Higgs factory physics

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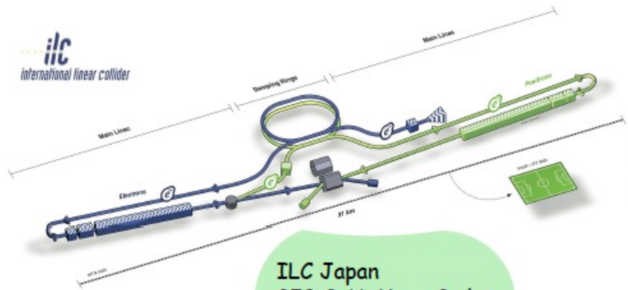
November 8, 2024

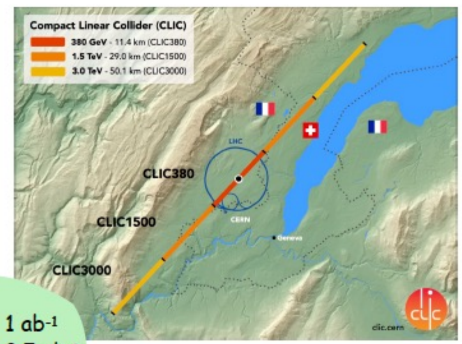
Linear e+e- / Circular e+e-



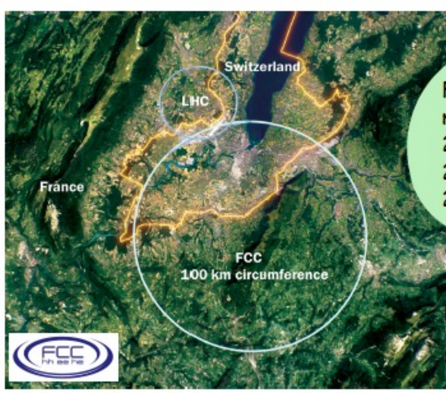
+ polarization

ILC Japan
250 GeV, 11y -> 2 ab^{-1}
500 GeV, 8.5y 4 ab^{-1}
1000 GeV, 8.5y 8 ab^{-1}

Cool Copper Collider
250 GeV -> $1.3 \times 10^{34}/cm^2s$
550 GeV $2.4 \times 10^{34}/cm^2s$

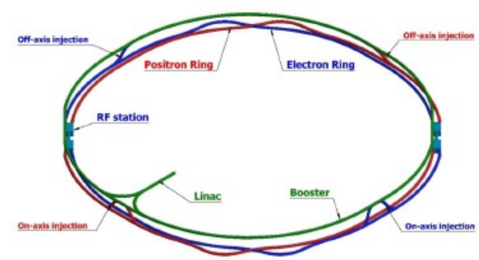


CLIC, CERN
380 GeV, 8y -> 1 ab^{-1}
1500 GeV, 7y 2.5 ab^{-1}
3000 GeV, 8.5y 5 ab^{-1}



FCC-ee, CERN
m_Z, 4y -> 150 ab^{-1}
2 m_W, 1-2y 10 ab^{-1}
240 GeV, 3y 5 ab^{-1}
2 m_{top}, 5y 1.5 ab^{-1}

Now, 10.8 ab^{-1}



CEPC, China
m_Z, 2y -> 16 ab^{-1}
2 m_W, 1y 2.6 ab^{-1}
240 GeV, 7y 5.6 ab^{-1}

Physics program

Higgs Precision: Higgs couplings, self coupling, width, mass

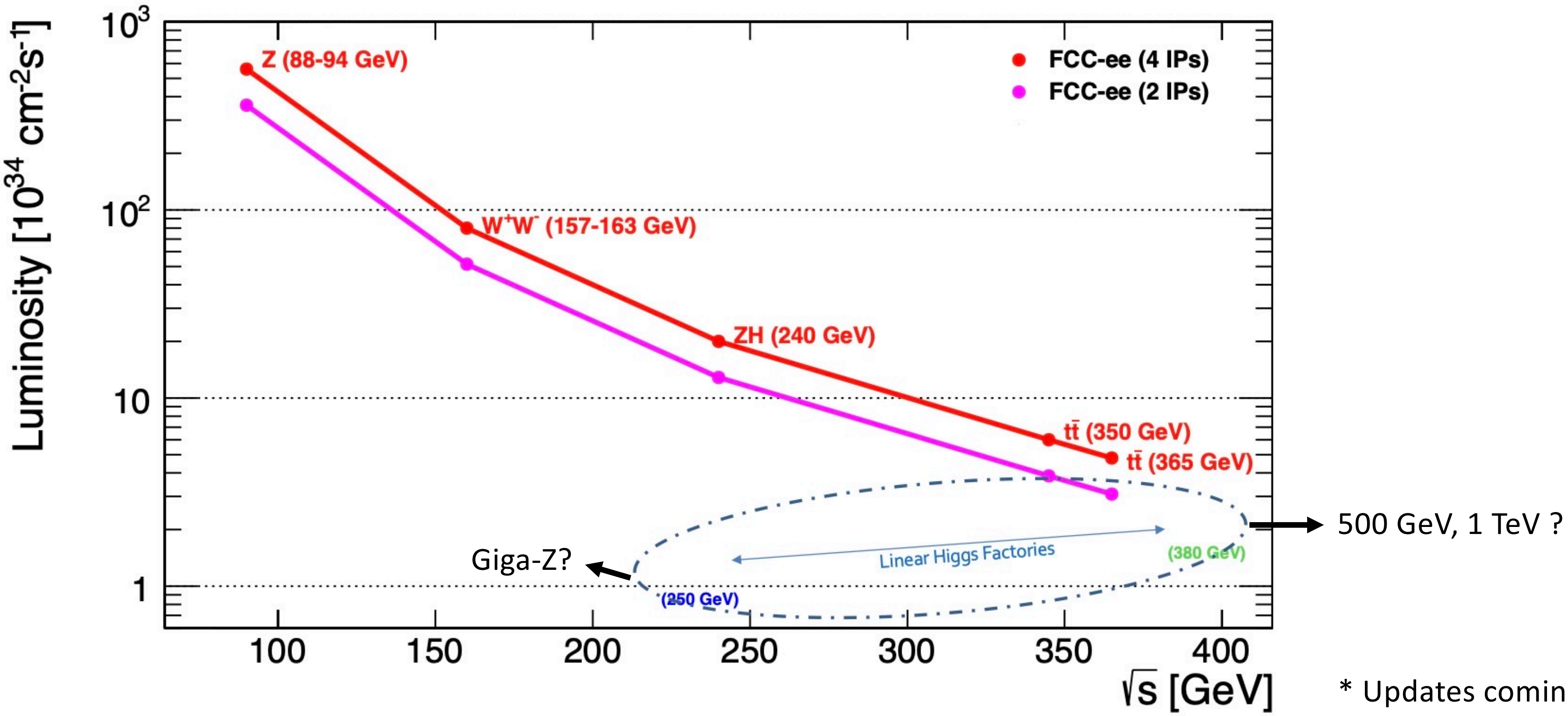
EW Precision (needed for max Higgs precision)

Broad programs

τ , B physics, light new particles (ALPs, dark photons,….)

