Review of Higgs Studies at Future Lepton Colliders

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April 13, 2016
Experimental Challenges for the LHC Run II, KITP

Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Intl. collab. to study:

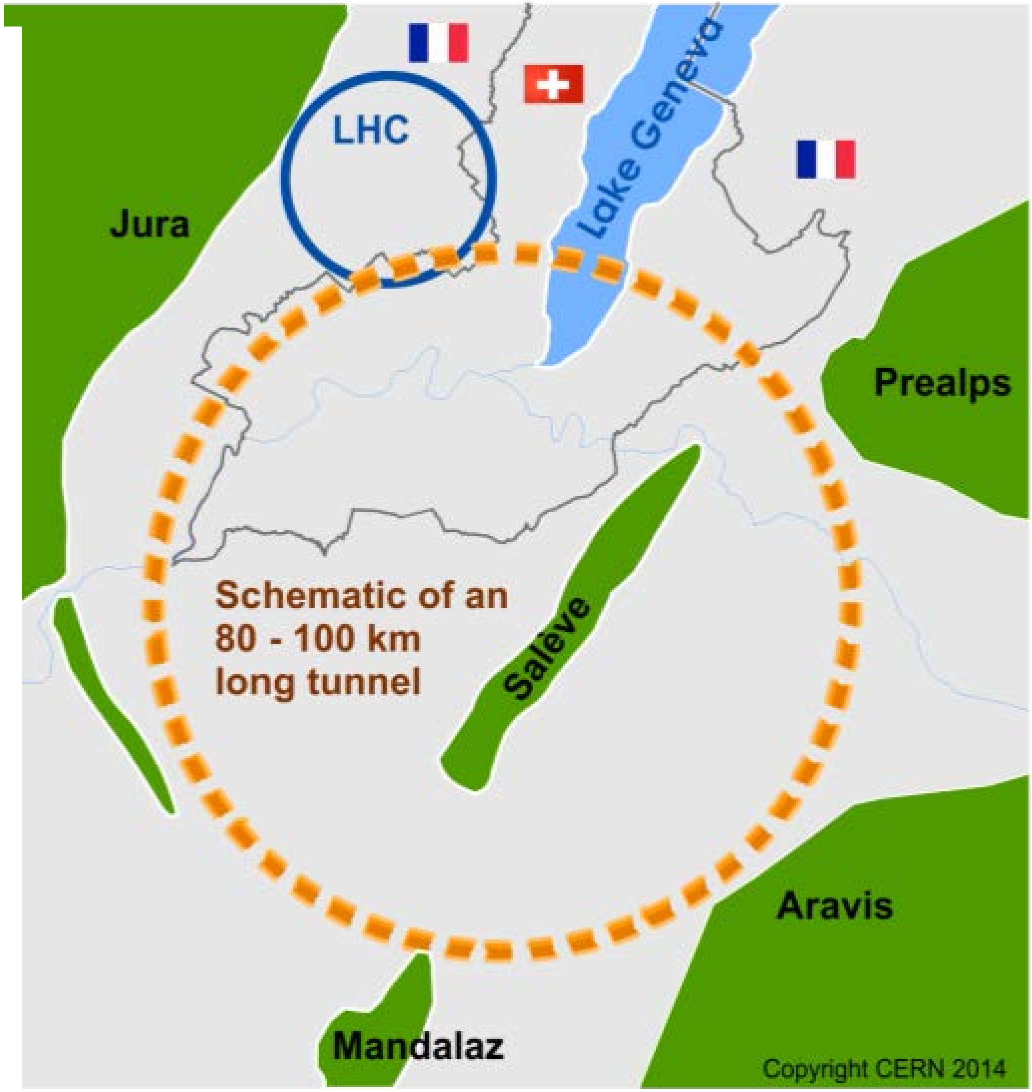
- ***pp*-collider (*FCC-hh*)** Ultimate goal, defining infrastructure.

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

- ***e^+e^-* collider (*FCC-ee*)** as potential first step ECM=90-400 GeV

- ***p-e* (*FCC-he*) option**

- **80-100 km infrastructure** in Geneva area



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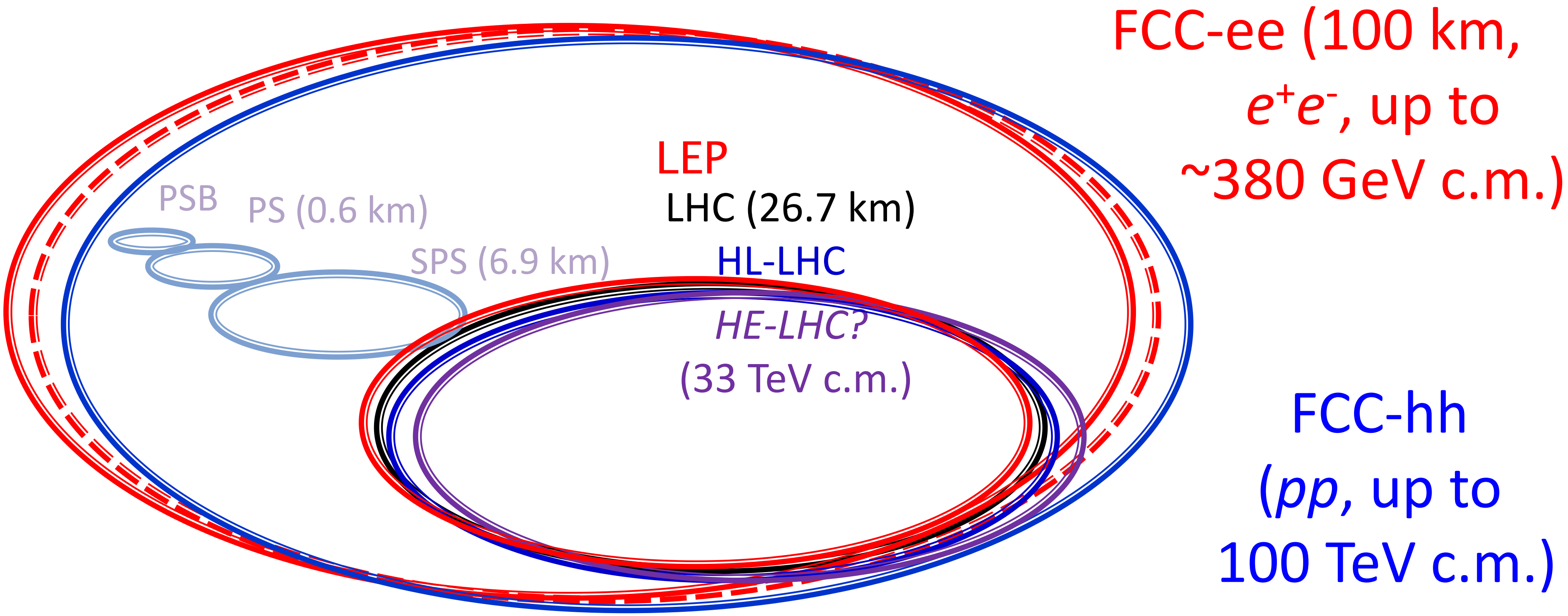
FCC-ee

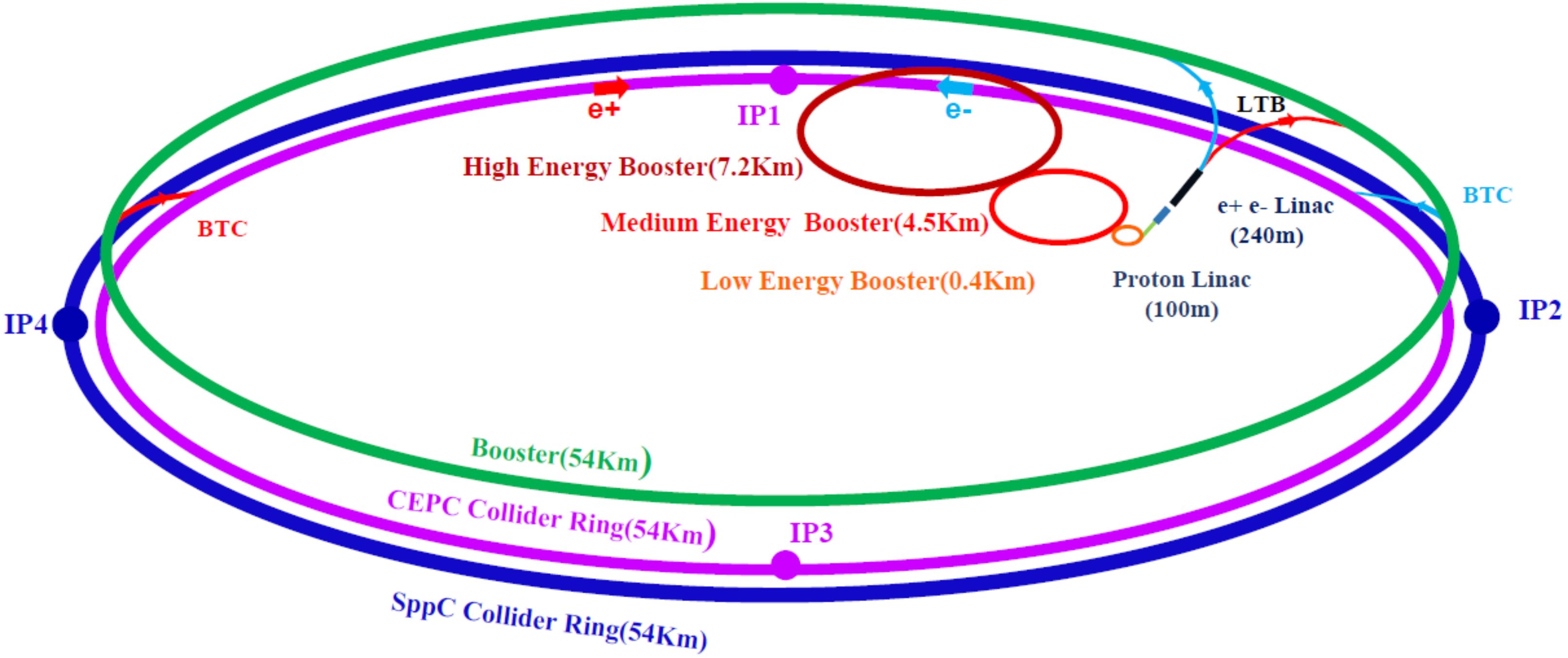
possible long-term strategy



60 years of *e^+e^- pp AA* (ep) physics @ highest energies

NB Great synergy and complementarity of FCC–ee and FCC–hh!

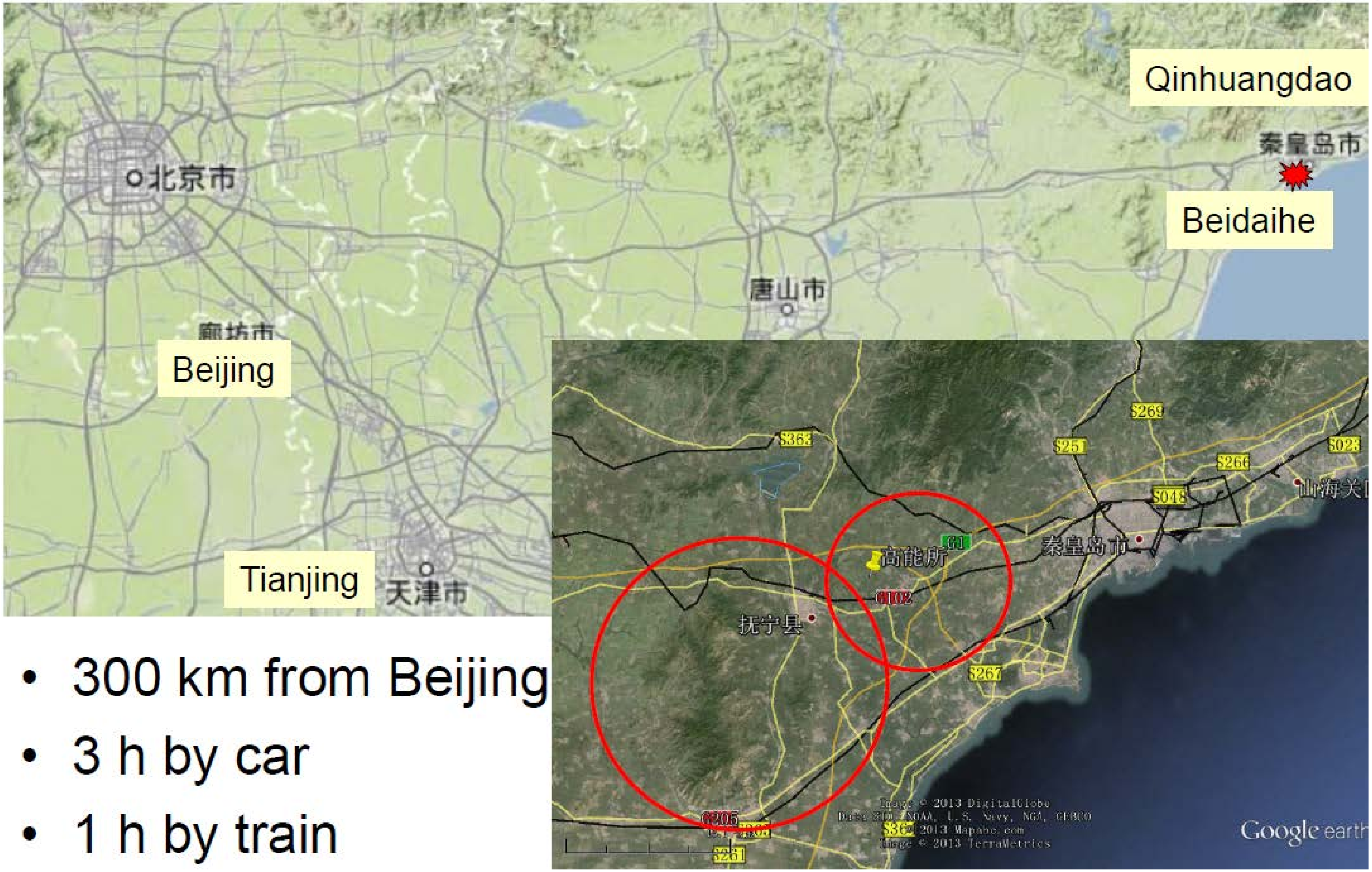
CEPC+SppC



LTB : Linac to Booster

BTC : Booster to Collider Ring

A Candidate Site



- 300 km from Beijing
- 3 h by car
- 1 h by train

Linear Colliders

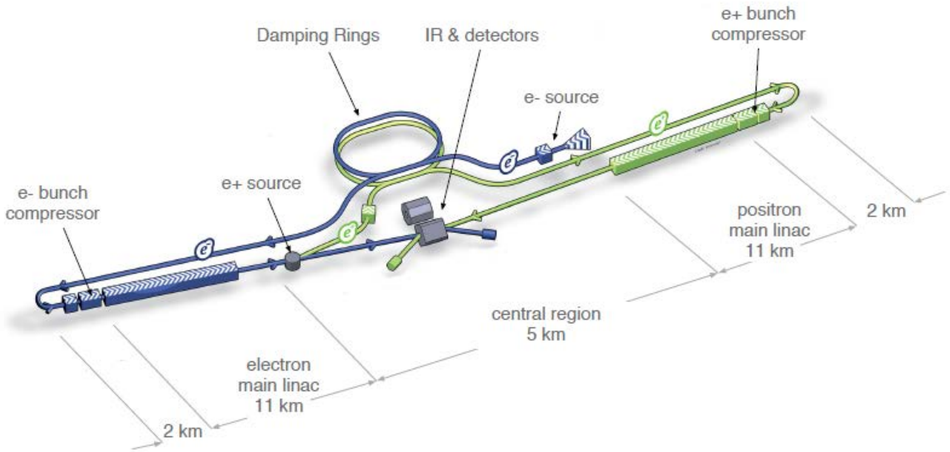
ILC International Linear Collider

e^+e^- linear collider with SCRF linac

$250 \leq \sqrt{s} \leq 1000$ GeV

31 km length ($\sqrt{s} \leq 500$ GeV)

49 km length ($\sqrt{s} = 1000$ GeV)



CLIC Compact Linear Collider

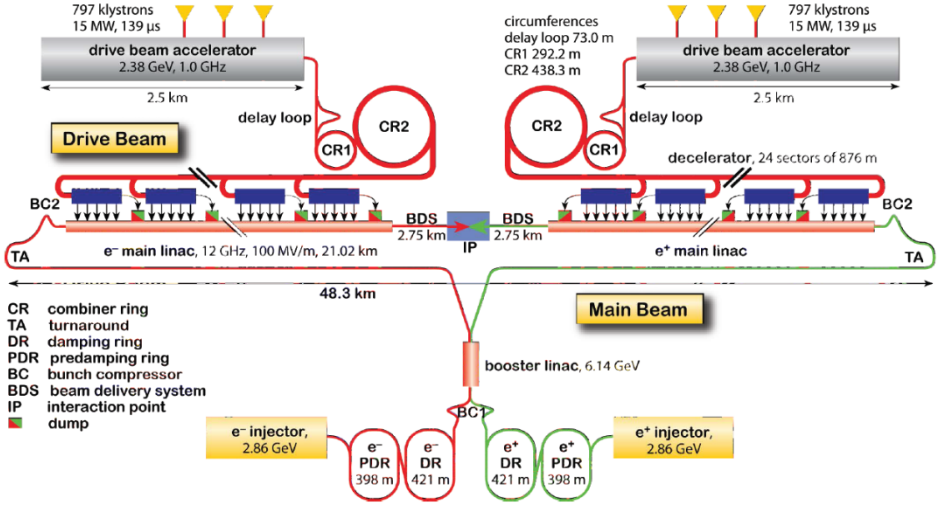
e^+e^- linear collider with X-Band linac

RF powered by a 2nd drive beam

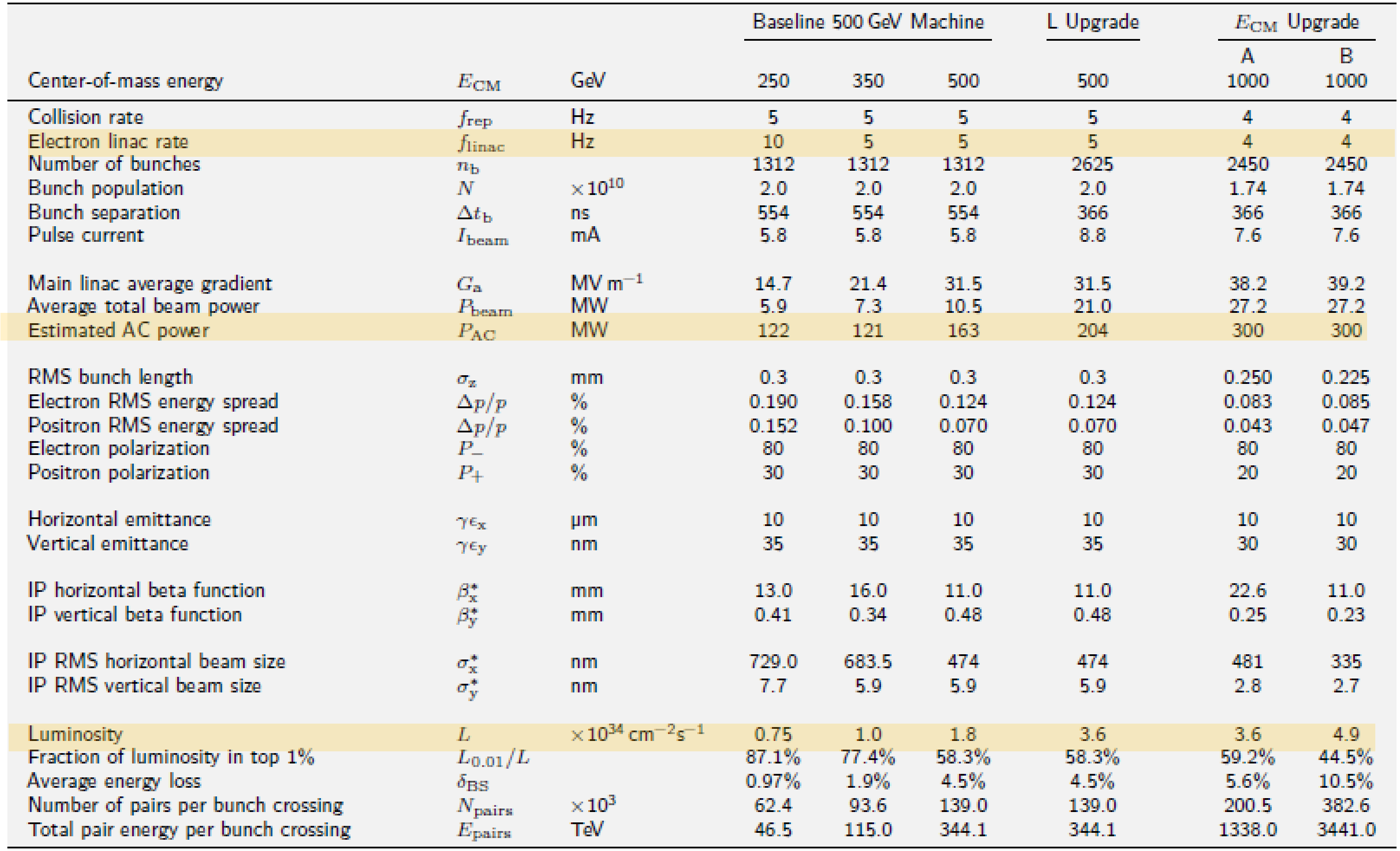
$350 \leq \sqrt{s} \leq 3000$ GeV

13 km length ($\sqrt{s} = 500$ GeV)

48 km length ($\sqrt{s} = 3000$ GeV)



ILC Machine Parameters from TDR



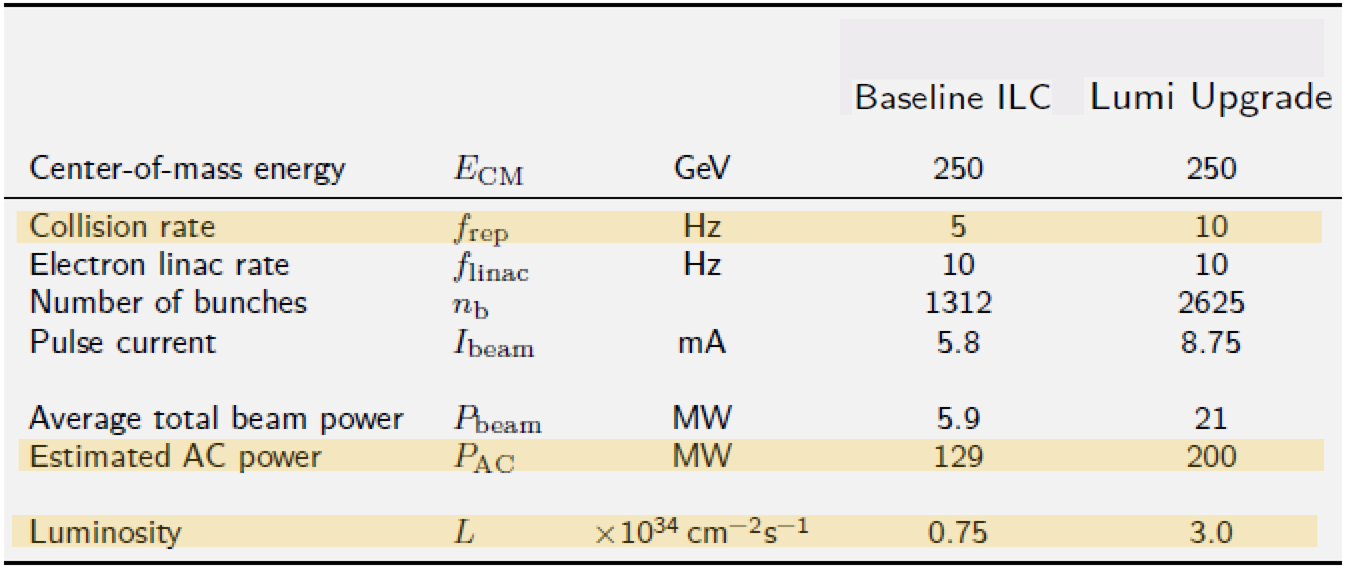
			Baseline 500 GeV Machine			L Upgrade	E_{CM} Upgrade	
							A	B
Center-of-mass energy	E_{CM}	GeV	250	350	500	500	1000	1000
Collision rate	f_{rep}	Hz	5	5	5	5	4	4
Electron linac rate	f_{linac}	Hz	10	5	5	5	4	4
Number of bunches	n_b		1312	1312	1312	2625	2450	2450
Bunch population	N	$\times 10^{10}$	2.0	2.0	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

Luminosity Upgrade for Ecm=250 GeV



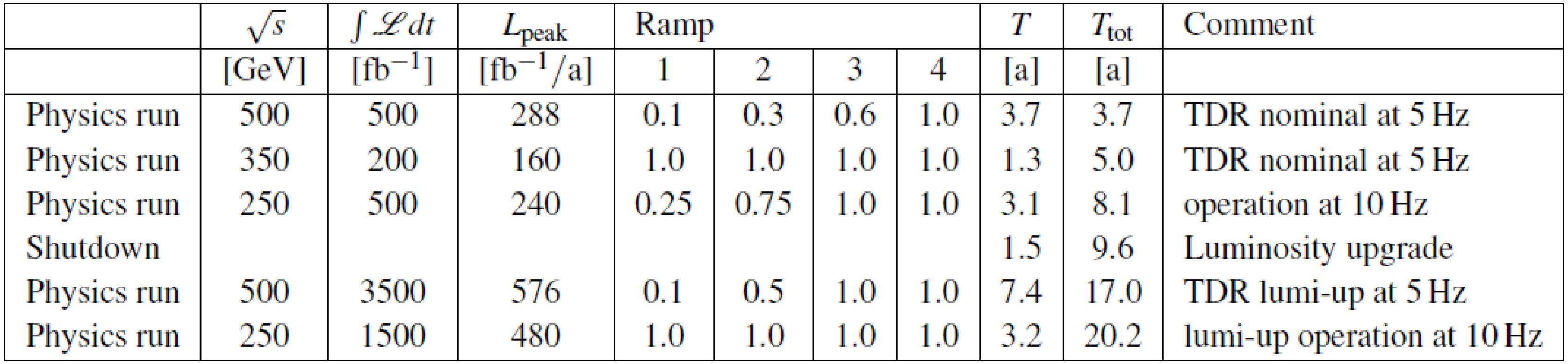
			Baseline ILC	Lumi Upgrade
Center-of-mass energy	E_{CM}	GeV	250	250
Collision rate	f_{rep}	Hz	5	10
Electron linac rate	f_{linac}	Hz	10	10
Number of bunches	n_{b}		1312	2625
Pulse current	I_{beam}	mA	5.8	8.75
Average total beam power	P_{beam}	MW	5.9	21
Estimated AC power	P_{AC}	MW	129	200
Luminosity	L	$\times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$	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 $3 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ luminosity with 200 MW total AC power.

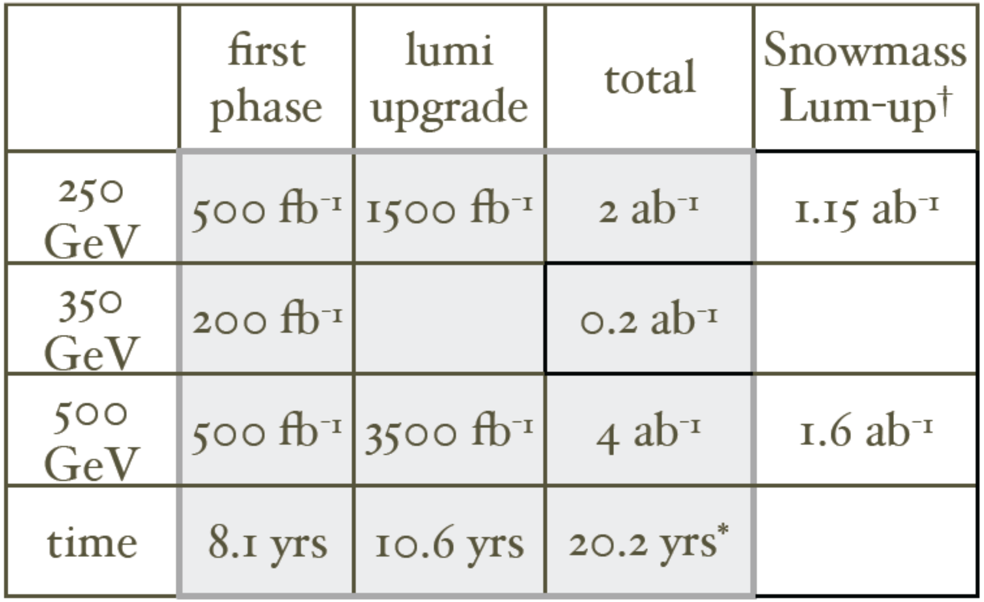
ILC Running Scenario



	$\sqrt{s}$	$\int \mathscr{L} dt$	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.

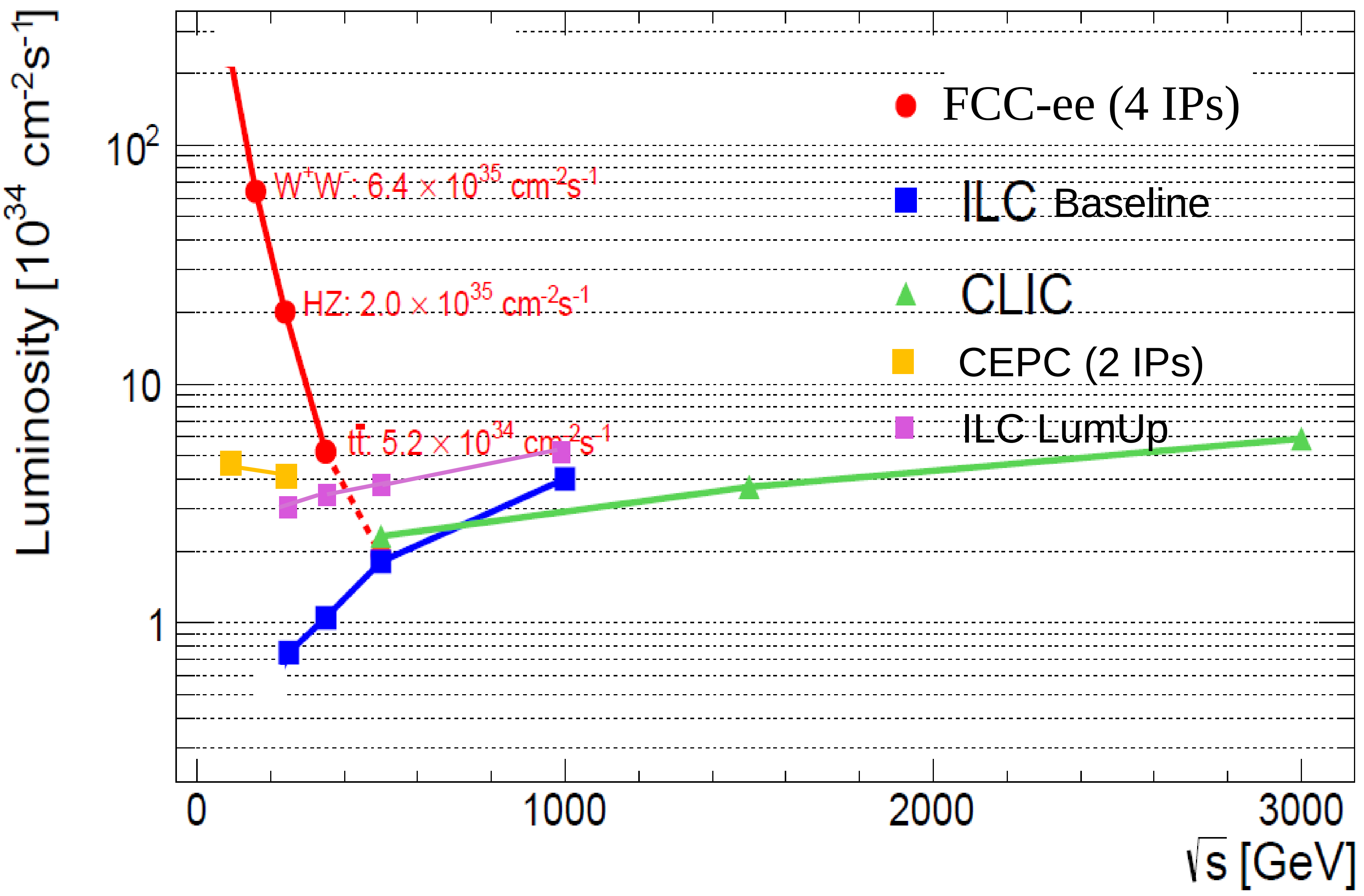
H-20



	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[*]	

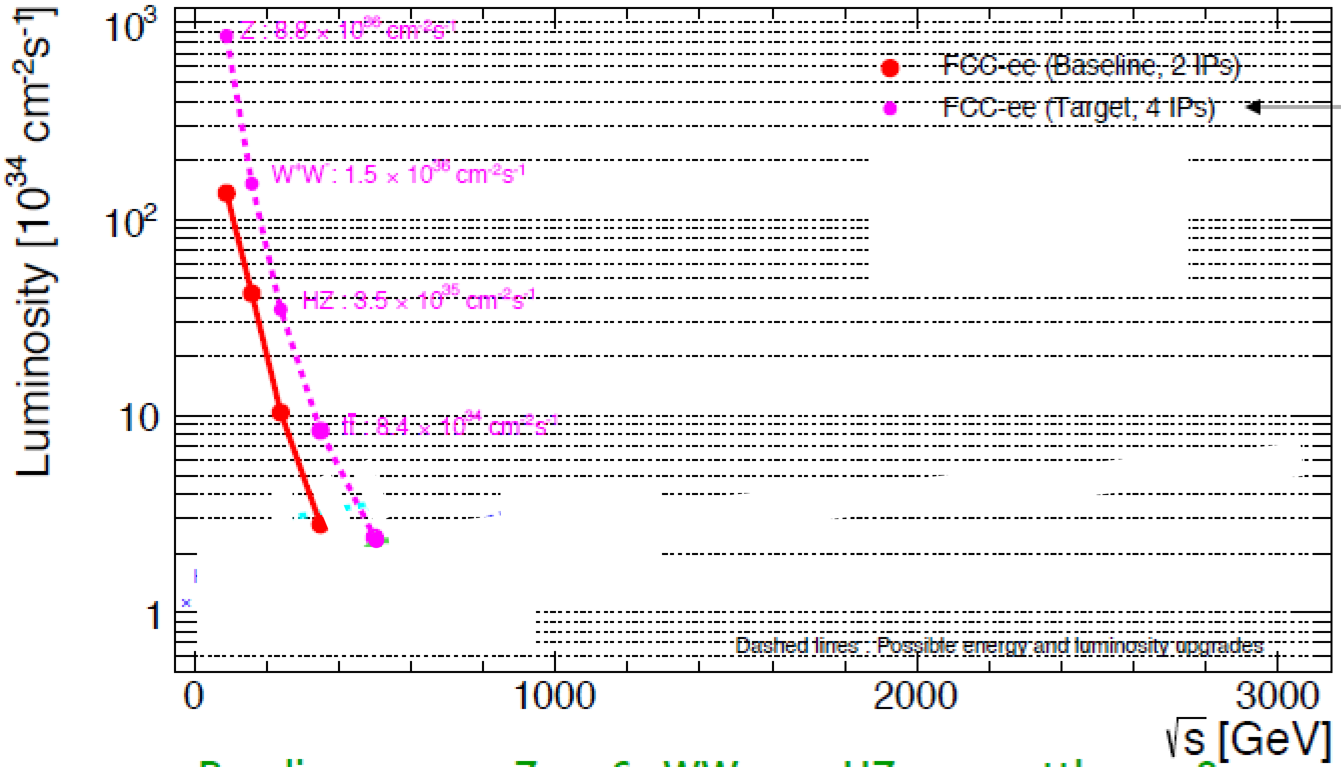
[*] includes 1.5 years for luminosity upgrade

[†] ILC Higgs whitepaper: arXiv:1310.0763


Luminosity [10^{34} cm^{-2}s^{-1}]
10^2
10
1
0
1000
2000
3000
√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

FCC-ee

- We have now coherent and sound optics for the first time !
  - Conservative parameters (see backup slides) but sound base towards the target

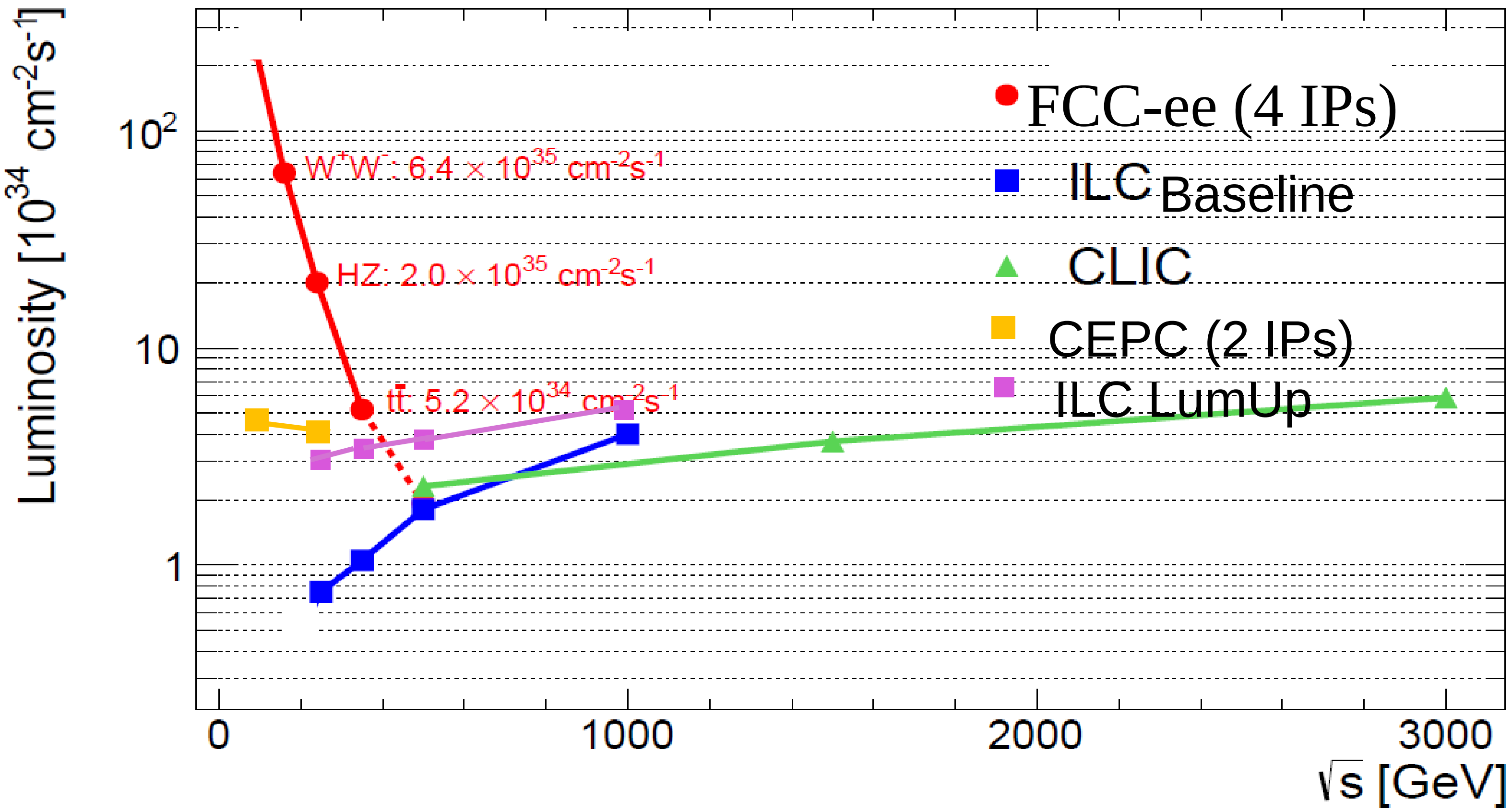


From F. Zimmermann,
FCC Week Washington

- Baseline now Z : 136 ; WW : 42 ; HZ : 10.4 ; ttbar : 2.8
- Baseline before Z : 84 ; WW : 42 ; HZ : 21.2 ; ttbar : 6.1 x 10^{34} $cm^{-2}s^{-1}$

➨ Target luminosities typically 5-6 times larger than baseline

$\sqrt{s} = 90,\ 160$ GeV



Not easy to run the ILC at these energies.

e.g. 150 GeV (125 GeV) e^- beam needed for positron production in baseline (lumi upgrade) design.

In the lumi upgrade config L=4×10^{33} @ 91 GeV and L=8×10^{33} @ 160 GeV .

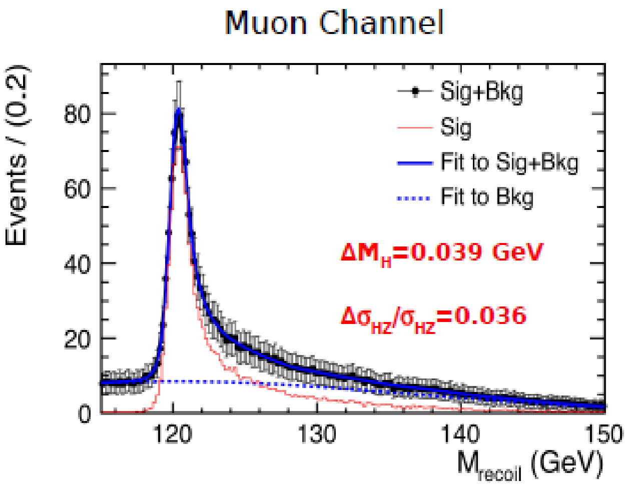
This would provide $\int L dt = 100\ \text{fb}^{-1}$ @ 91 GeV in 10 mos. and $\int L dt = 200\ \text{fb}^{-1}$ @ 160 GeV in 10 mos.

Overview of Higgs Physics at e^+e^- Colliders at $\sqrt{s} = 250, 350, 500, 1000$ GeV

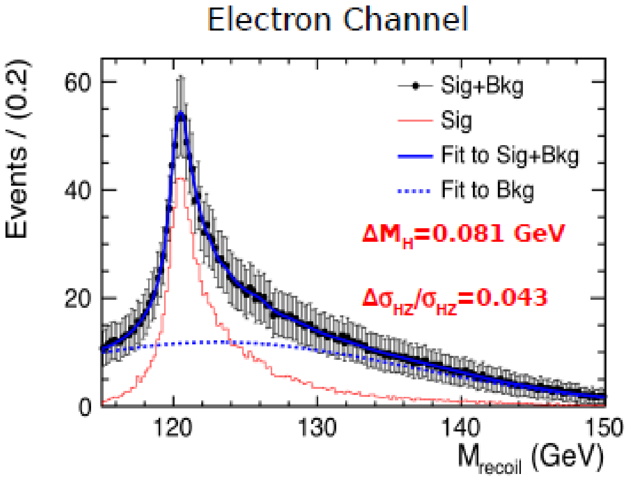
Measurement of $\sigma(e^+e^- \to ZH)$ $\sqrt{s} = 250$ GeV

Higgs Recoil Measurement of Higgs Mass and Higgstrahlung Cross Section

-- Key to model independent Higgs coupling measurements


Muon Channel

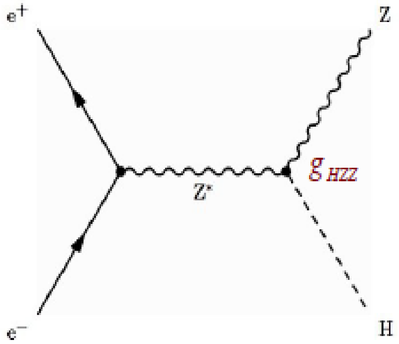
Very Precise Measurement
S/B = 8 in Peak Region


Electron Channel

Less Precise
Bremsstrahlung in detector material

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

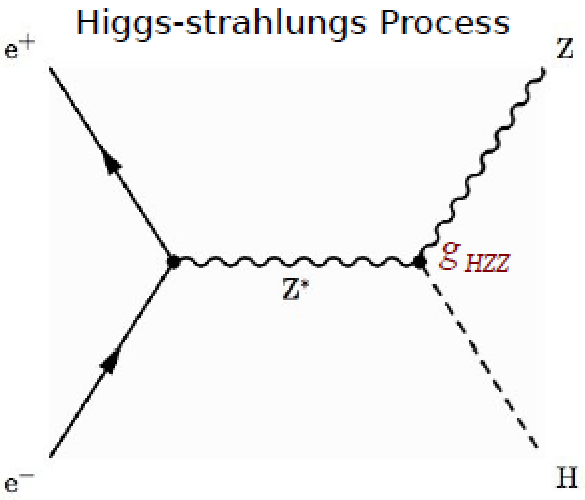
$\Delta M_H = .015$ GeV, $\Delta\sigma_{HZ} / \sigma_{HZ}$=1.2% for L=1150 fb^{-1}



$$\sigma_{HZ} \sim g_{HZZ}^2$$

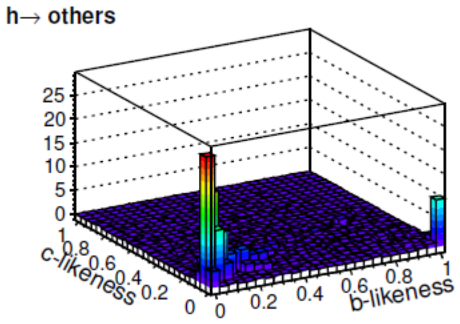
$$\Rightarrow \Delta g_{HZZ} / g_{HZZ} = 1.3\% \ (0.6\%) \text{ for L=250 (1150) fb}^{-1}$$

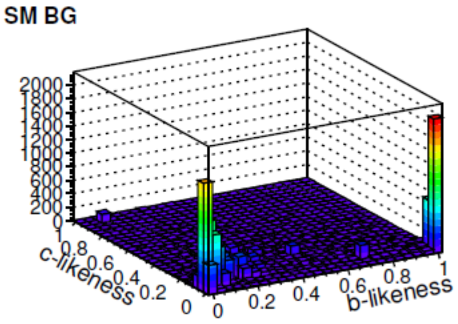
$\sigma \times$BR measurements using $e^+e^- \to ZH$ $\sqrt{s} = 250$ GeV

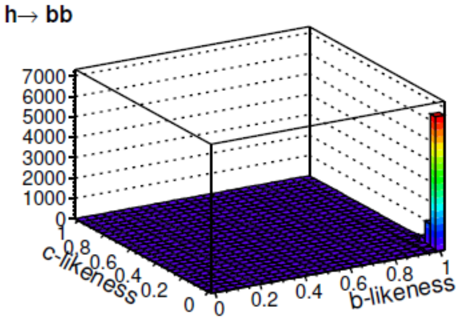

Higgs-strahlungs Process

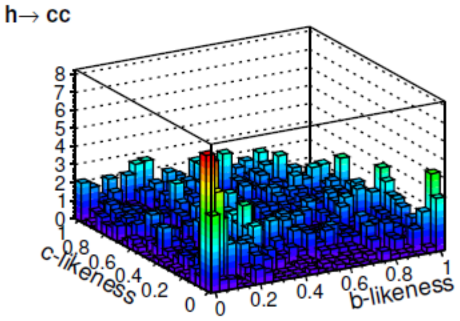
All Z decays are used for measurement of $\sigma \times$BR. These include Z $\to qq$ and Z $\to \nu\nu$.

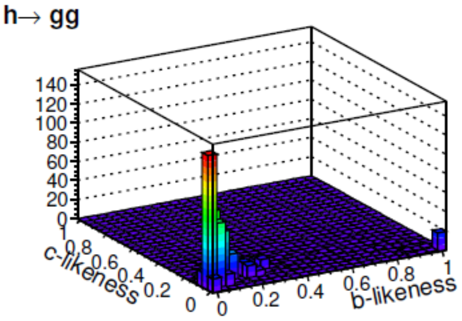
Flavor tagging very important for distinguishing different decay modes


h→ others

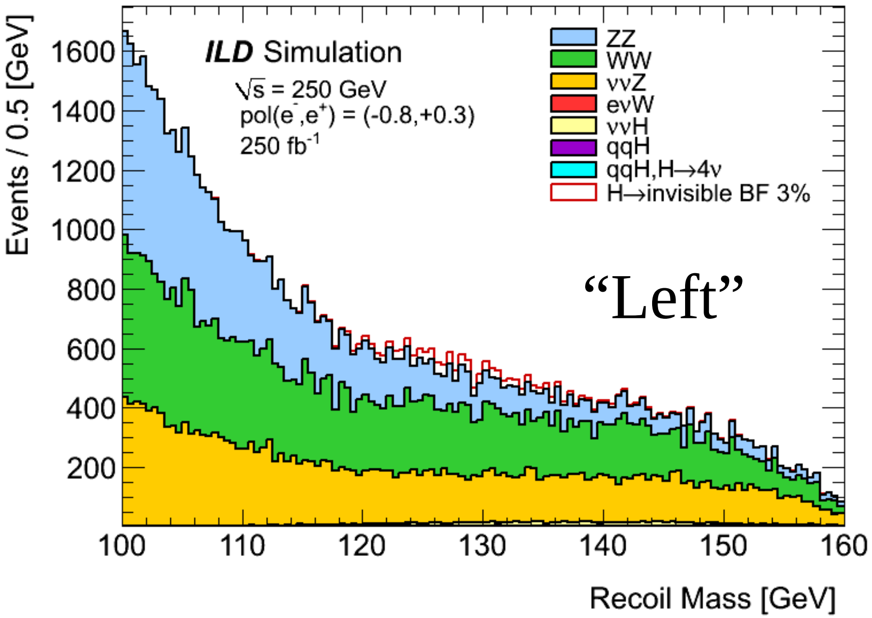

SM BG

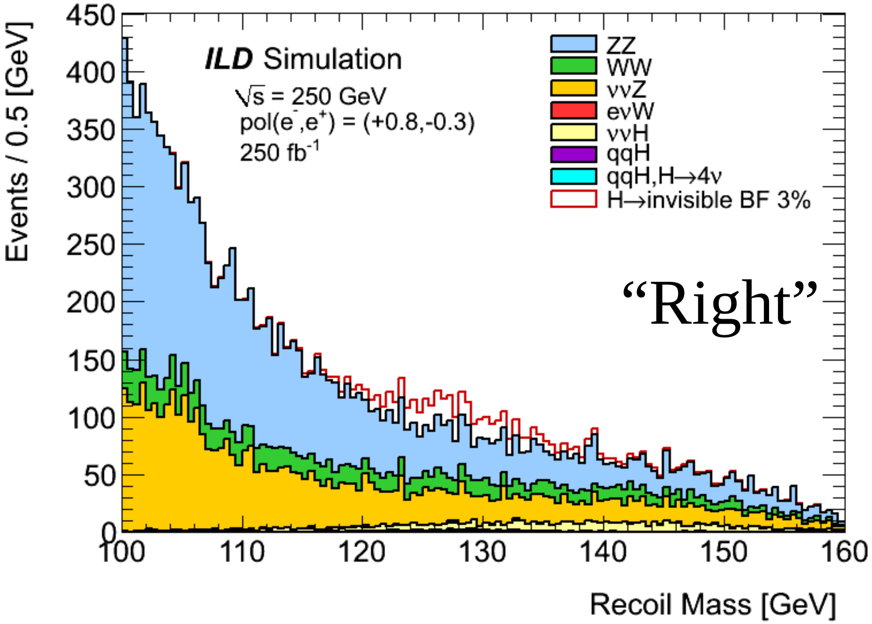

h→ bb


h→ cc

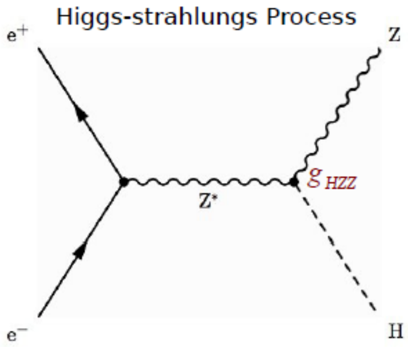

h→ gg

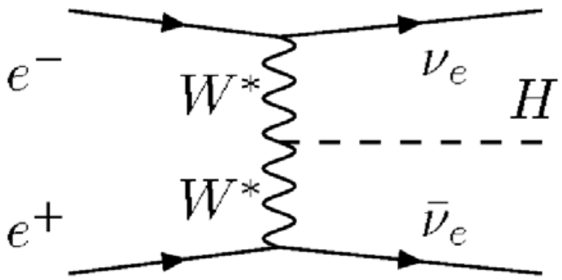
$e^+e^- \to ZH, \ \mathrm{Z} \to \mathrm{qq}, \ \mathrm{H} \to \mathrm{invisible} \qquad \sqrt{s} = 250\ \mathrm{GeV}$





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



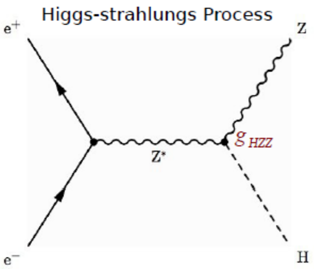


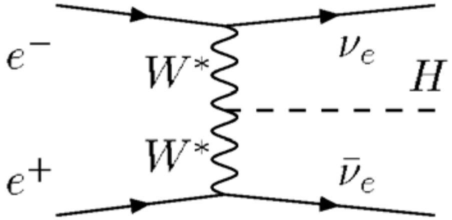
All of the Higgstrahlung studies that were done at $\sqrt{s} = 250$ GeV can also be done at $\sqrt{s} = 350$ GeV. Precisions for $\sigma \bullet BR$ are comparable, as is the precision for σ(ZH) once Z $\to q\bar{q}$ decays are included.

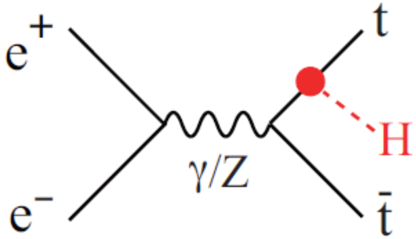
WW fusion production of the Higgs at $\sqrt{s} = 350$ GeV provides a much better measurement of g_{HWW} compared to $\sqrt{s} = 250$ GeV. This gives a much improved estimate of the total Higgs width Γ_H which in turn significantly improves the coupling errors obtained from $\sigma \bullet BR$ measurements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

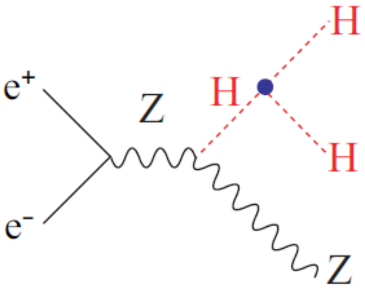
The recoil Higgs mass measurement is significantly worse at $\sqrt{s} = 350$ GeV with respect to $\sqrt{s} = 250$ GeV. However, there is hope that direct calorimeter Higgs mass measurements using $e^+e^- \to \nu\nu H$ will recover the precision.

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







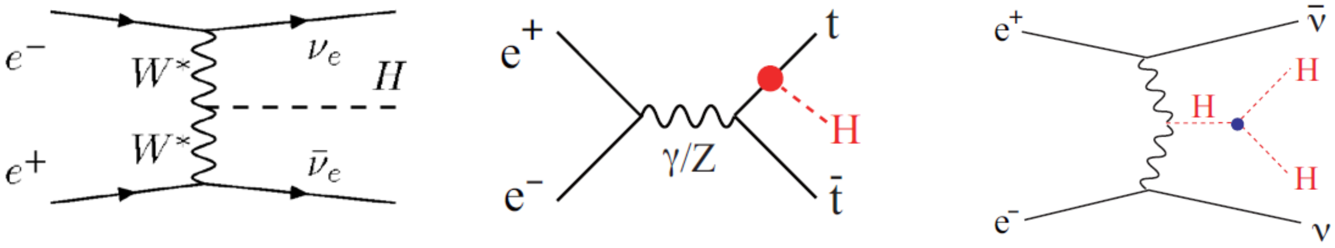


The g_{HWW} coupling can also be measured well at $\sqrt{s} = 500$ GeV through WW fusion production of the Higgs. Also the measurement of $\sigma(e^+e^- \to \nu\nu H) \times BR(H \to X)$ can be made for many Higgs decay modes $H \to X$.

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.

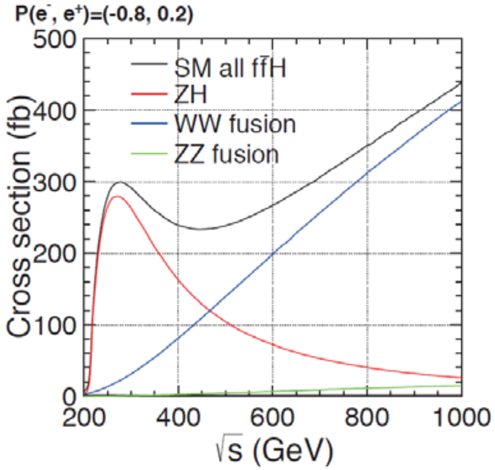
$e^+e^- \rightarrow \nu\nu H$, ttH , $\nu\nu HH$ $\sqrt{s} = 1$ TeV



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).

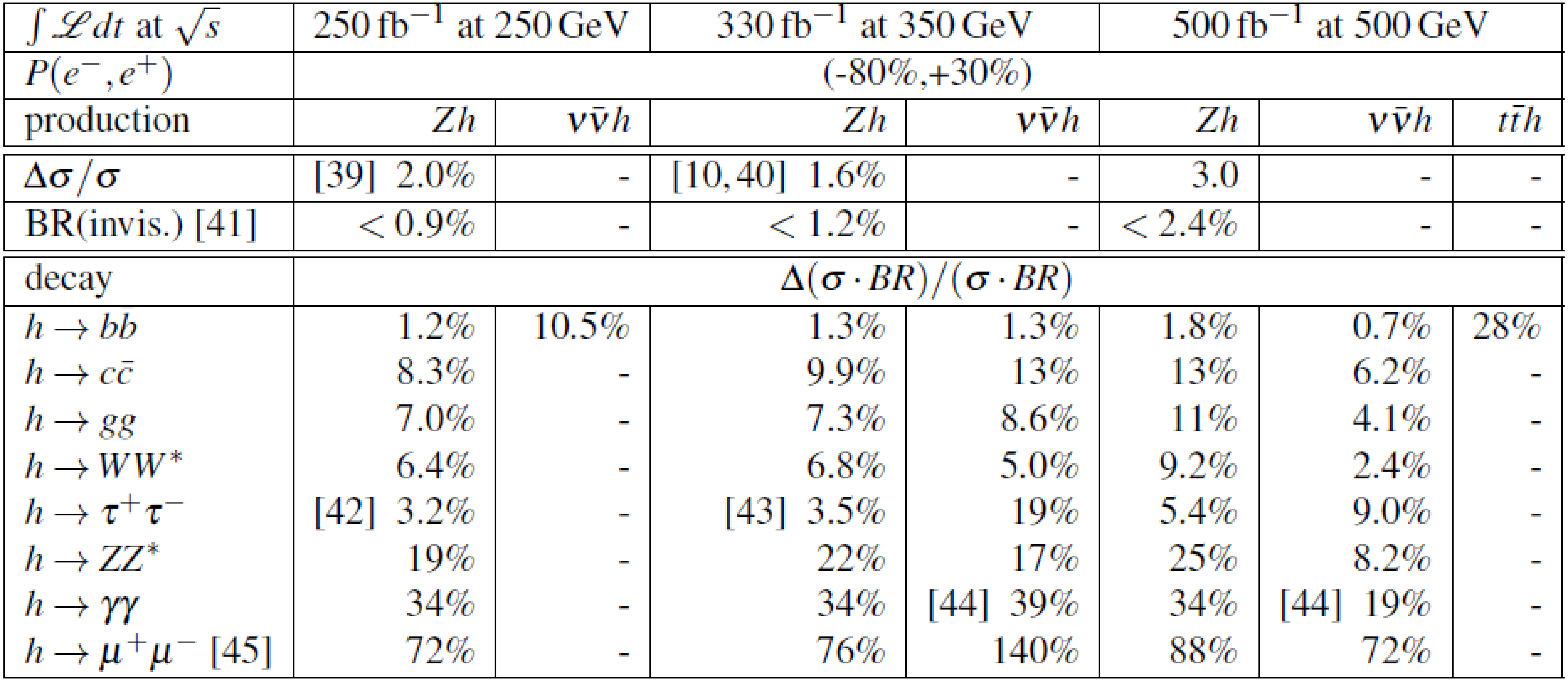
Search for additional Higgs bosons that might have been missed at LHC, and study new resonances below $\sqrt{s} = 1$ TeV that might be seen at LHC

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, especially if polarized beams are used:



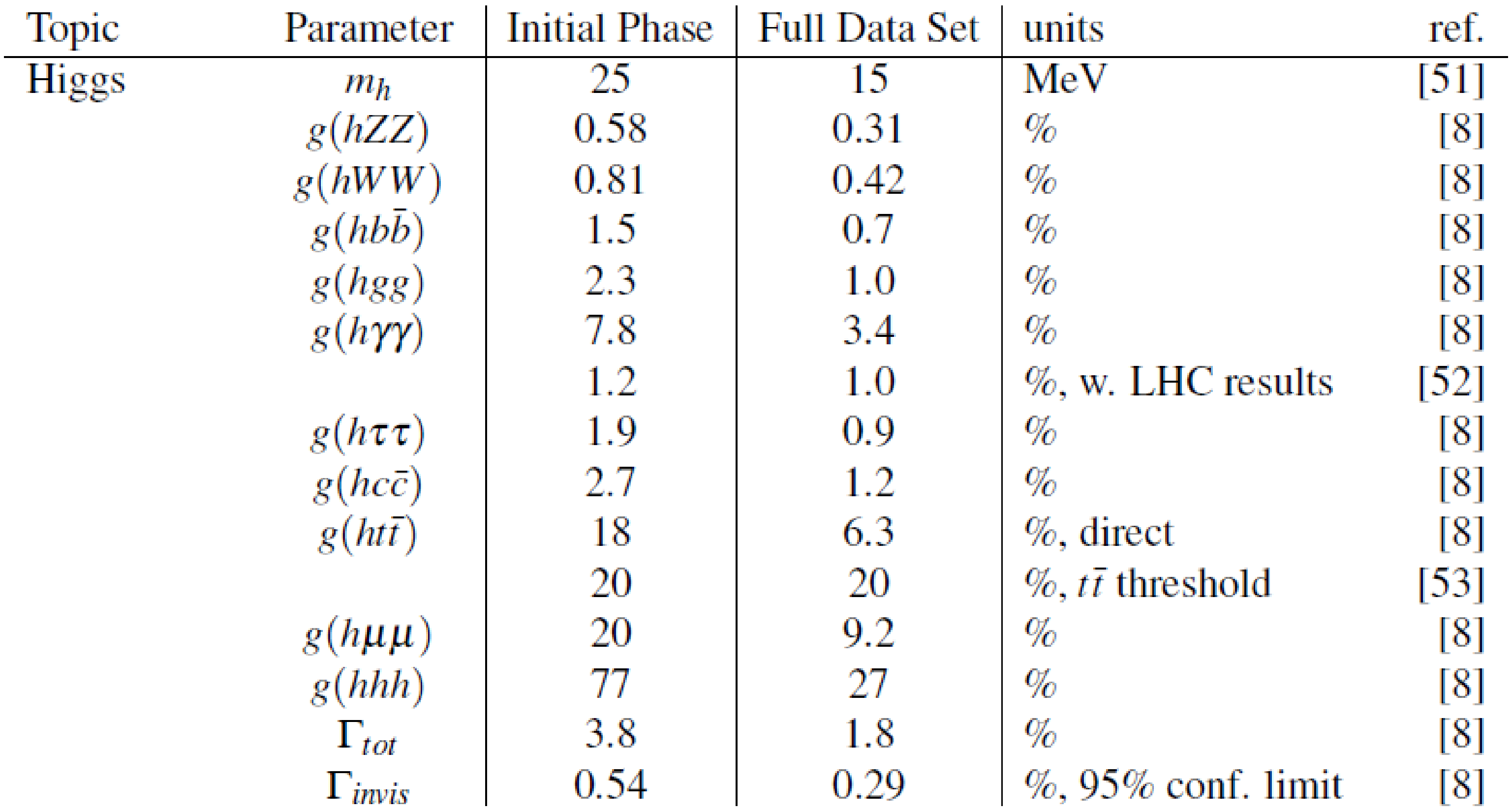
Summary of ILC Higgs Measurement Precisions

From "500 GeV ILC Operating Scenarios" arXiv : 1506.07830

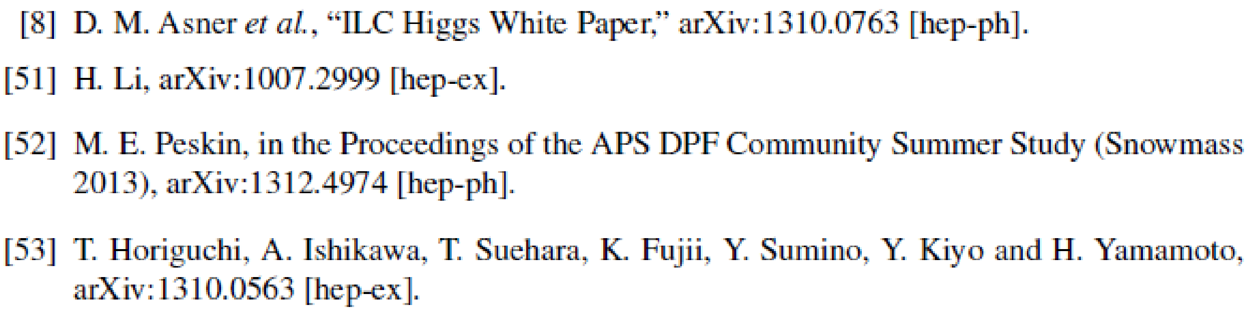


$\int \mathcal{L} dt$ at $\sqrt{s}$	$250\,\mathrm{fb}^{-1}$ at $250\,\mathrm{GeV}$		$330\,\mathrm{fb}^{-1}$ at $350\,\mathrm{GeV}$		$500\,\mathrm{fb}^{-1}$ at $500\,\mathrm{GeV}$		
$P(e^-,e^+)$	(-80%,+30%)						
production	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	$t\bar{t}h$
$\Delta\sigma/\sigma$	[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%	-

ILC Model Independent 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]



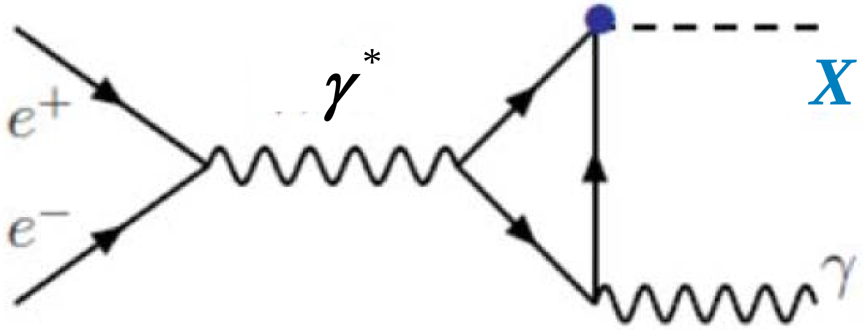
[8] D. M. Asner *et al.*, "ILC Higgs White Paper," arXiv:1310.0763 [hep-ph].

[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].

750 GeV DiPhoton Resonance at 1 TeV ILC



$$\Gamma_{\gamma\gamma}(X_{750}) \approx 10^3 \times SM\ \Gamma_{\gamma\gamma}(H_{125})$$

$$\sigma(e^+e^- \to \gamma X_{750}) \approx 1 - 100 \text{ fb} \quad \text{at } \sqrt{s} = 1 \text{ TeV}$$

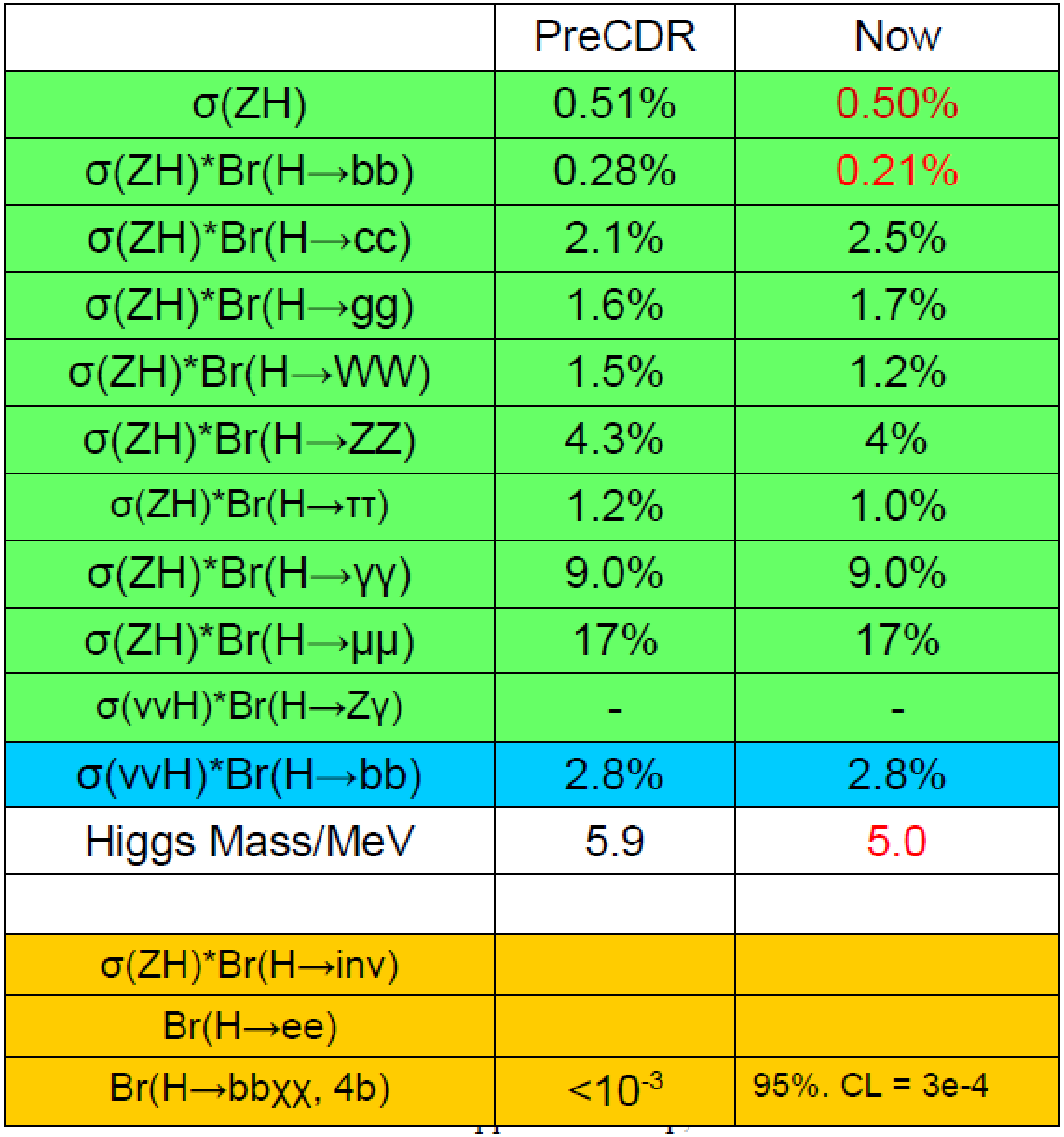
In principle this reaction has a threshold near 750 GeV, however the threshold dependence is given by $(1-M_X^2/s)^3$, meaning that in practice one should operate at 1 TeV

At 1 TeV, X is accompanied by a monochromatic photon with E_γ ~220GeV, which provides a very clean signature. This allows to measure the total cross section and therefore $\Gamma_{\gamma\gamma}$ at the % level. The $Z\gamma$ contribution can be separated from $\gamma\gamma$ by using an electron beam with longitudinal polarisation giving ALR.

F. Richard, arXiv:1604.01640

CEPC

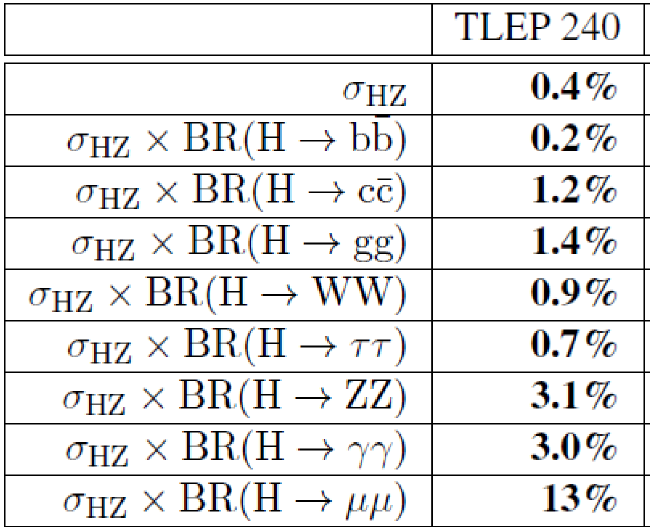
$5\ \mathrm{ab}^{-1}$



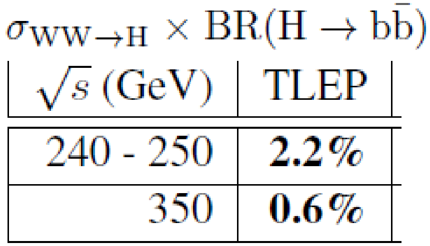
	PreCDR	Now
σ(ZH)	0.51%	0.50%
σ(ZH)*Br(H→bb)	0.28%	0.21%
σ(ZH)*Br(H→cc)	2.1%	2.5%
σ(ZH)*Br(H→gg)	1.6%	1.7%
σ(ZH)*Br(H→WW)	1.5%	1.2%
σ(ZH)*Br(H→ZZ)	4.3%	4%
σ(ZH)*Br(H→ττ)	1.2%	1.0%
σ(ZH)*Br(H→γγ)	9.0%	9.0%
σ(ZH)*Br(H→μμ)	17%	17%
σ(ννH)*Br(H→Zγ)	-	-
σ(ννH)*Br(H→bb)	2.8%	2.8%
Higgs Mass/MeV	5.9	5.0
σ(ZH)*Br(H→inv)		
Br(H→ee)		
Br(H→bbχχ, 4b)	$<10^{-3}$	95%. CL = 3e-4

FCC-ee

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

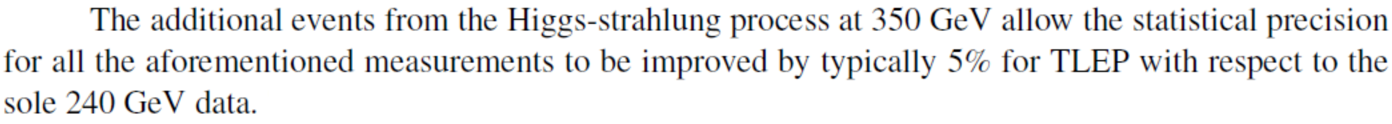


	TLEP 240
σ_{HZ}	**0.4%**
$\sigma_{\mathrm{HZ}} \times \mathrm{BR}(\mathrm{H} \to \mathrm{b\bar{b}})$	**0.2%**
$\sigma_{\mathrm{HZ}} \times \mathrm{BR}(\mathrm{H} \to \mathrm{c\bar{c}})$	**1.2%**
$\sigma_{\mathrm{HZ}} \times \mathrm{BR}(\mathrm{H} \to \mathrm{gg})$	**1.4%**
$\sigma_{\mathrm{HZ}} \times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



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

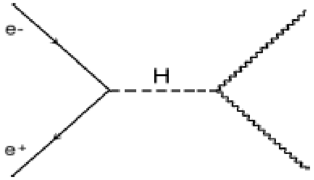
$\sqrt{s}$ (GeV)	TLEP
240 - 250	**2.2%**
350	**0.6%**



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.

FCC-ee

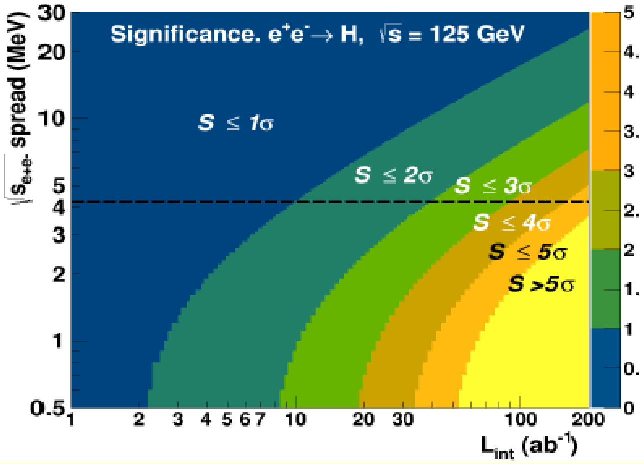
- Resonant s-channel Higgs production at FCC-ee ($\sqrt{s}$ = 125 GeV):

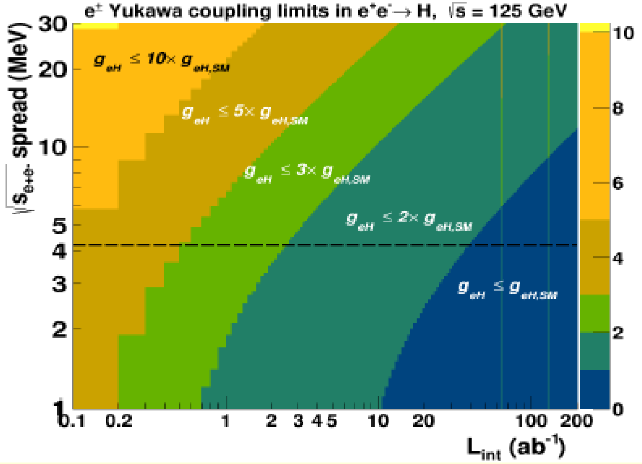


$\sigma(e^+e^- \to H)_{B\text{-}W}$ = 1.64 fb

$\sigma(e^+e^- \to H)_{visible}$ = 290 ab (ISR + $\sqrt{s}_{spread} = \Gamma_H$ = 4.2 MeV)

- Preliminary study for signal + background for "all" 10 decay channels.

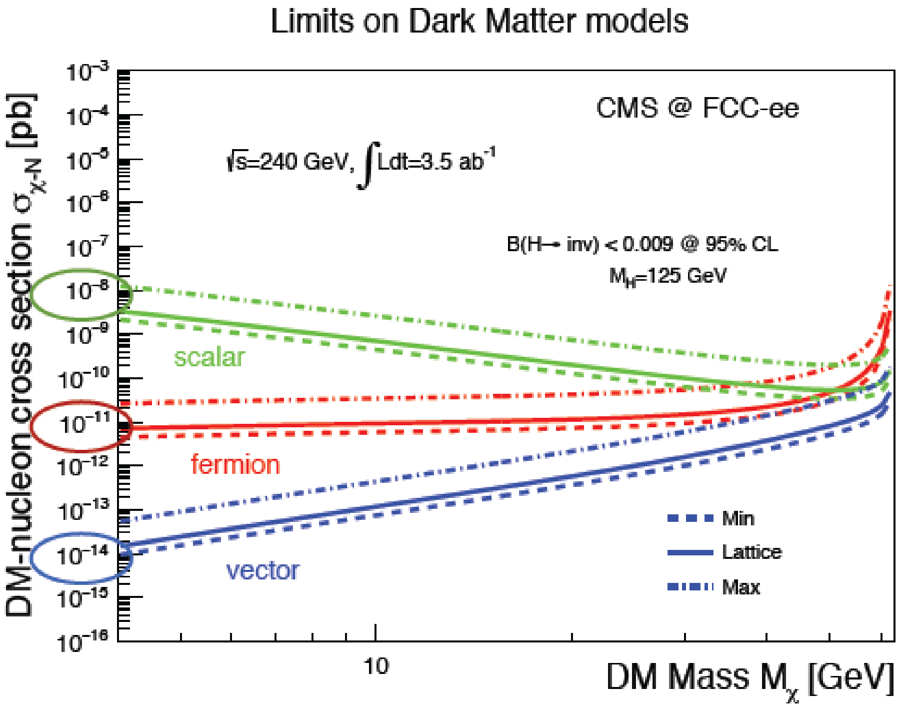


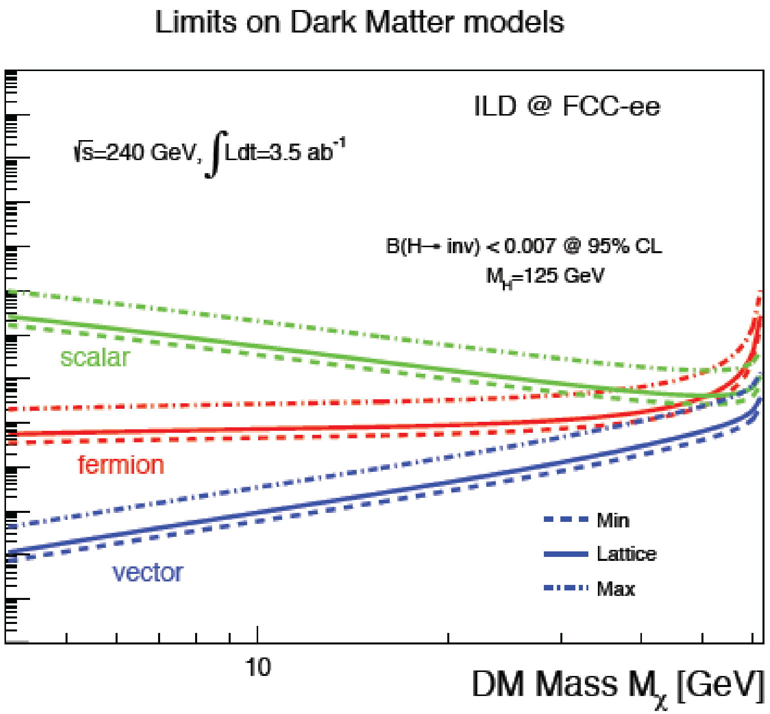


$\sqrt{s}_{spread} = \Gamma_H$, L_{int} = 10 ab^{-1}: S ≈ 0.7, BR(Hee) < 2.8×BR$_{SM}$, $g_{eH} < 1.7 \times g_{eH,SM}$ (95% CL)

- Challenging performances: Mono-chromatization to achieve $\sqrt{s}_{spread} \sim \Gamma_H$
- Fundamental & unique physics accessible:
  - → Electron Yukawa coupling
  - → Higgs width measurable ("natural" threshold scan)?

FCC-ee@3.5ab^{-1}

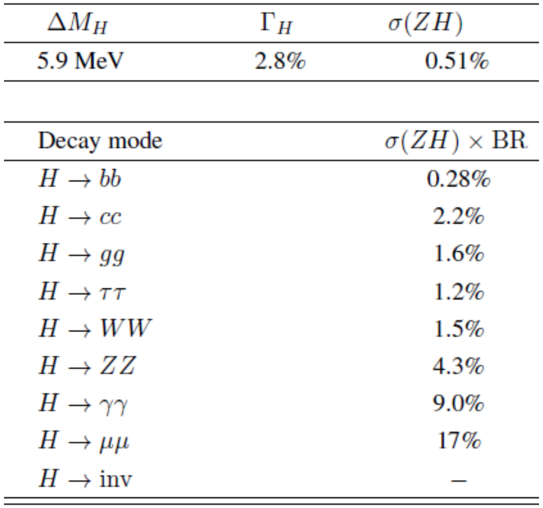




- We can exclude wrt to current CMS more ~2 order of magnitude lower DM-nucleon cross section

ILC + CEPC Model Independent Higgs Coupling Precision

Take CEPC errors on σ and σ•BR from pre Conceptual Design Report assuming 240 GeV with 5 ab^{-1} :



ΔM_H	Γ_H	$\sigma(ZH)$
5.9 MeV	2.8%	0.51%

Decay mode	$\sigma(ZH) \times$ BR
$H \to bb$	0.28%
$H \to cc$	2.2%
$H \to gg$	1.6%
$H \to \tau\tau$	1.2%
$H \to WW$	1.5%
$H \to ZZ$	4.3%
$H \to \gamma\gamma$	9.0%
$H \to \mu\mu$	17%
$H \to$ inv	–

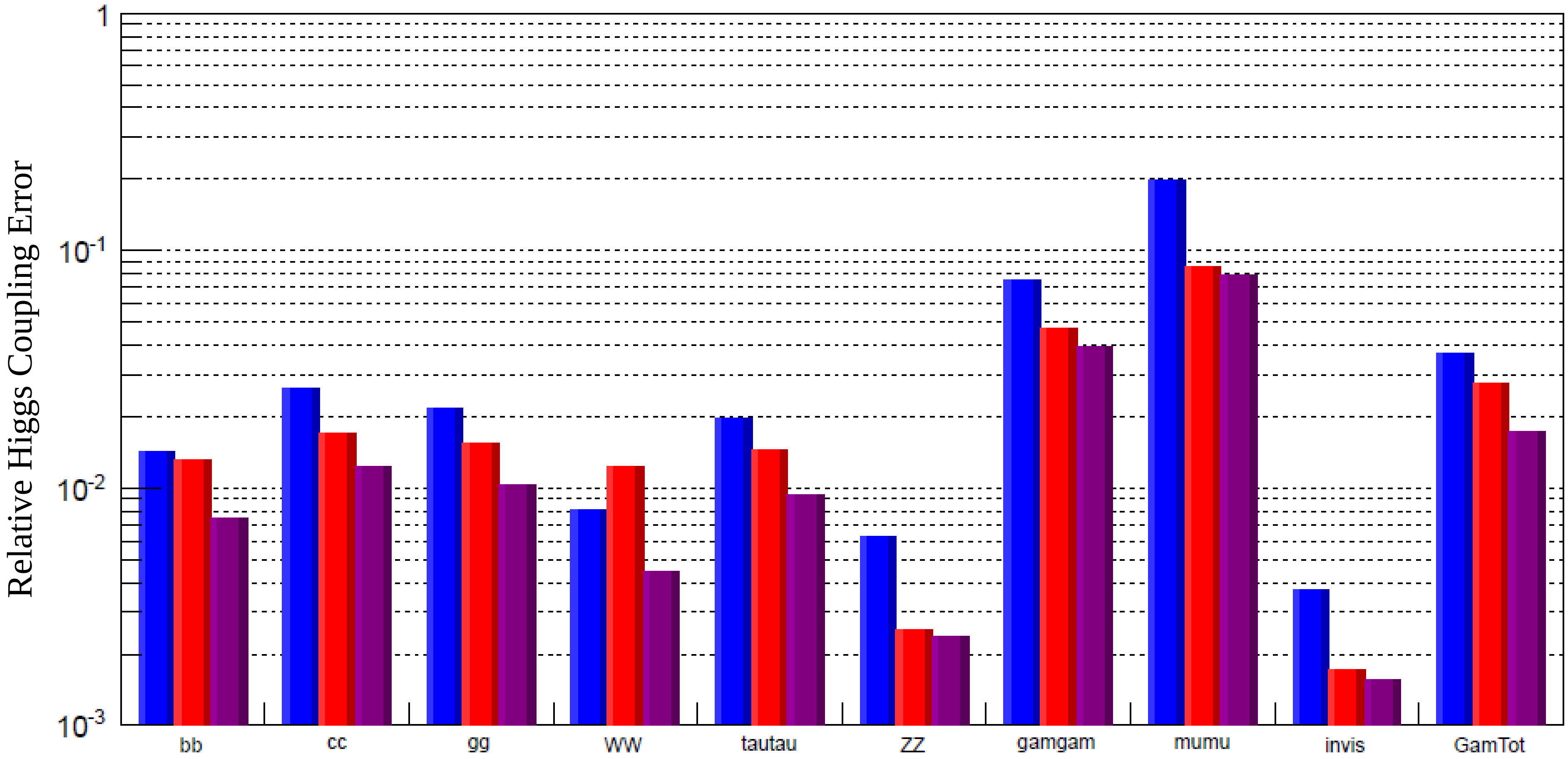
Take ILC errors on σ and σ•BR from arXiv:1506.07830 assuming 250+350+500 GeV with 2.0+0.2+4.0 ab^{-1} (H-20 scenario)

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 & CEPC separately and combined.

🟦 ILC 250+350+500 GeV with 500+200+500 fb^{-1} (H-20 scenario at 8.1 yrs)

🟥 CEPC 250 GeV with 5000 fb^{-1}

🟪 ILC + CEPC under the conditions listed above

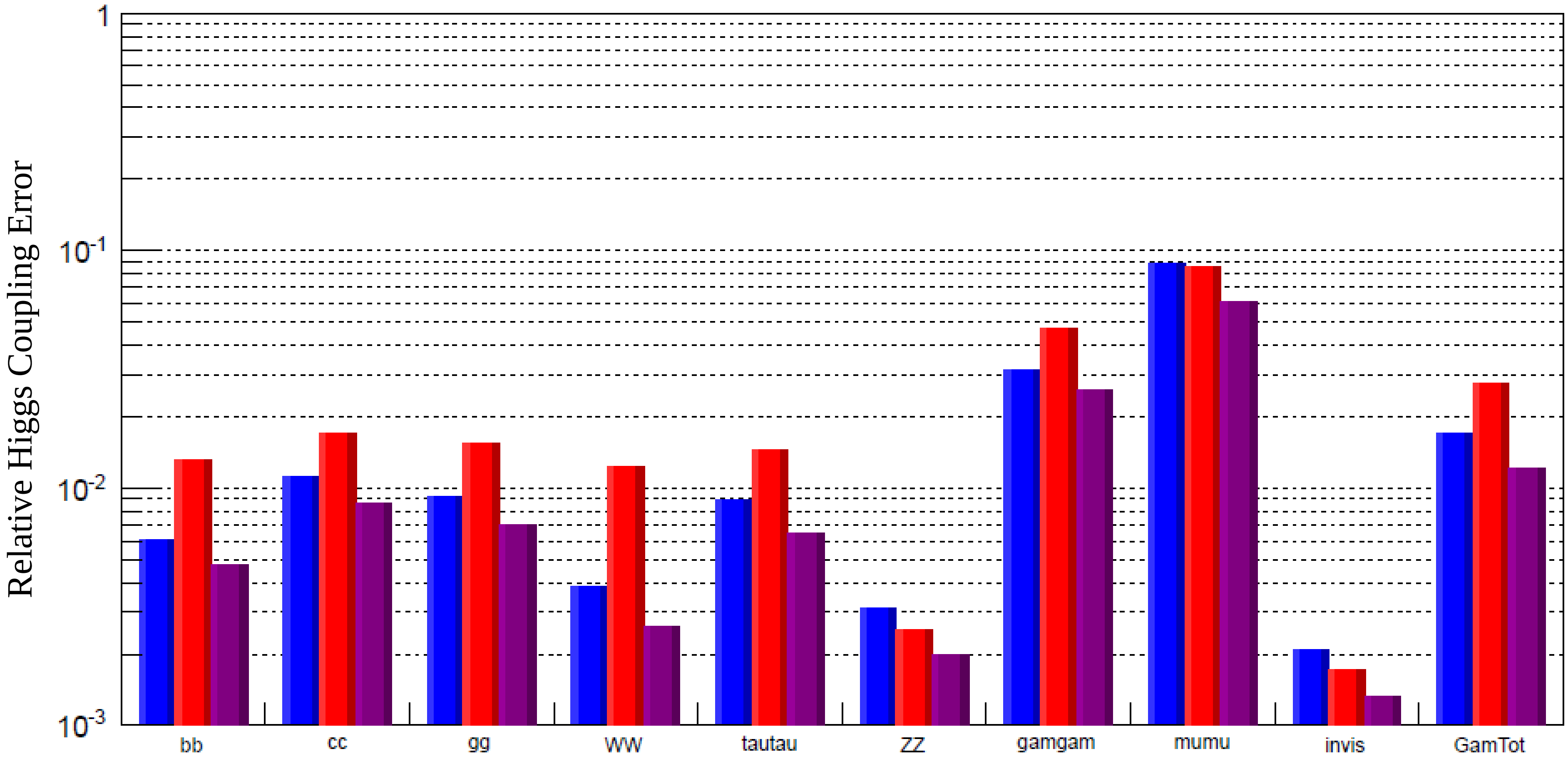


Best Δg : CEPC CEPC CEPC ILC CEPC CEPC CEPC CEPC CEPC CEPC

🟦 ILC 250+350+500 GeV with 2000+200+4000 fb^{-1} (H-20 scenario full run ⇒ 20.2 yrs)

🟥 CEPC 250 GeV with 5000 fb^{-1}

🟪 ILC + CEPC under the conditions listed above



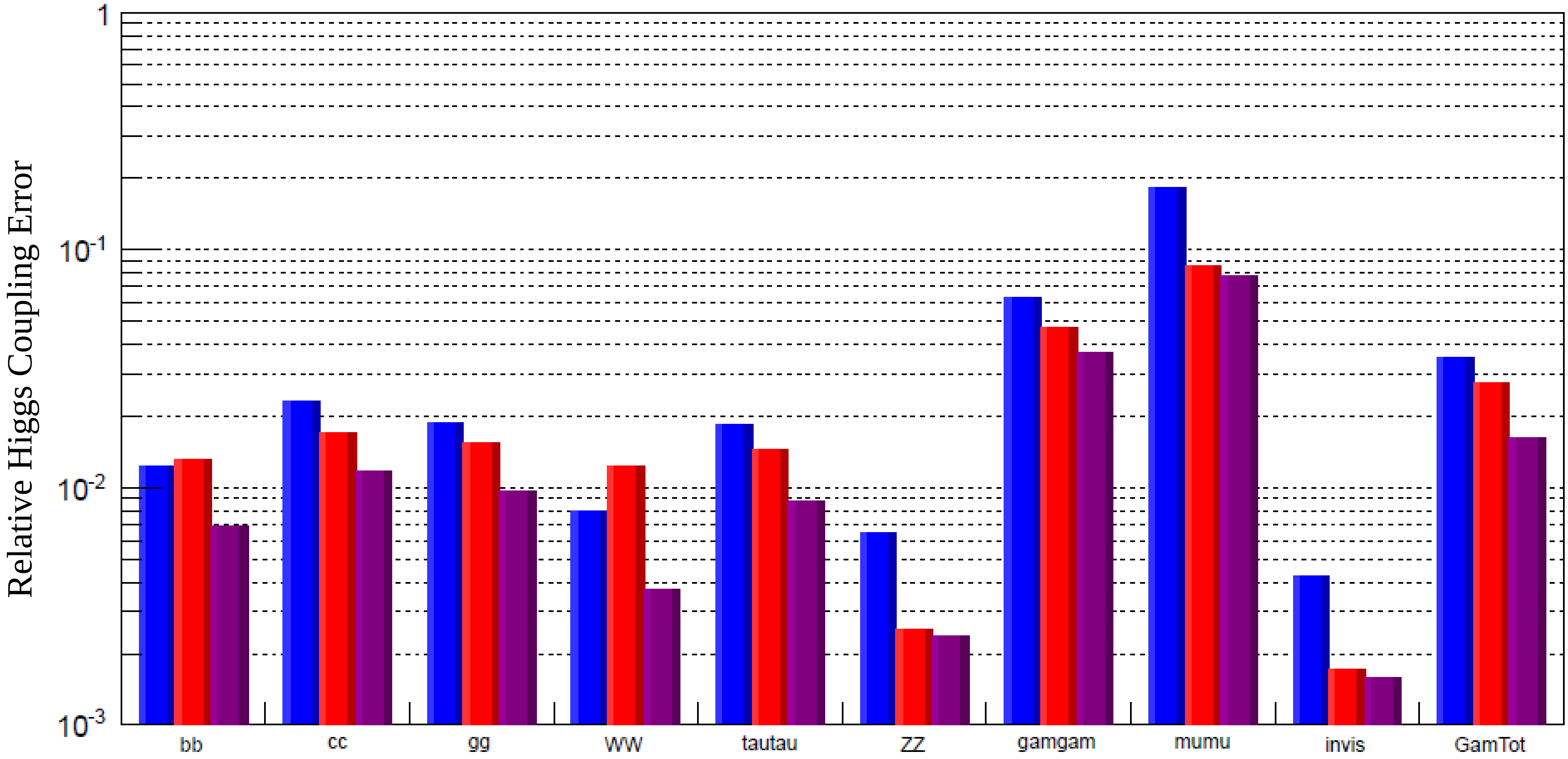
Best Δg : ILC ILC ILC ILC ILC CEPC ILC CEPC CEPC ILC

🟦 ILC 250+350+500 GeV with 340+200+1000 fb^{-1} (G-20 scenario at 8.1 yrs)

🟥 CEPC 250 GeV with 5000 fb^{-1}

🟪 ILC + CEPC under the conditions listed above

How does ILC help CEPC in a situation where CEPC has (mostly) the best individual results?



	bb	cc	gg	WW	tautau	ZZ	gamgam	mumu	invis	GamTot
CEPC Δg / Comb. Δg	**1.91**	**1.45**	**1.58**	**3.26**	**1.63**	**1.07**	**1.26**	**1.11**	**1.08**	**1.70**
Extra CEPC* Running (yr)	**26.5**	**11.0**	**15.0**	**96.3**	**16.6**	**1.4**	**5.9**	**2.3**	**1.7**	**18.9**

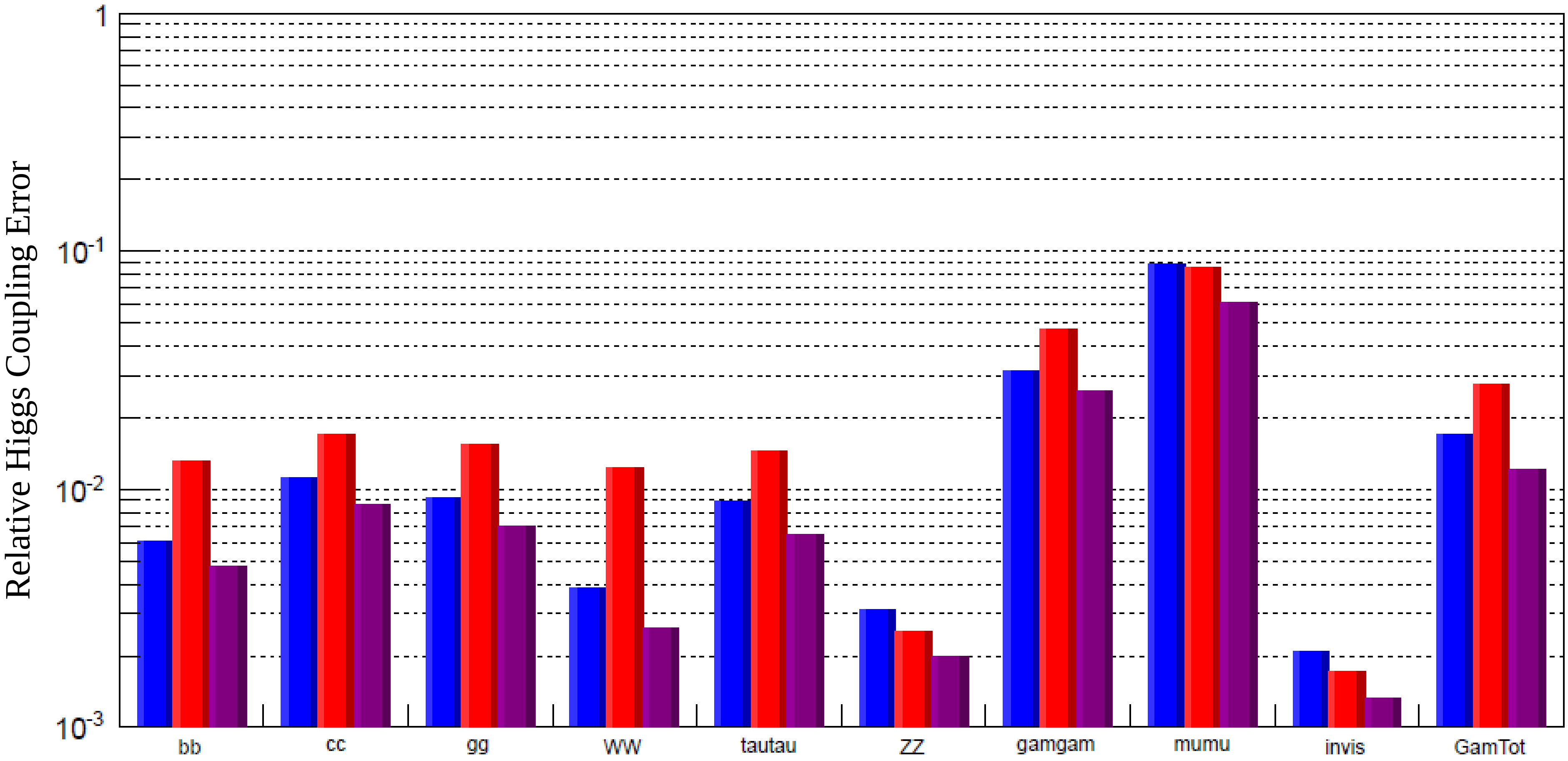
*Additional CEPC running required to match ILC contribution to Combination. Assumes all extra running at $\sqrt{s}$ = 250 GeV

🟦 ILC 250+350+500 GeV with 2000+200+4000 fb^{-1} (H-20 scenario full run ⇒ 20.2 yrs)

🟥 CEPC 250 GeV with 5000 fb^{-1}

🟪 ILC + CEPC under the conditions listed above

How does CEPC help ILC in a situation where ILC has (mostly) the best individual results?



ILC Δg / Comb. Δg	**1.28**	**1.31**	**1.31**	**1.47**	**1.37**	**1.58**	**1.21**	**1.44**	**1.58**	**1.42**
Extra ILC* Running (yr)	**10.4**	**10.4**	**10.4**	**10.4**	**10.4**	**10.4**	**10.4**	**10.4**	**10.4**	**10.4**

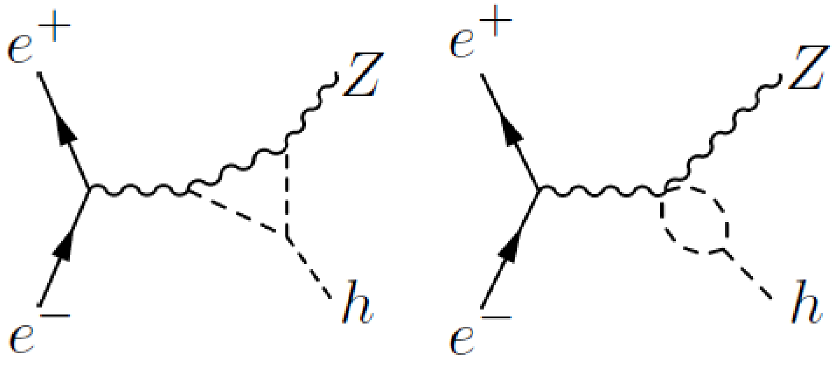
*Additional ILC running required to match CEPC contribution to Combination. Assumes all extra running at $\sqrt{s}$ = 250 GeV

Highlights of Combination of CEPC with ILC H-20 @ 20 yrs

	CEPC		ILC+CEPC
Δg_{HZZ}	0.26%	$\Rightarrow$	0.20%
Δg_{HWW}	1.22%	$\Rightarrow$	0.26% *
Δg_{Hbb}	1.30%	$\Rightarrow$	0.47%
$\Delta g_{H\tau\tau}$	1.44%	$\Rightarrow$	0.65%
Δg_{Hgg}	1.53%	$\Rightarrow$	0.70%

* Might be interesting to include $\sigma(WW \rightarrow H)$ in precision Higgs analyses

CEPC Higgs Self Coupling Measurement at Ecm=240 GeV



M. McCullough, arXiv:1312.3322

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

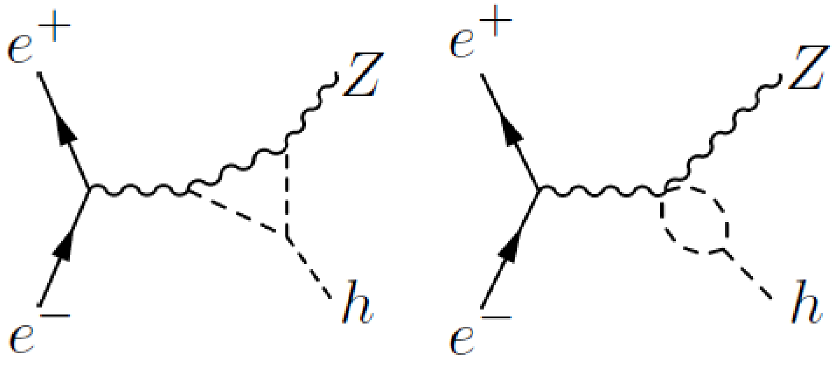
g_{hZZ} fixed to SM value $(\delta_z = 0)$

g_{hhZZ} fixed to SM value

$$\Rightarrow \ \delta_H = \frac{\delta_\sigma^{240}}{0.014} = \frac{0.0051}{0.014} = 36\%$$

Note : Oft quoted 30% error comes from combining CEPC with 50% HL-LHC meas.

CEPC Higgs Self Coupling Measurement at Ecm=240 GeV



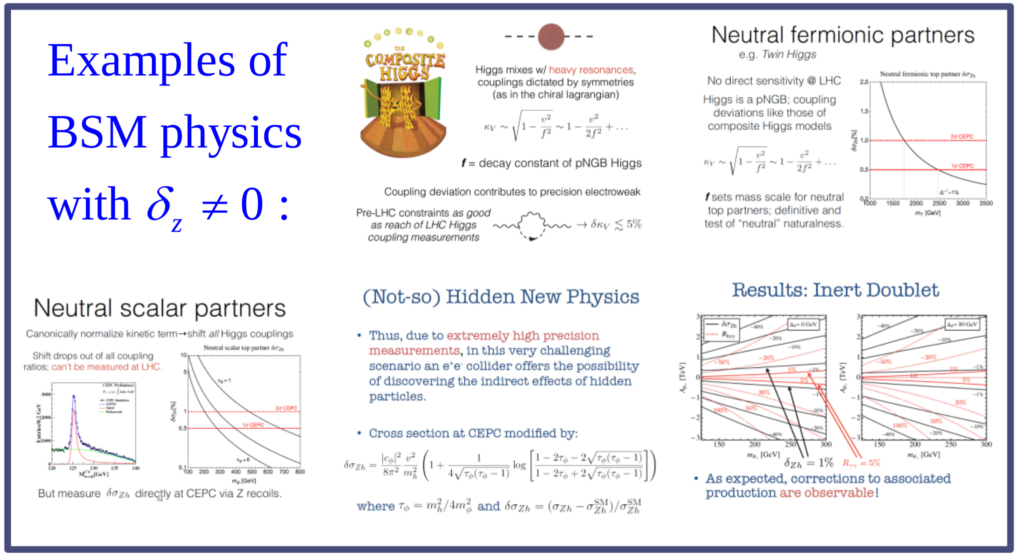
M. McCullough, arXiv:1312.3322

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

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

g_{hhZZ} fixed to SM value

$$\Rightarrow\ \delta_H = \frac{\delta_\sigma^{240}}{0.014} = \frac{0.0051}{0.014} = 36\%$$



Examples of BSM physics with $\delta_z \neq 0$:

Higgs mixes w/ heavy resonances, couplings dictated by symmetries (as in the chiral lagrangian)

$$\kappa_V \sim \sqrt{1-\frac{v^2}{f^2}} \sim 1-\frac{v^2}{2f^2}+\dots$$

f = decay constant of pNGB Higgs

Coupling deviation contributes to precision electroweak

Pre-LHC constraints as good as reach of LHC Higgs coupling measurements $\rightarrow \delta\kappa_V \lesssim 5\%$

Neutral fermionic partners

e.g. *Twin Higgs*

No direct sensitivity @ LHC

Higgs is a pNGB; coupling deviations like those of composite Higgs models

$$\kappa_V \sim \sqrt{1-\frac{v^2}{f^2}} \sim 1-\frac{v^2}{2f^2}+\dots$$

f sets mass scale for neutral top partners; definitive and test of "neutral" naturalness.

Neutral scalar partners

Canonically normalize kinetic term→shift *all* Higgs couplings

Shift drops out of all coupling ratios; can't be measured at LHC.

But measure $\delta\sigma_{Zh}$ directly at CEPC via Z recoils.

(Not-so) Hidden New Physics

- Thus, due to extremely high precision measurements, in this very challenging scenario an e⁺e⁻ collider offers the possibility of discovering the indirect effects of hidden particles.
- Cross section at CEPC modified by:

$$\delta\sigma_{Zh} = \frac{|c_\phi|^2}{8\pi^2}\frac{v^2}{m_h^2}\left(1+\frac{1}{4\sqrt{\tau_\phi(\tau_\phi-1)}}\log\left[\frac{1-2\tau_\phi-2\sqrt{\tau_\phi(\tau_\phi-1)}}{1-2\tau_\phi+2\sqrt{\tau_\phi(\tau_\phi-1)}}\right]\right)$$

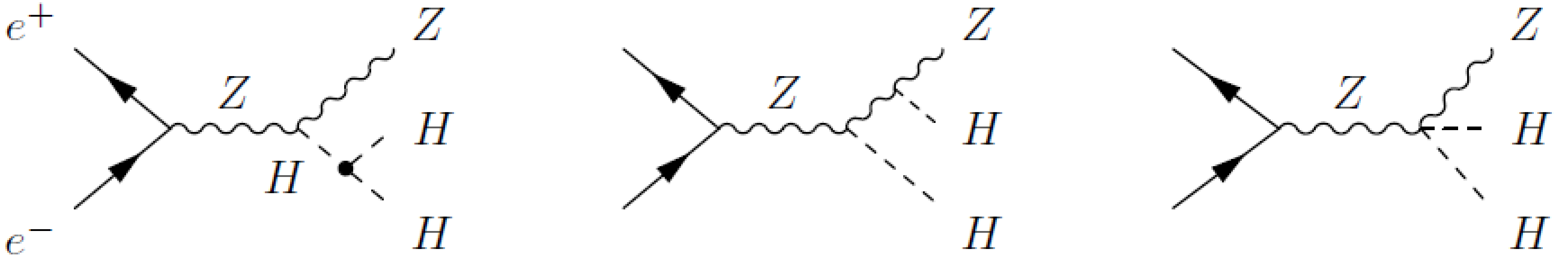
where $\tau_\phi = m_h^2/4m_\phi^2$ and $\delta\sigma_{Zh} = (\sigma_{Zh}-\sigma_{Zh}^{SM})/\sigma_{Zh}^{SM}$

Results: Inert Doublet

- As expected, corrections to associated production are observable!

Note : Oft quoted 30% error comes from combining CEPC with 50% HL-LHC meas.

ILC Higgs Self Coupling Measurement at Ecm=500 GeV



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

g_{hhZZ} fixed to SM value ← See following slides

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

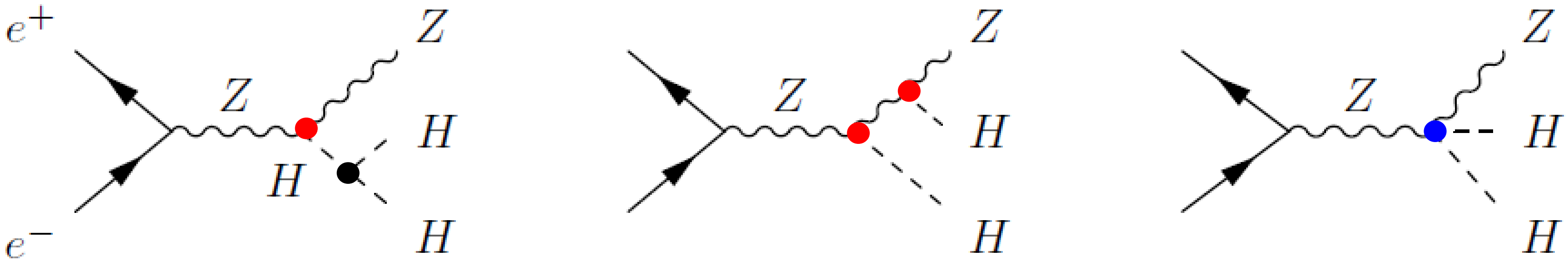
using HH → $b\bar{b}b\bar{b}$ & $b\bar{b}W^+W^-$

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

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

ILC Higgs Self Coupling Systematic Error

Uncertainties for g_{ZZH} g_{ZZHH} in $\sigma(e^+e^- \to HHZ)$



We assume that $\sigma(e^+e^- \to HHZ)$ can be described by an effective field theory (EFT) containing a general $SU(2)\times U(1)$ gauge invariant Lagrangian with dimension-6 operators in addition to the SM.

Using the convention of arXiv:1310.5150 we have, before EWSB, the following dim-6 operators:

$$\begin{aligned}\mathcal{L}_{\rm SILH} = {}& \frac{\bar c_H}{2v^2}\partial^\mu\left[\Phi^\dagger\Phi\right]\partial_\mu\left[\Phi^\dagger\Phi\right] + \frac{\bar c_T}{2v^2}\left[\Phi^\dagger \overleftrightarrow{D}^\mu \Phi\right]\left[\Phi^\dagger \overleftrightarrow{D}_\mu \Phi\right] - \frac{\bar c_6\lambda}{v^2}\left[\Phi^\dagger\Phi\right]^3 \\ &+ \frac{ig\ \bar c_W}{m_W^2}\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}^\mu\Phi\right]D^\nu W^k_{\mu\nu} + \frac{ig'\ \bar c_B}{2m_W^2}\left[\Phi^\dagger\overleftrightarrow{D}^\mu\Phi\right]\partial^\nu B_{\mu\nu} \\ &+ \frac{2ig\ \bar c_{HW}}{m_W^2}\left[D^\mu\Phi^\dagger T_{2k}D^\nu\Phi\right]W^k_{\mu\nu} + \frac{ig'\ \bar c_{HB}}{m_W^2}\left[D^\mu\Phi^\dagger D^\nu\Phi\right]B_{\mu\nu} \\ &+ \frac{g'^2\ \bar c_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \text{ other operators that are not relevant or that violate CP}\end{aligned}$$

Note there are only 8 EFT parameters: $\bar c_H$ $\bar c_T$ $\bar c_6$ $\bar c_W$ $\bar c_B$ $\bar c_{HW}$ $\bar c_{HB}$ $\bar c_\gamma$

ILC Higgs Self Coupling Systematic Error

The couplings $g^{(j)}_{xxx}$ and $g^{(j)}_{xxxx}$ take the following form in our EFT:

$g^{(1)}_{hhh}$	$1+\frac{7}{8}\bar{c}_6-\frac{1}{2}\bar{c}_H$
$g^{(2)}_{hhh}$	$\frac{g}{m_W}\bar{c}_H$
$g^{(1)}_{hzz}$	$\frac{2g}{c_W^2 m_W}\left[\bar{c}_{HB}s_W^2-4\bar{c}_\gamma s_W^4+c_W^2\bar{c}_{HW}\right]$
$g^{(2)}_{hzz}$	$\frac{g}{c_W^2 m_W}\left[(\bar{c}_{HW}+\bar{c}_W)c_W^2+(\bar{c}_B+\bar{c}_{HB})s_W^2\right]$
$g^{(3)}_{hzz}$	$\frac{g m_W}{c_W^2}\left[1-\frac{1}{2}\bar{c}_H-2\bar{c}_T+8\bar{c}_\gamma\frac{s_W^4}{c_W^2}\right]$
$g^{(1)}_{hww}$	$\frac{2g}{m_W}\bar{c}_{HW}$
$g^{(2)}_{hww}$	$\frac{g}{m_W}\left[\bar{c}_W+\bar{c}_{HW}\right]$
$\left\{g^{(1)}_{hhzz},g^{(2)}_{hhzz},g^{(1)}_{hhaz},g^{(2)}_{hhaz},g^{(1)}_{hhww},g^{(2)}_{hhww}\right\}$	$\frac{g}{2m_W}\left\{g^{(1)}_{hzz},g^{(2)}_{hzz},g^{(1)}_{haz},g^{(2)}_{haz},g^{(1)}_{hww},g^{(2)}_{hww}\right\}$
$g^{(3)}_{hhzz}$	$\frac{g^2}{2c_W^2}\left[1-6\bar{c}_T-\bar{c}_H+8\bar{c}_\gamma\frac{s_W^4}{c_W^2}\right]$
$g^{(1)}_{aww}$	$e\left[1-2\bar{c}_W\right]$
$g^{(2)}_{aww}$	$e\left[1-2\bar{c}_W-\bar{c}_{HB}-\bar{c}_{HW}\right]$
$g^{(1)}_{zww}$	$\frac{g}{c_W}\left[c_W^2-\bar{c}_{HW}+(2s_W^2-3)\bar{c}_W\right]$
$g^{(2)}_{zww}$	$\frac{g}{c_W}\left[c_W^2(1-\bar{c}_{HW})+s_W^2\bar{c}_{HB}+(2s_W^2-3)\bar{c}_W\right]$

$\bar{c}_6$ is uniquely accessible through the Higgs self coupling measurement. The other 7 EFT parameters appear in several places.

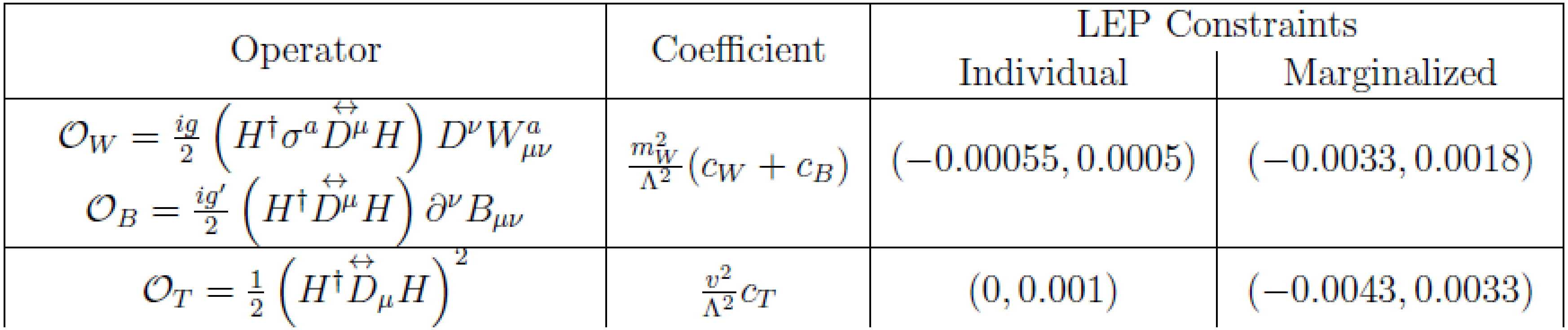
Note the relationships between the *hzz* & *hhzz* couplings.

The TGC's depend on $\bar{c}_W$, $\bar{c}_{HW}$, $\bar{c}_{HB}$ through the Goldstone bosons that are eaten by the *B* and *W* fields

ILC Higgs Self Coupling Systematic Error

The parameters $\bar{c}_W$, $\bar{c}_B$, $\bar{c}_T$ are constrained by electroweak precision tests.

From arXiv:1410.7703 :



Operator	Coefficient	LEP Constraints	
		Individual	Marginalized
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$ $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$	$\frac{m_W^2}{\Lambda^2}(c_W + c_B)$	$(-0.00055, 0.0005)$	$(-0.0033, 0.0018)$
$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$	$\frac{v^2}{\Lambda^2} c_T$	$(0, 0.001)$	$(-0.0043, 0.0033)$

By definition $\bar{c}_W \equiv \frac{M_W^2}{\Lambda^2} c_W$, $\bar{c}_T \equiv \frac{v^2}{\Lambda^2}$, etc.

We will assume in the following that, at the 10^{-3} level,

$$\bar{c}_W = -\bar{c}_B \qquad \bar{c}_T = 0$$

ILC Higgs Self Coupling Systematic Error

The TGC's $\Delta\kappa_\gamma$ and Δg_1^Z are related to EFT parameters by

$$\Delta\kappa_\gamma = \bar{c}_{HW} + \bar{c}_{HB}$$

$$\Delta g_1^Z = \bar{c}_W + \bar{c}_{HW}$$

At ILC with the full H-20 scenario the error on the TGC's are

$$\Delta(\Delta\kappa_\gamma) = 2\times10^{-4}$$

$$\Delta(\Delta g_1^Z) = 8\times10^{-4}$$

We can then assume at the 10^{-3} level that $\bar{c}_W = -\bar{c}_{HW} = \bar{c}_{HB}$

so that we can write $g_{hzz}^{(2)}$ and $g_{hww}^{(2)}$ as

$$g_{hzz}^{(2)} = \frac{g}{c_{\theta_W}^2 M_W}\left[\Delta g_1^Z c_{\theta_W}^2 + \Delta\kappa_\gamma s_{\theta_W}^2\right] \approx 0$$

$$g_{hww}^{(2)} = \frac{g}{M_W}\Delta g_1^Z \approx 0$$

ILC Higgs Self Coupling Systematic Error

Through EWPT's and ILC measurements of TGC's the number of independent EFT parameters has been reduced from 8 to just 4: $\overline{c}_H$, $\overline{c}_\gamma$, $\overline{c}_{HW}$, $\overline{c}_6$

The first two parameters are determined by $g^{(3)}_{hww}$ and $g^{(3)}_{hzz}$, the usual Higgs couplings to W and Z that are measured assuming the SM Lorentz structure. The relationship between the W coupling $g^{(3)}_{hww}$ and $\overline{c}_H$ is simply

$$g^{(3)}_{hww} \equiv g M_W (1 - \frac{1}{2} \overline{c}_H) \ .$$

The parameter $\overline{c}_\gamma$ is given by

$$8 \frac{s^4_{\theta_W}}{c^2_{\theta_W}} \overline{c}_\gamma = \frac{1}{g M_W} \left[c^2_{\theta_W} g^{(3)}_{hzz} - g^{(3)}_{hww} \right]$$

ILC Higgs Self Coupling Systematic Error

The EFT parameter $\overline{c}_{HW}$ is related to the "b" parameter of the HVV Lorentz structure studies by Fujii, Tian, Ogawa and others done here at KEK:

HWW arXiv:1011.5805

HZZ Talk by T. Ogawa at LCWS15 http://agenda.linearcollider.org/event/6662/

Let b_w & b_z be the "b" parameters of the HWW & HZZ analyses respectively.

$$\mathrm{g}^{(1)}_{\mathrm{hww}} = -2\frac{b_w}{\Lambda} \qquad \mathrm{g}^{(1)}_{\mathrm{hzz}} = -4\frac{b_z}{\Lambda}$$

$$\overline{c}_{HW} = -\frac{v}{2\Lambda} b_w \approx \frac{b_w}{8} \quad \text{for } \Lambda\text{=1 TeV assumed in the analysis}$$

$$\overline{c}_{HW} = \frac{1}{1-t^2_{\theta_W}}\left[\frac{1}{2gM_W}(\mathrm{g}^{(3)}_{\mathrm{hzz}} - \frac{1}{c^2_{\theta_W}}\mathrm{g}^{(3)}_{\mathrm{hww}}) - \frac{v}{\Lambda} b_z\right] \approx \frac{1}{1-t^2_{\theta_W}}\left[\frac{1}{2gM_W}(\mathrm{g}^{(3)}_{\mathrm{hzz}} - \frac{1}{c^2_{\theta_W}}\mathrm{g}^{(3)}_{\mathrm{hww}}) - \frac{b_z}{4}\right]$$

For full H20 $\Delta b_w = 0.18$ $\Delta b_z = 0.004$. Since Δb_z is much better right now we ignore the b_w measurement and use $\mathrm{g}^{(1)}_{\mathrm{hzz}} = -4\frac{b_z}{\Lambda} = -\frac{b_z}{v}$

ILC Higgs Self Coupling Systematic Error

Let's now rewrite the Lagrangian using our measured variables

$g^{(3)}_{\mathrm{hzz}}$ $g^{(3)}_{\mathrm{hww}}$ $g^{(1)}_{\mathrm{hzz}}$ and the one remaining unconstrained EFT parameter $\bar{c}_6$

$$\begin{aligned}\mathcal{L} = & -\frac{M_H^2}{2v}\left(\frac{g^{(3)}_{\mathrm{hww}}}{gM_W} + \frac{7}{8}\bar{c}_6\right)h^3 + \frac{g}{M_W}\left(1-\frac{g^{(3)}_{\mathrm{hww}}}{gM_W}\right)h\partial_\mu h\partial^\mu h \\ & +\frac{b_z}{4v}Z_{\mu\nu}Z^{\mu\nu}h + \frac{1}{2}g^{(3)}_{\mathrm{hzz}}Z_\mu Z^\mu h \\ & +\frac{b_z}{8v}Z_{\mu\nu}Z^{\mu\nu}h^2 + \frac{g^2}{8c^2_{\theta_W}}\left(\frac{g^{(3)}_{\mathrm{hww}}}{gM_W}+c^2_{\theta_W}\frac{g^{(3)}_{\mathrm{hzz}}}{gM_W}-1\right)Z_\mu Z^\mu h^2\end{aligned}$$

In this EFT approach all of the couplings in the calculation of $\sigma(e^+e^- \to HHZ)$ are tightly constrained by the other Higgs coupling measurements, TGC measurements, and EWPT's. The only unconstrained parameter is $\bar{c}_6$. If the best match to the measured $\sigma(e^+e^- \to HHZ)$ is $\bar{c}_6 = 0$ within sys+stat errors then we have observed SM Higgs self coupling.

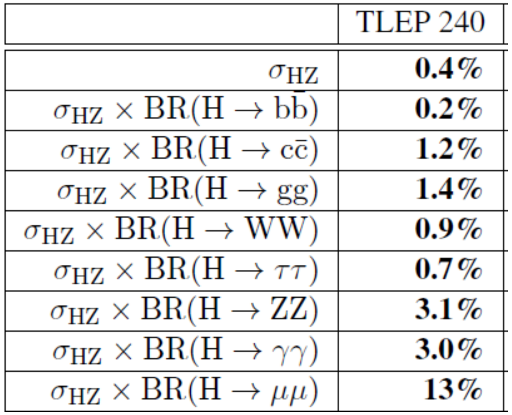
Other Higgs Measurements with CEPC & ILC H-20 at 20 yrs

	CEPC 250 GeV $5000\ \mathrm{fb}^{-1}$	ILC $250+350+500$ GeV $2000+250+4000\ \mathrm{fb}^{-1}$	*Combined*
Δm_H	5.9 MeV	12.5 MeV	5.3 MeV
$\frac{\Delta g_{HHH}}{g_{HHH}}$	36 %	27 %	22 %
$\frac{\Delta g_{ttH}}{g_{ttH}}$	–	5.9 %	5.9 %
$\frac{\Delta g_{ttH}}{g_{ttH}}$ (*)	–	2.4 %	2.4 %

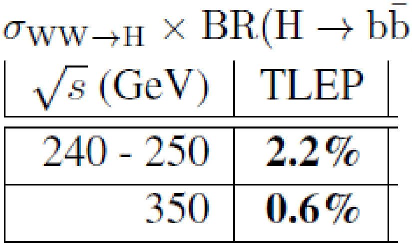
(*) Assumes ILC 500 GeV running actually takes place at $\sqrt{s} = 550$ GeV

ILC + FCC–ee Model Independent Higgs Coupling Precision

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

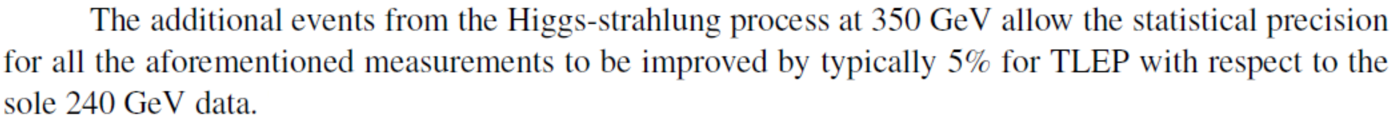


	TLEP 240
σ_{HZ}	**0.4%**
$\sigma_{\mathrm{HZ}} \times \mathrm{BR}(\mathrm{H} \to \mathrm{b\bar{b}})$	**0.2%**
$\sigma_{\mathrm{HZ}} \times \mathrm{BR}(\mathrm{H} \to \mathrm{c\bar{c}})$	**1.2%**
$\sigma_{\mathrm{HZ}} \times \mathrm{BR}(\mathrm{H} \to \mathrm{gg})$	**1.4%**
$\sigma_{\mathrm{HZ}} \times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



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

$\sqrt{s}$ (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 $\sigma\bullet$BR from arXiv:1506.07830 assuming 250+350+500 GeV with 2.0+0.2+4.0 ab^{-1} (H-20 scenario)

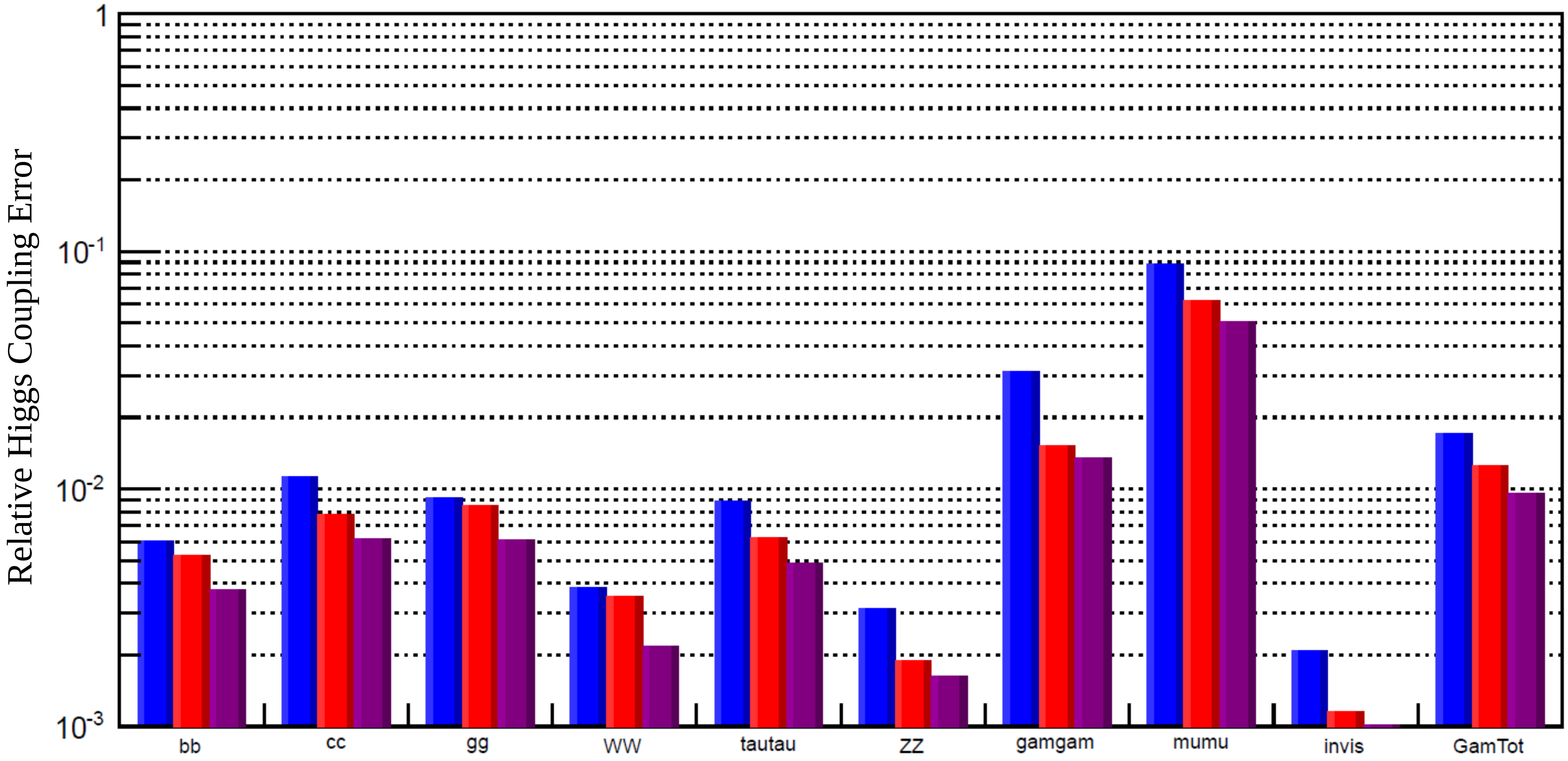
Perform model independent fit of b,c,g,W,τ,Z,γ,μ,invis Higgs couplings and total width using standard program (from Michael Peskin) for ILC & FCC-ee separately and combined.

🟦 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

How does ILC help FCC-ee?



	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**

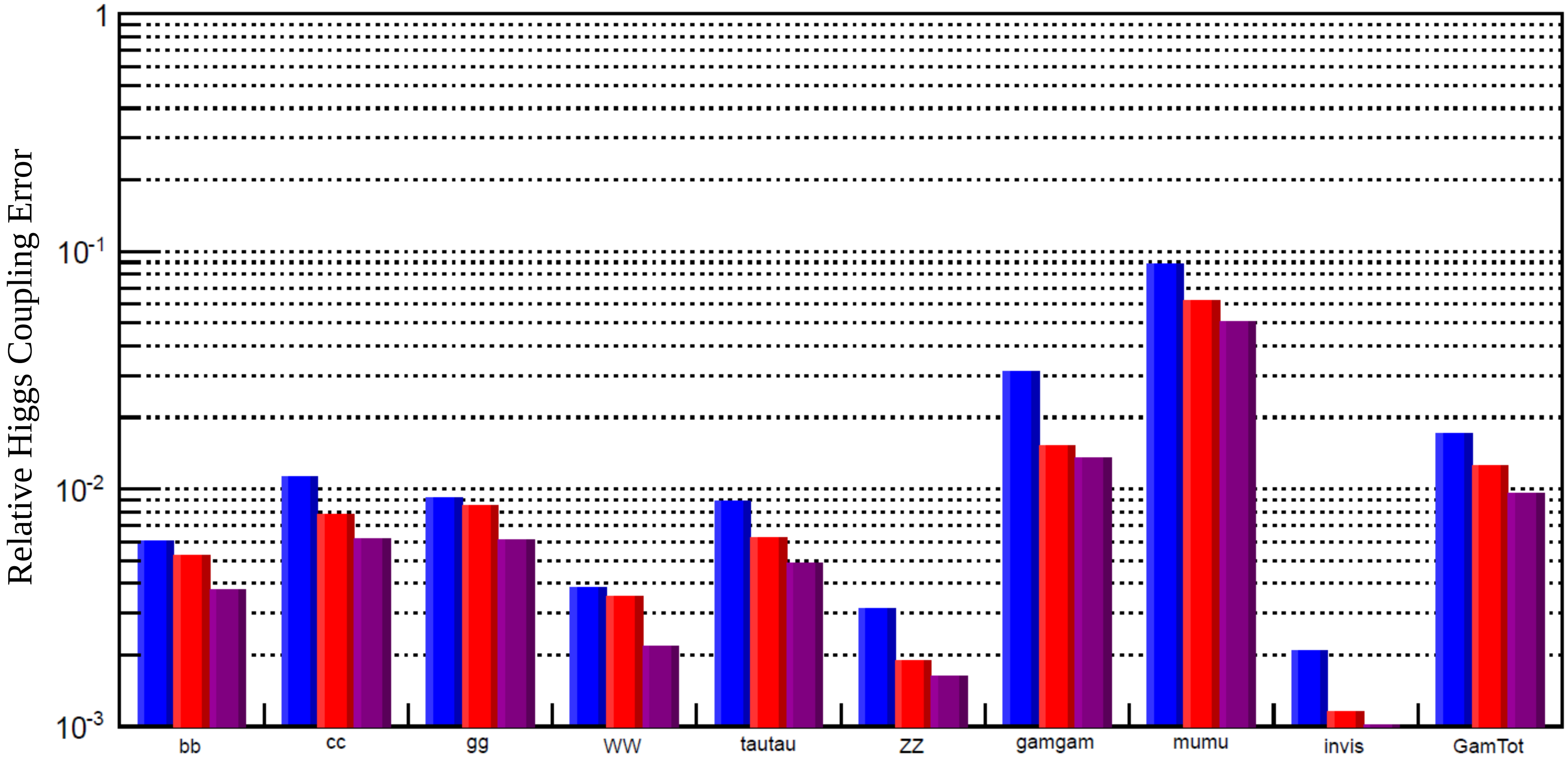
*Additional FCC-ee running required to match ILC contribution to Combination. Assumes the same 10:2.6 luminosity ratio for 240:350 GeV except ZZ & invis which assume that all extra running is at 240 GeV

🟦 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

How does FCC-ee help ILC ?



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%

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

	FCC-ee 240 +350 GeV $10.0+2.6\ \mathrm{ab}^{-1}$	ILC $250+350+500(550)$ GeV $2.0+0.25+4.0\ \mathrm{fb}^{-1}$	***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)

ILC + FCC-ee Summary
(Serves Also as Talk Summary)

- ILC helps FCC-ee:
  - The 0.25% measurement of $\sigma(\nu\nu h)$XBR(H→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 σ(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 σ(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→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 ΔBR(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 $\Delta g_{HHH} = 20\%$