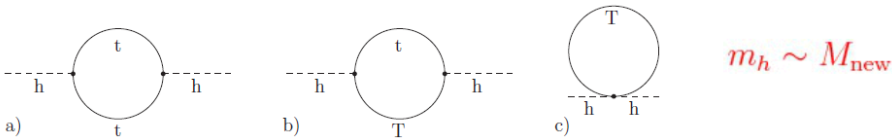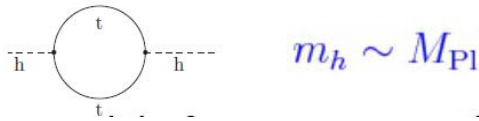# Precision Higgs Measurements at the 250 GeV ILC
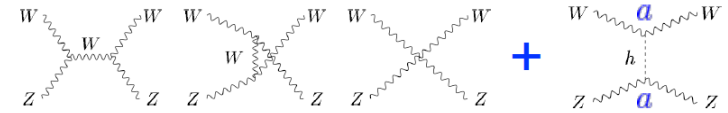
Tim Barklow (SLAC)
EPS–HEP 2017, Venice, Italy
July 7, 2017

Why is % level Higgs coupling accuracy interesting?

The Spin-less Higgs

$$m_h \sim M_{\text{Pl}}$$

$$m_h \sim M_{\text{new}}$$

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%

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

$\Gamma(h \to bb)/(SM)$
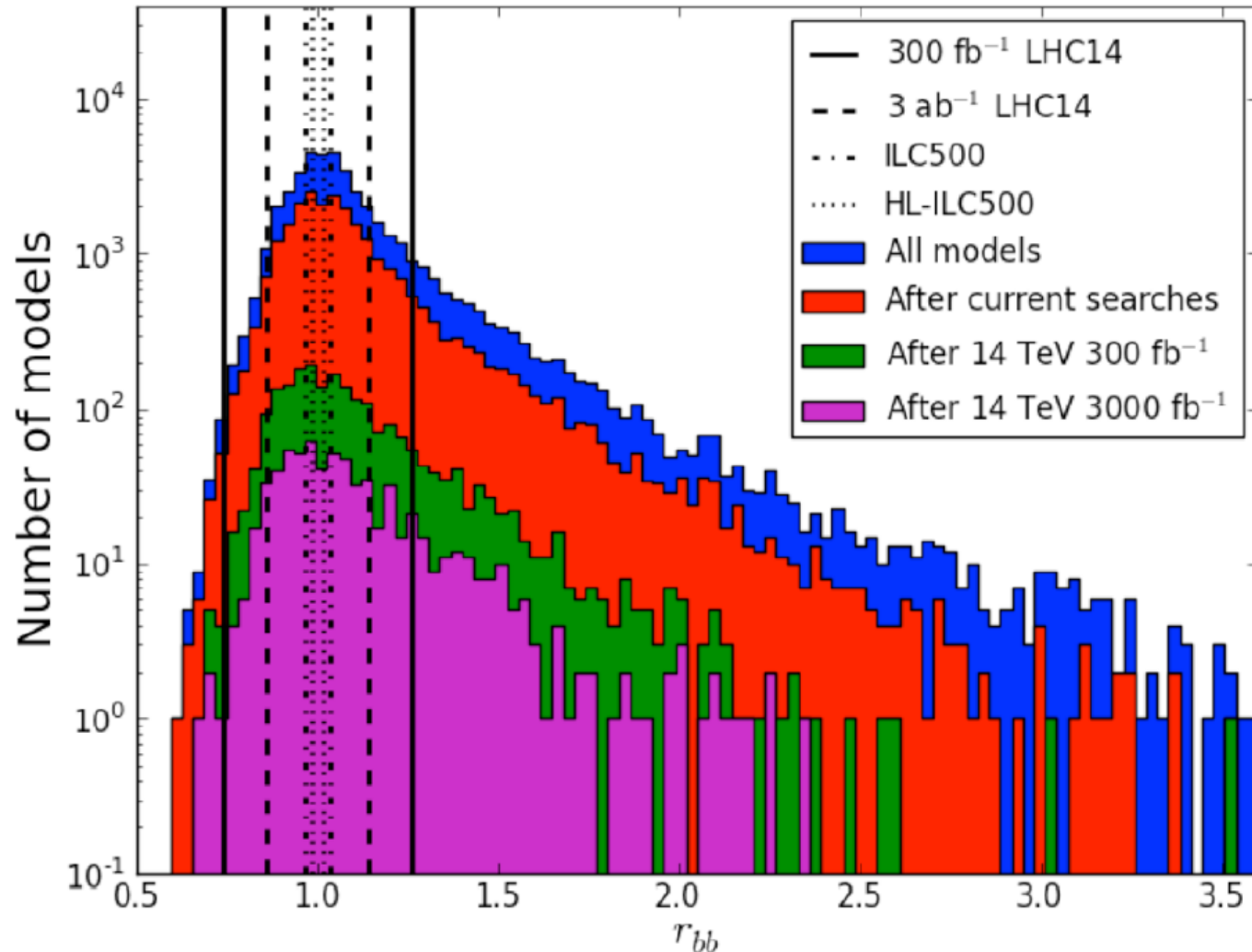
Cahill-Rowley, Hewett, Ismail, Rizzo

