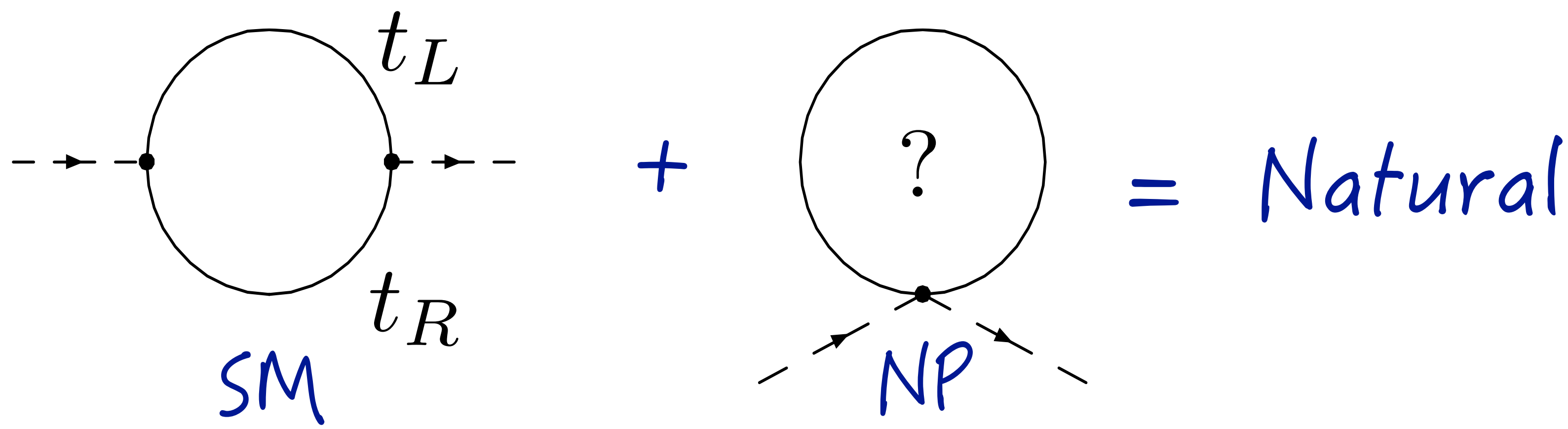
Exploring the Flavor of Twin

Roni Harnik
Fermilab

Chacko, Goh, RH (05)
...
RH, Stamou, Zupan (in progress)

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"

Outline

* Twin Higgs @ LHC
  - Sketch of Mechanism & low energy EFT
  - LHC Signals, (or lack thereof).
* Composite Twin Higgs*
  - Composite Higgs: Flavor vs naturalness
  - Composite Twin Higgs: Flavor vs naturalness
  - New flavor effects from twining.

*Several author's of composite Twin Higgs models in the room.

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

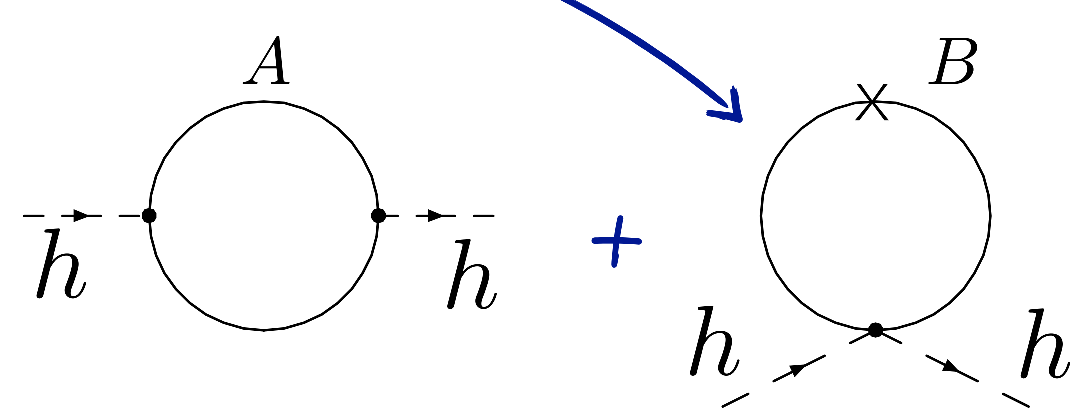
* Expanding H ala non-linear sigma model:

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

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

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

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



Cancelation: Linear model

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

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

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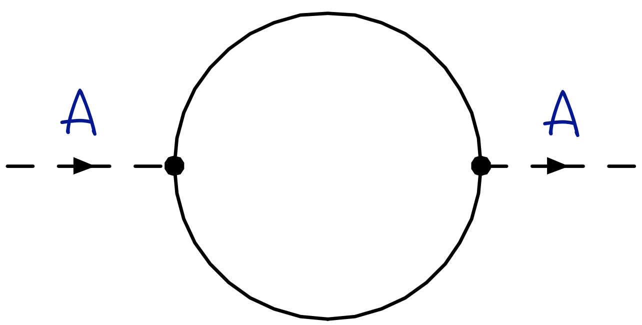

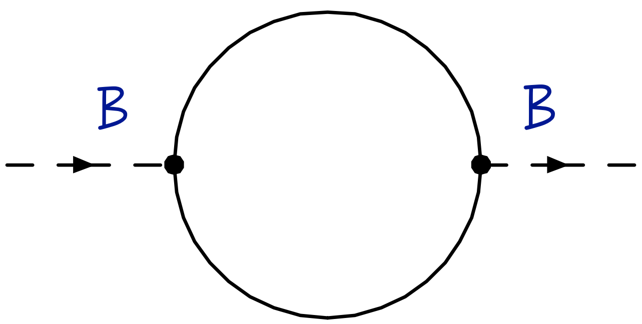

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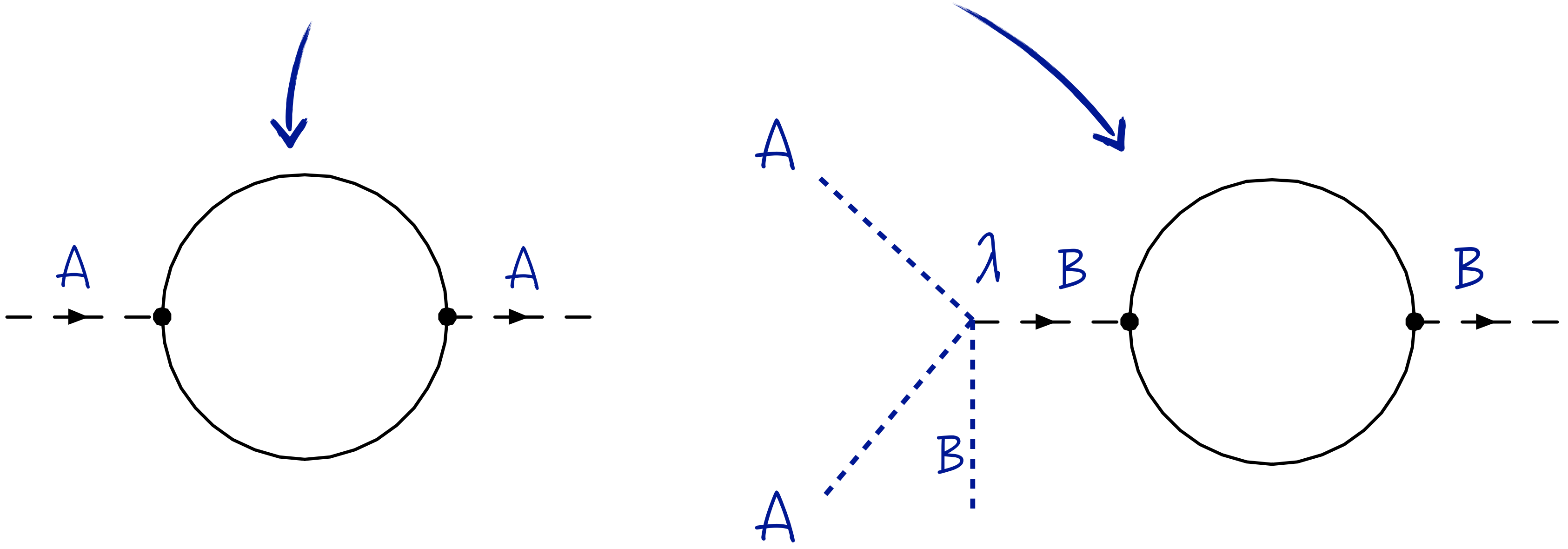

