Title: Naturalness in the Dark

Date: Oct 20, 2015 01:00 PM

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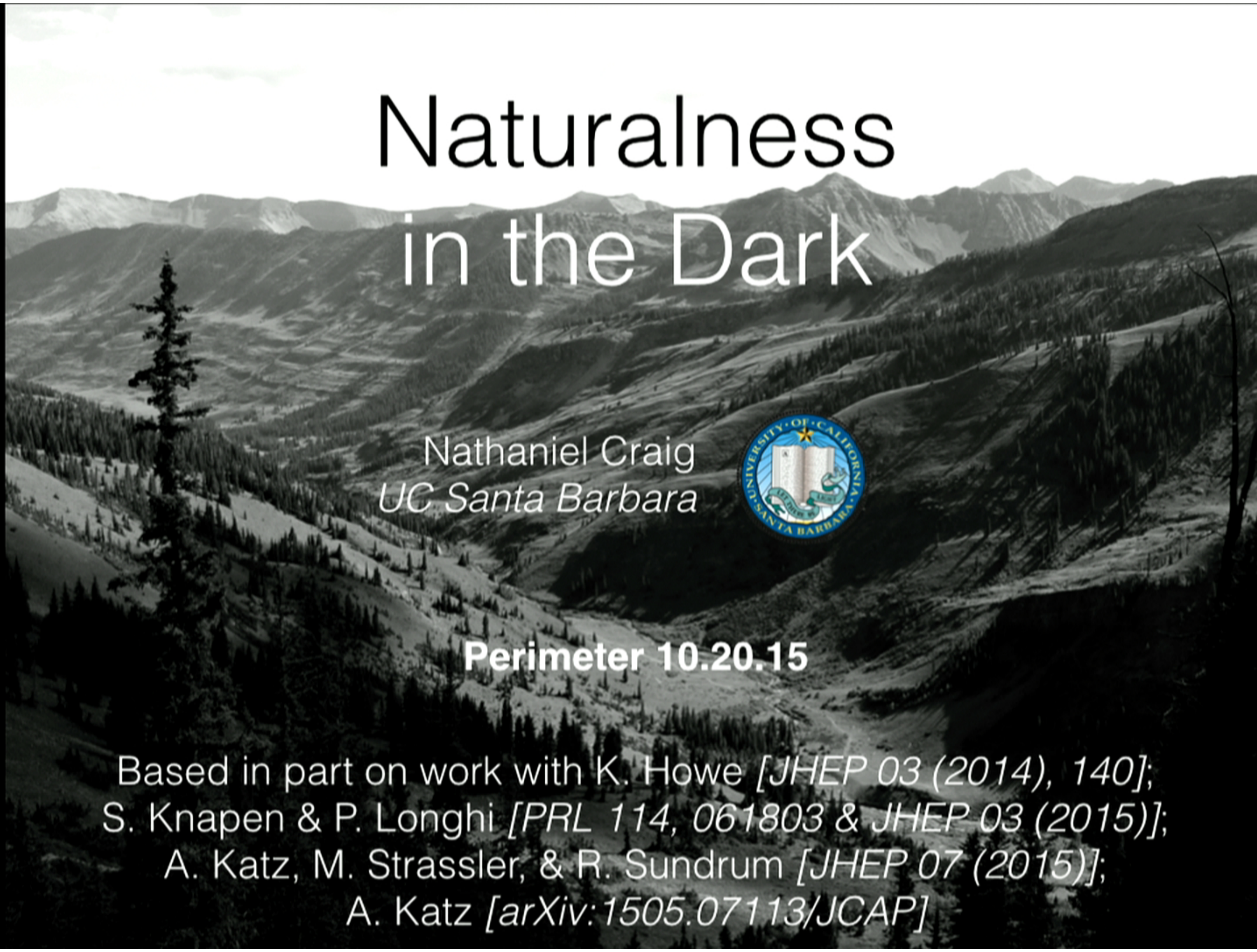
Abstract: <p>The search for physics beyond the Standard Model at the LHC is largely oriented towards new particles associated with solutions to the electroweak hierarchy problem. While the precise character of these partner states may vary from model to model, they typically possess large QCD production rates favorable for detection at hadron colliders. Null results in searches for partner particles during Run 1 of the LHC have placed the idea of electroweak naturalness under increasing strain. In this talk I'll discuss a broad class of natural theories where the new degrees of freedom relevant for naturalness lie in hidden sectors and are largely unconstrained by LHC data. Rather than rendering electroweak naturalness untestable, they give rise to entirely new signs of naturalness at the LHC, including displaced decays and other exotic signatures. They also furnish a variety of viable dark matter candidates testable at current and future experiments.</p>



Naturalness in the Dark

Nathaniel Craig
UC Santa Barbara

Perimeter 10.20.15

Based in part on work with K. Howe *[JHEP 03 (2014), 140]*;
S. Knapen & P. Longhi *[PRL 114, 061803 & JHEP 03 (2015)]*;
A. Katz, M. Strassler, & R. Sundrum *[JHEP 07 (2015)]*;
A. Katz *[arXiv:1505.07113/JCAP]*

Higgs & Hierarchy Problem

- Great triumph of Run 1 @ LHC: discovery of an SM-like Higgs @ 125 GeV.
- Great challenge for Run 2: quadratic sensitivity of elementary scalar to higher physical thresholds.
- We expect many scales above the weak scale: flavor, dark matter, neutrino mass, gauge coupling unification, PQ symmetry breaking, ...
- 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!

