Higgs precision physics at linear and circular e^+e^- colliders

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Based in part on work by T. Barklow, and on work done for this talk

UCSB

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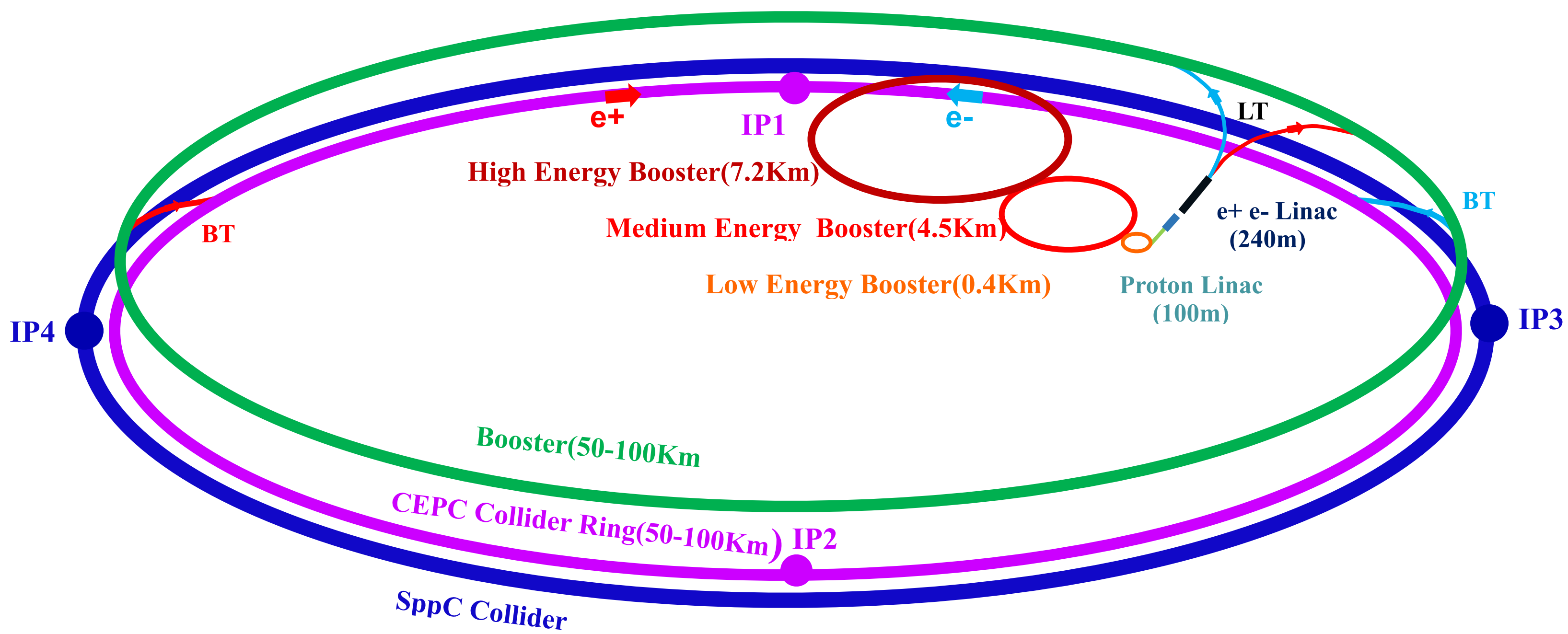
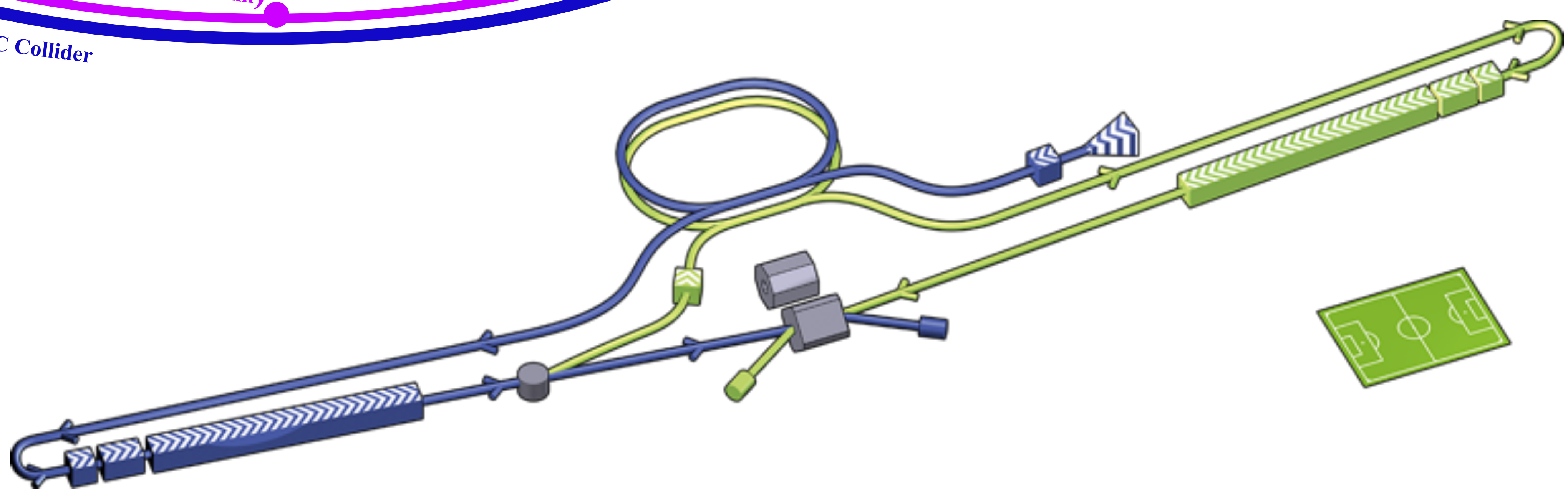
MORIOKA CITY, IWATE, JAPAN

The colliders

Four viable proposals on the table: ILC, CLIC; CEPC, FCC-ee



See plenary today by J. Gao



For the sake of time, this talk will focus on ILC and CEPC

Higgs Precision

CEPC (Pre-CDR)
5/ab

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

Decay mode	$\sigma(ZH) \times \mathrm{BR}$
$H \to bb$	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%
$H \to \mathrm{inv}$	–

ILC (1506.07830)
Scale up to H-20

$\int \mathscr{L} dt$ at $\sqrt{s}$	250 fb^{-1} at 250 GeV		330 fb^{-1} at 350 GeV		500 fb^{-1} at 500 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	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$						
$h \to b\bar{b}$	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%	-