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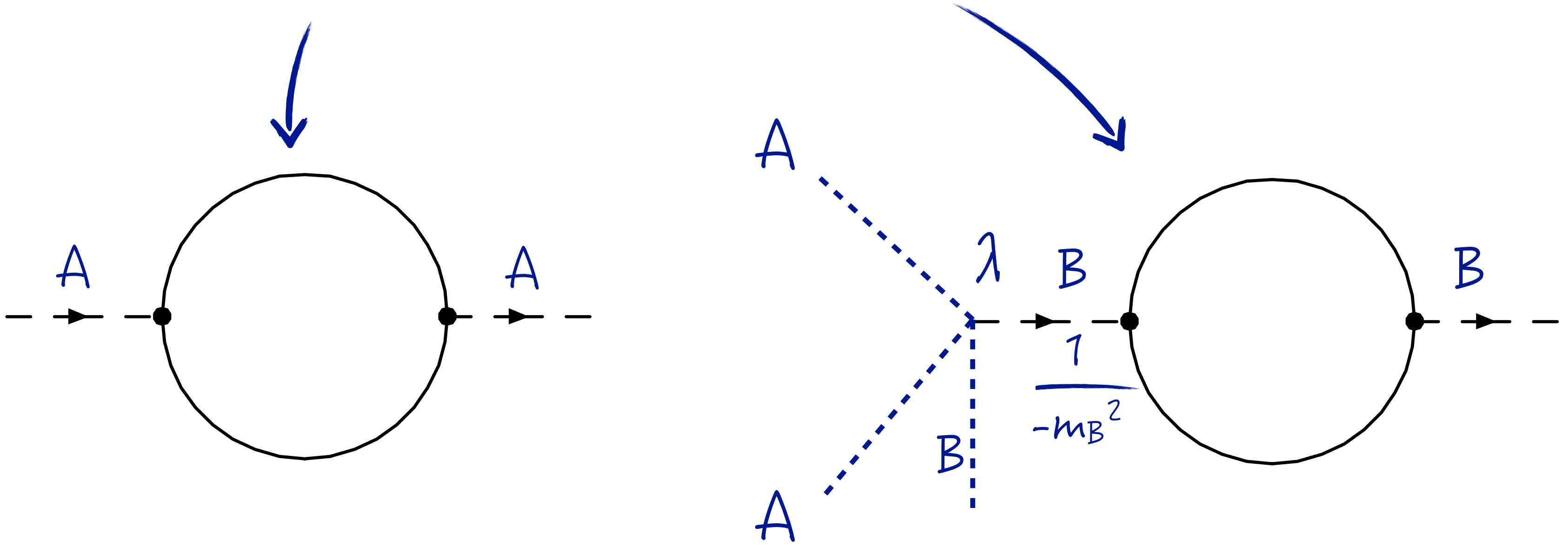

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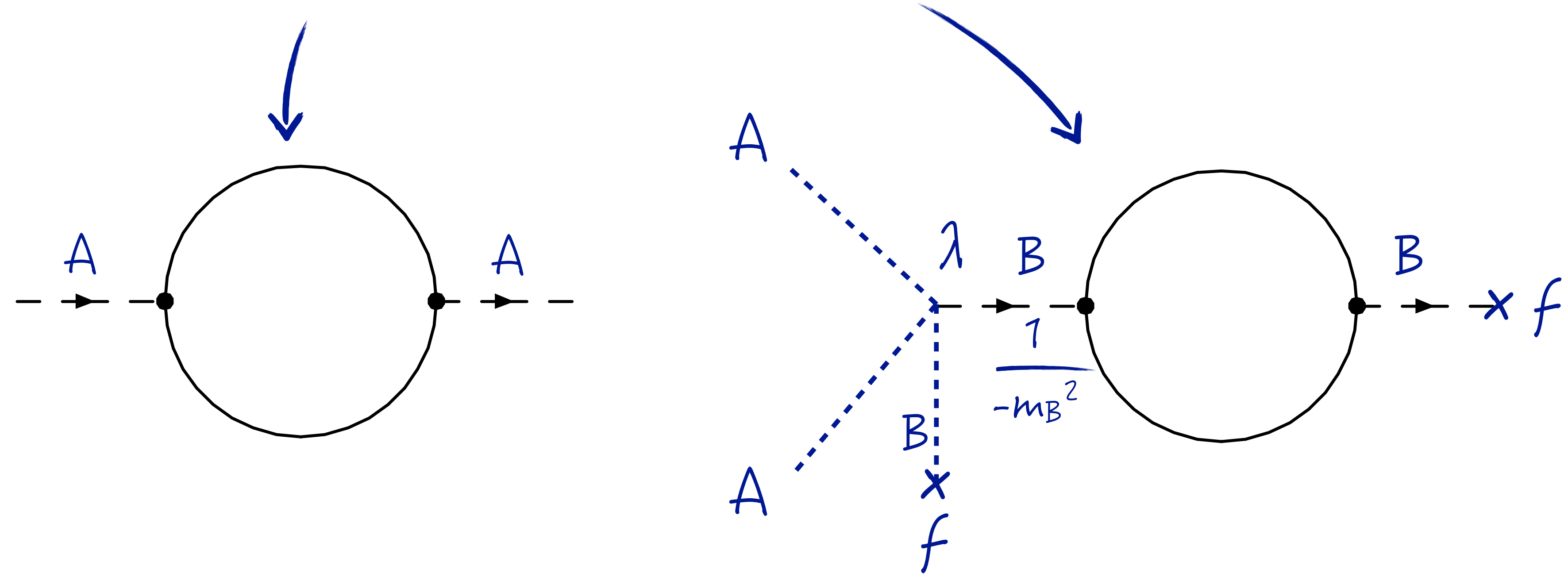

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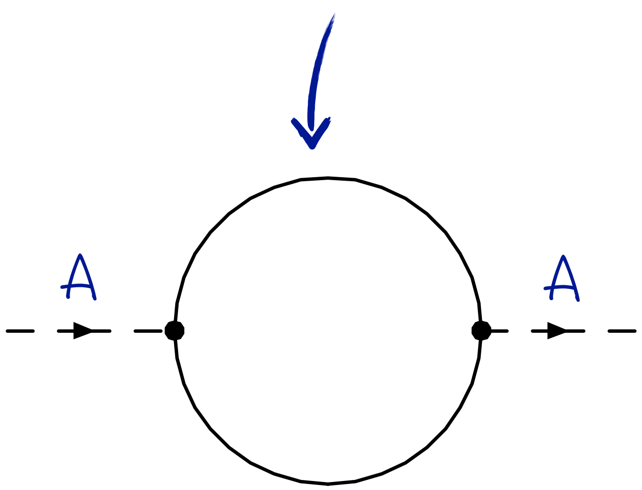
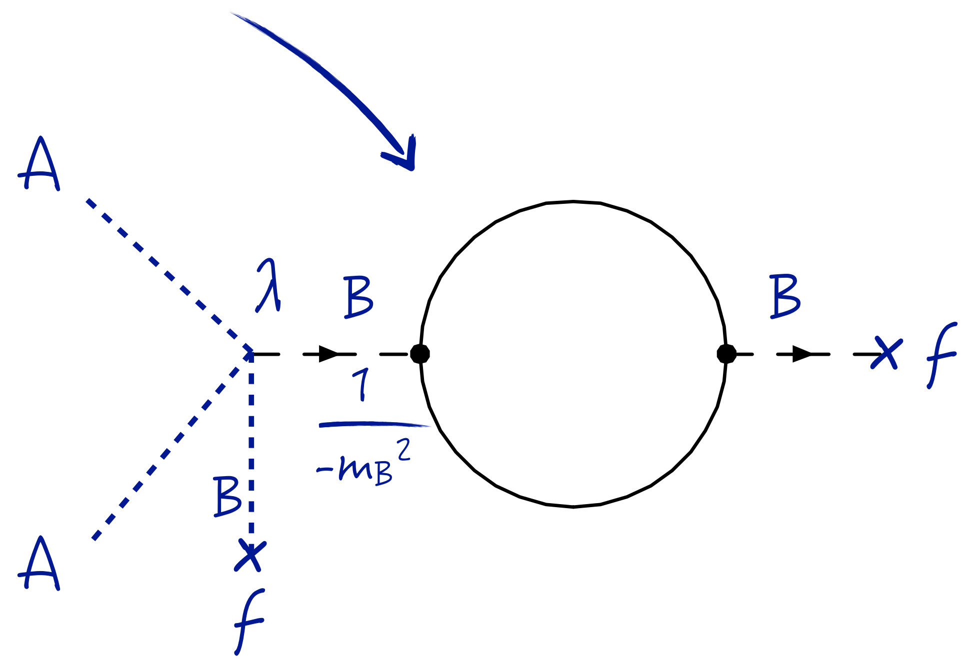




+ recall that $m_B{}^2 = \lambda f^2$

So...

* After all is said and done, what we have is:
  - 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?

Precision Higgs

* Like many PNGB models, Higgs couplings are reduced by a mixing angle. Universally.