Top Physics: couplings, mass, width

Scenarios



* Updates coming

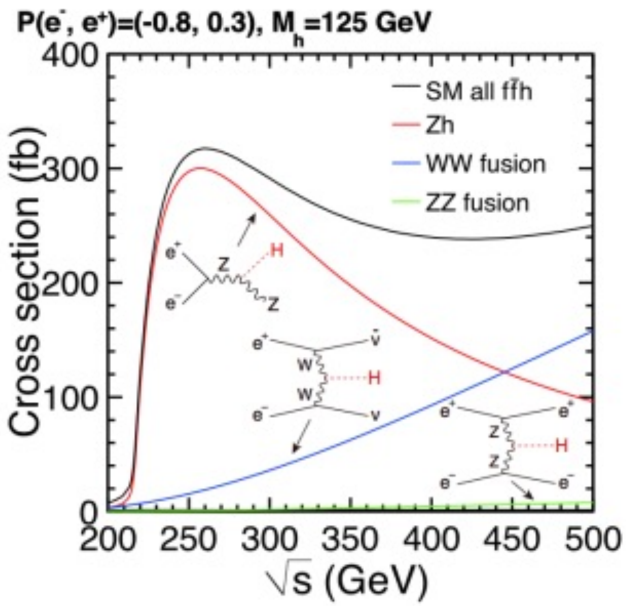
Precision

- Snowmass assumptions

Many updates since then

Collider	$\sqrt{s}$	P [%] e^-/e^+	L_{int} ab^{-1}
ILC	250 GeV 350 GeV 500 GeV 1 TeV	$\pm 80/\pm 30$ $\pm 80/\pm 30$ $\pm 80/\pm 30$ $\pm 80/\pm 20$	2 0.2 4 8
ILC-GigaZ	m_Z	$\pm 80/\pm 30$	0.1
CLIC	380 GeV 500 GeV 1 TeV	$\pm 80/0$ $\pm 80/0$ $\pm 80/0$	1 2.5 5
CEPC	m_Z $2m_W$ 240 GeV $2m_t$		60 / 100 3.6 / 6 12 / 20 – / 1
FCC-ee	m_Z $2m_W$ 240 GeV $2m_t$		150 10 5 1.5

Higgs factory



- Sensitivity to both Higgstrahlung and VBF improves precision on couplings
- At √s > 450 GeV, VBF dominates

1.5 ab^{-1} at 365 GeV
200K HZ events
50K WW →H events

5 ab^{-1} at 240 GeV
10^6 HZ events
25K WW→H events

Higgstrahlung cross section ~ 20% larger with polarization

Higgs in a nutshell

- Absolute measurements of couplings (recoil method)
  - (LHC makes assumptions)
- Improvement of coupling measurements from HL-LHC
- Width measurement ($e^+e^- \to ZH$, $H \to ZZ^*$ plus $WW \to H$)
- Higgs trilinear coupling
- Indirect sensitivity to new physics through loops
- Electron Yukawa at FCC-ee?
- Light quark Yukawas (much work since Snowmass)

Establish Higgs mechanism

Indirect new physics sensitivity

Flavor, Dark Matter?

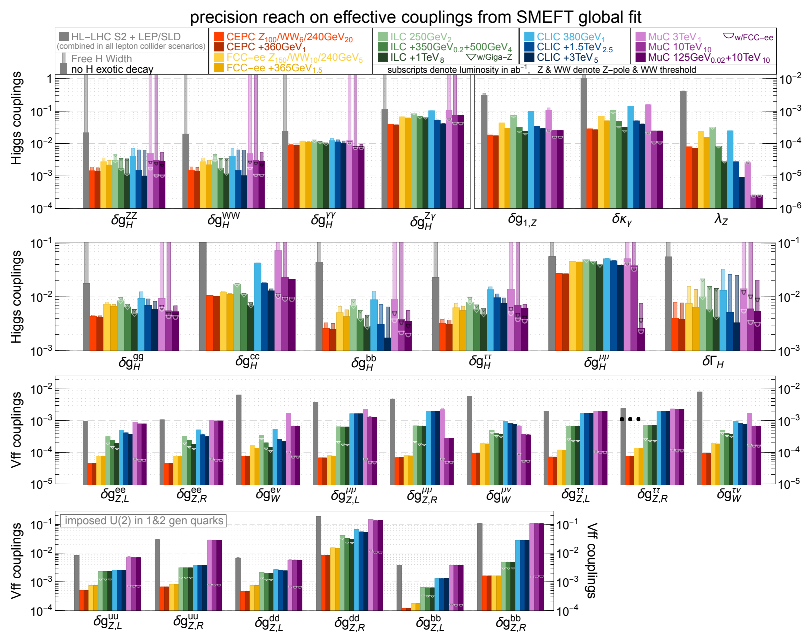
What this talk is

- This is not a sales pitch for the wonders of e^+e^- colliders
  - We're all convinced!
- I was asked to discuss some of the basic differences between opportunities at circular and linear colliders
  - I will point out some general physics features

