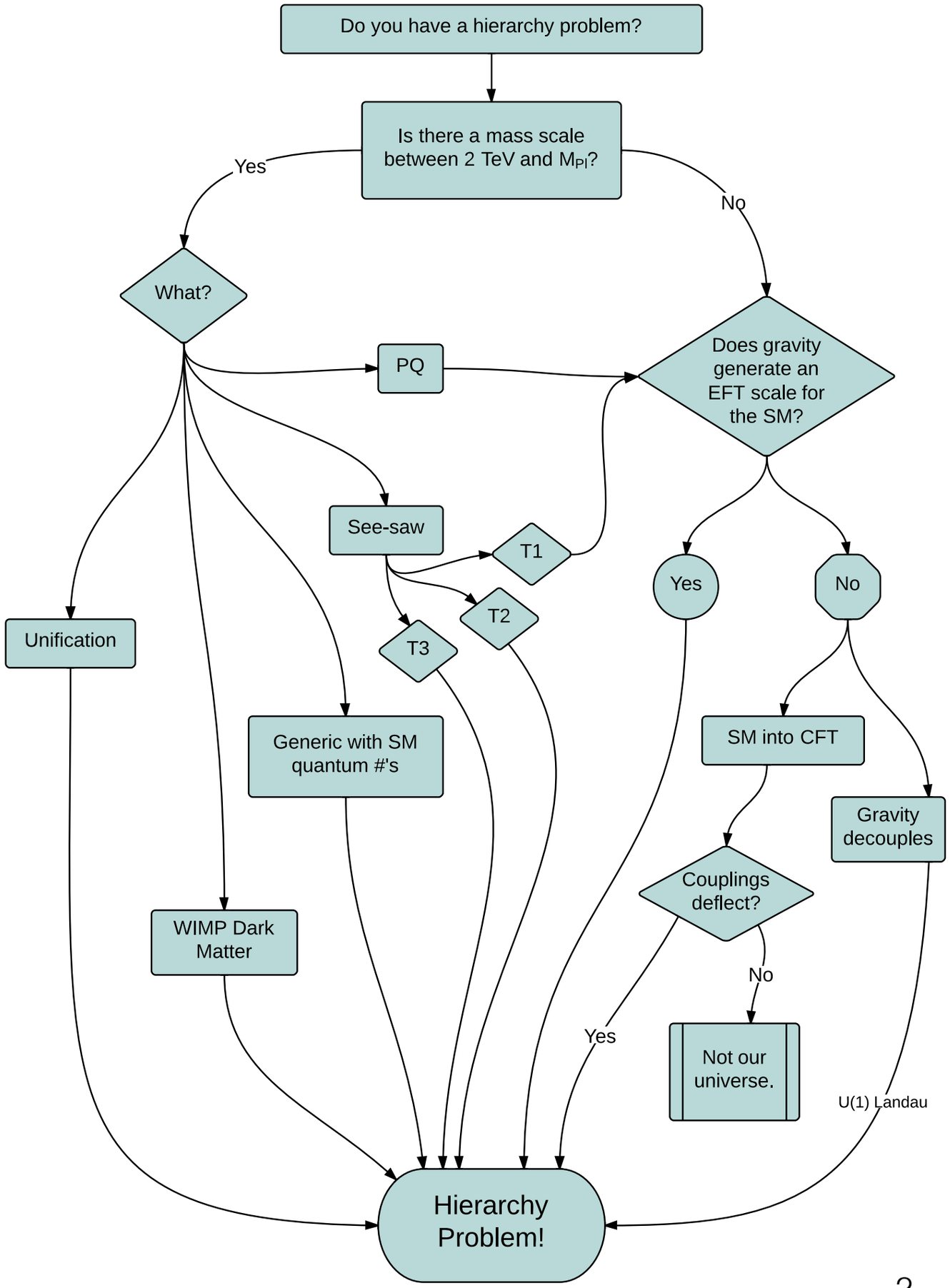
Santa Barbara

Pheno 2016



Hierarchy Problem

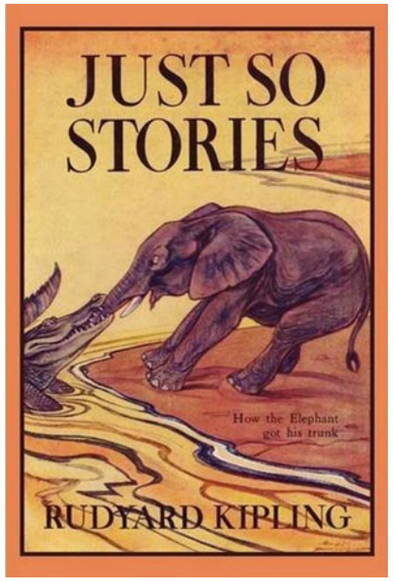
Elementary scalars are quadratically sensitive to physics at higher scales.

Independent of regularization scheme.

Model-building scales aside, gravity attests to presence of a higher scale.

No viable proposals for mitigating sensitivity to physics @ Planck scale *without* new physics @ weak scale.

Hierarchy problem only sharpened with the discovery of an elementary SM-like Higgs (+nothing else so far).



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

What's the scale?

The hierarchy problem is sensitivity to higher scales; quantify sensitivity of Higgs mass to new physics via ratio

$$\Delta \equiv \frac{2\delta m_H^2}{m_h^2}$$

A *guidepost* to where new physics should enter; in the SM with a uniform cutoff Λ, SM loops up to Λ give

$$\delta m_H^2(\mu) = \frac{\Lambda^2}{16\pi^2}\left[6\lambda(\mu) + \frac{9}{4}g_2^2(\mu) + \frac{3}{4}g_Y^2(\mu) - 6\lambda_t^2(\mu)\right]$$

Expect new physics to enter and alter SM at some scale*

Δ ≲1 (no tuning) requires Λ ≲ 500 GeV;

Δ ≲10 (10%-level tuning) requires Λ ≲ 1.6 TeV;

Δ ≲100 (1%-level tuning) requires Λ ≲ 5 TeV.

*Best-case scenario, no large logs

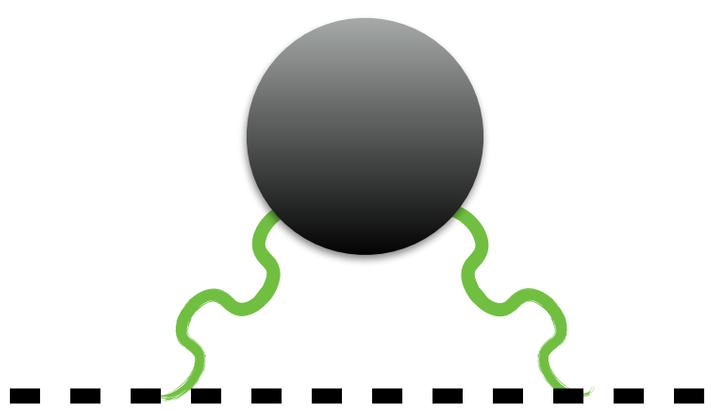
See also X. Tata

The naturalness strategy

This is a *strategy* for new physics near m_h, not a *no-lose theorem*, because the theory does not break down if it is unnatural.

But naturalness has often been a very *successful* strategy.

E.g. charged pions



Electromagnetic contribution to the charged pion mass sensitive to the cutoff of the pion EFT.

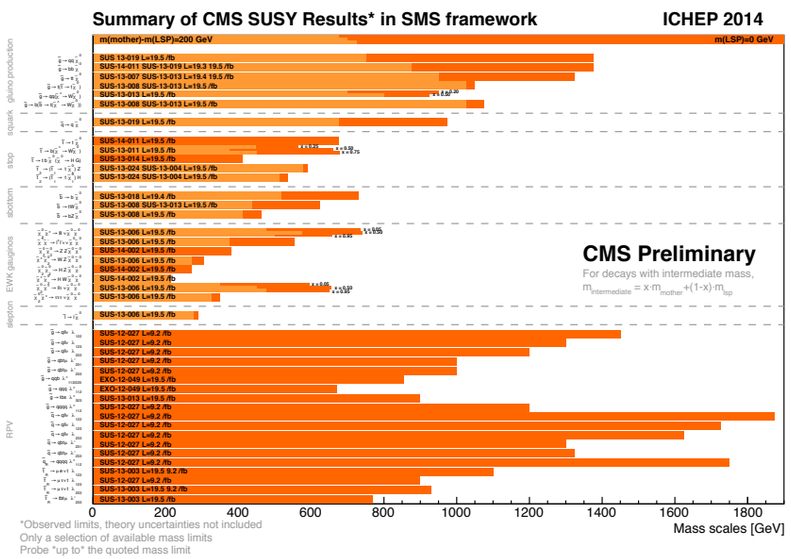
$$\delta m^2 \sim \frac{3e^2}{16\pi^2}\Lambda^2$$

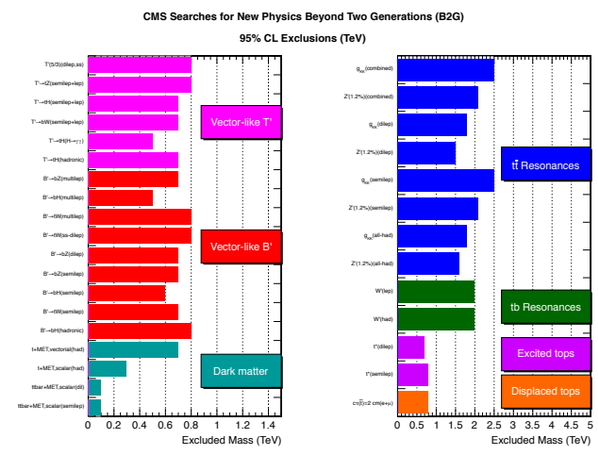
Naturalness suggests Λ~850 MeV.
Rho meson (new physics!) enters at 770 MeV: Δ~1

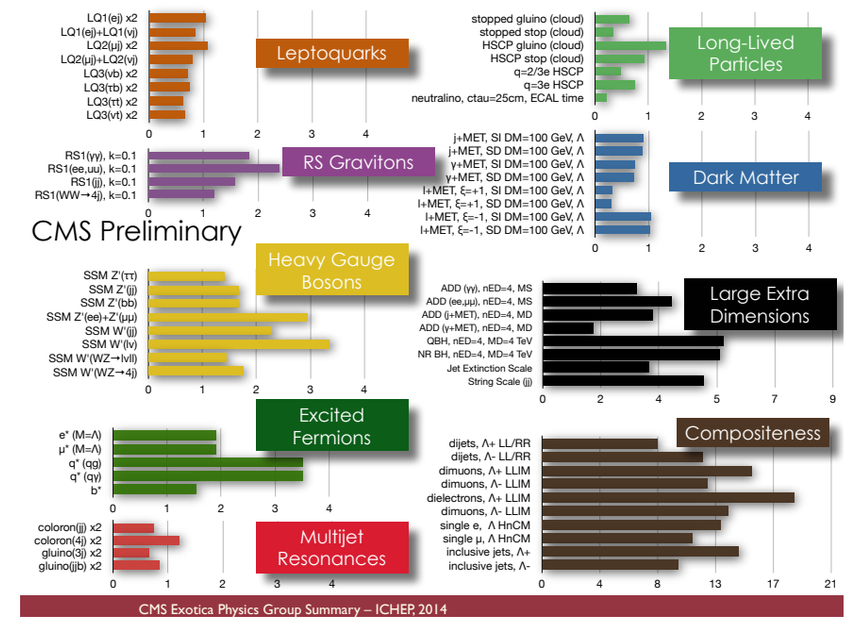
Naturalness scorecard

Phenomenon	Natural?
Charged pion mass	☑ Yes ☐ No
Charm mass	☑ Yes ☐ No
Proton mass	☑ Yes ☐ No
Cosmological constant	☐ Yes ☑ No
Higgs mass	☐ Yes ☐ No