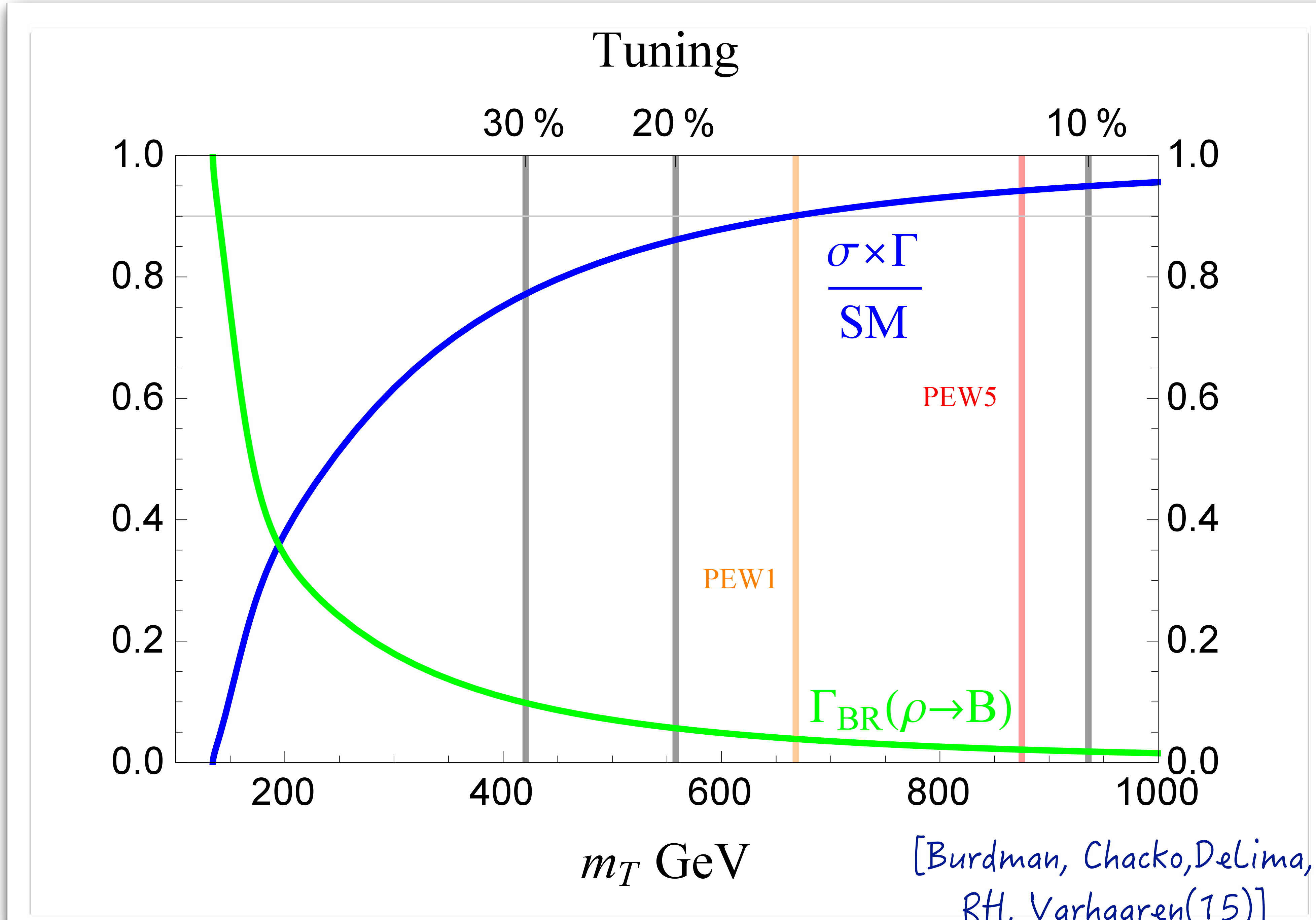
All SM Higgs σxBR's are modified by $\cos^4\left(\frac{v}{f}\right)$

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

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

Precision Higgs

Correlated coupling modifications & invisible decay:



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

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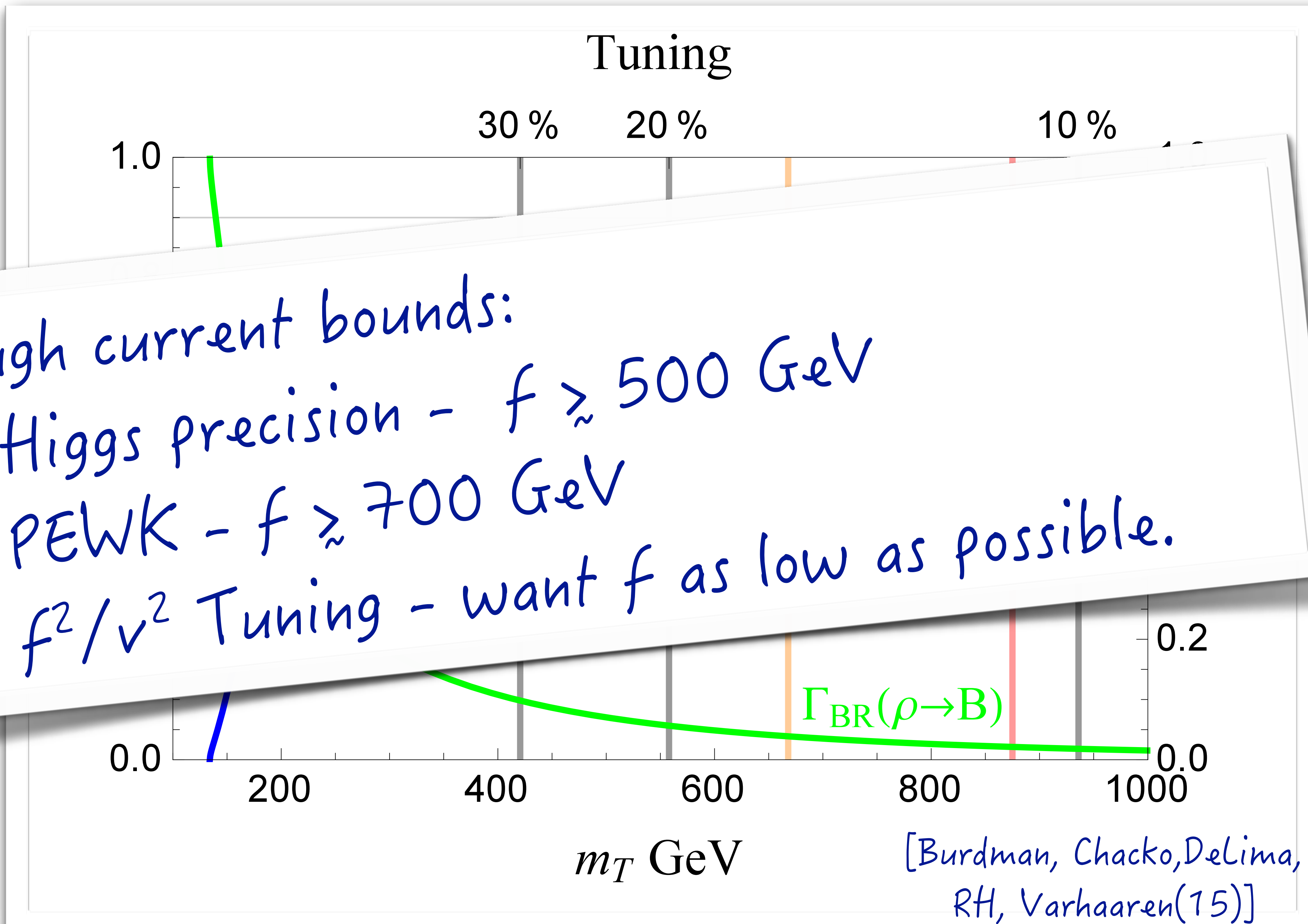


Rough current bounds:

* Higgs precision - $f \gtrsim 500$ GeV
* PEWK - $f \gtrsim 700$ GeV
* f^2/v^2 Tuning - want f as low as possible.

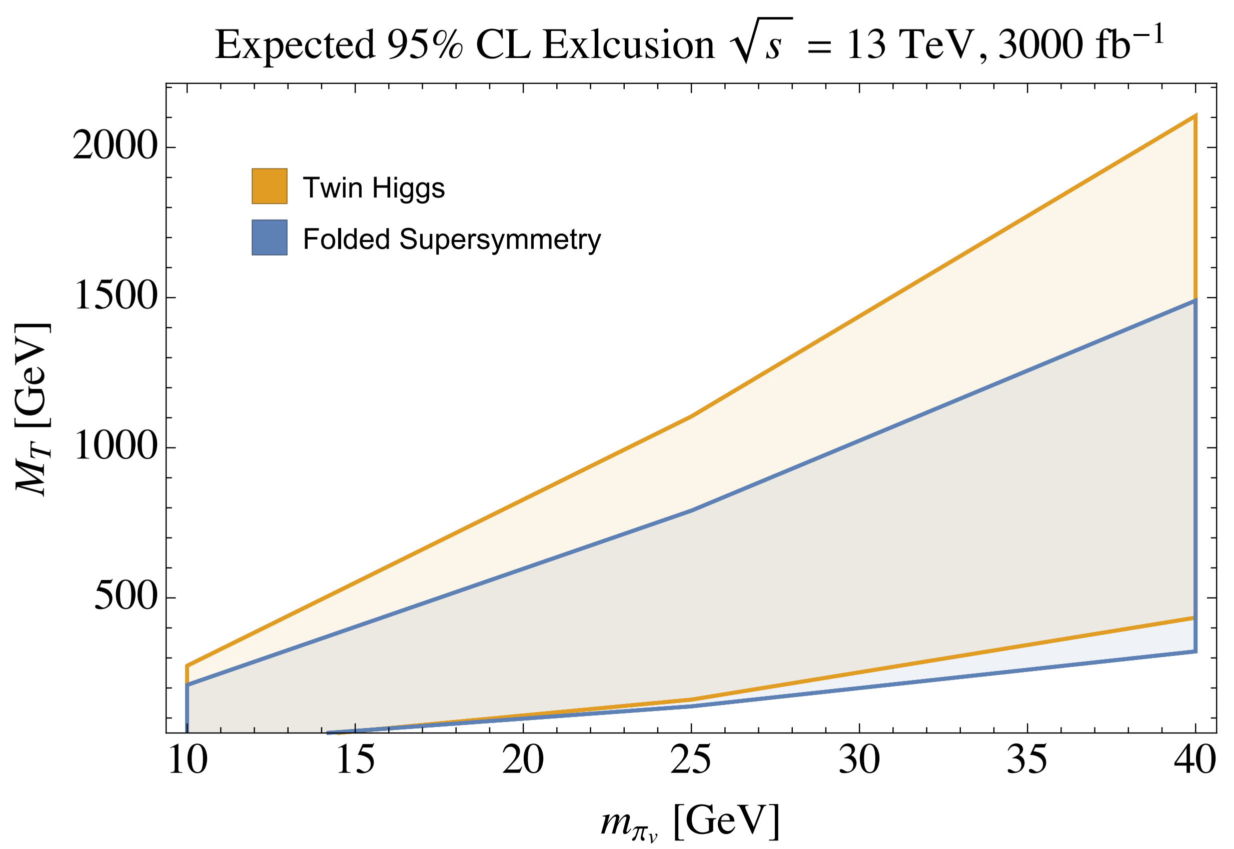
[Burdman, Chacko, DeLima, RH, Varhaaren(15)]