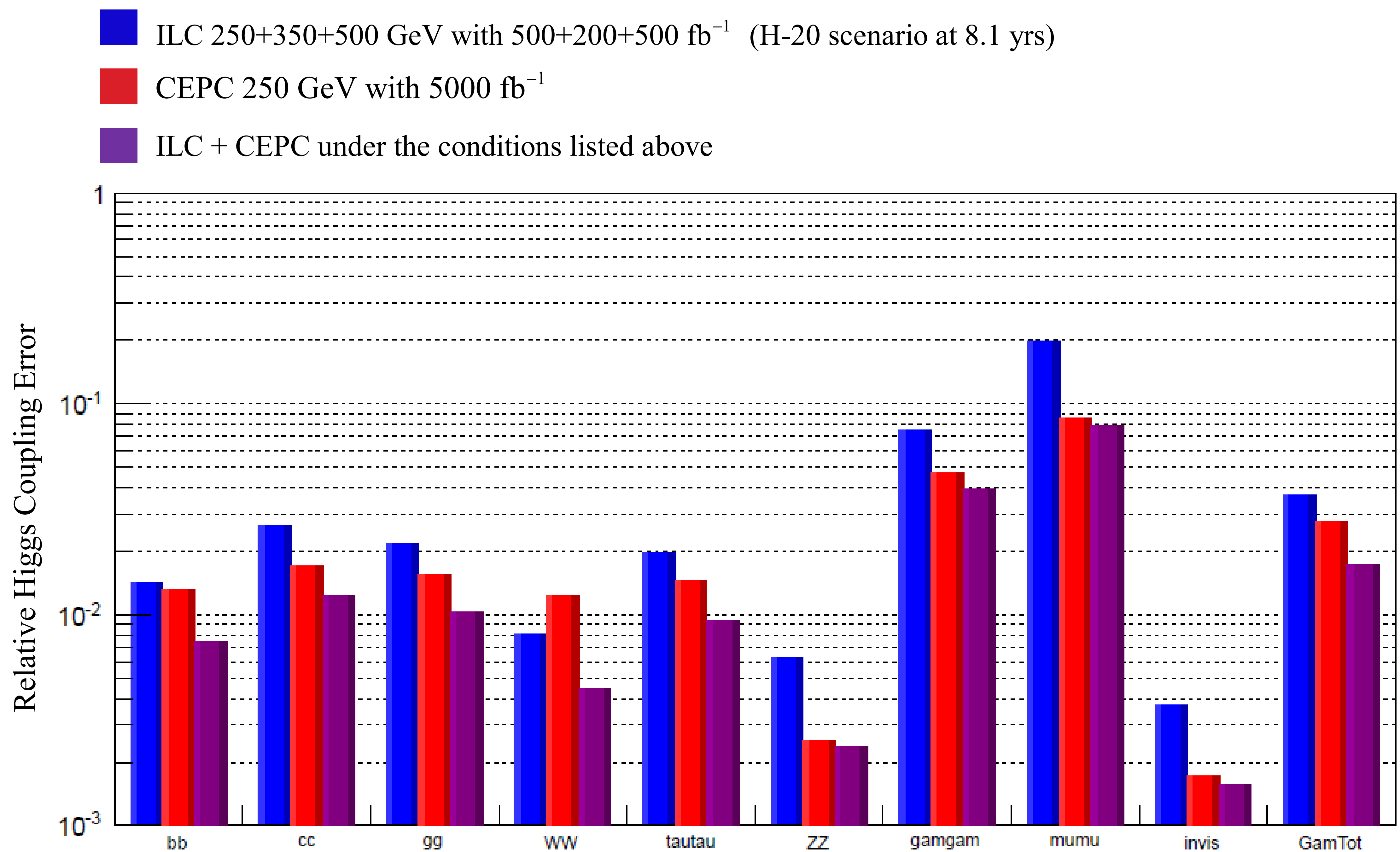
not going to contemplate re-staging in this talk

Clearest comparison: coupling fit

Fits courtesy of T. Barklow

[T. Barklow]

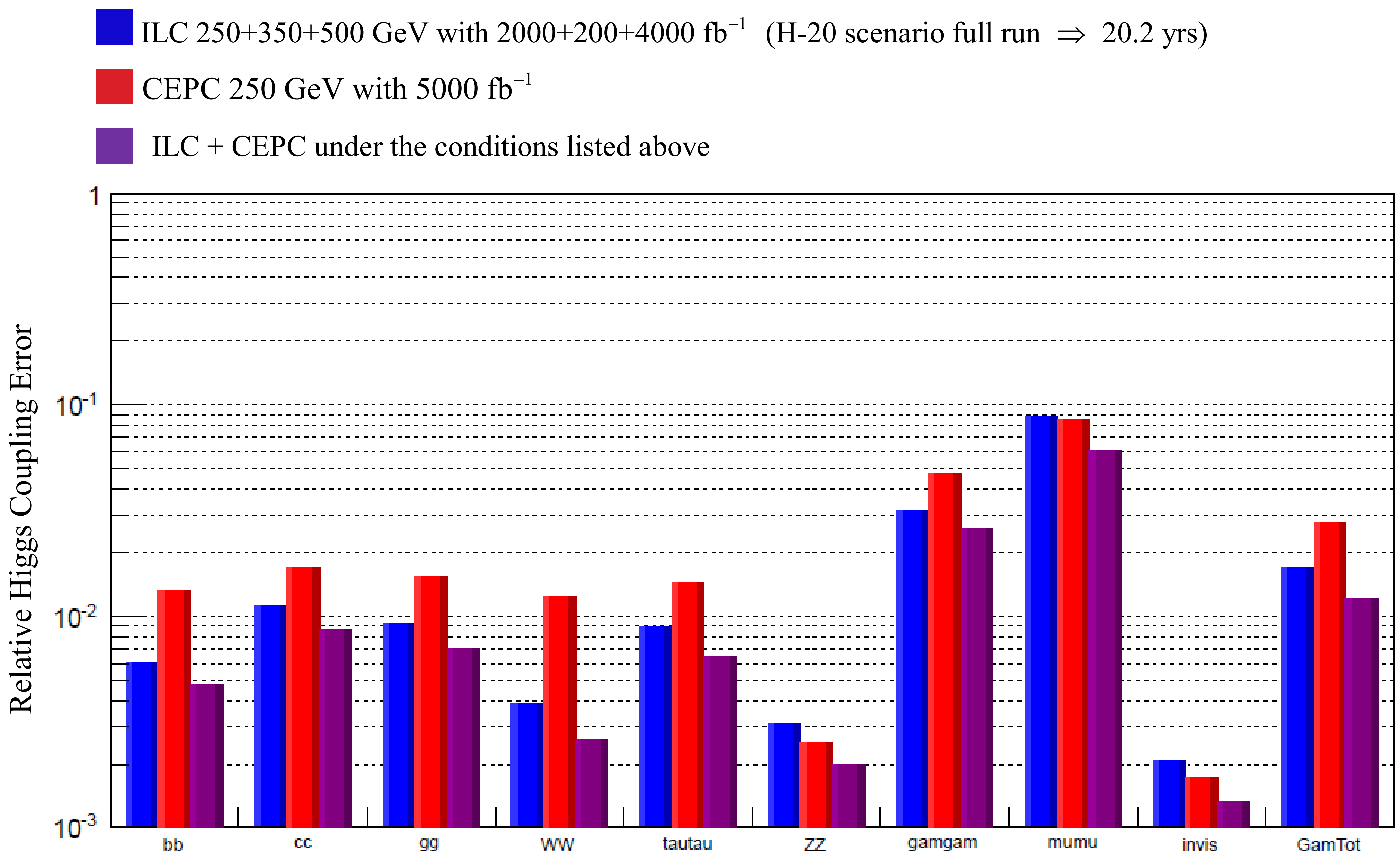
CEPC & ILC H-20(8.1)



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

[T. Barklow]