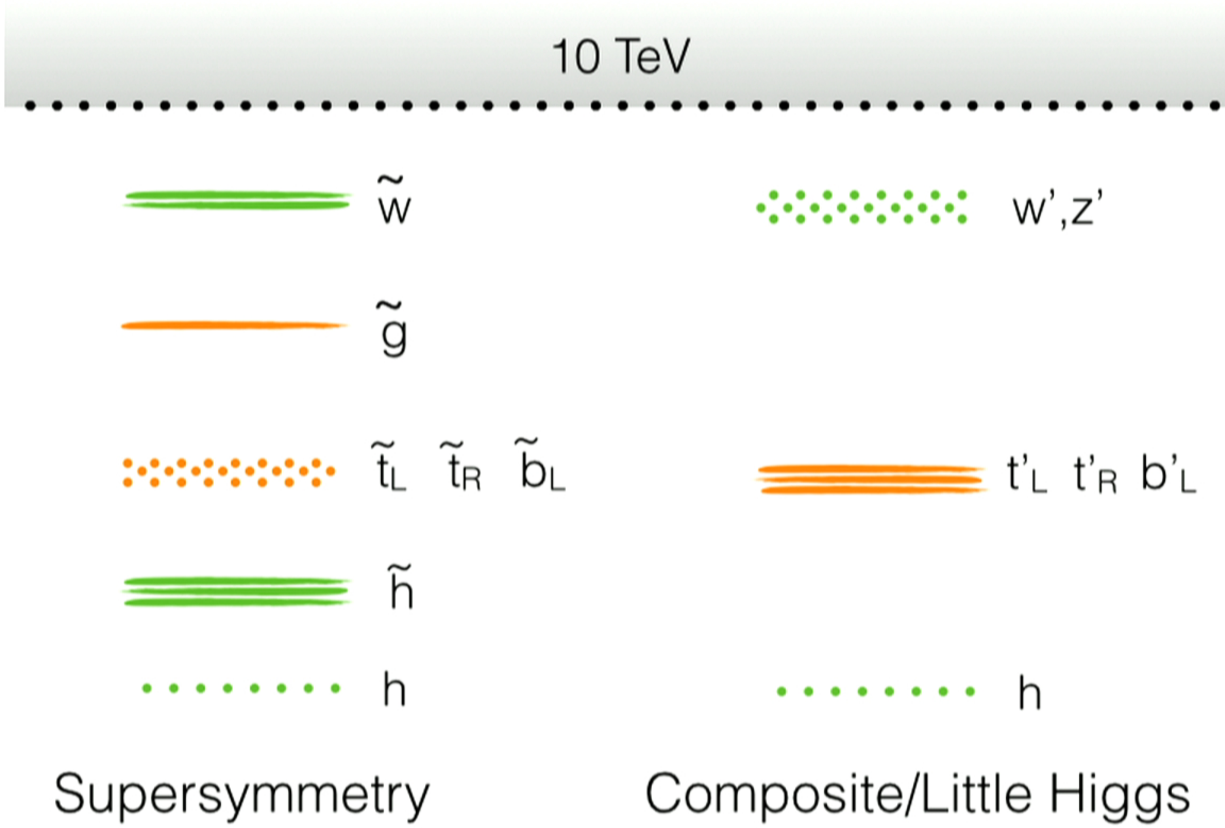
Hierarchy Solutions

Continuous symmetries 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 ways



Simple game for LHC: look for colored partners.

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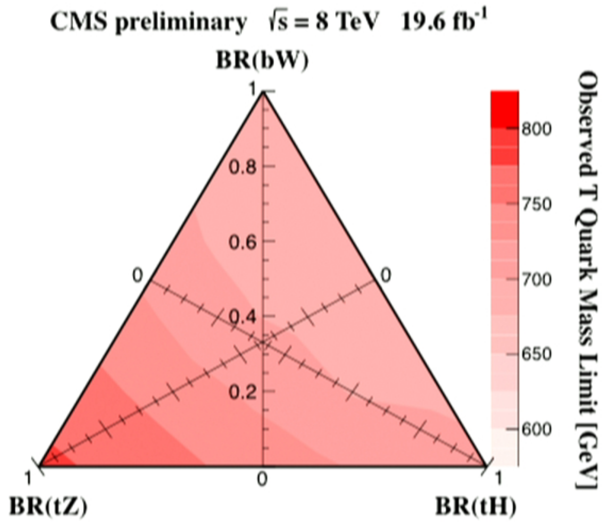
Missing top partner problem

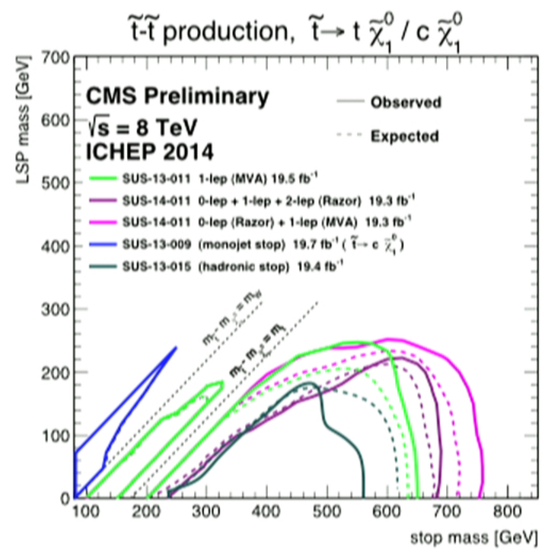
LHC searches driven by top partners

Global Symmetry



CMS B2G-12-015

Supersymmetry



Problem 1: nothing yet.

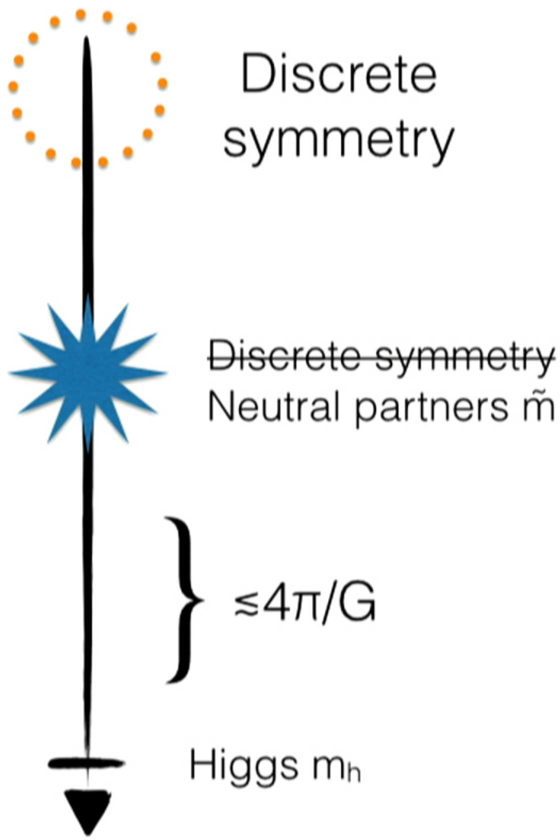
Problem 2: not much new to do.

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)

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”

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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.

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

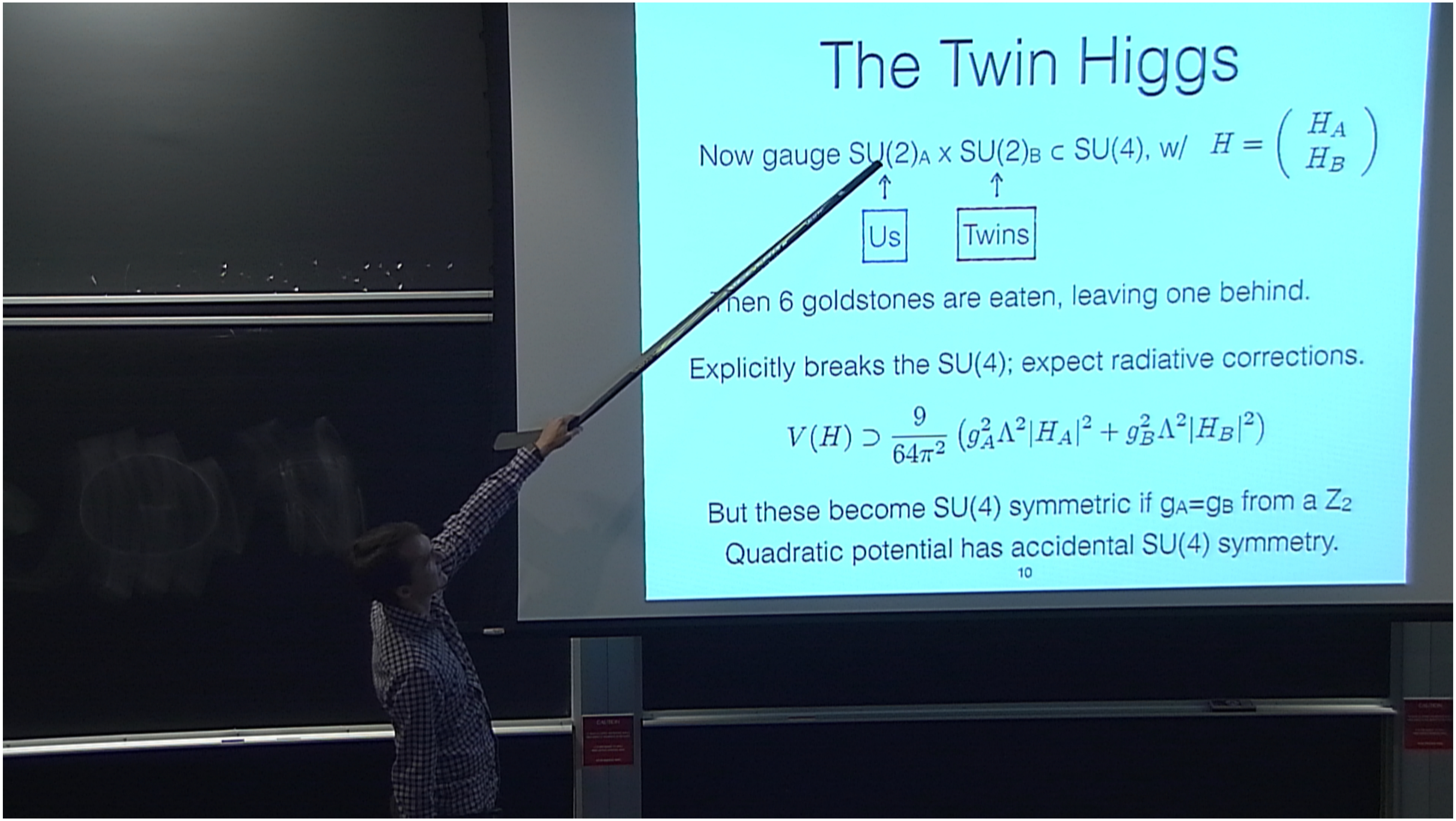
Then 6 goldstones are eaten, leaving one behind.