[Fraternal Twin Higgs, Craig et al (15)]

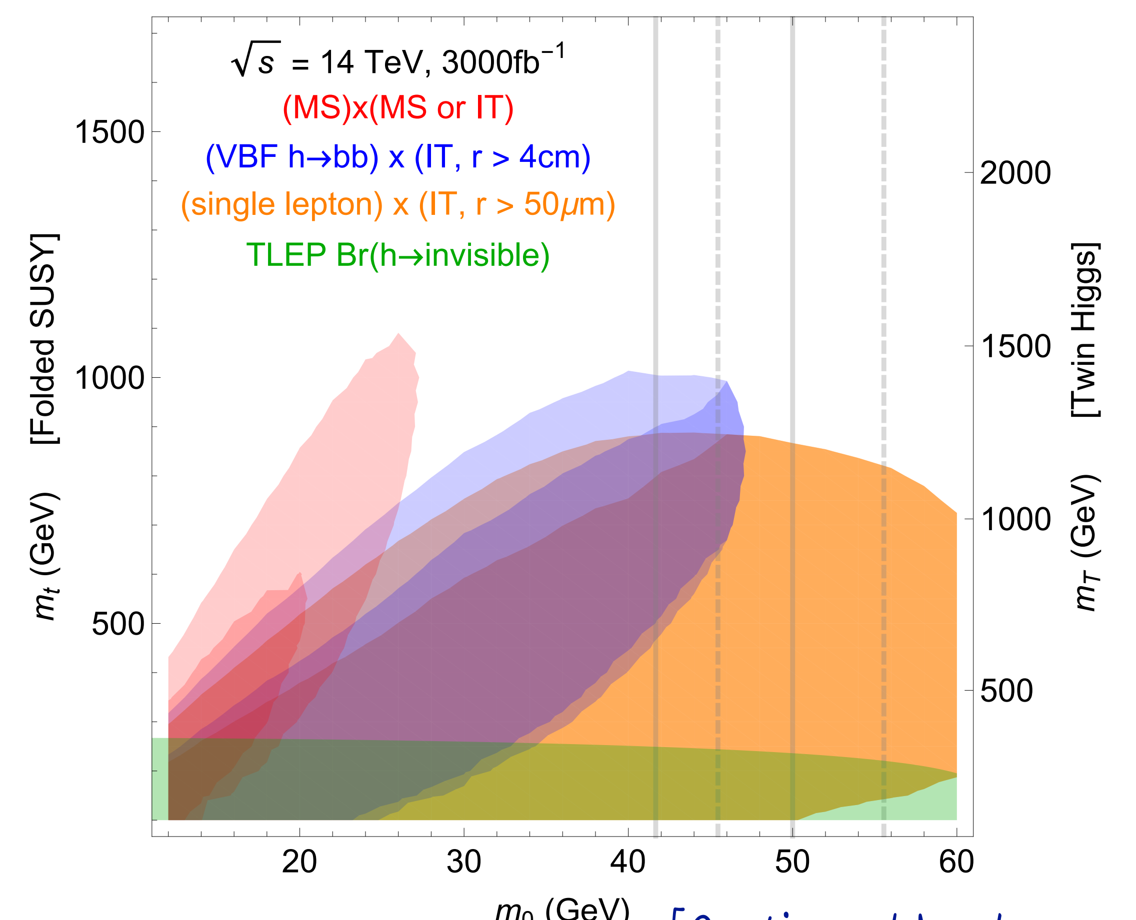
Displaced Higgs Decays

* Invisible may be visible!..
  If glueball is at bottom of the B sector.

* Decays back to SM via mixing with Higgs.
  Often displaced!



[Csaki, Kuflik, Lombardo, Slone (15)]



[Curtin and Verhaaren (15)]

Beyond LHC

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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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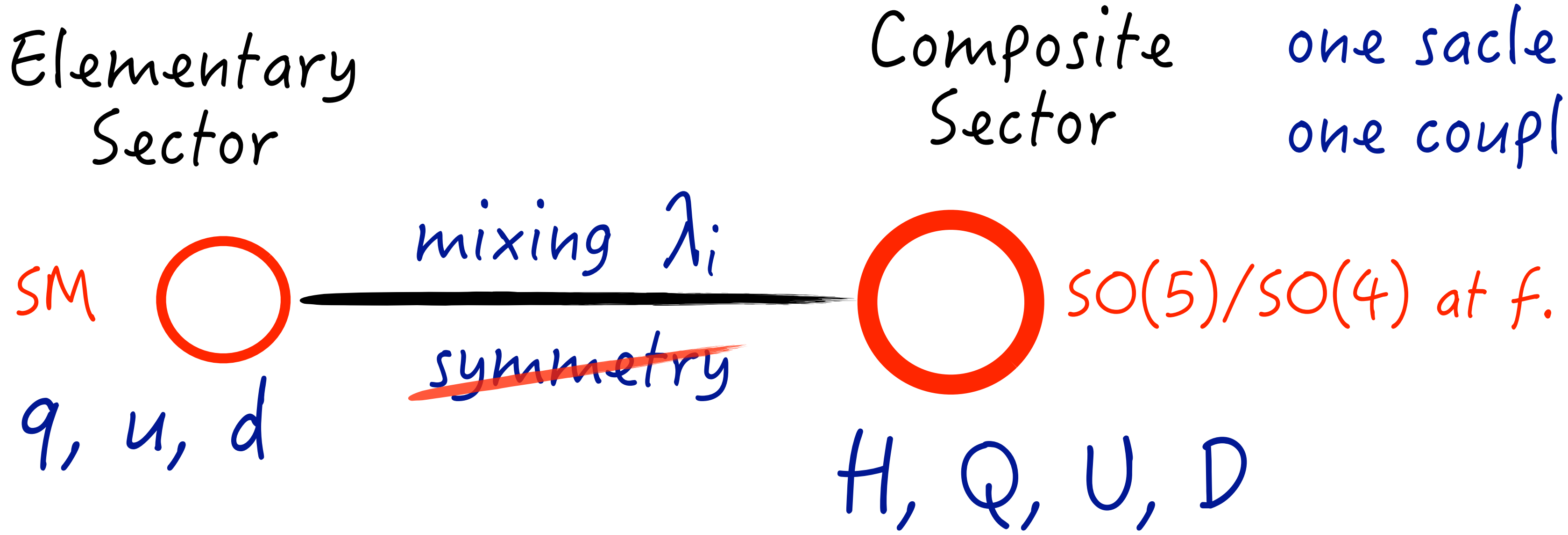
Composite (twin) Higgs
& Flavor

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

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

PNGB Higgs + Partial Compositeness



one sacle M_*,
one coupling $g_* \sim Y_*$

$$Y^u_{*ij} H Q_i U_j + Y^d_{*ij} H Q_i D_j$$

Y_* is flavor anarchic and big.

SM Flavor hierarchy:

$$y_{ij} = \lambda^L_i \lambda^R_j Y_*$$

Composite Higgs Potential

* The Higgs receives a potential at loop level due to composite-elementary mixing.

$$V(h) = -\alpha f^2 \sin^2\frac{h}{f} + \beta f^2 \sin^4\frac{h}{f}$$

Generically: $\alpha \sim \beta \sim (\text{loop factor}) \times M_*^2$ "UV effect"

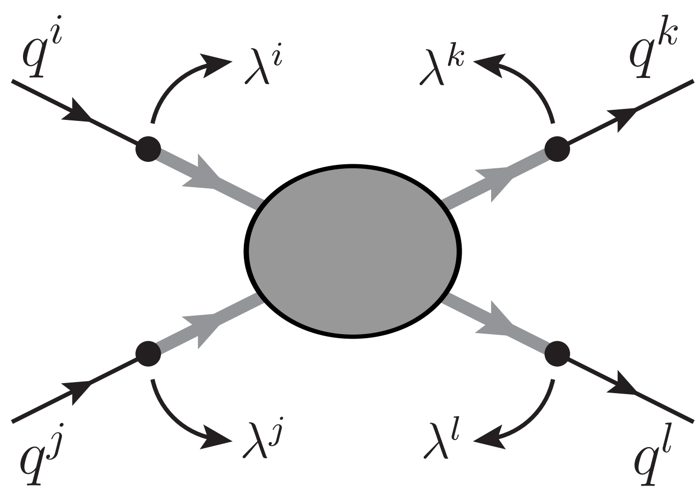
* To avoid large tuning the compositeness scale must be low, $M_* \sim g_* f \sim 2f$. "weak coupling".
* Tension with colored resonance searches.