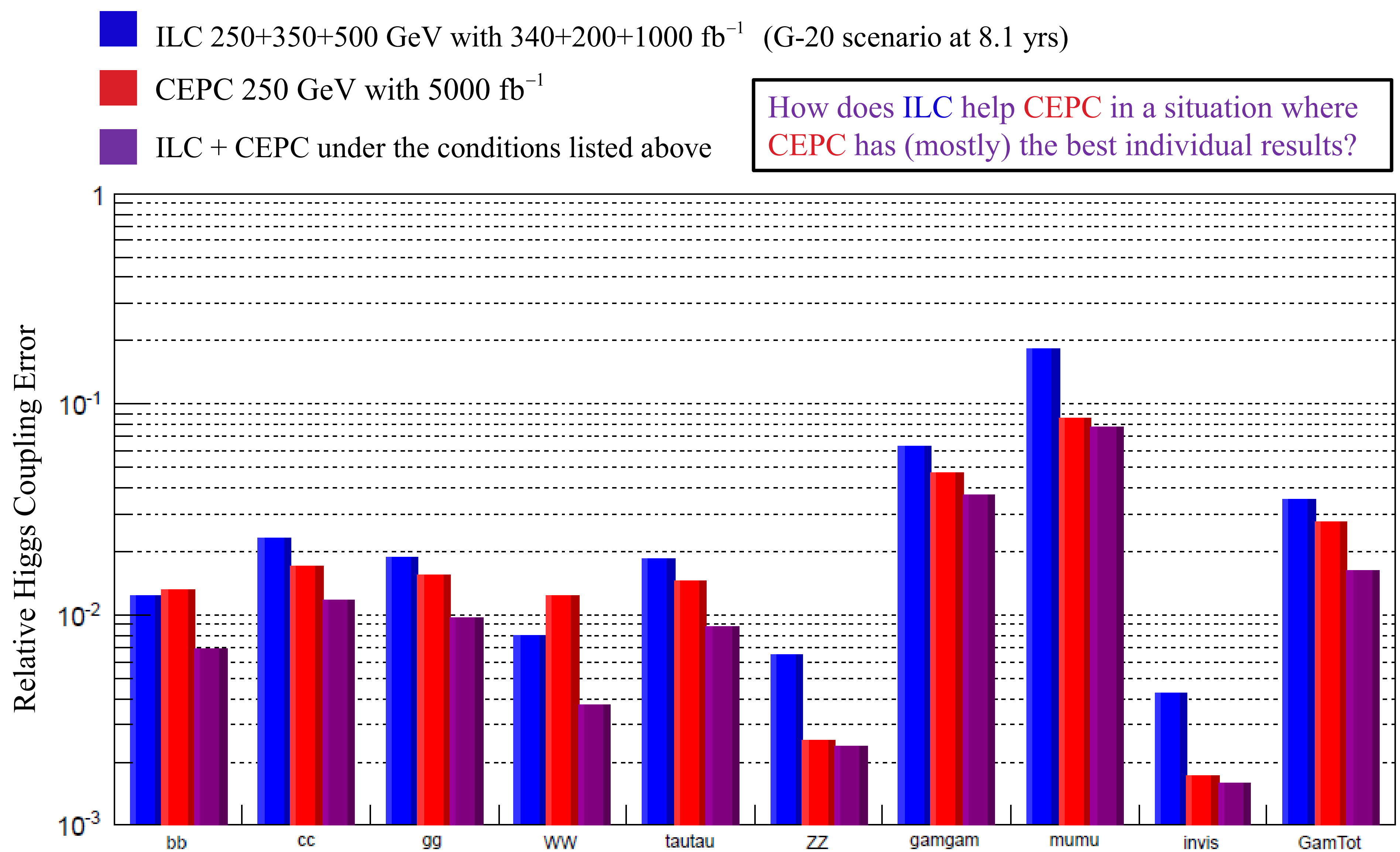
CEPC & ILC$_{H\text{-}20}$



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

[T. Barklow]

Complementarity of CEPC-ILC$_{H\text{-}20(8.1)}$



	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

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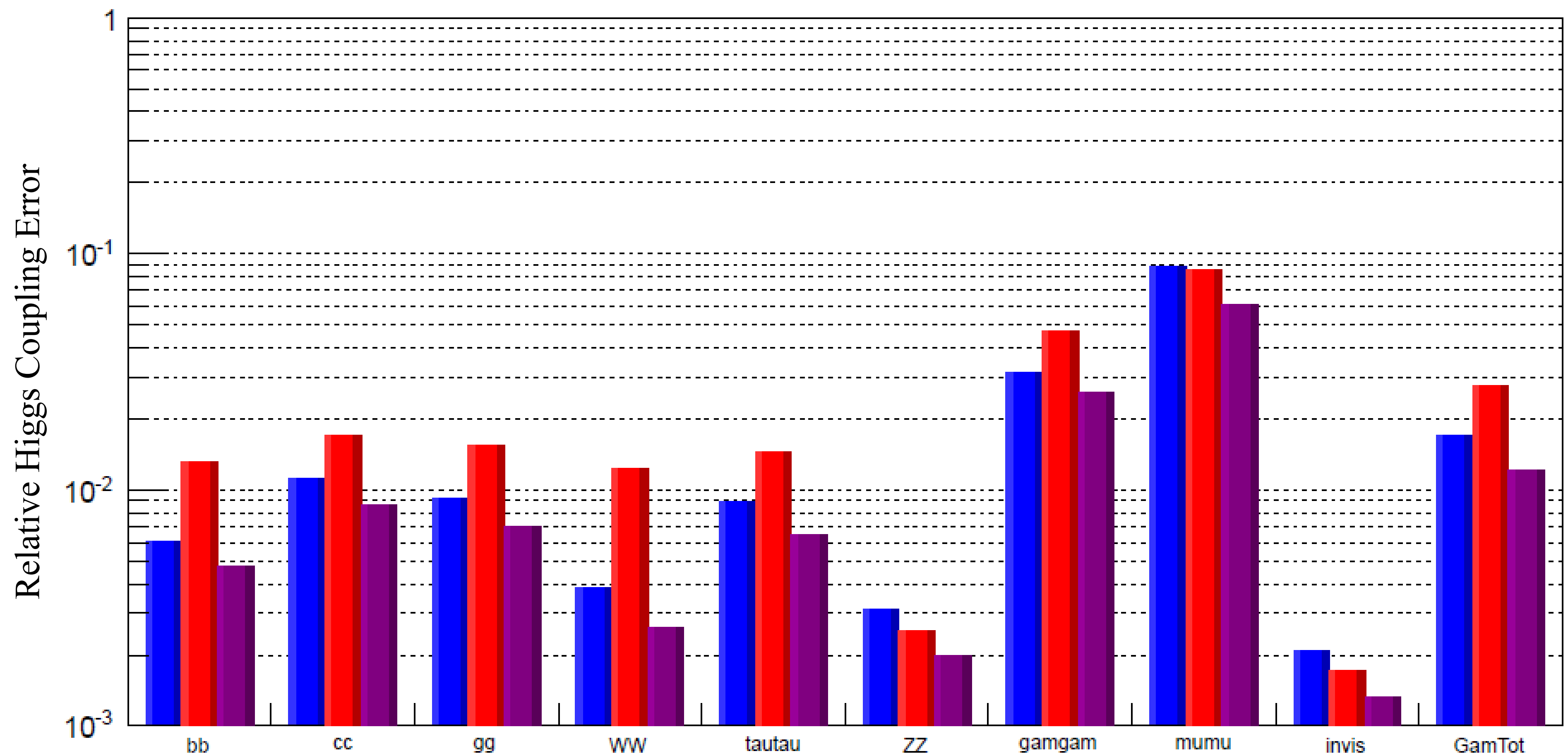
[T. Barklow]

Complementarity of CEPC-ILC$_{H-20}$

- 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

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
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

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What does it all mean?

Consistent lessons:

- Circular machines win on Zh, invisible, rare SM modes; linear machines can win on the rest.
- Complementarity is very impressive!

But which measurements to favor?

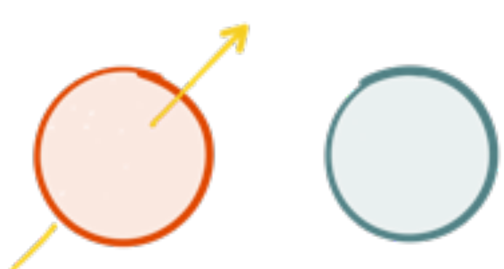
What does the precision mean?

Depends on what you want to learn.

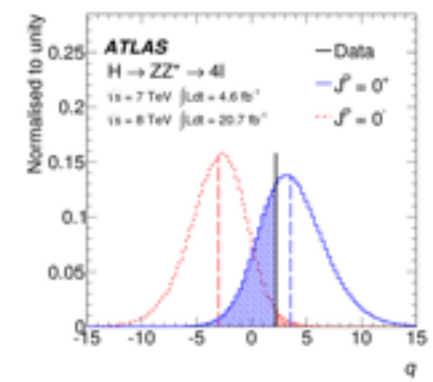
Back to my talk on Monday…

To understand the Higgs

For all the excitement of discovery, we still know *very little* about the Higgs

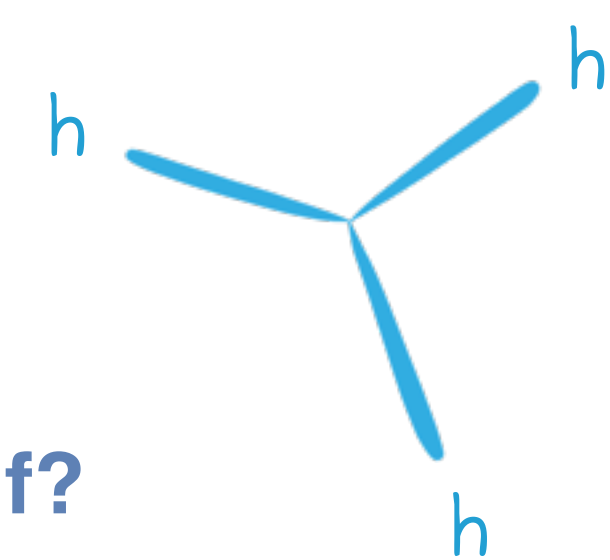


It appears to be a particle without *intrinsic spin*. We have seen spinless **composite particles** before. We have never seen an **elementary** spinless particle!