The "best" machine is the one that gets built

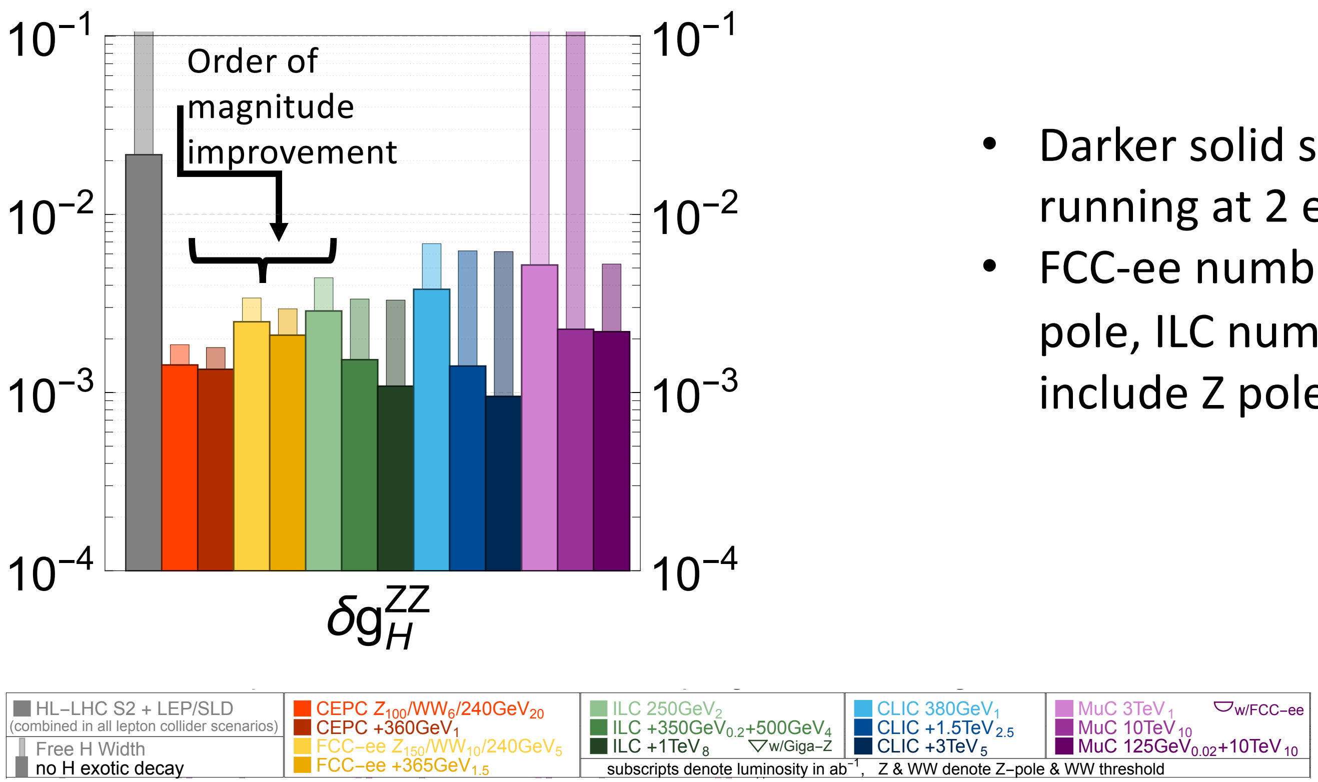
Higgs Coupling Measurements

- All Higgs Factories have similar reach with Snowmass assumptions: Polarization vs Luminosity
- Coupling measurements O(1%) at Higgs factories
- Running at 2 energies improves sensitivity at both FCC-ee and ILC
- Improvement in precision over LHC



[Snowmass], 2209.08078

Drill down on couplings



- Darker solid shades include running at 2 energies
- FCC-ee numbers include Z pole, ILC numbers do not include Z pole

Coupling updates (Thanks to M. Peskin)

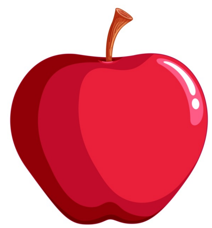
- ILC (2 ab^{-1} at 250 GeV), FCC-ee (10.5 ab^{-1} at 240 GeV), CEPC (20 ab^{-1} at 240 GeV)
- EFT fit

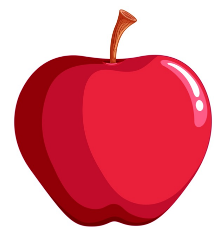
Coupling projections in %

All numbers include HL-LHC (which is crucial for $\mu\mu$ and $\gamma\gamma$)

Assume NNLO theory plus precision m_b, m_c from lattice

Coupling	ILC	FCC-ee	CEPC
bb	0.98	0.54	0.43
cc	1.82	0.89	0.68
gg	1.62	0.80	0.62
$\tau\tau$	1.12	0.60	0.48
WW	0.46	0.37	0.33
ZZ	0.46	0.36	0.32
$\mu\mu$	3.97	3.44	3.04
$\gamma\gamma$	1.09	0.97	0.92
Γ (MeV)	2.30	1.20	0.94
INV (95% EXC)	0.36	0.26	0.25
Untagged	1.60	0.78	0.60



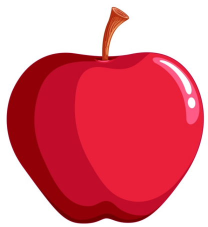


Coupling updates (Thanks to M. Peskin)

- ILC (2 ab^{-1} at 250 GeV+200 fb^{-1} at 350 GeV+ 4 ab^{-1} at 550 GeV), FCC-ee (10.5 ab^{-1} at 240 GeV + 3.25 ab^{-1} at 360 GeV+ Tera-Z), CEPC (20 ab^{-1} at 240 GeV +1 ab^{-1} at 360 GeV +Tera- Z)
- EFT fit

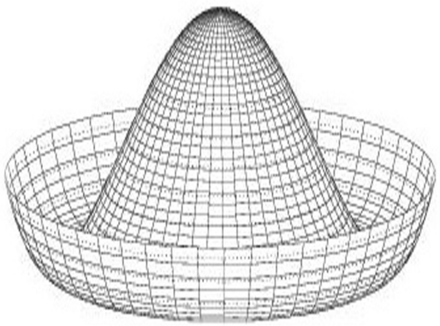
Coupling projections in %

Coupling	ILC (full)	FCC-ee (full)	CEPC (full)
bb	0.58	0.45	0.41
cc	1.17	0.79	0.65
gg	0.96	0.68	0.59
$\tau\tau$	0.75	0.51	0.45
WW	0.35	0.28	0.29
ZZ	0.35	0.27	0.28
$\mu\mu$	3.75	3.31	3.01
$\gamma\gamma$	1.00	0.94	0.91
Γ (MeV)	1.56	1.01	0.90
INV (95% EXC)	0.32	0.23	0.24
Untagged	1.19	0.66	0.58



Higgs Self Coupling

$$V = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$
$$= \frac{M_H^2}{2} H^2 + \lambda_3 H^3 + \lambda_4 H^4$$



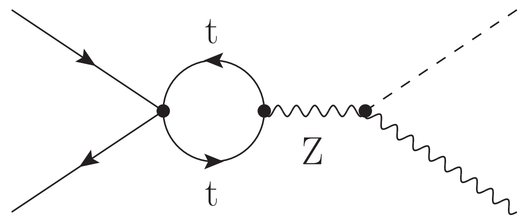
$$\lambda_3 = \frac{M_H^2}{2v} \sim .13v \qquad \lambda_4 = \frac{M_H^2}{8v^2} = .03$$

- We need to verify the shape of the Higgs potential
- Higgs trilinear is sensitive to beyond the SM physics
- λ_3 and λ_4 **ARE NOT FREE PARAMETERS**

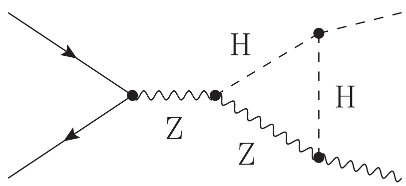
Consistent study requires use of effective field theory

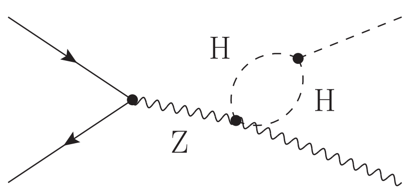
Indirect Access below HH Threshold

- Indirect sensitivity from effects in loops
- Many other operators contribute
- Can be cancellations/correlations
  - ie, only a clean measurement of trilinear coupling in specific UV scenarios



$\delta\sigma_{ZH}$ ~ .5%



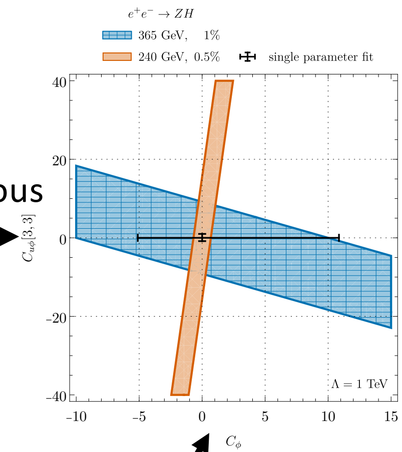


Note strong interplay with Z pole measurements

Higgs self-coupling from indirect measurements

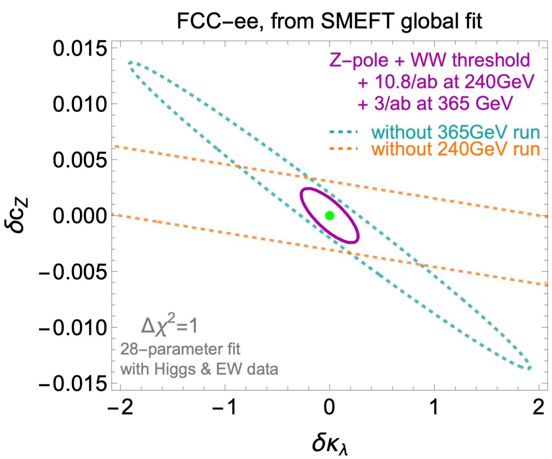
- Runs at different energies critical to separate effects of different operators

