# The Standard Model and the Higgs Boson

## 4. Standard Model Effective Field Theory

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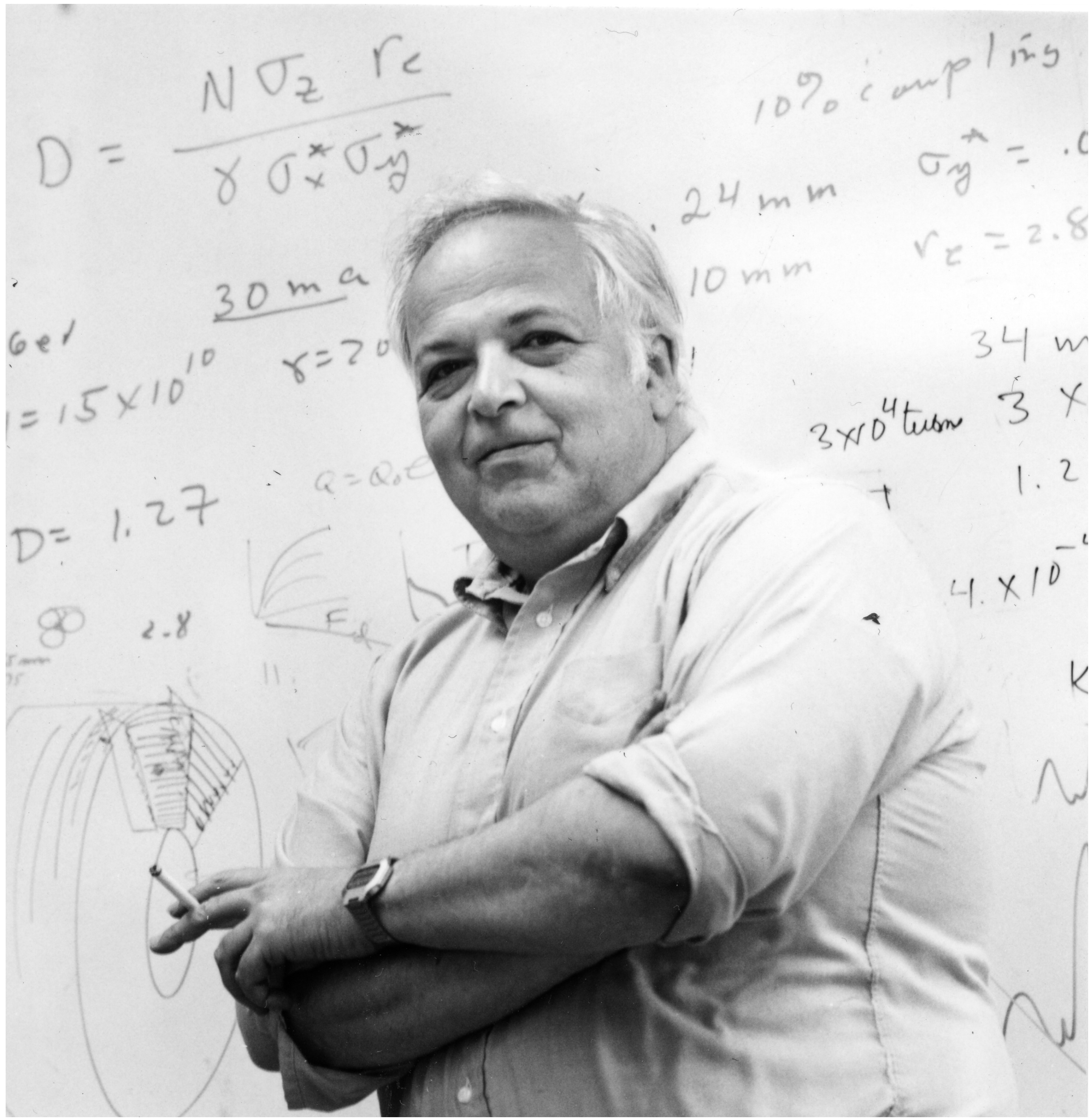
# In memoriam Burton Richter (1931-2018)



Gerson Goldhaber, Martin Perl, Burton Richter
and the ψ particle, November 1974

We have now seen that the Standard Model makes very precise predictions for the rates of electroweak and Higgs processes, and also that precision measurements of these rates are possible. Putting these together, we can do sensitive searches for physics beyond the Standard Model.

These searches are “indirect”. But there is no needed to quibble. The discovery of physics beyond the Standard Model in accelerator experiments would be a major advance in our knowledge.

These ideas imply: The purpose of precision measurement is not to decrease the size of error bars. It is to discover deviations from the Standard Model at high levels of confidence.

A particularly important object to study is the Higgs boson.

On one hand, almost all of the mysteries of the Standard Model — the origin of its spontaneous symmetry breaking, the pattern of quark and lepton masses, the origin of CP violation — are connected to the couplings of the Higgs boson. We do not know whether there is one Higgs doublet or a complex Higgs sector.

On the other hand, our experimental knowledge about the Higgs is still at a relatively low level of precision. I will argue in a moment that corrections to the Higgs boson properties are typically below the 10% level. To observed these corrections with confidence, we need measurements of Higgs couplings to 1% accuracy. Can we get there?

In this lecture, I will address the following question: If a deviation from the SM is seen, how do we parametrize it and, eventually, compare it to theoretical models of BSM physics ?

We have already discussed this question using the S, T formalism for precision electroweak. But this is only a partial answer.

Now, there is a much more systematic approach based on "Standard Model Effective Field Theory".

The starting point for this analysis is the statement:

The SM is the most general renormalizable quantum field theory with the particle content observed in nature.

If we omit the top quark or the Higgs boson from the SM, the theory knows this and predicts infinite corrections (proportional to $\log m_h^2$ or $\log m_t^2$ ) in the full SM. We have seen that loops containing the top quark can be enhanced by factors of $m_t^2/m_W^2$ .

This cannot happen when new physics is added to the SM. As long as the SU(2)xU(1) symmetry is preserved, any perturbation of the SM vertices by new heavy particles of mass M can be incorporated by a shift of the SM parameters. There can be residual effects not accounted in this way. But these must be represented by adding higher-dimension operators to the SM. These residual effects – the only effects that are observable – are explicitly suppressed by factors of $1/M^2$, $1/M^4$, etc.

Any theory of physics that is SU(2)xU(1)-invariant, with the particles of the SM plus new particles of higher mass M, is described by the effective Lagrangian:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{M^2}\sum_i \tilde{c}_i \mathcal{O}_{6i} + \frac{1}{M^4}\sum_i \tilde{d}_i \mathcal{O}_{8i} + \cdots$$

This effective Lagrangian (EFT) is “nonrenormalizable”, still we can calculate with it unambiguously. We organize perturbation theory as a double perturbation theory in $(g_i, 1/M^2)$. Here is how this works at 1-loop order:

All effects of order $1/M^0$ are described by the SM, possibly with shifted parameters. The SM parameters receive divergent corrections in perturbation theory. These divergences may include quadratic divergences of the form $\alpha_w \tilde{c}_i \Lambda^2/M^2$. They can still be removed by absorbing them into the SM parameters.

Effects of order $1/M^2$ are proportional to $\tilde{c}_i$. At 1-loop, these terms can receive divergent corrections of order $\alpha_w \tilde{c}_i (\log \Lambda^2)/M^2$. These can be absorbed into the coefficients $\tilde{c}_i$. This is an operator rescaling of the operators $\mathcal{O}_{6i}$, which may also include operator mixing.

The complete dimension-6 operator anomalous dimension matrix $\gamma_{ij}^{(6)}$ was recently computed by Manohar, Jenkins, and Trott, arXiv:1308.2627,1310.4838, 1312.2014. This controls (and resums) all logarithmic terms in this calculation.

One subtlety is that the SM equations of motion might give relations among operators. For example,

$$-\Phi^* D^2 \Phi = \mu^2 |\Phi|^2 + 2\lambda |\Phi|^4 + 3\frac{\tilde{c}_6}{M^2}|\Phi|^6$$

It is a theorem that matrix elements of quantities that are zero by the equations of motion do not contribute to S-matrix elements. So, we can eliminate combinations of operators that are zero by the equations of motion, both in the original Lagrangian and when these operators are generated by radiative corrections.

Effects of order $1/M^4$ are proportional to $\tilde{c}_i^2$ or $\tilde{d}_i$ . At 1-loop, these terms can receive divergent corrections of order $\alpha_w \tilde{c}_i^2 (\log \Lambda^2)/M^4$ . These generate dimension-8 operators (if those operators were not already present) and can be absorbed into the coefficients $\tilde{d}_i$ .

These arguments can be straightforwardly extended to terms of order $1/M^{2n}$ and to higher loops.

In the discussion to follow, I will work only in the simplest case: linear order in dimension-6 operators, and tree level. For LHC applications, it is especially important that we can, with effort, extend this analysis to higher orders.

Since we do not know the scale $M$, I will, for definiteness, replace the coefficients $\tilde{c}_i/M^2$ with coefficients $c_i/m_W^2$ .
Then the expectation is that $c_i \sim m_W^2/M^2$, and this is how the $c_i$ encode the scale of new physics.

