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Higgs couplings @ CLIC (and other future colliders)

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CLIC Detector and Physics Collaboration Meeting
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based on

arXiv:1905.03764 Higgs@FutureColliders WG **(with updated results to appear in v2)**

disclaimer: I am not an official member of the WG!

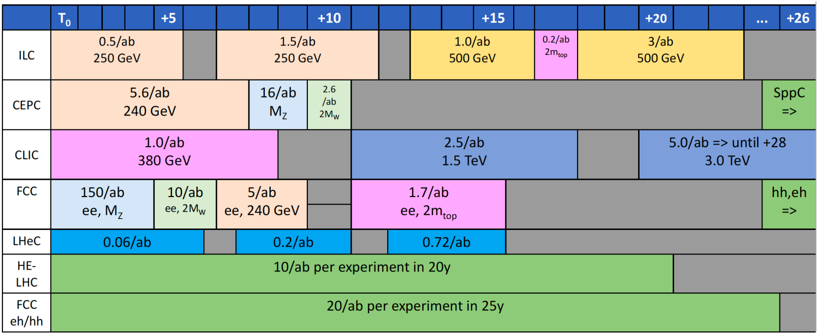
and

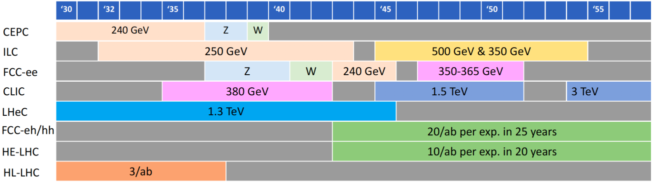
arXiv:1907.04311 J. de Blas, G. Durieux, C. Grojean, JG, A. Paul

Higgs couplings @ CLIC

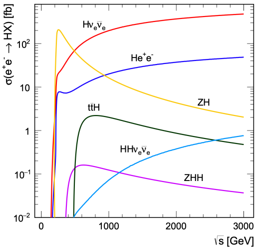
- **Hope for the best** — direct probing new physics at multi-TeVs!
  - What if we find light new particles?
    (Well, I'll throw my papers in the trash can...)
- **Prepare for the worst** — precision measurements!
  - Higgs (mainly in the WW fusion channel at high energies).
  - EW gauge bosons ($e^+e^- \to WW$ at high energies, *etc*).
  - Top (not covered in this talk).
- **EFT is good for CLIC.**
  - A systematic parameterization of BSM contributions to Higgs and EW couplings.
  - If $v \ll \Lambda$, leading order contributions are parametrized by D6 operators.
- **CLIC is also good for EFT!**
  - High precision is crucial for the validity of the EFT expansion.
  - High energy is not really a problem as long as we also have high precision.
    - (assuming the results are SM-like. If not, see the 1st point on this slide...)

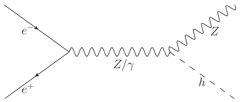
Current run scenarios (WG report)

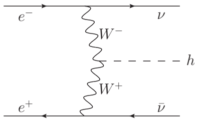


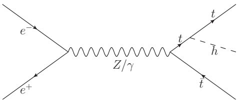


Higgs measurements









- $e^+e^- \to hZ$, cross section maximized at $\sim$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).
- FCC-hh: $gg \to hh$, $gg \to tth$, $h \to Z\gamma$, $h \to \mu\mu$, ...

