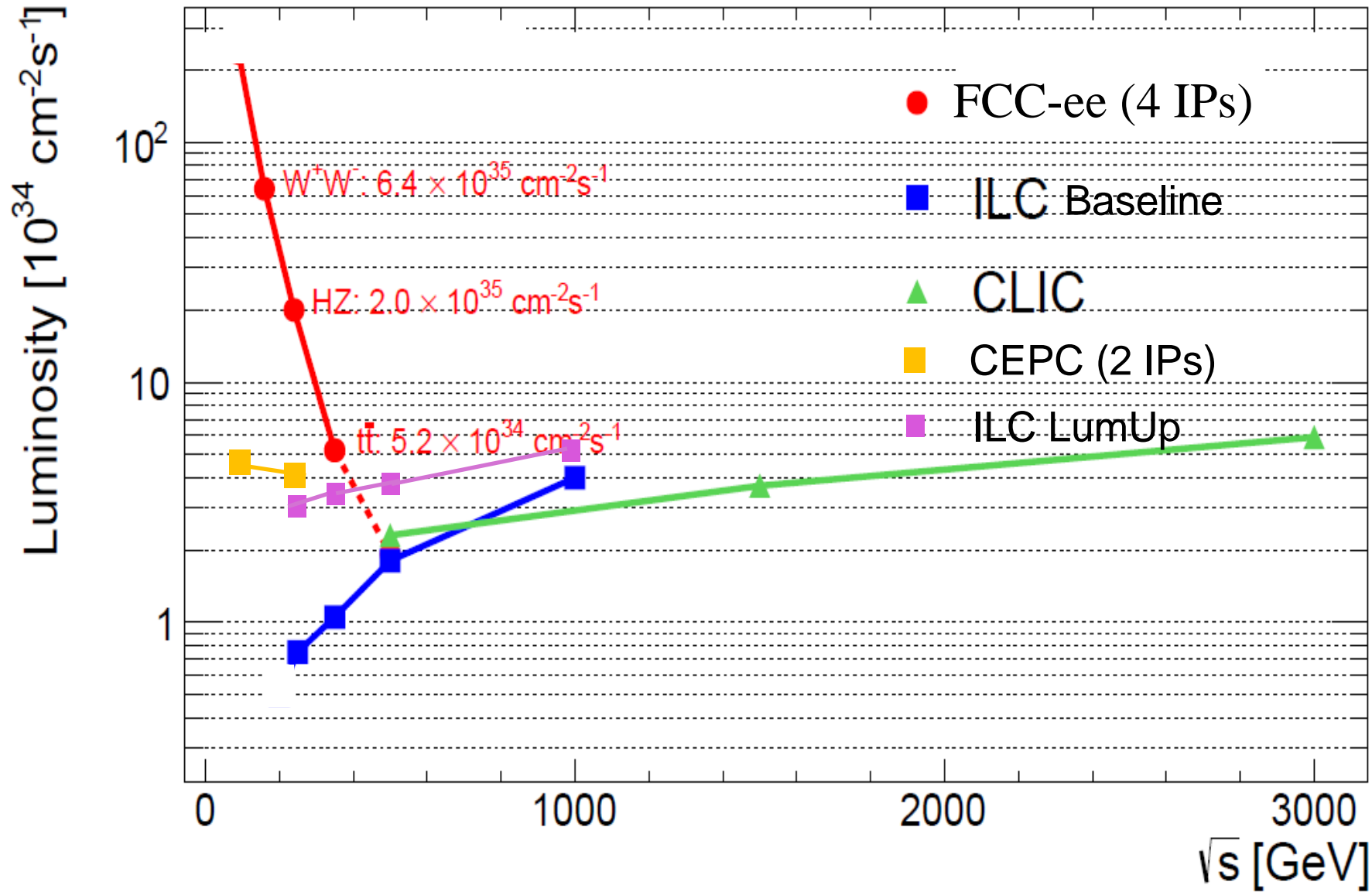


# Higgs Physics Complementarity for the ILC and Circular $e^+e^-$ Colliders

Tim Barklow (SLAC)

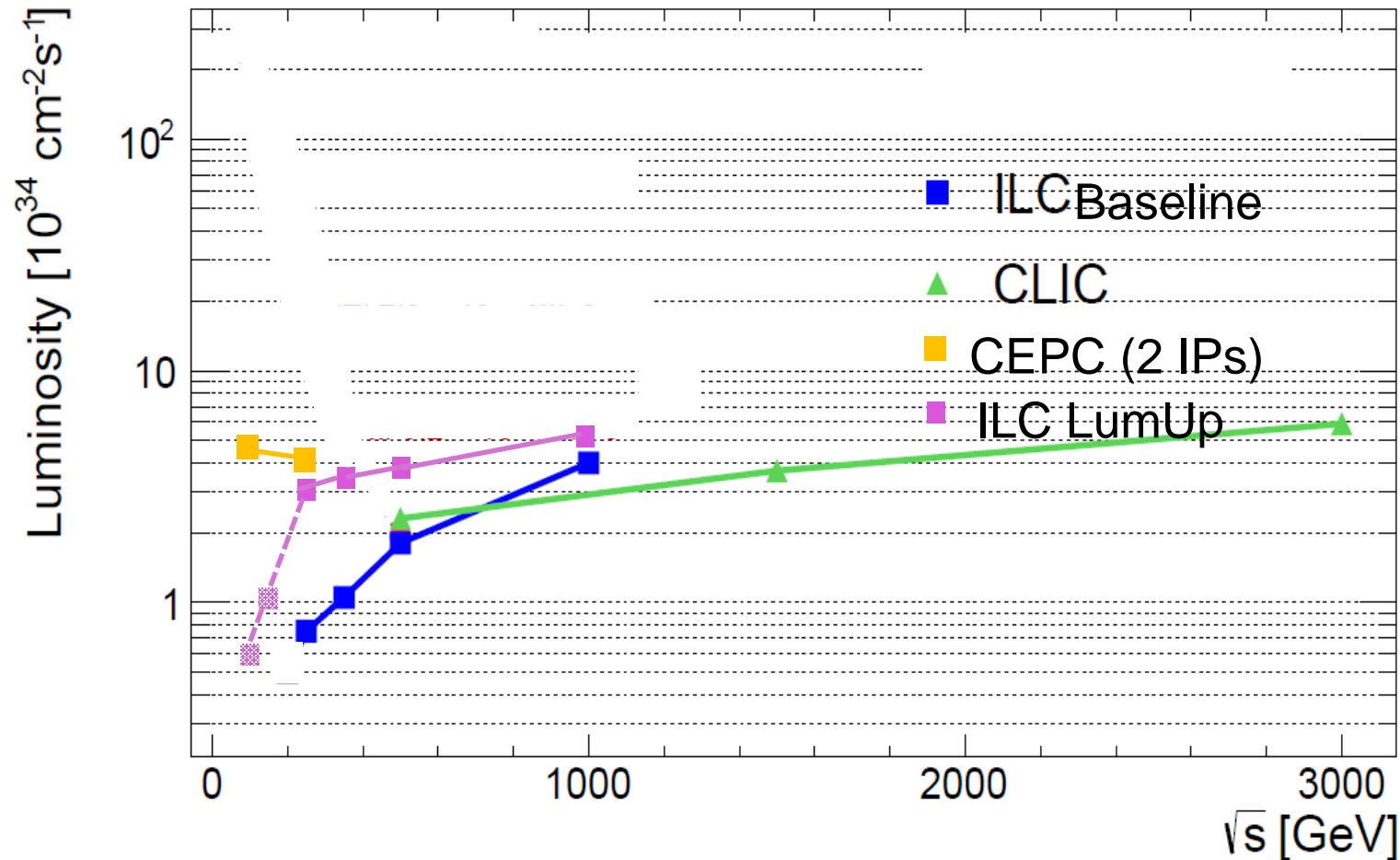
Nov 5, 2015

LCWS2015 Whistler, Canada



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

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



Currently no ILC design for  $\sqrt{s} = 90, 160 \text{ GeV}$ . 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 reasonable design goal might be  $L=5 \times 10^{33}$  @ 91 GeV and  $L=1 \times 10^{34}$  @ 160 GeV in the lumi upgrade config.

