



Game of EFT – a song of Higgs and EW

Jiayin Gu (顾嘉荫)

JGU Mainz

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to appear J. de Blas, G. Durieux, C. Grojean, JG, A. Paul

EFT @ CEPC

- ▶ Higgs is the primary goal!
- ▶ Also very precise EW measurements (**Z-pole, WW threshold, higher energies**).
- ▶ **EFT is good for CEPC.**
 - ▶ A systematic parameterization of BSM contributions to Higgs and EW couplings.
 - ▶ If $v \ll \Lambda$, leading order contributions are parametrized by D6 operators.
- ▶ **CEPC is also good for EFT!**
 - ▶ High precision, (relatively) low energy \Rightarrow ideal for EFT studies!
 - ▶ LHC is ideal for discovery, but

EFT global fit

- ▶ Assuming baryon and lepton numbers are conserved,

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4} \mathcal{O}_j^{(8)} + \dots \quad (1)$$

- ▶ Write down all D6 operators, **eliminate redundant ones** via field redefinition, integration by parts, equations of motion...
 - ▶ different choices of which operators to eliminate \Rightarrow different basis
- ▶ **59 operators (76 parameters)** for 1 generation, or **2499 parameters** for 3 generations. [arXiv:1008.4884] Grzadkowski, Iskrzyński, Misiak, Rosiek, [arXiv:1312.2014] Alonso, Jenkins, Manohar, Trott
 - ▶ **Don't worry!** Only a small subset is relevant for our study.
- ▶ Higgs + aTGC + EW = **28 parameters** in our framework
 - ▶ CP-even only, no fermion dipole interactions,
 - ▶ only consider the diagonal Yukawa couplings of $t, c, b, \tau, \mu,$
 - ▶ impose $U(2)$ on 1st and 2nd generation quarks, exclude $Z\bar{t}t$ and Wtb couplings.
 - ▶ We don't consider flavor violating Higgs or Z decays, which can be studied separately.

You can't really separate Higgs from the rest of the SM!

$$\begin{aligned} \mathcal{O}_{H\ell} &= iH^\dagger \overleftrightarrow{D}_\mu H \bar{\ell}_L \gamma^\mu \ell_L, \\ \mathcal{O}'_{H\ell} &= iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{\ell}_L \sigma^a \gamma^\mu \ell_L, \\ \mathcal{O}_{He} &= iH^\dagger \overleftrightarrow{D}_\mu H \bar{e}_R \gamma^\mu e_R \end{aligned}$$

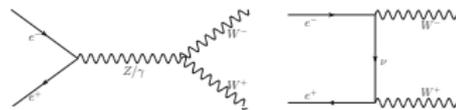
(or the ones with quarks)

- ▶ modifies gauge couplings of fermions,
- ▶ also generates $hVff$ type contact interaction.



$$\begin{aligned} \mathcal{O}_{HW} &= ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W_{\mu\nu}^a, \\ \mathcal{O}_{HB} &= ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \end{aligned}$$

- ▶ generate aTGCs $\delta g_{1,Z}$ and $\delta \kappa_\gamma$,
- ▶ also generates HVV anomalous couplings such as $hZ_\mu \partial_\nu Z^{\mu\nu}$.



You also have to measure the Higgs!

- ▶ Some operators can only be probed with the **Higgs particle**.
- ▶ $|H|^2 W_{\mu\nu} W^{\mu\nu}$ and $|H|^2 B_{\mu\nu} B^{\mu\nu}$
 - ▶ $H \rightarrow v/\sqrt{2}$, corrections to gauge couplings?
 - ▶ **Can be absorbed by field redefinition!** This applies to any operators in the form $|H|^2 \mathcal{O}_{\text{SM}}$.

$$\begin{aligned}
 c_{\text{SM}} \mathcal{O}_{\text{SM}} \quad \text{vs.} \quad & c_{\text{SM}} \mathcal{O}_{\text{SM}} + \frac{c}{\Lambda^2} |H|^2 \mathcal{O}_{\text{SM}} \\
 & = (c_{\text{SM}} + \frac{c v^2}{2 \Lambda^2}) \mathcal{O}_{\text{SM}} + \text{terms with } h \\
 & = c'_{\text{SM}} \mathcal{O}_{\text{SM}} + \text{terms with } h \quad (2)
 \end{aligned}$$

- ▶ probed by measurements of the $h\gamma\gamma$ and $hZ\gamma$ couplings, or the hWW and hZZ anomalous couplings.
- ▶ or Higgs in the loop (different story...)
- ▶ Yukawa couplings, Higgs self couplings, ...
- ▶ (Higgs measurements already thoroughly discussed, will now discuss EW measurements...)

