Game of EFT – a song of Higgs and EW

(Interplay of EW and Higgs measurements at future lepton colliders)

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arXiv:1907.04311 J. de Blas, G. Durieux, C. Grojean, JG, A. Paul

EFT (effective field theory) @ Future lepton colliders

- Higgs is the primary goal!
- Also very precise EW measurements (Z-pole, WW threshold, higher energies).
- **EFT is good for future lepton colliders.**
  - A systematic parameterization of BSM contributions to Higgs and EW couplings.
  - If $v \ll \Lambda$, leading order contributions are parametrized by D6 operators.
- **Future lepton colliders are also good for EFT!**
  - High precision, relatively low energy ($E \ll \Lambda$) $\Rightarrow$ ideal for EFT studies!
  - LHC is ideal for discovery, but ....
- **EFT certainly does not cover everything!**
  - What if we find light new particles? (I'll throw my papers in the trash can!)
  - Higgs or Z Exotic decays... (See other talks in this workshop.)

EFT global fit

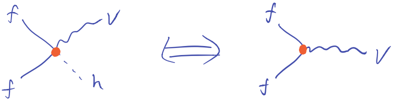
- Assuming baryon and lepton numbers are conserved,

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

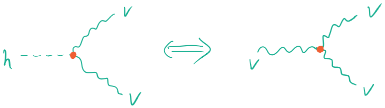
- Write down all D6 operators, **eliminate redundant ones** via field redefinition, integration by parts, equations of motion...
  - different choices of which operators to eliminate $\Rightarrow$ different basis
- **59** operators (**76** parameters) for 1 generation, or **2499** parameters for 3 generations. [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, τ, μ,
  - impose $U(2)$ on 1st and 2nd generation quarks, exclude $Zt\bar{t}$ 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!

- $\mathcal{O}_{H\ell} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{\ell}_L \gamma^\mu \ell_L$,
  $\mathcal{O}'_{H\ell} = iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{\ell}_L \sigma^a \gamma^\mu \ell_L$,
  $\mathcal{O}_{He} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{e}_R \gamma^\mu e_R$
  (or the ones with quarks)
  - modifies gauge couplings of fermions,
  - also generates $hVff$ type contact interaction.



- $\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$,
  $\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$
  - generate aTGCs $\delta g_{1,Z}$ and $\delta\kappa_\gamma$,
  - also generates HVV anomalous couplings such as $hZ_\mu \partial_\nu Z^{\mu\nu}$.



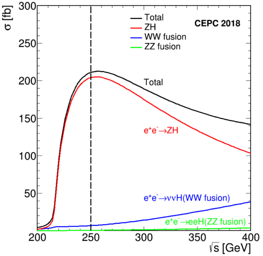
You also have to measure the Higgs!

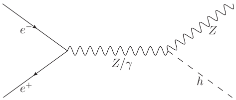
- Some operators can only be probed with the **Higgs particle**.
- $|H|^2 W_{\mu\nu} W^{\mu\nu}$ and $|H|^2 B_{\mu\nu} B^{\mu\nu}$
  - $H \to v/\sqrt{2}$, corrections to gauge couplings?
  - **Can be absorbed by field redefinition!** This applies to any operators in the form $|H|^2 \mathcal{O}_{\rm SM}$.

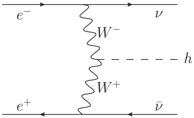
$$c_{\rm SM}\mathcal{O}_{\rm SM} \quad vs. \quad c_{\rm SM}\mathcal{O}_{\rm SM} + \frac{c}{\Lambda^2}|H|^2\mathcal{O}_{\rm SM}$$
$$= (c_{\rm SM} + \frac{c\,v^2}{2\,\Lambda^2})\mathcal{O}_{\rm SM} + \text{terms with } h$$
$$= c'_{\rm SM}\mathcal{O}_{\rm SM} + \text{terms with } h \qquad (2)$$

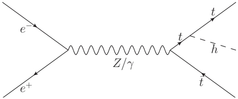
  - probed by measurements of the $h\gamma\gamma$ and $hZ\gamma$ couplings, or the hWW and hZZ anomalous couplings.
  - or Higgs in the loop (different story...)
- Yukawa couplings, Higgs self couplings, ...