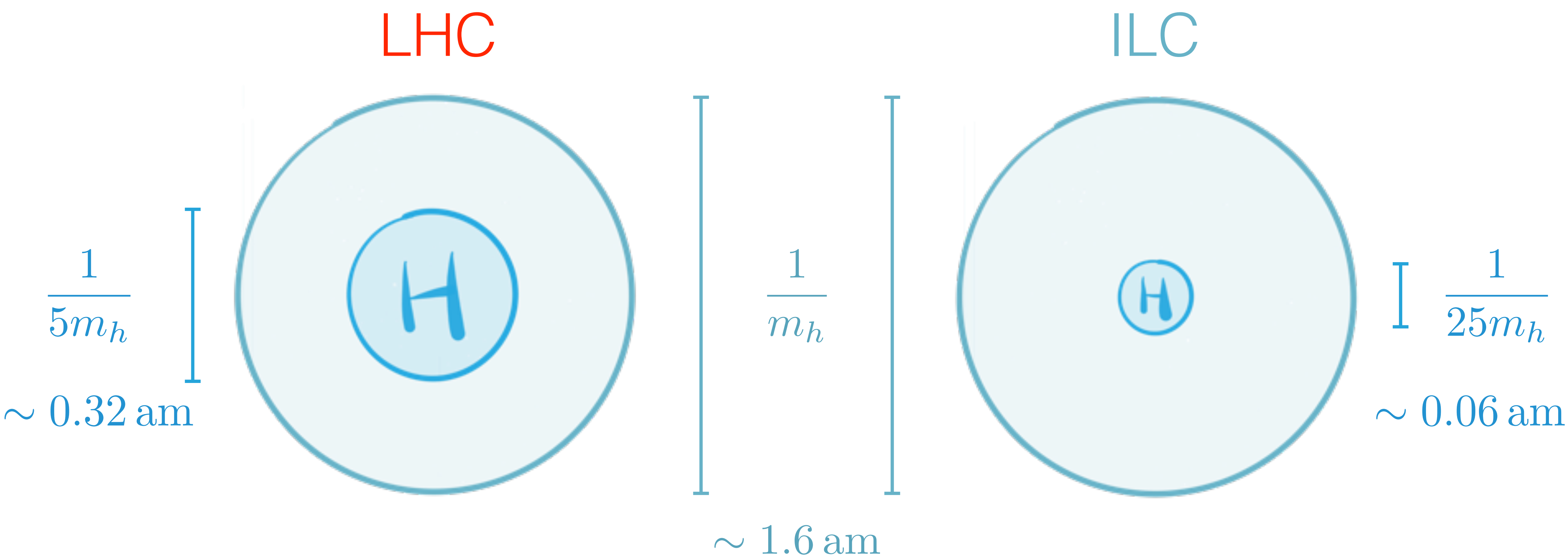
Is it elementary, or composite?

The Standard Model predicts that it interacts with itself, unlike any other particle in nature.



Does it interact with itself?

Elementary or composite?



What I really meant: Higgs has zero size in the SM. Its "size" comes from the scale of higher-dimensional operators in the Higgs EFT.

How strongly can we bound the operator

$$\mathcal{O}_H = \frac{1}{2}\left(\partial_\mu |H|^2\right)^2$$

Higgs wavefunction

$$\mathcal{O}_H = \frac{1}{2}\left(\partial_\mu |H|^2\right)^2$$

Appears in Lagrangian as $\mathcal{L} \supset \frac{c_H}{\Lambda^2}\mathcal{O}_H$ and after EWSB $H \to v + \frac{1}{\sqrt{2}}h$

$$\frac{c_H}{\Lambda^2} \cdot \frac{1}{2}\left(\partial_\mu |H|^2\right)^2 \to \left(\frac{2 c_H v^2}{\Lambda^2}\right) \cdot \frac{1}{2}(\partial_\mu h)^2$$

Correction to Higgs wavefunction in broken phase

Canonically normalizing $h \to \left(1 - c_H v^2/\Lambda^2\right) h$

shifts all Higgs couplings uniformly, e.g.

$$\frac{m_Z^2}{v} h Z_\mu Z^\mu \to \frac{m_Z^2}{v}\left(1 - c_H v^2/\Lambda^2\right) h Z_\mu Z^\mu$$

Bounding c_H

Since all couplings are shifted uniformly, disappears from BRs
Only appears in production rates (disappears from ratios)

⇒ Ideal for a direct measurement.

ILC direct Zh

(Yan et al. 1604.07524)

$\sqrt{s}$	250 GeV		350 GeV		500 GeV	
	$\int \mathcal{L}dt$	$\Delta\sigma_{ZH}/\sigma_{ZH}$	$\int \mathcal{L}dt$	$\Delta\sigma_{ZH}/\sigma_{ZH}$	$\int \mathcal{L}dt$	$\Delta\sigma_{ZH}/\sigma_{ZH}$
$e^-_L e^+_R$	1350 fb^{-1}	1.1%	115 fb^{-1}	5.0%	1600 fb^{-1}	2.9%
$e^-_R e^+_L$	450 fb^{-1}	2.2%	45 fb^{-1}	9.8%	1600 fb^{-1}	3.1%

My naive ILC combo: $\delta\sigma_{Zh}/\sigma_{Zh}$=0.88%

$$c_H \frac{v^2}{\Lambda^2} < 0.0044$$

$\Lambda > 2.6\,\mathrm{TeV}$ (c_H =1)

"r_H< 0.076 am"

CEPC direct Zh

(Pre-CDR)

$\sigma(ZH)$
0.51%

$$c_H \frac{v^2}{\Lambda^2} < 0.0025$$

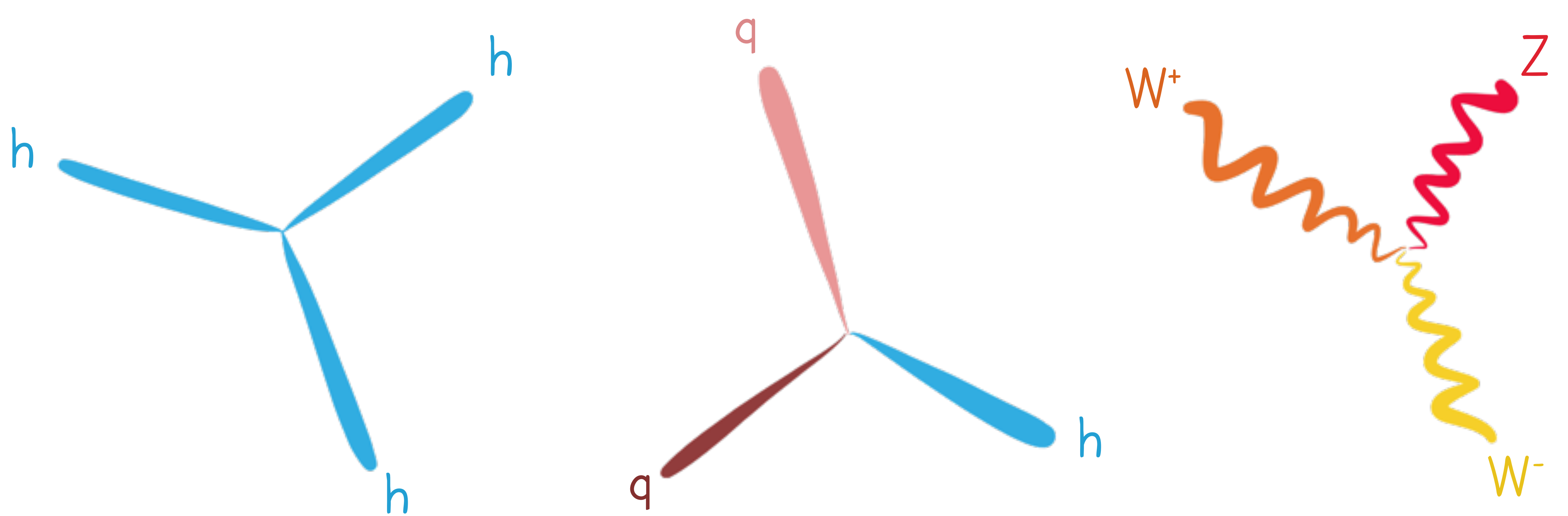
$\Lambda > 3.5\,\mathrm{TeV}$

"r_H< 0.056 am"

A self-interacting particle?

The Standard Model Higgs is predicted to interact with itself

If so, it would be unlike anything yet seen in nature
(all other interactions change particle identity)



The LHC cannot determine if the Higgs is self-interacting.
The ILC can provide compelling evidence for this self-interaction.
Any deviations would point to a wealth of unforeseen new physics.

Self-interactions

What I really meant: Higgs quartic is fixed in the SM, can phrase corrections in the language of the Higgs EFT
How strongly can we bound the operator

$$\mathcal{O}_6 = |H|^6$$

Appears in Lagrangian as $\mathcal{L} \supset \frac{c_6}{\Lambda^2}\mathcal{O}_6$ and after EWSB $H \to v + \frac{1}{\sqrt{2}} h$

Alters Higgs quartic relative to SM.