EW measurements

- ▶ Z-pole
 - ▶ $\sim 10^{11} - 10^{12}$ Zs at CEPC/FCC-ee.
 - ▶ How many Zs do we really need?
 - ▶ “EW Operators”: more is always better (but systematics will dominate at some point).
 - ▶ “Higgs Operators”: need the EW operators to be constrained sufficiently well.
- ▶ $e^+e^- \rightarrow WW$, threshold scan, or “free data” at 240 GeV and above.
 - ▶ **W mass**
 - ▶ from threshold scan, or from W reconstruction at higher energies
 - ▶ **W width**
 - ▶ direct measurement with threshold scan
 - ▶ can be derived from BR measurements, assuming W has no exotic decay.
 - ▶ **W branching ratios**
 - ▶ anomalous Triple Gauge Couplings (**aTGCs**)
 - ▶ Not well measured at threshold (dominated by the t -channel diagram).
 - ▶ Is the TGC dominance assumption valid?
 - ▶ **Optimal observables** can be used to extract the maximum amount of information in the WW differential distributions. (See e.g. Z.Phys. C62 (1994) 397-412 Diehl & Nachtmann)

Parametrization of Higgs couplings and aTGCs

- ▶ Write down all D6 operators and use e.o.m., field redefinitions, *etc.* to remove the redundant degrees of freedom.
 - ▶ Warsaw, SILH, SILH',

- ▶ Higgs basis: Since we need to calculate things in the broken electroweak phase, why don't we define the basis in the broken phase as well? (A. Falkowski, LHCHSWG-INT-2015-001) (see also "BSM Primary Effects" [arXiv:1405.0181] Gupta, Pomarol, Riva)
 - ▶ Full SM gauge symmetry \Rightarrow not all couplings are independent. *e.g.* Couplings of h to W can be written in terms of couplings of h to Z and γ .
 - ▶ Higgs couplings + aTGCs = 12 parameters

$$\delta c_Z, c_{ZZ}, c_{Z\Box}, c_{\gamma\gamma}, c_{Z\gamma}, c_{gg}, \delta y_t, \delta y_c, \delta y_b, \delta y_\tau, \delta y_\mu, \lambda_Z.$$
 - ▶ $\delta c_Z \leftrightarrow h Z^\mu Z_\mu, c_{ZZ} \leftrightarrow h Z^{\mu\nu} Z_{\mu\nu}, c_{Z\Box} \leftrightarrow h Z_\mu \partial_\nu Z^{\mu\nu}$
 - ▶ **advantage: can be sort of interpreted as "Higgs couplings"**

- ▶ Why don't we take this idea further and just define some "effective couplings"? (Peskin *et al.*)

How to make your banana look like an apple



- ▶ EFT fit results projected on Effective Higgs couplings ([arXiv:1708.08912], [arXiv:1708.09079], Peskin *et al.*)
 - ▶ $g(hZZ)$, $g(hWW)$ are defined at the scale of the relevant Higgs decay.
 $g(hZZ) \propto \sqrt{\Gamma(h \rightarrow ZZ)}$, $g(hWW) \propto \sqrt{\Gamma(h \rightarrow WW)}$.
 - ▶ Not necessarily a basis, but can be made into a basis. (Maybe call it the “Peskin basis”?)
 - ▶ **It looks like κ but it is not κ !** (both intuitive and confusing....)
- ▶ Used in ILC and FCC-ee official documents.
- ▶ Also useful for comparing results in different basis...

Parametrization in Z -pole and W mass/width/BR

- ▶ To make our lives easier, we could (using field redefinitions, e.o.m., ...)
 - ▶ parameterize all corrections at Z -pole in terms of modifications of Zff couplings (and same for W);
 - ▶ impose the relation $\delta g^{hZf} = \delta g^{Zf}$, $\delta g^{hWf} = \delta g^{Wf}$.



- ▶ Can use “couplings” instead of “operators” to parameterize EW corrections (52 real parameters without flavor assumption)

$$\delta m_{(W)}, \quad \delta g_L^{Wf}, \quad \delta g_L^{Ze}, \quad \delta g_R^{Ze}, \quad \delta g_L^{Zu}, \quad \delta g_R^{Zu}, \quad \delta g_L^{Zd}, \quad \delta g_R^{Zd}, \quad \delta g_R^{Wq},$$

$$\delta g_L^{Z\nu} = \delta g_L^{Ze} + \delta g_L^{Wf}, \quad \delta g_L^{Wq} = \delta g_L^{Zu} V - V \delta g_L^{Zd}.$$

- ▶ 52 real parameters without flavor assumption, 16 (diagonal ones) are included.

