EFT Analysis of Higgs Boson at Higgs Factories

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Background

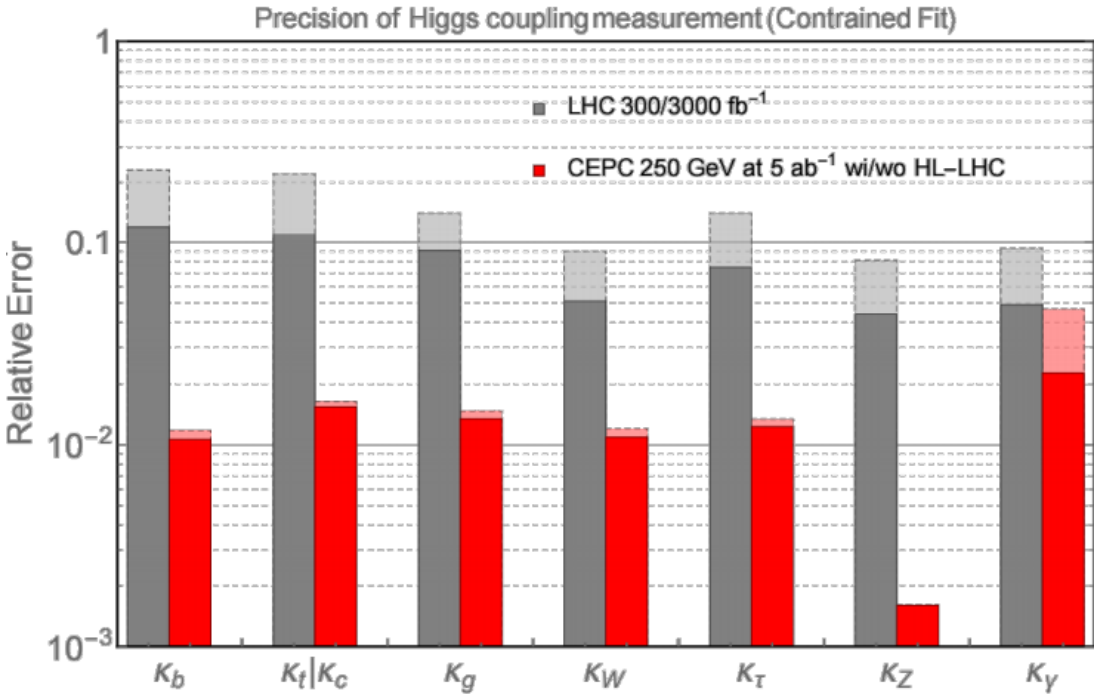
- The Standard Model is extremely robust
- Most notable prediction: Higgs Boson
- Caveat: Lot’s of unanswered problems
- Example: Neutrino mass generation, dark matter, …

How do we move forward?

- Lot’s of theories
- Means to test predictions: Higgs
- The theories all make different predictions
- Should make unbiased predictions

κ-framework

- Perturb Higgs couplings from SM values by κ
- Very well-studied
  - (M.E. Peskin arXiv:1312.4974, M. Klute et. al. arXiv:1301.1322, etc..)
- Problem: Violates gauge invariance and unitarity



(Plot pulled from Z. Liu's slides)

Effective Field Theory Approach

- A way to model new physics while preserving symmetries

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^{d-4}} \mathcal{O}_i$$

- Results in corrections to observables of $\mathcal{O}\left(\Lambda^{4-d}\right)^*$
- Only dim. 5 EW operator → Majorana ν mass
- ⇒ Leading order contribution is dimension six

Operators

- Assume SM symmetries
- A min. of 59 non-redundant dim. six EW operators in the SILH basis (arXiv:1303.3876)
- Focus on only 10
  - 9 complete CP-even basis for Higgs strahlung + $\mathcal{O}_{6H}$