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

# EW Precision Measurements with CEPC & ILC

	CEPC	ILC
	91 +160 GeV 100 + 500 fb <sup>-1</sup>	91 +160 GeV 100 + 200 fb <sup>-1</sup>
$\Delta A_{LR}$	–	$1 \times 10^{-4}$
$\Delta \sin^2 \theta_W^{eff}$	$2.7 \times 10^{-5}$	$1.3 \times 10^{-5}$
$\Delta M_Z$	0.5 MeV	1.6 MeV
$\Delta \Gamma_Z$	0.5 MeV	0.5 MeV
$\Delta \alpha_s(M_Z^2)$	$1.0 \times 10^{-4}$	$5.0 \times 10^{-4}$
$\Delta N_\nu$	0.001	0.004
$\Delta A_b$	–	0.001
$\Delta R_b \equiv \Delta \frac{\Gamma_b}{\Gamma_{had}}$	$1.7 \times 10^{-4}$	$1.4 \times 10^{-4}$
$\Delta R_l \equiv \Delta \frac{\Gamma_{had}}{\Gamma_l}$	0.007	–
$\Delta M_W$	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	H20 @ 8yrs	H20 @ 20yrs	units	ref.
		Initial Phase	Full Data Set		
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]
	$\Gamma_{tot}$	3.8	1.8	%	[8]
	$\Gamma_{invis}$	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  $\sigma$  and  $\sigma \cdot \text{BR}$  from pre Conceptual Design Report assuming 240 GeV with 5  $\text{ab}^{-1}$  :

$\Delta M_H$	$\Gamma_H$	$\sigma(ZH)$
5.9 MeV	2.8%	0.51%

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

Take ILC errors on  $\sigma$  and  $\sigma \cdot \text{BR}$  from arXiv:1506.07830 assuming 250+350+500 GeV with either:

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

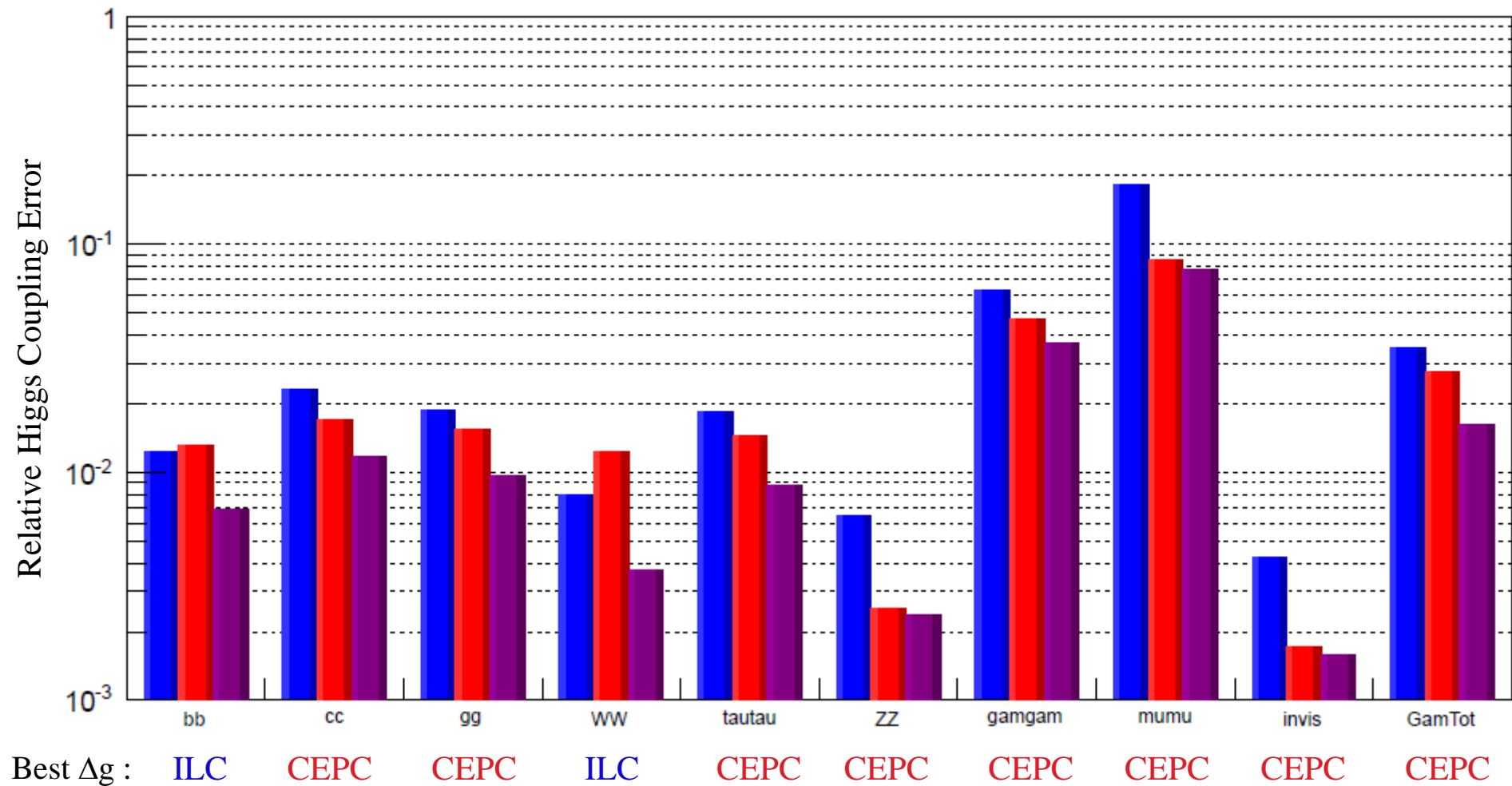
Perform model independent fit of b,c,g,W, $\tau$ ,Z, $\gamma$ , $\mu$ ,invis Higgs couplings and total width using standard program (from Michael Peskin) for ILC & CEPC separately and combined.



■ ILC 250+350+500 GeV with 340+200+1000 fb<sup>-1</sup> (G-20 scenario at 8.1 yrs)