tW anomalous coupling

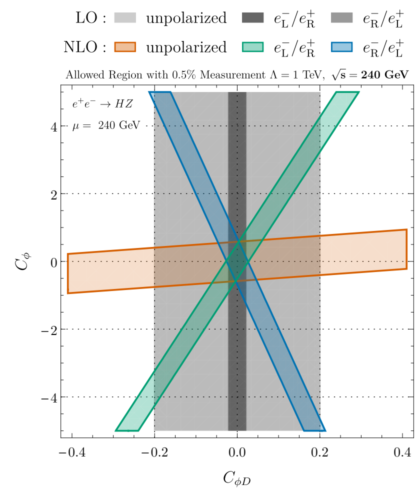


Higgs tri-linear

Modification of HZZ vertex (contributes at tree level)



Higgs tri-linear

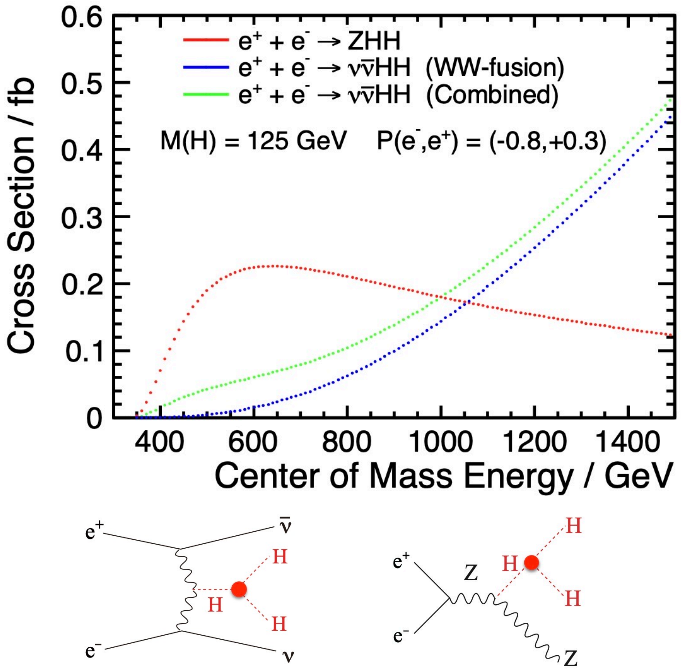


- Polarization gives another handle to separate effects
- 2 energies can separate effects

- Not yet clear how to extract best value of Higgs tri-linear from indirect measurements

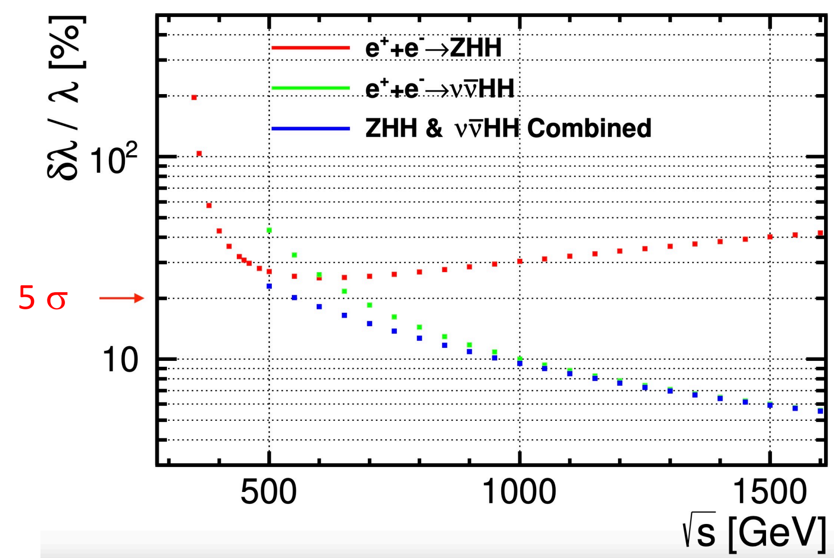
[1809.10041](), [2409.11466]()

Higgs self coupling from direct production



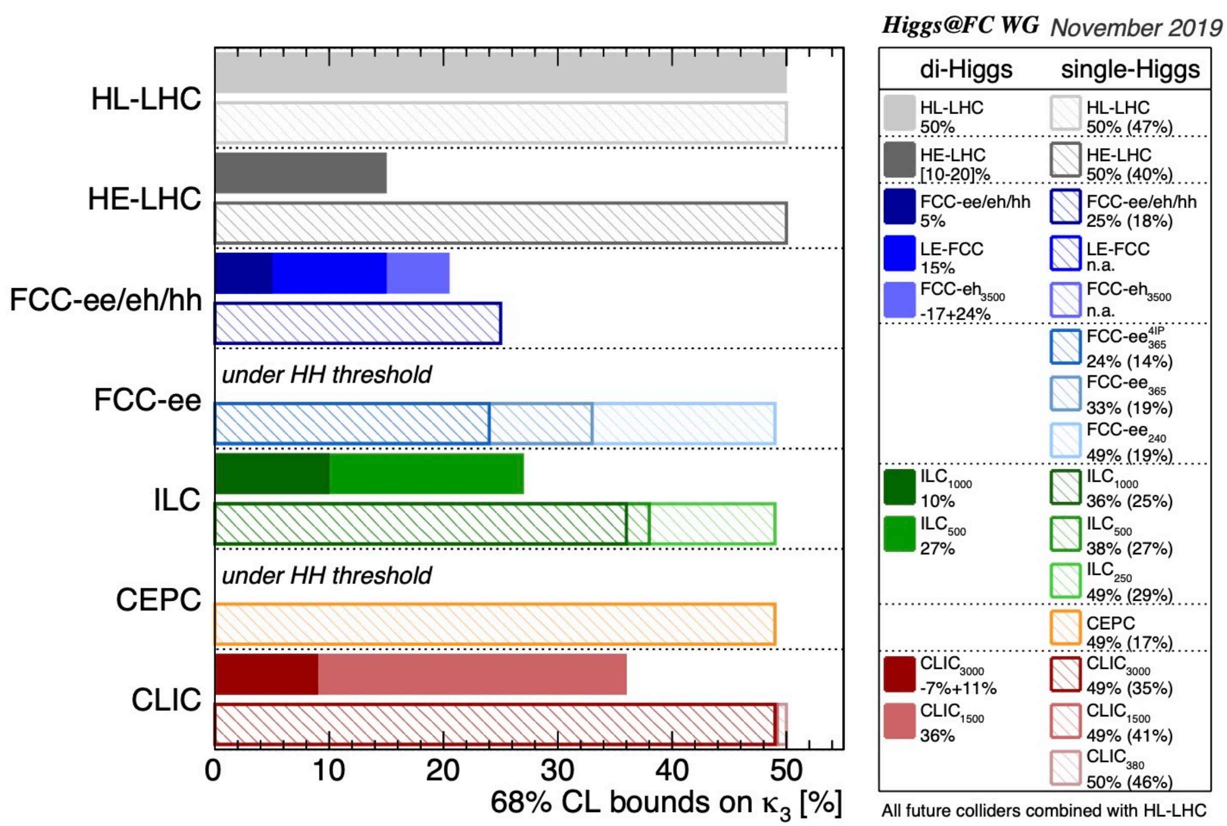
Tian, LCWS2024

23% measurement at 500 GeV



*Assumed luminosity scaled with energy

Higgs self-coupling



Direct and indirect measurements have different theory assumptions.