Before we consider the general case, let's look at some examples of the use of dimension-6 operators to parametrize new physics.

At the Snowmass 1982 workshop, a hot topic was how to test for the compositeness of quarks and leptons. Eichten, Lane, and I proposed that, if the SM fermions were composite, then there would be contact interactions with coefficients unsuppressed by coupling constants. For the electron, there are 3 possible terms

$$\Delta\mathcal{L} = \frac{2\pi}{\Lambda^2}\left[\eta_{LL} j^\mu_L j_{\mu L} + 2\eta_{LR} j^\mu_L j_{\mu R} + \eta_{LR} j^\mu_R j_{\mu R}\right]$$

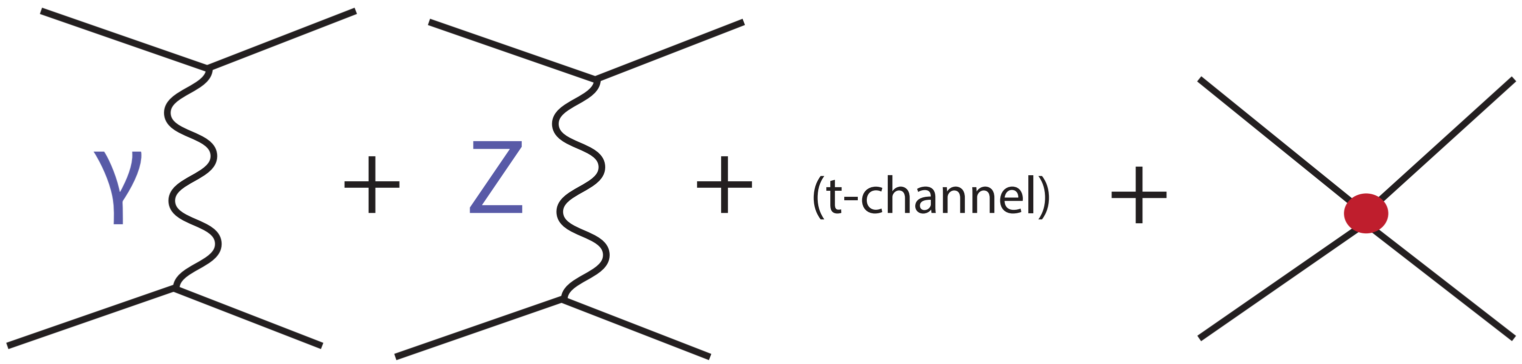
with

$$j^\mu_L = e^\dagger_L \overline{\sigma} e_L \qquad j^\mu_R = e^\dagger_R \sigma e_R$$

For quark-quark scattering, there are 17 possible terms that are SU(2)xU(1)-invariant.

We set the largest η parameter equal to 1 and then interpreted Λ as the compositeness scale.

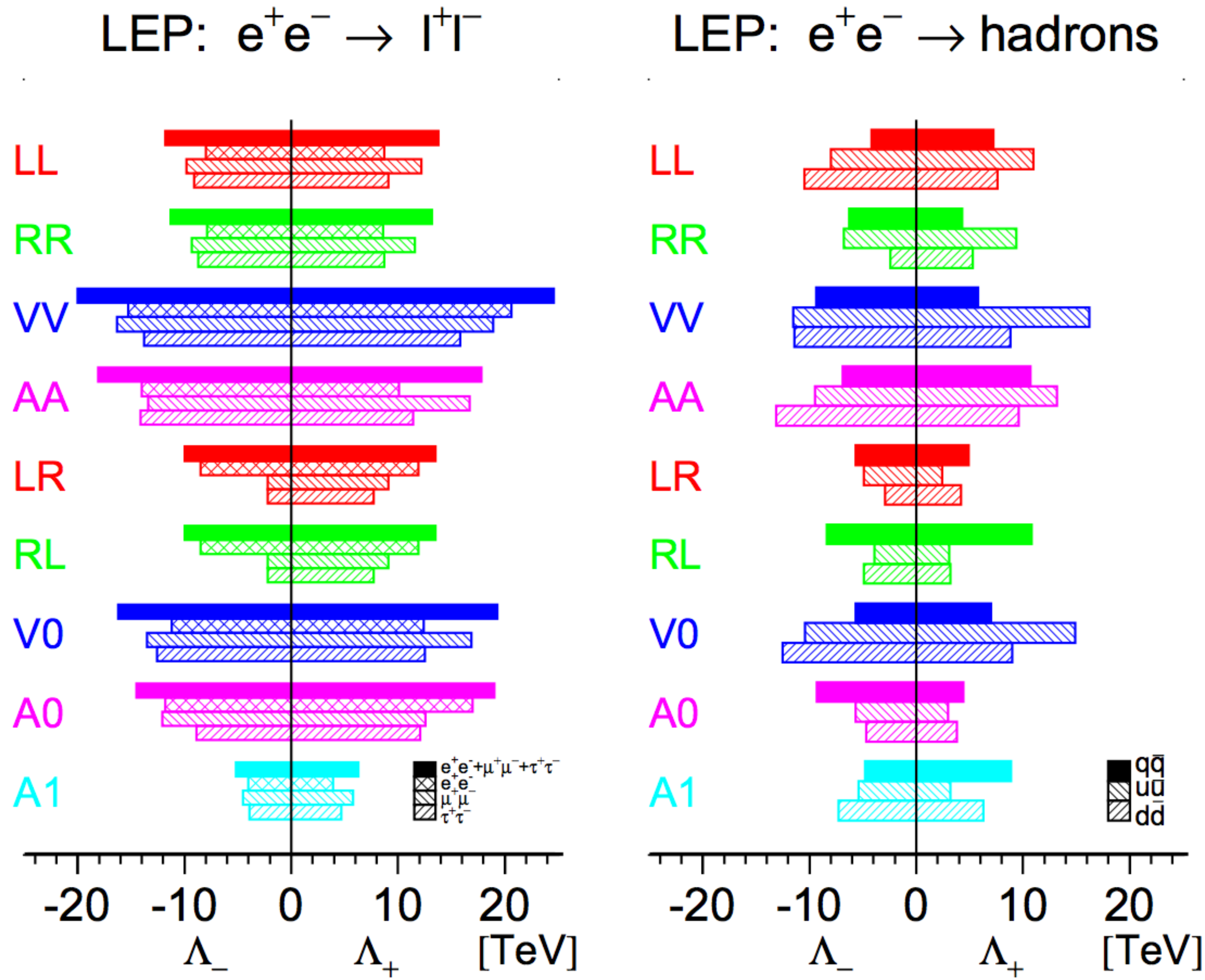
The complete amplitude for $e^+e^- \to e^+e^-$ is given by




so the contact interaction correction is of relative order

$$1/(\alpha\Lambda^2)$$

that is, it is surprisingly large.    The three η parameters can be disentangled using angular distributions.  LEP 2 at 200 GeV set limits on the compositeness scale of  8 TeV.




LEP Electroweak WG, arXiv:1302.3415

Another example is found in the S and T parameters

Consider the addition to the SM Lagrangian

$$\Delta\mathcal{L} = \frac{c_T}{2v^2} j^\mu_\Phi j_{\Phi\mu} + \frac{4gg' c_{WB}}{m_W^2} \Phi^\dagger t^a \Phi W^a_{\mu\nu} B^{\mu\nu}$$

where

$$j^\mu_\Phi = \Phi^\dagger D^\mu \Phi - D_\mu \Phi^\dagger \ \Phi$$

To understand the consequences of this, set $\Phi \to \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$

Then

$$\Phi^\dagger t^a \Phi \to = -\frac{1}{4} v^2 \delta^{a3} \qquad j^\mu_\Phi \to -\frac{1}{2}\frac{g}{c_w} v^2 Z^\mu$$

We see that these are exactly corrections to S and T. Working out the details,

$$\alpha S = 32 s_w^2 c_{WB} \qquad \alpha T = c_T$$

It turns out that U is generated only by dimension-8 operators.

This formalism is also used to describe new physics corrections to $e^+e^- \to W^+W^-$. We saw in lecture 2 that the amplitudes for longitudinal W pair production have a delicate cancellation that is dictated by the GBET. It is possible that effects of new physics can upset this cancellation.