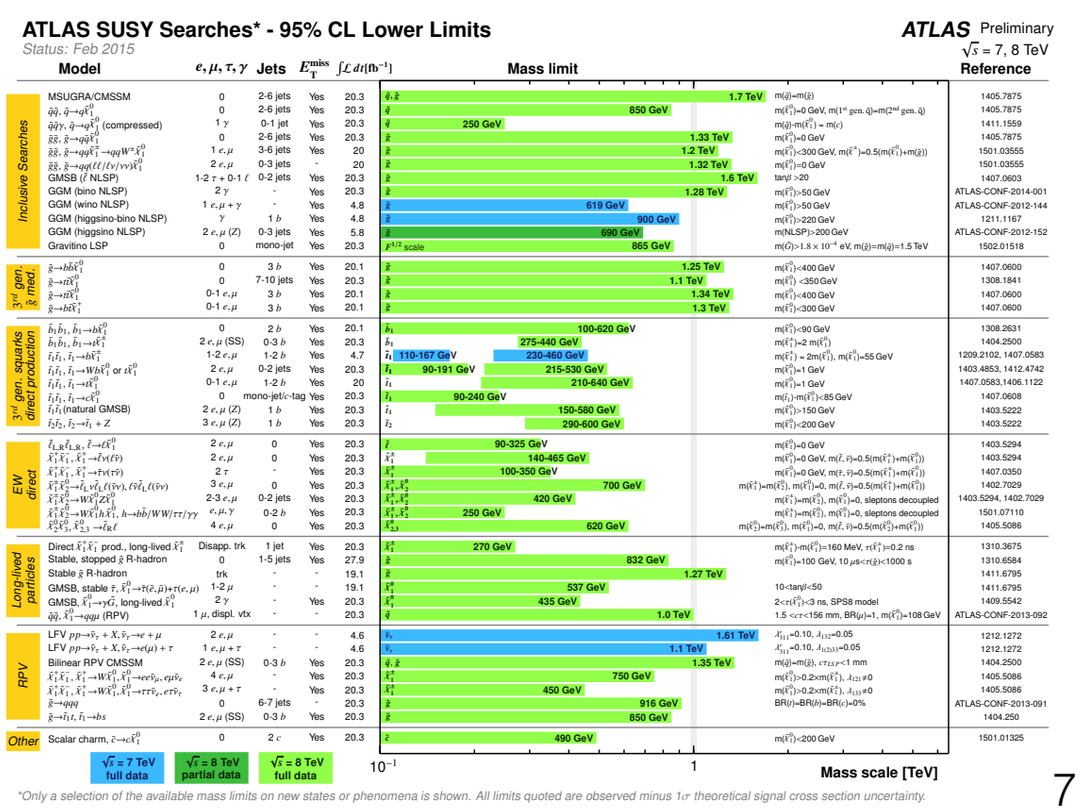
A physics driver @ LHC

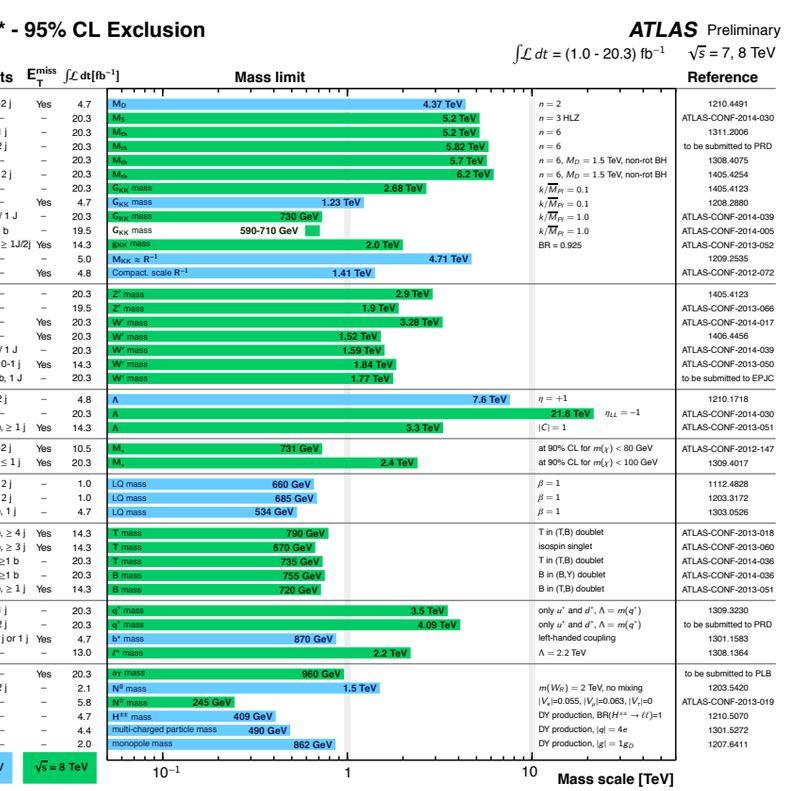






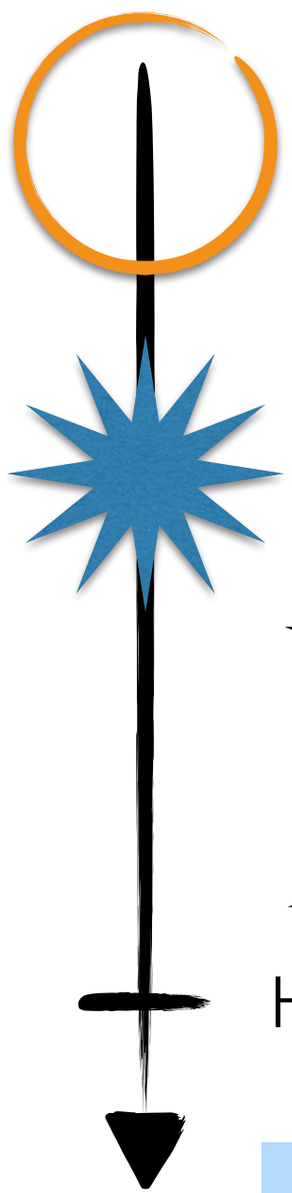
170 of these 226 channels tied to naturalness





Hierarchy Solutions

Extend the SM with a symmetry acting on the Higgs



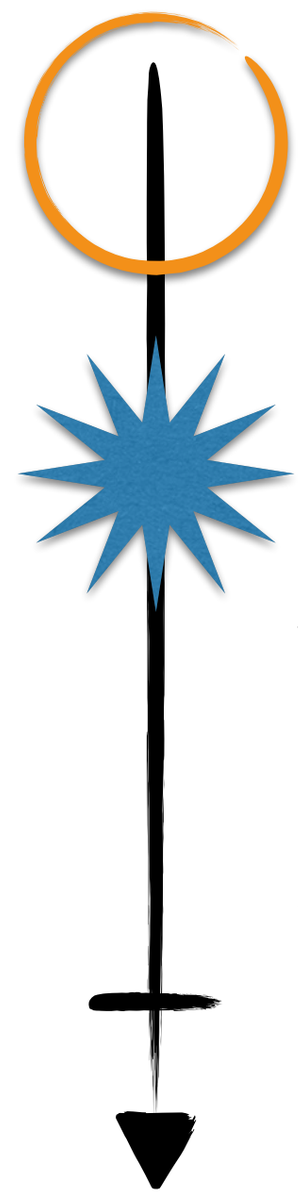
Supersymmetry

~~Supersymmetry~~
Sparticles $\tilde{m}$

$\lesssim 4\pi/G$

Higgs m_h

See also X. Tata



Global symmetry

~~Global symmetry~~
Partner particles $\tilde{m}$

$\lesssim 4\pi/G$

Higgs m_h

See also A. Pomarol

New particles

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

Supersymmetry

$$\phi \to \phi + \epsilon\psi$$
$$\psi \to \psi + c^\mu \partial_\mu \phi$$

Opposite-statistics partner
for every SM particle

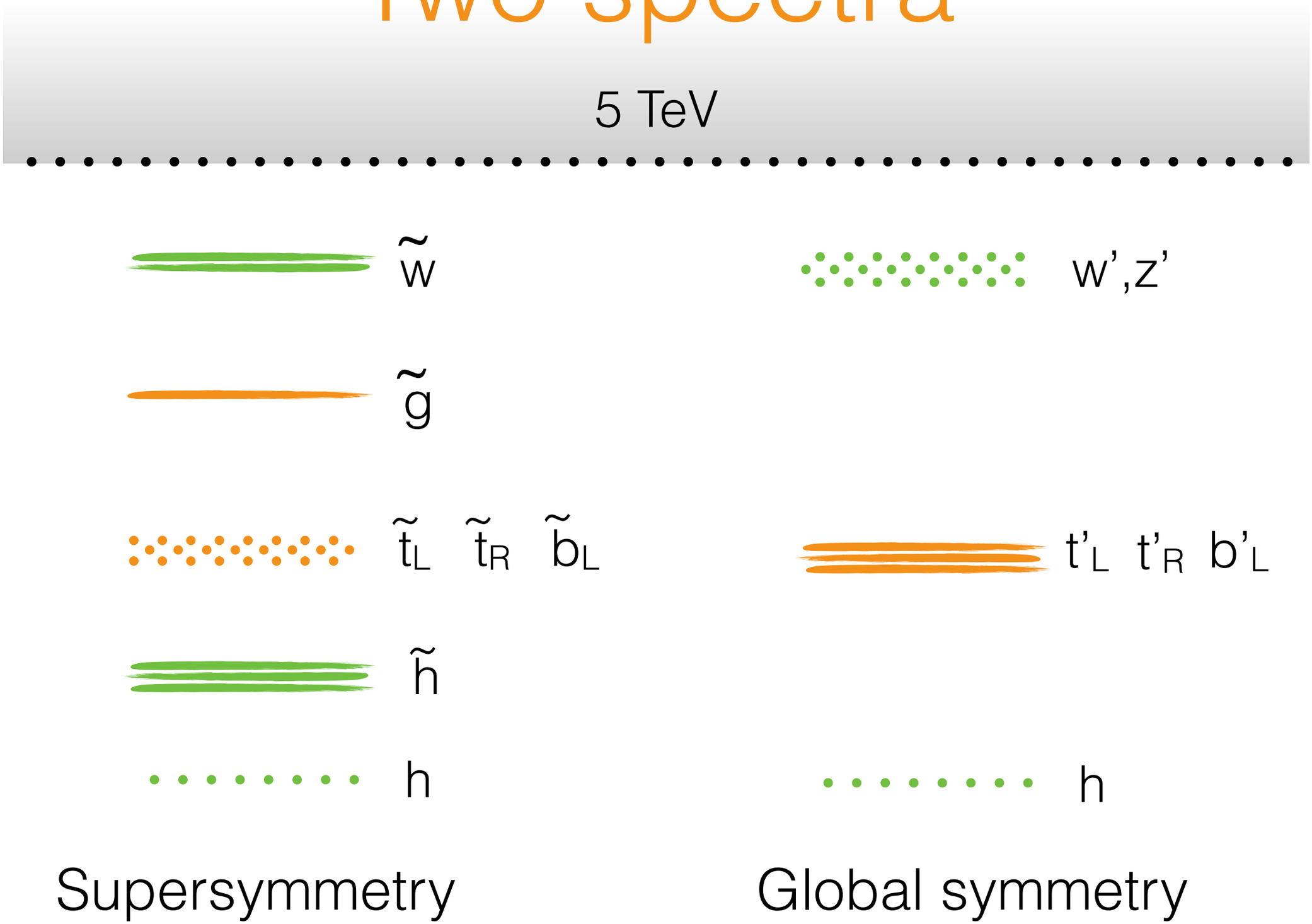
Global symmetry

$$\Phi \to (1 + i\alpha T)\Phi$$

Same-statistics partner
for every SM particle

Contribute to the Higgs mass: $m_h^2 \sim \frac{3y_t^2}{4\pi^2}\tilde{m}^2 \log(\Lambda^2/\tilde{m}^2)$