(we also need to tune α to get correct vev, not the topic of this talk)

[Agashe, Perez, Soni][Csaki, Falkowski, Weiler]...

FCNCs in Composite Higgs

Consider the LR operator for K-$\bar{K}$ mixing, O_4:



$$C_4 \sim \lambda_1^L \lambda_2^R \lambda_2^R \lambda_1^L \frac{g_*^2}{M_*^2}$$

$$\sim \frac{m_s m_d}{v^2} \frac{g_*^2}{Y_*^2} \frac{1}{M_*^2}$$

$$M_* \gtrsim 10 \text{ TeV}$$

Flavor wants a high compositeness scale.
Higgs naturalness wants it low.

Flavor symmetries in the composite sector?
[Csaki, Falkowski, Weiler][Redi, Weiler]... :-|

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]

How does this affect CH?

Composite Twin Higgs Potential

* The UV contribution to the potential is a function of $\sin^2 h + \cos^2 h$. → no potential!

* An IR effect (CW):

$$V(h) = -cf^2\left[\sin^4\frac{h}{f} + \cos^4\frac{h}{f}\right]$$

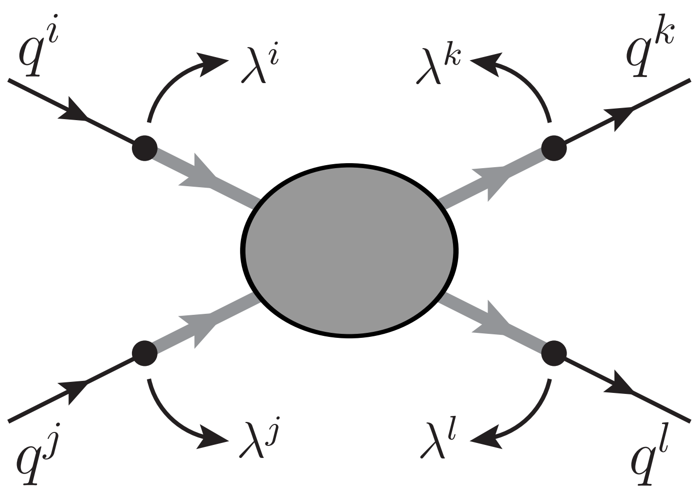
$$c \sim (\text{loop factor}) \times y_t^4 \times \log$$

* M_* is free to go up to $4\pi \times f$. As high as 10 TeV. A strongly coupled theory.

* Addresses the "where is everybody problem".

FCNCs in Composite Twin Higgs

$\bar{K}$-K mixing – the calculation is essentially identical:



$$C_4 \sim \lambda_1^L \lambda_2^R \lambda_2^R \lambda_1^L \frac{g_*^2}{M_*^2}$$

$$\sim \frac{m_s m_d}{v^2} \underbrace{\frac{g_*^2}{Y_*^2}}_{O(1)} \frac{1}{M_*^2}$$

$M_* \gtrsim 10$ TeV now looks much better.

Flavor wants a high compositeness scale.
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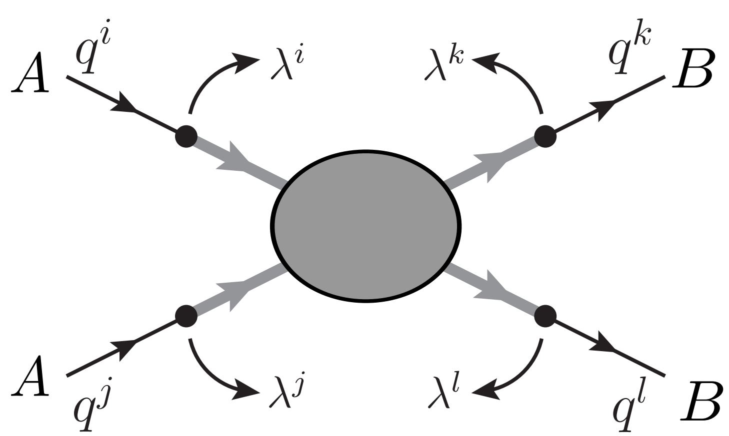
[RH, Stamou, Zupan in progress]

New Flavor Effects in Twin

* Doubling elementary sector → new worries.
* Some resonances will couple to both sectors.



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

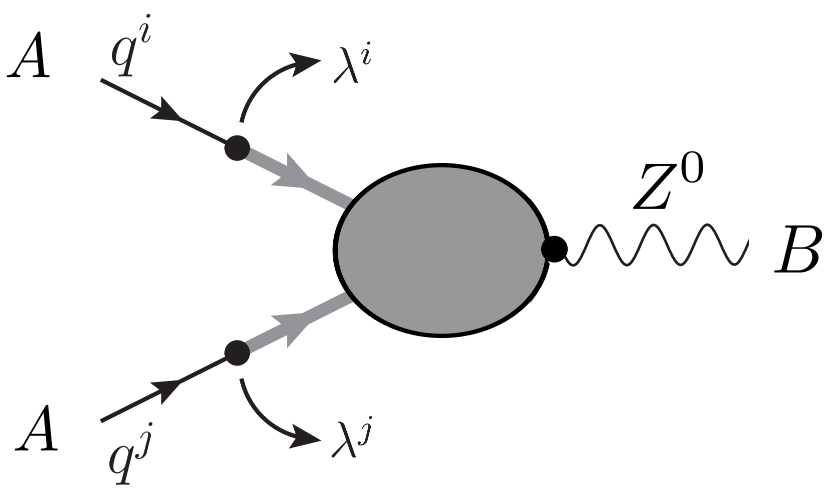
$t \to c + Z_B^* \to (c + \text{inv})$ or $(c$ + displaced stuff!$)$.

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

DM pheno [e.g. Farina (15)]

Funny Z couplings

* Another worry?



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

invisible Z decay ?

$t \to c\, Z_B^*$?

$k \to \pi\, Z_B^*$?

Funny Z couplings

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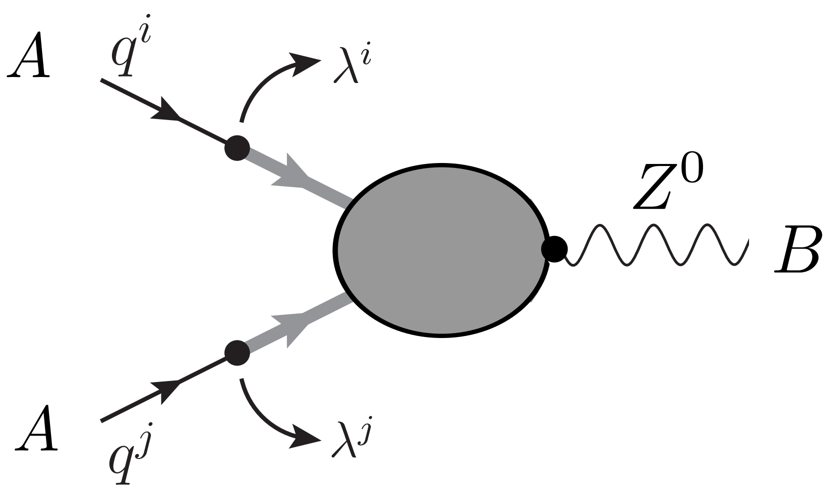

$$\overset{?}{\sim} \quad \frac{\lambda_i \lambda_j}{M_*^2} (q_i^A \gamma_\mu q_j)(H_B^\dagger \overleftrightarrow{D}^\mu H_B) \qquad + (A \leftrightarrow B)$$

No! These couplings are forbidden by custodial symmetry.

Recall: in CH, custodial symmetry can protect Z couplings if P_{LR} is preserved. [Agashe, Contino, DaRold, Pomarol]

Custodial protection

* For us, A↔B Z couplings are **always** forbidden.

Proof: $SO(8) \supset SO(4)_A \times SO(4)_B$

there is a nice spurion proof, but here I'll take a shortcut and make use of someone in the room.

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A-matter is singlet under $SO(4)_B$. P_{LR}^B ✓

there is a nice spurion proof, but here I'll take a shortcut and make use of someone in the room.

More Exotic Effects

* Work in progress:
  - LFV
  - Mixed A-B dipole.
  - What if the mirror photon has a mass?
  - ...

Conclusions

* Twin Higgs models can address the question "where is everybody?"

* Allows Composite Higgs models to be truly strongly coupled, raise mass of resonances.