observables

- ▶ A complete list of (pseudo-)observables, preferably without assumptions on flavor universality. (m_Z , G_F and α are used as inputs.)
 - ▶ Γ_Z , σ_{had} ,
 - ▶ R_e , R_μ , R_τ , R_b , R_c ,
 - ▶ $A_{\text{FB}}^{0,e}$, $A_{\text{FB}}^{0,\mu}$, $A_{\text{FB}}^{0,\tau}$, $A_{\text{FB}}^{0,b}$, $A_{\text{FB}}^{0,c}$,
 - ▶ A_e and A_τ from A_τ polarization in $e^+e^- \rightarrow Z \rightarrow \tau^+\tau^-$.
- ▶ Do not include “derived quantities.”
 - ▶ N_ν
 - ▶ $\sin \theta_W^{\text{eff}}$
 - ▶ S & T
- ▶ W mass & width, BR
 - ▶ $e^+e^- \rightarrow WW$ (aTGCs)

A refined TGC analysis using Optimal Observables

▶ TGCs are sensitive to the differential distributions!

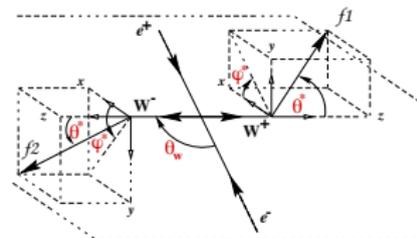
- ▶ Current method: fit to binned distributions of all angles.
- ▶ Correlations among angles are ignored.



▶ What are optimal observables?

(See e.g. Z.Phys. C62 (1994) 397-412 Diehl & Nachtmann)

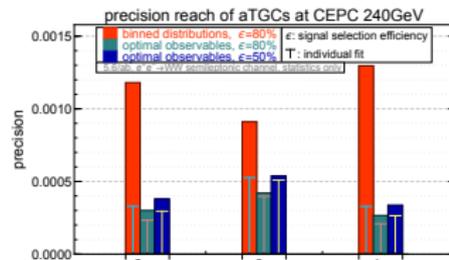
- ▶ For a given sample, there is an upper limit on the precision reach of the parameters.
- ▶ In the limit of large statistics (everything is Gaussian) and small parameters (leading order dominates), this “upper limit” can be derived analytically!



- ▶ $\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}|_{SM} + \sum_i S(\Omega)_i g_i$. The optimal observables are simply the $S(\Omega)_i$.

▶ Very idealized! How well can we actually do?

- ▶ Choose a conservative 50% efficiency to compensate the omission of systematics...



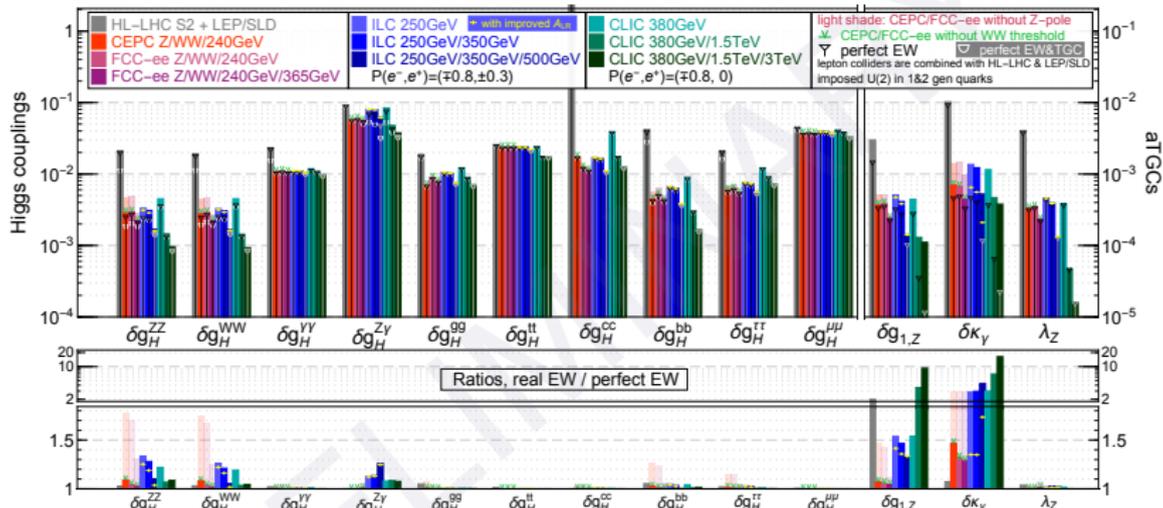
Run Scenarios

$\int \mathcal{L} dt$ [ab ⁻¹]					
unpolarized	Z-pole	WW thres.	240 GeV	350 GeV	365 GeV
CEPC	8	2.6	5.6		
FCC-ee	150	10	5	0.2	1.5
ILC			250 GeV	350 GeV	500 GeV
$P(e^-, e^+) = (-0.8, +0.3)$?		0.9	0.135	1.6
$P(e^-, e^+) = (+0.8, -0.3)$?		0.9	0.045	1.6
CLIC			380 GeV	1.5 TeV	3 TeV
$P(e^-, e^+) = (-0.8, 0)$?		0.5	2	4
$P(e^-, e^+) = (+0.8, 0)$?		0.5	0.5	1

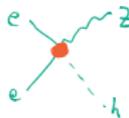
- ▶ FCC-ee has a top threshold run and also better EW programs.
- ▶ Linear colliders have the option of longitudinal beam polarizations.