■ CEPC 250 GeV with 5000 fb<sup>-1</sup>

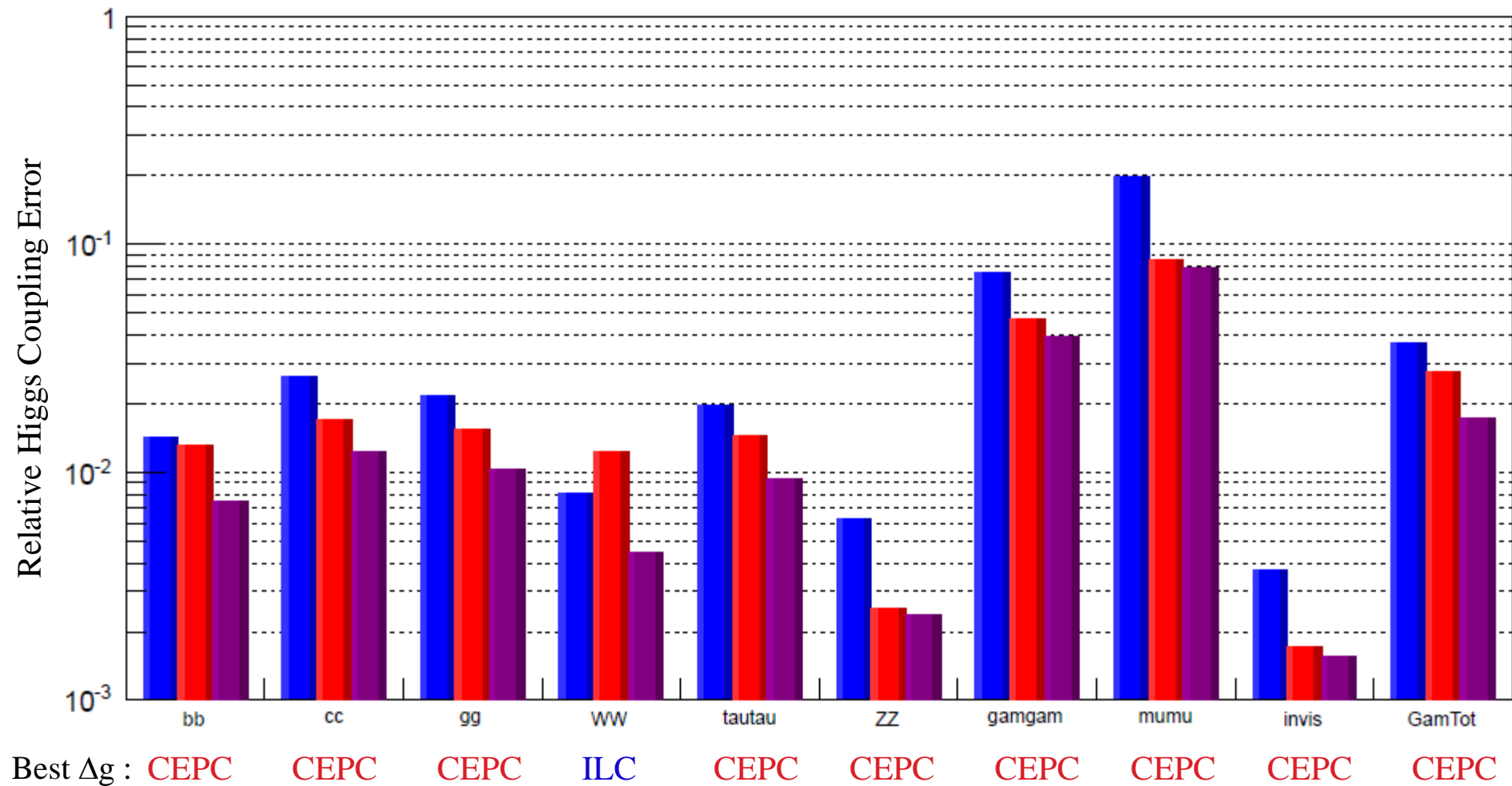
■ ILC + CEPC under the conditions listed above



■ ILC 250+350+500 GeV with 500+200+500 fb<sup>-1</sup> (H-20 scenario at 8.1 yrs)

■ CEPC 250 GeV with 5000 fb<sup>-1</sup>

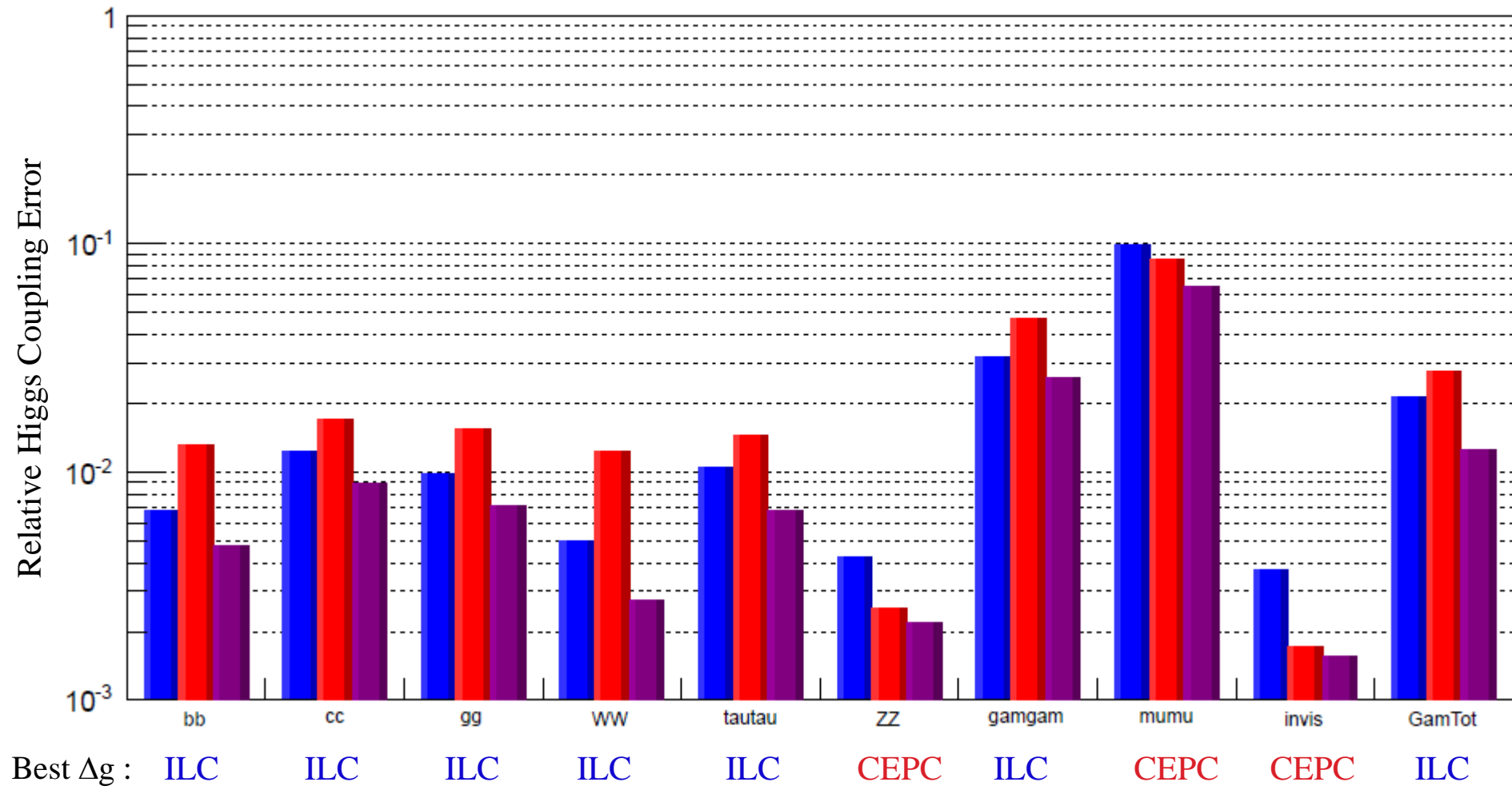
■ ILC + CEPC under the conditions listed above



■ ILC 250+350+500 GeV with 500+200+5000 fb<sup>-1</sup> (G-20 scenario full run ⇒ 19.7 yrs)