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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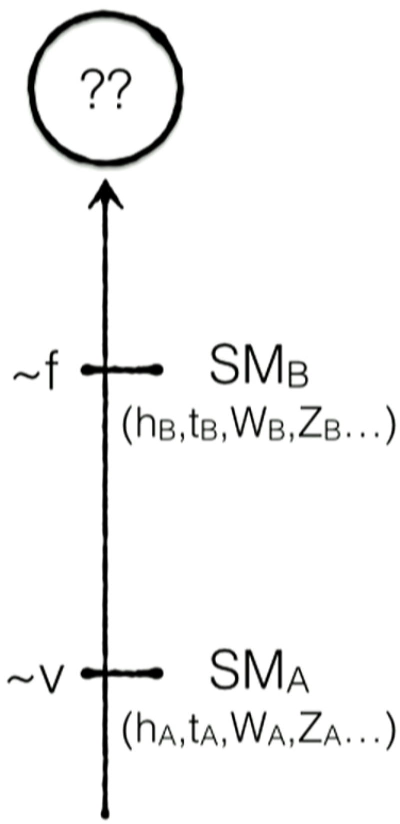
The Twin Higgs

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

$SM_A \times SM_B \times Z_2$



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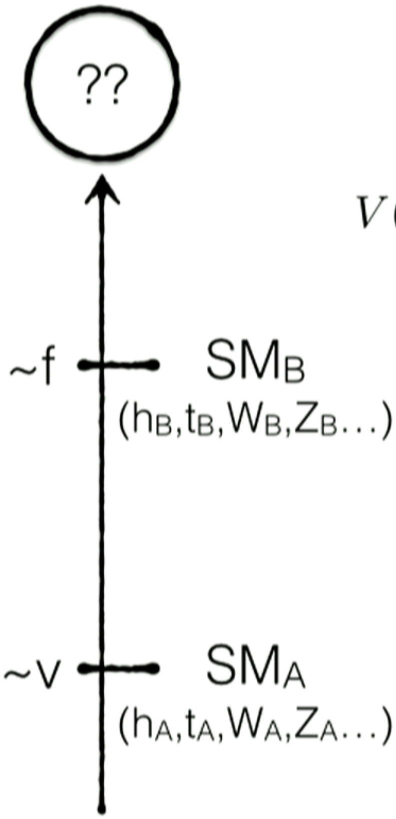


$SM_A \times SM_B \times Z_2$

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

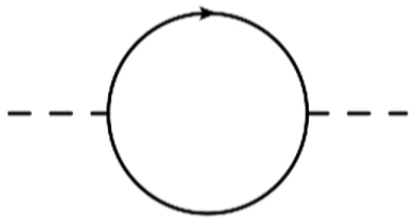
$$|\langle H_A\rangle|^2 + |\langle H_B\rangle|^2 = f^2$$

Breaks "quadratic" SU(4), higgses EWK_A & EWK_B

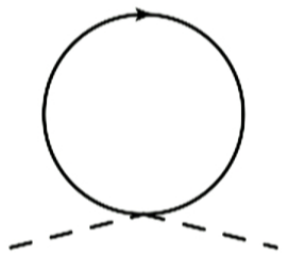
Gives a radial mode, a goldstone mode, and **eaten goldstones.**

$v \ll f$ for SM-like Higgs to be the goldstone

The Twin Top



Standard Model



Twin top

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

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

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

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

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Twin Higgs Slogan

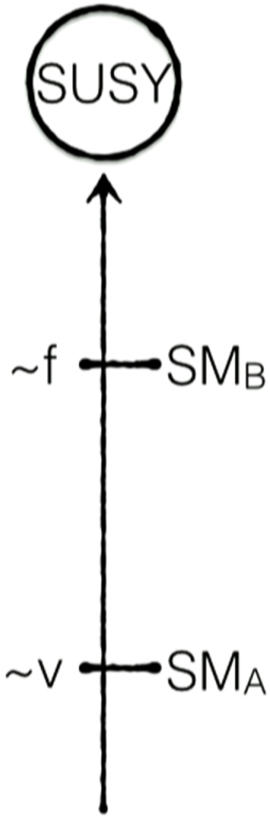
"Higgs is pseudo-goldstone of the accidental global symmetry of the quadratic action obeying a discrete symmetry"*

*plus a symmetric quartic.

Why not?

- **Not UV complete** (Still need to solve hierarchy problem of the radial mode).
- **Not quite enough** (Symmetry protecting Higgs is Z_2 but also need an SU(4) quartic?).
- **Not cosmologically sound** (Z_2 gives a lot of light states in the twin sector).
- **Not clear** if the Twin Higgs is a pathology or an example of a general framework.

A UV Completion



The SUSY Twin Higgs

NC, K. Howe [JHEP 03 (2014), 140]

Consider $MSSM_A \times MSSM_B \times Z_2$

SUSY requires usual 2HDM for both A and B sectors:

$$H_u = \begin{pmatrix} h_u^A \\ h_u^B \end{pmatrix}, \quad H_d = \begin{pmatrix} h_d^A \\ h_d^B \end{pmatrix}.$$

Singlet S gives SU(4) symmetric quartic automatically from Z_2:

$$W_{SU(4)} = \mu H_u H_d + \lambda S H_u H_d + M_S S S$$

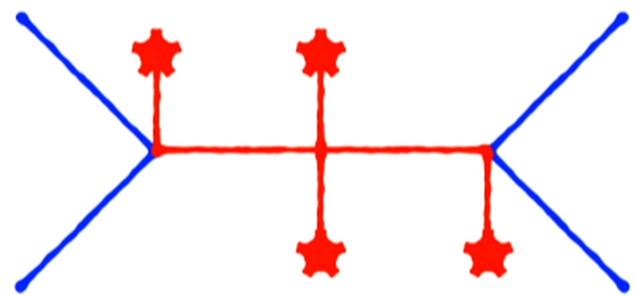
$\lambda \to \infty$ gives the SU(4) symmetric limit of the theory.

