Higgs Physics at the ILC

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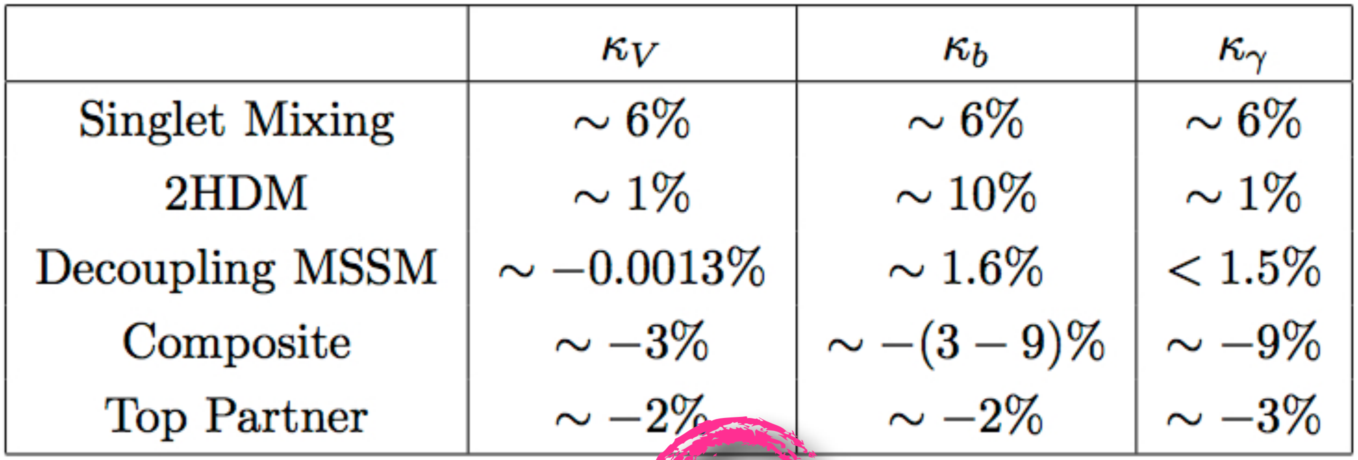
Scalars 2013
Warsaw
15 September 2013

Precision Higgs couplings at the ILC

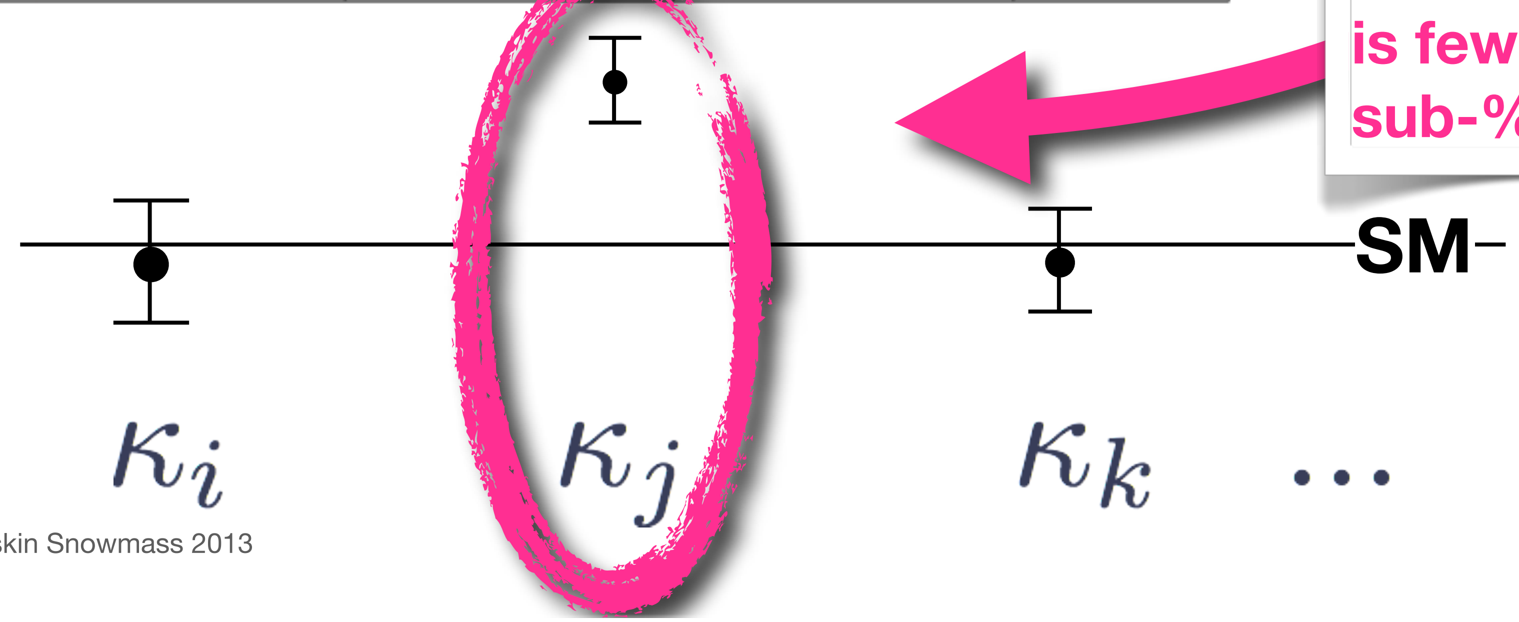
Reference: *ILC Higgs White Paper*,
by D. Asner, T. Barklow, H. Fujii, H.E. Haber,
S. Kanemura, A. Miyamoto and G. Weiglein,
contribution to the Snowmass 2013 Proceedings
(to appear on the arXiV at the end of Sept. 2013)

precision for precision’s sake?

No - this is a discovery search



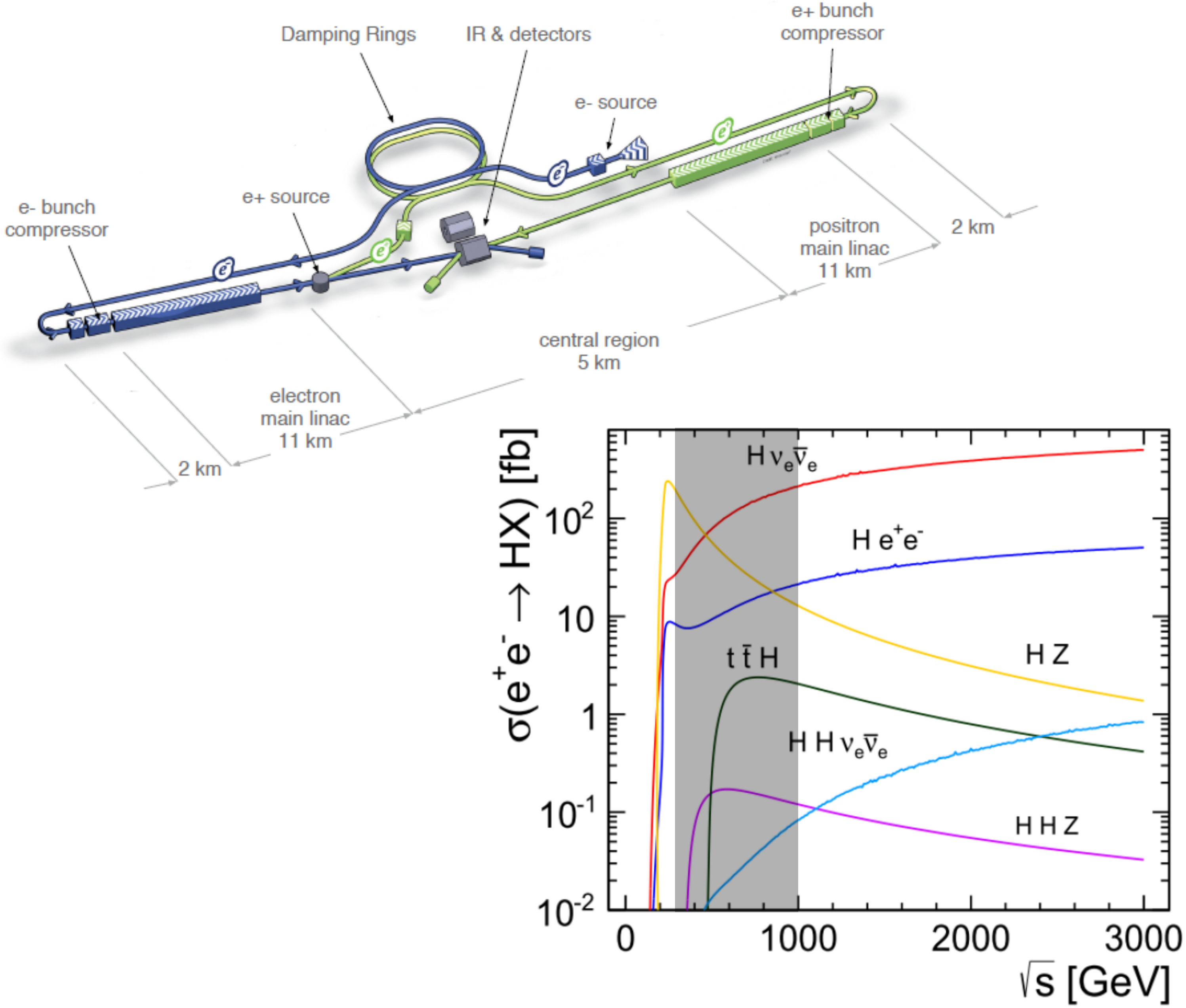
	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$



Benchmark for discovery is few % to sub-%

Brock/Peskin Snowmass 2013

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

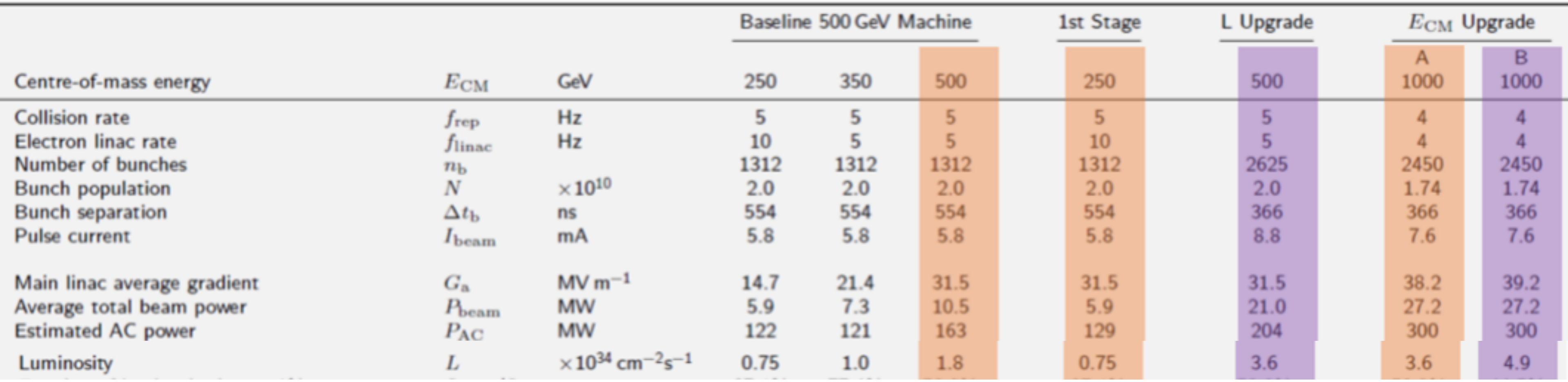


Energy/Luminosity running scenarios

🟧 Baseline Luminosity

🟪 Upgrade Luminosity

From the ILC Technical Design Report



			Baseline 500 GeV Machine			1st Stage	L Upgrade	E_{CM} Upgrade	
								A	B
Centre-of-mass energy	E_{CM}	GeV	250	350	500	250	500	1000	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
Luminosity	L	$\times 10^{34}$ cm^{-2}s^{-1}	0.75	1.0	1.8	0.75	3.6	3.6	4.9

Luminosity (in units of 10^{34} cm^{-2} s^{-1})

CM Energy:	250 GeV	500 GeV	1000 GeV
Baseline design	0.75	1.8	3.6
Luminosity upgrade	3.0*	3.6	4.9

*not in ILC TDR; high rep rate operation proposed by Marc Ross and Nick Walker

Luminosity Upgrade at E_{cm}=250 GeV

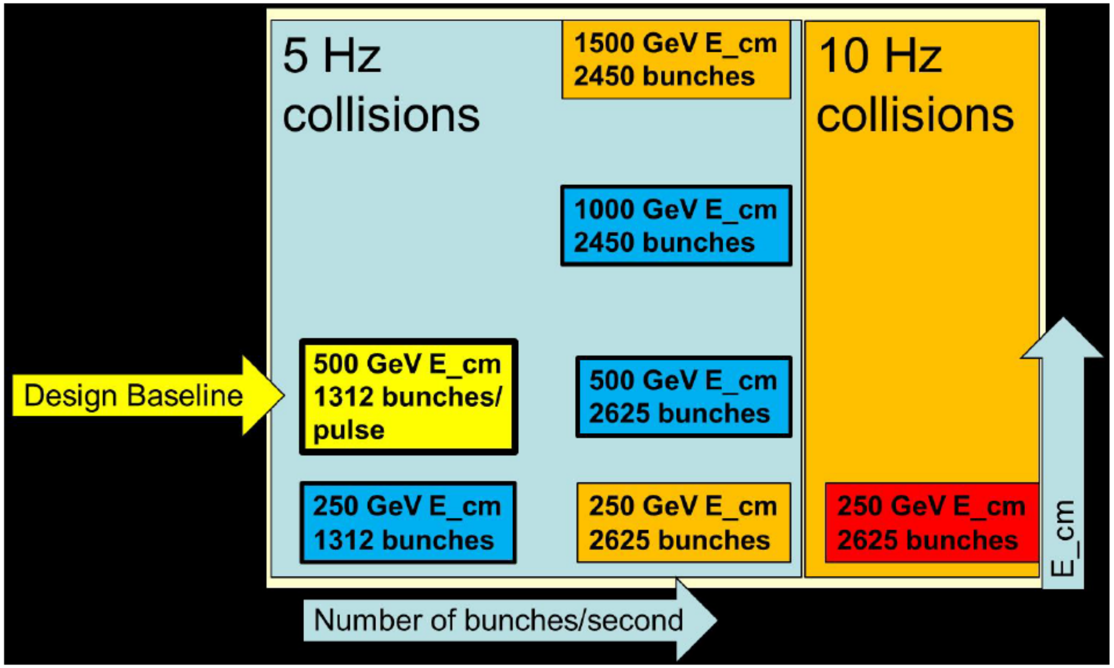
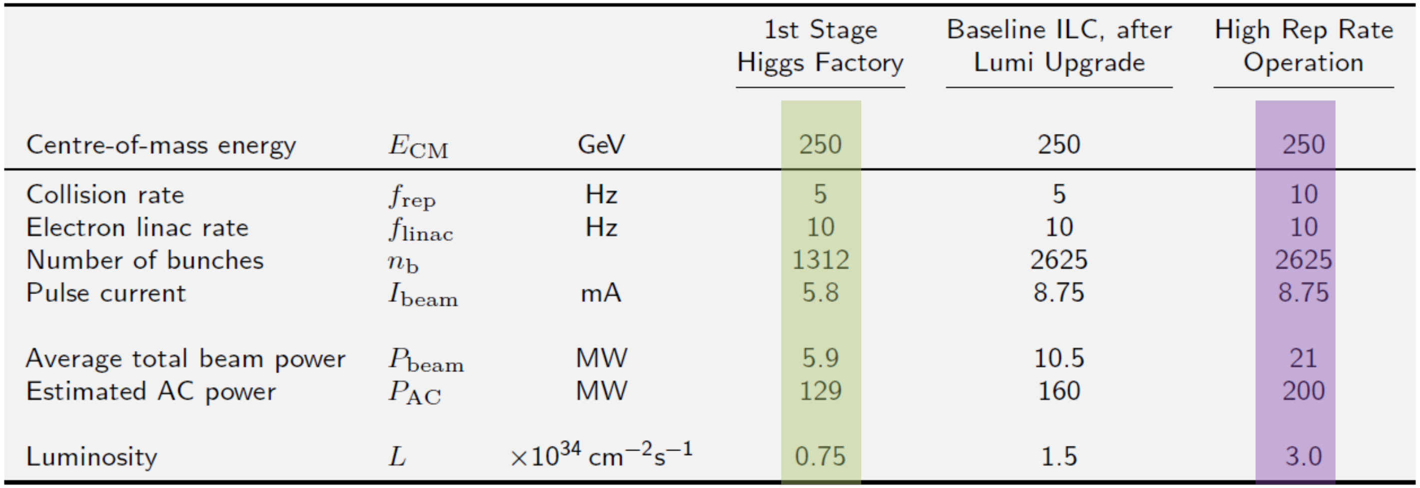


Table 1.2. ILC Higgs factory operational modes

🟩 Baseline Luminosity

🟪 Upgrade Luminosity



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

Energy/Luminosity scenarios

Stage #	nickname	$E_{cm}(1)$ (GeV)	Lumi (1) (fb^{-1})	$E_{cm}(2)$ (GeV)	Lumi (2) (fb^{-1})	$E_{cm}(3)$ (GeV)	Lumi (3) (fb^{-1})	Runtime (years)
1	ILC (250)	250	250					1.1
2	ILC (500)	250	250	500	500			2.0
3	ILC (1000)	250	250	500	500	1000	1000	2.9
4	ILC(LumUp)	250	1150	500	1600	1000	2500	5.8

- At each stage, the *accumulated* luminosity of a given energy is listed. The runtimes listed consist of actual elapsed *cumulative* running time at the end of each stage. Assuming that the ILC runs for 1/3 of the time, then the actual time elapsed is equal to the runtime times 3.

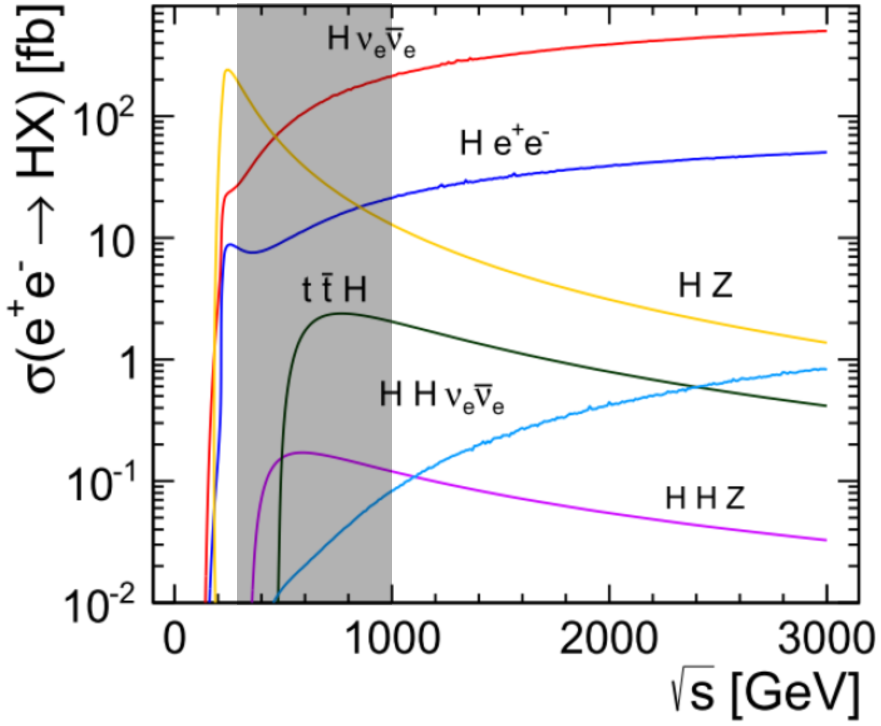
- Assume that the ILC is run at its baseline luminosity at 250 GeV (stage 1), then at 500 GeV (stage 2), and finally at 1000 GeV (stage 3)

- Then, stage 4 repeats the successive stages 1, 2 and 3 at the upgraded luminosity.

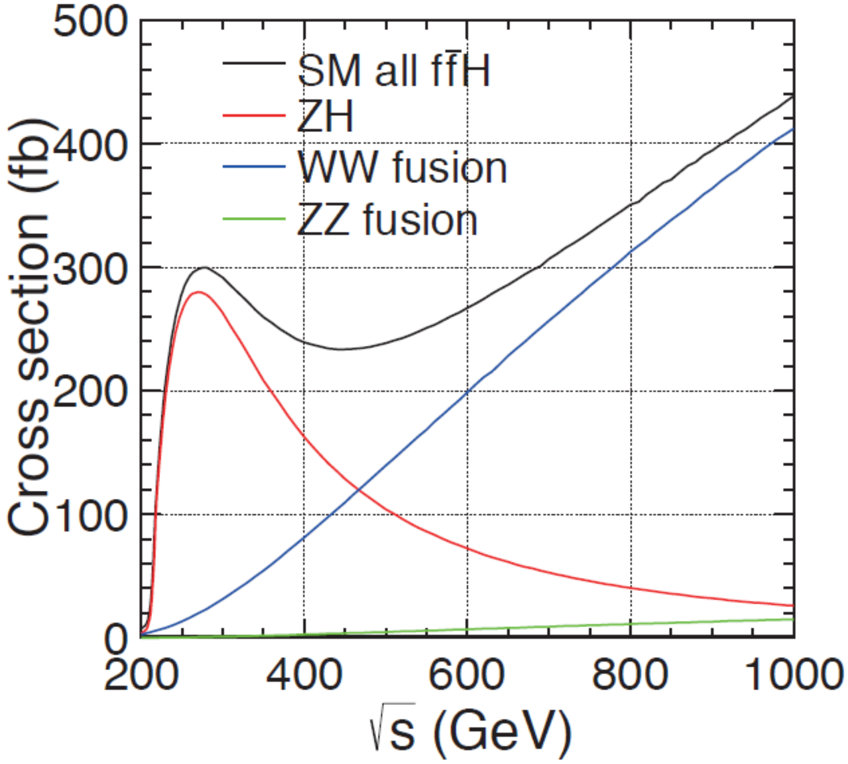
In real time, this entire program would require 5.8 x 3 = 17.4 years.

Beam polarization can increase the vector boson fusion cross section, $W^+W^- \rightarrow H$, by as much as a factor of two.

P(e^-,e^+)=(0,0)

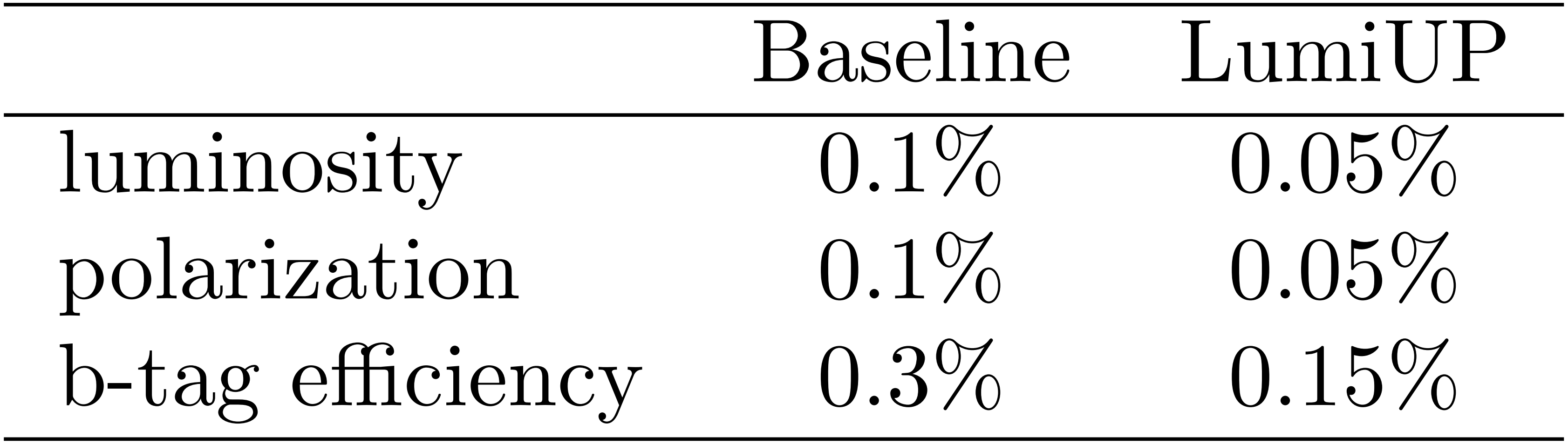


P(e^-, e^+)=(-0.8, 0.2)



Simulations: Full simulations performed with ILD and/or SiD dectector.

Systematic errors:

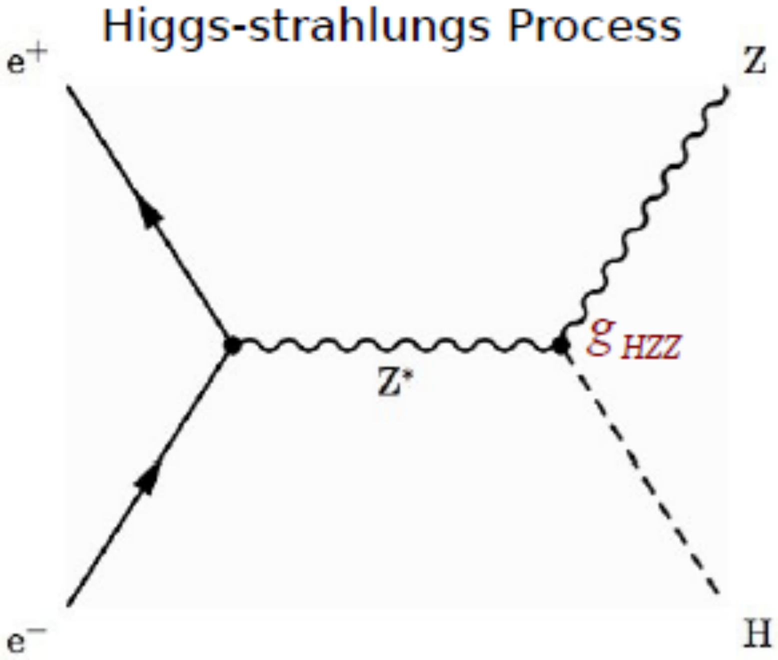


	Baseline	LumiUP
luminosity	0.1%	0.05%
polarization	0.1%	0.05%
b-tag efficiency	0.3%	0.15%

What does the ILC actually experimentally measure?

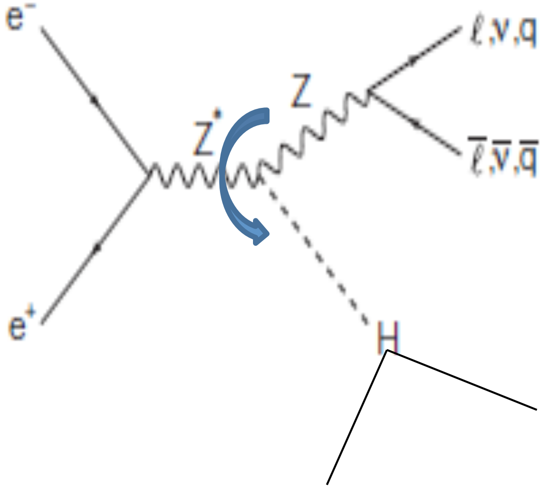
1. $\sigma(e^+e^- \to ZH)$ at $\sqrt{s} = 250$ GeV.

- The *Z* can be reconstructed in charged lepton and quark channels.
- The *H* can be "seen" in the mass spectrum recoiling against the *Z* (including the invisible Higgs decays).
- The *H* can be reconstructed in its main decay channels.



Invisible Higgs Decay

- In the SM, an invisible Higgs decay is H → ZZ* →4ν process and its BF is small ~0.1%
- If we found sizable invisible Higgs decays, it is clear new physics signal.
  - The decay products are dark matter candidates.



- At the LHC, one can search for invisible Higgs decays by using recoil mass from Z or summing up BFs of observed decay modes with some assumptions.
  - The upper limit is O(10%).
- At the ILC, we can search for invisible Higgs decays using a recoil mass technique with model independent way!
  - e+e- → ZH

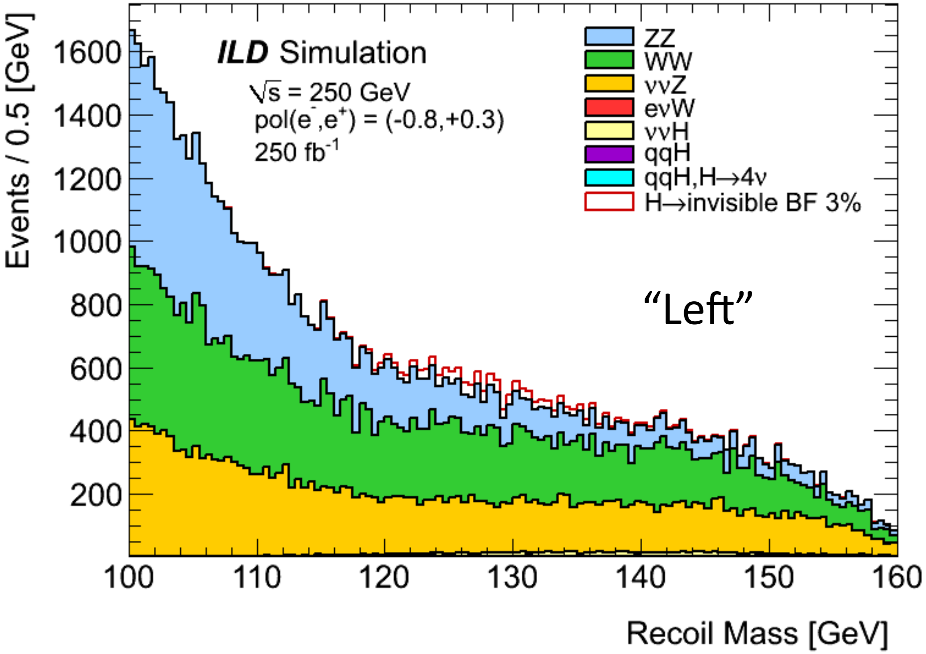
$$P_H = \underset{\text{known}}{\underset{\uparrow}{P_{e+e-}}} - \underset{\text{measured}}{\underset{\uparrow}{P_Z}}$$

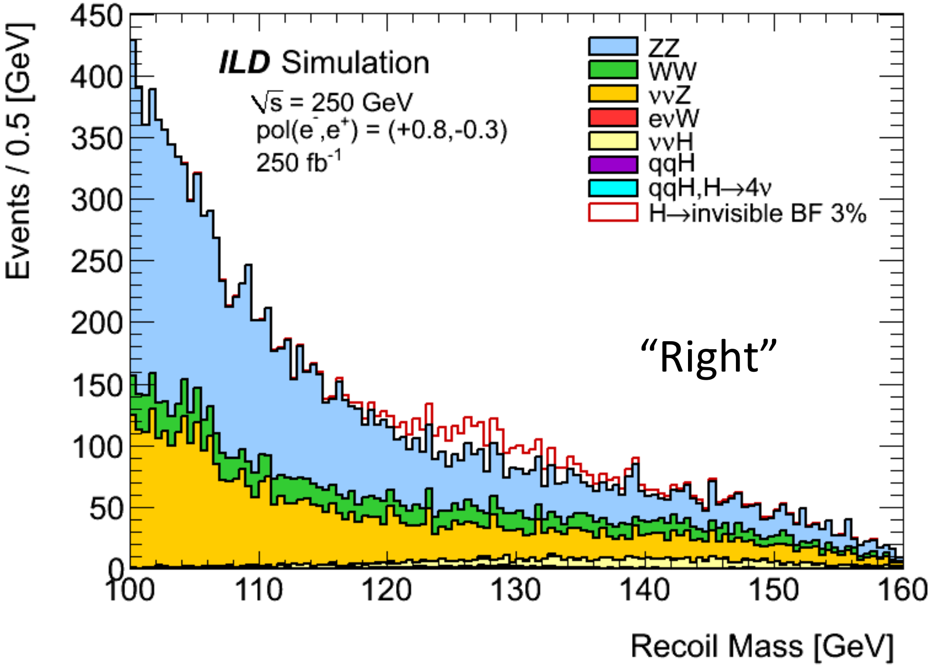
$e^+e^- \to ZH,\ \ \mathrm{Z} \to \mathrm{qq},\ \ \mathrm{H} \to \mathrm{invisible} \qquad \sqrt{s} = 250\ \mathrm{GeV}$

Signal+Background

Polarizations P(e+,e-)=(+30%,-80) [denoted below as “Left”]
=(-30%, +80%) [denoted below as “Right”]

- If BF(H→invisible) = 3%
  - Signal is clearly seen for “Right” polarization





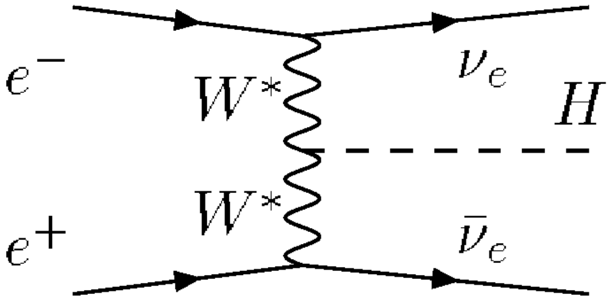
2. By explicitly reconstructing H, one obtains

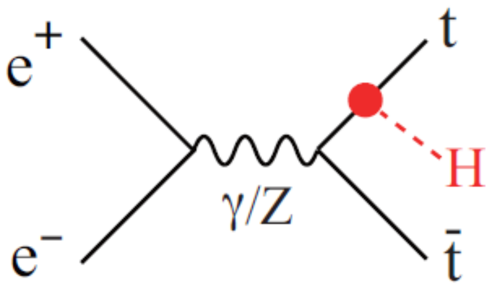
$$\sigma_{ZH} \times \mathrm{Br}(H \to XX)$$

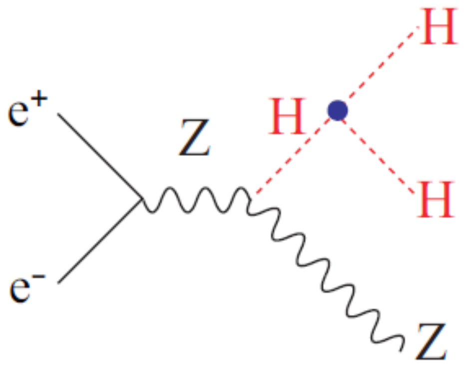
for $XX = b\bar{b}$, $c\bar{c}$, gg, WW^*, $\tau^+\tau^-$, ZZ^*, $\gamma\gamma$ and $\mu^+\mu^-$. Strictly speaking g stands for a hadron jet not identified as a b or c quark. For a SM-like Higgs boson, the Higgs decay into gg dominates over the decays into $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$. (Likewise, Higgs decay into e^+e^- is assumed to be negligible.)

3. Since the ZH production cross section dominates the cross section for $e^+e^- \to \nu\bar{\nu}W^+W^- \to \nu\bar{\nu}H$ at $\sqrt{s} = 250$ GeV, one can only measure $\sigma_{\nu\bar{\nu}H} \times \mathrm{Br}(H \to b\bar{b})$.

4. $e^+e^- \to \nu\bar{\nu}H$, $t\bar{t}H$ and ZHH at $\sqrt{s} = 500$ GeV







- The WW fusion cross section is now competitive with the ZH cross section. Thus, one can now measure

$$\sigma_{\nu\bar{\nu}H} \times \mathrm{Br}(H \to XX)\,,$$

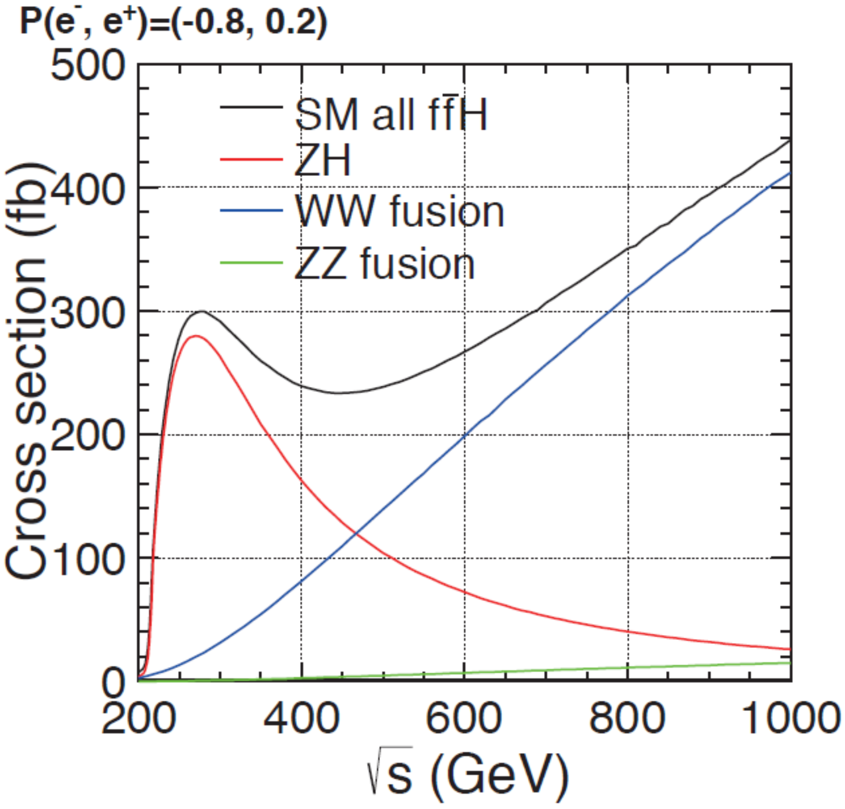
for all the relevant Higgs channels.

- The cross section for $e^+e^- \to t\bar{t}H$ is enhanced near threshold, and yields a measurement of $\sigma_{t\bar{t}H} \times \mathrm{Br}(H \to b\bar{b})$. From this, one can determine the top quark–Higgs Yukawa coupling.

- The process $e^+e^- \to ZHH$ is sensitive to the HHH coupling, although there are other diagrams contributing to ZHH production that do not depend on the triple Higgs vertex.

5. $e^+e^- \to \nu\bar{\nu}H$, $t\bar{t}H$ and $\nu\bar{\nu}HH$ at $\sqrt{s} = 1$ TeV

At $\sqrt{s} = 1$ TeV, the ILC provides better measurements of the top quark Yukawa coupling and the triple Higgs coupling. Moreover, the Higgs production rate has increased significantly from its rate at $\sqrt{s} = 500$ GeV due to the increasing WW fusion cross section.



Expected precision for cross section and cross section times branching ratio at the baseline luminosity and a one year runtime (i.e. three years in real time) for each energy/luminosity

$\sqrt{s}$ and $\mathcal{L}$ (P_{e^-}, P_{e^+})	$250\,\mathrm{fb}^{-1}$ at $250\,\mathrm{GeV}$ $(-0.8,+0.3)$		$500\,\mathrm{fb}^{-1}$ at $500\,\mathrm{GeV}$ $(-0.8,+0.3)$				$1\,\mathrm{ab}^{-1}$ at $1\,\mathrm{TeV}$ $(-0.8,+0.2)$		
	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%		

For invisible decays, the 95% CL upper limit is given.
Note: Mass measurement at E_{CM}=250 GeV yields ΔM_H=32 MeV.

Expected accuracies for cross section and cross section times branching ratio at the upgraded luminosity and a one year runtime (i.e. three years in real time) for each energy/luminosity

$\sqrt{s}$ and $\mathcal{L}$ (P_{e^-}, P_{e^+})	$1150\,\mathrm{fb}^{-1}$ at $250\,\mathrm{GeV}$ $(-0.8,+0.3)$		$1600\,\mathrm{fb}^{-1}$ at $500\,\mathrm{GeV}$ $(-0.8,+0.3)$				$2.5\,\mathrm{ab}^{-1}$ at $1\,\mathrm{TeV}$ $(-0.8,+0.2)$		
	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%		

For invisible decays, the 95% CL upper limit is given.

Note: Mass measurement at E_{CM}=250 GeV yields ΔM_H=15 MeV.

Model-independent determinations of Higgs couplings

Example--consider the following four independent measurements:

$$Y_1 = \sigma_{ZH} = F_1 \cdot g^2_{HZZ}$$

$$Y_2 = \sigma_{ZH} \times \mathrm{Br}(H \to b\bar{b}) = F_2 \cdot \frac{g^2_{HZZ} g^2_{Hb\bar{b}}}{\Gamma_T}$$

$$Y_3 = \sigma_{\nu\bar{\nu}H} \times \mathrm{Br}(H \to b\bar{b}) = F_3 \cdot \frac{g^2_{HWW} g^2_{Hb\bar{b}}}{\Gamma_T}$$

$$Y_4 = \sigma_{\nu\bar{\nu}H} \times \mathrm{Br}(H \to WW^*) = F_4 \cdot \frac{g^4_{HWW}}{\Gamma_T}$$

Γ_T is the Higgs total width, g_{HZZ}, g_{HWW}, and $g_{Hb\bar{b}}$ are the Higgs couplings to ZZ, WW, and $b\bar{b}$, respectively, and F_1, F_2, F_3, F_4 are calculable quantities. For example,

$$F_2 = \left(\frac{\sigma_{ZH}}{g^2_{HZZ}}\right)\left(\frac{\Gamma_{H\to b\bar{b}}}{g^2_{Hb\bar{b}}}\right) .$$

The couplings are obtained as follows:

1. From $Y_1 \quad \Longleftrightarrow \quad g_{HZZ}$
2. From $Y_1Y_3/Y_2 \quad \Longleftrightarrow \quad g_{HWW}$
3. From g_{HWW} and $Y_4 \quad \Longleftrightarrow \quad \Gamma_T$
4. From g_{HZZ}, g_{HWW}, Γ_T and Y_2 or $Y_3 \quad \Longleftrightarrow \quad g_{Hb\bar{b}}$

We perform a global fit for the Higgs couplings and Γ_T using σ_{ZH} and the 33 $\sigma \times$ Br's listed in the previous tables. Each observable Y_i can be written formally as

$$Y_i = Y_i'(F_i, g_{HXX}, \Gamma_T)\,,$$

where g_{HXX} runs over the various possible Higgs couplings. The F_i are theoretical quantities with some error. We expect that $\Delta F_i = 0.5\%$ is a reasonable assumption at the time of ILC running (some suggest that errors as low as 0.1% are achievable).

Let $(\Delta Y_i)^2$ be the sum in quadrature of the error on the measurement Y_i and the total theory error for Y_i'. We obtain the g_{HXX} by minimizing the chi-square function,

$$\chi^2 = \sum_i \left(\frac{Y_i - Y_i'}{\Delta Y_i} \right)^2 .$$

Summary of expected accuracies $\Delta g_i/g_i$ and Γ_T for model independent determinations of the Higgs boson couplings

Mode	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	4.9 %	1.2 %	1.1 %	0.6 %
ZZ	1.3 %	1.0 %	1.0 %	0.5 %
$t\bar{t}$	–	14 %	3.2 %	2.0 %
$b\bar{b}$	5.3 %	1.7 %	1.3 %	0.8 %
$\tau^+\tau^-$	5.8 %	2.4 %	1.8 %	1.0 %
$c\bar{c}$	6.8 %	2.8 %	1.8 %	1.1 %
$\mu^+\mu^-$	91 %	91 %	16 %	10 %
Γ_T	12 %	5.0 %	4.6 %	2.5 %
hhh	–	83 %	21 %	13 %
BR(invis.)	< 0.9 %	< 0.9 %	< 0.9 %	< 0.4 %

The theory errors are $\Delta F_i/F_i$=0.5%. For the invisible branching ratio, the numbers quoted are 95% confidence upper limits.

Model-independent determinations of Higgs cross sections and branching ratios

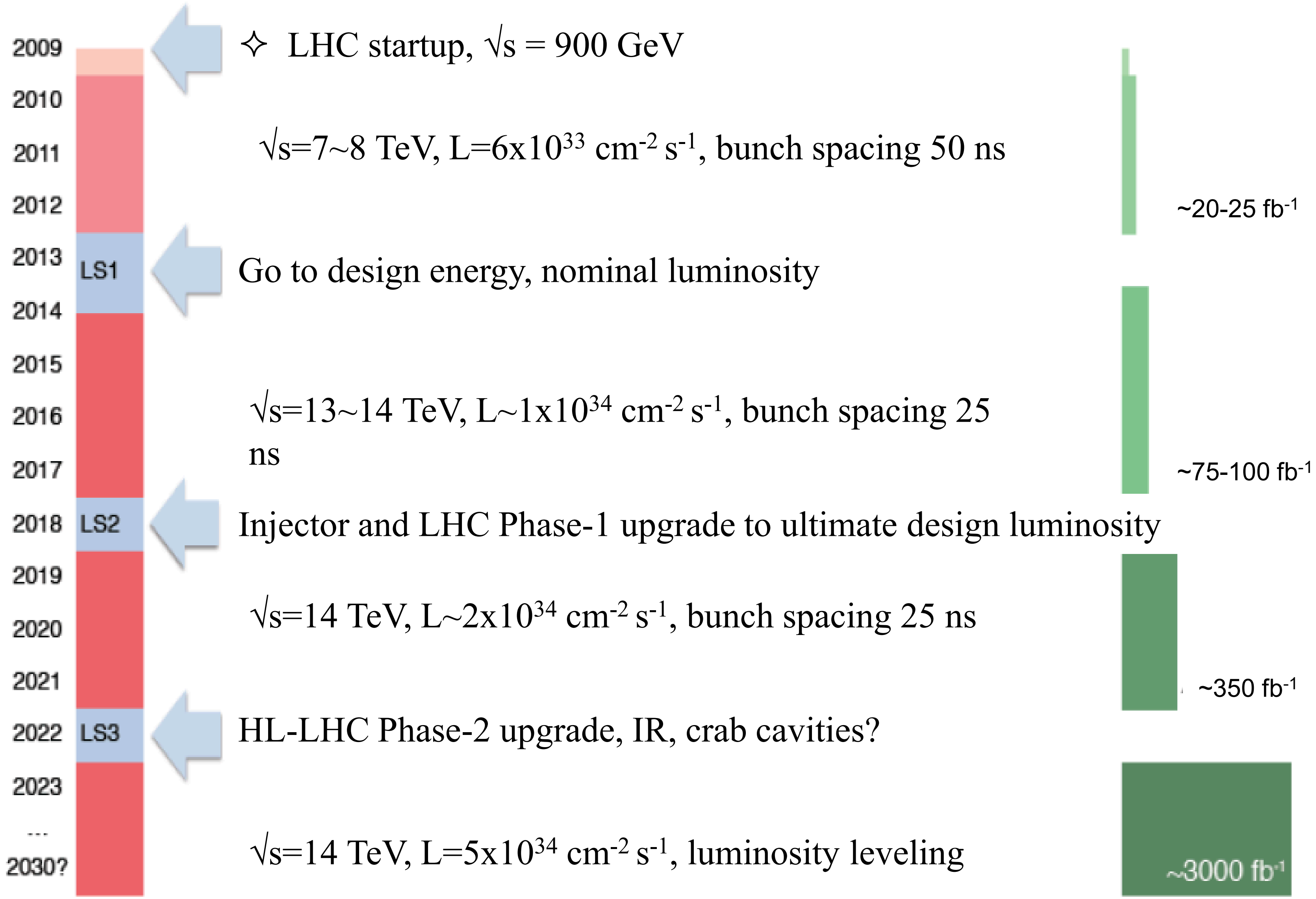
We choose the fit parameters to be three cross sections, σ_{ZH}, $\sigma_{\nu\bar{\nu}H}$, $\sigma_{t\bar{t}H}$, and eight branching ratios, $\mathrm{Br}(H \to b\bar{b})$, $\mathrm{Br}(H \to c\bar{c})$, $\mathrm{Br}(H \to gg)$, $\mathrm{Br}(H \to WW^*)$, $\mathrm{Br}(H \to ZZ^*)$, $\mathrm{Br}(H \to \tau^+\tau^-)$, $\mathrm{Br}(H \to \mu^+\mu^-)$, $\mathrm{Br}(H \to \gamma\gamma)$.

For example, in the ILC(1000) luminosity scenario we use the measured cross-section σ_{ZH}, the 33 independent $\sigma \times \mathrm{Br}$ measurements and the appropriately redefined Y_i' functions to solve for the 11 fit parameters through the minimization of an alternate χ^2 function.

Summary of expected accuracies for the three cross sections and eight branching ratios obtained from an eleven parameter global fit of all available data.

	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 %

The LHC Timeline



✧ LHC startup, $\sqrt{s}$ = 900 GeV

$\sqrt{s}$=7~8 TeV, L=6x10^{33} cm^{-2} s^{-1}, bunch spacing 50 ns

Go to design energy, nominal luminosity

$\sqrt{s}$=13~14 TeV, L~1x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns

Injector and LHC Phase-1 upgrade to ultimate design luminosity

$\sqrt{s}$=14 TeV, L~2x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns

HL-LHC Phase-2 upgrade, IR, crab cavities?

$\sqrt{s}$=14 TeV, L=5x10^{34} cm^{-2} s^{-1}, luminosity leveling

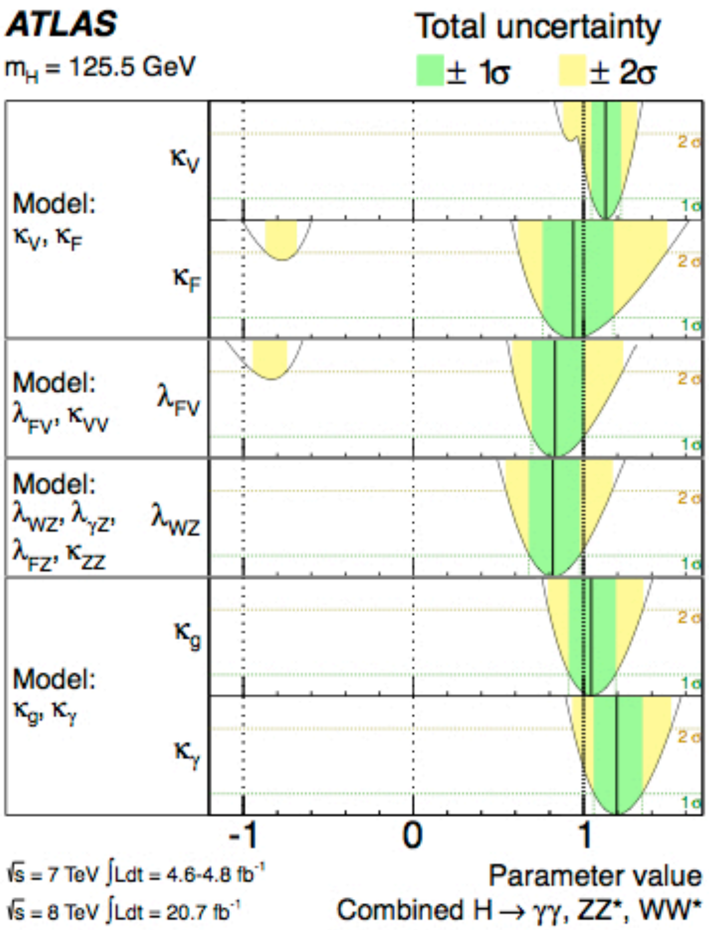
Comparing LHC and ILC Projected Precision

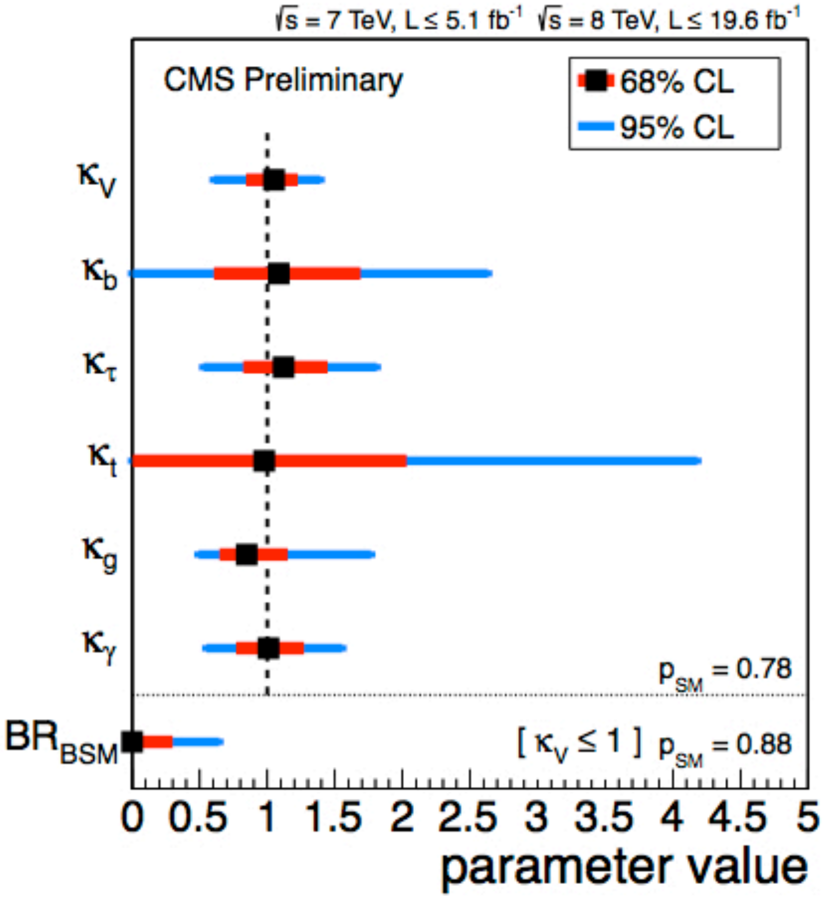
ATLAS and CMS have provided projections for the ultimate accuracies of Higgs coupling measurements based on the currently planned six year program (accumulating 300 fb^{-1} of data) and a proposed high-luminosity ten year program (accumulating 3000 fb^{-1} of data).

Results are quoted in terms of the LHC Higgs Cross Section Working Group (HXSWG) benchmark Higgs coupling parameterizations. In one example, deviations from SM-Higgs couplings are expressed in terms of κ_g, κ_γ, κ_W, κ_Z, κ_b, κ_t, κ_τ and a dependent parameter κ_H (κ_i) which parameterize the departures from the Standard Model couplings and width. In addition, it is assumed that $\kappa_c=\kappa_t$, $\kappa_\mu=\kappa_\tau$, etc. and the total Higgs width is the sum of the partial widths for all SM Higgs decays.

We can adopt the same model-dependent assumptions for our ILC analysis by imposing these assumptions as constraints on our model-independent χ^2 function.

to date:

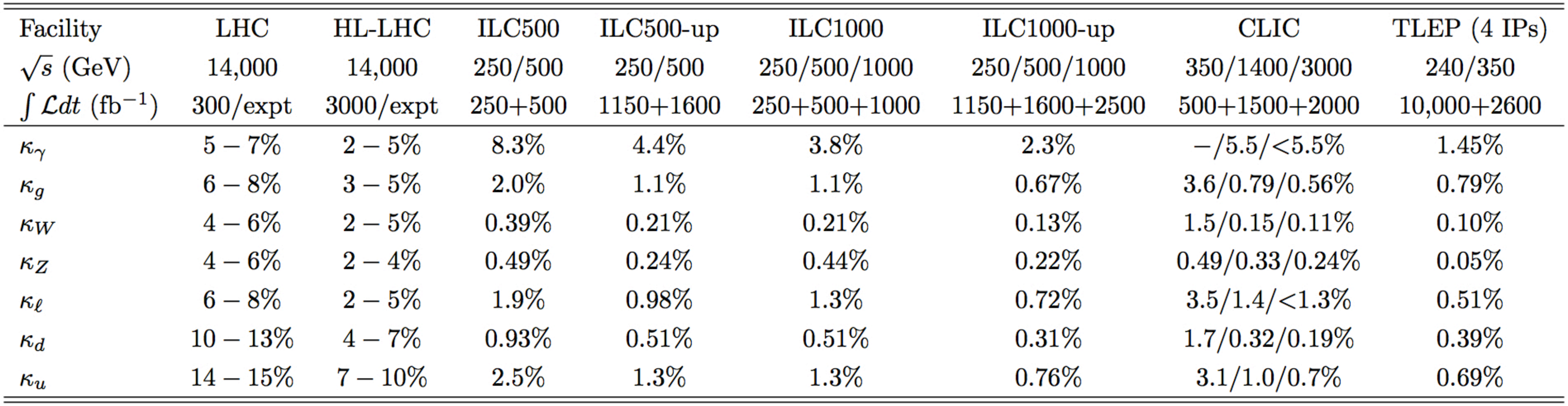

ATLAS
m_H = 125.5 GeV
Total uncertainty
🟩 ± 1σ
🟨 ± 2σ
Model: κ_V, κ_F
κ_V
κ_F
Model: $\lambda_{FV}, \kappa_{VV}$
λ_{FV}
Model: $\lambda_{WZ}, \lambda_{\gamma Z}, \lambda_{FZ}, \kappa_{ZZ}$
λ_{WZ}
Model: κ_g, κ_γ
κ_g
κ_γ
2σ
1σ
-1
0
1
Parameter value
$\sqrt{s}$ = 7 TeV $\int Ldt$ = 4.6-4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV $\int Ldt$ = 20.7 fb^{-1}
Combined H → γγ, ZZ*, WW*


$\sqrt{s}$ = 7 TeV, L ≤ 5.1 fb^{-1} $\sqrt{s}$ = 8 TeV, L ≤ 19.6 fb^{-1}
CMS Preliminary
68% CL
95% CL
κ_V
κ_b
κ_τ
κ_t
κ_g
κ_γ
p_{SM} = 0.78
BR_{BSM}
[$\kappa_V \leq 1$] p_{SM} = 0.88
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
parameter value

couplings by facility

Extrapolating LHC requires a strategy

2 numbers shown:
optimistic*– conservative



Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	5 – 7%	2 – 5%	8.3%	4.4%	3.8%	2.3%	–/5.5/<5.5%	1.45%
κ_g	6 – 8%	3 – 5%	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	4 – 6%	2 – 5%	0.39%	0.21%	0.21%	0.13%	1.5/0.15/0.11%	0.10%
κ_Z	4 – 6%	2 – 4%	0.49%	0.24%	0.44%	0.22%	0.49/0.33/0.24%	0.05%
κ_ℓ	6 – 8%	2 – 5%	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
κ_d	10 – 13%	4 – 7%	0.93%	0.51%	0.51%	0.31%	1.7/0.32/0.19%	0.39%
κ_u	14 – 15%	7 – 10%	2.5%	1.3%	1.3%	0.76%	3.1/1.0/0.7%	0.69%

$$^{*}\ \delta(\text{sys}) \propto \frac{1}{\sqrt{\mathcal{L}}} \quad \& \quad \delta(\text{theory}) \downarrow 1/2$$

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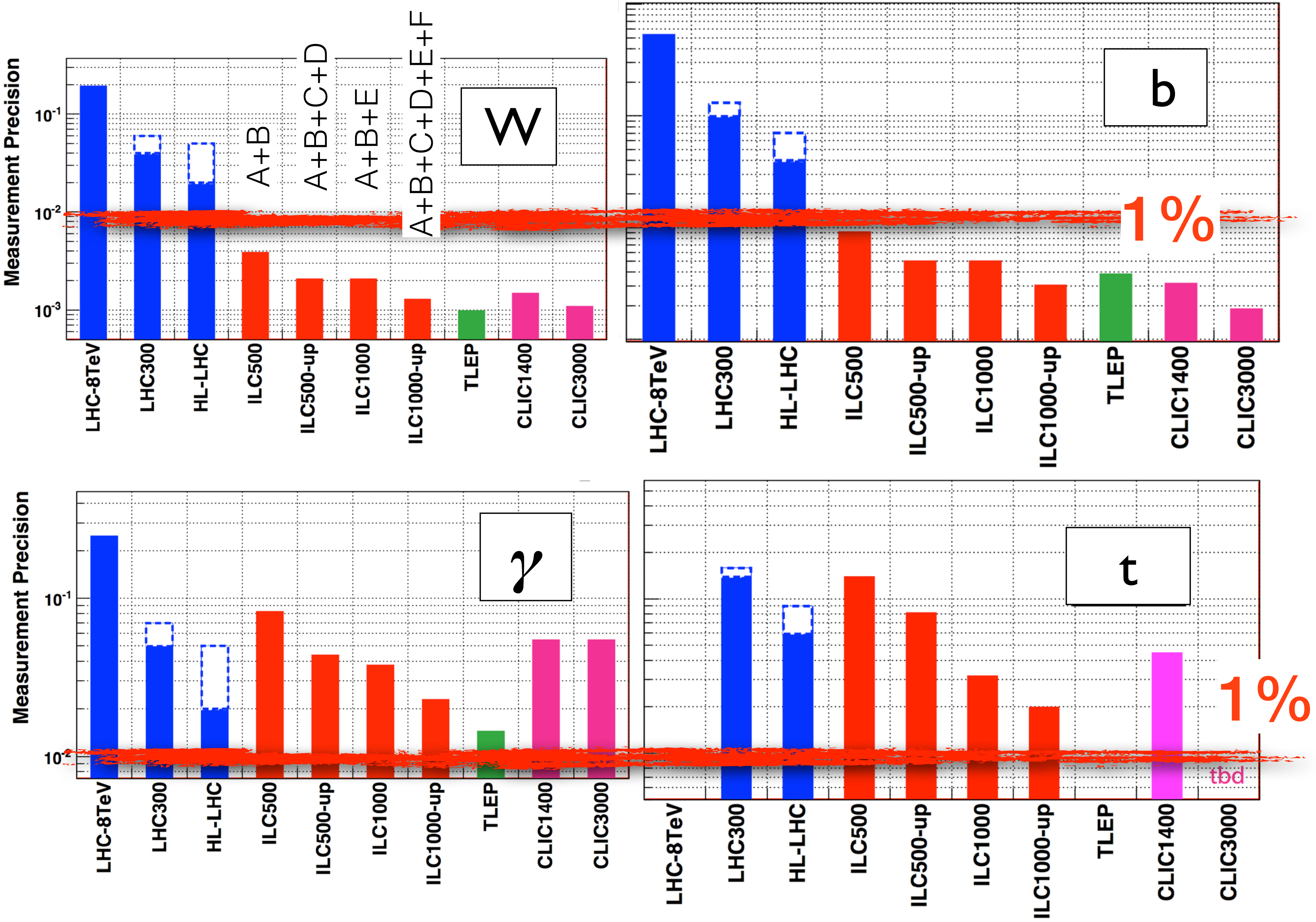
Precision in kappa by facility

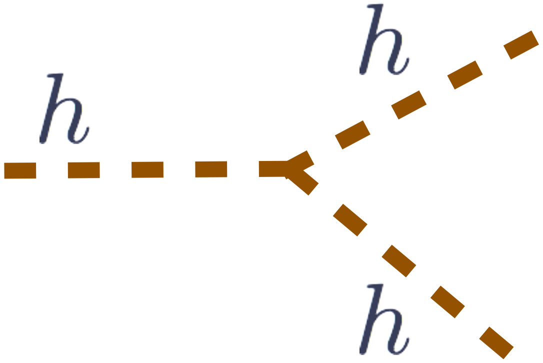


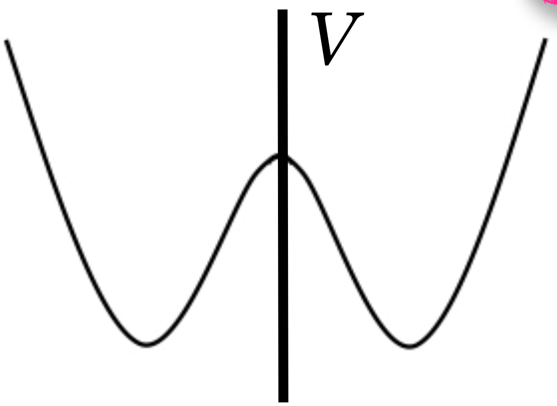
Higgs Self-Coupling

Critical feature of SM

- extremely challenging

$$V = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$





	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000	500	1600‡	500/1000	1600/2500‡	1500	+2000	3000	3000
λ	50%	83%	46%	21%	13%	21%	10%	20%	8%

Higgs self-coupling is difficult to measure precisely at any facility.

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The Bottom Line

- The ILC will provide the next significant step in the precision study of Higgs boson properties. LHC precision measurements in the 5—10% range will be brought down to the 1% level.

- The ILC is able to provide a model-independent determination of Higgs couplings via the measurement of σ_{ZH}, in addition to measuring σ x Br in numerous channels. (In contrast, LHC only can measure σ x Br).

- Together with the LHC Higgs data, the ILC will provide critical measurements that can probe new physics beyond the Standard Model and provide important clues as to what may lie ahead.

Back-up slides

Summary of expected accuracies $\Delta g_i/g_i$ and Γ_T using the model-dependent seven parameter HXSWG benchmark parameterization, assuming all theory errors are 0.5%

Mode	ILC(250)	ILC(500)	ILC(1000)	ILC(LumUp)
$\gamma\gamma$	17 %	8.3 %	3.8 %	2.3 %
gg	6.1 %	2.0 %	1.2 %	0.7 %
WW	4.7 %	0.5 %	0.3 %	0.2 %
ZZ	0.8 %	0.5 %	0.5 %	0.3 %
$t\bar{t}$	6.4 %	2.6 %	1.4 %	0.9 %
$b\bar{b}$	4.7 %	1.0 %	0.6 %	0.4 %
$\tau^+\tau^-$	5.2 %	2.0 %	1.3 %	0.8 %
Γ_T	9.0 %	1.8 %	1.1 %	0.9 %