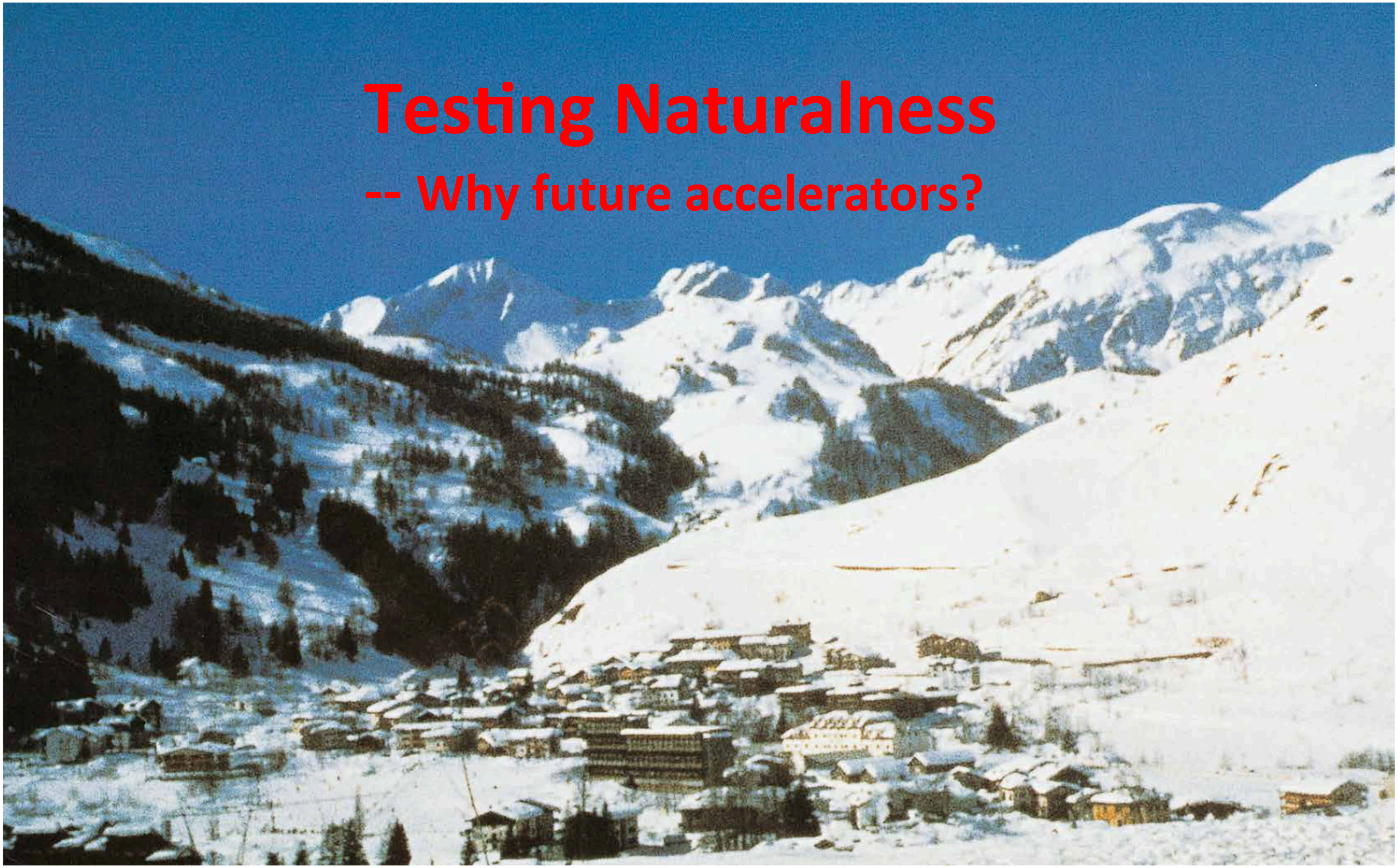
Testing Naturalness

Les Rencontres de Physique de la Vallée d'Aoste

La Thuile, Aosta Valley, Italy

Ian Low
CERN/Argonne/Northwestern

March 1, 2018



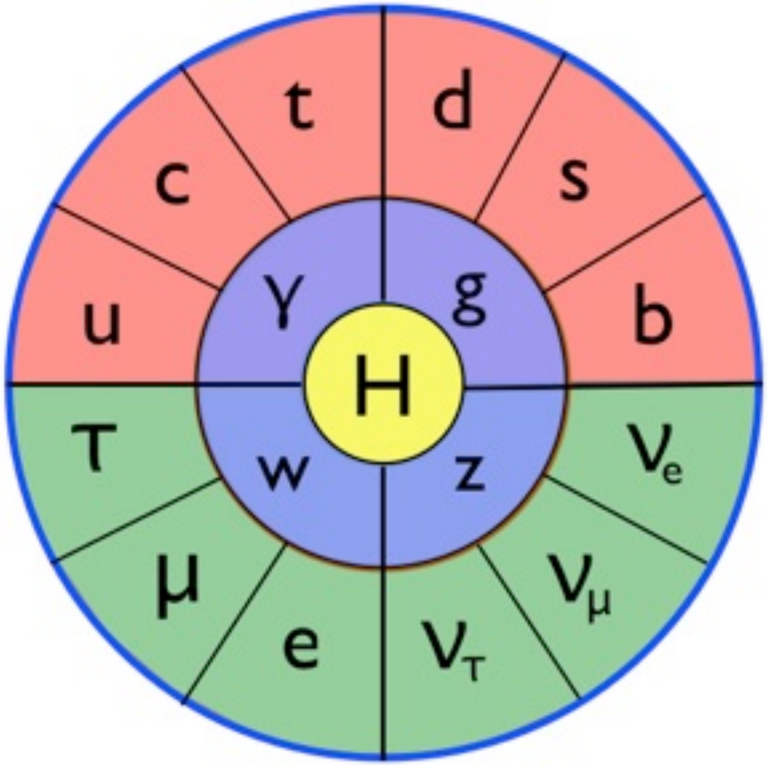
Testing Naturalness

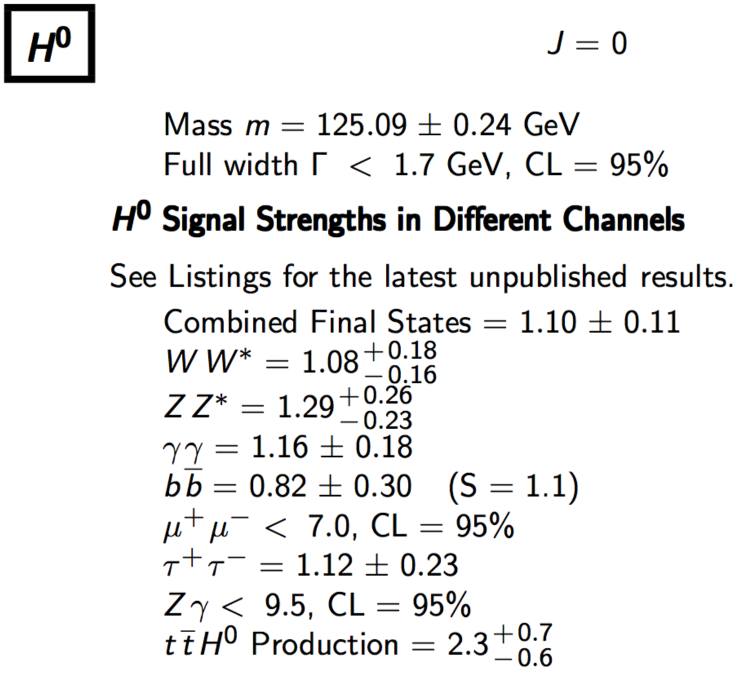
-- Why future accelerators?

Les Rencontres de Physique
de la Vallée d'Aoste
La Thuile, Aosta Valley, Italy

Ian Low
CERN/Argonne/Northwestern
March 1, 2018

After the discovery of the Higgs boson in 2012, we have a complete model of particle physics:





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

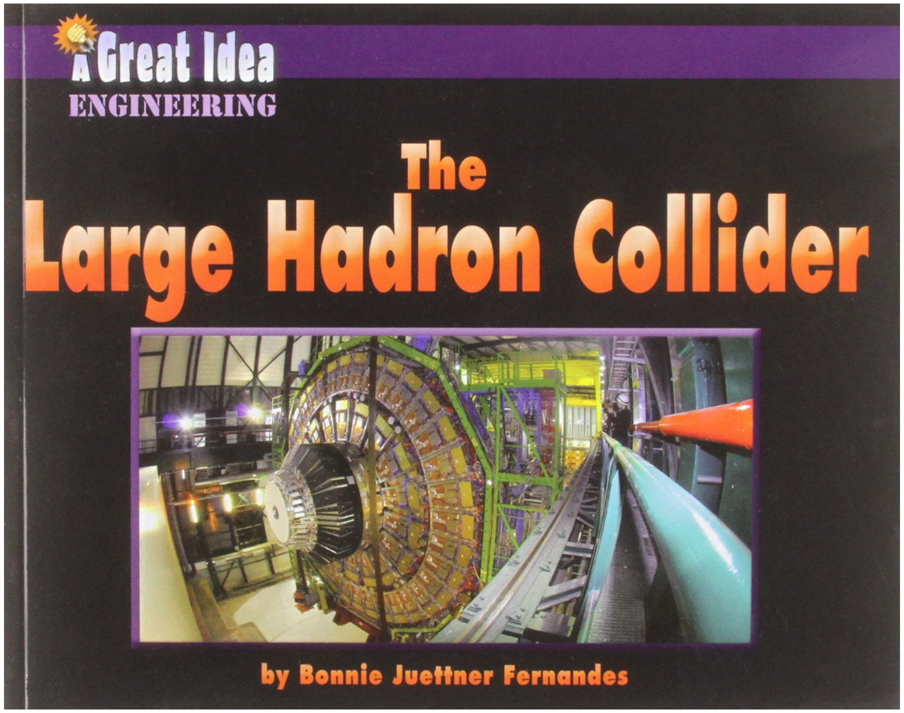
See Listings for the latest unpublished results.