Two spectra

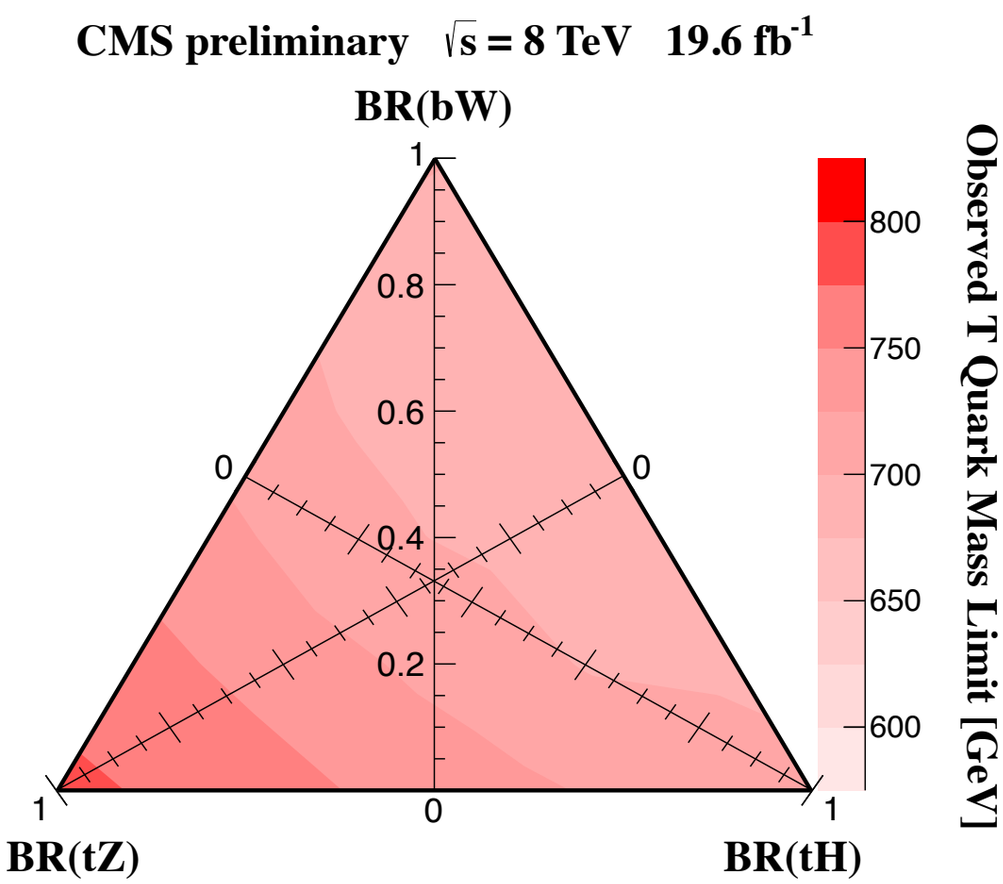


Simple game for LHC: look for colored partners.

Missing top partner problem

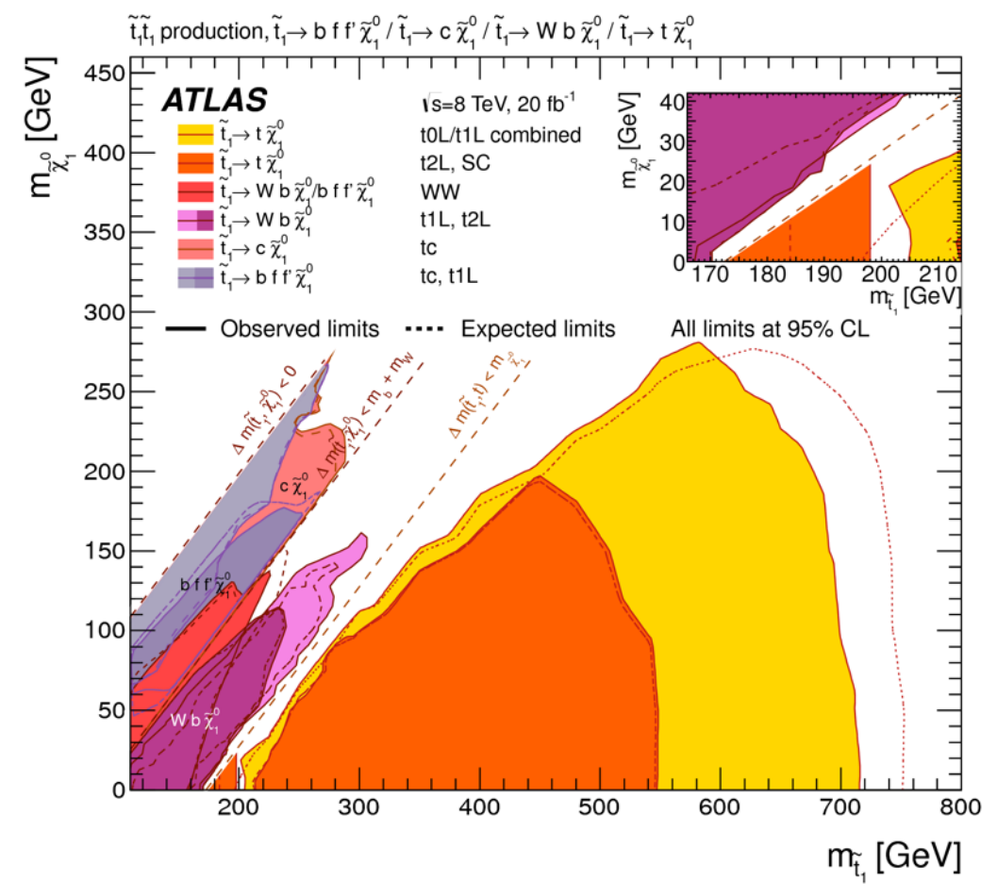
LHC searches driven by top partners

Global Symmetry



CMS B2G-12-015

Supersymmetry



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

Problem 2: not much new to do.

Naturalness being so desirable a gift that we cling to supersymmetry in spite of the absence of experimental evidence.

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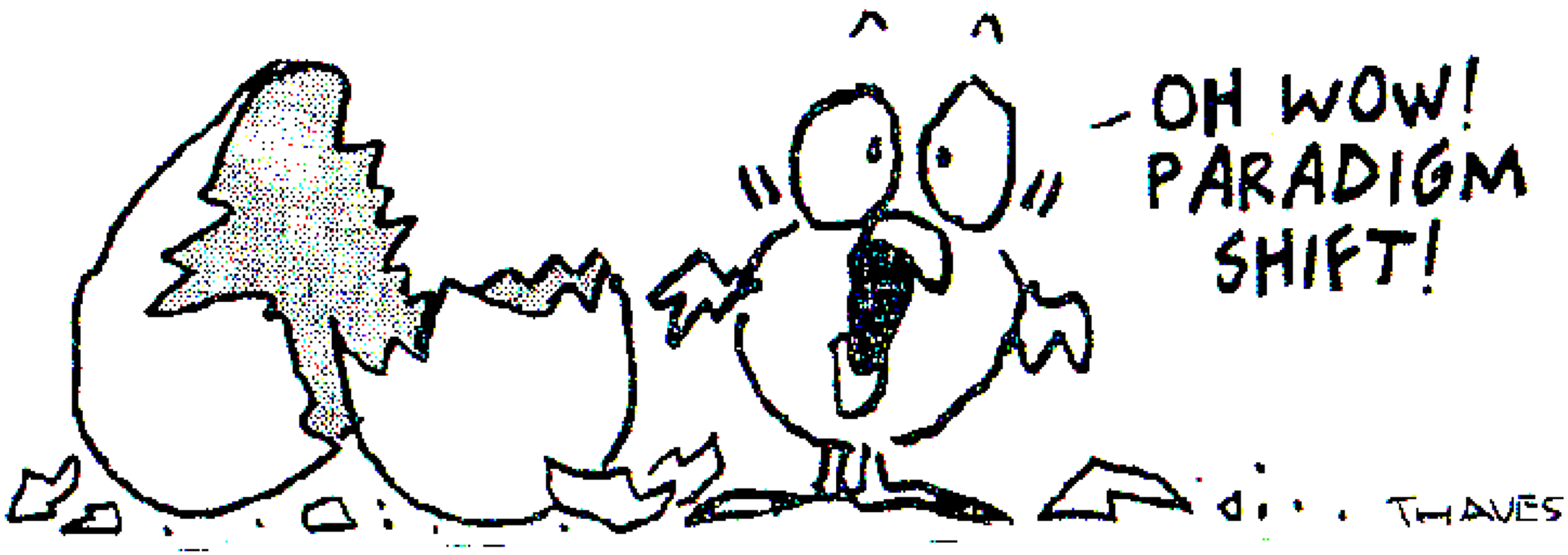
NATURALNESS WITHOUT SUPERSYMMETRY?