Slightly tedious; use m_Z, G_F, $\alpha_{em}(q^2=0)$, m_H inputs

$$\frac{m_H^2}{2\sqrt{2}v} h^3 \to \frac{m_H^2}{2\sqrt{2}v}\left(1 + 8\frac{v^2}{m_H^2}\frac{v^2}{\Lambda^2}c_6\right) h^3$$

in my conventions for v, c_6.

Bounding c_6

Fractional shift in trilinear

$$\kappa_\lambda = 1 + 8\frac{v^2}{m_H^2}\frac{v^2}{\Lambda^2}c_6$$

ILC via ZHH

- results in 26.6% precision on λ_{SM}

From C. Dürig's talk

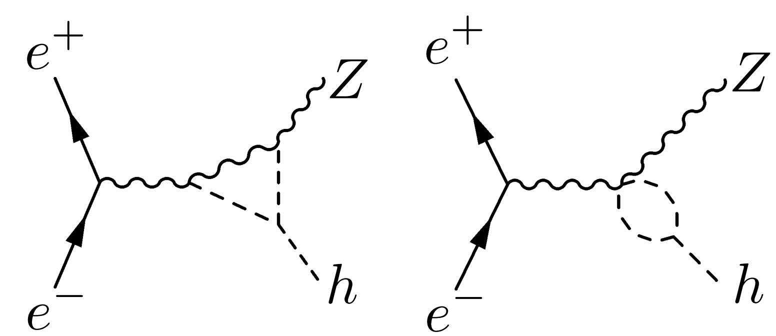
$$c_6\frac{v^2}{\Lambda^2} < 0.017$$

Λ > 1.3 TeV (c_6=1)

CEPC via ZH

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

[McCullough 1312.3322]



*We'll discuss the subtleties later; for now assume we only turn on c_6.

$$c_6\frac{v^2}{\Lambda^2} < 0.023$$

Λ > 1.1 TeV (c_6=1)

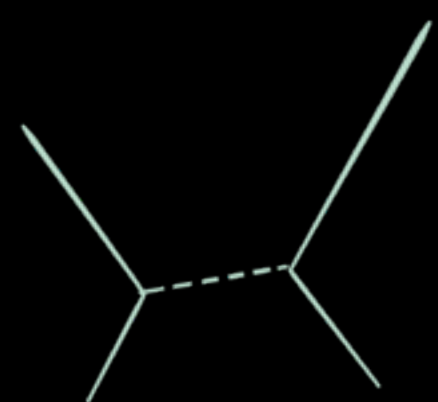
In reality, don't typically expect O_H or O_6 to show up in isolation.

Can study complete set of EFT operators, or can restrict to motivated classes.

There is a particularly well-motivated restriction…

The Higgs Force

Higgs mediates a new force



$$\frac{V_{\text{Higgs}}(r)}{V_{\text{Weak}}(r)} \sim \frac{y^2}{g^2} e^{-(m_h - m_Z)r}$$

Extremely weak, but the strongest possible force for new particles neutral under the SM.

What I really meant: the Higgs portal

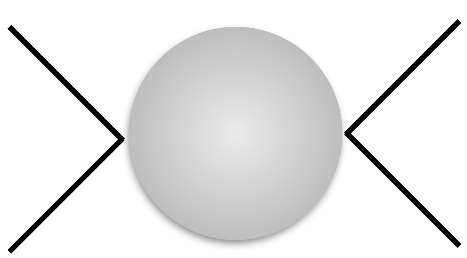
$$\mathcal{L} \supset X|H|^2 \qquad\qquad X = \Phi, \Phi^2, |\Phi|^2, \ldots$$

Higgs Force Observables

If new particles are light, look for them directly via on-shell or off-shell Higgs.

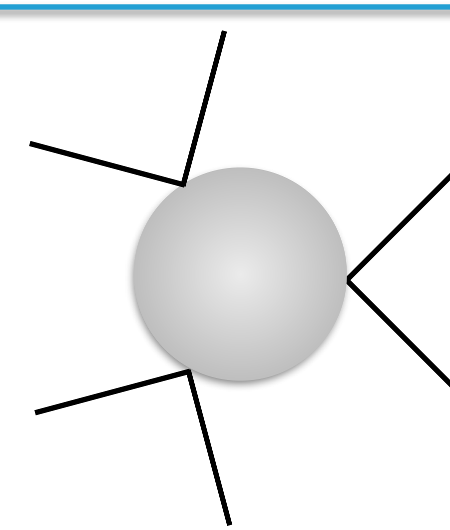
If new particles are heavy, integrate out and go to dim-6 EFT

Integrating out singlet physics only generates O_H, O_6 at dim-6



only f(∂|H|²)

$$\mathcal{O}_H = \frac{1}{2}\left(\partial_\mu |H|^2\right)^2$$



only f(|H|²)

$$\mathcal{O}_6 = |H|^6$$

So O_H, O_6 completely characterize Higgs coupling deviations from Standard Model singlets at dim-6

Bounding the Higgs Force

Measure Zh, ZZh, keep track of c_6, c_H everywhere

Already understand effects in Zh

Need to track of c_6, c_H effects at ILC in ZZh

Measurement prospects for λ_{SM}

- for HH → bbbb

$$\boxed{\frac{\Delta\sigma(\text{ZHH})}{\sigma(\text{ZHH})} = 21.1\% \quad \to \quad 5.9\sigma \text{ discovery}}$$

- combined with HH → bbWW*

$$\boxed{\frac{\Delta\sigma(\text{ZHH})}{\sigma(\text{ZHH})} = 16.8\% \quad \to \quad 8.0\sigma \text{ discovery}}$$

From C. Dürig's talk

c_H shows up in h^3 and $h\partial h\partial h$

$$\frac{\sigma(e^+e^- \to Zhh)}{\sigma_{SM}} = 1 - \underline{3.6\, c_H} + \underline{7.4\,(16 c_{WW})} + 0.56\, c_6$$

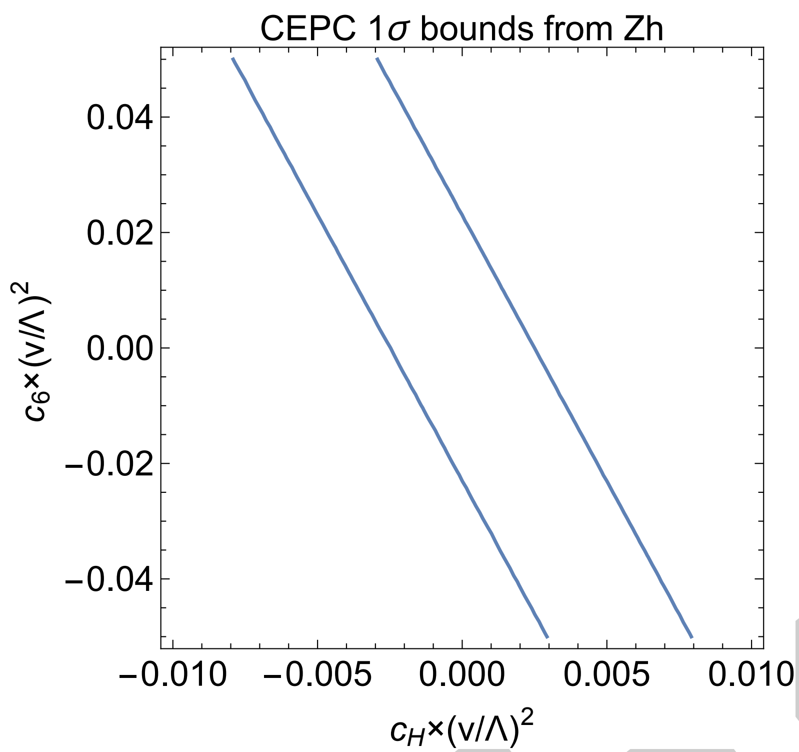
Higgs wavefunction renormalization & new vertex $\Delta\mathcal{L} = \frac{c_H}{v_0} h\partial_\mu h \partial^\mu h$

