Higgs Coupling Fits

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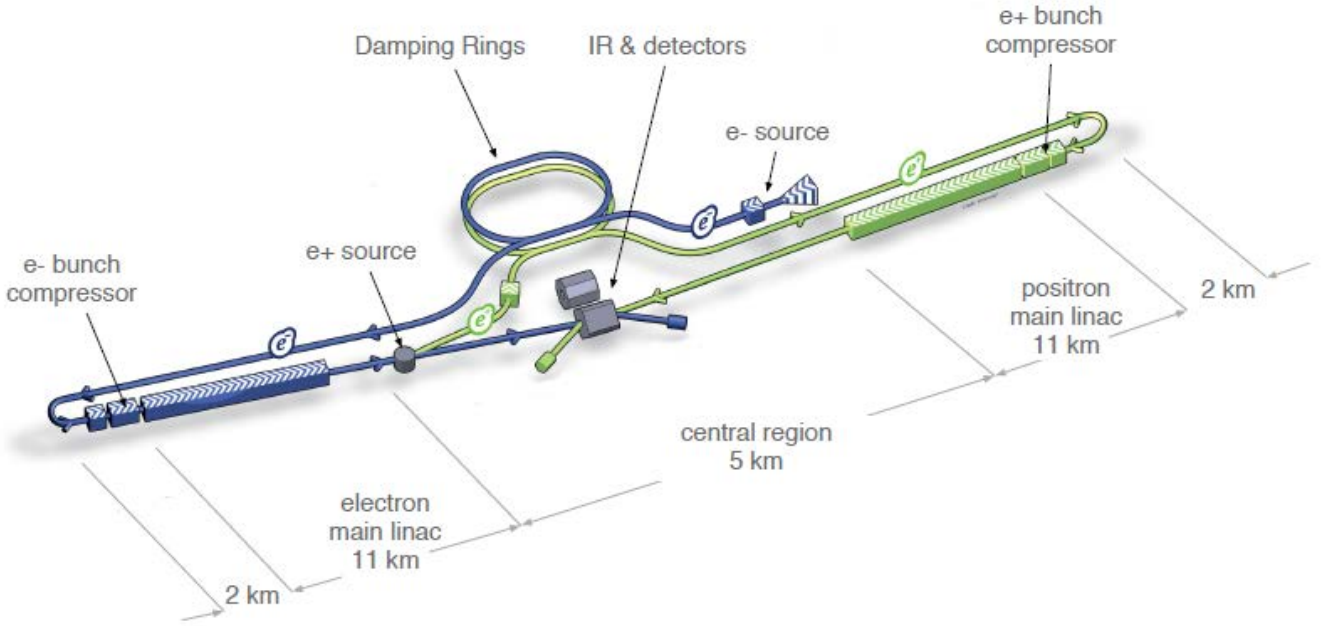
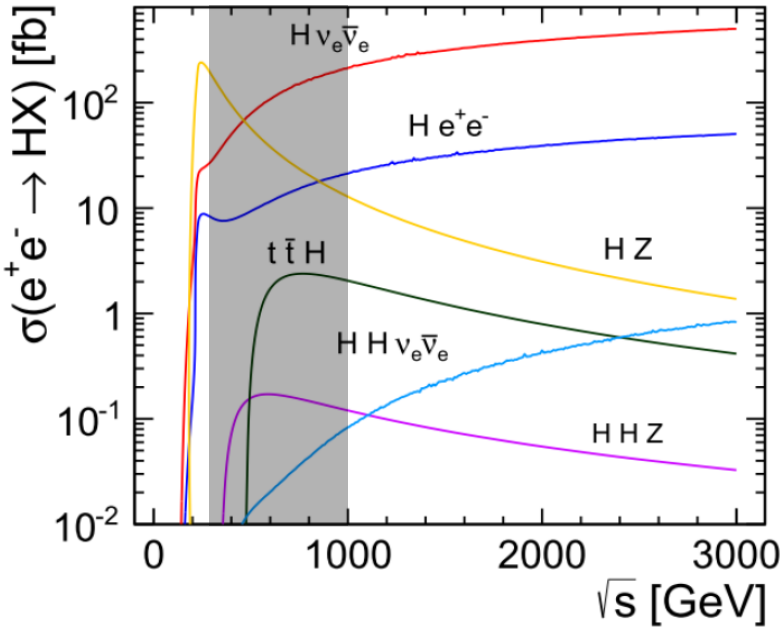
ILC : e^+e^- Linear Collider at 250 GeV < $\sqrt{s}$ < 1000 GeV