I. JACK and D.R.T. JONES

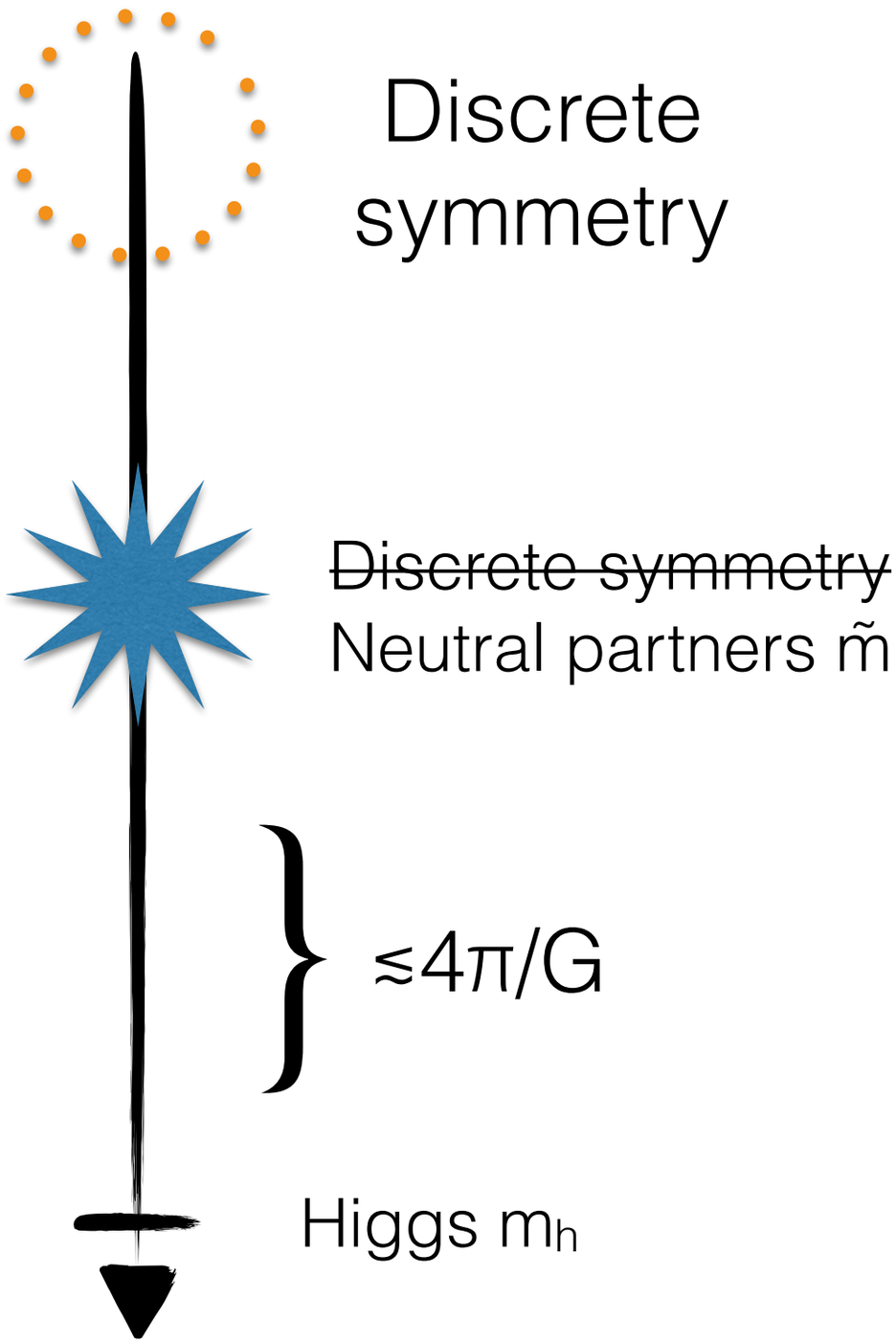
DAMTP, University of Liverpool, Liverpool L69 3BX, UK

Received 17 October 1989; revised manuscript received 27 October 1989

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,

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

$SU(4) \to SU(3)$ 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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$$V(H) \supset \frac{9}{64\pi^2} g^2 \Lambda^2 \left(|H_A|^2 + |H_B|^2 \right)$$

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Quadratic potential has accidental SU(4) symmetry.

The Twin Higgs

Achieve this protection for the entire SM by $SM_A \times SM_B \times Z_2$

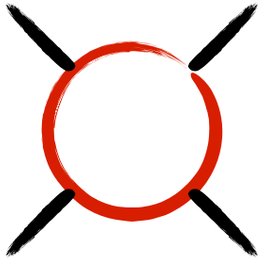
SM_A = us, SM_B = twin sector

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

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

One-loop Z_2-preserving, SU(4)-breaking quartic:

$$V \supset \delta(|H_A|^4 + |H_B|^4) \qquad \delta \sim \frac{y_t^4}{16\pi^2}\log(\Lambda/f)$$



(only quadratic insensitivity to cutoff)

The Twin Higgs

Naive vacuum: $$\langle H_A \rangle^2 = \langle H_B \rangle^2 = \frac{f^2}{2}$$

f is not far from ***v***, and the cutoff is ~TeV. Not much of a protection, and O(50%) deviations in Higgs couplings.

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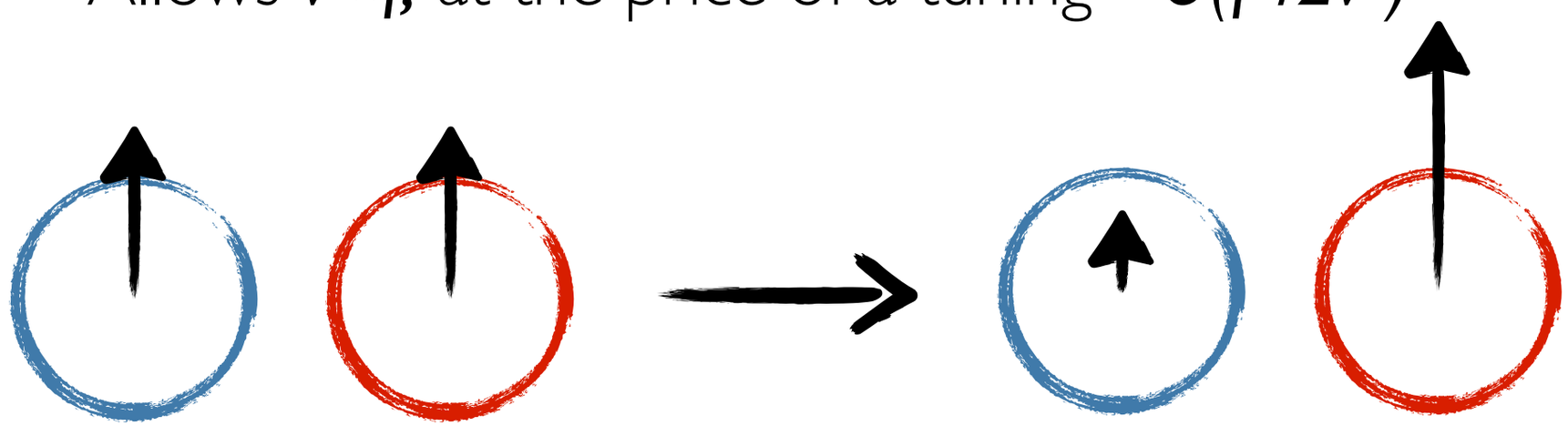
Option 1: softly break Z_2 $$V_{soft}(H) = \delta m_H^2 |H_A|^2$$

Allows $v \ll f$, at the price of a tuning $\sim O(f^2/2v^2)$



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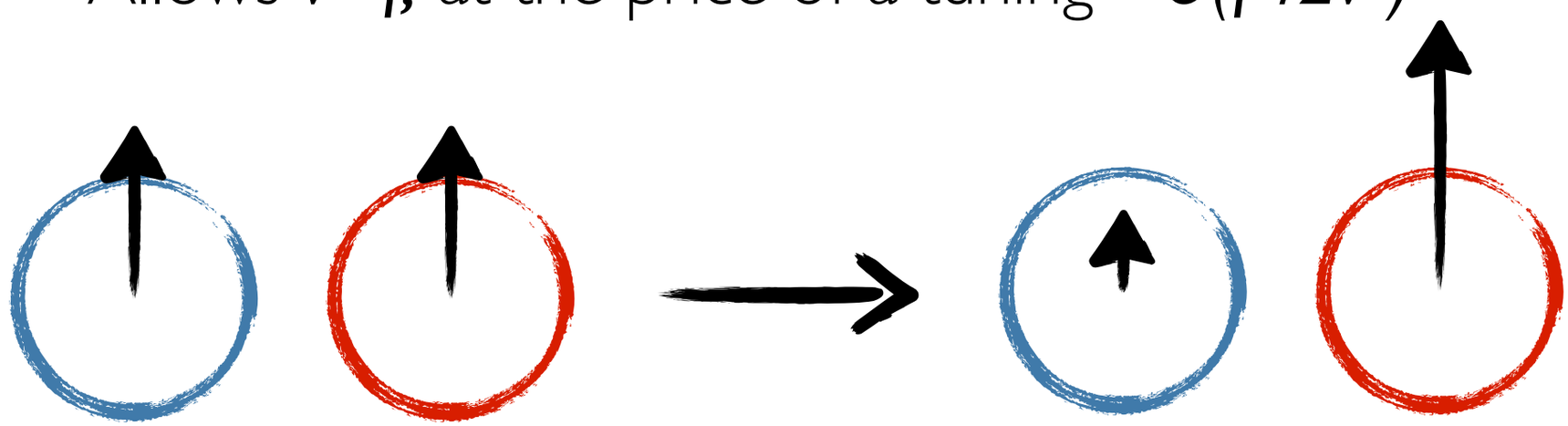