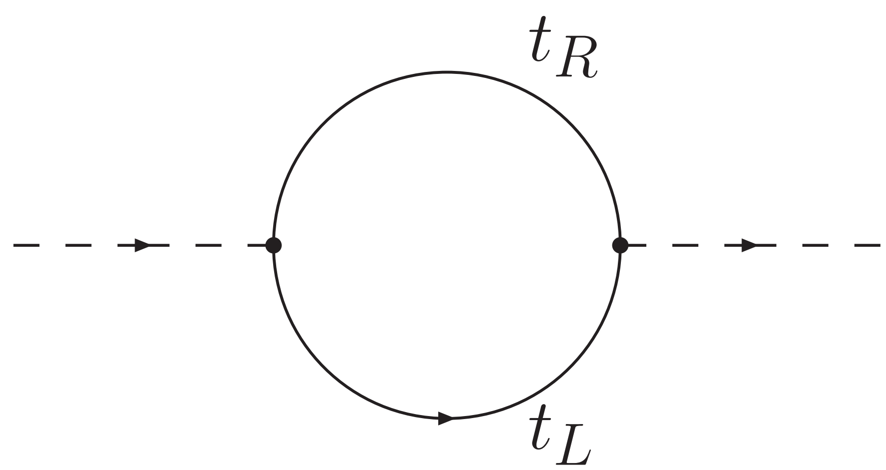
* Tension with Flavor limits are reduced.

* Flavor processes that involve the twin sector should be considered. Can lead to new signals, or exhibit new (old) protection mechanisms.

Deleted Scenes

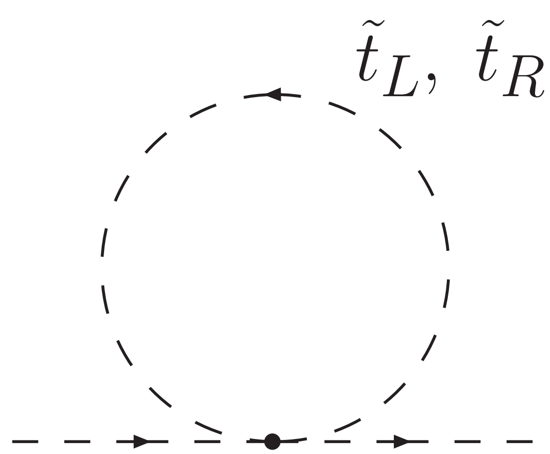
(Un)Colored Top Partners

color factor:



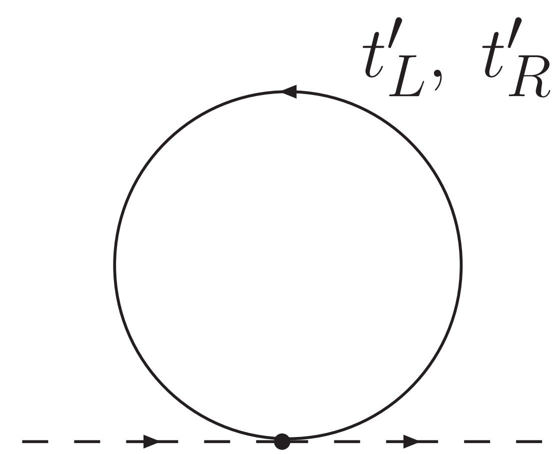
Standard Model

$\times 3$



Supersymmetry

or



Composite Higgs

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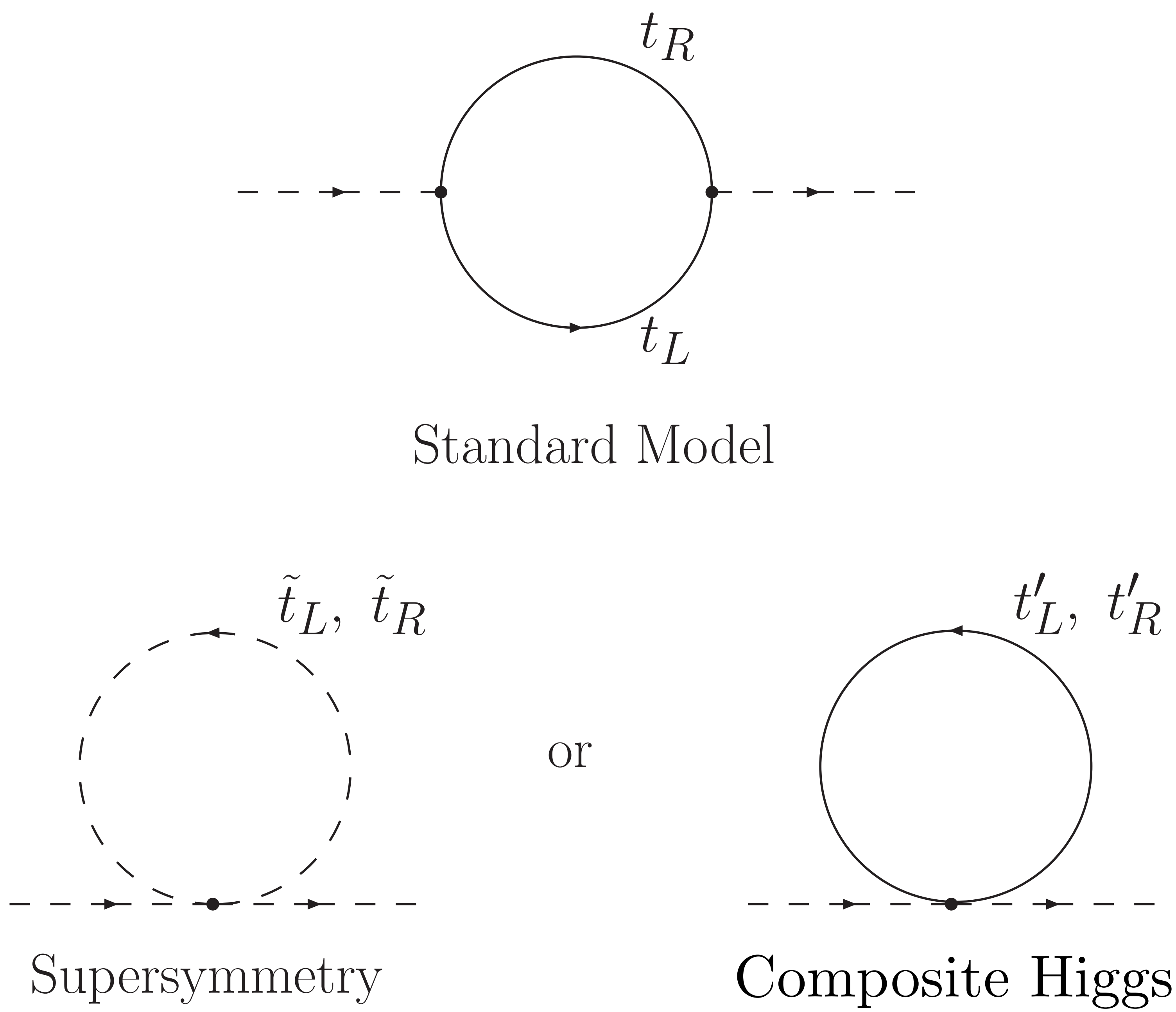
(Un)Colored Top Partners



color factor:

$\times 3$

$\times \not{3}$ 3'

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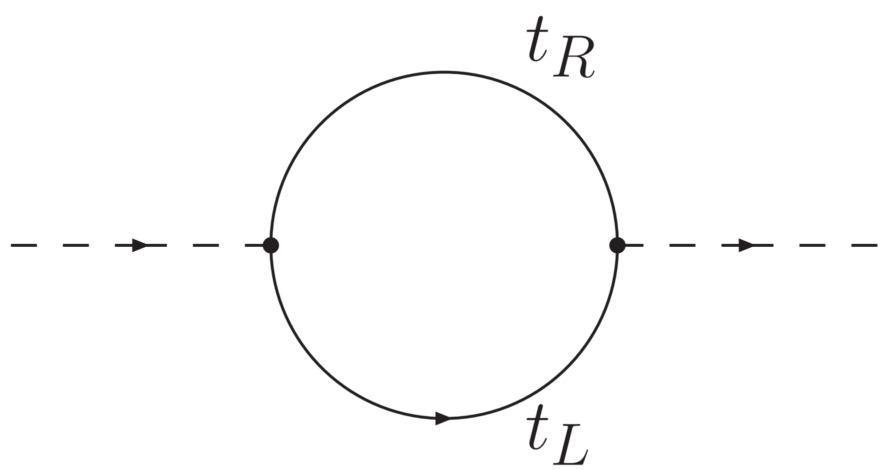

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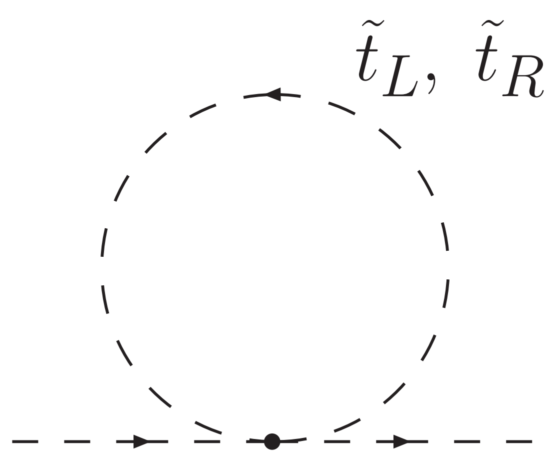

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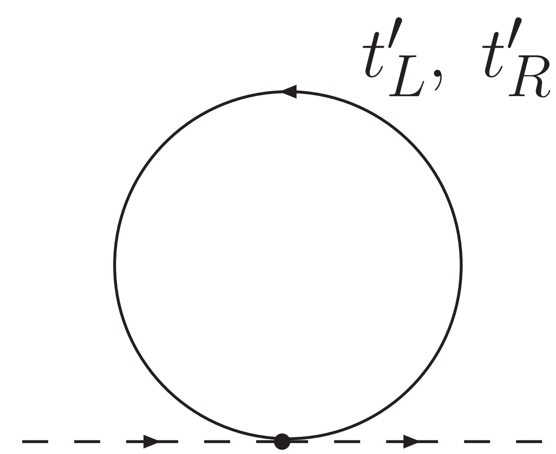

Composite Higgs

$\times$ ~~3~~ 3'

symmetry does not commute with color.