“Full fit” projected on the Higgs couplings (and aTGCs)

precision reach on effective couplings from full EFT global fit



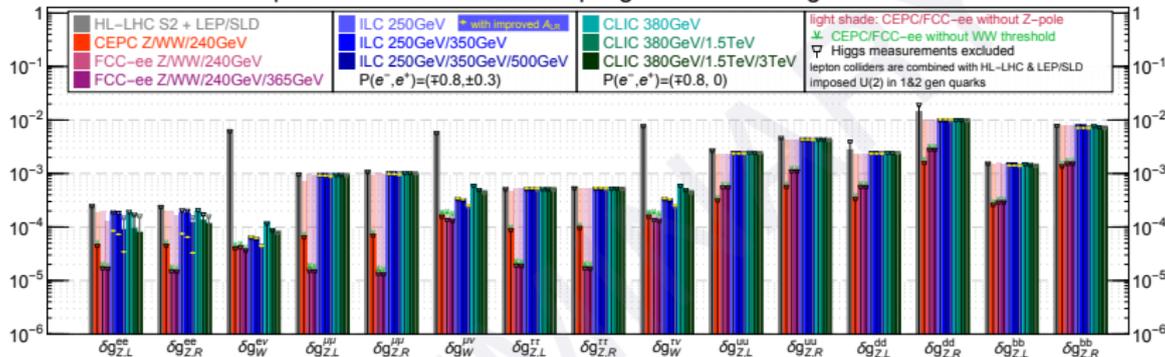
- ▶ 28-parameter fit, projected on the Higgs couplings & aTGCs.
- ▶ The hZZ and hWW couplings are not independent!
- ▶ Z-pole measurements are important for the hZZ and hWW couplings!



Reach on the $(h)Vff$ couplings

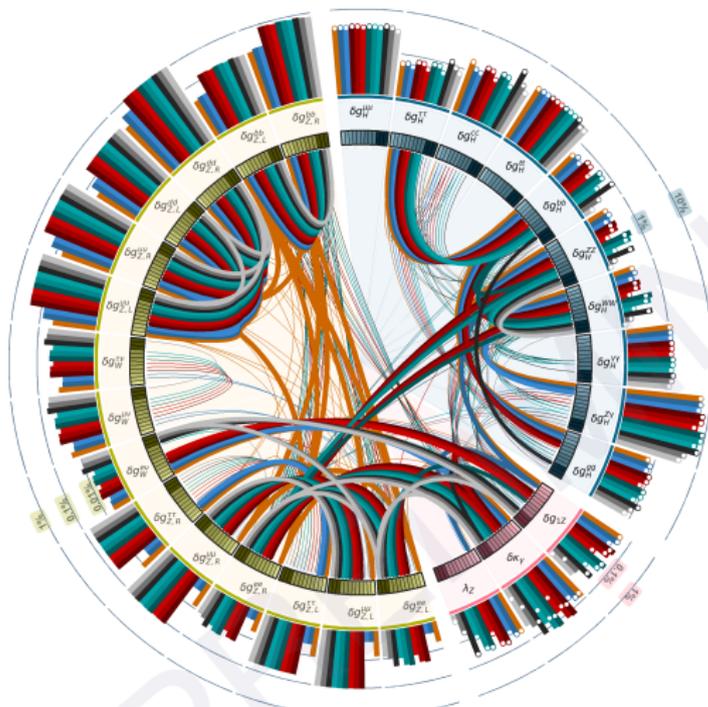


precision reach on EW couplings from full EFT global fit



- ▶ $(h)Zff$ couplings are still best probed by future Z-pole runs.
- ▶ Higgs and diboson measurements at high energy (at linear colliders) are also sensitive to the $(h)Zee$ couplings, but can not resolve them from other parameters.
- ▶ Linear colliders: Using radiative return to measure Z observables at high energy? (e.g. A_{LR})

Entering the new era of circular bar plots!



- ▶ Precision reach on the outside...
- ▶ Correlations on the inside...
- ▶ Without future Z-pole run \Rightarrow larger correlation among the hWW , hZZ couplings, aTGCs and the Zee couplings.