A UV Completion

Higgs mass prediction: $m_h^2 = 2 m_Z^2 \cos^2(2\beta) + \ldots$

An attractive tree-level prediction!

Factor of 2 relative to MSSM comes from A+B quartics.



Punchline: With O(10%) tuning for **μ~1TeV** and **$m_{\tilde{t}}$~3.5TeV**, the SUSY extension of the twin Higgs gives a UV complete theory exhibiting no conventional signs of supersymmetry at the LHC.

The General Framework

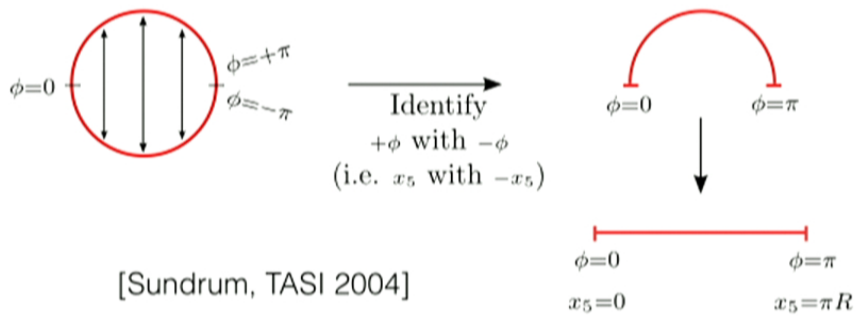
"The twin Higgs is an example of ???"

NC, S. Knapen & P. Longhi [PRL 114, 061803 & JHEP 03 (2015)]

$SM_A \times SM_B \times Z_2$ looks like it came from an orbifold.

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

[Dixon, Harvey, Vafa, Witten, `85 & `86, Dixon, Friedan, Martinec, Shenker, `86]



[Sundrum, TASI 2004]

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

Field theory orbifolds

Our approach: study essential physics via
field theory orbifolds.

[Kachru, Silverstein '98, Bershadsky, Johansen '98, Schmaltz '99]

- Start with a parent symmetry, identify a discrete global symmetry.
- Obtain a daughter symmetry by eliminating all fields not invariant under discrete symmetry.
- In the large N limit, correlation functions (two-point functions!) of the parent and daughter theory are identical.
- Given a continuous symmetry solution to hierarchy problem, orbifold probably solves it too…

Corresponds to zero mode spectrum of a higher-dim. geometric orbifold. Serves as a **model generator** for the possible light physics descending from a geometric orbifold.

The Twin Higgs is an Orbifold

Parent: $SU(6) \times SU(4)/Z_2$

various U(1) choices

Daughter: $[SU(3) \times SU(2)]^2 \times S_2$

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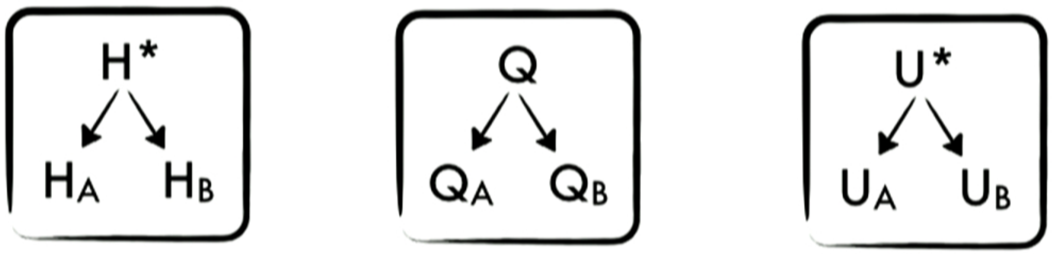


*start with SU(2) flavor symmetry

$$HQU \rightarrow H_A Q_A U_A, \quad H_B Q_B U_B \qquad |H|^4 \longrightarrow (|H_A|^2 + |H_B|^2)^2$$

Couplings in daughter sectors are equal,
Higgs quartic still SU(4) symmetric.

The Generalization

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

- Recipe seems to be SU(3N)xSU(2N)/Γ. We expect many such theories give orbifold Higgs models.

- The obvious abelian generalization: $\Gamma = Z_N$ instead of Z_2. Straightforward; N sectors instead of 2.

- What about non-abelian discrete symmetries? e.g. S_N, A_N, etc. Expect something qualitatively new.

The S_3 Higgs

Parent: $SU(18) \times SU(12)/S_3$

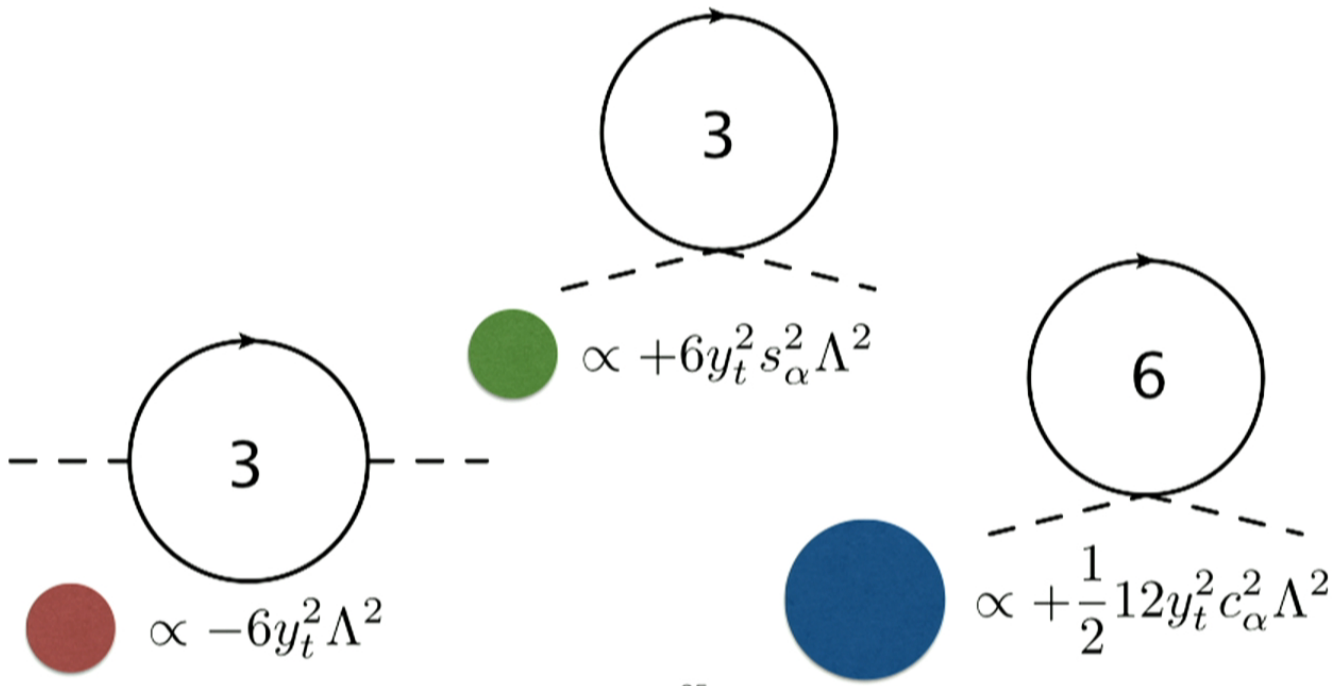
Daughter: $[SU(3) \times SU(2)]^2 \times [SU(6) \times SU(4)]$

2x [SU(3)xSU(2): H Q U] + [SU(6)xSU(4): H_C U_C H_D U_D Q]

"Higgs is pseudo-goldstone of the orbifolded SU(12) symmetry"

Top partners are a mix of SU(3) fermions and SU(6) fermions!
Couplings in SU(6) sector rescale under orbifold as needed.