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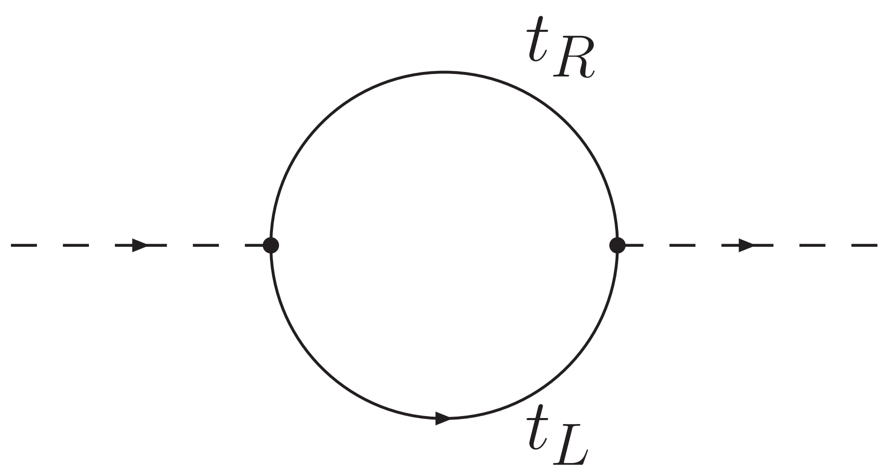

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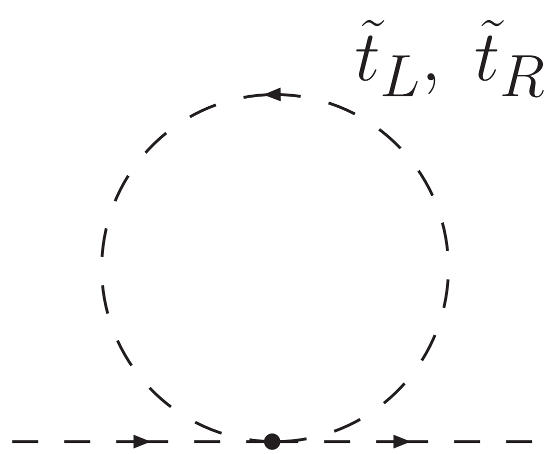

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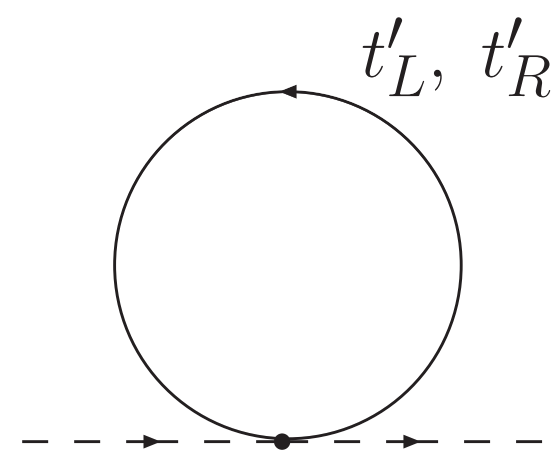

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Folded SUSY

Burdman, Chacko, Goh, RH (06')

Twin Higgs

Chacko, Goh ,RH (05')

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.

Radiative Corrections

* At 1-loop:

$$\Delta V =$$

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

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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)

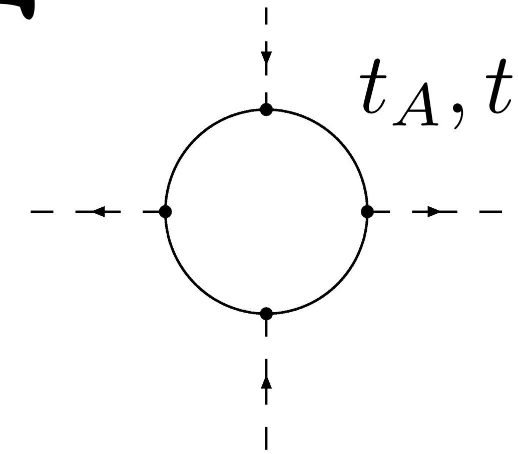
$$\Pi = \left(\begin{array}{ccc|c} 0 & 0 & 0 & h_1 \\ 0 & 0 & 0 & h_2 \\ 0 & 0 & 0 & 0 \\ \hline h_1^* & h_2^* & 0 & 0 \end{array}\right)$$

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

Higgs Couplings

* Higgs gauge boson couplings: $|D_\mu^A H_A|^2 + |D_\mu^B H_B|^2$
* 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 $\cos^4(\frac{v}{f})$

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
→ modified Higgs couplings are constrained.

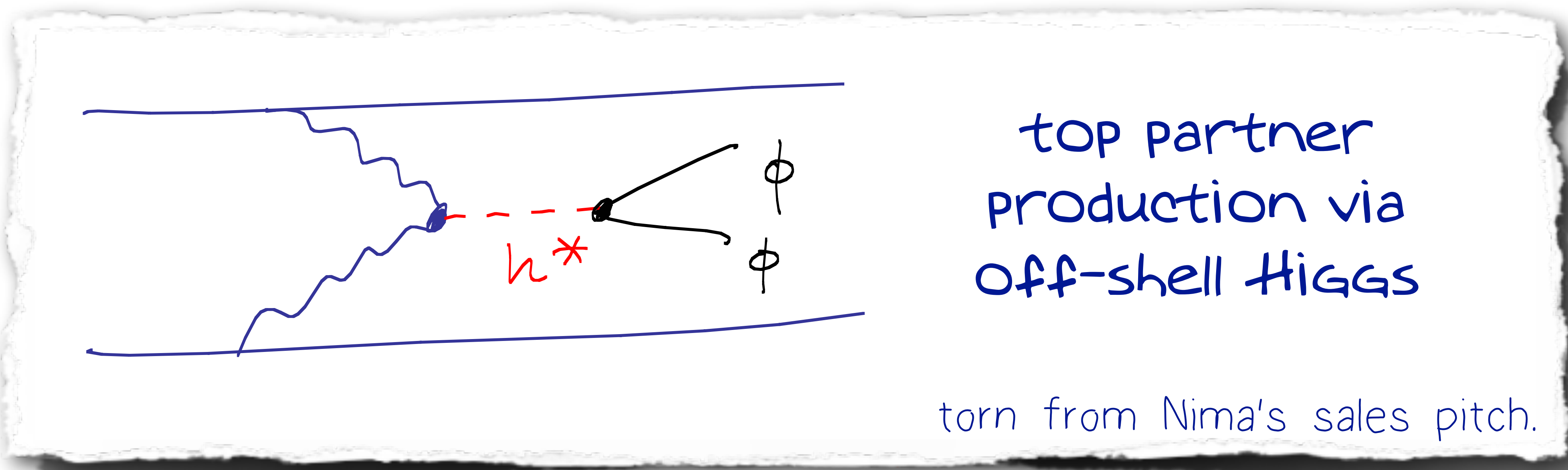
* Coupling modifications are "made up" by states at cutoff or by heavy Higgs for strong/weak UV completion (respectively).

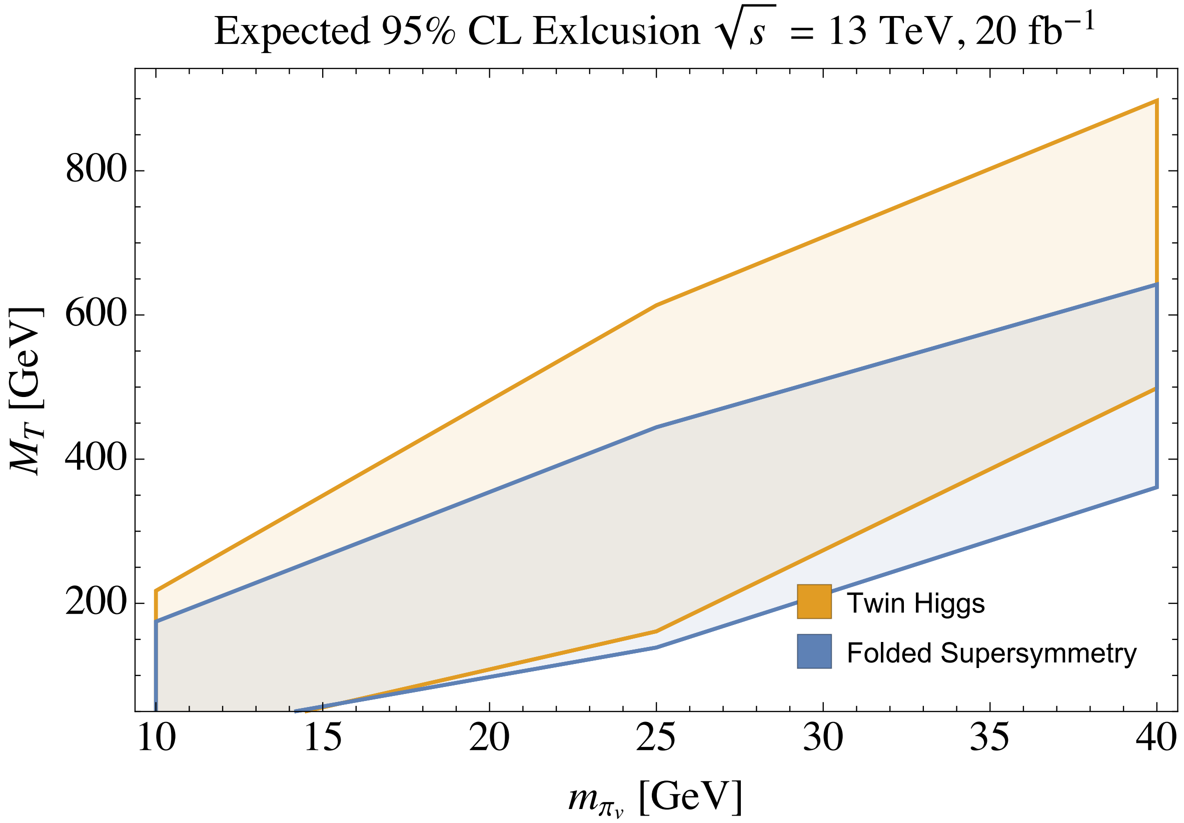
$$\Delta S \approx \frac{1}{6\pi}\left(\frac{v}{f}\right)^2 \log\left(\frac{m_{h_2}}{m_h}\right) \qquad \Delta T \approx -\frac{3}{16\pi\cos^2\theta_W}\left(\frac{v}{f}\right)^2 \log\left(\frac{m_{h_2}}{m_h}\right)$$

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

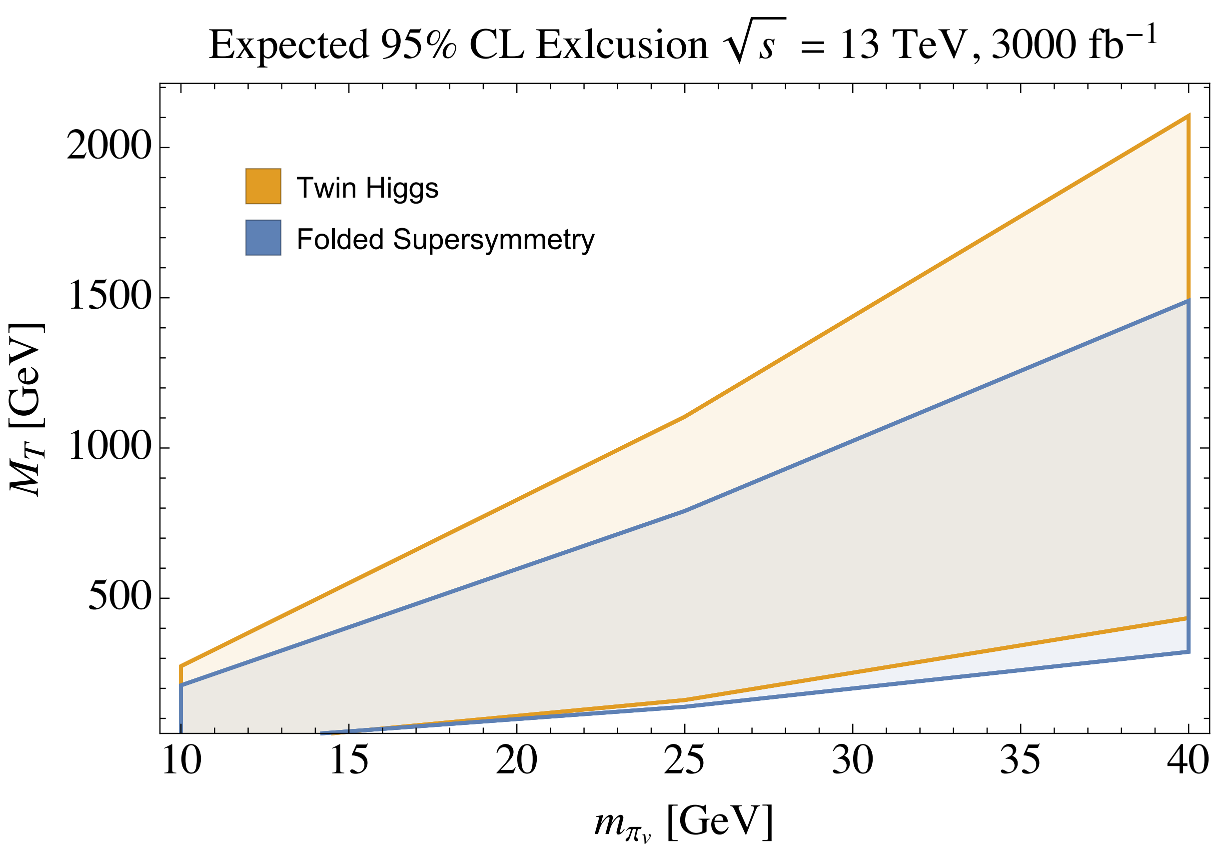
Other Signals

* 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:

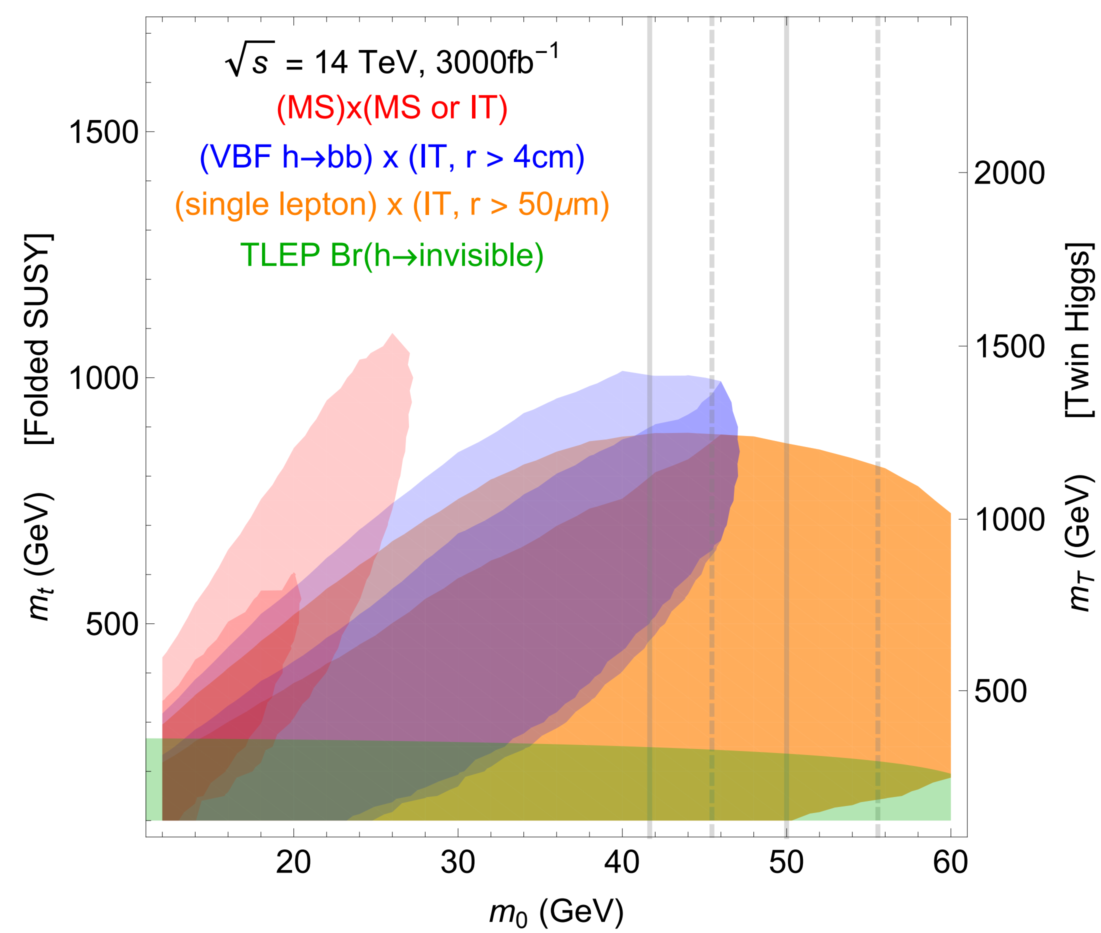




Expected 95% CL Exlcusion $\sqrt{s}$ = 13 TeV, 20 fb^{-1}
M_T [GeV]
m_{π_v} [GeV]
Twin Higgs
Folded Supersymmetry



Expected 95% CL Exlcusion $\sqrt{s}$ = 13 TeV, 3000 fb^{-1}
Twin Higgs
Folded Supersymmetry
M_T [GeV]
m_{π_v} [GeV]



$\sqrt{s}$ = 14 TeV, 3000fb^{-1}
(MS)x(MS or IT)
(VBF h→bb) x (IT, r > 4cm)
(single lepton) x (IT, r > 50μm)
TLEP Br(h→invisible)
m_t (GeV) [Folded SUSY]
m_T (GeV) [Twin Higgs]
m_0 (GeV)