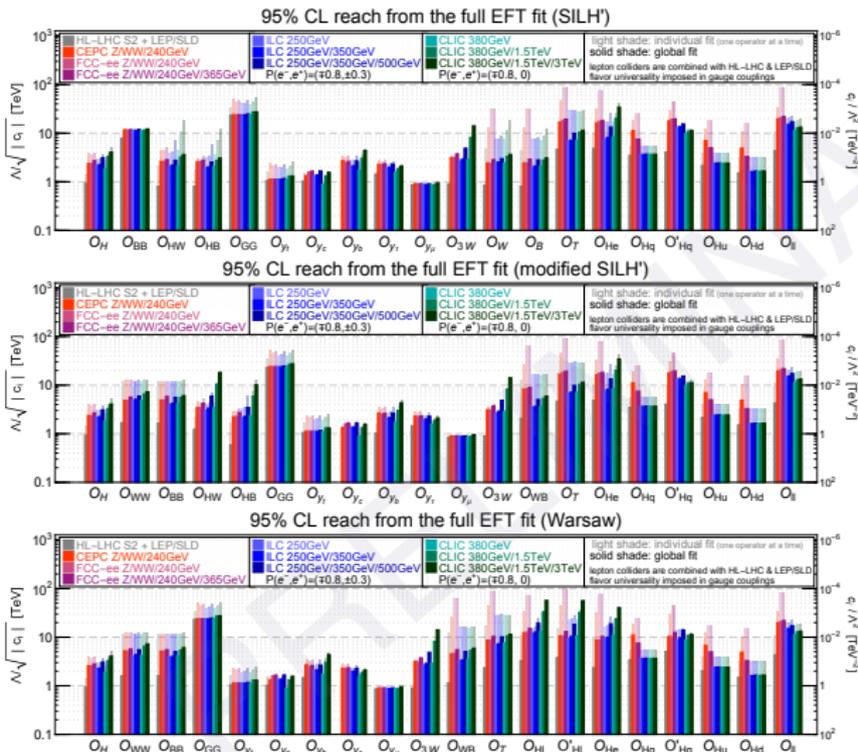


D6 operators

$\mathcal{O}_H = \frac{1}{2}(\partial_\mu H ^2)^2$	$\mathcal{O}_{GG} = g_s^2 H ^2 G_{\mu\nu}^A G^{A,\mu\nu}$
$\mathcal{O}_{WW} = g^2 H ^2 W_{\mu\nu}^a W^{a,\mu\nu}$	$\mathcal{O}_{y_u} = y_u H ^2 \bar{q}_L H u_R + \text{h.c.} \quad (u \rightarrow t, c)$
$\mathcal{O}_{BB} = g'^2 H ^2 B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{y_d} = y_d H ^2 \bar{q}_L H d_R + \text{h.c.} \quad (d \rightarrow b)$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W_{\mu\nu}^a$	$\mathcal{O}_{y_e} = y_e H ^2 \bar{l}_L H e_R + \text{h.c.} \quad (e \rightarrow \tau, \mu)$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W_{\mu\nu}^a W_{\nu\rho}^b W^{c\rho\mu}$
$\mathcal{O}_W = \frac{ig}{2} (H^\dagger \sigma^a \overleftrightarrow{D}_\mu H) D^\nu W_{\mu\nu}^a$	$\mathcal{O}_B = \frac{ig'}{2} (H^\dagger \overleftrightarrow{D}_\mu H) \partial^\nu B_{\mu\nu}$
$\mathcal{O}_{WB} = gg' H^\dagger \sigma^a H W_{\mu\nu}^a B^{\mu\nu}$	$\mathcal{O}_{H\ell} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{\ell}_L \gamma^\mu \ell_L$
$\mathcal{O}_T = \frac{1}{2} (H^\dagger \overleftrightarrow{D}_\mu H)^2$	$\mathcal{O}'_{H\ell} = iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{\ell}_L \sigma^a \gamma^\mu \ell_L$
$\mathcal{O}_{\ell\ell} = (\bar{\ell}_L \gamma^\mu \ell_L)(\bar{\ell}_L \gamma_\mu \ell_L)$	$\mathcal{O}_{H\ell} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{e}_R \gamma^\mu e_R$
$\mathcal{O}_{Hq} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{q}_L \gamma^\mu q_L$	$\mathcal{O}_{Hu} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{u}_R \gamma^\mu u_R$
$\mathcal{O}'_{Hq} = iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{q}_L \sigma^a \gamma^\mu q_L$	$\mathcal{O}_{Hd} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{d}_R \gamma^\mu d_R$

- ▶ SILH' basis (eliminate \mathcal{O}_{WW} , \mathcal{O}_{WB} , $\mathcal{O}_{H\ell}$ and $\mathcal{O}'_{H\ell}$)
- ▶ Modified-SILH' basis (eliminate \mathcal{O}_W , \mathcal{O}_B , $\mathcal{O}_{H\ell}$ and $\mathcal{O}'_{H\ell}$)
- ▶ Warsaw basis (eliminate \mathcal{O}_W , \mathcal{O}_B , \mathcal{O}_{HW} and \mathcal{O}_{HB})

Pick your favorite basis!



- ▶ Modified-SILH' is most convenient in the limit of perfect EW (Z-pole, W mass/width/BR).
- ▶ Now we can choose any of them...

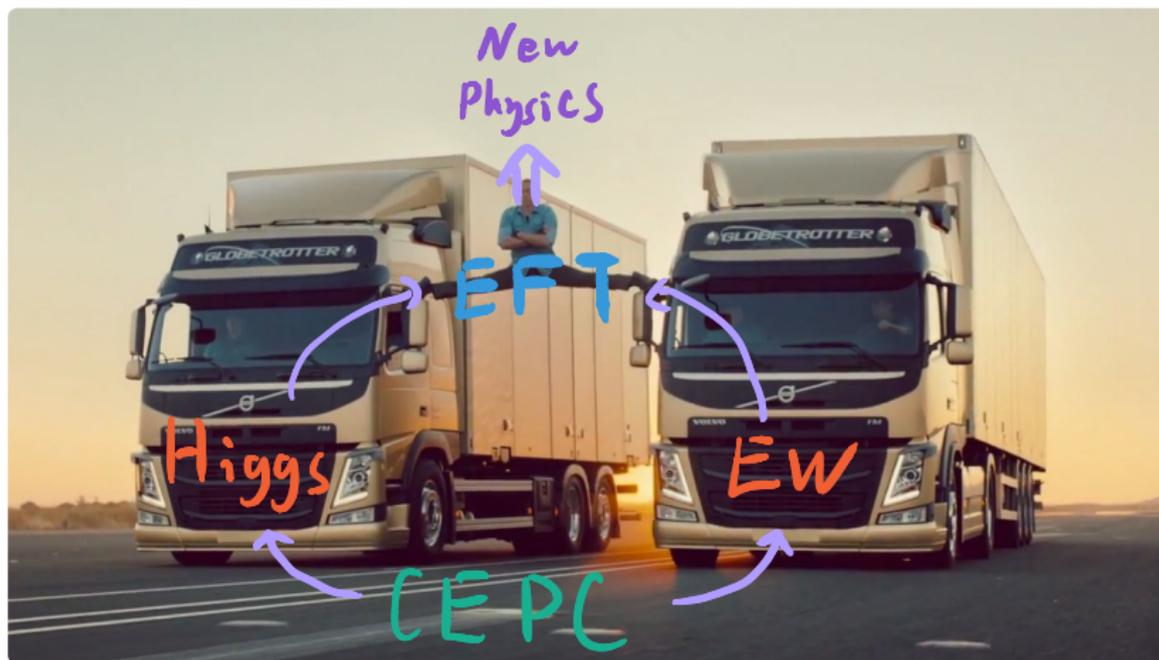
Future plans

- ▶ Complete the list of EW observables (already done by Zhijun).
- ▶ **We need a realistic $e^+e^- \rightarrow WW$ (TGC) analysis!**
 - ▶ 3 TGC \Rightarrow full EFT parameterization.
 - ▶ Use optimal observables to extract information in the angular distribution.
- ▶ A more proper Z-pole fit (parametric uncertainties, theory uncertainties)
- ▶ EFT loops contributions to Z-pole observables?

Conclusion



Conclusion



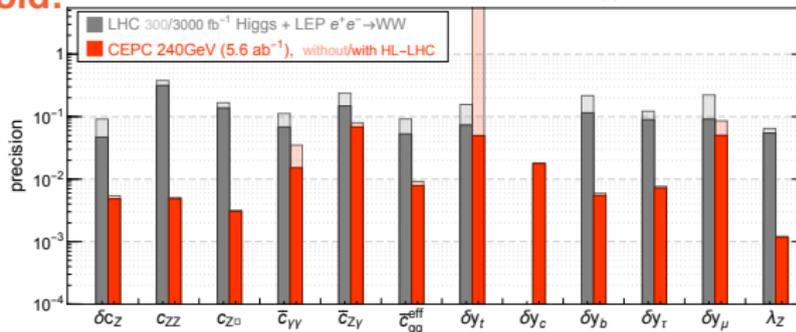
Note: Obviously EFT is not the only tool to probe new physics at CEPC.

backup slides

CEPC: old vs. new (Higgs basis)

old:

precision reach of the 12-parameter EFT fit (Higgs basis)