Combined Final States $= 1.10 \pm 0.11$
$W W^* = 1.08^{+0.18}_{-0.16}$
$Z Z^* = 1.29^{+0.26}_{-0.23}$
$\gamma\gamma = 1.16 \pm 0.18$
$b\bar{b} = 0.82 \pm 0.30$ (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 $= 2.3^{+0.7}_{-0.6}$

We’ve come a long way since 1964, but there’re still many questions we have no answer to.

We’ve come a long way since 1964, but there’re still many questions we have no answer to.

I was reminded of one such question a few years back, when I was reading my kids a nice children’s book on the LHC:



A Great Idea
ENGINEERING
The
Large Hadron Collider
by Bonnie Juettner Fernandes

For primary school age.
ISBN: 9781603575805

My then 7-year-old asked the following question that I (still) have no answer to:

My then 7-year-old asked the following question that I (still) have no answer to:

What is the Higgs made of?

My then 7-year-old asked the following question that I (still) have no answer to:

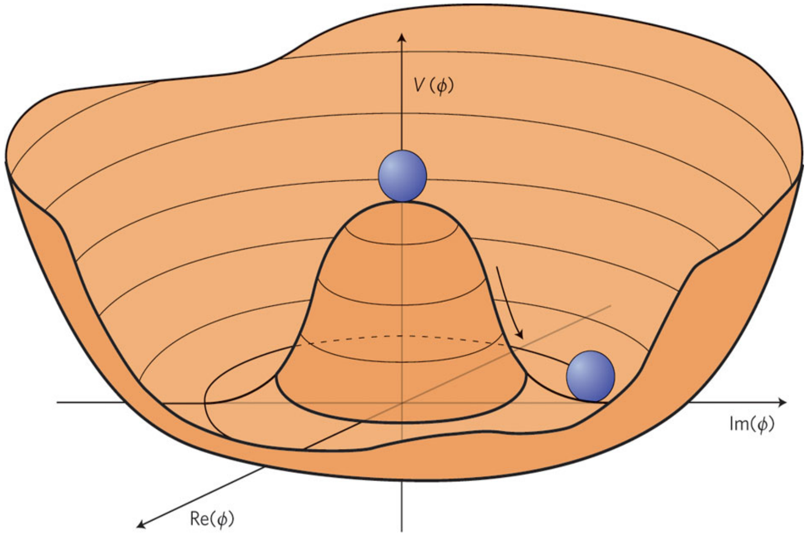
What is the Higgs made of?

(When I couldn’t answer his question, he was not impressed: )

A physics Ph.D. could rephrase slightly:

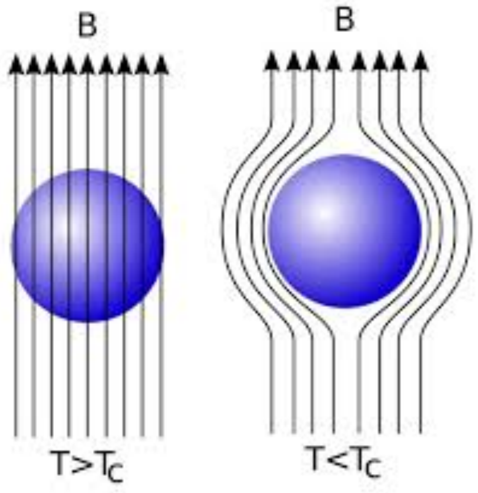
What is the microscopic theory that gives rise to the Higgs boson and its potential?

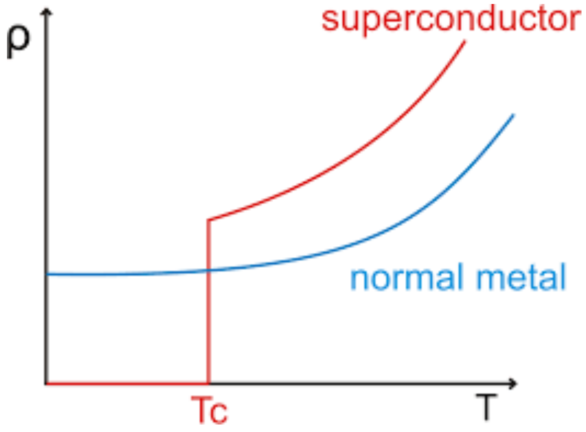
$$V(H) = -\mu^2|H|^2 + \lambda|H|^4$$



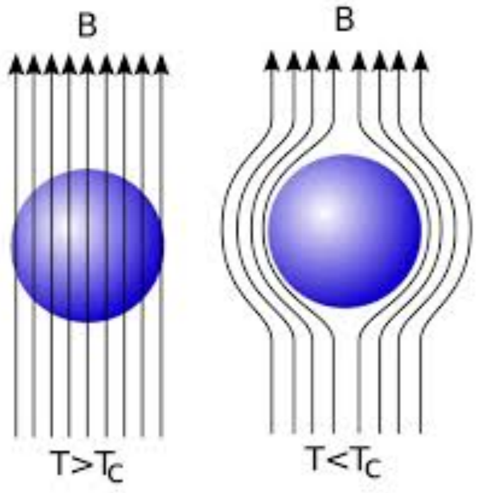
Our colleagues in condensed matter physics are very used to asking, and studying, this kind of questions.

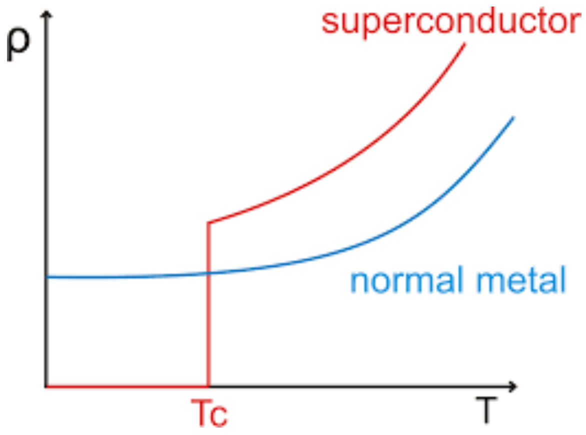
One of the most beautiful examples is the superconductivity discovered in 1911:





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

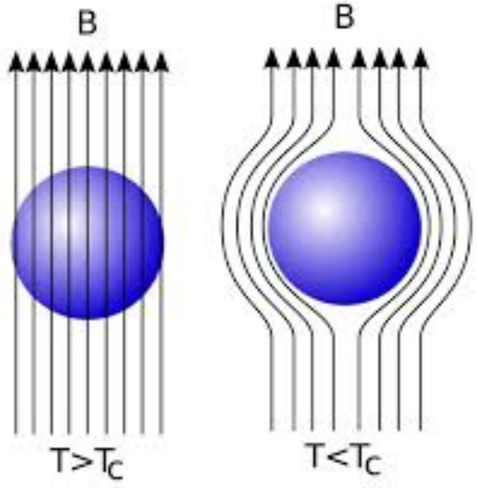


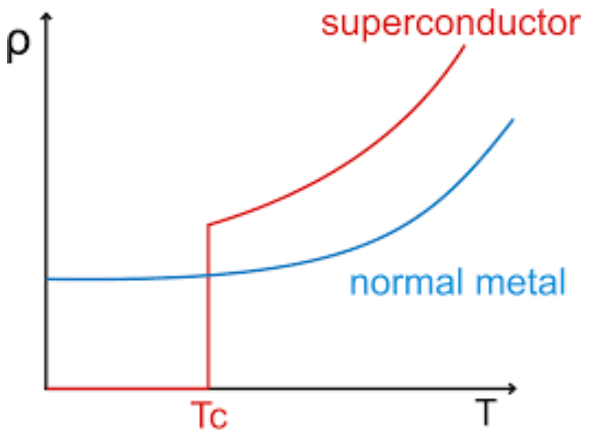


Ginzburg-Landau theory from 1950 offered a macroscopic (ie effective) theory for conventional superconductivity,