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

SUSY

MSSM (tanβ = 5, M_A = 700 GeV)

Higgs Coupling Deviation from SM

t b τ c Z W

ILC Projection [Ref. arXiv:1310.0763]
250 GeV, 1150 fb⁻¹ ⊕ 500 GeV, 1600 fb⁻¹

Composite Higgs

MCHM5 (f = 1.5 TeV)

Higgs Coupling Deviation from SM

t b τ c Z W

ILC Projection [Ref. arXiv:1310.0763]
250 GeV, 1150 fb⁻¹ ⊕ 500 GeV, 1600 fb⁻¹
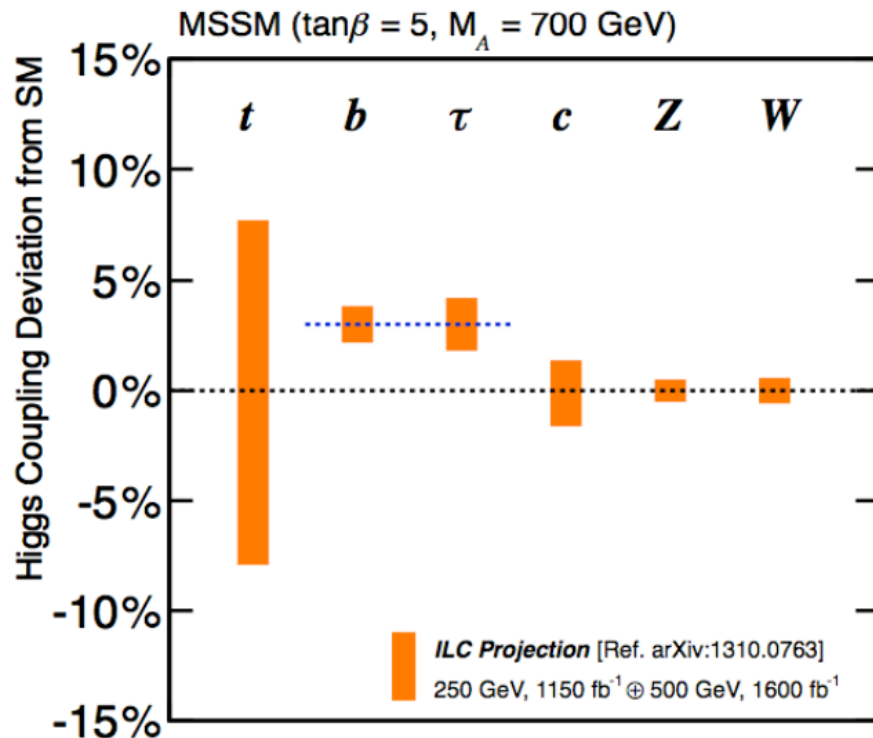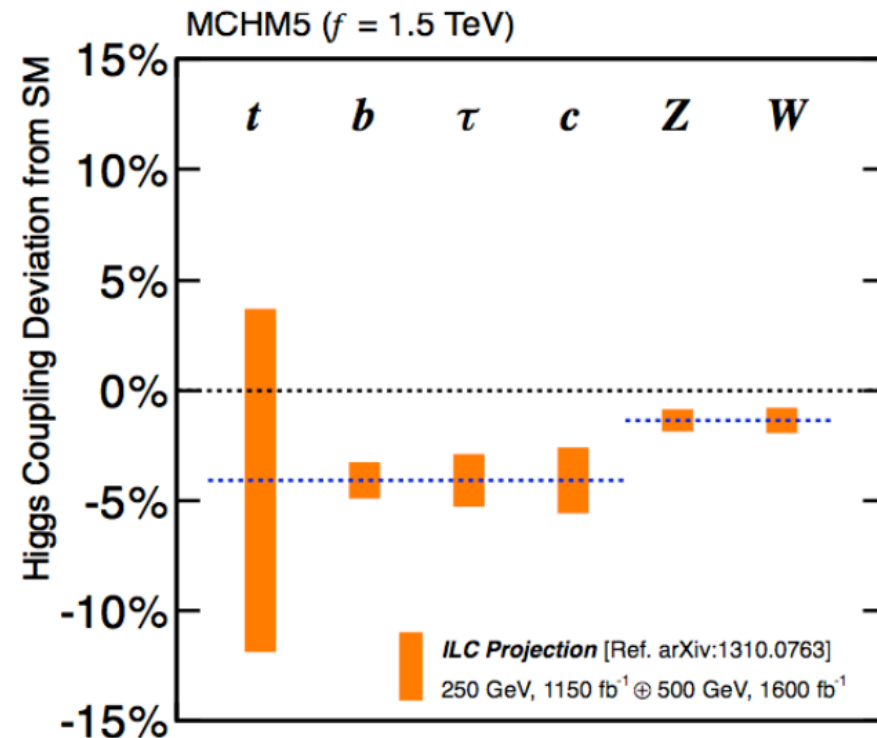
Kanemura, Tsumura, Yagyu, Yokoya