Higgs measurements





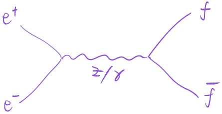




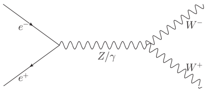
- $e^+e^- \to hZ$, cross section maximized at around 250 GeV.
- $e^+e^- \to \nu\bar{\nu}h$, cross section increases with energy.
- $e^+e^- \to t\bar{t}h$, can be measured with $\sqrt{s} \gtrsim 500$ GeV.
- $e^+e^- \to Zhh$ and $e^+e^- \to \nu\bar{\nu}hh$ (triple Higgs coupling, not included here).

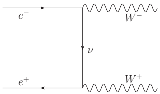
EW measurements

- ***Z*-pole**
  - $\sim 10^{11} - 10^{12}$ *Z*s at CEPC/FCC-ee.
  - How many *Z*s do we really need?



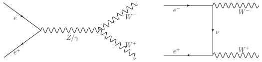
- $e^+e^- \to WW$, threshold scan, or “free data” at 240 GeV and above.
  - *W* mass, width, branching ratios.
  - anomalous Triple Gauge Couplings (**aTGCs**)
    - 3-TGC parameterization $\Rightarrow$ full EFT parameterization
    - optimal observables...



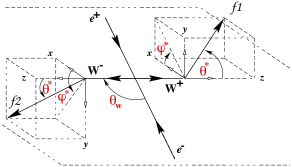


A refined TGC analysis using Optimal Observables

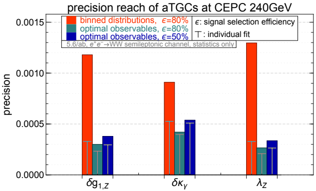
- TGCs are sensitive to the differential distributions!
  - Current method: fit to binned distributions of all angles.
  - Correlations among angles are ignored.



- 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!



- $\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}|_{\rm SM} + \sum_i S(\Omega)_i\, g_i$. 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...

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, LHCHXSWG-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

$$\delta c_Z\,,\quad c_{ZZ}\,,\quad c_{Z\Box}\,,\quad c_{\gamma\gamma}\,,\quad c_{Z\gamma}\,,\quad c_{gg}\,,\quad \delta y_t\,,\quad \delta y_c\,,\quad \delta y_b\,,\quad \delta y_\tau\,,\quad \delta y_\mu\,,\quad \lambda_Z\,.$$

  - $\delta c_Z \leftrightarrow hZ^\mu Z_\mu\,, \quad c_{ZZ} \leftrightarrow hZ^{\mu\nu} Z_{\mu\nu}\,, \quad c_{Z\Box} \leftrightarrow hZ_\mu \partial_\nu Z^{\mu\nu}$
  - **advantage: can be sort of interpreted as "Higgs couplings"**

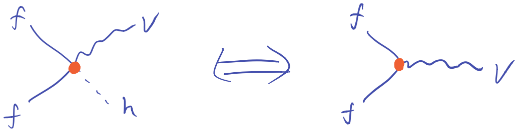
- **Let's take this further and make EFT look as much like "κ" as we can!** (Peskin *et al.*)

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 relavent Higgs decay. $g(hZZ) \propto \sqrt{\Gamma(h \to ZZ)}\,, \quad g(hWW) \propto \sqrt{\Gamma(h \to WW)}\,.$
  - 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 and the Higgs@Future Colliders WG report.
- 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 $Zf\bar{f}$ 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)