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

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 $|\Psi|^2$ as the number density of Cooper pairs

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

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

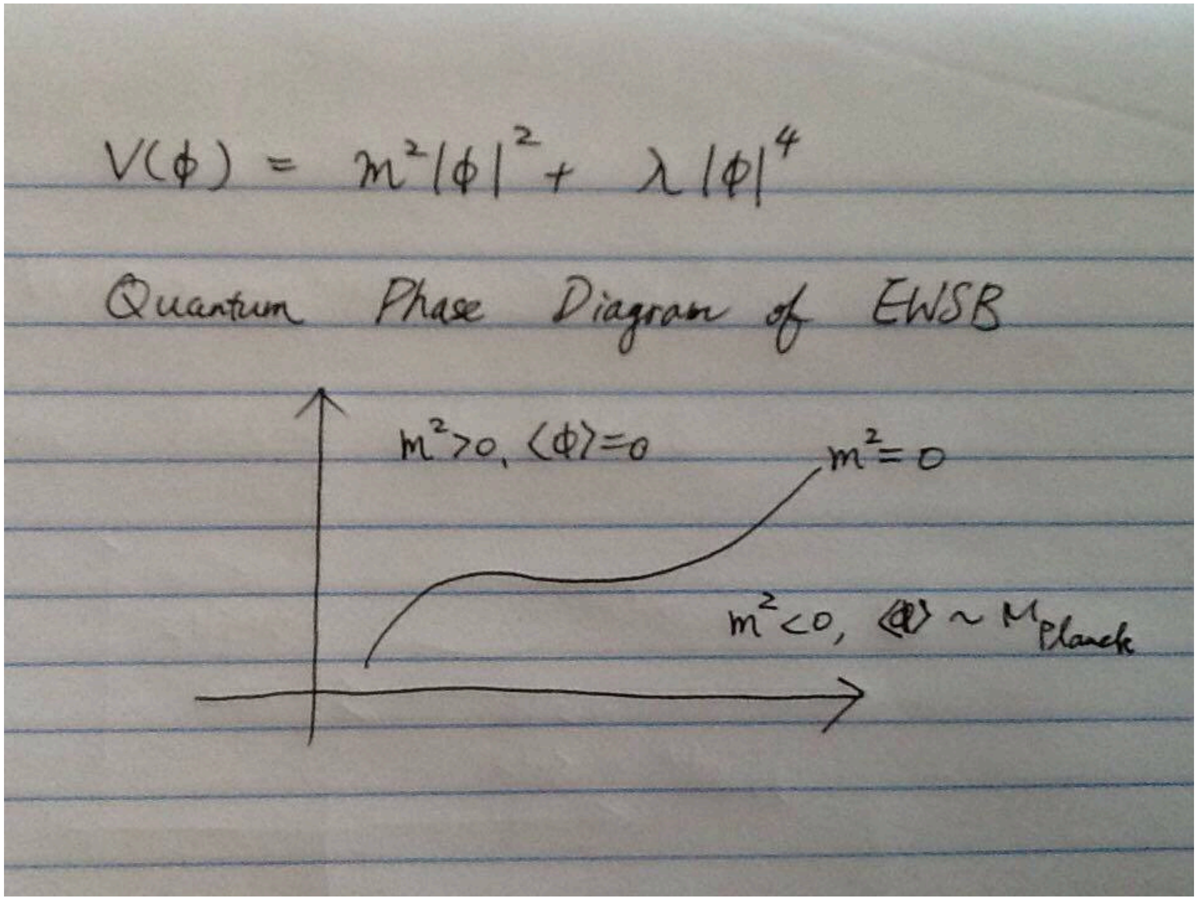
1) interpret $|\Psi|^2$ as the number density of Cooper pairs

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

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

In fact, we have NOT even measured the Ginzburg-Landau potential of the Higgs!

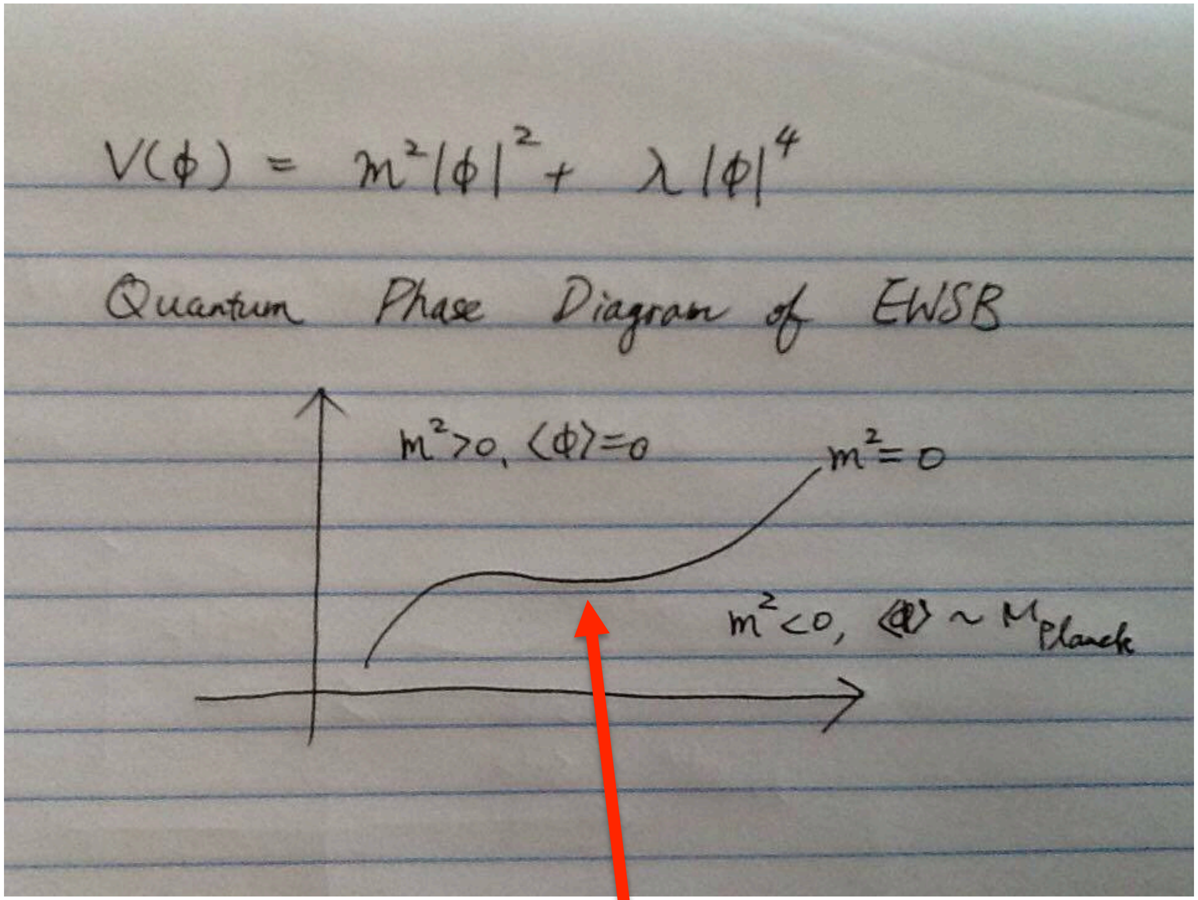
The question on the microscopic origin of the Higgs potential can be formulated in terms of phase transition and criticality:



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

Quantum Phase Diagram of EWSB

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



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

Quantum Phase Diagram of EWSB

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.

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."

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!

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:

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.

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.

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?"

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.

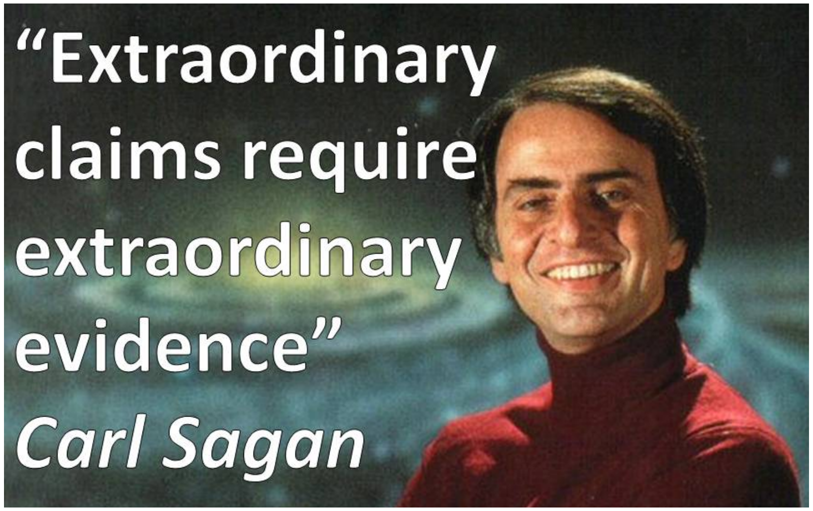
Some other people say, what about just accept the “fine-tuning” -- that one could be in a vacuum that is so close to the critical line for “no good reasons”.

Let’s recall that such a situation has never occurred ***naturally*** in (condensed matter) systems with spontaneous symmetry breaking.

Some other people say, what about just accept the “fine-tuning” -- that one could be in a vacuum that is so close to the critical line for “no good reasons”.

Let’s recall that such a situation has never occurred *naturally* in (condensed matter) systems with spontaneous symmetry breaking.

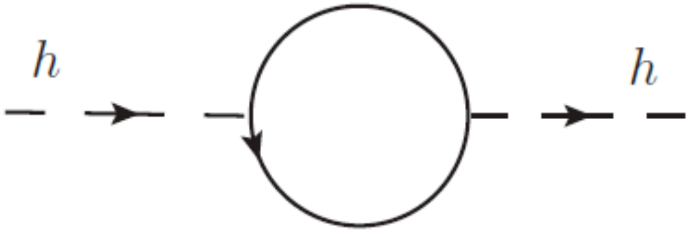
This would be an extraordinary claim and make electroweak symmetry breaking the most bizarre quantum criticality in nature!



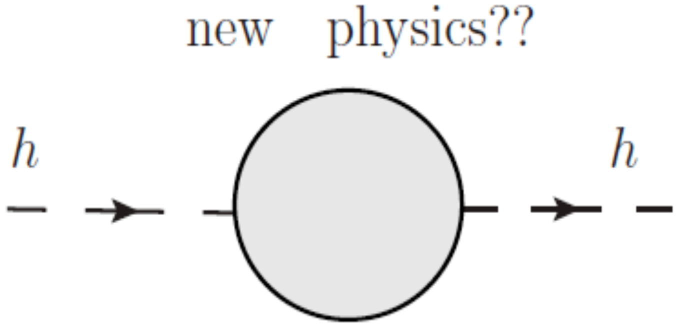
So how do we measure if the electroweak critical line is a locus of enhanced symmetry?

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

At a technical level, this is realized by proposing new “symmetry partners” of the top quark coupling with the Higgs:



$$\propto -\frac{3\lambda_t^2}{8\pi^2}\Lambda^2$$



This is the most salient feature common to popular models explaining the naturalness problem: the existence of the symmetry-partner of the top!

The presence of top partners often modifies the top Yukawa coupling.

This is the most salient feature common to popular models explaining the naturalness problem: the existence of the symmetry-partner of the top!

The presence of top partners often modifies the top Yukawa coupling.

Three routes to testing naturalness:

- Direct searches of the colored top partner.
- Indirect searches of the uncolored top partner through exotic decays of the 125 GeV Higgs.
- Precise measurements of the top Yukawa coupling.

This is the most salient feature common to popular models explaining the naturalness problem: the existence of the symmetry-partner of the top!

The presence of top partners often modifies the top Yukawa coupling.

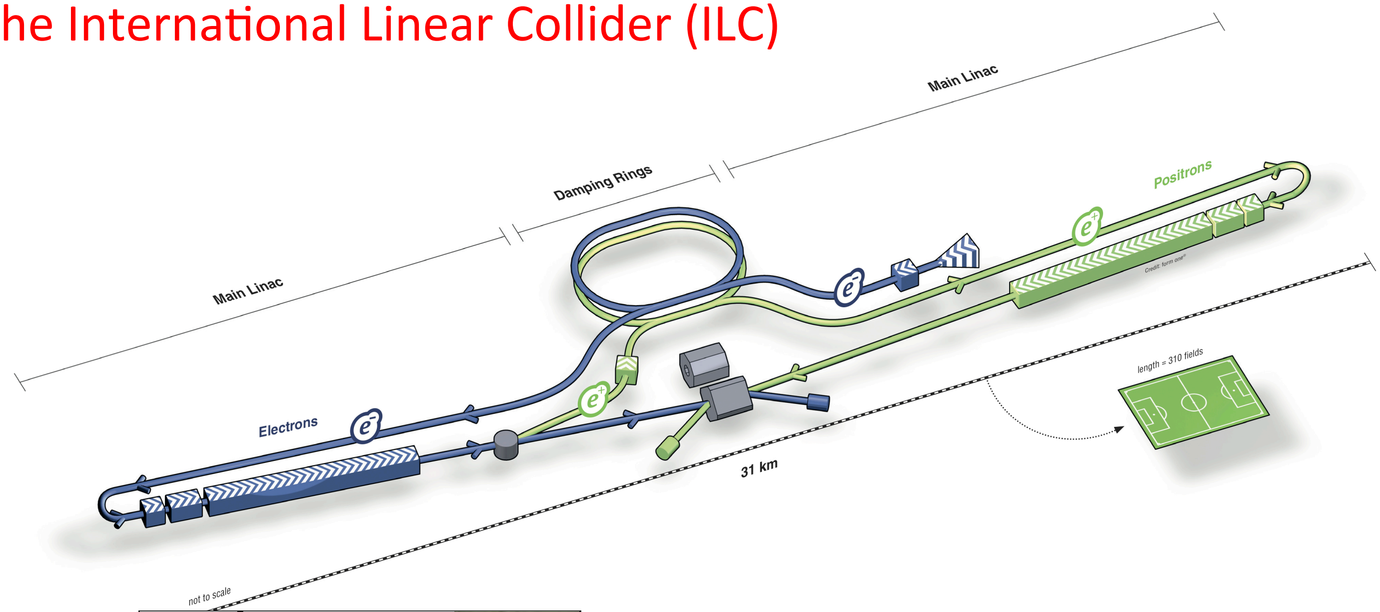
Three routes to testing naturalness:

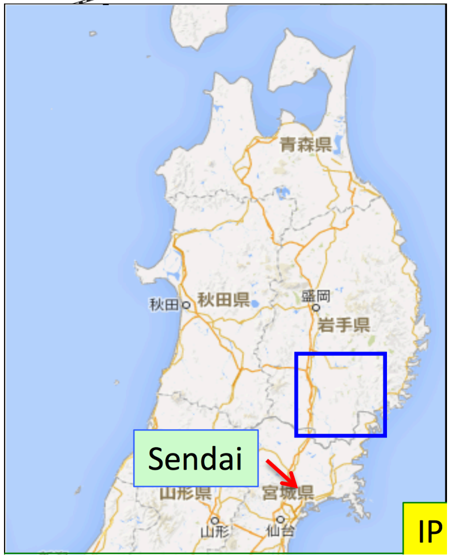
- Direct searches of the colored top partner.
- Indirect searches of the uncolored top partner through exotic decays of the 125 GeV Higgs.
- Precise measurements of the top Yukawa coupling.

Every route requires a new accelerator!!

There are several proposals under discussion:

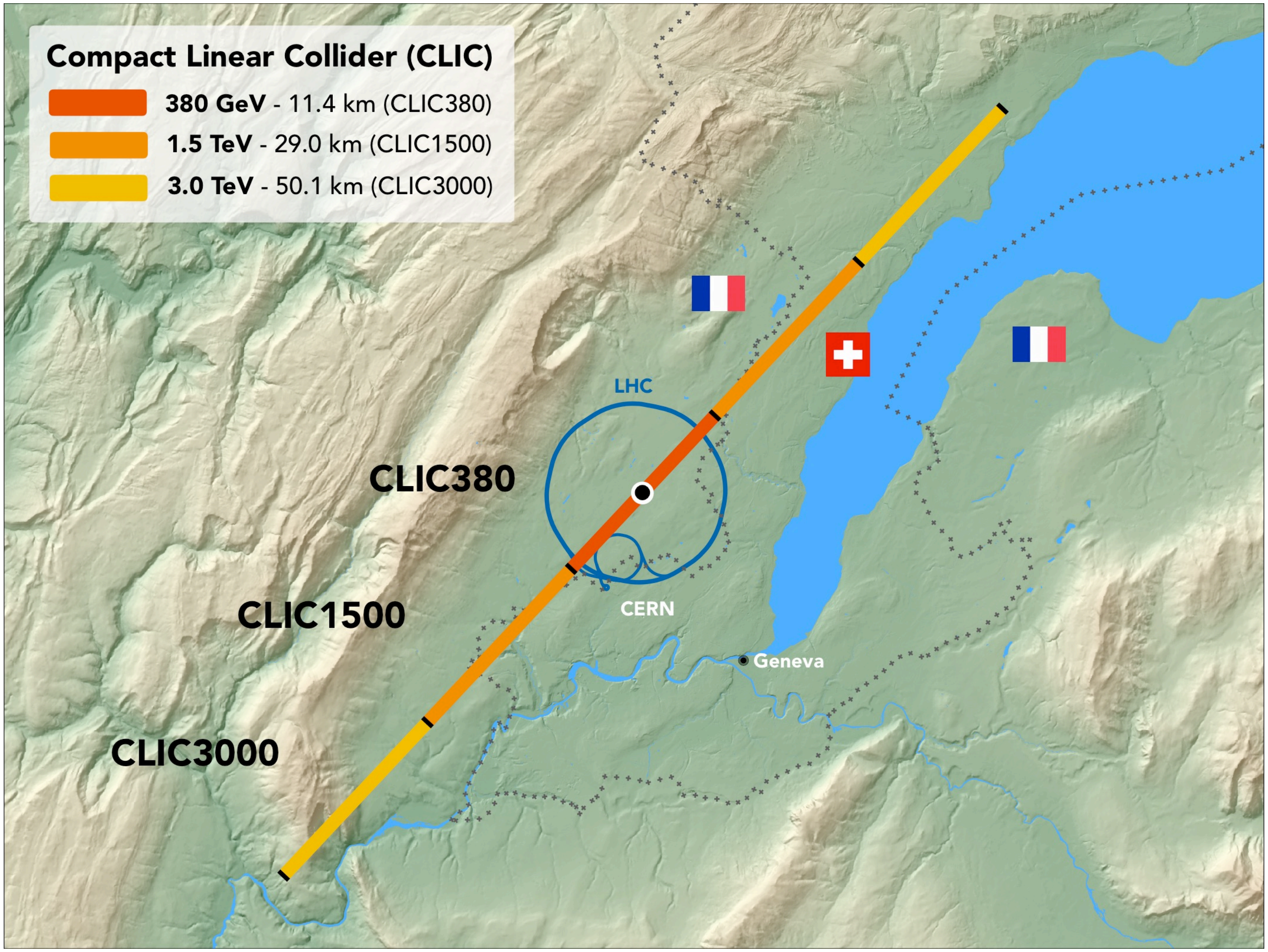
- The International Linear Collider (ILC)



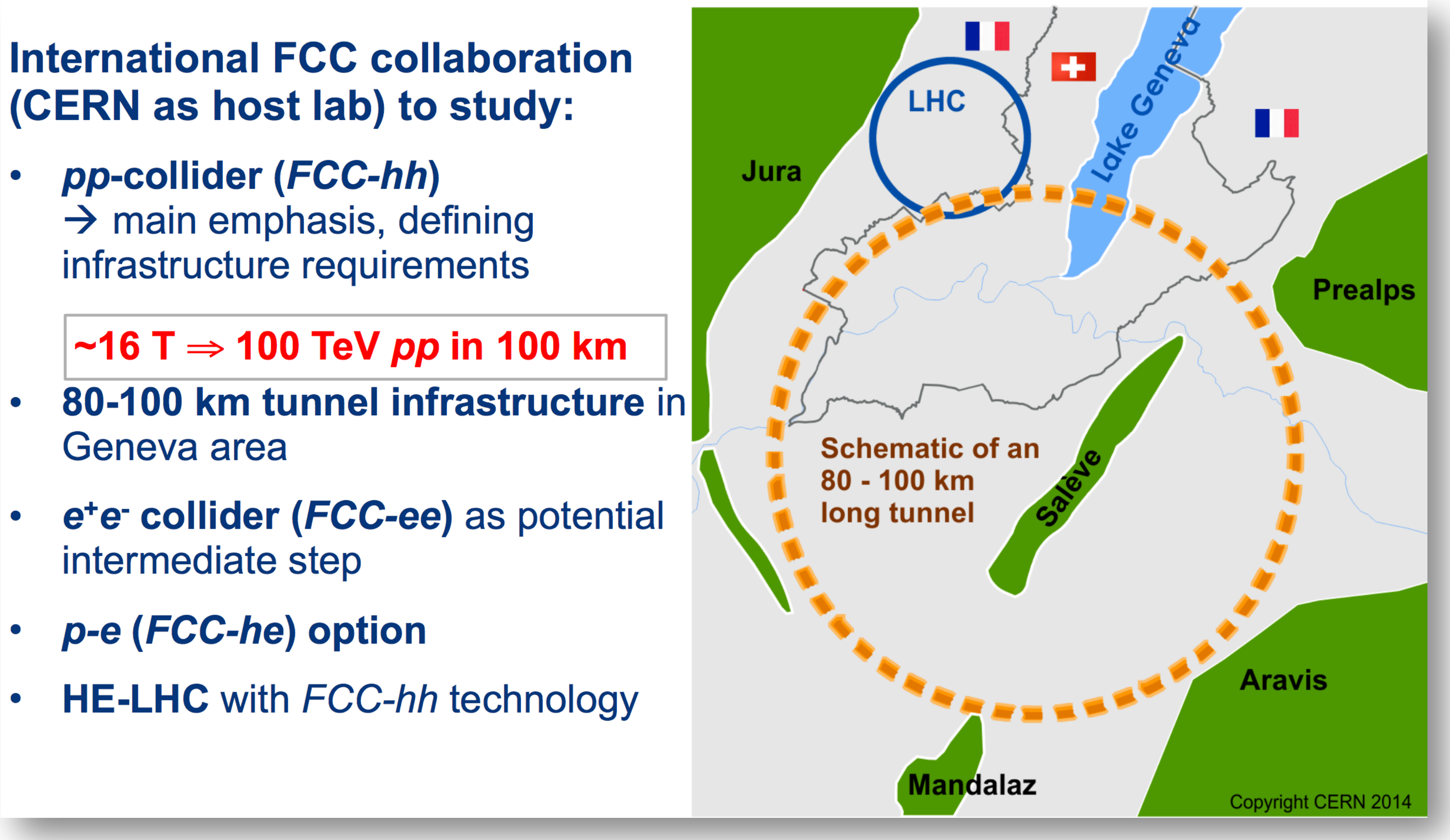


Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35 x10^{34} cm^{-2}s^{-1}
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	7.7 nm＠250GeV
SRF Cavity G. Q_0	31.5 MV/m Q_0 = 1x10 ^{10}

- The Compact Linear Collider (CLIC)



- Future Circular Collider (FCC)



International FCC collaboration (CERN as host lab) to study:

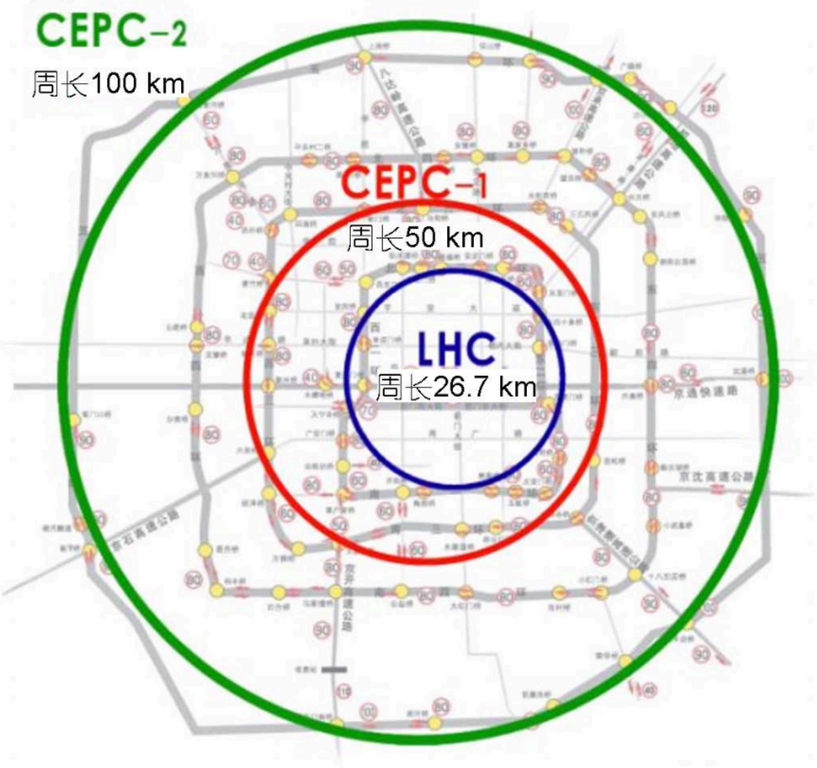
- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

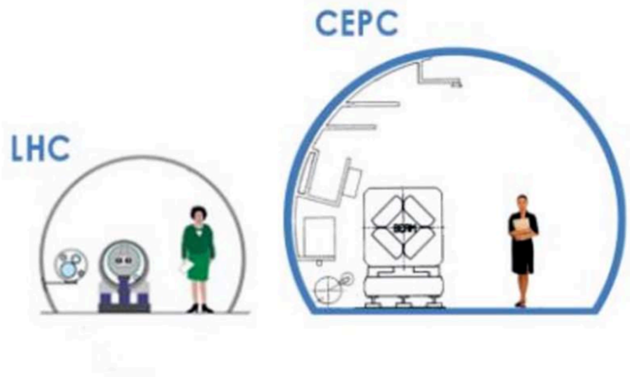
- **80-100 km tunnel infrastructure** in Geneva area
- ***e^+e^-* collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**
- **HE-LHC** with *FCC-hh* technology

- Circular Electron-Positron Collider (CEPC)

Can be later upgraded to a 100 TeV pp collider.



1) Qin huang dao，Heihe （Completed in 2014）
2) Huanging，Shanxi（Completed in 2017)
3)Shen shan，Guangdong (Completed in 2016)
4) Baoding (Xiong an), Hebei (Started in August 2017, near Beijing
5) Zhejiang (under contact)
6) Jiangsu (under contact)



Below I will discuss two studies on testing naturalness at future colliders:

- Measuring the top Yukawa coupling at the e+e- Higgs factory.
- Measuring couplings of the fermionic top partner at a future hadron collider.

An e+e- Higgs factory will normally operate below the top threshold, but the top Yukawa enters into Higgs decays to two gluons and two photons at the loop-level. Use the EFT langauge:

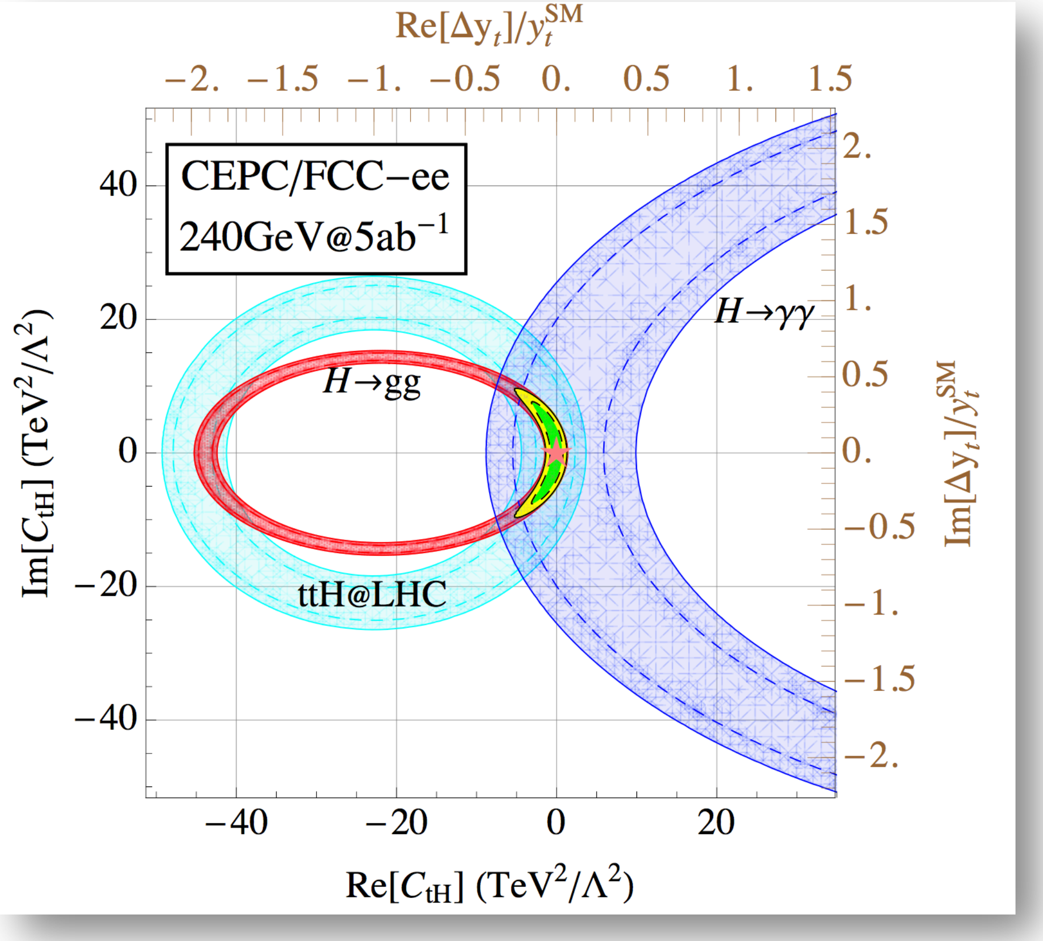
$$\mathcal{O}_{tH} = \frac{1}{\Lambda^2}(H^\dagger H)(\bar{q}_L \tilde{H} t_R)$$

This operator modifies the Htt coupling:

$$m_t = y_t^{\mathrm{SM}} \frac{v}{\sqrt{2}} \qquad\qquad v = 246 \;\; \mathrm{GeV}$$

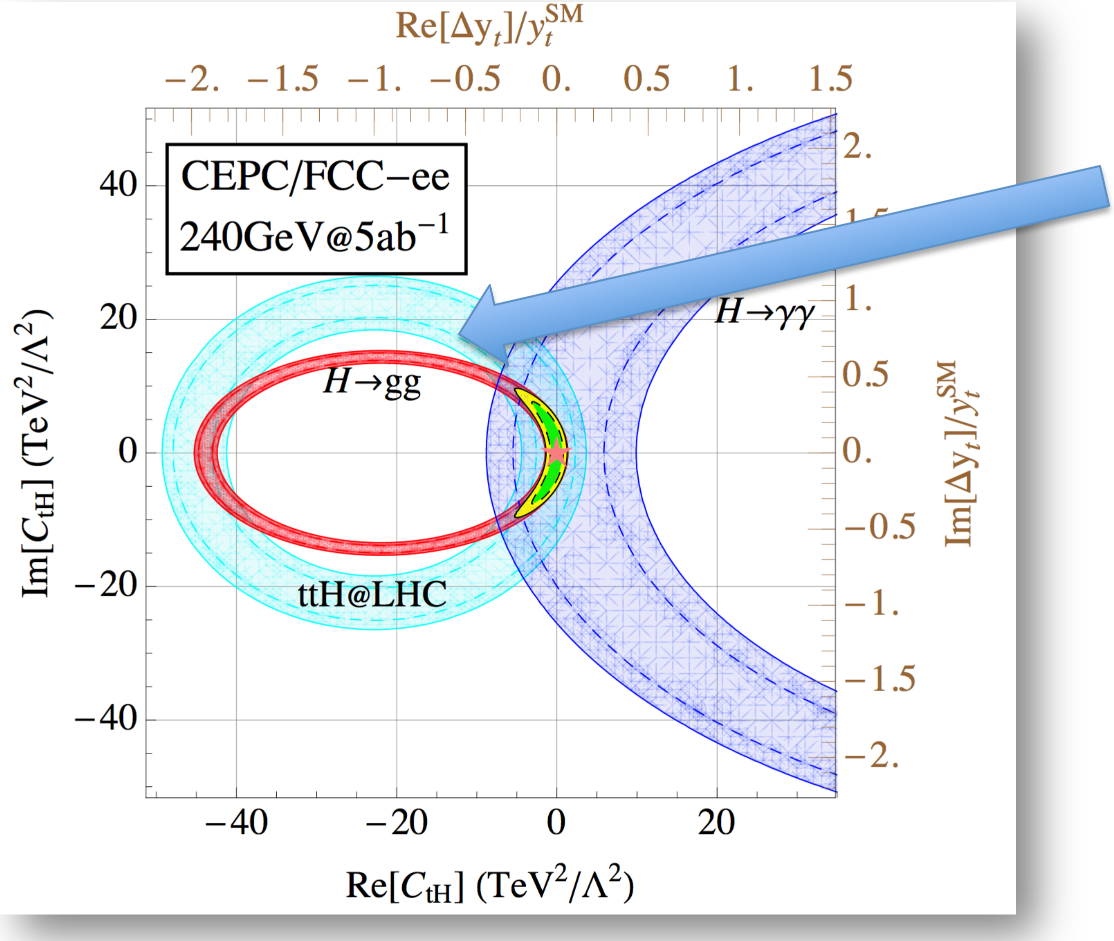
$$\Delta y_t = y_t^{\mathrm{SM}} \left(\underset{\substack{\nearrow \\ \boxed{\text{CP-even}}}}{\mathrm{Re}[C_{tH}]} \frac{v^3}{2 m_t \Lambda^2} + i\, \underset{\substack{\uparrow \\ \boxed{\text{CP-odd}}}}{\mathrm{Im}[C_{tH}]} \frac{v^3}{2 m_t \Lambda^2} \right)$$

We make the simplifying assumption of turning on $\mathcal{O}_{tH} = \frac{1}{\Lambda^2}(H^\dagger H)(\bar{q}_L \tilde{H} t_R)$ only:



Working in progress with Zhen Liu and Lian-Tao Wang

We make the simplifying assumption of turning on $\mathcal{O}_{tH} = \frac{1}{\Lambda^2}(H^\dagger H)(\bar{q}_L \tilde{H} t_R)$ only:

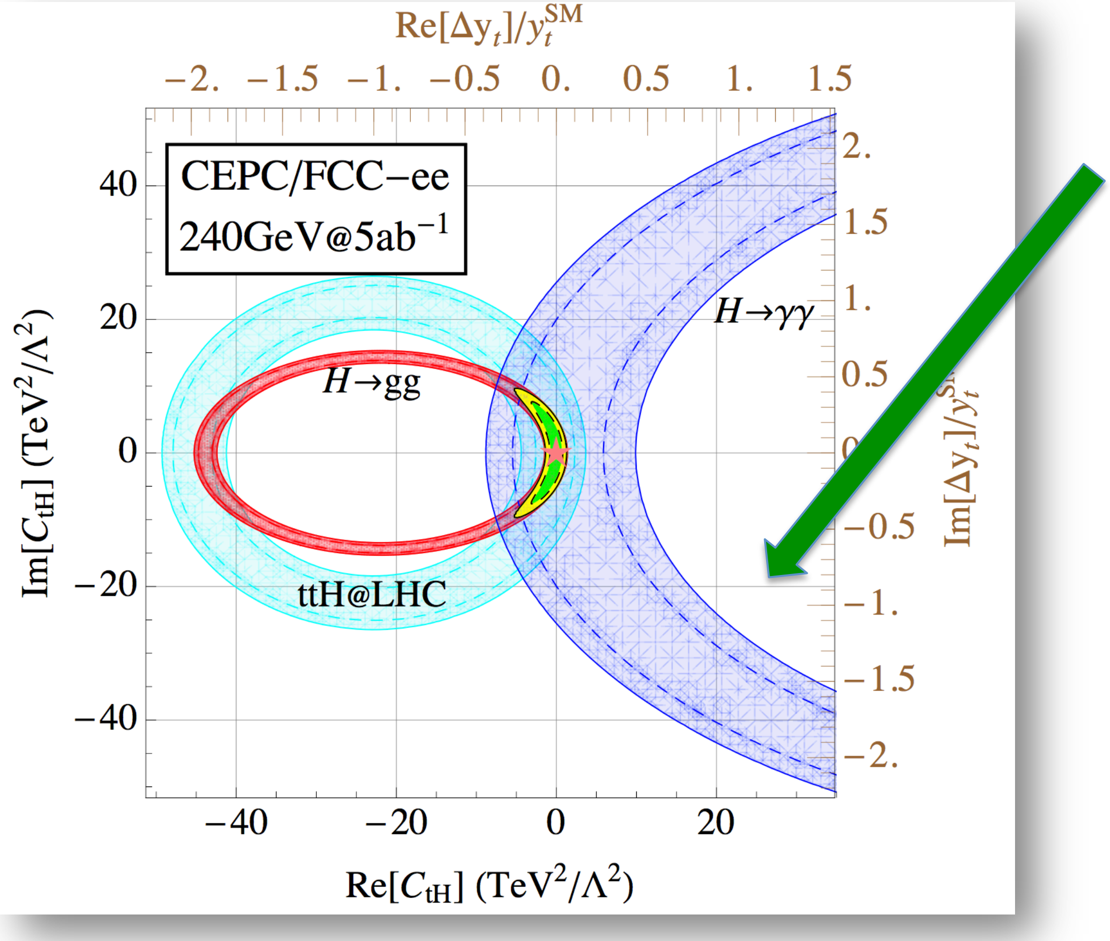


In Hgg partial width, a negative Re[C_{tH}] would interfere destructively with the SM contribution, thereby reducing the signal strength.

This could be compensated by turning on the Im[C_{tH}] .

Working in progress with Zhen Liu and Lian-Tao Wang

We make the simplifying assumption of turning on $\mathcal{O}_{tH} = \frac{1}{\Lambda^2}(H^\dagger H)(\bar{q}_L \tilde{H} t_R)$ only:

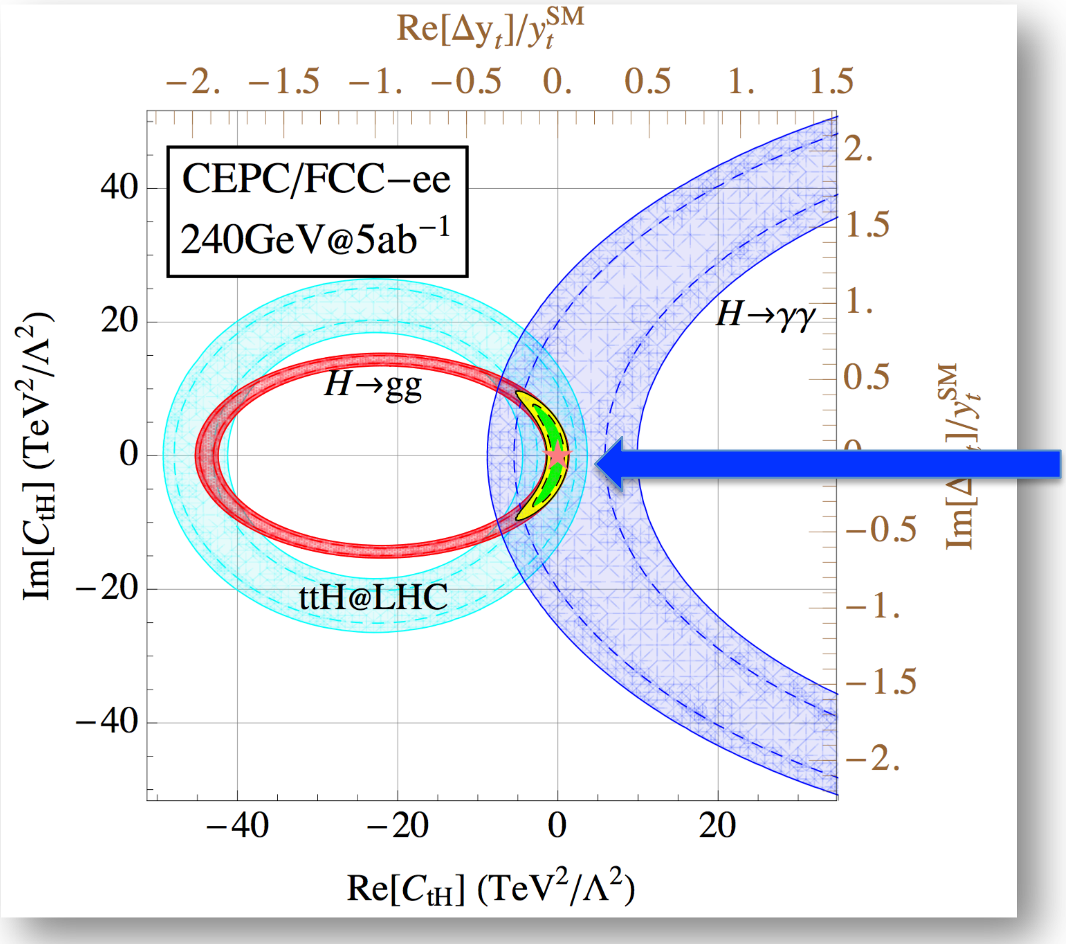


In Hγγ partial width, the SM top loop is interferes destructively with the Dominant W-boson loop.

Therefore a positive Re[C_{tH}] would reduce the signal strength.

Working in progress with Zhen Liu and Lian-Tao Wang

We make the simplifying assumption of turning on $\mathcal{O}_{tH} = \frac{1}{\Lambda^2}(H^\dagger H)(\bar{q}_L \tilde{H} t_R)$ only:



Because of the opposite behaviors of the top loop in Hgg and Hγγ widths, their constraints on O_{tH} are complimentary to each other.

Working in progress with Zhen Liu and Lian-Tao Wang

The top partner (the vector-like quark) in composite Higgs models, and similary their counterpart of top squark in supersymmetry, serves two purposes:

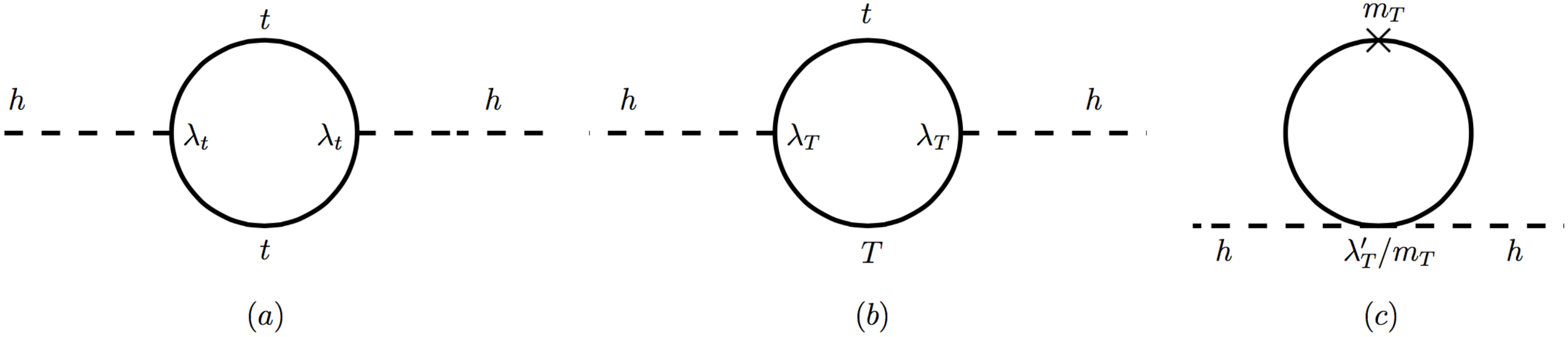
The top partner (the vector-like quark) in composite Higgs models, and similary their counterpart of top squark in supersymmetry, serves two purposes:

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.

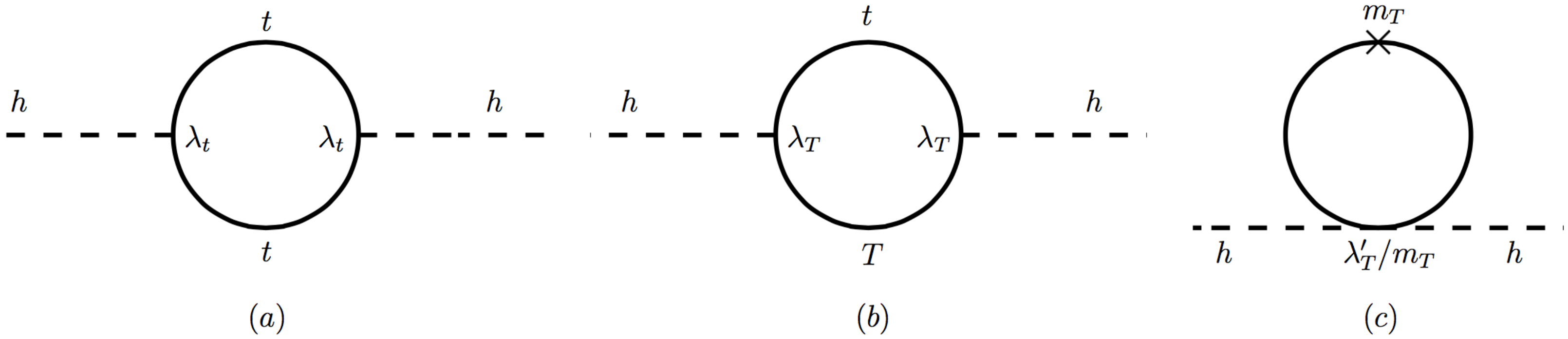
2) the top partners are also responsible for cancelling the top quadratic divergences in the Higgs mass-squared:



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:



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

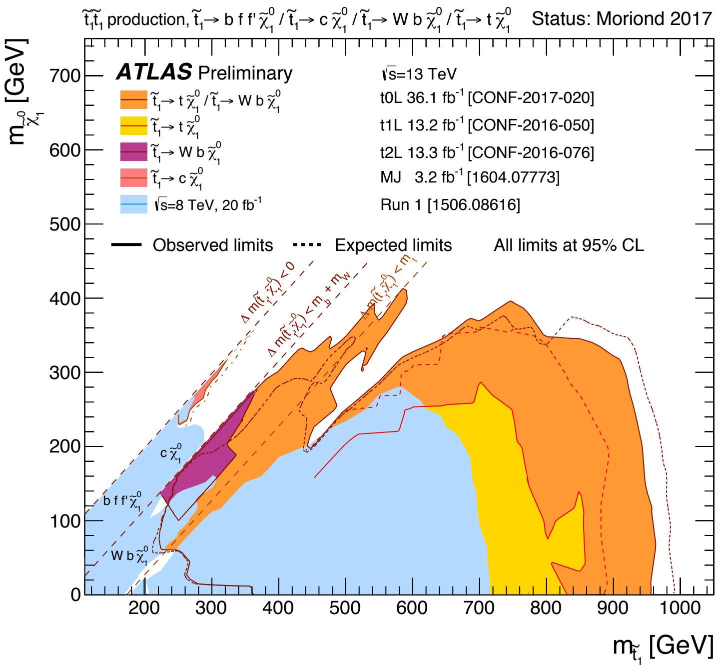
This relation is an unambiguous prediction of an enhanced symmetry!

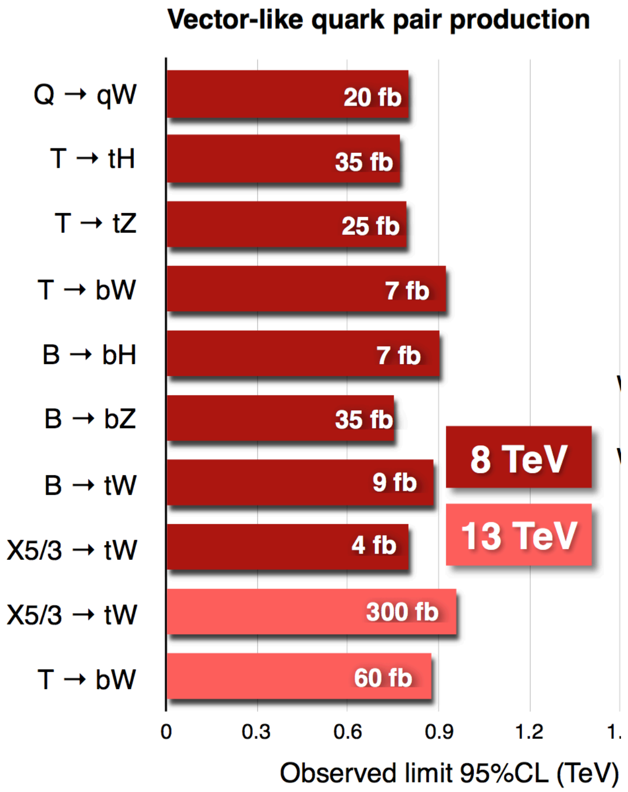
Two-step program to test Naturalness and the existence of a new symmetry:

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??

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 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 ?

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

We consider the decay channel:

(B^0 = Z or h)

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

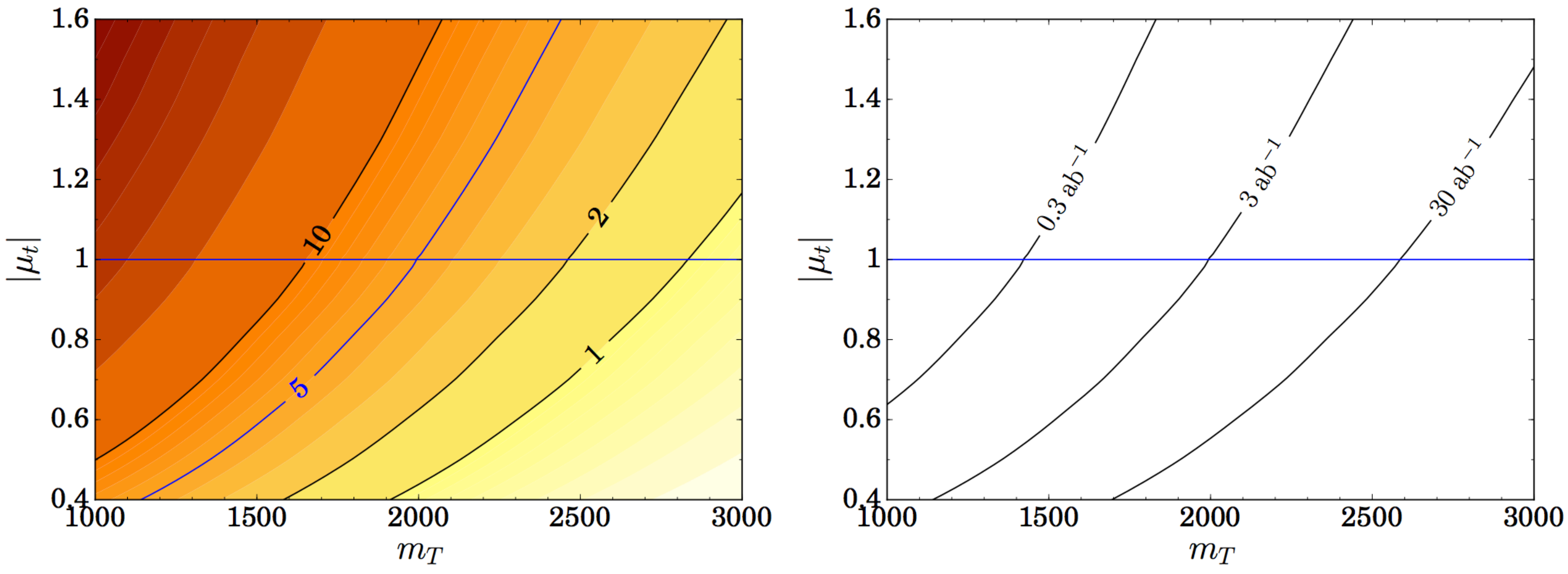
In particular, for multi-TeV top partners the boson in the decay of T is going to be boosted:

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

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

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

When all is said and done:



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

(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 $3\,\mathrm{ab}^{-1}$ in Figure (a) and for a fixed significance of 5σ with luminosities of 0.3, 3, $30\,\mathrm{ab}^{-1}$ 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.