Probing 6D Operators at Future e-e+ Colliders

LYU Kunfeng, HKUST

Based on 1711.04046, in collaboration with Wen Han Chiu, Iris Leung, Tao Liu and Lian-Tao Wang

Motivation

- UV physics typically generates a set of operators in low-energy EFT. Many analyses have been done on the probe for these EFT operators, in various contexts.
- We will pursue a relatively complete analysis on the sensitivities at future e-e+ colliders, by taking into account the correlation among the relevant operators.
- According to such analyses, we hope to obtain a global picture on the scientific performance of several e-e+ collider configurations proposed, including ILC, FCC-ee and CEPC

Six-Dimensional Operators

$\mathcal{O}_{WW} = g^2\|H\|^2 W^a_{\mu\nu} W^{a,\mu\nu}$	$\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$	$\mathcal{O}^{(3)l}_L = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu \sigma^a L_L)$
$\mathcal{O}_{WB} = gg' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_H = \frac{1}{2}(\partial_\mu \|H\|^2)^2$	$\mathcal{O}^{(3)l}_{LL} = (\bar{L}_L \gamma_\mu \sigma^a L_L)(\bar{L}_L \gamma^\mu \sigma^a L_L)$
$\mathcal{O}_{BB} = g'^2 \|H\|^2 B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_6 = \lambda \|H^\dagger H\|^3$	$\mathcal{O}^l_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu L_L)$
$\mathcal{O}_{3W} = g \frac{\varepsilon_{abc}}{3!} W^{a\nu}_\mu W^{b\rho}_\nu W^{a\mu}_\rho$		$\mathcal{O}^e_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{l}_R \gamma^\mu l_R)$

10 CP even operators relevant to ZH process and O3W

- Renormalize wavefunction
- Shift EW inputs (G_F, M_Z, α) scheme
- Induce new vertices

Field Redefinition

$$h = Z_h h' = \left(1 - \frac{v^2}{2\Lambda^2} c_H\right) h'$$

$$Z^\mu = Z_Z Z'^\mu = \left(1 + \frac{v^2}{\Lambda^2} c_w s_w g g' c_{WB}\right) Z'^\mu$$

$$A^\mu = Z_A A'^\mu + \delta Z_X Z'^\mu$$

$$= \left(1 - \frac{v^2}{\Lambda^2} c_w s_w g g' c_{WB}\right) A'^\mu - \frac{v^2}{\Lambda^2}(c_w^2 - s_w^2) g g' c_{WB} Z'^\mu$$

Input Shift

$$G_F^{sm} = G_F^{(r)} \left(1 + \frac{2\left(c_{LL}^{(3)l} - c_L^{(3)l}\right) v_{sm}^2}{\Lambda^2}\right)$$

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

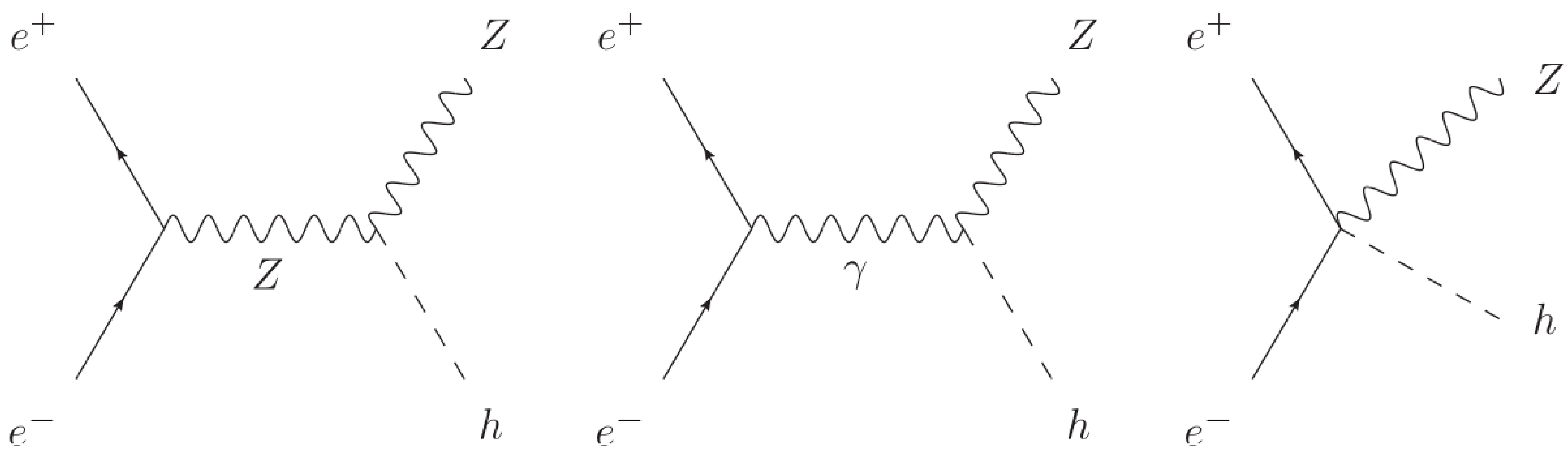
$$\alpha^{sm} = \alpha^{(r)}(1 - 2\delta Z_A)$$

