Snowmass 2021- EF01 & EF04 WG meeting
Sept 24, 2020

Snowmass 2021: SMEFT fits

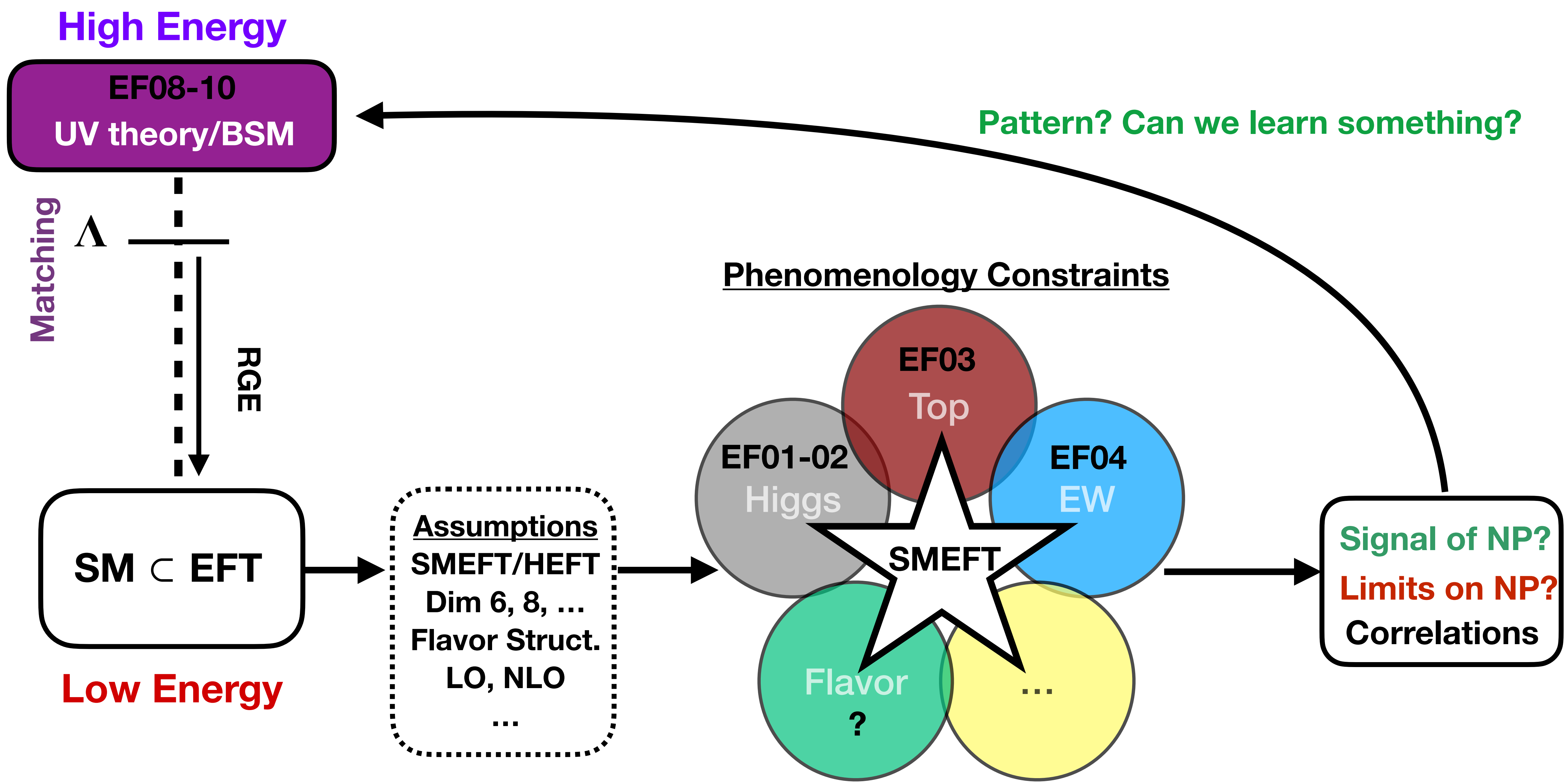
J. de Blas[1] and C. Grojean[2,3]

[1]Institute for Particle Physics Phenomenology
Durham University

[2]DESY (Hamburg)
[3]Humboldt-Unniversität Berlin

SMEFT studies

- The Goal: combine inputs from the different EF to obtain a global SMEFT fit which can be used to learn from BSM scenarios



SMEFT fits

Open questions and ideas for Snowmass 2021

Summarized here for completeness
See other talks in the meeting today for more info and details

Important topics not covered in ESU studies

Some topics related to EW/Higgs physics

- **EW precision observables:**
  - ✓ Detailed assessment of impact of SM uncertainties for EWPO in SMEFT fits.
  - ✓ Clarify systematics for heavy flavor observables (A_q, R_q).
  - ✓ Exploit EW obs. outside the Z-pole (low and high energy) ⇒ add 4-fermion ops.
  - ✓ Flavor (and CP violation): not explored in the ESU SMEFT fits.
- **Higgs and Multi-boson processes:**
  - ✓ Boosted Higgs, Higgs off-shell measurements, …
  - ✓ Full EFT studies of $e^+e^- \to W^+W^-$. Use of "optimal" observables.
  - ✓ High-E probes of EFT effects that grow with the energy.
  - ✓ Vector boson scattering: not included in ESU studies.
- **Interplay EW/Higgs/Top:** Top sector only explored superficially:
  - ✓ Consider effects from 4-fermion operators or top dipole operators.
  - ✓ Exploit NLO effects of Top couplings in H/EW.
- **SMEFT assumptions:**
  - ✓ Impact of SMEFT uncertainties: NLO, (dim-6)^2 vs. dim 8, …
  - ✓ Non-universality: combine with flavor data to explore more flavor BSM scenarios

Questions on the theory assumptions

Relevant for BSM interpretations/frontiers

- What is the impact of the theory assumptions made in the ESU2020 studies:

✓ Impact of NLO corrections: for recent studies, see e.g.

C. Hartmann, M. Trott,
Phys.Rev.Lett. 115 (2015) 19, 191801, arXiv:1507.03568 [hep-ph]
C. Hartmann, W. Shepherd, M. Trott,
JHEP 03 (2017) 060, arXiv:1611.09879 [hep-ph]

S. Dawson, P.P. Giardino,
Phys.Rev.D 97 (2018) 9, 093003, arXiv:1801.01136 [hep-ph]
Phys.Rev.D 98 (2018) 9, 095005, arXiv:1807.11504 [hep-ph]
Phys.Rev.D 101 (2020) 1, 013001, arXiv:1909.02000 [hep-ph]

- In general, ~O(10%) modifications if constrained at tree level
- Gives access to more operators/effects
- But also open flat directions ⇒ Need more observables to close a global fit

✓ Impact of (dim 6)^2, dim 8, … terms:

- More relevant in E-enhanced effects? (ILC 1 TeV, CLIC 3TeV)
- Validity of EFT description
- Gives access to more effects, e.g. RH CC in W processes

Questions on the theory assumptions

Relevant for BSM interpretations/frontiers

- What is the impact of the theory assumptions made in the ESU2020 studies:
  - ✓ Flavour/CP assumptions: ESU2020 assumed CP-even neutral diagonal non-universal flavor assumptions:

$$\left[Y_f Y_f^\dagger, C_{\phi f}\right] = 0, \quad \left[Y_f^\dagger Y_f, C_{\phi f}^{(1),(3)}\right] = 0, \quad [Y_f, C_{f\phi}] = 0, \quad \ldots$$

where, e.g.

$$\mathcal{O}_{\phi u} = (\phi^\dagger i D_\mu \phi)\, \overline{u}_R \gamma^\mu u_R$$
$$\mathcal{O}_{d\phi} = (\phi^\dagger \phi)\, \overline{q}_L \phi d_R$$

> Alignment pattern complicated (but possible) from BSM point of view/interpretation
> ⇒ Relax + combine with flavor projections?
>
> ⇒ How far can we go away from fermion universality w/o the above conditions?

- Beyond the standard SMEFT fits:
  - ✓ Parameterize extra light d.o.f. in H decays (consistently)?
  - ✓ Is SMEFT the right approach? → Higgs/EW Effective Field Theory (HEFT)?
    - More general structure of couplings (non-linear EWSB breaks TH correlations)
    - Cut-off $O(4\pi v)$~3 TeV
    - How far can we go in constraining the HEFT?
    - To what extent we can test which one is the right eff. description of EWSB?

SMEFT fits
Organization of work

More lessons from ESU 2020 studies

Preparation of EW/Higgs studies

- **ESU 2020:** Performed by a group of 11 people (Higgs@FutureColliders WG) who needed to:
  - ✓ Review available inputs from each future collider
  - ✓ Agree on what compare
  - ✓ Under which assumptions
  - ✓ How to present results
  - ✓ Plus do all the work…

> We basically had all inputs from the different projects.
> No scrutiny work was performed on such inputs.
> Just worked with what was given.

- Converging on the first set of preliminary results took from Jan, 2019 to mid May, 2019

- **Snowmass 2021:** Can build on top of ESU studies, but <u>need to agree on same considerations</u> and:
  - ✓ Prepare all the new studies beyond what was included in ESU 2020
  - ✓ Need coordination between different EF WGs, all involving significant more people ⇒ Harder to converge?

⇒ It may take even longer… And there is not much more time

Planning the Snowmass 2021 EFT fit studies

Setting the goal(s)

- Need agreement on (incomplete list):
  - ✓ Define minimum goal for the Snowmass EFT fit:
    - SMEFT only? HEFT?
    - LO vs. NLO (where available, RGE)?, dim 6 only?, truncation,…
    - Flavor/CP assumptions
    - Add theory constraints (e.g. unitarity, positivity)?
  - ✓ Machines and scenarios to be compared:
    - e.g. maybe no need to consider HE-LHC anymore…
      What about FCC-hh at 37 TeV? Do we include muon colliders (far future)?
    - Stand-alone colliders or combined with HL-LHC projections?
  - ✓ Inputs available/coherently used across future colliders:
    - For coherent comparison, new studies should ideally be prepared for all machines where such analyses are possible
    - Otherwise, rely on extrapolations?

Planning the Snowmass 2021 EFT fit studies

Setting the goal(s): Bare minimum ⇒ Extend ESU SMEFT fits

Neutral Diagonal (non-Flav. Universal): SMEFT$_{\text{ND}}$ fit

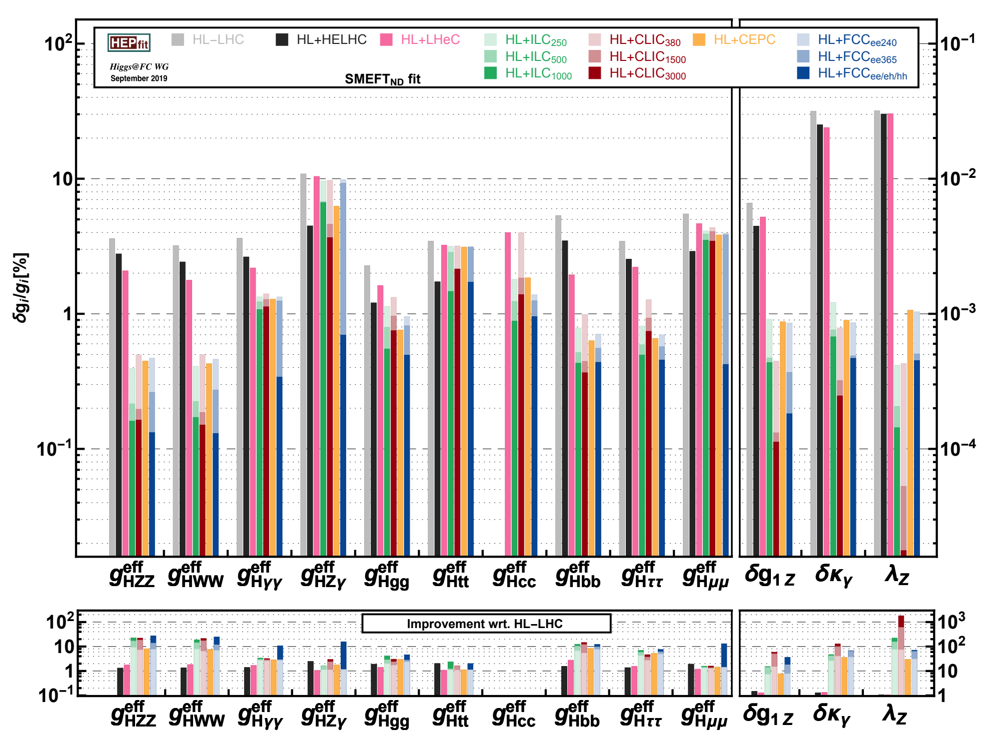
- Fit to EW + Higgs + WW (aTGC) + (minimum) Top data.
- Dim-6 + truncation at linear level. TH unc.: SM only.
- CP-even. *Hff* and *Vff* (*HVff*) diagonal in the physical basis
- *Vff* (*HVff*) flavour universality respected by first 2 quark families

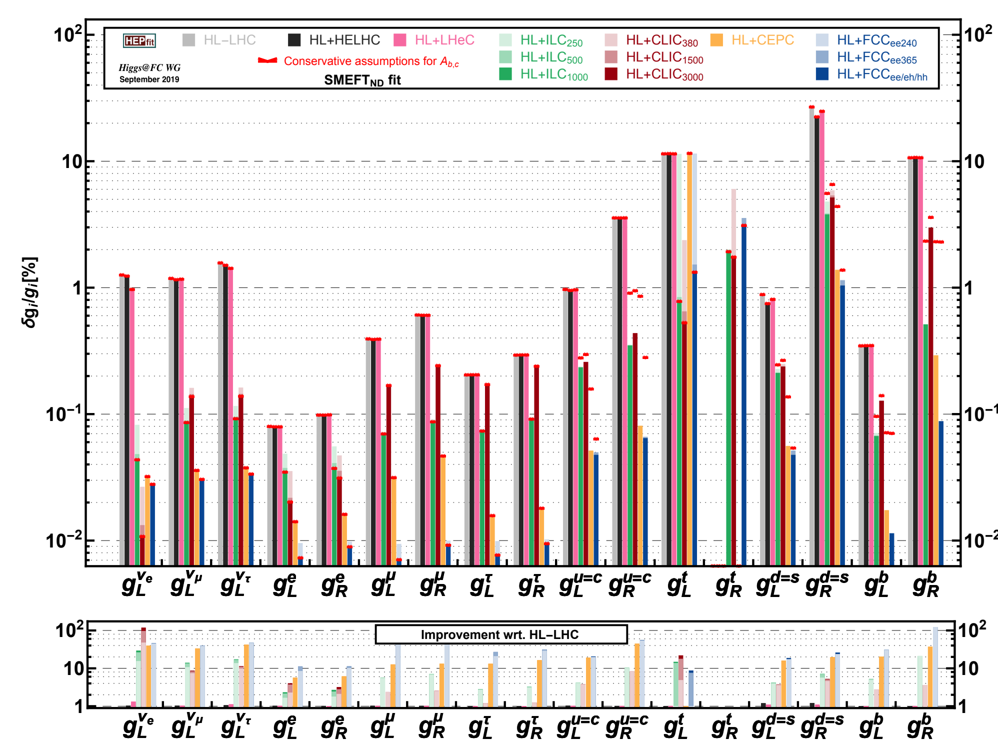
-Designed for exploration of H & EW capabilities at future colliders
-Cumbersome from BSM viewpoint (FCNC)

Parameter counting in the parameterization of LHCHXSWG-INT-2015-001

$$\text{SMEFT}_{\text{ND}} \equiv \{\delta m,\ c_{gg},\ \delta c_z,\ c_{\gamma\gamma},\ c_{z\gamma},\ c_{zz},\ c_{z\Box},\ \delta y_t,\ \delta y_c,\ \delta y_b,\ \delta y_\tau,\ \delta y_\mu,\ \lambda_z\}$$
$$+\{(\delta g_L^{Zu})_{q_i}, (\delta g_L^{Zd})_{q_i}, (\delta g_L^{Z\nu})_{\ell}, (\delta g_L^{Ze})_{\ell}, (\delta g_R^{Zu})_{q_i}, (\delta g_R^{Zd})_{q_i}, (\delta g_R^{Ze})_{\ell}\}_{q_1=q_2\neq q_3,\ \ell=e,\mu,\tau}$$

5 SM + 30 New Physics Parameters





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5 SM + 30 New Physics Parameters

Minimum SMEFT$_{\mathrm{SM21}}$ fit ?

- Consistent treatment of: - WW
  - Top observables (directly & indirectly?)
- Add: - 2→2 fermion processes away from Z pole
  - Multi-boson processes
  - CP and flavor violation
  - High-E probes, differential info

Choice of processes mostly motivated to extend SMEFT$_{\mathrm{ND}}$ fit including more types of EFT interactions, e.g. 4F, dipoles, CP-odd
Different machines sensitive to diff. # of ops. →How to define sensible comparison?

- TH: - Extend treatment of theory uncertainties including EFT errors where relevant
  - Issues with EFT validity (high-E regime?)
  - With and without theory constraints

Update

Planning the Snowmass 2021 EFT fit studies

Some practicalities

- Issues related on how to combine different contributing studies into the final SMEFT fit:
  - ✓ Work always globally ⇒ No 1-operators bounds, but simultaneous on ALL combinations of Wilson Coefficients (WC) that can be constrained by each individual study (in any basis*) ⇒ Provide covariances ⇒ Combine in global fit
    - Simple and OK if working at dim. 6 + obs. truncated at linear level
    - Otherwise need the full (log)likelihood for the combination

    *** As long as all individual studies are performed consistently at the same order in the EFT expansion. Otherwise, agreement on basis may be needed.**
  - ✓ Theory:
    - Uncertainties: Add to resulting WC covariance matrix? Estimation and modeling should be consistent across studies
    - Constraints: Better to add in the final combination (e.g. via priors)?
  - ✓ How to present results so they are useful for:

    (1) Comparing the capabilities of each machine in determining different interactions

    (2) BSM interpretation (⇒use global WC limits + correlations)

Summary

- Several interesting fronts to make progress beyond the ESU 2020 SMEFT fit studies…

- …but time is short and goes fast:

  ✓ It will take time to get all new studies ready…

  ✓ …plus we need to allocate extra time for combination in the final Snowmass 2021 SMEFT fit(s).

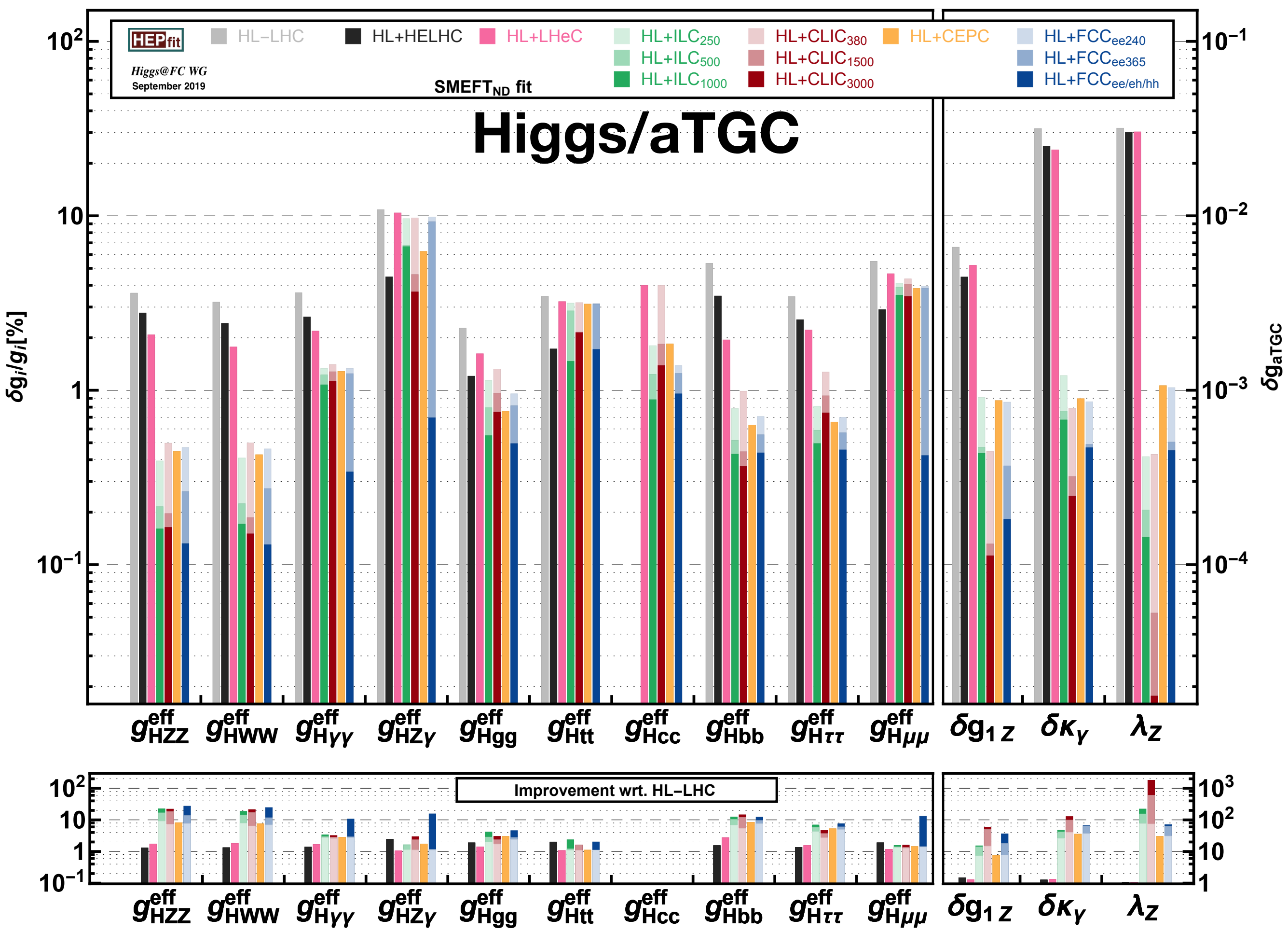
- It is crucial to start organizing and agreeing in all the relevant aspects ASAP.

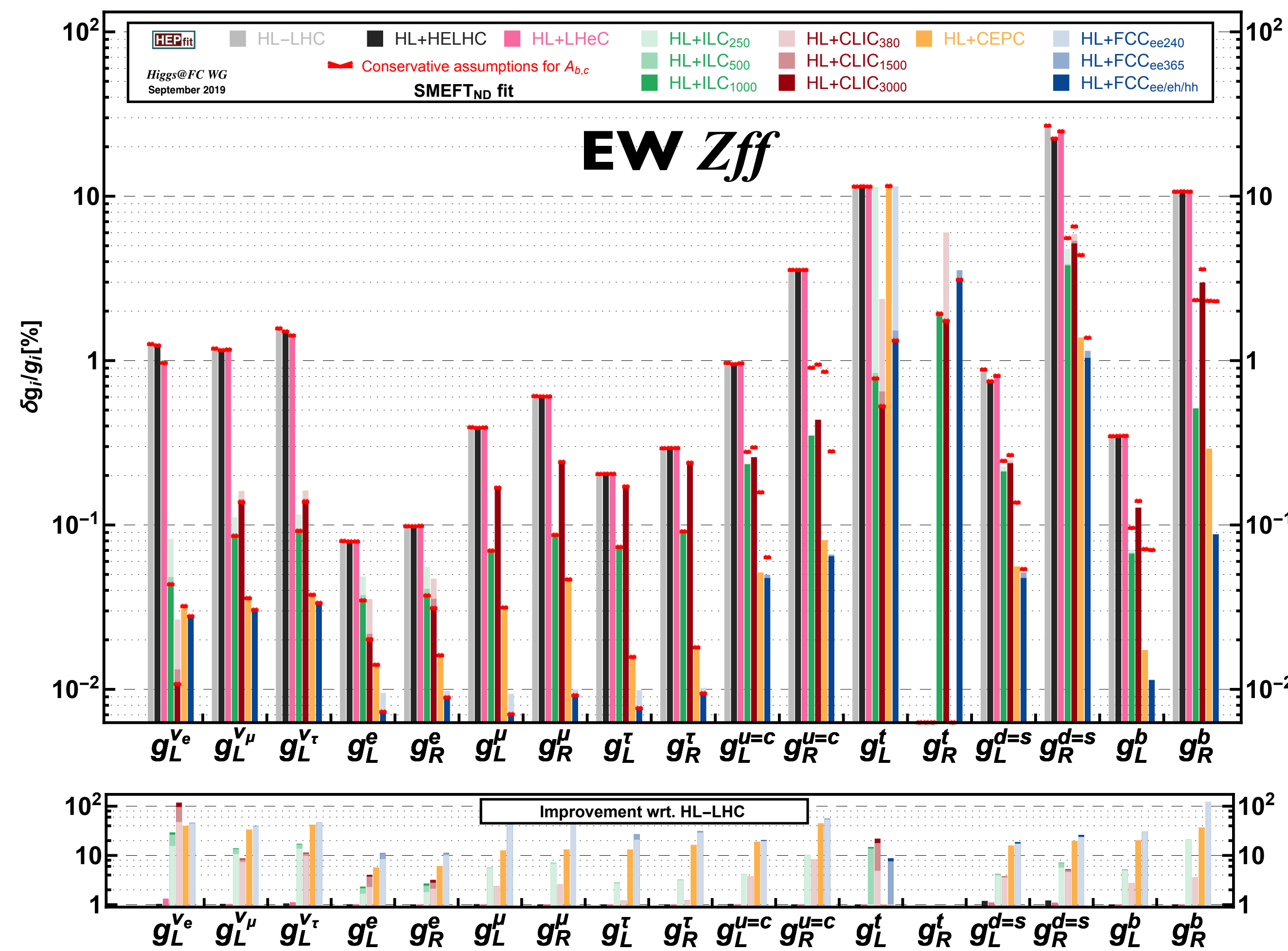
Backup Slides

SMEFT studies: Presentation of Results

ESU results presented in terms of:

EW/Higgs pseudo-observables





- Dimension 6 SMEFT fit to Higgs + EW (EWPO and aTGC) + Top (Ztt)
- Results projected into "effective couplings" for comparison of collider capabilities:

$$g^{\text{eff}\;2}_{HX} \equiv \frac{\Gamma_{H\to X}}{\Gamma^{\text{SM}}_{H\to X}} \qquad \Gamma_{Z\to e^+e^-} = \frac{\alpha\, M_Z}{6\sin^2\theta_w\cos^2\theta_w}(|g_L^e|^2 + |g_R^e|^2), \qquad A_e = \frac{|g_L^e|^2 - |g_R^e|^2}{|g_L^e|^2 + |g_R^e|^2}$$

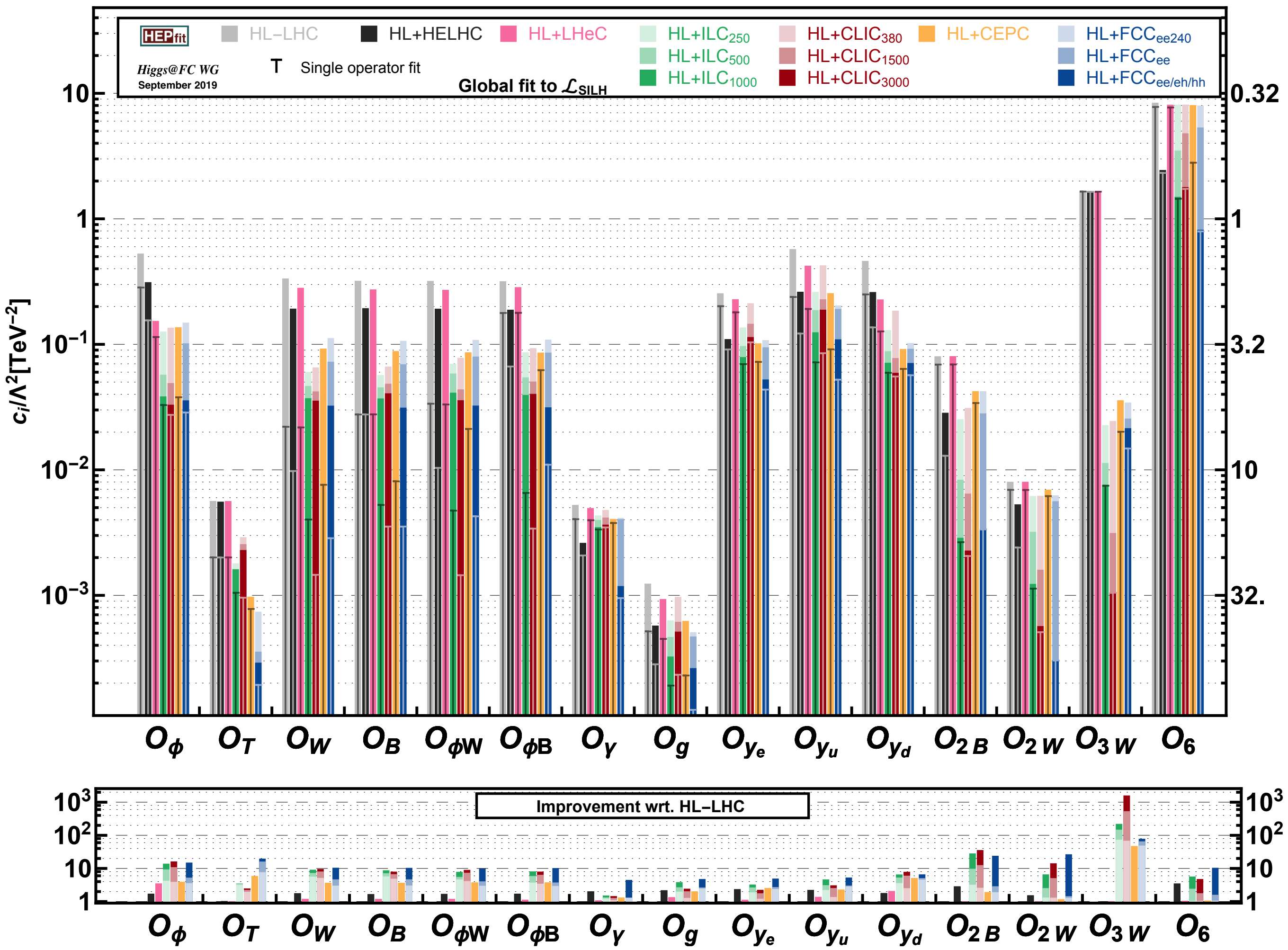
European Strategy Update

J. de Blas
C. Grojean

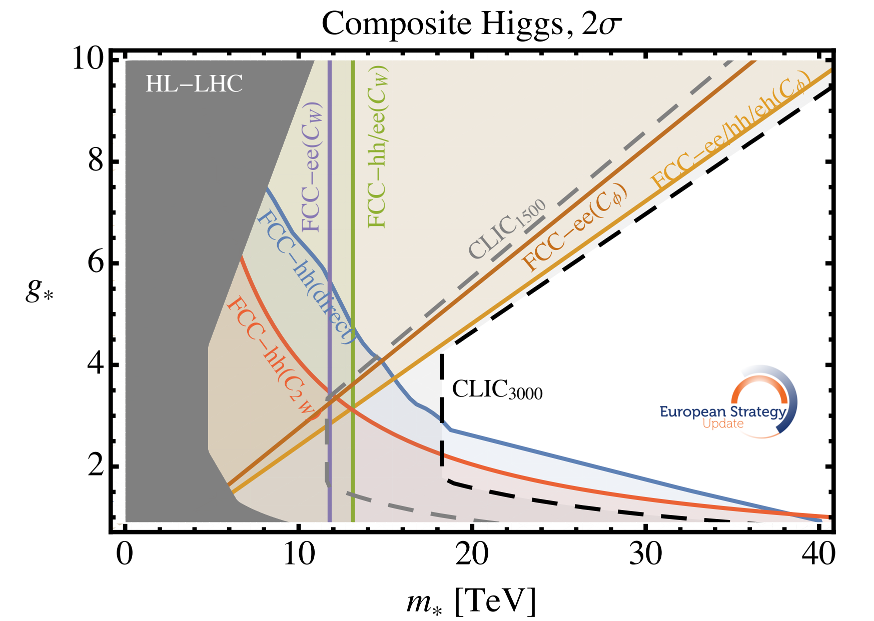
SMEFT studies: Presentation of Results

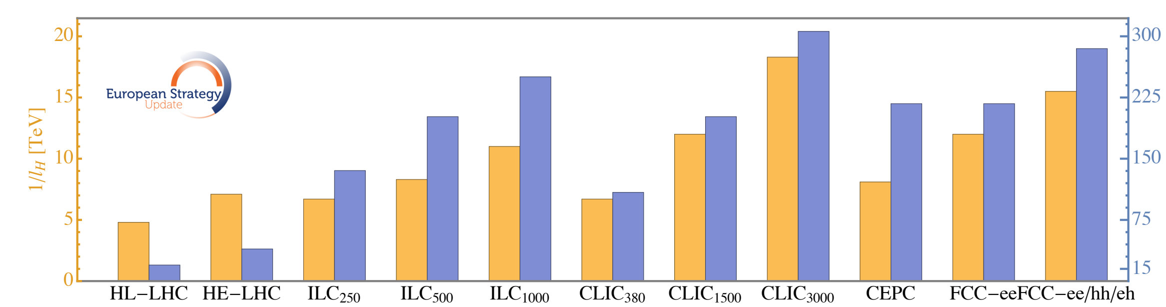
ESU results presented in terms of:

Extra results given in terms of NP interaction scale, for BSM interpretation



From 1-op lim.





- SILH Effective Lagrangian. Fits including same data + High E probes in difermion and diboson processes

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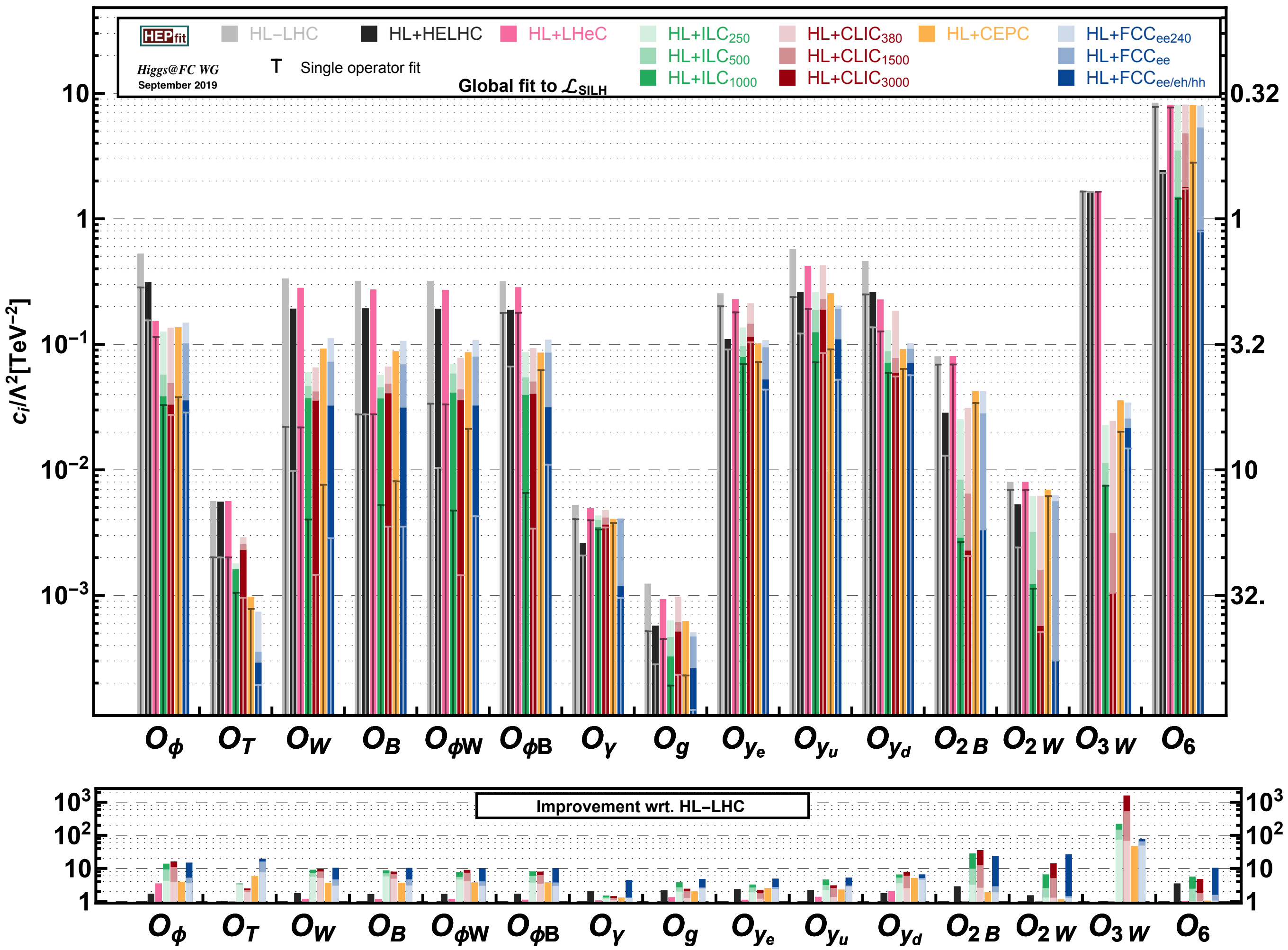
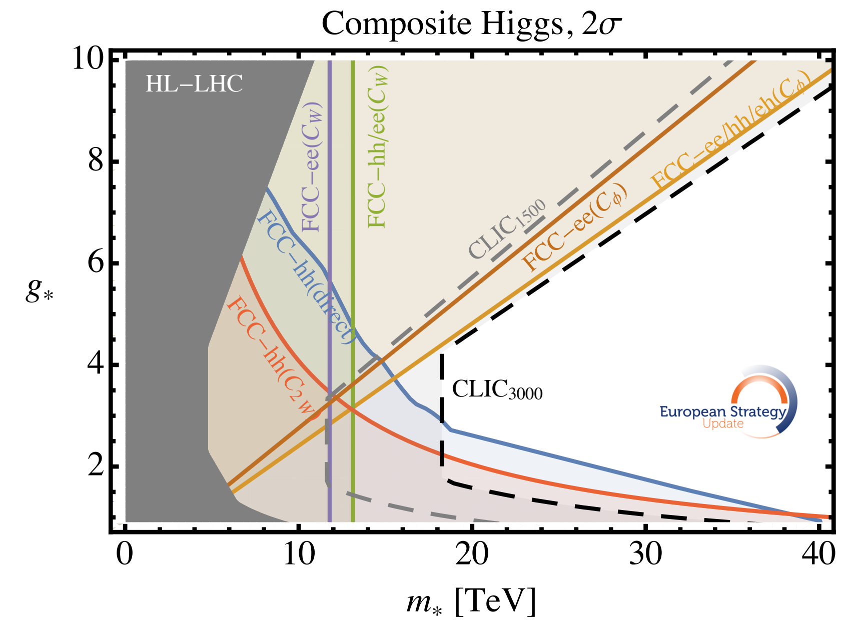
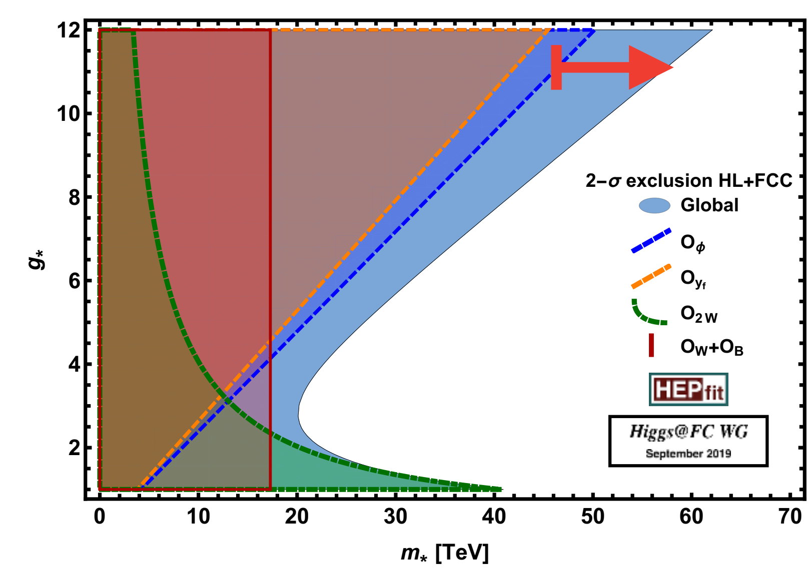


From
1-op lim.

vs. global

BSM correlations
⇒Stronger lim.





- SILH Effective Lagrangian. Fits including same data + High E probes in difermion and diboson processes

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SMEFT studies: ESU Inputs

- Inputs included in the fits. (Used **as provided** in the ESU input documents.)

Higgs

Rates (signal strength)

$$\mu \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma^{\mathrm{SM}} \cdot \mathrm{BR}^{\mathrm{SM}}}$$

(Inclusive) cross section

$$\sigma_{ZH} \equiv \sigma(e^+e^- \to ZH)$$

Only possible at lepton colliders

aTGC

$$\delta g_{1z}, \delta\kappa_\gamma, \lambda_z$$

EWPO

$$M_Z,\ \Gamma_Z,\ \Gamma_{Z\to f},\ A^f_{FB,LR},\ \ldots$$

$$M_W,\ \Gamma_W,\ \Gamma_{W\to f}$$

Z physics via Z-pole:

$$\sqrt{s} = M_Z: \quad e^+e^- \to Z \to X$$

or Rad. Return:

$$\sqrt{s} > M_Z: \quad e^+e^- \to \gamma Z \to \gamma X$$

	Higgs	aTGC	EWPO	Top EW
FCC-ee	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	Yes (aTGC dom.)	Yes	Yes (365 GeV, Ztt)
ILC	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	Yes (HE limit)	Yes (Rad. Return, Giga-Z)	Yes (500 GeV, Ztt)
CEPC	Yes (μ, σ_{ZH}) (Complete with HL-LHC)	Yes (aTGC dom)	Yes	No
CLIC	Yes (μ, σ_{ZH})	Yes (Full EFT parameterization)	Yes (Rad. Return, Giga-Z)	Yes
HE-LHC	Extrapolated from HL-LHC	N/A → LEP2	LEP/SLD + HL-LHC (M_W, $\sin^2\theta_w$)	-
FCC-hh	Yes (μ, BR_i/BR_j) Used in combination with FCCee/eh	From FCC-ee	From FCC-ee	-
LHeC	Yes (μ)	N/A → LEP2	LEP/SLD + HL-LHC (M_W, $\sin^2\theta_w$)	-
FCC-eh	Yes (μ) Used in combination with FCCee/hh	From FCC-ee	From FCC-ee + Zuu, Zdd	-