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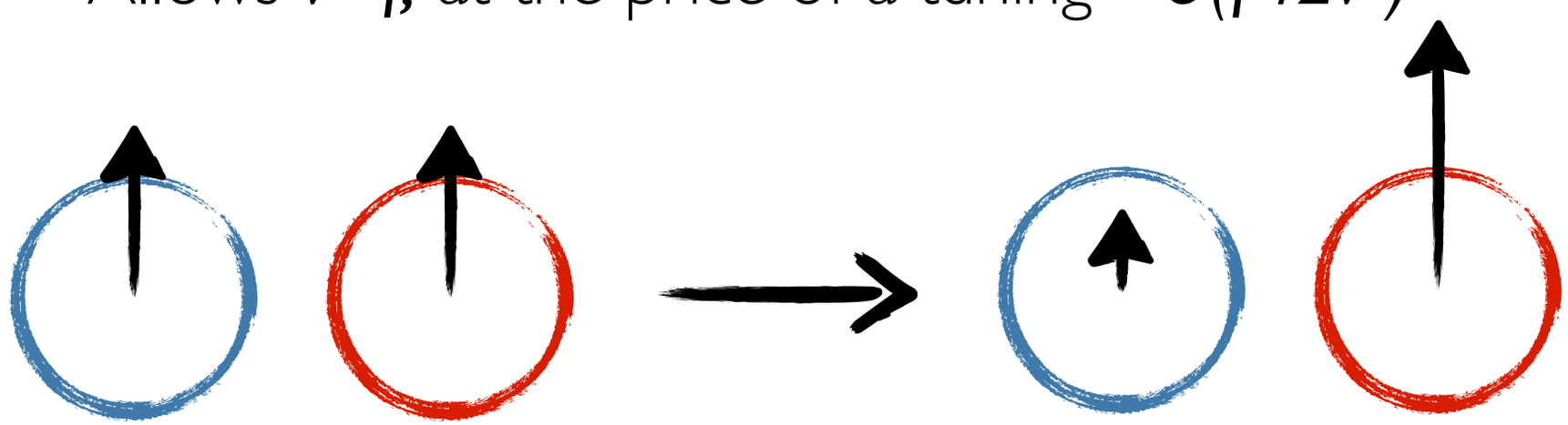
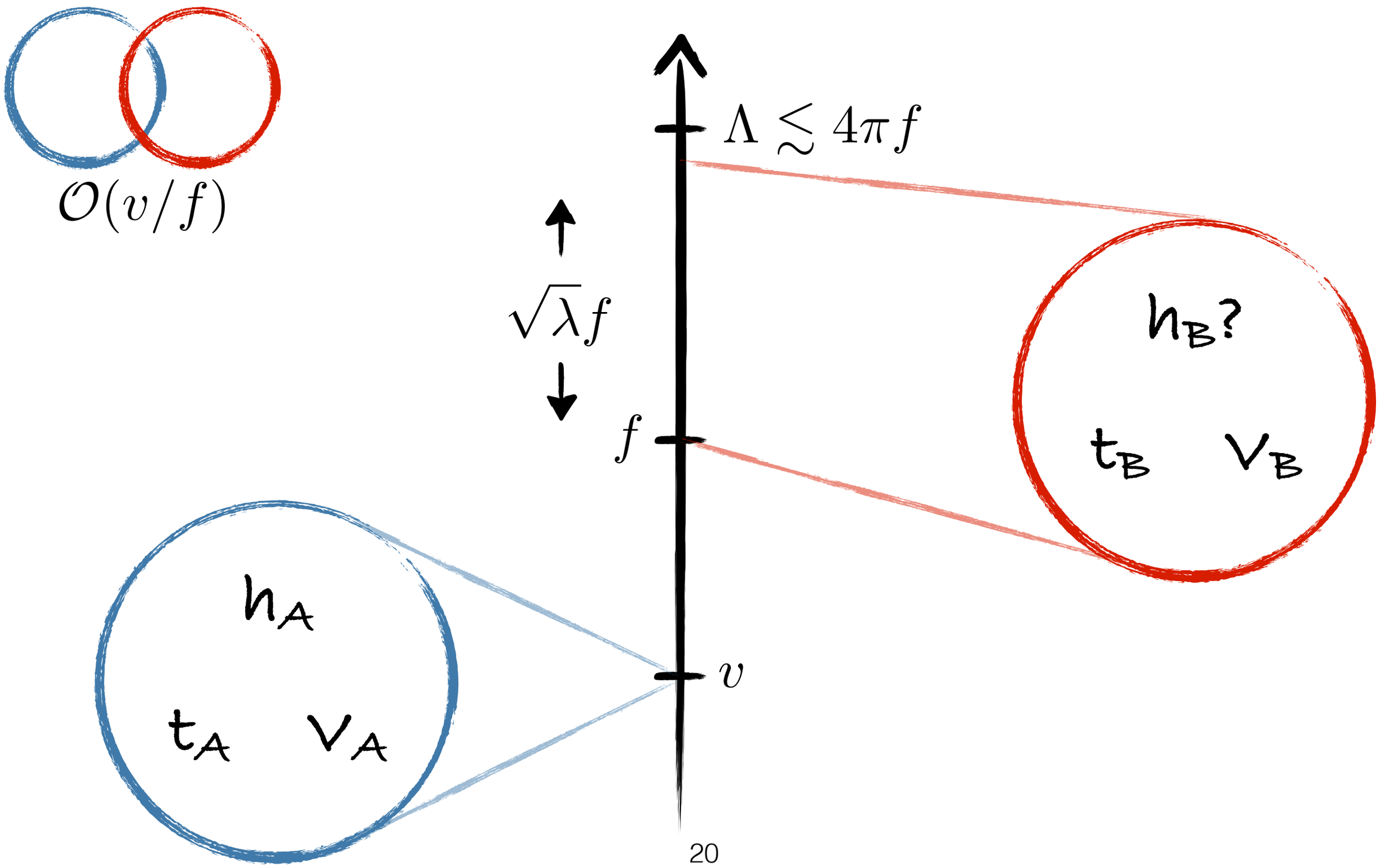


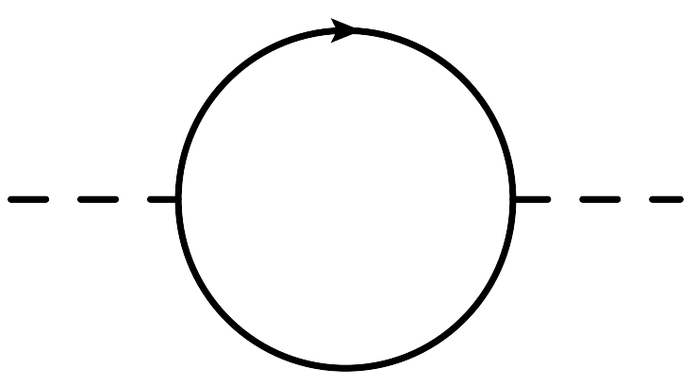
Option 2: hard breaking of Z_2 $$V_{hard}(H) = \delta_{A,B} |H_{A,B}|^4$$

Option 3: tadpole breaking of Z_2 [Beauchesne, Earl, Gregoire '15]

The Twin Higgs



The Twin Top



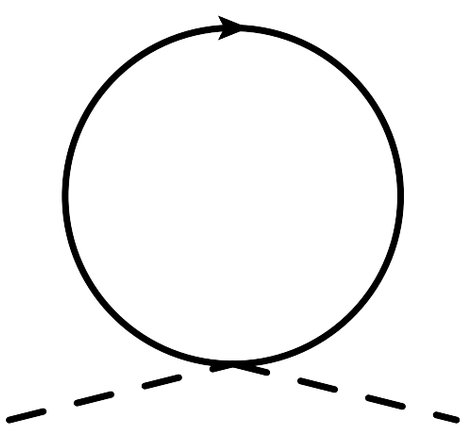
Standard Model

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

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

$$\downarrow \qquad\qquad \downarrow$$

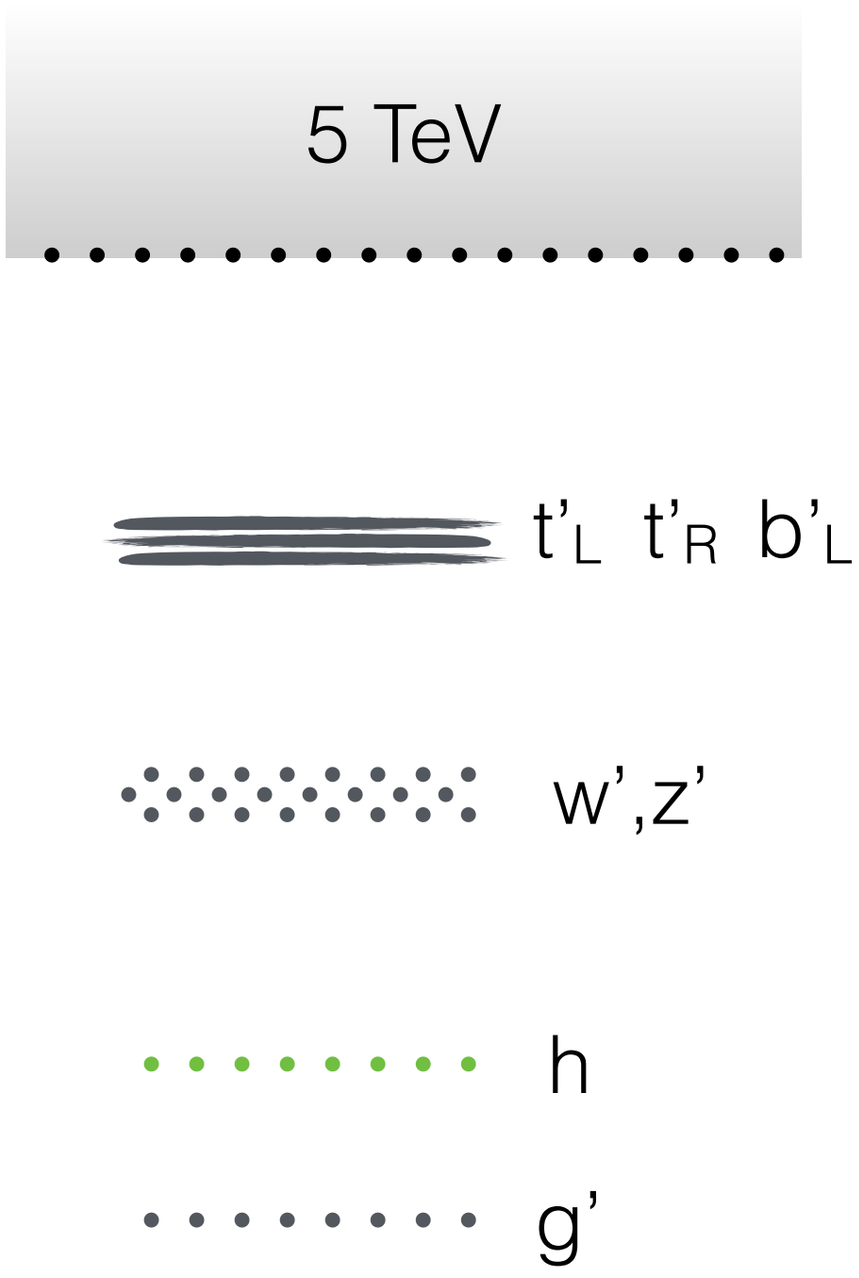
$$h + \ldots \qquad\qquad f - \frac{h^2}{2f} + \ldots$$



Twin top

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

“Neutral” naturalness



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.

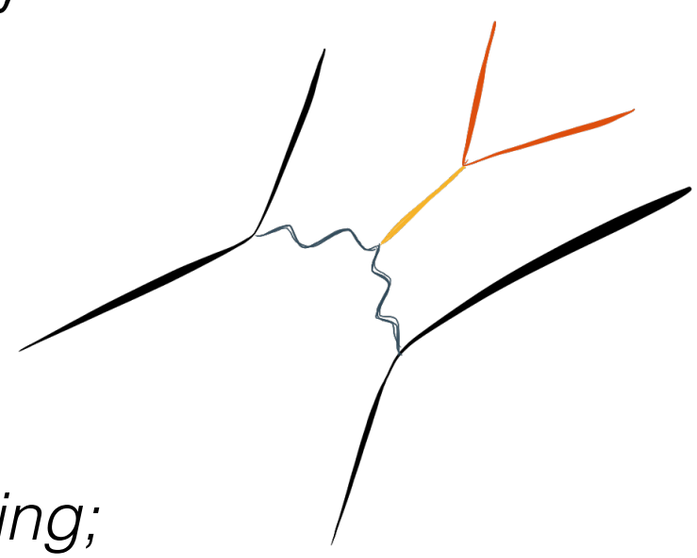
[NC, Knapen, Longhi ’14; Geller, Telem ’14; NC, Katz, Strassler, Sundrum ’15; Barbieri, Greco, Rattazzi, Wulzer ’15; Low, Tesi, Wang ’15, NC, Knapen, Longhi, Strassler ‘16]

Finding a mirror

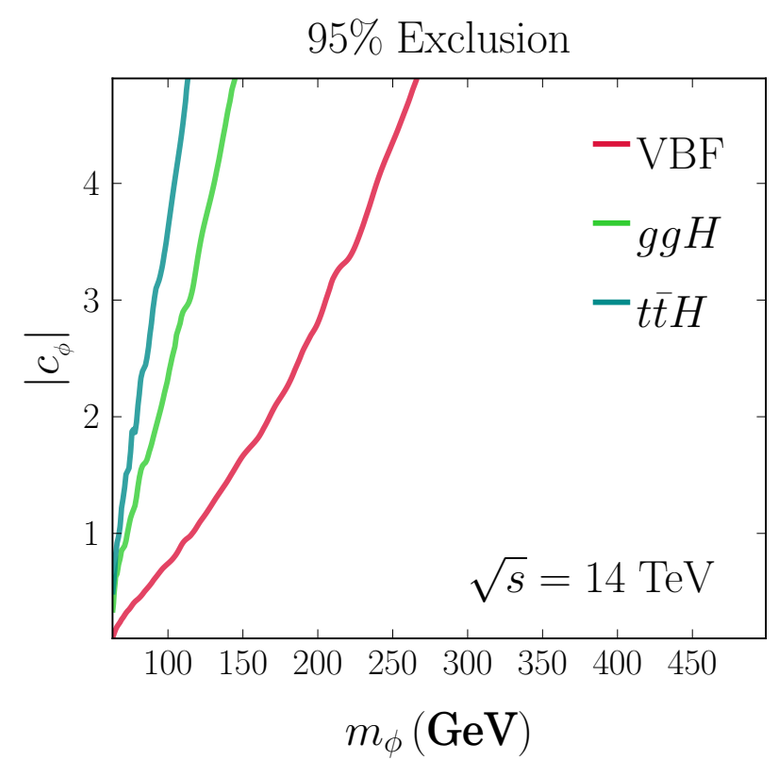
No longer produce partner particles through strong interactions

- Partner states are SM neutral, couple only to the Higgs. Lighter than $m_h/2$: modest invisible Higgs decays.

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

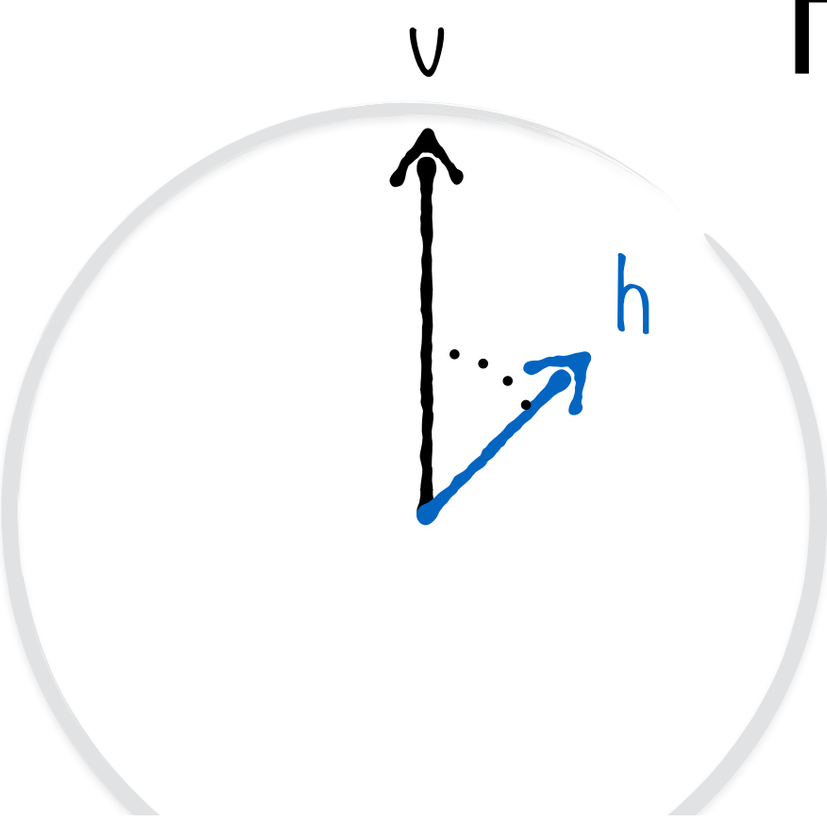


Hard but very interesting; directly probe naturalness



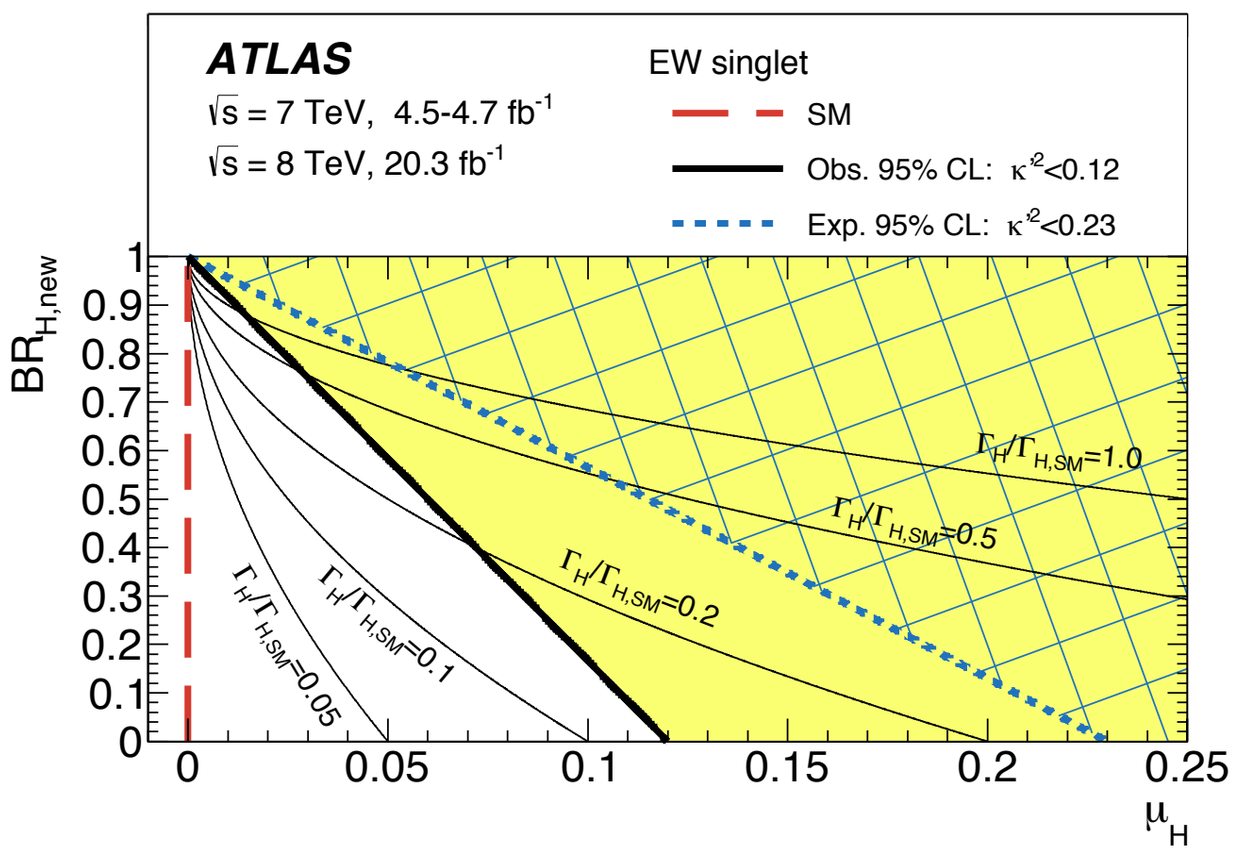
[NC, Lou, McCullough, Thalapillil '14]

Higgs Properties



In SM, Higgs is a fluctuation around its vacuum expectation value

In twin theories, Higgs is misaligned with the VEV by a small amount



Gives universal shift in Higgs couplings

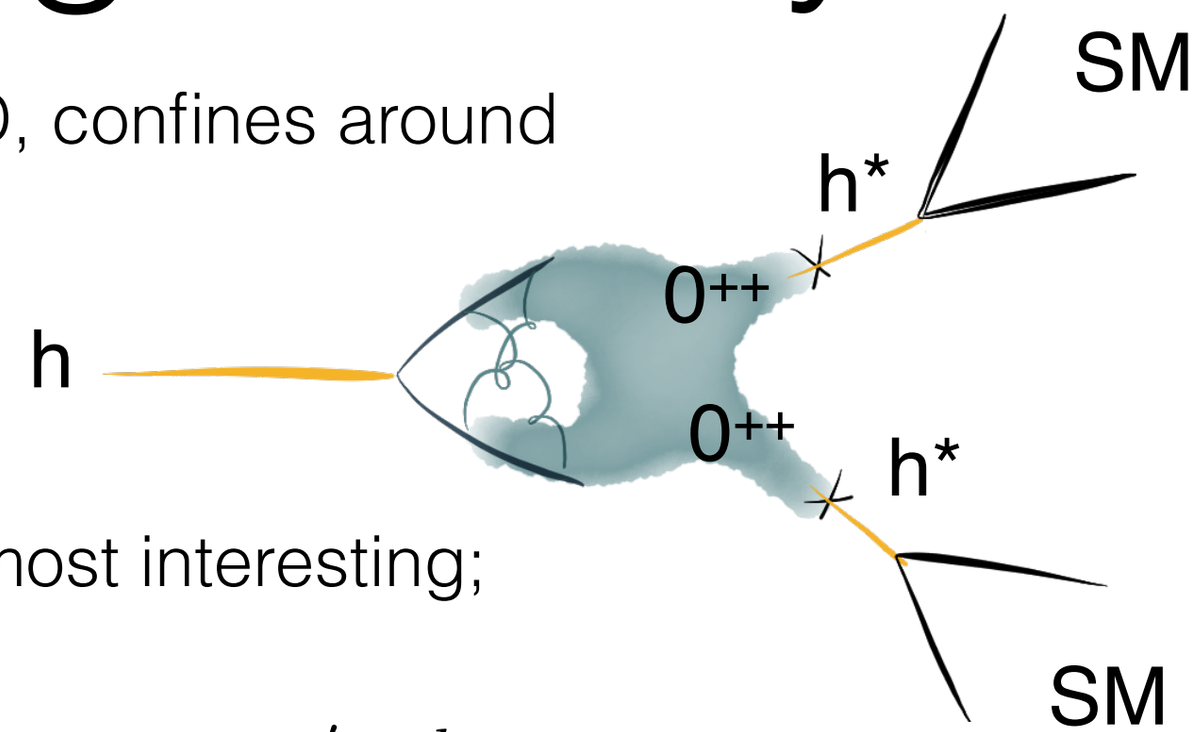
Current bounds place twin sector ~3 x SM scale

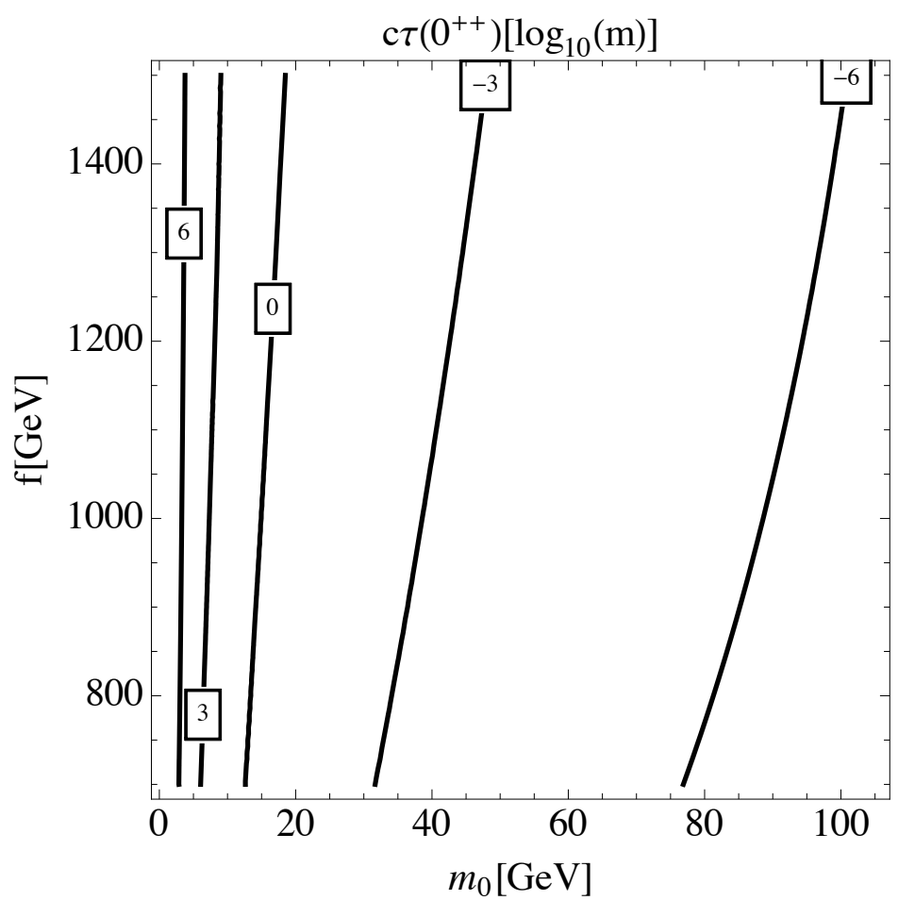
Interesting for LHC Run 2 but unlikely to improve much

[NC, Katz, Strassler, Sundrum '15; Curtin, Verhaaren '15; Chacko, Curtin, Verhaaren '16]

Exotic Higgs Decays

- Twin sector must have twin QCD, confines around QCD scale
- Higgs boson couples to bound states of twin QCD
- Various possibilities. Glueballs most interesting; have same quantum # as Higgs





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

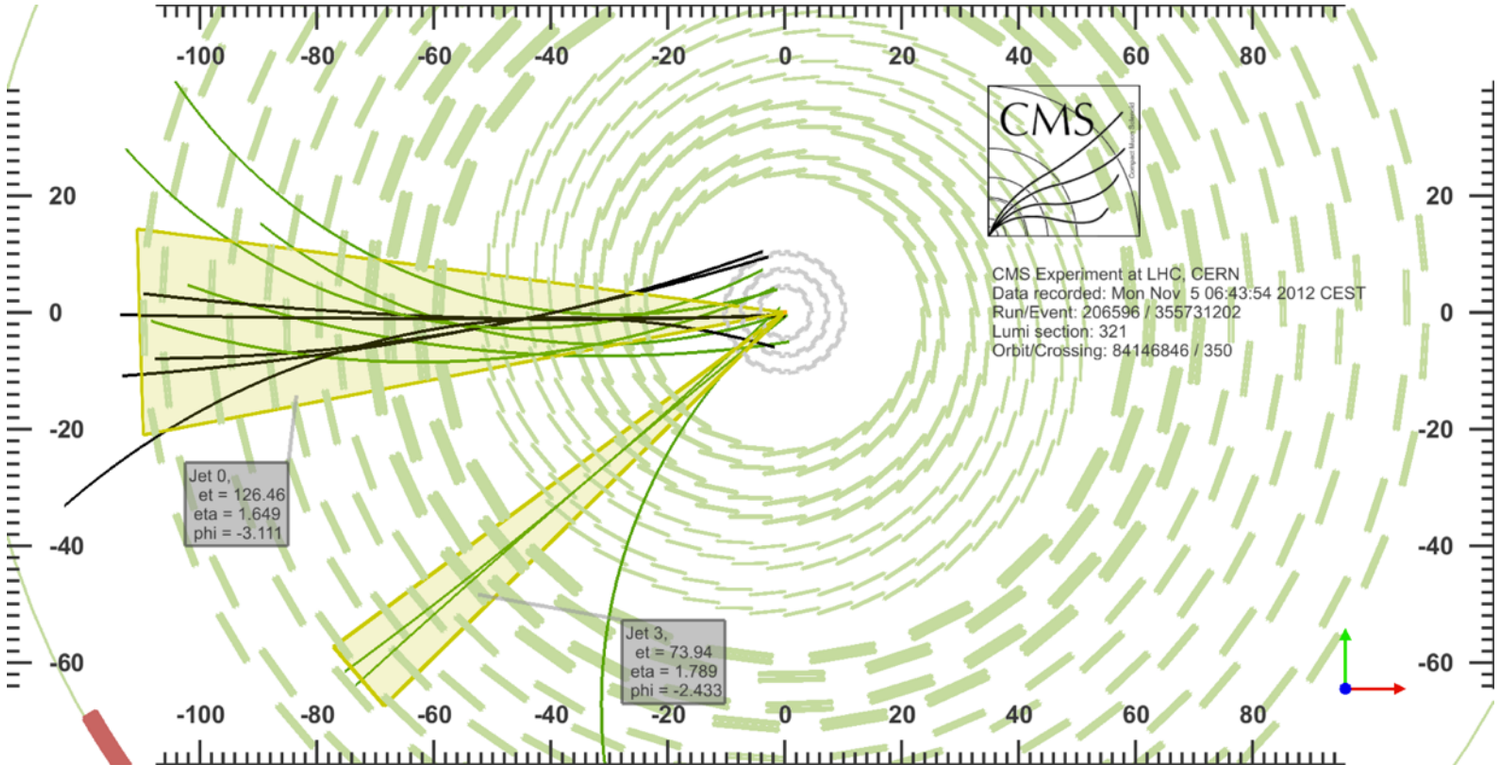
Produce in rare Higgs decays (BR~10^{-3}-10^{-4})

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

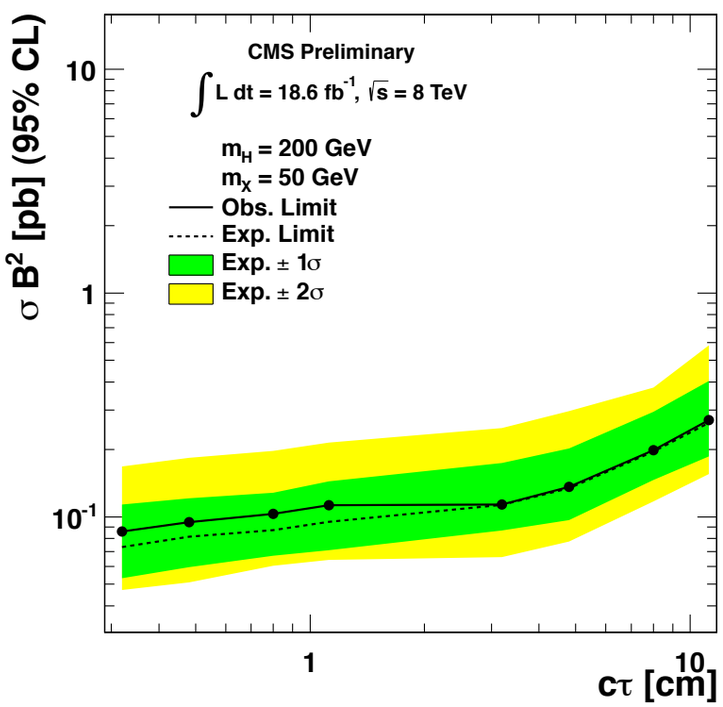
Decay back to SM via Higgs

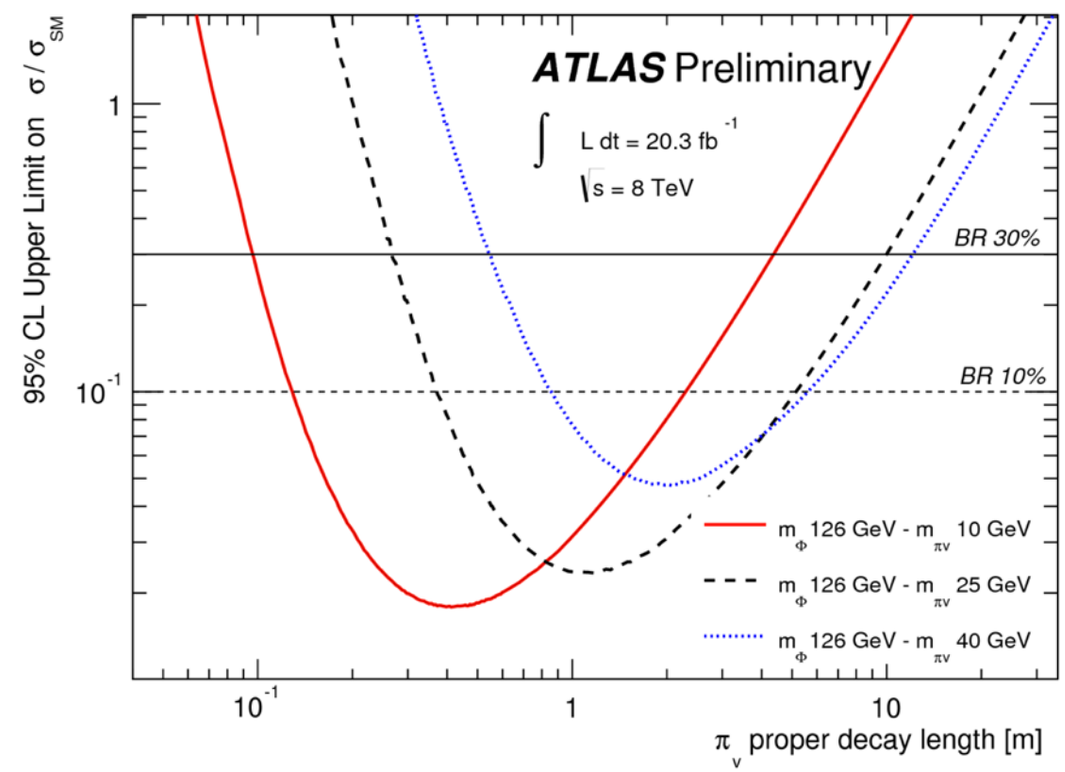
$$0^{++} \to h^* \to f\bar{f}$$

Long-lived, decay length is macroscopic; length scale ~ LHC detectors



Looking for displaced decays





Run 1 searches at LHC in right direction but not sensitive
Compelling prospects for Run 2…

[Csaki, Kuflik,Lombardo, Slone, '16]

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; Cai, Cheng, Terning '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; NC, Knapen, Longhi, Strassler '16]

Partner quantum #s	Global	SUSY
QCD x EWK	Composite / Little Higgs	MSSM
Neutral x EWK	Quirky Little Higgs [Cai, Cheng, Terning '08]	Folded SUSY [Burdman, Chacko, Harnik '06]
Neutral x Neutral	Twin Higgs	????

