The Twin Higgs: Can Naturalness Hide?

Twin Higgs: Zackaria Chacko, Hock-Seng Goh, RH hep-ph/0506256
Folded SUSY: Brudman, Chacko, Goh, RH hep-ph/0609152

Liberal use of Nathaniel's work.

Discussions N. Arkani-Hamed, N. Craig, Z. Chacko, G. Perez.

Where is everybody?

* LHC run 1:
  We found a Higgs. Nothing else so far.
* We know how EW symmetry is broken.
* The burning question:
  Is the EW scale natural or tuned?

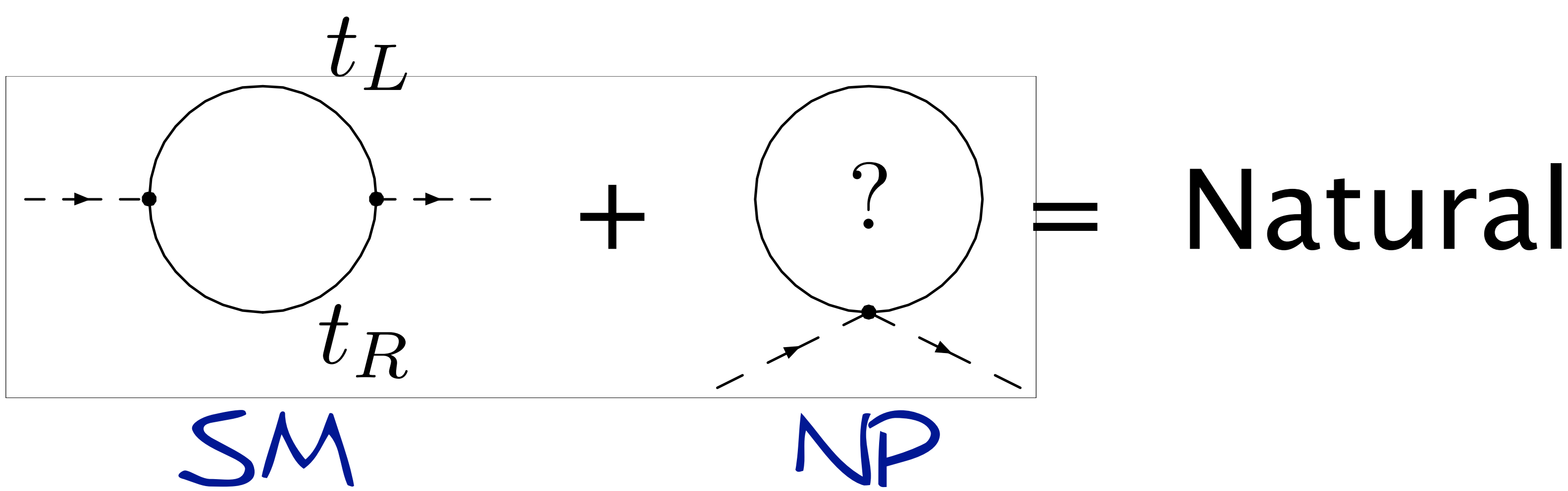
Our hope:

LHC will address this question.
(Evidence of naturalness will be found).

This may still happen in run II.
But what if it doesn't? Is the world tuned?

Naturalness and LHC

* Why did we expect LHC to find the evidence for naturalness?



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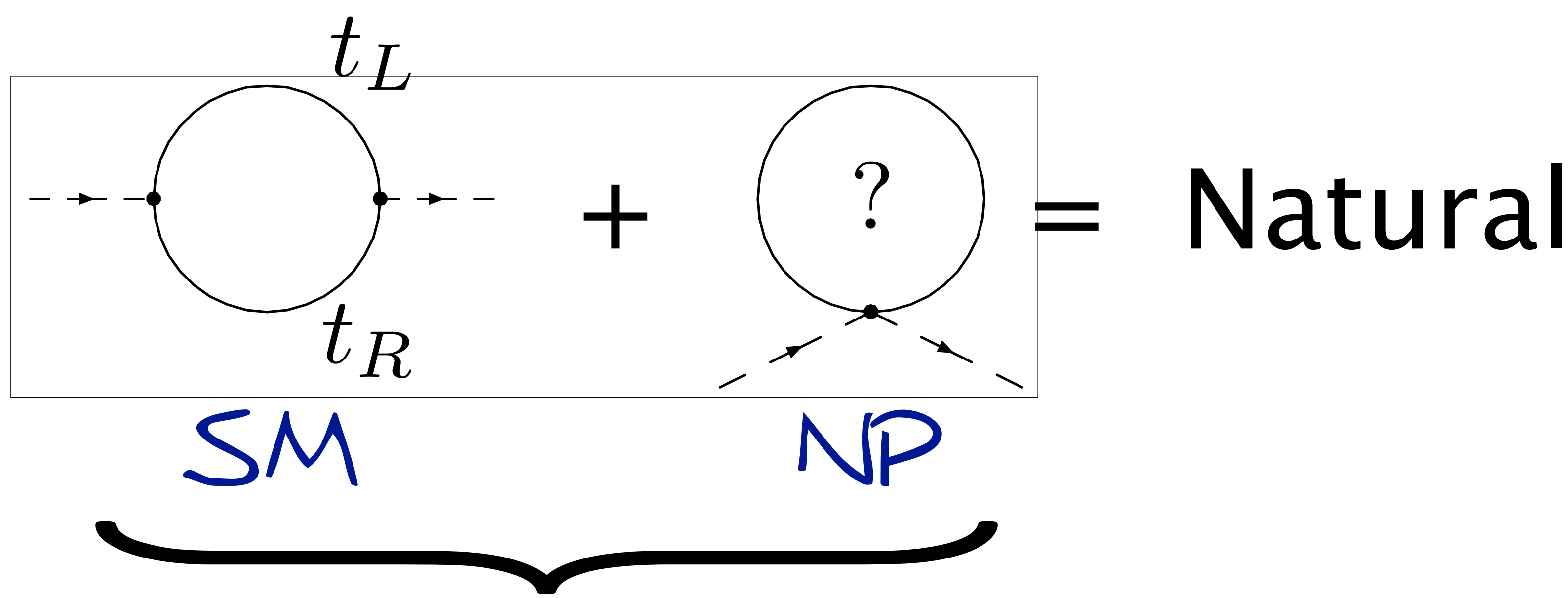

NP is related to the SM top by a symmetry.
NP is around a TeV.

Colored NP at a TeV!
Will be produced abundantly at LHC!

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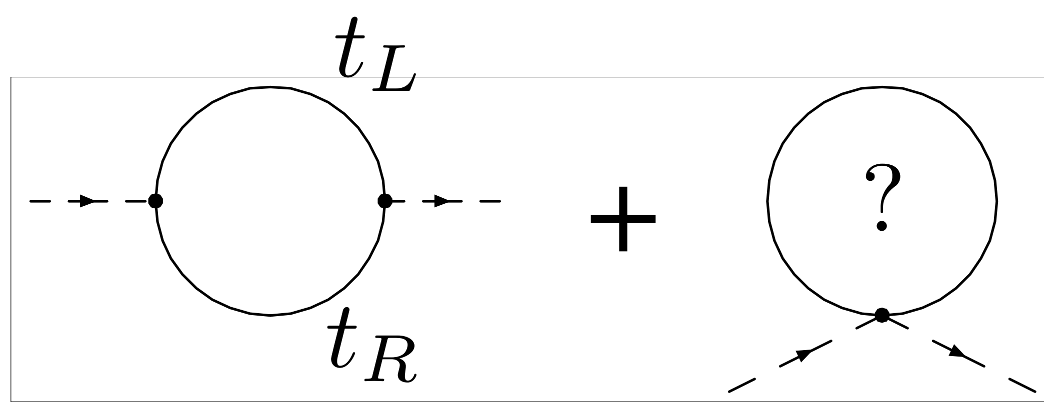


= Natural

SM NP

NP is related to the SM top by a symmetry.

NP is around a TeV.

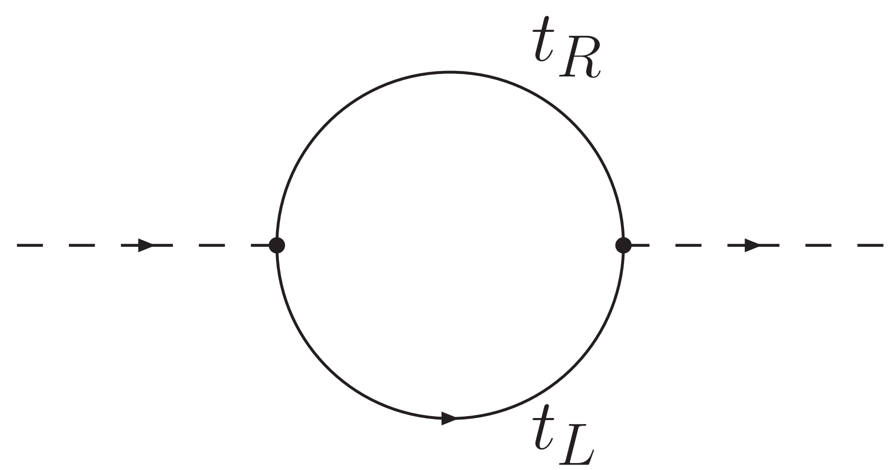
Colored NP at a TeV!

Will be produced abundantly at LHC!

Not Necessarily True.

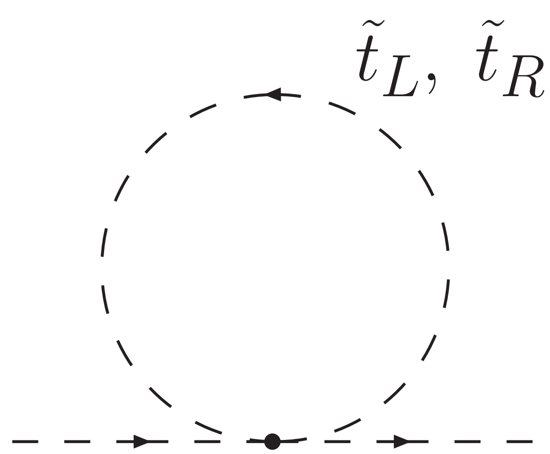
Just a Factor of 3

color factor:



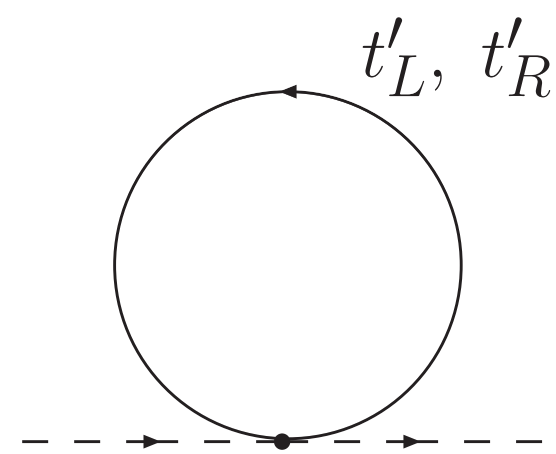
Standard Model

$\times 3$



Supersymmetry

or



Little Higgs

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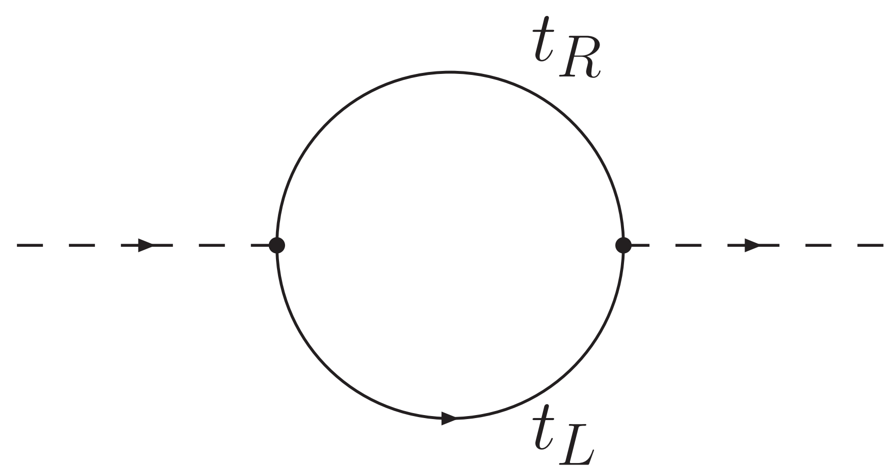

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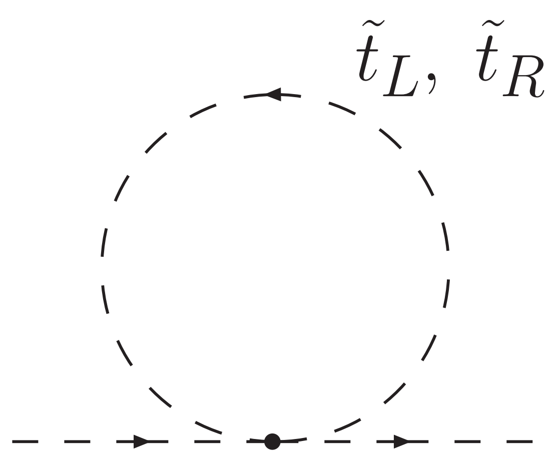

