Higgs Coupling Systematics

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ILC Higgs Coupling Precisions

		H20 @ 8yrs	**H20 @ 20yrs**		
Topic	Parameter	Initial Phase	Full Data Set	units	ref.
Higgs	m_h	25	15	MeV	[51]
	$g(hZZ)$	0.58	0.31	%	[8]
	$g(hWW)$	0.81	0.42	%	[8]
	$g(hb\bar{b})$	1.5	0.7	%	[8]
	$g(hgg)$	2.3	1.0	%	[8]
	$g(h\gamma\gamma)$	7.8	3.4	%	[8]
		1.2	1.0	%, w. LHC results	[52]
	$g(h\tau\tau)$	1.9	0.9	%	[8]
	$g(hc\bar{c})$	2.7	1.2	%	[8]
	$g(ht\bar{t})$	18	6.3	%, direct	[8]
		20	20	%, $t\bar{t}$ threshold	[53]
	$g(h\mu\mu)$	20	9.2	%	[8]
	$g(hhh)$	77	27	%	[8]
	Γ_{tot}	3.8	1.8	%	[8]
	Γ_{invis}	0.54	0.29	%, 95% conf. limit	[8]

[8] D. M. Asner *et al.*, "ILC Higgs White Paper," arXiv:1310.0763 [hep-ph].

[51] H. Li, arXiv:1007.2999 [hep-ex].

[52] M. E. Peskin, in the Proceedings of the APS DPF Community Summer Study (Snowmass 2013), arXiv:1312.4974 [hep-ph].

[53] T. Horiguchi, A. Ishikawa, T. Suehara, K. Fujii, Y. Sumino, Y. Kiyo and H. Yamamoto, arXiv:1310.0563 [hep-ex].

Higgs Physics Systematic Errors

Given that the statistical errors of many of the Higgs cross section and $\sigma \bullet$BR reach the several per-mil level for the full H20 program, systematic errors must typically be 0.1% or less.

The following systematic errors have been considered:

- Flavor Tagging
- Luminosity
- Polarization
- Model Independence of ZH Recoil Measurements
- Theory Error
- Δg_{ZZH} & Δg_{ZZHH} in Higgs self coupling measurement

Higgs Physics Systematic Errors

Luminosity, Polarization, & Flavor Tagging Systematic Errors Assumed in 2013 Snowmass Higgs White Paper:

	Baseline	LumUp
luminosity	0.1%	0.05%
polarization	0.1%	0.05%
b-tag efficiency	0.3%	0.15%

$$\frac{\Delta L}{L} = \frac{2\Delta\theta}{\theta_{min}}, \qquad \theta_{min} = 46 \text{ mrad} \quad \Delta\theta < 0.02 \text{ mrad} \quad \Delta R(\text{sensors}) < 30\ \mu\text{m}$$

polarization obtained from polarimeters upstream and downstream of IP

+ physics processes such as $e^+e^- \to W^+W^-$

b-tag efficiency errors obtained from a study by Tomohiko Tanabe and Taikan Suehara using $e^+e^- \to ZZ \to l^+l^-b\bar{b}$ as a control sample; could be improved with additional control sample processes

Higgs Physics Systematic Errors -- Model Independence of ZH Recoil Measurements

Analytic Calculation of Systematic Error for the Model Independence of Hadronic ZH Recoil Measurement:

$$\text{sys err} = \frac{1}{2}\frac{N^2}{\Omega}\sum_i BR_i^2 \left(\frac{\Delta\sigma \bullet BR_i}{\sigma \bullet BR_i}\right)^2 \delta_i^2 + BR_i^2 \Delta\xi_i^2$$

$N \equiv L\,\sigma_{ZH} =$ Total number of Higgstrahlung events

$\Omega =$ Number of signal + background events in $\sigma(ZH \to q\,\bar{q} + X)$ analysis

$\xi_i =$ efficiency for events from Higgs decay i to pass $\sigma(ZH \to q\,\bar{q} + X)$ analysis

$\delta_i = \xi_i - <\xi>$ = shift in decay mode efficiency w.r.t. average (BR weighted) efficiency

In the absence of a model independent BSM Higgs decay analysis, this systematic error is dominated by $BR_{bsm}\Delta\xi_{bsm}$ where,
BR_{bsm} is derived from the global coupling fit and
$\Delta\xi_{bsm}$ is given by the range of Higgs decay mode efficiencies from invisible to fully hadronic multijet

sys error = 11% of statistical error at $\sqrt{s} = 350$ GeV

ILC model independent global coupling fit using 32 $\sigma \bullet BR$ measurements Y_{i} and σ_{ZH} measurement Y_{33}

$$\chi^2 = \sum_{i=1}^{i=33} \left(\frac{Y_i - Y_i'}{\Delta Y_i}\right)^2 ,$$

$$Y_i' = F_i \cdot \frac{g^2_{HZZ} g^2_{Hb\bar{b}}}{\Gamma_0}, \text{ or } Y_i' = F_i \cdot \frac{g^2_{HWW} g^2_{Hb\bar{b}}}{\Gamma_0}, \text{ or } Y_i' = F_i \cdot \frac{g^2_{Htt} g^2_{Hb\bar{b}}}{\Gamma_0}$$

$$F_i = S_i G_i \quad \text{where } S_i = \left(\frac{\sigma_{ZH}}{g_Z^2}\right), \ \left(\frac{\sigma_{\nu\bar{\nu}H}}{g_W^2}\right), \ \text{or } \left(\frac{\sigma_{t\bar{t}H}}{g_t^2}\right), \ \text{and } G_i = \left(\frac{\Gamma_i}{g_i^2}\right).$$

The cross section calculations S_i do not involve QCD ISR.

The partial width calculations G_i do not require quark masses as input.

It is felt that the total theory errors for S_i and G_i - as well as the errors on the SM calculations for σ_i and Γ_i - will be at the 0.1% level at the time of ILC running.

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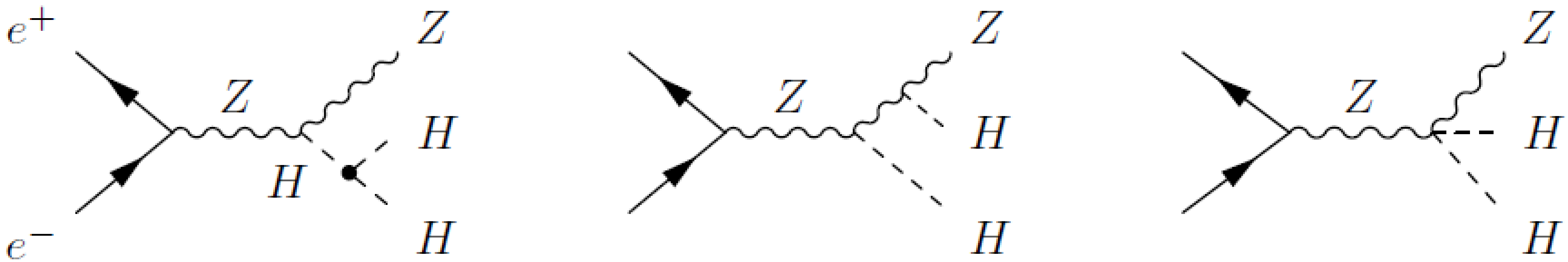
ILC Higgs Self Coupling Measurement at $\sqrt{s} = 500$ GeV From $\sigma(e^+e^- \to ZHH)$