Operators
$\mathcal{O}_{WW} = g^2 \lvert H \rvert^2 W^a_{\mu\nu} W^{a,\mu\nu}$
$\mathcal{O}_{BB} = g'^2 \lvert H \rvert^2 B_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{WB} = g g' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_H = \frac{1}{2}\left(\partial_\mu \lvert H \rvert^2\right)^2$
$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$
$\mathcal{O}_{6H} = \left\lvert H^\dagger H \right\rvert^3$
$\mathcal{O}_L^{(3)l} = \left(i H^\dagger \sigma_a \overleftrightarrow{D}_\mu H\right)\left(\bar{L}_L \gamma^\mu \sigma^a L_L\right)$
$\mathcal{O}_{LL}^{(3)l} = \left(\bar{L}_L \gamma_\mu \sigma^a L_L\right)\left(\bar{L}_L \gamma^\mu \sigma^a L_L\right)$
$\mathcal{O}_L^l = \left(i H^\dagger \overleftrightarrow{D}_\mu H\right)\left(\bar{L}_L \gamma^\mu L_L\right)$
$\mathcal{O}_R^e = \left(i H^\dagger \overleftrightarrow{D}_\mu H\right)\left(\bar{l}_R \gamma^\mu l_R\right)$

Contribution to Observables

- Field redefinition and mixing:
  - Example:

$$\Delta\mathcal{L} \supset \frac{1}{2}\left(1 + \frac{v^2}{\Lambda^2} c_H\right) \partial_\mu h \partial^\mu h$$

$$\Rightarrow h \to \frac{1}{\sqrt{1 + \frac{v^2}{\Lambda^2} c_H}} h \simeq \left(1 - \frac{v^2}{2\Lambda^2} c_H\right) h \equiv (1 + \delta Z_h) h$$

Contribution to Observables

- Modification of EWPO and Z-Pole observables
  - Example:

$$\Delta\mathcal{L} \supset -\frac{1}{2}M_Z^2 Z_\mu Z^\mu - \frac{1}{8}\frac{g^2v^2}{c_w^2\Lambda^2}c_T Z_\mu Z^\mu$$

$$\rightarrow -\frac{1}{2}\left(M_Z^2 - \frac{1}{4}\frac{g^2v^4}{c_w^2\Lambda^2}c_T\right)(1+\delta Z_Z)^2 Z_\mu Z^\mu$$

$$\simeq -\frac{1}{2}\left(1+\delta Z_Z - \frac{v^2}{2\Lambda^2}c_T\right)^2 M_Z^2 Z_\mu Z^\mu$$

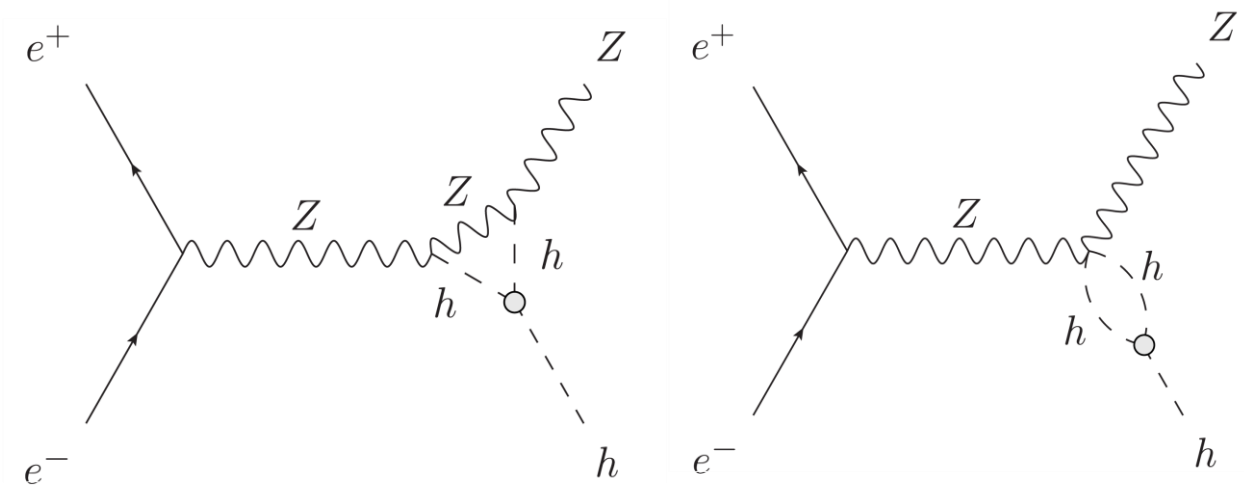
$$\Rightarrow M_Z^{(r)} = \left(1+\delta Z_Z - \frac{v^2}{2\Lambda^2}c_T\right)M_Z^{(sm)}$$