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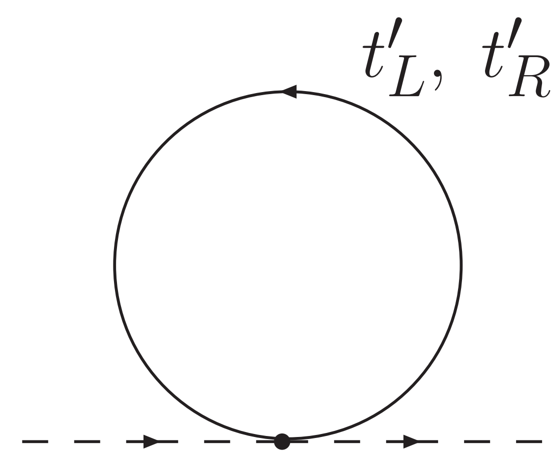
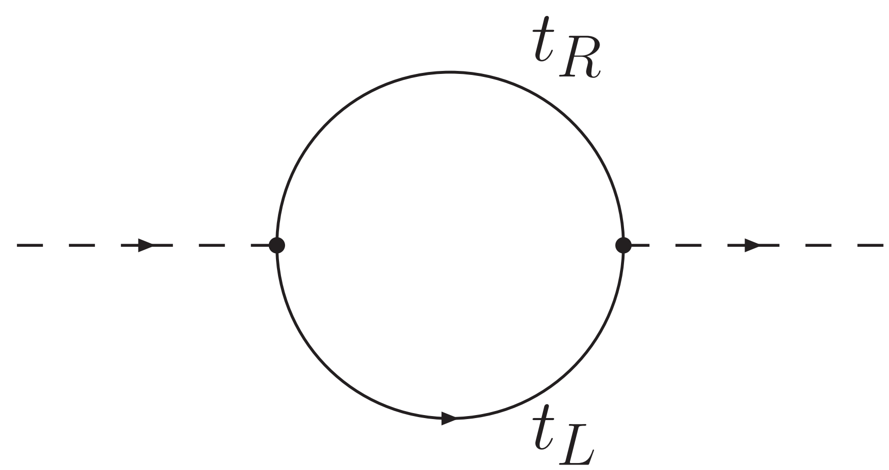


Little Higgs

$\times$ ~~3~~ 3'

Just a Factor of 3



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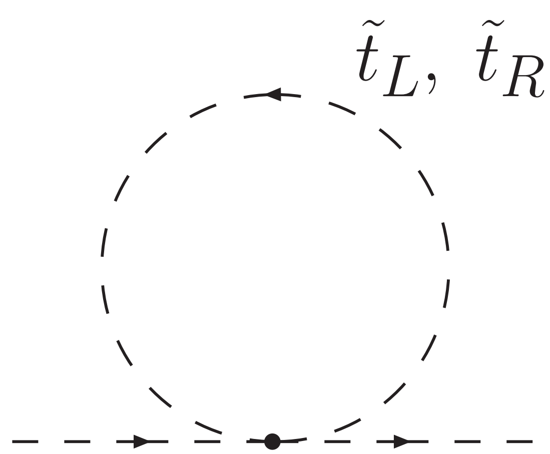

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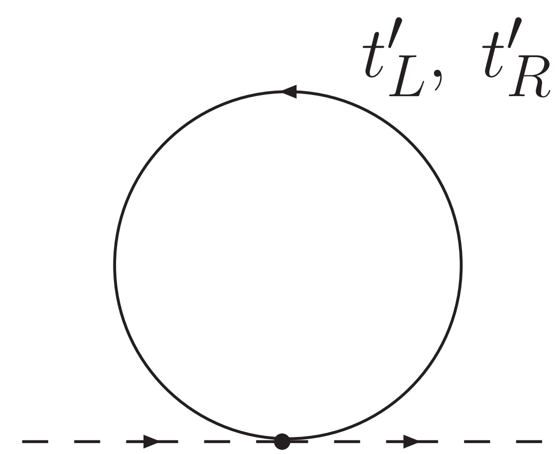

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symmetry does not commute with color.

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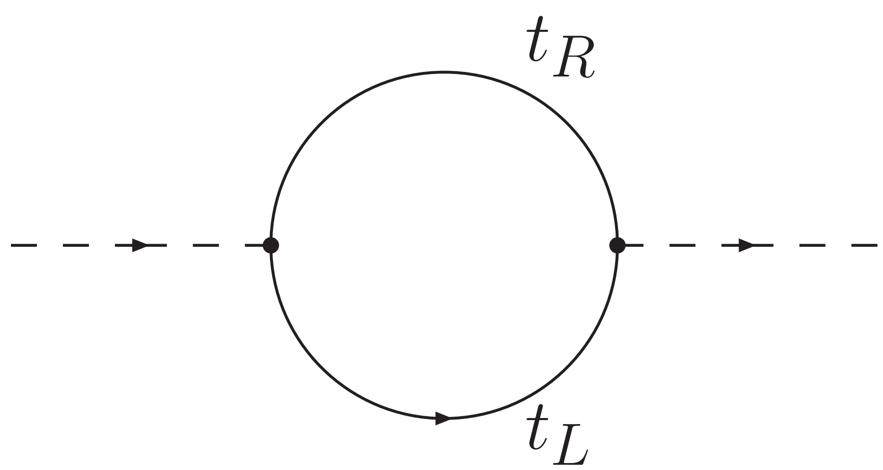

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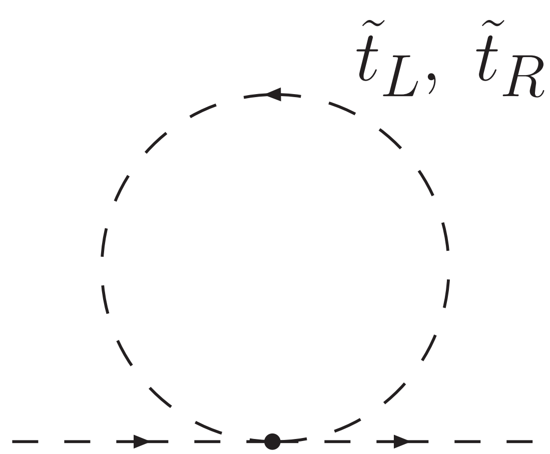

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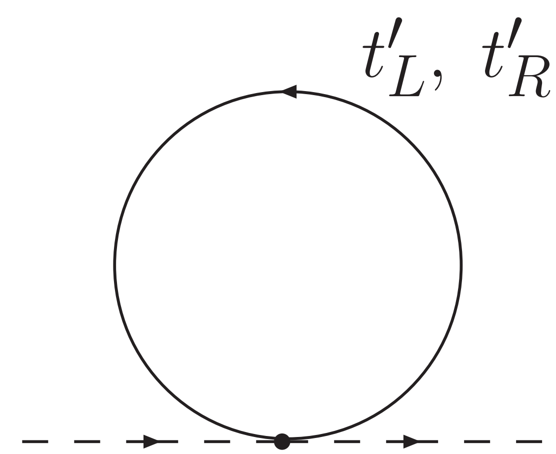

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Folded SUSY

Burdman, Chacko, Goh, RH (06')

Twin Higgs

Chacko, Goh ,RH (05')

Outline

* Review: Twin Higgs
  - The Mechanism.
  - Varieties of twin models.
* What can LHC discover?
* What can Future Colliders Discover?
* A no lose theorem?

To "prove" a theorem we should pick the difficult path at every step.

The Mechanism.

The Higgs is a PNGB of an approximate SU(4).

A Toy Example

* A global SU(4) symmetry w/ one fundamental:

$$V(H) = -m^2|H|^2 + \lambda|H|^4$$

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

$$SU(4) \longrightarrow SU(3)$$

7 Goldstones

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7 Goldstones

taxonomy:

"weakly coupled": λ~O(1-few)
(linear sigma model)

"strongly coupled": λ~16π²
(non-linear sigma model)

$SU(2)_A \times SU(2)_B$

* Gauge a subgroup (a.k.a Z_2 orbifold of SU(4)):

$$SU(2)_A \times SU(2)_B$$

our SM   twin SM

* In some basis, H transforms as

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix}$$

6 eaten.
1 Goldstone left.

* Gauging $SU(2)_A \times SU(2)_B$ breaks global $SU(4)$.

Radiative Corrections

* At 1-loop:

$$\Delta V =$$

Radiative Corrections

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$$\Delta V = \frac{9g_A^2\Lambda^2}{64\pi^2}H_A^\dagger H_A$$

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* Impose a Z_2 "twin" symmetry: $A \longleftrightarrow B$

$g_A = g_B$

$$\Delta V = \frac{9g^2\Lambda^2}{64\pi^2}\left(H_A^\dagger H_A + H_B^\dagger H_B\right)$$

SU(4) invariant!

Does not give a Goldstone mass.

Twin Mechanism

(~~Global Symmetry~~) + (Discrete Symmetry)

↓

Quadratic terms are globally symmetric.
No quadratic divergences.

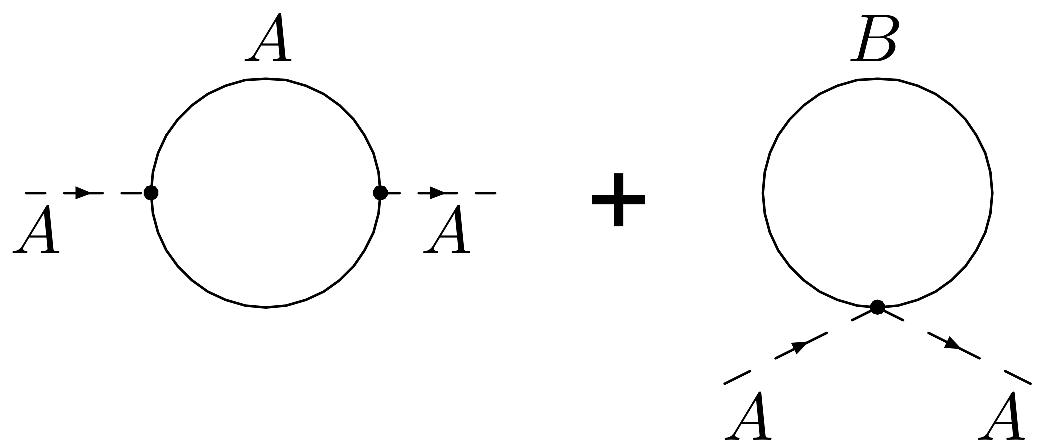
* Quartic terms can violate global symmetry.
Goldstone mass only log divergent.

$SM_A \times SM_B$

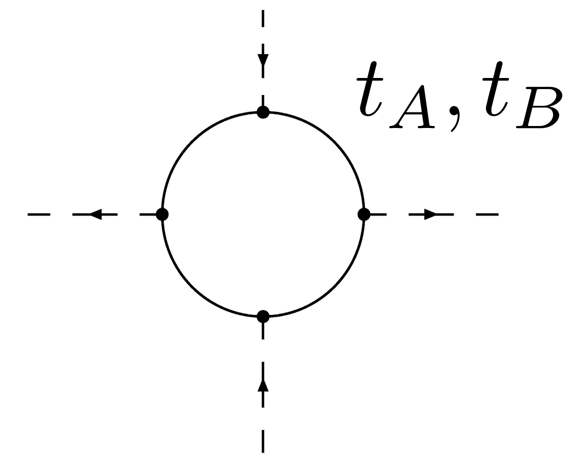
- Double all of the SM. Impose Z_2.
  (a.k.a orbifold of SU(6)×SU(4) by a Z_2).
- In particular $\mathcal{L} \supset y_t H_A \bar{t}_A t_A + y_t H_B \bar{t}_B t_B$
- Z_2: quadratic divergence has the form

$$c\Lambda^2 \left(|H_A|^2 + |H_B|^2\right)$$

SU(4) invariant.



SU(4) breaking



* Radiative corrections induce

$$\Delta V = \kappa \left(|H_A|^4 + |H_B|^4 \right)$$

$$\text{with} \quad \kappa \sim \frac{y_t^4}{16\pi^2} \log \frac{\Lambda}{f}$$

* Goldstone mass is $m_h \sim \frac{y_t^2}{4\pi} f$.

* Adding mixed "top partners" at 5-6 TeV keeps this quartic finite with a correct Higgs mass.

$$\begin{aligned} Q_L &= (\mathbf{6}, \bar{\mathbf{4}}) \\ &= (\mathbf{3},\mathbf{2};\mathbf{1},\mathbf{1}) + (\mathbf{1},\mathbf{1};\mathbf{3},\mathbf{2}) + (\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{2}) + (\mathbf{1},\mathbf{2};\mathbf{3},\mathbf{1}) \end{aligned}$$

Soft Breaking

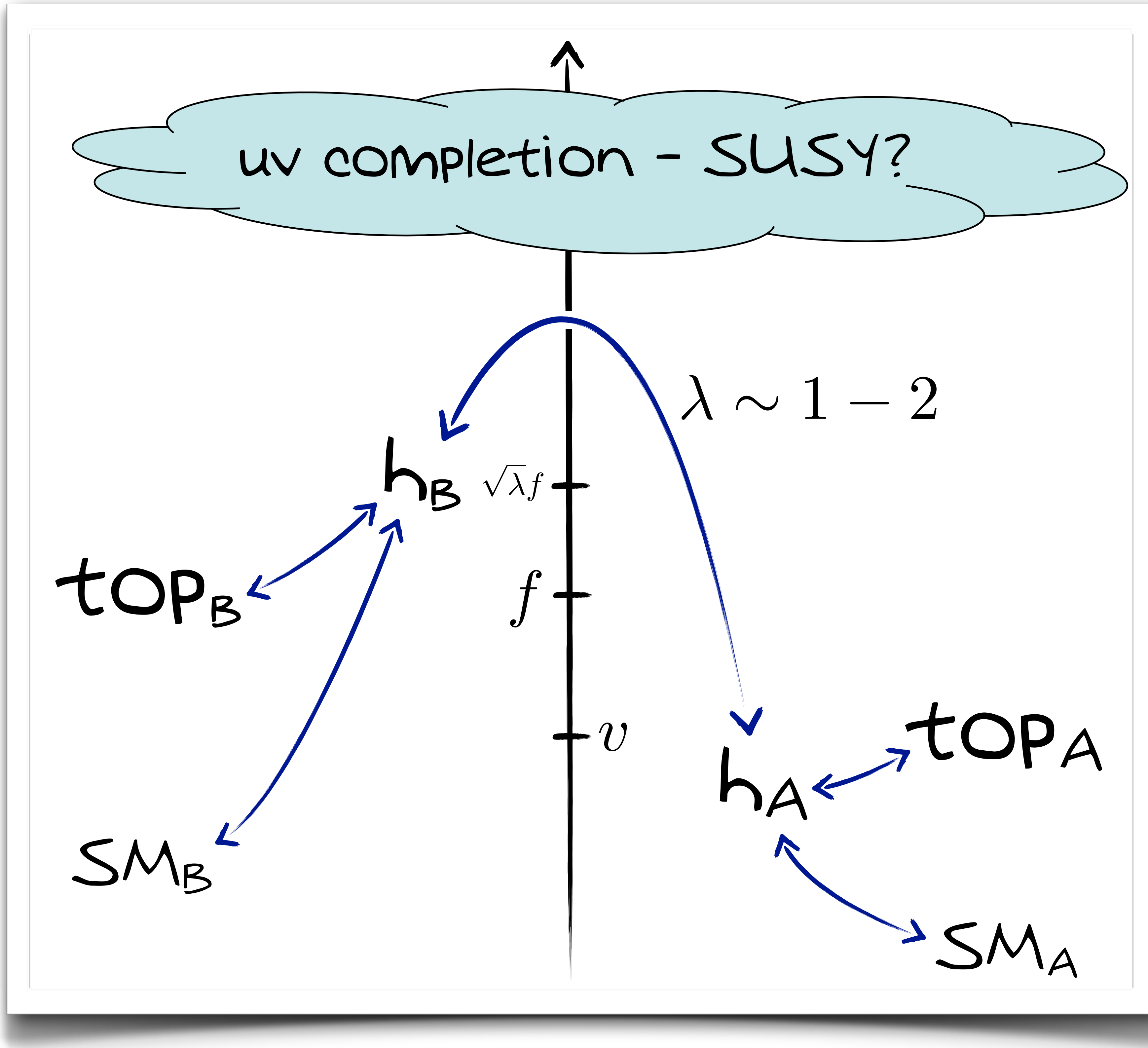
- The potential as is gives $v_A = v_B \sim \frac{f}{\sqrt{2}}$
- But then $\Lambda \sim 4\pi f$ is too low.

- Add $V_{soft} = \mu^2 |H_A|^2$ to get $v < f$.
- A mild cancelation needed to get EW scale

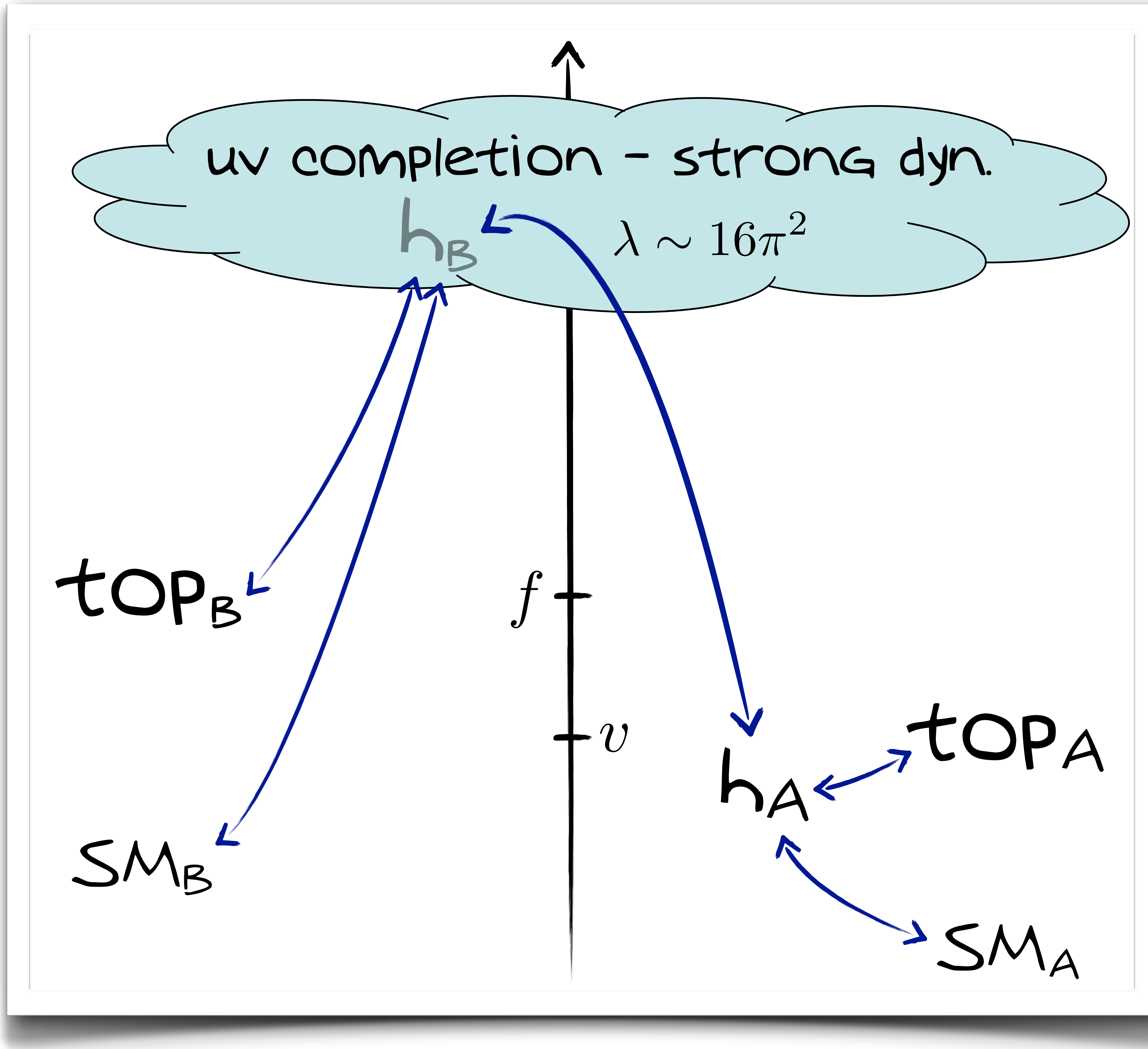
Λ (TeV)	f (GeV)	M (TeV)	M_B (TeV)	μ (GeV)	m_h (GeV)	Tuning
10	800	6	1	239	122	0.134
6	500	5.5	1	145	121	0.378
10	800	—	0	355	166	0.112
6	500	—	0	203	153	0.307

So let's summarize the moving parts....

Sketch - Weak Coupling



Sketch - Strong Coupling

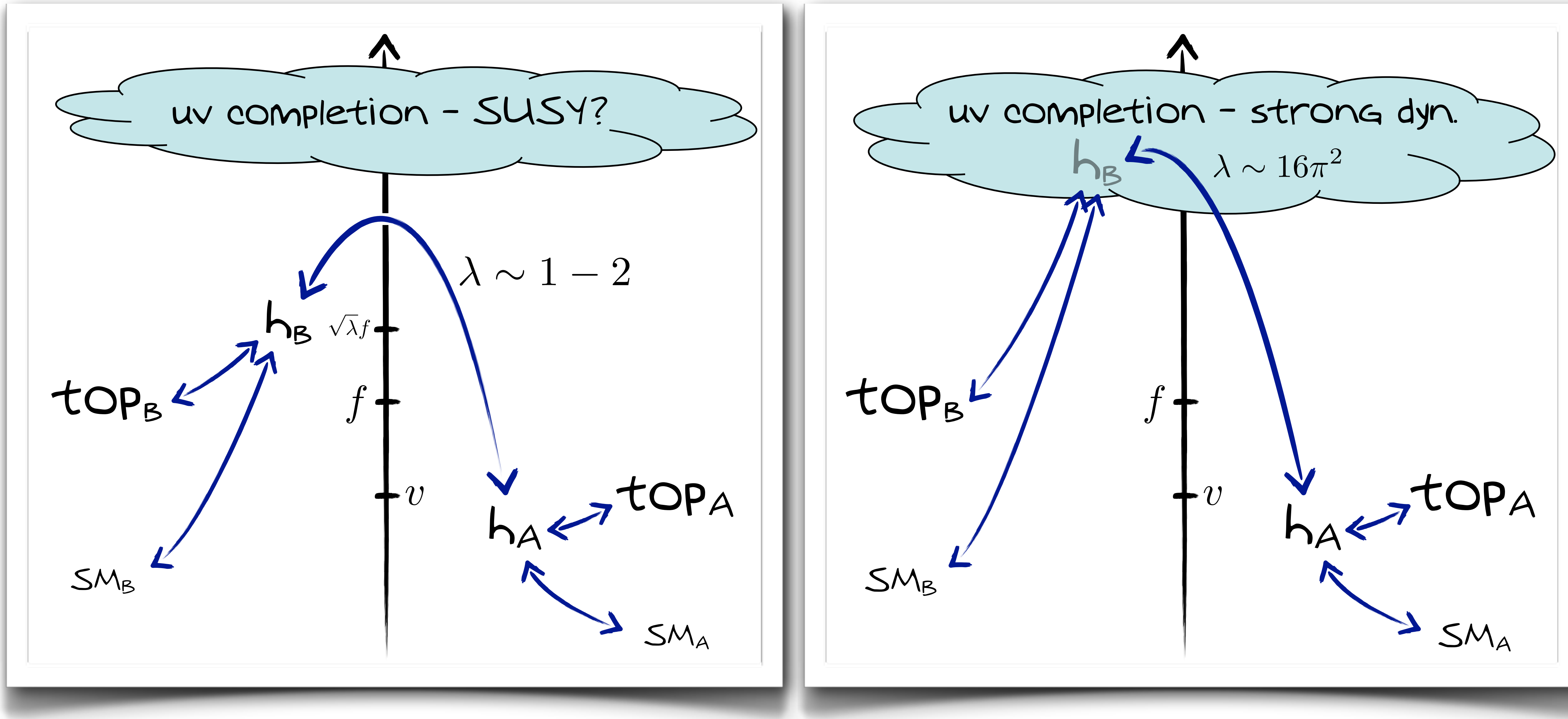


With these moving parts we have a natural model. Yet *all* new states below a few TeV are complete SM singlets.

LHC signatures will be subtle at best.

Still, what are its signatures?
LHC? Higgs Factory?
100 TeV?

Where can we look for signs of NP?



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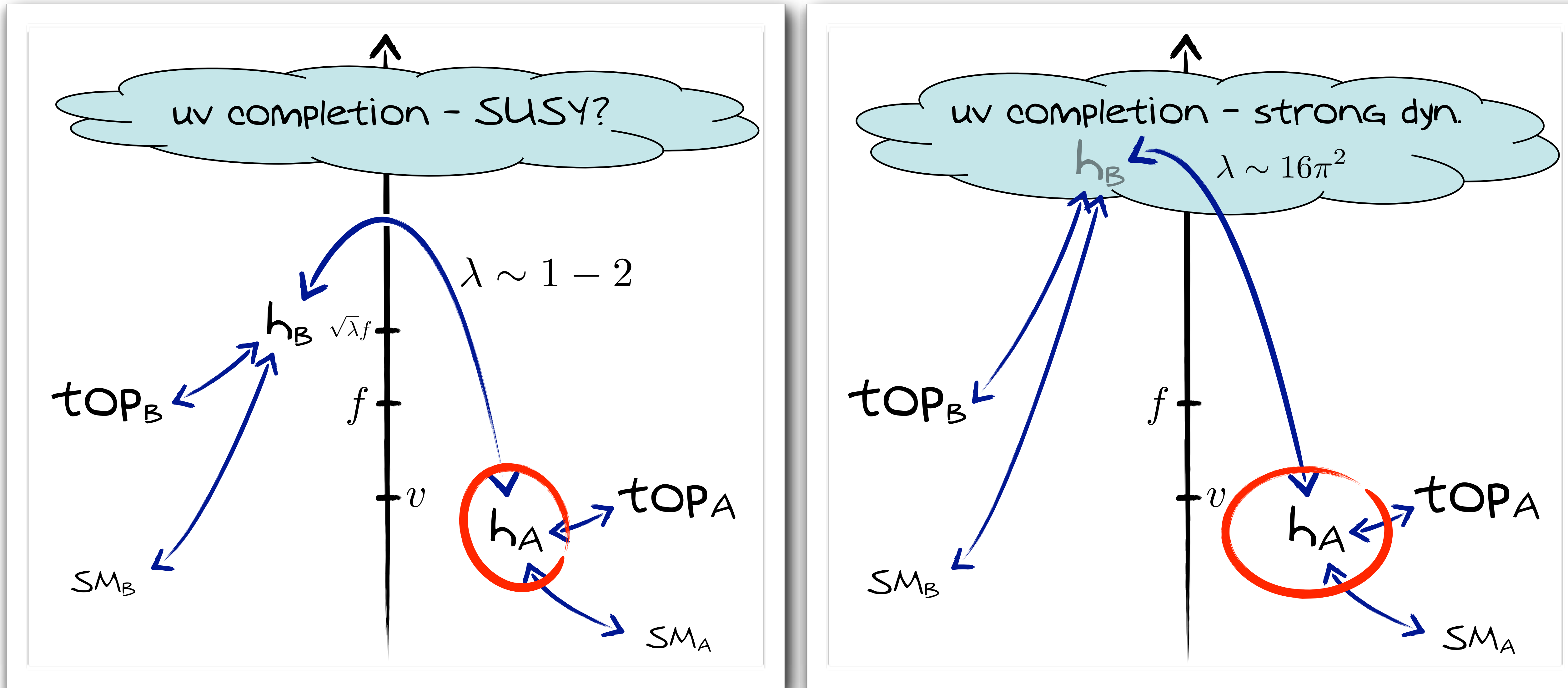


Precision Higgs tests:

Modified Higgs couplings and invisible decays.

Precision Higgs

* All SM Higgs couplings are universally suppressed:

$$\Gamma_{h\to X} = \cos^2\left(\frac{v}{f}\right)\Gamma^{\rm SM}_{h\to X} \approx \left(1-\frac{v^2}{f^2}\right)\Gamma^{\rm SM}_{h\to X}$$

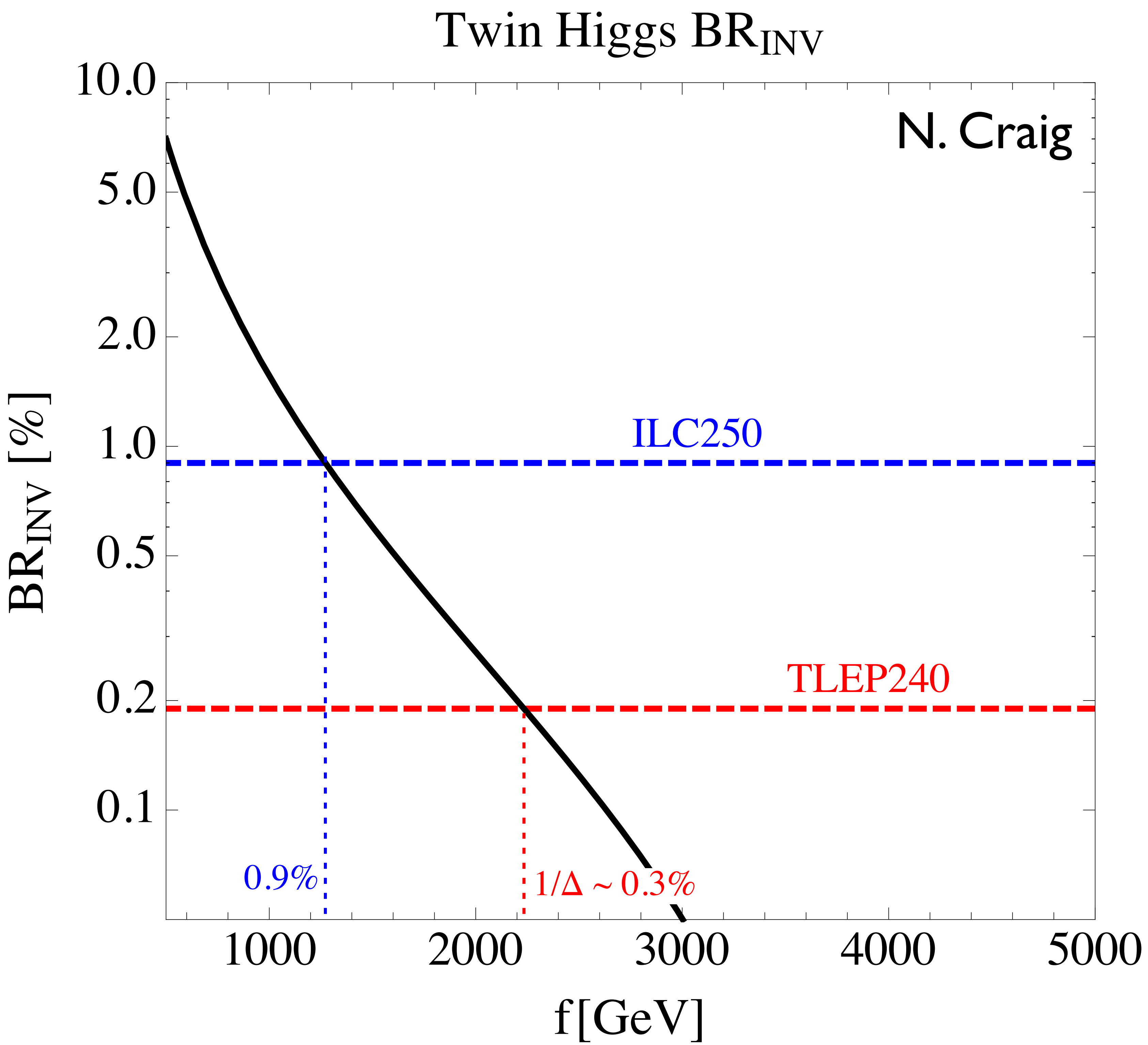
* Ratios of Higgs rates are SM-like.
* A correlated invisible decay

$$\Gamma_{h\to {\rm inv}} = \sin^2\left(\frac{v}{f}\right)\Gamma^{\rm SM}_{h\to b\bar{b}} \approx \frac{v^2}{f^2}\Gamma^{\rm SM}_{h\to b\bar{b}}$$

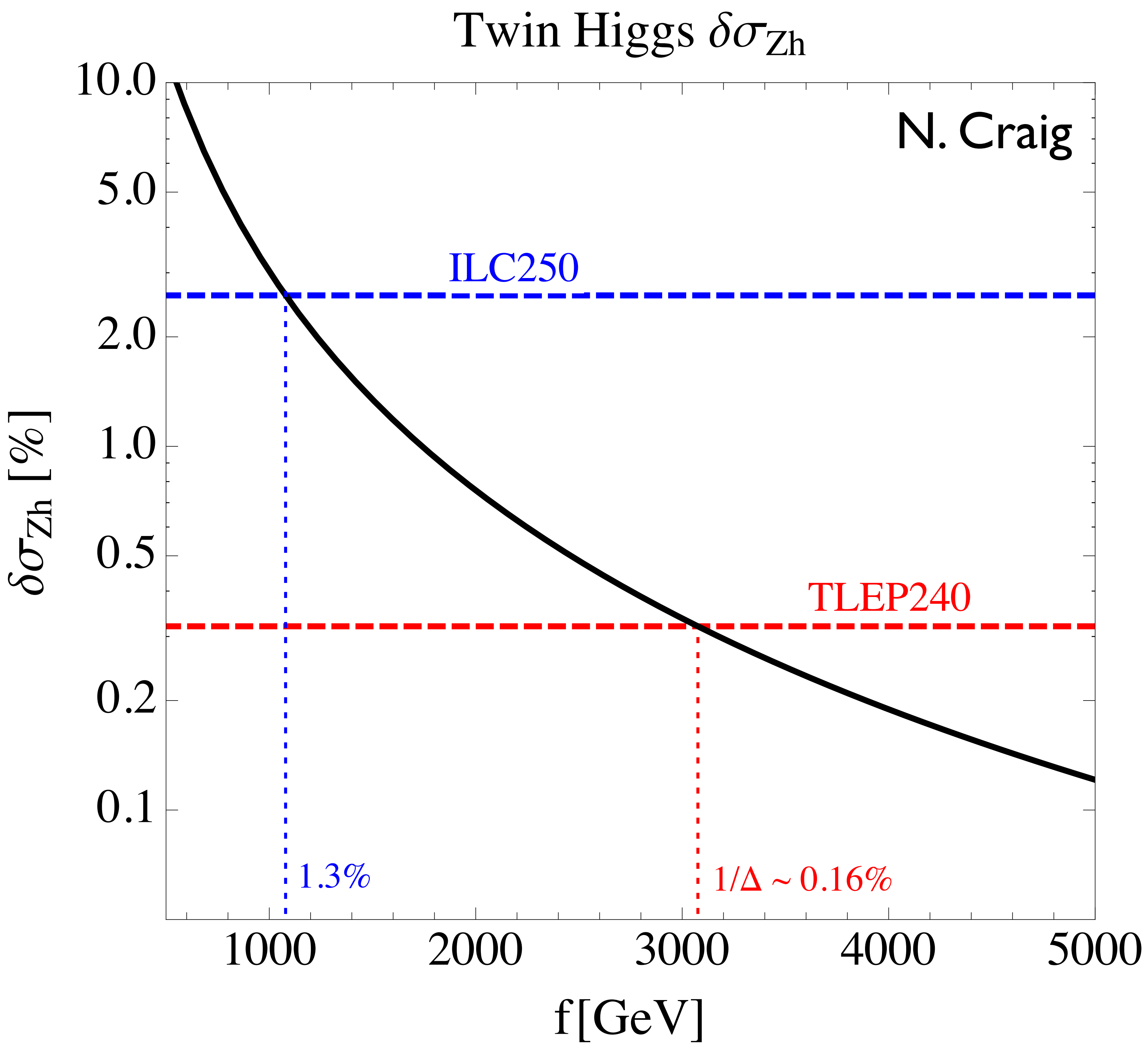
(assuming the b Yukawa respects the Z_2 !!!).

* Both are set by the tuning in the model, $\dfrac{2v^2}{f^2}$.

Precision Higgs



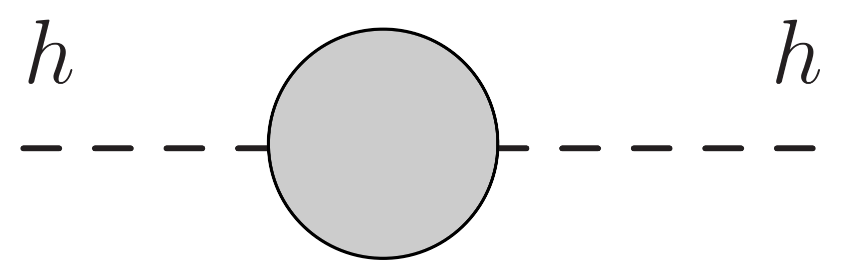
Precision Higgs



Non-Colored Partners

* But what if we came up with a model in which there is *no* tree level mixing?

$$\delta Z_h, \delta m_h^2 \sim$$



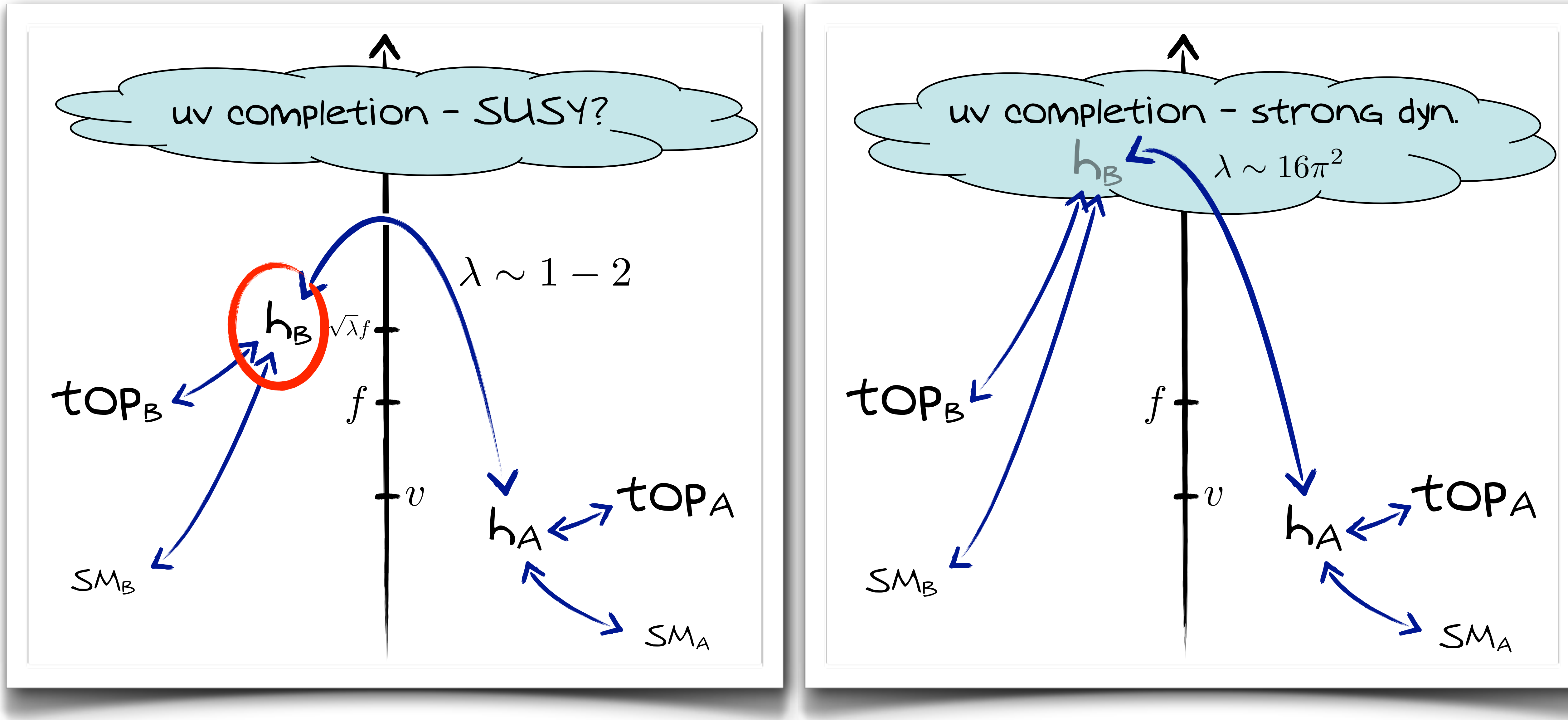
$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}\delta Z_h (\partial_\mu h)^2 + \ldots$$

All Higgs couplings are modified by δZ_h.

of order 1% modifications.

torn from Craig, Englert, McCullough 1305.5252.

Where can we look for signs of NP?



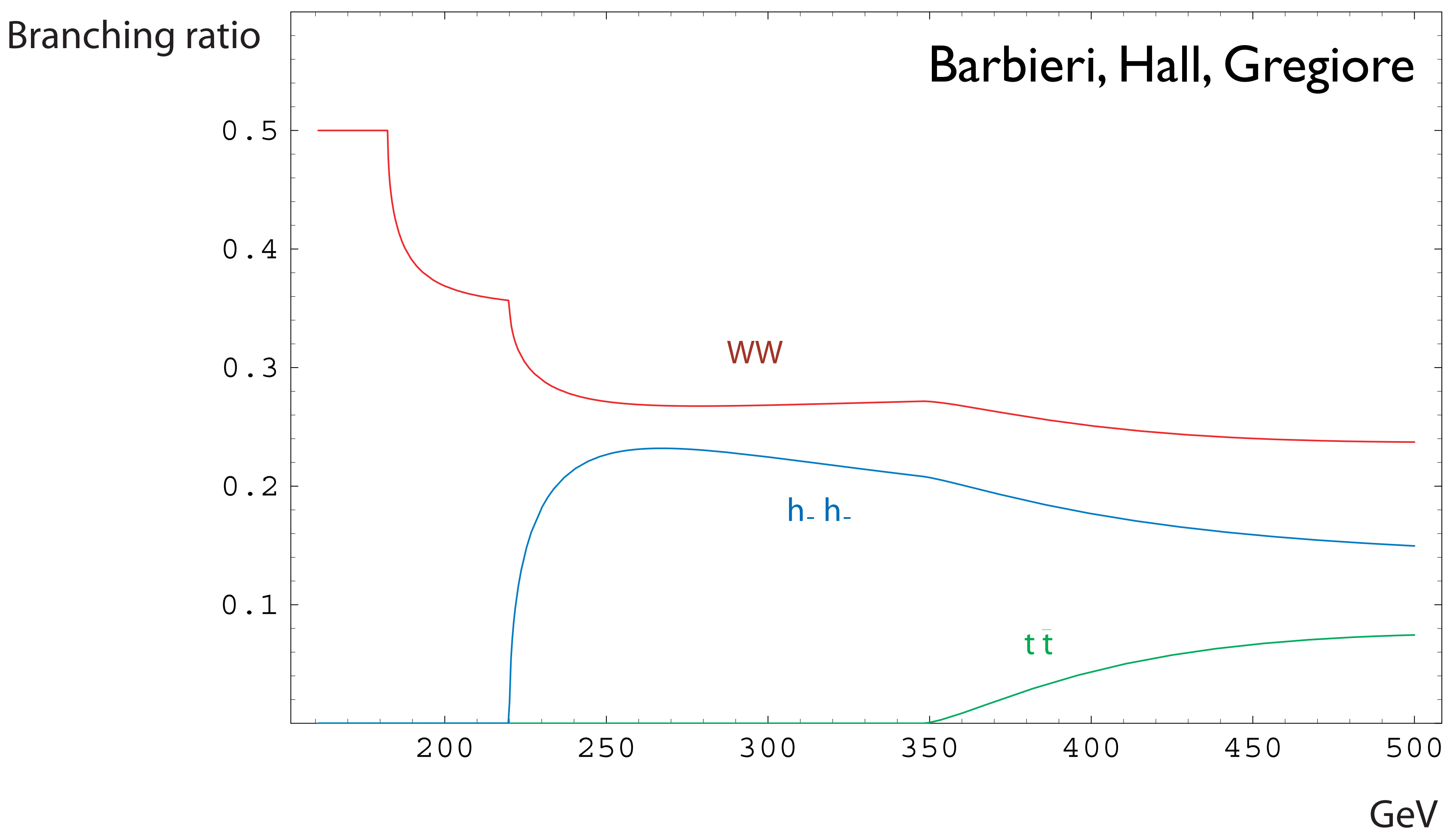
UV Completion - linear model:

A heavy Higgs.

Decays to invisibly or to W's, Higgses, tops.

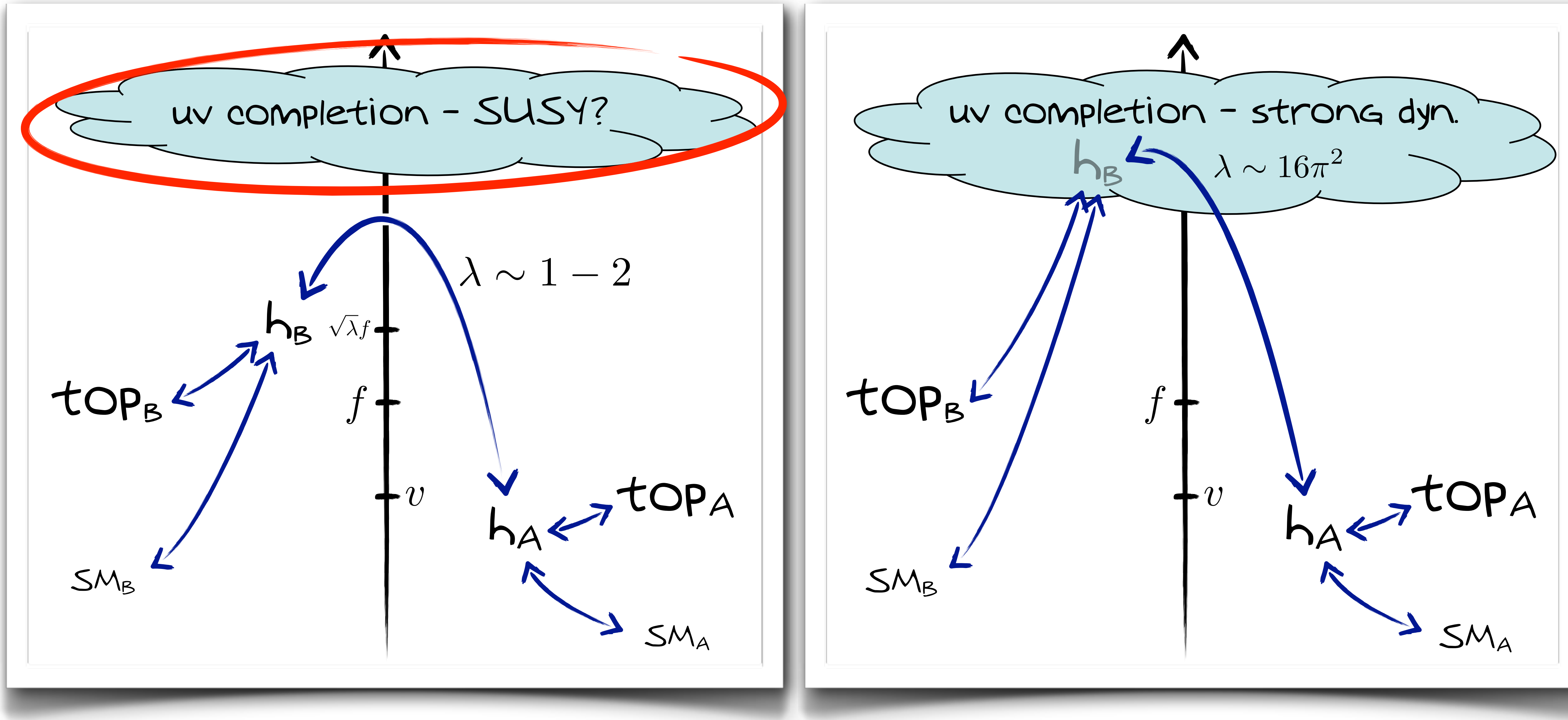
Heavy Higgs

- The heavy Higgs decays ~50% invisibly.
- The rest of the BR is dominated by WW, hh, and tt.



may be LHC accessible. (see Nate's talk)

Where can we look for signs of NP?



UV Completion - linear model:

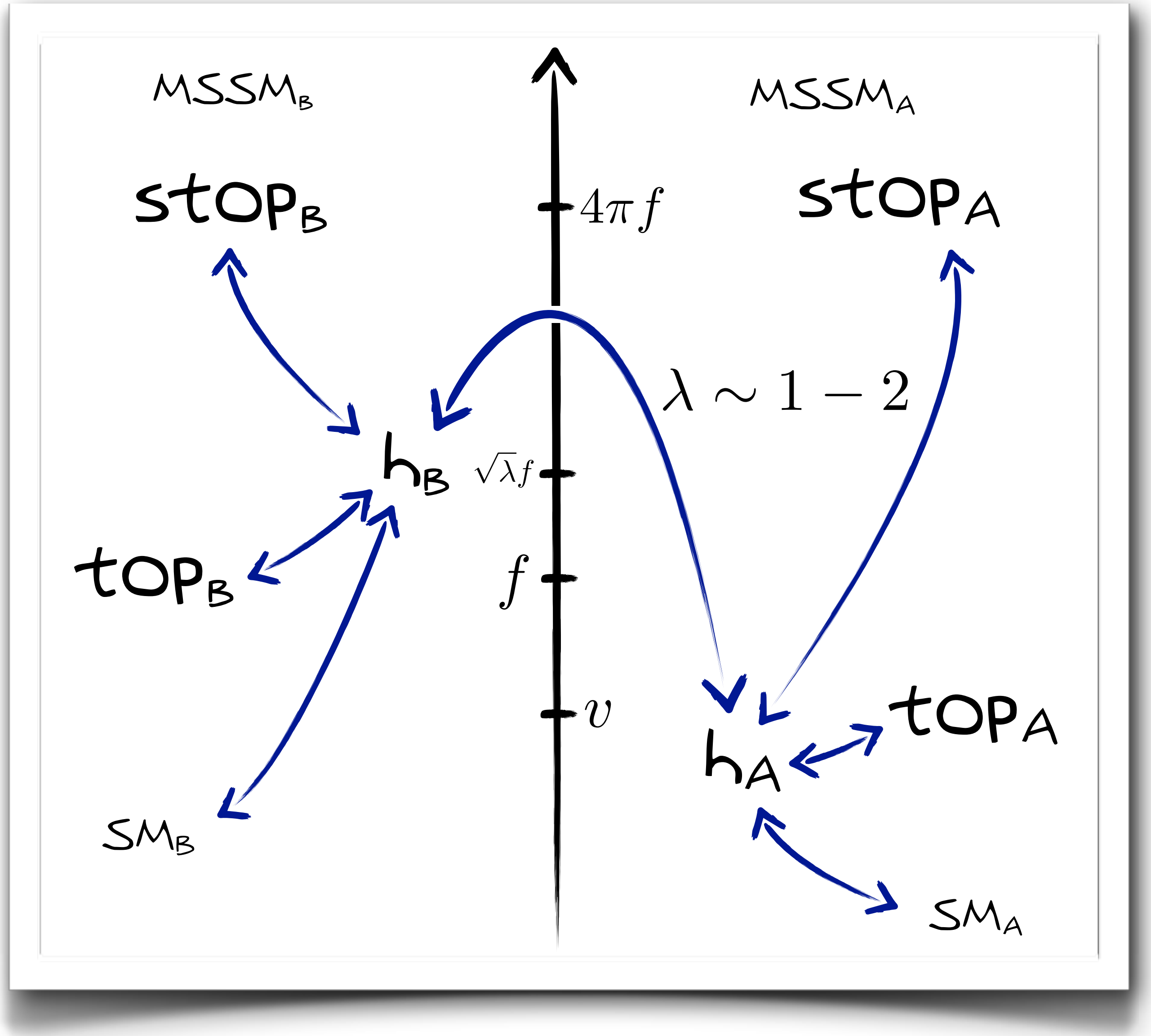
Re-do of the search for naturalness,

but now at a few TeV.

S. Chang, L. Hall, N. Weiner (06)
N. Craig, K. Howe (13)

Twin SUSY

* Introduce SUSY at ~few TeV.
* MSSM solves the big hierarchy. The scale f is natural.
* Doubling of MSSM Does the last bit, from f to v.



Stops accessible only at 100 TeV.