- 23% sensitivity: 5σ discovery
- 50% sensitivity: H^3 coupling non-zero @95% CL

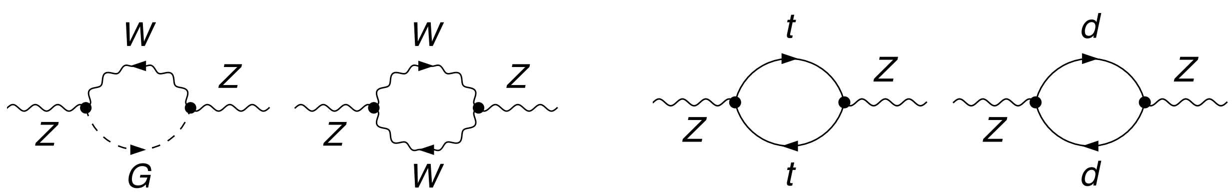
Old plot, but underlying physics is the same

Why Precision Electroweak?

- Relationships between SM parameters changed by loop corrections

$$M_W^2 = \frac{M_Z^2}{2}\left\{1 + \sqrt{1 - \frac{4\pi\alpha}{\sqrt{2}G_\mu M_Z^2}(1+\Delta r)}\right\}$$

- Could be new particles in loops



- Interpretation of results requires precise knowledge of SM parameters
- *eg* prediction of H→ $\gamma\gamma$ depends on SM inputs, so you need them to search for BSM physics

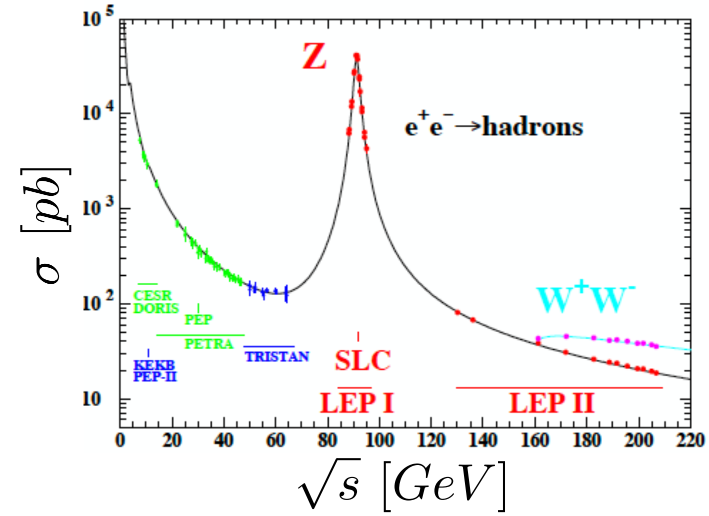
Precision Z pole

- Z pole run:
  - LEP/SLC ~ 10^7 Z → O(.1%)
  - ILC (Giga-Z) 10^9 Z
  - FCC-ee (Tera-Z) 10^{12} Z
- Many observables at Z pole: M_Z , Γ_Z , A_{FB} ….
  - Unpolarized beams sensitive to fermion couplings to Zs

$$A_f = \frac{g_{fL}^2 - g_{fR}^2}{g_{fL}^2 + g_{fR}^2} \qquad A_{FB}^f = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{4} A_e A_f$$

- Lower luminosity at linear collider, but can be somewhat compensated by polarization
  - More observables with polarization

$$A_{LR,FB} = \frac{3}{4} A_f \qquad A_{LR,FB} = \frac{3}{4} A_f$$



Z Pole

- m_Z, Γ_Z, $\alpha_s(m_Z)$ improvements by factors of 20-50 from today
- First direct measurement of $\alpha(m_Z)$
- More lumi at circular colliders, but beam polarization at linear colliders improves sensitivity and can help control systematics
- Below WW threshold, beam energy can be precisely calibrated using resonant depolarization at circular colliders giving precise m_z, m_W
- Linear colliders need physical mass (Z) for calibration
- At linear colliders, largest experimental systematic from polarization calibration
- At circular collider, modeling uncertainties for hadronic final states dominant systematic error

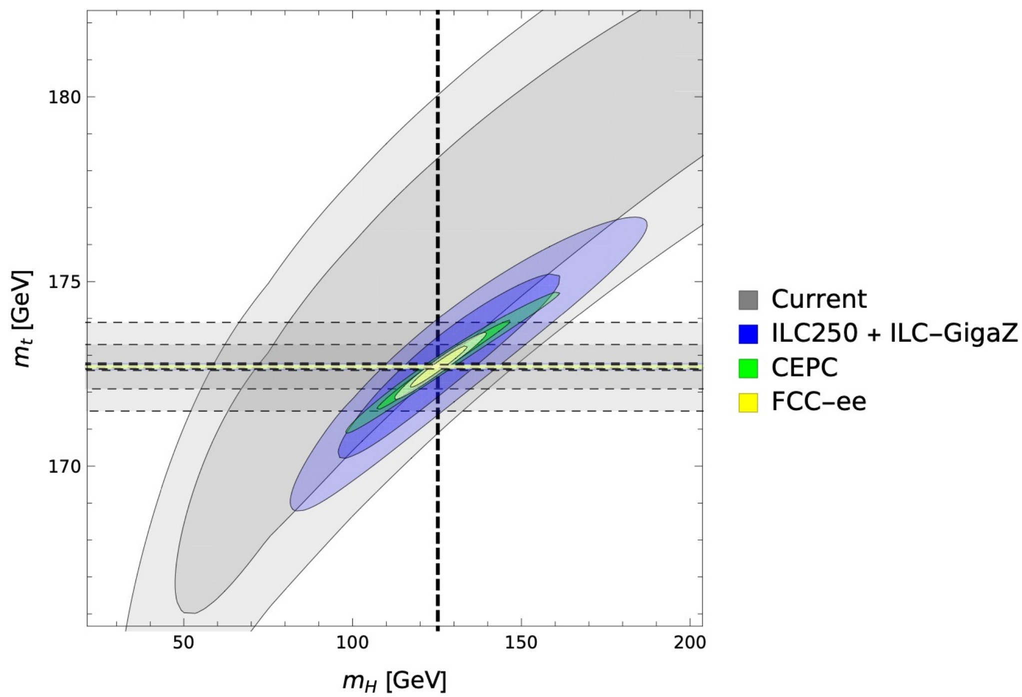
Quantity	current	ILC250	ILC-GigaZ	FCC-ee	CEPC	CLIC380
$\Delta\alpha(m_Z)^{-1}$ ($\times 10^3$)	17.8*	17.8*		3.8 (1.2)	17.8*	
Δm_W (MeV)	12*	0.5 (2.4)		0.25 (0.3)	0.35 (0.3)	
Δm_Z (MeV)	2.1*	0.7 (0.2)	0.2	0.004 (0.1)	0.005 (0.1)	2.1*
Δm_H (MeV)	170*	14		2.5 (2)	5.9	78
$\Delta\Gamma_W$ (MeV)	42*	2		1.2 (0.3)	1.8 (0.9)	
$\Delta\Gamma_Z$ (MeV)	2.3*	1.5 (0.2)	0.12	0.004 (0.025)	0.005 (0.025)	2.3*
ΔA_e ($\times 10^5$)	190*	14 (4.5)	1.5 (8)	0.7 (2)	1.5 (2)	60 (15)
ΔA_μ ($\times 10^5$)	1500*	82 (4.5)	3 (8)	2.3 (2.2)	3.0 (1.8)	390 (14)
ΔA_τ ($\times 10^5$)	400*	86 (4.5)	3 (8)	0.5 (20)	1.2 (20)	550 (14)
ΔA_b ($\times 10^5$)	2000*	53 (35)	9 (50)	2.4 (21)	3 (21)	360 (92)
ΔA_c ($\times 10^5$)	2700*	140 (25)	20 (37)	20 (15)	6 (30)	190 (67)
$\Delta\sigma^0_{\rm had}$ (pb)	37*			0.035 (4)	0.05 (2)	37*
δR_e ($\times 10^3$)	2.4*	0.5 (1.0)	0.2 (0.5)	0.004 (0.3)	0.003 (0.2)	2.5 (1.0)
δR_μ ($\times 10^3$)	1.6*	0.5 (1.0)	0.2 (0.2)	0.003 (0.05)	0.003 (0.1)	2.5 (1.0)
δR_τ ($\times 10^3$)	2.2*	0.6 (1.0)	0.2 (0.4)	0.003 (0.1)	0.003 (0.1)	3.3 (5.0)
δR_b ($\times 10^3$)	3.1*	0.4 (1.0)	0.04 (0.7)	0.0014 (< 0.3)	0.005 (0.2)	1.5 (1.0)
δR_c ($\times 10^3$)	17*	0.6 (5.0)	0.2 (3.0)	0.015 (1.5)	0.02 (1)	2.4 (5.0)

