Testing Naturalness

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We've come a long way since the Higgs was first proposed in 1964,

H^0 $J = 0$

Mass $m = 125.09 \pm 0.24$ GeV

Full width $\Gamma < 1.7$ GeV, CL = 95%

H^0 Signal Strengths in Different Channels

See Listings for the latest unpublished results.

Combined Final States = 1.10 ± 0.11

$W W^* = 1.08^{+0.18}_{-0.16}$

$Z Z^* = 1.29^{+0.26}_{-0.23}$

$\gamma\gamma = 1.16 \pm 0.18$

$b\bar{b} = 0.82 \pm 0.30$ (S = 1.1)

$\mu^+\mu^- < 7.0$, CL = 95%

$\tau^+\tau^- = 1.12 \pm 0.23$

$Z\gamma < 9.5$, CL = 95%

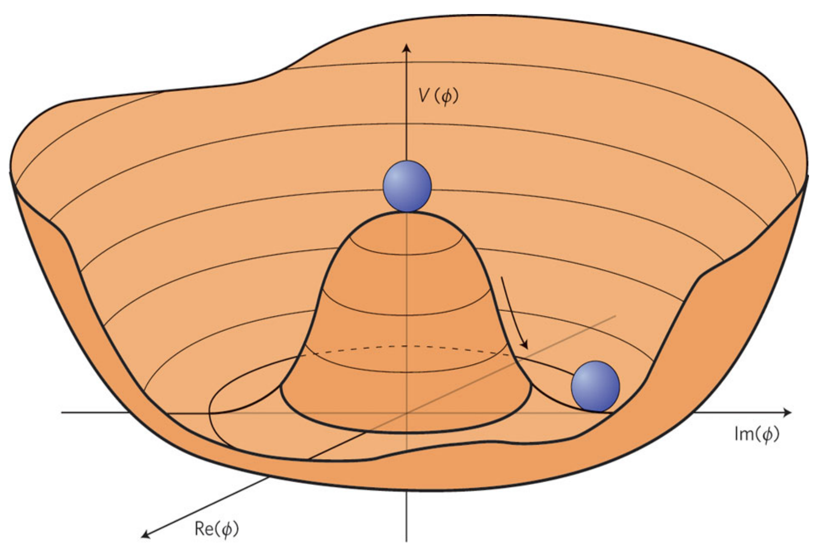
$t\bar{t}H^0$ Production = $2.3^{+0.7}_{-0.6}$

but there're still many interesting questions we have no answer to…

One example:

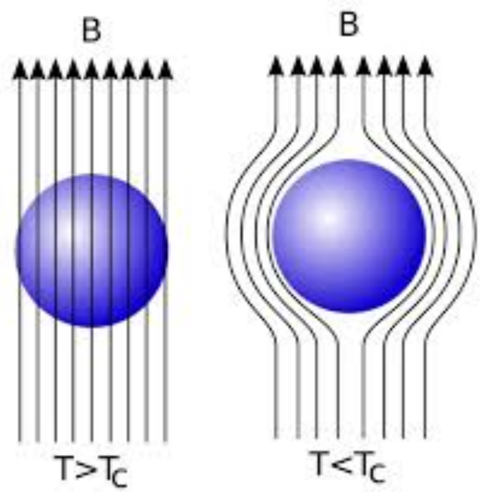
What is the microscopic theory that gives rise to the Higgs boson and its potential?

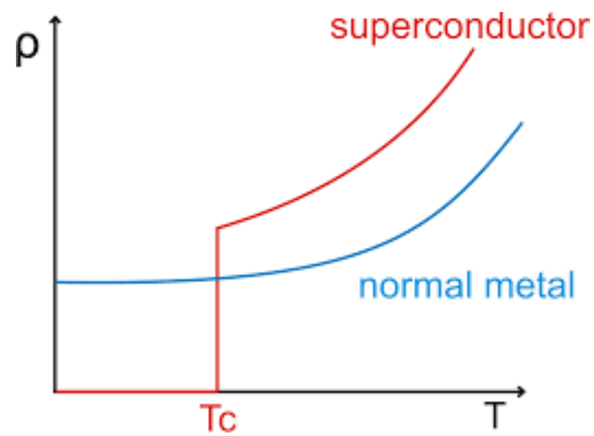
$$V(H) = -\mu^2|H|^2 + \lambda|H|^4$$



Our colleagues in condensed matter physics are very used to asking, and studying, this kind of questions.

One of the most beautiful examples is the superconductivity discovered in 1911:





Ginzburg-Landau theory from 1950 offered a macroscopic (ie effective) theory for conventional superconductivity,

$$V(\Psi) = \alpha(T)|\Psi|^2 + \beta(T)|\Psi|^4 \qquad \alpha(T) \approx a^2(T - T_c) \qquad \text{and} \qquad \beta(T) \approx b^2$$

What is the microscopic origin of the Ginzburg-Landau potential for superconductivity?

In 1957 Bardeen, Cooper and Schrieffer provided the microscopic (fundamental) theory that allows one to

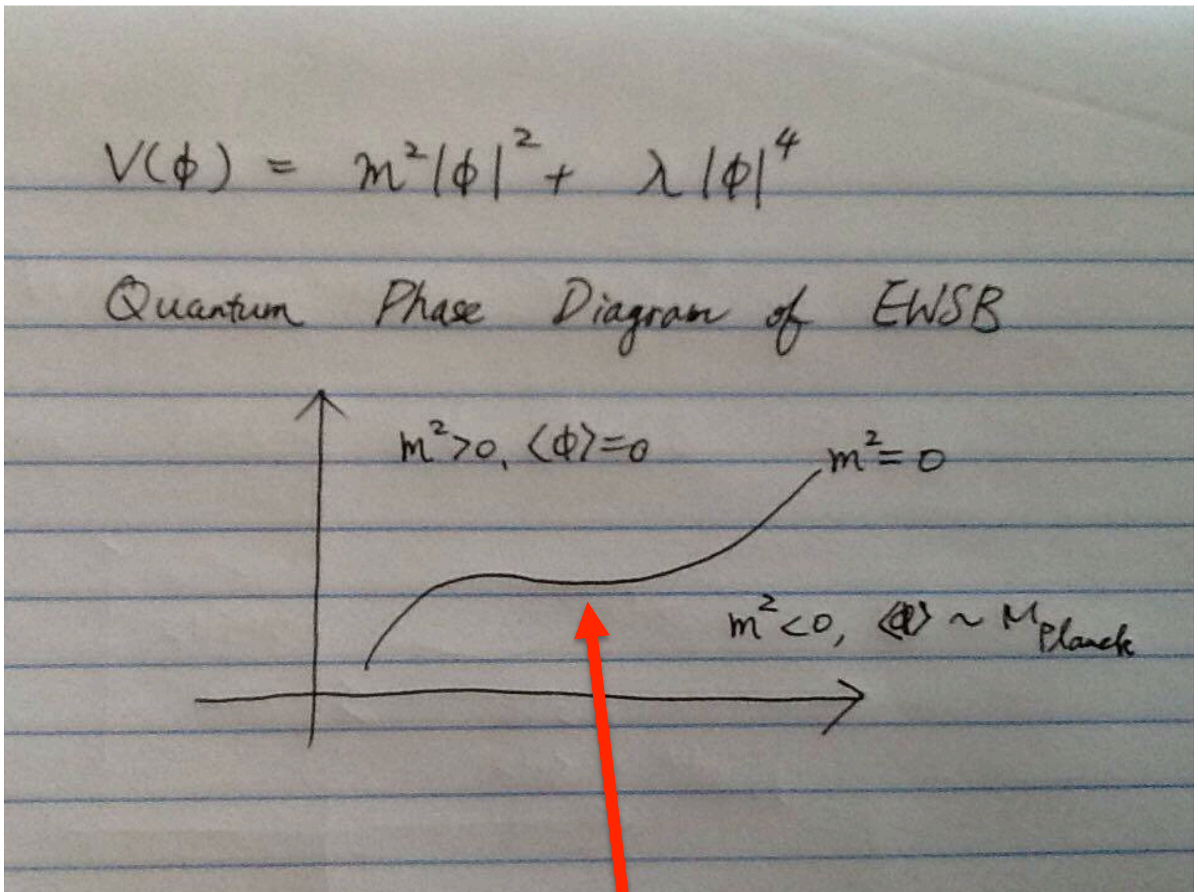
1) interpret $|\Psi|$ as the number density of Cooper pairs

2) calculate coefficients of $|\Psi|^2$ and $|\Psi|^4$ in the potential.

We do not know the corresponding microscopic theory for Higgs potential.

In fact, we have NOT even measured the Higgs potential.

The question on the microscopic origin of the Higgs potential can be formulated in terms of phase transition and criticality:



Mh=125 GeV. We are sitting extremely close to the criticality. **WHY??**

One popular (appealing) possibility -- the critical line is a locus of enhanced symmetry.

This could be why the electroweak vacuum likes to sit, practically, on top of the critical line.

Theorists could come up with (pretty much) only two examples of such enhanced symmetries:

- Bosonic symmetry: the (spontaneously broken) global symmetry.
  The Higgs is a pseudo-Nambu-Goldston boson and the model goes by the name of "composite Higgs models."

- Fermionic symmetry: the (broken) supersymmetry.

The fact that we have not seen signs of SUSY or CHM only **deepens** the mystery, of why we are sitting close to the critical line of EWSB!

Some of our colleagues argued that the SM by itself is UV-complete and, therefore, there's no need for new physics.

This is a reasoning that has failed **many times** through out the course of the history:

- QED (photons+electrons) is a UV-complete theory. But physics didn't stop there.
- QCD (gluons+quarks) is also a UV-complete theory. Again physics didn't stop there.
- SM with one generation of fermion is UV-complete. "WHO ORDERED THAT?"

Not to mention there is also all these empirical evidence on physics beyond the SM: Dark matter, Baryon asymmetry and etc.

So how do we measure if the electroweak critical line is a locus of enhanced symmetry?

The most direct approach, is to look for partners of the SM particles under the (enhanced) symmetry.

One salient common feature of all models is the existence of the symmetry-partner of the SM top quark → the top partner.

Top partners can be either spin-0 in Supersymmetry (the top squark) or spin-1/2 in composite Higgs models (the vector-like quark).

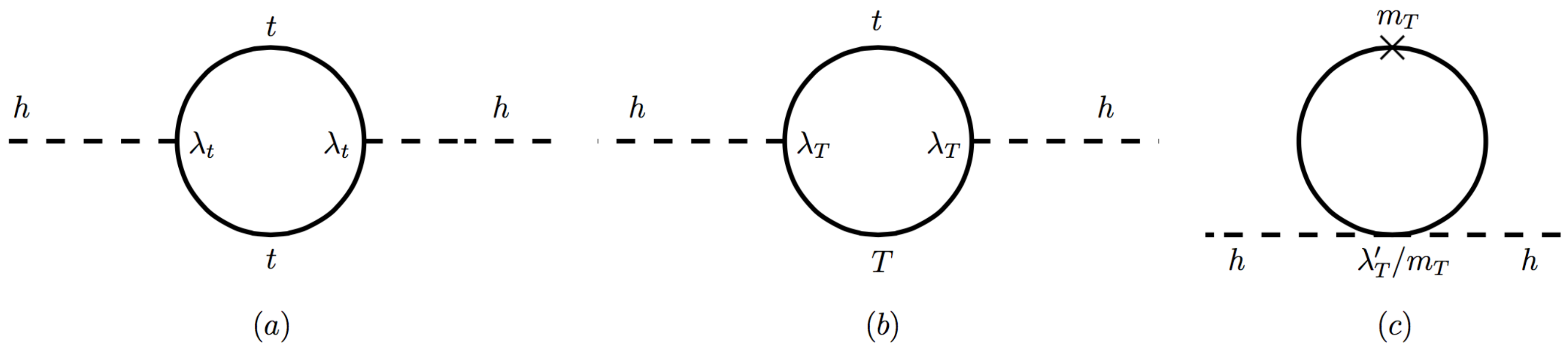
They serve two purposes:

1) Their existence provides a "microscopic origin" for the special "minus sign" in the Higgs potential:

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

This sign could be generated by top partners at the loop-level through the celebrated Coleman-Weinberg mechanism.

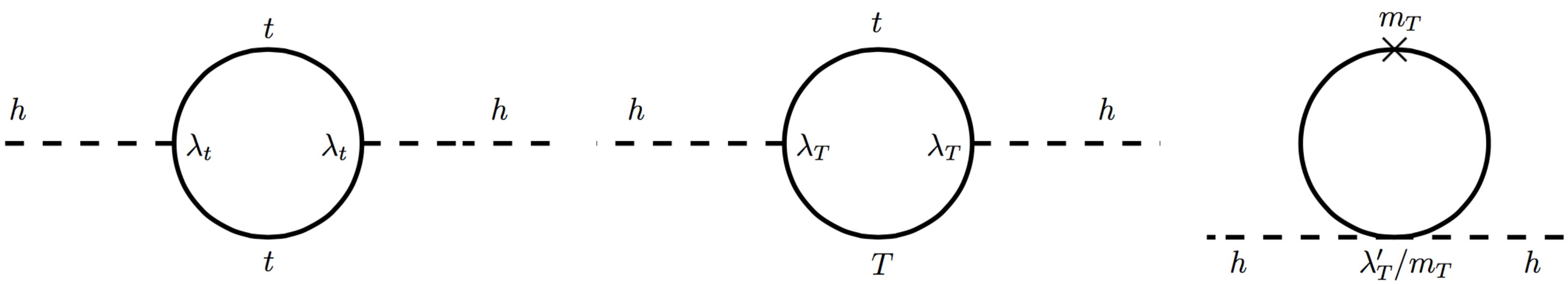
2) the top partners are also responsible for cancelling the top quadratic divergences in the Higgs mass-squared:



They must have a significant coupling to the Higgs, but they are not necessarily colored!

(The uncolored partners (ie Neutral Naturalness) can be inferred from exotic Higgs decays.)

In particular, the different couplings are related by the enhanced symmetry:



(a) (b) (c)

$$\lambda'_T = \lambda_t^2 + \lambda_T^2$$

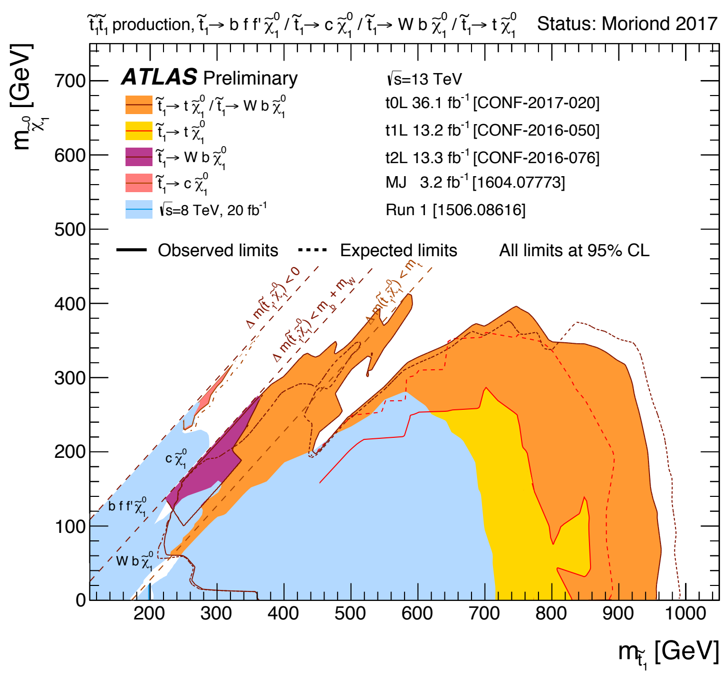
This relation is an unambiguous prediction of an enhanced symmetry!

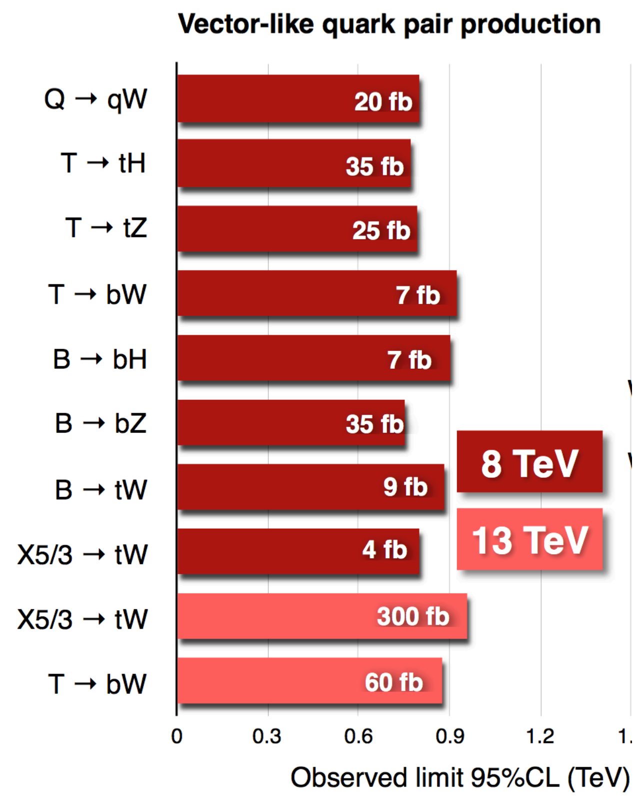
Two-step program to test Naturalness and the existence of a new symmetry:

1. Find the (colored) top partner.

2. Test the naturalness relation among the couplings to the Higgs.

Colored top partners have been searched for extensively at the LHC:





One might ask:

why worry about step 2) when we have seen no empirical sign of a top partner??

The answer:

We live in a unique juncture in history!

As part of the planning for a new generation of particle accelerators, we would like to know the ability of a new hadron machine to unambiguously establish the Naturalness principle, should a top partner-like particle be discovered.

Our goal:

How well can we test the presence of a new symmetry in relation to Naturalness ?

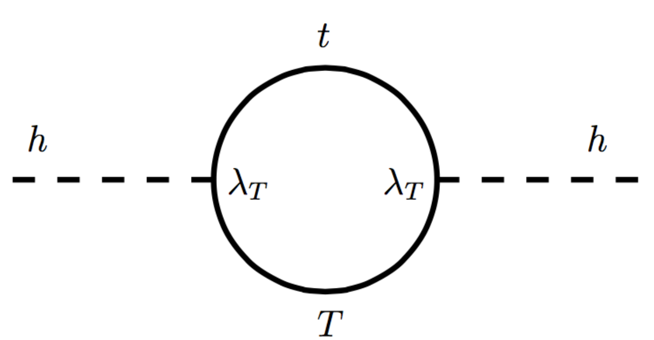
We will focus on a fermionic top partner first.

(Colored scalars generically have smaller production rates than fermions at the same mass. So the reach for scalars will be worse.)

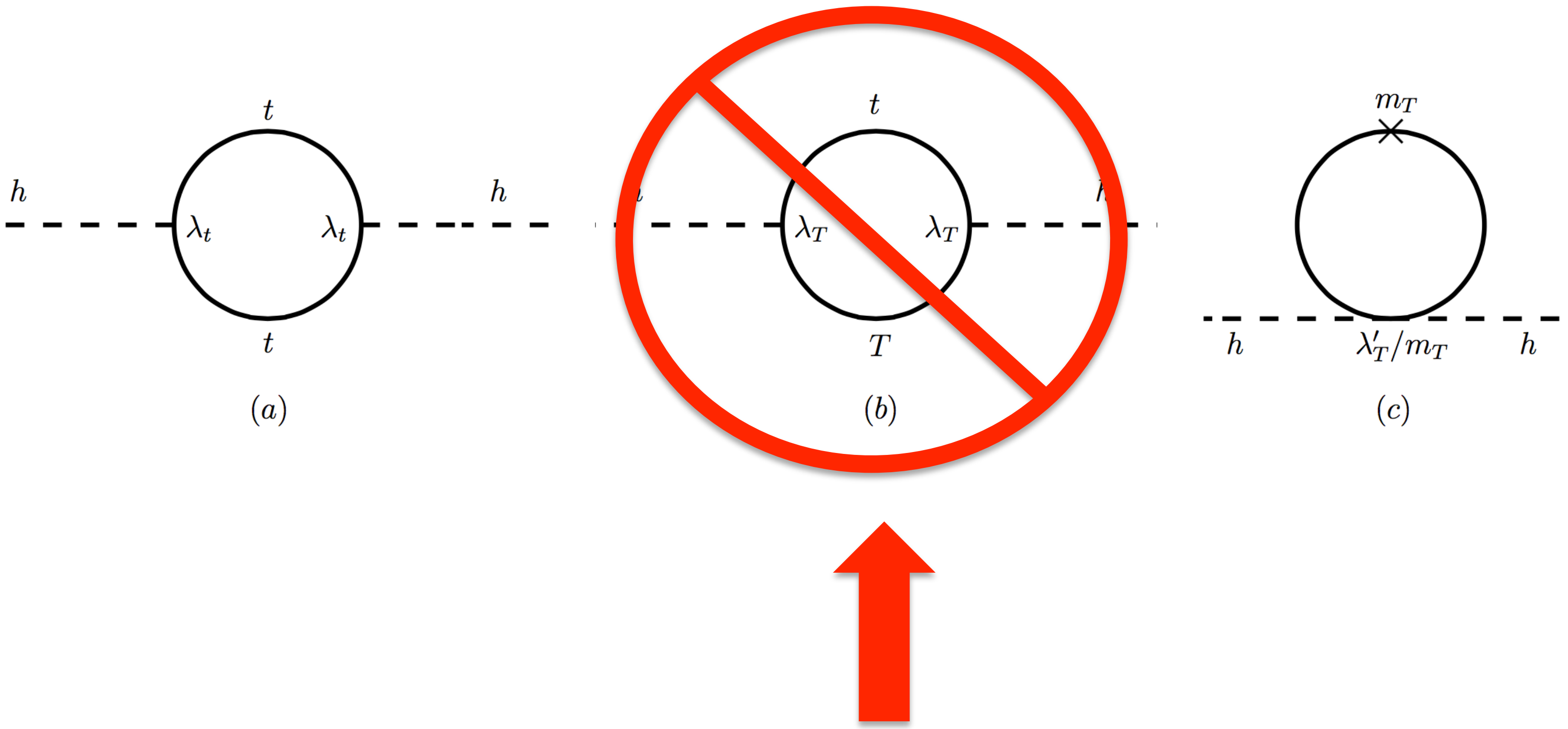
C.-R. Chen, T. Liu, J. Hajer, IL and H. Zhang: 1705.07743

There have been previous studies on testing the cancellation of quadratic divergences:

Perelstein, Peskin, and Pierce: hep-ph/0310039



But the particular coupling they relied on is not generic:



If T-parity is imposed, this particular coupling vanishes!

H.-C. Cheng, IL and L.-T. Wang: hep-ph/0510225

As an exploratory study, we constructed a simplified model for a fermionic top partner, by introducing a vector-like pair of weak isospin singlet (U, U^c):

$$\mathcal{L}_U = u_3^c \left(c_0 f U + c_1 H^\dagger q_3 + \frac{c_2}{2f} |H|^2 U + \frac{c_3}{6f^2} |H|^2 H^\dagger q_3 + \dots \right)$$
$$+ U^c \left(\widehat{c}_0 f U + \widehat{c}_1 H^\dagger q_3 + \frac{\widehat{c}_2}{2f} |H|^2 U + \frac{\widehat{c}_3}{6f^2} |H|^2 H^\dagger q_3 + \dots \right) + \text{h.c.}\ .$$

$$|H|^2 = H^\dagger H$$

Mass eigenstates before EWSB:

$$t'^c = \frac{\widehat{c}_0 u_3^c - c_0 U^c}{c}\ , \qquad t' = q_3$$
$$T'^c = \frac{\widehat{c}_0 U^c + c_0 u_3^c}{c}\ , \qquad T' = U$$

$$m_{T'} = fc\ , \qquad c = \sqrt{c_0^2 + \widehat{c}_0^2}$$

The quadratically divergent part of the Coleman-Weinberg potential is

$$V_{\text{quad}}^{T} = \frac{\Lambda^2}{16\pi^2}\,\mathrm{tr}\,\mathcal{M}^2\ , \qquad\qquad \mathcal{M}^2 = \mathcal{M}(H)^\dagger \mathcal{M}(H)\ ,$$

$$\mathcal{M}(H) = \begin{pmatrix} 0 & 0 \\ 0 & m_{T'} \end{pmatrix} + \begin{pmatrix} \lambda_{t'} & 0 \\ \lambda_{T'} & 0 \end{pmatrix} H + \begin{pmatrix} 0 & \alpha_{t'} \\ 0 & \alpha_{T'} \end{pmatrix} \frac{|H|^2}{2m_{T'}} + \mathcal{O}\left(H^3\right)$$

Cancellation of quadratic divergences in the Higgs mass now leads to

$$\mathrm{tr}\,\mathcal{M}^2 = \text{constant} + \mathcal{O}\left(H^3\right)$$

$$\alpha_{T'} = -\left|\lambda_{T'}\right|^2 - \left|\lambda_{t'}\right|^2$$

$$\lambda_{T'} = \frac{c_0 c_1 + \widehat{c}_0 \widehat{c}_1}{c}$$

$$\alpha_{T'} = c_0 c_2 + \widehat{c}_0 \widehat{c}_2$$

$$\lambda_{t'} = \frac{\widehat{c}_0 c_1 - c_0 \widehat{c}_1}{c}$$

The simplified model covers many models:

$$|c_1|^2 + c_0 c_2 = -|\widehat{c}_1|^2 - \widehat{c}_0 \widehat{c}_2$$

Model	Coset		SU(2)	c_0	c_1	c_2	$\widehat{c}_0$	$\widehat{c}_1$	$\widehat{c}_2$
Toy model	$\frac{SU(3)}{SU(2)}$	[22]	**1**	λ_1	$-\lambda_1$	$-\lambda_1$	λ_2	0	0
Simplest	$\left(\frac{SU(3)}{SU(2)}\right)^2$	[23]	**1**	λ	$-\lambda$	$-\lambda$	λ	λ	$-\lambda$
Littlest Higgs	$\frac{SU(5)}{SO(5)}$	[14]	**1**	λ_1	$-\sqrt{2}i\lambda_1$	$-2\lambda_1$	λ_2	0	0
Custodial	$\frac{SO(9)}{SO(5)\,SO(4)}$	[20]	**2**	y_1	$\frac{i}{\sqrt{2}}y_1$	$-\frac{1}{2}y_1$	y_2	0	0
T-parity invariant	$\frac{SU(3)}{SU(2)}$	[19]	**1**	λ	$-\lambda$	$-\lambda$	$-\lambda$	$-\lambda$	λ
T-parity invariant	$\frac{SU(5)}{SO(5)}$	[19]	**1**	λ	$-\sqrt{2}i\lambda$	-2λ	$-\lambda$	$-\sqrt{2}i\lambda$	2λ
Mirror twin Higgs	$\frac{SU(4)\,U(1)}{SU(3)\,U(1)}$	[24]	**1**	0	$i\lambda_t$	0	λ_t	0	$-\lambda_t$

It is straightforward to construct a similar effective Lagrangian for one SU(2) doublet partner.

There are further complications and simplifications after EWSB.

- The complication:

$$t^c = t'^c + \mathcal{O}\left(\frac{v^2}{m_{T'}^2}\right) , \qquad t = t' - \lambda_{T'}^* \frac{v}{m_{T'}} T' + \mathcal{O}\left(\frac{v^2}{m_{T'}^2}\right) ,$$

$$T^c = T'^c + \mathcal{O}\left(\frac{v^2}{m_{T'}^2}\right) , \qquad T = T' + \lambda_{T'} \frac{v}{m_{T'}} t' + \mathcal{O}\left(\frac{v^2}{m_{T'}^2}\right) ,$$

$$\mathcal{L}_T = m_T T^c T + \lambda_t v t^c t + \frac{\lambda_t}{\sqrt{2}} h t^c t + \frac{\lambda_T}{\sqrt{2}} h T^c t + \frac{a_t v}{\sqrt{2} m_T} h t^c T + \frac{a_T v}{\sqrt{2} m_T} h T^c T$$
$$+ \frac{\alpha_t}{4 m_T} h^2 t^c T + \frac{\alpha_T}{4 m_T} h^2 T^c T + \frac{b_t v}{4 m_T^2} h^2 t^c t + \frac{b_T v}{4 m_T^2} h^2 T^c t + \mathcal{O}\left(h^3, \frac{v^2}{m_T^2}\right) + \text{h.c.}$$

$$a_t = \alpha_{t'} + \lambda_{T'}^* \lambda_{t'} \ , \qquad a_T = \alpha_{T'} + |\lambda_{T'}|^2 \ ,$$

$$b_t = \beta_{t'} - \alpha_{t'} \lambda_{T'} \ , \qquad b_T = \beta_{T'} - \alpha_{T'} \lambda_{T'} \ .$$

- The simplification:

The previous “Naturalness relation”

$$\alpha_{T'} = -\left|\lambda_{T'}\right|^2 - \left|\lambda_{t'}\right|^2$$

now simplifies to

$$\boxed{a_T = -\left|\lambda_t\right|^2 + \mathcal{O}\left(\frac{v^2}{m_T^2}\right)}$$

$$\mathcal{L}_T = m_T T^c T + \lambda_t v t^c t + \frac{\lambda_t}{\sqrt{2}} h t^c t + \frac{\lambda_T}{\sqrt{2}} h T^c t + \frac{a_t v}{\sqrt{2} m_T} h t^c T + \frac{a_T v}{\sqrt{2} m_T} h T^c T$$
$$+ \frac{\alpha_t}{4 m_T} h^2 t^c T + \frac{\alpha_T}{4 m_T} h^2 T^c T + \frac{b_t v}{4 m_T^2} h^2 t^c t + \frac{b_T v}{4 m_T^2} h^2 T^c t + \mathcal{O}\left(h^3, \frac{v^2}{m_T^2}\right) + \text{h.c.}$$

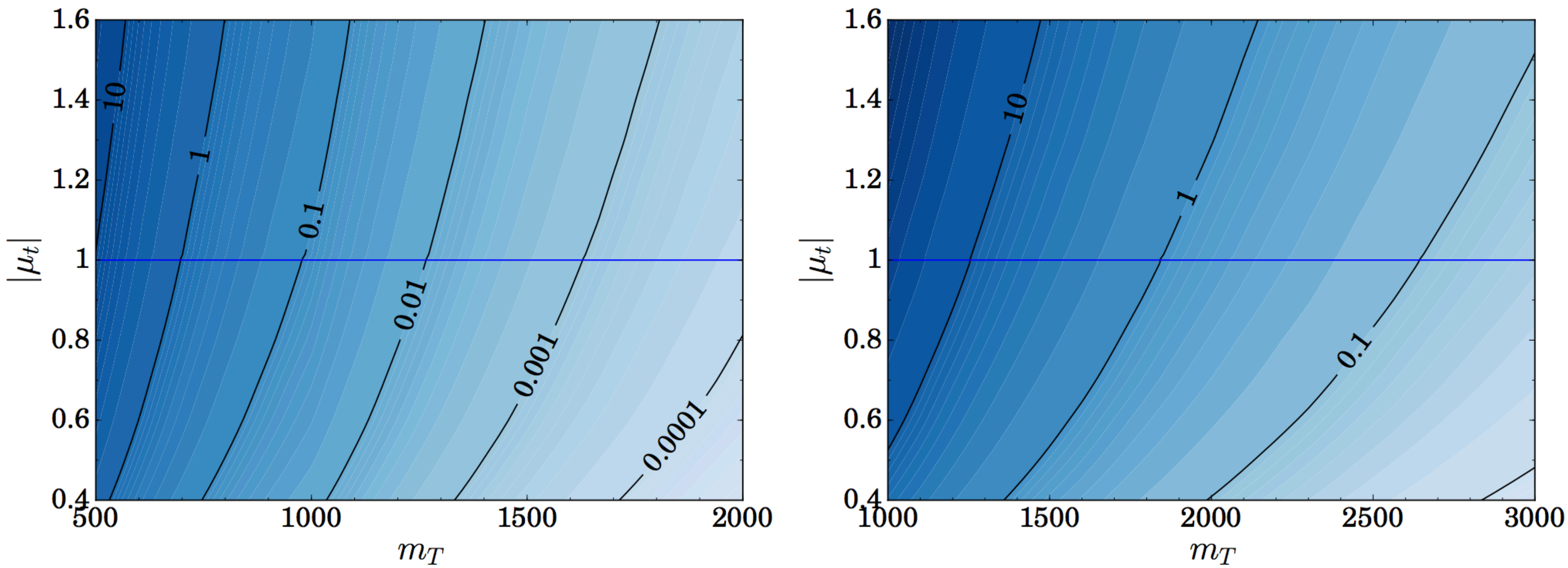
Practically, this is a very useful simplification. We only need to make two measurements:

- SM top quark coupling to the Higgs →
  Can be measured using pp → tth at the (HL)-LHC and ILC.

- A single top partner coupling to the Higgs →
  Base our study on pp-> TTh at a futuristic(!) 100 TeV pp collider.

We employ the LO production cross-section of TTh from Madgraph:

(The contours are in unit of fb!)



(a) 14 TeV (b) 100 TeV

$$\mu_t = -\frac{a_T}{\lambda_t^2} + \mathcal{O}\left(\frac{v^2}{m_T^2}\right)$$

We consider the decay channel:

(B^0 = Z or h)

$$pp \to \bar{T}Th \to (\bar{t}B^0)(tB^0)h$$

In particular, for multi-TeV top partners the boson in the decay of T is going to be boosted:

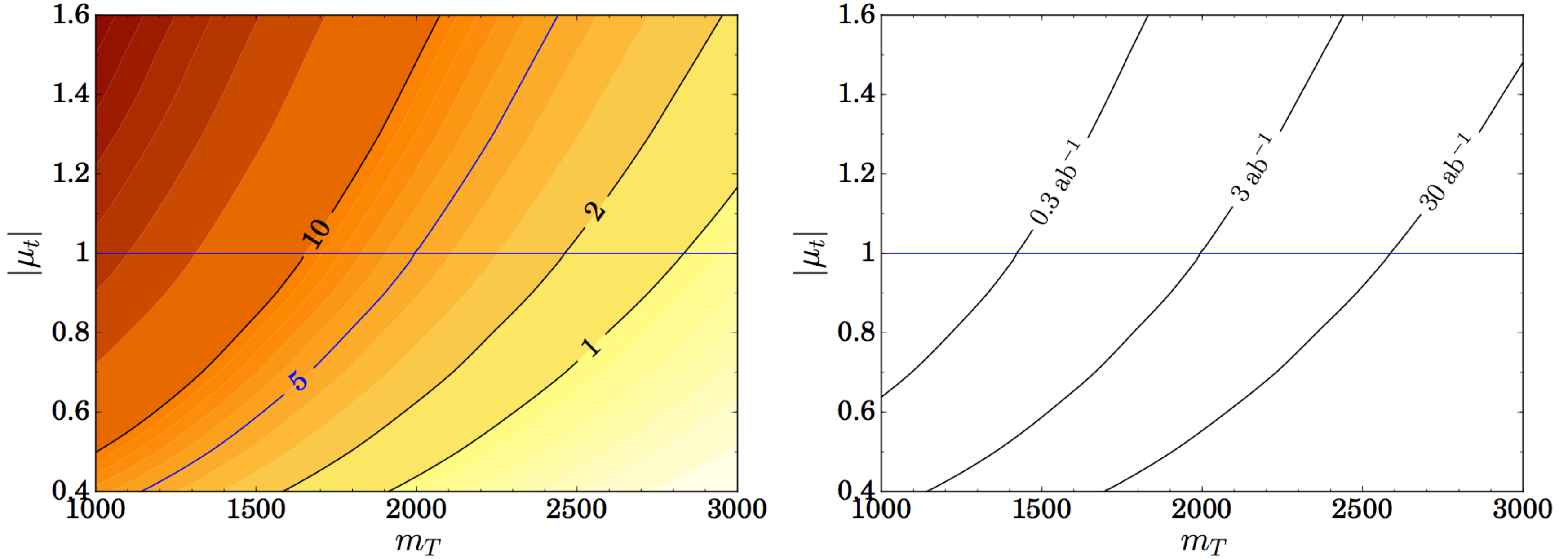
$$pp \to \bar{T}Th \to (\bar{t}B^0)(tB^0)h \to (\bar{t}j)(tj)h$$

Irreducible background: $pp \to \bar{t}t + 3B^0$

Reducible background: $pp \to \bar{t}t + jjjj$

One of my collaborators (Jan Hajer) wrote a fancy Boosted Decision Tree to perform the multivariate analysis.

When all is said and done:



(a) Luminosity of $3\,\text{ab}^{-1}$.

(b) Significance of 5σ.

Figure 3: Discovery reach defined as $Z(b|b+s)$ for pair production of top partners in association with one Higgs boson at 100 TeV. We present the reaches for a fixed luminosity of $3\,\text{ab}^{-1}$ in Figure (a) and for a fixed significance of 5σ with luminosities of 0.3, 3, $30\,\text{ab}^{-1}$ in Figure (b).

Assuming top Yukawa has been measured to SM value.

Concluding Remark:

- The Higgs boson is the most exotic state of matter and the electroweak criticality is the most bizarre type of quantum criticality in Nature.

- Our understanding so far is quite preliminary (at the level of Ginzburg-Landau picture for the superconductivity).

  Need to pin down a microscopic picture.

- Testing Naturalness is an integral component toward establishing the microscopic origin of the Higgs boson and its potential.