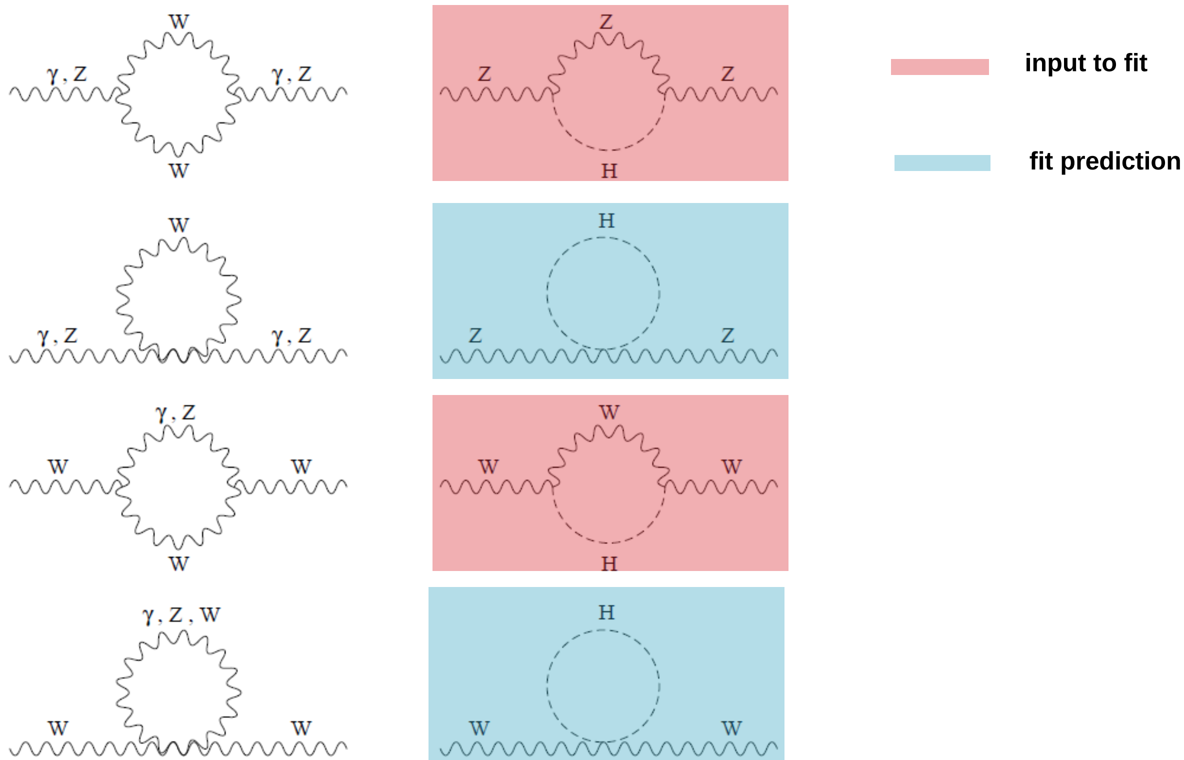
g_{hZZ} fixed to value from $\sigma(ZH)$ measurement

To handle g_{hhZZ} one can

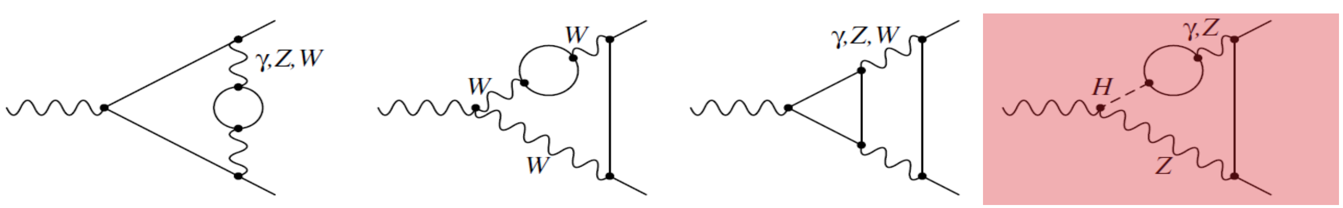
(1) Assume g_{hhZZ} is fixed to SM value
(2) Assume g_{hhZZ} is fixed to some value related to measured g_{hZZ}
(3) Use EW precision measurements to limit g_{hhZZ} through radiative corrections
(3) Directly measure g_{hhh} & g_{hhZZ} simultaneously.

Higgs Physics Systematic Errors -- g_{ZZH} , g_{ZZHH} in Higgs self coupling meas.

Limits on ZZHH coupling can be obtained from Electroweak Fits where M_H, g_{ZZH} , g_{WWH} will be very well measured input variables at time of $\sigma(ZHH)$ measurement (idea thanks to K. Fujii and J. Tian)



One-loop bosonic contributions to vector-boson self-energies.



Genuine two-loop Zl^+l^- vertex diagrams contributing to $\sin^2\theta_{\rm eff}^{\rm lept}$.

Higgs Physics Systematic Errors -- g_{ZZH} , g_{ZZHH} in Higgs self coupling meas.

ZZH coupling will not in general be a single number. One must consider the more general Lorentz structure of effective field theories:

$$\begin{aligned}
\mathcal{L}^{\rm anom}_{H,Z,W} = & -v\lambda g^{(1)}_{HHH} H^3 + \frac{1}{2} g^{(2)}_{HHH} H\partial_\mu H \partial^\mu H - \frac{1}{4} g^{(1)}_{HZZ} Z_{\mu\nu} Z^{\mu\nu} H - \frac{1}{4} g^{(2)}_{HZZ} Z_\nu \partial_\mu Z^{\mu\nu} H \\
& + \frac{1}{2} g^{(3)}_{HZZ} Z_\mu Z^\mu H - \frac{1}{2} g^{(1)}_{HAZ} Z_{\mu\nu} F^{\mu\nu} H - g^{(2)}_{HAZ} Z_\nu \partial_\mu F^{\mu\nu} H \\
& - \frac{1}{8} g^{(1)}_{HHZZ} Z_{\mu\nu} Z^{\mu\nu} H^2 - \frac{1}{2} g^{(2)}_{HHZZ} Z_\nu \partial_\mu Z^{\mu\nu} H^2 - \frac{1}{4} g^{(3)}_{HHZZ} Z_\mu Z^\mu H^2 \\
& - \frac{1}{2} g^{(1)}_{HWW} W^{\mu\nu} W^\dagger_{\mu\nu} H - \left[g^{(2)}_{HWW} W^\nu \partial^\mu W^\dagger_{\mu\nu} H + h.c. \right] + g\, m_W W^\dagger_\mu W^\mu H \\
& - \frac{1}{4} g^{(1)}_{HHWW} W^{\mu\nu} W^\dagger_{\mu\nu} H^2 - \frac{1}{2} \left[g^{(2)}_{HHWW} W^\nu \partial^\mu W^\dagger_{\mu\nu} H^2 + h.c. \right] + \frac{1}{4} g^2 W^\dagger_\mu W^\mu H^2
\end{aligned}$$

In total eight coefficients, namely, $\bar{c}_6$, $\bar{c}_H$, $\bar{c}_T$, $\bar{c}_\gamma$, $\bar{c}_B$, $\bar{c}_W$, $\bar{c}_{HB}$, $\bar{c}_{HW}$, govern the dyanmics of ZHH and $\nu\bar{\nu}HH$ production

$$g^{(1)}_{HHH} = 1 + \frac{5}{2}\bar{c}_6, \qquad g^{(2)}_{HHH} = \frac{g}{m_W}\bar{c}_H$$

$$g^{(1)}_{HZZ} = \frac{2g}{c_W^2 m_W}\left[\bar{c}_{HB} s_W^2 - 4\bar{c}_\gamma s_W^4 + c_W^2 \bar{c}_{HW}\right]$$

$$g^{(2)}_{HZZ} = \frac{g}{c_W^2 m_W}\left[(\bar{c}_{HW} + \bar{c}_W) c_W^2 + (\bar{c}_B + \bar{c}_{HB}) s_W^2\right], \qquad g^{(3)}_{HZZ} = \frac{g m_Z}{c_W}\left[1 - 2\bar{c}_T\right]$$

$$g^{(1)}_{HAZ} = \frac{g s_W}{c_W m_W}\left[\bar{c}_{HW} - \bar{c}_{HB} + 8\bar{c}_\gamma s_W^2\right]$$

$$g^{(2)}_{HAZ} = \frac{g s_W}{c_W m_W}\left[\bar{c}_{HW} - \bar{c}_{HB} - \bar{c}_B + \bar{c}_W\right]$$

$$g^{(1)}_{HHZZ} = \frac{g^2}{c_W^2 m_W^2}\left[\bar{c}_{HB} s_W^2 - 4\bar{c}_\gamma s_W^4 + \bar{c}_{HW} c_W^2\right]$$

$$g^{(2)}_{HHZZ} = \frac{g^2}{2 c_W^2 m_W^2}\left[(\bar{c}_{HW} + \bar{c}_W) c_W^2 + (\bar{c}_B + \bar{c}_{HB}) s_W^2\right], \qquad g^{(3)}_{HHZZ} = \frac{g^2}{2 c_W^2}\left[1 - 6\bar{c}_T\right]$$

$$g^{(1)}_{HWW} = \frac{2g}{m_W}\bar{c}_{HW}, \qquad g^{(2)}_{HWW} = \frac{g}{2m_W}\left[\bar{c}_W + \bar{c}_{HW}\right]$$

$$g^{(1)}_{HHWW} = \frac{g^2}{m_W^2}\bar{c}_{HW}, \qquad g^{(2)}_{HHWW} = \frac{g^2}{4m_W^2}\left[\bar{c}_W + \bar{c}_{HW}\right]$$