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

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

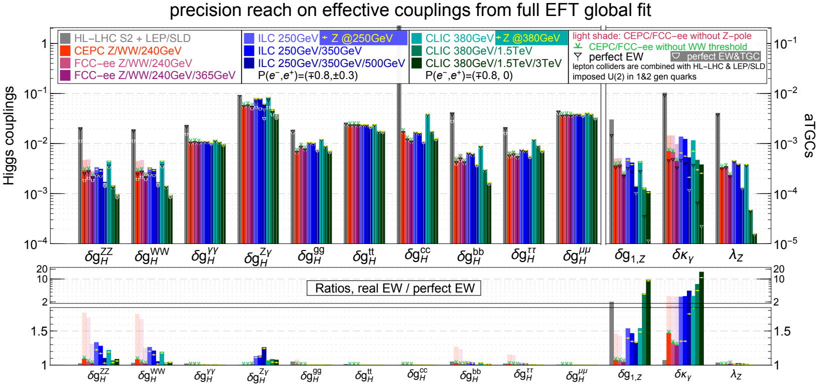
- 52 real parameters without flavor assumption, 16 (diagonal ones) are included.

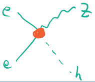
Run Scenarios

$\int \mathcal{L}dt$ [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

- Hopefully the most up-to-date scenarios?...
- Possible Giga-Z run at linear colliders?
- We also considered $P(e^-, e^+) = (\mp 0.8, 0)$ and unpolarized beams for ILC.

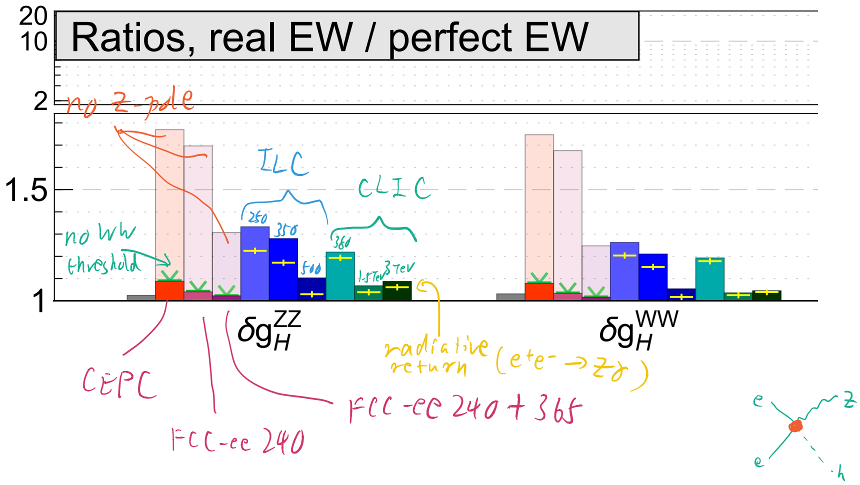
“Full fit” projected on the Higgs couplings (and aTGCs)





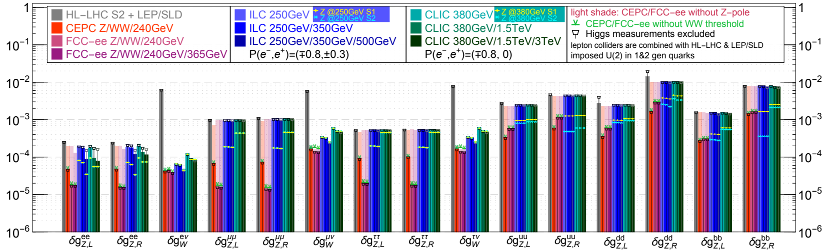
- 28-parameter fit, projected on the Higgs couplings & aTGCs.
- The *hZZ* and *hWW* couplings are not independent!
- *Z*-pole measurements are important for the *hZZ* and *hWW* couplings!

Z-pole run is also important for Higgs couplings!