Table 3: EWPOs at future e^+e^- colliders: statistical error (estimated experimental systematic error). Δ (δ) stands for absolute (relative) uncertainty, while * indicates inputs taken from current data [6]. See Refs. [23, 30, 35, 36, 46, 47].

[Snowmass]

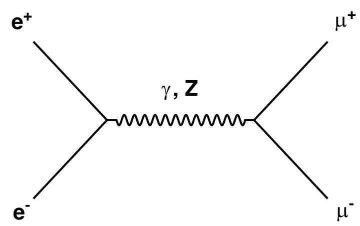
Precision

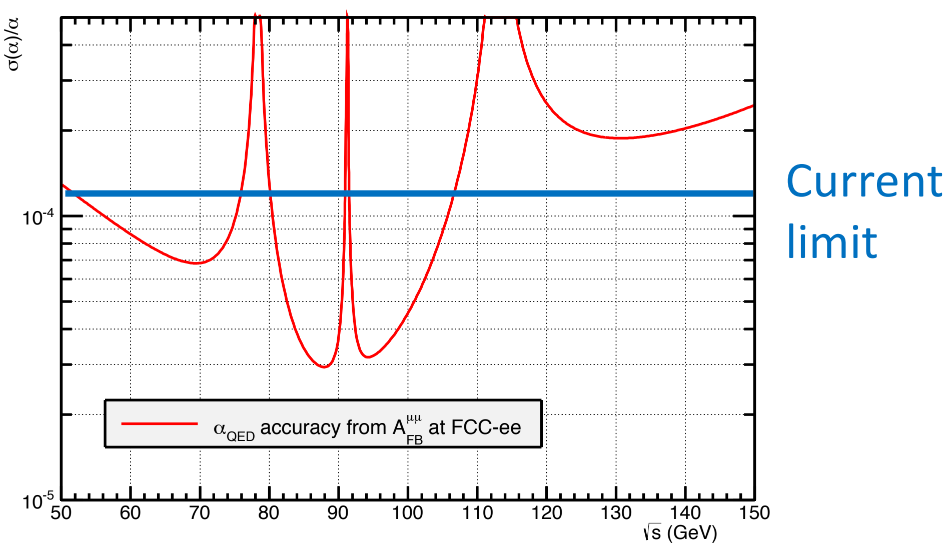
- Verify consistency of SM at levels far beyond current knowledge



Measurement of α_{QED}

- $A_{\mu\mu}^{FB}(M_Z)$ gives first direct measurement of $\alpha_{QED}(M_Z)$
- Measurement is statistics dominated and needs more theory





1512.05544

Don't want to be limited by theory

- Need a concerted theory effort

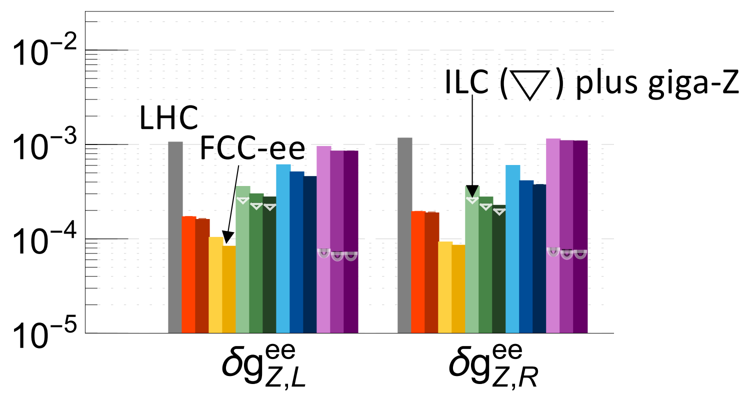
[Freitas,Heinemeyer,Beneke,Blondel,Dittmaier,Gluza,Hoang,Jadach,Janot,Reuter,Reimann;Schwinn,Skrzypek,Weinzierl]

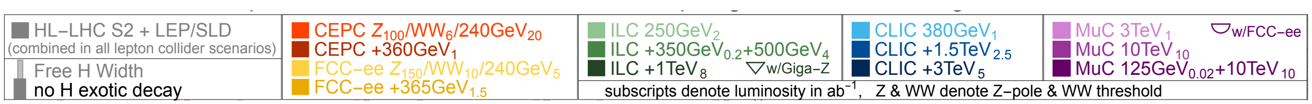
	current exp.	FCC_{ee}, CEPC /ILC	current th.	$\sim$3(4)-loop
M_W [MeV]	12	0.5/3	4 $(\alpha^3, \alpha^2\alpha_s)$	1
Γ_Z [MeV]	2.3	0.1/1	0.4 $(\alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2)$	0.15
R_ℓ $[10^{-3}]$	25	1/10	5 $(\alpha^3, \alpha^2\alpha_s)$	1.5
R_b $[10^{-5}]$	66	6/15	10 $(\alpha^3, \alpha^2\alpha_s)$	5
$\sin^2\theta^\ell_{eff}$ $[10^{-5}]$	$\sim$13	0.6/1.3	4.5 $(\alpha^3, \alpha^2\alpha_s)$	1.5

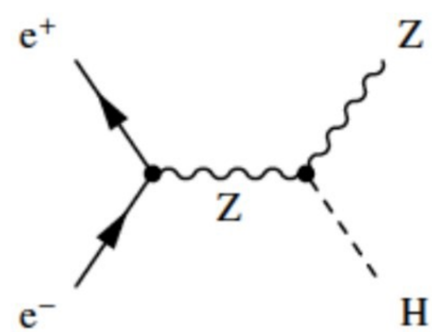
Why do we need precision?