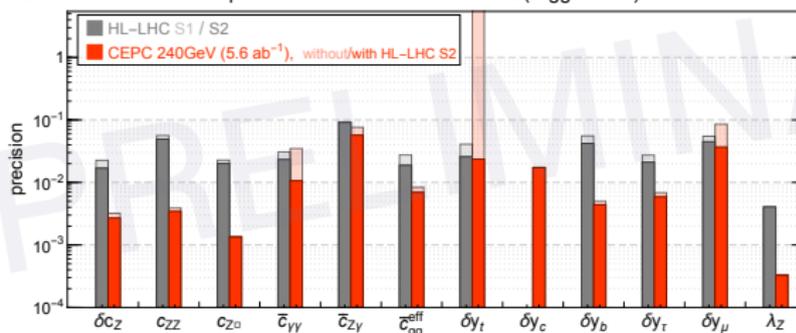


▶ Full fit: only the Higgs parameters are shown.

▶ HL-LHC: ATLAS and CMS are combined. (The correlation between ATLAS/CMS are not provided by the WG.)

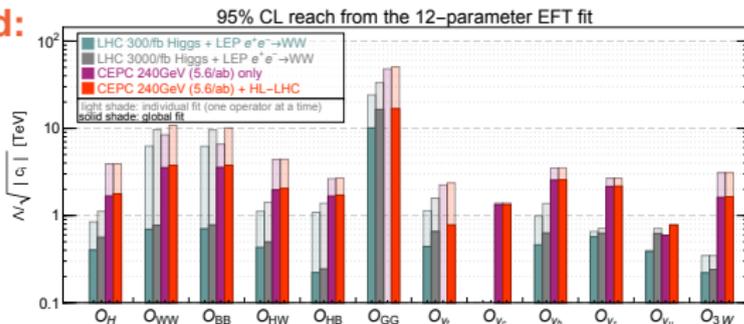
new:

precision reach of the full EFT fit (Higgs basis)



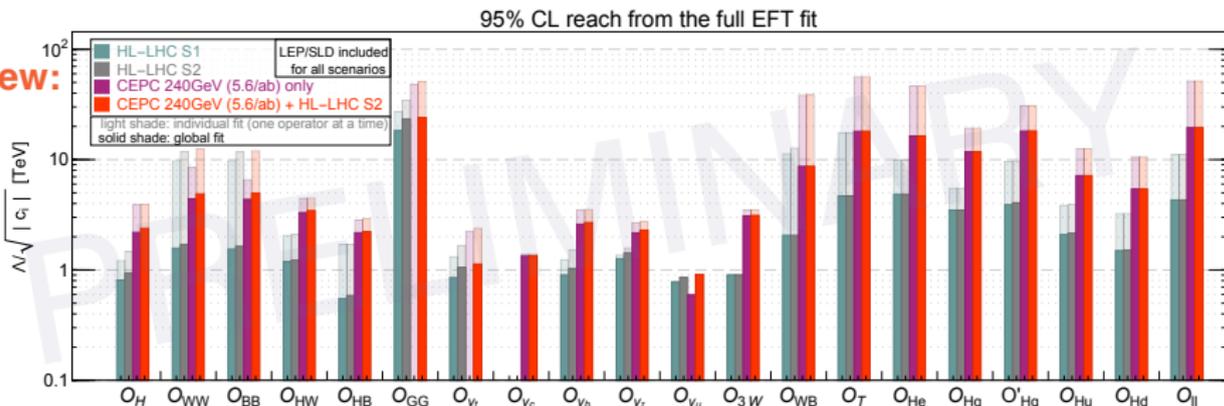
CEPC: old vs. new (modified-SILH' basis)

old:



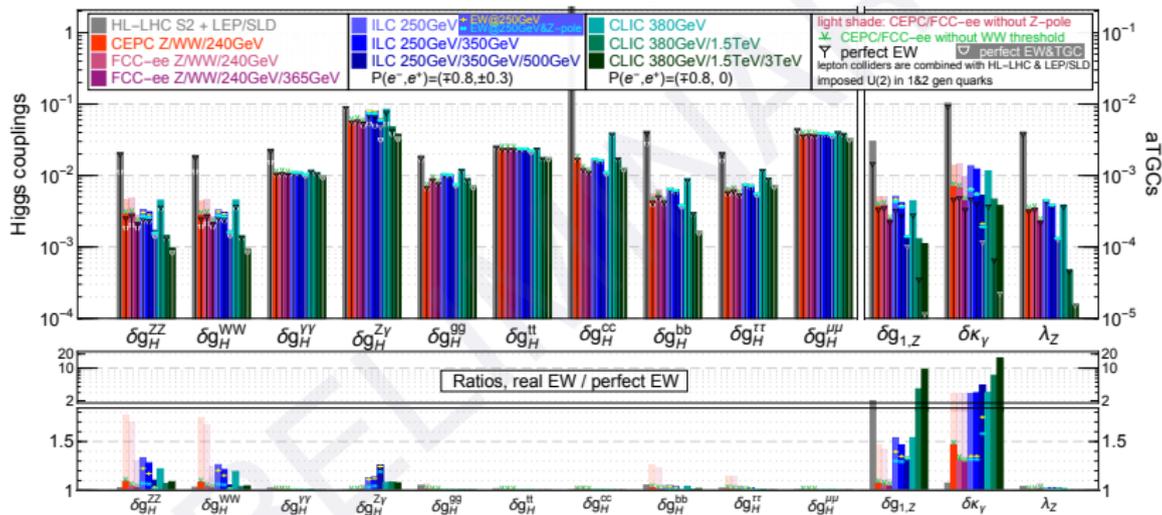
- ▶ Flavor universality imposed on gauge couplings for now (can be removed later).