Contribution to Observables

- Modification of existing vertices
  - Example:

$$\mathcal{O}_{6H} \Rightarrow \Delta\mathcal{L} \supset -\frac{m_h^2}{2v}\left(1 - \frac{2v^4}{m_h^2\Lambda^2}c_{6H}\right)h^3$$

  - Contributes to Zh at loop level[1]

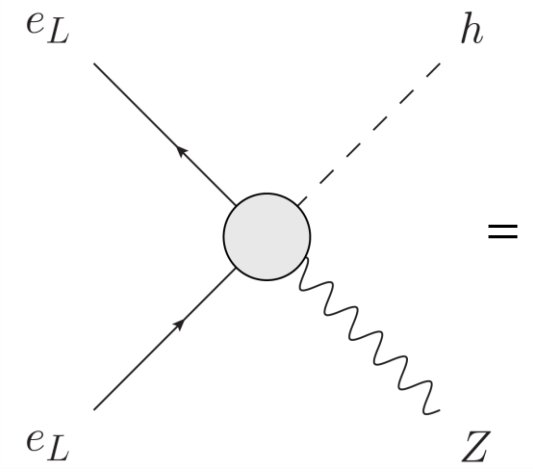


[1]A detailed study was conducted by M. McCullough (arXiv:1312.3222)

Contribution to Observables

- Introducing new vertices
  - Example:

$$\Delta\mathcal{L} \supset -\frac{gv}{c_w\Lambda^2}c_L^{(3)l}\bar{e}_L\gamma^\mu e_L Z_\mu h$$



$$= -i\frac{gv}{c_w\Lambda^2}c_L^{(3)l}\gamma^\mu$$

Constraints From CEPC

- Methodology similar to that used by S.F. Ge et al. (arXiv:1603.03385)
- Choose input basis: M_Z, α, G_F
- Derive LO corrections to SM observables

$$X^{(r)} = \left(1 + \frac{\delta X}{X^{(\mathrm{SM})}}(c_i, M_Z, \alpha, G_F)\right) X^{(\mathrm{SM})}$$

- Assume SM value = experimental central value
- ⇒Corrections to SM $\leq$ Experimental bounds

Required Precision

- Mostly follow the constraints given by the CEPC pre-CDR
- For observables with small statistical uncertainties, take 2 cases
  - Optimistic case: Minimal systematic uncertainties
  - Pessimistic case: Systematics $\sim$ Statistical uncertainties
- Current data obtained from PDG

Required Precisions

	Current Precision	Expected Precision
M_Z	2.3×10^{-5}	$0.55 - 1.1 \times 10^{-5}$
G_F	5.14×10^{-7}	–
α	3.29×10^{-10}	–
$\sigma(Zh)_{250}$	–	0.51%
M_W	1.87×10^{-4}	$3.7 - 6.2 \times 10^{-5}$
N_ν	0.27%	0.1%
A_{FB}^b	1.7%	0.15%
R_b	0.3%	0.08%
R_τ	0.2%	0.05%
R_μ	0.2%	0.05%
$\sin^2 \theta_W^{\text{eff}}$	0.07%	0.01%

IHEP-CEPC-DR-2015-01

Single Parameter Fit

	N_ν	A_{FB}^b	R_b	R_μ	R_τ	$\sin^2\theta_W^{\text{eff}}$	M_W	$\sigma(Zh)$
$c_{WW}/\Lambda_{\text{TeV}}^2$	–	0.0091	0.183	0.0223	0.0223	0.006	0.103	0.0224
$c_{BB}/\Lambda_{\text{TeV}}^2$	–	0.124	2.532	0.307	0.307	0.0794	0.473	0.684
$c_{WB}/\Lambda_{\text{TeV}}^2$	–	0.0073	0.238	0.167	0.166	0.00429	0.00598	0.155
$c_H/\Lambda_{\text{TeV}}^2$	–	–	–	–	–	–	–	0.08
$c_T/\Lambda_{\text{TeV}}^2$	0.0297	0.0033	0.200	0.0894	0.09	0.002	0.0014	0.124
$c_{6H}/\Lambda_{\text{TeV}}^2$	–	–	–	–	–	–	–	0.71
$c_{LL}^{(3)l}/\Lambda_{\text{TeV}}^2$	0.0149	0.0017	0.101	0.0448	0.0451	0.001	0.0025	0.0172
$c_L^{(3)l}/\Lambda_{\text{TeV}}^2$	0.0149	0.0012	0.100	0.0040	0.045	0.00073	0.0025	0.0081
$c_L^l/\Lambda_{\text{TeV}}^2$	–	0.0046	–	0.00367	0.004	0.0027	–	0.0047
$c_R^e/\Lambda_{\text{TeV}}^2$	–	0.0034	–	0.005	0.0037	0.002	–	0.007

The red shows the most constraint cases.

