Universität Regensburg

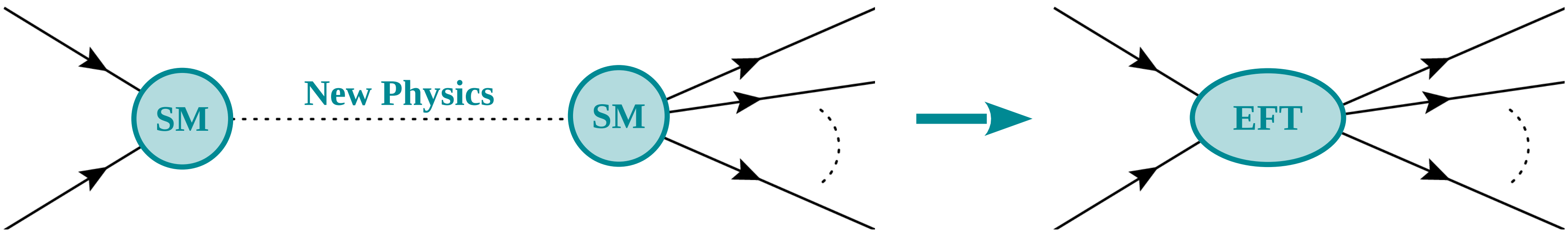
Prospects for New Discoveries Through Precision Measurements at e+e- Colliders

Based on: KA, S. Dawson, P. P. Giardino, R. Szafron: arXiv:2406.03557 and arXiv:2409.11466

Konstantin Asteriadis | University of Regensburg | 05.11.2024

HIGGS 2024 – Uppsala

Effective Theories (EFT) as Tools for BSM Searches

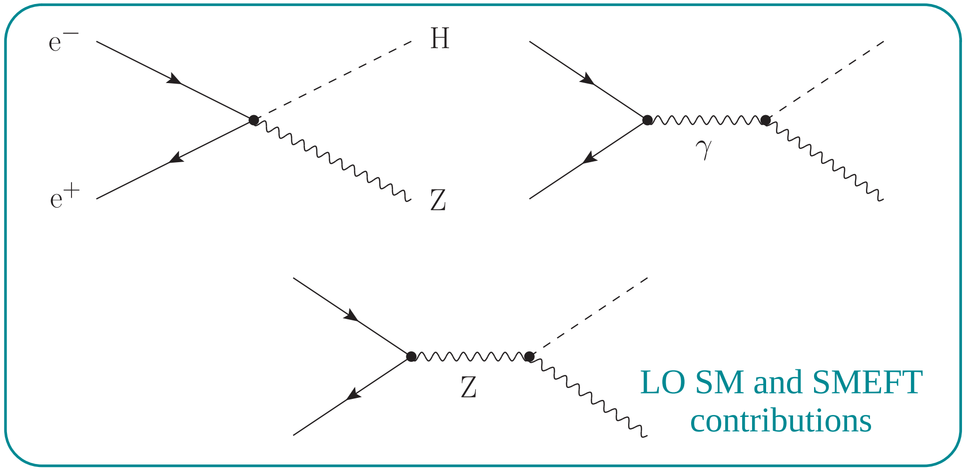


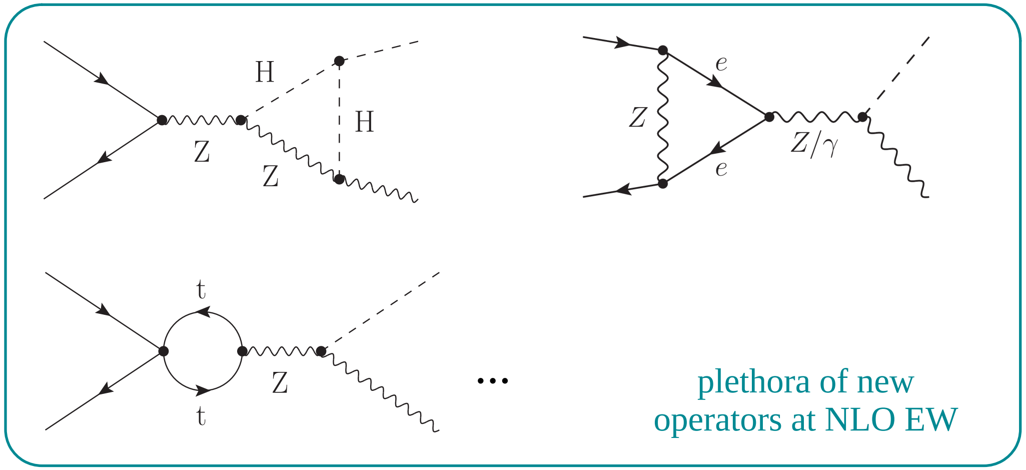
- Ideal case, detect new particles directly ...
- Otherwise detect "heavy" new physics indirectly
- EFT's and the Standard Model Effective Theory (SMEFT) in particular can be a great tool to parametrize such heavy effects systematically

$$L_{\text{SMEFT}} = L_{\text{SM}} + \sum_i \frac{C_i^6 O_i^6}{\Lambda^2} + \sum_i \frac{C_i^8 O_i^8}{\Lambda^4} + \mathcal{O}\left(\frac{1}{\Lambda^6}\right)$$

- Only assumptions in SMEFT: *i)* new operators respect SM gauge symmetries, and *ii)* no new light particles → renormalizable order-by-order in scale of new physics $1/\Lambda$