Energy/Lumi Scenarios for Snowmass

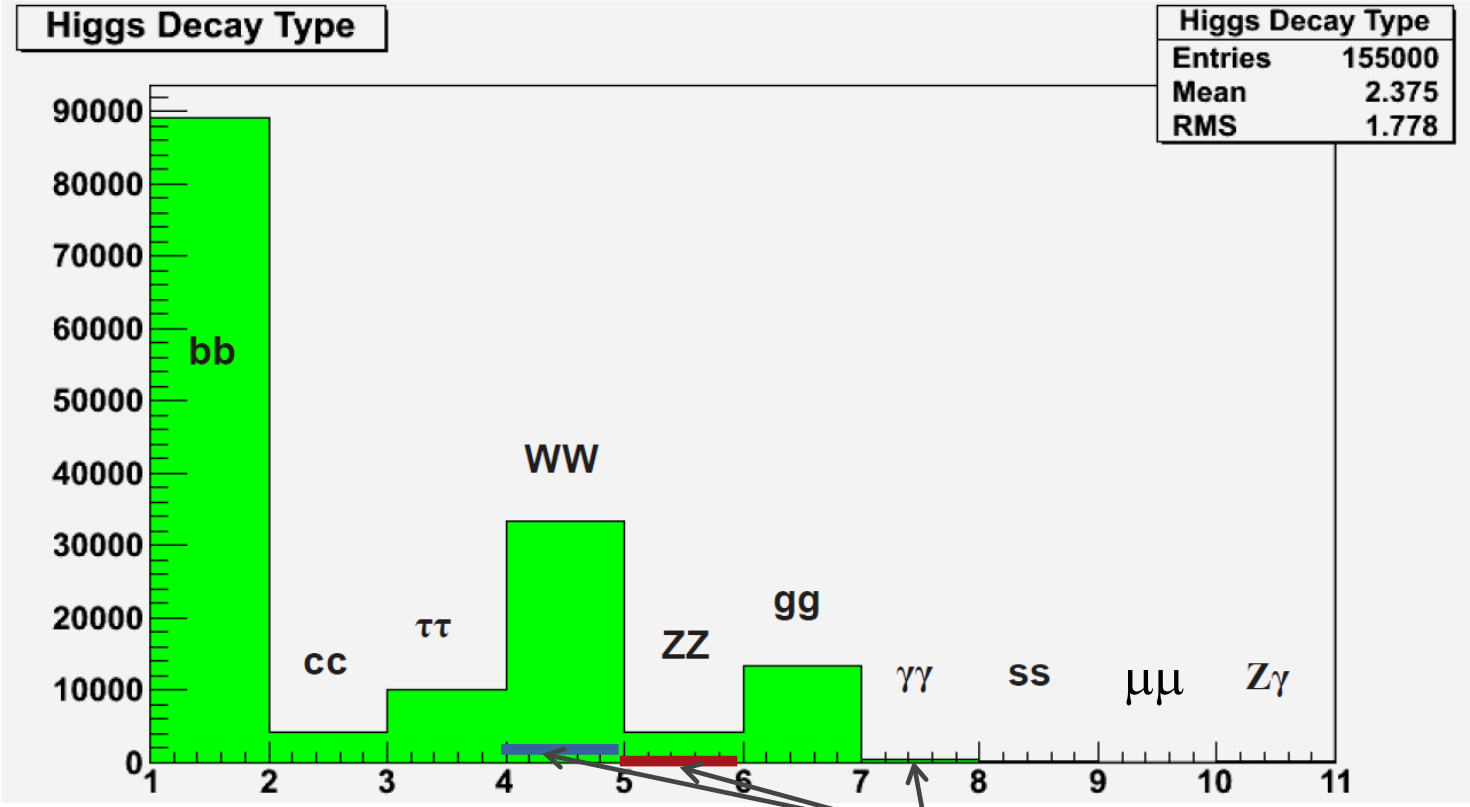
- Each scenario corresponds to accumulated luminosity at a certain point in time.
- Assumption: run for $3X10^7$ s at baseline lumi at each of Ecm=250,500,1000 GeV, in that order. Then go back and run for $3X10^7$ s at upgrade lumi at each of Ecm=250,500,1000 GeV.

Nickname	Ecm(1) (GeV)	Lumi(1) (fb^{-1})	+	Ecm(2) (GeV)	Lumi(2) (fb^{-1})	+	Ecm(3) (GeV)	Lumi(3) (fb^{-1})	Runtime (yr)	Wallplug E (MW-yr)
ILC(250)	250	250							1.1	130
ILC(500)	250	250		500	500				2.0	270
ILC(1000)	250	250		500	500		1000	1000	2.9	540
ILC(LumUp)	250	1150		500	1600		1000	2500	5.8	1220

QUALITATIVE DIFFERENCES BETWEEN ILC & LHC

- All beam crossings are triggered at the ILC
- All background is electroweak.
- Roughly, the detection efficiency is independent of decay mode $\Rightarrow \Delta(\sigma \cdot BR) / \sigma \cdot BR \propto 1/\sqrt{BR}$

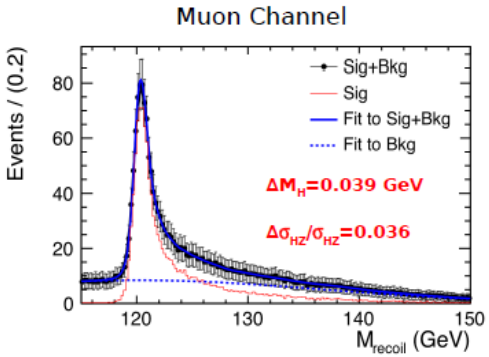
- LHC Higgs detection efficiency is uneven across decay modes.
- Higgs was discovered in decays modes with γ, e, μ, which have relatively small BR's
- Qualitatively, there is complementarity between the ILC and LHC with respect to decay modes.



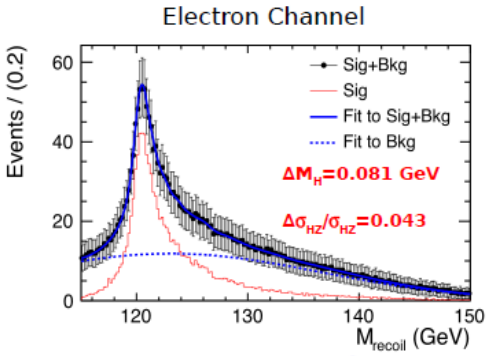
QUALITATIVE DIFFERENCES BETWEEN ILC & LHC

- Almost all ILC Higgs measurements are measurements of $\sigma \cdot BR$.
- One crucial measurement is different: the Higgs recoil measurement of $\sigma(e^+e^- \to ZH)$.
- σ_{ZH} is the key that unlocks the door to model independent measurements of the Higgs BR's and Γ_{tot} at the ILC.

- All LHC Higgs measurements are measurements of $\sigma \cdot BR$



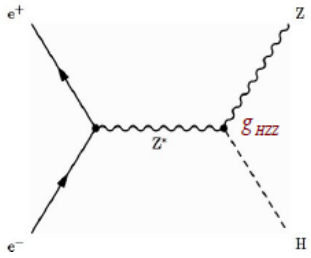
Very Precise Measurement
S/B = 8 in Peak Region



Less Precise
Bremsstrahlung in detector material

Combined: $\Delta M_H = .032$ GeV, $\Delta\sigma_{HZ} / \sigma_{HZ}$=2.5% for L= 250 fb^{-1}

$\Delta M_H = .015$ GeV, $\Delta\sigma_{HZ} / \sigma_{HZ}$=1.2% for L=1150 fb^{-1}



$\sigma_{HZ} \sim g^2_{HZZ}$

$\Rightarrow \Delta g_{HZZ} / g_{HZZ}$ = 1.3% (0.6%) for L=250 (1150) fb^{-1}

ILC model independent global coupling fit using 32 $\sigma \cdot BR$ 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.

We are confident that the total theory errors for S_i and G_i will be at the 0.1% level at the time of ILC running.

ILC Measurement Summary

Table 5.1. Expected accuracies for cross section and cross section times branching ratio measurements for the 125 GeV h boson assuming you run 3×10^7 s at the baseline differential luminosity for each center of mass energy. For invisible decays of the Higgs, the number quoted is the 95% confidence upper limit on the branching ratio.

$\sqrt{s}$ and $\mathcal{L}$ (P_{e^-}, P_{e^+})	250 fb^{-1} at 250 GeV (-0.8,+0.3)		500 fb^{-1} at 500 GeV (-0.8,+0.3)				1 ab^{-1} at 1 TeV (-0.8,+0.2)		
	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	$t\bar{t}h$	Zhh	$\nu\bar{\nu}h$	$t\bar{t}h$	$\nu\bar{\nu}hh$
$\Delta\sigma/\sigma$	2.6%	-	3.0	-		42.7%			26.3%
BR(invis.)	< 0.9 %	-	-	-	-				
mode	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$								
$h \to b\bar{b}$	1.2%	10.5%	1.8%	0.7%	28%		0.5%	6.0%	
$h \to c\bar{c}$	8.3%	-	13%	6.2%			3.1%		
$h \to gg$	7.0%	-	11%	4.1%			2.3%		
$h \to WW^*$	6.4%	-	9.2%	2.4%			1.6%		
$h \to \tau^+\tau^-$	4.2%	-	5.4%	9.0%			3.1%		
$h \to ZZ^*$	19%	-	25%	8.2%			4.1%		
$h \to \gamma\gamma$	34%	-	34%	23%			8.5%		
$h \to \mu^+\mu^-$	100%	-	-	-			31%		

Table 5.2. Expected accuracies for cross section and cross section times branching ratio measurements for the 125 GeV h boson assuming you run 3×10^7 s at the sum of the baseline and upgrade differential luminosities for each center of mass energy. For invisible decays of the Higgs, the number quoted is the 95% confidence upper limit on the branching ratio.

$\sqrt{s}$ and $\mathcal{L}$ (P_{e^-}, P_{e^+})	1150 fb^{-1} at 250 GeV (-0.8,+0.3)		1600 fb^{-1} at 500 GeV (-0.8,+0.3)				2.5 ab^{-1} at 1 TeV (-0.8,+0.2)		
	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	$t\bar{t}h$	Zhh	$\nu\bar{\nu}h$	$t\bar{t}h$	$\nu\bar{\nu}hh$
$\Delta\sigma/\sigma$	1.2%	-	1.7	-		23.7%			16.7%
BR(invis.)	< 0.4 %	-	-	-			-		
mode	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$								
$h \to b\bar{b}$	0.6%	4.9%	1.0%	0.4%	16%		0.3%	3.8%	
$h \to c\bar{c}$	3.9%	-	7.2%	3.5%			2.0%		
$h \to gg$	3.3%	-	6.0%	2.3%			1.4%		
$h \to WW^*$	3.0%	-	5.1%	1.3%			1.0%		
$h \to \tau^+\tau^-$	2.0%	-	3.0%	5.0%			2.0%		
$h \to ZZ^*$	8.8%	-	14%	4.6%			2.6%		
$h \to \gamma\gamma$	16%	-	19%	13%			5.4%		
$h \to \mu^+\mu^-$	46.6%	-	-	-			20%		

THE QUALITATIVE DIFFERENCES BETWEEN ILC & LHC
LEAD TO QUANTITATIVE IMPROVEMENTS OVER LHC

7 Parameter HXSWG Benchmark *

	LHC		ILC(1000)	ILC(LumUp)	
			250+500+1000	250+500+1000	$\sqrt{s}$ (GeV)
Mode	300 fb^{-1}	3000 fb^{-1}	250+500+1000	1150+1600+2500	L (fb^{-1})
$\gamma\gamma$	$(5-7)\%$	$(2-5)\%$	3.8 %	2.3 %	
gg	$(6-8)\%$	$(3-5)\%$	1.1 %	0.7 %	
WW	$(4-5)\%$	$(2-3)\%$	0.3 %	0.2 %	
ZZ	$(4-5)\%$	$(2-3)\%$	0.5 %	0.3 %	
$t\bar{t}$	$(14-15)\%$	$(7-10)\%$	1.3 %	0.9 %	
$b\bar{b}$	$(10-13)\%$	$(4-7)\%$	0.6 %	0.4 %	
$\tau^+\tau^-$	$(6-8)\%$	$(2-5)\%$	1.3 %	0.7 %	

* Assume $\kappa_c = \kappa_t$ & $\Gamma_{tot} = \sum_{\text{SM decays i}} \Gamma_i^{SM} \kappa_i^2$

Other Higgs Couplings

	LHC		ILC(1000)	ILC(LumUp)	
			250+500+1000	250+500+1000	$\sqrt{s}$ (GeV)
Mode	300 fb^{-1}	3000 fb^{-1}	250+500+1000	1150+1600+2500	L (fb^{-1})
$c\bar{c}$	-	-	1.8 %	1.0 %	
$\mu^+\mu^-$	30%	10%	16 %	10 %	
$\Gamma_T(h)$	-	-	4.5 %	2.3 %*	
hhh	-	50%	21 %	13 %*	
BR(invis.)	< (17 – 28)%	< (6-17)%	< 0.9 %	< 0.4 %	

* Does not include results from searches for non-SM decays, including invisible decays. The error on the total width will improve significantly once these results are incorporated into the fit.

* Current full simulation result using $H \to b\bar{b}$, WW * only. Results will improve as more Higgs decay modes are added, and as jet combinatoric problems are solved.

Alternate Luminosity Scenario

Nickname	Ecm(1) (GeV)	Lumi(1) (fb^{-1})	+	Ecm(2) (GeV)	Lumi(2) (fb^{-1})	Runtime (yr)	Wallplug E (MW-yr)
ILC(250)	250	250				1.1	130
ILC(500)	250	250		500	500	2.0	270
ILC500(LumUp)	250	1150		500	1600	3.9	660

7 Parameter HXSWG Benchmark *

	ILC500(LumUp)	ILC(LumUp)
$\sqrt{s}$ (GeV)	250+500	250+500+1000
L (fb^{-1})	1150+1600	1150+1600+2500
$\gamma\gamma$	4.4 %	2.3 %
gg	1.1 %	0.7 %
WW	0.3 %	0.2 %
ZZ	0.3 %	0.3 %
$t\bar{t}$	1.4 %	0.9 %
$b\bar{b}$	0.6 %	0.4 %
$\tau^+\tau^-$	1.0 %	0.7 %

* Assume $\kappa_c = \kappa_t$ & $\Gamma_{tot} = \sum_{\text{SM decays i}} \Gamma_i^{SM} \kappa_i^2$

Alternate Luminosity Scenario

Nickname	Ecm(1) (GeV)	Lumi(1) (fb^{-1})	+	Ecm(2) (GeV)	Lumi(2) (fb^{-1})	Runtime (yr)	Wallplug E (MW-yr)
ILC(250)	250	250				1.1	130
ILC(500)	250	250		500	500	2.0	270
ILC500(LumUp)	250	1150		500	1600	3.9	660

Other Higgs Couplings

	ILC500(LumUp)	ILC(LumUp)
$\sqrt{s}$ (GeV)	250+500	250+500+1000
L (fb^{-1})	1150+1600	1150+1600+2500
$c\bar{c}$	1.5 %	1.0 %
$\mu^+\mu^-$	42 %	10 %
$\Gamma_T(h)$	2.5 %	2.3 %
hhh	46 %	13 %
BR(invis.)	< 0.4 %	< 0.4 %

Combining LHC Results with Results from Various Future e^+e^- Colliders
(from D. Zerwas and the SFITTER Group)

coupling	LHC +ILC	LHC +ILC Lumi-up	HL-LHC +ILC Lumi-up	HL-LHC +CLIC	HL-LHC +ILC Lumi-up +CLIC	HL-LHC +TLEP +CLIC
Γ_H	2.0 – 2.0%	1.1 – 1.1%	1.1 – 1.1%	4.4 – 7.3%	0.9 – 1.0%	1.1 – 1.2%
$\mathrm{BR}_{\mathrm{inv}}$	0.8 – 0.8%	0.4 – 0.4%	0.4 – 0.4%	2.2 – 3.9%	0.4 – 0.4%	0.5 – 0.5%
κ_γ	2.4 – 2.7%	2.0 – 2.2%	1.3 – 2.0%	1.8 – 3.4%	1.2 – 2.0%	1.2 – 1.6%
κ_g	1.3 – 1.3%	0.8 – 0.8%	0.8 – 0.8%	1.3 – 2.0%	0.6 – 0.6%	0.6 – 0.6%
κ_W	0.5 – 0.5%	0.3 – 0.3%	0.3 – 0.3%	1.1 – 1.9%	0.3 – 0.3%	0.3 – 0.3%
κ_Z	0.6 – 0.6%	0.3 – 0.3%	0.3 – 0.3%	1.1 – 1.9%	0.3 – 0.3%	0.3 – 0.3%
κ_μ	13.8 – 14.2%	9.9 – 9.9%	7.0 – 7.8%	5.2 – 6.0%	4.6 – 4.7%	4.0 – 4.1%
κ_τ	1.5 – 1.6%	0.9 – 0.9%	0.7 – 0.9%	1.3 – 2.3%	0.7 – 0.8%	0.5 – 0.6%
κ_c	1.6 – 1.6%	0.9 – 0.9%	0.9 – 0.9%	1.4 – 2.1%	0.7 – 0.7%	0.7 – 0.7%
κ_b	0.8 – 0.8%	0.5 – 0.5%	0.5 – 0.5%	1.1 – 1.9%	0.3 – 0.3%	0.4 – 0.4%
κ_t	2.8 – 2.9%	1.9 – 1.9%	1.7 – 1.8%	3.5 – 4.5%	1.7 – 1.8%	3.2 – 3.8%
Δ_γ	2.5 – 2.8%	2.0 – 2.2%	1.5 – 2.1%	2.8 – 4.6%	1.4 – 2.0%	1.7 – 2.0%
Δ_g	3.8 – 3.8%	2.5 – 2.5%	2.3 – 2.4%	4.1 – 4.8%	2.1 – 2.3%	4.0 – 4.7%

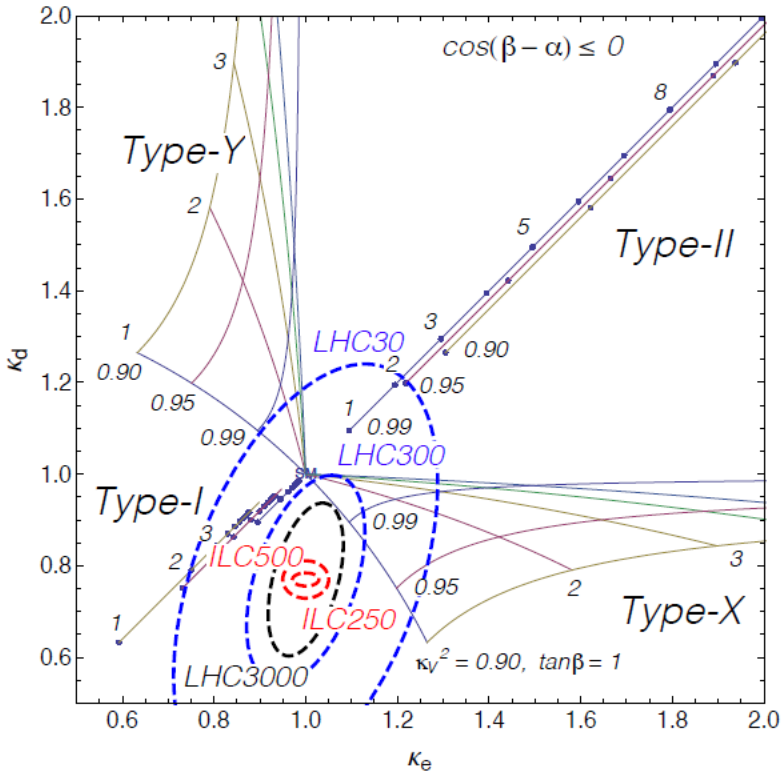
What do these precision values mean?

For Higgs couplings, better precision means greater discovery potential.

Typical coupling variations for several BSM Higgs models:

	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$

2HDM:



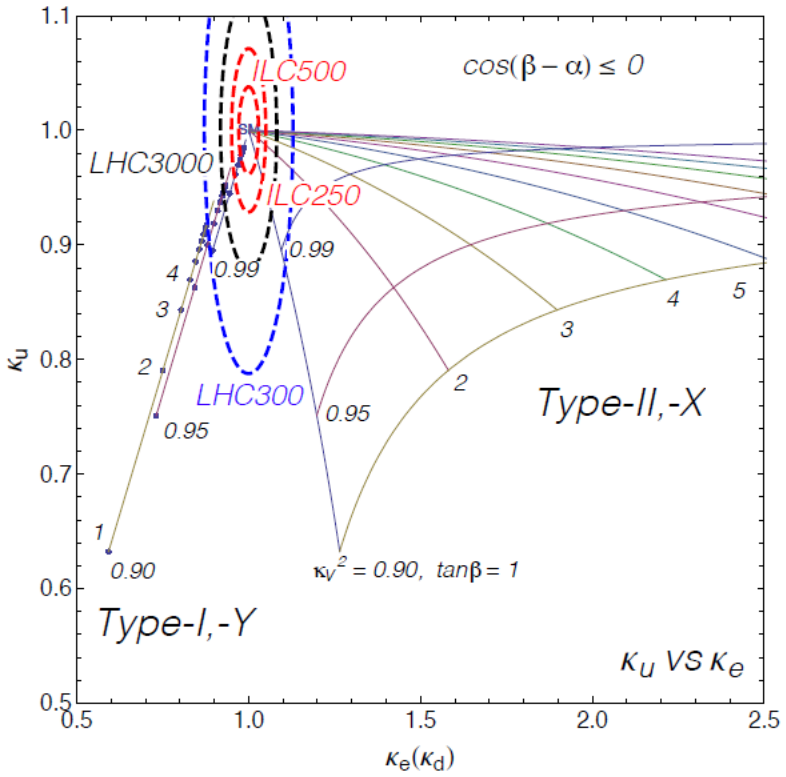


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Table 6.3. Summary of expected accuracies for the three cross sections and eight branching ratios obtained from an eleven parameter global fit of all available data. The four columns refer to ILC energy and luminosity scenarios 1,2,3, and 4 respectively.

	ILC(250)	ILC500	ILC(1000)	ILC(LumUp)
process		$\Delta\sigma/\sigma$		
$e^+e^- \to ZH$	2.6 %	2.0 %	2.0 %	1.0 %
$e^+e^- \to \nu\bar{\nu}H$	11 %	2.3 %	2.2 %	1.1 %
$e^+e^- \to t\bar{t}H$	-	28 %	6.3 %	3.8 %
mode		$\Delta\mathrm{Br}/\mathrm{Br}$		
$H \to ZZ$	19 %	7.5 %	4.2 %	2.4 %
$H \to WW$	6.9 %	3.1 %	2.5 %	1.3 %
$H \to b\bar{b}$	2.9 %	2.2 %	2.2 %	1.1 %
$H \to c\bar{c}$	8.7 %	5.1 %	3.4 %	1.9 %
$H \to gg$	7.5 %	4.0 %	2.9 %	1.6 %
$H \to \tau^+\tau^-$	4.9 %	3.7 %	3.0 %	1.6 %
$H \to \gamma\gamma$	34 %	17 %	7.9 %	4.7 %
$H \to \mu^+\mu^-$	100 %	100 %	31 %	20 %