Once, the search for these effects was called a search for violation of SU(2)xU(1) gauge invariance. Today, SU(2)xU(1) is well tested and is, in fact, part of the foundation of the SM. But, dimension-6 operators can upset the cancellation and give effects enhanced by

$$c_i \cdot \frac{s}{m_W^2}$$

Consider, in particular, the operators

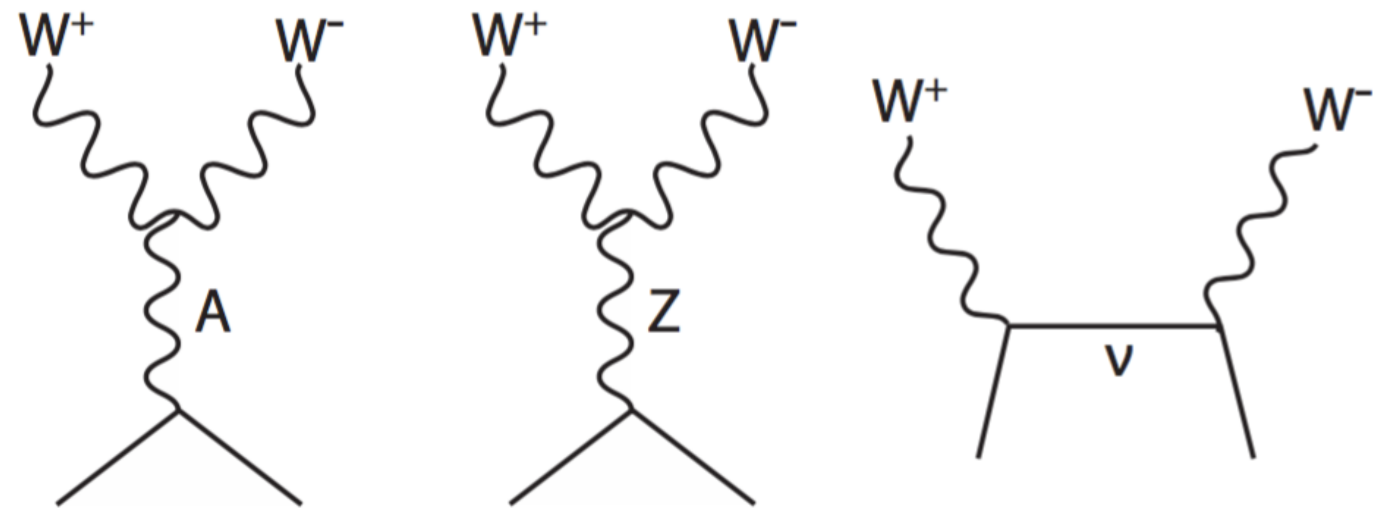
$$+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu}+\frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu}$$
$$+\frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu}+\frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu}$$

Setting Φ to its vev, the first three operators give a field rescaling of γ, W, Z, and also a γ-Z mixing term

$$\delta Z_W = \zeta_W = (8c_{WW})$$
$$\delta Z_Z = \zeta_Z = c_w^2(8c_{WW}) + 2s_w^2(8c_{WB}) + s_w^4/c_w^2\,(8c_{BB})$$
$$\delta Z_A = \zeta_A = s_w^2(8c_{WW}) - 2s_w^2(8c_{WB}) + s_w^2(8c_{BB})$$
$$\delta Z_{AZ} = \zeta_{AZ} = s_w c_w(8c_{WW}) - s_w c_w(1 - s_w^2/c_w^2)(8c_{WB}) - s_w^3/c_w\,(8c_{BB})$$

These operators also contain direct 3V interactions.

In the literature, the γWW and ZWW vertices are parametrized by an effective interaction




$$\Delta\mathcal{L}_{TGC} = ig_V\Big\{V^\mu(\hat{W}^-_{\mu\nu}W^{+\nu} - \hat{W}^+_{\mu\nu}W^{-\nu}) + \kappa_V W^+_\mu W^-_\nu \hat{V}^{\mu\nu} + \frac{\lambda_V}{m_W^2}\hat{W}^{-\rho}_\mu \hat{W}^+_{\rho\nu}\hat{V}^{\mu\nu}\Big\},$$

The effect of the new operators is to modify 5 of the 6 parameters ( $g_A = e$ by QED gauge invariance).

$$g_Z = gc_w(1 + \frac{1}{2}\delta Z_Z + \frac{s_w}{c_w}\delta Z_{AZ})$$

$$\kappa_A = 1 + (8c_{WB})$$

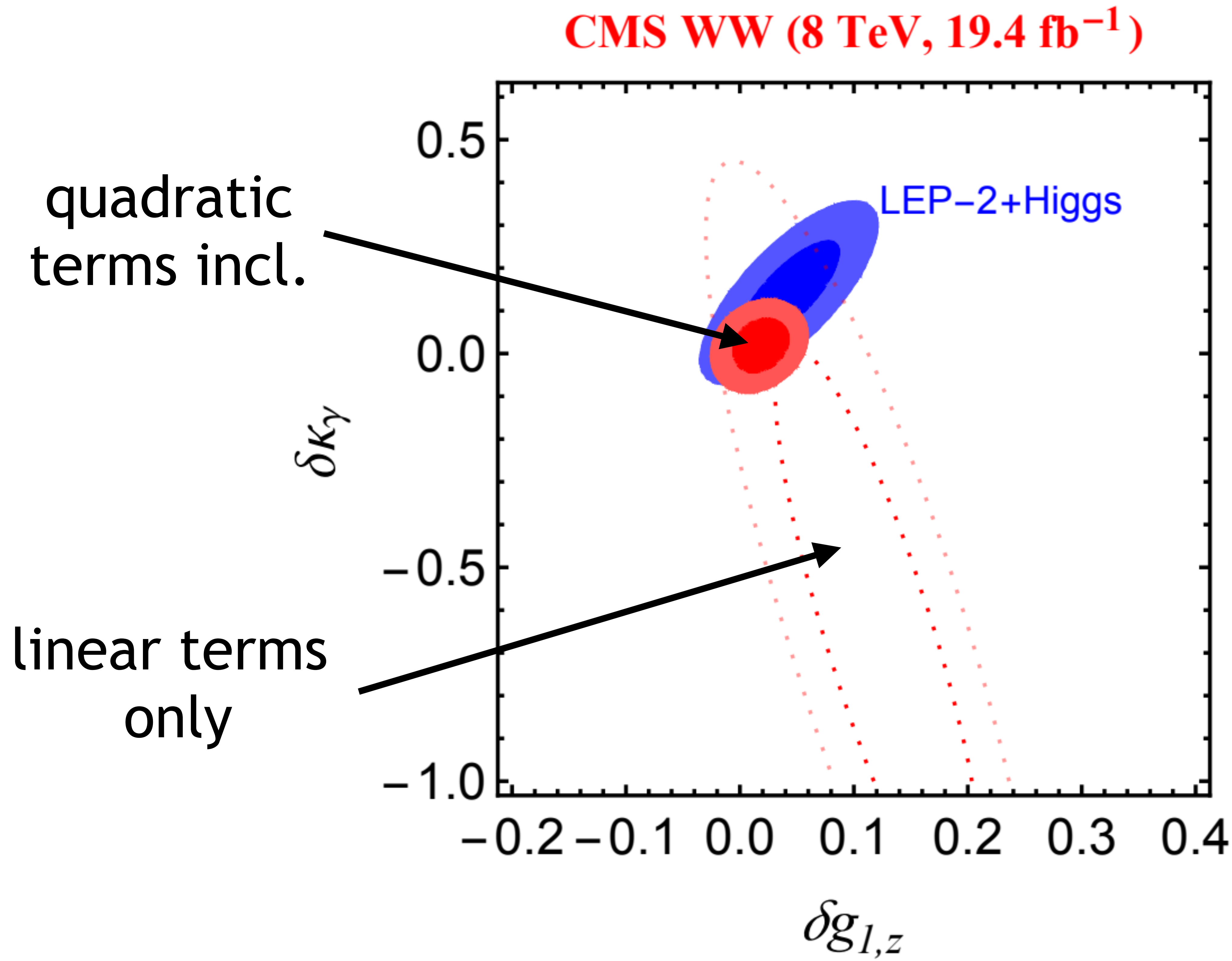
$$\kappa_Z = 1 - \frac{s_w^2}{c_w^2}(8c_{WB})$$