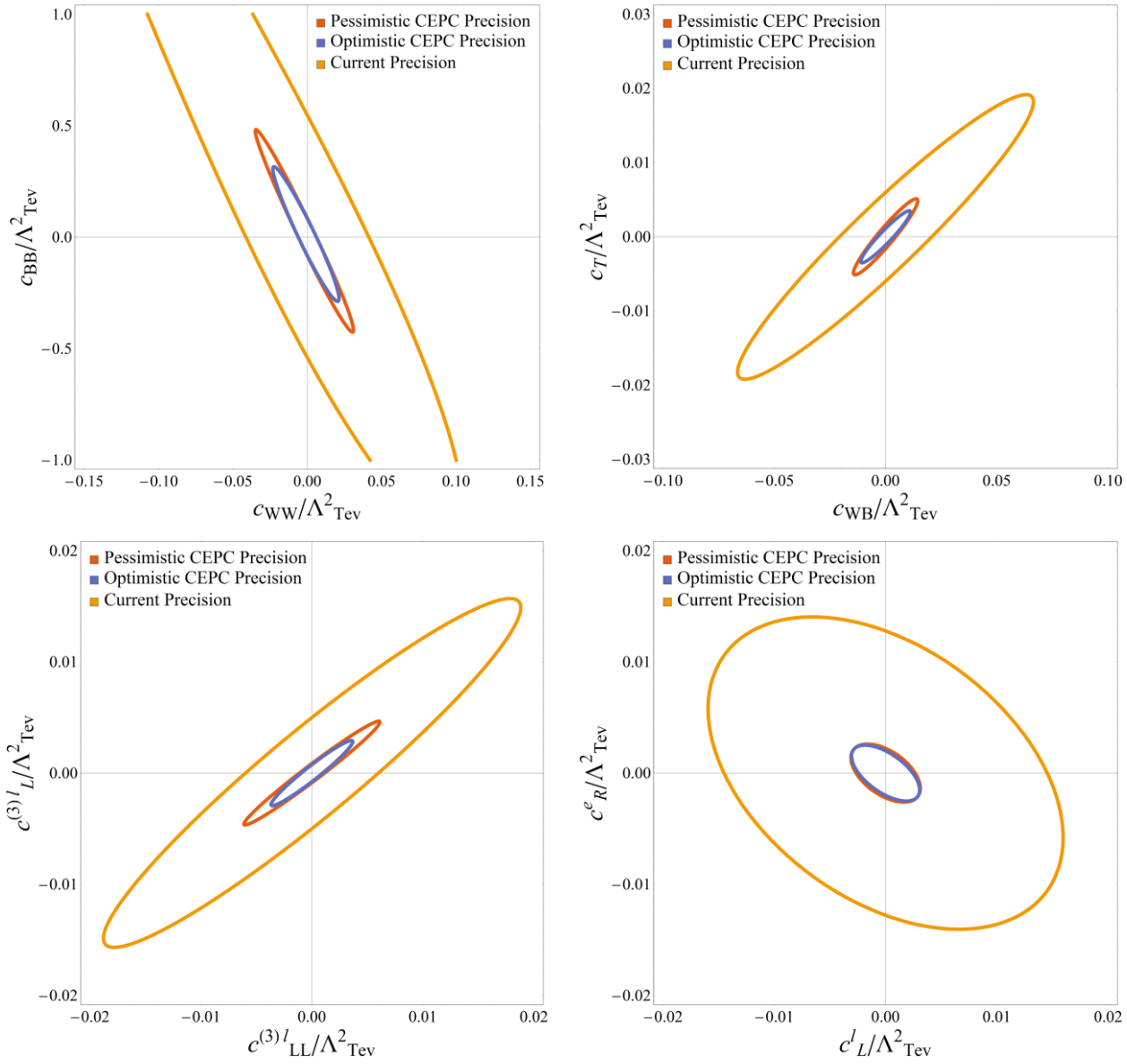
Two Parameter Fit

- Previous studies only constrain independent operators
- Correlation is important depending on the full theory
- Multiple operators typically induced simultaneously[1]
- Use χ^2 analysis
- Constrain parameters using 2-3 observables
- We assume other Wilson coefficients zero and focus on the two parameters.