Higgs Effective Field Theory

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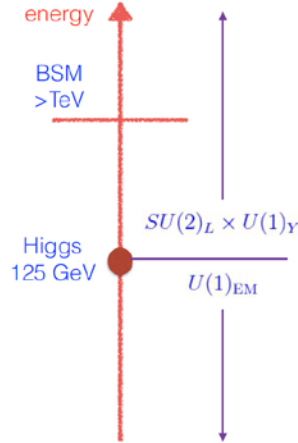
- In this situation, BSM corrections to Higgs properties are parametrically small:

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

- 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

energy

BSM
>TeV

Higgs
125 GeV

$SU(2)_L \times U(1)_Y$

$U(1)_{EM}$

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

$$\Delta \mathcal{L} = \frac{c_H}{2v^2} \partial^\mu (\Phi^\dagger \Phi) \partial_\mu (\Phi^\dagger \Phi) + \frac{c_T}{2v^2} (\Phi^\dagger \overset{\leftrightarrow}{D}{}^\mu \Phi)(\Phi^\dagger \overset{\leftrightarrow}{D}_\mu \Phi) - \frac{c_6 \lambda}{v^2} (\Phi^\dagger \Phi)^3$$

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

$$+ \frac{g'^2 c_{BB}}{m_W^2} \Phi^\dagger \Phi B_{\mu\nu} B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2} \epsilon_{abc} W^a_{\mu\nu} W^{b\nu}{}_\rho W^{c\rho\mu}$$

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

$$+ i \frac{c_{HE}}{v^2} (\Phi^\dagger \overset{\leftrightarrow}{D}{}^\mu \Phi)(\overline{e}\gamma_\mu e) \ .$$

After EWSB

$$\Delta \mathcal{L}_h = -(1+\eta_h)\lambda_0 v_0 h^3 + \frac{\theta_h}{v_0} h \partial_\mu h \partial^\mu h + (1+\eta_Z)\frac{m_Z^2}{v_0} Z_\mu Z^\mu h + \frac{1}{2}(1+\eta_{2Z})\frac{m_Z^2}{v_0^2} Z_\mu Z^\mu h^2$$

$$+ (1+\eta_W)\frac{2m_W^2}{v_0} W^+_\mu W^{-\mu} h + (1+\eta_{2W})\frac{m_W^2}{v_0^2} W^+_\mu W^{-\mu} h^2$$

$$+ \frac{1}{2}\left(\zeta_Z \frac{h}{v_0} + \frac{1}{2}\zeta_{2Z}\frac{h^2}{v_0^2}\right)\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu} + \left(\zeta_W \frac{h}{v_0} + \frac{1}{2}\zeta_{2W}\frac{h^2}{v_0^2}\right)\hat{W}^+_{\mu\nu}\hat{W}^{-\mu\nu} + \cdots$$

$$\Delta \mathcal{L}_{TGC} = ig_V \Big\{ g_{1V} V^\mu (\hat{W}^-_{\mu\nu} W^{+\nu} - \hat{W}^+_{\mu\nu} W^{-\nu}) + \kappa_V W^+_\mu W^-_\nu \hat{V}^{\mu\nu}$$

$$+ \frac{\lambda_V}{m_W^2} \hat{W}^{-\rho}_\mu \hat{W}^+_{\rho\nu} \hat{V}^{\mu\nu} \Big\} \ ,$$