Modified coupling

New Lorentz structure

$$\mathcal{L}_{Zh} \supset \frac{2m_Z^2}{v}(1+c_{ZZ}^{(1)})hZ_\mu Z^\mu + c_{ZZ}^{(2)} hZ_{\mu\nu}Z^{\mu\nu} + c_{AZ} hZ_{\mu\nu}A^{\mu\nu} + g_L^{(1)} Z_\mu \bar{e}_L\gamma^\mu e_L + g_R^{(1)} Z_\mu \bar{e}_R \gamma^\mu e_R + g_L^{(2)} hZ_\mu \bar{e}_L \gamma^\mu e_L + g_R^{(2)} hZ_\mu \bar{e}_R\gamma^\mu e_R + eA_\mu(\bar{e}_L\gamma^\mu e_L + \bar{e}_R\gamma^\mu e_R)$$

New Vertices



Observables

- Signal rates of Higgs events
- Z-pole observables and EWPO
- Angular observables in Higgs events (Craig et al. arXiv:1512.06877)

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

- Assume measured value = SM prediction

  ➔ The allowed BSM correction is within experimental precision

EWPT observables

Observables	ILC		FCC-ee		CEPC	
N_ν	0.0013 [4]	Z lineshape,100fb^{-1}	1.58×10^{-3} [34]	Z pole,150ab^{-1}	0.0018 [19]	240 GeV, 100fb^{-1}
A^b_{FB}	-	-	-	-	$(\pm15\pm2_{\rm in})\times10^{-4}$ [6]	Z pole, 150fb^{-1}
A^μ_{FB}	-	-	7.1×10^{-4} [34, 40]	Z pole,150ab^{-1}	-	-
A_b	0.001 [4]	Z pole,100fb^{-1}	-	-	-	-
R_b	6.5×10^{-4} [4]	Z pole,100fb^{-1}	3.6×10^{-4} [34, 40]	Z pole,150ab^{-1}	8×10^{-4} [6]	Z pole, 100fb^{-1}
R_μ	2×10^{-4} [35]	Z pole,100fb^{-1}	6.1×10^{-5} [34, 40]	Z pole,150ab^{-1}	5×10^{-4} [6]	Z pole, 100fb^{-1}
R_τ	2×10^{-4} [35]	Z pole,100fb^{-1}	6.1×10^{-5} [34, 40]	Z pole,150ab^{-1}	5×10^{-4} [6]	Z pole, 100fb^{-1}
Γ_Z(MeV)	$\pm1\pm0.21_{\rm in}$ [4, 38]	Z pole,100fb^{-1}	$\pm0.1\pm0.08_{\rm th}\pm0.065_{\rm in}$ [38, 40]	Z pole,150ab^{-1}	$\pm0.1\pm0.08_{\rm th}\pm0.13_{\rm in}$ [6, 38]	Z pole, 150fb^{-1}
$\sin^2\theta^{\rm lep}_{\rm eff}(10^{-5})$	$\pm1.3\pm1.5_{\rm th}\pm2.2_{\rm in}$ [4, 38]	Z pole,100fb^{-1}	$\pm0.3\pm1.5_{\rm th}\pm1.6_{\rm in}$ [38, 40]	Z pole,150ab^{-1}	$\pm2.3\pm1.5_{\rm th}\pm2.5_{\rm in}$ [6, 38]	Z pole, 150fb^{-1}
m_W (MeV)	$\pm2.5\pm1_{\rm th}\pm2.8_{\rm in}$ [38, 41]	250GeV, 2ab^{-1}	$\pm1.2\pm1_{\rm th}\pm0.91_{\rm in}$ [34, 38]	WW threshold,10ab^{-1}	$\pm3\pm1_{\rm th}\pm3.8_{\rm in}$ [6, 38]	240GeV,5ab^{-1}

