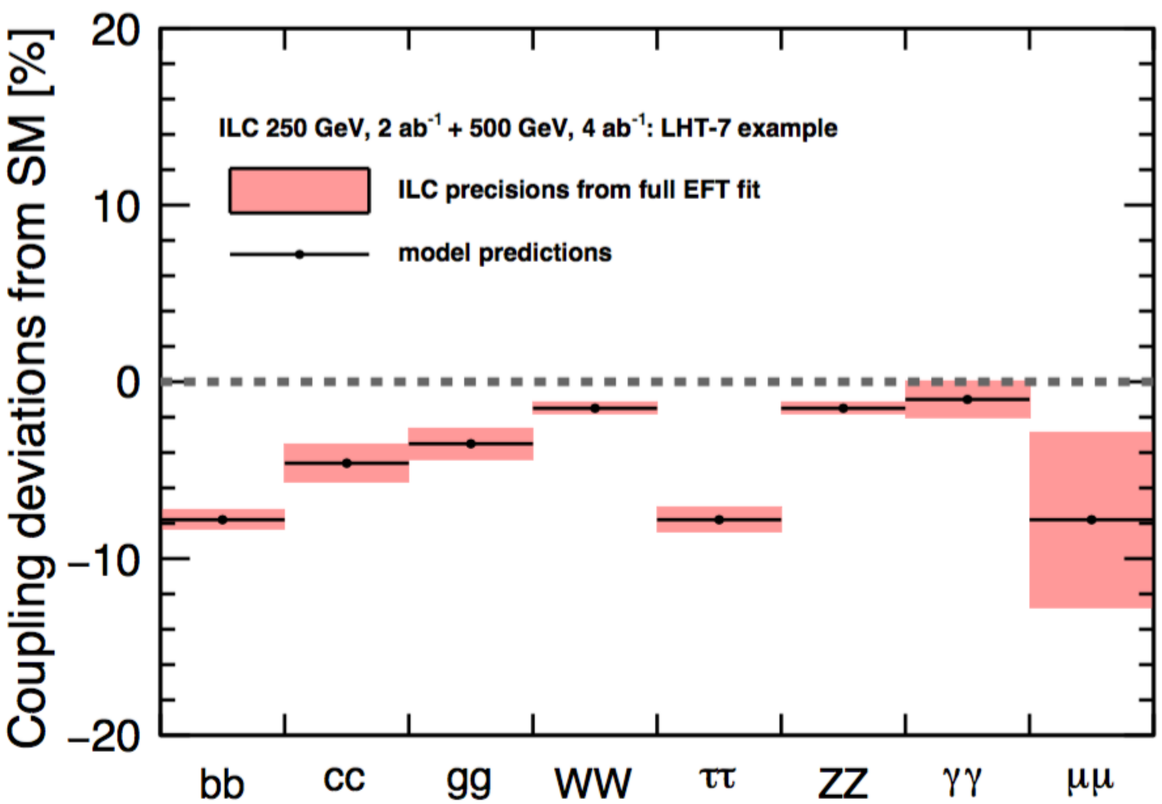
Precision Higgs Coupling Analysis at e+e- Colliders using Effective Field Theory



M. E. Peskin
September 2017

based on work with:

Tim Barklow, Keisuke Fujii, Sunghoon Jung, Robert Karl, Jenny List, Tomohisa Ogawa, Junping Tian

arXiv:1708.08912 arXiv:1708.09079

In elementary particle physics today, we have a Standard Model that works extremely well but is manifestly incomplete.

The most important goal of particle physics is to discover experimental clues to new particles and interactions that lie beyond the Standard Model.

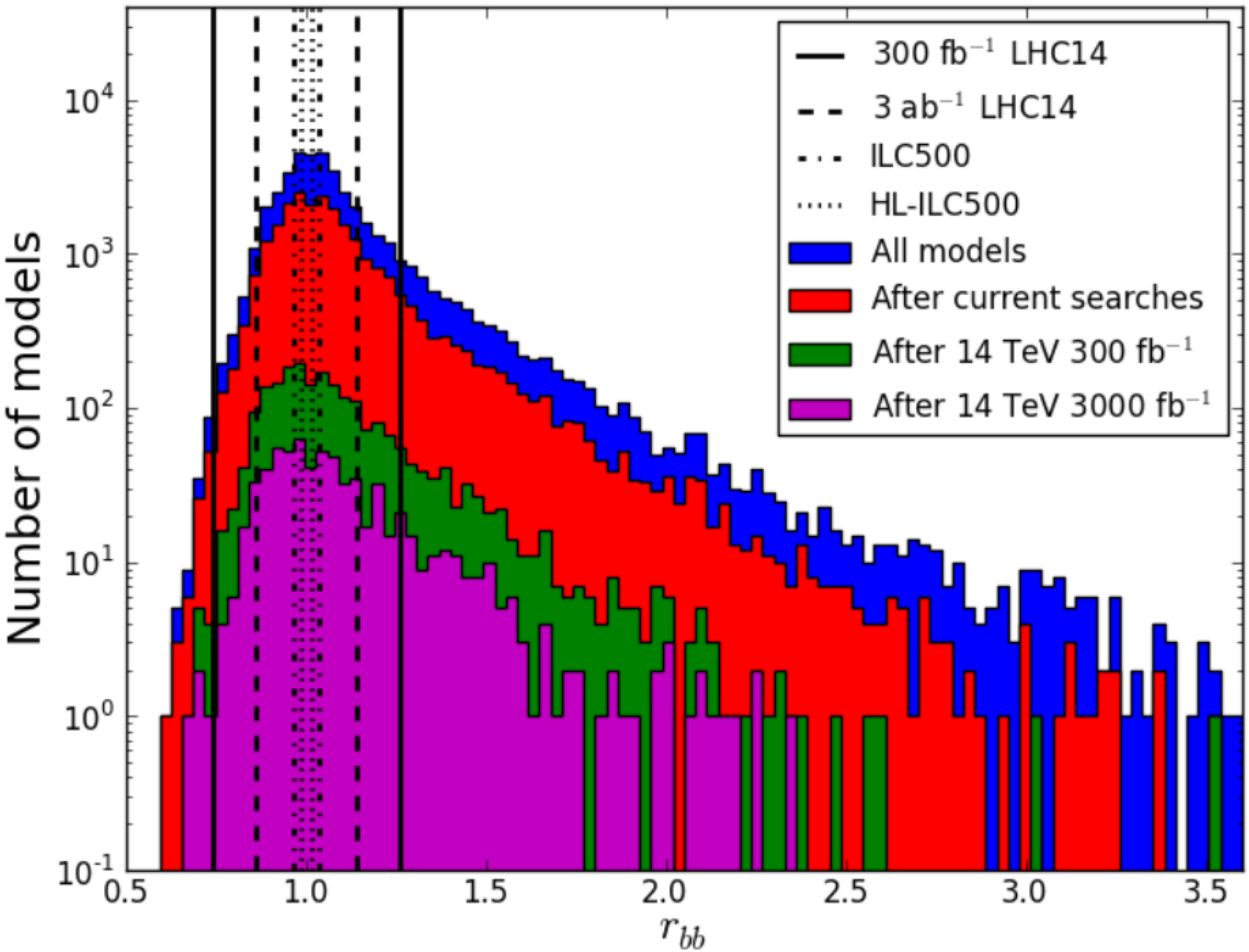
The most important opportunity for discovery that we have not yet already exploited is the precision study of the Higgs boson.

advantages:

Almost all free parameters of the SM involve the Higgs boson mass, potential, and couplings. None of these numbers are explained. All are put in by hand.

