Twin Higgs & Flavor

Roni Harnik
Fermilab

Chacko, Goh, RH (05)

...

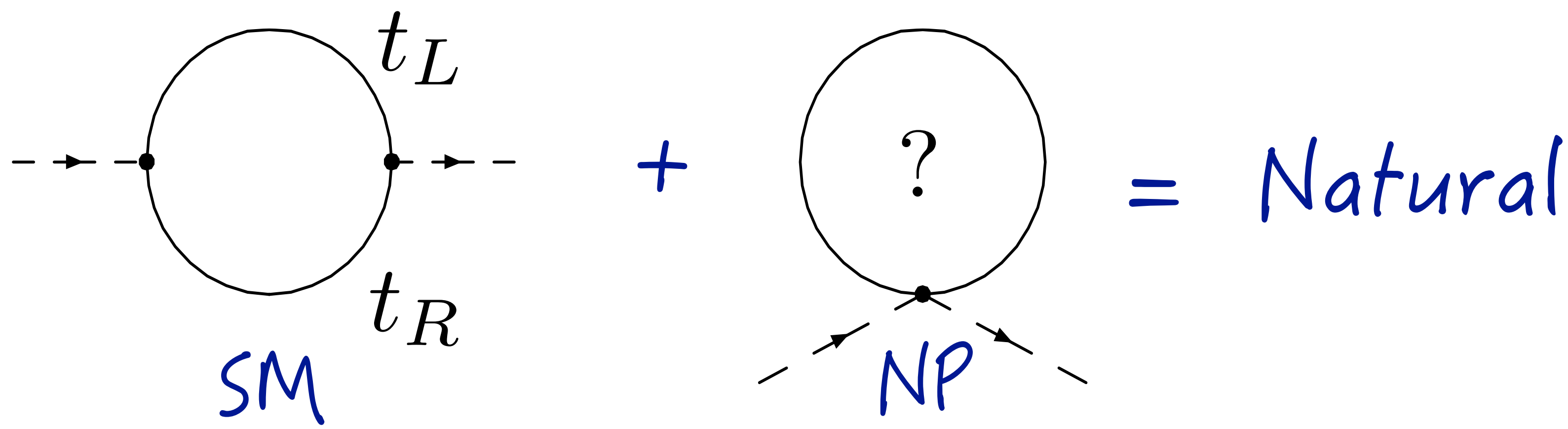
RH, Stamou, Zupan (in progress)

Its 6 am in Chicago.
A great time to give a talk!

*Pick your explicative

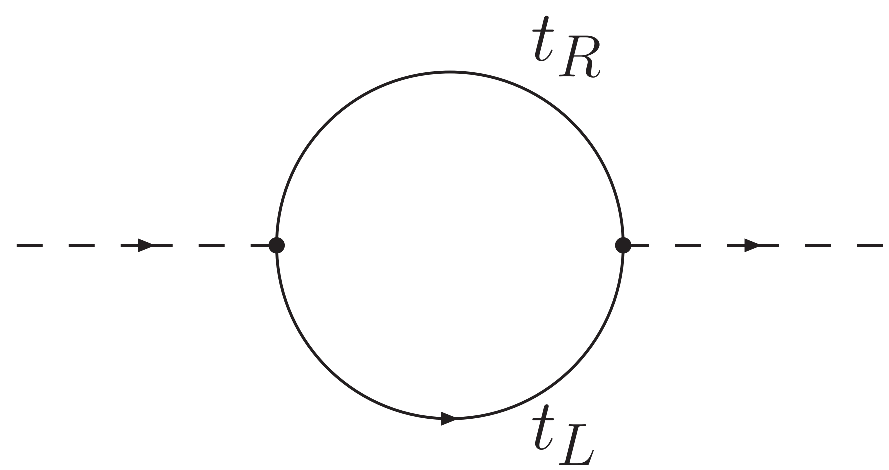
Where the #$@* is everybody?

* LHC found the Higgs and nothing else new.
* The burning question:
  Where are the symmetry partners of the top?



Keen interest in top partners that are elusive by construction.
UnColored? "Neutral Naturalness"

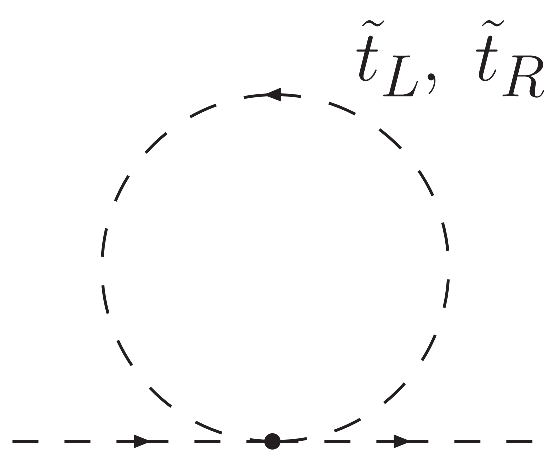
Just a Factor of 3



Standard Model

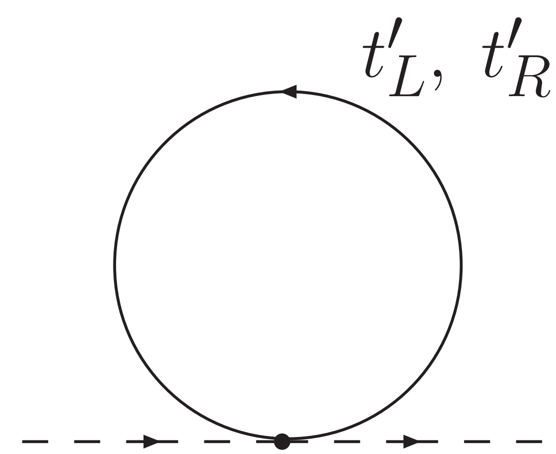
color factor:

$\times 3$



Supersymmetry

or



Little Higgs

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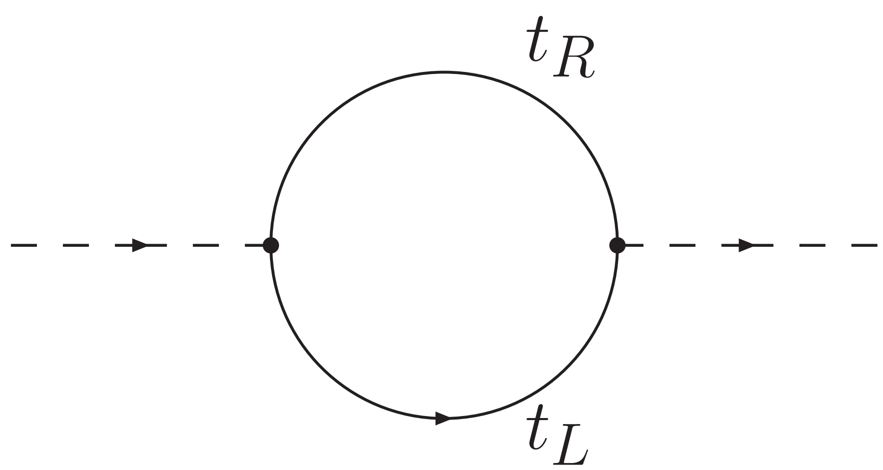

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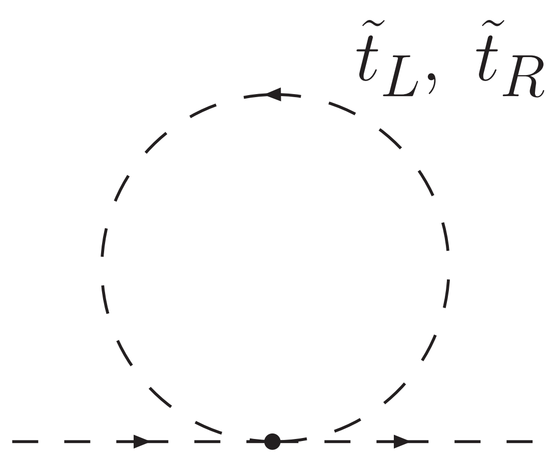

