Naturalness

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UCSB

Aspen 2015: Exploring the Physics Frontier with Circular Colliders

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In a theory where m_h is calculable, we see a hierarchy problem: threshold corrections to m_h *at least* around a new scale Λ.

Natural if $\Lambda \gtrsim m_h$

($\Lambda \gg m_h$ unnatural or UV miracle)

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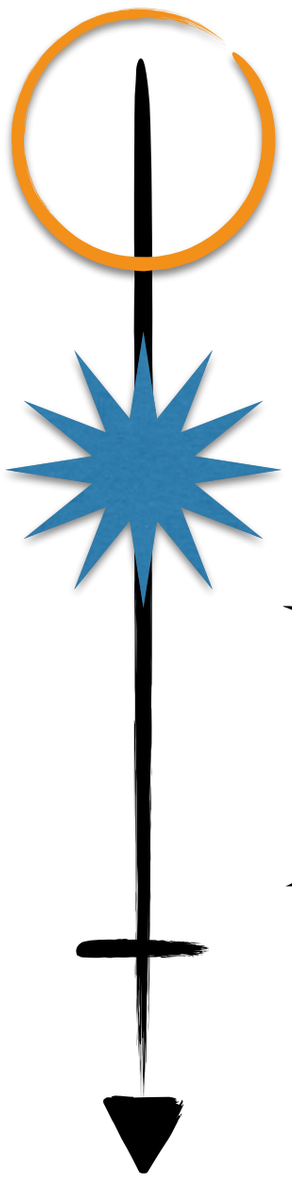
($\Lambda \gg m_h$ unnatural or UV miracle)

Potentially natural theories: Higgs mass is calculable and plausibly $\Lambda \gtrsim m_h$.

Conventional symmetries



Supersymmetry

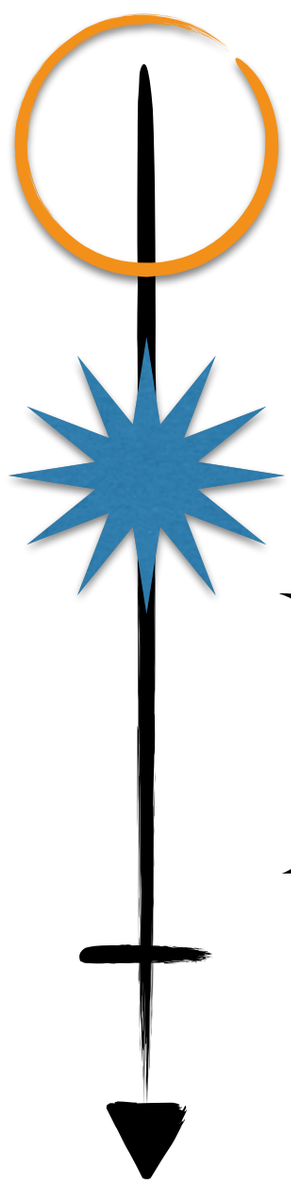
SUSY breaking
Sparticles m̃

≲4π/G

Higgs m_h

(compositeness, SUSY, turtles)

Global symmetry



Global symm. breaking
Partner particles m̃

≲4π/G

Higgs m_h

Continuous symmetries → partner states w/ SM quantum #s

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

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

“Colored” naturalness

Supersymmetry

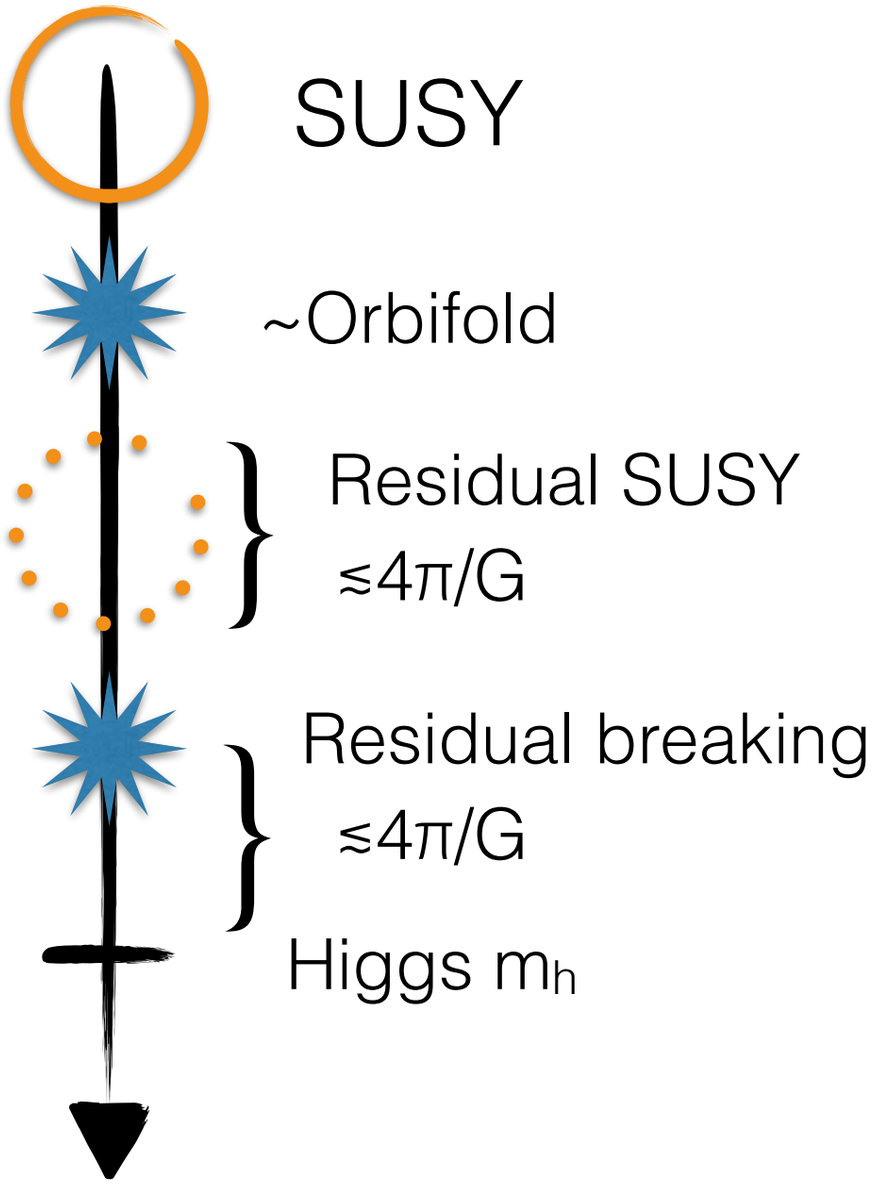
Composite/Little Higgs

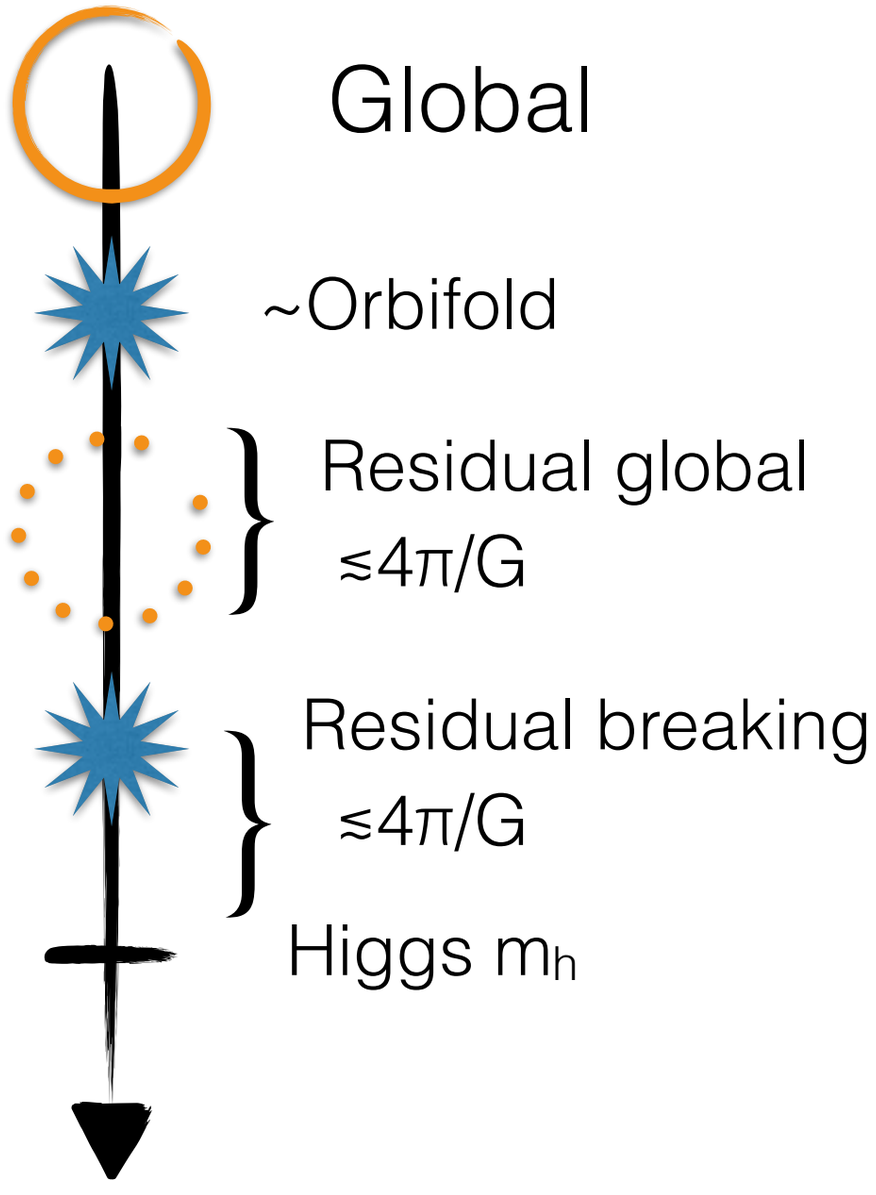
Simple game for LHC: look for colored partners.