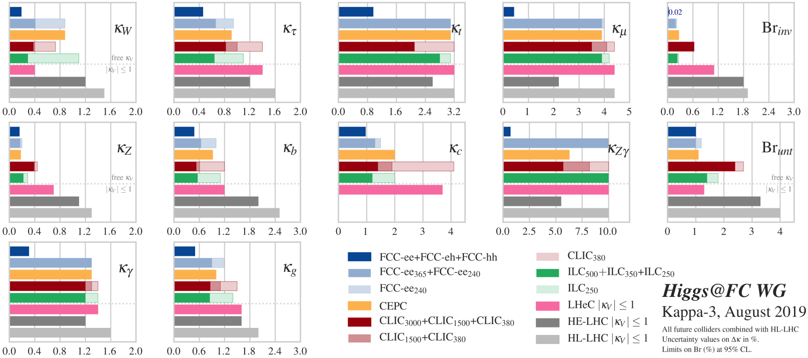
κ fit

- **Simple, intuitive, ...**

$$g_h^{\rm SM} \to \kappa\, g_h^{\rm SM}\,.$$

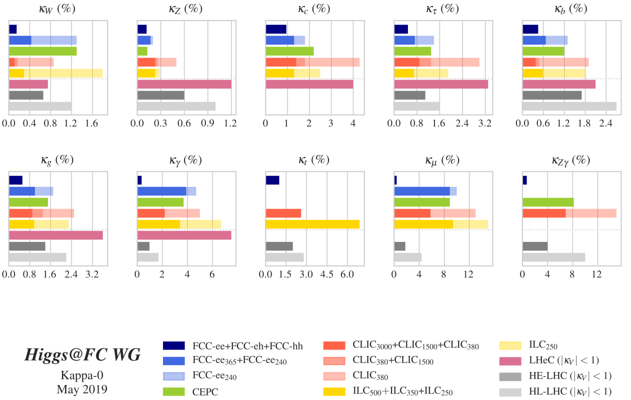
- **... but has some limitations.**
  - Anomalous couplings (such as $hZ^{\mu\nu}Z_{\mu\nu}$) are assumed to be zero.
  - Gauge invariance is often not imposed (hZZ, hWW, $h\gamma\gamma$, $hZ\gamma$ all assumed to be independent).
- **scenarios:**
  - Impose $\kappa_Z = \kappa_W \quad (\equiv \kappa_V)$? (gauge invariance/custodial symmetry)
  - Allow invisible and/or undetected Higgs decays?
  - Impose $\kappa_V < 1$?

κ fit (WG report)



- Independent κ_Z and κ_W, free Γ_h (with $\kappa_V < 1$ for hadron colliders).
- Free $\Gamma_h \Rightarrow$ flat direction in $\sigma \times \mathrm{BR}$, resolved by inclusive $\sigma(hZ)$.

κ fit assuming no Higgs exotic decays (WG report)



- Note the significant improvement on κ_W for CLIC!
- (Also note that HL-LHC is not combined to other future colliders here.)

EFT global fit

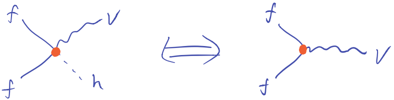
- Assuming baryon and lepton numbers are conserved,

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

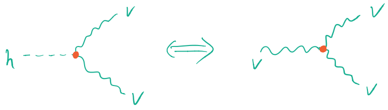
- Write down all D6 operators, **eliminate redundant ones** via field redefinition, integration by parts, equations of motion...
  - different choices of which operators to eliminate $\Rightarrow$ different basis
- **59** operators (**76** parameters) for 1 generation, or **2499** parameters for 3 generations. [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 (+2 if included).
  - 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.

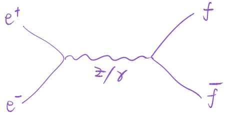


- $\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$,
  $\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$
  - generate aTGCs $\delta g_{1,Z}$ and $\delta\kappa_\gamma$,
  - also generates HVV anomalous couplings such as $hZ_\mu \partial_\nu Z^{\mu\nu}$.

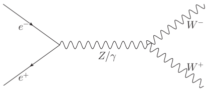


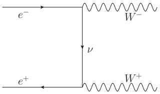
EW measurements

- *Z*-pole
  - $\sim 10^{11} - 10^{12}$ *Z*s at CEPC/FCC-ee.
  - How many *Z*s do we really need?
  - CLIC and ILC: (See Philipp's talk tomorrow.)
    - Dedicated Giga-*Z* program.
    - Radiative return ($e^+e^- \to Z\gamma$) at higher energies.



- $e^+e^- \to WW$, threshold scan, or "free data" at higher energies.
  - *W* mass, width, branching ratios.
  - anomalous Triple Gauge Couplings (**aTGCs**)
    - 3-TGC parameterization $\Rightarrow$ **full EFT parameterization**
    - Optimal observables (See *e.g.* Z.Phys. C62 (1994) 397-412 Diehl & Nachtmann)
    - Only an ideal theorists' analysis is performed....





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 $|H|^2 \mathcal{O}_{\rm SM}$.

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

  - 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, ...

Parametrization of Higgs and EW couplings

- Write down all D6 operators and eliminate the redundant ones.
  - Warsaw, SILH, SILH', ...
- Since we need to calculate things in the broken electroweak phase, why don't we define the basis in the broken phase as well?
  - **Higgs basis** (A. Falkowski, LHCHXSWG-INT-2015-001)
  - 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

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

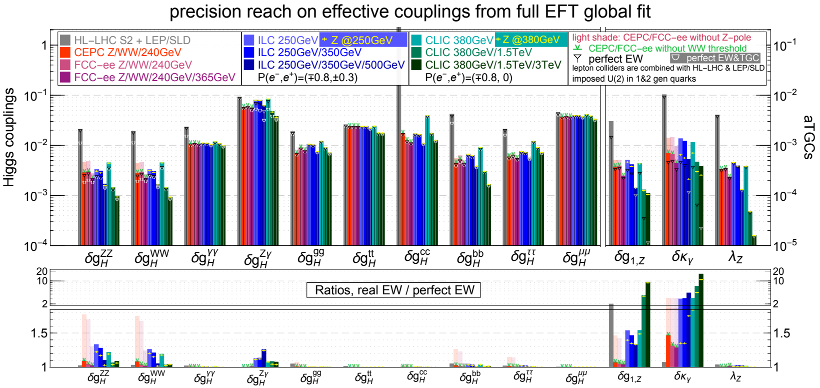
  - $\delta c_Z \leftrightarrow hZ^\mu Z_\mu, \quad c_{ZZ} \leftrightarrow hZ^{\mu\nu} Z_{\mu\nu}, \quad c_{Z\Box} \leftrightarrow hZ_\mu \partial_\nu Z^{\mu\nu}$
  - **advantage: can be sort of interpreted as "Higgs couplings"**
  - EW: parameterize in terms of δm_W and the Vff couplings, and impose $\delta g_{Vff} = \delta g_{hVff}$ (**16** parameters).

- **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

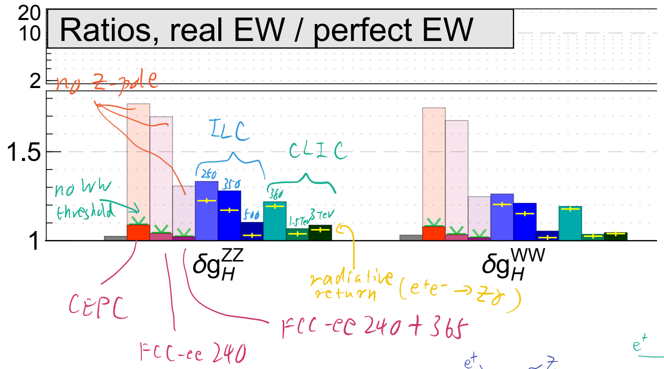
- EFT fit results projected on Effective Higgs couplings ([arXiv:1708.08912], [arXiv:1708.09079], Peskin *et al.*)
  - $g(hZZ)$, $g(hWW)$ are defined at the scale of the relavent Higgs decay. $g(hZZ) \propto \sqrt{\Gamma(h \to ZZ)}\,, \quad g(hWW) \propto \sqrt{\Gamma(h \to WW)}\,.$
  - Not necessarily 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...

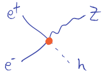
"Full fit" projected on the Higgs couplings and aTGCs

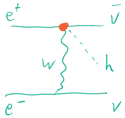


- 28-parameter fit, projected on the Higgs couplings & aTGCs.
- The *hZZ* and *hWW* couplings are not independent!

Impact of *Z*-pole measurements

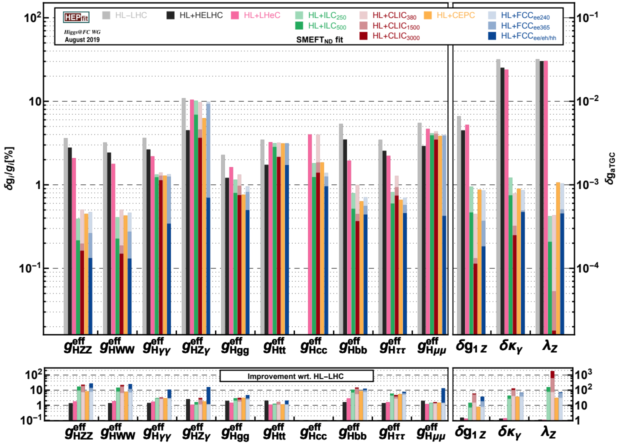






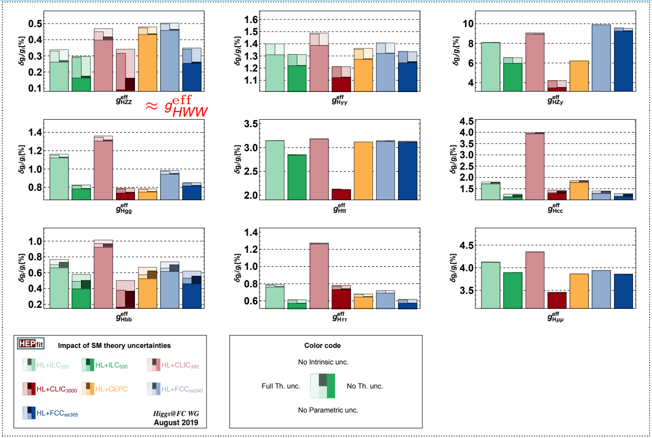
- *WW* fusion is the main channel at CLIC.
- The *Z*-pole measurements are crucial for circular colliders, but not for CLIC.

Comparison with the WG results



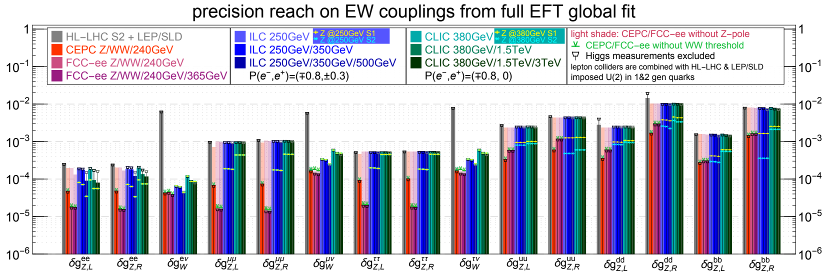
- Limited by the inputs from different colliders, the treatments on $e^+e^- \to WW$ are not fully consistent.
- Theory uncertainties (not considered in [arXiv:1907.04311]).

Impact of theory uncertainties (WG report)



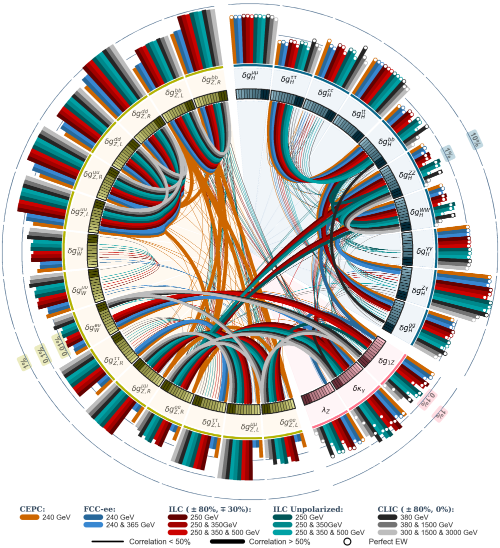
- **left column: Intrinsic uncertainties**
  (∼ 0.5%, assuming NNLO in EW couplings are known, has a larger impact on $e^+e^- \to \nu\bar{\nu}h$.)
- **right column: parametric uncertainties** (*e.g.* $h \to WW/ZZ$ is sensitive to m_h.)

Reach on the (h)Vff couplings



- $(h)Zff$ couplings are still best probed by future Z-pole runs.
- Linear colliders: Radiative return $e^+e^- \to Z\gamma$ offers some competitive researches in some cases. (Based on preliminary estimations. Needs further studies.)

Entering the new era of circular bar plots!



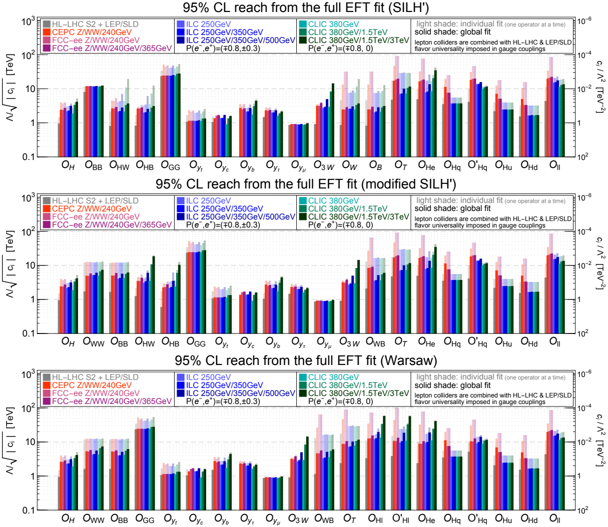
- Precision reach on the outside...
- Correlations on the inside...
- Without future Z-pole run ⇒ larger correlation among the hWW, hZZ couplings, aTGCs and the Zee couplings.

D6 operators

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

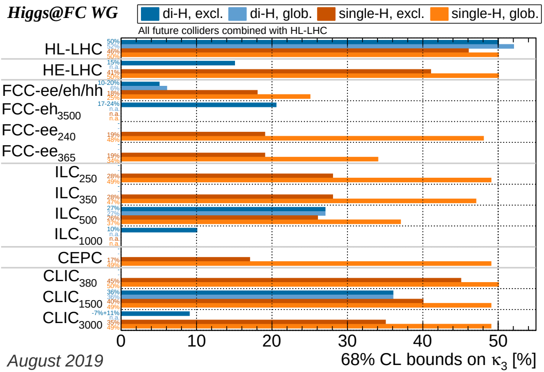
- SILH' basis (eliminate $\mathcal{O}_{WW}$, $\mathcal{O}_{WB}$, $\mathcal{O}_{H\ell}$ and $\mathcal{O}'_{H\ell}$)
- Modified-SILH' basis (eliminate $\mathcal{O}_W$, $\mathcal{O}_B$, $\mathcal{O}_{H\ell}$ and $\mathcal{O}'_{H\ell}$)
- Warsaw basis (eliminate $\mathcal{O}_W$, $\mathcal{O}_B$, $\mathcal{O}_{HW}$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

Pick your favorite basis!



- One could “avoid” the large flat directions in the diboson measurement with a suitable basis choice.

A quick summary on the triple Higgs coupling (WG report)



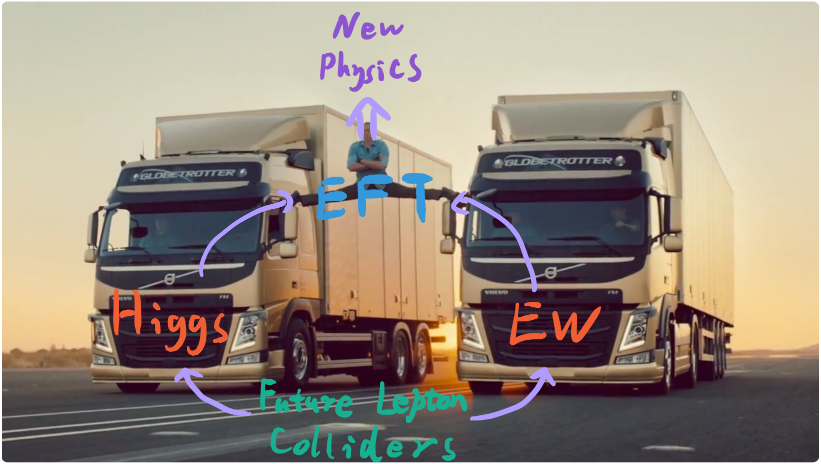
- All scenarios are combined with HL-LHC measurements...
- The HL-LHC 2H measurements are combined into all the 1H scenarios...

- with double Higgs measurements
  - HL-LHC: $\sim 50\%$
    (combine two detectors and all channels)
  - ILC 500 GeV: $\sim 27\%$
  - CLIC 3 TeV: $\sim 10\%$
    ([arXiv:1901.05897] Roloff *et al.*)
  - **Robust even in global fits!**
- single Higgs measurements only
  - FCC-ee 240 GeV & 365 GeV: $\sim$ 40-50%

Conclusion

- **CLIC is** (not just) **a precision Higgs machine!**
- The $e^+e^- \to WW$ (TGC) measurement is **crucial** for the EFT analysis.
  - Going beyond theorists' naive analysis...
  - 3 TGC $\Rightarrow$ full EFT parameterization.
  - Use optimal observables to extract information in the angular distribution.
- Reducing theory uncertainties?
  - Still have 10-20 years to do the calculations...
- Towards a **EW + Higgs + top** combined fit?
  - Global fit of top operators. (See *e.g.* [arXiv:1807.02121] Durieux, Perelló, Vos, Zhang.)
  - Top loop contributions in Higgs processes. (See *e.g.* [arXiv:1809.03520] Durieux, JG, Vryonidou, Zhang.)

Conclusion



but it's not the full picture...

Conclusion

We need both precision measurements and direct searches!

backup slides

Higgs width (WG report)

Collider	$\delta\Gamma_H$ (%) from Ref.	Extraction technique standalone result	$\delta\Gamma_H$ (%) kappa-3 fit
ILC_{250}	2.4	EFT fit [3]	2.4
ILC_{500}	1.6	EFT fit [3, 11]	1.1
$CLIC_{350}$	4.7	κ-framework [85]	2.6
$CLIC_{1500}$	2.6	κ-framework [85]	1.7
$CLIC_{3000}$	2.5	κ-framework [85]	1.6
CEPC	3.1	$\sigma(ZH, \nu\bar{\nu}H)$, $BR(H \to Z, b\bar{b}, WW)$ [90]	1.8
FCC-ee_{240}	2.7	κ-framework [1]	1.9
FCC-ee_{365}	1.3	κ-framework [1]	1.2

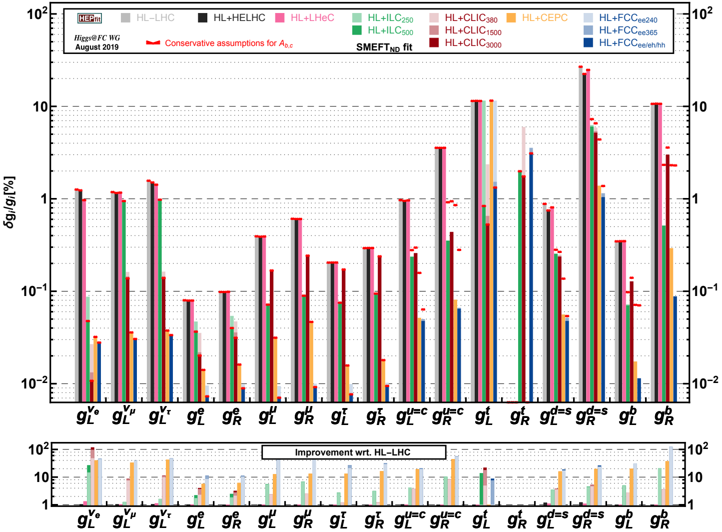
- EFT *vs.* kappa **(Not an apple-to-apple comparison!)**

$$\sigma(hZ)\,\mathrm{BR}(h \to xx) = \sigma(hZ) \times \frac{\Gamma(h \to xx)}{\Gamma_{\mathrm{total}}}$$

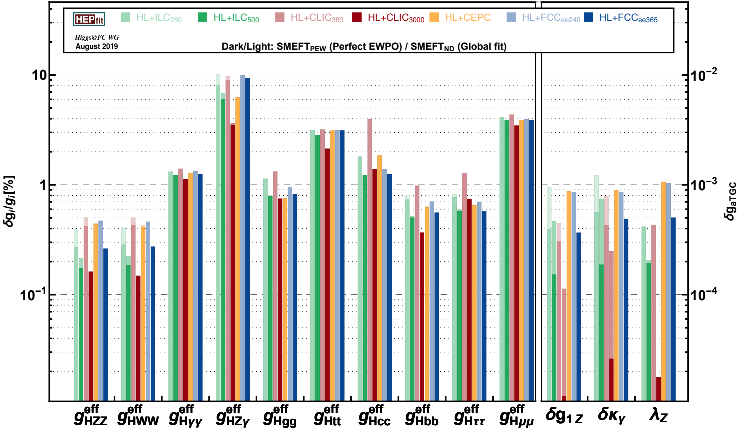
- EFT fit $\Rightarrow$ essentially imposing $\kappa_Z = \kappa_W$.
- κ_3 **fit**: $\kappa_Z = \kappa_W$ not imposed, **HL-LHC included**!
- $\mathrm{BR} > 0 \ \Rightarrow$ bounds on $\delta\Gamma_H$ are asymmetric...

  (*e.g.* for CLIC 380 GeV + HL-LHC, for the $\Delta\chi^2 = 1$ bound I got $-1.6\% \lesssim \delta\Gamma_H \lesssim 3.6\%$.)

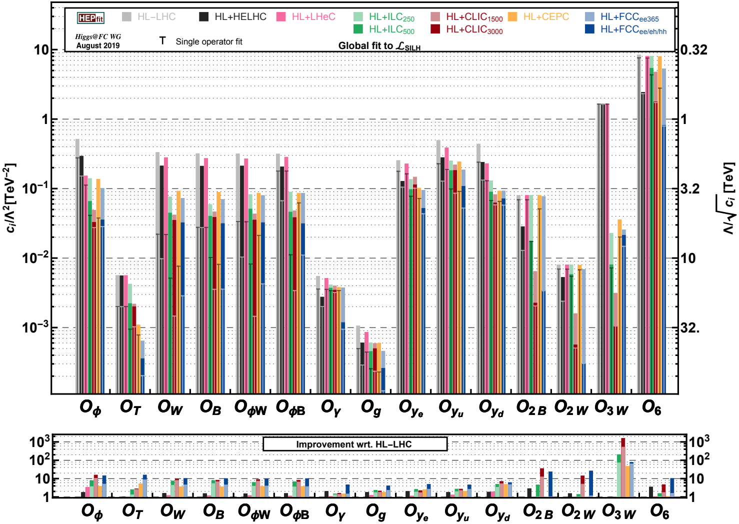
WG report, (h)Vff couplings



WG report, Impact of EW measurements on Higgs couplings

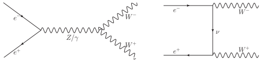


WG report, constrained SILH fit

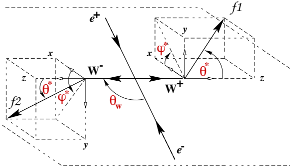


A refined TGC analysis using Optimal Observables

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

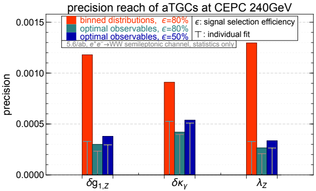


- What are optimal observables?
  (See *e.g.* Z.Phys. C62 (1994) 397-412 Diehl & Nachtmann)
  - For a given sample, there is an upper limit on the precision reach of the parameters.
  - In the limit of large statistics (everything is Gaussian) and small parameters (leading order dominates), this "upper limit" can be derived analytically!



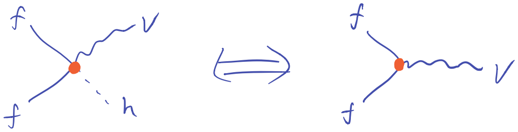
- $\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}|_{\rm SM} + \sum_i S(\Omega)_i g_i$. The optimal observables are simply the $S(\Omega)_i$.

- Very idealized! How well can we actually do?
  - Choose a conservative 50% efficiency to compensate the omission of systematics...



Parametrization 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 $\delta g^{hZf} = \delta g^{Zf}$, $\delta g^{hWf} = \delta g^{Wf}$.



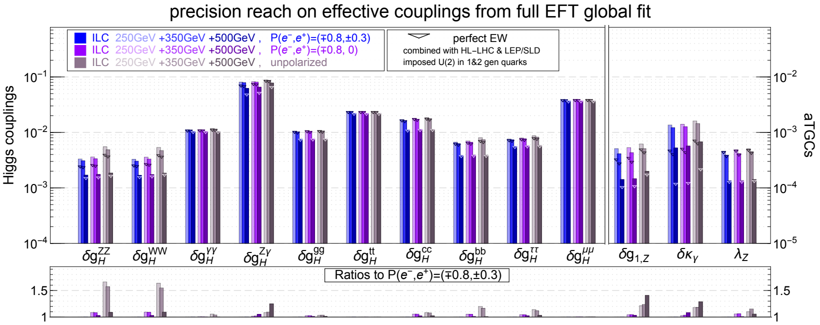
- Can use "couplings" instead of "operators" to parameterize EW corrections (52 real parameters without flavor assumption)

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

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

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

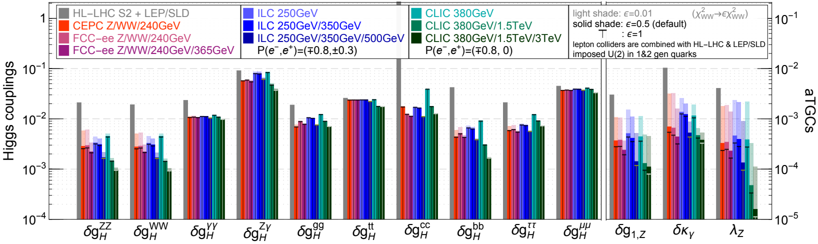
ILC polarization



- 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).

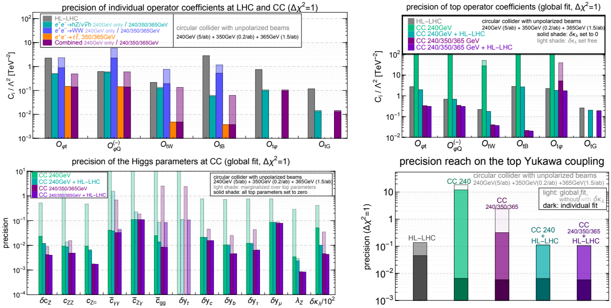
Impact of $e^+e^- \to WW$ measurements

precision reach with different assumptions on $e^+e^- \to WW$ 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

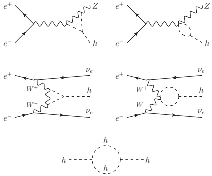


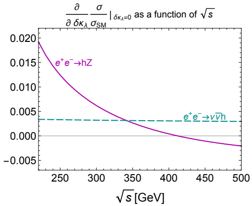
$$O_{t\varphi} = \bar{Q}t\tilde{\varphi}\,(\varphi^\dagger\varphi) + h.c.,$$
$$O^{(1)}_{\varphi Q} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{Q}\gamma^\mu Q),$$
$$O^{(3)}_{\varphi Q} = (\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{Q}\gamma^\mu\tau^I Q),$$
$$O_{\varphi t}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

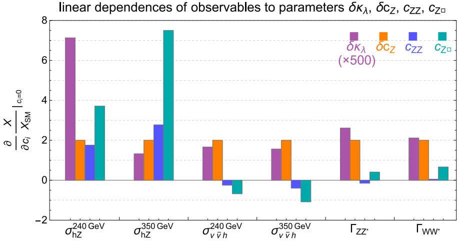
- Higgs precision measurements have sensitivity to the top operators in the loops, but it is challenging to discriminate many parameters in a global fit.
- HL-LHC helps, but a Top threshold run is better.
- Indirect bounds on the top Yukawa coupling.

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

[arXiv:1711.03978] Di Vita, Durieux, Grojean, Gu, Liu, Panico, Riembau, Vantalon

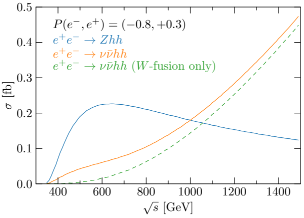


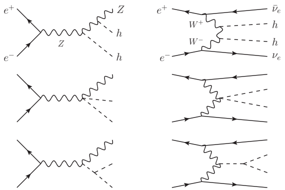




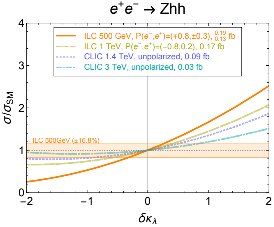
- One loop corrections to all Higgs couplings (production and decay).
- 240 GeV: *hZ* near threshold (more sensitive to $\delta\kappa_\lambda$)
- at 350 GeV:
  - WW fusion
  - *hZ* at a different energy
- $h \to WW^*/ZZ^*$ also have some discriminating power (but turned out to be not enough).

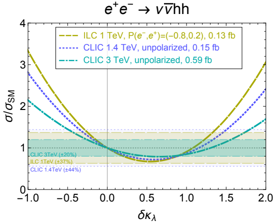
Double-Higgs measurements ($e^+e^- \to Zhh$ & $e^+e^- \to \nu\bar{\nu}hh$)

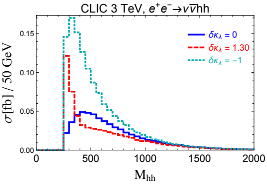




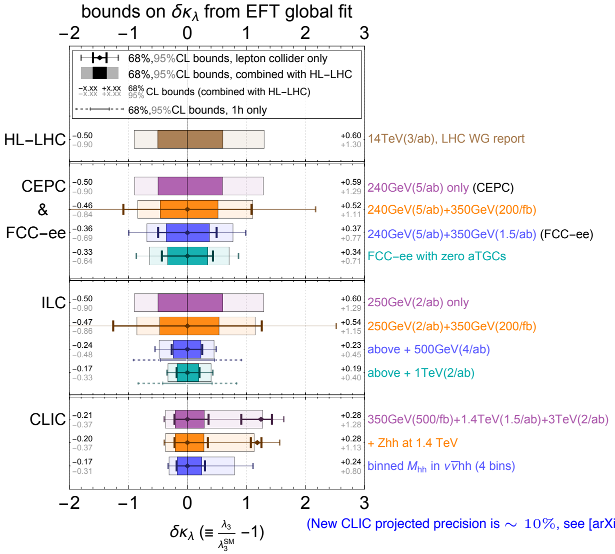
- Destructive interference in $e^+e^- \to \nu\bar{\nu}hh$! The square term is important.
- *hh* invariant mass distribution helps discriminate the "2nd solution."







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

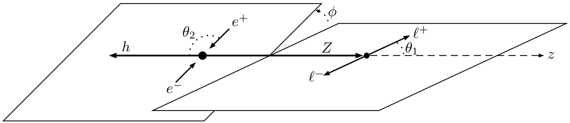


(New CLIC projected precision is $\sim 10\%$, see [arXiv:1901.05897] Roloff *et al.*)

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)

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

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

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