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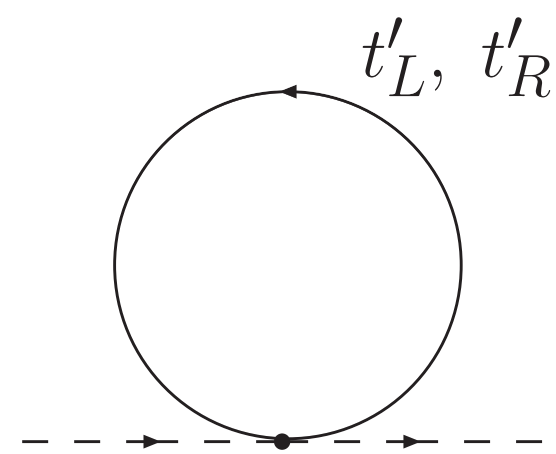

Little Higgs

$\times$ ~~3~~ 3'

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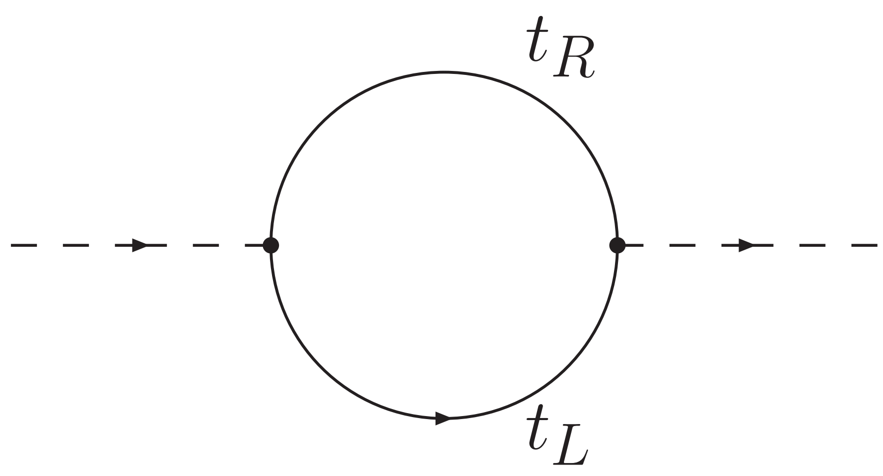

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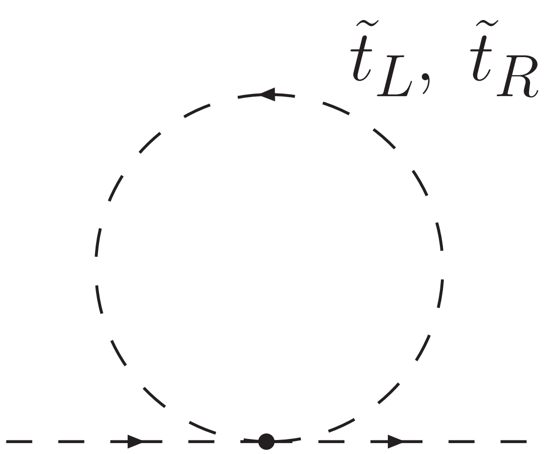

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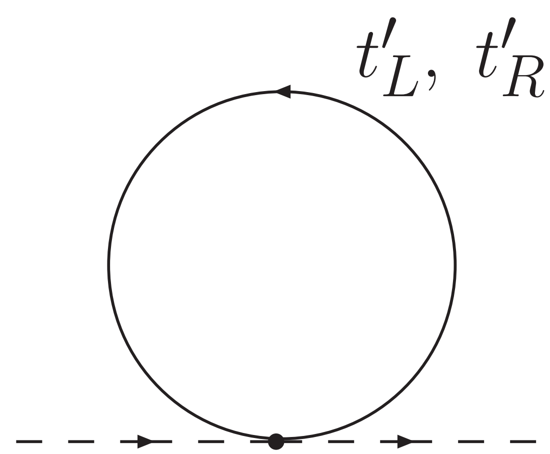

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symmetry does not commute with color.

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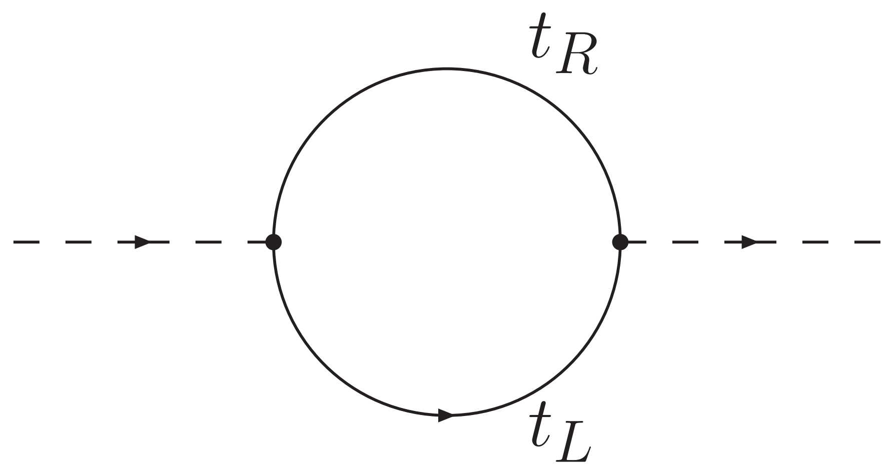

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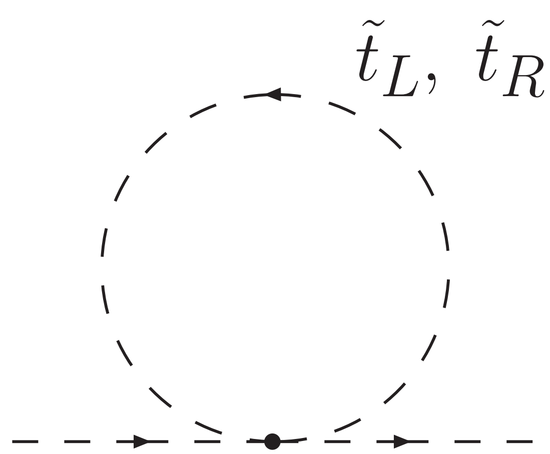

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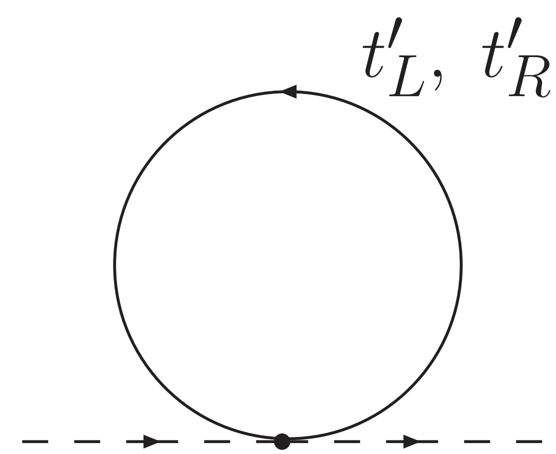

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Folded SUSY

Burdman, Chacko, Goh, RH (06')

Twin Higgs

Chacko, Goh ,RH (05')

Outline

* Twin Higgs @ LHC
  - Sketch of Mechanism & low energy EFT
  - LHC Signals, (or lack thereof).
* Twin Higgs Beyond LHC
  - Beyond the Low Energy Theory - Composite Twin Higgs
  - Two types of Flavor violation:

    Composite Higgs ("old")

    Composite Twin Higgs ("new")

work in progress.
Spoiler: no numbers!