We’ve had 30 years to grow comfortable with conventional theories, but naturalness need not adhere to convention.

To truly test naturalness, we should consider the most radical theories that still play by the same rules (calculable Higgs mass controlled by symmetries).

Unconventional symmetries



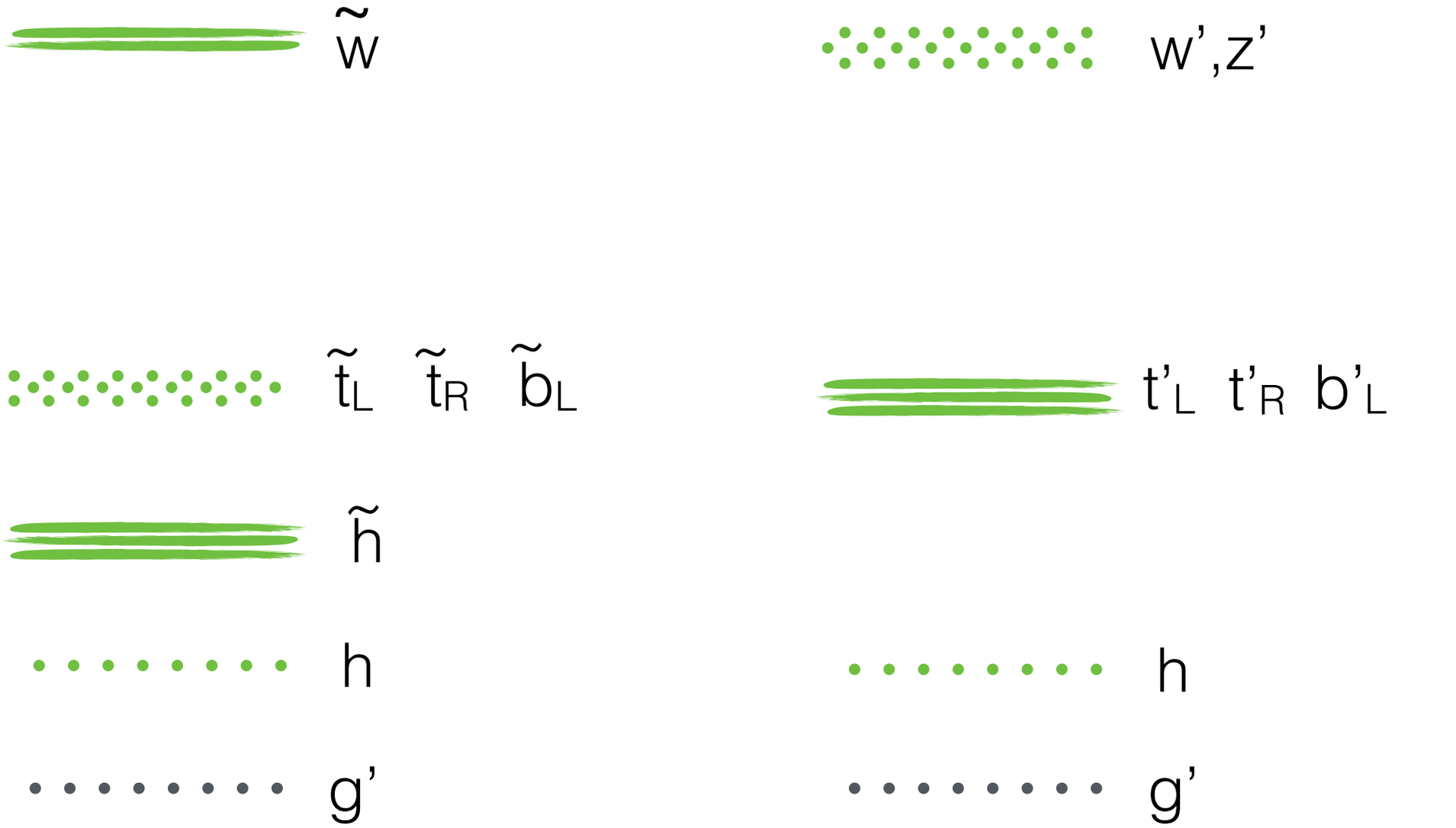


Residual symmetries → partner states without SM quantum #s

$$m_h^2 \sim \frac{3y_t^2}{4\pi^2}\tilde{m}^2 \log(\Lambda^2/\tilde{m}^2)$$ Totally natural: $\tilde{m} \lesssim 200\,\mathrm{GeV}$

“Electroweak” naturalness

10 TeV

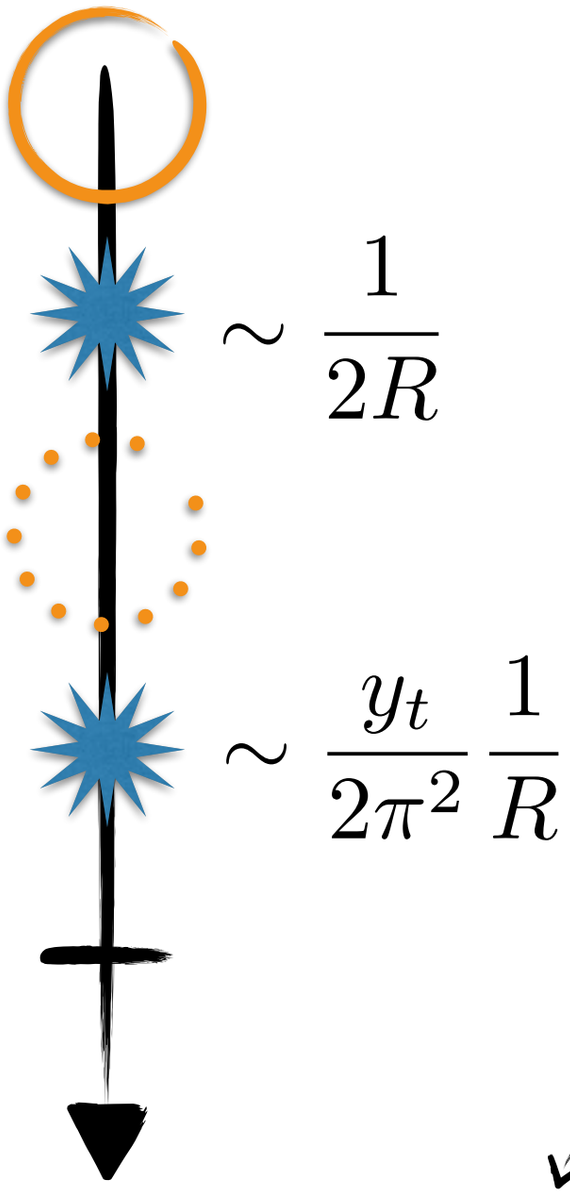


Folded SUSY
[Burdman, Chacko, Harnik]

Quirky Little Higgs
[Cai, Cheng, Terning]

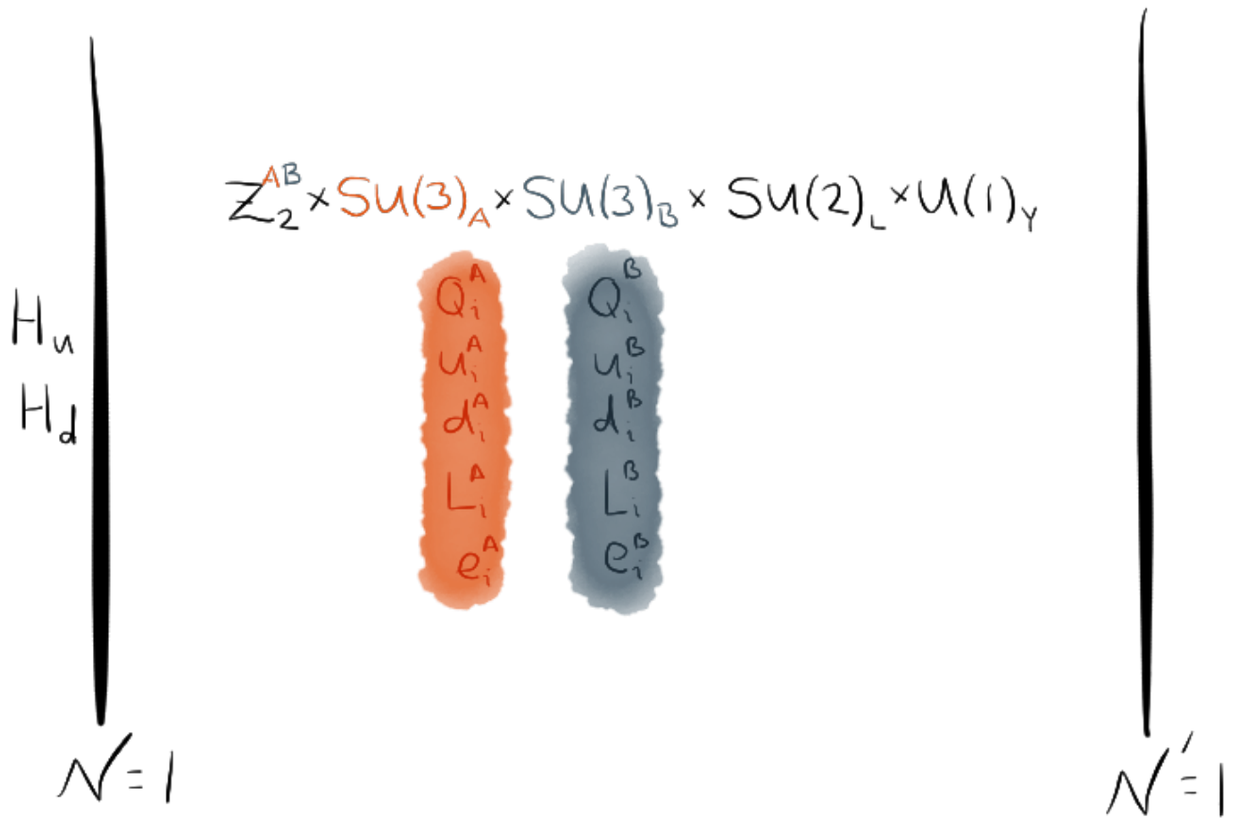
A model: Folded SUSY

[Burdman, Chacko, Harnik '06]



$$\sim \frac{1}{2R}$$

$$\sim \frac{y_t}{2\pi^2}\frac{1}{R}$$



Couplings fixed by SUSY

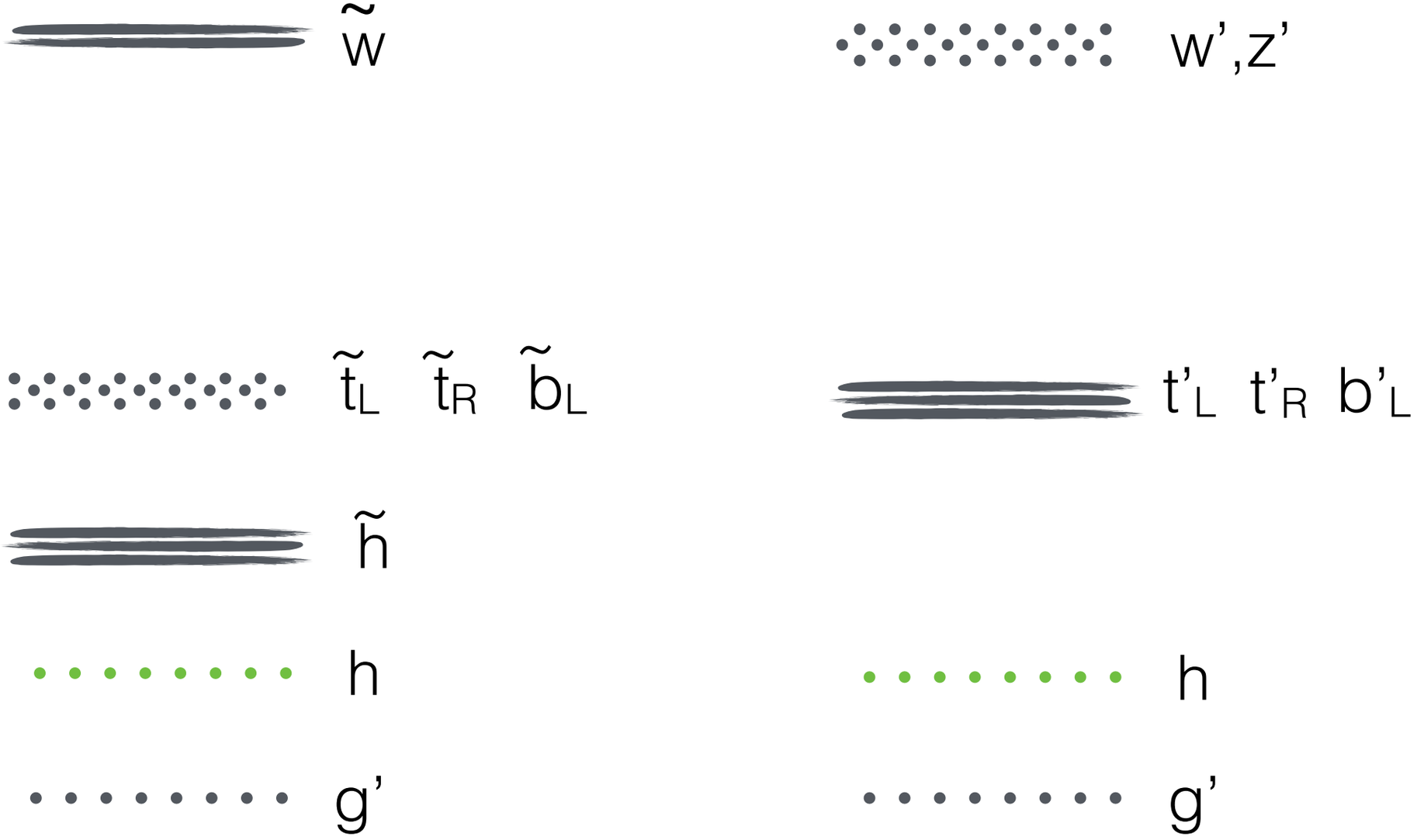
$$\mathcal{L} \supset \lambda_t H_u q_3^A u_3^A + \lambda_t^2 |H_u \cdot \tilde{q}_3^B|^2 + \lambda_t^2 |H_u|^2 |\tilde{u}_3^B|^2$$

Charged under $SU(3)_A$

Charged under $SU(3)_B$

“Neutral” naturalness

10 TeV



(No known examples…yet)

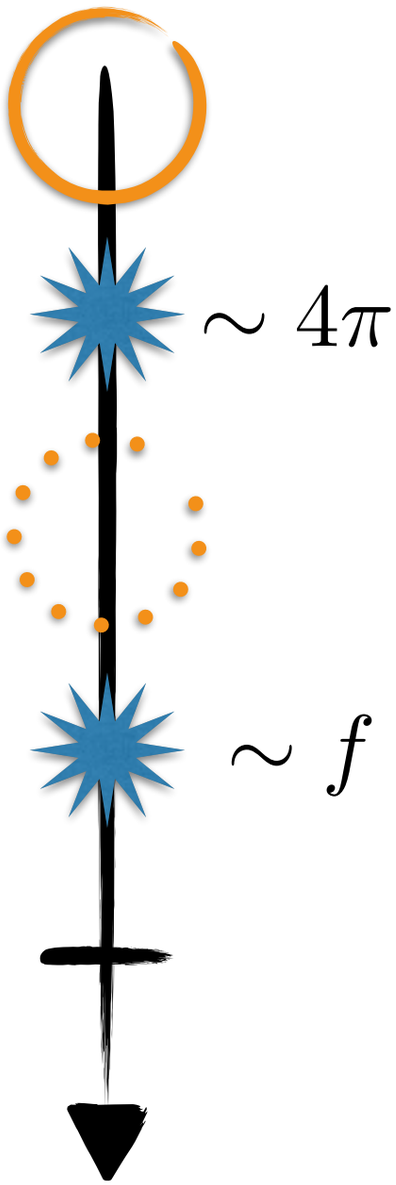
[Your name here!]

Twin Higgs

[Chacko, Goh, Harnik]

A model: Twin Higgs

[Chacko, Goh, Harnik '05]



Standard Model $\xleftrightarrow{Z_2}$ **Standard Model**

Weak gauge symmetry is $SU(2)_{us} \times SU(2)_{twin}$

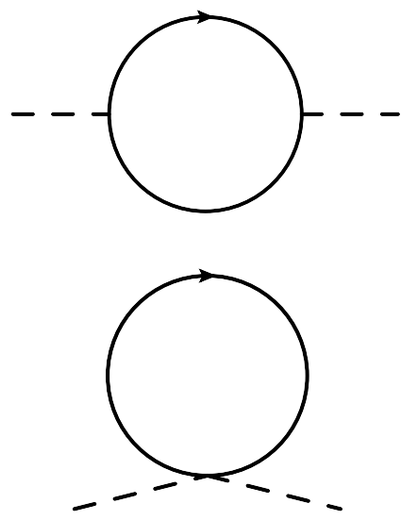
But thanks to Z_2, radiative corrections to the Higgs mass are SU(4) symmetric.

Higgs is a PNGB of ~SU(4), but partner states not charged under the SM.