■ CEPC 250 GeV with 5000 fb<sup>-1</sup>

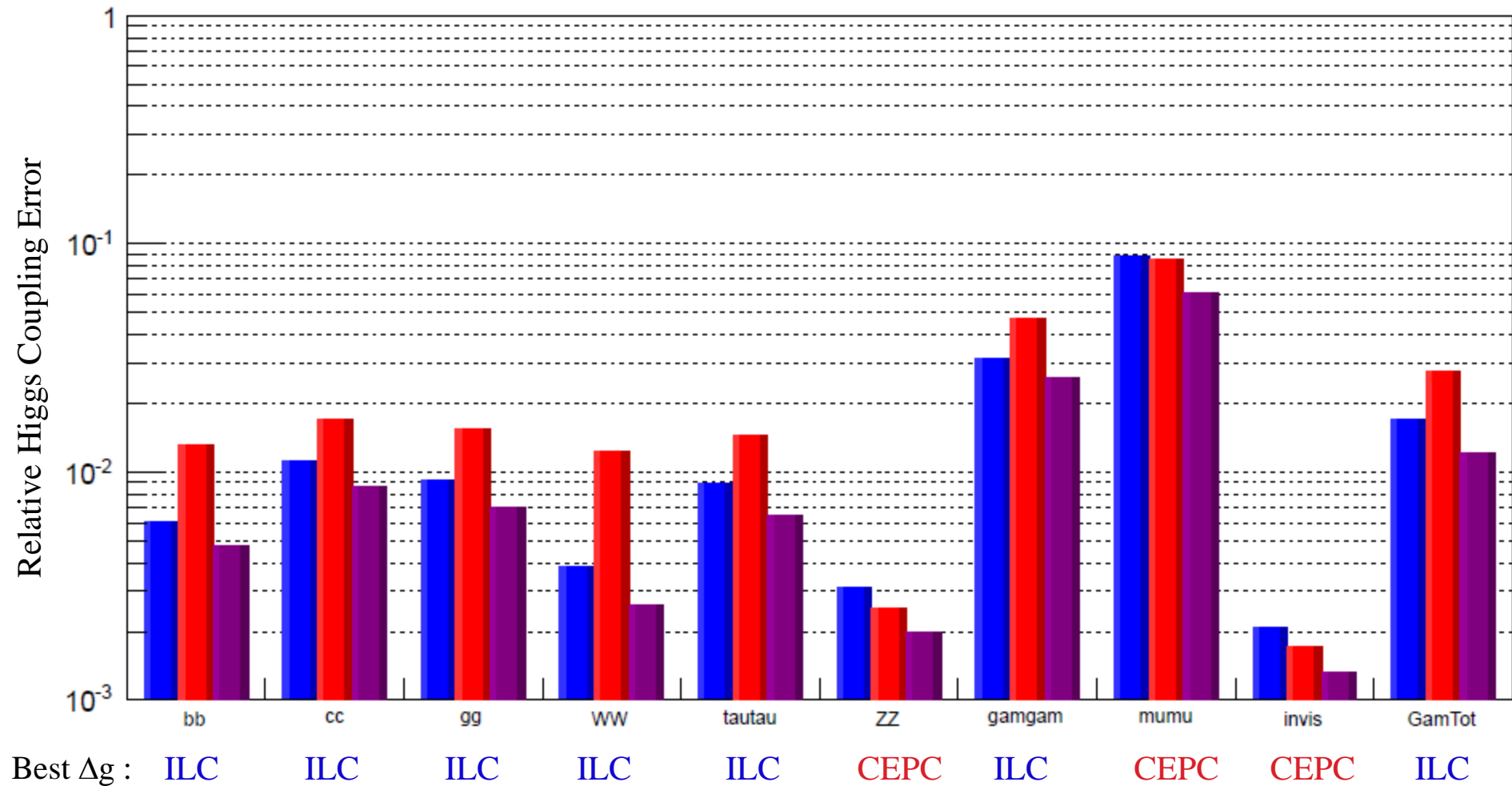
■ ILC + CEPC under the conditions listed above



■ ILC 250+350+500 GeV with 2000+200+4000 fb<sup>-1</sup> (H-20 scenario full run ⇒ 20.2 yrs)

■ CEPC 250 GeV with 5000 fb<sup>-1</sup>

■ ILC + CEPC under the conditions listed above

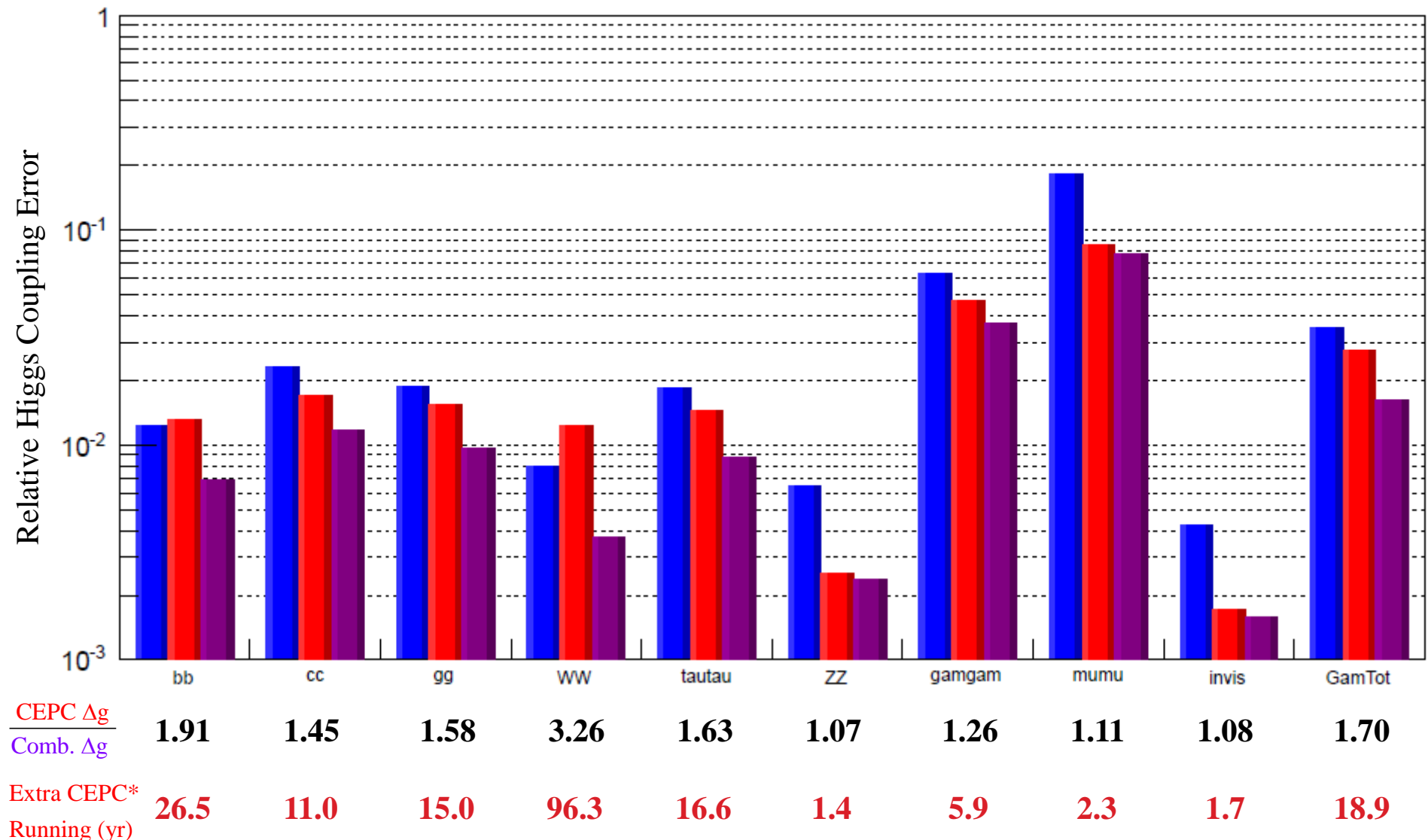


■ ILC 250+350+500 GeV with 340+200+1000 fb<sup>-1</sup> (G-20 scenario at 8.1 yrs)