new:



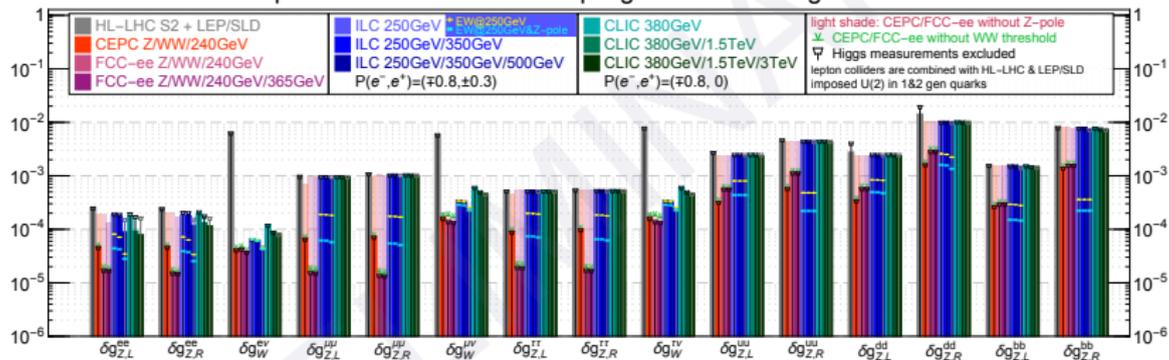
ILC with Giga Z ... (preliminary!)

precision reach on effective couplings from full EFT global fit

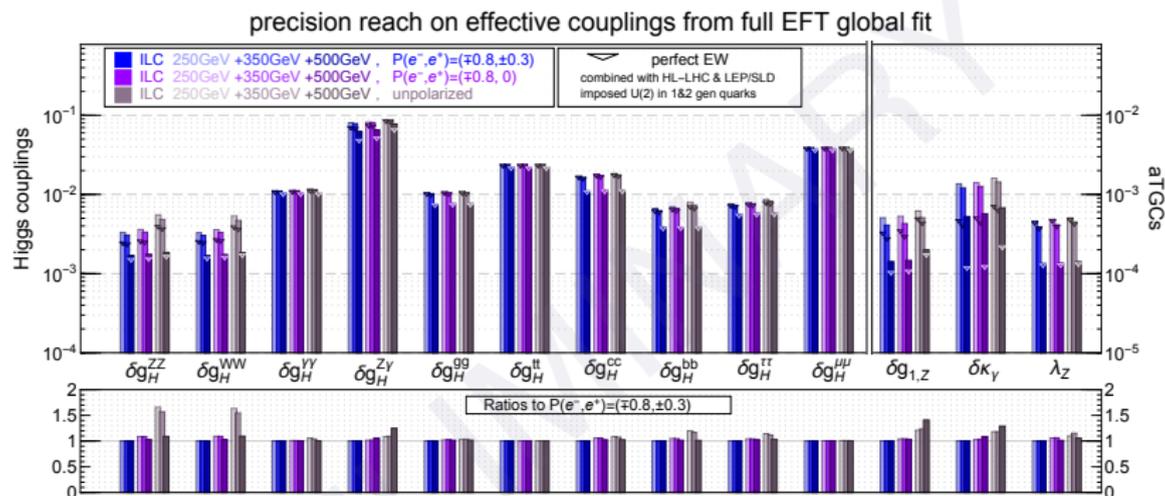


LC with Giga Z ... (preliminary!)

precision reach on EW couplings from full EFT global fit



ILC polarization



- ▶ Polarized beams: assuming the luminosity is equally divided into $(-, +)$ and $(+, -)$ polarizations.
- ▶ Beam polarizations can probe different combinations of EFT parameters in $e^+ e^- \rightarrow hZ$ (and so can runs at different energies).