The 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:

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

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

$$\sigma(e^+e^- \to Zh) = (SM) \cdot (1 + 2\eta_Z + (5.5)\zeta_Z)$$

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

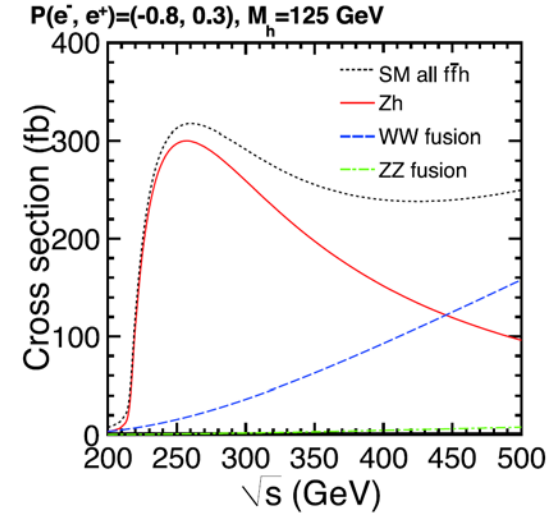and we can't use $\dfrac{\sigma(e^+e^- \to Zh)}{BR(h \to ZZ^*)}$ to extract Γ_h

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

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

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

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

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.

P(e⁻, e⁺)=(-0.8, 0.3), M_h=125 GeV
Cross section (fb)
- SM all f̄fh
- Zh
- WW fusion
- ZZ fusion
$\sqrt{s}$ (GeV)

Within the κ framework it is impossible to achieve better than 1.5% accuracy on any Higgs coupling (other than hZZ) by running at $\sqrt{s} = 250$ GeV only with a luminosity < 4 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 the requisite luminosity to achieve <1.5% accuracy on several Higgs couplings running only at $\sqrt{s} = 250$ GeV is cut in half in the EFT framework. This is due to the relationship between the hZZ and hWW couplings in the $SU(2) \times U(1)$ invariant EFT framework:

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

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, τ, μ, 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

Measureables:

EWPO's:
$\alpha(m_Z), G_F, m_W, m_Z, m_h, A_{LR}(l), \Gamma(Z \rightarrow l^+ l^-)$

LHC:
$BR(h \rightarrow \gamma\gamma) / BR(h \rightarrow ZZ)$

ILC TGC's:
$g_{1Z}, \kappa_\gamma, \lambda_\gamma$

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

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

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

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

Measureables:

ILC $\sigma \times$ BR

	250 GeV		500 GeV	
	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$
$h \to invis.$	0.9		3.4	
$h \to b\bar{b}$	1.2	10.5	2.54	0.99
$h \to c\bar{c}$	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 $e^+e^- \to Zh$ (see talk this conf. by T. Ogawa)
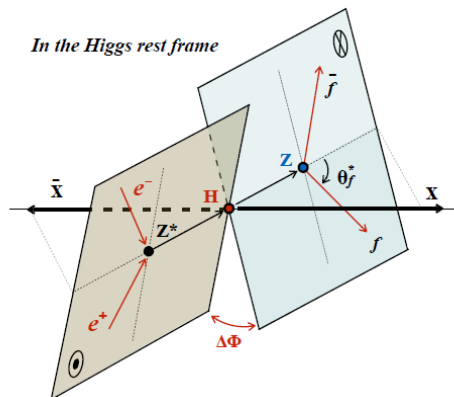
Angular Asymmetry derived from the new structures

