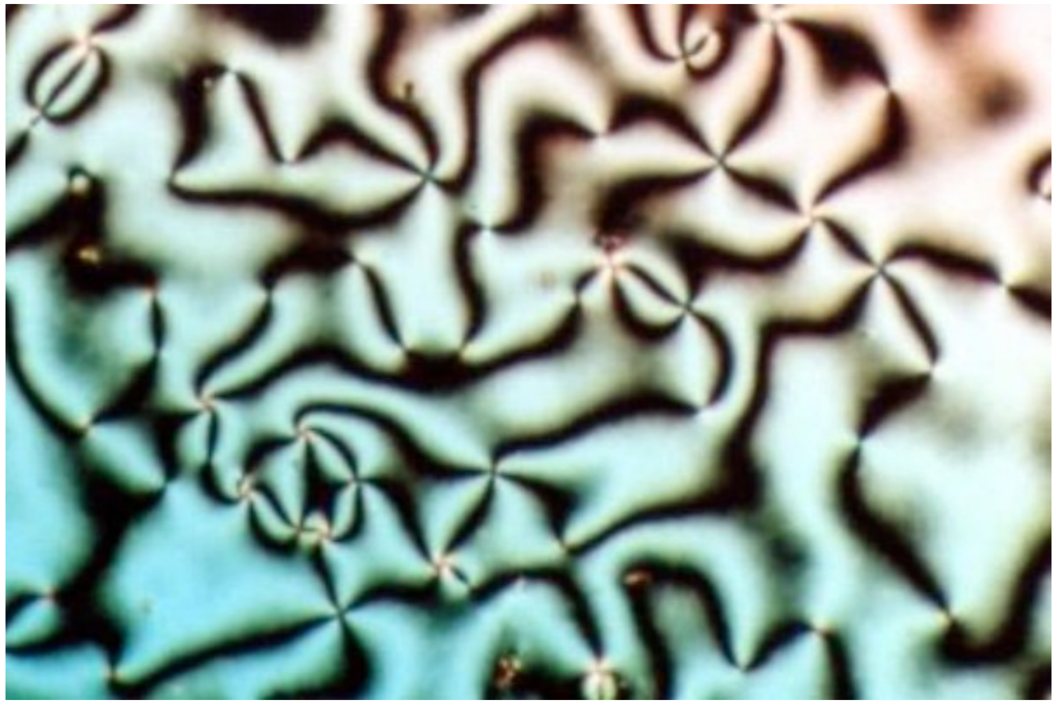
Searching for New Physics using Precision Standard Model Measurements



M. E. Peskin
SM@50
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Indeed, shouldn’t we believe that the Standard Model is exactly correct ?

Ability to fit the data is not everything. The Standard Model fails to explain many of the most important aspects of particle physics. In fact, it is incapable of explaining these features:

the spectrum of quark and lepton masses
the origin of the matter/antimatter asymmetry
the existence of dark matter

Hamming:
“The purpose of computing is insight, not numbers.”

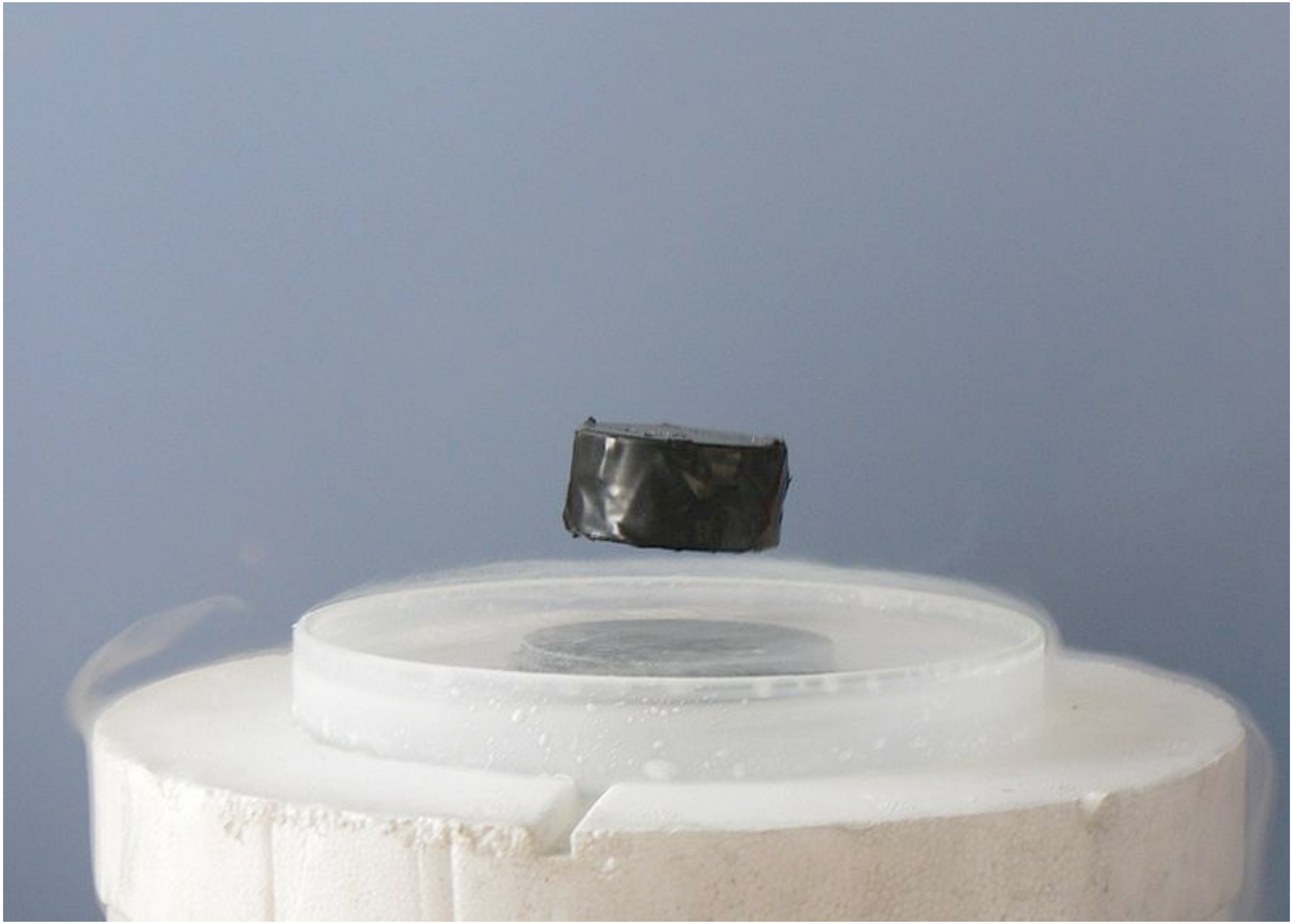
Most importantly for me, the Standard Model is incapable of explaining the phase transition to an ordered state that breaks SU(2)xU(1). The full explanation of this ordering within the Standard Model is:

1. The most general renormalizable potential for the Higgs field is

$$V = \mu^2 |\Phi|^2 + \lambda |\Phi|^4$$

2. For some reason, $\mu^2 < 0$.

The value of μ^2 receives large additive radiative corrections with both signs. Sophisticated people call this the "gauge hierarchy problem". In fact, it is the problem that we have no clue as where μ^2 comes from.



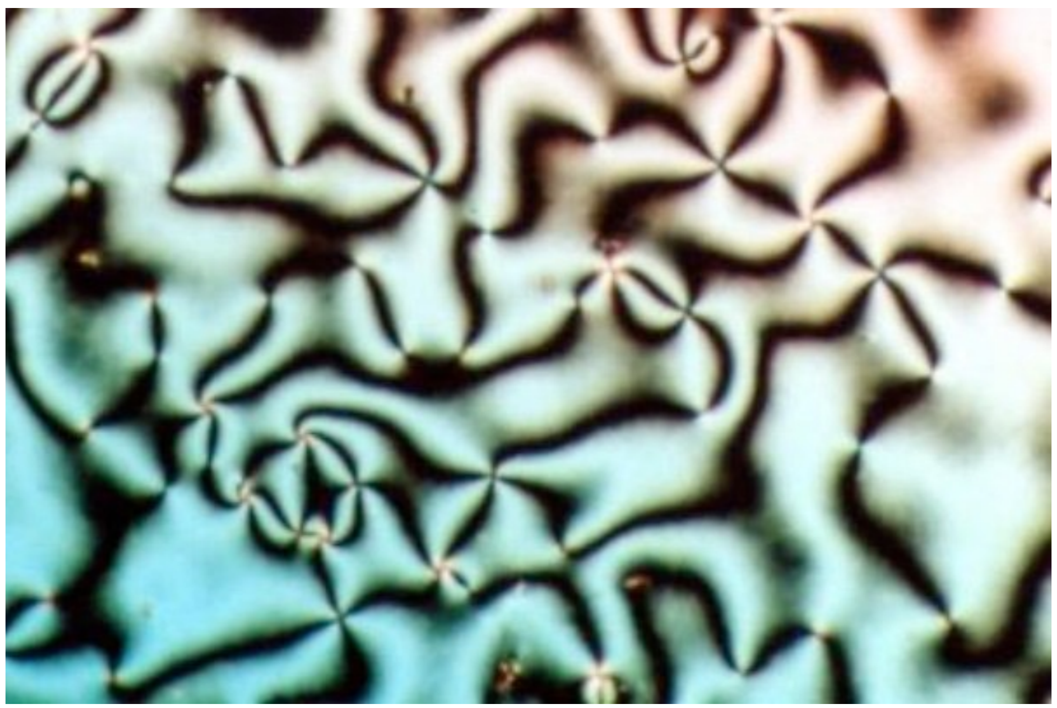
There is a strong analogy here to the theory of superconductivity.

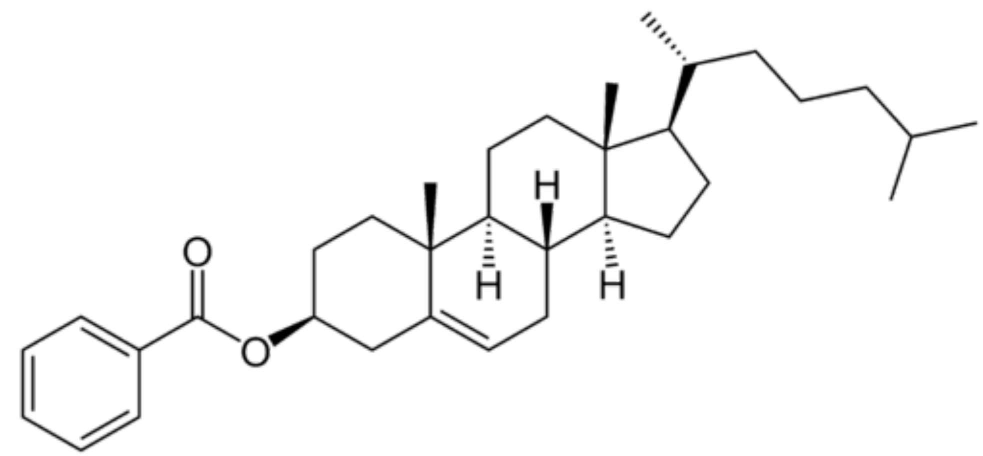
In 1950, Landau and Ginzburg proposed a phenomenological theory that explained many properties: the thermodynamics of the phase transition, the critical magnetic field, the presence of Type I and Type II, etc.

However, this theory gave no fundamental understanding of superconductivity. That was found only in 1957, by Bardeen, Cooper, and Schrieffer.

For the electroweak phase transition, we are still in the Landau-Ginzburg era.

Actually, all phase transitions studied in condensed matter physics have fascinating physical explanations.





nematic liquid crystal:
cholesterol benzoate

It is myopic to think that the Higgs phase transition in the early universe was not equally fascinating.

Still, an explanation of the Higgs phase transition requires new particles and forces beyond the Standard Model.

There is no evidence for these today. How can we find it?

Over the past decades, we have searched for Beyond-Standard-Model effects in many ways:

direct particle searches at Tevatron and LHC
searches for BSM mechanisms of CP violation
direct and indirect searches for dark matter

In all cases, a large parameter space of possibilities has been excluded, and the limits of the technique with current facilities are in sight.

In this talk, I will present the search for new physics through precision studies of the electroweak interactions.

I have already explained that the Standard Model provides an excellent explanation of current electroweak measurements. This also means that we have excellent sensitivity to possible new physics effects.

Particle searches at the LHC suggest that the required new interactions come from a mass scale M higher than those we currently probe.

The we can parametrize new interactions systematically:

The Standard Model is the most general dimension-4 Lagrangian with SU(3)xSU(2)xU(1) symmetry and the known particle content.

New physics effects will be visible if they contribute perturbations of dimension 6 and higher.

dim 6 $\rightarrow \; m_Z^2/M^2$ dim 8 $\rightarrow \; m_Z^4/M^4$

Foundational papers:

Ken Wilson, “Non-Lagrangian Models of Current Algebra”, Phys. Rev. 179, 1499 (1969).

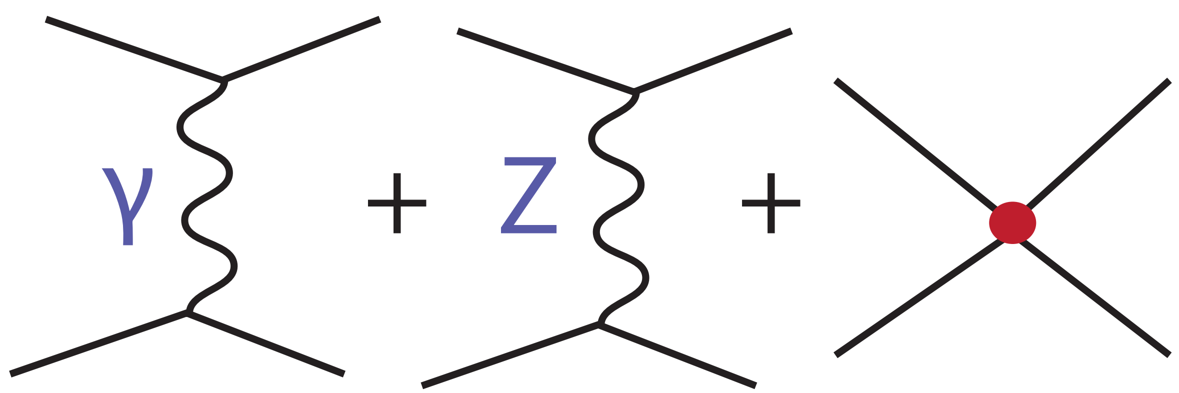
Steven Weinberg, “Phenomenological Lagrangians”, Physica A96, 327 (1979).

example: compositeness of the electron

If the electron is composite, we expect strong interactions at the scale of the electron radius. Parametrize these as: (Eichten, Lane, MEP)

$$\Delta L = \frac{2\pi}{M^2}\left[\eta_{LL}(L^\dagger\overline{\sigma}^\mu L)^2 + 2\eta_{LR}(L^\dagger\overline{\sigma}^\mu L)(e_R^\dagger\sigma_\mu e_R) + \eta_{RR}(e_R^\dagger\sigma_\mu e_R)^2\right]$$

That is, Bhabha scattering now has the form



LEP 2 set very strong limits,

$$M > 8 - 10\ \mathrm{TeV}$$

for the various choices of the η coefficients.

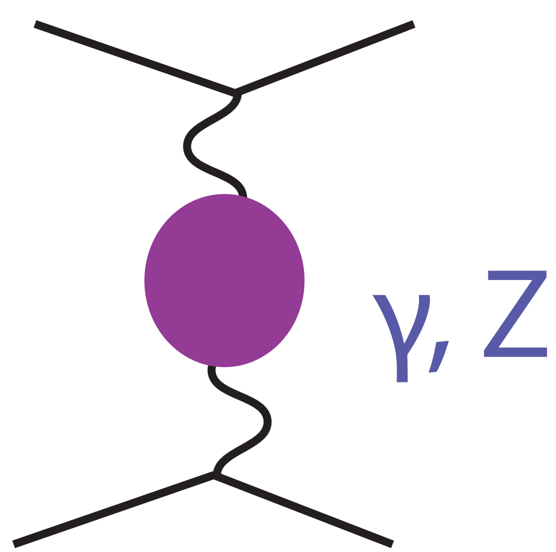
This is $r_e < 6 \times 10^{-19}\ \mathrm{m}$

LHC limits on quark compositeness are only comparably strong, and are model-dependent (considering only 1 possible operator out of 17).

Another historical example comes in the "oblique" approximation to the Z boson radiative corrections.

Lynn, Stuart, MEP: In many models, new particles couple only weakly to light quarks and leptons. Their strongest couplings are to W, Z, t .

So, approximate the new physics corrections to precision electroweak measurements as coming from vacuum polarization diagrams only (oblique corrections) :



Takeuchi and MEP: Vacuum polarization diagrams have a simple structure, so it is possible to make a general analysis of these corrections.

Though we did not orignally express it in this way, the leading corrections correspond to adding 2 dimension-6 operators.

Define the vacuum polarization amplitudes

$$= ie^2\Pi_{QQ}g^{\mu\nu}$$

$$= i\frac{e^2}{s_w c_w}(\Pi_{3Q} - s_w^2\Pi_{QQ})g^{\mu\nu}$$

$$= i\frac{e^2}{s_w^2 c_w^2}(\Pi_{33} - 2s_w^2\Pi_{3Q} + s_w^2\Pi_{QQ})g^{\mu\nu}$$

$$= i\frac{e^2}{s_w^2}\Pi_{11}g^{\mu\nu}$$

Each amplitude has a Taylor expansion in q^2/M^2 :

$$\Pi_{QQ}(q^2) = Aq^2 + \cdots$$

$$\Pi_{3Q}(q^2) = Bq^2 + \cdots$$

$$\Pi_{33}(q^2) = C + Dq^2 + \cdots$$

$$\Pi_{11}(q^2) = E + Fq^2 + \cdots$$

$$c_w = \cos\theta_w \qquad s_w = \sin\theta_w$$

Of the 6 constants on the previous slide, 3 contribute to the renormalizations of g , g' , v . This leaves 3 combinations that are finite at 1 loop. These are

$$S = \frac{16\pi}{m_Z^2}[\Pi_{33}(m_Z^2) - \Pi_{33}(0) - \Pi_{3Q}(m_Z^2)]$$

$$T = \frac{4\pi}{s_w^2 m_W^2}[\Pi_{11}(0) - \Pi_{33}(0)]$$

$$U = \frac{16\pi}{m_Z^2}[\Pi_{11}(m_Z^2) - \Pi_{11}(0) - \Pi_{33}(m_Z^2) + \Pi_{33}(0)]$$

Roughly, T parametrizes the correction to $m_W = m_Z \cos\theta_w$, S parametrizes the q^2/M^2 correction, and U, with both suppressions, is very small in most BSM models.

S, T are generated by dim-6, U by dim-8 operators.

The leading oblique corrections to electroweak observables can then be expressed as, for example,

$$\frac{m_W^2}{m_Z^2} - c_0^2 = \frac{\alpha c^2}{c^2 - s^2}\left(-\frac{1}{2}S + c^2 T\right)$$

$$s_*^2 - s_0^2 = \frac{\alpha}{c^2 - s^2}\left(\frac{1}{4}S - s^2 c^2 T\right)$$

This allows experiment to place constraints that can then be applied to a large class of models.

Some guidance about the expected sizes of S and T is given by the result for one new electroweak doublet:

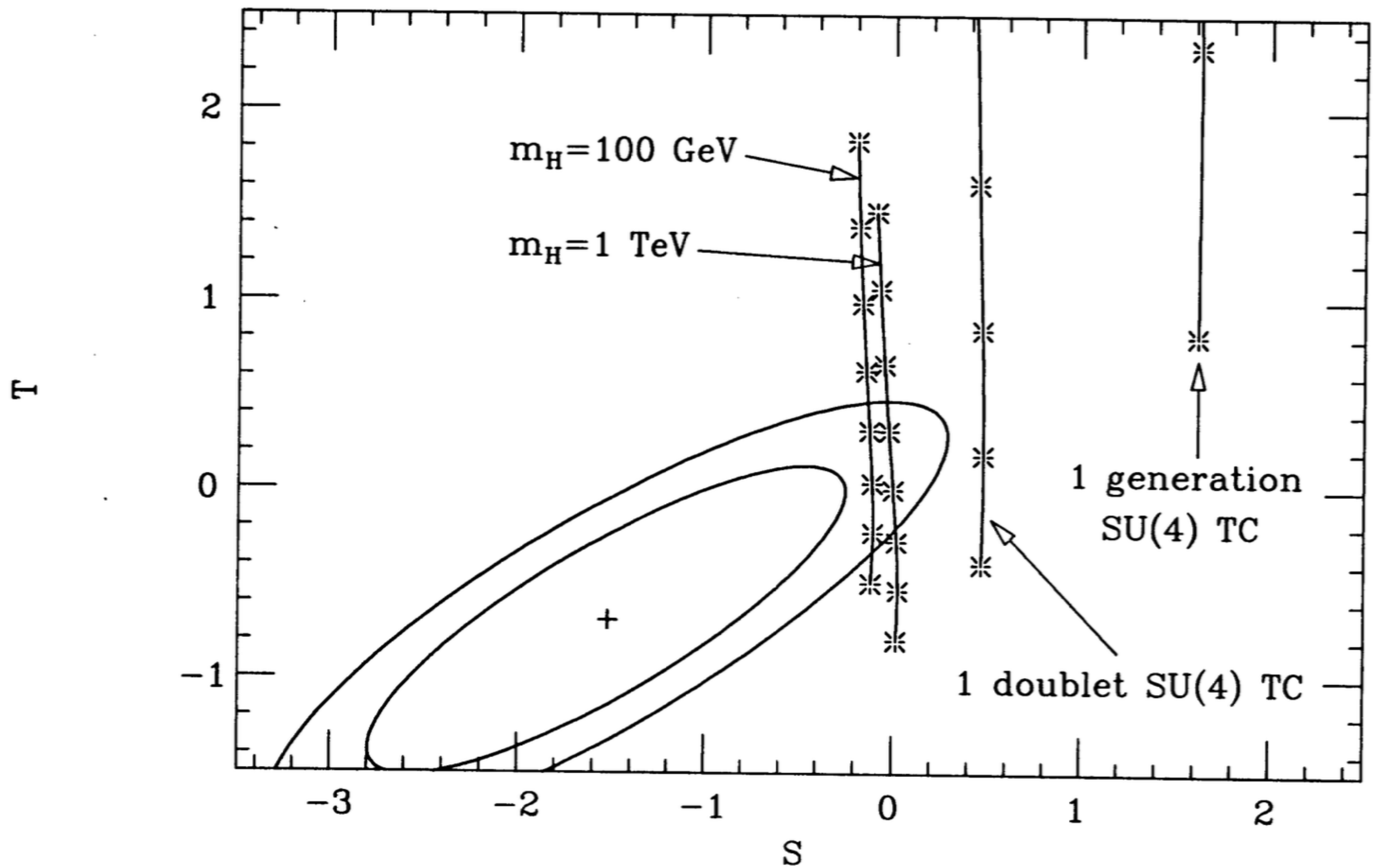
$$S = \frac{1}{6\pi} \qquad\qquad T = \frac{|m_U^2 - m_D^2|}{m_Z^2}$$

The effects of the SM top quark and Higgs boson can also be expressed (approximately) in the S,T framework

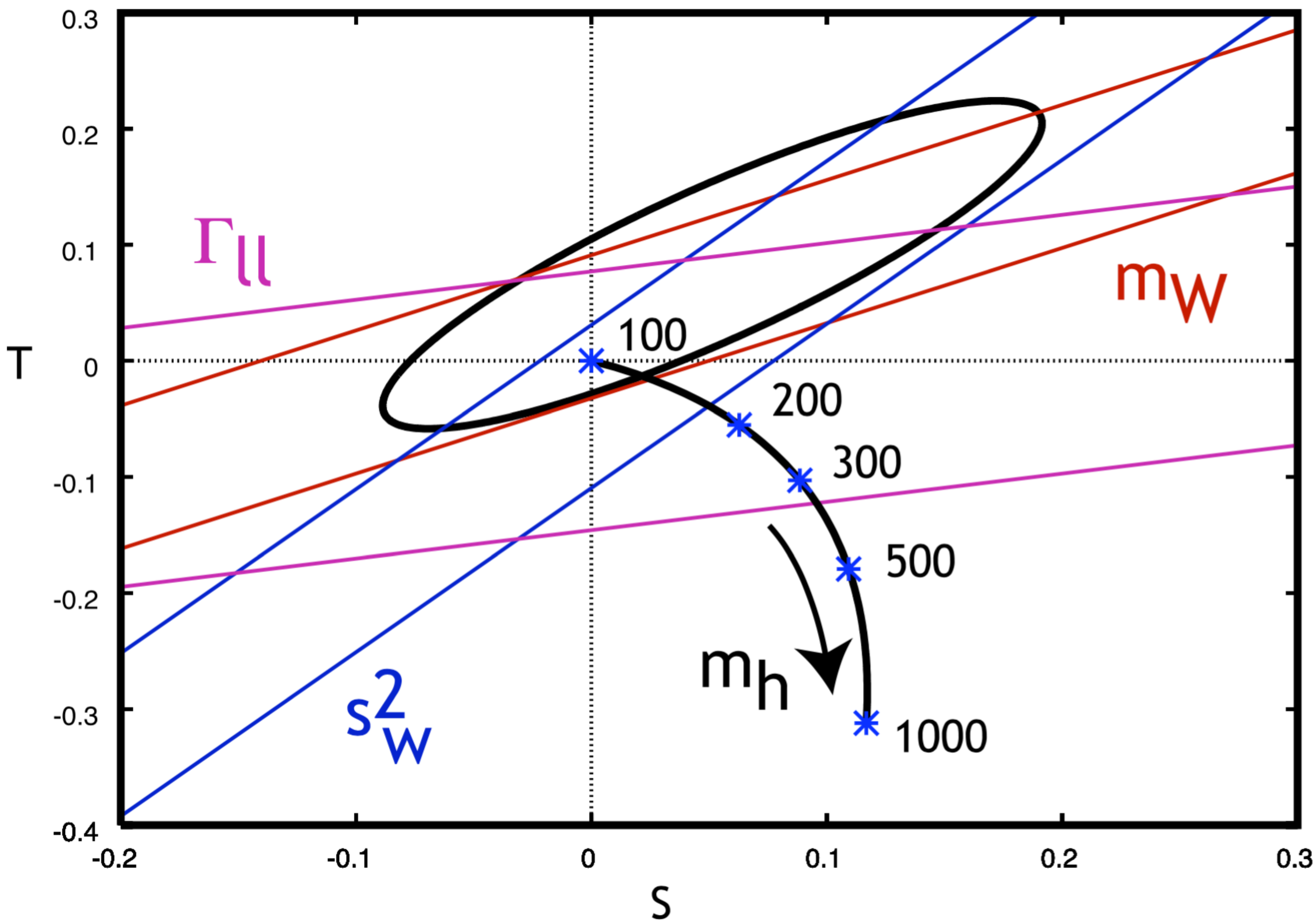
top: $$S = \frac{1}{6\pi}\log\frac{m_t^2}{m_Z^2} \qquad T = \frac{3}{16\pi s^2 c^2}\frac{m_t^2}{m_Z^2}$$

Higgs: $$S = \frac{1}{12\pi}\log\frac{m_h^2}{m_Z^2} \qquad T = -\frac{3}{16\pi c^2}\log\frac{m_h^2}{m_Z^2}$$

S,T fit circa. 1991

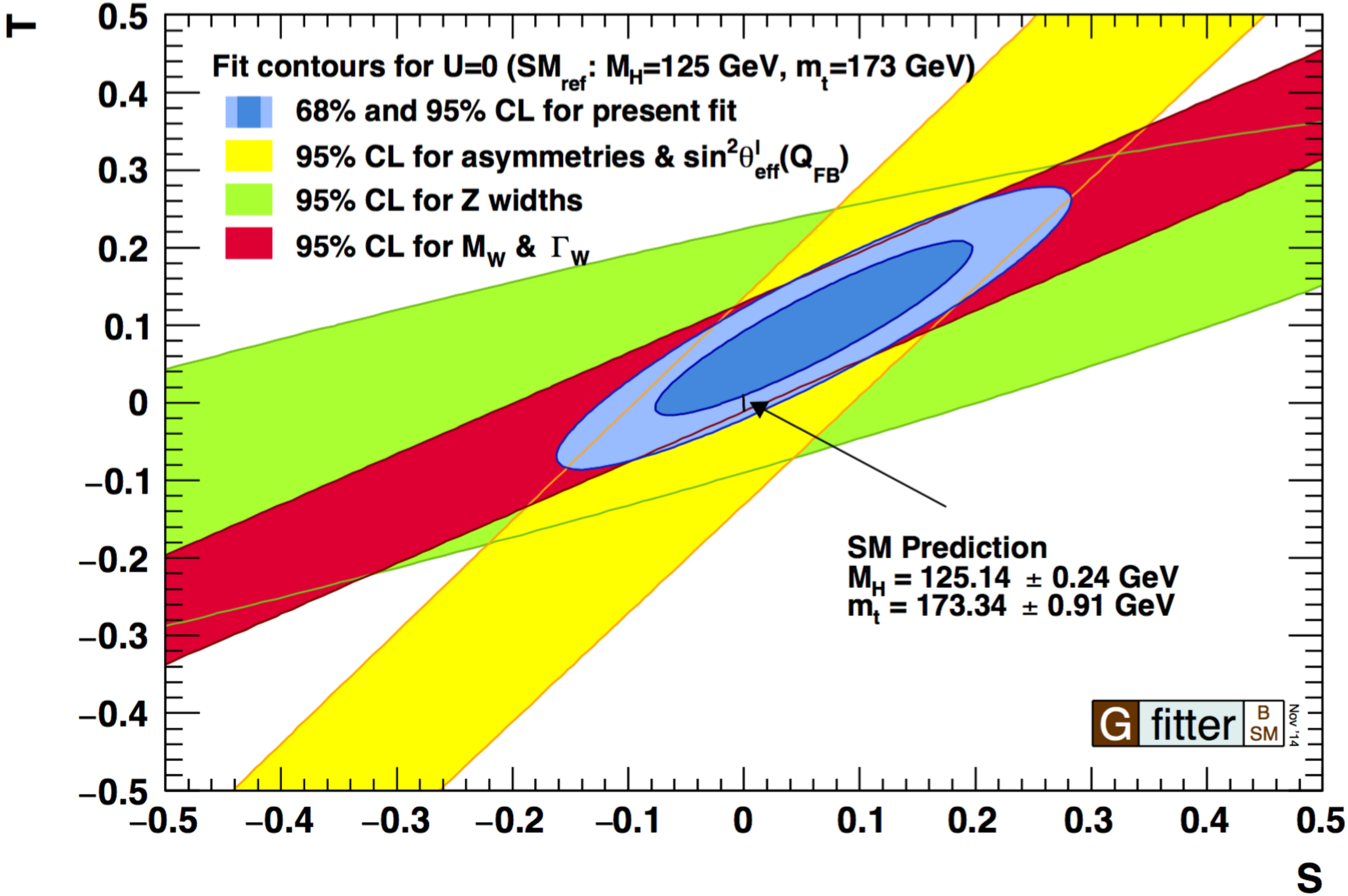


S,T fit circa 2008



LEP EWWG: within the MSM $m_h < 144\ (182)\ \mathrm{GeV}\quad (95\%\ \mathrm{CL})$

S,T fit c. 2014



Fit contours for U=0 (SM$_{ref}$: M$_H$=125 GeV, m$_t$=173 GeV)
68% and 95% CL for present fit
95% CL for asymmetries & $\sin^2\theta^l_{eff}(Q_{FB})$
95% CL for Z widths
95% CL for M_W & Γ_W
SM Prediction
M_H = 125.14 ± 0.24 GeV
m_t = 173.34 ± 0.91 GeV
G fitter B SM
Nov '14
T
S
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
−0.4
−0.5

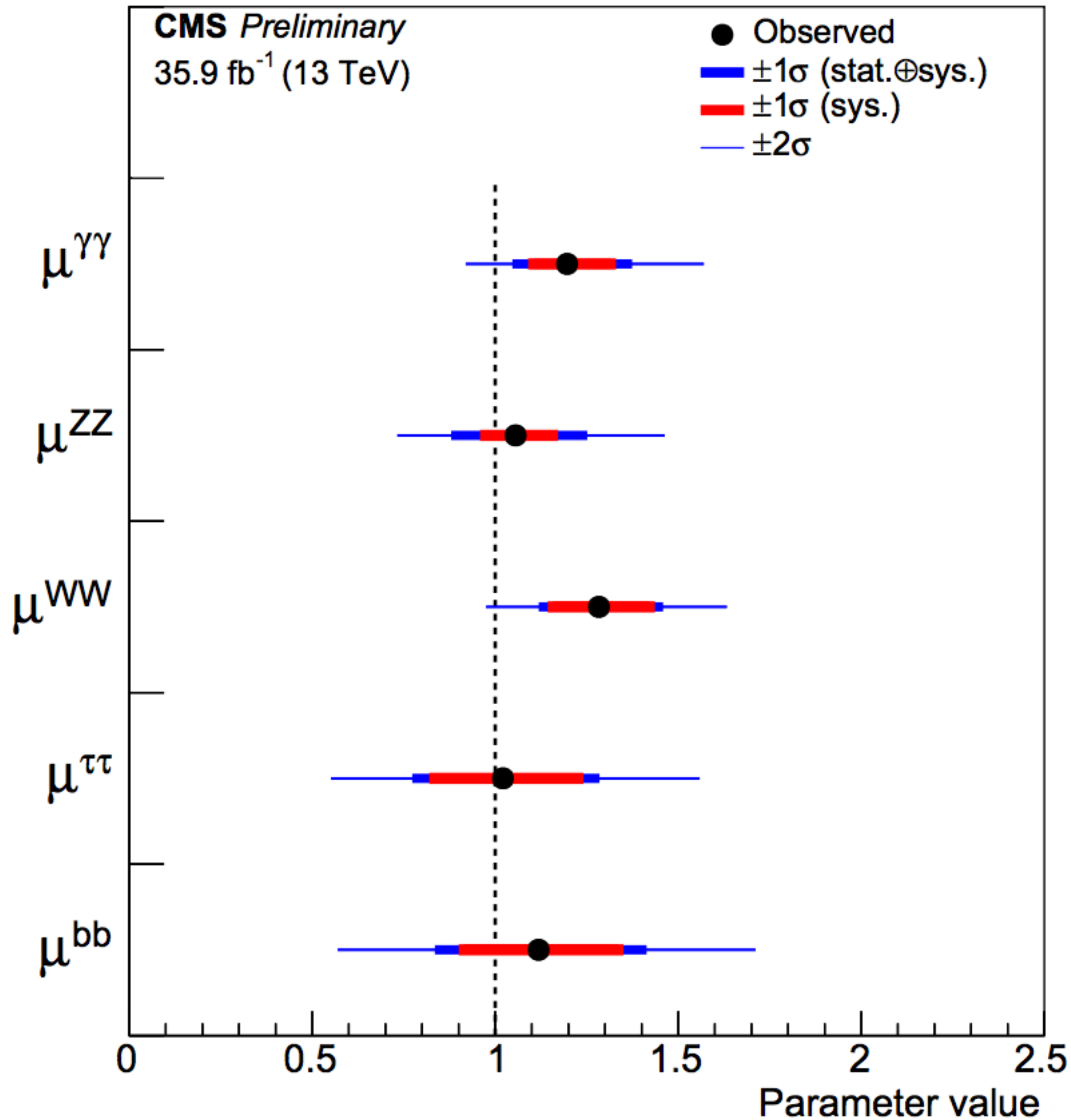
The next logical target of electroweak precision measurement is the Higgs boson.

The mass of the Higgs boson is now known to be 125 GeV. This measurement fixes the last free parameter of the Standard Model. With this parameter known, all Higgs production and decay amplitudes can be predicted - within the Standard Model - to high precision.

Any deviation from these predictions would be a signal of new interactions beyond the Standard Model.

The verification (or exclusion) of these predictions is the unfinished business of the Standard Model.

Here is the current determination of the Higgs boson couplings are given by the CMS experiment at the LHC:



Many decay modes of the Higgs boson are accessible to experimental measurement.

Different models of new physics affect the Higgs boson couplings in different ways. Roughly:

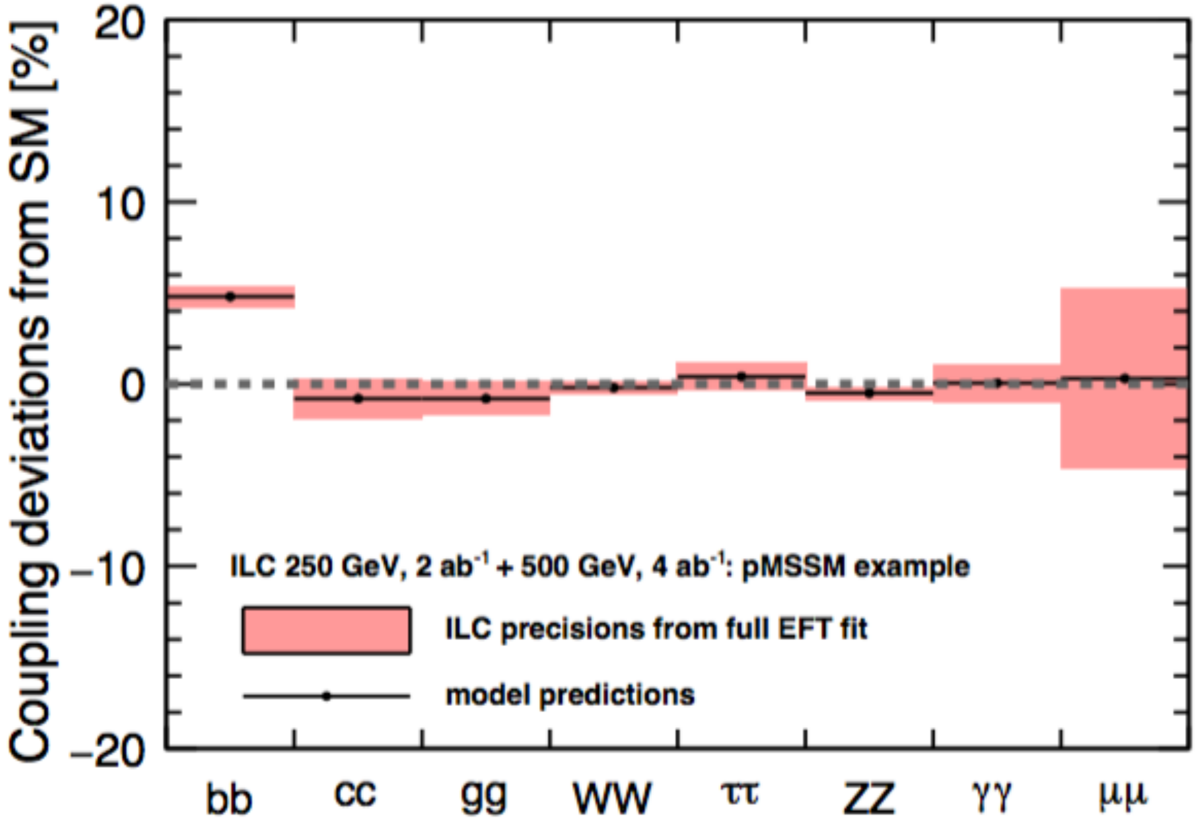
coupling to b, τ : supersymmetry, 2-Higgs doublet

coupling to W, Z : composite Higgs

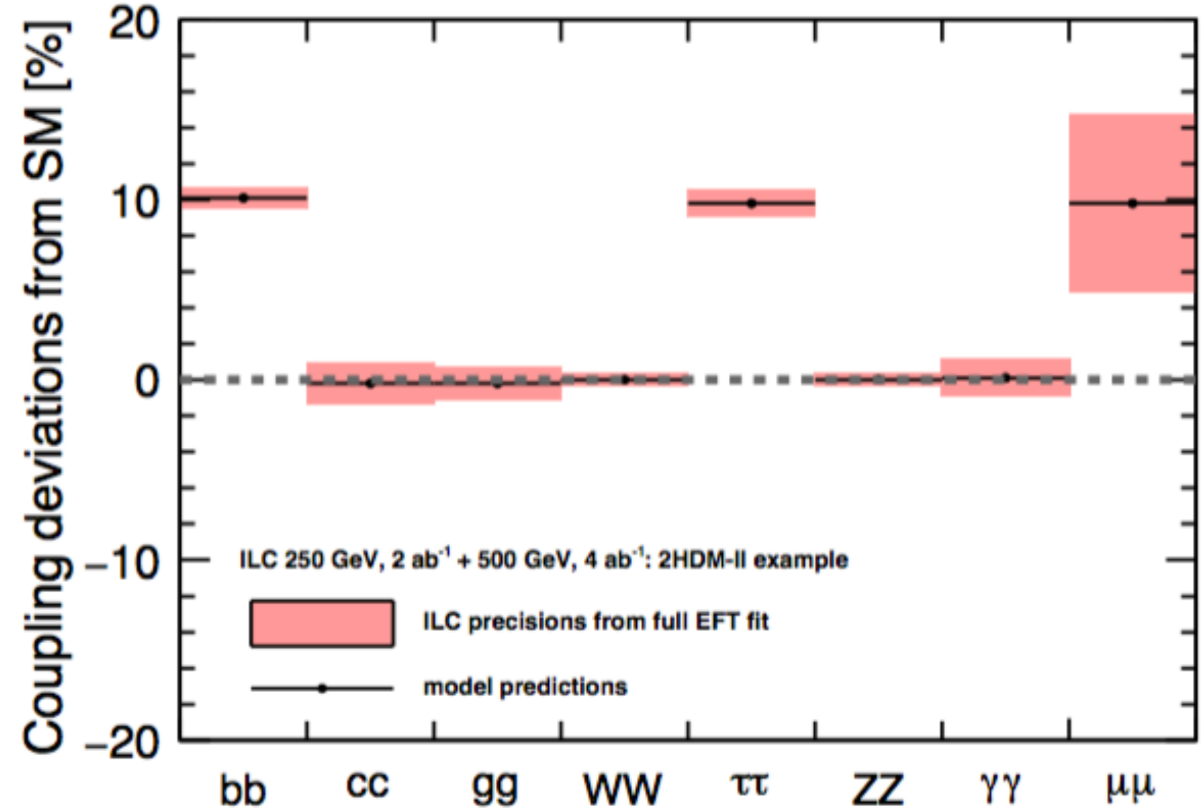
coupling to γ, g, t : top condensation, top partners

The measurement of anomalies in Higgs couplings cuts into parameter space in a matter orthogonal to the search for the new particles of these models.

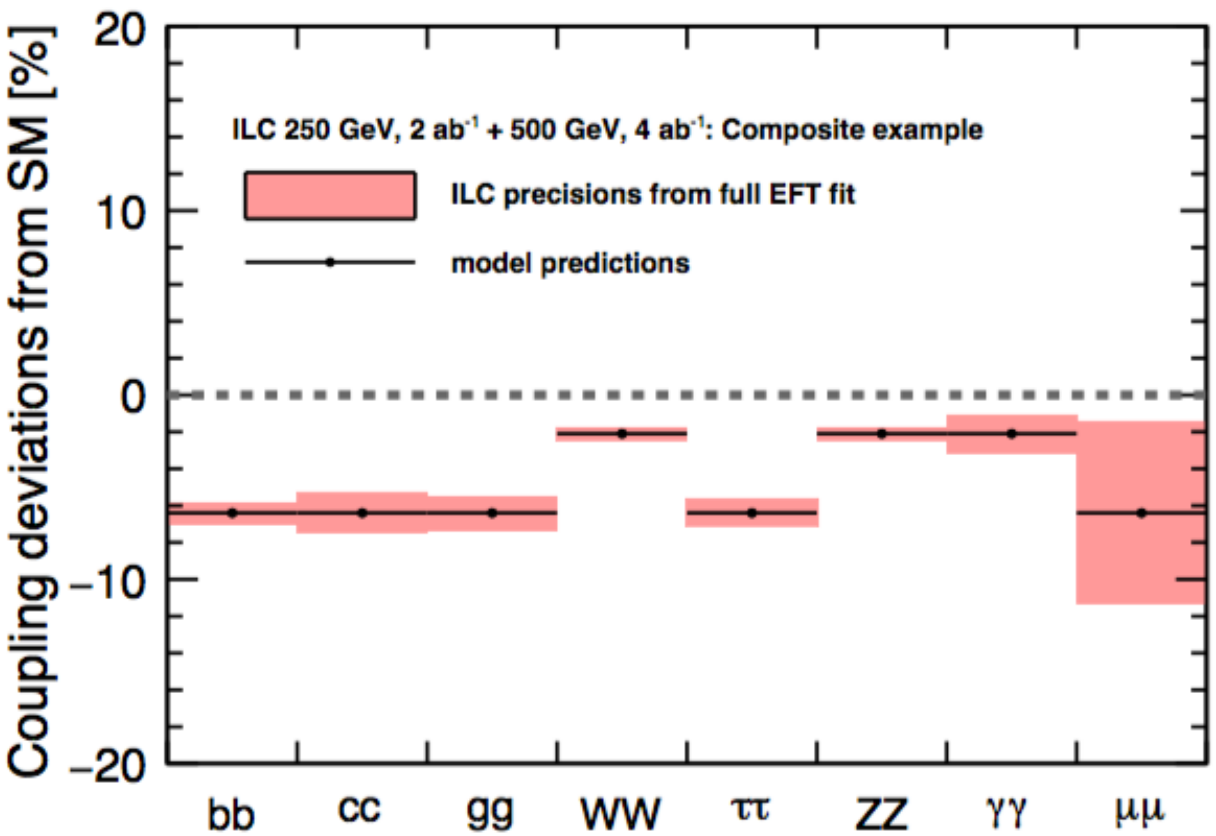
heavy SUSY



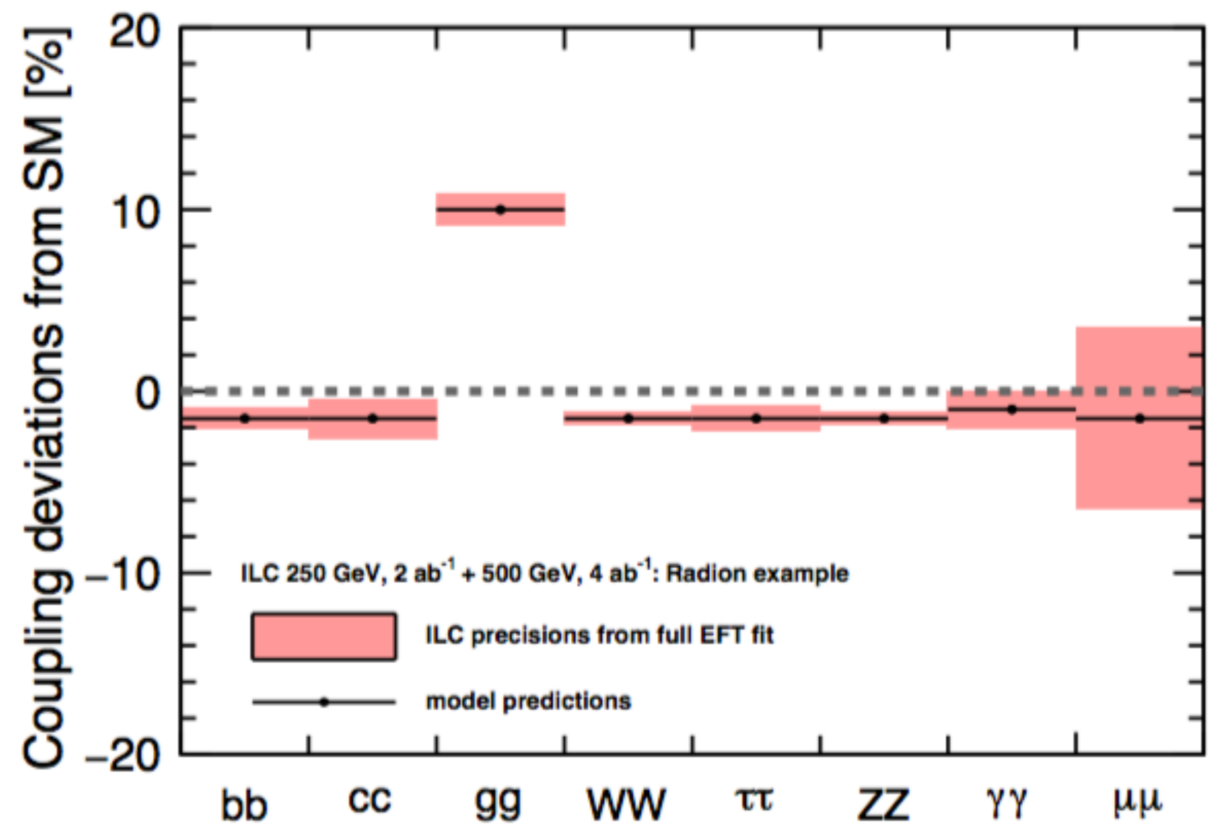
2 Higgs doublet

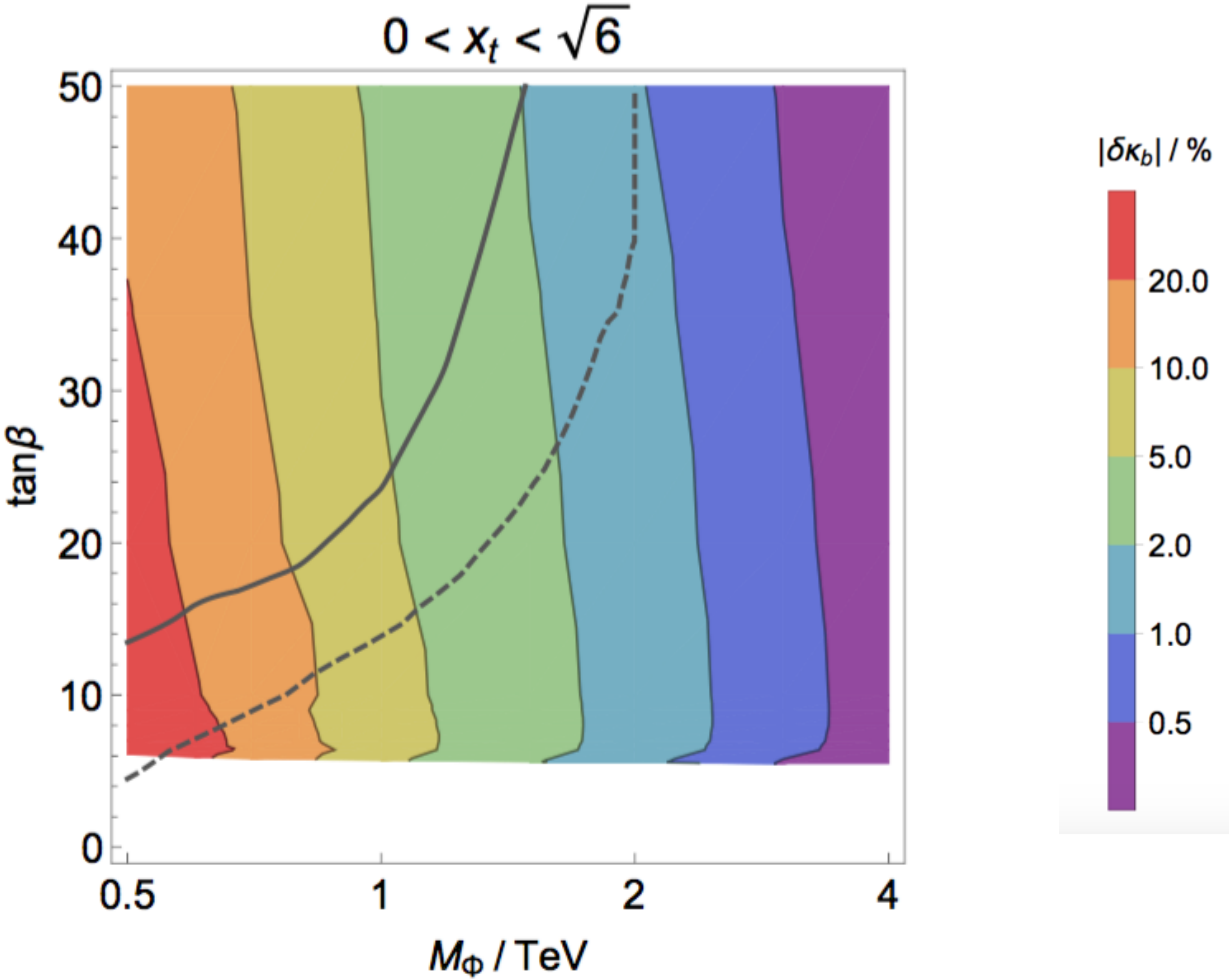


Composite Higgs



Higgs-Radion mixing





Wells and Zhang : models with b-τ unification

Unfortunately, the predicted coupling deviations are small, typically below 10% in all of these models.

This is not surprising. Parametrically, the effects are of order m_h^2/M^2 , since they come from dim-6 operators.

The LHC experiments are projected to reach 5-10% coupling measurements in the high-luminosity era.

5% x (3 σ) = not in the game

Fortunately, the Higgs boson can be studied also in e+e- annihilation. The peak of the cross section for

$$e^+e^- \to Z + h$$

is at 250 GeV. This energy would be accessible to a next-generation, high-luminosity e+e- accelerator.

Deviations in the Higgs boson couplings to b, c, τ, g are each controlled by a single coefficient in the dim-6 Lagrangian. However, the couplings of W and Z have two possible independent structures:

$$\Delta L_{hWW} = 2(1+\eta_W)m_h^2\frac{h}{v}W^+_\mu W^{-\mu} + \zeta_W\frac{h}{v}W^+_{\mu\nu}W^{-\mu\nu}$$

$$\Delta L_{hZZ} = (1+\eta_Z)m_h^2\frac{h}{v}Z_\mu Z^\mu + \frac{1}{2}\zeta_Z\frac{h}{v}Z_{\mu\nu}Z^{\mu\nu}$$

So it is a problem to find an appropriate framework to describe new physics contributions to these couplings in a model-independent way.

We (T. Barklow et al, arXiv:1708.08912) claim that the parametrization of new physics by dimension-6 operators gives a very effective method for analyzing the Higgs boson couplings.

A problem with this approach is its possible model-dependence. There are 59 baryon-number conserving dim-6 operators even for 1 generation of fermions.

We find that 17 of these operators contribute to Higgs and other relevant processes at e+e- colliders at the (electroweak) tree level.

We find that it is possible to constrain all 17 of these coefficients simultaneously using the large number of observables available from precision electroweak, $e^+e^- \to W^+W^-$, and e+e- Higgs reactions.

$$
\begin{aligned}
\Delta\mathcal{L} = {} & \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) \\
& -\frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3 \\
& +\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu} \\
& +\frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu} \\
& +i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu L) + 4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu t^a L) \\
& +i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e)\ . \\
& -\sum_i\left\{c_{\ell i\Phi}\frac{y_\tau \ell i}{v^2}(\Phi^\dagger\Phi)\overline{L}_i\cdot\Phi\,\ell_{iR} + c_{qi\Phi}\frac{y_\tau qi}{v^2}(\Phi^\dagger\Phi)\overline{Q}_i\cdot\Phi\,q_{iR}\right\} \\
& +\mathcal{A}\frac{h}{v}G_{\mu\nu}G^{\mu\nu}\ .
\end{aligned}
$$

Higgs Z factor

triple Higgs

h + W,Z,γ

Precision EW

h + q, l, g

For example, here is the solution to the problem of multiple possible Higgs couplings for W and Z:

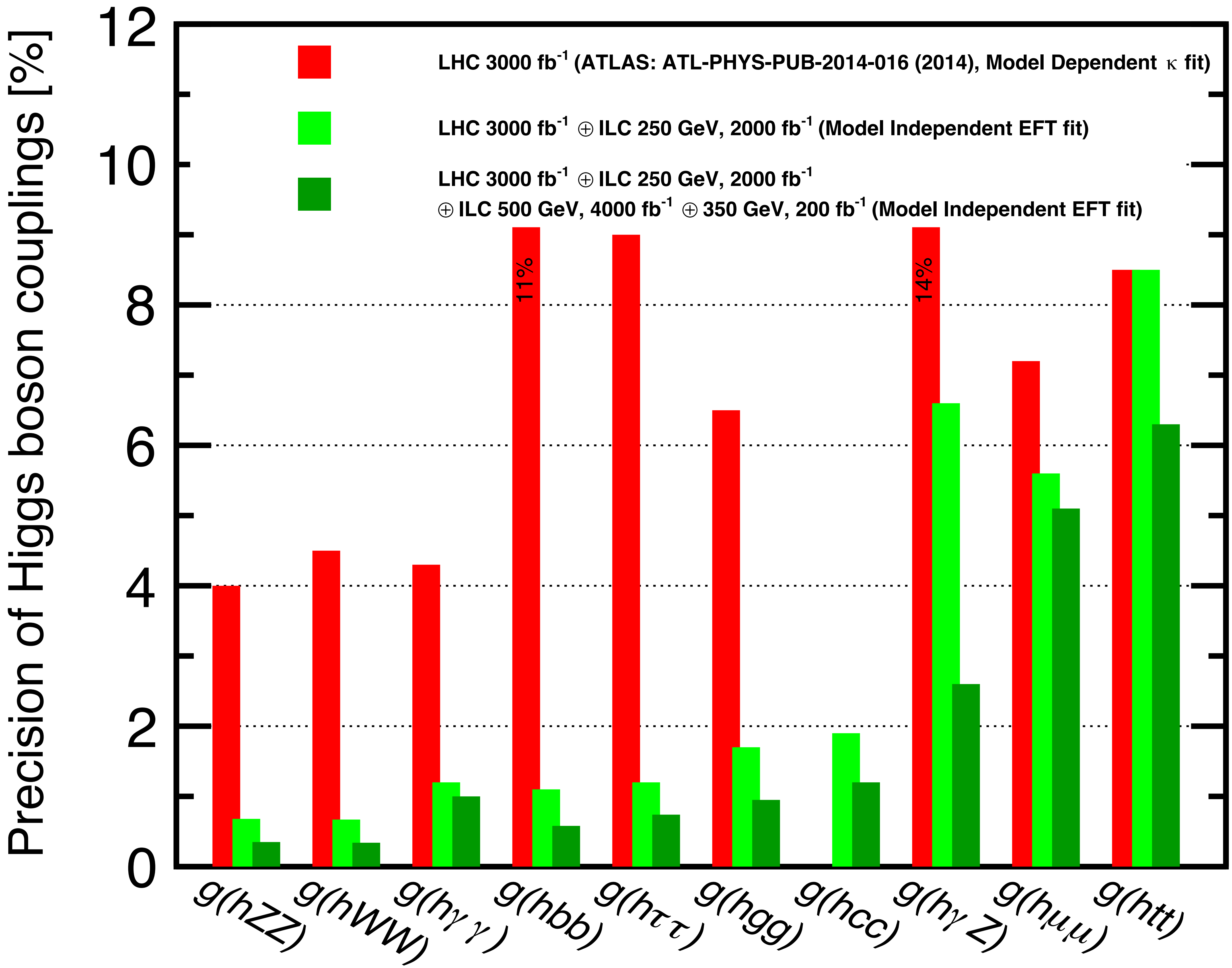
The dim-6 Lagrangian gives nontrivial but tractable relations between the Z and W parameters:

$$\eta_W = -\frac{1}{2}c_H \qquad \eta_Z = -\frac{1}{2}c_H - c_T$$

$$\begin{aligned} \zeta_W &= (8c_{WW}) \\ \zeta_Z &= c_w^2(8c_{WW}) + 2s_w^2(8c_{WB}) + (s_w^4/c_w^2)(8c_{BB}) \end{aligned}$$

The parameter ζ_Z is very sensitive to the polarization asymmetry in $\sigma(e^+e^- \to Zh)$. (This gives special power to an accelerator with beam polarization.)

Here are our projections for Higgs coupling accuracies with the expected data set of the International Linear Collider (ILC):

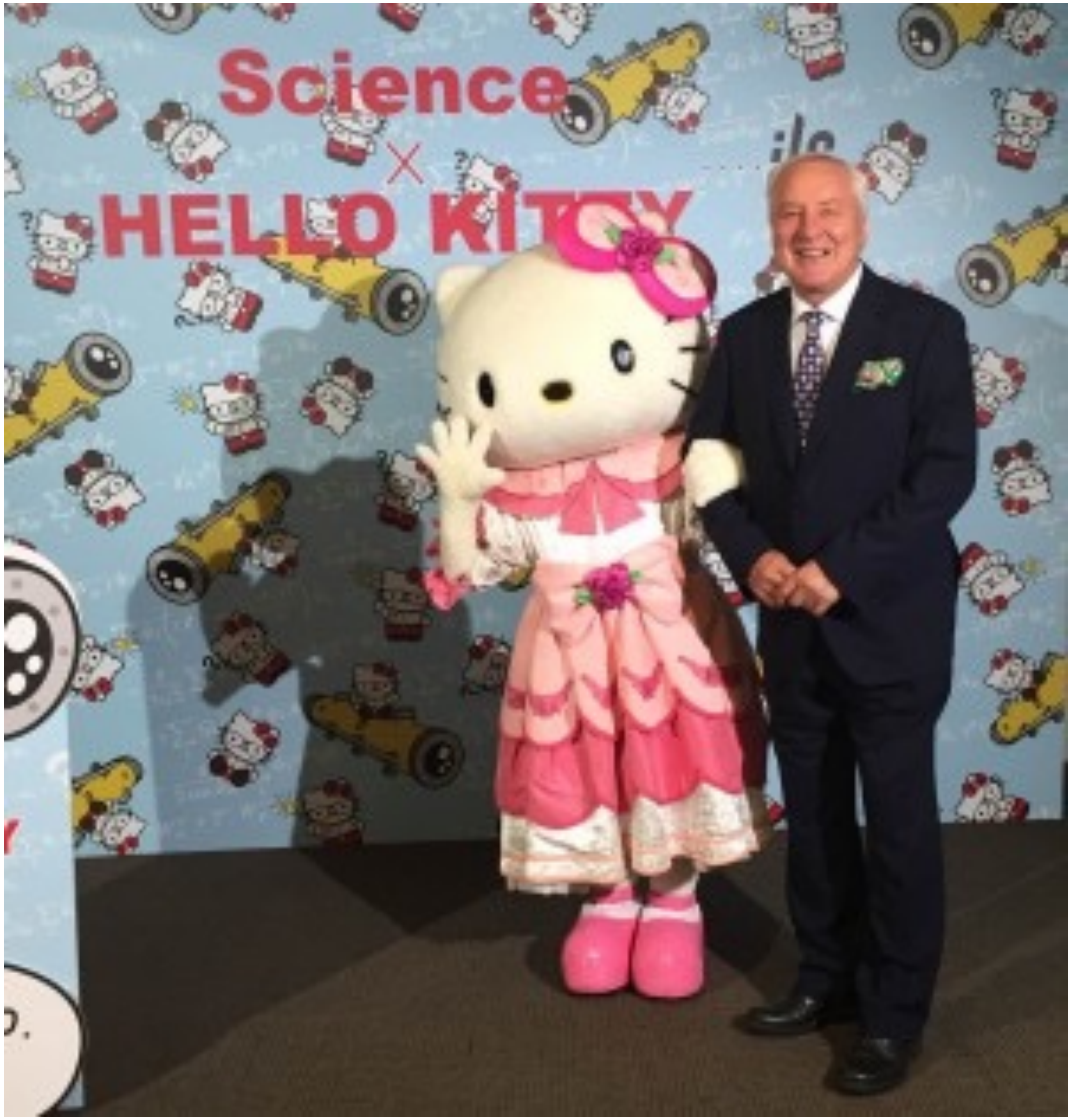


Several proposals for e+e- Higgs factories are now being discussed. The one closest to a real decision is the International Linear Collider in Japan.

The Technical Design Report was submitted in 2013. Japan is a consensus-based society, and so this began a period of long deliberation with all stakeholders.

After many years, this process seems to be coming to an end. Final committee reports are being submitted now. A decision by the government is required before the beginning of the 2019-2020 European Strategy for Particle Physics study.

Hon. Shintaro Ito (Sendai) meeting with the American Linear Collider Coordinating Committee, AWLC 2017 at SLAC, June 2017



Lyn Evans, LCC director, with Hello Kitty

Please watch for news of ILC later this year.

I hope that you will also make clear to others how important this precision Higgs measurement program is for the future of our field.

Don't let anyone tell you that we can ignore the physics of the Higgs field and only think about physics at

$$10^{12} - 10^{16} - 10^{19} \text{ GeV}$$

The nature of the Higgs boson and the solution to the problem of the Higgs phase transition affects how we must think about all higher mass scales.

The Standard Model has unfinished business, most of all the nature of the Higgs field phase transition and ordered state.

Precision measurements on the Higgs boson can reveal the new interactions responsible, and give clues to their nature.

We should not miss the opportunity to make these measurements.