The Higgs field is a scalar that couples to all SM particles, and more strongly to the heaviest ones. The invariant $\Phi^\dagger\Phi$ is a complete singlet that can couple to any particles, even those with no SM interactions.

Radiative corrections from new physics at TeV energies will affect the properties of the 125 GeV Higgs boson.



Cahill-Rowley, Hewett, Ismail, Rizzo

difficulties, at hadron colliders:

The expected effects of new physics on the 125 GeV Higgs boson are small, at the few-percent level, due to Haber's decoupling theorem.

Higgs events are not characteristic at hadron colliders, except in a few rare modes. Typical Higgs boson samples are 10% Higgs, 90% other.

Not all Higgs decay modes can be observed at hadron colliders. So, it is not possible there to determine Higgs couplings in a model-independent way. LHC experiments typically measure μ, a combination of couplings.

A MONK ASKED THE MASTER,
"DOES A DOG HAVE BUDDHA NATURE?"
THE MASTER SAID, "MU."

the book of MU

essential writings on zen's most important koan

EDITED BY JAMES ISHMAEL FORD & MELISSA MYOZEN BLACKER

WITH A FOREWORD BY JOHN TARRANT

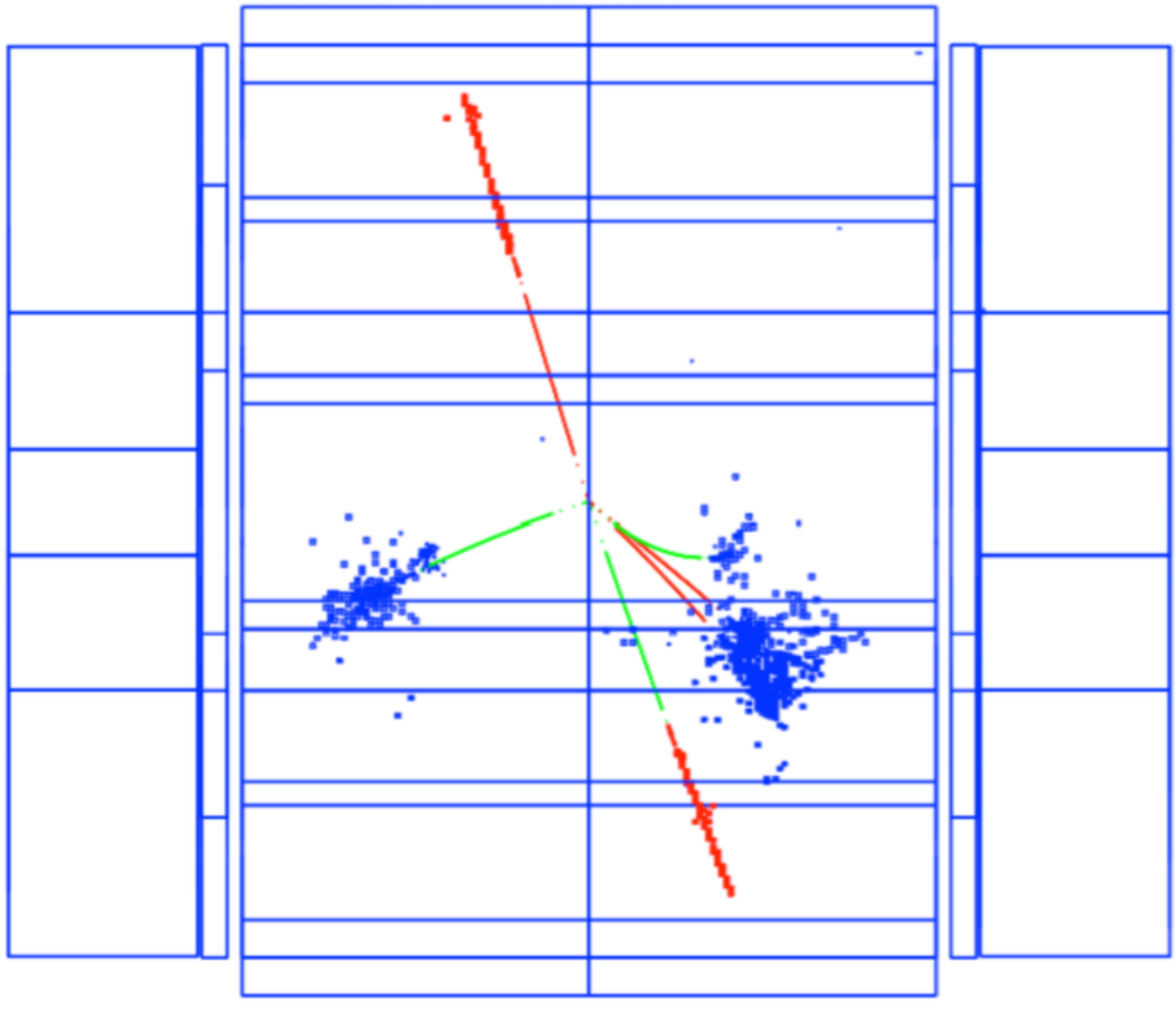
Future e+e- colliders at 250 GeV (e.g. ILC or CEPC) can overcome these difficulties.

Higgs events are readily isolated from background. All standard Higgs decay modes are visible.

Measurement accuracies are such that 1% coupling measurements are feasible.

The absolute cross section for $e^+e^- \to Zh$ can be measured.

At 250 GeV, to first approximation, any Z boson at $E_{lab} = 110\ \mathrm{GeV}$ is recoiling against a Higgs boson.



(thanks to Manqi Ruan)

But, though we can measure BR's, there is a potential problem in converting these to absolute coupling strengths. An apparently model-independent way to perform the conversion uses

$$\frac{\sigma(e^+e^- \to Zh)}{BR(h \to ZZ^*)} = \frac{\sigma(e^+e^- \to Zh)}{\Gamma(h \to ZZ^*)/\Gamma_h} \sim \Gamma_h$$

But, in the SM, $BR(h \to ZZ^*) \sim 3\%$. Then we lose a factor 30 in statistics to measure this ratio. For 2 ab-1 of data, this gives normalization errors on the Higgs couplings of 3%.

There is another problem: The statement that

$$BR(h \to ZZ^*) \sim \sigma(e^+e^- \to Zh) \sim g(hZZ)^2$$

is model-dependent. Actually, there are two possible (CP conserving) forms for the hZZ coupling

$$\delta\mathcal{L} = (1+\eta_Z)\frac{m_Z^2}{v} h Z_\mu Z^\mu + \zeta_Z \frac{h}{2v} Z_{\mu\nu} Z^{\mu\nu}$$

The ζ_Z term is momentum-dependent, and so its effect varies depending on whether the Z is on-shell or off-shell.

$$\begin{aligned}\sigma(e^+e^- \to Zh) &= (SM)\cdot(1+2\eta_Z+(5.7)\zeta_Z)\\ \Gamma(h \to WW^*) &= (SM)\cdot(1+2\eta_W-(0.78)\zeta_W)\\ \Gamma(h \to ZZ^*) &= (SM)\cdot(1+2\eta_Z-(0.50)\zeta_Z)\ .\end{aligned}$$

Can we extract accurate, model-independent values of the Higgs couplings from e+e- data ?