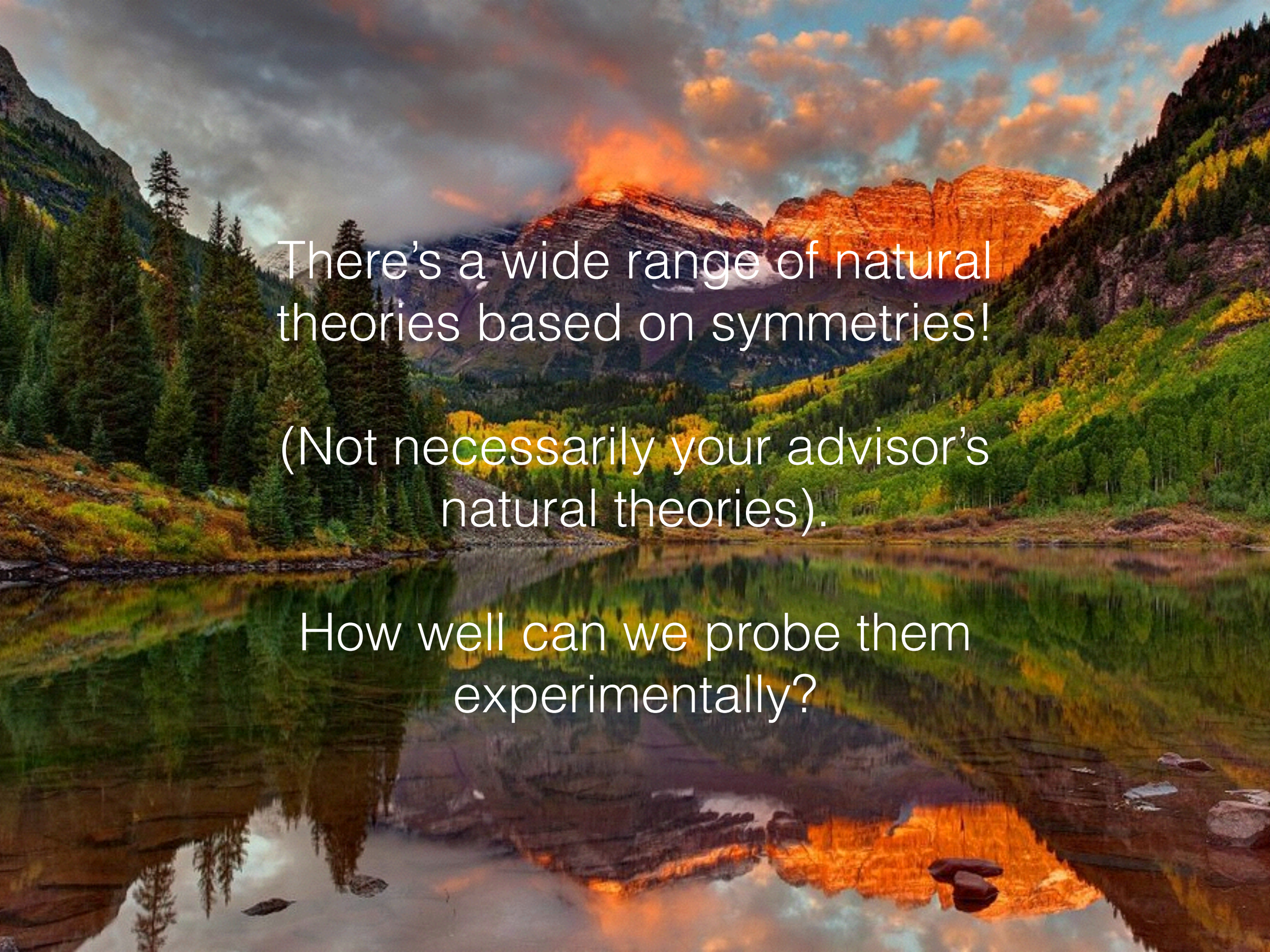
$$\mathcal{L} \supset -y_t H_A Q_3^A \bar{u}_3^A - y_t H_B Q_3^B \bar{u}_3^B$$

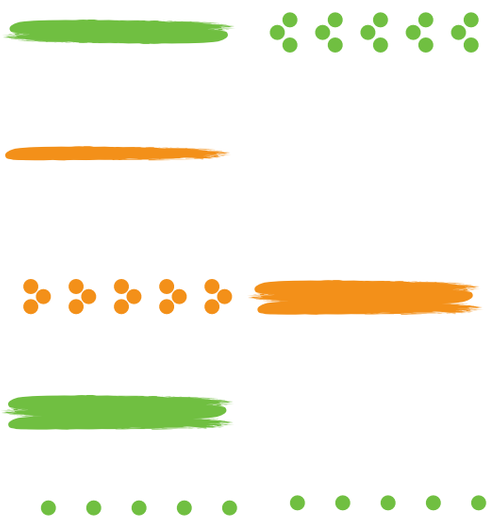
$$\downarrow \qquad\qquad \downarrow$$

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



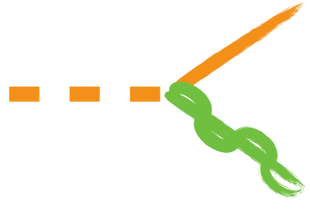
There are many more theories of this kind [NC, S Knapen, P Longhi]


There's a wide range of natural theories based on symmetries!
(Not necessarily your advisor's natural theories).
How well can we probe them experimentally?

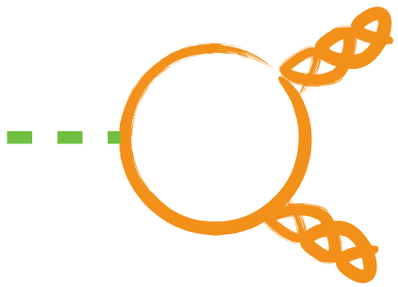


Colored naturalness

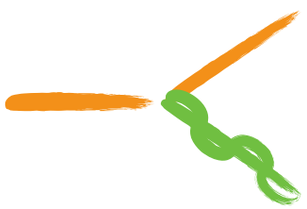
Experimental handles

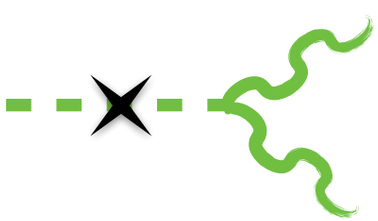


- SUSY: Direct searches (and indirect searches).
  - Look for colored partner states (stops, gluinos)
  - Look for O(loop*v/m) Higgs coupling deviations.



- Global: Direct and indirect searches.
  - Look for colored partner states (vector-like t’)
  - Look for O(v/f) Higgs coupling deviations.



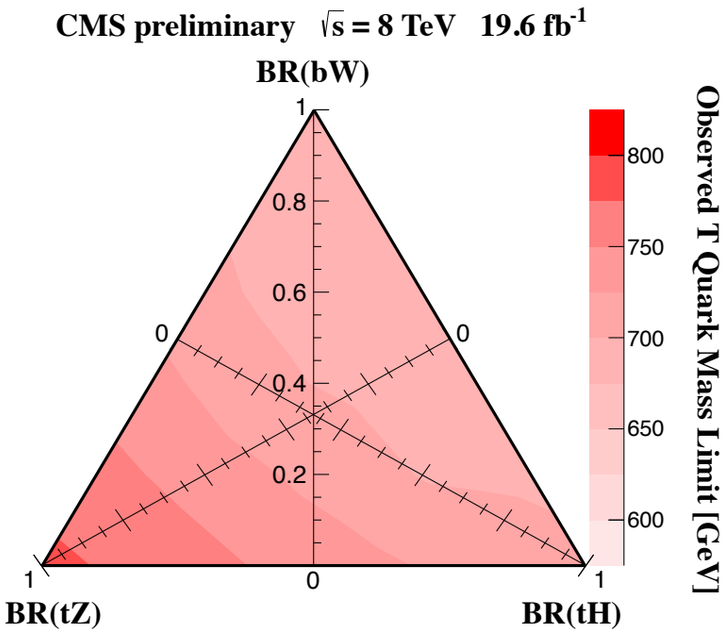


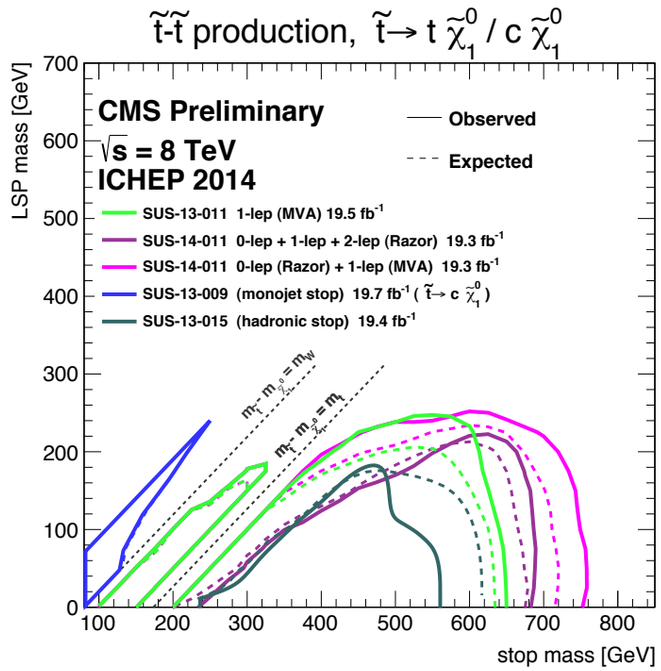
This is our current search program for naturalness.

