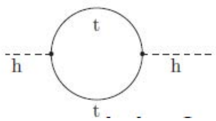
Higgs Coupling Precision at the ILC Using the EFT Formalism

Tim Barklow (SLAC)
ILC Project Meeting, DESY
September 15, 2017

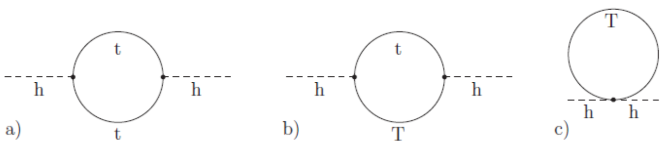
This is a talk about achieving percent level precision for many Higgs couplings at the ILC.

Why is % level Higgs coupling accuracy so interesting?

The Spin-less Higgs

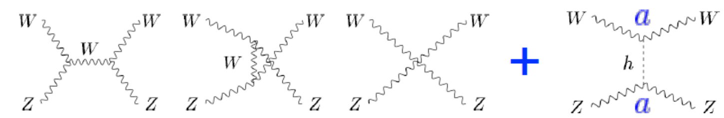


$m_h \sim M_{\rm Pl}$



$m_h \sim M_{\rm new}$

Higgs and Unitarity



$$\Lambda \sim \frac{4\pi v}{\sqrt{1-a^2}}$$

$\Delta g(hWW) = 10\%$ ➡ $\Lambda \sim 8$ TeV

$\Delta g(hWW) = 1\%$ ➡ $\Lambda \sim 23$ TeV

$\Delta g(hWW) = 0.3\%$ ➡ $\Lambda \sim 42$ TeV

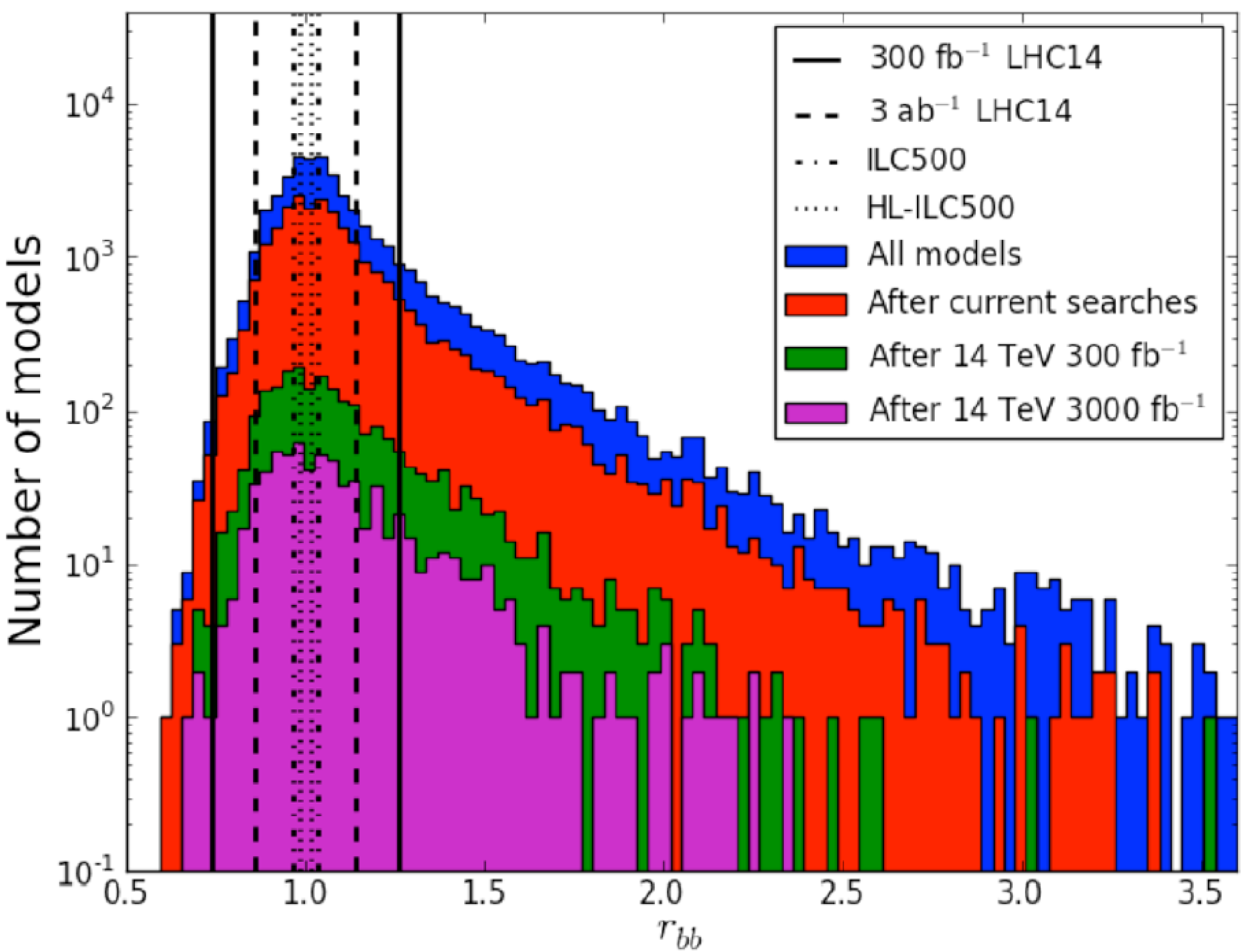
Electroweak Phase Transition

- Electroweak Baryogenesis only works if EWPT is 1st order
- In the SM, EWPT is 2nd order $\Longrightarrow$ no EW Baryogenesis
- New particles, coupled to the Higgs could lead to 1st order EWPT
- Almost all 1st order EWPT models predict large shift in Higgs self coupling
- In many 1st order EWPT models the Higgs couplings to gluons, γ's, W/Z are shifted by 1-5%

3

Direct LHC Searches and e⁺e⁻ Precision Higgs Couplings Measurements are Complementary. For example, for SUSY:

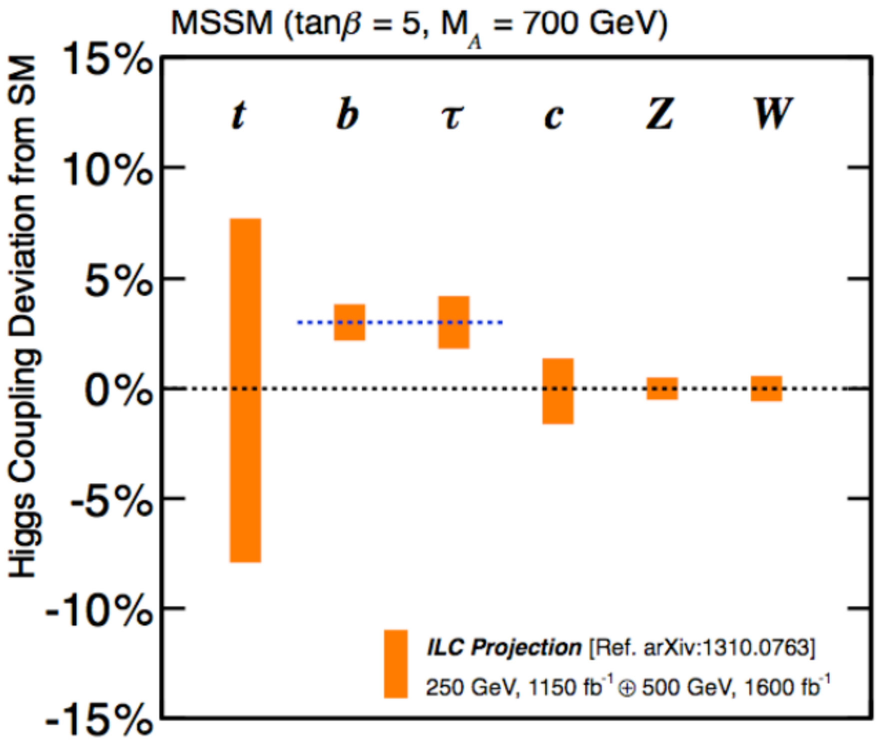
$\Gamma(h \to bb)/(SM)$

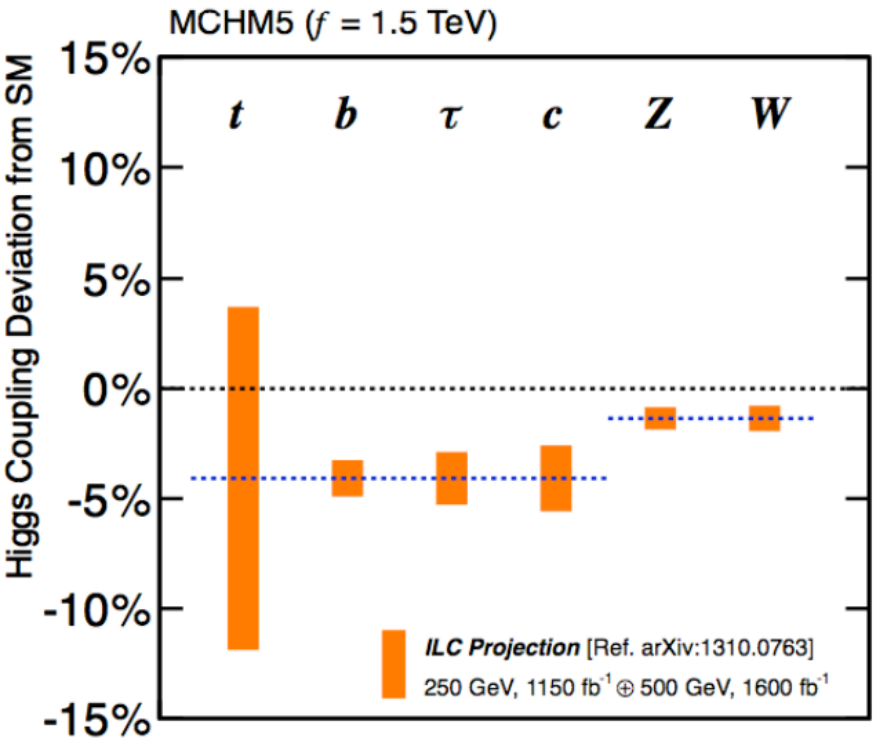


Cahill-Rowley, Hewett, Ismail, Rizzo

Excellent Model Discrimination with e^+e^- Precision Measurements of Many Higgs Couplings

SUSY | Composite Higgs





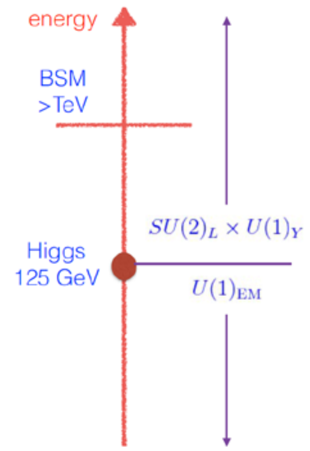
Kanemura, Tsumura, Yagyu, Yokoya

Higgs Effective Field Theory

- LHC results strongly suggest that there is a significant mass gap between the Higgs and BSM particles
- In this situation, BSM corrections to Higgs properties are parametrically small:

$$\delta O \sim m_h^2/M_{\rm BSM}^2$$

- Moreover, BSM physics must respect the full gauge symmetry of the SM
- Effective Field Theory (EFT) gives a systematic way to parametrize correction to Higgs properties under these conditions, by adding "effective operator" terms to the SM Lagrangian



General $SU(2)\times U(1)$ gauge invariant Lagrangian with dimension-6 operators in addition to the SM.

$$\begin{aligned}\Delta\mathcal{L} = & \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3 \\ & + \frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu} \\ & + \frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu} \\ & + i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\overline{L}\gamma_\mu L) + 4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu \Phi)(\overline{L}\gamma_\mu t^a L) \\ & + i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\overline{e}\gamma_\mu e) \; - c_{\tau\Phi}\frac{y_\tau}{v^2}(\Phi^\dagger\Phi)\overline{L}_3 \cdot \Phi\tau_R + h.c.\end{aligned}$$

After EWSB

$$\Delta\mathcal{L}_h = \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{2}m_h^2 h^2 - (1+\eta_h)\overline{\lambda} v h^3 + \frac{\theta_h}{v} h\partial_\mu h \partial^\mu h$$
$$+(1+\eta_W)\frac{2m_W^2}{v}W_\mu^+ W^{-\mu} h + (1+\eta_{WW})\frac{m_W^2}{v^2}W_\mu^+ W^{-\mu} h^2$$
$$+(1+\eta_Z)\frac{m_Z^2}{v}Z_\mu Z^\mu h + \frac{1}{2}(1+\eta_{ZZ})\frac{m_Z^2}{v^2}Z_\mu Z^\mu h^2$$
$$+\zeta_W \hat{W}^+_{\mu\nu}\hat{W}^{-\mu\nu}\left(\frac{h}{v} + \frac{1}{2}\frac{h^2}{v^2}\right) + \frac{1}{2}\zeta_Z \hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu}\left(\frac{h}{v} + \frac{1}{2}\frac{h^2}{v^2}\right)$$
$$+\frac{1}{2}\zeta_A \hat{A}_{\mu\nu}\hat{A}^{\mu\nu}\left(\frac{h}{v} + \frac{1}{2}\frac{h^2}{v^2}\right) + \zeta_{AZ}\hat{A}_{\mu\nu}\hat{Z}^{\mu\nu}\left(\frac{h}{v} + \frac{1}{2}\frac{h^2}{v^2}\right) .$$