A strategy: Effective Field Theory

The SM is the most general dimension-4 Lagrangian with SU(3)xSU(2)xU(1) gauge symmetry.

Represent the most general effects of new physics effects by adding the most general set of gauge-invariant dimension-6 operators.

There are 84 of these (for 1 generation). If we demand baryon number and CP conservation, there are only 59.

If we can determine these coefficients independently by fitting a large sample of data, including Higgs data, we will determine the shifts in Higgs couplings from the SM in a way that is highly model-independent.

To use data from e+e- only, it is possible to consider a smaller set of parameters.

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.

Now we just need to estimate the constraints on these parameters that we will find from e+e- measurements.

The dimension-6 coefficients modify Higgs couplings, but also precision electroweak observables and the cross section and distributions for $e^+e^- \to W^+W^-$. All of these measurements work together to fix the full set of couplings.

I will work at the tree level in dimension-6 coefficients. I will ignore c_6 — the shift of the triple Higgs coupling — until the end of the lecture. c_6 does not affect single-Higgs amplitudes at tree level.

Actually, we will need to include several more parameters, for a total of 22.

The SM couplings g, g', v, λ are renormalized by the dimensional-6 operators, so we must let them float.

We include 2 parameters for the rates of possible invisible and exotic Higgs decays.

Similar analyses have been carried out by:

Ge, He, Zhao, arXiv:1603.03385
Ellis, Roloff, Sanz, You, arXiv:1701.04804
Durieux, Grojean, Gu, Wang, arXiv:1704.02333

but we are the first to include all relevant operators.

Before beginning the full analysis, I will explain the answer to the question about Higgs couplings posed at the beginning of the lecture.

In the EFT, the ζ_Z and ζ_W terms come from

$$+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu} + \frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu}$$

These give field strength renormalizations

$$\begin{aligned}
\delta Z_W &= (8c_{WW}) \\
\delta Z_Z &= c_w^2(8c_{WW}) + 2s_w^2(8c_{WB}) + s_w^4/c_w^2(8c_{BB}) \\
\delta Z_A &= s_w^2\Big((8c_{WW}) - 2(8c_{WB}) + (8c_{BB})\Big) \\
\delta Z_{AZ} &= s_w c_w\Big((8c_{WW}) - (1-\frac{s_w^2}{c_w^2})(8c_{WB}) - \frac{s_w^2}{c_w^2}(8c_{BB})\Big)
\end{aligned}$$

and Higgs couplings to field strengths proportional to these factors.

The difference of the W and Z coefficients is controlled.

The parameter $8c_{WB}$ affects the S parameter and the W magnetic moment, so precision electroweak and WW measurements are essential for the precise relation.

Similarly, the SM-like hWW and hZZ coefficients are related:

$$\eta_W = -\frac{1}{2}c_H + 2\delta m_W - \delta v$$
$$\eta_Z = -\frac{1}{2}c_H + 2\delta m_Z - \delta v - c_T$$

c_T is essentially the T parameter and so must be small.

So, by making use of precision electroweak and WW data, we can tie together the Higgs couplings to Z and W, improving the available statistics by a factor 10.

We need to constrain η_Z and ζ_Z separately. This can be done by including new observables from $e^+e^- \to Zh$.

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):

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

$e^-_L e^+_R$

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

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

$e^-_R e^+_L$

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

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

So η_Z and ζ_Z can be obtained separately from the cross section and polarization asymmetry. They can also be separated by measurement of the angular distributions.

The reconstruction of the angular distribution in this reaction has been studied with full simulation in the ILD detector by my collaborators Fujii, Ogawa, and Tian.

The effect on Higgs coupling measurements can be seen in a simplified analysis using only c_H, $8c_{WW}$, and coefficients appearing in Higgs decays.

	κ fit	angl. only	pol. only	both	full EFT fit
$g(hb\bar{b})$	3.21	3.87	0.94	0.94	1.04
$g(hc\bar{c})$	3.52	4.19	1.73	1.73	1.79
$g(hgg)$	3.43	4.10	1.54	1.54	1.60
$g(hWW)$	3.31	3.77	0.46	0.45	0.65
$g(h\tau\tau)$	3.25	3.91	1.07	1.07	1.16
$g(hZZ)$	0.36	3.51	0.45	0.44	0.66
$g(h\mu\mu)$	13.1	14.7	12.8	12.8	5.53
$g(hb\bar{b})/g(hWW)$	0.85	0.92	0.83	0.83	0.82
$g(hWW)/g(hZZ)$	3.29	0.26	0.02	0.02	0.07
Γ_h	6.53	7.64	2.20	2.18	2.38
$\sigma(e^+e^- \to Zh)$	0.72	0.80	0.72	0.70	0.70
$BR(h \to inv)$	0.39	0.36	0.30	0.30	0.30
$BR(h \to other)$	1.57	1.71	1.53	1.51	1.50

250 GeV, 2 ab-1, errors in %

Now let’s build up the formulae for the full 22 parameter fit. I will explain this in stages (gradus ad Parnassum)

Precision electroweak:

Use only leptonic and Z, W observables. We must take into account the effects that shift the Z and W couplings to leptons:

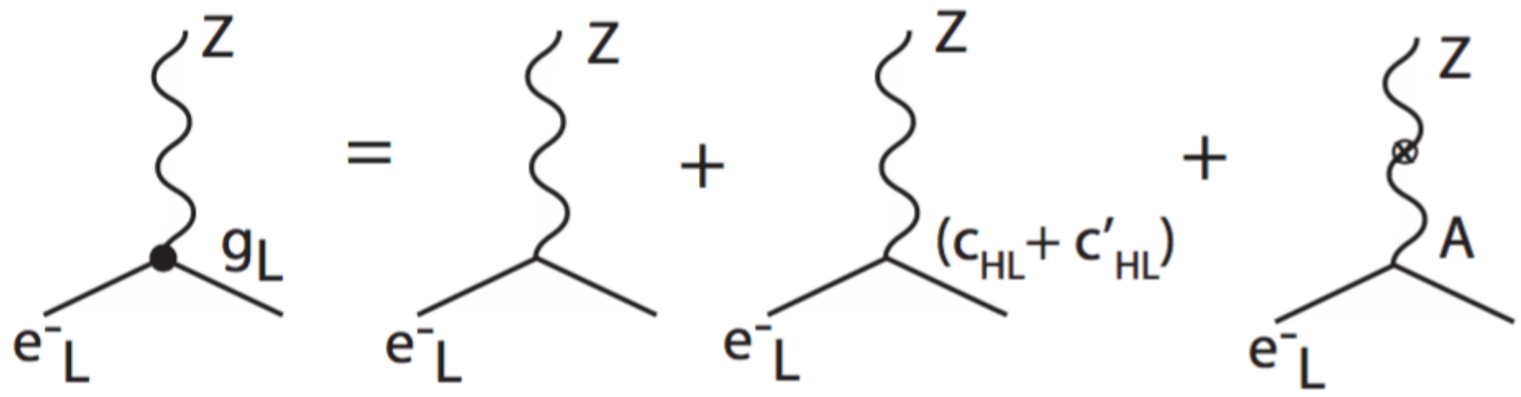


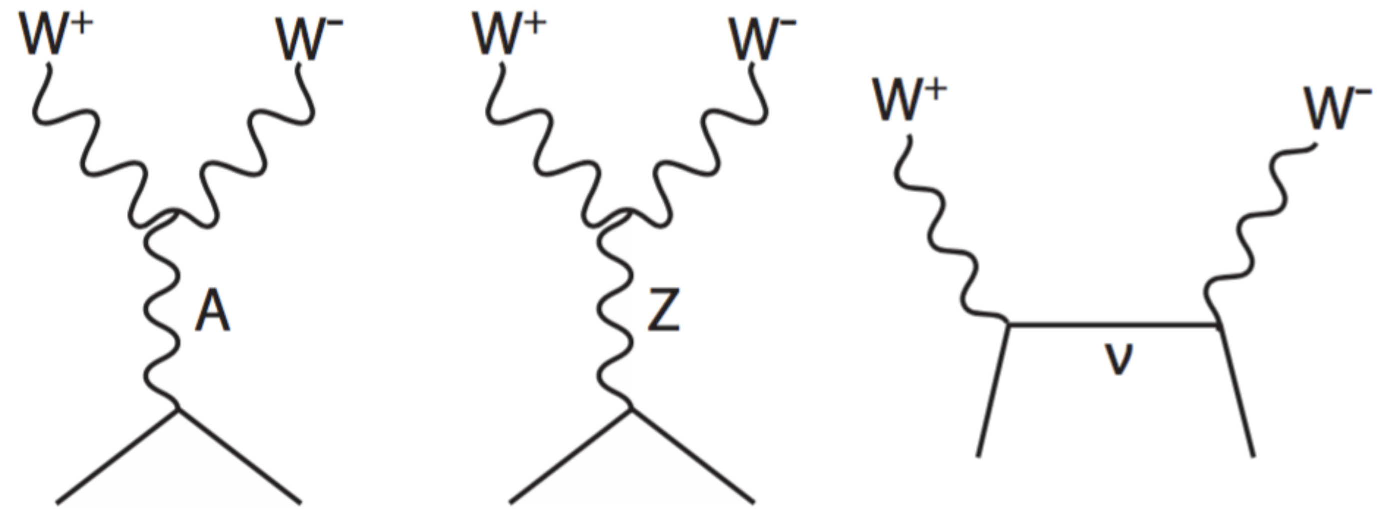
Table of inputs

(Γ_Z and Γ_W are not used at this stage)

Observable	current value	current σ	future σ	SM best fit value
$\alpha^{-1}(m_Z^2)$	128.9220	0.0178		(same)
G_F (10^{-10} GeV^{-2})	1166378.7	0.6		(same)
m_W (MeV)	80385	15	5	80361
m_Z (MeV)	91187.6	2.1		91188.0
m_h (MeV)	125090	240	15	125110
A_ℓ	0.14696	0.0013		0.147937
Γ_ℓ (MeV)	83.984	0.086		83.995
Γ_Z (MeV)	2495.2	2.3		2494.3
Γ_W (MeV)	2085	42	2	2088.8

Using 7 inputs, we can constrain 4 SM parameters plus 3 EFT coefficients.

$$e^+e^- \to W^+W^-$$



The γWW and ZWW vertices are described by an effective interaction

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

in which terms are shifted by

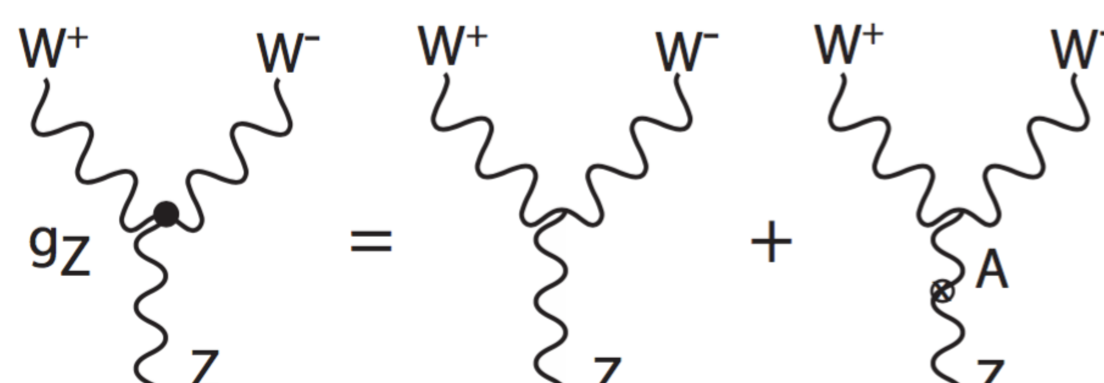
$$\kappa_A = 1 + (8c_{WB})$$

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

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

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

This takes into account the shift of the ZWW coupling



In addition, the cross section has terms enhanced by s/m_W^2 due to the shifts of the lepton couplings to W and Z. The full "unitarity-violating terms" for production of longitudinal W bosons are

$e^-_R e^+_L$

$$\mathcal{A}_R = e^2\kappa_A + g_R g_Z \kappa_Z$$

$e^-_L e^+_R$

$$\mathcal{A}_L = e^2\kappa_A + g_L g_Z \kappa_Z - \frac{g_W^2}{2}$$

In principle, one should refit an analysis of W anomalous couplings with the full EFT expressions. In our study, we take account only of the leading terms by writing

$$(g_{Z,eff} - 1) = \frac{1}{g^2 c_w^2}\Big(2\Delta\mathcal{A}_L - \Delta\mathcal{A}_R\Big)$$
$$(\kappa_{A,eff} - 1) = \frac{1}{g^2}\Big(2\Delta\mathcal{A}_L + \frac{c_w^2 - s_w^2}{s_w^2}\Delta\mathcal{A}_R\Big)$$
$$\lambda_{A,eff} = \lambda_A$$

LHC constraints on the Higgs boson:

Even HL-LHC will place few truly strong constraints on the Higgs boson couplings. However, we expect strong constraints on the modes in which h can be seen as a resonance. Thus we include the ratios of branching ratios,

$$\frac{BR(h \to \gamma\gamma)}{BR(h \to ZZ^*)} \qquad \frac{BR(h \to Z\gamma)}{BR(h \to ZZ^*)}$$

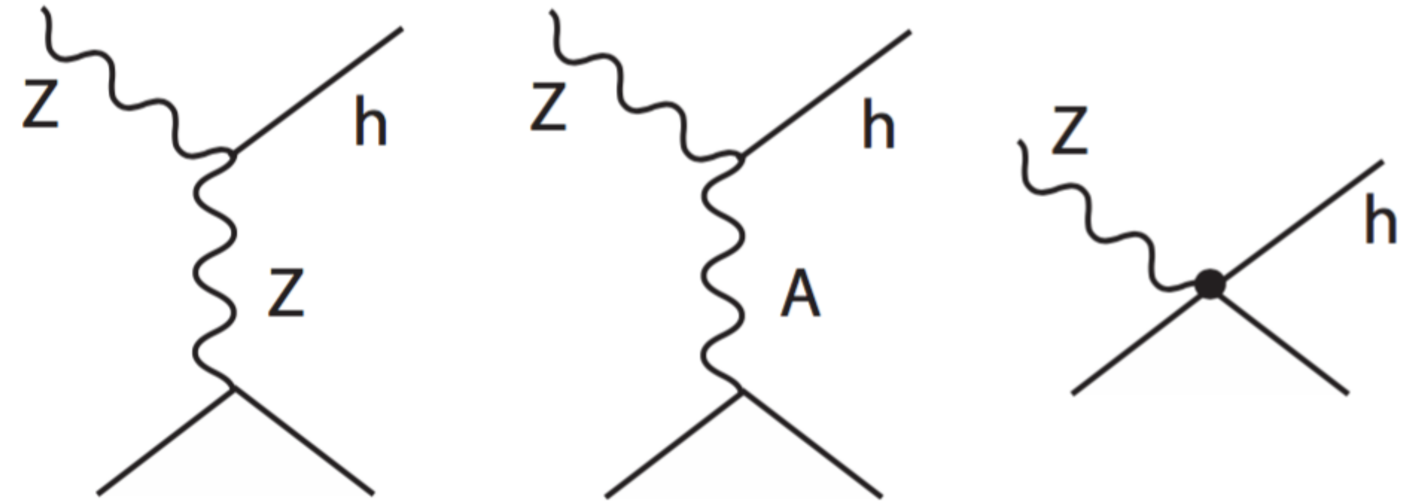
with 2% and 30% measurements expected.