Twin Higgs.
The Mechanism.

The Higgs is a PNGB of an approximate symmetry.

[Chacko, Goh, RH (05)]

$SU(4) \supset SM_A \times SM_B \times Z_2$

* The model consists of $SM_A \times SM_B \times Z_2$.

e.g. $\mathcal{L} \supset y_t H_A \bar{t}_A t_A + y_t H_B \bar{t}_B t_B$

* The global symmetry of the Higgs sector is a larger $SU(4)/SU(3)$ or $SO(8)/SO(7)$.

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix}$$ is a fundamental.

SU(4) breaking: $\langle H \rangle^2 = \langle H_A \rangle^2 + \langle H_B \rangle^2 = f^2$

H has 7 Goldstones. 6 are eaten. 1 is the Higgs boson.

Cancelation

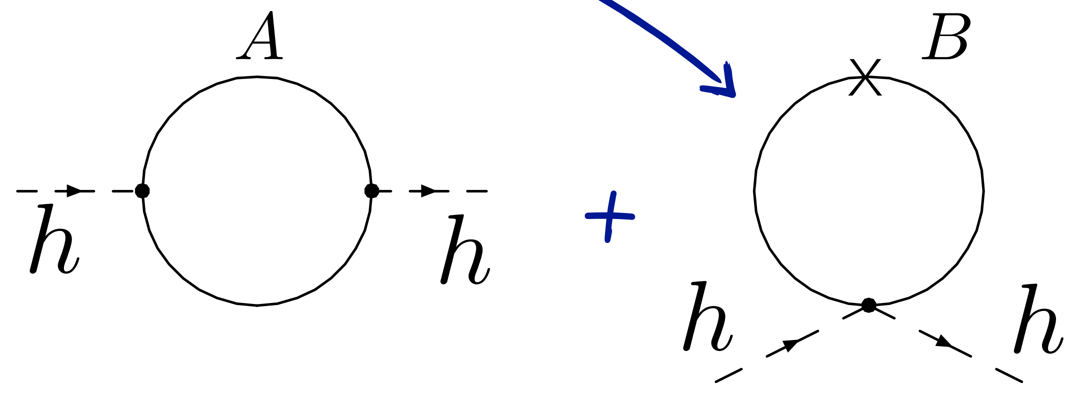
* Expanding H ala non-linear sigma model:

$$H_A = f \sin\frac{h}{f} = h + \ldots$$

$$H_B = f \cos\frac{h}{f} = f - \frac{|h|^2}{2f} + \ldots$$

$$\mathcal{L} \supset y_t H_A \bar{t}_A t_A + y_t H_B \bar{t}_B t_B$$

$$= y_t h\, \bar{t}_A t_A + y_t \left(f - \frac{|h|^2}{2f} \right) \bar{t}_B t_B + \ldots$$



Cancelation: Linear model

* If you don't like the non-linear representation, here it is in the linear one:

$$V(H) = -m^2|H|^2 + \lambda|H|^4 \longrightarrow \langle|H|^2\rangle = \frac{M^2}{2\lambda} \equiv f^2$$

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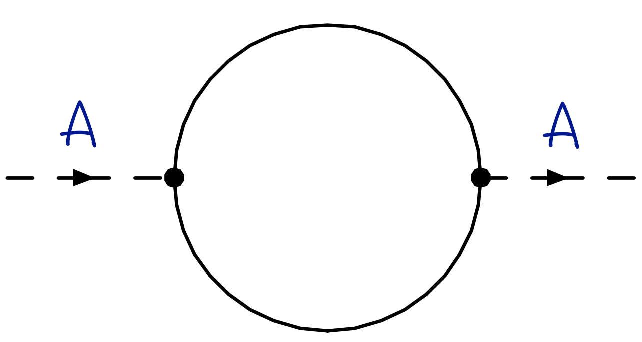

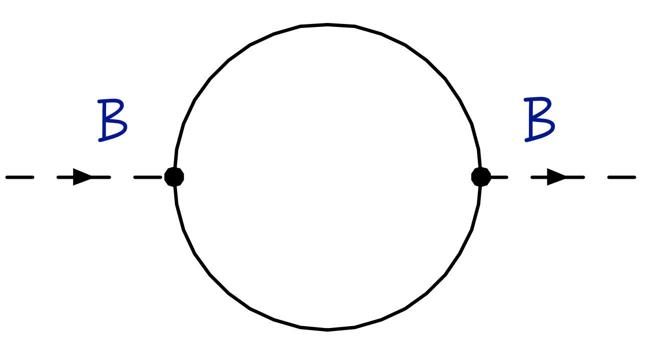

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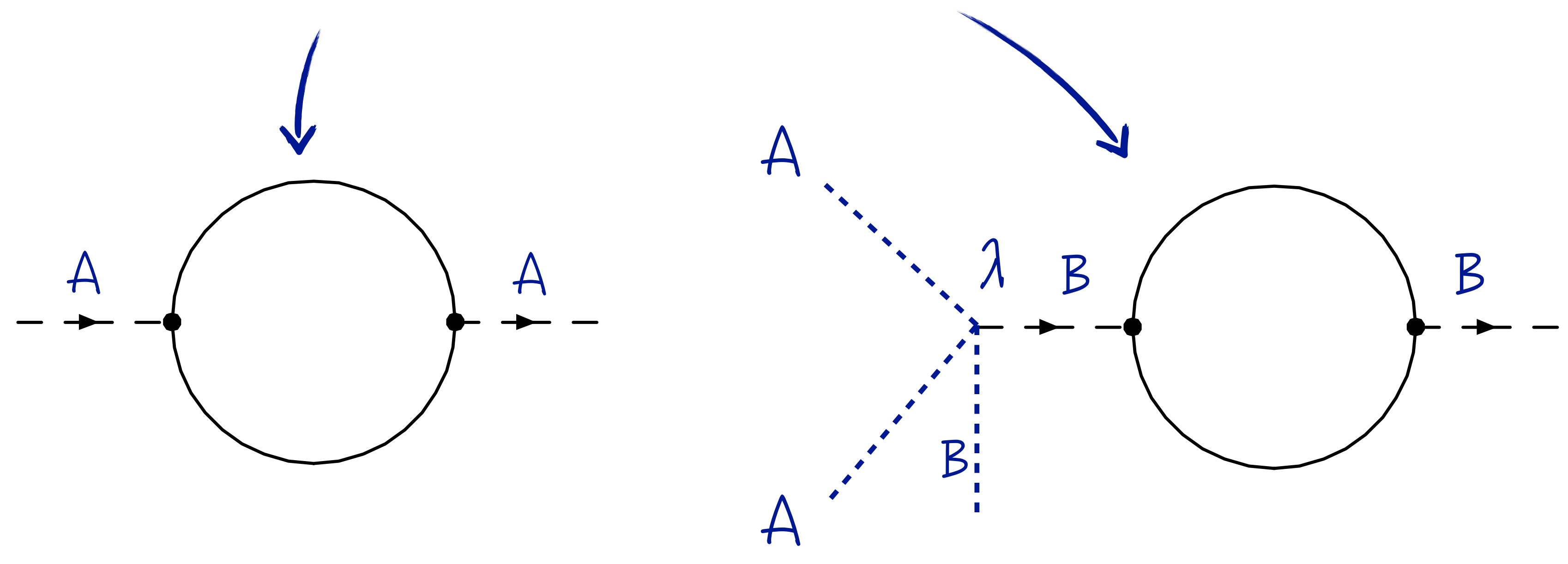

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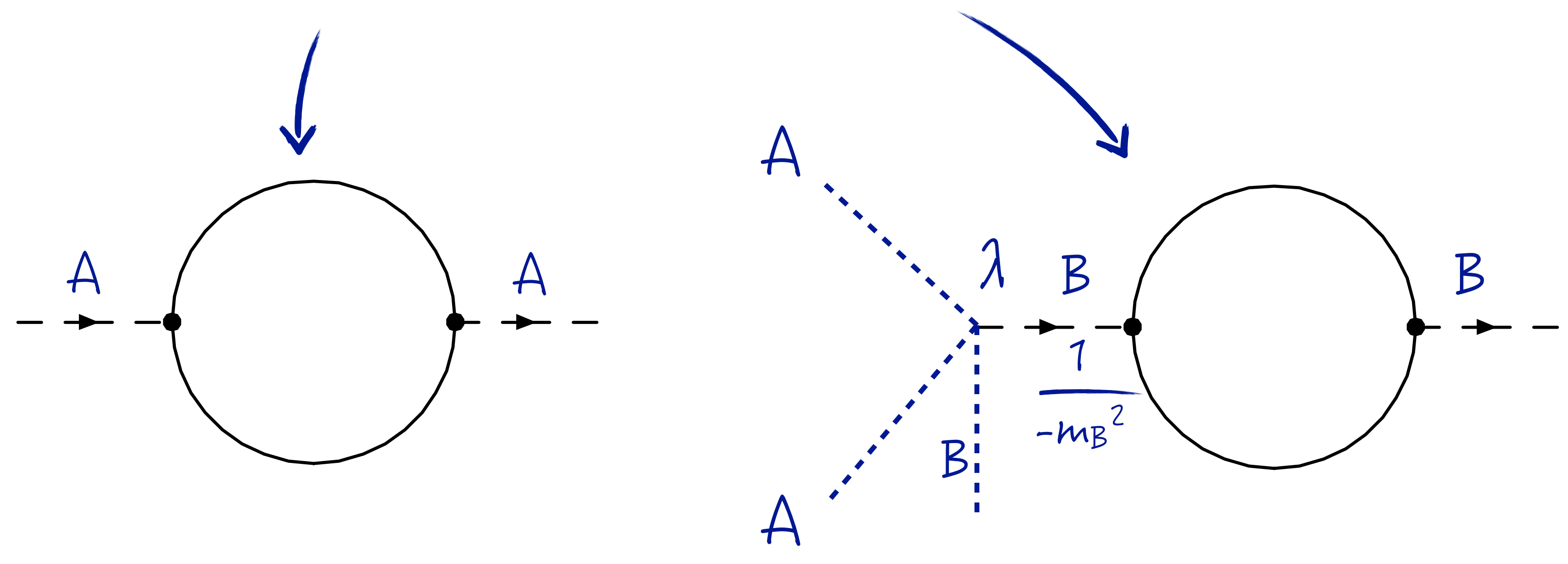

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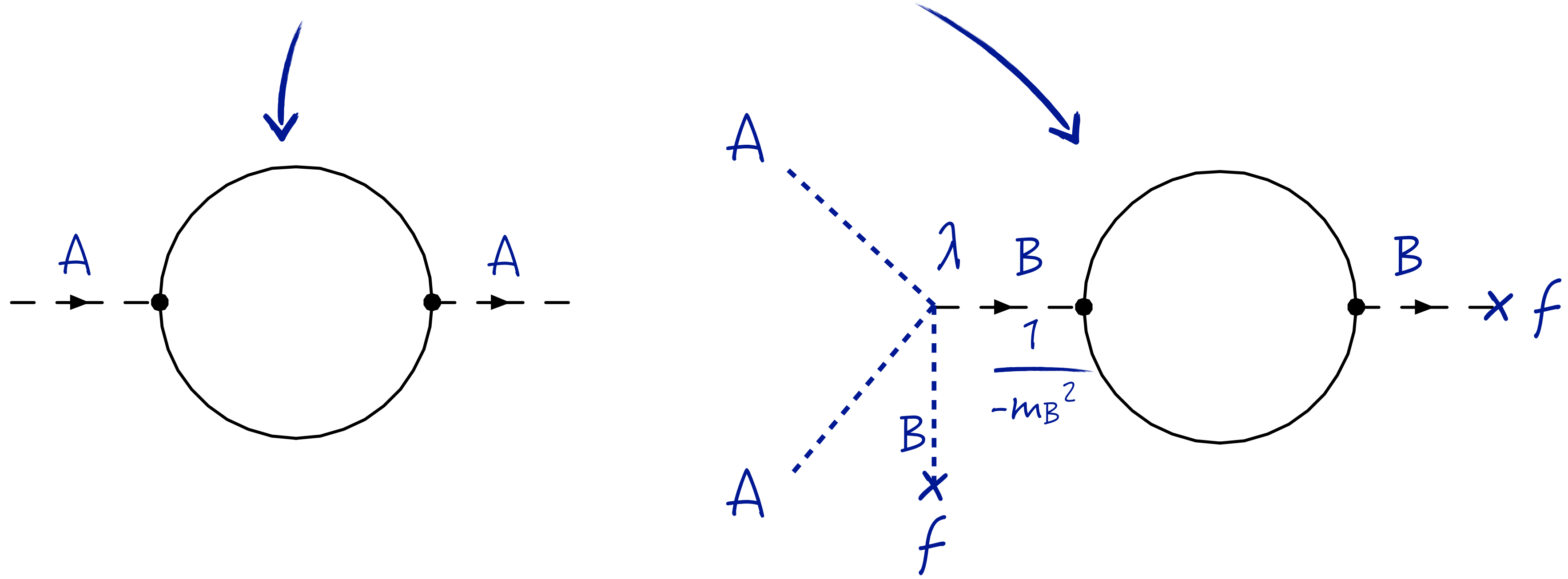

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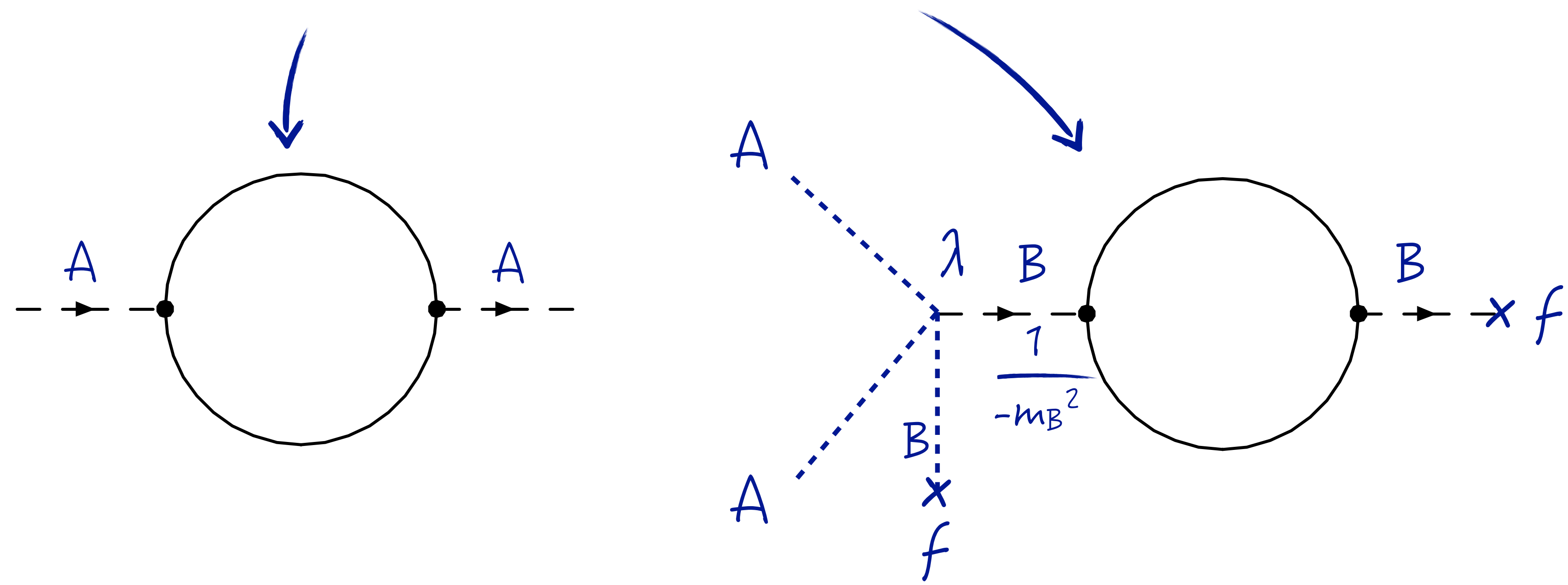


+ recall that $m_B{}^2 = \lambda f^2$

Twin Mechanism

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

↓ $H_A^2 + H_B^2$ is only Z_2 sym quadratic.

Quadratic terms are globally symmetric.
No quadratic divergences.

* Note: Quartic terms can violate global symmetry.
Goldstone mass comes from quartic.

So...

* Let's summarize what we have:
  - Higgs is protected by a symmetry.
  - The model is natural up to Λ beyond LHC scale.
  - All new particles below Λ are complete SM singlets.
* What's the phenomenology?
  - Early LHC finds the Higgs and nothing else! (check).
  - Then what?

Higgs Couplings

* Higgs gauge boson couplings: $|D^A_\mu H_A|^2 + |D^B_\mu H_B|^2$
* Recall $H_A^\dagger H_A = h^\dagger h - \frac{(h^\dagger h)^2}{3f^2} + \ldots$
* Higgs boson couplings are modified by $\cos(\frac{v}{f})$.

* This is universal to all Higgs couplings.

  (in linear language: h is mixing with a singlet H_B)

All SM Higgs σxBR's are modified by $\cos^4(\frac{v}{f})$

Invisible Decay

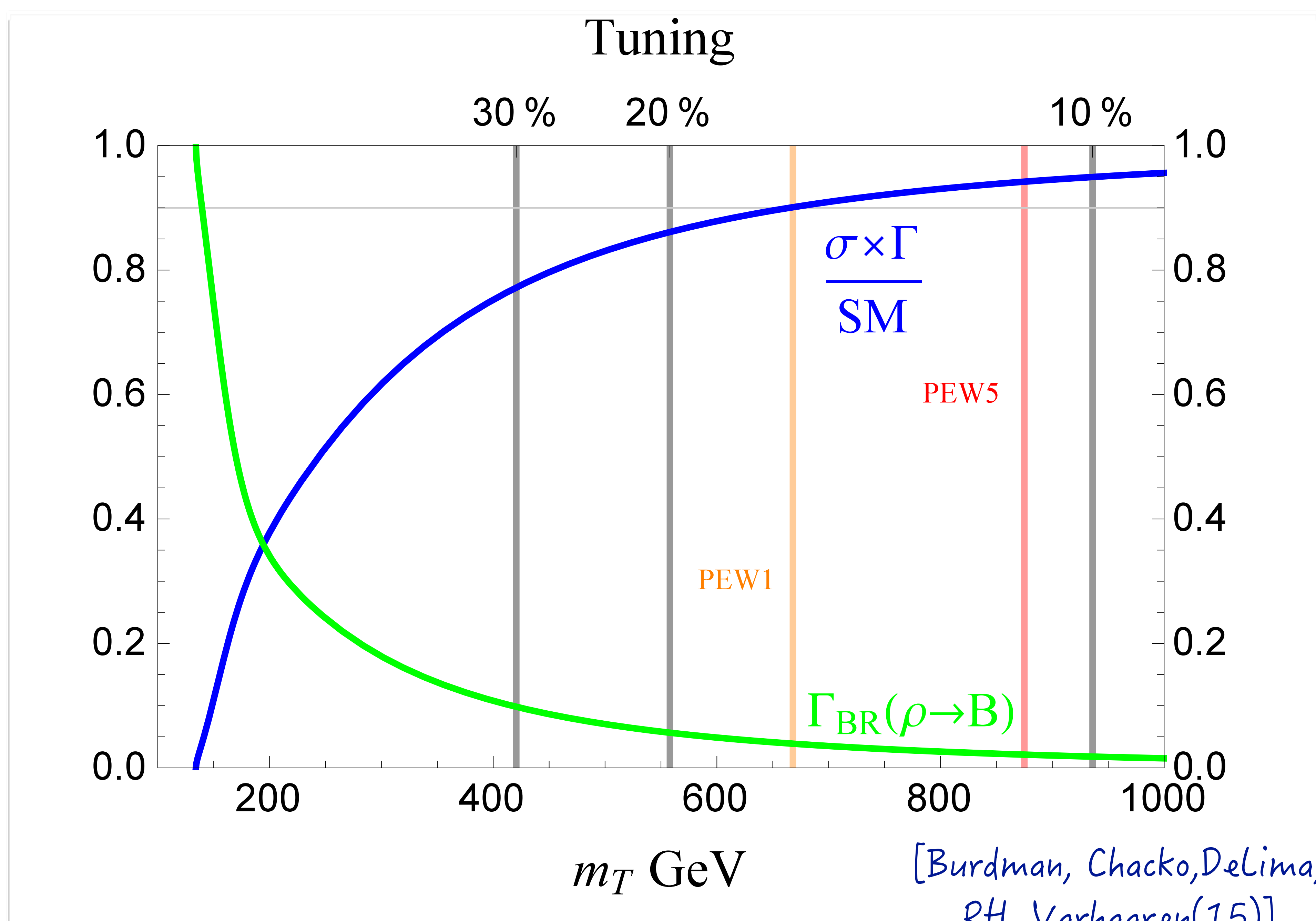
- The bottom Yukawa: $y_b H_A \bar{b}_A b_A + y_b H_B \bar{b}_B b_B$
- Expanding $H_B \rightarrow$ a coupling of h to b_B: $y_b \sin\left(\frac{v}{f}\right)$

$$BR_{(h\rightarrow inv)} = \sin^2\left(\frac{v}{f}\right)$$

- One parameter, v/f, is setting both Higgs coupling modification and BR_{inv}. A prediction.

Observables

Higgs coupling modifications & invisible decay:

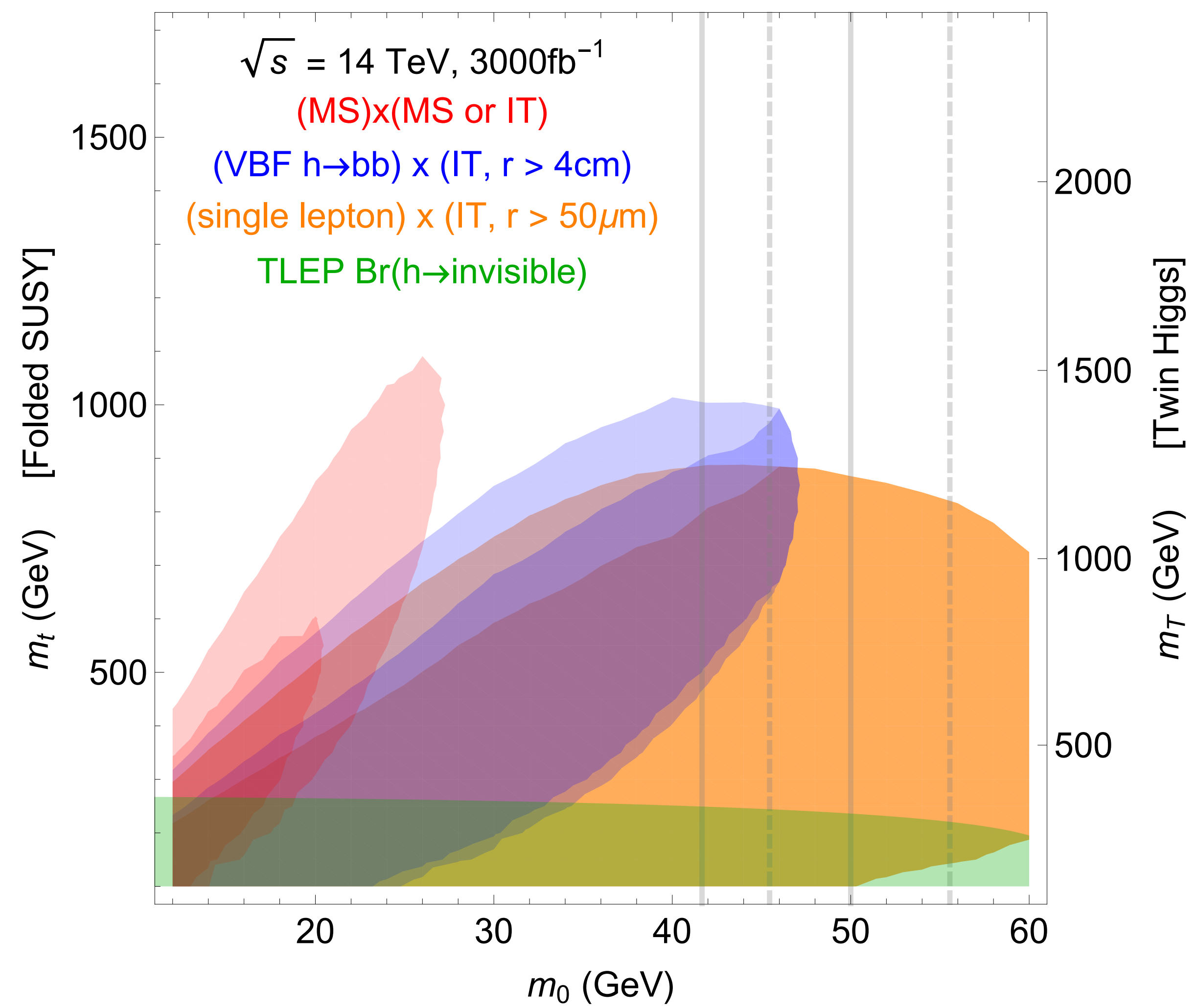


[Burdman, Chacko, DeLima, RH, Varhaaren(15)]

Exotic Higgs Decays

- Glueball may be at the bottom of the B sector aka fraternal Twin Higgs, [Craig et al (15)].
- Decays back to SM via mixing with Higgs. Often displaced!

h → displaces stuff



[Curtin and Verhaaren (15)]

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  - SUSY [Chang, Weiner Hall (06), Craig, Howe (14)]
  - Composite Higgs and/or RS [Geller, Telem (14)] [Barbieri et al (15)] [Low, Tesi, Wang (15)]
  - Orbifold? [Craig et al (14)]

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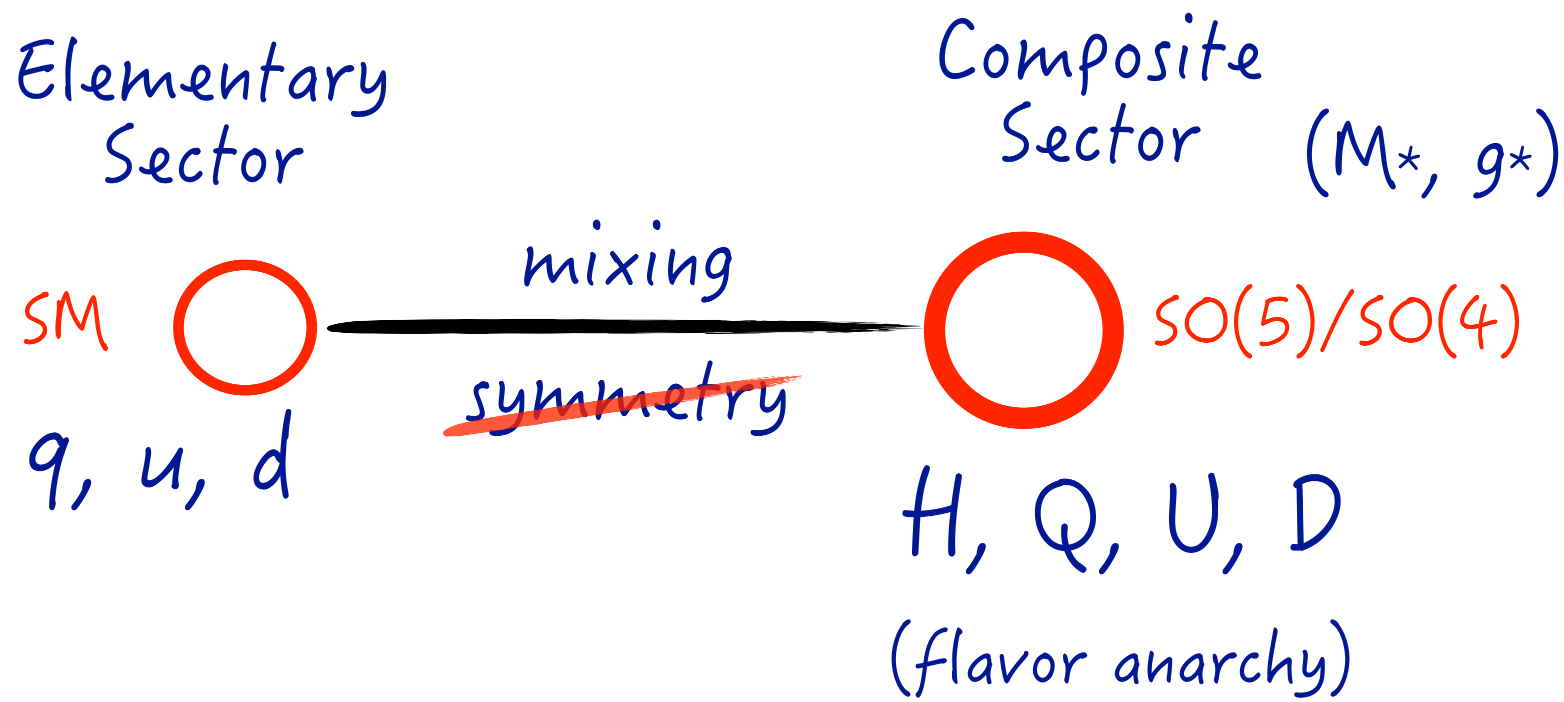
Composite Twin Higgs & Flavor

Ongoing work with Stamou and Zupan.
Watch for related work by Csaki, Geller, Telem, Weiler

Partial Compositeness

* The partial compositeness paradigm:



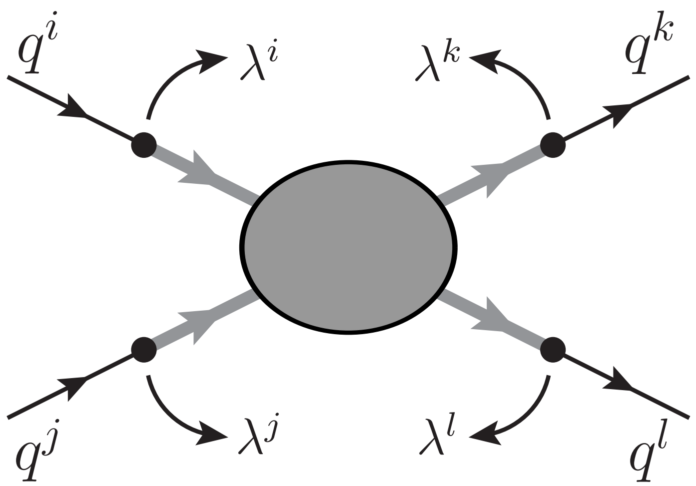
There are many possibilities and opportunities for flavor and CH. Many choices for fermion reps. etc.

[Csaki, Falkowski, Weiler][Redi, Weiler][Agashe, Contino, Pomarol for δg_Z]...

A nice review: [Panico, Wulzer (15)]

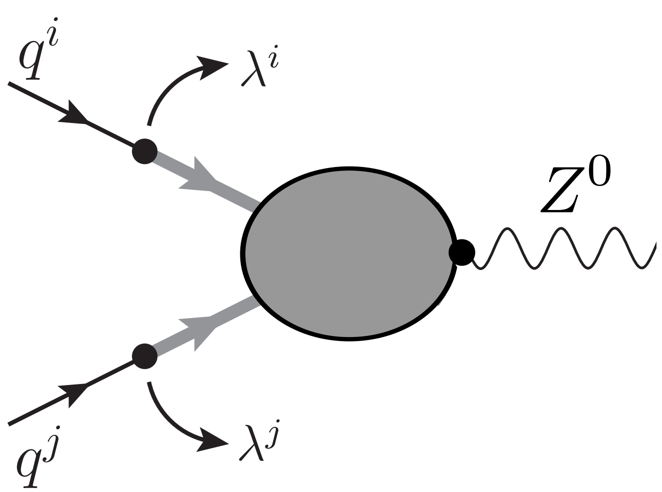
Composite Higgs Constraints

Some things to worry about within CH models:



$$\sim \lambda_i \lambda_j \lambda_k \lambda_l \frac{g_*^2}{M_*^2} (\bar{q_i} \gamma_\mu q_j)(\bar{q_k} \gamma^\mu q_l)$$

e.g. K-$\bar{K}$ mixing.



$$\sim \frac{\lambda_i \lambda_j}{M_*^2} (q_i \gamma_\mu q_j)(H^\dagger D^\mu H)$$

Modified Z couplings.

Composite Higgs Constraints

* For example, CP violation in kaon mixing is quite constraining - roughly $M_* \lesssim$ 10-30 TeV.

* Similar constraints will apply to Composite Twin Higgs. (in progress).

* The tension may be milder for Twin case because it allows M_*, smaller mixing. (in progress)

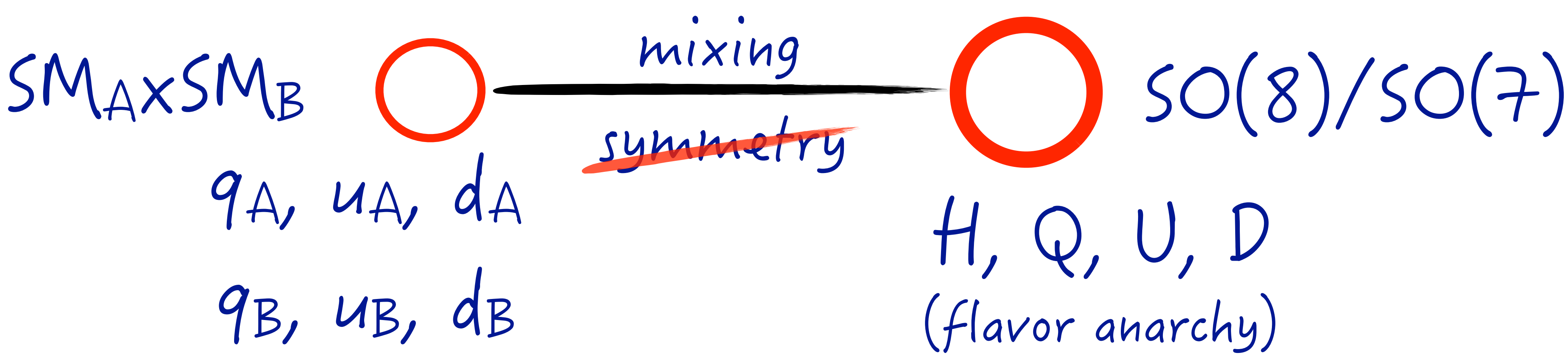
* As in CH, Flavor Symmetries, MFV can be invoked.

Twin Composite Higgs

* Twin CH requires doubling elementary sector.
* Requires SO(8) for T-param. and protecting the Higgs at 1-loop.

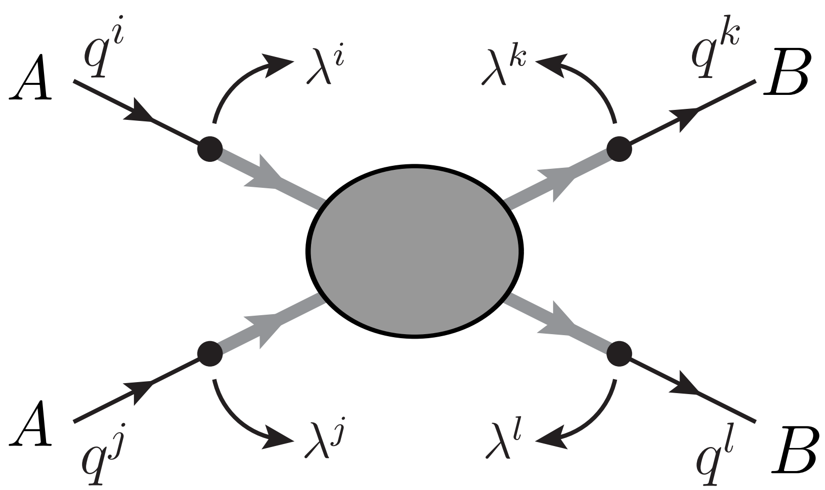
[Chacko, Goh, RH]
[Barbieri, Greco, Rattazzi, Wulzer]

* Enlarged fermions representations.
* Allows higher M_* (strong coupling g_*).

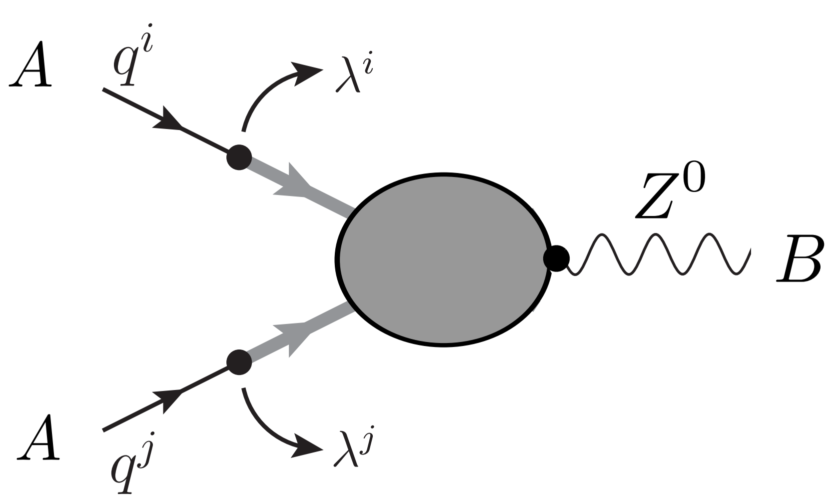


Twin Constraints

* Doubling elementary sector introduces additional worries.



$$\sim C_{AB}\, \lambda_i \lambda_j \lambda_k \lambda_l \frac{g_*^2}{M_*^2} (\bar{q}_i^A \gamma_\mu q_j^A)(\bar{q}_k^B \gamma^\mu q_l^B)$$



$$\sim C_{AZ_B} \frac{\lambda_i \lambda_j}{M_*^2} (q_i^A \gamma_\mu q_j)(H_B^\dagger \overleftrightarrow{D}^\mu H_B) \quad + (A \leftrightarrow B)$$

What are the Wilson Coefficients? Observables?