Top partners are linear combination of fermions charged under hidden color groups of different size.



Why is this exciting?

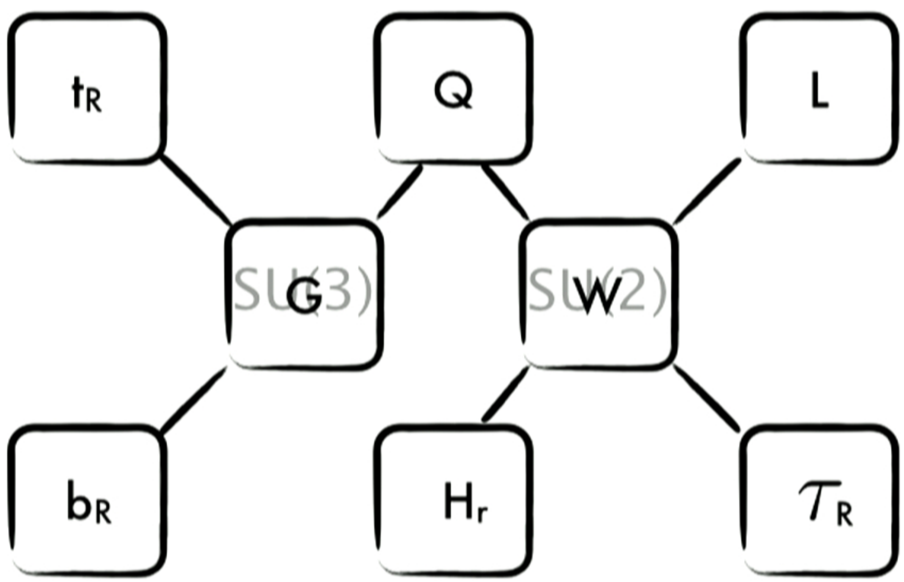
- Opens the door to a broad range of natural theories with radically different structure.
- Light states associated with naturalness lie in hidden sectors connected via the Higgs portal.
- Conventional searches for naturalness are irrelevant; points to new and different signs of naturalness.
- Gives a natural home to wide range of hidden sector phenomena.

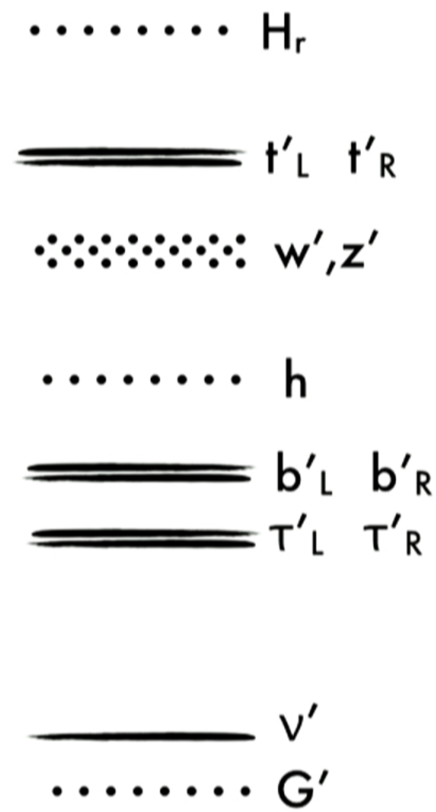
Naturalness in the dark

NC, A. Katz, M. Strassler, & R. Sundrum [JHEP 07 (2015)]

The minimal model

Just Z_2 partner states for the third generation.





Simple possibility in an orbifold model

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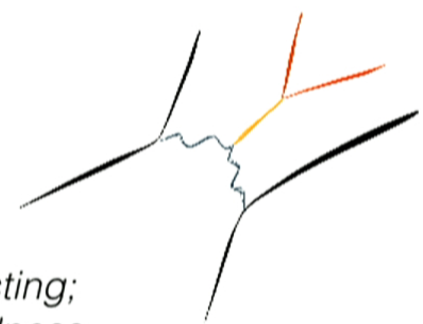
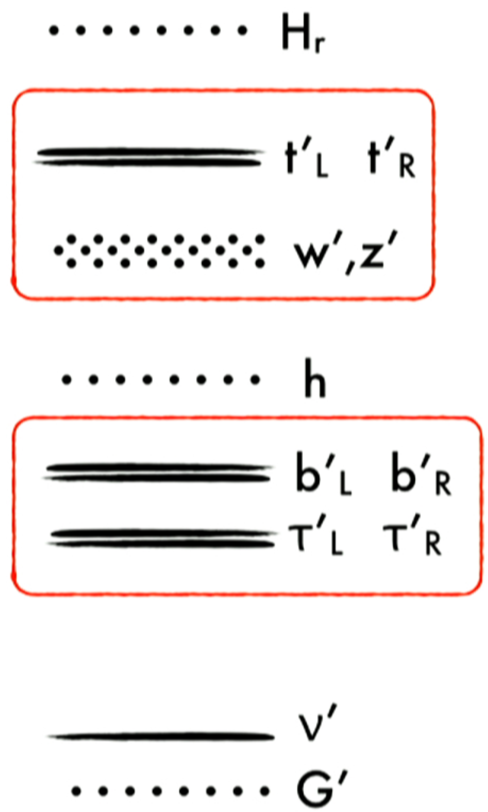
What to look for?

[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.

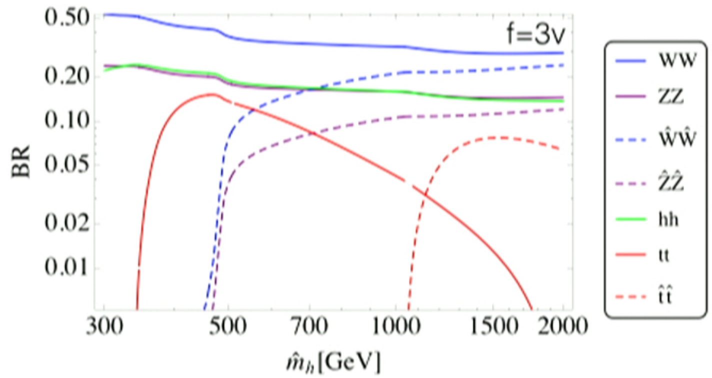


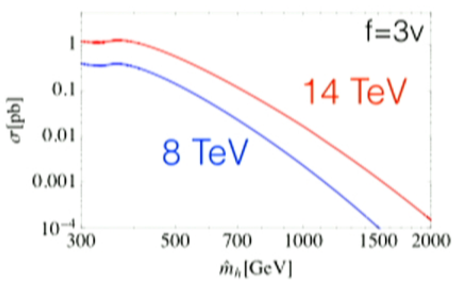
Hard but very interesting; directly probe naturalness



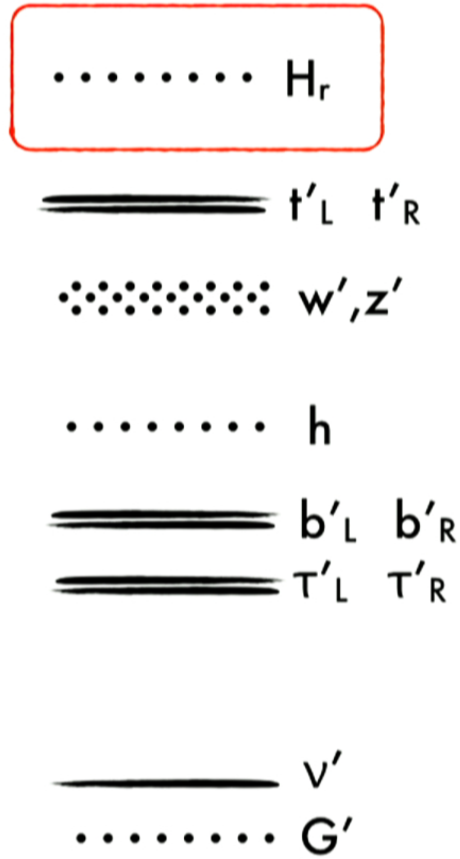
What to look for?