These have very strong effect, because the SM contributions are loop-level, but the EFT perturbations are tree-level:

$$\delta\Gamma(h \to \gamma\gamma) = 528\,\delta Z_A - c_H + 4\delta e + 4.2\,\delta m_h - 1.3\,\delta m_W - 2\delta v$$

$$\delta\Gamma(h \to Z\gamma) = 290\,\delta Z_{AZ} - c_H - 2(1 - 3s_W^2)\delta g + 6c_w^2\delta g' + \delta Z_A + \delta Z_Z$$
$$+9.6\,\delta m_h - 6.5\,\delta m_Z - 2\delta v$$

$e^+e^- \to Zh$



The full tree-level expressions for the a and b parameters are:

$$a_L = \delta g_L + 2\delta m_Z - \delta v + \eta_Z + \frac{(s - m_Z^2)}{2m_Z^2(1/2 - s_w^2)}(c_{HL} + c'_{HL}) + k_Z \delta m_Z + k_h \delta m_h$$

$$b_L = \zeta_Z + \frac{s_w c_w}{(1/2 - s_w^2)} \frac{(s - m_Z^2)}{s} \zeta_{AZ} \ .$$

$$a_R = \delta g_R + 2\delta m_Z - \delta v + \eta_Z - \frac{(s - m_Z^2)}{2m_Z^2(s_w^2)} c_{HE} + k_Z \delta m_Z + k_h \delta m_h$$

$$b_R = \zeta_Z - \frac{c_w}{s_w} \frac{(s - m_Z^2)}{s} \zeta_{AZ} \ .$$

Note here also the s/m_Z^2 enhancement of the c_{HL} parameters.

At this point, we have enough constraints to fix the 9 EFT parameters that do not require Higgs decays.

Input full-sim ILC results for the W anomalous couplings (List and Karl) and the Zh process (Fujii, Ogawa, Tian).

	250 GeV				
c_I	prec. EW	$+\,WW$	+ LHC	$+\,Zh$	ILC 250
c_T	0.011	0.051	0.051	0.048	0.052
c_{HE}	0.043	0.026	0.085	0.047	0.055
c_{HL}	0.042	0.035	0.035	0.032	0.039
c'_{HL}	–	0.028	0.028	0.028	0.047
$8c_{WB}$	–	0.078	0.080	0.076	0.090
$8c_{BB}$	–	–	0.20	0.16	0.11
$8c_{WW}$	–	–	0.21	0.13	0.13
c_H	–	–	–	1.12	1.20

250 GeV, 2 ab-1, errors in %

250 GeV

c_I	prec. EW	$+WW$	+ LHC	$+Zh$	ILC 250
c_T	0.011	0.051	0.051	0.048	0.052
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c_{HL}	0.042	0.035	0.035	0.032	0.039
c'_{HL}	–	0.028	0.028	0.028	0.047
$8c_{WB}$	–	0.078	0.080	0.076	0.090
$8c_{BB}$	–	–	0.20	0.16	0.11
$8c_{WW}$	–	–	0.21	0.13	0.13
c_H	–	–	–	1.12	1.20

500 GeV

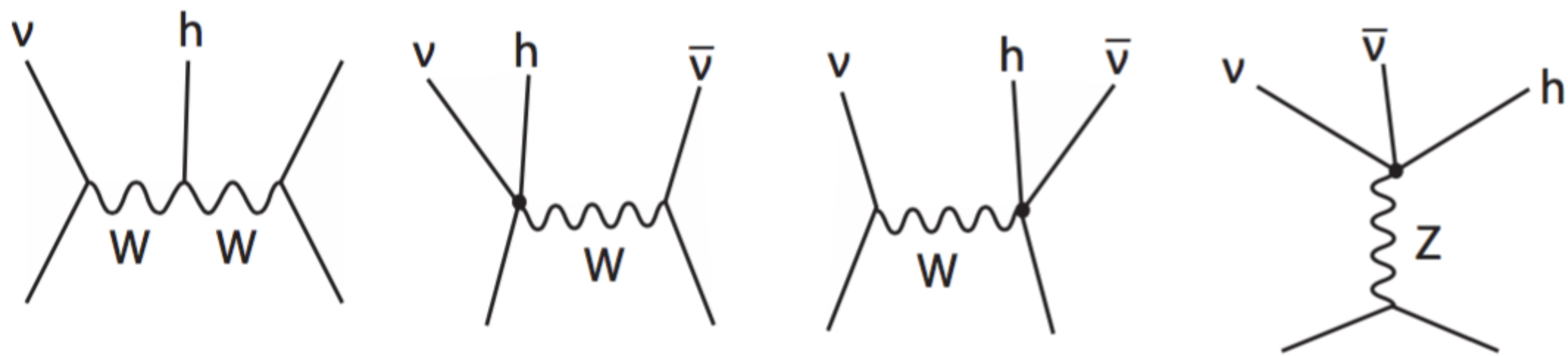
c_I	prec. EW	$+WW$	+ LHC	$+Zh$	ILC 500	250+500
c_T	0.011	0.046	0.047	0.041	0.037	0.030
c_{HE}	0.043	0.015	0.077	0.040	0.010	0.009
c_{HL}	0.042	0.030	0.030	0.027	0.016	0.013
c'_{HL}	–	0.027	0.028	0.026	0.014	0.011
$8c_{WB}$	–	0.070	0.072	0.067	0.052	0.041
$8c_{BB}$	–	–	0.20	0.15	0.088	0.062
$8c_{WW}$	–	–	0.21	0.11	0.044	0.039
c_H	–	–	–	4.78	1.24	0.65

effect of adding 500 GeV, 4 ab-1 - complete ILC

errors in %

We can be more ambitious:

Add measurements of $e^+e^- \to \nu\bar{\nu}h$ and Higgs decays



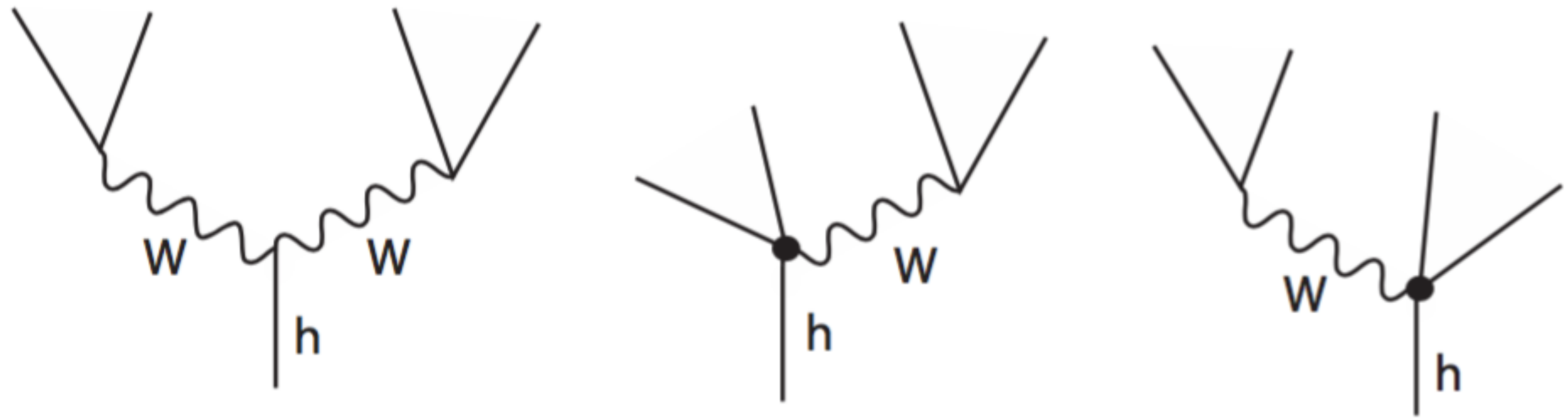
for $\sqrt{s} = 250$ GeV,

$$\sigma/(SM) = 1 + 2\eta_W - 2\delta v + 2\delta g_W - 1.6\delta m_W - 3.7\delta m_h \\ -0.22\zeta_W - 6.4c'_{HL} - 0.37(c_{HL} - c'_{HL}) \ ,$$

$\sqrt{s} = 500$ GeV,

$$\sigma/(SM) = 1 + 2\eta_W - 2\delta v + 2\delta g_W - 0.85\delta m_W - 1.2\delta m_h \\ -0.39\zeta_W - 8.8c'_{HL} - 0.19(c_{HL} - c'_{HL}) \ .$$

for $h \to WW^*$, $h \to ZZ^*$ decays, new diagram come into play



These involve the c_{HX} coefficients for quarks as well as leptons. Fortunately, the combinations that come in are precisely (to tree level) the ones that shifts the W and Z widths. For W:

$$\Gamma/(SM) = 1 + 2\eta_W - 2\delta v - 11.7\delta m_W + 13.6\delta m_h \\ -0.75\zeta_W - 0.88 C_W + 1.06\delta\Gamma_W \ ,$$

$$\Gamma_W = \frac{g^2 m_W}{48\pi}(\sum_X \mathcal{N}_X) \cdot (1 + 2\delta g + \delta m_W + \delta Z_W + 2C_W)$$

With these results, we can include all $\sigma \cdot BR$ measurements into the fit. For inputs, we use an extensive table of results extracted from full simulation by Tim Barklow and the DESY and KEK ILC groups:

-80% e^-, +30% e^+ polarization:

	250 GeV		350 GeV		500 GeV	
	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$
σ [45,46,47,48]	2.0		1.8		4.2	
$h \to invis.$ [49,50]	0.86		1.4		3.4	
$h \to b\bar{b}$ [51,52,53,54]	1.3	8.1	1.5	1.8	2.5	0.93
$h \to c\bar{c}$ [51,52]	8.3		11	19	18	8.8
$h \to gg$ [51,52]	7.0		8.4	7.7	15	5.8
$h \to WW$ [54,55,56]	4.6		5.6 *	5.7 *	7.7	3.4
$h \to \tau\tau$ [58]	3.2		4.0 *	16 *	6.1	9.8
$h \to ZZ$ [2]	18		25 *	20 *	35 *	12 *
$h \to \gamma\gamma$ [59]	34 *		39 *	45 *	47	27
$h \to \mu\mu$ [60,61]	72 *		87 *	160 *	120 *	100 *
a [23]	7.6		2.7 *		4.0	
b	2.7		0.69 *		0.70	
$\rho(a,b)$	-99.17		-95.6 *		-84.8	

Here are some final results for various proposed colliders:

	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
Γ_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 %

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:

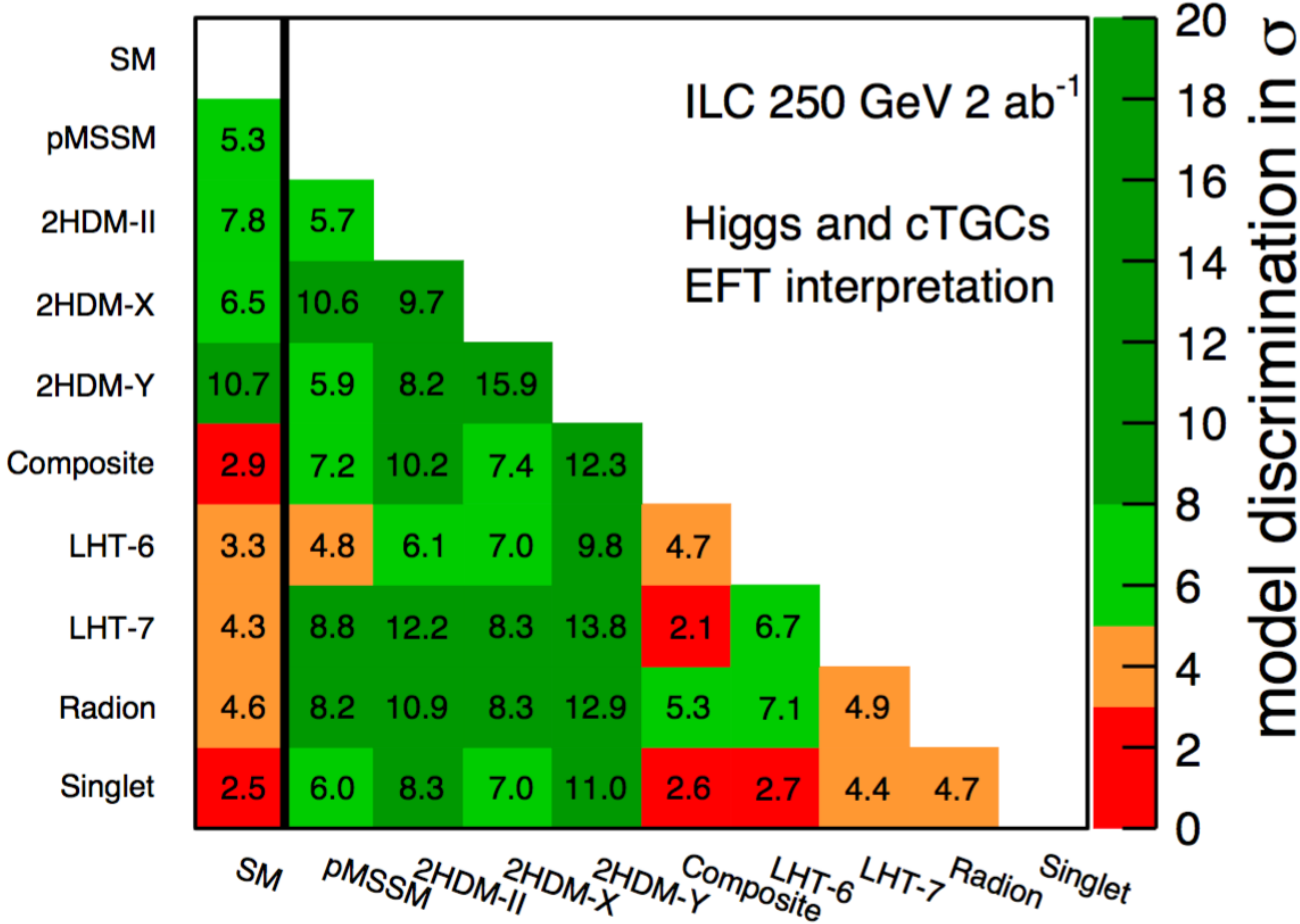
1. PMSSM model with b squarks at 3.4 TeV.
2. Type II Higgs-doublet model with H at 600 GeV
3. Type X 2-Higgs-doublet model with H at 450 GeV
4. Type Y 2-Higgs-doublet model with H at 600 GeV
5. MCHM5 Composite Higgs model, with f = 1.2 TeV
6. Little Higgs model w. T-parity, f = 0.8 TeV
7. Little Higgs 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.)