$$\Delta\mathcal{L}_{eehZ} = -\frac{g}{2c_w}(c_{HL} - c'_{HL})(\overline{\nu}_L\gamma_\mu\nu_L)Z^\mu(1 + 2\frac{h}{v} + \frac{h^2}{v^2})$$
$$-\frac{g}{2c_w}(c_{HL} + c'_{HL})(\overline{e}_L\gamma_\mu e_L)Z^\mu(1 + 2\frac{h}{v} + \frac{h^2}{v^2})$$
$$-\frac{g}{2c_w}(c_{HE})(\overline{e}_R\gamma_\mu e_R)Z^\mu(1 + 2\frac{h}{v} + \frac{h^2}{v^2})$$
$$\frac{g}{\sqrt{2}}(c'_{HL})(\overline{e}_L\gamma_\mu\nu_L\ W^{-\mu} + \overline{\nu}_L\gamma_\mu e_L\ W^{+\mu}(1 + 2\frac{h}{v} + \frac{h^2}{v^2})$$

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

similar qqhW, qqhZ contact terms
for hadronic W,Z decays in h $\to$ WW,ZZ

7

The couplings η_x ζ_x as well as TGC's & EWPO's are functions of the dim 6 operator coefficients c_J .

Some examples:

Higgs couplings

$$\eta_Z = (-c_T - \frac{1}{2}c_H - c'_{HL})$$
$$\eta_{2Z} = (-5c_T - c_H - 2c'_{HL})$$
$$\eta_W = (-\frac{1}{2}c_H - c'_{HL})$$
$$\eta_{2W} = (-c_H - c'_{HL}) \ .$$

$$\zeta_W = \zeta_{2W} = 8(c_{WW})$$
$$\zeta_Z = \zeta_{2W} = 8(c_0^2 c_{WW} + 2s_0^2 c_{WB} + \frac{s_0^4}{c_0^2} c_{BB})$$

TGC's

$$\Delta_g = \frac{1}{c_0^2 - s_0^2}(\frac{1}{2}c_T - c'_{HL} - 8\frac{s_0^2}{c_0^2}c_{WB})$$
$$\Delta_\kappa = +8c_{WB}$$
$$\Delta_\lambda = -6\frac{e_0^2}{s_0^2}c_{3W}$$

EWPO's

$$m_W^2/m_Z^2 = c_0^2 + \frac{c_0^2}{c_0^2 - s_0^2}(c_0^2 c_T - 2s_0^2(c'_{HL} + 8c_{WB})$$
$$s_*^2 = s_0^2 + \frac{s_0^2}{c_0^2 - s_0^2}(c'_{HL} + 8c_{WB} - c_0^2 c_T) - \frac{1}{2}c_{HE} - s_0^2(c_{HL} - c_{HE})$$

The κ framework for parameterizing BSM Physics in Higgs Couplings is not model independent

In the κ framework SM Higgs couplings are scaled by factor κ_i so that

$$\sigma(e^+e^- \to Zh) \sim \kappa_Z^2$$
$$\Gamma(h \to ZZ^*) \sim \kappa_Z^2$$

Relations such as the following that are used to calculate the total Higgs width remain valid for $\kappa_Z \neq 1$:

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

In the dim 6 EFT framework the Lorentz structure for the hZZ vertex includes the momentum-dependent Z field strength tensor:

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

Integration over phase space gives different dependencies on ζ_Z for cross sections and partial widths:

$$\sigma(e^+e^- \to Zh) = (SM)\cdot(1 + 2\eta_Z + (5.5)\zeta_Z)$$
$$\Gamma(h \to ZZ^*) = (SM)\cdot(1 + 2\eta_Z - (0.50)\zeta_Z)$$

and we can't use $\dfrac{\sigma(e^+e^- \to Zh)}{BR(h \to ZZ^*)}$ to extract Γ_h

In practice, since $BR(h \to ZZ^*)$ is so small, the WW fusion process is used in combination with Higgsstrahlung BR measurements to obtain Γ_h within the κ framework, even at $\sqrt{s} = 250$ GeV

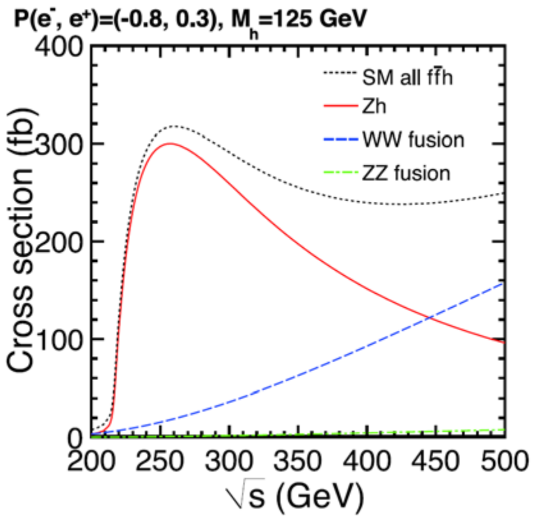
κ framework using WW fusion:

$$\sigma(e^+e^- \to \nu_e \bar{\nu}_e h) \sim \kappa_W^2$$

$$\Gamma(h \to WW^*) \sim \kappa_W^2$$

$$\frac{[\sigma(e^+e^- \to \nu_e \bar{\nu}_e h) \cdot BR(h \to b\bar{b})]}{BR(h \to b\bar{b}) BR(h \to WW^*)} = \frac{\sigma(e^+e^- \to \nu_e \bar{\nu}_e h)}{\Gamma(h \to WW^*)/\Gamma_h} \sim \Gamma_h$$

This gives a more accurate estimate of Γ_h than $\sigma(e^+e^- \to Zh)$ and $BR(h \to ZZ^*)$ at $\sqrt{s} = 250$ GeV, but an even more accurate estimate is made if WW fusion data is collected at $\sqrt{s} = 350$ or 500 GeV.



Within the κ framework it is impossible to achieve better than 2% accuracy on any Higgs coupling (other than hZZ) by running soley at $\sqrt{s} = 250$ GeV with a luminosity 2 ab^{-1} . For this reason it was long advocated that ILC running at $\sqrt{s} = 350$ GeV or 500 GeV was essential to obtaining interesting Higgs coupling accuracy. As we shall see this is not the case in the EFT framework. Many couplings can be measured with O(1%) running solely at $\sqrt{s} = 250$ GeV with 2 ab^{-1} luminosity. This is due to the relationship between the hZZ and hWW couplings in the $SU(2) \times U(1)$ invariant EFT framework:

$$\eta_Z = (-c_T - \frac{1}{2} c_H - c'_{HL}) \quad \approx \quad \eta_W = (-\frac{1}{2} c_H - c'_{HL})$$

(c_T is tightly constrained by precision electroweak constraints)

In order to estimate the Higgs coupling accuracy within the EFT framework a linear least squares fit of 20 parameters is performed using EWPO's, LHC measurements of ratios of Higgs partial widths, and ILC measurements of Higgs cross sections, Higgs cross section times branching ratios, and TGC's.