■ CEPC 250 GeV with 5000 fb<sup>-1</sup>

■ ILC + CEPC under the conditions listed above

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



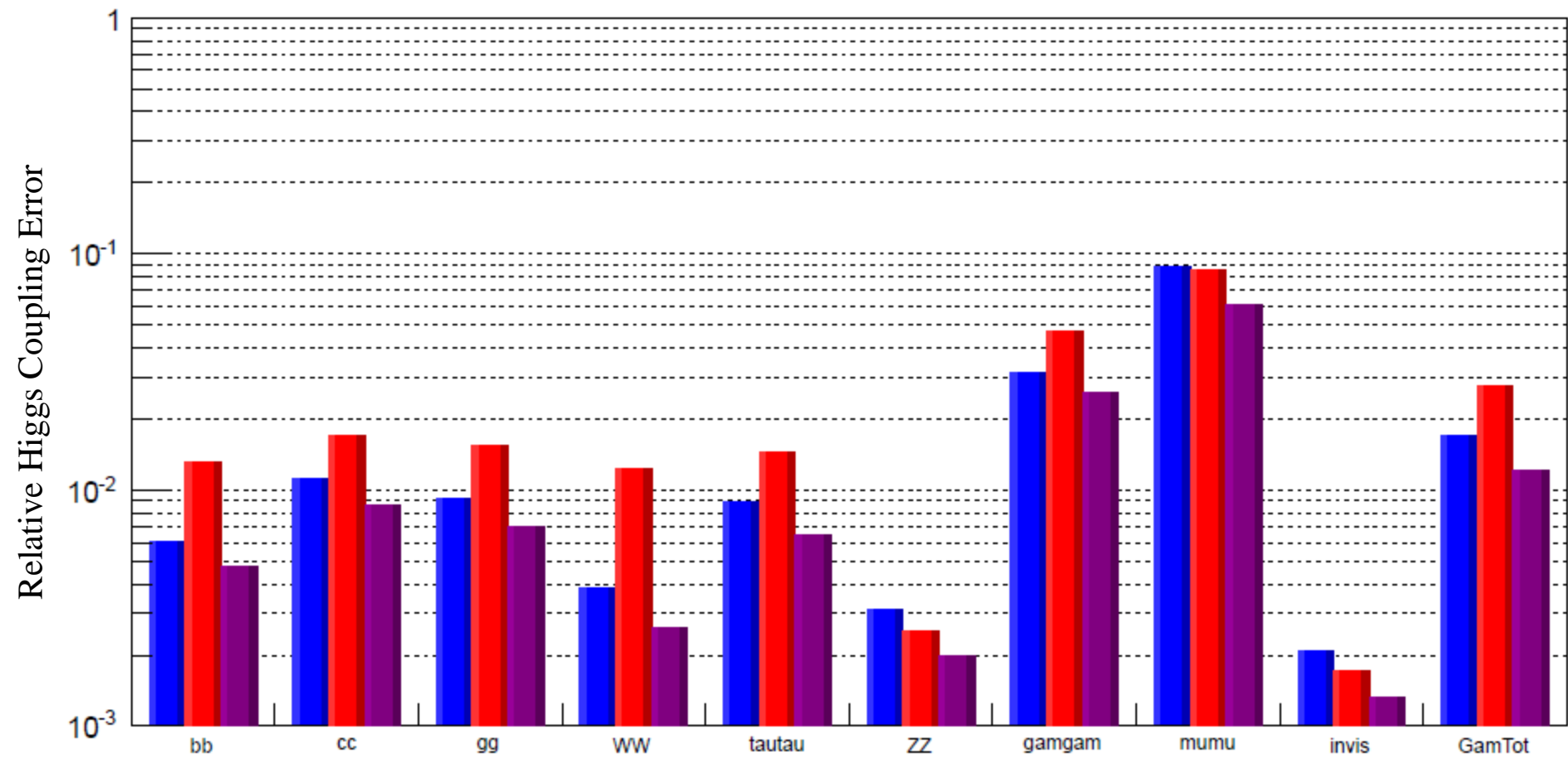
\*Additional CEPC running required to match ILC contribution to Combination. Assumes all extra running at  $\sqrt{s} = 250$  GeV

■ ILC 250+350+500 GeV with 2000+200+4000 fb<sup>-1</sup> (H-20 scenario full run ⇒ 20.2 yrs)

■ CEPC 250 GeV with 5000 fb<sup>-1</sup>

■ ILC + CEPC under the conditions listed above

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



	bb	cc	gg	WW	tautau	ZZ	gamgam	mumu	invis	GamTot
$\frac{\text{ILC } \Delta g}{\text{Comb. } \Delta g}$	<b>1.28</b>	<b>1.31</b>	<b>1.31</b>	<b>1.47</b>	<b>1.37</b>	<b>1.58</b>	<b>1.21</b>	<b>1.44</b>	<b>1.58</b>	<b>1.42</b>
Extra ILC* Running (yr)	<b>10.4</b>	<b>10.4</b>	<b>10.4</b>	<b>10.4</b>	<b>10.4</b>	<b>10.4</b>	<b>10.4</b>	<b>10.4</b>	<b>10.4</b>	<b>10.4</b>

\*Additional ILC running required to match CEPC contribution to Combination. Assumes all extra running at  $\sqrt{s} = 250$  GeV 14

## Highlights of Combination of CEPC with ILC G-20 @ 8.1 yrs

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

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

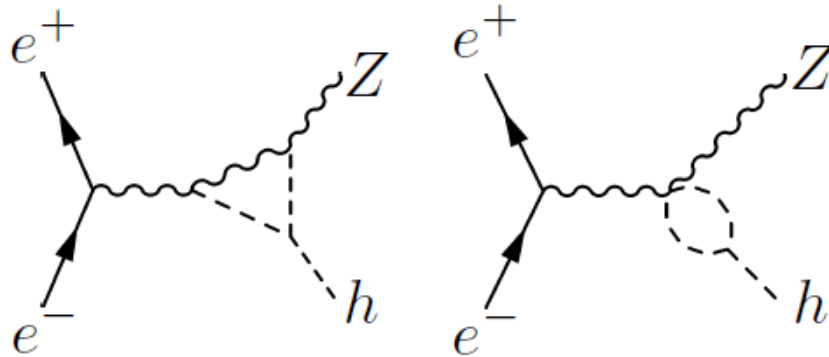
## Highlights of Combination of CEPC with ILC H-20 @ 20 yrs

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

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



# CEPC Higgs Self Coupling Measurement at $E_{cm}=240$ GeV



M. McCullough, arXiv:1312.3322

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

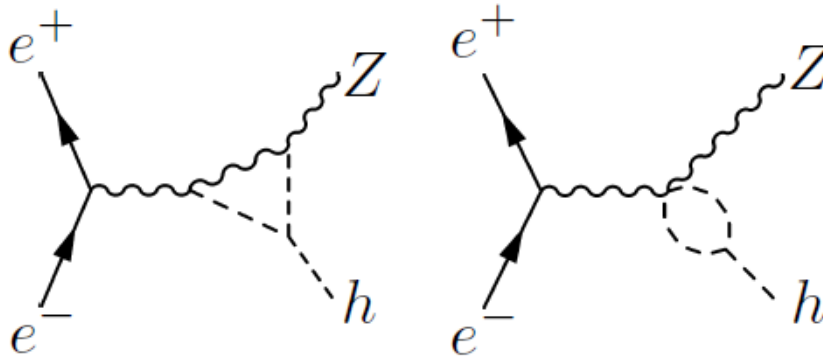
$g_{hZZ}$  fixed to SM value ( $\delta_z = 0$ )

$g_{hhZZ}$  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 E<sub>cm</sub>=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  $\delta_z \neq 0$ :



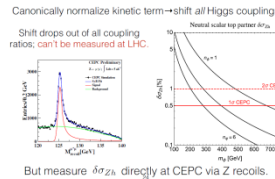
Higgs mixes w/ heavy resonances, couplings dictated by symmetries (as in the chiral lagrangian)  
 $\kappa_V \sim \sqrt{1 - \frac{v^2}{f^2}} \approx 1 - \frac{v^2}{2f^2} + \dots$   
 $f$  = decay constant of pNGB Higgs

Coupling deviation contributes to precision electroweak  
 Pre-LHC constraints as good as reach of LHC Higgs coupling measurements

Neutral fermionic partners  
 e.g. *Twin Higgs*

No direct sensitivity @ LHC  
 Higgs is a pNGB, coupling deviations like those of composite Higgs models  
 $\kappa_V \sim \sqrt{1 - \frac{v^2}{f^2}} \approx 1 - \frac{v^2}{2f^2} + \dots$   
 $f$  sets mass scale for neutral top partners; definitive and test of "neutral" naturalness.