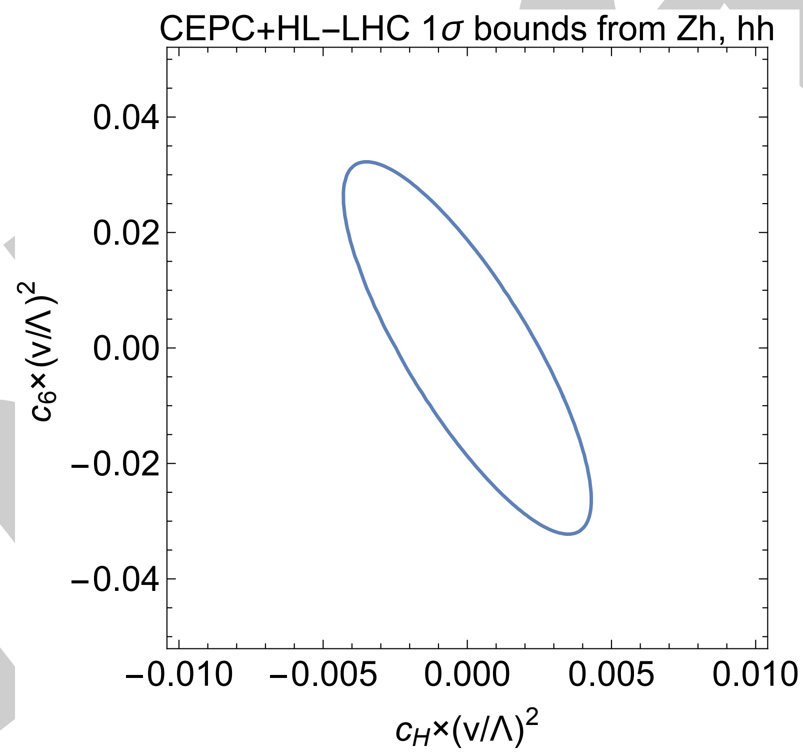
dim-6 vertices enhanced by (s/m_Z^2)

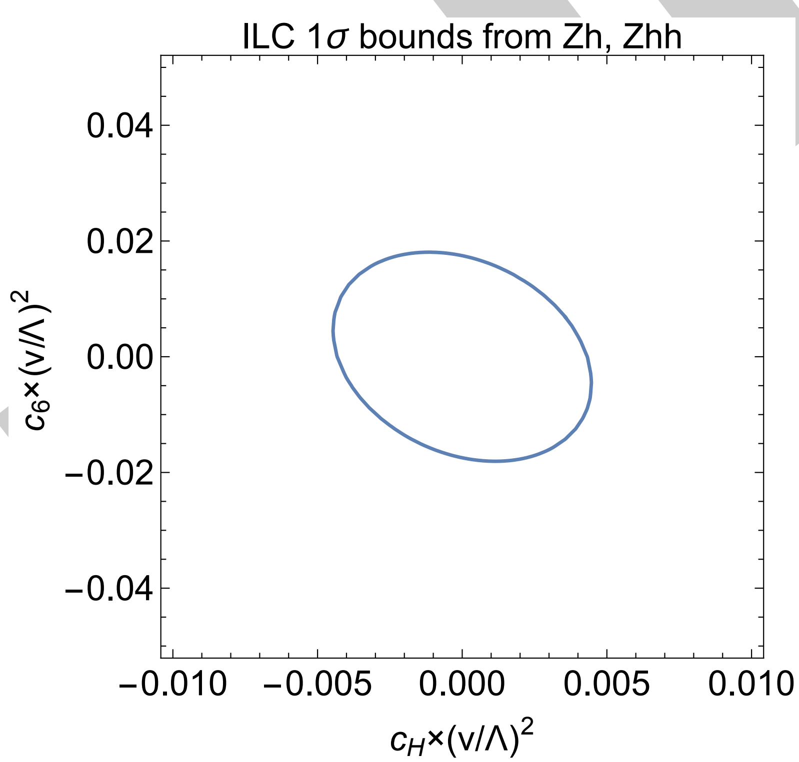
Barklow et al., from T. Tanabe's talk @ HC2016

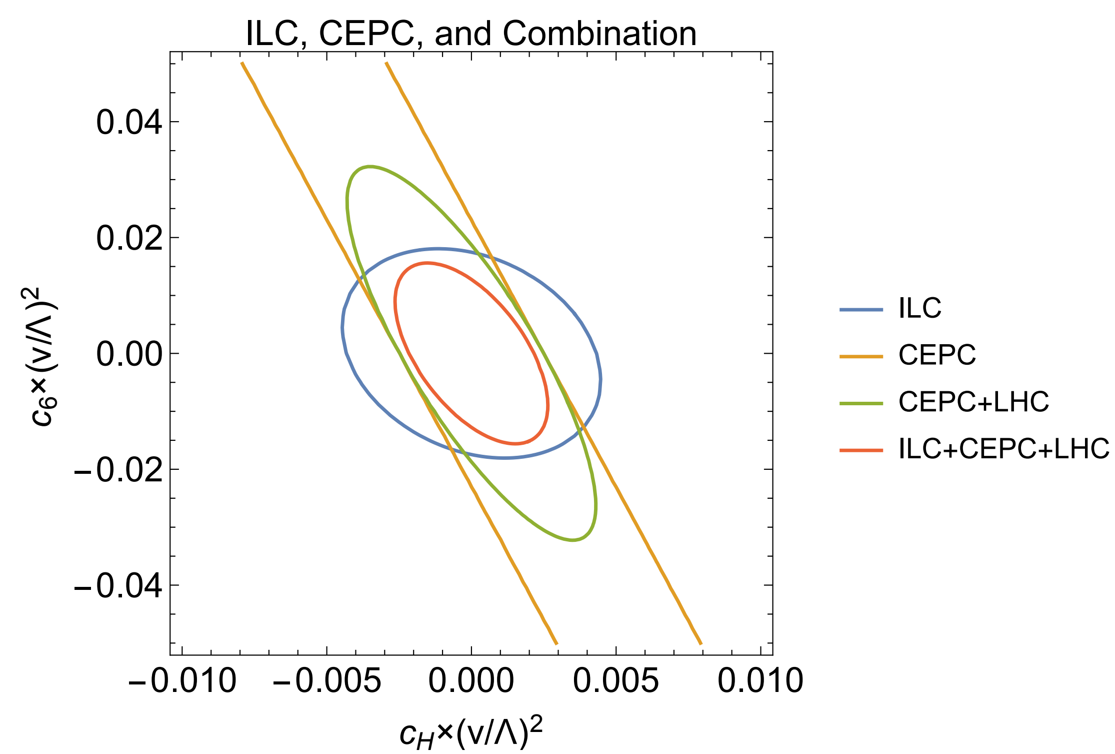
Note: their conventions for c_H, c_6.
Convert to mine, can check that I reproduce quoted trilinear bound.

Bounding the Higgs Force









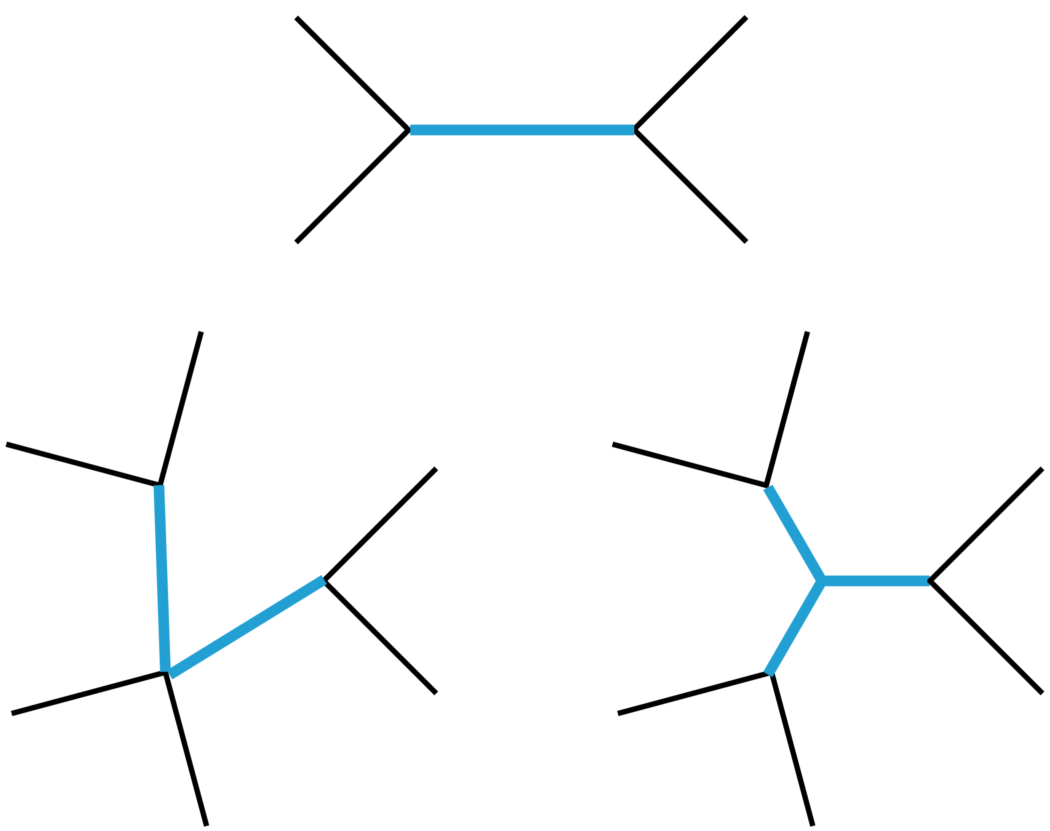
A calculable example

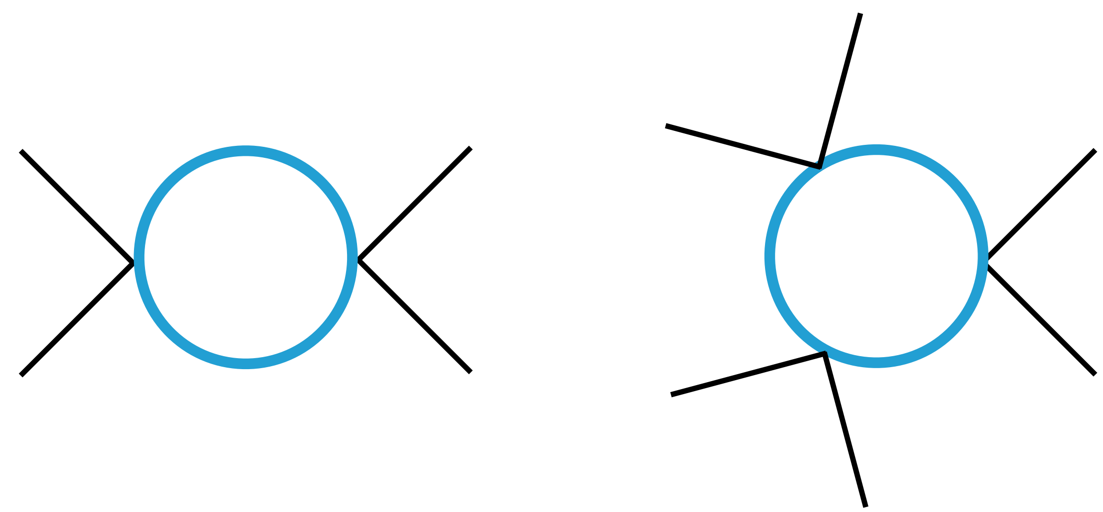
Is this good sensitivity? Need an example: real singlet scalar

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu \Phi\right)^2 - \frac{1}{2}m^2\Phi^2 - A|H|^2\Phi - \frac{1}{2}k|H|^2\Phi^2 - \frac{1}{6}\mu\Phi^3 - \frac{1}{24}\lambda\Phi^4$$

$$\Delta\mathcal{L}_{\text{tree}} = \frac{A^2}{m^4}\mathcal{O}_H + \left(-\frac{kA^2}{2m^4} + \frac{1}{6}\frac{\mu A^3}{m^6}\right)\mathcal{O}_6$$

$$\Delta\mathcal{L}_{\text{loop}} = \frac{1}{16\pi^2}\frac{1}{m^2}\left(\frac{k^2}{12}\mathcal{O}_H - \frac{k^3}{12}\mathcal{O}_6\right)$$



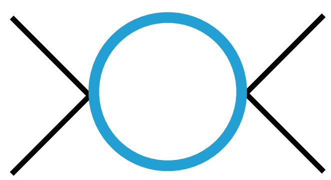


1-loop depends only on $\Phi^2 H^2$

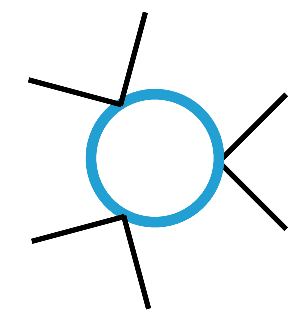
[Henning, Lu, Murayama '14]

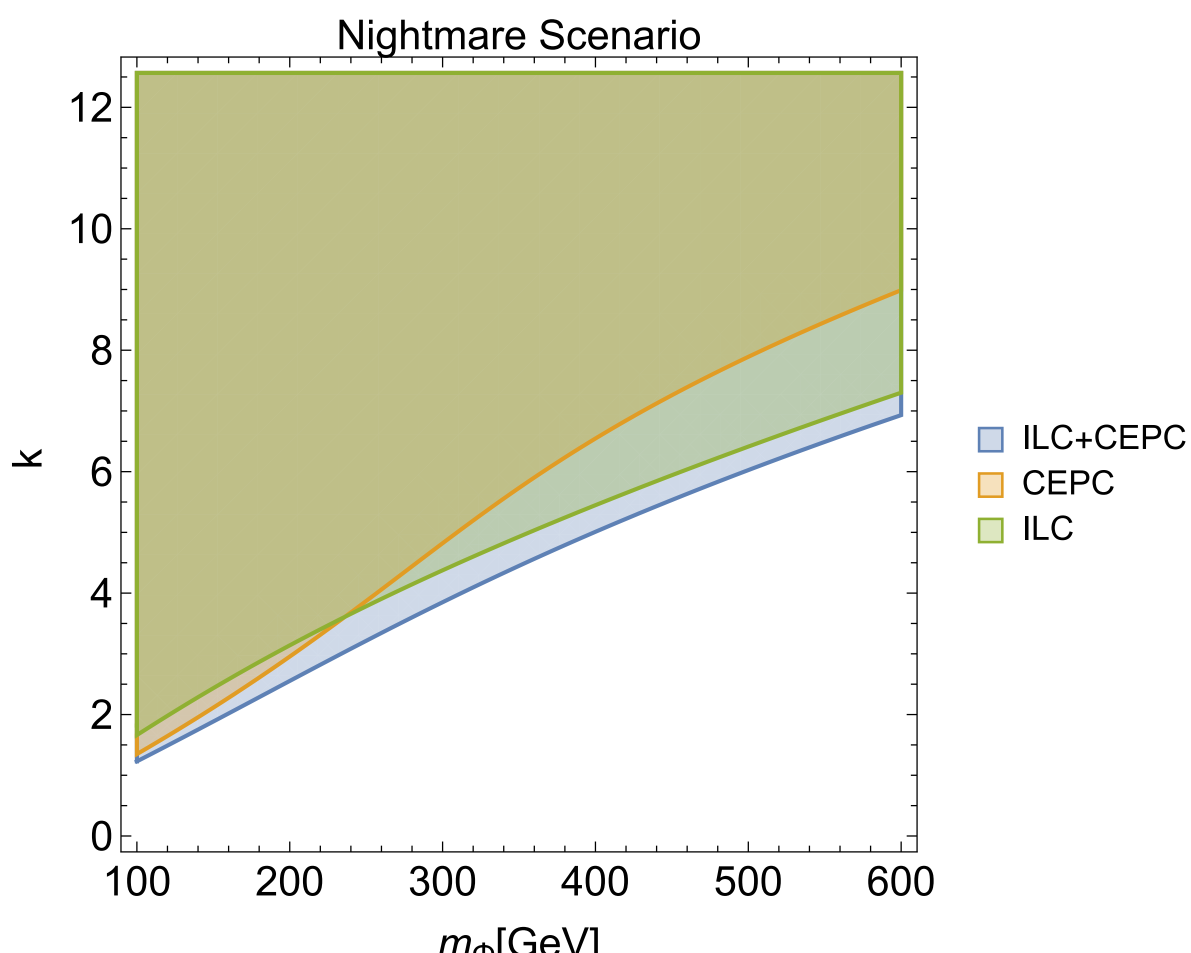
A calculable example

$$\frac{c_H}{\Lambda^2} = \left(\frac{A^2}{m^2} + \frac{1}{16\pi^2}\frac{k^2}{12}\right)\frac{1}{m^2} \qquad \frac{c_6}{\Lambda^2} = \left(-\frac{kA^2}{2m^2} + \frac{\mu A^3}{6m^4} - \frac{1}{16\pi^2}\frac{k^3}{12}\right)\frac{1}{m^2}$$



Case 1: “Nightmare scenario”:
Z_2 sets A=0, only see singlet in loops



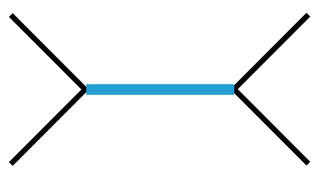


At low mass, most sensitivity coming from Zh. At higher masses, larger k, eventually trilinear measurement takes over.