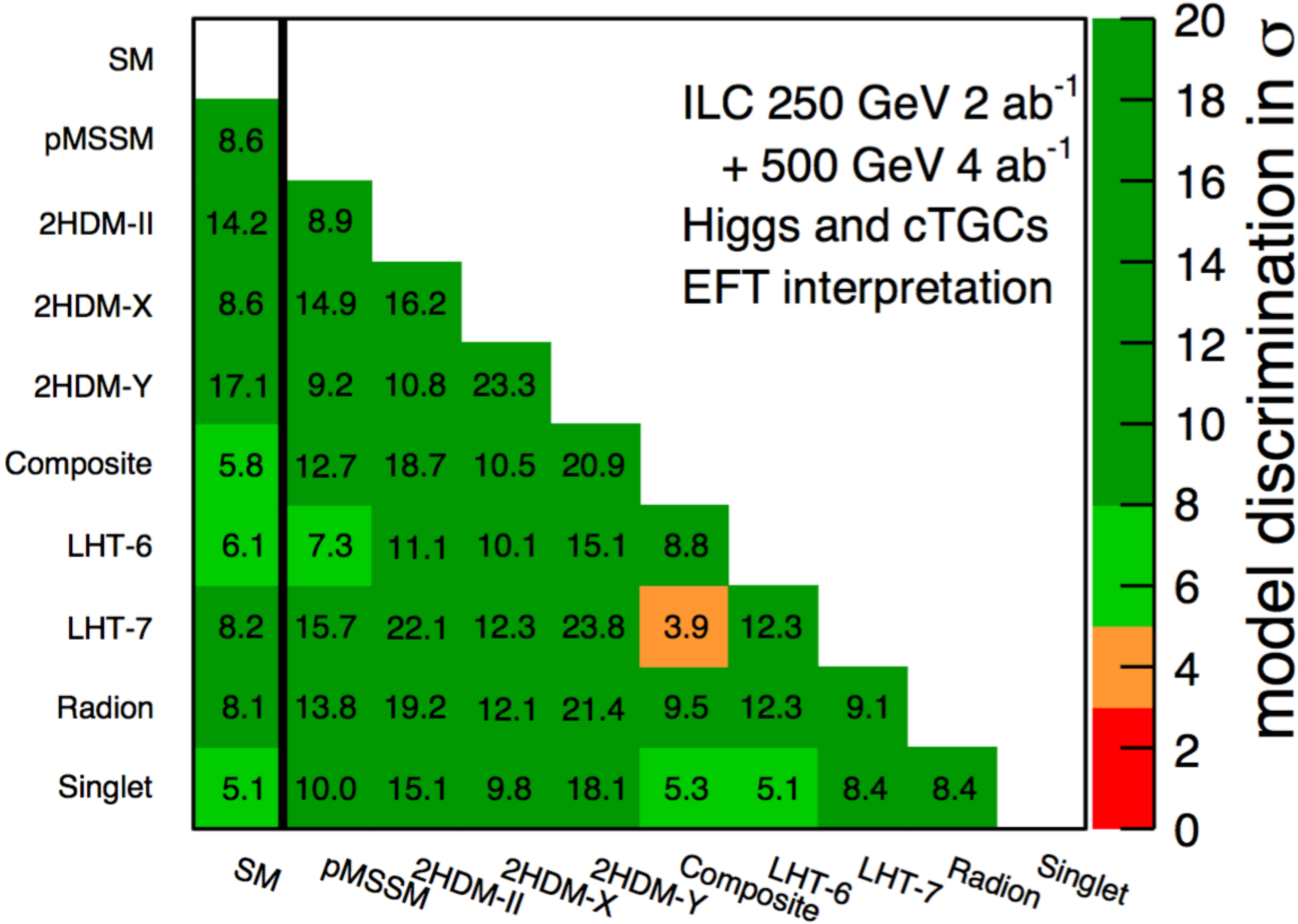
their coupling deviations:

	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [35]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [37]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [37]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [37]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [39]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [40]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [41]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [42]	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [43]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