Colored naturalness

Where we are:

~7% level

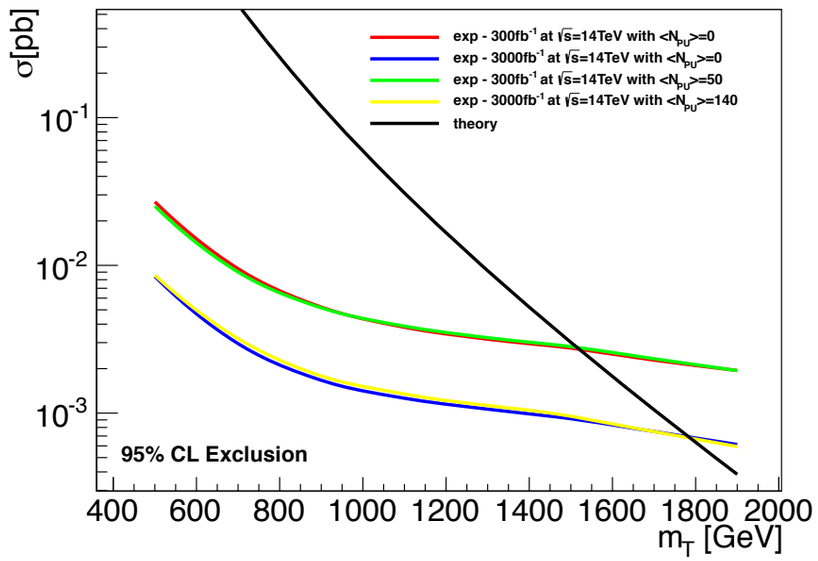


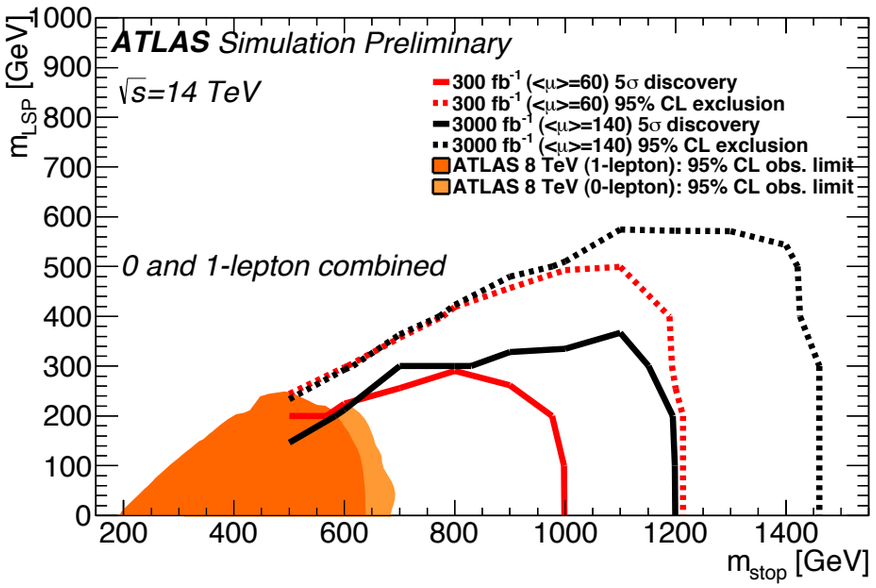


Where we'll be @ end of LHC:

~1% level (global)
~2% level (SUSY)

[Bhattacharya, George, Heintz, Kumar, Narain, Stupak]





Colored naturalness

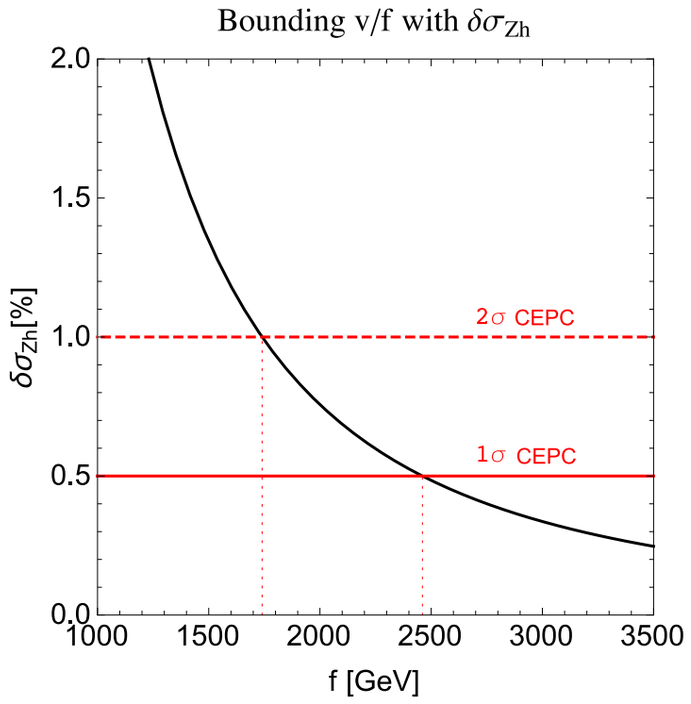
Where we'll be @ Higgs factory:

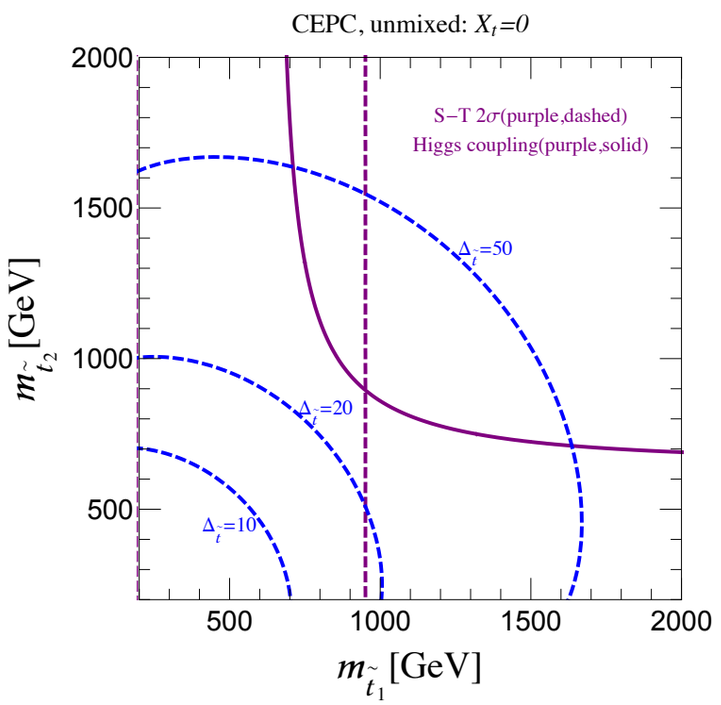
~2% level (global)
~5% level (SUSY)

Where we'll be @ 100 TeV:

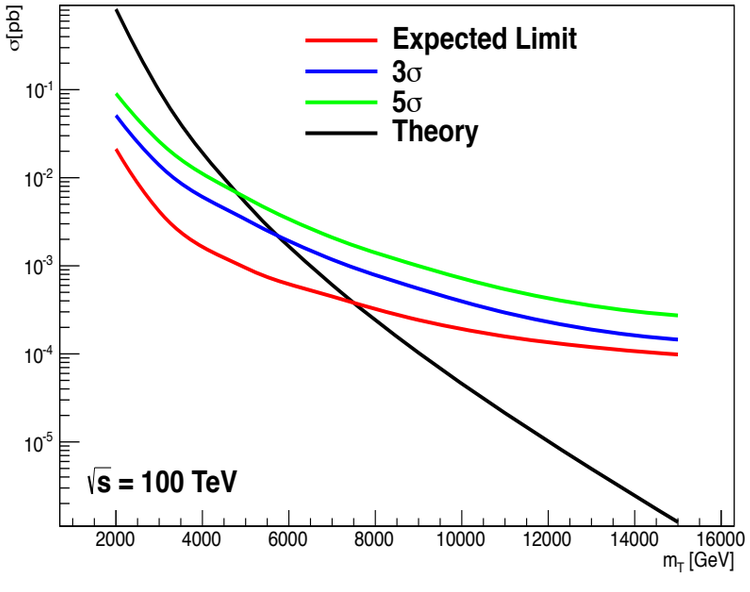
~.05% level

[Fan, Reece, Wang]

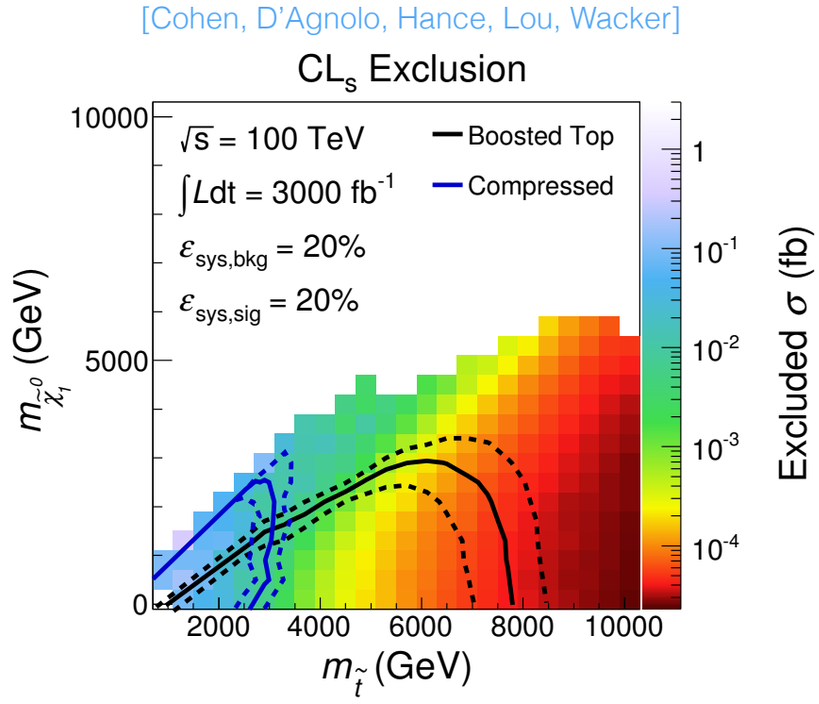




[Ahuja, Black]

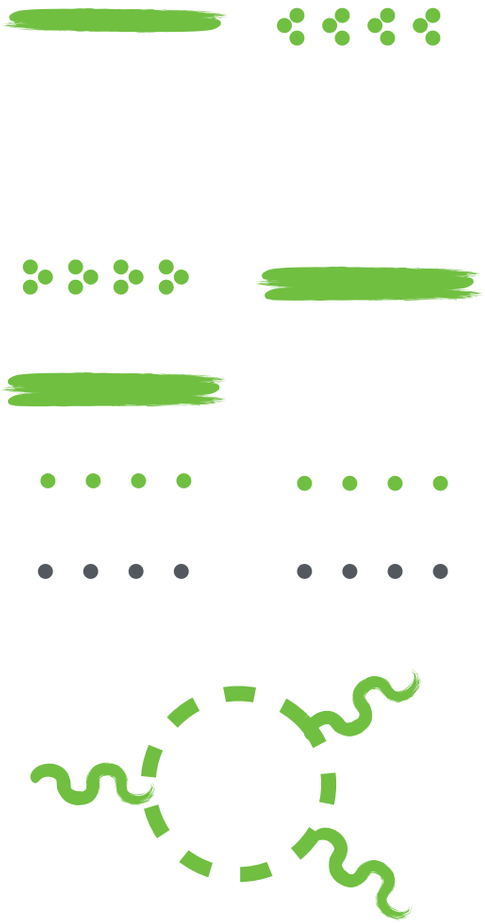


[Cohen, D'Agnolo, Hance, Lou, Wacker]



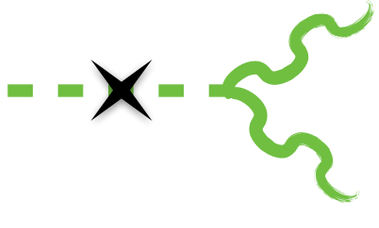
EWK naturalness

Experimental handles



- SUSY: Direct searches (and indirect searches).
  - Look for electroweak resonances and displaced decays.
  - Look for O(loop*v/m) Higgs coupling deviations.
  - *Look for the UV completion*

- Global: Direct and indirect searches.
  - Look for electroweak resonances and displaced decays.
  - Look for O(v/f) Higgs coupling deviations.
  - *Look for the UV completion*

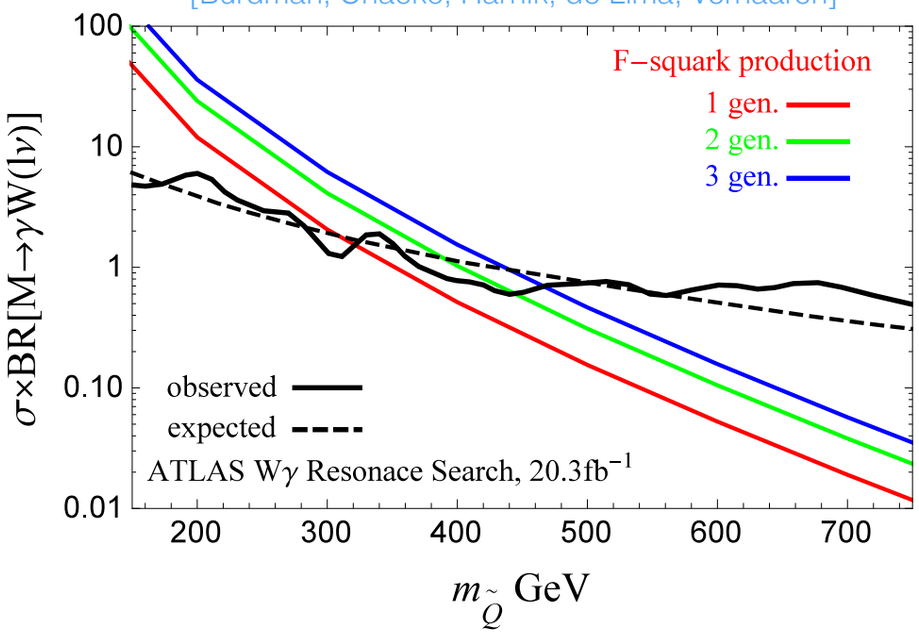


EWK naturalness

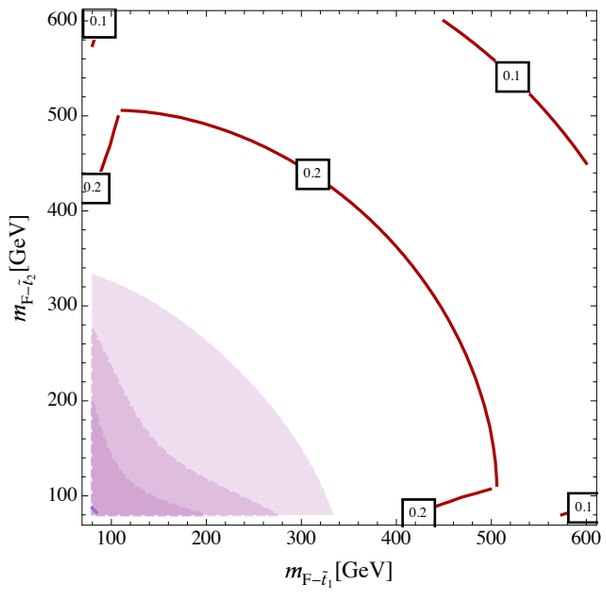
Where we are:

~natural

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



[Fan, Reece]



Where we'll be @ end of LHC:

~10% level

Diboson resonance searches, displaced decays

Work in progress, [Curtin, Chacko, Verhaaren], [Cohen, NC, Lou, Pinner]

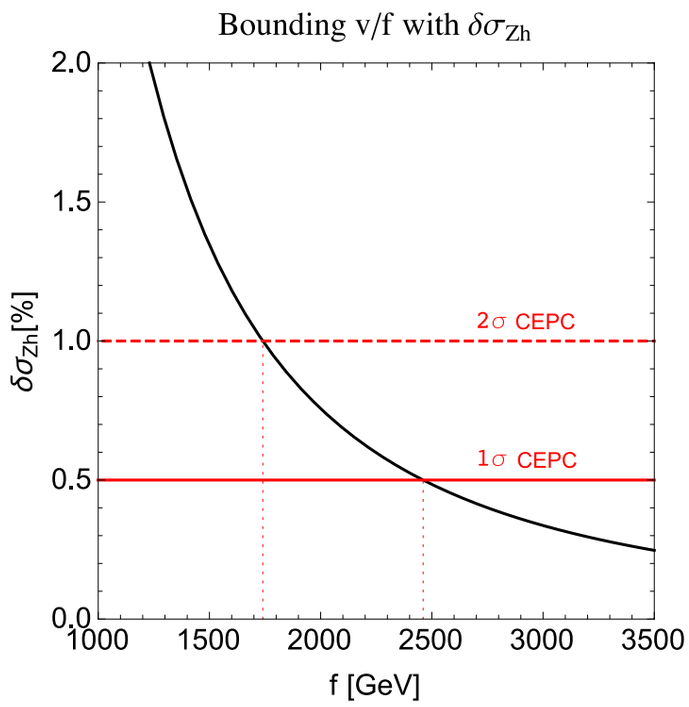
EWK naturalness

Where we'll be @ Higgs factory:

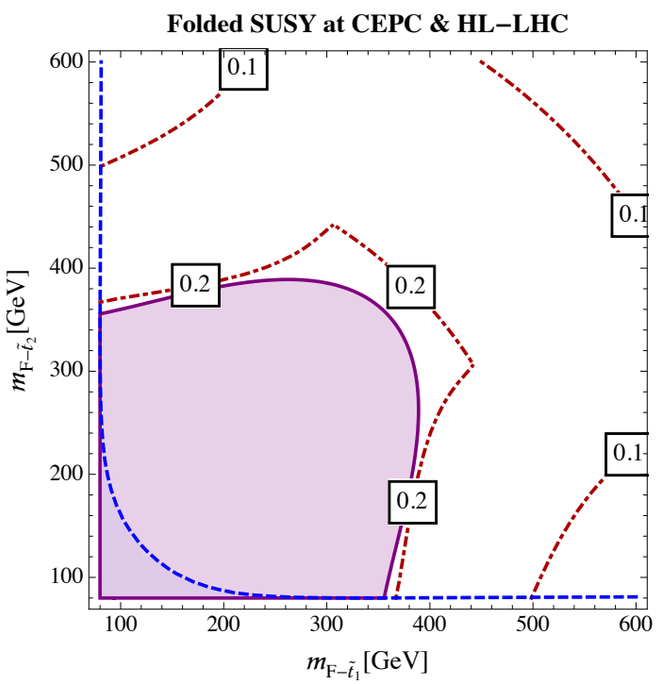
~2% level (global)
~5% level (SUSY)