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



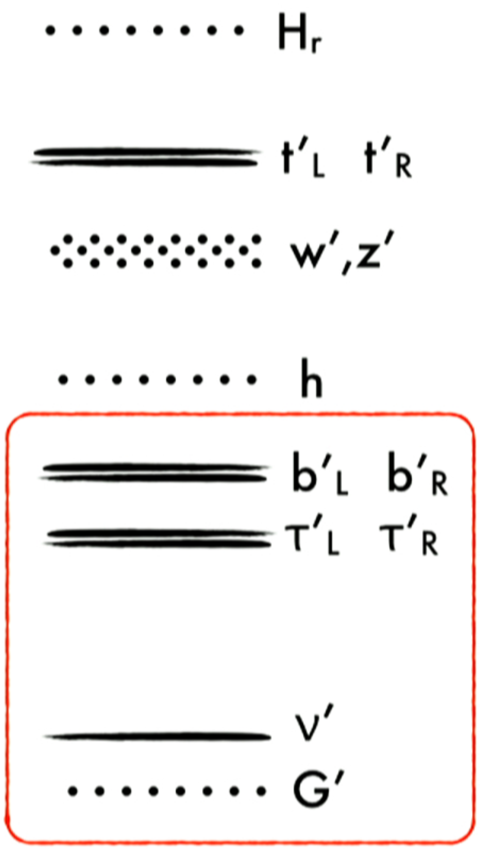


Current searches not constraining; very interesting for 13/14 TeV LHC



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…

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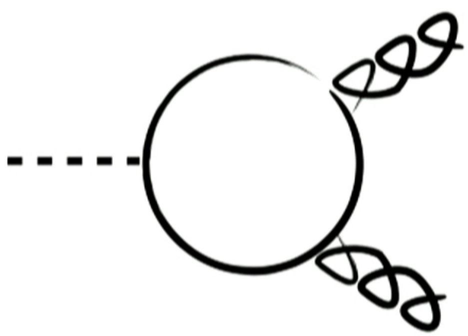
Dark Glueballs

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

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

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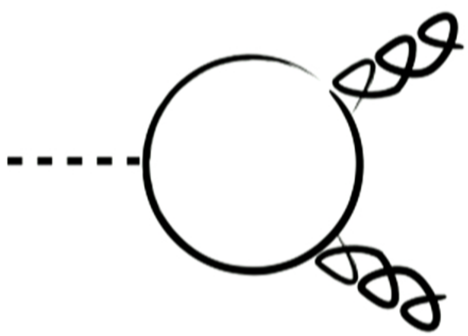

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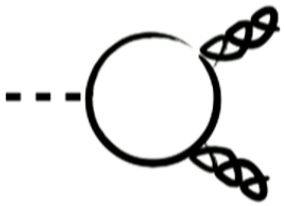
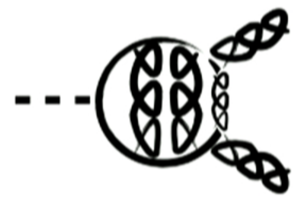


Into the dark



Irreducible:

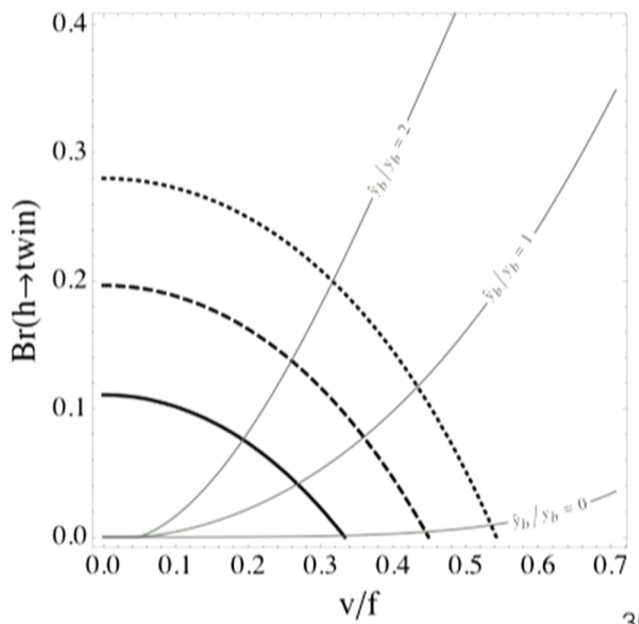
$h \rightarrow g'g' \rightarrow \ldots$

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

Reducible:

$h \rightarrow b'b' \rightarrow \ldots$

Large corrections to perturbative rate, few bottomonium states below m_h



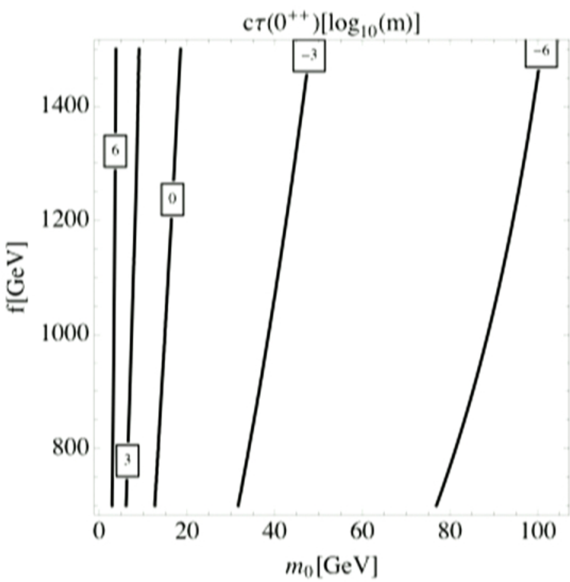
Irreducible through the orbifold top coupling. **Reducible** through the orbifold bottom coupling, sensitive to yukawa & bottomonium spectrum; also constrained by Higgs couplings.

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!