Table 10.1. Summary of expected accuracies $\Delta g_i/g_i$ for model independent determinations of the Higgs boson couplings. The theory errors are $\Delta F_i/F_i = 0.1\%$. For the invisible branching ratio, the numbers quoted are 95% confidence upper limits. The four columns refer to ILC energy and luminosity scenarios 1,2,3, and 4 respectively.

	ILC(250)	ILC(500)	ILC(1000)	ILC(LumUp)
$\sqrt{s}$ (GeV)	250	250+500	250+500+1000	250+500+1000
L (fb^{-1})	250	250+500	250+500+1000	1150+1600+2500
$\gamma\gamma$	18 %	8.4 %	4.0 %	2.4 %
gg	6.4 %	2.3 %	1.6 %	0.9 %
WW	4.8 %	1.1 %	1.1 %	0.6 %
ZZ	1.3 %	1.0 %	1.0 %	0.5 %
$t\bar{t}$	–	14 %	3.1 %	1.9 %
$b\bar{b}$	5.3 %	1.6 %	1.3 %	0.7 %
$\tau^+\tau^-$	5.7 %	2.3 %	1.6 %	0.9 %
$c\bar{c}$	6.8 %	2.8 %	1.8 %	1.0 %
$\mu^+\mu^-$	91%	91%	16 %	10 %
$\Gamma_T(h)$	12 %	4.9 %	4.5 %	2.3 %
hhh	–	83 %	21 %	13 %
BR(invis.)	< 0.9 %	< 0.9 %	< 0.9 %	< 0.4 %

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Table 10.4. Summary of expected accuracies $\Delta g_i/g_i$ for model independent determinations of the Higgs boson couplings. The theory errors are $\Delta F_i/F_i = 0.1\%$. For the invisible branching ratio, the numbers quoted are 95% confidence upper limits.

	ILC(250)	ILC(500)	ILC500(LumUp)
$\sqrt{s}$ (GeV)	250	250+500	250+500
L (fb^{-1})	250	250+500	1150+1600
$\gamma\gamma$	18 %	8.4 %	4.5 %
gg	6.4 %	2.3 %	1.2 %
WW	4.8 %	1.1 %	0.6 %
ZZ	1.3 %	1.0 %	0.5 %
$t\bar{t}$	–	14 %	7.8 %
$b\bar{b}$	5.3 %	1.6 %	0.8 %
$\tau^+\tau^-$	5.7 %	2.3 %	1.2 %
$c\bar{c}$	6.8 %	2.8 %	1.5 %
$\mu^+\mu^-$	91 %	91 %	42 %
$\Gamma_T(h)$	12 %	4.9 %	2.5 %
hhh	–	83 %	46 %
BR(invis.)	< 0.9 %	< 0.9 %	< 0.4 %

ILC Accelerator Parameters from TDR

Baseline Luminosity

Upgrade Luminosity

			Baseline 500 GeV Machine			1st Stage	L Upgrade	E_{CM} Upgrade	
Centre-of-mass energy	E_{CM}	GeV	250	350	500	250	500	A 1000	B 1000
Collision rate	f_{rep}	Hz	5	5	5	5	5	4	4
Electron linac rate	f_{linac}	Hz	10	5	5	10	5	4	4
Number of bunches	n_b		1312	1312	1312	1312	2625	2450	2450
Bunch population	N	$\times 10^{10}$	2.0	2.0	2.0	2.0	2.0	1.74	1.74
Bunch separation	Δt_b	ns	554	554	554	554	366	366	366
Pulse current	I_{beam}	mA	5.8	5.8	5.8	5.8	8.8	7.6	7.6
Main linac average gradient	G_a	MV m^{-1}	14.7	21.4	31.5	31.5	31.5	38.2	39.2
Average total beam power	P_{beam}	MW	5.9	7.3	10.5	5.9	21.0	27.2	27.2
Estimated AC power	P_{AC}	MW	122	121	163	129	204	300	300
RMS bunch length	σ_z	mm	0.3	0.3	0.3	0.3	0.3	0.250	0.225
Electron RMS energy spread	$\Delta p/p$	%	0.190	0.158	0.124	0.190	0.124	0.083	0.085
Positron RMS energy spread	$\Delta p/p$	%	0.152	0.100	0.070	0.152	0.070	0.043	0.047
Electron polarisation	P_-	%	80	80	80	80	80	80	80
Positron polarisation	P_+	%	30	30	30	30	30	20	20
Horizontal emittance	$\gamma\epsilon_x$	µm	10	10	10	10	10	10	10
Vertical emittance	$\gamma\epsilon_y$	nm	35	35	35	35	35	30	30
IP horizontal beta function	β_x^*	mm	13.0	16.0	11.0	13.0	11.0	22.6	11.0
IP vertical beta function	β_y^*	mm	0.41	0.34	0.48	0.41	0.48	0.25	0.23
IP RMS horizontal beam size	σ_x^*	nm	729.0	683.5	474	729	474	481	335
IP RMS veritcal beam size	σ_y^*	nm	7.7	5.9	5.9	7.7	5.9	2.8	2.7
Luminosity	L	$\times 10^{34}$ cm^{-2}s^{-1}	0.75	1.0	1.8	0.75	3.6	3.6	4.9
Fraction of luminosity in top 1%	$L_{0.01}/L$		87.1%	77.4%	58.3%	87.1%	58.3%	59.2%	44.5%
Average energy loss	δ_{BS}		0.97%	1.9%	4.5%	0.97%	4.5%	5.6%	10.5%
Number of pairs per bunch crossing	N_{pairs}	$\times 10^3$	62.4	93.6	139.0	62.4	139.0	200.5	382.6
Total pair energy per bunch crossing	E_{pairs}	TeV	46.5	115.0	344.1	46.5	344.1	1338.0	3441.0