$$\lambda_A = \lambda_Z = -6g^2 c_{3W}$$

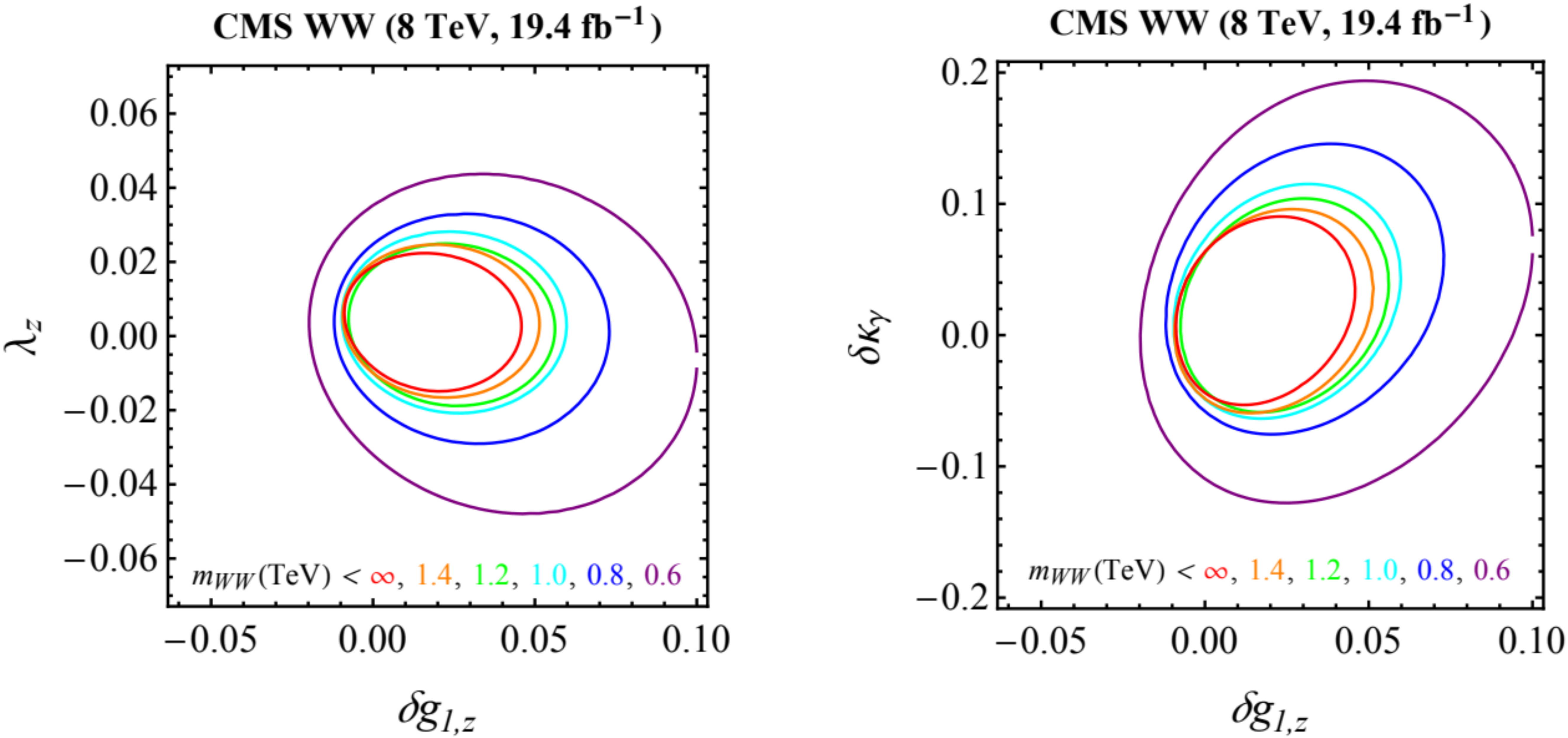
Note that the 5 shifts come from 3 EFT coefficients. The other 2 directions are turned on by dimension-8 operators.

These interactions are now being probed at the LHC.

The LHC gives access to large values of $\hat{s}/m_W^2$, giving high sensitivity to these $c_i$. However, this is a bargain with the devil. If $\hat{s}/m_W^2$ is too large, it is no longer correct to keep only the terms linear in $c_i$, that is, the interfererence term between new physics and SM amplitudes. Terms with $c_i^2$ can also be important. But these are of the same order as effects of dimension-8 operators. Then (IMHO) the analysis cannot be trusted.




Falkowski, Ganzalez-Alonso, Greljo, Marzocca, Son, arXiv:1609.06312




Falkowski, Ganzalez-Alonso, Greljo, Marzocca, Son,
arXiv:1609.06312

Deviations of the Higgs couplings from the SM predictions can also be discussed in this framework.

For definiteness, consider $h \to \tau^+\tau^-$ . The operator

$$\Delta\mathcal{L} = -c_{\tau\Phi}\frac{y_\tau}{v^2}(\Phi^\dagger\Phi)L^\dagger \cdot \Phi\tau_R + h.c.$$

gives

$$m_\tau = \frac{y_\tau v}{\sqrt{2}}(1+\frac{1}{2}c_{\tau\Phi}) \qquad g_{h\tau\tau} = y_\tau(1+\frac{3}{2}c_{\tau\Phi})$$

so the relation between the mass and Higgs coupling is broken. Also the operator

$$\Delta\mathcal{L} = \frac{c_H}{2v^2}\partial_\mu(\Phi^\dagger\Phi)\partial^\mu(\Phi^\dagger\Phi)$$

gives a field rescaling of the Higgs field that modifies all couplings. Finally,

$$\delta\Gamma(h \to \tau^+\tau^-) = 1 - c_H + 2c_{\tau\Phi}$$

Notice that, when dimension-6 operators are added, the natural flavor conservation of the SM is no longer required. Using the above coupling, we could have

$$\Delta\mathcal{L} = -c_{\tau\Phi}\frac{Y^{ij}}{v^2}L_i^\dagger\cdot\Phi e_{jR} + h.c. - c_{\tau\Phi}\frac{Y'^{ij}}{v^2}(\Phi^\dagger\Phi)L_i^\dagger\cdot\Phi\tau_{jR} + h.c.$$

Without flavor symmetry, there is no reason for Y and Y' to be diagonalized in the same basis.

The underlying BSM theory, which is integrated out, needs to supply this flavor symmetry. Alternatively, we could see Higgs decay processes such as

$$h \to \tau\mu$$

arising from dimension-6 operators.

The situation of $h \to W^+W^-$ is more complicated. The operators

$$\Delta\mathcal{L} = \frac{c_H}{2v^2}\partial_\mu(\Phi^\dagger\Phi)\partial^\mu(\Phi^\dagger\Phi) + \frac{g^2 c_{WW}}{m_W^2}(\Phi^\dagger\Phi)W^a_{\mu\nu}W^{a\mu\nu}$$

give modifications of the hWW vertex of two different structures

$$(1+\eta_W)\frac{2m_W^2}{v}hW^+_\mu W^{-\mu} + \zeta_W\frac{1}{v}W^+_{\mu\nu}W^{-\mu\nu}$$

which have different physical origin and so must be separately extracted from experimental data.

Fortunately, we have seen $c_{WW}$ earlier in this lecture.

A joint analysis of all data with all relevant operators can potentially be helpful here.

This raises the question:

How many of these dimension-6 operators are there, anyway ? Actually, it is easy to write many dimension-6 operators, but probably this is an overcomplete basis, since we can remove operators that are zero by the equations of motion.

The correct list was given by

Grzadkowski, Iskrzynski, Misiak, and Rosiek,
arXiv:1008.4884

It turns out that there are 59 baryon- and lepton-number conserving SU(2)xU(1) invariant dimension-6 operators (for the case of 1 fermion generation).

For any given process, only a subset of these operators contribute. However, typically, this subset is larger than what you would naively guess.

The field strength rescalings affect all processes with the affected fields. Additional operators alter the fermion-Z couplings. These effects are constrained by precision electroweak measurements but nevertheless contribute to any process with quark or lepton initial states.

A typical such operator is $\frac{c_{HL}}{v^2} j^\mu_\Phi (L^\dagger \overline{\sigma}_\mu L)$

with $$j^\mu_\Phi = \Phi^\dagger D^\mu \Phi - D_\mu \Phi^\dagger \ \Phi \approx -\frac{1}{2}\frac{g}{c_w} v^2 Z^\mu$$

This gives direct Higgs couplings in addition to the Z vertex modification.

At the LHC, where we have many species of quark that are not easily distinguished experimentally, and where quark-quark scattering contributes to many processes, it looks hopeless to perform a complete analysis with the full set of relevant observables.

In e+e- annihilation, where the initial particles are definitely e+e- and the quarks appear minimally, there is a chance to perform an analysis (tree-level, anyway) that is completely general.

We demonstrate this in

Barkow, Fujii, Jung, Karl, List, Ogawa, Peskin, and Tian, arXiv:1708.08912, arXiv:1708.09079

Using the equations of motion, we aggressively reduce the number of operators, removing operators with quarks.

First, consider only operators with γ, W, Z, h only (using equations of motion to minimize this set. There are 7 of these:

$$\frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3$$
$$+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu}$$
$$+\frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu}$$

Add operators that modify the couplings of leptons to SM bosons. (Here I will assume lepton universality.)

$$+i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu L) + 4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu t^a L)$$
$$+i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e) \ .$$

Add operators that modify the chirality-flip fermion-Higgs couplings $-c_{\tau\Phi}\frac{y_\tau}{v^2}(\Phi^\dagger\Phi)\overline{L}_3\cdot\Phi\tau_R + h.c.$

1 operator each for b, c, τ, μ – and g .

We will also need to include 2 more combinations of $c_{HL}$-type operators that shift the W and Z widths.

The total number of dimension-6 operators needed is 17. No other operators (except one eeμμ 4-fermion operator) contribute to any process we consider at the tree level.

CP - violating operators contribute to our observables in order $c^2$ . If these can be bounded $c \lesssim 1\%$ , they are irrelevant to our analysis.