- These observables only depend on 6 Wilson coefficients

$$c_{WB}, c_T, c_{LL}^{(3)l}, c_L^l, c_L^{(3)l}, c_R^e$$

Precision of Higgs Events + Diboson process

Observables	ILC		FCC-ee		CEPC	
$\sigma(Zh)$	2.0% [25]	250GeV,2ab^{-1}	0.5% [34]	240GeV,5ab^{-1}	0.5% [6]	240GeV,5ab^{-1}
	4.2% [25]	500GeV,4ab^{-1}	-	-	-	-
$\sigma(\nu\bar{\nu}h)$	3.89% [5]	250GeV,2ab^{-1}	0.97% [19]	350GeV,1.5ab^{-1}	2.86% [19]	240GeV,5ab^{-1}
	1.45% [5]	500GeV,4ab^{-1}	-	-	-	-
$\sigma(Zhh)$	15.0% [5]	500GeV,4ab^{-1}	-	-	-	-
$\sigma(W^+W^-)$	0.0200%[39]	250GeV,2ab^{-1}	0.0136% [39]	240GeV,5ab^{-1}	0.0136% [39]	240GeV,5ab^{-1}
	0.0191% [39]	500GeV,4ab^{-1}	-	-	-	-
$\mathcal{A}_{\theta_1}$	0.0083 [32]	250GeV,2ab^{-1}	0.0060 [32]	240GeV,5ab^{-1}	0.0060 [32]	240GeV,5ab^{-1}
$\mathcal{A}_{c\theta_1,c\theta_2}$	0.0092 [32]	250GeV,2ab^{-1}	0.0067 [32]	240GeV,5ab^{-1}	0.0067 [32]	240GeV,5ab^{-1}
$\mathcal{A}_{\phi}^{(3)}$	0.0092 [32]	250GeV,2ab^{-1}	0.0067 [32]	240GeV,5ab^{-1}	0.0067 [32]	240GeV,5ab^{-1}
$\mathcal{A}_{\phi}^{(4)}$	0.0092 [32]	250GeV,2ab^{-1}	0.0067 [32]	240GeV,5ab^{-1}	0.0067 [32]	240GeV,5ab^{-1}

ILC Polarized Beam P(e-,e+) = (-0.8,0.3)

Fitting Strategy

$$\chi^2 = \sum_i \frac{(\mu^i_{NP} - \mu^i_{SM})^2}{\sigma^2_{\mu i}}$$

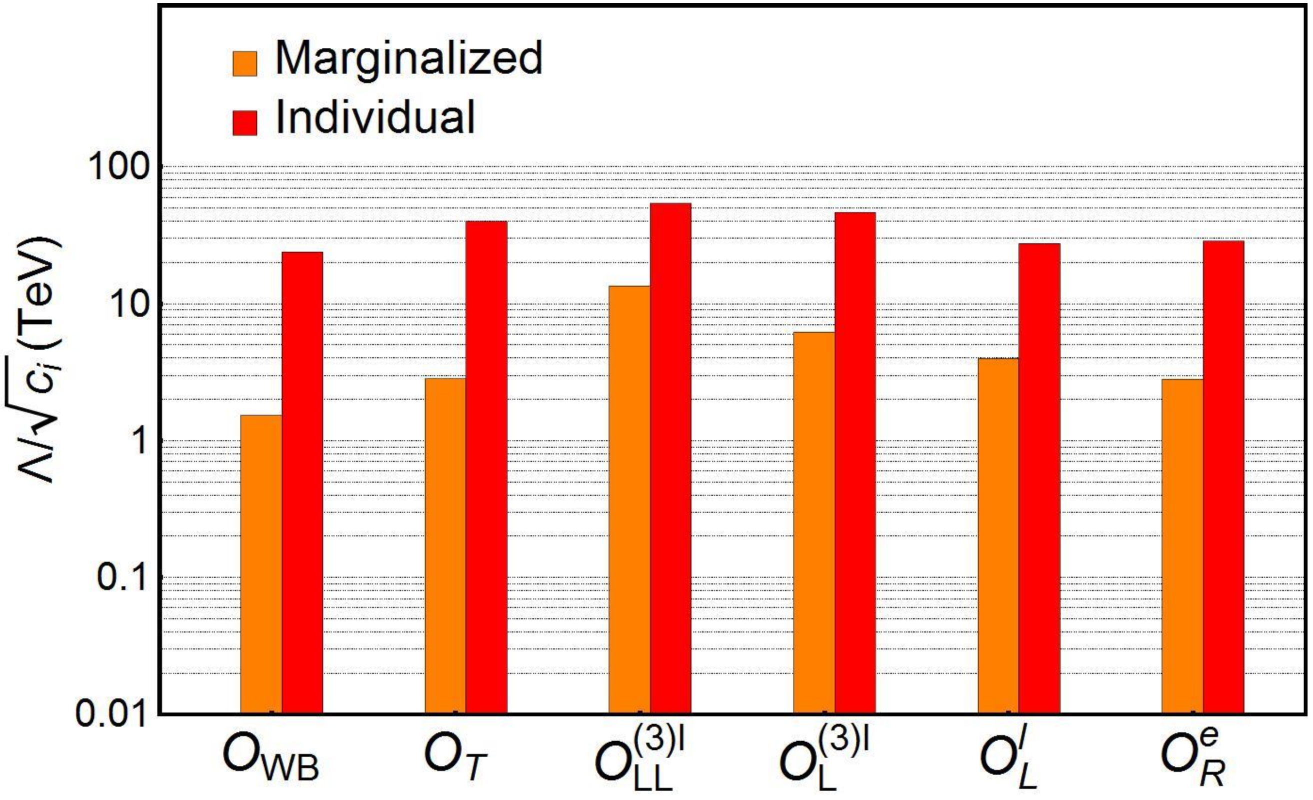
- Calculate the shift in observables in terms of Wilson coefficients (only linear terms)
- Combine different observables using χ^2 fit
- Individual Fitting:

  Turn on one operator each time
- In order to study the correlation among operators, marginalized fitting is exploited:

  Turn on multiple operators one time and then make projection

CEPC results

EWPO + Z pole observables

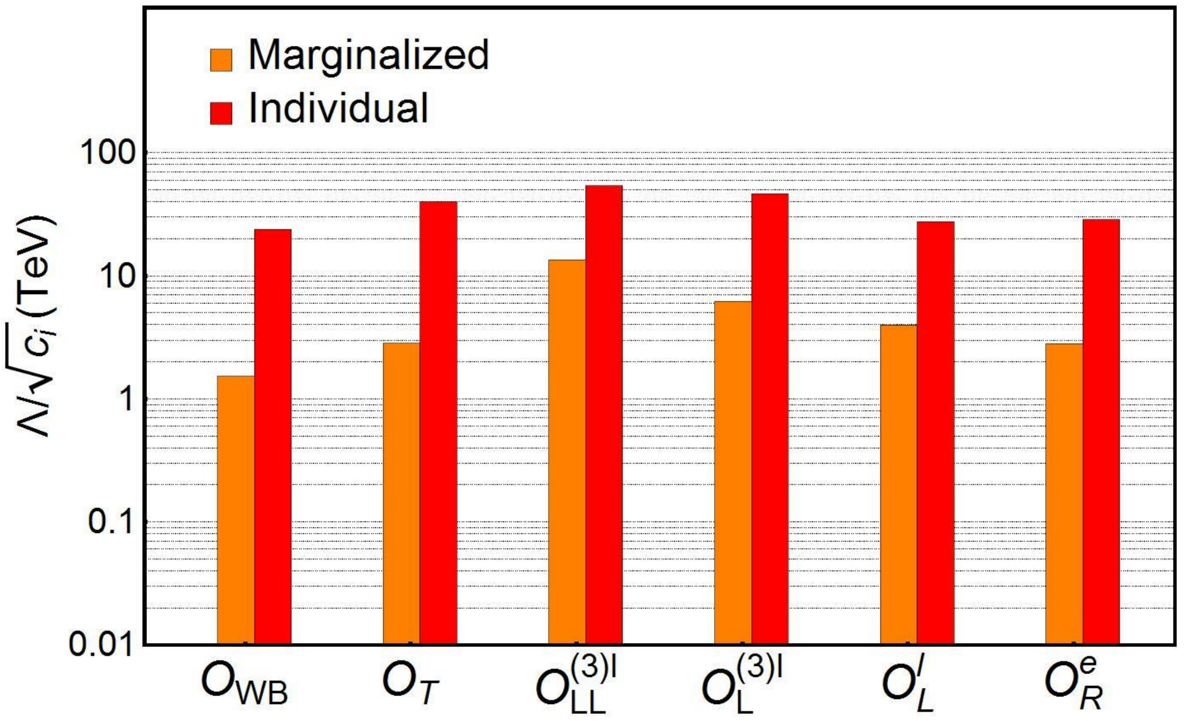


$$\xi_0 = -1.1c_{WB} + 2c_T - 4c_L^{(3)l} + 4c_{LL}^{(3)l} \qquad \xi_\pm = c_L^{(3)l} \pm c_L^l$$

	Other dependency
N_ν	ξ_0 ξ_+ ξ_- c_R^e
A_b R_b	ξ_0
A_{FB}^b A_{FB}^μ $\sin^2\theta_{\rm eff}^{\rm lep}$	ξ_0 ξ_+ c_R^e
R_μ R_τ	ξ_0 ξ_+ c_R^e
Γ_Z	
m_W	