A plethora of new naturalness-related signatures to look for @ LHC and beyond

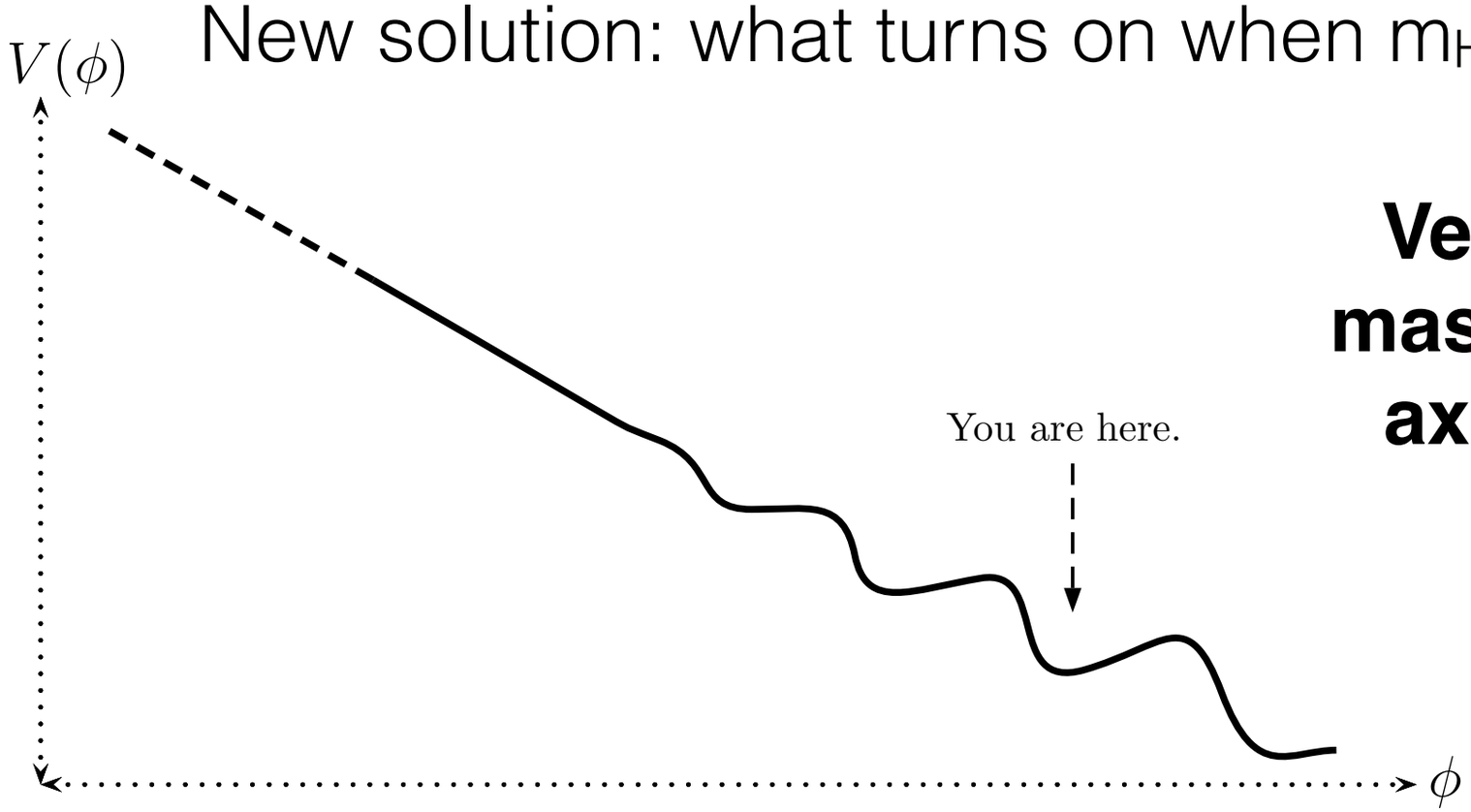
Much to look forward to at LHC Run 2

Not symmetries?

*What if the weak scale is selected by **dynamics**, not symmetries?*

Old idea: couple Higgs to field whose minimum sets $m_H=0$
Old problem: How to make $m_H=0$ a special point of potential?

New solution: what turns on when m_H^2 goes negative?



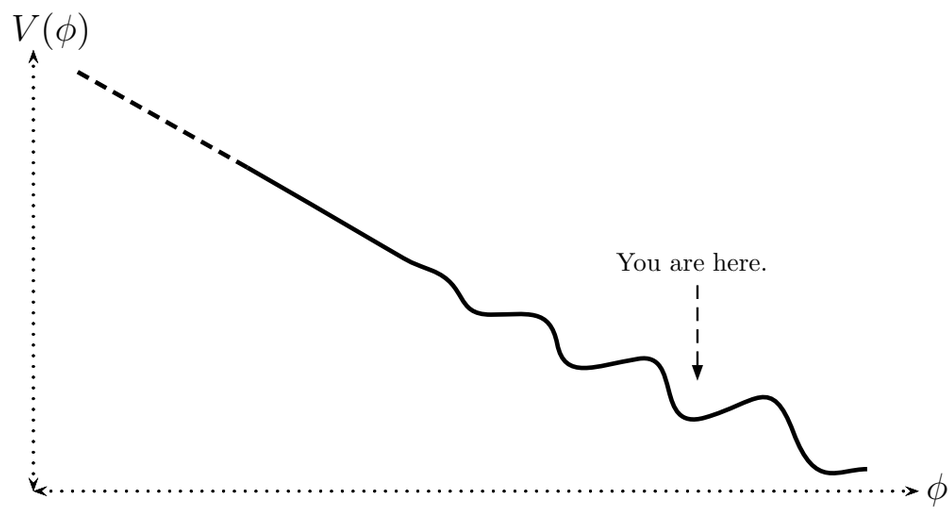
Vev gives **quark masses** which give **axion potential**!

"Relaxion"

[Graham, Kaplan, Rajendran '15]

$$(-M^2 + g\phi)|H|^2 + V(g\phi) + \frac{1}{32\pi^2}\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu}$$

$$\Rightarrow \quad (-M^2 + g\phi)|H|^2 + V(g\phi) + \Lambda^4 \cos(\phi/f)$$



But: immense energy stored in rolling field, still need to stop. **Inflation** is a good source of friction.

Just need Higgs + non-compact axion + inflation w/

- Very low Hubble scale ($\ll \Lambda_{QCD}$)
- 10 Giga-years of inflation

Warning: likely just transferring fine-tuning to inflationary sector.

[Di Chiara, Kannike, Marzola, Racciopi, Raidal, Spethmann '15; Fowlie, Balasz, White, Marzola, Raidal '16]

Minimal model: cutoff is $M < \left(\frac{\Lambda^4 M_P^3}{f}\right)^{1/6} \theta^{1/4} \sim 30 \text{ TeV} \times \left(\frac{10^9 \text{ GeV}}{f}\right)^{1/6} \left(\frac{\theta}{10^{-10}}\right)^{1/4}$

In vacuum, axion gives O(1) contribution to θ_{QCD}

See also: [Espinosa, Grojean, Panico, Pomarol, Servant '15; Hardy '15; Gupta, Komargodski, Perez, Ubaldi '15; Batell, Giudice, McCullough '15]

Not symmetries?

Fix: make it someone else's QCD + axion

Field	$SU(3)_N$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
L	$\square$	$-$	$\square$	$-1/2$
L^c	$\overline{\square}$	$-$	$\square$	$+1/2$
N	$\square$	$-$	$-$	0
N^c	$\overline{\square}$	$-$	$-$	0

I.e. axion of a different SU(3); need to tie in Higgs vev

1. New quarks must get most of mass from Higgs:

$$\mathcal{L} \supset m_L L L^c + m_N N N^c + y H L N^c + y' H^\dagger L^c N$$

2. Must confine, but with light flavor $\Lambda^4 \simeq 4\pi f_{\pi'}^3 m_N$

…still new physics @ weak scale

Now $m_N \geq yy' v^2/m_L$ (smallest see-saw mass from EWSB if L heavy)

But also
$$\begin{cases} m_N \geq \frac{yy'}{16\pi^2} m_L \log(M/m_L) & \text{(Radiative Dirac mass)} \\ m_N \geq yy' f_{\pi'}^2/m_L & \text{(Higgs wiggles biggest)} \end{cases}$$

These bounds imply $f_{\pi'} < v$ and $m_L < \dfrac{4\pi v}{\sqrt{\log(M/m_L)}}$

Can't decouple new degrees of freedom.
New confining physics near weak scale!

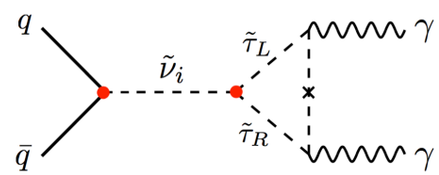
Couples to Higgs; hidden valley signatures

$$M < \left(\frac{\Lambda^4 M_P^3}{f}\right)^{1/6} \sim 3 \times 10^5 \text{ TeV} \times \left(\frac{10^9 \text{ GeV}}{f}\right)^{1/6} \left(\frac{f_{\pi'}}{30 \text{ GeV}}\right)^{1/2} \left(\frac{yy'}{10^{-2}}\right)^{1/6} \left(\frac{300 \text{ GeV}}{m_L}\right)^{1/6}$$

The 750 GeV elephant in the room

Supersymmetry

RPV sneutrino
[Allanach, Dev, Renner, Sakurai 1512.07645]



$$\Gamma(\phi \to \gamma\gamma) = \frac{(m_1^2 c_W^2 + m_2^2 s_W^2) M_\phi^3}{32\pi F^2}$$

Sgoldstino
[Petersson, Torre 1512.05333]

Sbino (dirac gauginos)
[Carpenter, Colburn, Goodman 1512.06107]

$$\begin{pmatrix} & A_\mu & \\ \psi & & \lambda \\ & \Phi & \end{pmatrix}$$

Compositeness

E.g. $SO(6) \to SO(5) \to SO(4)$

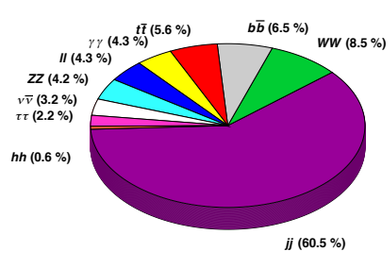
[No, Sanz, Setford 1512.05700]

Generally expect heavy resonances + vector-like matter. Hard to understand lack of Higgs mixing.

Relaxion

Ingredients seem to be there (bifundamental matter, etc.)
Not sure what X(750) should be.

Extra dimensions



KK graviton
[Giddings, Zhang 1602.02793]
Tension with dileptons

Radion
[Ahmed, Dillon, Grzadkowski, Gunion, Jiang]
Hard to match rate, incalculable?

Neutral naturalness

Doesn't want to be a twin Higgs due to Higgs mixing. Ingredients are there in a UV completion.

If X(750) is a (pseudo)scalar, electroweak tuning comparable to CC

Conclusion

Phenomenon	Natural?
Charged pion mass	☑ Yes ☐ No
Charm mass	☑ Yes ☐ No
Proton mass	☑ Yes ☐ No
Cosmological constant	☐ Yes ☑ No
Higgs mass	☐ Yes ☐ No

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- Robust program of LHC searches for conventional approaches based on continuous symmetries
- Entirely new approaches now being explored, based on discrete symmetries, dynamics, ….
- With new signatures and new possibilities, the verdict on weak-scale naturalness is still out. **Exciting times to be in the hunt!**