Neutral scalar partners

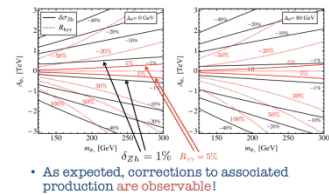


(Not-so) Hidden New Physics

- 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:  

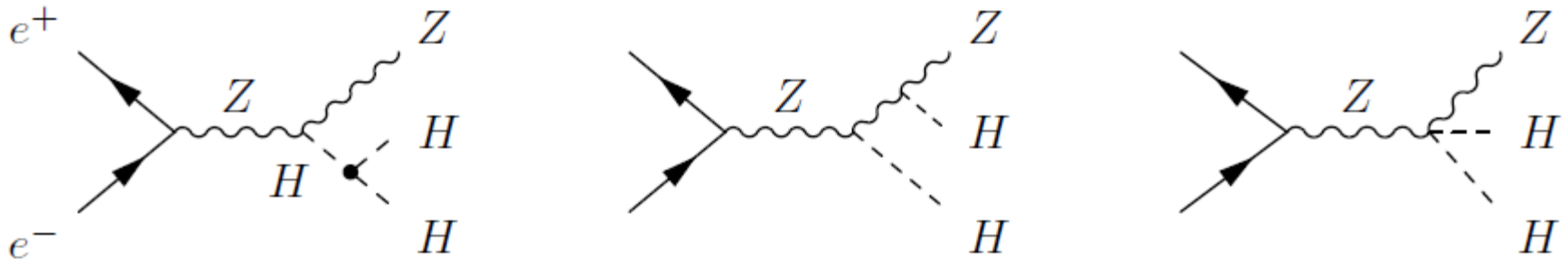
$$\delta\sigma_{Zh} = \frac{|c_h|^2 v^2}{8\pi^2 m_h^2} \left( 1 + \frac{1}{4\sqrt{\tau_0}(\tau_0 - 1)} \log \left[ \frac{1 - 2\tau_0 - 2\sqrt{\tau_0}(\tau_0 - 1)}{1 - 2\tau_0 + 2\sqrt{\tau_0}(\tau_0 - 1)} \right] \right)$$
 where  $\tau_0 = m_h^2/4m_{\tilde{t}_0}^2$  and  $\delta\sigma_{Zh} = (\sigma_{Zh} - \sigma_{Zh}^{SM})/\sigma_{Zh}^{SM}$

Results: Inert Doublet



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

# ILC Higgs Self Coupling Measurement at $E_{cm}=500$ GeV



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

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

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

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

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

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	ILC	<i>Combined</i>
	250 GeV 5000 fb <sup>-1</sup>	250 + 350 + 500 GeV 500 + 250 + 500 fb <sup>-1</sup>	
$\Delta m_H$	5.9 MeV	25 MeV	5.7 MeV
$\frac{\Delta g_{HHH}}{g_{HHH}}$	36 %	76 %	33 %
$\frac{\Delta g_{t\bar{t}H}}{g_{t\bar{t}H}}$	—	16.6 %	16.6 %
$\frac{\Delta g_{t\bar{t}H}^{(*)}}{g_{t\bar{t}H}}$	—	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 <sup>-1</sup>	ILC 250 + 350 + 500 GeV 2000 + 250 + 4000 fb <sup>-1</sup>	<i>Combined</i>
$\Delta m_H$	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  $\sigma(ZHH)$  measurement (and others I assume) help interpret precision CEPC  $\sigma(ZH)$  meas.
- New particle searches at 500 GeV

## ▶ CEPC helps ILC:

- Many EW precision measurements:  $M_Z$ ,  $\Gamma_Z$ ,  $\alpha_s$ ,  $N_\nu$ ,  $M_W$ , ...
- 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  $\sigma$  and  $\sigma \cdot \text{BR}$  from arXiv:1308.6176 assuming 240+350 GeV with 10.0 + 2.6  $\text{ab}^{-1}$  :

	TLEP 240
$\sigma_{\text{HZ}}$	<b>0.4%</b>
$\sigma_{\text{HZ}} \times \text{BR}(\text{H} \rightarrow \text{bb})$	<b>0.2%</b>
$\sigma_{\text{HZ}} \times \text{BR}(\text{H} \rightarrow \text{c}\bar{\text{c}})$	<b>1.2%</b>
$\sigma_{\text{HZ}} \times \text{BR}(\text{H} \rightarrow \text{gg})$	<b>1.4%</b>
$\sigma_{\text{HZ}} \times \text{BR}(\text{H} \rightarrow \text{WW})$	<b>0.9%</b>
$\sigma_{\text{HZ}} \times \text{BR}(\text{H} \rightarrow \tau\tau)$	<b>0.7%</b>
$\sigma_{\text{HZ}} \times \text{BR}(\text{H} \rightarrow \text{ZZ})$	<b>3.1%</b>
$\sigma_{\text{HZ}} \times \text{BR}(\text{H} \rightarrow \gamma\gamma)$	<b>3.0%</b>
$\sigma_{\text{HZ}} \times \text{BR}(\text{H} \rightarrow \mu\mu)$	<b>13%</b>

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

$\sqrt{s}$ (GeV)	TLEP
240 - 250	<b>2.2%</b>
350	<b>0.6%</b>

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  $\sigma$  and  $\sigma \cdot \text{BR}$  from arXiv:1506.07830 assuming 250+350+500 GeV with either:

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

Perform model independent fit of b,c,g,W, $\tau$ ,Z, $\gamma$ , $\mu$ ,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 . This is being looked into by FCC-ee

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



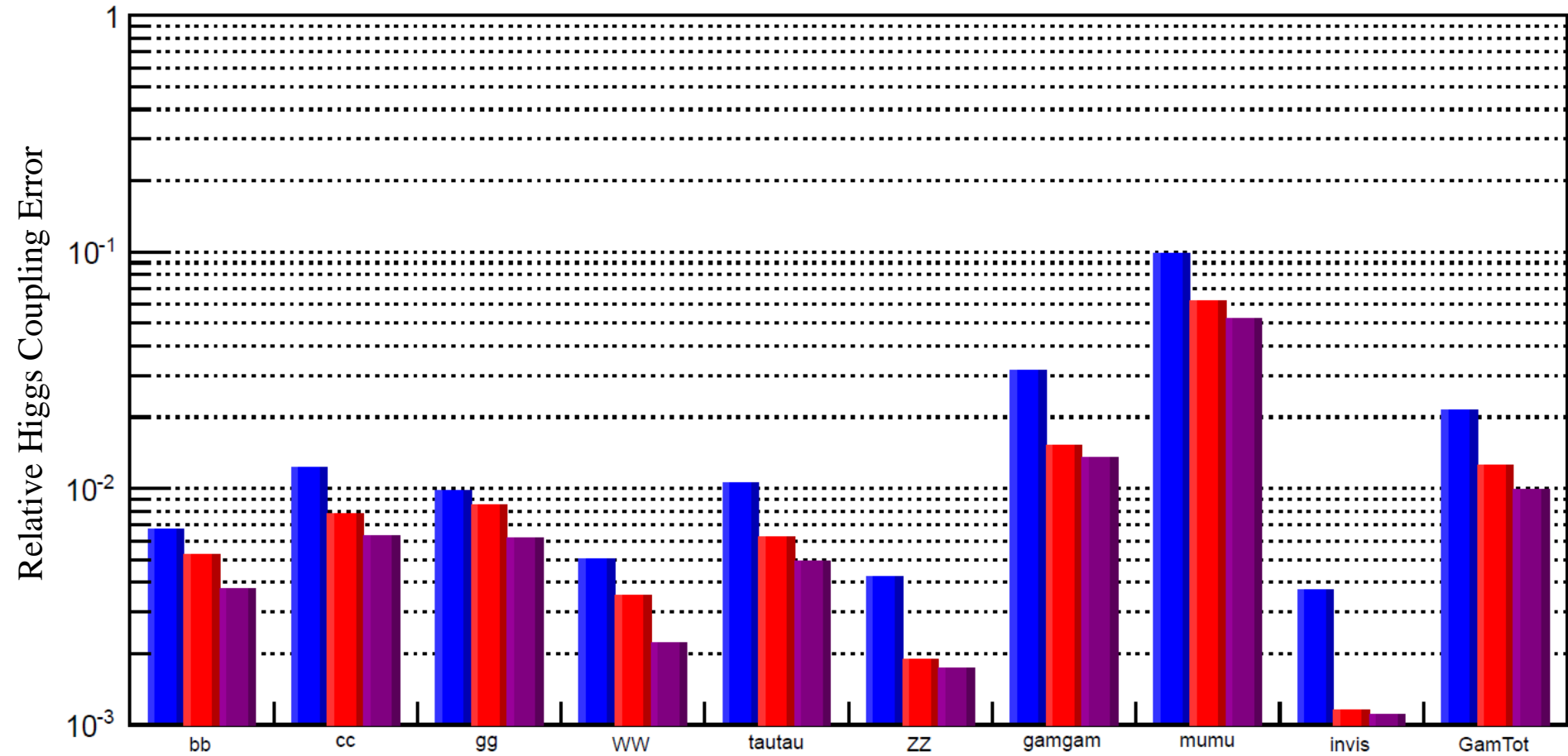
Because it is the only way to consistently combine FCC-ee and ILC results I will, for this talk, use these results for FCC-ee.