New (and old) Constraints

* What can these operators do?

$t \to c + Z_B^* \to (c + \text{inv})$ or (c + **displaced stuff**).

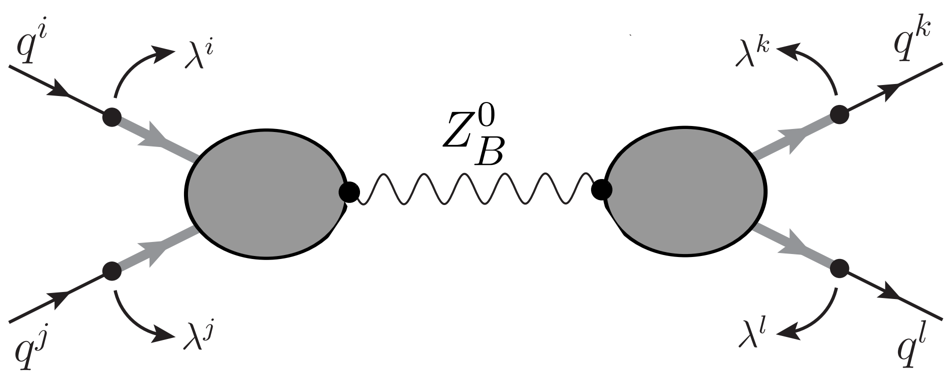
$K \to \pi +$ B-stuff aka "fake $K \to \pi + \nu\nu$"

Invisible or **displaced** Z decays

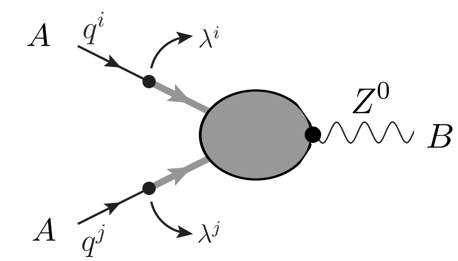
Additional contributions to K-K mixing.

CLFV

...



Coupling to Z_B

* In specific models, what generates  ?

* Several possibilities, here is an example -

Field	U(6)× SO(8)
H	$(\mathbf{1},\,\mathbf{8})$
$\mathcal{Q}_i$, $\bar{\mathcal{Q}}_i$	$(\mathbf{6},\mathbf{8})$, $(\bar{\mathbf{6}},\mathbf{8})$
$\mathcal{U}_i$, $\bar{\mathcal{U}}_i$	$(\bar{\mathbf{6}},\mathbf{1})$, $(\mathbf{6},\mathbf{1})$
$\mathcal{D}_i$, $\bar{\mathcal{D}}_i$	$(\bar{\mathbf{6}},\mathbf{28})$, $(\mathbf{6},\mathbf{28})$

Q ⊃ an exotic X_Q

X_Q = fundamental under QCD_A and EW_B

D ⊃ an exotic X_D

X_D = fundamental under QCD_A, EW_B and EW_B

Coupling to Z_B

* X_Q has quantum number of $H_B U_A$.
  Can mix with U_A!

* X_D has quantum number of $H_B Q_A$.
  Can mix with Q_A!

* Anarchic Yukawa's induce this mixing:

$$Y_{ij} H Q_i U_j + Y_{ij} H Q_i D_j \supset Y_{ij} H_B X_{Q_i} U_j^A + Y_{ij} H_B Q_i^A X_{D_j}$$

$\rightarrow$ mixing is flavor anarchic $\propto Y_{ij} f$

Recall: X's charged under EW_B $\rightarrow$ Couple to Z_B.

Coupling to Z_B

Summary: new "AB-type" effect from exotic mixing

$$\sim \frac{(Yf)^2}{M_*^2} \times (\text{equivalent CH } \delta g_Z)$$

In the truly strongly coupled limit $g_* \sim Y$,
AB operators are of the same size as AA.

Can potentially lead to new observables.
(displaced vertices?)

There are other potential contributions to δg_{Z_B}.
(Work in progress).

Conclusions

* Twin Higgs models can address the question "where is everybody?"
* Allows Composite Higgs models to be truely strongly coupled, raise mass of resonances.
* Like in CH, Flavor is an interesting story for CTH. Many possibilities.
* Flavor processes that involve the twin sector should be considered. Can lead to new signals?

Deleted Scenes

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.

$SM_A \times SM_B$

* Double all of the SM. Impose a Z_2.
  (a.k.a orbifold of SU(6)xSU(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!

* Only Higgs sector has extended global symm.
  That is sufficient for naturalness (@one-loop).

Cancelation

* How does the twin cancelation come about?
* Lets think about the theory of Goldstones:
  (a.k.a. broken SU(4) generators)

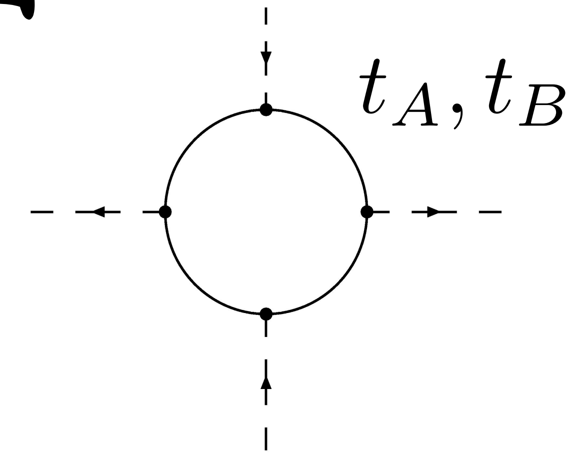
$$\Pi = \left(\begin{array}{ccc|c} 0 & 0 & 0 & h_1 \\ 0 & 0 & 0 & h_2 \\ 0 & 0 & 0 & 0 \\ \hline h_1^* & h_2^* & 0 & 0 \end{array}\right)$$

This beast transforms non-linearly under SU(4).

For convenience, construct a linearly transforming combination:

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix} = \exp\left(\frac{i}{f}\Pi\right)\begin{pmatrix} 0 \\ 0 \\ 0 \\ f \end{pmatrix}$$

SU(4) Breaking



- Radiative corrections induce

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

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

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

- Adding mixed "top partners" at 5-6 TeV keeps this quartic finite, 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 $v < f$.

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

O(8)

* O(8) can protect the Higgs from explicit U(4) breaking effects.
* O(8) is explicitly broken to $SU(2)_A \times SU(2)_B$.
* But each generator breaks O(8) to an SU(4).
* This collective symmetry breaking is enough to protect the Higgs at order g^2.

Chacko, Goh, Harnik (hep-ph/0512088)
For an elegant spurion analysis see-
Barbieri, Greco, Rattazzi, Wulzer (1501.07803)
(talks by Wulzer and RH)

Precision EWK

* Precision EW measurements place a constraint on the scale f but depend on UV completion.
* SM Higgs loops contribute to S & T
$\rightarrow$ modified Higgs couplings are constrained.
* Coupling modifications are "made up" by states at cutoff or by heavy Higgs for strong/weak UV completion (respectively).

$$\Delta S \approx \frac{1}{6\pi}\left(\frac{v}{f}\right)^2 \log\left(\frac{m_{h_2}}{m_h}\right) \qquad \Delta T \approx -\frac{3}{16\pi\cos^2\theta_W}\left(\frac{v}{f}\right)^2 \log\left(\frac{m_{h_2}}{m_h}\right)$$

Franco, Mishima, Silverstini (13) Falkowski, Riva, Urbano (13)

Other Signals

* Other collider signals depend on the UV:
  - Weakly coupled UV Completion - Heavy Higgses at ~TeV, superpartners at few TeV (e.g. Craig and Howe)
  - Strongly coupled UV completion - loads of resonances for discovery at the 100 TeV machine! :-)
  - More @ 100 TeV: