Higgs Physics at the ILC

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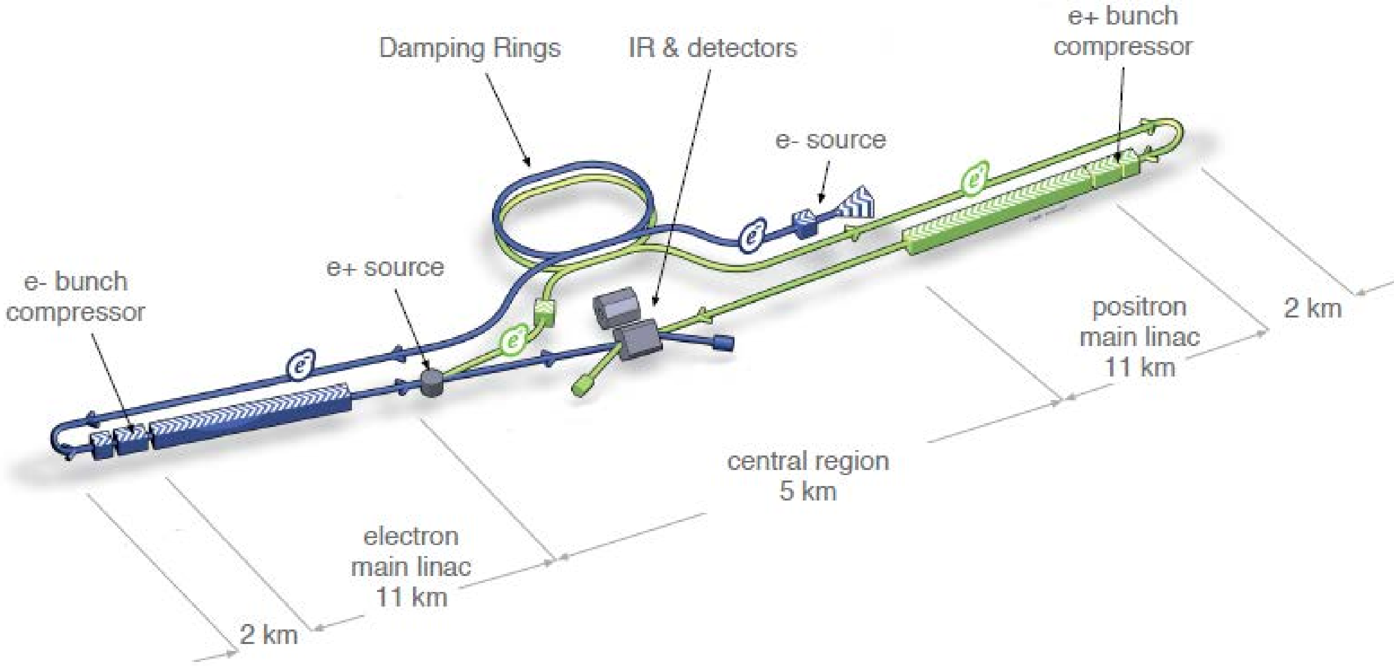
FCC-ee Workshop on Higgs Physics

ILC International Linear Collider

e^+e^- linear collider with Superconducting RF linac

$250 \leq \sqrt{s} \leq 500$ GeV 31 km in length



ILC Machine Parameters from TDR

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

Note there are two types of upgrades:

Luminosity upgrade: Install extra klystrons and modulators so number of bunches can be doubled; envisioned after 8 years of baseline running

Energy upgrade: Increase accel. gradient, lengthen linac, or both. TDR config assumes 49 km. length; envisioned after 20 years of running

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Luminosity Upgrade for Ecm=250 GeV

			Baseline ILC	Lumi Upgrade
Center-of-mass energy	E_{CM}	GeV	250	250
Collision rate	f_{rep}	Hz	5	10
Electron linac rate	f_{linac}	Hz	10	10
Number of bunches	n_b		1312	2625
Pulse current	I_{beam}	mA	5.8	8.75
Average total beam power	P_{beam}	MW	5.9	21
Estimated AC power	P_{AC}	MW	129	200
Luminosity	L	$\times 10^{34}\ cm^{-2}s^{-1}$	0.75	3.0

The $\sqrt{s} = 250$ GeV lumi is quadrupled by doubling the number of bunches ***and*** the collision rep rate

The 10 Hz operation which in the baseline was split between 5 Hz collision and 5 Hz e^+ production is now 100% collision in the lumi upgrade config. A longer undulator should be ready that can produce sufficient e^+ yield with 125 GeV electrons

Note the AC power is 200 MW, the same as the 5 Hz lumi upgrade power at $\sqrt{s} = 500$ GeV.
Also note that ILC produces 3×10^{34} $cm^{-2}s^{-1}$ luminosity with 200 MW total AC power.

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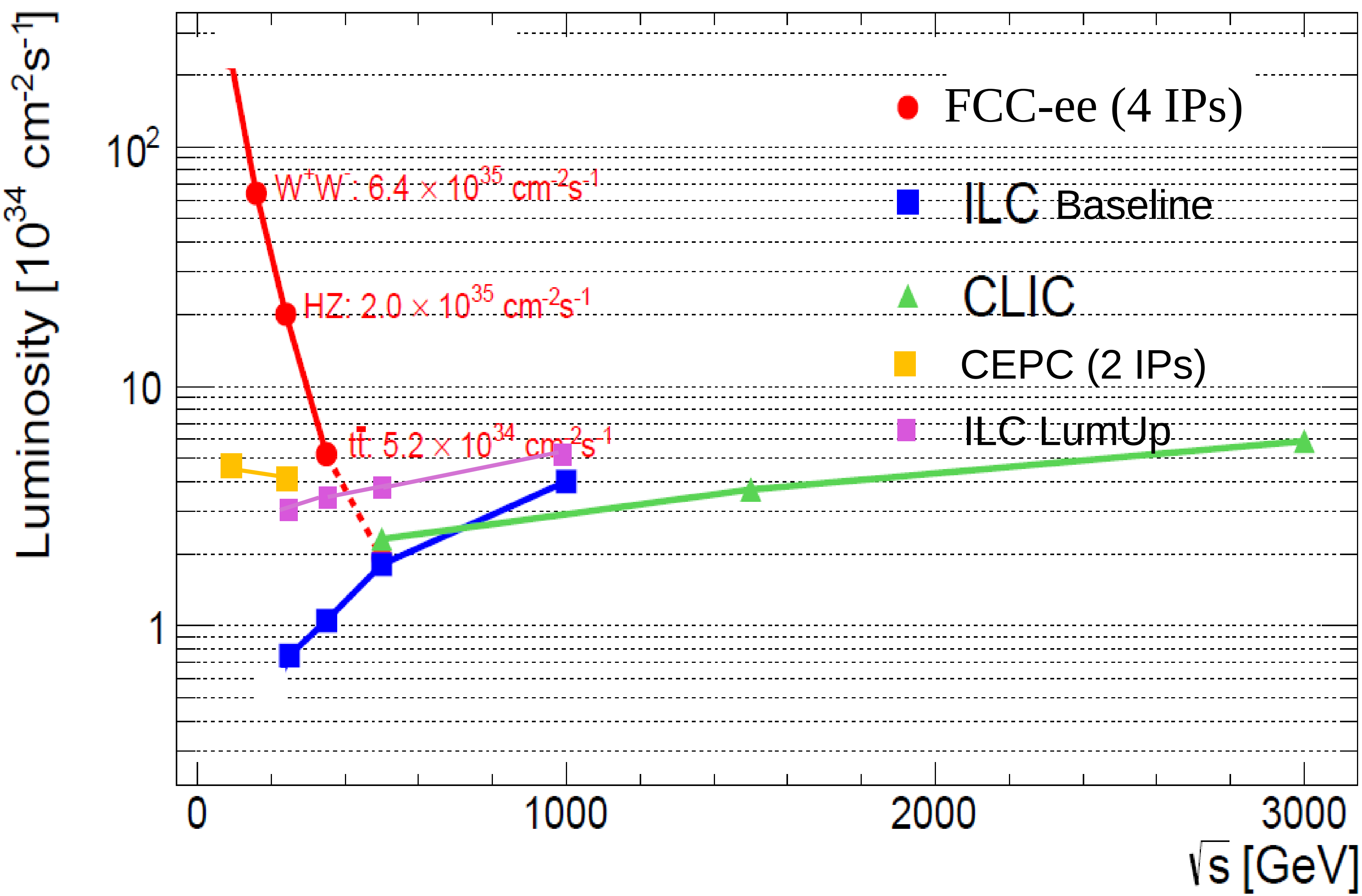
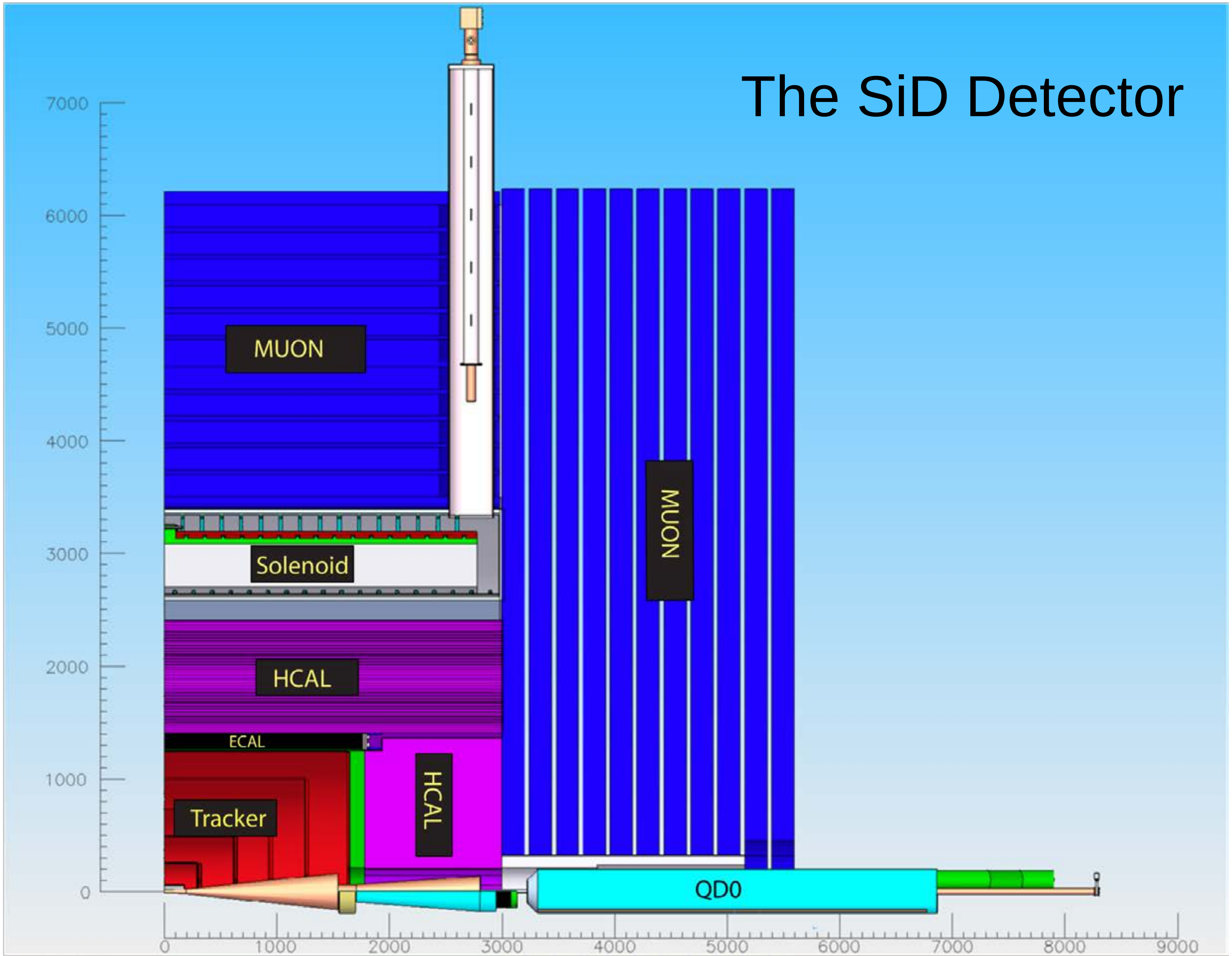
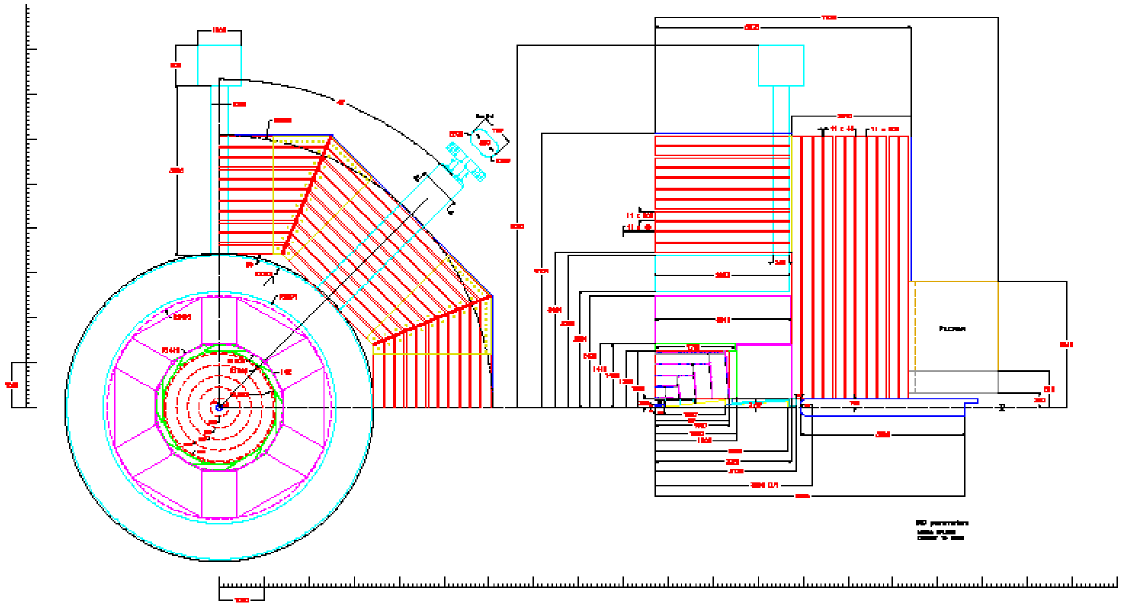


Luminosity [10^{34} cm^{-2}s^{-1}]
10^2
10
1
0
1000
2000
3000
$\sqrt{s}$ [GeV]
W^+W^-: 6.4×10^{35} cm^{-2}s^{-1}
HZ: 2.0×10^{35} cm^{-2}s^{-1}
$t\bar{t}$: 5.2×10^{34} cm^{-2}s^{-1}
FCC-ee (4 IPs)
ILC Baseline
CLIC
CEPC (2 IPs)
ILC LumUp

Full Simulation Performed with ILD and/or SiD Detector



SiD Global Parameters



Detector	Technology	Radius (m)		Axial (z) (m)	
		Min	*Max*	*Min*	*Max*
Vertex Detector	Pixels	0.014	0.06		0.18
Central Tracking	Strips	0.206	1.25		1.607
Endcap Tracker	Strips	0.207	0.492	0.85	1.637
Barrel Ecal	Silicon-W	1.265	1.409		1.765
Endcap Ecal	Silicon-W	0.206	1.25	1.657	1.8
Barrel Hcal	RPCs	1.419	2.493		3.018
Endcap Hcal	RPCs	0.206	1.404	1.806	3.028
Coil	5 tesla	2.591	3.392		3.028
Barrel Iron	RPCs	3.442	6.082		3.033
Endcap Iron	RPCs	0.206	6.082	3.033	5.673

Combining barrel and endcaps these trackers and calorimeters cover $|\cos\theta| \leq 0.99$

LumiCal and BeamCal are used for $|\cos\theta| > 0.99$

Pulsed power is possible due to low duty cycle 5 Hz rep rate: eliminates need for cooling

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500 GeV ILC Operating Scenarios arXiv : 1506.07830

Construct 500 GeV from start

- 500 GeV scenarios study
  - TDR Baseline
  - Emphasizes higher energy - strength of ILC
- Study parameters
  - assume 20 years of operation
  - compare 3 scenarios (studied more)
    - G20, H20, I20
  - Snowmass white paper studied also for comparison
    - arXiv:1310.0763 [hep-ph]

Assumptions

- Full calendar year is assumed to be 8 months at a 75% efficiency (the RDR assumption). This corresponds to Y = 1.6 x 10^7 seconds of integrated running. (significantly higher than a Snowmass year of 10^7 seconds.)
- A **ramp-up** of luminosity performance is in general assumed after:
  - (a) initial construction and after 'year 0' commissioning;
  - (b) after a downtime for a luminosity upgrade;
  - (c) a change in operational mode which may require some learning curve (e.g. going to 10-Hz collisions).
- For initial physics run *after construction and year 0 commissioning*, the RDR ramp of 10%, 30%, 60% and 100% is assumed over the first four years.
- The ramp *after the shutdowns for installation of the luminosity upgrade* is assumed slightly shorter (10%, 50%, 100%) with no year 0.
- *Going down in centre of mass energy* from 500 GeV to 350 GeV or 250 GeV is assumed to have no ramp, since there is no machine modification.
- *Going to 10-Hz operation at 50% gradient* does assume a ramp (25%, 75%, 100%), since 10-Hz affects the entire machine.
- A major 18 month shutdown is assumed for the luminosity upgrade.
- Unlike TDR: 10-Hz and 7-Hz operation assumed at 250 GeV and 350 GeV

Preferred Scenario

	$\sqrt{s}$	$\int \mathscr{L} dt$	L_{peak}	Ramp				T	T_{tot}	Comment
	[GeV]	[fb^{-1}]	[fb^{-1}/a]	1	2	3	4	[a]	[a]	
Physics run	500	500	288	0.1	0.3	0.6	1.0	3.7	3.7	TDR nominal at 5 Hz
Physics run	350	200	160	1.0	1.0	1.0	1.0	1.3	5.0	TDR nominal at 5 Hz
Physics run	250	500	240	0.25	0.75	1.0	1.0	3.1	8.1	operation at 10 Hz
Shutdown								1.5	9.6	Luminosity upgrade
Physics run	500	3500	576	0.1	0.5	1.0	1.0	7.4	17.0	TDR lumi-up at 5 Hz
Physics run	250	1500	480	1.0	1.0	1.0	1.0	3.2	20.2	lumi-up operation at 10 Hz

Table 7: Scenario H-20: Sequence of energy stages and their real-time conditions.

H-20

	first phase	lumi upgrade	total	Snowmass Lum-up†
250 GeV	500 fb^{-1}	1500 fb^{-1}	2 ab^{-1}	1.15 ab^{-1}
350 GeV	200 fb^{-1}		0.2 ab^{-1}	
500 GeV	500 fb^{-1}	3500 fb^{-1}	4 ab^{-1}	1.6 ab^{-1}
time	8.1 yrs	10.6 yrs	20.2 yrs*	

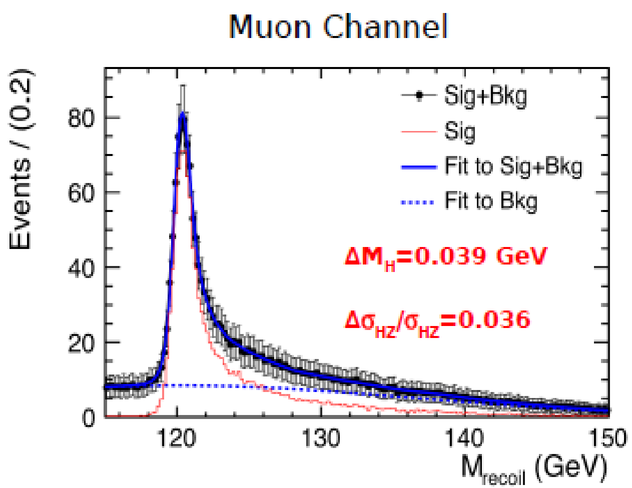
* includes 1.5 years for luminosity upgrade

† ILC Higgs whitepaper: arXiv:1310.0763

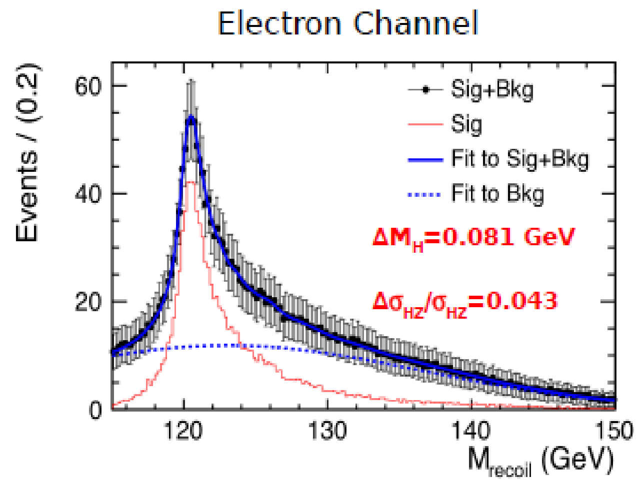
Higgs Physics at the ILC

ILC Measurement of $\sigma(e^+e^- \to ZH)$ $\sqrt{s} = 250$ GeV

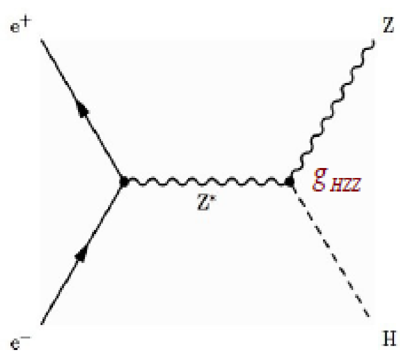
Higgs Recoil Measurement of Higgs Mass and Higgstrahlung Cross Section



Very Precise Measurement
S/B = 8 in Peak Region



Less Precise
Bremsstrahlung in detector material



ILC: $\Delta M_H = .032$ 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}

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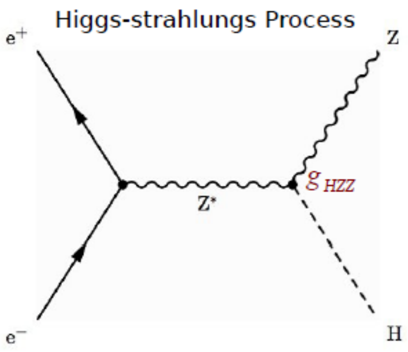
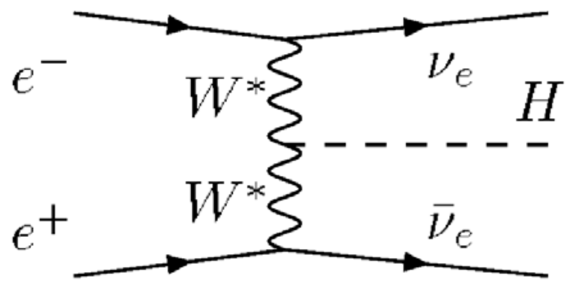
$e^+e^- \to ZH,\ \nu\nu\mathrm{H}\ \sqrt{s} = 350$ GeV



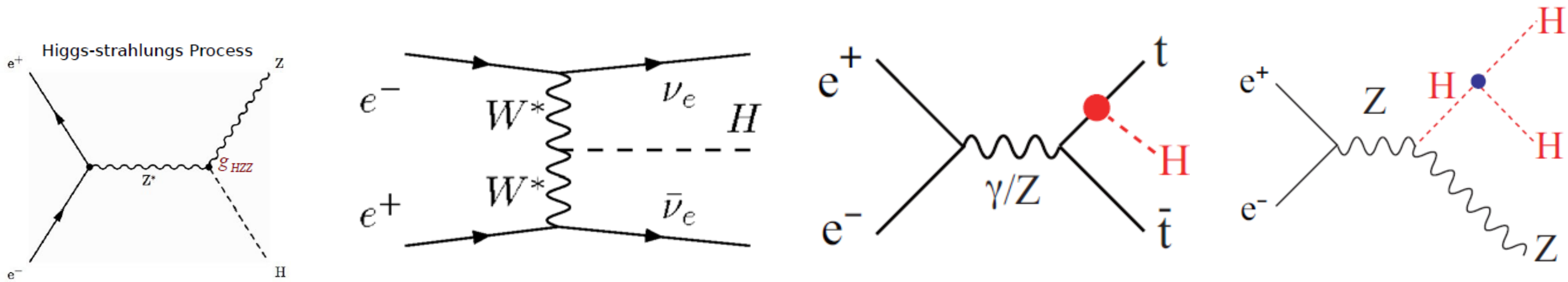


All of the Higgstrahlung studies that were done at $\sqrt{s} = 250$ GeV can also be done at $\sqrt{s} = 350$ GeV. Precisions for $\sigma \bullet BR$ are comparable, as is the precision for σ(ZH) once Z $\to q\bar{q}$ decays are included.

WW fusion production of the Higgs at $\sqrt{s} = 350$ GeV provides a much better measurement of g_{HWW} compared to $\sqrt{s} = 250$ GeV. This gives a much improved estimate of the total Higgs width Γ_H which in turn significantly improves the coupling errors obtained from $\sigma \bullet BR$ measurements made at $\sqrt{s} = 250$ GeV.

The recoil Higgs mass measurement is significantly worse at $\sqrt{s} = 350$ GeV with respect to $\sqrt{s} = 250$ GeV. However, there is hope that direct calorimeter Higgs mass measurements using $e^+e^- \to \nu\nu H$ will recover the precision.

$e^+e^- \to ZH, \nu\nu H, t\bar{t}H, ZHH \; \sqrt{s} = 500$ GeV

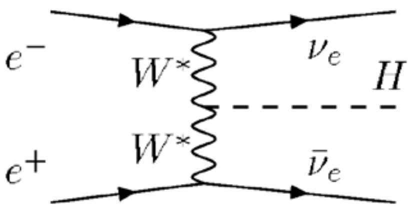


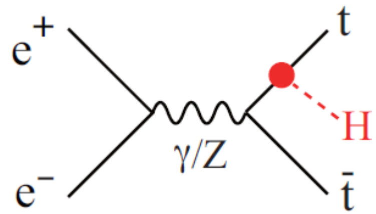
The g_{HWW} coupling can also be measured well at $\sqrt{s} = 500$ GeV through WW fusion production of the Higgs. Also the measurement of $\sigma(e^+e^- \to \nu\nu H) \times BR(H \to X)$ can be made for many Higgs decay modes $H \to X$.

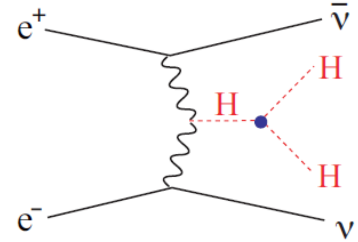
Through $e^+e^- \to ttH$ the top Yukawa coupling can be measured to $\Delta y_t / y_t = 16.6\%$ with 500 fb^{-1} at $\sqrt{s} = 500$ GeV. With same luminosity at $\sqrt{s} = 550$ GeV the precision is $\Delta y_t / y_t = 6.73 \Rightarrow$ strong motivation to increase nominal energy to $\sqrt{s} = 550$ GeV

The ZHH channel is open at $\sqrt{s} = 500$ GeV. The Higgs self coupling can be measured to 27% with 4 ab^{-1} assuming the true value is the SM value.

$e^+e^- \to \nu\nu H$, ttH , $\nu\nu HH$ ILC Energy Upgrade $\sqrt{s}$= 1 TeV



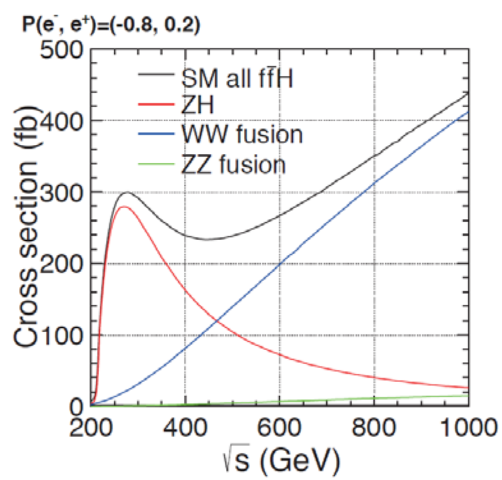




At $\sqrt{s} = 1$ TeV the ILC provides better measurements of the top Yukawa coupling and Higgs self coupling. For example the Higgs self coupling can be measured to an accuracy of 10% with 4 ab^{-1} at $\sqrt{s} = 1$ TeV (again, assuming the true value is the SM value).

Search for additional Higgs bosons that might have been missed at LHC.

In addition, the ILC becomes a Higgs factory again since the total Higgs cross section is larger than the total cross sections at 250 GeV, specially if polarized beams are used:



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Summary of ILC Higgs Measurement Precisions

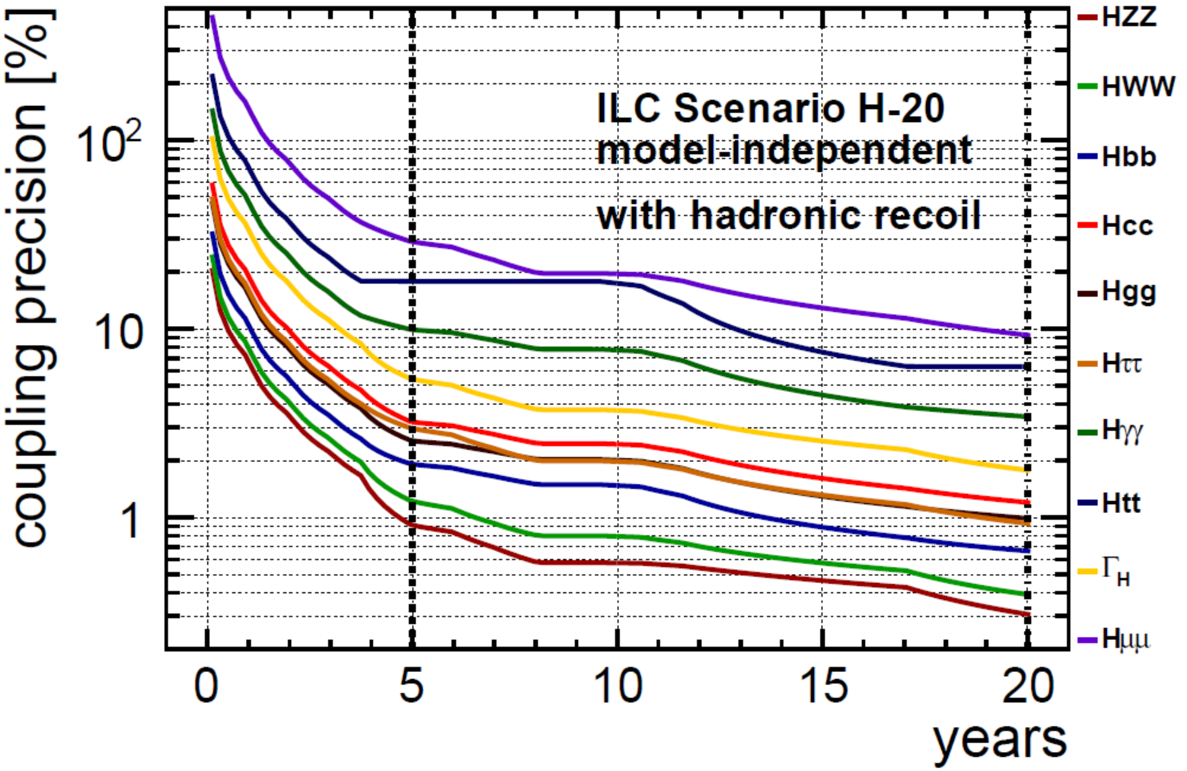
From "500 GeV ILC Operating Scenarios" arXiv : 1506.07830

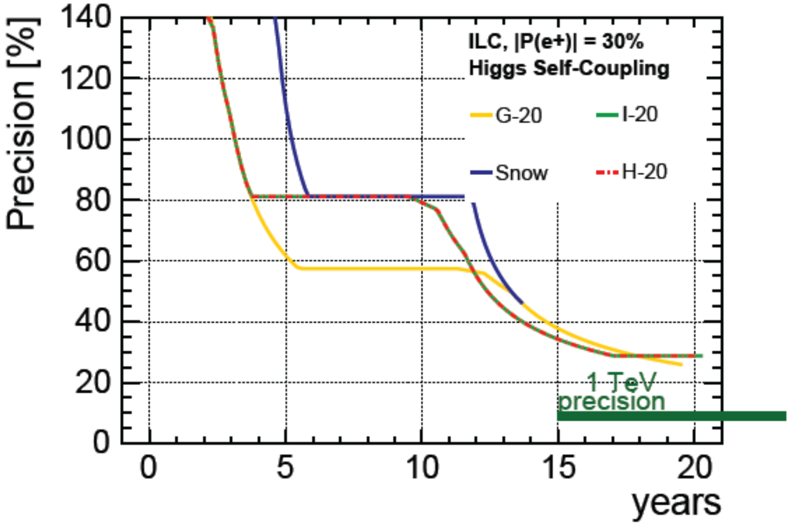
$\int \mathscr{L} dt$ at $\sqrt{s}$	$250\,\text{fb}^{-1}$ at $250\,\text{GeV}$		$330\,\text{fb}^{-1}$ at $350\,\text{GeV}$		$500\,\text{fb}^{-1}$ at $500\,\text{GeV}$		
$P(e^-, e^+)$	(-80%,+30%)						
production	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	$t\bar{t}h$
$\Delta\sigma/\sigma$	[39] 2.0%	-	[10,40] 1.6%	-	3.0	-	-
BR(invis.) [41]	$< 0.9\%$	-	$< 1.2\%$	-	$< 2.4\%$	-	-
decay	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$						
$h \to bb$	1.2%	10.5%	1.3%	1.3%	1.8%	0.7%	28%
$h \to c\bar{c}$	8.3%	-	9.9%	13%	13%	6.2%	-
$h \to gg$	7.0%	-	7.3%	8.6%	11%	4.1%	-
$h \to WW^*$	6.4%	-	6.8%	5.0%	9.2%	2.4%	-
$h \to \tau^+\tau^-$	[42] 3.2%	-	[43] 3.5%	19%	5.4%	9.0%	-
$h \to ZZ^*$	19%	-	22%	17%	25%	8.2%	-
$h \to \gamma\gamma$	34%	-	34%	[44] 39%	34%	[44] 19%	-
$h \to \mu^+\mu^-$ [45]	72%	-	76%	140%	88%	72%	-

For scenario H-20 with 2 ab^{-1} at 250 GeV and 4 ab^{-1} at 500 GeV the ILC has

$$\frac{\Delta\sigma(ZH)}{\sigma(ZH)} = 0.59\% \quad \text{and} \quad \frac{\Delta\sigma(\nu\bar{\nu}H) \bullet BR(H \to b\bar{b})}{\sigma(\nu\bar{\nu}H) \bullet BR(H \to b\bar{b})} = 0.25\%$$

ILC Higgs Coupling Precision vs Time





Higgs Physics: ILC vs FCC-ee

Take FCC-ee errors on σ and σ•BR from arXiv:1308.6176 assuming 240+350 GeV with 10.0 + 2.6 ab^{-1} :

	TLEP 240
σ_{HZ}	**0.4%**
$\sigma_{HZ} \times BR(H \to b\bar{b})$	**0.2%**
$\sigma_{HZ} \times BR(H \to c\bar{c})$	**1.2%**
$\sigma_{HZ} \times BR(H \to gg)$	**1.4%**
$\sigma_{HZ} \times BR(H \to WW)$	**0.9%**
$\sigma_{HZ} \times BR(H \to \tau\tau)$	**0.7%**
$\sigma_{HZ} \times BR(H \to ZZ)$	**3.1%**
$\sigma_{HZ} \times BR(H \to \gamma\gamma)$	**3.0%**
$\sigma_{HZ} \times BR(H \to \mu\mu)$	**13%**

$\sigma_{WW \to H} \times BR(H \to b\bar{b})$

$\sqrt{s}$ (GeV)	TLEP
240 - 250	**2.2%**
350	**0.6%**

The additional events from the Higgs-strahlung process at 350 GeV allow the statistical precision for all the aforementioned measurements to be improved by typically 5% for TLEP with respect to the sole 240 GeV data.

➡ Branching fraction to invisible tested directly to 0.19% @ 95% CL

Take ILC errors on σ and σ•BR from arXiv:1506.07830 assuming 250+350+500 GeV with either:

0.5+0.2+5.0 ab^{-1} (G-20 scenario) or 2.0+0.2+4.0 ab^{-1} (H-20 scenario)

Perform model independent fit of b,c,g,W,τ,Z,γ,μ,invis Higgs couplings and total width using standard program (from Michael Peskin) for ILC & FCC-ee separately and combined.

The coupling fit results I obtain for FCC-ee alone differ slightly from those reported in arXiv:1308.6176

Coupling	arXiv:1308.6176	My fit
g_{HZZ}	**0.15%**	0.19%
g_{HWW}	**0.19%**	0.35%
g_{Hbb}	**0.42%**	0.52%
g_{Hcc}	**0.71%**	0.78%
g_{Hgg}	**0.80%**	0.85%
$g_{H\tau\tau}$	**0.54%**	0.63%
$g_{H\mu\mu}$	**6.2%**	6.2%
$g_{H\gamma\gamma}$	**1.5%**	1.5%

Because it is the only way to consistently combine FCC-ee and ILC results I will, for the rest of the talk, use these results for FCC-ee. The discrepancy is not understood at this time -- will try to clear it up at a later date.

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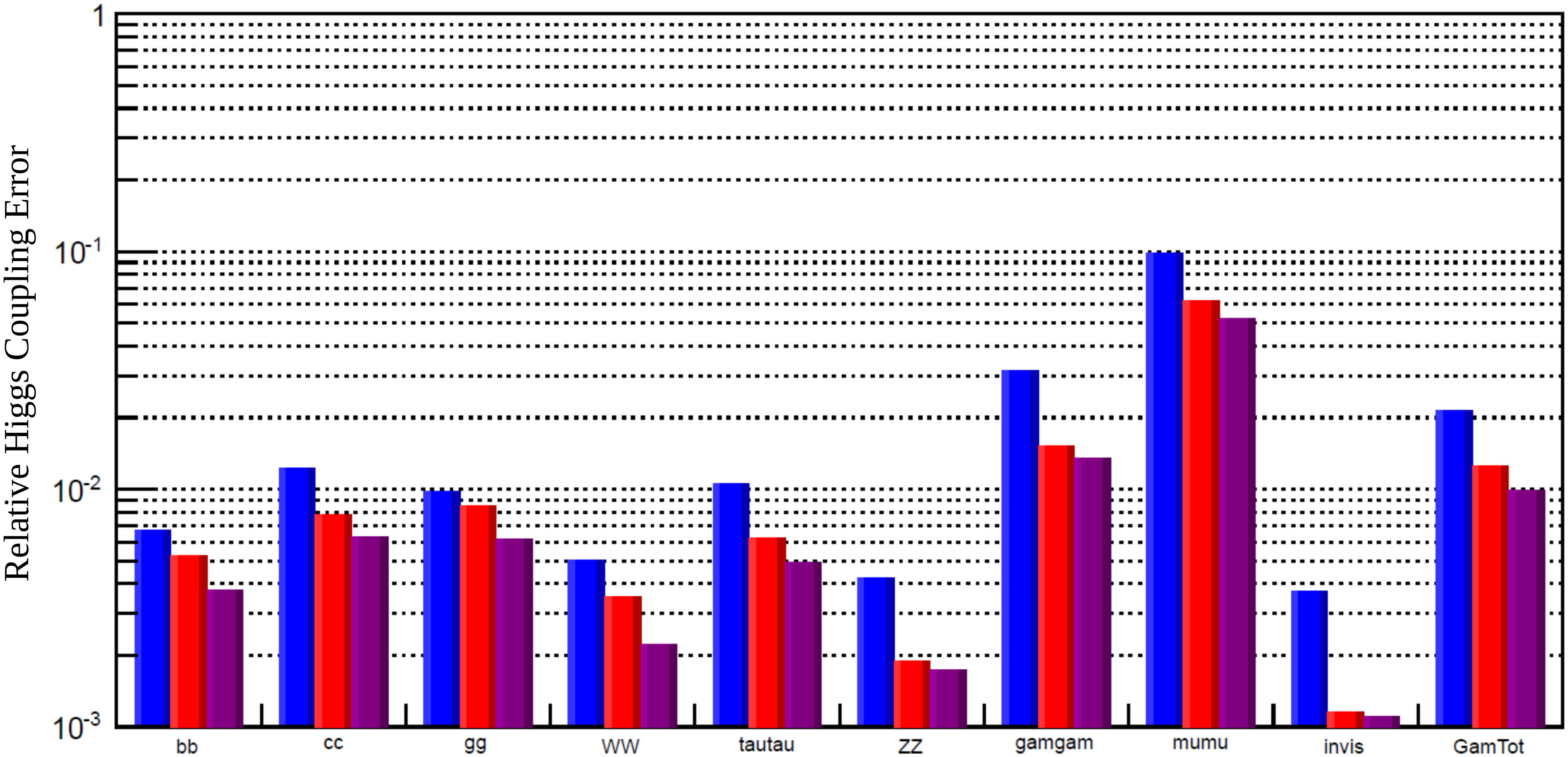
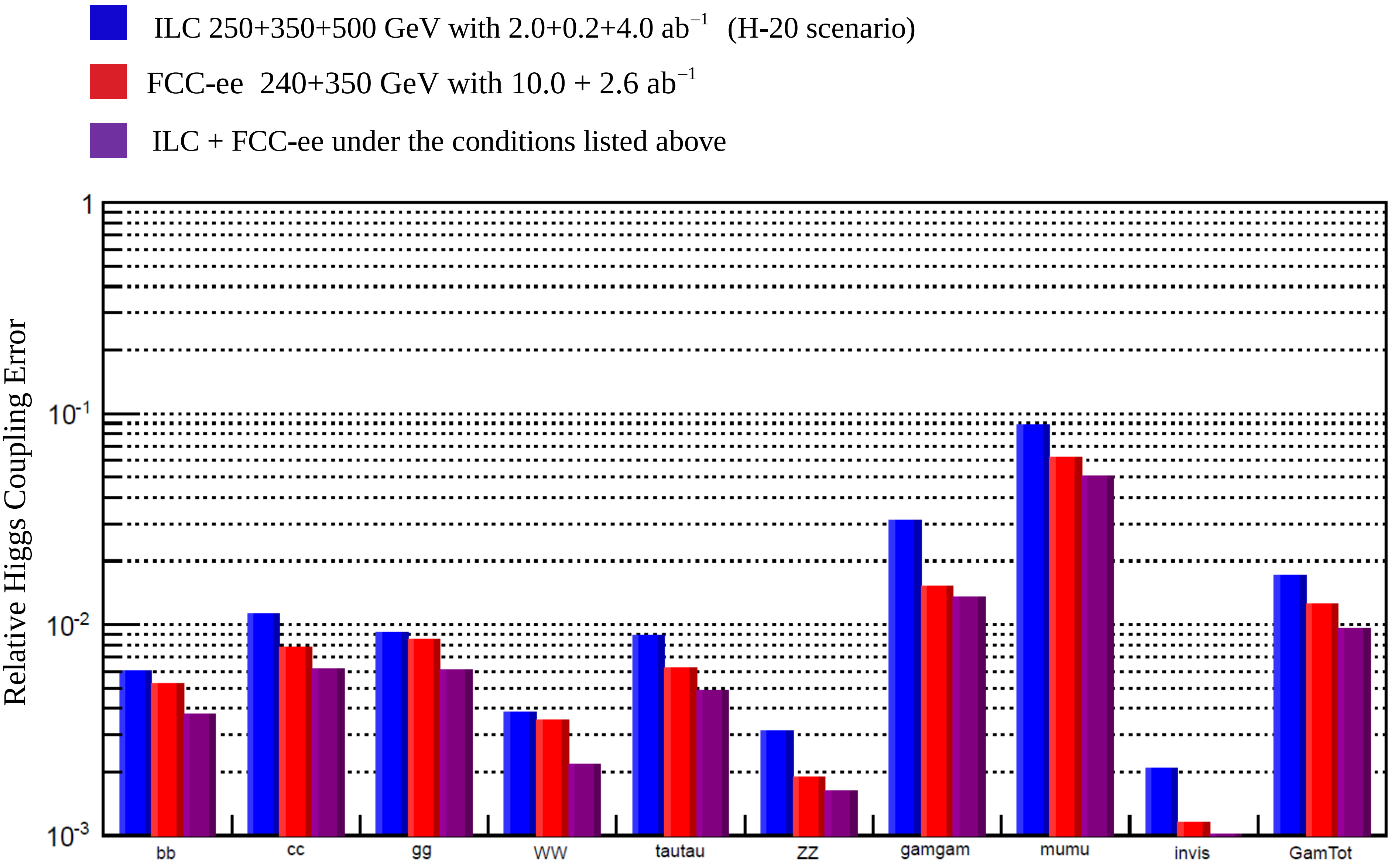
ILC 250+350+500 GeV with 0.5+0.2+5.0 fb^{-1} (G-20 scenario)

FCC-ee 240+350 GeV with 10.0 + 2.6 ab^{-1}

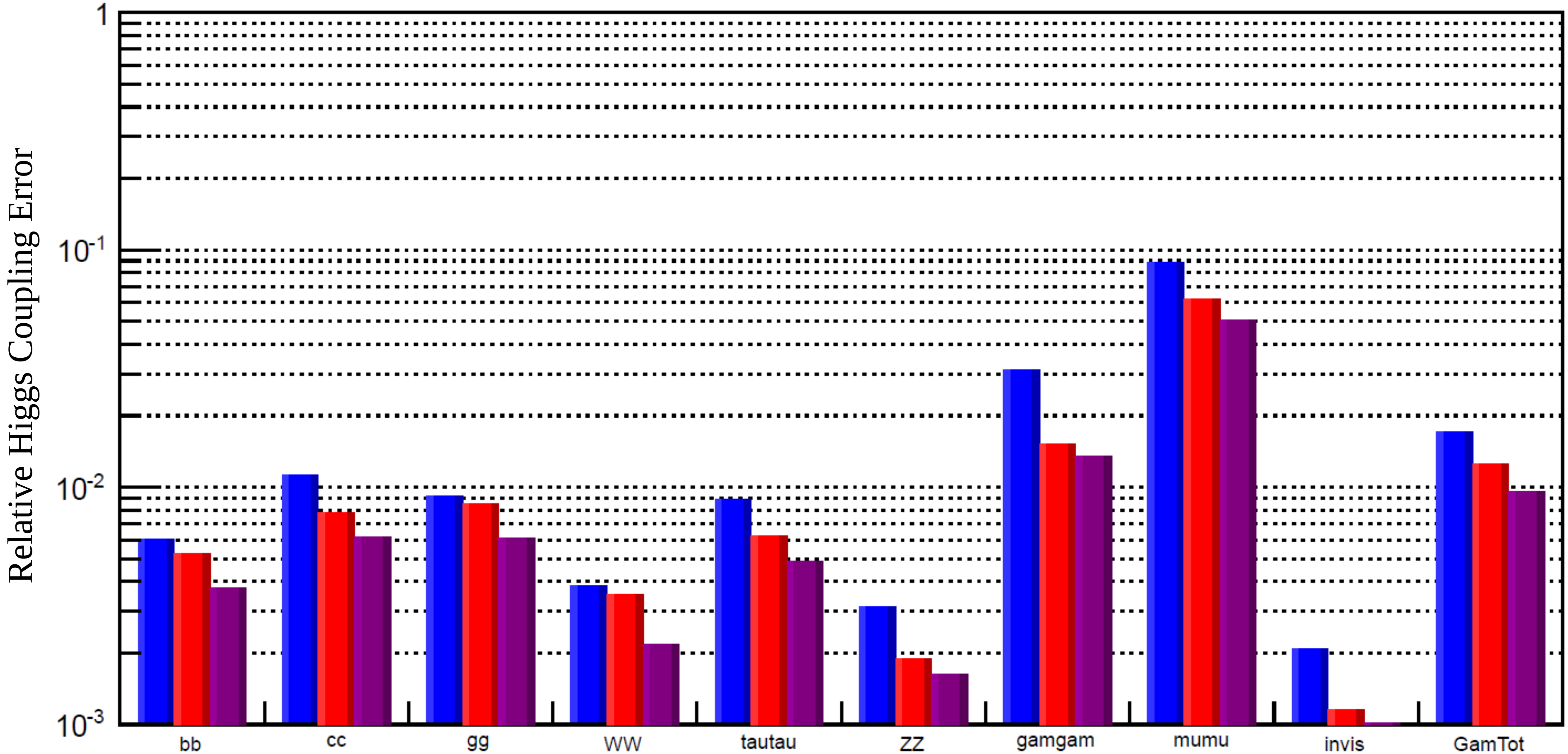
ILC + FCC-ee under the conditions listed above




ILC 250+350+500 GeV with 2.0+0.2+4.0 ab^{-1} (H-20 scenario)
FCC-ee 240+350 GeV with 10.0 + 2.6 ab^{-1}
ILC + FCC-ee under the conditions listed above
Relative Higgs Coupling Error
1
10^{-1}
10^{-2}
10^{-3}
bb
cc
gg
WW
tautau
ZZ
gamgam
mumu
invis
GamTot

How does ILC help FCC-ee?

- ILC 250+350+500 GeV with 2.0+0.2+4.0 ab^{-1} (H-20 scenario)
- FCC-ee 240+350 GeV with 10.0 + 2.6 ab^{-1}
- ILC + FCC-ee under the conditions listed above



	bb	cc	gg	WW	tautau	ZZ	gamgam	mumu	invis	GamTot
FCC-ee Δg / Comb. Δg	**1.38**	**1.26**	**1.40**	**1.62**	**1.29**	**1.17**	**1.13**	**1.22**	**1.14**	**1.30**
Extra FCC-ee* Running (yr)	**9.0**	**5.9**	**9.6**	**16.2**	**6.6**	**1.8**	**2.8**	**4.9**	**1.5**	**6.9**

*Additional FCC-ee running required to match ILC contribution to Combination. Assumes the same 10:2.6 luminosity ratio for 240:350 GeV except ZZ & invis which assume that all extra running is at 240 GeV

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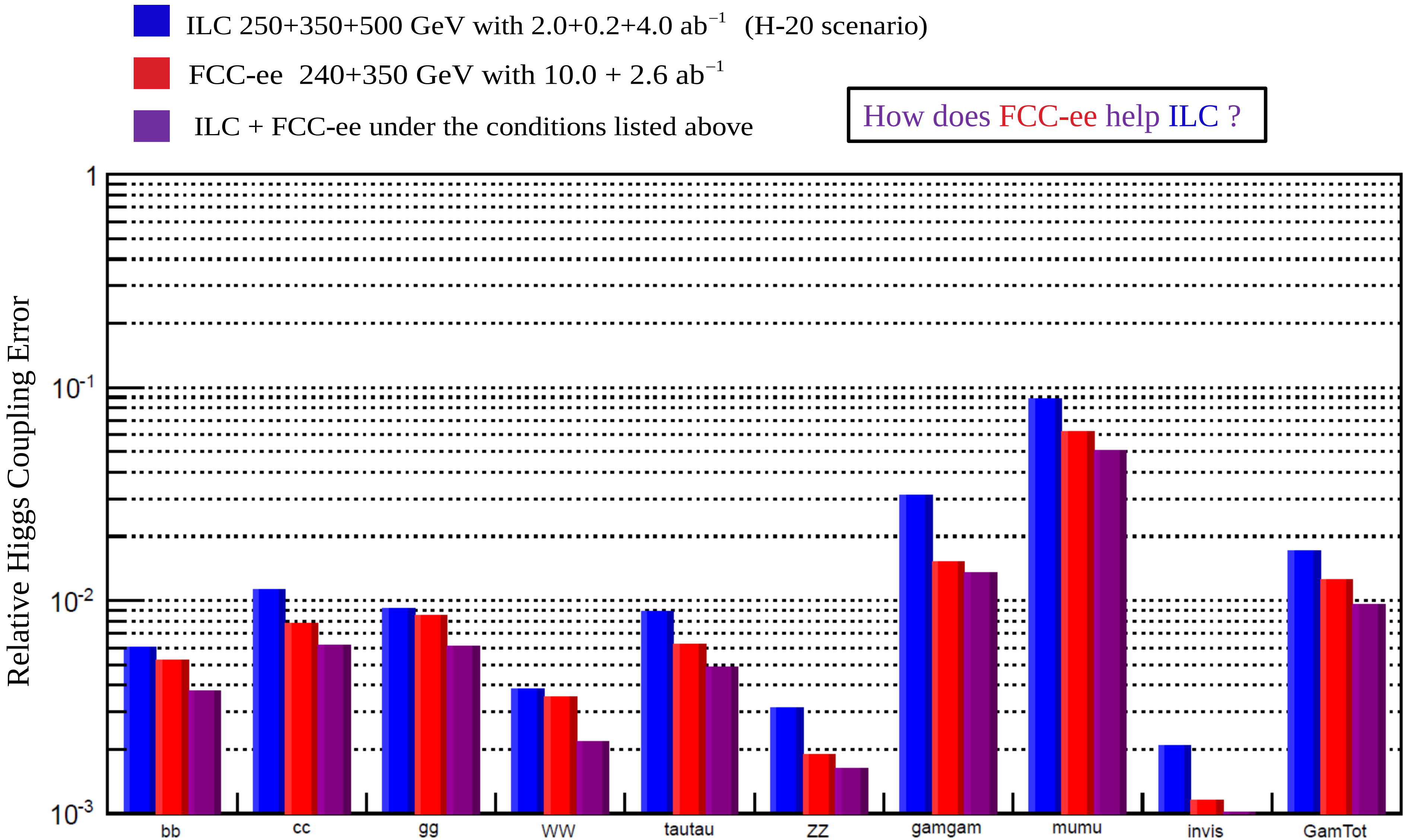
How does FCC-ee help ILC ?



	bb	cc	gg	WW	tautau	ZZ	gamgam	mumu	invis	GamTot
ILC Δg / Comb. Δg	**1.60**	**1.82**	**1.51**	**1.76**	**1.82**	**1.93**	**2.32**	**1.74**	**2.06**	**1.78**
Extra ILC* Running (yr)	**17.3**	**25.7**	**14.2**	**23.3**	**25.7**	**16.7**	**48.7**	**22.5**	**16.7**	**24.1**

*Additional ILC running required to match FCC-ee contribution to Combination. Assumes the same 1:2 luminosity ratio for 250:500 GeV except ZZ & invis which assumes all extra running at 250 GeV.

Highlights of Combination of FCC-ee with ILC H-20

	ILC	FCC-ee	ILC+FCC-ee
Δg_{HZZ}	0.31%	0.19%	0.16%
Δg_{HWW}	0.38%	0.35%	0.22%
Δg_{Hbb}	0.60%	0.52%	0.38%
$\Delta g_{H\tau\tau}$	0.89%	0.63%	0.49%
Δg_{Hgg}	0.92%	0.85%	0.61%

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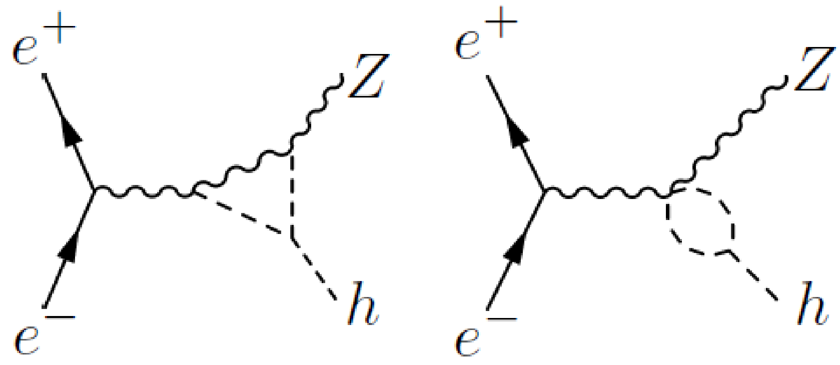
FCC-ee Higgs Self Coupling Measurement at Ecm=240 GeV



M. McCullough, arXiv:1312.3322

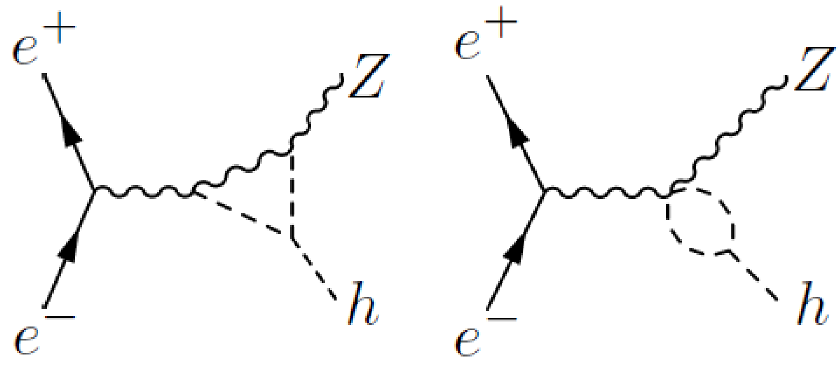
$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

g_{hZZ} fixed to SM value $(\delta_z = 0)$

g_{hhZZ} fixed to SM value

$$\Rightarrow\ \delta_H = \frac{\delta_\sigma^{240}}{0.014} = \frac{0.004}{0.014} = 29\%$$

FCC-ee Higgs Self Coupling Measurement at Ecm=240 GeV



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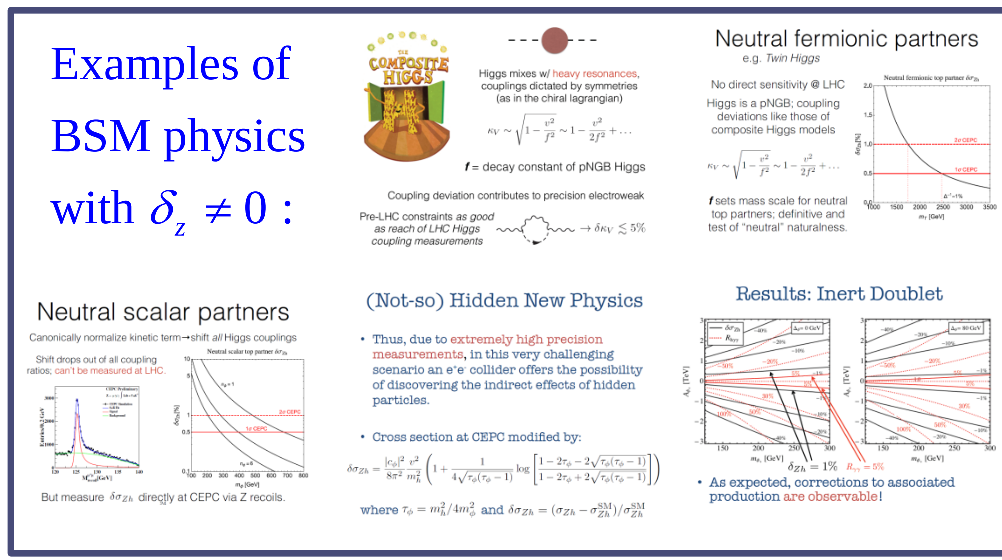
$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

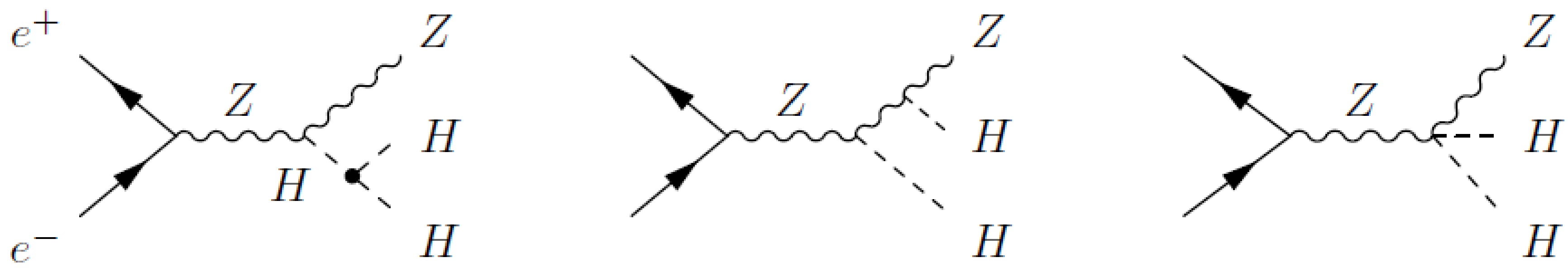


g_{hZZ} fixed to SM value $(\delta_z = 0)$

g_{hhZZ} fixed to SM value

$$\Rightarrow \delta_H = \frac{\delta_\sigma^{240}}{0.014} = \frac{0.004}{0.014} = 29\%$$

ILC Higgs Self Coupling Measurement at Ecm=500 GeV



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

g_{hhZZ} fixed to SM value $\leftarrow$ Needs to be more fully addressed in ILC studies

Extract g_{hhh} from measurement of $\sigma(ZHH)$

using HH $\rightarrow$ $b\bar{b}b\bar{b}$ & $b\bar{b}W^+W^-$

$$\frac{\Delta\sigma(ZHH)}{\sigma(ZHH)} = 16\% \Rightarrow \frac{\Delta g_{hhh}}{g_{hhh}} = 27\%$$ for ILC scenario H-20 @ 20 years.

Note : This assumes SM g_{HHH} . If $g_{HHH} = 2 \times \text{SM}$ then $\frac{\Delta g_{hhh}}{g_{hhh}} = 27\,\% \Rightarrow \frac{\Delta g_{hhh}}{g_{hhh}} = 14\,\%$.

Other Higgs Measurements with FCC-ee & ILC H-20

	FCC-ee 240 +350 GeV $10.0+2.6\ ab^{-1}$	ILC $250+350+500(550)$ GeV $2.0+0.25+4.0\ fb^{-1}$	*Combined*
Δm_H	11 MeV	12.5 MeV	8.3 MeV
$\frac{\Delta g_{HHH}}{g_{HHH}}$	29 %*	27 %*	20 %
$\frac{\Delta g_{ttH}}{g_{ttH}}$	13%	5.9 (2.4) %	5.4 (2.4) %
$\frac{g_{eeH}}{g_{eeH}^{SM}}$	$< 2.2 @ 3\sigma$	–	$< 2.2 @ 3\sigma$

* Loop contribution to σ(ZH)

* Tree-level contribution to σ(ZHH)

Summary

- ILC helps FCC-ee:
  - The 0.25% measurement of $\sigma(\nu\nu h)XBR(H\rightarrow bb)$ reduces errors on all Higgs couplings
  - The 2.4% Top Yukawa coupling measurement from ttH production improves upon the 13% measurement from the tt threshold scan.
  - ILC $\sigma(ZHH)$ measurement provides a 27% tree-level determination of the Higgs self-coupling, and could help clarify a Higgs self-coupling interpretation of the precision FCC-ee $\sigma(ZH)$ measurement.

- FCC-ee helps ILC:
  - Precision measurement of g_{HZZ} and various σXBR at 240 GeV help turn the ILC 0.25% measurement of $\sigma(\nu\nu h)XBR(H\rightarrow bb)$ into $\Delta g_{WW} = 0.22\%$
  - Much better meas. of Higgs invisible width, BSM decays, rare decays such as $\gamma\gamma$ and $\mu\mu$ Note: $\sum BR_i = 1$ can be used to improve all coupling errors if $\Delta BR(H \rightarrow BSM) < 1\%$
  - Unique access to Higgs coupling to 1st generation fermions.

- FCC-ee+ILC combination helps the particle physics community:
  - Higgs Z coupling error $\Delta g_{HZ} = 0.16\%$
  - Higgs W coupling error $\Delta g_{WW} = 0.22\%$
  - Higgs b coupling error $\Delta g_{bb} = 0.38\%$
  - Higgs self coupling error $\Delta g_{HHH} = 20\%$