20 parameters:

9 operators modifying h, γ, W, Z interactions
5 operators modifying h coupling to $b,\ c,\ \tau,\ \mu,\ g$
2 parameters to account for invisible and exotic Higgs decays
4 SM parameters g, g', v, λ that get shifted by the dim 6 operator coefficients

(also some qqhW & qqhZ contact terms that are controlled with precision measurements of the W & Z boson widths)

Measureables:

EWPO's:

$\alpha(\mathrm{m}_Z), G_F, m_W, m_Z, m_h, A_{LR}(l), \Gamma(Z \to l^+ l^-)$

LHC:

$BR(h \to \gamma\gamma) / BR(h \to ZZ)$

ILC TGC's:

$g_{1Z}\ , \kappa_\gamma\ , \lambda_\gamma$

ILC polarized $\sigma(e^+e^- \to Zh)$

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

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

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

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

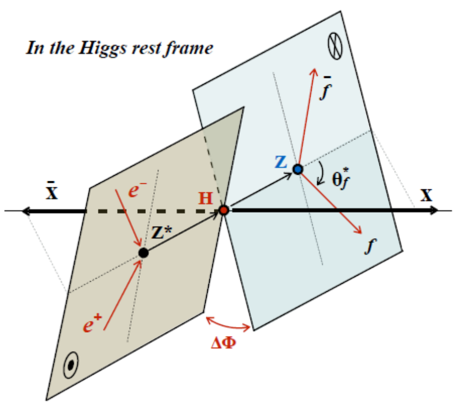
$$b_R = c_w^2(1 - \frac{s - m_Z^2}{s})(8c_{WW})\ .$$

Measureables:

ILC $\sigma \times$BR

	250 GeV		500 GeV	
	Zh	$\nu\overline{\nu}h$	Zh	$\nu\overline{\nu}h$
$h \to invis.$	0.9		3.4	
$h \to b\overline{b}$	1.2	10.5	2.54	0.99
$h \to c\overline{c}$	8.3		18.4	8.8
$h \to gg$	7.0		15.6	5.8
$h \to WW$	6.4		13.0	3.4
$h \to \tau\tau$	3.2		7.6	12.7
$h \to ZZ$	19		35	11.6
$h \to \gamma\gamma$	34		48	27
$h \to \mu\mu$	72		124	102

ILC Angular Analysis of $e^+e^- \to Zh$



Angular Asymmetry derived from the new structures

The Lorentz structure

$$\mathcal{L}_{ZZH} = M_Z^2\left(\frac{1}{v} + \frac{a_Z}{\Lambda}\right) Z_\mu Z^\mu H + \frac{b_Z}{2\Lambda}\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu} H + \frac{\tilde{b}_Z}{2\Lambda}\hat{Z}_{\mu\nu}\widetilde{\hat{Z}}^{\mu\nu} H$$

- "a_Z" is a simple normalization parameter which affects the overall cross section of processes. (just rescales the SM-coupling)
- "b_Z" has a different tensor structure which affects **momentum spectra and changes angular/spin correlations.**
- "$b_Z t$" is a CP-violating parameter which affects **angular/spin correlations.**

Evolution of EFT parameter measurements

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

@ 500 GeV Higgs meas. give better precision on c_{HE} and c_{HL} than EWPO's

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

14

Higgs Coupling Precision (%)

	ILC 250 GeV 2 ab^{-1} κ fit
$g(hb\bar{b})$	2.1
$g(hc\bar{c})$	2.7
$g(hgg)$	2.4
$g(hWW)$	1.9
$g(h\tau\tau)$	2.3
$g(hZZ)$	0.36
$g(h\gamma\gamma)$	7.4
$g(h\mu\mu)$	14
$g(hbb)/g(hWW)$	0.85
$g(hWW)/g(hZZ)$	3.29
Γ_h	4.4
$\sigma(e^+e^- \to Zh)$	0.72
$BR(h \to inv)$	0.39
$BR(h \to other)$	1.6
$g(hhh)$	–

15

Higgs Coupling Precision (%)

	ILC 250 GeV 2 ab^{-1} κ fit	ILC 250 GeV 2 ab^{-1} EFT
$g(hb\bar{b})$	2.1	1.0
$g(hc\bar{c})$	2.7	1.8
$g(hgg)$	2.4	1.6
$g(hWW)$	1.9	0.65
$g(h\tau\tau)$	2.3	1.2
$g(hZZ)$	0.36	0.66
$g(h\gamma\gamma)$	7.4	1.2
$g(h\mu\mu)$	14	5.5
$g(hbb)/g(hWW)$	0.85	0.82
$g(hWW)/g(hZZ)$	3.29	0.07
Γ_h	4.4	2.4
$\sigma(e^+e^- \to Zh)$	0.72	0.70
$BR(h \to inv)$	0.39	0.30
$BR(h \to other)$	1.6	1.5
$g(hhh)$	–	–

Higgs Coupling Precision (%)

	ILC 250 GeV 2 ab^{-1} κ fit	ILC 250 GeV 2 ab^{-1} EFT	ILC 250 + 500 GeV 2 ab^{-1} + 4 ab^{-1} κ fit
$g(hb\bar{b})$	2.1	1.0	0.70
$g(hc\bar{c})$	2.7	1.8	1.2
$g(hgg)$	2.4	1.6	1.0
$g(hWW)$	1.9	0.65	0.42
$g(h\tau\tau)$	2.3	1.2	0.90
$g(hZZ)$	0.36	0.66	0.31
$g(h\gamma\gamma)$	7.4	1.2	3.4
$g(h\mu\mu)$	14	5.5	5.0
$g(hbb)/g(hWW)$	0.85	0.82	–
$g(hWW)/g(hZZ)$	3.29	0.07	–
Γ_h	4.4	2.4	1.8
$\sigma(e^+e^- \to Zh)$	0.72	0.70	0.62
$BR(h \to inv)$	0.39	0.30	0.29
$BR(h \to other)$	1.6	1.5	–
$g(hhh)$	–	–	27

17

Higgs Coupling Precision (%)