results: ILC 250 GeV 2 ab-1



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

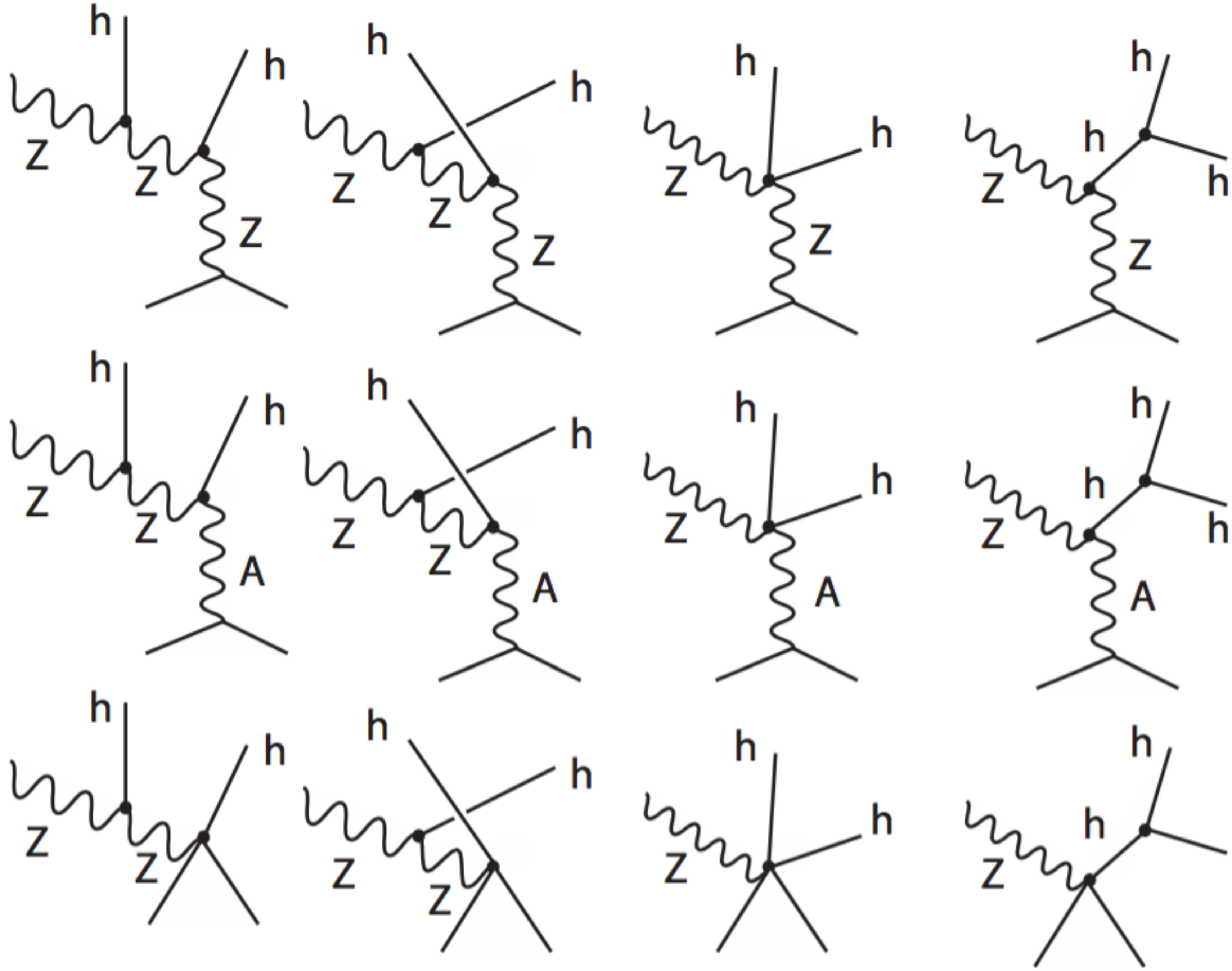


One final issue:
determination of the triple Higgs coupling

A change in the triple Higgs coupling shifts the rate of 2-Higgs production. Studies at many future e+e- and pp colliders claim sensitivity to this.

For ILC at 500 GeV, 4 ab-1, we claim a 27% measurement from $e^+e^- \to Zhh$. If the coupling is doubled, as is needed in some electroweak baryogenesis models, we claim a 15% measurement.

However, it is very artificial to assume that the triple Higgs coupling (c_6) is shifted while all other EFT coefficients are zero. So, we should explore the systematic error associated with uncertainties in other EFT parameters.



$$\sigma/(SM) = 1 + 1.15\delta g_L + 0.85\delta g_R + 1.40\eta_Z + 1.02\eta_{ZZ} + 18.6\zeta_Z + 2.0\zeta_{AZ}$$
$$+0.56\eta_h - 1.58\theta_h + 62.1(c_{HL} + c'_{HL}) - 53.5c_{HE}$$
$$-3.9\delta m_h + 3.5\delta m_Z \; .$$

(includes $\sigma/(SM) = 1 + 0.56c_6 + \cdots$)

Fortunately, we have very good control over the other EFT coefficients that appear in this formula:

A	$[< A^2 >]^{1/2}$	A	$[< A^2 >]^{1/2}$
c_H	0.65	$(c_{HL} + c'_{HL})$	0.014
$(8c_{WW})$	0.039	c_{HE}	0.009
$(-4.15c_H + 15.1(8c_{WW}))$	2.8	$62.1(c_{HL} + c'_{HL}) - 53.5c_{HE}$	0.85

The final systematic error on the cross section from other EFT terms is 2.4%, giving a 5% error on c_6 .

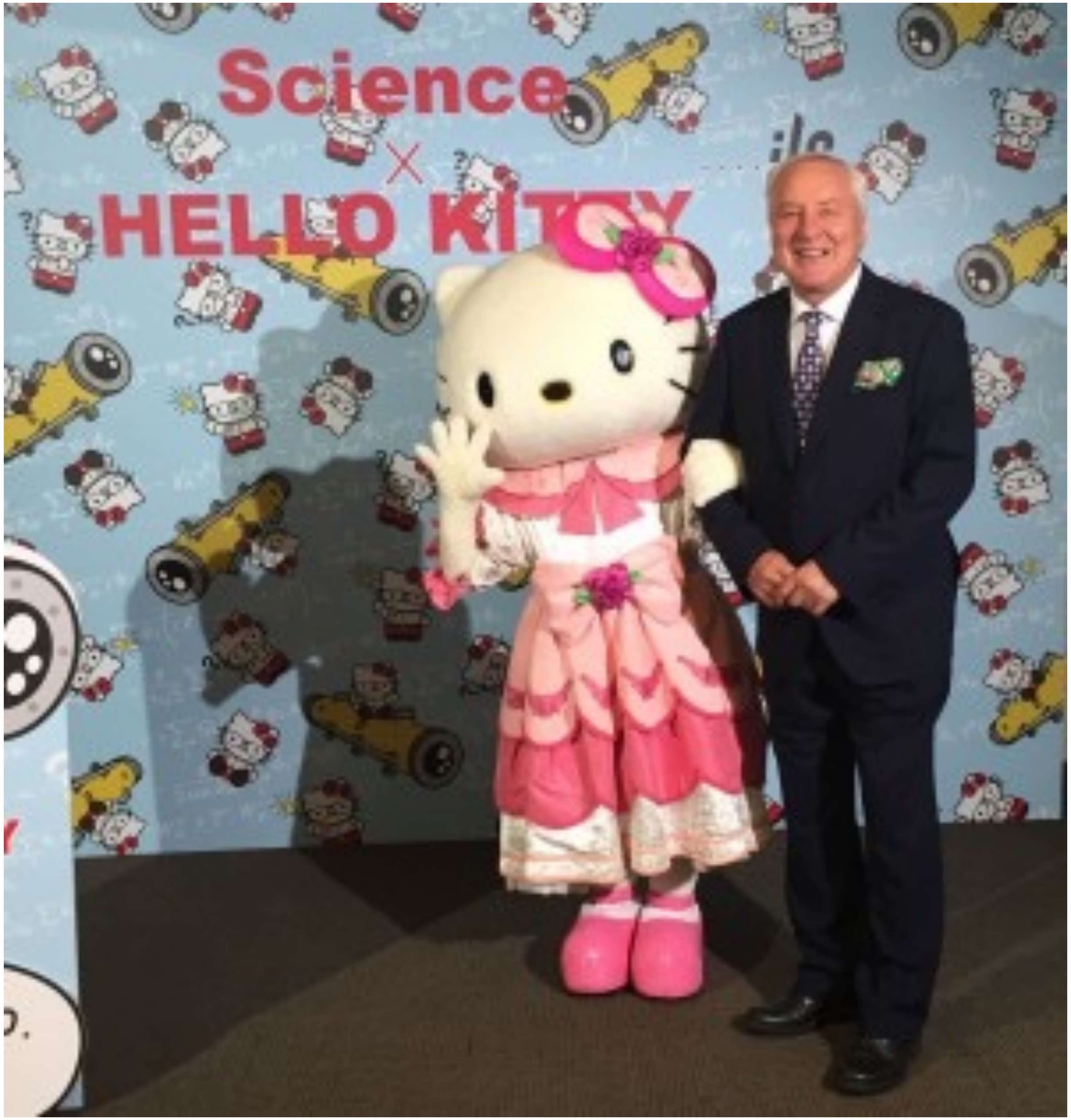
To our understanding, an analysis of this type is almost impossible for the process $gg \to hh$ needed at hadron colliders.

Conclusions:

An e+e- collider at 250 GeV will be a powerful tool to determine the couplings of the Higgs boson with high precision.

This machine will search for evidence of BSM physics in a manner orthogonal to particle searches at the LHC and with impressive reach beyond the LHC capabilities.

An energy extension to 500 GeV or above will allow a full exploration of the Higgs couplings, including the triple Higgs coupling.


Science
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HELLO

Somewhere on the road to Morioka: