Higgs Physics Complementarity for the ILC and Circular e+e- Colliders

Tim Barklow (SLAC)

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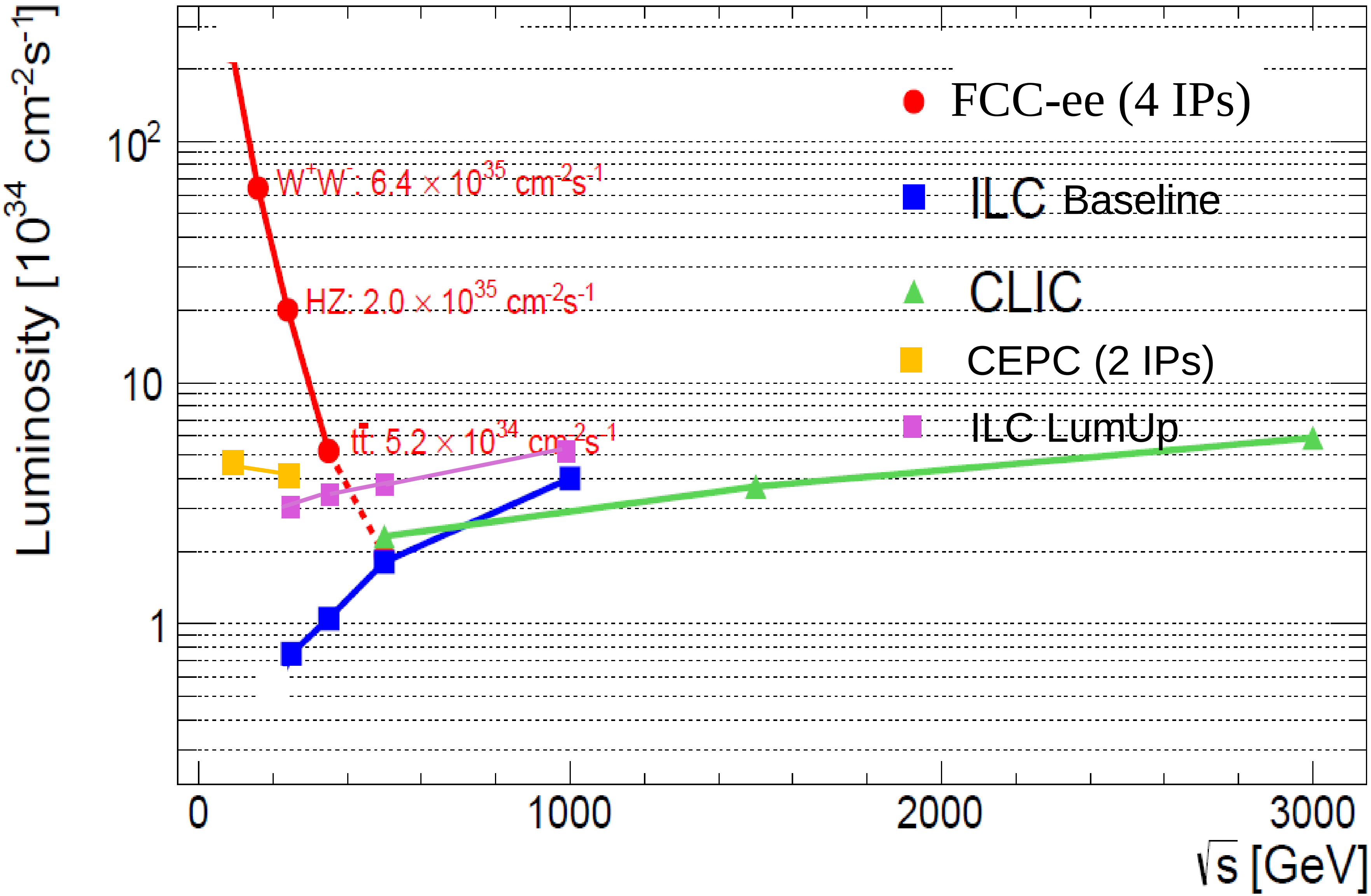
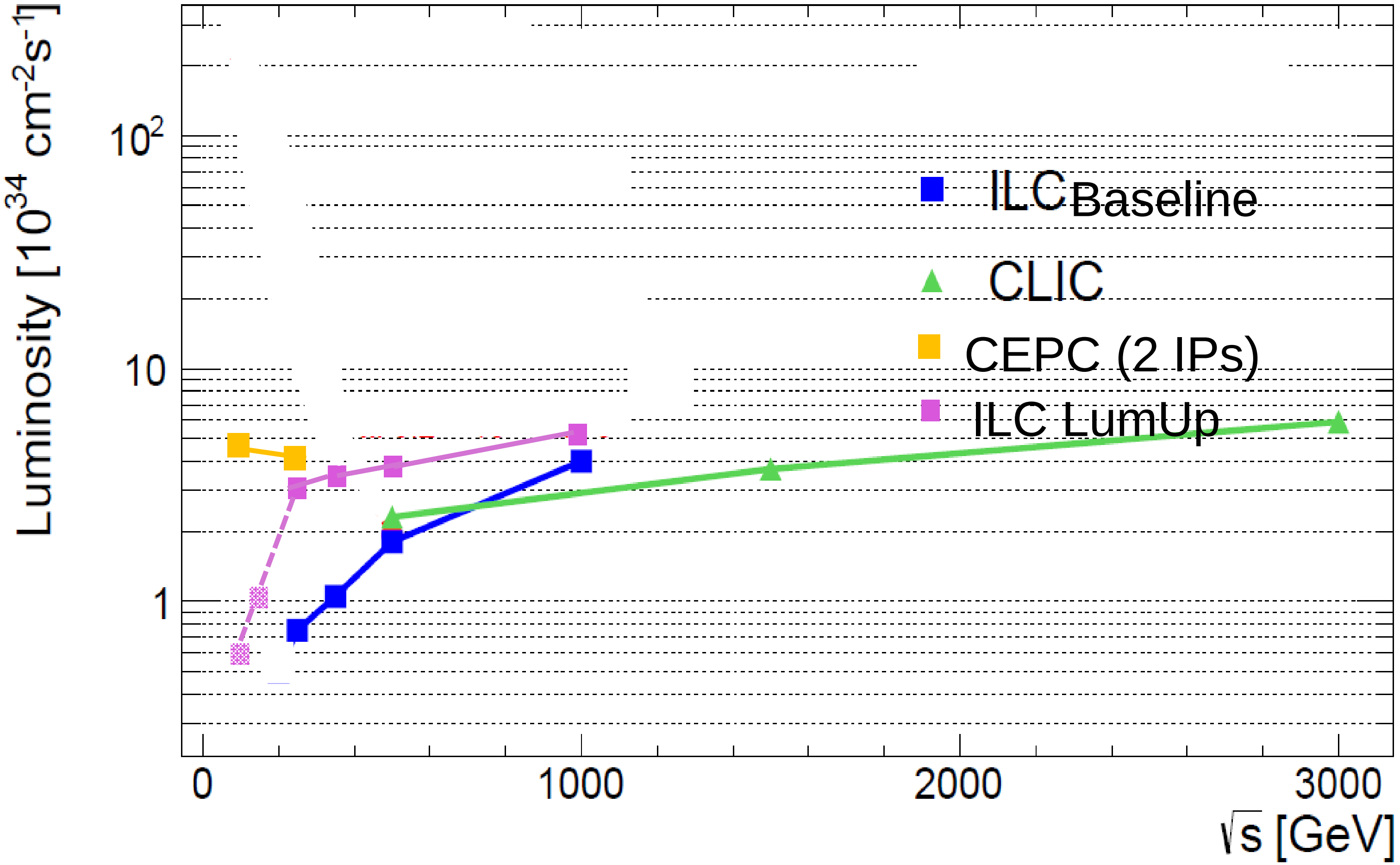


Luminosity [10^{34} cm^{-2}s^{-1}]
10^2
10
1
0
1000
2000
3000
$\sqrt{s}$ [GeV]
W+W-: 6.4 × 10^35 cm-2s-1
HZ: 2.0 × 10^35 cm-2s-1
tt: 5.2 × 10^34 cm-2s-1
FCC-ee (4 IPs)
ILC Baseline
CLIC
CEPC (2 IPs)
ILC LumUp

EW Precision Measurements at $\sqrt{s} = 91$ & 160 GeV

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



Currently no ILC design for $\sqrt{s} = 90,\ 160$ 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.

A resonable design goal might be L=5×10^{33} @ 91 GeV and L=1×10^{34} @ 160 GeV in the lumi upgrade config.

This would provide $\int Ldt = 100\ \text{fb}^{-1}$ @ 91 GeV in 8 mos. and $\int Ldt = 200\ \text{fb}^{-1}$ @ 160 GeV in 8 mos.

EW Precision Measurements with CEPC & ILC

	CEPC 91 +160 GeV $100+500\ \text{fb}^{-1}$	ILC $91+160$ GeV $100+200\ \text{fb}^{-1}$
ΔA_{LR}	–	1×10^{-4}
$\Delta\sin^2\theta_W^{eff}$	2.7×10^{-5}	1.3×10^{-5}
$\Delta \mathrm{M}_Z$	0.5 MeV	1.6 MeV
$\Delta\Gamma_Z$	0.5 MeV	0.5 MeV
$\Delta\alpha_S(\mathrm{M}_Z^2)$	1.0×10^{-4}	5.0×10^{-4}
ΔN_ν	0.001	0.004
ΔA_b	–	0.001
$\Delta R_b\equiv\Delta\frac{\Gamma_b}{\Gamma_{had}}$	1.7×10^{-4}	1.4×10^{-4}
$\Delta R_l\equiv\Delta\frac{\Gamma_{had}}{\Gamma_l}$	0.007	–
$\Delta \mathrm{M}_W$	2.5 MeV	4 MeV

Note : This is probably the maximum integrated luminosity at these energies during the lifetime of the ILC. On the other hand CEPC can readily accumulate much more luminosity at these energies.

Higgs Physics

ILC Higgs Coupling Precisions

Topic	Parameter	Initial Phase (H20 @ 8yrs)	Full Data Set (H20 @ 20yrs)	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].

ILC + CEPC

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

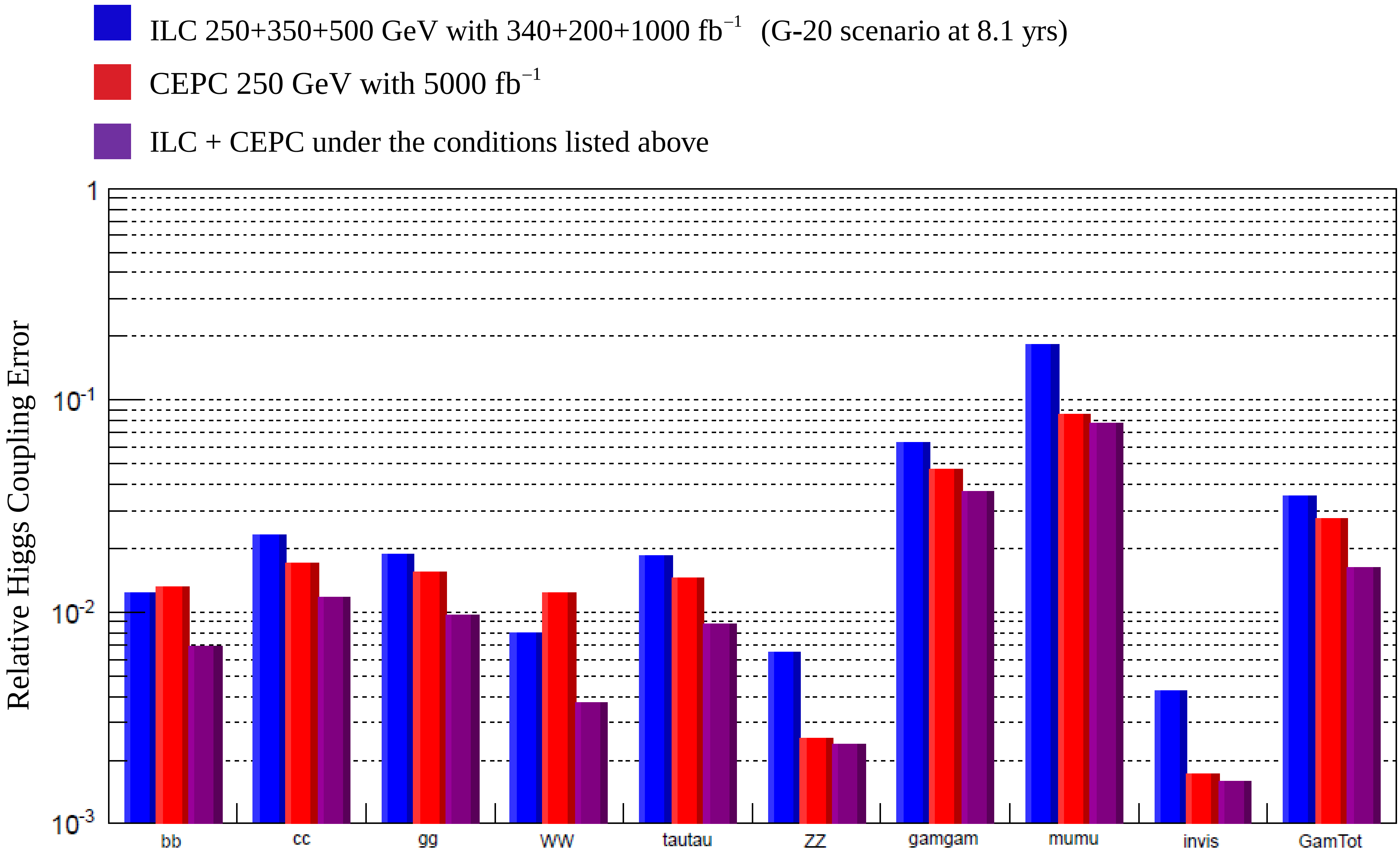
ΔM_H	Γ_H	$\sigma(ZH)$
5.9 MeV	2.8%	0.51%

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 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 & CEPC separately and combined.



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

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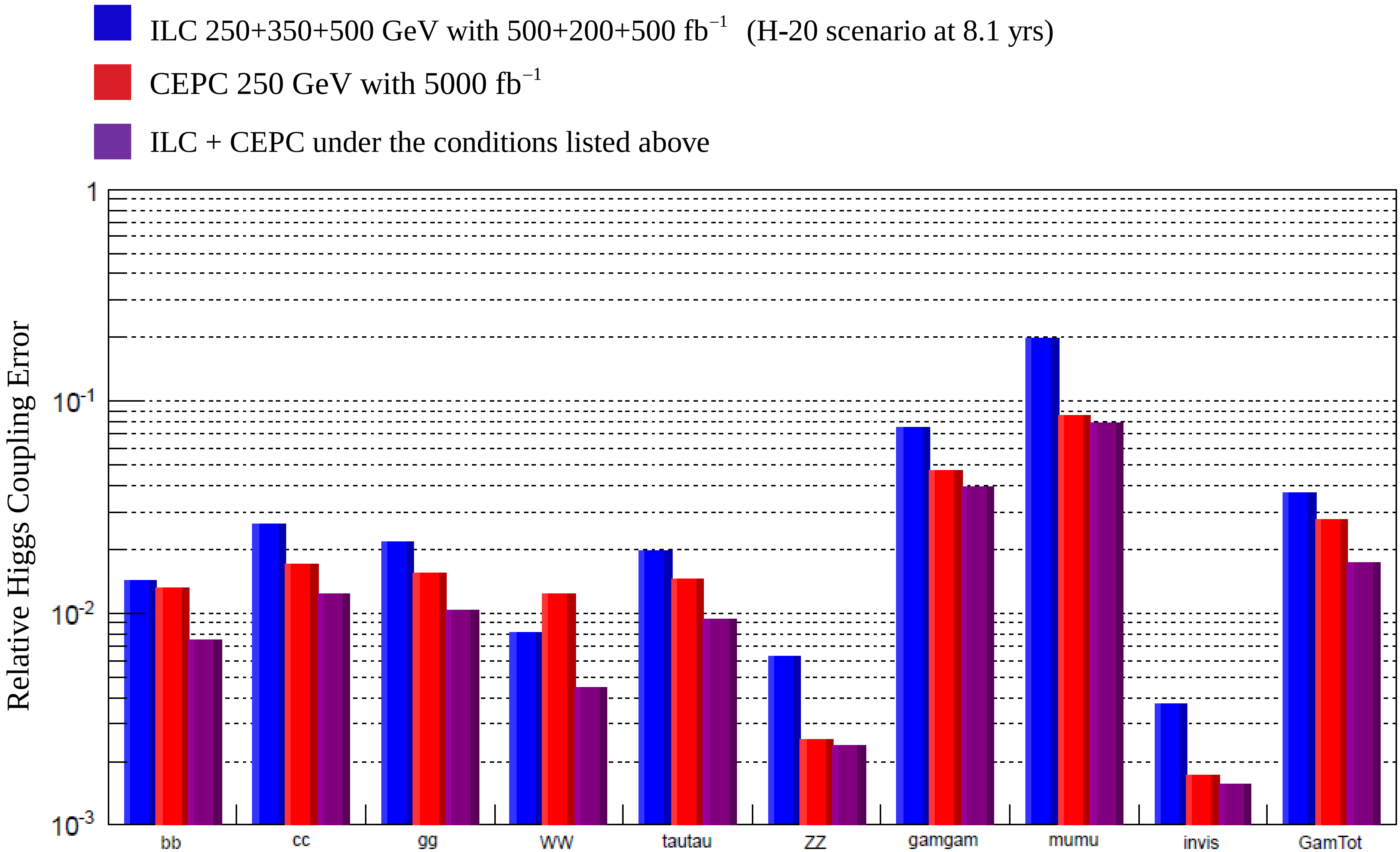
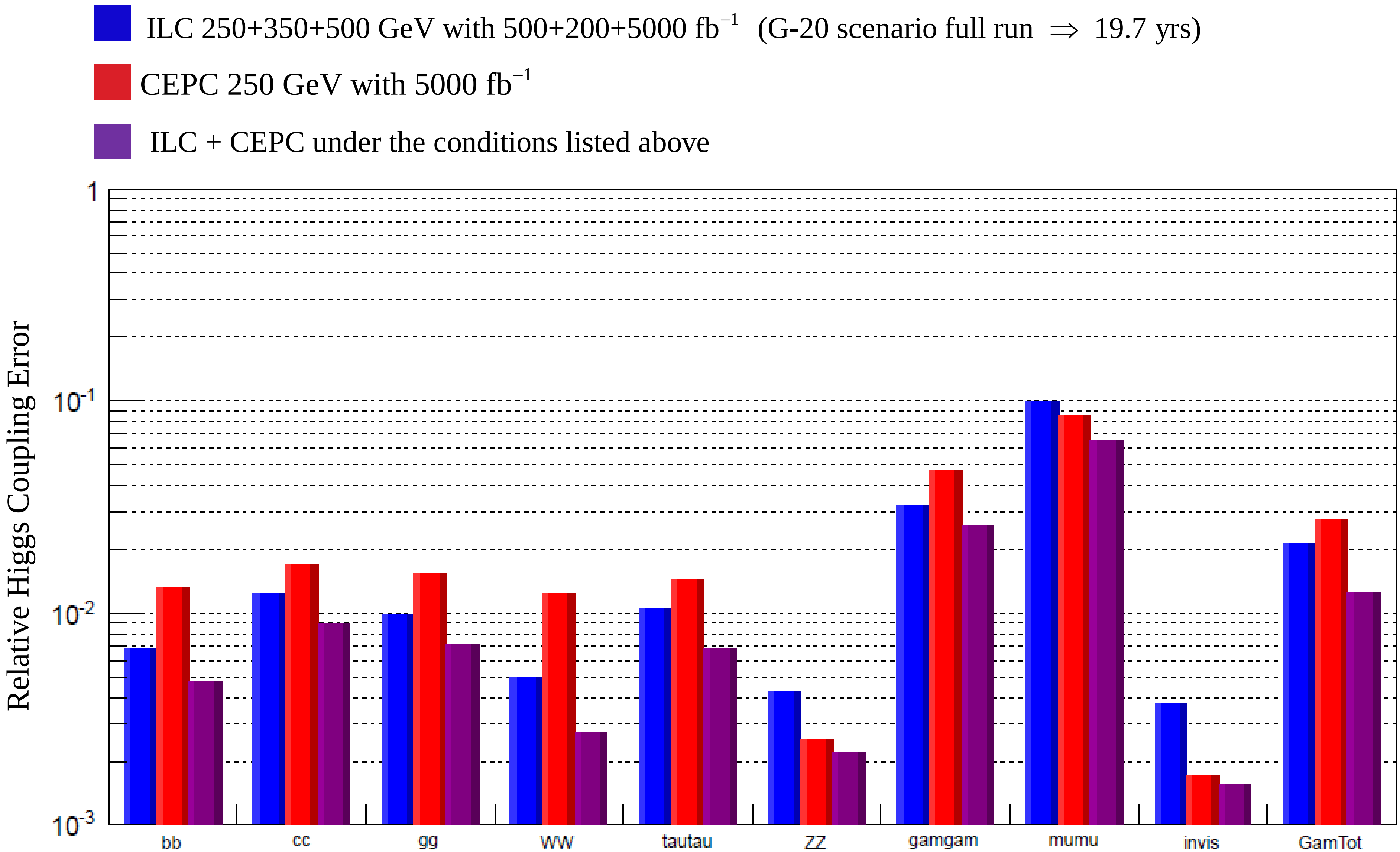


Best Δg : CEPC CEPC CEPC ILC CEPC CEPC CEPC CEPC CEPC CEPC

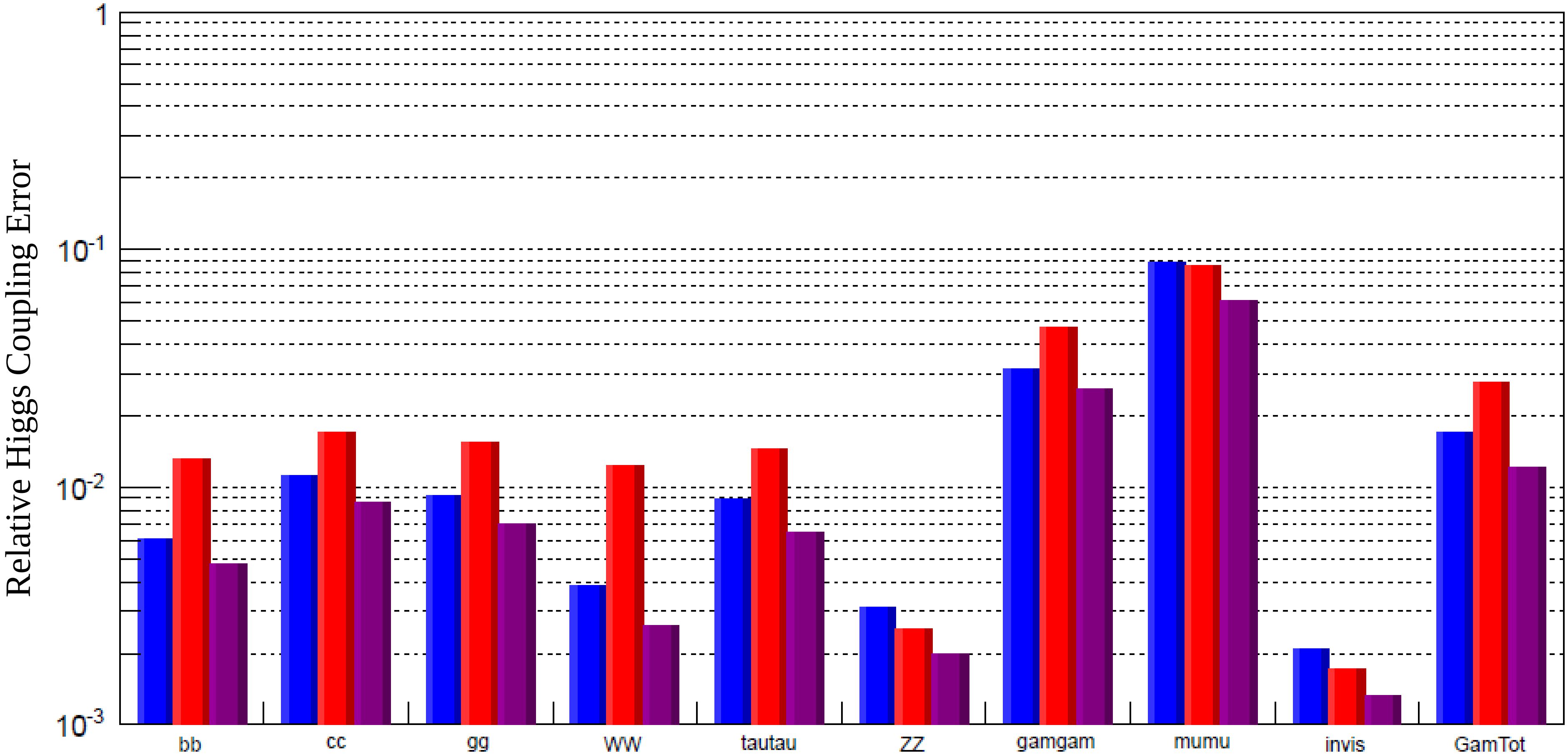


Best Δg : ILC ILC ILC ILC ILC CEPC ILC CEPC CEPC ILC

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

CEPC 250 GeV with 5000 fb^{-1}

ILC + CEPC under the conditions listed above



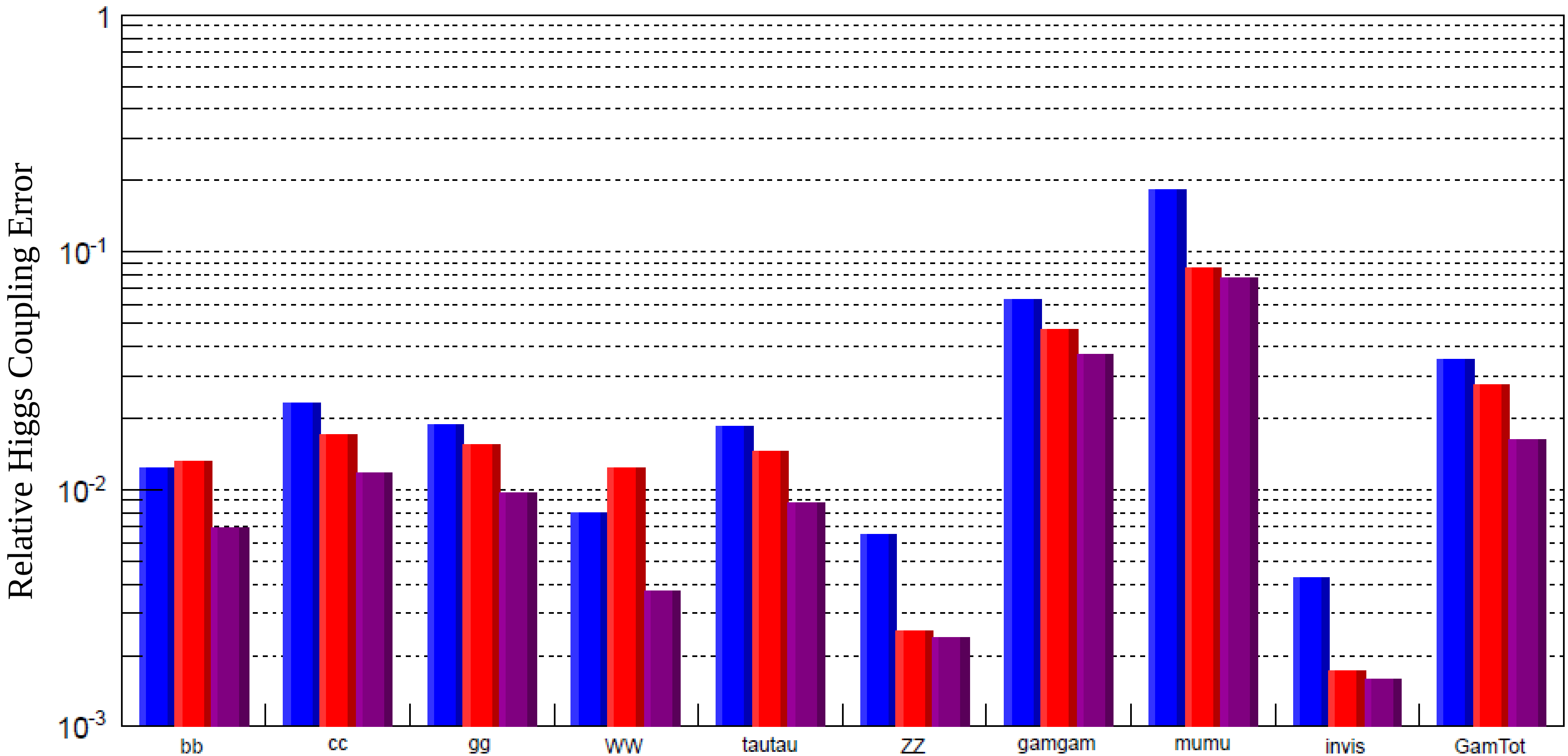
Best Δg : ILC ILC ILC ILC ILC CEPC ILC CEPC CEPC ILC

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)

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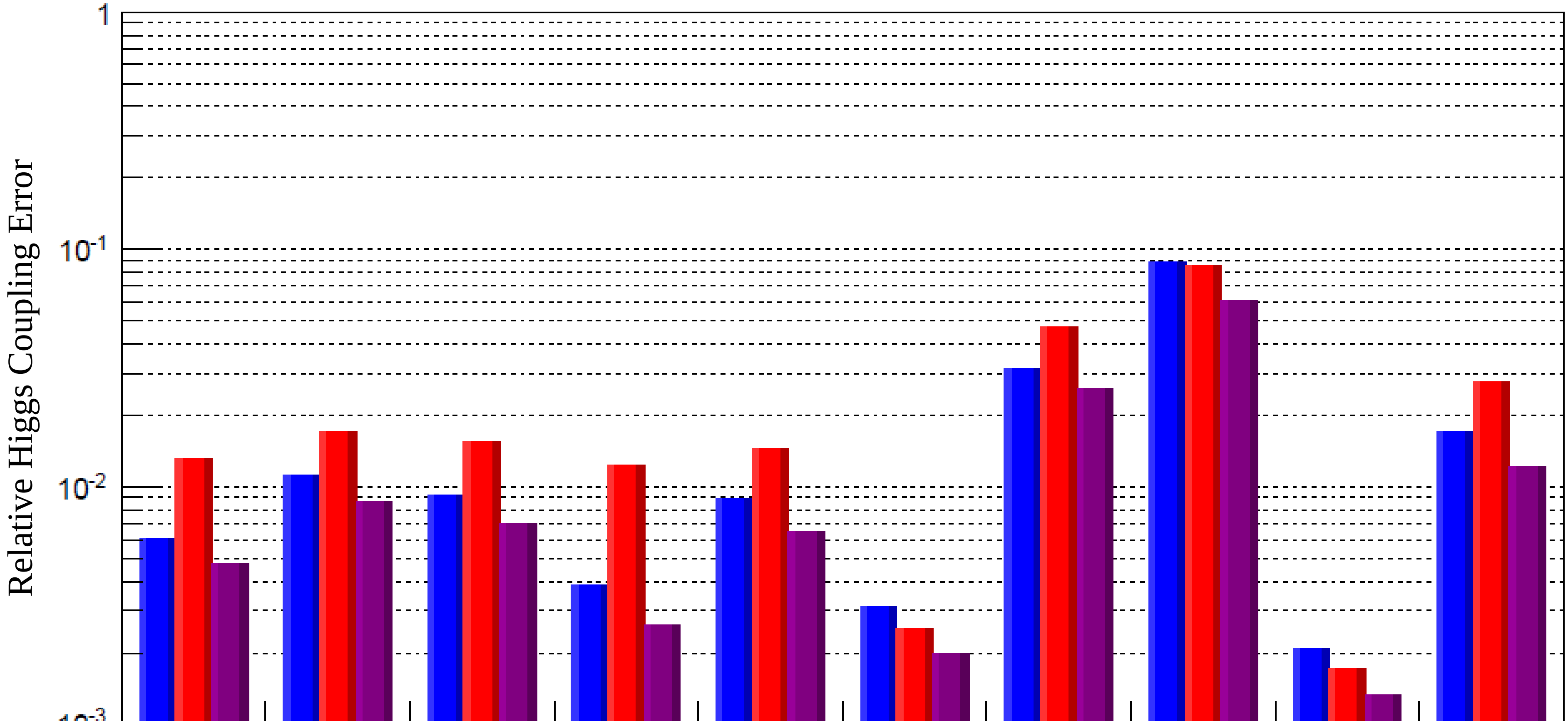


	bb	cc	gg	WW	tautau	ZZ	gamgam	mumu	invis	GamTot
ILC Δg / Comb. Δg	**1.28**	**1.31**	**1.31**	**1.47**	**1.37**	**1.58**	**1.21**	**1.44**	**1.58**	**1.42**
Extra ILC* Running (yr)	**10.4**	**10.4**	**10.4**	**10.4**	**10.4**	**10.4**	**10.4**	**10.4**	**10.4**	**10.4**

*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 G-20 @ 8.1 yrs

	CEPC		ILC+CEPC
Δg_{HZZ}	0.26%	$\Rightarrow$	0.22%
Δg_{HWW}	1.22%	$\Rightarrow$	0.38% *
Δg_{Hbb}	1.30%	$\Rightarrow$	0.68%
$\Delta g_{H\tau\tau}$	1.44%	$\Rightarrow$	0.88%
Δg_{Hgg}	1.53%	$\Rightarrow$	0.97%

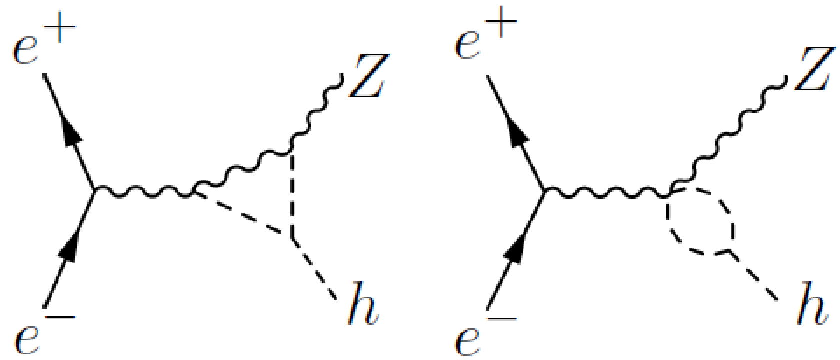
* Might be interesting to include $\sigma(WW \to H)$ in precision Higgs analyses

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%

* Again, might be interesting to include $\sigma(WW \to H)$ in precision Higgs analyses

CEPC Higgs Self Coupling Measurement at Ecm=240 GeV



M. McCullough, arXiv:1312.3322

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

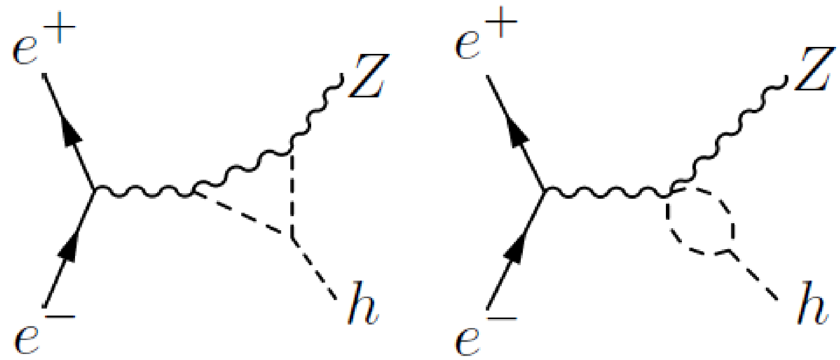
g_{hZZ} fixed to SM value $(\delta_z = 0)$

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.

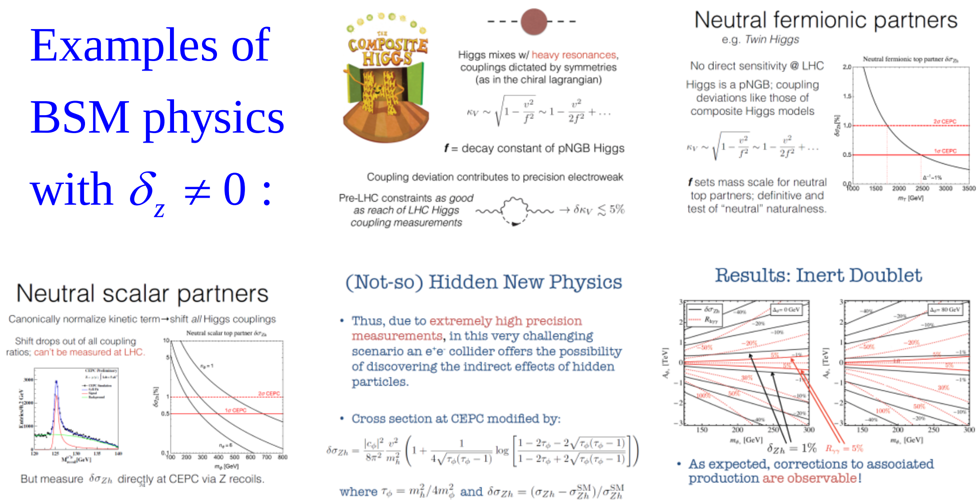
CEPC Higgs Self Coupling Measurement at Ecm=240 GeV



M. McCullough, arXiv:1312.3322

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

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



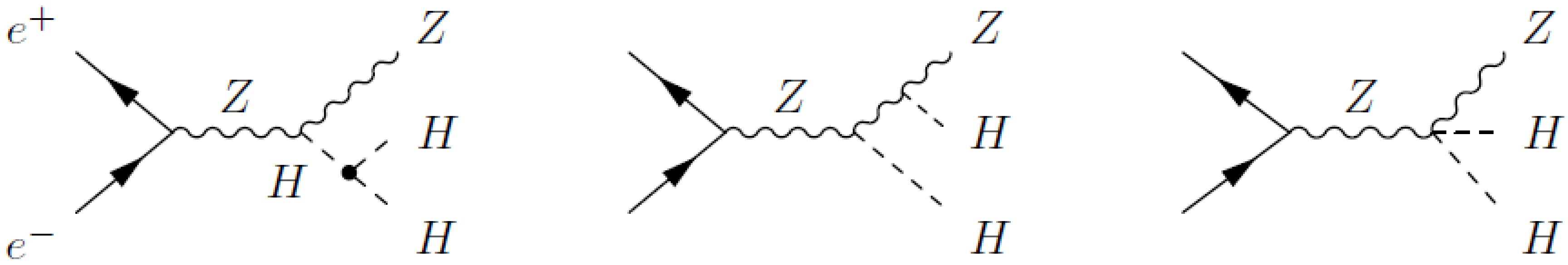
g_{hZZ} fixed to SM value $(\delta_z = 0)$

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.

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

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

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

Other Higgs Measurements with CEPC & ILC G-20 at 8.1 yrs

	CEPC 250 GeV $5000\ \mathrm{fb}^{-1}$	ILC $250+350+500$ GeV $500+250+500\ \mathrm{fb}^{-1}$	***Combined***
Δm_H	5.9 MeV	25 MeV	5.7 MeV
$\dfrac{\Delta g_{HHH}}{g_{HHH}}$	36 %	76 %	33 %
$\dfrac{\Delta g_{ttH}}{g_{ttH}}$	–	16.6 %	16.6 %
$\dfrac{\Delta g_{ttH}^{(*)}}{g_{ttH}}$	–	6.7 %	6.7 %

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

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

	CEPC 250 GeV 5000 fb^{-1}	ILC $250+350+500$ GeV $2000+250+4000$ 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 +CEPC Summary

- ILC helps CEPC:
  - A_{LR} measurement and top mass
  - Precise g_{HWW} measurement reduces errors on all Higgs couplings
  - Top Yukawa coupling
  - ILC σ(ZHH) measurement (and others I assume) help interpret precision CEPC σ(ZH) meas.
  - New particle searches at 500 GeV

- CEPC helps ILC:
  - Many EW precision measurements: M_Z, Γ_Z, α_S, Nν, MW, …
  - Precise g_{HZZ} measurement reduces errors on all Higgs couplings
  - Much better meas. of Higgs invisible width, BSM decays, rare decays such as $\gamma\gamma$ and $\mu\mu$
  - In general, CEPC gives ILC more flexibility to concentrate on higher E_{cm} running.

- CEPC+ILC combination helps the particle physics community:
  - Higgs Z coupling error $\Delta g_{HZ} = 0.2\%$
  - Higgs W coupling error $\Delta g_{WW} = 0.3\%$
  - Higgs b coupling error $\Delta g_{bb} = 0.5\%$
  - Higgs self coupling error $\Delta g_{HHH} = 22\%$

ILC + 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%**

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

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

$\sqrt{s}$ (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.

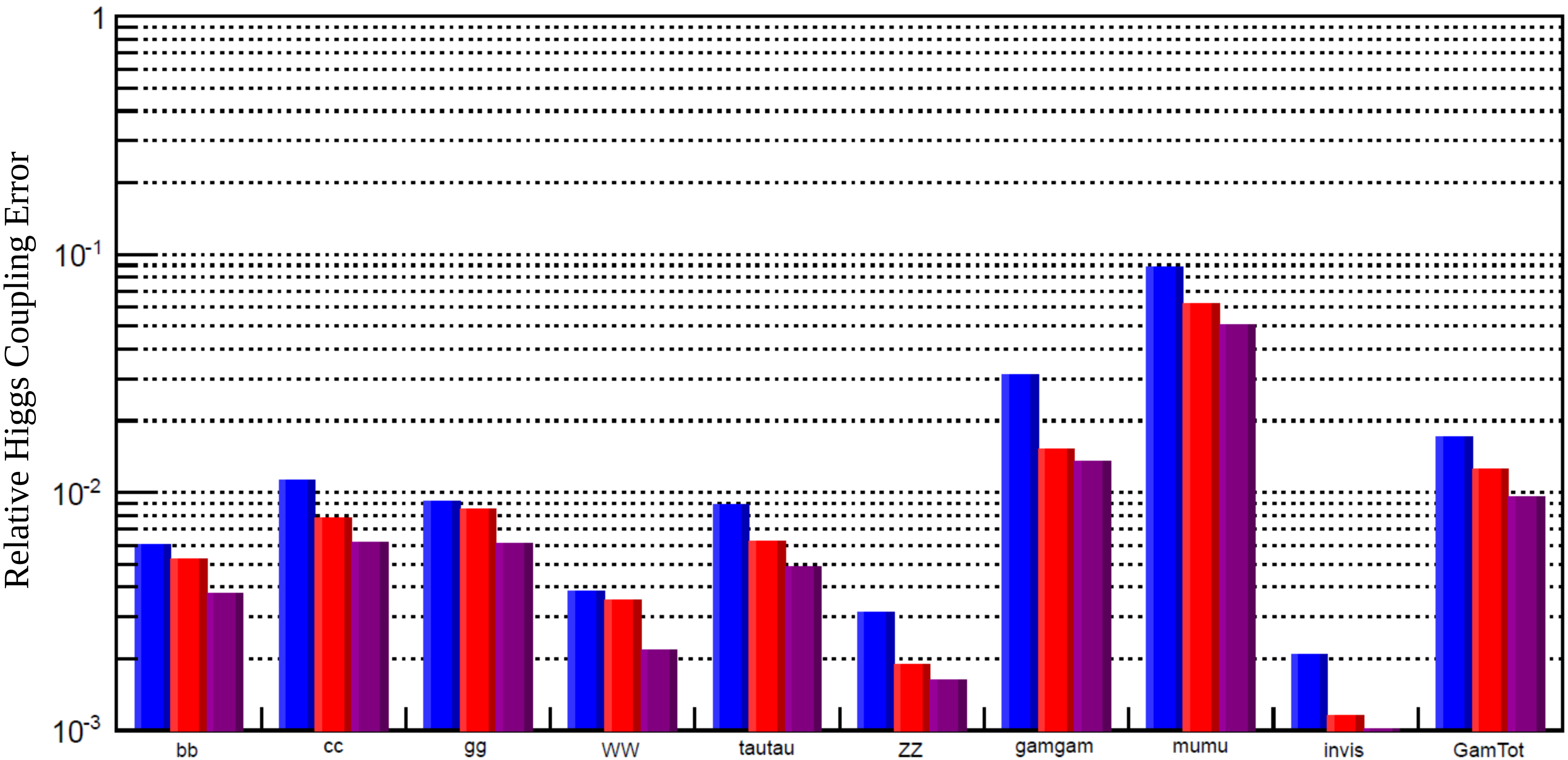
Take ILC errors on σ and σ•BR from arXiv:1506.07830 assuming 250+350+500 GeV with either:

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.

How does ILC help FCC-ee?

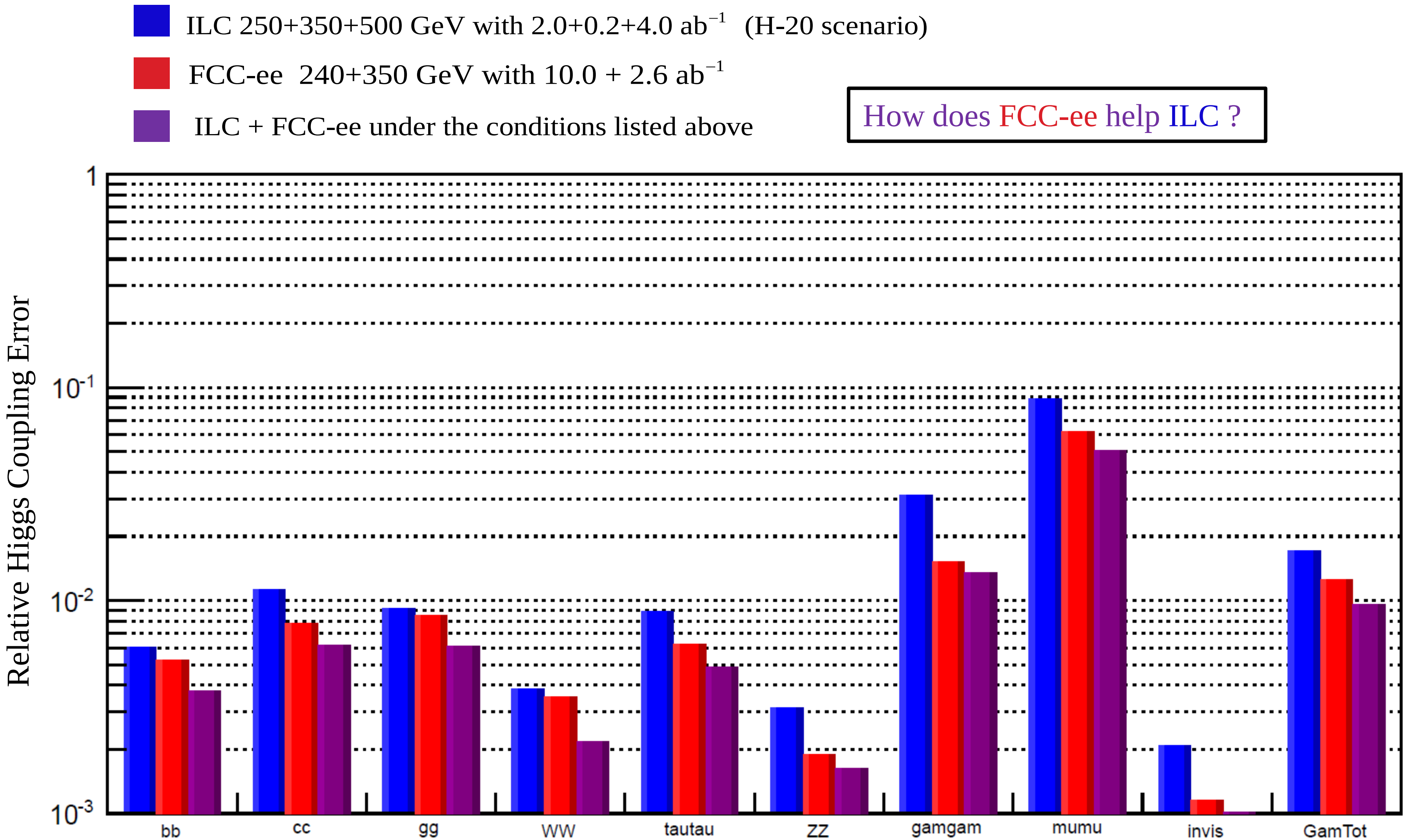
- ILC 250+350+500 GeV with 2.0+0.2+4.0 ab^{-1} (H-20 scenario)
- FCC-ee 240+350 GeV with 10.0 + 2.6 ab^{-1}
- ILC + FCC-ee under the conditions listed above



	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

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.