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

Higgs Z factor

triple Higgs

h + W,Z,γ

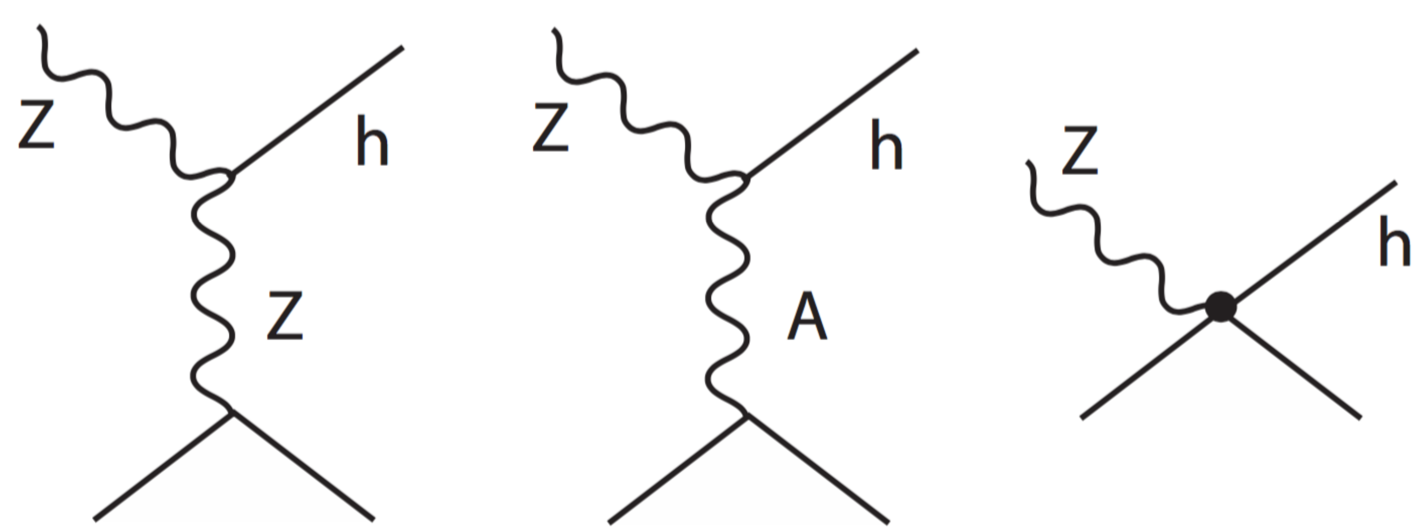
Precision EW

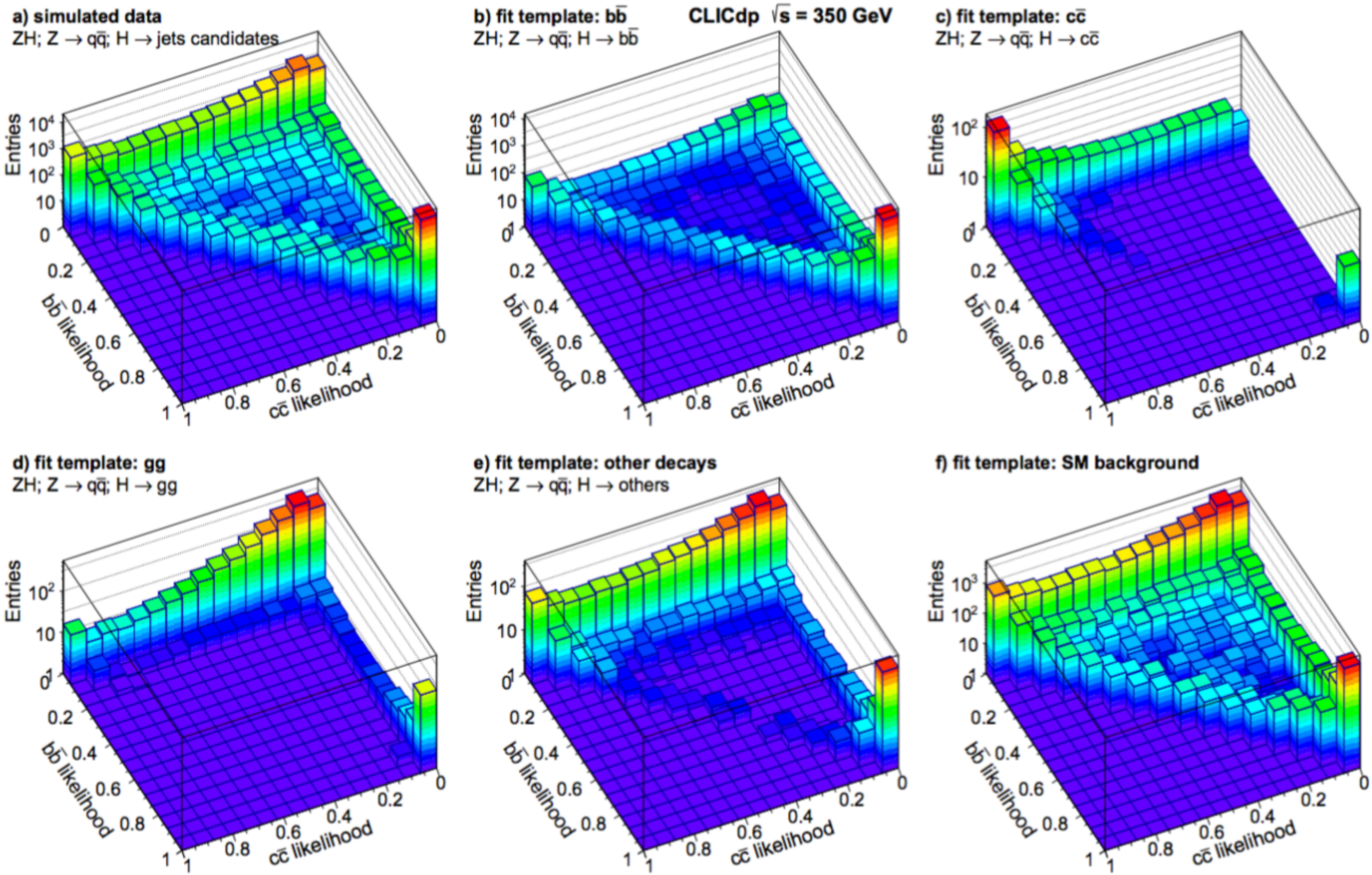
h + q, l, g

In our analysis, we combine precision electroweak data with prospective data from the International Linear Collider (ILC) on $e^+e^- \to W^+W^-$ and $e^+e^- \to Zh$ .

The process $e^+e^- \to Zh$ is quite remarkable. Higgs bosons are tagged by the presence of the Z (at a lab energy of 110 GeV for a CM energy of 250 GeV. All Higgs decay modes, even invisible or partially invisible ones, are observable. In the e+e- environment, the hadronic Higgs decay modes can be observed and distinguished.

It has extra features importance for our purposes here.






CLIC Higgs analysis group

We need to constrain $\eta_Z$ and $\zeta_Z$ separately.

Assuming CP, $e^+e^- \to Zh$ has only two independent helicity amplitudes for each beam polarization. This is captured by parameters a ($hZ_\mu Z^\mu$ part) and b ($hZ_{\mu\nu}Z^{\mu\nu}$ part):

$$\sigma = \frac{2}{3}\frac{\pi\alpha_w^2}{c_w^4}\frac{m_Z^2}{(s-m_Z^2)}\frac{2k_Z}{\sqrt{s}}(2+\frac{E_Z^2}{m_Z^2})\cdot Q_Z^2\cdot\left[1+2a+2\,\frac{3\sqrt{s}E_Z/m_Z^2}{(2+E_Z^2/m_Z^2)}\,b\right]$$

$e^-_L e^+_R$

$$Q_{ZL} = (\frac{1}{2}-s_w^2)\ , \qquad a_L = -c_H/2$$

$$b_L = c_w^2(1+\frac{s_w^2}{1/2-s_w^2}\frac{s-m_Z^2}{s})(8c_{WW})$$

$e^-_R e^+_L$

$$Q_{ZR} = (-s_w^2)\ , \qquad a_R = -c_H/2$$

$$b_R = c_w^2(1-\frac{s-m_Z^2}{s})(8c_{WW})\ .$$

Notice that a is independent of beam polarization, while b, proportional to $\zeta_Z$, flips sign.

Assembling data from all of the relevant reactions, we can separately constrain 22 parameters — 4 Standard Model parameters ($g$, $g'$, $v$, $\lambda$), 16 dimension-6 operator coefficients ($c_6$ does not appear), and 2 additional parameters to account for invisible and exotic Higgs decays.

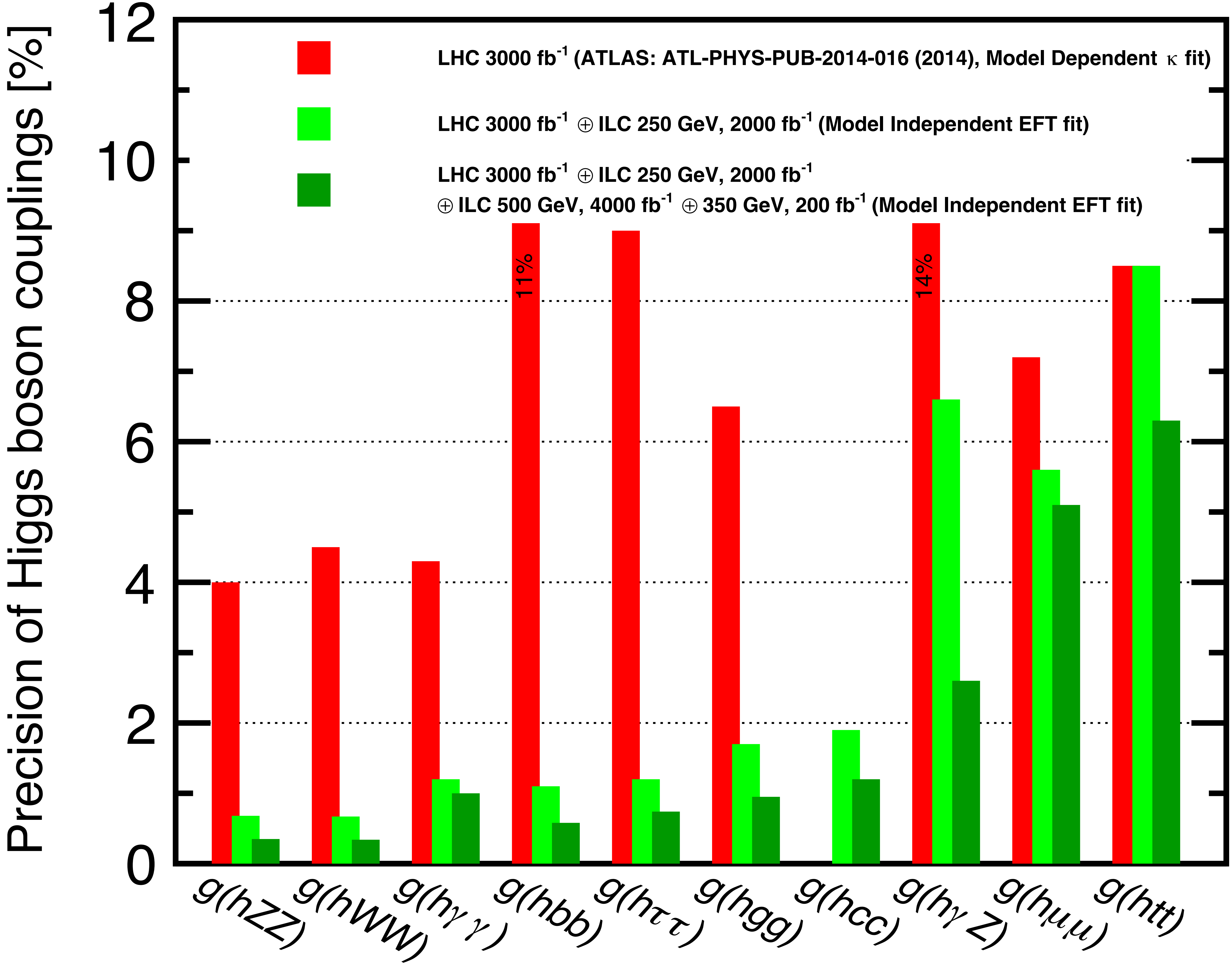
This analysis applies to the most general new physics model for which the effective field theory approach is valid.

We can interpret our results in terms of the expected precision of Higgs coupling determinations. Note that the extracted Higgs couplings are absolutely normalized and the Higgs width is also determined by the analysis.

Here are some final results for various proposed colliders:

| | ILC | CLIC | CEPC | FCC-ee | ILC500 |
|---|---|---|---|---|---|
| | 2 $ab^{-1}$ w. pol. | 2 $ab^{-1}$ 350 GeV | 5 $ab^{-1}$ no pol. | + 1.5 $ab^{-1}$ at 350 GeV | full ILC 250+500 GeV |
| $g(hb\bar{b})$ | 1.04 | 1.08 | 0.98 | 0.66 | 0.55 |
| $g(hc\bar{c})$ | 1.79 | 2.27 | 1.42 | 1.15 | 1.09 |
| $g(hgg)$ | 1.60 | 1.65 | 1.31 | 0.99 | 0.89 |
| $g(hWW)$ | 0.65 | 0.56 | 0.80 | 0.42 | 0.34 |
| $g(h\tau\tau)$ | 1.16 | 1.35 | 1.06 | 0.75 | 0.71 |
| $g(hZZ)$ | 0.66 | 0.57 | 0.80 | 0.42 | 0.34 |
| $g(h\gamma\gamma)$ | 1.20 | 1.15 | 1.26 | 1.04 | 1.01 |
| $g(h\mu\mu)$ | 5.53 | 5.71 | 5.10 | 4.87 | 4.95 |
| $g(hbb)/g(hWW)$ | 0.82 | 0.90 | 0.58 | 0.51 | 0.43 |
| $g(hWW)/g(hZZ)$ | 0.07 | 0.06 | 0.07 | 0.06 | 0.05 |
| $\Gamma_h$ | 2.38 | 2.50 | 2.11 | 1.49 | 1.50 |
| $\sigma(e^+e^- \to Zh)$ | 0.70 | 0.77 | 0.50 | 0.22 | 0.61 |
| $BR(h \to inv)$ | 0.30 | 0.56 | 0.30 | 0.27 | 0.28 |
| $BR(h \to other)$ | 1.50 | 1.63 | 1.09 | 0.94 | 1.15 |

errors in %



Precision of Higgs boson couplings [%]
0
2
4
6
8
10
12
LHC 3000 fb-1 (ATLAS: ATL-PHYS-PUB-2014-016 (2014), Model Dependent κ fit)
LHC 3000 fb-1 ⊕ ILC 250 GeV, 2000 fb-1 (Model Independent EFT fit)
LHC 3000 fb-1 ⊕ ILC 250 GeV, 2000 fb-1
⊕ ILC 500 GeV, 4000 fb-1 ⊕ 350 GeV, 200 fb-1 (Model Independent EFT fit)
11%
14%
g(hZZ)
g(hWW)
g(hγγ)
g(hbb)
g(hττ)
g(hgg)
g(hcc)
g(hγZ)
g(hμμ)
g(htt)

It is instructive to compare the sensitivity to Higgs couplings to the predicts of BSM models. We approached this in the following way:

We chose a set of BSM models of various types that give substantial deviations in the Higgs couplings but for which the new particles are too heavy to be discovered at HL-LHC.

For each pair of models, including the SM, we computed the $\delta\chi^2$ between the predictions, using the covariance matrix that comes out of our fit.

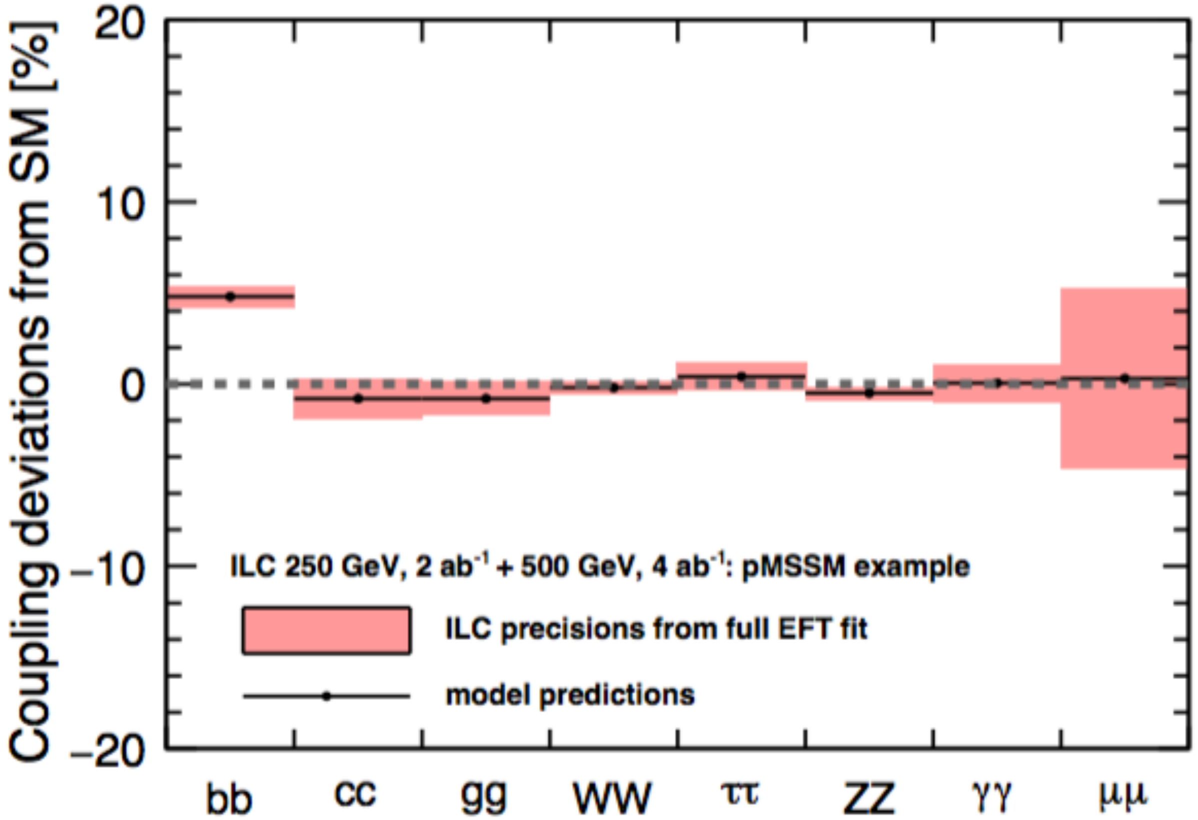
The addresses the question of whether these models can be distinguished from the SM and whether they can be distinguished from one another.

the models:

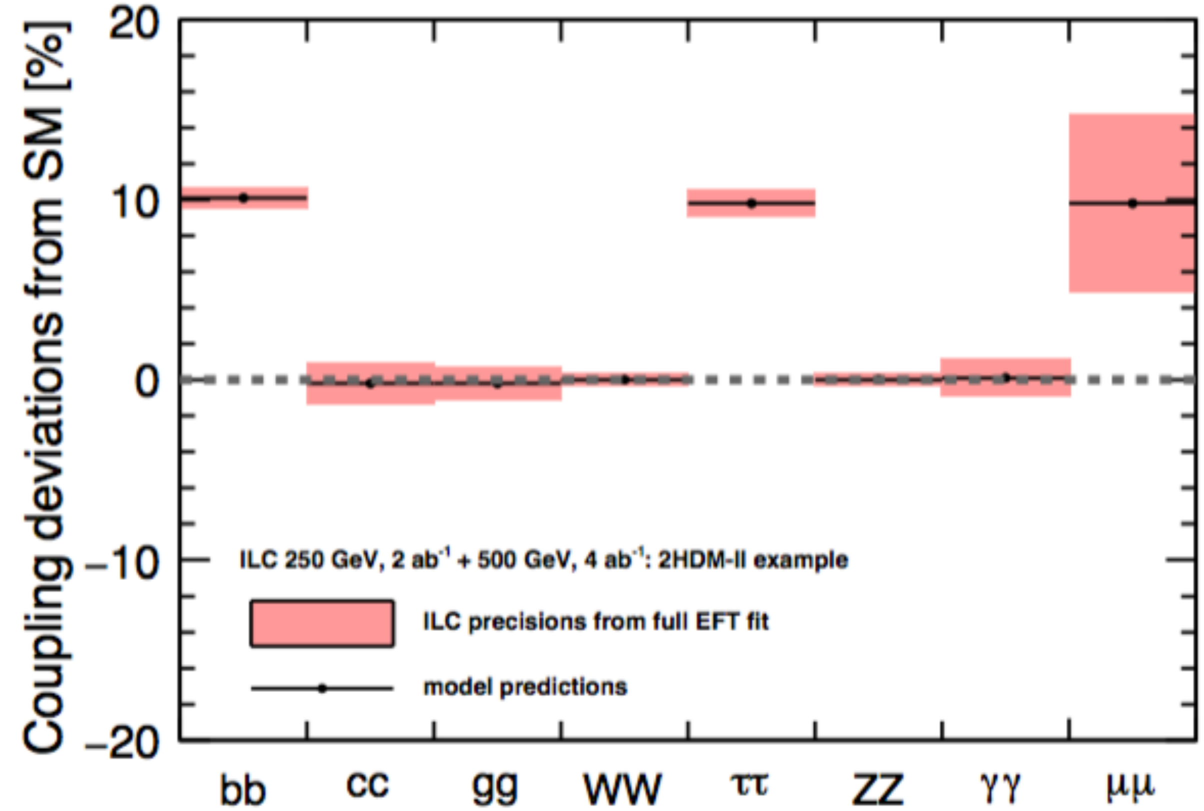
1. PMSSM model with b squarks at 3.4 TeV.
2. Type II Higgs-doublet model with H at 600 GeV
3. Type X 2-Higgs-doublet model with H at 450 GeV
4. Type Y 2-Higgs-doublet model with H at 600 GeV
5. MCHM5 Composite Higgs model, with f = 1.2 TeV
6. Little Higgs model w. T-parity, f = 0.8 TeV
7. Little Higgs model w. T-parity, f = 1 TeV, extension for light quark Yukawa couplings
8. Higgs-radion mixing model, radion at 500 GeV
9. Higgs singlet mixing model, singlet at 2.8 TeV

(Your additional suggestions would be appreciated.)