	ILC 250 GeV 2 ab^{-1} EFT	CEPC 250 GeV 5 ab^{-1} EFT
$g(hb\bar{b})$	1.0	0.98
$g(hc\bar{c})$	1.8	1.4
$g(hgg)$	1.6	1.3
$g(hWW)$	0.65	0.80
$g(h\tau\tau)$	1.2	1.1
$g(hZZ)$	0.66	0.80
$g(h\gamma\gamma)$	1.2	1.3
$g(h\mu\mu)$	5.5	5.1
$g(hbb)/g(hWW)$	0.82	0.58
$g(hWW)/g(hZZ)$	0.07	0.07
Γ_h	2.4	2.1
$\sigma(e^+e^- \to Zh)$	0.70	0.50
$BR(h \to inv)$	0.30	0.30
$BR(h \to other)$	1.5	1.1
$g(hhh)$	–	–

Higgs Coupling Precision (%)

	ILC 250 GeV 2 ab^{-1} EFT	FCC-ee 250 + 350 GeV 5 ab^{-1} + 1.5 ab^{-1} EFT	ILC 250 + 500 GeV 2 ab^{-1} + 4 ab^{-1} EFT
$g(hb\bar{b})$	1.0	0.66	0.55
$g(hc\bar{c})$	1.8	1.2	1.1
$g(hgg)$	1.6	0.99	0.89
$g(hWW)$	0.65	0.42	0.34
$g(h\tau\tau)$	1.2	0.75	0.71
$g(hZZ)$	0.66	0.42	0.34
$g(h\gamma\gamma)$	1.2	1.0	1.0
$g(h\mu\mu)$	5.5	4.9	5.0
$g(hbb)/g(hWW)$	0.82	0.51	0.43
$g(hWW)/g(hZZ)$	0.07	0.06	0.05
Γ_h	2.4	1.5	1.5
$\sigma(e^+e^- \to Zh)$	0.70	0.22	0.61
$BR(h \to inv)$	0.30	0.27	0.28
$BR(h \to other)$	1.5	0.94	1.2
$g(hhh)$	–	–	27

Higgs Coupling Precision (%)

	ILC 250 GeV $2\ ab^{-1}$ EFT	ILC 250 + 500 GeV $2\ ab^{-1} + 4\ ab^{-1}$ EFT
$g(hb\bar{b})$	1.0	0.55
$g(hc\bar{c})$	1.8	1.1
$g(hgg)$	1.6	0.89
$g(hWW)$	0.65	0.34
$g(h\tau\tau)$	1.2	0.71
$g(hZZ)$	0.66	0.34
$g(h\gamma\gamma)$	1.2	1.0
$g(h\mu\mu)$	5.5	5.0
$g(hbb)/g(hWW)$	0.82	0.43
$g(hWW)/g(hZZ)$	0.07	0.05
Γ_h	2.4	1.5
$\sigma(e^+e^- \to Zh)$	0.70	0.61
$BR(h \to inv)$	0.30	0.28
$BR(h \to other)$	1.5	1.2
$g(hhh)$	–	27

- Selection of 9 models with all new particles outside of projected reach of direct searches at HL-LHC

	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [34]	[illegible]	[illegible]	[illegible]	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [36]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [36]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [36]	+10.1	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.1	-0.2
5	Composite Higgs [38]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [39]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [40]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [41]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-1.5	-1.0	-1.5
9	Higgs Singlet [42]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-3.5	-3.5	-3.5