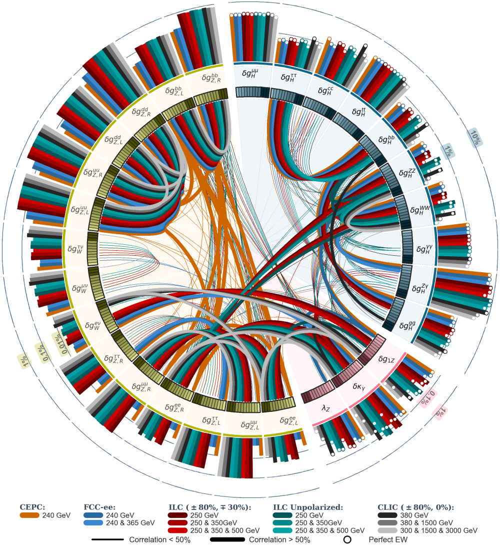
Reach on the (h)Vff couplings

precision reach on EW couplings from full EFT global fit



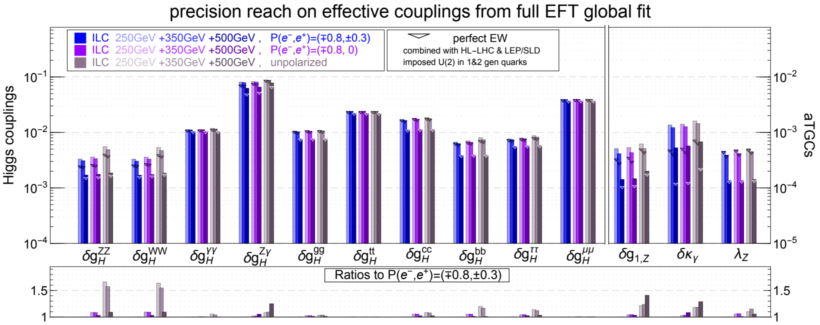
- $(h)Zff$ couplings are still best probed by future Z-pole runs.
- Higgs and diboson measurements at high energy (at linear colliders) are also sensitive to the $(h)Zee$ couplings, but can not resolve them from other parameters.
- Linear colliders: Using radiative return $(e^+e^- \to Z\gamma)$ to measure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

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.

ILC polarization



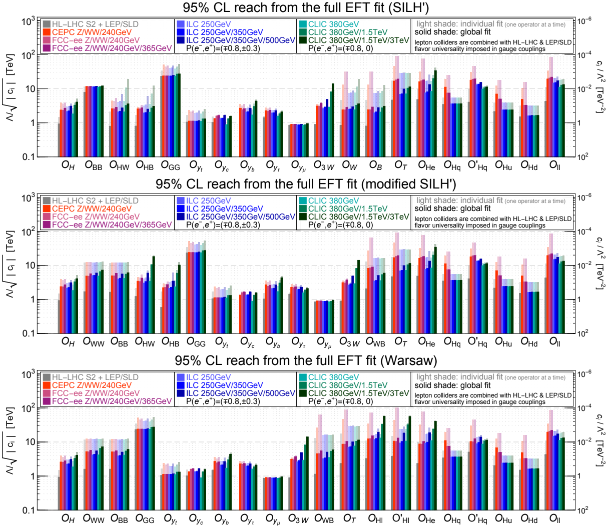
- Polarized beams: assuming the luminosity is equally divided into $(-,+)$ and $(+,-)$ polarizations.
- Beam polarizations can probe different combinations of EFT parameters in $e^+e^- \to hZ$ (and so can runs at different energies).

D6 operators

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

- 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!



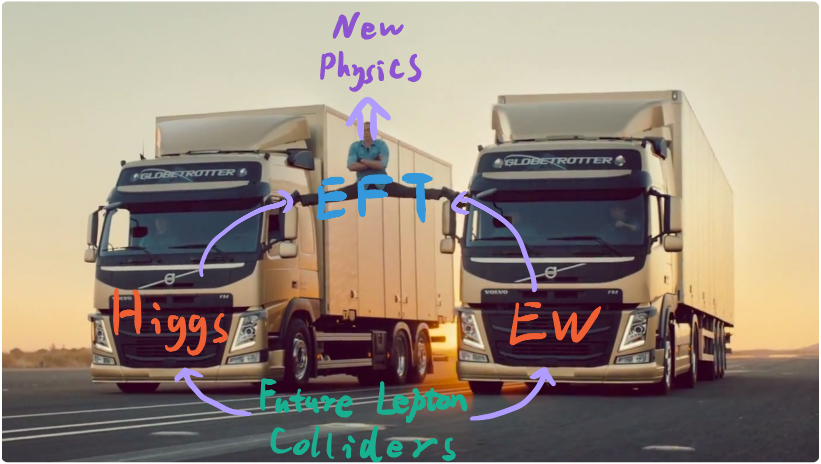
- Modified-SILH’ is most convenient in the limit of perfect EW (*Z*-pole, *W* mass/width/BR).
- Now we can choose any of them...