Note the relationship here between triple and quartic coupling parameters

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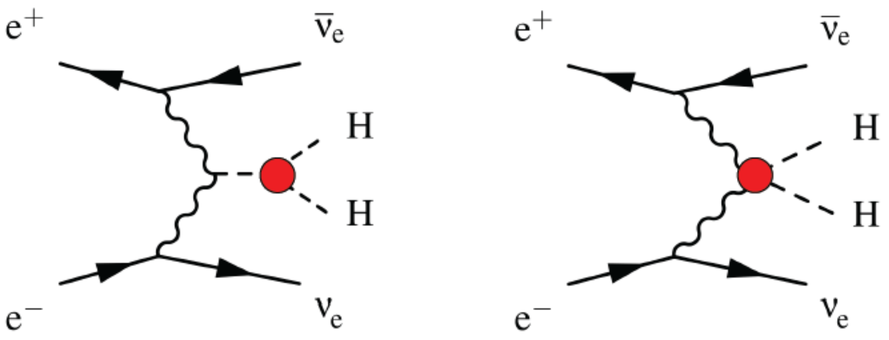
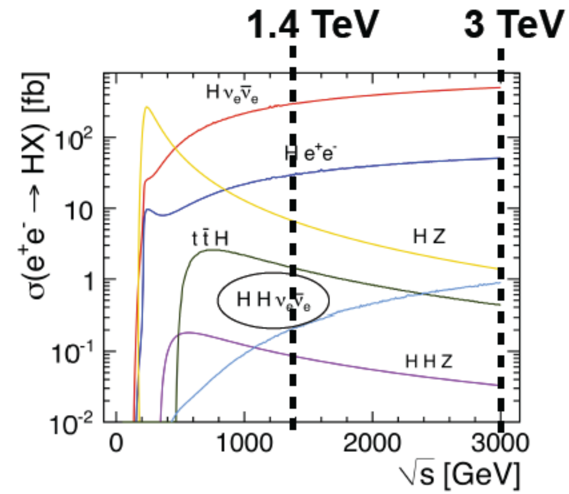
Higgs Physics Systematic Errors -- g_{ZZH} , g_{ZZHH} in Higgs self coupling meas.

CLIC fits for either g_{HHH} or g_{WWHH} , but not both simultaneously:





- The $HH\nu_e\bar{\nu}_e$ cross section is sensitive to the Higgs self coupling, λ, and the quartic HHWW coupling
- Only 225 (1200) $e^+e^- \to HH\nu_e\bar{\nu}_e$ events at 1.4 (3) TeV

→ high energy and luminosity crucial

Measurement	1.4 TeV	3 TeV
$\Delta(g_{HHWW})$	7% (preliminary)	3% (preliminary)
Δ(λ)	32%	16%
Δ(λ) for $P(e^-)$ = -80%	24%	12%

Towards the Ultimate ILC Higgs Coupling Precision

or why it is important to pursue a good $BR(H \to BSM)$ measurement even if, as a result of this effort, no BSM decays are found.

Perform coupling fit with $\sum_i BR_i = 1$ including $\Delta BR(H \to BSM)$ for

(the constraint $\sum_i BR_i = 1$ is model independent if $\Delta BR(H \to BSM)$ is included in the fit)

ILC Higgs Coupling Precision assuming 20 year H20 scenario

$BR(H \to BSM)$ (95% CL)	no meas.	$< 7.2\%$	$< 3.6\%$	$< 1.8\%$	$< 0.9\%$	$< 0.09\%$
ZZ	0.31%	0.29%	0.26%	0.22%	0.20%	0.19%
WW	0.38%	0.36%	0.31%	0.25%	0.21%	0.19%
bb	0.60%	0.57%	0.52%	0.46%	0.42%	0.40%
$\tau^+\tau^-$	0.88%	0.86%	0.83%	0.79%	0.77%	0.76%
gg	0.92%	0.91%	0.88%	0.86%	0.85%	0.84%
cc	1.1%	1.1%	1.1%	1.1%	1.1%	1.0%
$\gamma\gamma$	3.1%	3.1%	3.1%	3.1%	3.1%	3.1%
Γ_{tot}	1.7%	1.6%	1.3%	1.0%	0.84%	0.74%

Summary

- With statistical precision reaching a few per-mil, systematic errors for Higgs coupling measurements become important. Arguments were made that both experimental and theoretical systematic errors can be held to the 0.1% level, but much work is needed to realize this.
- The systematic uncertainties for the Higgs self coupling measurement due to the unknown quartic ZZHH coupling are not yet known. There are several ideas for dealing with the quartic ZZHH coupling, and effort is needed to determine which method or combination of methods is best.
- Most ILC analyses assume the SM Lorentz structure for vertices when performing fits. More effort should be put into determining the coefficients of operators in effective field theories with more general Lorentz structure. Here the Higgs coupling results should be combined with triple gauge boson coupling and precision electroweak results to obtain the best estimate of EFT parameters.
- BSM decays, or the limits on BSM decays, play an interesting role in both the model independence of the hadronic recoil ZH cross section analysis, and in the achievement of the ultimate Higgs coupling precision at the ILC.