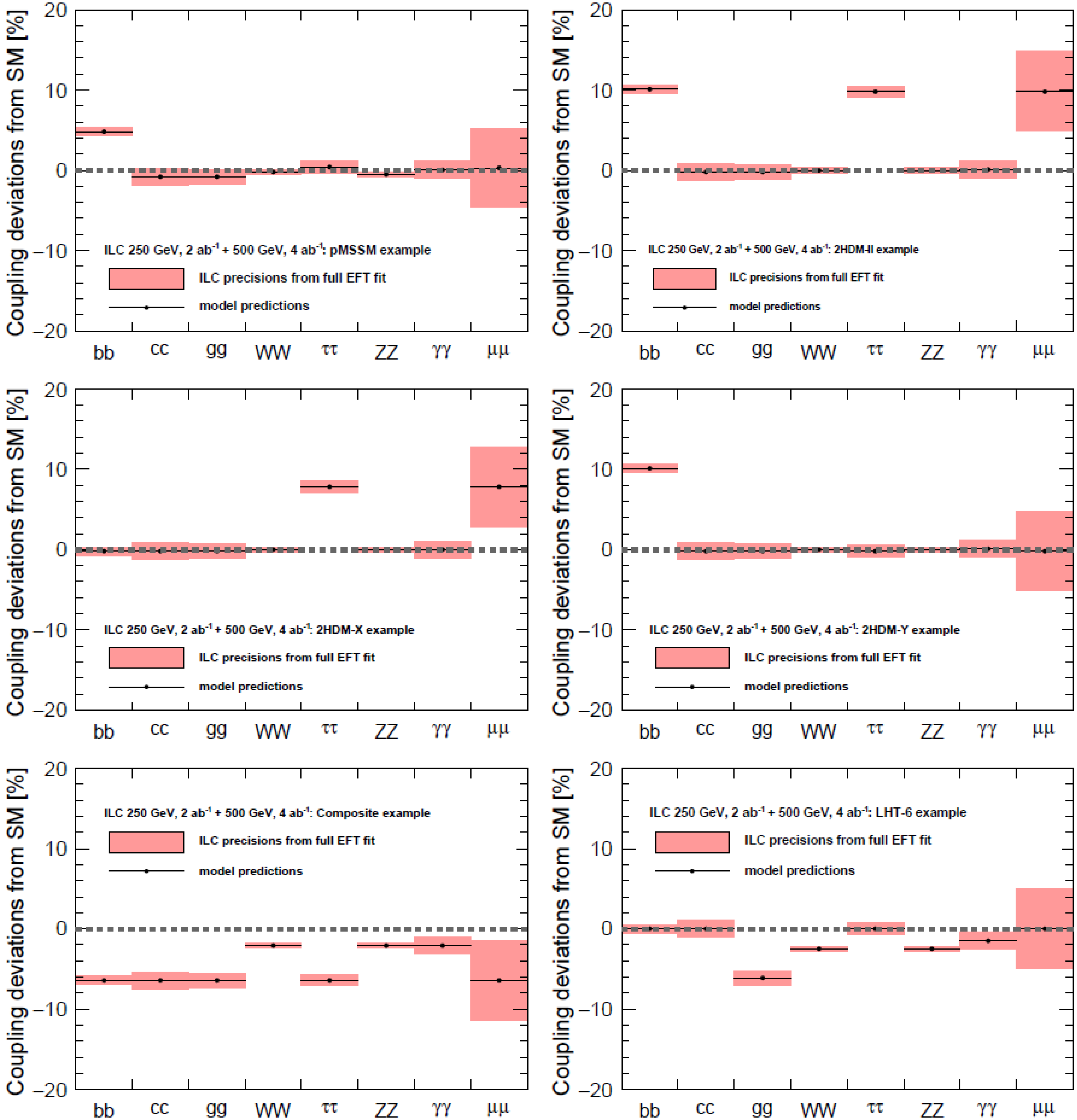
NATURALNESS

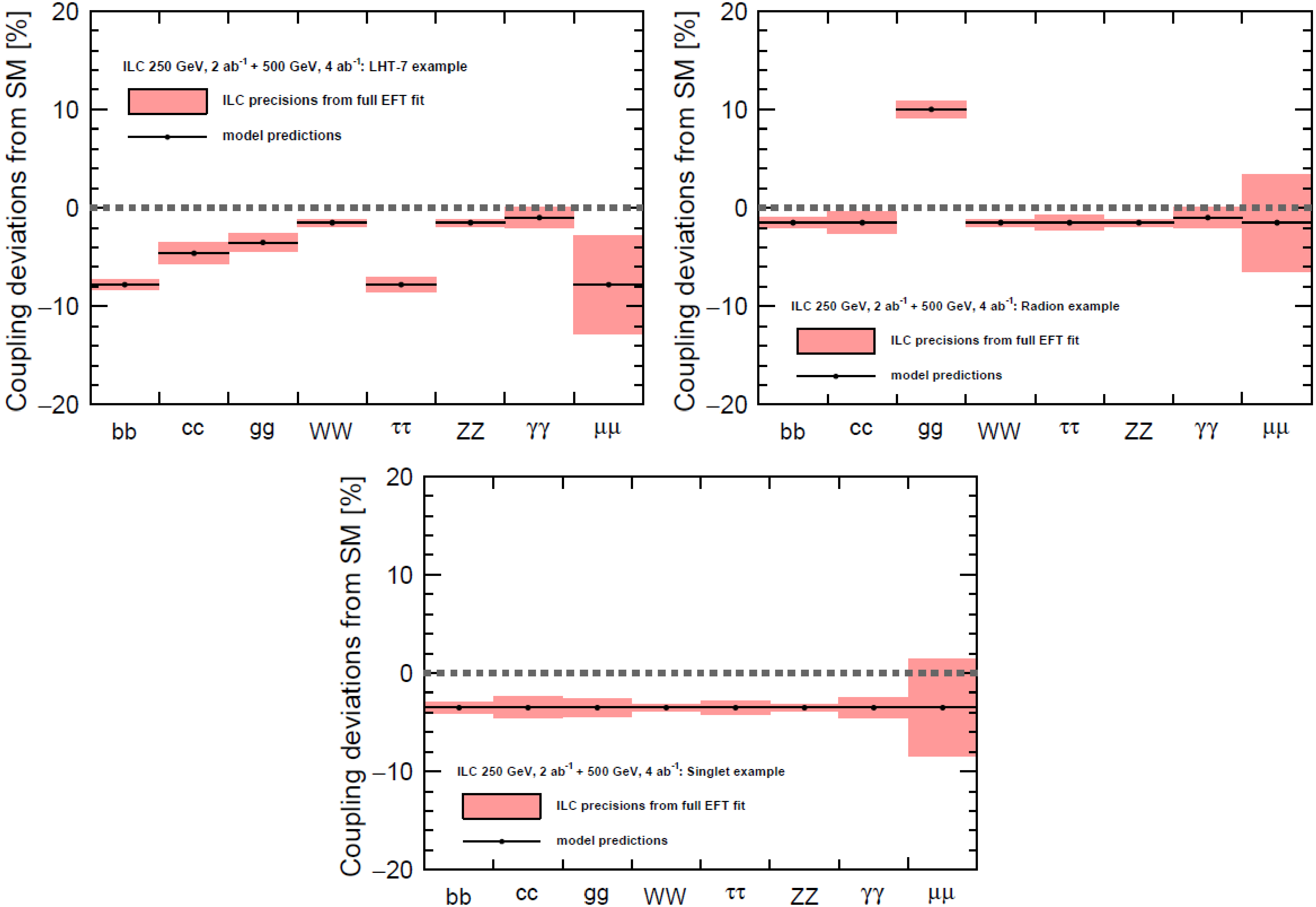
COMPOSITENESS

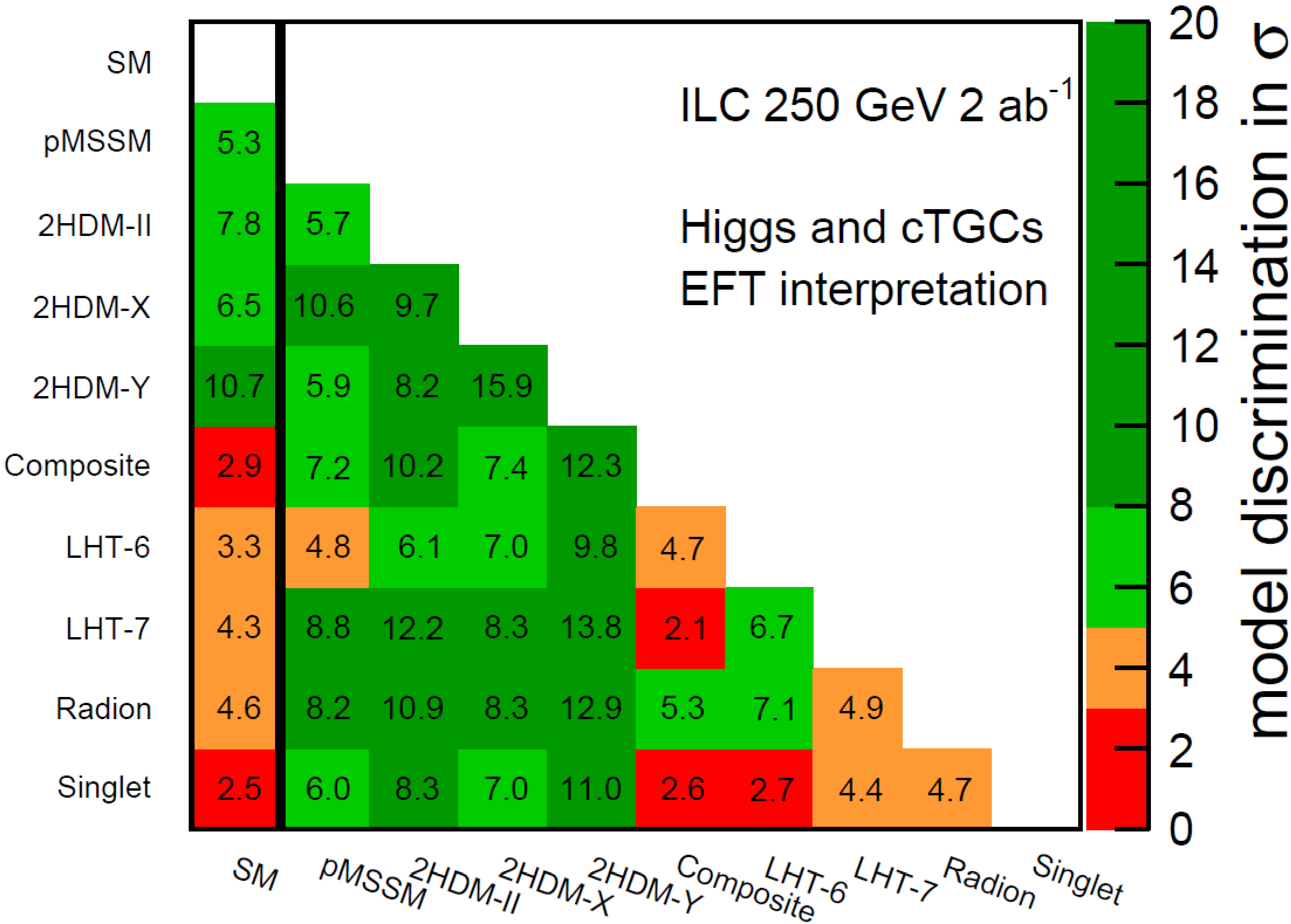
EW BARYOGENESIS

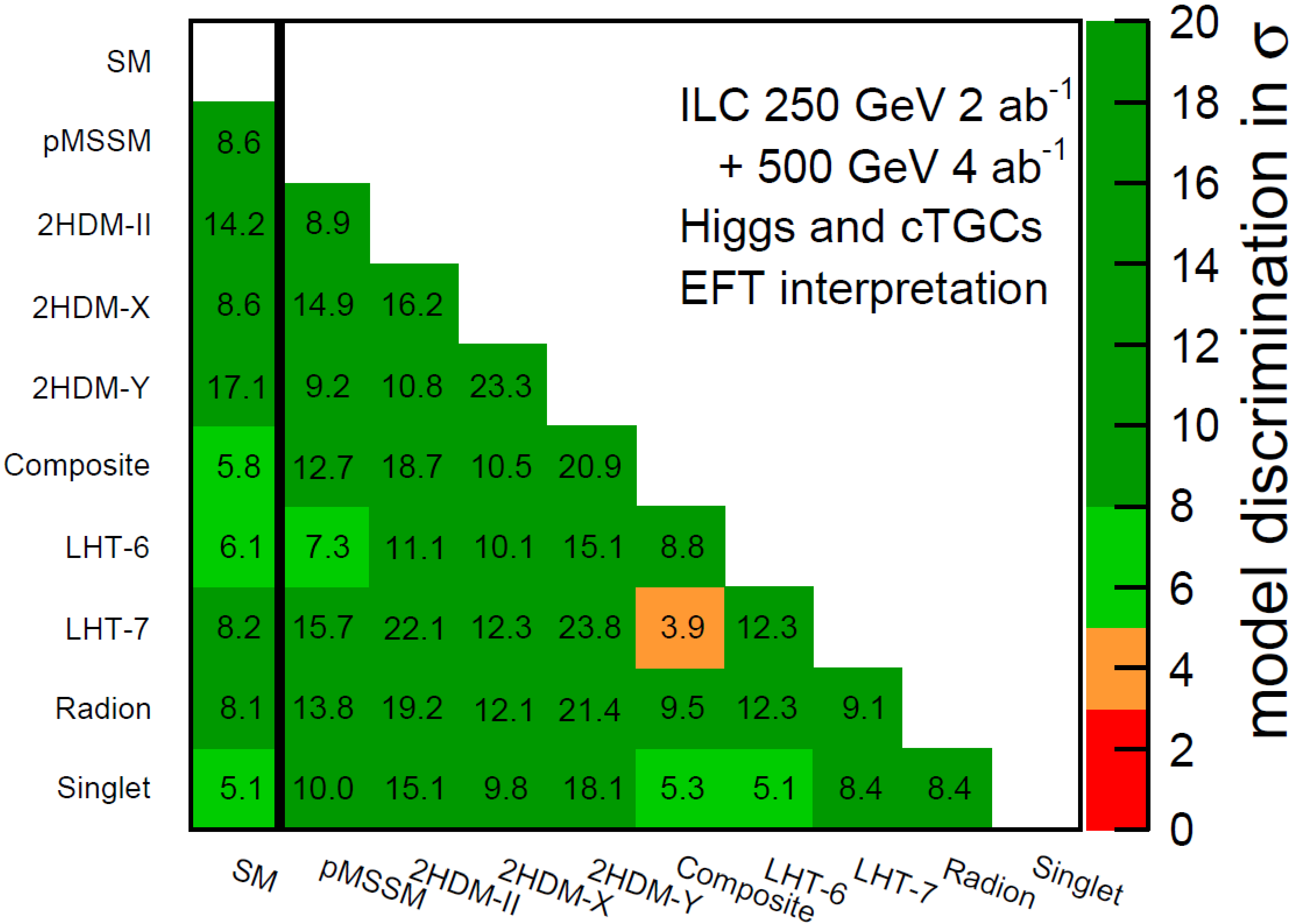
Quantify model discrimination using χ^2 deviation of Model A given Model b

$$(\chi^2)_{AB} = (g_A^T - g_B^T)\,[VCV^T]^{-1}\,(g_A - g_B)$$


Coupling deviations from SM [%]
bb
cc
gg
WW
ττ
ZZ
γγ
μμ
ILC 250 GeV, 2 ab^{-1} + 500 GeV, 4 ab^{-1}: pMSSM example
ILC 250 GeV, 2 ab^{-1} + 500 GeV, 4 ab^{-1}: 2HDM-II example
ILC 250 GeV, 2 ab^{-1} + 500 GeV, 4 ab^{-1}: 2HDM-X example
ILC 250 GeV, 2 ab^{-1} + 500 GeV, 4 ab^{-1}: 2HDM-Y example
ILC 250 GeV, 2 ab^{-1} + 500 GeV, 4 ab^{-1}: Composite example
ILC 250 GeV, 2 ab^{-1} + 500 GeV, 4 ab^{-1}: LHT-6 example
ILC precisions from full EFT fit
model predictions