Zee couplings needed to get maximum precision from $e^+e^- \rightarrow ZH$ measurements

Higgs coupling projections typically assume these improvements on Z couplings!







ILC gets precision Zee couplings without Giga-Z

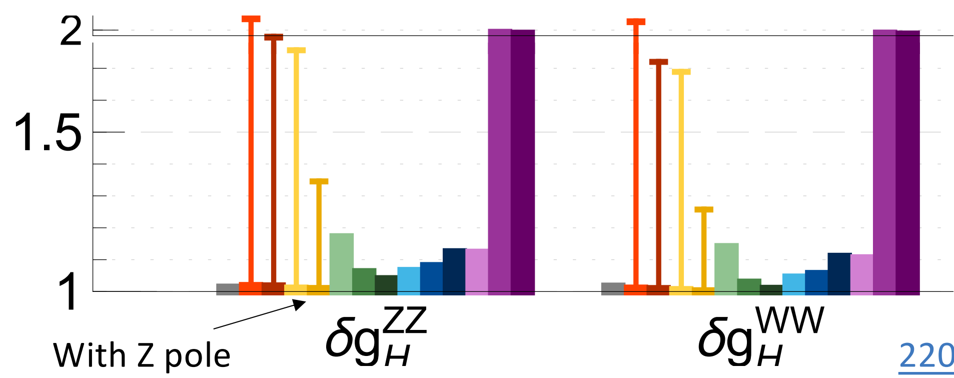
2206.08326 [Snowmass]

More on precision

Precision measurements at Z pole and WW threshold improve precision on Higgs couplings and 3 gauge boson couplings by roughly a factor of 2 at FCC-ee

No improvement in Z pole measurements

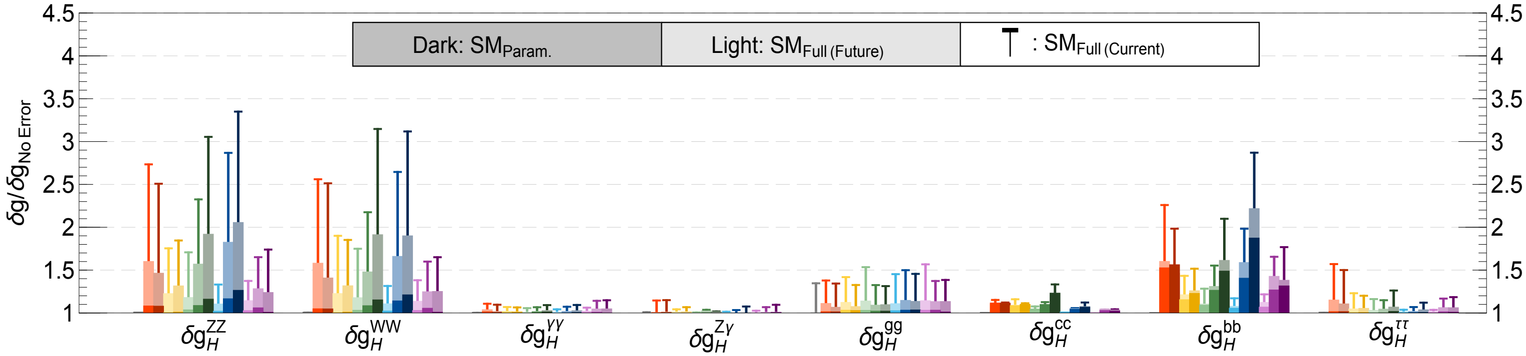
Measurement precision/ precision with perfect EW measurements



With Z pole

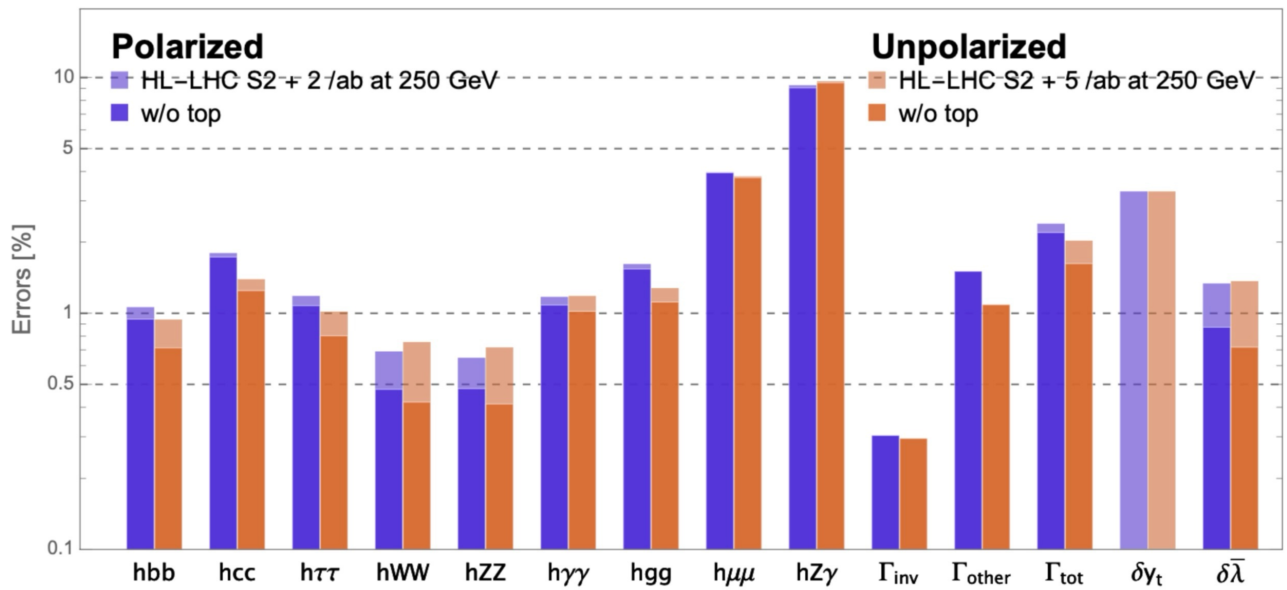
[2209.08078, [Snowmass]]

More improvements



Top physics

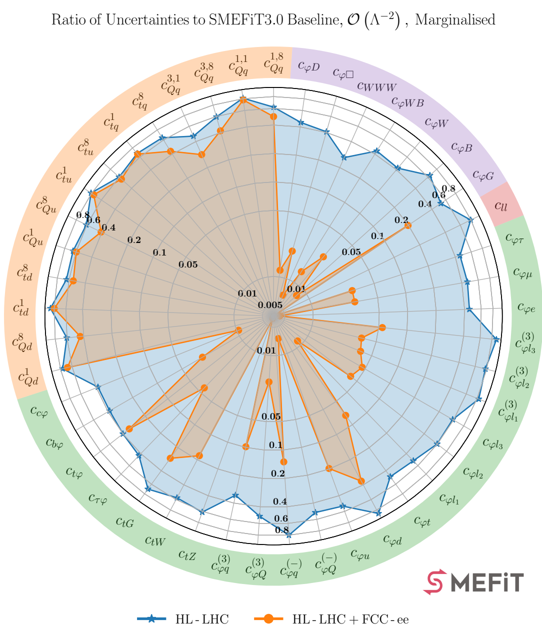
- e^+e^- threshold scan:
  - δm_t ~ 50 MeV
  - $\delta\Gamma_t$ = 45 MeV
  - (Currently, δm_t=330 MeV)
- Improvement in Higgs fits with top data
- Dominant uncertainty is theory
  - Need 3-4 loop EW corrections with masses