Correlation Plots

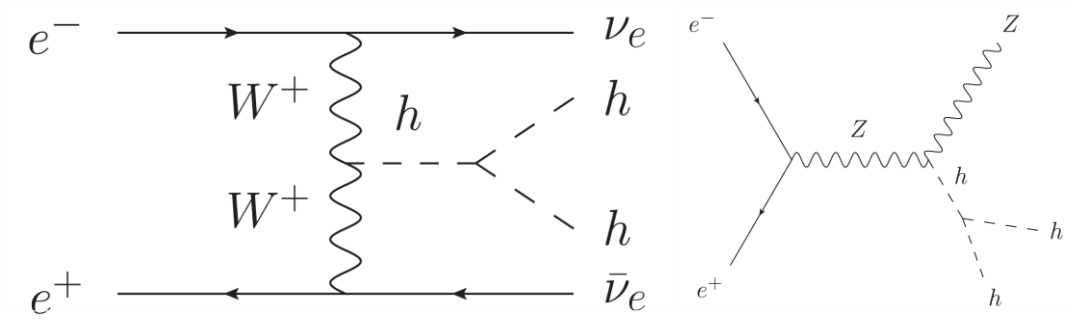
General comments:

- Range of allowed c_i increase noticeably vs single operator case
- Most can be constrained to $\mathcal{O}(10^{-2})$ at CEPC



Constraining c_{6H} and c_H

- All Wilson coefficients except c_{6H} is well constrained
- Because $\mathcal{O}_{6H}$ enters Higgs strahlung at loop level
- Need other processes



- These processes do not take place at CEPC

Precision Inputs From Various Colliders

Channel	Expected Precision of σ
Zh (250 GeV CEPC)	0.5%
Zh (240 GeV FCC-ee)	0.4%
Zh (250 GeV 2 ab^{-1} ILC)	0.9%
$\nu\bar{\nu}h$(350 GeV FCC-ee)	0.75%
Zhh(500 GeV 4 ab^{-1} ILC)	15.1%
$\nu\bar{\nu}hh$ (1 TeV 5 ab^{-1} ILC)	12%