Lumi Upgrade at Ecm=250 GeV*

* not in TDR – private communication from Marc Ross and Nick Walker

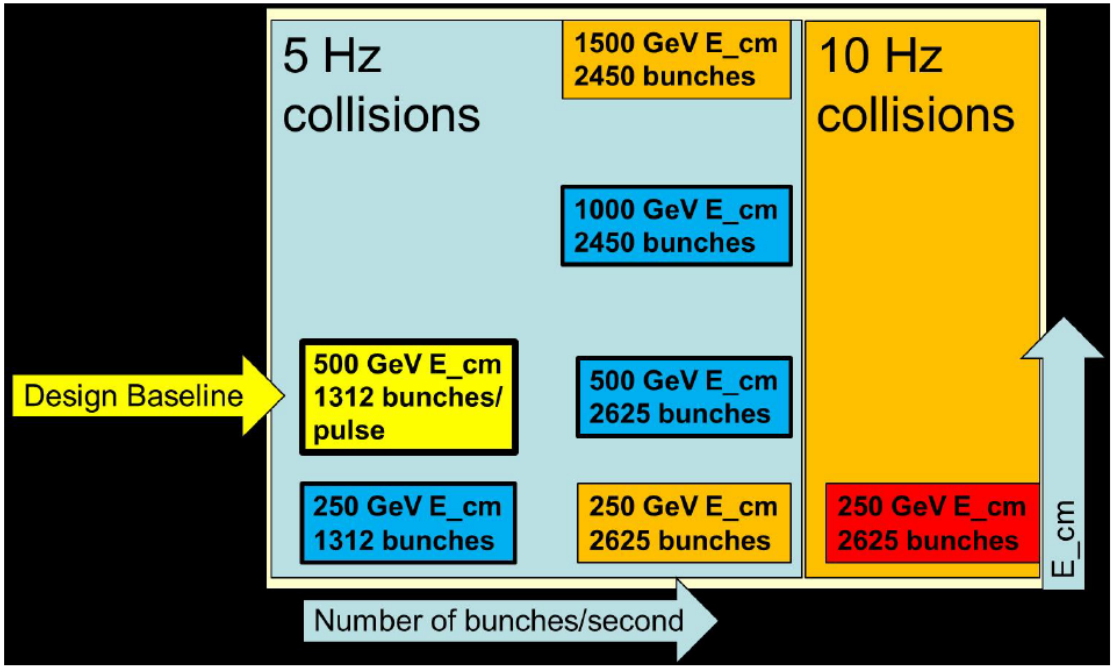

Table 1.2. ILC Higgs factory operational modes

			1st Stage Higgs Factory	Baseline ILC, after Lumi Upgrade	High Rep Rate Operation
Centre-of-mass energy	E_{CM}	GeV	250	250	250
Collision rate	f_{rep}	Hz	5	5	10
Electron linac rate	f_{linac}	Hz	10	10	10
Number of bunches	n_b		1312	2625	2625
Pulse current	I_{beam}	mA	5.8	8.75	8.75
Average total beam power	P_{beam}	MW	5.9	10.5	21
Estimated AC power	P_{AC}	MW	129	160	200
Luminosity	L	$\times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	0.75	1.5	3.0

Baseline Luminosity

Upgrade Luminosity