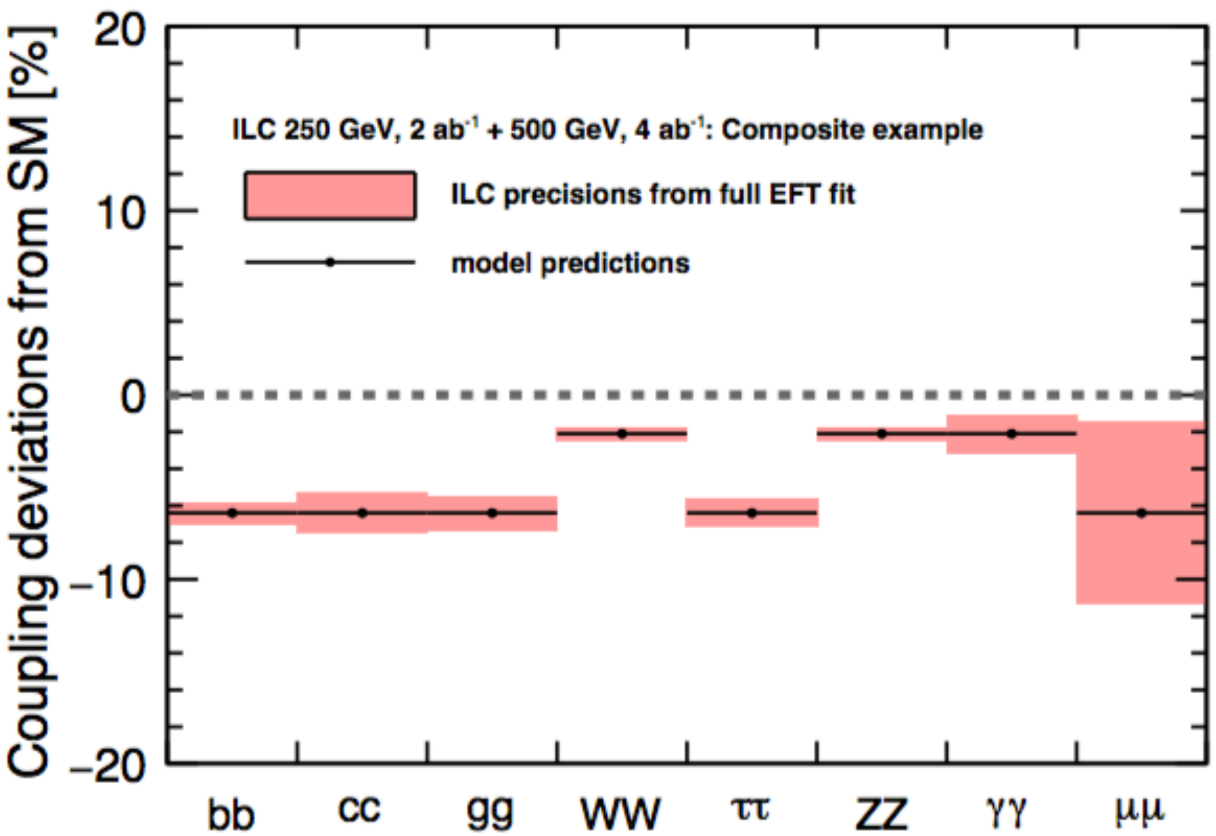
## heavy SUSY



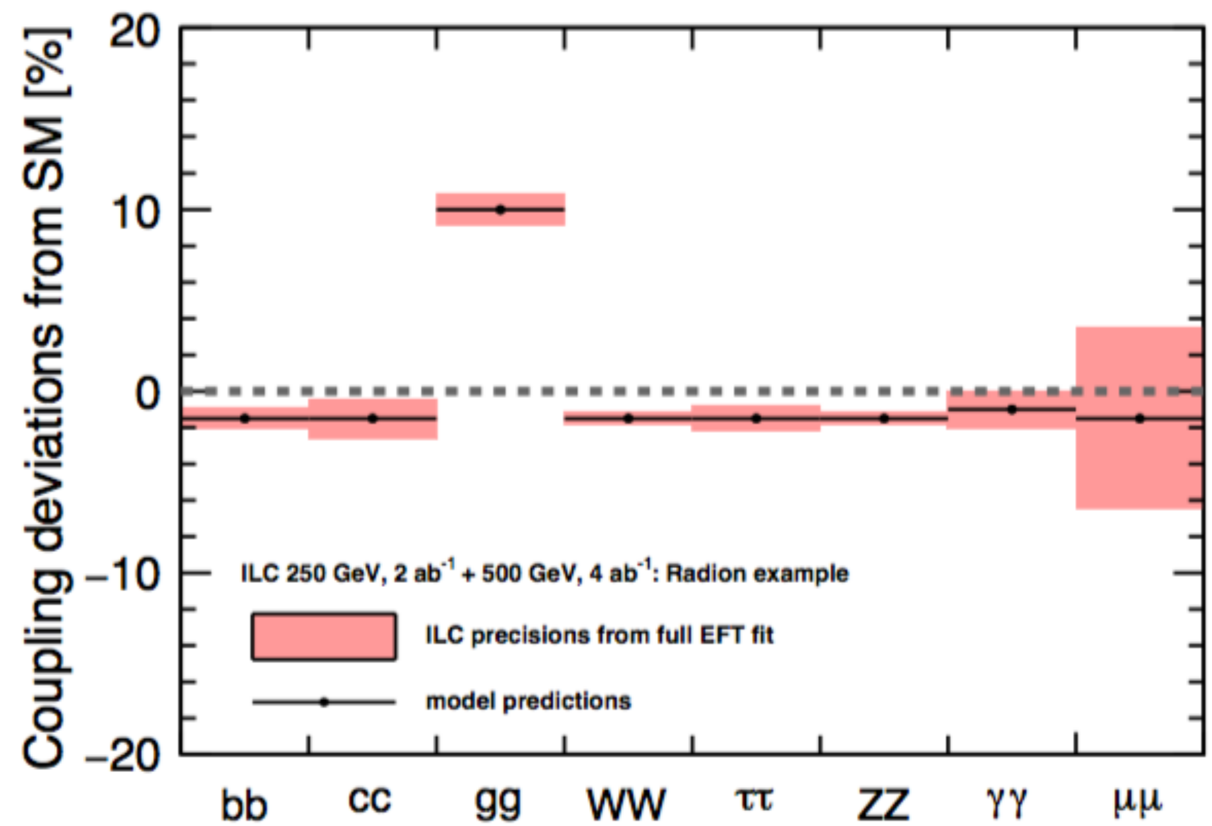

## 2 Higgs doublet



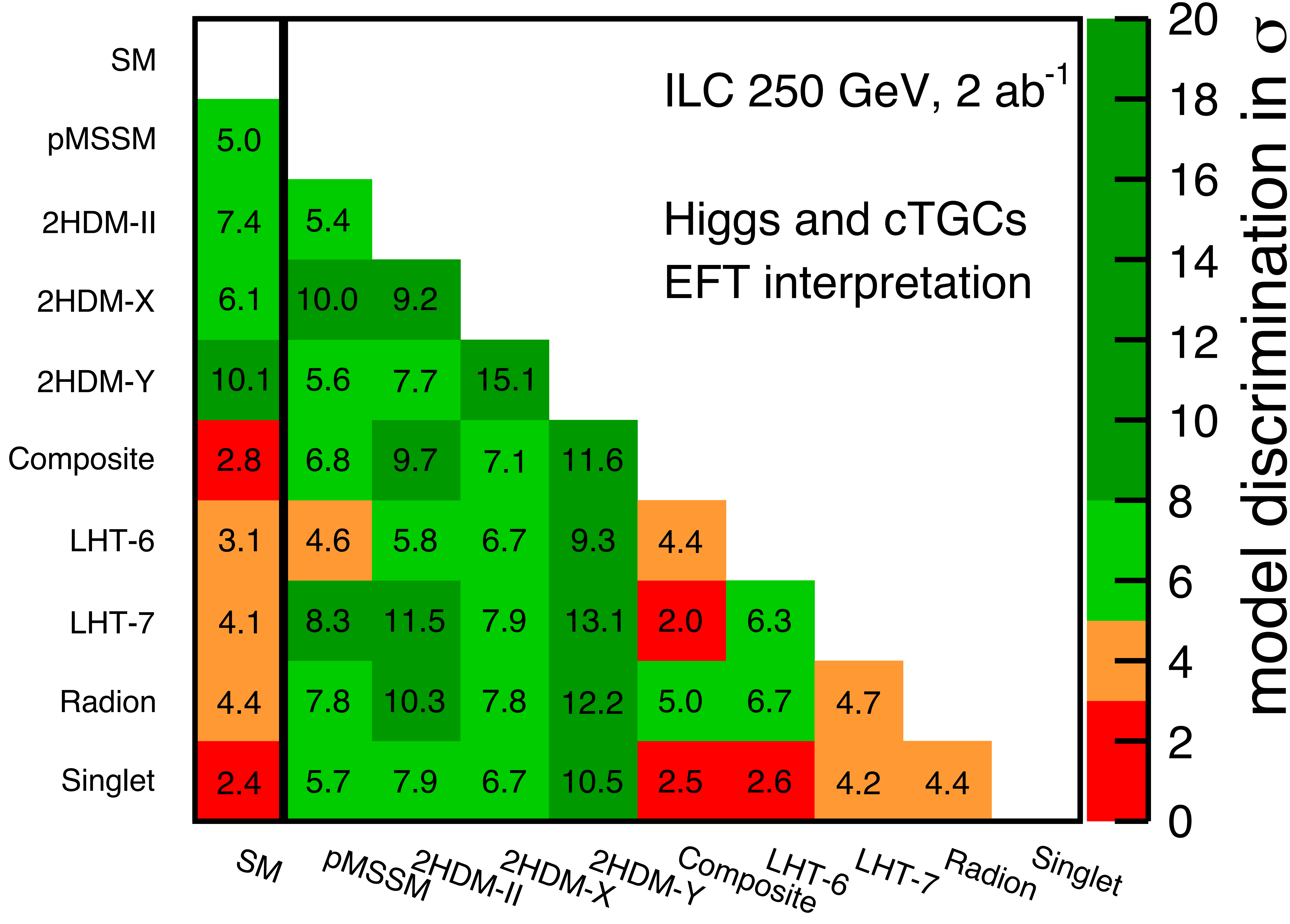

## Composite Higgs



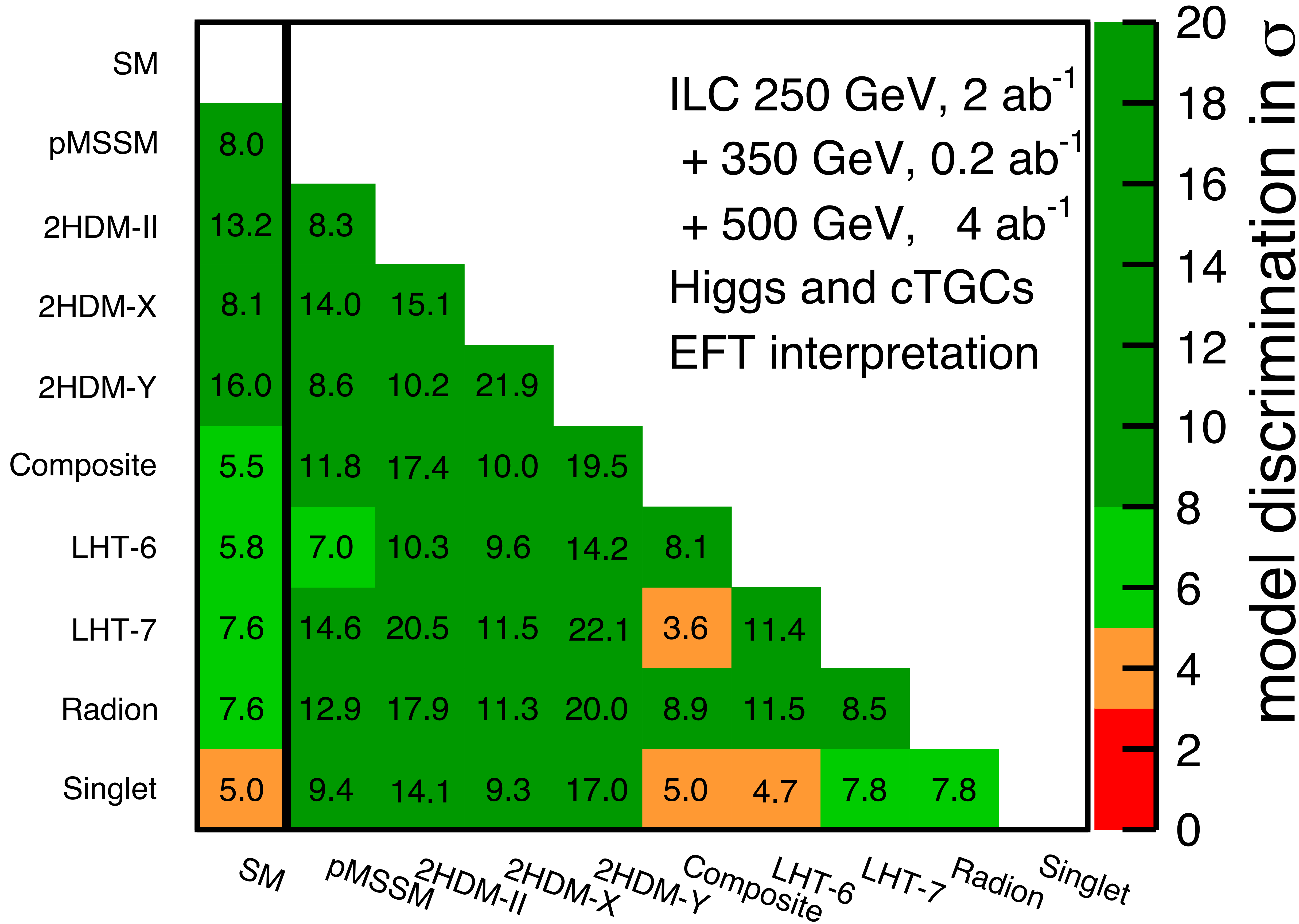

## Higgs-Radion mixing



# results: ILC 250 GeV 2 ab-1



results: ILC 250 GeV 2 ab-1 + 500 GeV 4 ab-1



We have seen that Standard Model Effective Field Theory is a powerful tool for interpreting deviations from the SM that might be found in future experiments.

It also allows us to estimate the capabilities of future accelerators.   These turn out to be very powerful in exploring for new physics beyond the SM.

I hope I have also communicated some of my enthusiasm for an e+e- Higgs factory as the next logical step for high energy physics.