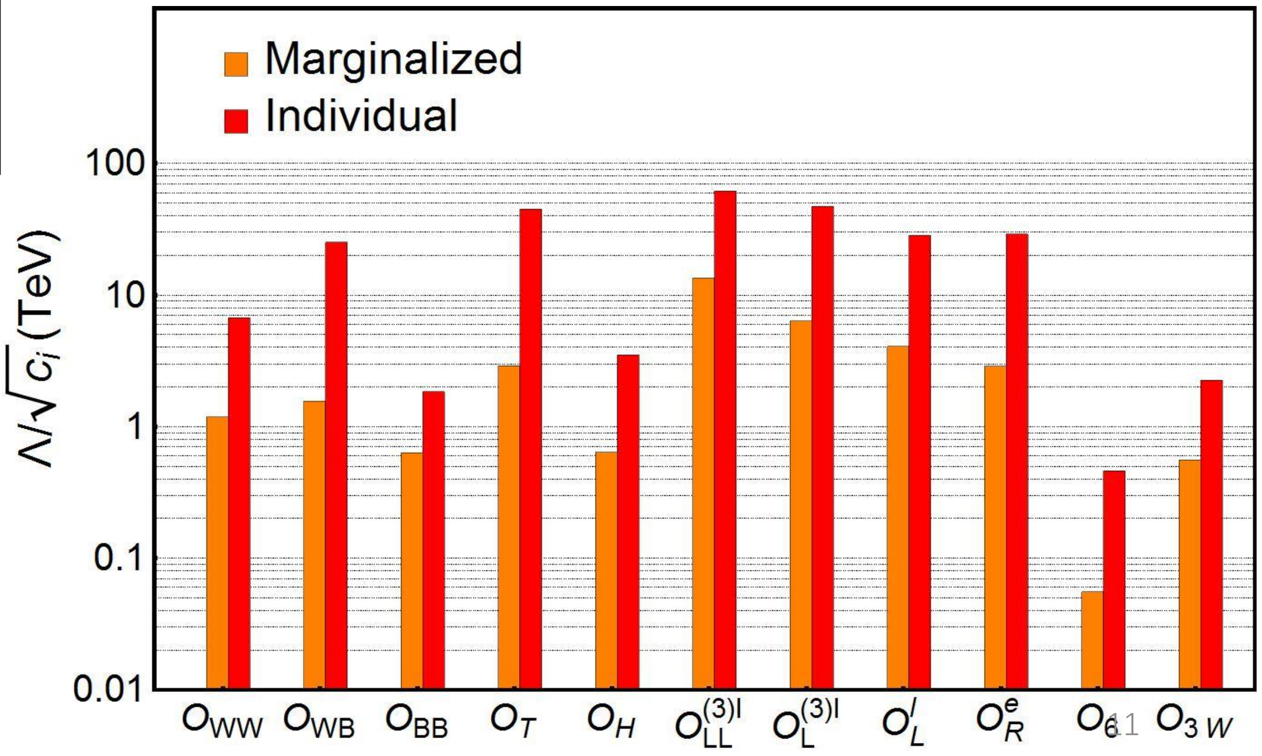
Due to the relative low precision of A_b R_b and lack of 6-th observables to break the degeneracy, the constraint of the 6 operators are not high enough

EWPO + Z pole observables

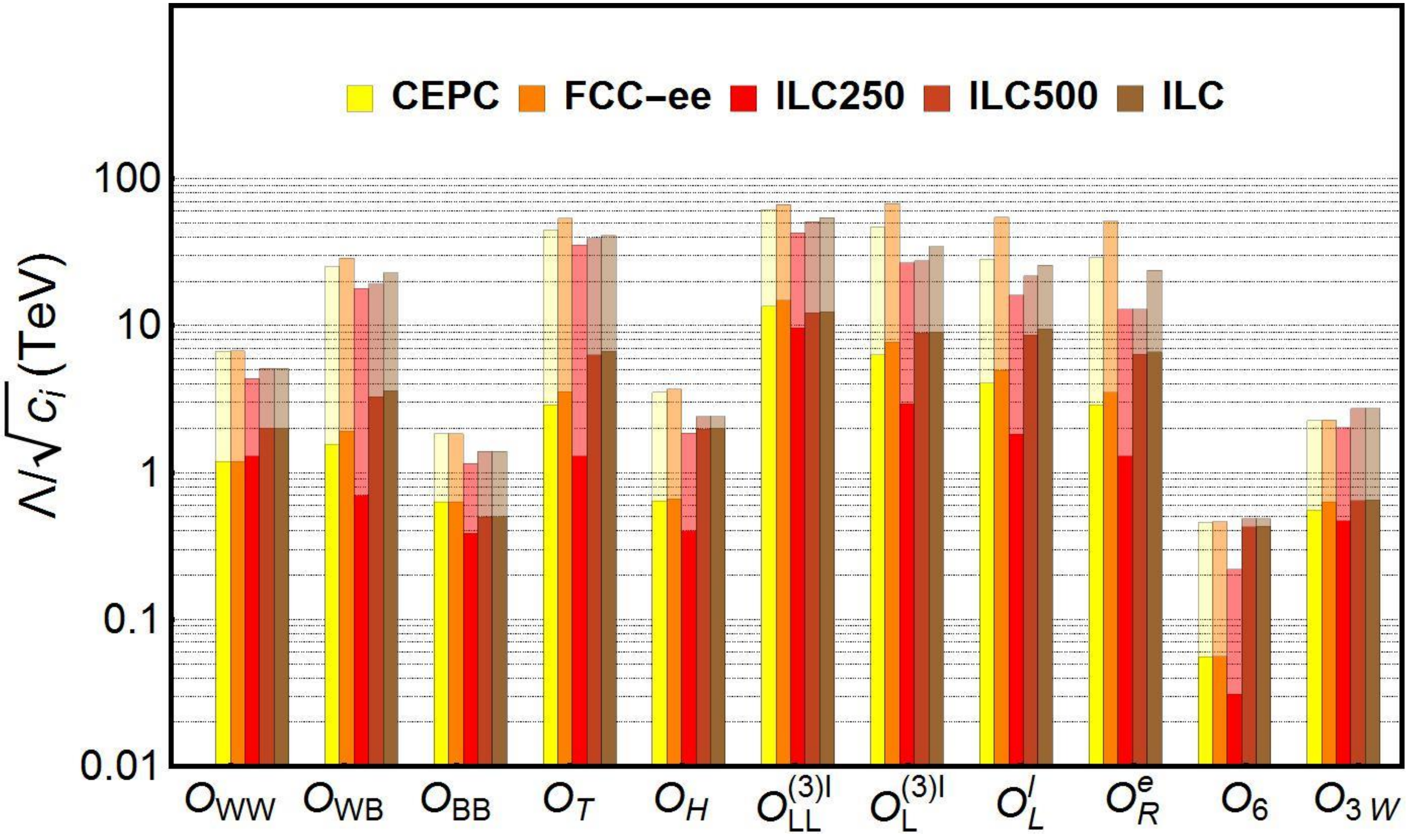


Higgs measurements and diboson process do not help much in this regard but they can be applied to constrain the other operators under consideration.

CEPC results with all observables



Comparative study at future e-e+ collider



Light: Individual Fitting
Dark: Marginalized Fitting

ILC 250 : ILC data at 250 GeV + EWPOs at LEP
ILC500 : ILC 250 + ILC data at 500 GeV
ILC: ILC 500 with LEP replaced by GigaZ

FCC-ee performs better than CEPC due to the higher luminosity

ILC 250 and ILC 500

There is a big uncertainty about the GigaZ operation. But, the measurement at 500 GeV can largely compensate the relevant sensitivity loss.

	$\mathcal{O}_{WW}$	$\mathcal{O}_{WB}$	$\mathcal{O}_{BB}$	$\mathcal{O}_{T}$	$\mathcal{O}_{H}$	$\mathcal{O}_{LL}^{(3)l}$	$\mathcal{O}_{L}^{(3)l}$	$\mathcal{O}_{L}^{l}$	$\mathcal{O}_{R}^{e}$	$\mathcal{O}_{6}$	$\mathcal{O}_{3W}$
ILC250	1.30	0.697	0.384	1.29	0.401	9.62	2.92	1.83	1.29	0.0309	0.469
$+\sigma(W^+W^-)$	1.30	2.17	0.386	4.08	0.468	9.63	6.78	6.11	4.08	0.0389	0.523
$+\sigma(Zh)$	1.75	2.21	0.493	4.16	0.897	9.78	6.89	6.21	4.16	0.0895	0.531
$+\sigma(Zhh)$	1.95	3.22	0.498	6.19	1.28	12.2	8.83	8.45	6.20	0.428	0.644
$+\sigma(\nu\nu h)$ = ILC500	2.01	3.29	0.498	6.34	1.97	12.3	8.90	8.60	6.36	0.428	0.647

After adding the four channels in ILC 500

(1) Higgs cubic coupling (O6) can be probed at tree level
(2) Previous 6 operators contributing to EWPOs can be greatly enhanced
(3) ILC 250 behave poorer than CEPC and FCC-ee but ILC 500 performs better.
(4) O3W operator is still poorly constrained due to the noninterference at massless limit, angular analysis needs to be added.