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

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

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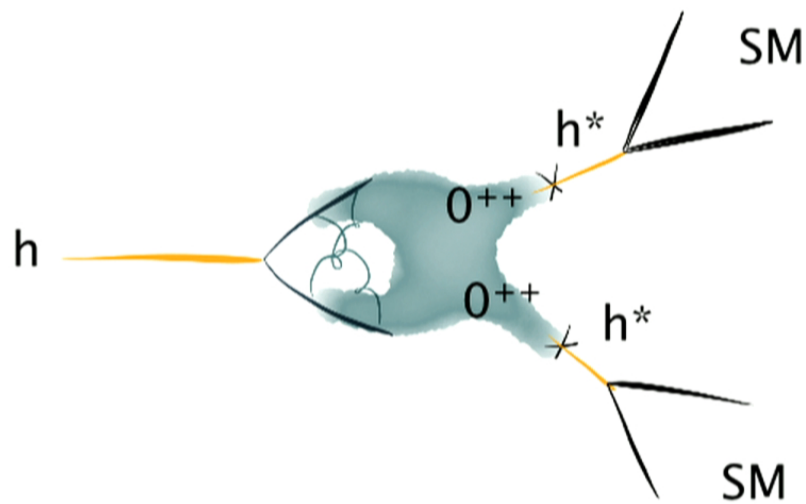
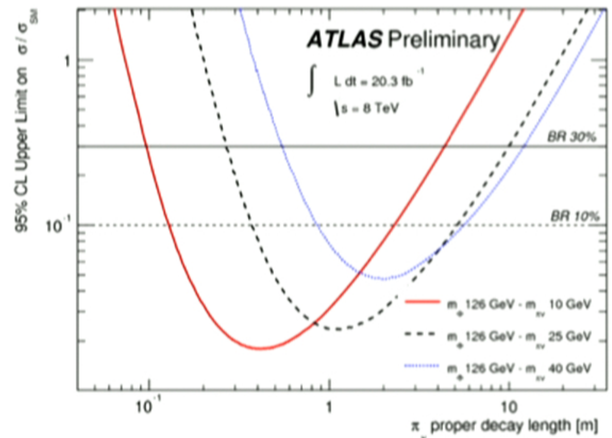
Displaced decays

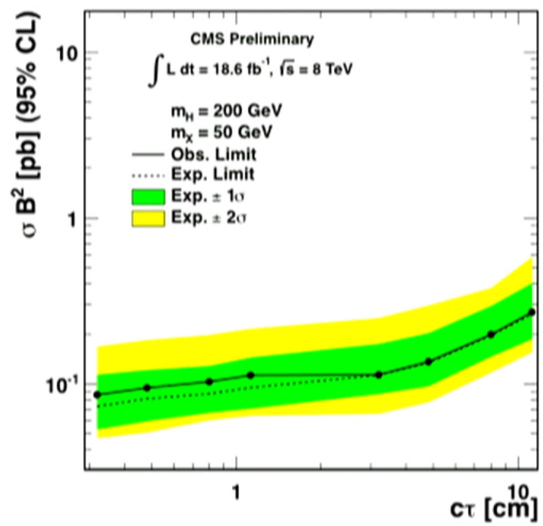


Rates small, signals spectacular. Best possible handle.

Existing searches

- ATLAS: use HCAL and edge of ECAL, sensitivity to long decay lengths (can also use muon chambers). Not reliant on vertexing.
- CMS: use inner tracker, sensitivity to short decay lengths. Reliant on vertexing.
- Signal: displaced decays of SM Higgs with BR at least ~ 10^{-3} (σ.Br~20fb during Run 1)





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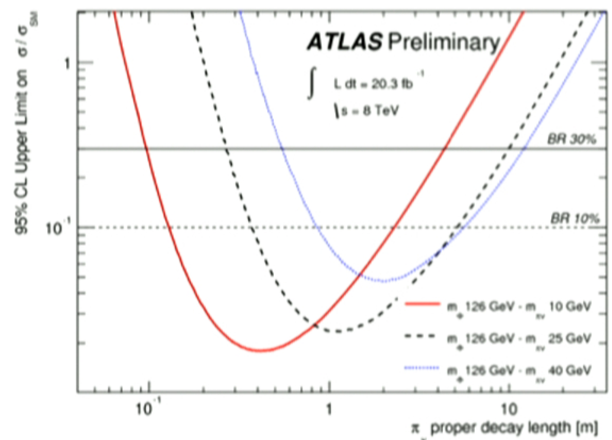

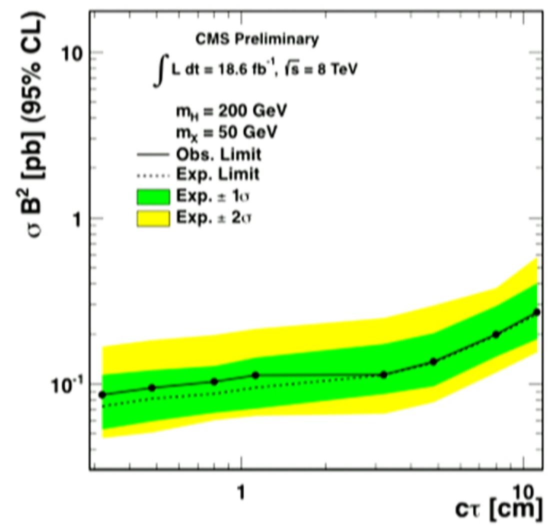

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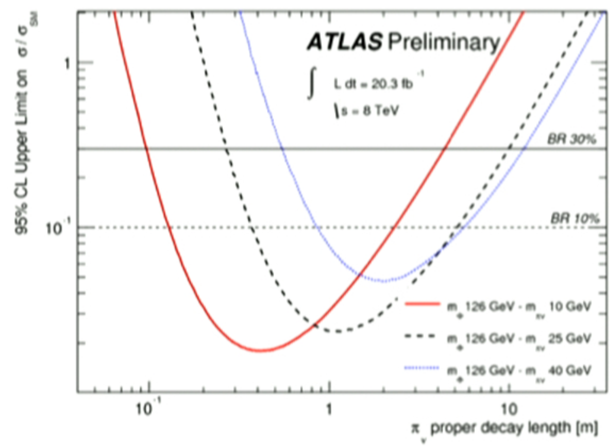
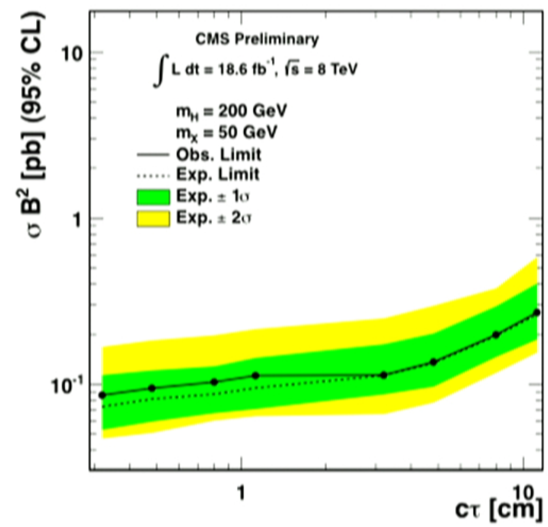




Looking to Run 2

- Run 1 sensitivity at ATLAS and CMS at the level of 100 fb; signal likely in the range of ~tens fb, possibly more.
- Very plausible at Run 2 with focus on displaced decays.
- Existing searches sensitive to inclusive production, but don't use Higgs associated production.
- Associated production drops xsec by OOM but improves sensitivity; ~few events sufficient for discovery.