Where we'll be @ 100 TeV:

at least ~1% level

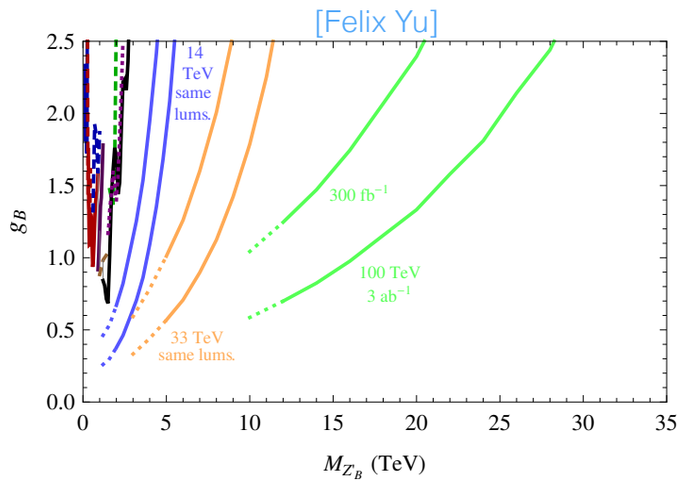


[Fan, Reece, Wang]



Colored sparticles, heavy resonances @ ~1/R

[Felix Yu]



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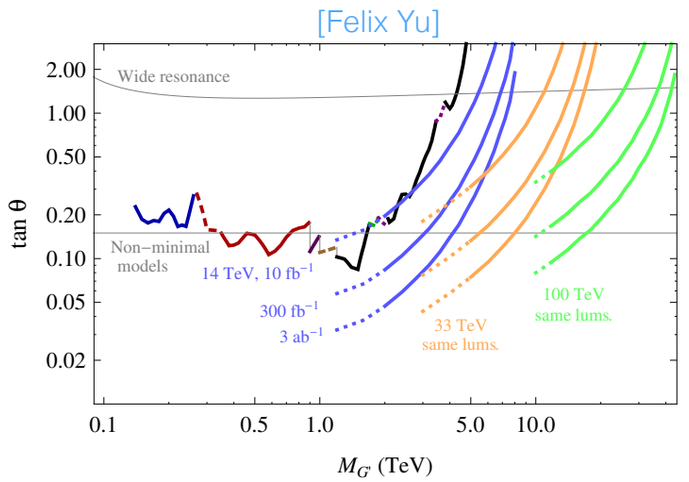
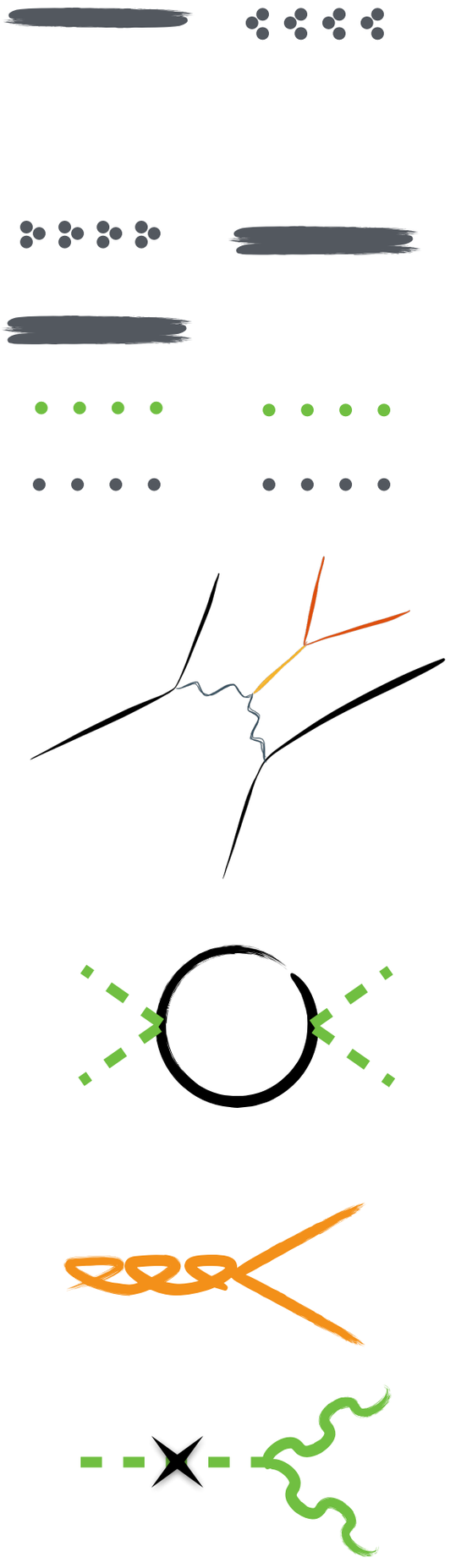


1/R ≲ 20 TeV → m̃ ≲ 1.5 TeV



Neutral naturalness

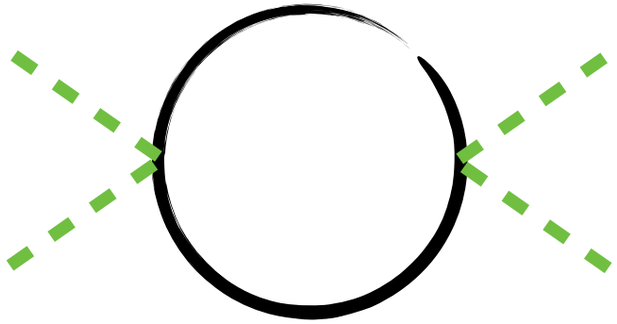
Experimental handles

- SUSY: Direct searches (and indirect searches).
  - Look for off-shell Higgs portal.
  - Look for O(loop*v/m) Higgs coupling deviations.
  - *Look for the UV completion.*
- Global: Direct and indirect searches.
  - Look for O(v/f) Higgs coupling deviations.
  - Look for displaced decays [NC, Katz, Strassler, Sundrum]
  - *Look for the UV completion.*

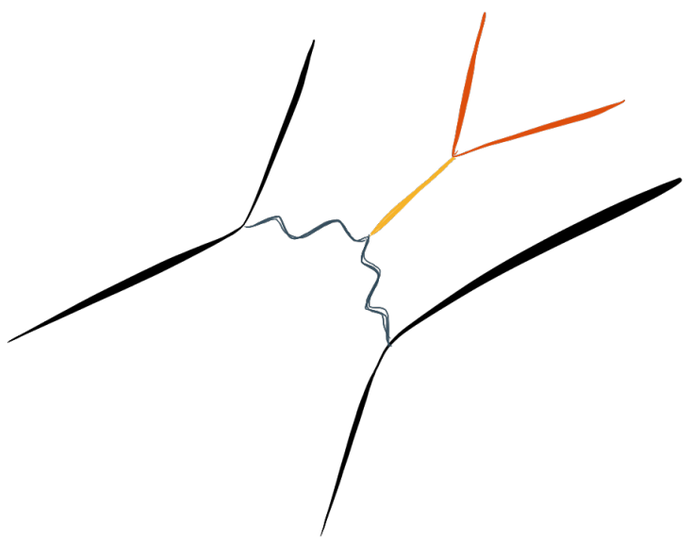
Neutral naturalness

Higgs couplings: accustomed to looking for corrections to loop-level couplings ($h \to \gamma\gamma$, gg), but even loops of neutral states can be seen.

[NC, Englert, McCullough; Henning, Lu, Murayama; NC, Farina, McCullough, Perelstein]



$$\frac{c_H}{m_\phi^2}\left(\partial_\mu |H|^2\right)^2 \to \delta\sigma_{Zh} = -2c_H\frac{v^2}{m_\phi^2}$$



Direct searches: states lighter than $m_h/2$ can easily be constrained by non-SM Higgs width; if heavier than $m_h/2$, can still produce via an off-shell Higgs. Look for associated production + invisible.

[Curtin, Meade, Yu; NC, Lou, McCullough, Thalapillil]

Neutral naturalness

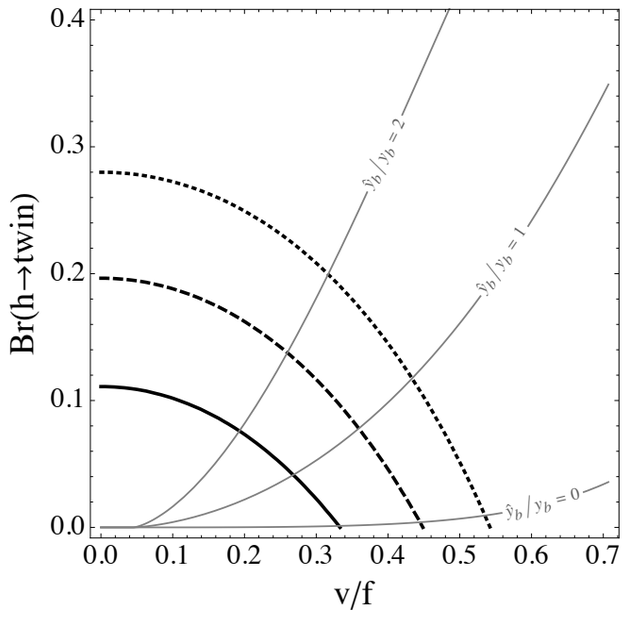
Where we are:

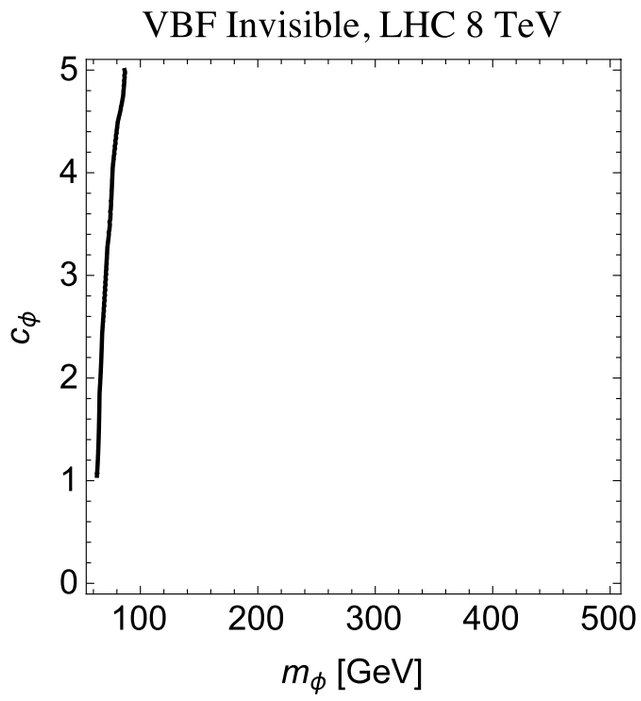
natural (at worst 30% for global)

Where we'll be @ end of LHC:

natural (at worst 20% for global)

[NC, Katz, Strassler, Sundrum]



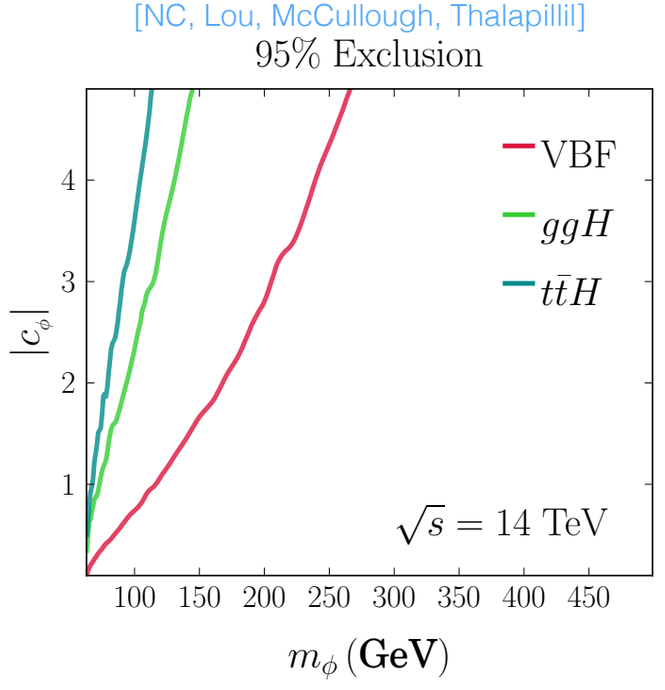


95% CL bounds

$v/f \lesssim 0.31\,(0.25)$
(ATLAS)

$\mathrm{Br}(\mathrm{inv.}) \lesssim 10\%$

[NC, Lou, McCullough, Thalapillil]



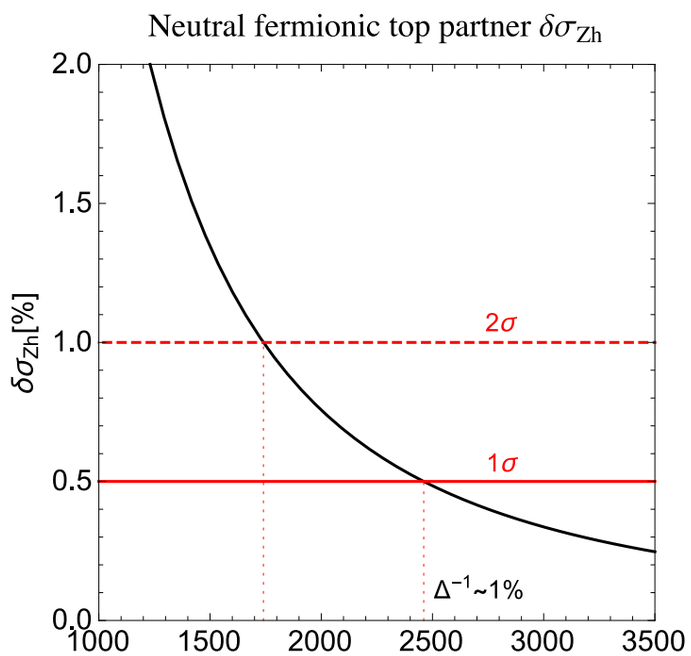
Neutral naturalness

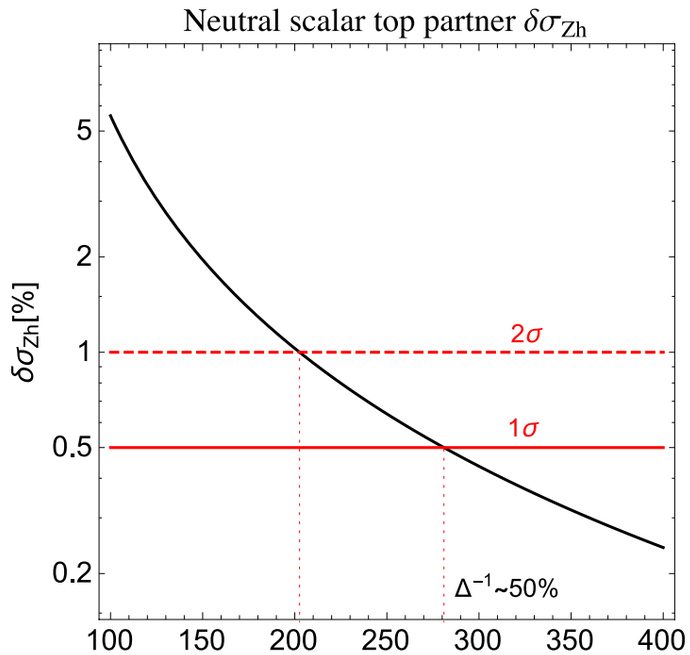
Where we'll be
@ Higgs factory:

~1% level (global)
~50% level (SUSY)

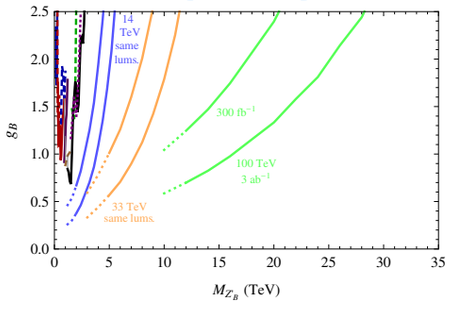
Where we'll be
@ 100 TeV:

~1% level

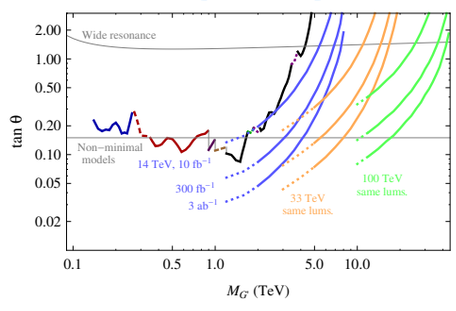




[Felix Yu]



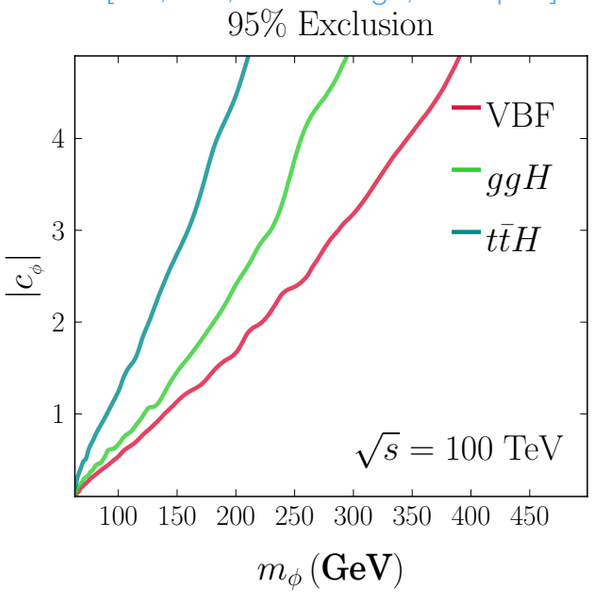
[Felix Yu]



$4\pi f \lesssim 20$ TeV → $f \lesssim 1.6$ TeV

(Twin Higgs: radial Higgs mode, expect comparable limits)

[NC, Lou, McCullough, Thalapillil]



Conclusions

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- Taking naturalness seriously opens the door to many novel theories for the weak scale with unconventional signatures.

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- The LHC will eventually probe our conventional theories to the ~1% level.

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- The LHC will eventually probe our conventional theories to the ~1% level.
- But it will leave novel theories essentially untested, and the status of naturalness truly unresolved.

Conclusions

- Taking naturalness seriously opens the door to many novel theories for the weak scale with unconventional signatures.

- The LHC will eventually probe our conventional theories to the ~1% level.

- But it will leave novel theories essentially untested, and the status of naturalness truly unresolved.

- A Higgs factory & 100 TeV collider can probe all natural symmetry-based theories to the ~1% level with powerful complementarity — essentially a no-lose theorem.

Conclusions

- Taking naturalness seriously opens the door to many novel theories for the weak scale with unconventional signatures.

- The LHC will eventually probe our conventional theories to the ~1% level.

- But it will leave novel theories essentially untested, and the status of naturalness truly unresolved.

- A Higgs factory & 100 TeV collider can probe all natural symmetry-based theories to the ~1% level with powerful complementarity — essentially a no-lose theorem.

- Same likely extends to even *more* radical proposals…