Higgstrahlung in the SM and SMEFT



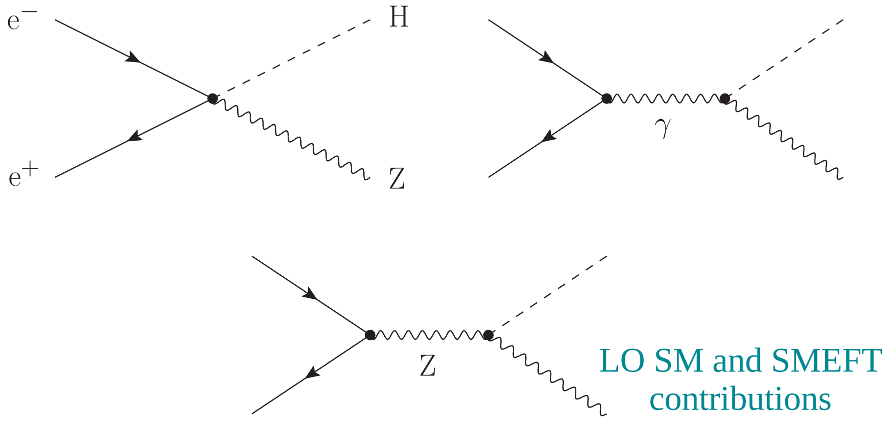


- SM results available at NLO EW [Fleischer, Jegerlehner ‘83; Kniehl ‘92, Denner, Kublbeck, Mertig, Bohm ‘92; Bondarenko, Dydyshka, Kalinovskaya, Rumyantsev, Sadykov, Yermolchyk ‘19]
  ... many pieces known at NNLO accuracy [Sun, Feng, Jia, Sang ‘17; Gong, Li, Xu, Yang, Zhao ‘17; Song, Freitas ‘21; Chen, Guan, He, Li, Liu, Ma ‘22; Freitas, Song, Xie ‘23]

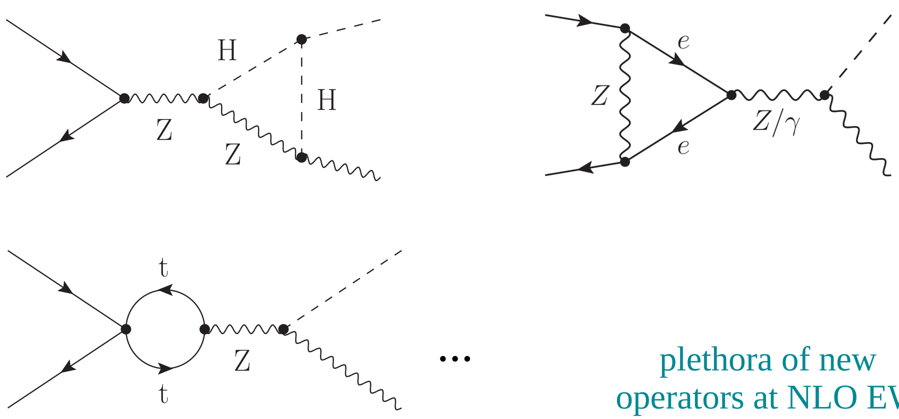
- $e^+ e^- \to HZ$ in SMEFT at LO extensively studied using LEP data

- The precise measurement of $\sigma(e^+e^- \to HZ)$ at a potential future accelerator can be an important source of information on New Physics

Higgstrahlung in the SM and SMEFT



LO SM and SMEFT contributions



plethora of new operators at NLO EW

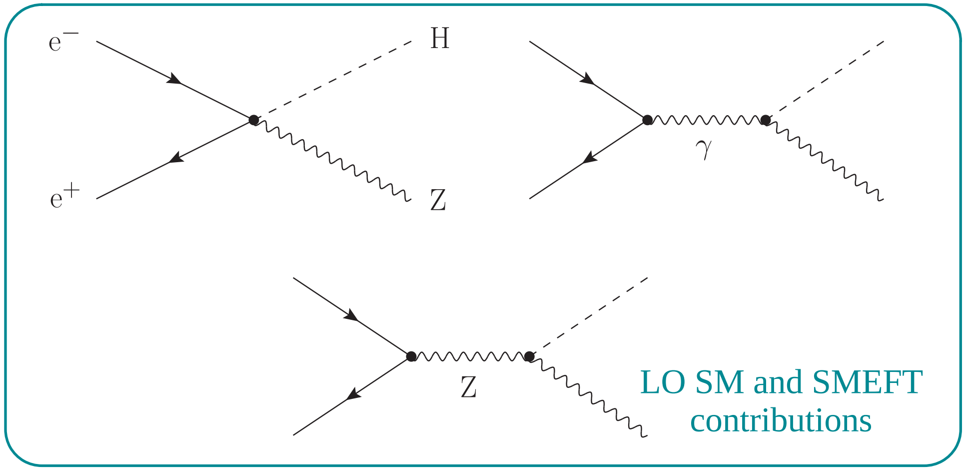
- Precision of future e^+e^- collider might allow …

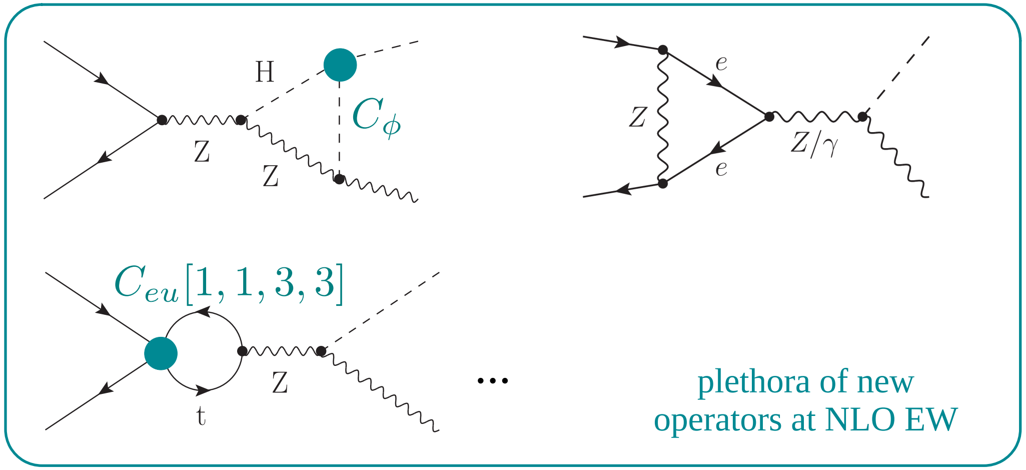
  … the study of operators **not present** at LO

  … more reliable bounds on operators **present** at LO

- **Next step: SMEFT at NLO in the electro-weak expansion**
  [KA, Dawson, Giardino, Szafron 2409.11466]

Higgstrahlung in the SM and SMEFT





- Fully differential NLO EW calculation including ... [KA, Dawson, Giardino, Szafron 2409.11466]

  ... potentially polarized beams

  ... all dimension-6 SMEFT operators

- O(10) Operators at LO → around 80 contribute to this process at NLO
- **At NLO sensitive to poorly constrained interactions (Higgs tri-linear, 4-fermion, ...)**
- **New mechanism for CP violation in Higgsstrahlung at NLO EW and $O(1/\Lambda^2)$**

Higgstrahlung in SMEFT at NLO

[SM checked agains: A. Freitas and Q. Song Phys. Rev. Lett. 130 no. 3, (2023) 031801]

SM LO and virtual NLO but excluding QED contributions

SM virtual and real QED contributions

$$\sigma_{\mathrm{NLO}} = \sigma^{W}_{\mathrm{SM,NLO}} \left(1 + \delta_{\mathrm{SM,QED}} + \frac{1}{\Lambda^2} \sum_i C_i(\mu) \left\{ \Delta^{(\mathrm{NLO})}_{i,\mathrm{weak}} + \overline{\Delta}_i \ln \frac{\mu^2}{s} + \Delta_{i,\mathrm{QED}} \right\} \right)$$

EFT results including LO and IR finite virtual contributions

EFT RGE contributions

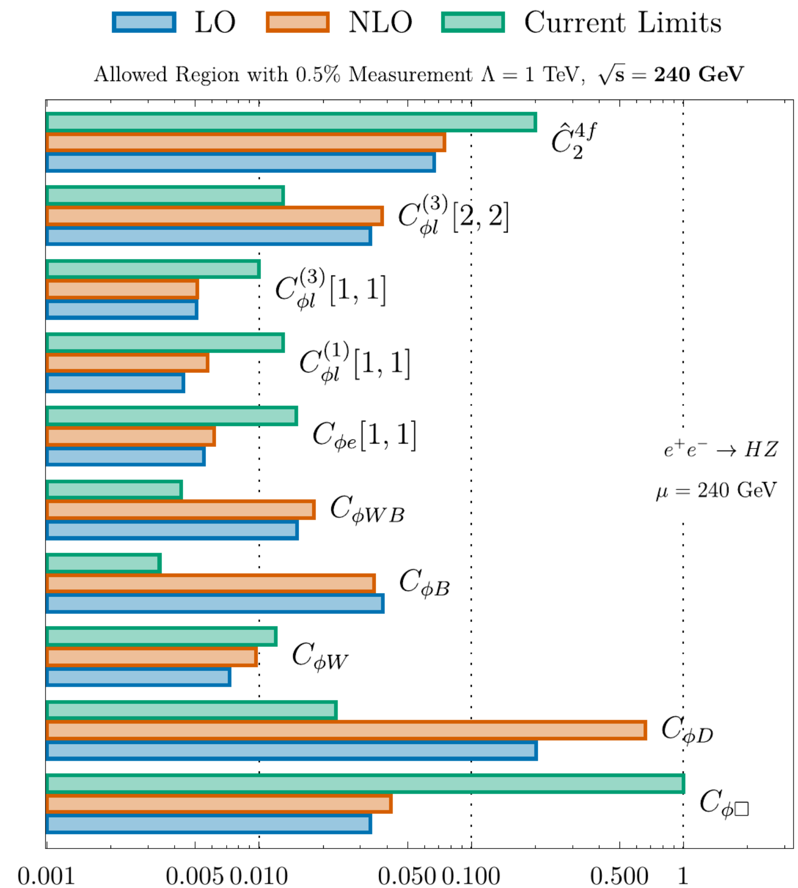
EFT real and virtual IR divergent contributions

- Virtual and real corrections are computed with $m_e = 0$ (consistently neglect contributions $\sim m_e$)
- Finite electron mass $m_e = 0.511$ MeV is recovered using massification jet functions / electron-structure functions
- We assume that new physics exists at scales $\Lambda \gtrsim 1$ TeV

SMEFT Operators Present at LO

- We consider future measurements at
  - 240 GeV with a precision of 0.5%;
  - 365 GeV and 500 GeV with a precision of 1%;

  both for polarized and unpolarized beams
- Single parameter bounds in general very similar at LO and NLO and no significant energy dependence [Global single parameter fits: J. Ellis, M. Madigan, K. Mimasu, V. Sanz, and T. You JHEP 04 (2021) 279]
- Noteworthy exception: $C_{\phi D}$ with ~ 0.2 at LO and ~ 0.7 at NLO



Unpolarized	$\sqrt{s}$ [GeV]	$\Delta_i^{(\mathrm{LO})}/\Lambda^2$	$\Delta_{i,\mathrm{weak}}^{(\delta\mathrm{NLO})}/\Lambda^2$	$\Delta_{i,\mathrm{QED}}/\Lambda^2$	$\Delta_i^{(\mathrm{NLO})}/\Lambda^2$	$\bar{\Delta}_i/\Lambda^2$
$C_{\phi D}$	240	$2.08 \cdot 10^{-2}$	$-1.20 \cdot 10^{-2}$	$-2.46 \cdot 10^{-3}$	$6.34 \cdot 10^{-3}$	$-1.12 \cdot 10^{-3}$
	365	$2.08 \cdot 10^{-2}$	$-1.35 \cdot 10^{-2}$	$2.36 \cdot 10^{-3}$	$9.69 \cdot 10^{-3}$	$-1.17 \cdot 10^{-3}$
	500	$2.09 \cdot 10^{-2}$	$-1.65 \cdot 10^{-2}$	$4.18 \cdot 10^{-3}$	$8.66 \cdot 10^{-3}$	$-1.25 \cdot 10^{-3}$

cancellation between LO contribution and NLO correction

... actually cancellation between left and right polarization

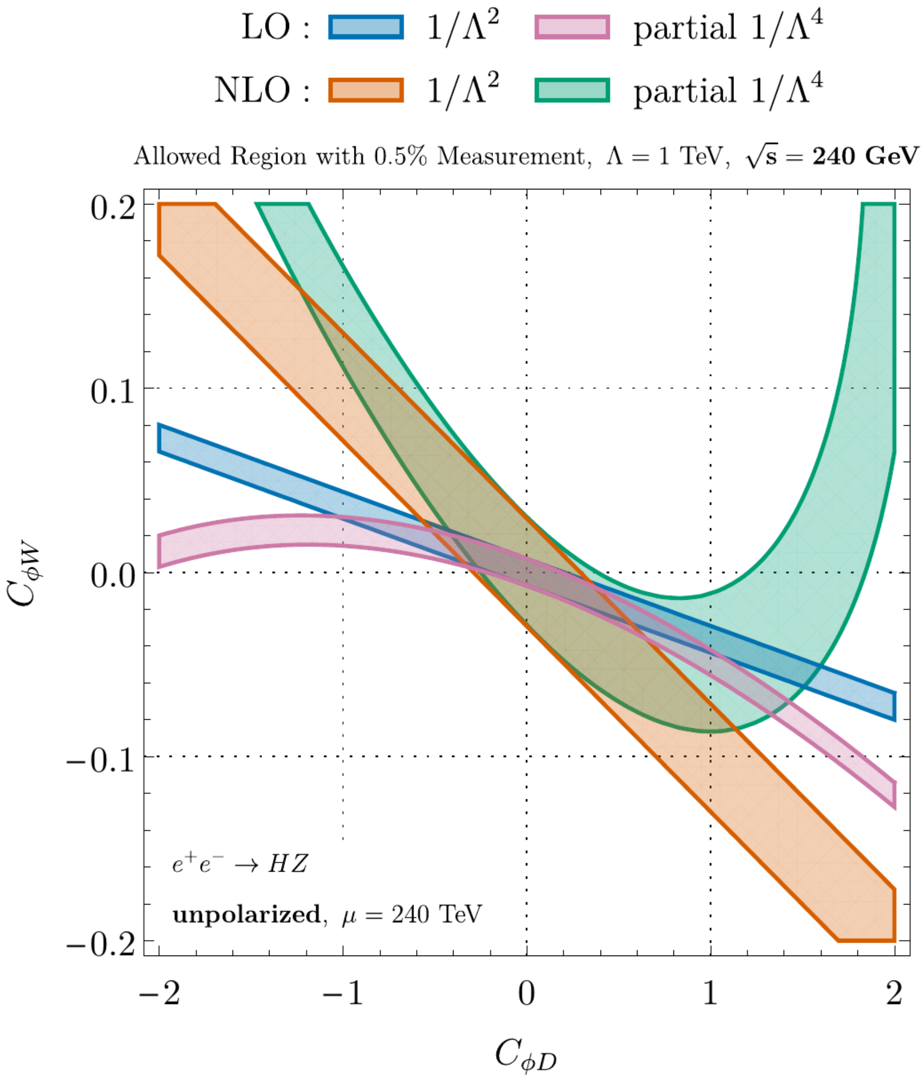
	$\sqrt{s}$ [GeV]	$\Delta_{i,\mathrm{weak}}^{(\mathrm{NLO}),L}/\Lambda^2$	$\bar{\Delta}_i^L/\Lambda^2$	$\Delta_{i,\mathrm{weak}}^{(\mathrm{NLO}),R}/\Lambda^2$	$\bar{\Delta}_i^R/\Lambda^2$	$\Delta_{i,\mathrm{weak}}^{(\mathrm{NLO})}/\Lambda^2$	$\bar{\Delta}_i/\Lambda^2$
$C_{\phi D}$	240	$1.80 \cdot 10^{-1}$	$-9.33 \cdot 10^{-3}$	$-1.97 \cdot 10^{-1}$	$8.79 \cdot 10^{-3}$	$8.80 \cdot 10^{-3}$	$-1.12 \cdot 10^{-3}$
	365	$1.71 \cdot 10^{-1}$	$-9.19 \cdot 10^{-3}$	$-1.91 \cdot 10^{-1}$	$8.53 \cdot 10^{-3}$	$7.34 \cdot 10^{-3}$	$-1.17 \cdot 10^{-3}$
	500	$1.66 \cdot 10^{-1}$	$-9.13 \cdot 10^{-3}$	$-1.86 \cdot 10^{-1}$	$8.03 \cdot 10^{-3}$	$4.49 \cdot 10^{-3}$	$-1.25 \cdot 10^{-3}$

SMEFT Operators Present at LO

- Differences between **LO** and **NLO** limits in correlated parameter fits can be quite different

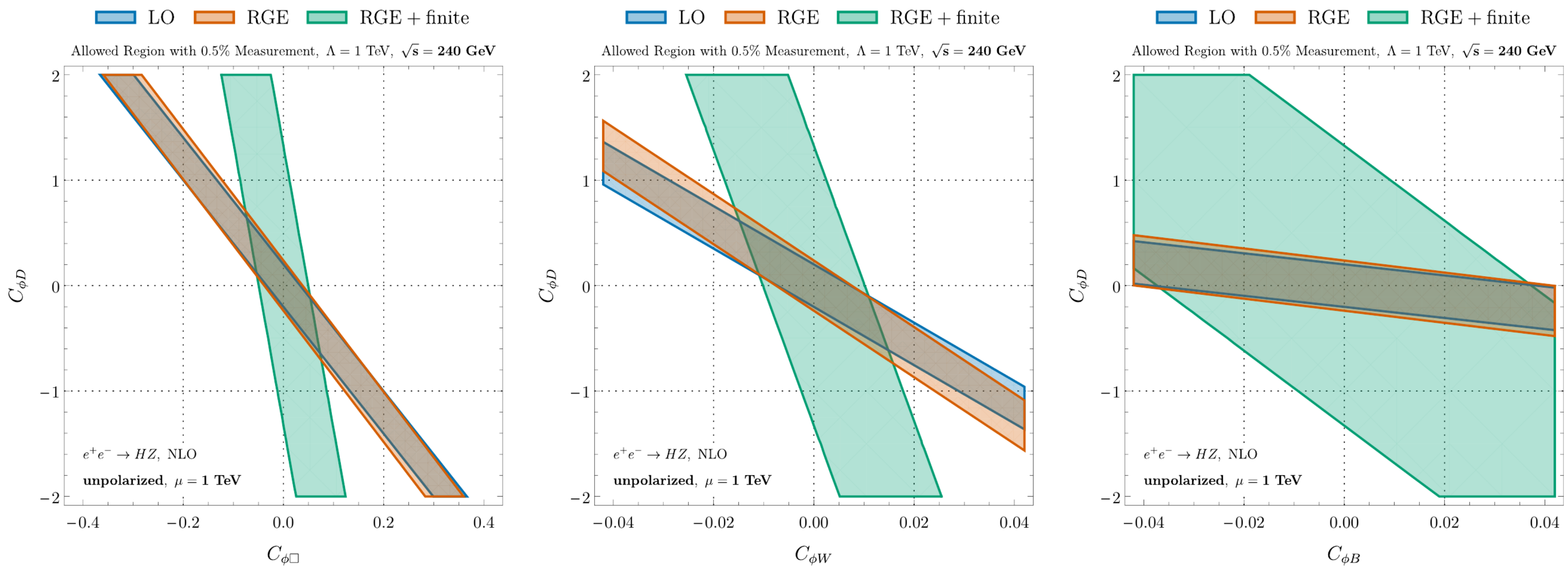
  → Effects of NLO corrections in global fits are relevant

- Assuming (LO SMEFT)^2 contribution is dominant we can also get an idea of the "validity" of the result



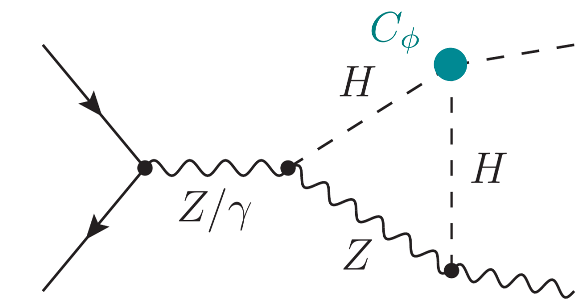
Importance of finite contributions

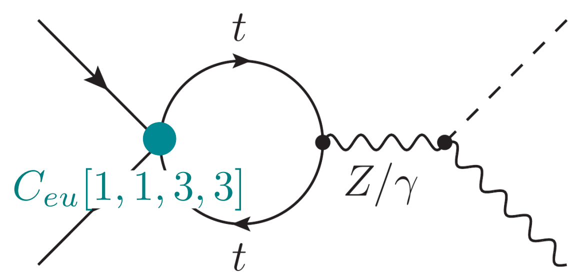
- SMEFT Wilson coefficients are regulated in $\overline{\text{MS}}$ → Scale dependent contributions can be obtained from RGE evolution [Jenkins, Manohar, Trott '13 '14; Alonso, Jenkins, Manohar, Trott '14]
- Finite contributions only from an exact higher order computations
- **In many cases the effect of the finite contributions are much larger than those of the RGE contributions**

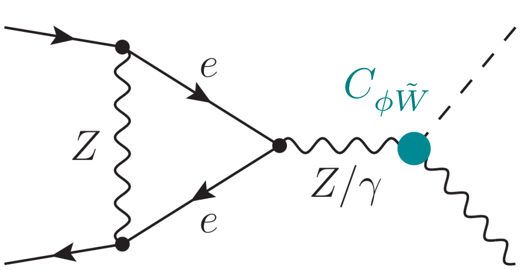


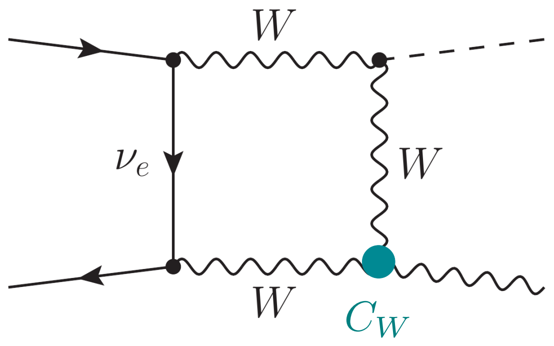
New Operators at NLO

- Through quantum corrections at NLO EW sensitive to
  - Higgs tri-linear coupling,
  - Anomalous top-quark couplings,
  - Modifications of the gauge triple-coupling
  - ...
- All well motivated by many models such as Higgs doublet or complex singlet models
- In addition: CP odd operators

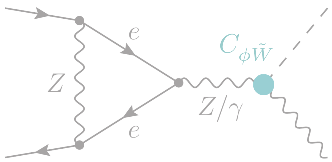


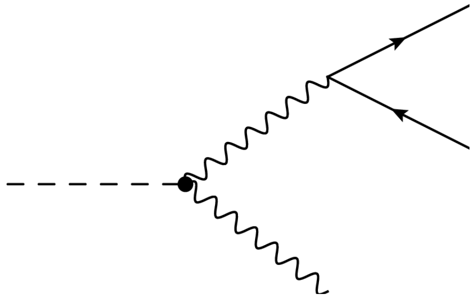


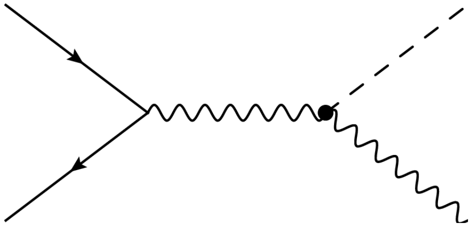




CP Violation in Higgstrahlung / Higgs decay





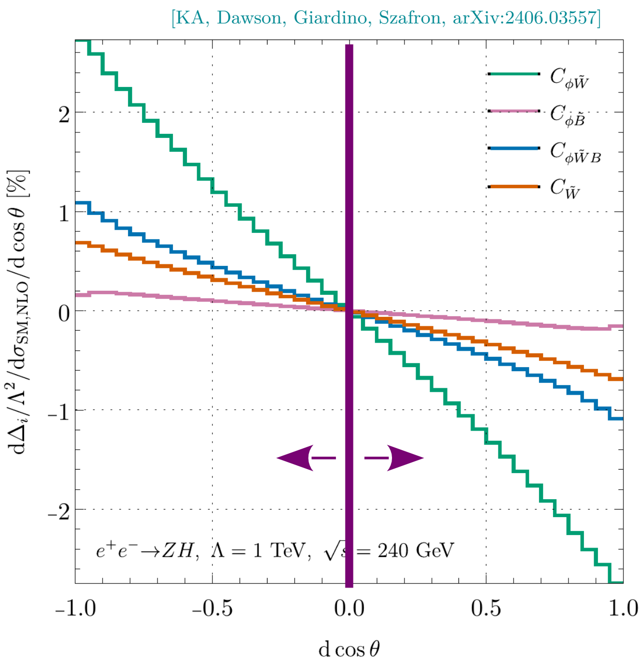


$$\sim 1 + i\frac{O_{\rm CP}}{\Lambda^2} + \mathcal{O}(1/\Lambda^4)$$

→ no interference with SM that is real at LO

- CP violation in higher orders of EFT expansion $\sim 1/\Lambda^4$
  - Plethora of studies of H → 4 leptons at LHC both from ATLAS and CMS both in SM and SMEFT
  - CP violation in SMEFT at $O(1/\Lambda^4)$ at a potential future lepton collider [JHEP 03, 050 (2016)]
  - **Requires complicated angular analysis of the 4 lepton final state**
  - See Matthew Forslund talk tomorrow (6.11. / 14:10)
- CP violation in higher orders of perturbation theory where virtual corrections can develop imaginary contributions [KA, Dawson, Giardino, Szafron 2406.03557]
  - **Simpler analysis since CP violation in Higgs (or Z) phase space**

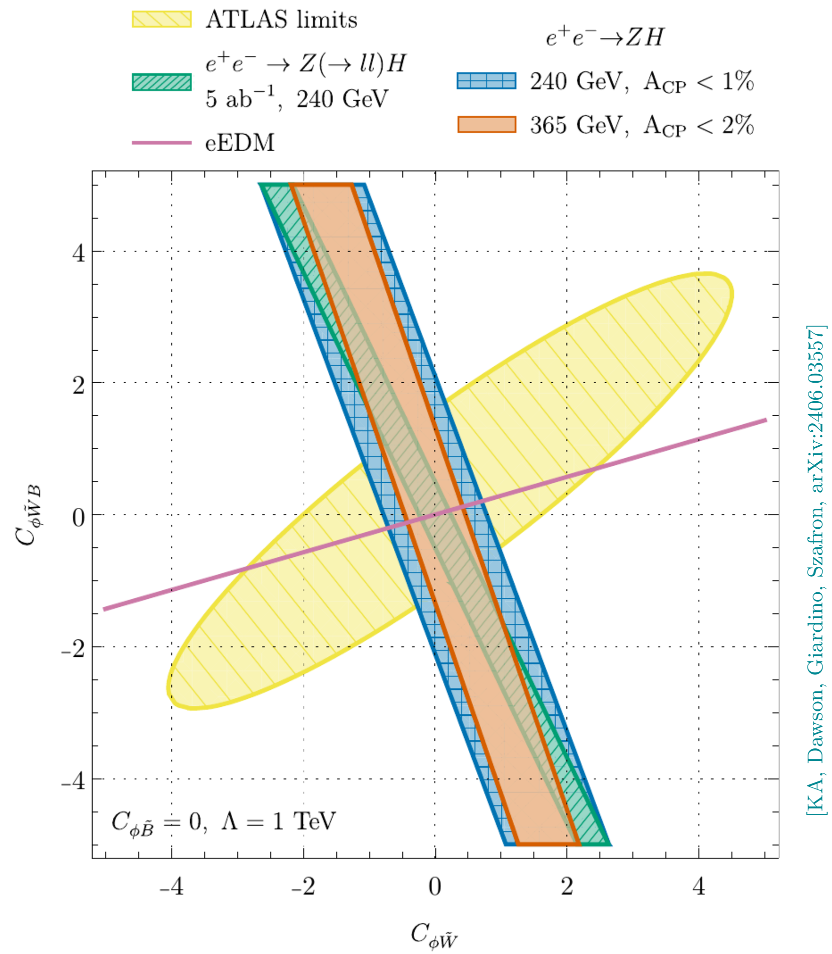
CP Violation in Higgstrahlung



- Four CP violating operators
- 2 – 3% differences close to the beam line
- Define forward-backward asymmetry

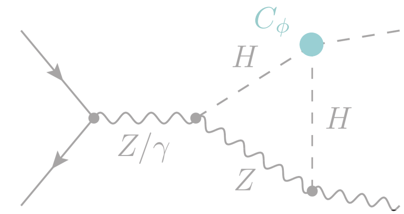
$$A_{\mathrm{CP}} = \frac{\sigma(\cos\theta < 0) - \sigma(\cos\theta > 0)}{\sigma_{\mathrm{SM,NLO}}}$$

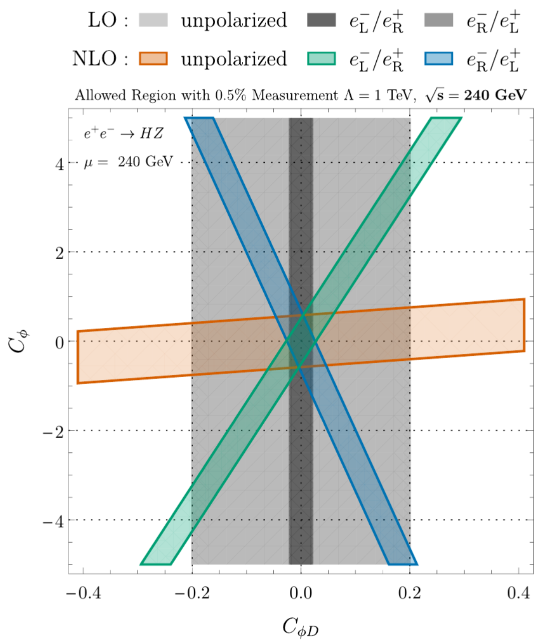
- **Comparable discriminating power as more complicated decay studies**

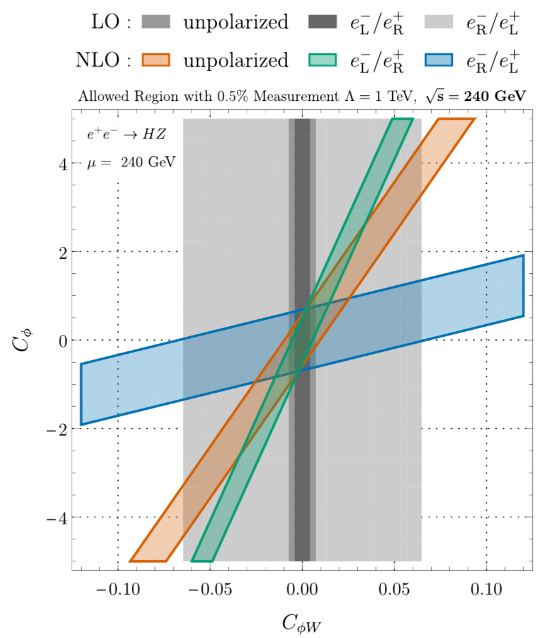


- Limits from H → 4 lepton decay at LHC [ATLAS, JHEP 05, 105 (2024)]
- Strong limits from electron electric dipole moment (eEDM) that also depends on SMEFT coefficients [ACME, Nature 562, 355 (2018)]
- Potential limits through angular observables [JHEP 03, 050 (2016)]