Application to Composite Higgs Models

- Scenario: a light composite Higgs associated with strong dynamics at a higher scale
- SILH parametrization

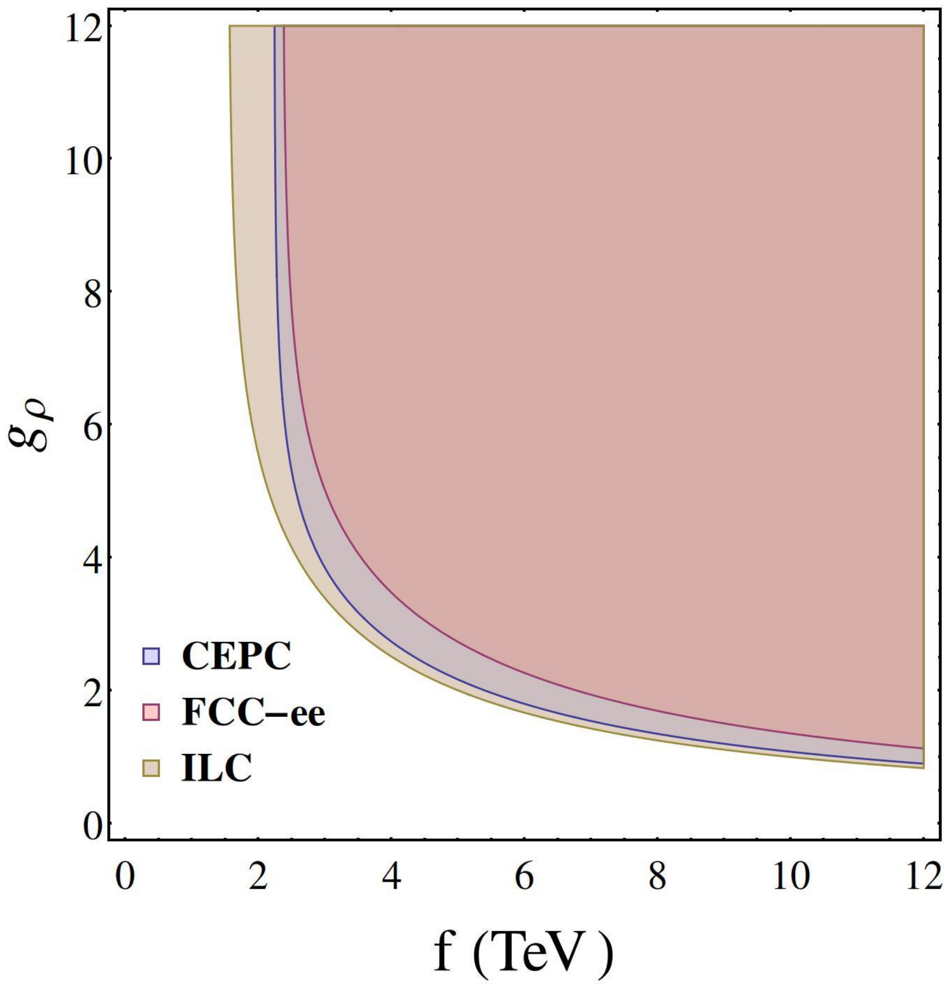
$$\mathcal{L}_{\rm SILH} = \frac{\tilde{c}_H}{f^2}\mathcal{O}_H + \frac{\tilde{c}_T}{f^2}\mathcal{O}_T - \frac{\tilde{c}_6\lambda}{f^2}\mathcal{O}_6 + \frac{\tilde{c}_W}{m_\rho^2}\mathcal{O}_W + \frac{\tilde{c}_B}{m_\rho^2}\mathcal{O}_B + \frac{\tilde{c}_{HW}}{16\pi^2 f^2}\mathcal{O}_{HW} + \frac{\tilde{c}_{HB}}{16\pi^2 f^2}\mathcal{O}_{HB} + \frac{\tilde{c}_\gamma g'^2}{16\pi^2 f^2 g_\rho^2}\mathcal{O}_{BB} + \frac{3! g^2 \tilde{c}_{3W}}{16\pi^2 m_\rho^2}\mathcal{O}_{3W}$$

$$\mathcal{L}_{\rm SILH} \supset \frac{c_H}{\Lambda^2}\mathcal{O}_H + \frac{c_T}{\Lambda^2}\mathcal{O}_T + \frac{c_L^{(3)l}}{\Lambda^2}\mathcal{O}_L^{(3)l} + \frac{c_L^l}{\Lambda^2}\mathcal{O}_L^l + \frac{c_R^e}{\Lambda^2}\mathcal{O}_R^e$$