The Lorentz structure

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

· "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.**

Result of Linear Least Squares Fit

	ILC250 2 ab^{-1} w. pol.	CEPC 5 ab^{-1} no pol.	FCC-ee 10 ab^{-1} no pol.	full ILC 2 ab^{-1} + 4 ab^{-1} 250+500 GeV
$g(hb\bar{b})$	1.46	1.03	0.81	0.58
$g(hc\bar{c})$	2.06	1.38	1.04	1.12
$g(hgg)$	1.91	1.29	0.98	0.92
$g(hWW)$	1.00	0.78	0.66	0.28
$g(h\tau\tau)$	1.56	1.09	0.85	0.76
$g(hZZ)$	0.98	0.76	0.65	0.27
$g(h\gamma\gamma)$	1.37	1.21	1.12	0.99
$g(h\mu\mu)$	12.8	8.11	5.75	8.63
$g(hbb)/g(hWW)$	1.08	0.68	0.48	0.49
$g(hWW)/g(hZZ)$	0.034	0.037	0.036	0.018
Γ_h	3.12	2.34	1.69	1.39
$\sigma(e^+e^- \rightarrow Zh)$	0.70	0.44	0. 31	0.47
$BR(h \rightarrow inv)$	0.34	0.24	0.19	0.32
$BR(h \rightarrow other)$	1.60	1.02	0.73	0.94

- 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]				-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					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]						-1.5	-1.0	-1.5
9	Higgs Singlet [42]	-3.5					-3.5	-3.5	-3.5

NATURALNESS

COMPOSITENESS

EW BARYOGENESIS

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

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

ILC250, 2 ab^{-1}

Higgs and cTGCs

EFT interpretation

	SM	pMSSM	2HDM-II	2HDM-X	2HDM-Y	Composite	LHT-6	LHT-7	Radion	Singlet
SM										
pMSSM	6.4									
2HDM-II	7.7	6.9								
2HDM-X	8.1	12.8	11.1							
2HDM-Y	12.0	8.2	9.8	19.2						
Composite	2.3	7.1	9.1	8.4	12.8					
LHT-6	3.0	5.5	6.0	8.6	11.2	4.0				
LHT-7	3.6	8.5	11.0	8.9	14.2	2.2	5.8			
Radion	4.7	8.8	11.1	9.6	14.3	5.1	7.1	4.3		
Singlet	3.4	7.5	9.8	9.0	13.4	3.6	5.4	3.5	2.1	

model discrimination in σ

ILC250+500, H20

Higgs and cTGCs

EFT interpretation

	SM	pMSSM	2HDM-II	2HDM-X	2HDM-Y	Composite	LHT-6	LHT-7	Radion	Singlet
SM										
pMSSM	10.5									
2HDM-II	14.3	11.3								
2HDM-X	10.0	17.7	18.1							
2HDM-Y	18.1	12.2	12.0	26.2						
Composite	5.5	13.2	17.9	10.6	21.1					
LHT-6	6.4	9.5	11.2	11.8	16.3	8.1				
LHT-7	7.5	15.8	21.3	11.8	23.8	4.0	11.6			
Radion	8.2	15.0	19.8	13.1	22.6	9.2	12.4	8.5		
Singlet	7.5	13.6	18.1	12.4	21.4	7.1	9.4	7.9	4.5	

model discrimination in σ

Applying EFT to ILC Triple Higgs Coupling Measurement
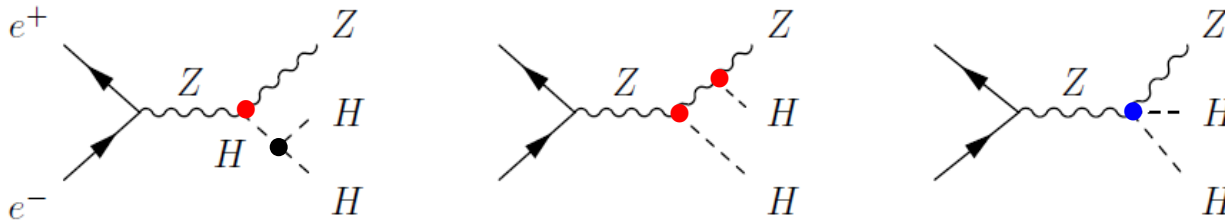
$$\frac{\sigma_{Zhh}}{\sigma_{SM}} - 1 = 0.565c_6 - 3.58c_H + 16.0(8c_{WW}) + 8.40(8c_{WB}) + 1.26(8c_{BB})$$

$$-6.48c_T - 65.1c'_{HL} + 61.1c_{HL} + 52.6c_{HE},$$

$$c_6 = \frac{1}{0.565}\left[\frac{\sigma_{Zhh}}{\sigma_{SM}} - 1 - \sum_i a_i c_i\right]$$

$$\Delta c_6 = \frac{1}{0.565}\left[(\frac{\Delta\sigma_{Zhh}}{\sigma_{SM}})^2 + \sum_{i,j} a_i a_j (V_c)_{ij}\right]^{\frac{1}{2}}$$

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

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