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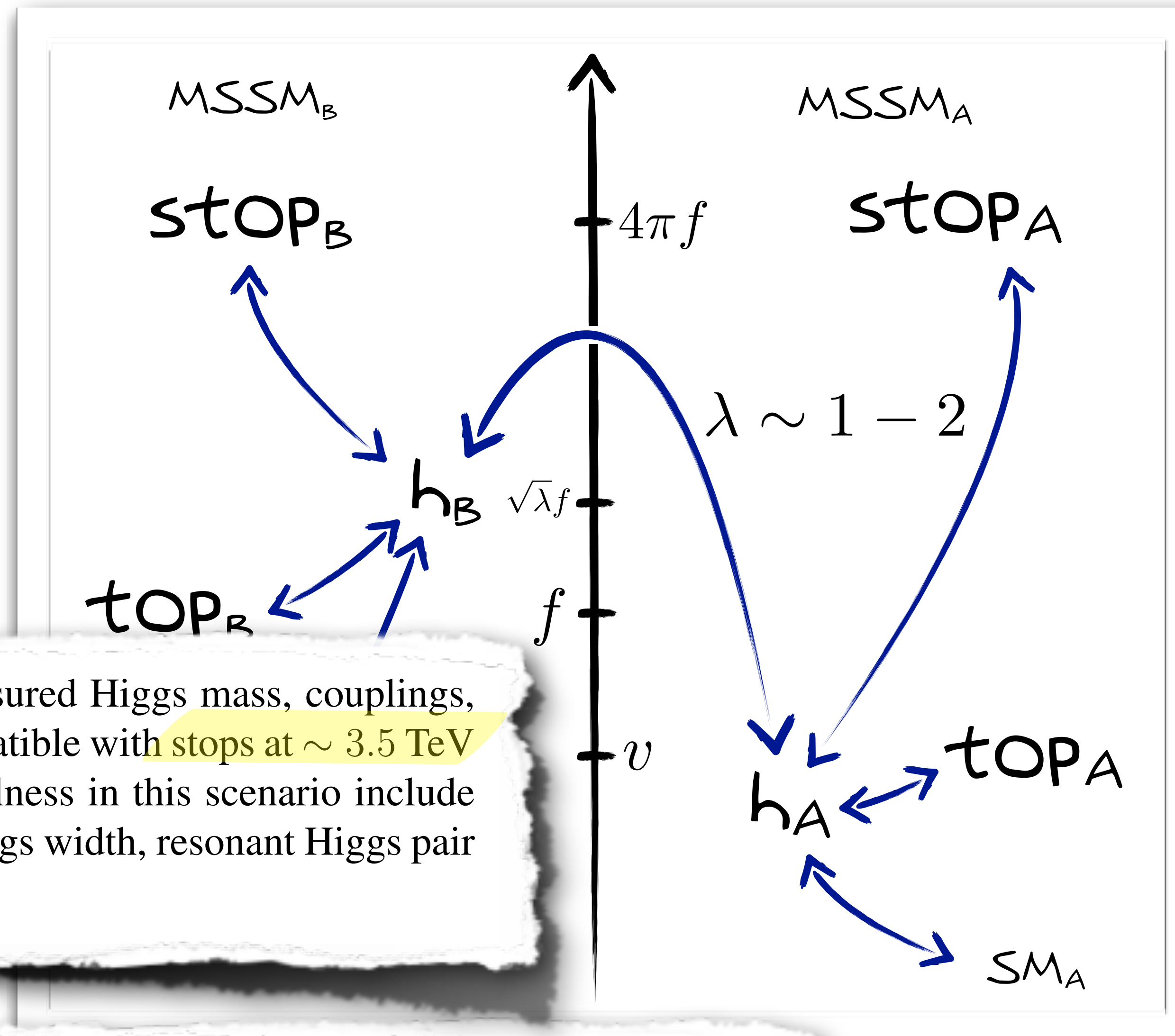
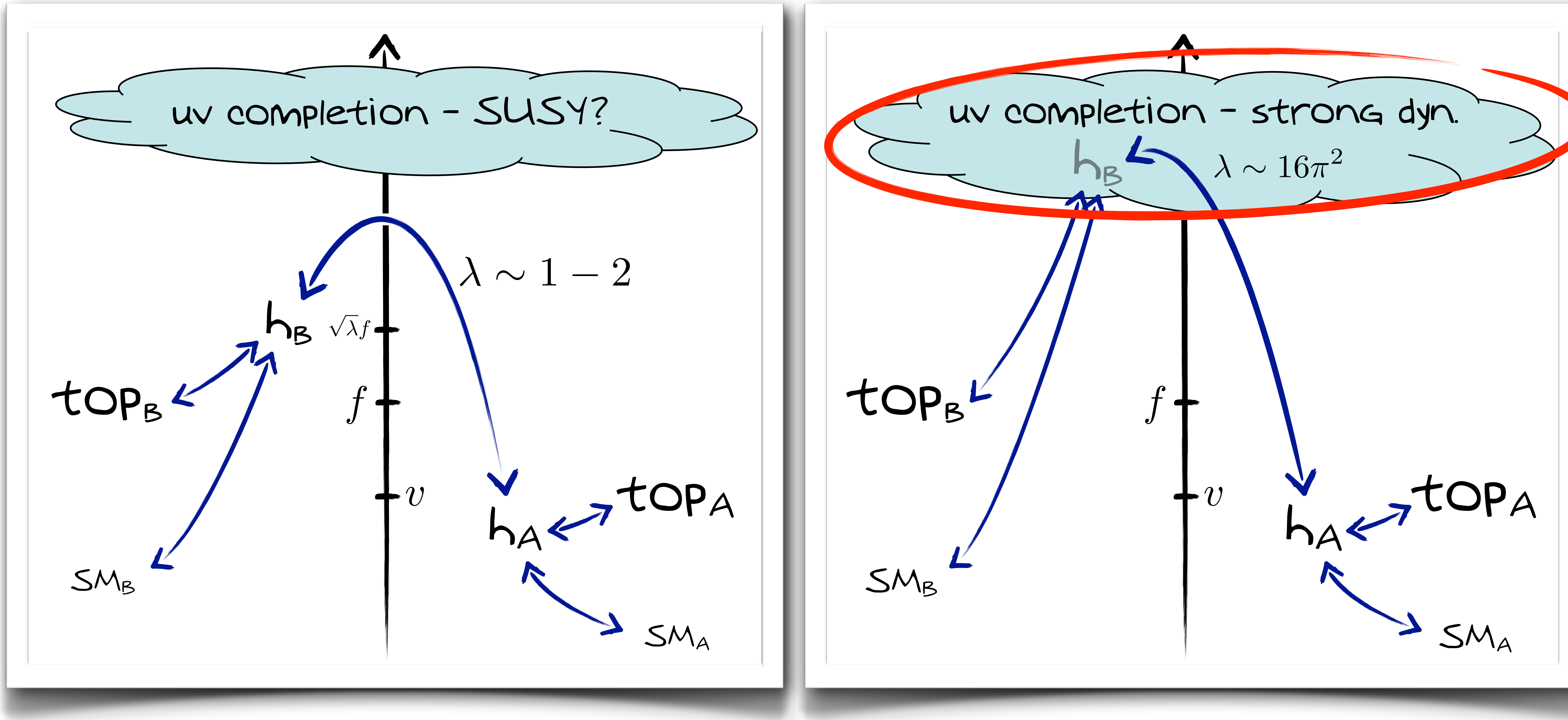


We find the measured Higgs mass, couplings, and percent-level naturalness of the weak scale are compatible with stops at $\sim$ 3.5 TeV and higgsinos at $\sim$ 1 TeV. The primary signs of naturalness in this scenario include modifications of Higgs couplings, a modest invisible Higgs width, resonant Higgs pair production, and an invisibly-decaying heavy Higgs.

Furthermore, if we discard the requirement of perturbative MSSM-like gauge coupling unification, a Higgs compositeness scale of $\sim$ 50 TeV allows 10%-level tuning with superpartners entirely out of reach of the LHC.

Stops accessible only at 100 TeV.

Where can we look for signs of NP?



UV Completion - non-linear model:

Strong dynamics at 5-10 TeV. Resonances...

New Strong Dynamics

* We imagine new QCD-like dynamics at 5-10 TeV.
* The Higgs doublet is a pion of this "techni-QCD".

The constituents *must* be charged under EW.

The top *could* be a composite as well.

Colored states.
Piece of cake at 100 TeV.

$$
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\end{aligned}
$$

top$_A$ top$_B$ exotics

New Strong Dynamics

* We imagine new QCD-like dynamics at 5-10 TeV.
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↓

Can we make a generic statement?

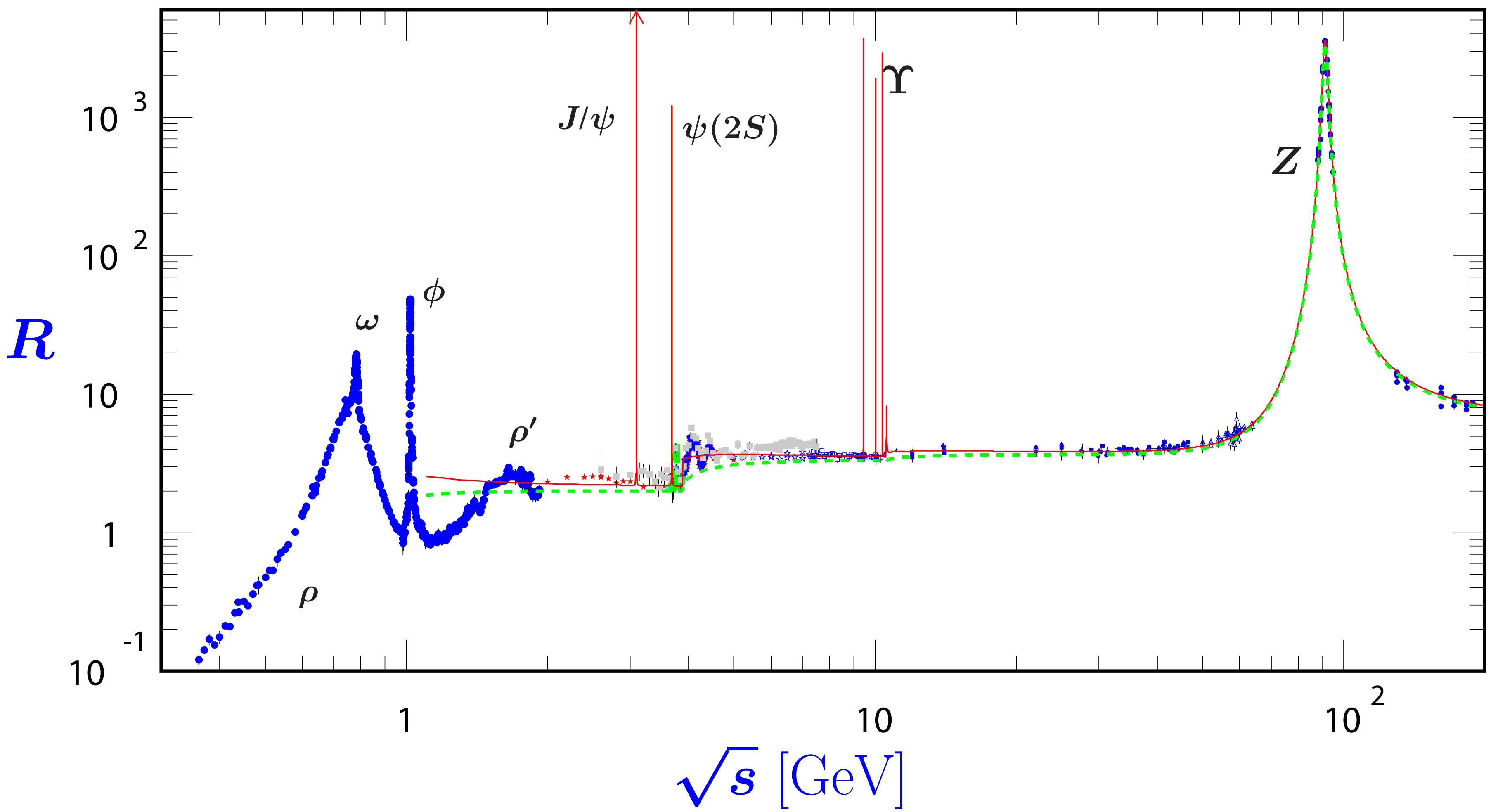
The top *could* be a composite as well.

↓

Colored states.
Piece of cake at 100 TeV.

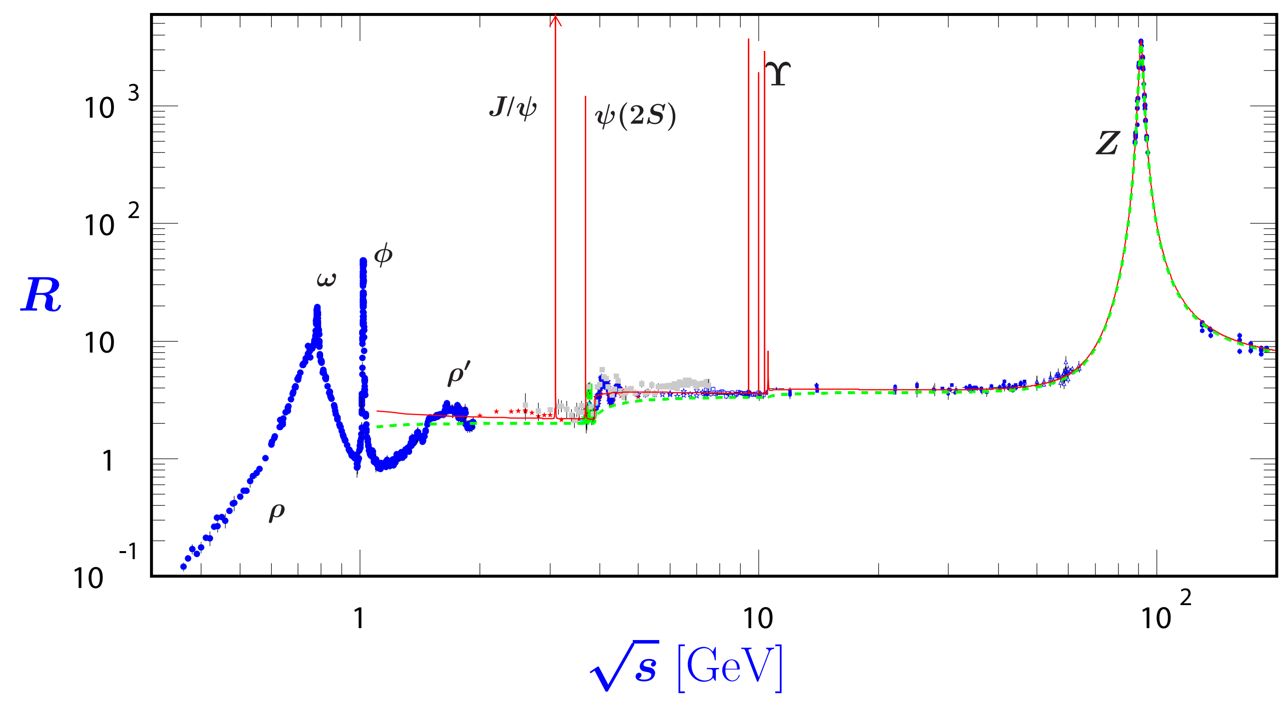
Weak Resonances

- What is the 100 Tev sensitivity to weakly charged techi-sectors? (for any composite Higgs setup).
- We have one precedent for probing a strong sector with external weak probes:



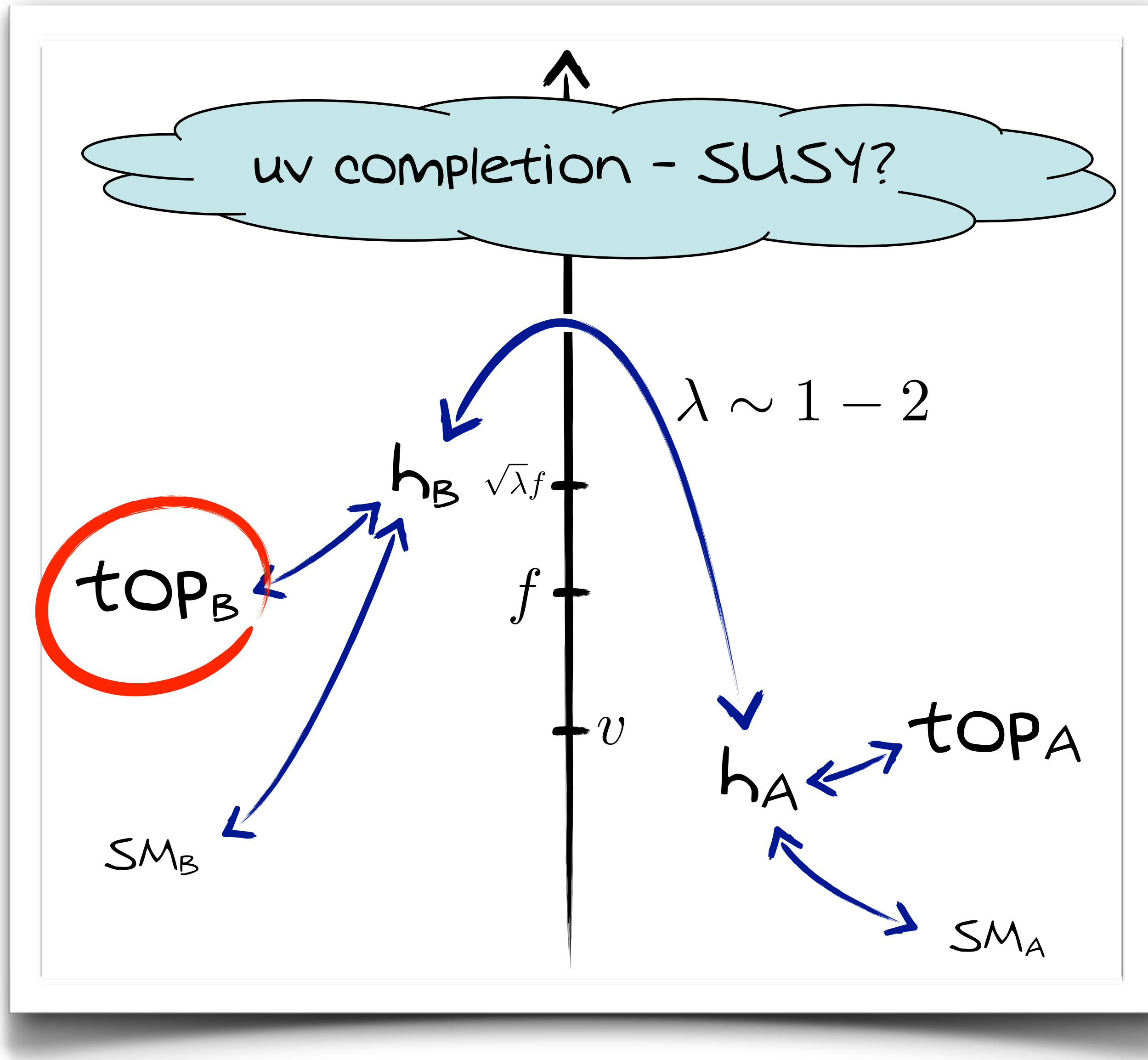
Weak Resonances

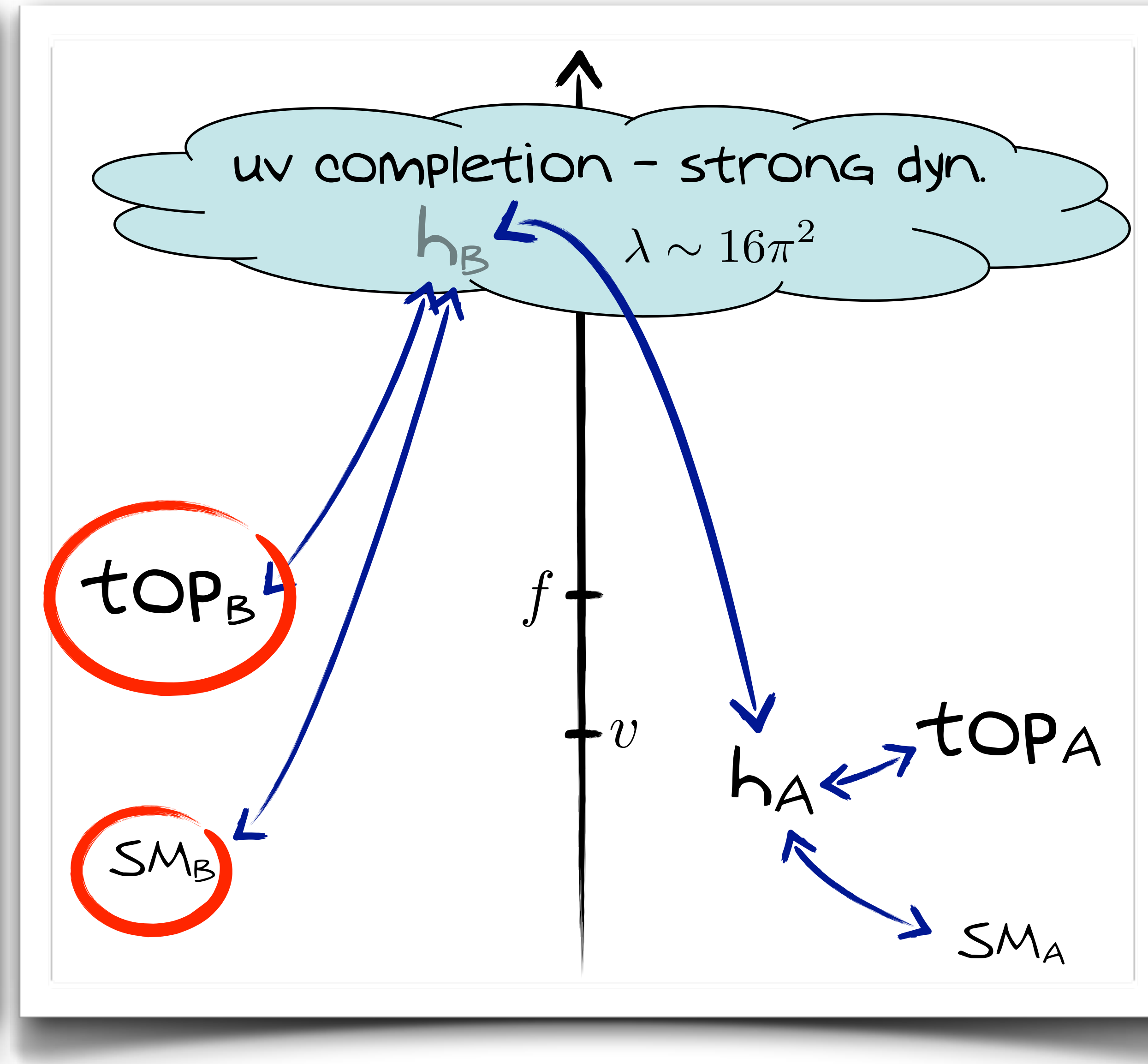
* It seems reasonable that there will be
  - Wide W'-like states (rho-like) going to Higgses (pions).
  - Narrower states that must undergo weak decay.
  - Pair produced states.



Calls for a taxonomical study based on quantum numbers and spins of resonances.

Where can we look for signs of NP?





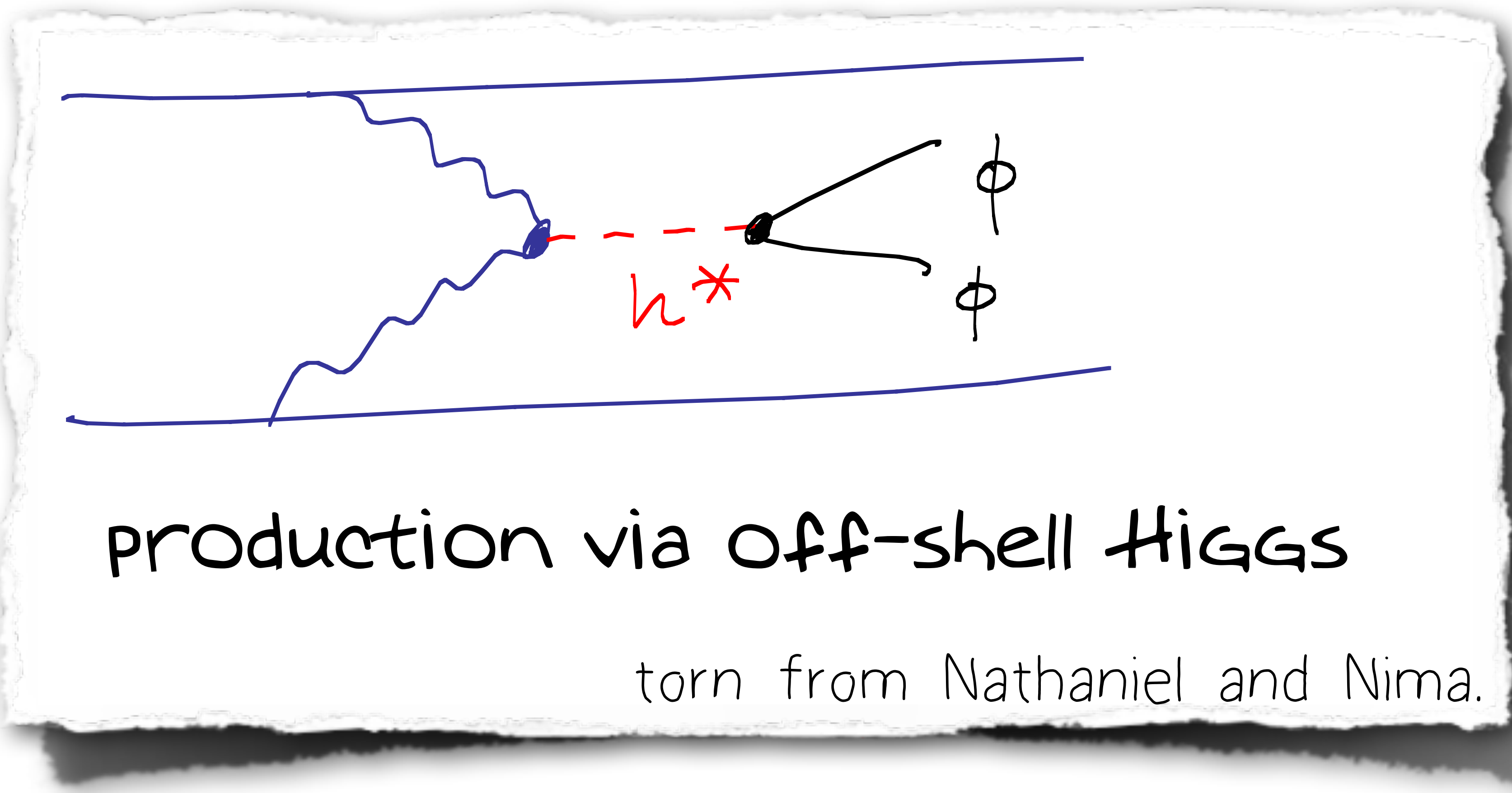
The Top Partners:

Direct production of top partners

(or other SM_B states).

Colorless Tops

* Minimally we have a coupling of the partner to the Higgs:



* Partner decays invisibly - background study needed.
* Partner could decay visibly, Hidden-valley style! (high multiplicity from hidden showers, displaced vertices, etc.)

Cosmology

* Twin baryons could be dark matter.
* Light twin matter is dangerous during BBN.
  - Small Z_2 breaking in light yukawa sector. Make twin matter Heavier than a few GeV. (Barbieri, Gregiore, Hall)
  - More entropy production in our QCD transition?
  - Late inflation?

* LHC implications are drastic enough to overshadow these issues.

Conclusion and Outlook

* We have natural models with colorless partners (including some models I did not discuss).
* Twin Higgs can be remarkably elusive at LHC.
* Seems within reach of a 100 TeV machine & TLEP:
  - Precision Higgs studies and invisible decay (or hidden valley decays).
  - Producing UV completion states.
  - Producing top partners.

A no-loose theorem is within reach.

Deleted scenes.

LHC Signals

* A standard model Higgs.

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* If we are luck we can measure-
  - Higgs decay to invisibles, $\mathrm{BR} \sim O(v^2/f^2)$.
  - Modification of $ZZh, WWh, tth, h^3, \ldots$ also of $O(v/f)$. (correlations).

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  - Modification of $ZZh, WWh, tth, h^3, \ldots$ also of $O(v/f)$. (correlations).
* If we are *really* lucky (work in progress):

  Twin hadrons decay back to SM with displaced vertices. A "Hidden Valley" signal (Strassler and Zurek).

Folded SUSY (Disney version)

Usually:
Supersymmetry commutes with gauge transformations. → Superpartners *always* have the same quantum numbers as SM counterparts.

How can we get non-colored partners?

Inspiration: **The Large-N Orbifold Correspondence**

Kachru & Silverstein (98)
Bershadsky & Johansen (98)
Schmaltz (99)

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t

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$$t$$

$$Q^{\alpha} \updownarrow$$

$$\tilde{t}$$

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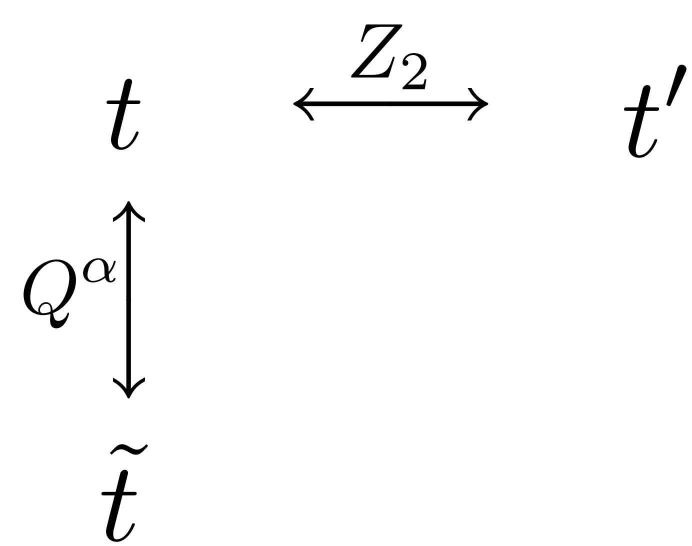

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$$
\begin{array}{ccc}
t & \overset{Z_2}{\longleftrightarrow} & t' \\
Q^\alpha \updownarrow & & \updownarrow Q^\alpha \\
\tilde{t} & \underset{Z_2}{\longleftrightarrow} & \tilde{t}'
\end{array}
$$

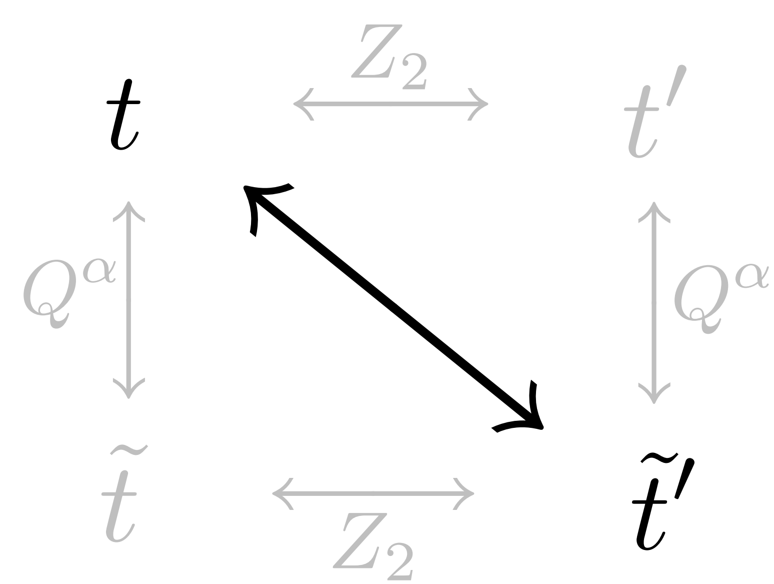
Inspiration: **The Large-N Orbifold Correspondence**

Kachru & Silverstein (98)
Bershadsky & Johansen (98)
Schmaltz (99)

Folded SUSY (Disney version)

Usually:
Supersymmetry commutes with gauge transformations. → Superpartners *always* have the same quantum numbers as SM counterparts.

How can we get non-colored partners?



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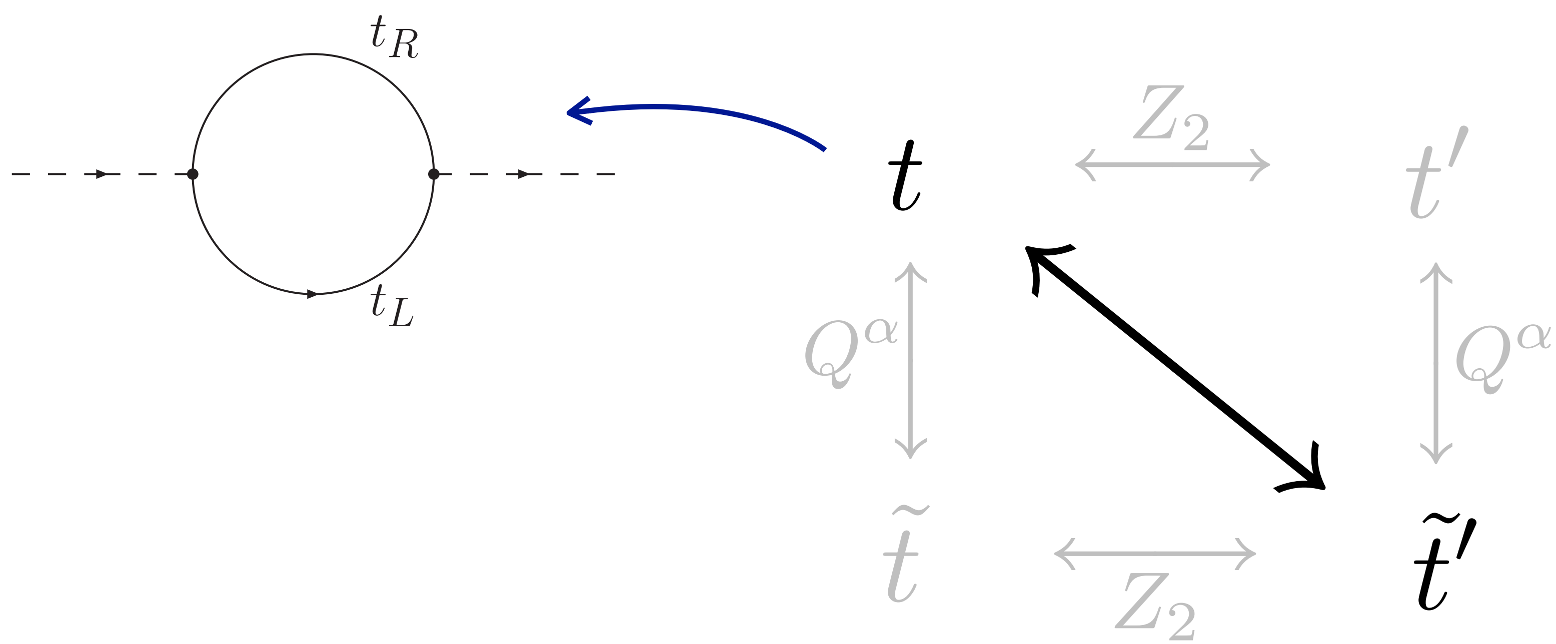

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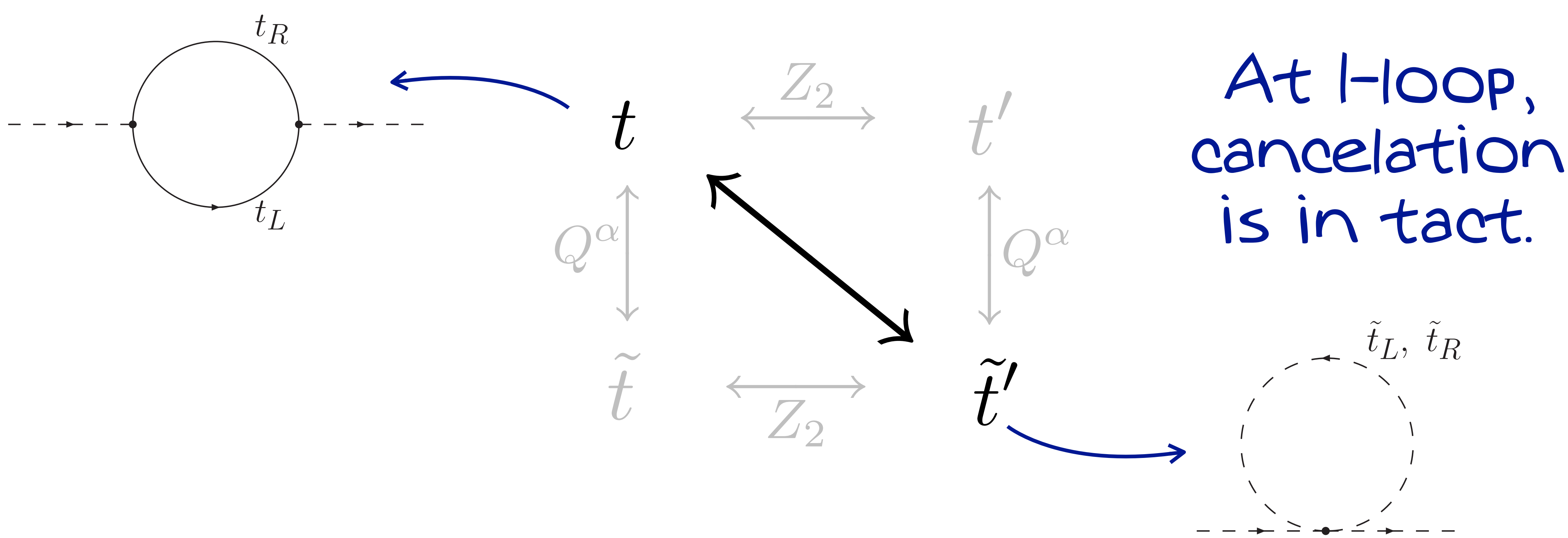

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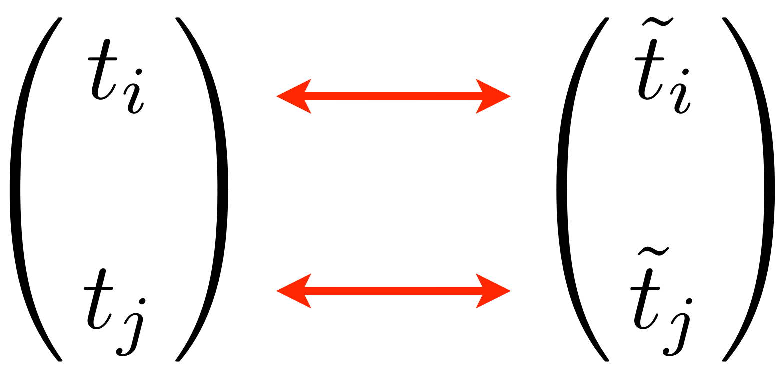
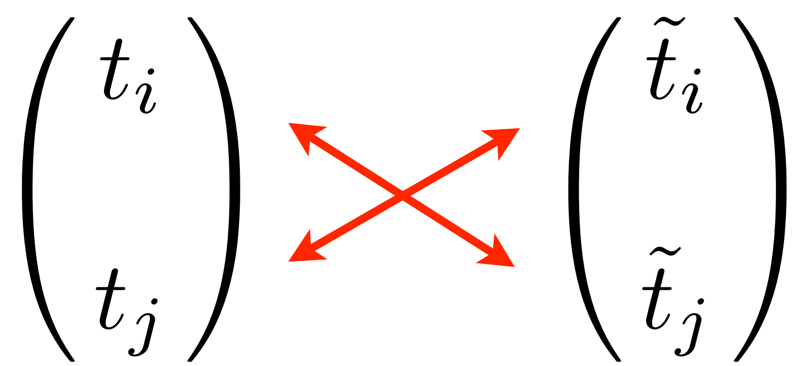
Folded SUSY

* The Higgs is protected twice:



Supersymmetric



Folded-Supersymmetric

We get to choose which states to keep at low energies.