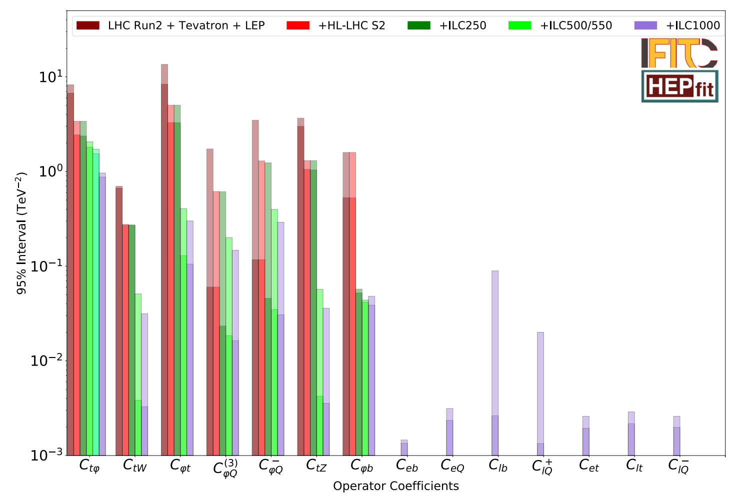


Top mass fundamental input into theory predictions for Higgs physics

2006.14631

Insight into top interactions





Note improvement on top couplings with increased energy

2206.08326

FCC-ee→ typical reduction in uncertainty on top operators by factor ~.6-.4 from LHC (FCC-ee with10 ab^{-1})

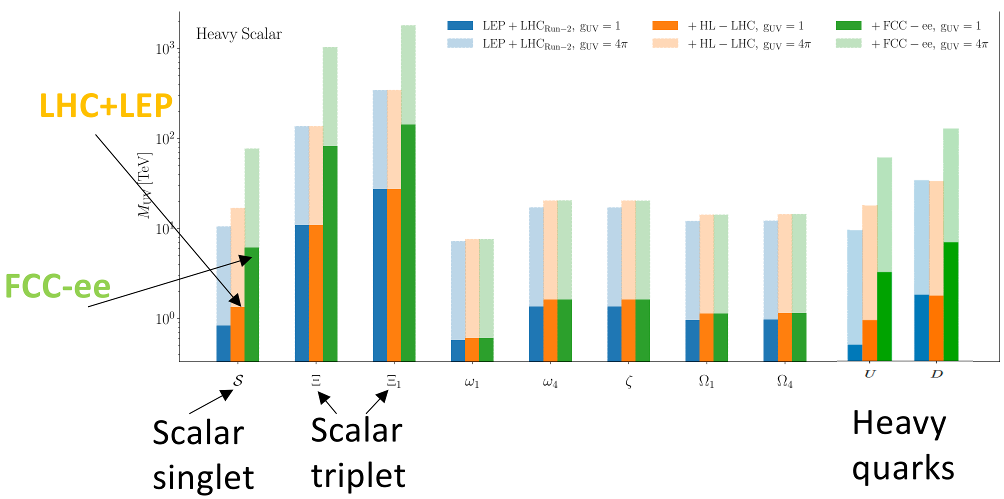
2404.12809

Precision and new physics

- Heavy new physics manifests itself in deviations from predicted SM interactions
- Can parameterize in terms of effective field theory (SMEFT)

$$L_{SMEFT} = L_{SM} + \Sigma_i \frac{C_i}{\Lambda^2} O_i$$

- Match Cs to specific UV models



When new physics contributes to EWPOs, large increase in precision at e^+e^- colliders

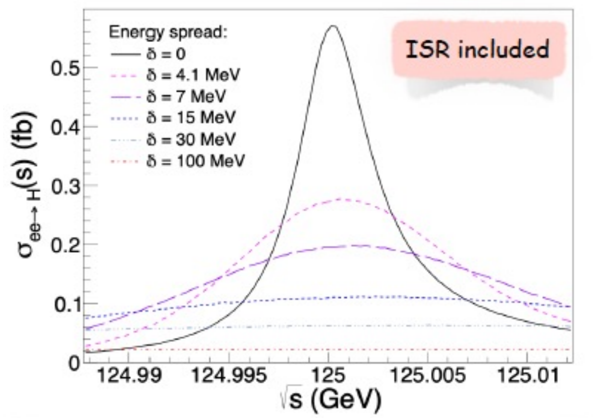
Sadly, there is no target

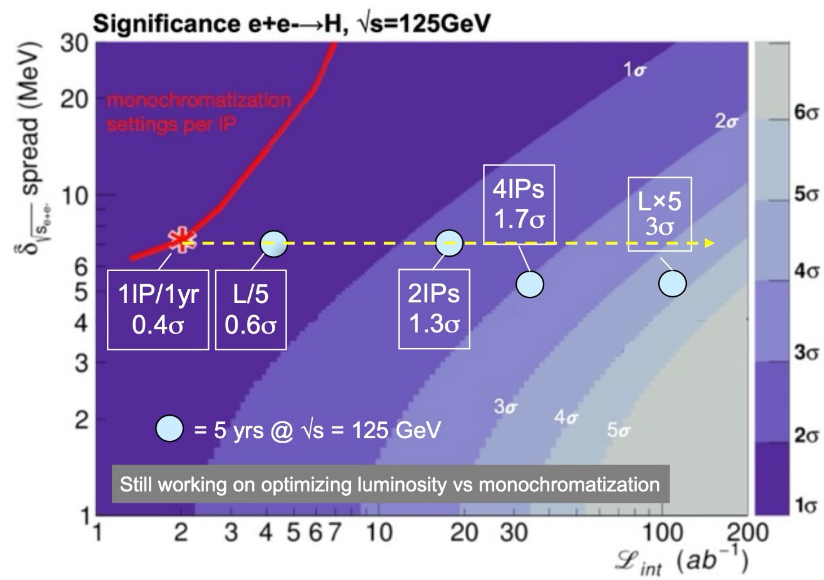
[2404.12809](2404.12809)

Fit includes top and WW data

Electron Yukawa (Aspirational)

- Run on the Higgs pole, $e^+e^- \rightarrow H$
- Want to establish Higgs coupling to 1st generation
- Need M_H to a few MeV, very large luminosity, precise control of beam energy





Note luminosity requirement

2107.02686

Closing Thoughts

- All proposed e^+e^- colliders give outstanding insights into Higgs couplings and SM parameters
- All proposed e^+e^- colliders give insights into BSM physics
- Many more opportunities than presented here
  - I did not discuss physics at the WW threshold
  - I did not discuss flavor (B and τ)
  - I did not discuss light quark Yukawas
- To maximize impact of the experimental measurements, a concerted theory effort is needed