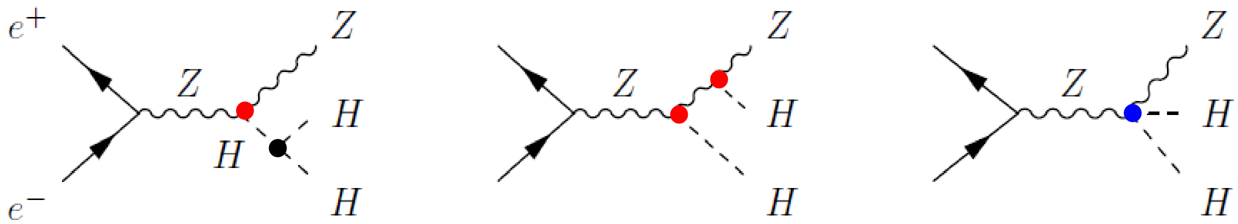

Coupling deviations from SM [%]
20
10
0
−10
−20
ILC 250 GeV, 2 ab⁻¹ + 500 GeV, 4 ab⁻¹: LHT-7 example
ILC precisions from full EFT fit
model predictions
bb
cc
gg
WW
ττ
ZZ
γγ
μμ
ILC 250 GeV, 2 ab⁻¹ + 500 GeV, 4 ab⁻¹: Radion example
ILC 250 GeV, 2 ab⁻¹ + 500 GeV, 4 ab⁻¹: Singlet example

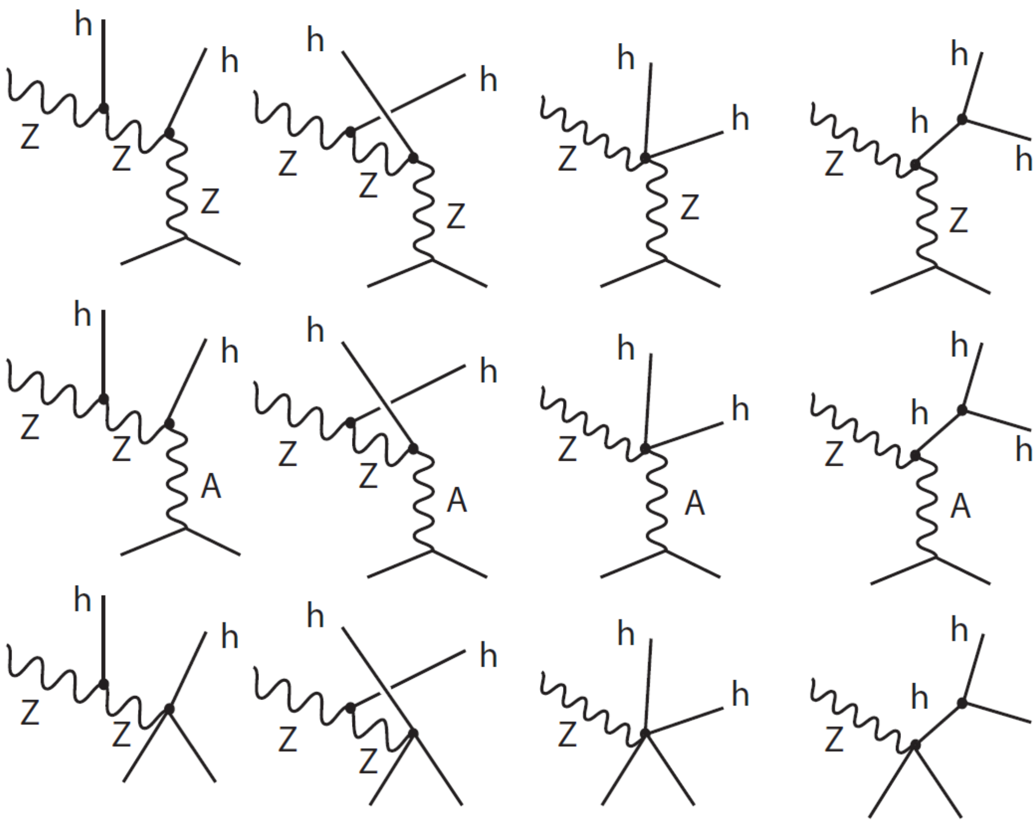

ILC 250 GeV 2 ab-1
Higgs and cTGCs
EFT interpretation
model discrimination in σ
SM
pMSSM
2HDM-II
2HDM-X
2HDM-Y
Composite
LHT-6
LHT-7
Radion
Singlet
5.3
7.8 5.7
6.5 10.6 9.7
10.7 5.9 8.2 15.9
2.9 7.2 10.2 7.4 12.3
3.3 4.8 6.1 7.0 9.8 4.7
4.3 8.8 12.2 8.3 13.8 2.1 6.7
4.6 8.2 10.9 8.3 12.9 5.3 7.1 4.9
2.5 6.0 8.3 7.0 11.0 2.6 2.7 4.4 4.7
0 2 4 6 8 10 12 14 16 18 20


ILC 250 GeV 2 ab^-1
+ 500 GeV 4 ab^-1
Higgs and cTGCs
EFT interpretation
SM
pMSSM 8.6
2HDM-II 14.2 8.9
2HDM-X 8.6 14.9 16.2
2HDM-Y 17.1 9.2 10.8 23.3
Composite 5.8 12.7 18.7 10.5 20.9
LHT-6 6.1 7.3 11.1 10.1 15.1 8.8
LHT-7 8.2 15.7 22.1 12.3 23.8 3.9 12.3
Radion 8.1 13.8 19.2 12.1 21.4 9.5 12.3 9.1
Singlet 5.1 10.0 15.1 9.8 18.1 5.3 5.1 8.4 8.4
SM pMSSM 2HDM-II 2HDM-X 2HDM-Y Composite LHT-6 LHT-7 Radion Singlet
0 2 4 6 8 10 12 14 16 18 20
model discrimination in σ

25

Applying EFT to ILC Triple Higgs Coupling Measurement





26

Applying EFT to ILC Triple Higgs Coupling Measurement

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

$$\eta_h = \delta\overline{\lambda} + \delta v - \frac{3}{2}c_H + c_6$$

$$c_6 = \frac{1}{0.56}\left[\frac{\sigma_{Zhh}}{\sigma_{SM}} - 1 - \sum_i a_i c_i\right]$$

$$\Delta c_6 = \frac{1}{0.56}\left[\left(\frac{\Delta\sigma_{Zhh}}{\sigma_{SM}}\right)^2 + \sum_{i,j} a_i a_j (V_c)_{ij}\right]^{\frac{1}{2}}$$

Given the full ILC program of 2 ab^{-1} at 250 GeV and 4 ab^{-1} at 500 GeV

$$\left[\sum_{i,j} a_i a_j (V_c)_{ij}\right]^{\frac{1}{2}} = 0.04 \quad \ll \quad \frac{\Delta\sigma_{Zhh}}{\sigma_{SM}} = 0.168$$

Applying EFT to ILC Triple Higgs Coupling Measurement

Note that at a hadron collider:

- Many more unknown dim-6 op coefficients
- Fewer measurements to constrain coeff
- Leading production process gg→hh is loop level

ILC uniquely positioned to extract Higgs self coupling from double Higgs production