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

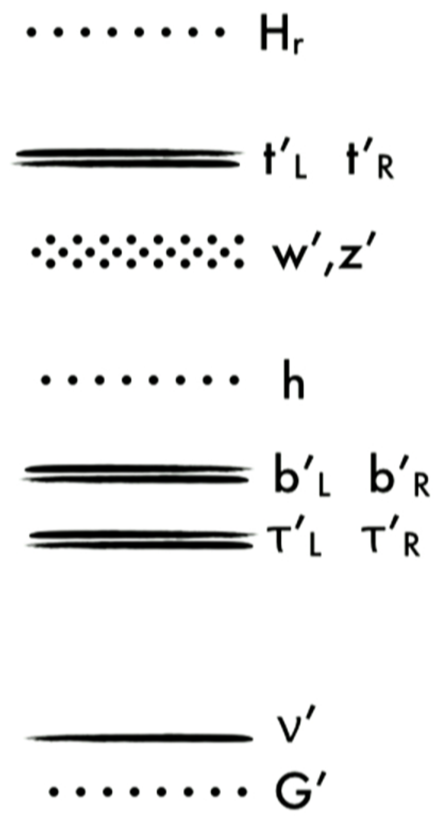
Dark matter

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

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

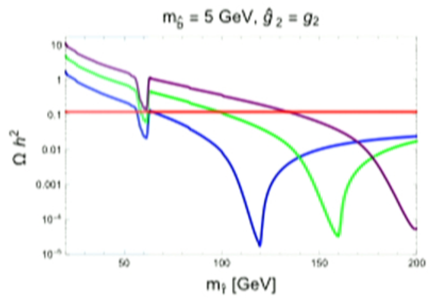
Various mechanisms for symmetric or asymmetric abundance.

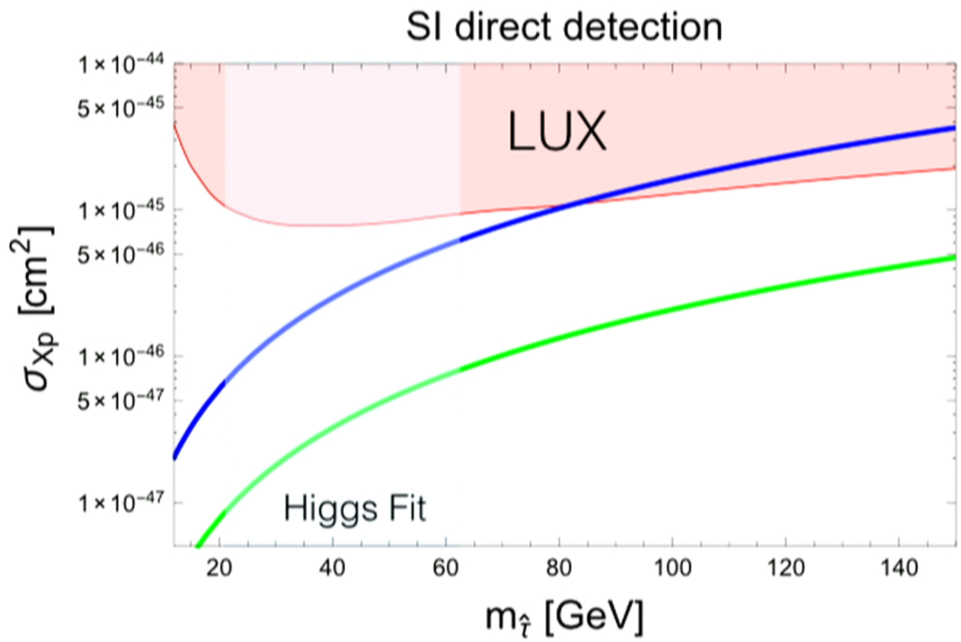
Simplest case: no light twin U(1); DM candidate is twin tau.



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

Direct detection





Natural parameter space right on the edge of direct detection

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

Pandora's box

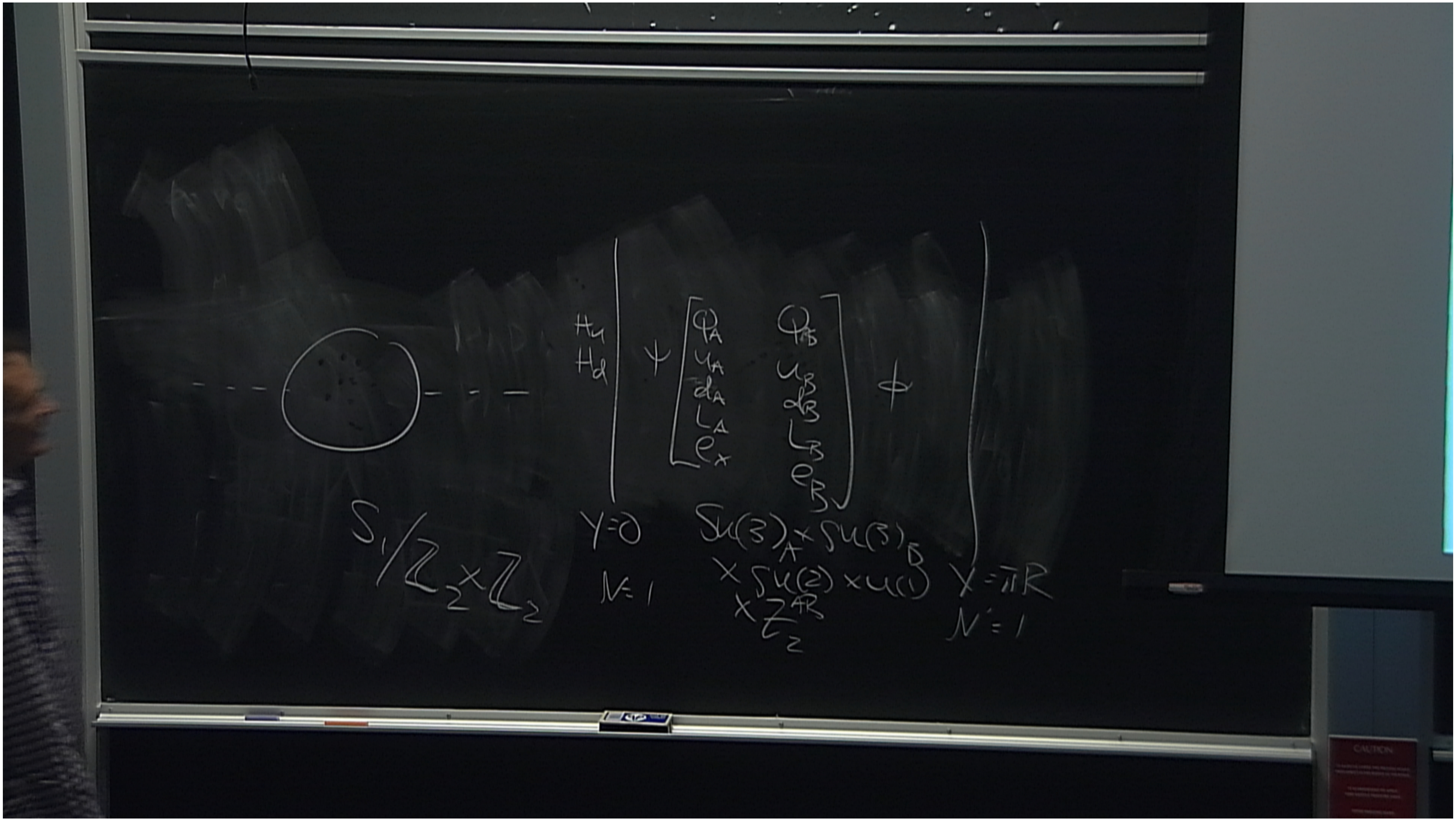
- In all of these theories, naturalness lies in hidden sectors connected via the Higgs portal

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

- Hidden valley phenomenology @ LHC
- Dark matter candidates (WIMP, SIMP, asymmetric)
- Additional sterile neutrino species…

There's a lot going on just a little ways outside the lamppost. Goodness knows what else is out there...

Thank you!



Hu
Hd
ψ
QA uA dA LA eA
QB uB dB LB eB
φ
S1/Z2×Z2
y=0
N=1
SU(3)A×SU(3)B
×SU(2)×U(1)
×Z2 4R
y=πR
N=1