arXiv: 1602.05043v2
IHEP-CEPC-DR-2015-01
arXiv: 1506.07830v1
arXiv: 1310.0763v3

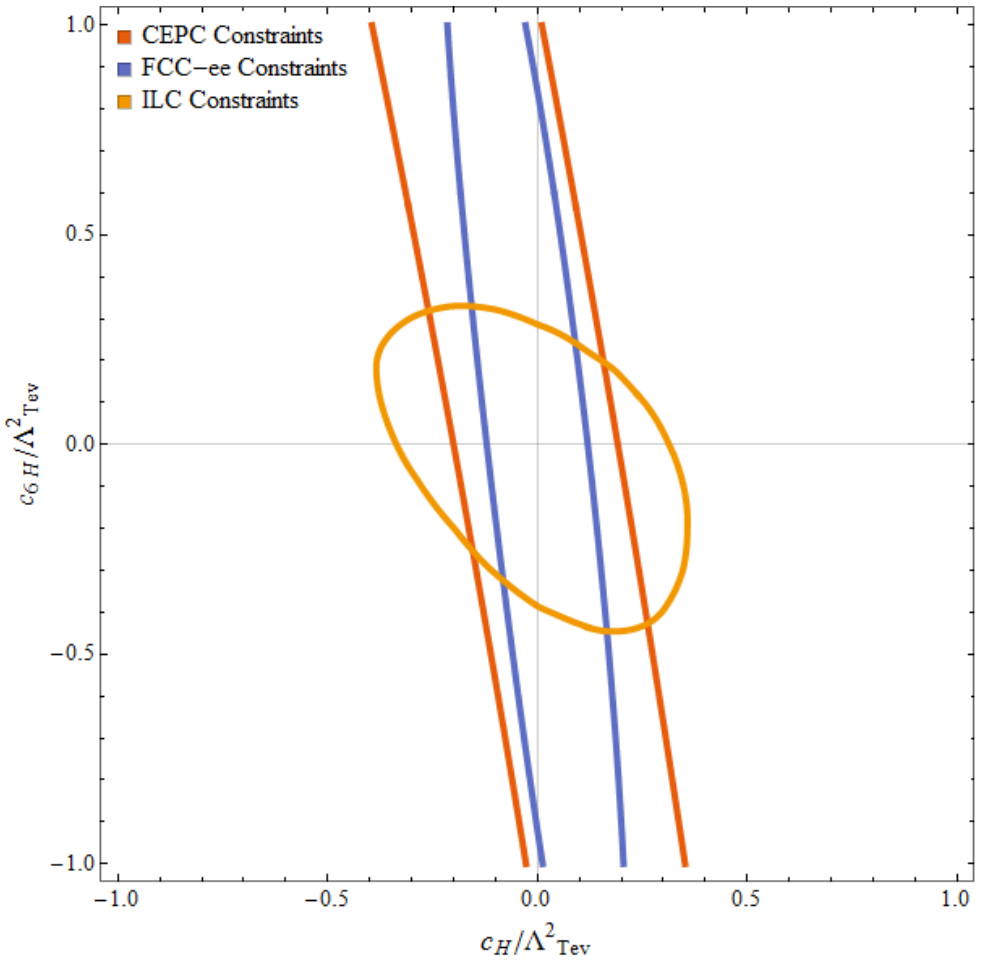
Constraints on c_{6H}

- Fit using: $\sigma(Zh), \sigma(\nu\bar{\nu}h)_{350}$, $\sigma(Zhh)_{500}$ and $\sigma(\nu\bar{\nu}hh)_{1000}$
- CEPC Constraints:

  $5\ \mathrm{ab}^{-1}$ of $250\ \mathrm{GeV}$ data at CEPC
- FCC-ee constraints:

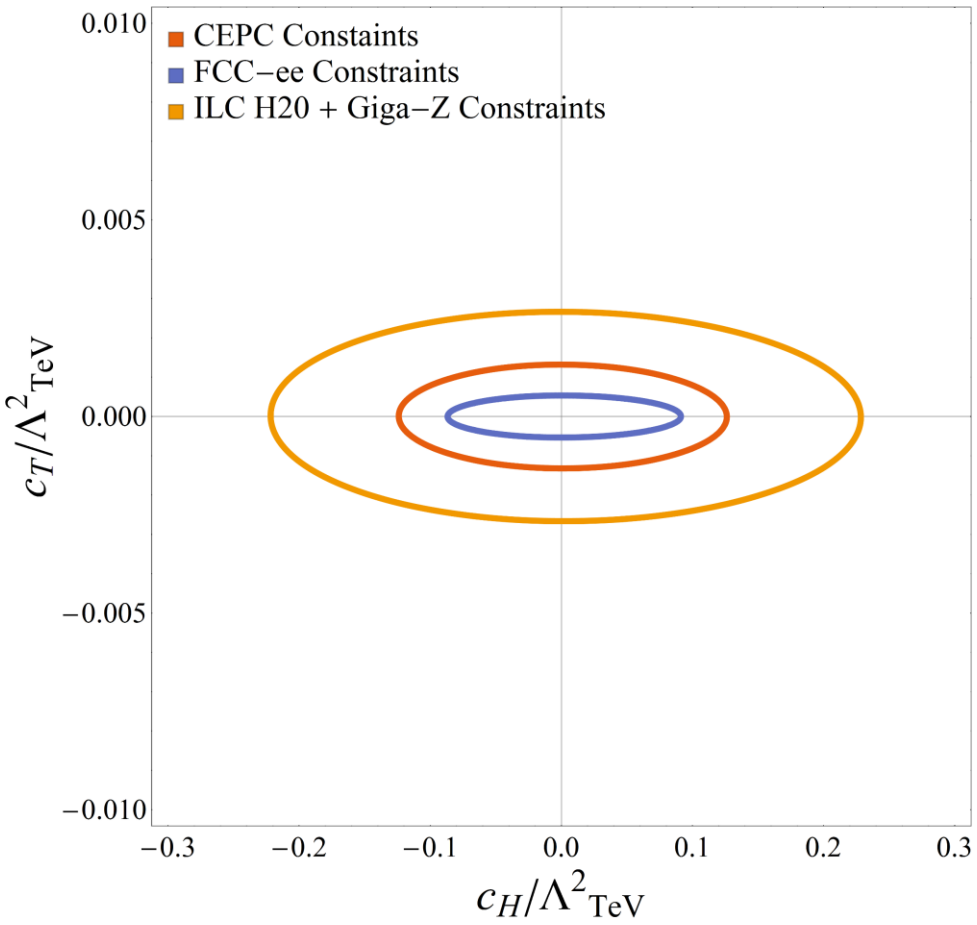
  $10\ \mathrm{ab}^{-1}$ of $240\ \mathrm{GeV}$ data, $2.5\ \mathrm{ab}^{-1}$ of $350\ \mathrm{GeV}$ data
- ILC Constraints:

  $2\ \mathrm{ab}^{-1}$ at $250\ \mathrm{GeV}$, $4\ \mathrm{ab}^{-1}$ at $500\ \mathrm{GeV}$ and $5\ \mathrm{ab}^{-1}$ at $1\ \mathrm{TeV}$



Comparison of Colliders

- Observables: $\sigma(Zh)$, M_W and $\sigma(\nu\bar{\nu}h)_{350}$



Summary

- Parameter space for “complete” Higgs Strahlung basis well constrained at CEPC
- For operators which contribute at loop level, other colliders are more useful

Backups

Minimal Toy Model

- As previously mentioned, multiple operator are typically simultaneously induced
- Illustrate this using toy models

$c_L^l - c_L^{(3)l}$ correlation

- Based off of the work in 1612.02040 by Yun Jiang
- Integrating out a new vector like heavy lepton yields three operators

Case	$SU(2)_L$	$U(1)_Y$	$J_L^{\mathfrak{L}}$	$\mathcal{O}_L^l$	$\mathcal{O}_L^{(3)l}$	$\mathcal{O}_{eH}$	$\mathcal{O}_{He}^{(1)}$
$\mathcal{L}_I^{(1)}$	1	-1	$\bar{L}_L H$	√	√	√	
$\mathcal{L}_I^{(3)}$	3	-1	$\sigma^I \bar{L}_L H$	√	√	√	

$$\mathcal{L}_{\mathfrak{L}}^{\text{int}} = \lambda(J_L^{\mathfrak{L}}\mathfrak{L}_R + J_R^{\mathfrak{L}}\mathfrak{L}_L + \text{h.c.})$$

Singlet

$$\mathcal{L}_{\mathfrak{L}}^0 = \bar{\mathfrak{L}}_L i\not{D}\mathfrak{L}_L + \bar{\mathfrak{L}}_R i\not{D}\mathfrak{L}_R - M_1(\bar{\mathfrak{L}}_L\mathfrak{R} + \bar{\mathfrak{R}}_L\mathfrak{L})$$

$$\mathcal{L}_{\text{eff}} \sim \frac{\lambda_1}{2M_1^2}(\mathcal{O}_L^{3l} + \mathcal{O}_L^l)$$

Triplet

$$\mathcal{L}_{\mathfrak{L}}^0 = \bar{\mathfrak{L}}_L i\not{D}\mathfrak{L}_L + \bar{\mathfrak{L}}_R i\not{D}\mathfrak{L}_R - M_3 Tr[\bar{\mathfrak{L}}_L\mathfrak{R} + \bar{\mathfrak{R}}_L\mathfrak{L}]$$

$$\mathcal{L}_{\text{eff}} \sim \frac{\lambda_3}{2M_3^2}(-\mathcal{O}_L^{3l} + 3\mathcal{O}_L^l)$$

These two cases mixes

$\mathcal{O}_{eH} = (H^\dagger H)(\bar{L}_L H e_R)$ does not contribute to the processes of interest

c_{6H}-c_H correlation

- There are many models that can contribute to higgs self interaction.
- Example: Higgs inflation (H.J. He et. al. arXiv:1506.03302).
- Here we consider a simple scenario, introducing a UV massive scalar S

$$\mathcal{L}_{SH} = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 + \Lambda_S S H^\dagger H + \lambda H^\dagger H S^2$$

- After integrating out S, we can get the dim-6 operators

$$\mathcal{L}_{EFT} \sim \frac{3\lambda\Lambda_S^2}{2m_S^4}\mathcal{O}_{6H} + \frac{2\Lambda_S^2}{m_S^4}\mathcal{O}_H$$