Conclusion

- **We need to measure the Higgs, and we also need to measure the EW gauge bosons.**
- **We need a realistic $e^+e^- \to WW$ (TGC) analysis!**
  - Going beyond theorists' naive analysis...
  - 3 TGC $\Rightarrow$ full EFT parameterization.
  - Use optimal observables to extract information in the angular distribution.
- Towards a EW + Higgs + top combined fit?
  - Top gauge & Yukawa couplings...
  - For the top loop contributions in Higgs processes, see *e.g.* [arXiv:1809.03520] G. Durieux, JG, E. Vryonidou, C. Zhang.
- Triple Higgs coupling.... (see backup slides)

Conclusion

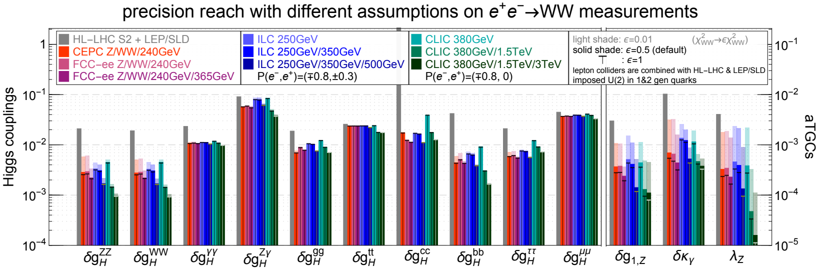
Conclusion



Note: Obviously EFT is not the only tool to probe new physics at future lepton colliders.

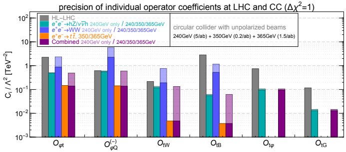
backup slides

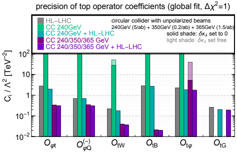
Impact of $e^+e^- \to WW$ measurements

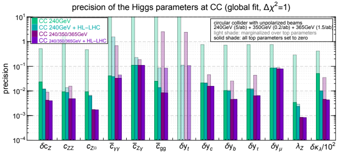


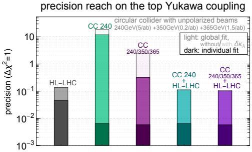
- Scaling the χ^2 of $e^+e^- \to WW$ measurements (from theorists' naive analysis).

Top operators in loops [arXiv:1809.03520] G. Durieux, JG, E. Vryonidou, C. Zhang





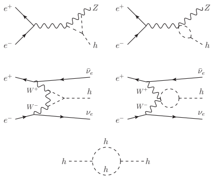


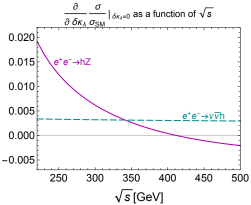


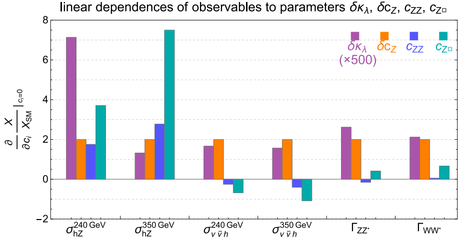
$$O_{t\varphi} = \bar{Q}t\tilde{\varphi}\,(\varphi^\dagger\varphi) + h.c.,$$
$$O^{(1)}_{\varphi Q} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{Q}\gamma^\mu Q),$$
$$O^{(3)}_{\varphi Q} = (\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{Q}\gamma^\mu\tau^I Q),$$
$$O_{\varphi t} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{t}\gamma^\mu t),$$
$$O_{tW} = (\bar{Q}\sigma^{\mu\nu}\tau^I t)\,\tilde{\varphi}W^I_{\mu\nu} + h.c.,$$
$$O_{tB} = (\bar{Q}\sigma^{\mu\nu} t)\,\tilde{\varphi}B_{\mu\nu} + h.c.,$$
$$O_{tG} = (\bar{Q}\sigma^{\mu\nu} T^A t)\,\tilde{\varphi}G^A_{\mu\nu} + h.c.\,.$$

- Higgs precision measurements have sensitivity to the top operators in the loops, but it is challenging to discriminate many parameters in a global fit.
- HL-LHC helps, but a Top threshold run is better.
- Indirect bounds on the top Yukawa coupling.

Triple Higgs coupling at circular colliders (240 & 350 GeV)

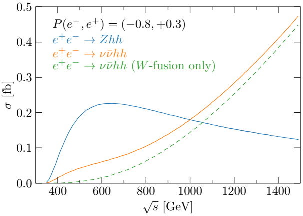


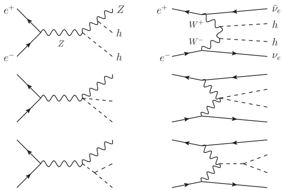




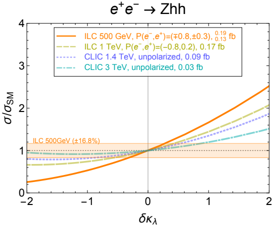
- One loop corrections to all Higgs couplings (production and decay).
- 240 GeV: hZ near threshold (more sensitive to $\delta\kappa_\lambda$)
- at 350 GeV:
  - WW fusion
  - hZ at a different energy
- $h \to WW^* / ZZ^*$ also have some discriminating power (but turned out to be not enough).

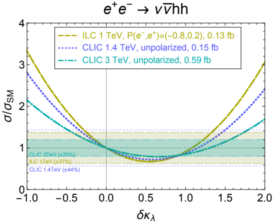
Double-Higgs measurements ($e^+e^- \to Zhh$ & $e^+e^- \to \nu\bar{\nu}hh$)

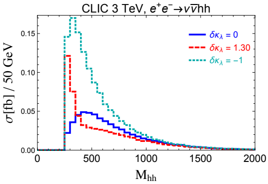




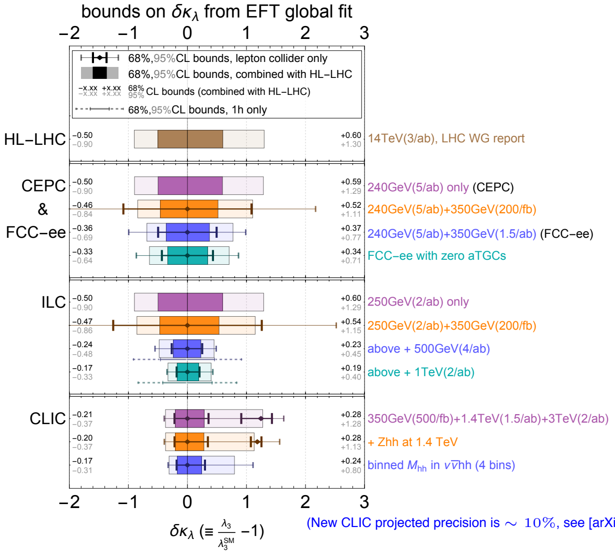
- Destructive interference in $e^+e^- \to \nu\bar{\nu}hh$! The square term is important.
- *hh* invariant mass distribution helps discriminate the "2nd solution."