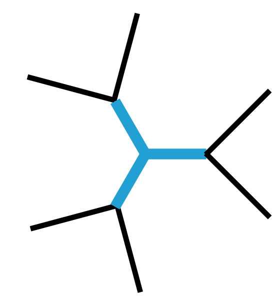
*Obviously, take EFT @ low m_Φ with a grain of salt, though full calc. is comparable.

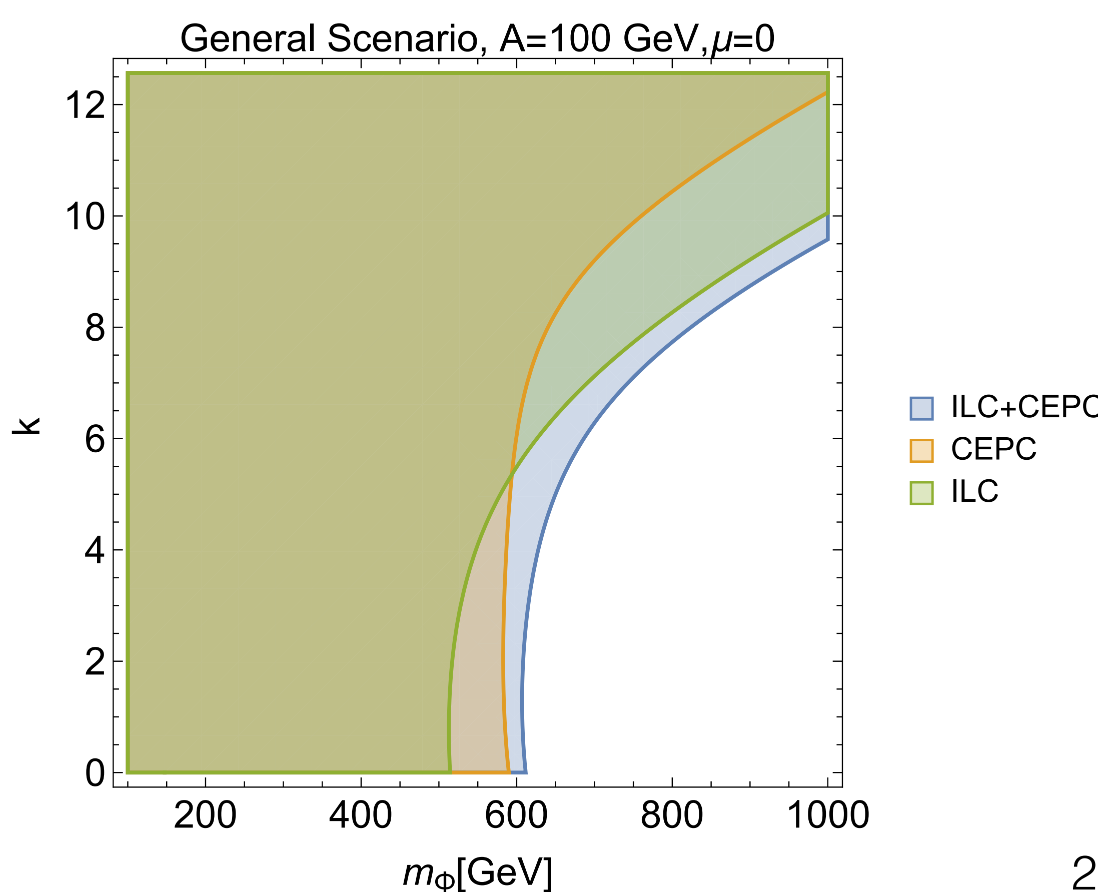
A calculable example

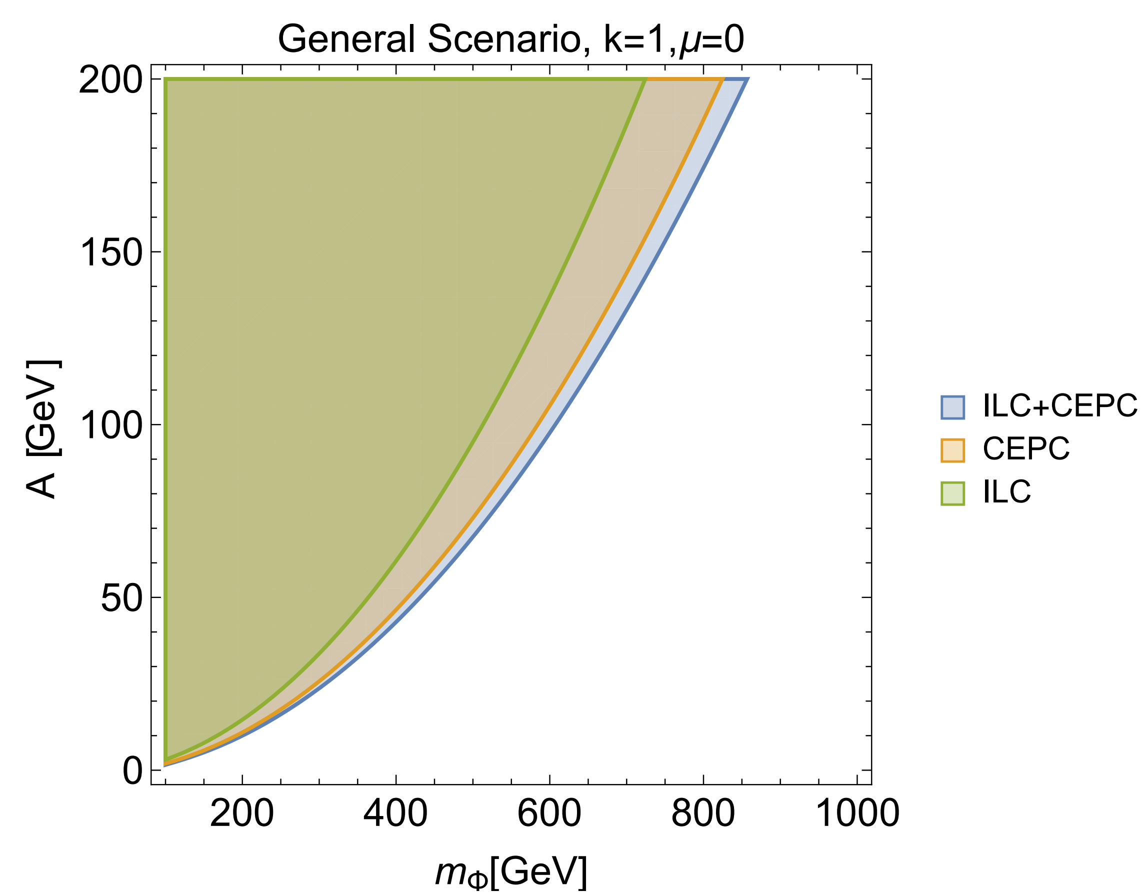
$$\frac{c_H}{\Lambda^2} = \left(\frac{A^2}{m^2} + \frac{1}{16\pi^2}\frac{k^2}{12}\right)\frac{1}{m^2} \qquad \frac{c_6}{\Lambda^2} = \left(-\frac{kA^2}{2m^2} + \frac{\mu A^3}{6m^4} - \frac{1}{16\pi^2}\frac{k^3}{12}\right)\frac{1}{m^2}$$



Case 2: General A, μ, k
(*susceptible to LHC direct searches)







Conclusions

- Impressive precision and complementarity between linear and circular lepton colliders.
- Helpful to focus on places where lepton colliders provide qualitatively new insight: Higgs wavefunction and self-coupling.
- Clearer tradeoffs between wavefunction & self-coupling, both provide compelling sensitivity. Makes a strong case for lepton colliders as tools for probing SM-neutral physics.
- **We will be fortunate to have *any* of these machines.**
- But I want to discover new particles neutral under the SM, and have asked for both circular and linear colliders for Christmas.

Thank you!