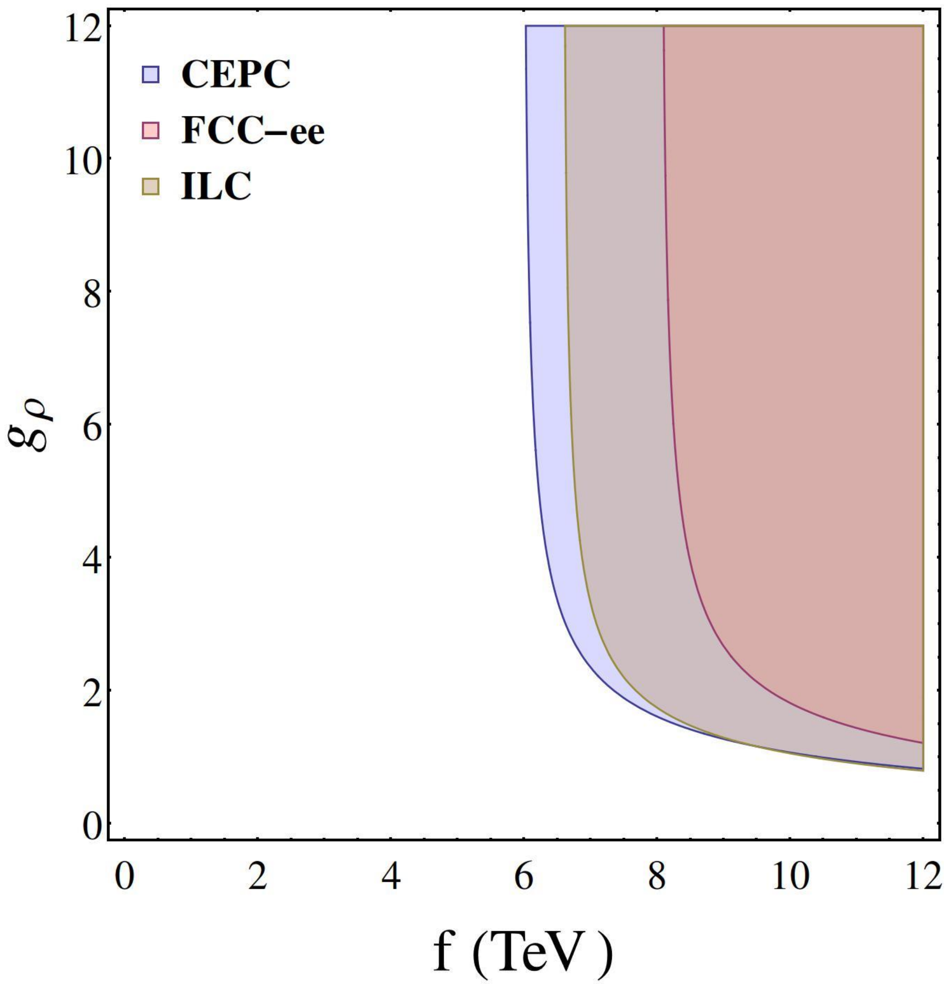
- Holographic Composite Higgs Model $\quad \tilde{c}_T = 0 \quad \tilde{c}_H = 1 \quad \tilde{c}_W = \tilde{c}_B \approx 1.0$
- Littlest Higgs Model $\quad \tilde{c}_T = -\frac{1}{16} \quad \tilde{c}_H = \frac{1}{4} \quad \tilde{c}_W = \frac{1}{2} \quad \tilde{c}_B = 0$

- After plugging in c_i, there remain only two free parameters, g_ρ and m_ρ ($m_\rho = g_\rho f$)
- Using all observables except Z pole observables involving hadronic sector.

Holographic Composite higgs model



Littlest higgs model



Summary

- We make both individual and marginalized fitting in three future lepton colliders, giving optimistic and conservative results.
- In the optimistic case, $\{\mathcal{O}_{WB}, \mathcal{O}_T, \mathcal{O}_{LL}^{(3)l}, \mathcal{O}_L^{(3)l}, \mathcal{O}_L^l, \mathcal{O}_R^e\}$ can be probed to dozens of TeV while $\{\mathcal{O}_{WW}, \mathcal{O}_{BB}, \mathcal{O}_H, \mathcal{O}_{3W}\}$ can only reach up to TeV or several TeVs at three colliders.
- In the conservative case operators $\{\mathcal{O}_{WB}, \mathcal{O}_T, \mathcal{O}_{LL}^{(3)l}, \mathcal{O}_L^{(3)l}, \mathcal{O}_L^l, \mathcal{O}_R^e\}$ can be probed to ~O(1-10)TeV while $\{\mathcal{O}_{WW}, \mathcal{O}_{BB}, \mathcal{O}_H, \mathcal{O}_{3W}\}$ can only be probed to sub-TeV.
- ILC 500 GeV is high beneficial and can compensate the relatively lower precision of EWPOs at ILC 250.
- As an application, fitting in SILH scenario can probe the breaking scale up to several TeV.

Thank you!

Backup

Degeneracy for EWPOs

$$N_\nu \quad A_b \quad R_b \quad A_{FB}^b \quad A_{FB}^\mu \quad \sin^2\theta_{\rm eff}^{\rm lep} \quad R_\mu \quad R_\tau$$

$$\frac{\Delta g_L^i}{g_L^i} - \frac{\Delta g_R^i}{g_R^i} \qquad \frac{\Delta g_L^\nu}{g_L^\nu} - \frac{\Delta g_R^l}{g_R^l} \qquad \sim 2\delta\theta_w - \delta Z_X + \cdots$$