A summary of the projected reaches on $\delta\kappa_\lambda$ (with updated HL-LHC projection)



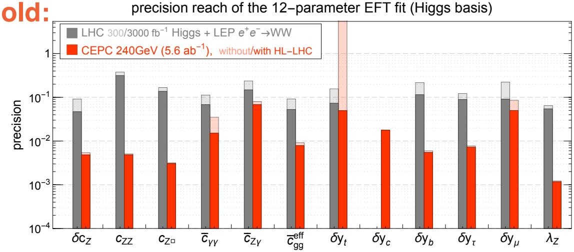
(New CLIC projected precision is $\sim 10\%$, see [arXiv:1901.05897] Roloff *et al.*)

EW observables

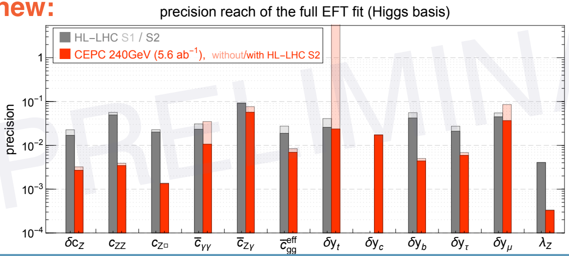
- A complete list of (pseudo-)observables, preferably without assumptions on flavor universality. (m_Z, G_F and α are used as inputs.)
  - Γ_Z, $\sigma_{\rm had}$,
  - R_e, R_μ, R_τ, R_b, R_c,
  - $A_{\rm FB}^{0,e}$, $A_{\rm FB}^{0,\mu}$, $A_{\rm FB}^{0,\tau}$, $A_{\rm FB}^{0,b}$, $A_{\rm FB}^{0,c}$,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

CEPC: old *vs.* new (Higgs basis)

old:



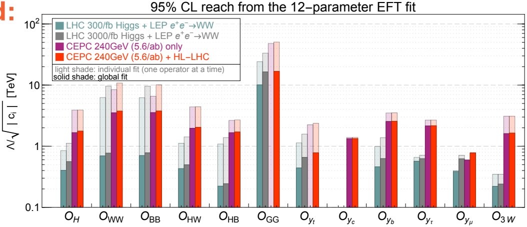
new:



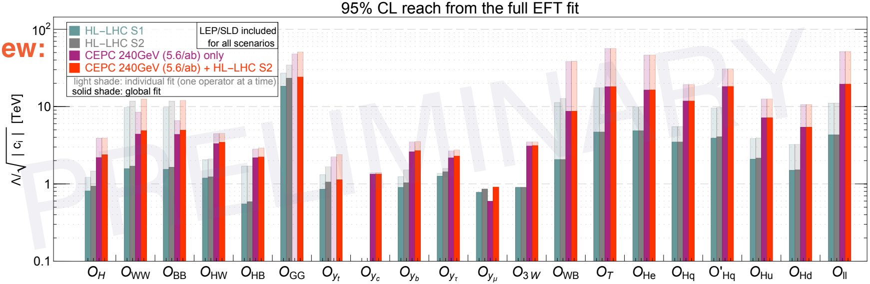
- Full fit: only the Higgs parameters are shown.
- HL-LHC: ATLAS and CMS are combined. (The correlation between ATLAS/CMS are not provided by the WG.)

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

old:

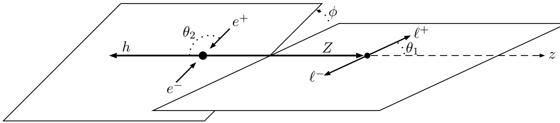


new:



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

angular observables in $e^+e^- \to hZ$



- Angular distributions in $e^+e^- \to hZ$ can provide information in addition to the rate measurement alone.
- Previous studies
  - [arXiv:1406.1361] M. Beneke, D. Boito, Y.-M. Wang
  - [arXiv:1512.06877] N. Craig, JG, Z. Liu, K. Wang
- 6 independent asymmetry observables from 3 angles

$$\mathcal{A}_{\theta_1}\ ,\ \ \mathcal{A}_{\phi}^{(1)}\ ,\ \ \mathcal{A}_{\phi}^{(2)}\ ,\ \ \mathcal{A}_{\phi}^{(3)}\ ,\ \ \mathcal{A}_{\phi}^{(4)}\ ,\ \ \mathcal{A}_{c\theta_1,c\theta_2}\ .$$

- Focusing on leptonic decays of Z (good resolution, small background, statistical uncertainty dominates).
- Optimal observables can further improve the sensitivity.