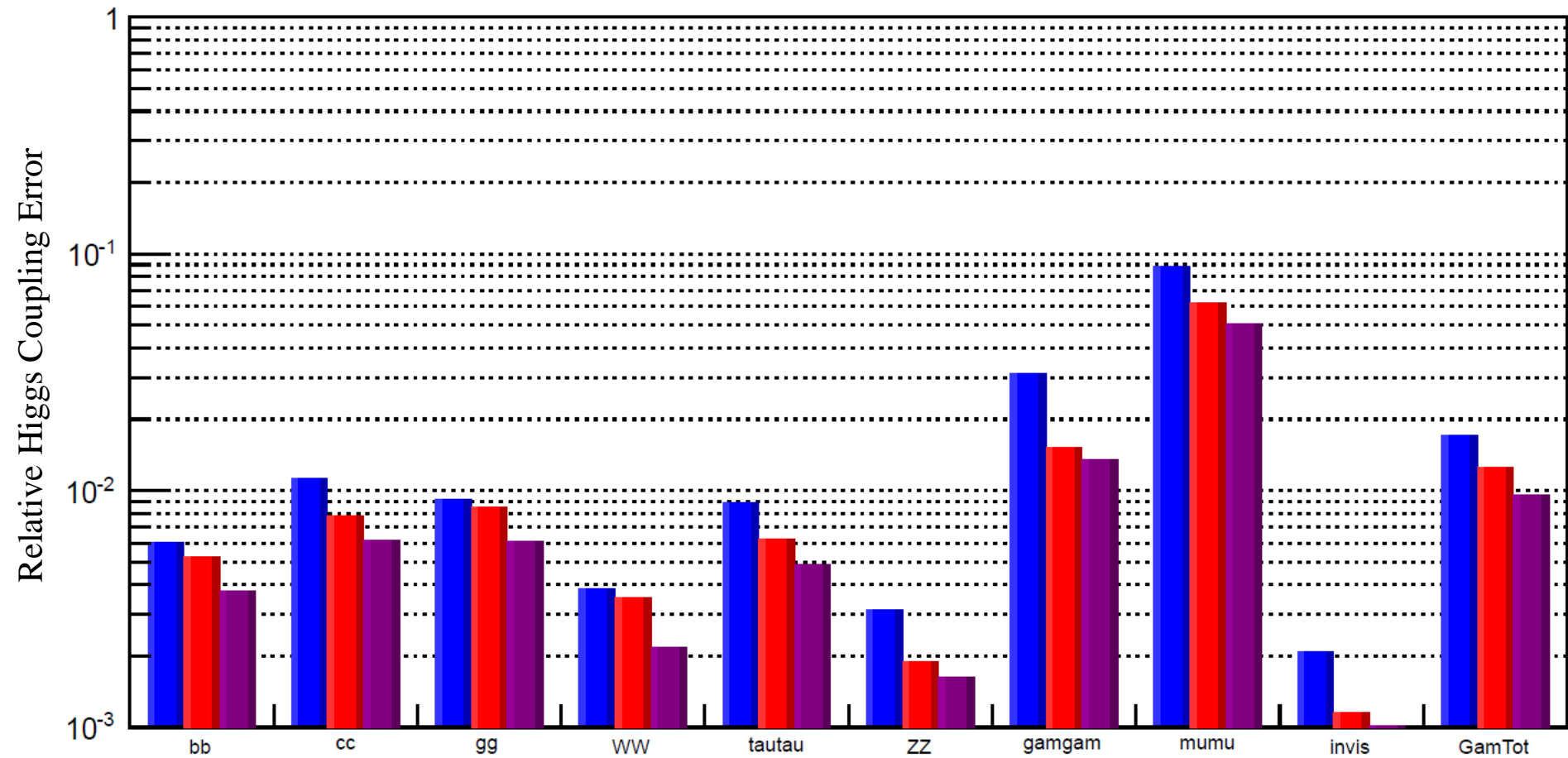
■ ILC 250+350+500 GeV with 0.5+0.2+5.0 fb<sup>-1</sup> (G-20 scenario)

■ FCC-ee 240+350 GeV with 10.0 + 2.6 ab<sup>-1</sup>

■ ILC + FCC-ee under the conditions listed above



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

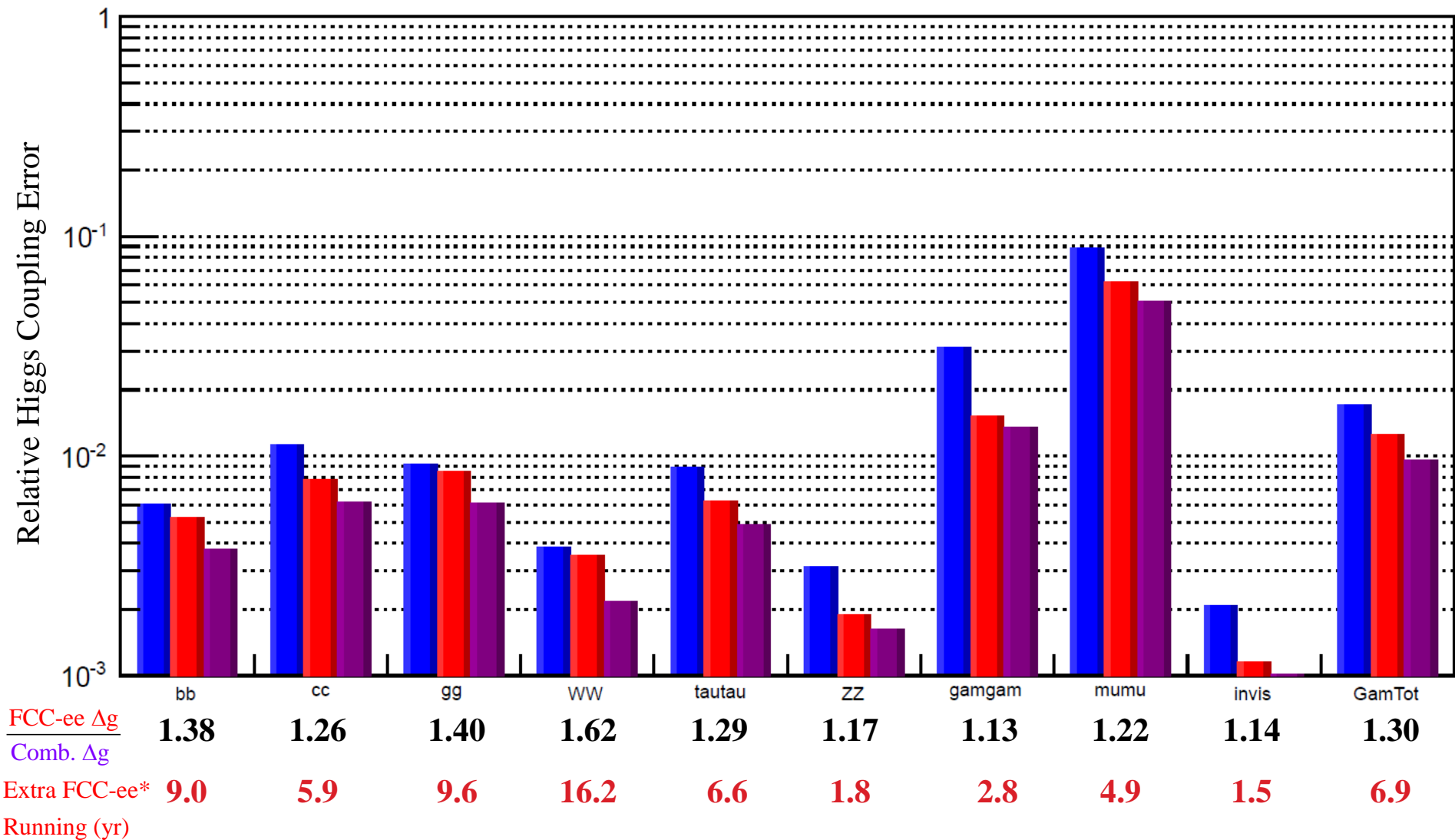


■ ILC 250+350+500 GeV with 2.0+0.2+4.0  $\text{ab}^{-1}$  (H-20 scenario)

■ FCC-ee 240+350 GeV with 10.0 + 2.6  $\text{ab}^{-1}$

■ ILC + FCC-ee under the conditions listed above

How does ILC help FCC-ee?



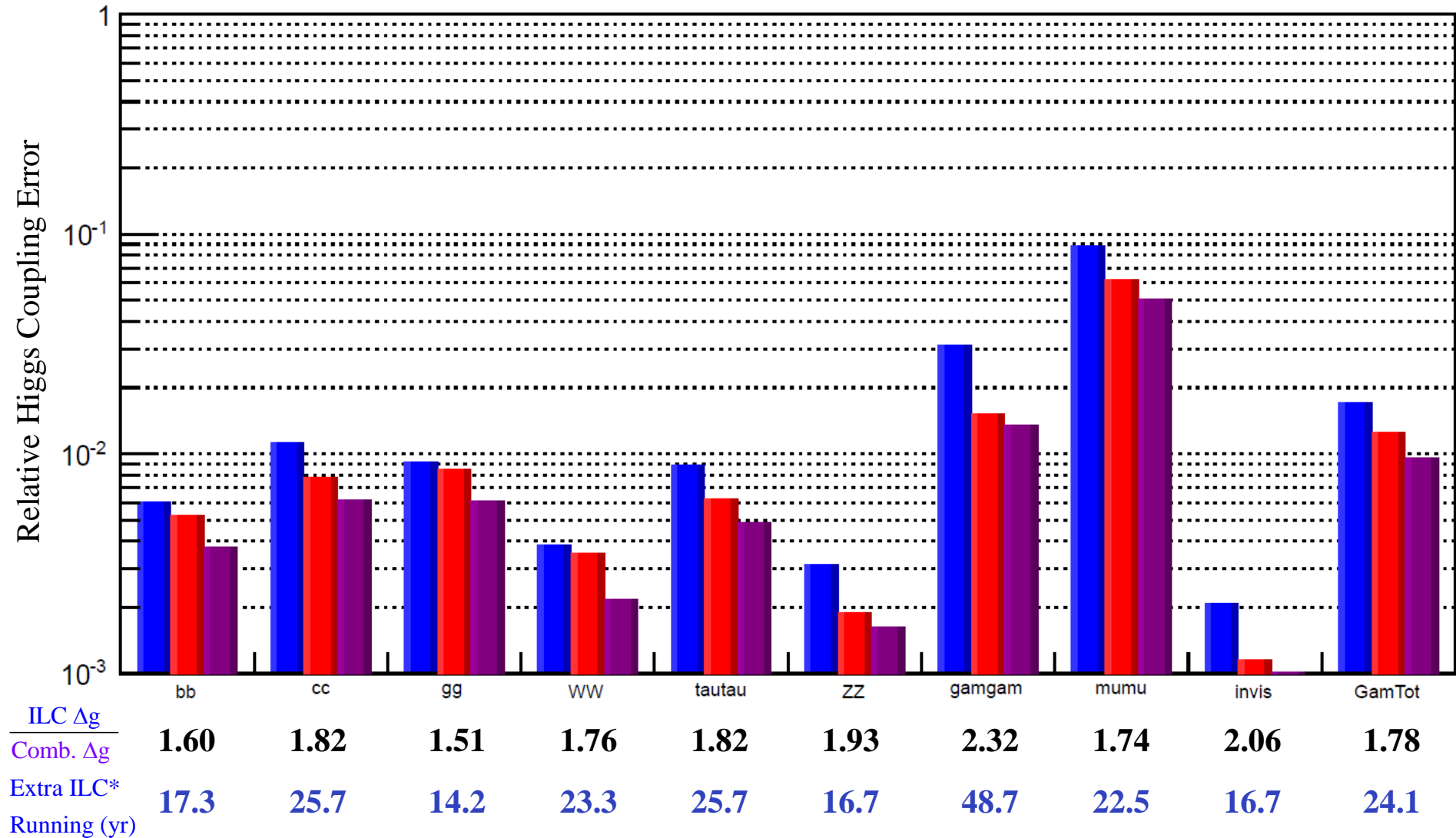
\*Additional FCC-ee running required to match ILC contribution to Combination. Assumes the same 10:2.6 luminosity ratio for 240:350 GeV except ZZ & invis which assume that all extra running is at 240 GeV

■ ILC 250+350+500 GeV with 2.0+0.2+4.0  $\text{ab}^{-1}$  (H-20 scenario)

■ FCC-ee 240+350 GeV with 10.0 + 2.6  $\text{ab}^{-1}$

■ ILC + FCC-ee under the conditions listed above

How does FCC-ee help ILC ?



ILC  $\Delta g$   
 Comb.  $\Delta g$   
 Extra ILC\*  
 Running (yr)

\*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
$\Delta g_{HZZ}$	0.31%	0.19%	0.16%
$\Delta g_{HWW}$	0.38%	0.35%	0.22%
$\Delta g_{Hbb}$	0.60%	0.52%	0.38%
$\Delta g_{H\tau\tau}$	0.89%	0.63%	0.49%
$\Delta g_{Hgg}$	0.92%	0.85%	0.61%

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

	FCC-ee	ILC	<i>Combined</i>
	240 + 350 GeV 10.0 + 2.6 ab <sup>-1</sup>	250 + 350 + 500(550) GeV 2.0 + 0.25 + 4.0 fb <sup>-1</sup>	
$\Delta m_H$	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  $\sigma(\text{ZH})$

\* Tree-level contribution to  $\sigma(\text{ZHH})$

# ILC + FCC-ee Summary

## ▶ ILC helps FCC-ee:

- The 0.25% measurement of  $\sigma(\nu\nu h) \times BR(H \rightarrow bb)$  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  $\sigma \times BR$  at 240 GeV help turn the ILC 0.25% measurement of  $\sigma(\nu\nu h) \times BR(H \rightarrow bb)$  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 1<sup>st</sup> 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  $\Delta g_{HHH} = 20\%$