Towards v2.0 of the CEPC EFT fit

(why EW measurements are important for Higgs couplings)

Jiayin Gu (顾嘉荫)

JGU Mainz

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based on current work by J. de Blas, G. Durieux, C. Grojean, JG, A. Paul

EFT fit v1.0

- Why EFT fit?
  - A systematic parameterization of BSM contributions to Higgs couplings. (If $v \ll \Lambda$, leading order contributions are parametrized by D6 operators.)
  - EFT vs. "κ": EFT automatically includes the hVV anomalous couplings and imposes gauge invariance.
- Higgs ($e^+e^- \to hZ$, $e^+e^- \to \nu\bar{\nu}h$, Higgs decays) and diboson ($e^+e^- \to WW$) measurements.
  - $e^+e^- \to WW$ probes the anomalous triple gauge couplings (aTGCs).
- A lot of parameters! We can reduce the parameter space by assuming the new physics ...
  - is CP-even,
  - does not generate dipole interaction of fermions,
  - has no corrections to Z-pole observables and W mass.
- Only 12 combinations of operators are relevant for the measurements considered (with the inclusion of the Yukawa couplings of t, c, b, τ, μ).

EFT fit v1.0

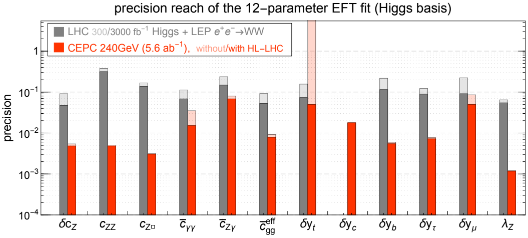
- Higgs basis (LHCHXSWG-INT-2015-001, A. Falkowski) with the following 12 parameters,

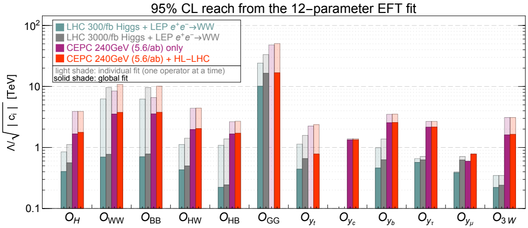
$$\delta c_Z\,,\quad c_{ZZ}\,,\quad c_{Z\Box}\,,\quad c_{\gamma\gamma}\,,\quad c_{Z\gamma}\,,\quad c_{gg}\,,\quad \delta y_t\,,\quad \delta y_c\,,\quad \delta y_b\,,\quad \delta y_\tau\,,\quad \delta y_\mu\,,\quad \lambda_Z\,.$$

- The Higgs basis is defined in the broken electroweak phase.
  - $\delta c_Z \leftrightarrow hZ^\mu Z_\mu, \quad c_{ZZ} \leftrightarrow hZ^{\mu\nu}Z_{\mu\nu}, \quad c_{Z\Box} \leftrightarrow hZ_\mu \partial_\nu Z^{\mu\nu}.$
- Couplings of h to W are written in terms of couplings of h to Z and γ.
- 3 aTGC parameters ($\delta g_{1,Z}$, $\delta\kappa_\gamma$, λ_Z), 2 written in terms of Higgs parameters.
- It can be easily mapped to the following basis with D6 operators.

$\mathcal{O}_H = \frac{1}{2}(\partial_\mu \lvert H^2 \rvert)^2$	$\mathcal{O}_{GG} = g_s^2 \lvert H\rvert^2 G^A_{\mu\nu} G^{A,\mu\nu}$
$\mathcal{O}_{WW} = g^2 \lvert H\rvert^2 W^a_{\mu\nu} W^{a,\mu\nu}$	$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{Q}_L \tilde{H} u_R + \text{h.c.}$ $(u \to t, c)$
$\mathcal{O}_{BB} = g'^2 \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{Q}_L H d_R + \text{h.c.}$ $(d \to b)$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar{L}_L H e_R + \text{h.c.}$ $(e \to \tau, \mu)$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{c\,\rho\mu}$

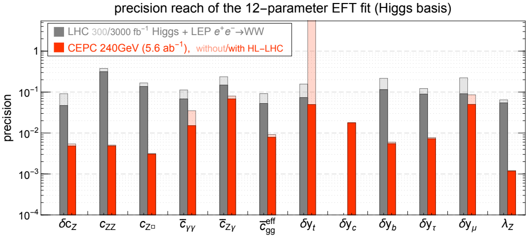
EFT fit v1.0

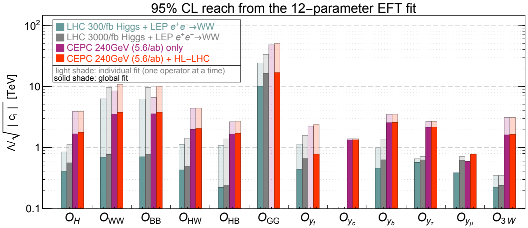




- Results in the CEPC Higgs whitepaper (arXiv:1810.09037) and the CDR.
  (covered by Zhen Liu in the previous talk)

EFT fit v1.0





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- Now we wait for 20 years until all the data is taken ...
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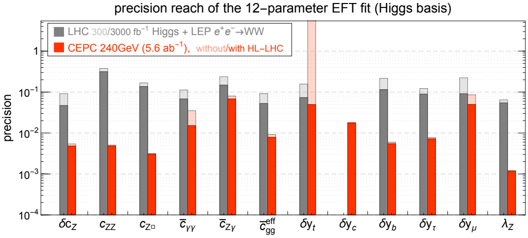
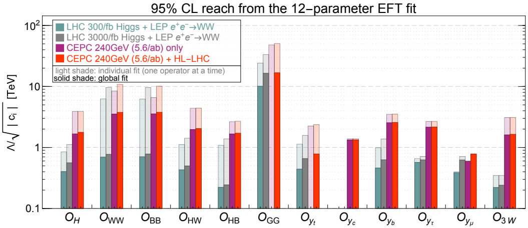
EFT fit v1.0





- See the CEPC Higgs whitepaper (arXiv:1810.09037) and the CDR.
  (covered by Zhen Liu in the previous talk)
- ~~Now we wait for 20 years until all the data has been taken ...~~
- **Still a lot of work to be done before that!**

What have we missed?

- Leading order EFT contributions only (except for the top loop in *hgg* coupling). Possible large loop contributions can come from
  - triple Higgs coupling (talk by Zhen Liu, or see arXiv:1711.03978),
  - top-related operators (talk by Cen Zhang).
- We don't have a real TGC analysis!
  - The Higgs coupling results are sensitive to the reach on aTGCs.
  - A simplified TGC analysis is used at the moment.
  - Can we do better?
- Z-pole measurements are assumed to be perfect.
  - Is it a reasonable assumption?
  - Is the future Z-pole run important?

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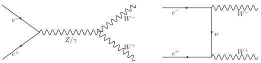
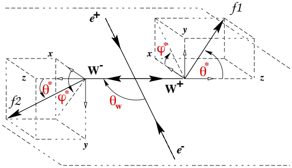
- *Z*-pole measurements are assumed to be perfect.
  - Is it a reasonable assumption? **(It depends...)**
  - Is the future *Z*-pole run important? **(Yes!)**

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.

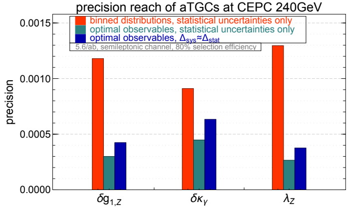


- What are optimal observables?
  (See *e.g.* Z.Phys. C62 (1994) 397-412 Diehl & Nachtmann)
  - For a given sample, there is an upper limit on the precision reach of the parameters.
  - In the limit of large statistics (everything is Gaussian) and small parameters (leading order dominates), this "upper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

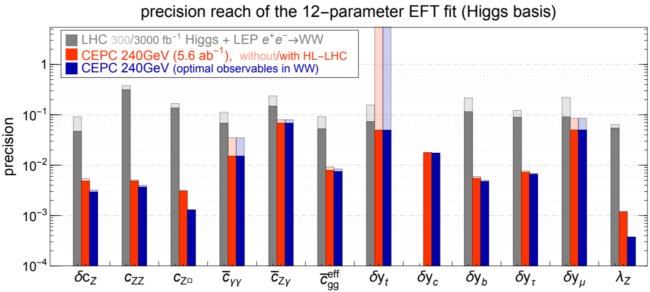


- $\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}|_{\rm SM} + \sum_i S(\Omega)_i \, g_i$. The optimal observables are simply the $S(\Omega)_i$.

- Very idealized! How well can we actually do?
  - Assume $\Delta_{\rm sys} \approx \Delta_{\rm stat}$?



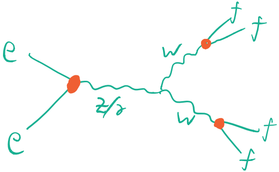
Impact on the Higgs fit

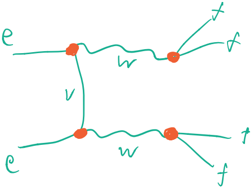


- $\delta g_{1,Z}$, $\delta\kappa_\gamma$ $\to$ c_{ZZ} , $c_{Z\Box}$, $c_{\gamma\gamma}$, $c_{Z\gamma}$
- How well can we actually do? Need an experimental analysis!
- Note: other EW parameters can also enter $e^+e^- \to WW$!

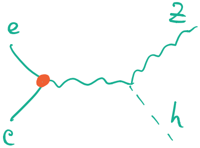
EW corrections, how could they enter?

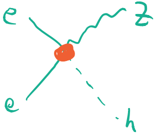
- $e^+e^- \to WW$

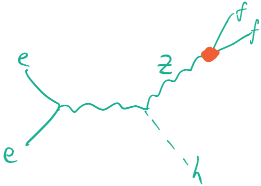




- hZ production, and the decay of Z

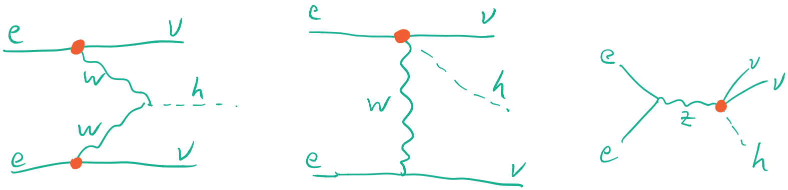




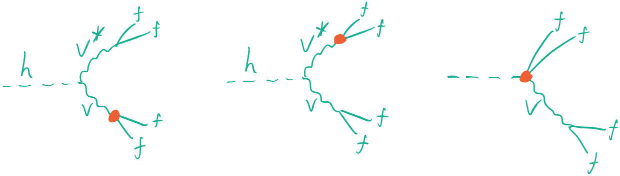


EW corrections, how could they enter?

- *WW* fusion production

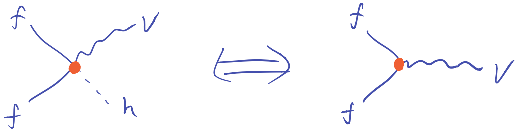


- $h \to WW^*$, $h \to ZZ^*$



Choice of basis...

- 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;
  - 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)

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

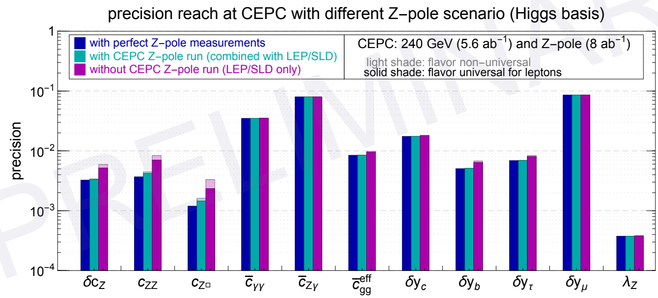
$$\delta g_L^{Z\nu} = \delta g_L^{Ze} + \delta g_L^{Wl}\,,\qquad \delta g_L^{Wq} = \delta g_L^{Zu} V - V \delta g_L^{Zd}\,.$$

- Now we are in the good old Higgs basis. (Surprise!) But it is straight forward to translate to other basis.

Simplifications

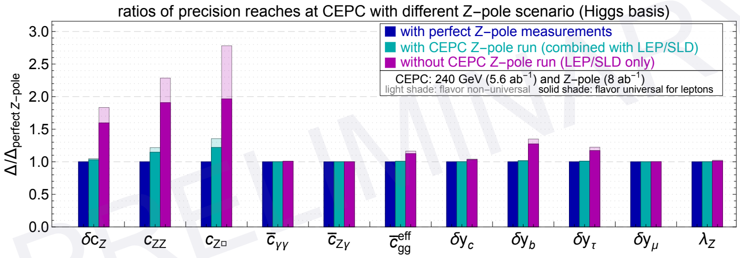
- Lots of parameters! But only the gauge couplings of e and ν_e enter the production of Higgs and *WW* processes.
- For *WW*, separate the production and decay
  - Total cross section and differential distributions $\Rightarrow$ aTGCs,
  - Branching ratios $\Rightarrow$ *Wff* couplings.
- **We will also cheat a little bit (for now)...**
  - Take the combined $e^+e^- \to hZ$ measurements and do not look into Z decay channels...
  - Only look at inclusive $h \to WW^*$ and $h \to ZZ^*$ measurements and do not separate different different $4f$ channels... (Corrections proportional to $\delta\Gamma_W$ and $\delta\Gamma_Z$, see *e.g.* arXiv:1708.09079, Peskin *et al.*)
- Can focus on the lepton couplings and δm_W, $\delta\Gamma_W$, $\delta\Gamma_Z$.

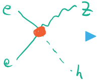
Results on Higgs couplings



- Three *Z*-pole scenarios: perfect / CEPC / LEP&SLD.
- Flavor: universal vs. non-universal

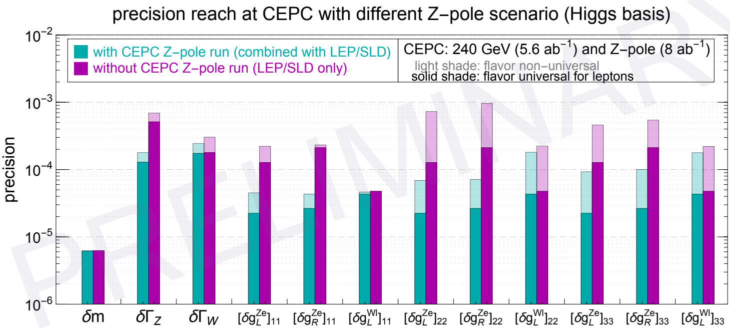
Results on Higgs couplings (Comparison with the perfect Z-pole case)





- The *hZee* contact interactions grow with energy, so they have a larger impact on the $e^+e^- \to hZ$ production.
- The *Zee* couplings also enter $e^+e^- \to WW$ and affect the reaches on aTGCs.
- The *hZZ* and *hWW* couplings are constrained less well.
- $\Delta g(hWW) \uparrow \quad \Rightarrow \quad \Delta\Gamma_{h\to WW} \uparrow \quad \Rightarrow \quad \Delta g(hbb) \uparrow$

Results on *Vff* couplings



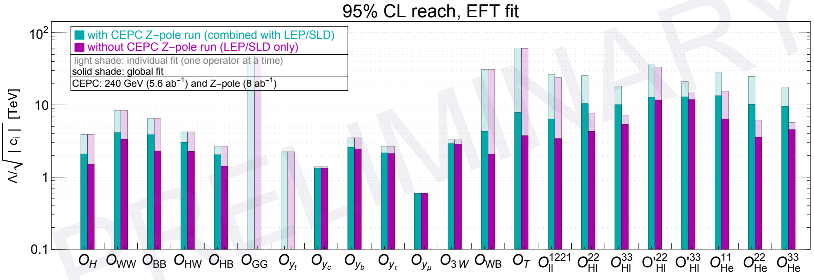
- $\frac{m_W}{m_W^{\rm SM}} = 1 + \delta m, \qquad \frac{\Gamma_Z}{\Gamma_Z^{\rm SM}} = 1 + \delta\Gamma_Z, \qquad \frac{\Gamma_W}{\Gamma_W^{\rm SM}} = 1 + \delta\Gamma_W,$
  $g_L^{Zf\bar{f}} \propto T_f^3 - s_W^2 Q_f + \delta g_L^{Zf}, \qquad g_R^{Zf\bar{f}} \propto -s_W^2 Q_f + \delta g_R^{Zf}, \qquad g_L^{W\ell\nu} \propto 1 + \delta g_L^{W\ell}.$
- Γ_W is constrained (indirectly) to be $\lesssim 0.7$ MeV, already better than the direct bound (2.8 MeV).
- flavor universality $\Rightarrow$ $[\ ]_{11} = [\ ]_{22} = [\ ]_{33}$

Results in terms of D6 operators

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

- “Modified SILH’ basis” ($O_W\,,\ O_B \to O_{WW}\,,\ O_{WB}$)
- $\mathcal{O}^{11}_{Hl}$ and $\mathcal{O}'^{11}_{Hl}$ are eliminated via e.o.m. in this basis.
- For the moment we don’t explicitly consider the *Vqq* operators, but only include their inclusive effects in $\delta\Gamma_W$, $\delta\Gamma_Z$.

Results in terms of D6 operators



- The first 12 parameters can not be probed by Z-pole measurements at leading order (no effect on individual fit), but the Z-pole measurements can constrain the other operator that also contribute to Higgs/WW processes.
- Some operators can be well-constrained by *WW* measurements (*e.g.* $O'^{22}_{H\ell}$ and $O'^{33}_{H\ell}$).

To-do list (for us)

- Look into the sub channels of $e^+e^- \to hZ$, $\mathbf{Z \to ff}$ and $h \to WW^*/ZZ^* \to \mathbf{4f}$.
- Circular vs. Linear
  - Is it worth doing a Giga-Z run?
  - Can the beam polarizations help?
- Comparison and combination with HL-LHC.
  (The new HL-LHC numbers will come out soon!)
  - The $hVqq$ contract interactions could have a huge impact on Vh production (and a sizable impact on VBF as well)!
  - The Vqq couplings are not very well constrained for the 1st generation.

Wishlist (for CEPC EW and Higgs working groups)

- Z-pole
  - A full list of projected precisions of the observables ...

$$\Gamma_Z\,,\quad \sigma_{\rm had}\,,\quad R_{e/\mu/\tau/c/b}\,,\quad A_{\rm FB}^{0,e/\mu/\tau/c/b}\,,\quad A_{e/\tau}\,,\ldots$$

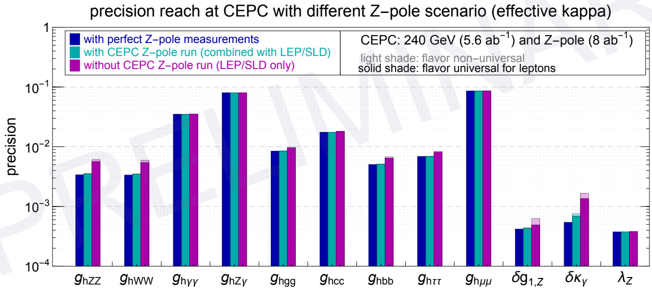
  - ... without the assumption of lepton universality.
- $e^+e^- \to WW$
  - Cross section and branching ratio measurements.
  - A realistic TGC analysis using the optimal observable!
    (LEP has done it, but need to include also corrections to *Vff* couplings.)
- For the Higgs measurements, report separately the precisions of the sub-channels in $e^+e^- \to hZ$, $\mathrm{Z} \to \mathrm{ff}$ and $h \to WW^*/ZZ^* \to \mathrm{4f}$.
  - Most information already available in the CDR, but not scaled to 240 GeV?

backup slides

How about the *WW* threshold run?

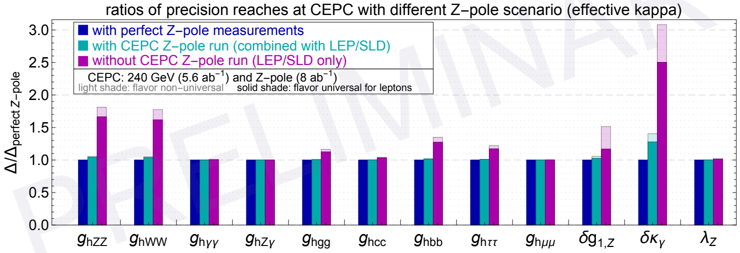
- The *WW* threshold hold run has a small impact in our EFT fit.
- m_W can also be measured relatively well at 240 GeV (2-3 MeV).
- Γ_W can be constrained indirectly by *WW* measurements at 240 GeV, assuming *W* has no exotic decays.
- The threshold run is not so sensitive to the aTGCs. ($e^+e^- \to WW$ is dominated by the *t*-channel diagram near the threshold.)

Results in the "Peskin" basis



- Used in arXiv:1708.08912 and arXiv:1708.09079 by Peskin *et al.*
- "Higgs couplings" defined at the scale of decay (*e.g.* $g_{hZZ} \propto \sqrt{\Gamma_{h\to ZZ}}$).

Results in the “Peskin” basis



- $\Gamma_{h\to WW}$ has a sizable contribution to the Higgs total width, which has an impact on the extraction of other couplings (in particular g_{hbb}).
- Also note the impacts on aTGCs.

The “12-parameter” framework in the Higgs basis

- The relevant terms in the EFT Lagrangian are

$$\mathcal{L} \supset \mathcal{L}_{hVV} + \mathcal{L}_{hff} + \mathcal{L}_{\rm tgc} \,, \quad (1)$$

- the Higgs couplings with a pair of gauge bosons

$$\begin{aligned}\mathcal{L}_{hVV} = \frac{h}{v}\Big[& (1+\delta c_W)\frac{g^2 v^2}{2} W_\mu^+ W_\mu^- + (1+\delta c_Z)\frac{(g^2+g'^2)v^2}{4} Z_\mu Z_\mu \\ & + c_{WW}\frac{g^2}{2} W^+_{\mu\nu} W^-_{\mu\nu} + c_{W\Box}\, g^2 (W^-_\mu \partial_\nu W^+_{\mu\nu} + \mathrm{h.c.}) \\ & + c_{gg}\frac{g_s^2}{4} G^a_{\mu\nu} G^2_{\mu\nu} + c_{\gamma\gamma}\frac{e^2}{4} A_{\mu\nu} A_{\mu\nu} + c_{Z\gamma}\frac{e\sqrt{g^2+g'^2}}{2} Z_{\mu\nu} A_{\mu\nu} \\ & + c_{ZZ}\frac{g^2+g'^2}{4} Z_{\mu\nu} Z_{\mu\nu} + c_{Z\Box}\, g^2 Z_\mu \partial_\nu Z_{\mu\nu} + c_{\gamma\Box}\, g g' Z_\mu \partial_\nu A_{\mu\nu} \Big] . \quad (2)\end{aligned}$$

The “12-parameter” framework in the Higgs basis

- Not all the couplings are independent, for instance one could write the following couplings as

$$\begin{aligned}
\delta c_W &= \delta c_Z + 4\delta m \,, \\
c_{WW} &= c_{ZZ} + 2 s_{\theta_W}^2 c_{Z\gamma} + s_{\theta_W}^4 c_{\gamma\gamma} \,, \\
c_{W\Box} &= \frac{1}{g^2 - g'^2} \left[g^2 c_{Z\Box} + g'^2 c_{ZZ} - e^2 s_{\theta_W}^2 c_{\gamma\gamma} - (g^2 - g'^2) s_{\theta_W}^2 c_{Z\gamma} \right] \,, \\
c_{\gamma\Box} &= \frac{1}{g^2 - g'^2} \left[2 g^2 c_{Z\Box} + (g^2 + g'^2) c_{ZZ} - e^2 c_{\gamma\gamma} - (g^2 - g'^2) c_{Z\gamma} \right] \,,
\end{aligned} \qquad (3)$$

- we only consider the diagonal elements in the Yukawa matrices relevant for the measurements considered,

$$\mathcal{L}_{hff} = -\frac{h}{v} \sum_{f=t,c,b,\tau,\mu} m_f (1 + \delta y_f) \bar{f}_R f_L + \mathrm{h.c.} \,. \qquad (4)$$

TGC

$$\mathcal{L}_{\rm tgc} = igs_{\theta_W}A^\mu(W^{-\nu}W^+_{\mu\nu} - W^{+\nu}W^-_{\mu\nu}) + ig(1+\delta g_1^Z)c_{\theta_W}Z^\mu(W^{-\nu}W^+_{\mu\nu} - W^{+\nu}W^-_{\mu\nu}) + ig\left[(1+\delta\kappa_Z)c_{\theta_W}Z^{\mu\nu} + (1+\delta\kappa_\gamma)s_{\theta_W}A^{\mu\nu}\right]W^-_\mu W^+_\nu + \frac{ig}{m_W^2}(\lambda_Z c_{\theta_W}Z^{\mu\nu} + \lambda_\gamma s_{\theta_W}A^{\mu\nu})W^{-\rho}_v W^+_{\rho\mu}\,, \tag{5}$$

- $V_{\mu\nu} \equiv \partial_\mu V_\nu - \partial_\nu V_\mu$ for $V = W^\pm$, Z, A,. Imposing Gauge invariance one obtains $\delta\kappa_Z = \delta g_{1,Z} - t^2_{\theta_W}\delta\kappa_\gamma$ and $\lambda_Z = \lambda_\gamma$.
- 3 aTGCs parameters $\delta g_{1,Z}$, $\delta\kappa_\gamma$ and λ_Z, 2 of them related to Higgs observables by

$$\delta g_{1,Z} = \frac{1}{2(g^2-g'^2)}\left[-g^2(g^2+g'^2)c_{Z\Box} - g'^2(g^2+g'^2)c_{ZZ} + e^2g'^2c_{\gamma\gamma} + g'^2(g^2-g'^2)c_{Z\gamma}\right]\,,$$

$$\delta\kappa_\gamma = -\frac{g^2}{2}\left(c_{\gamma\gamma}\frac{e^2}{g^2+g'^2} + c_{Z\gamma}\frac{g^2-g'^2}{g^2+g'^2} - c_{ZZ}\right)\,. \tag{6}$$