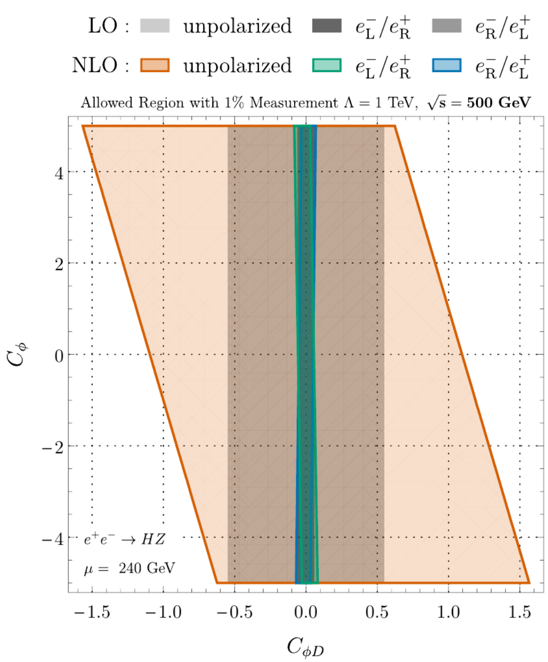
Higgs tri-linear Coupling

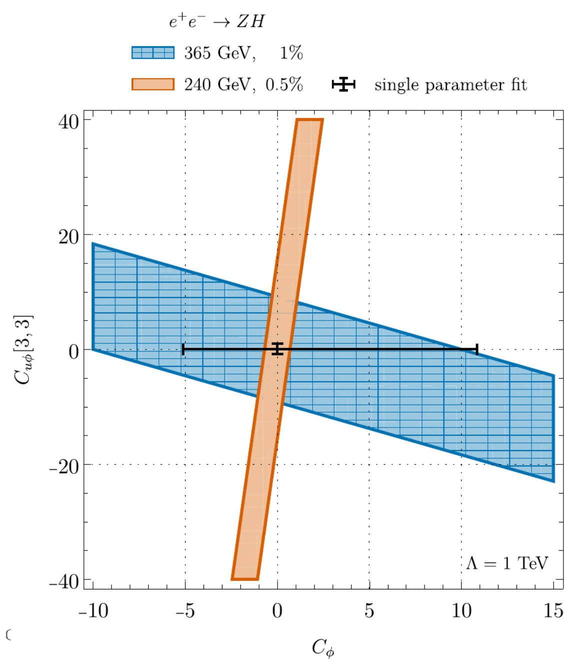






- Including or excluding contributions from different operators impacts the size of the constraints
- **Considering different polarizations can be complementary**

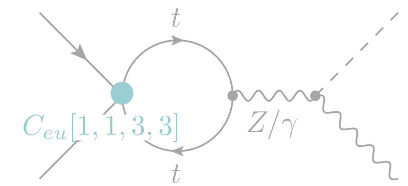




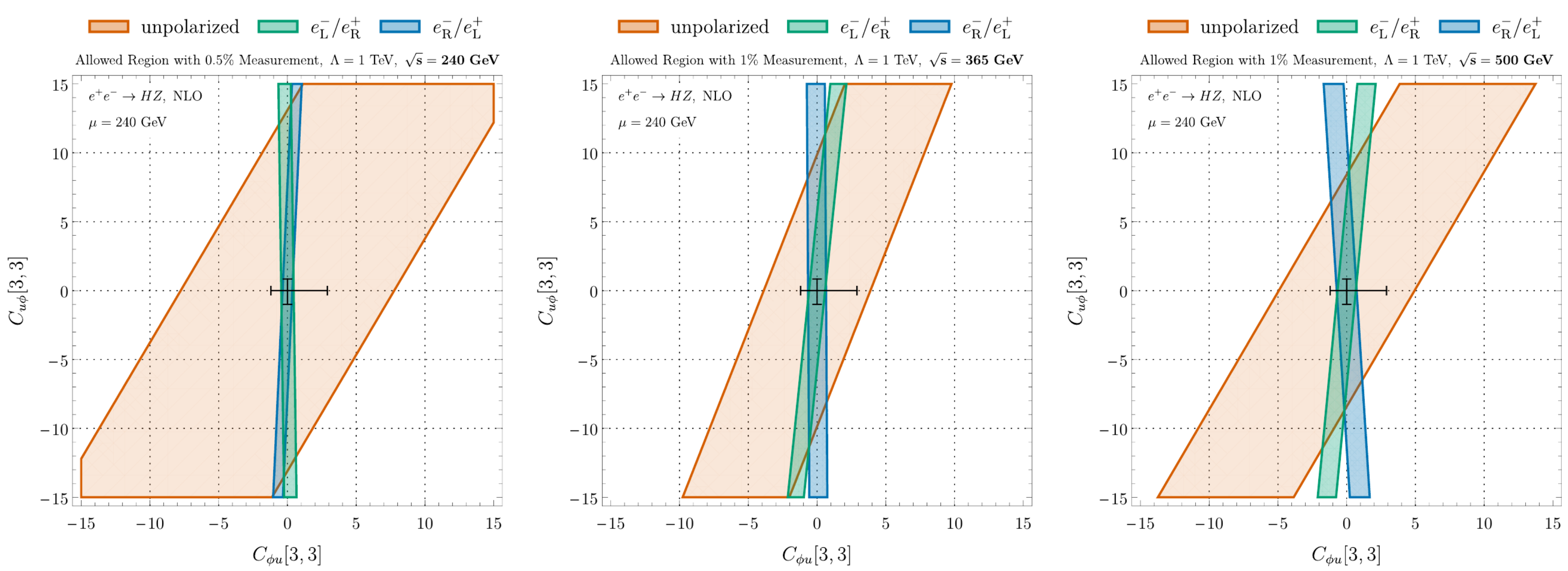
- The correlation between operators can have a large dependence over the energy
- **Measurement at two energy scales can be complementary**

Single parameter limits from global fit to LHC Higgs data [JHEP 04, 279 (2021)] and HH searches [ATLAS, arXiv:2404.05498]

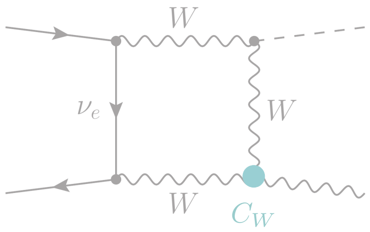
Anomalous top-quark couplings



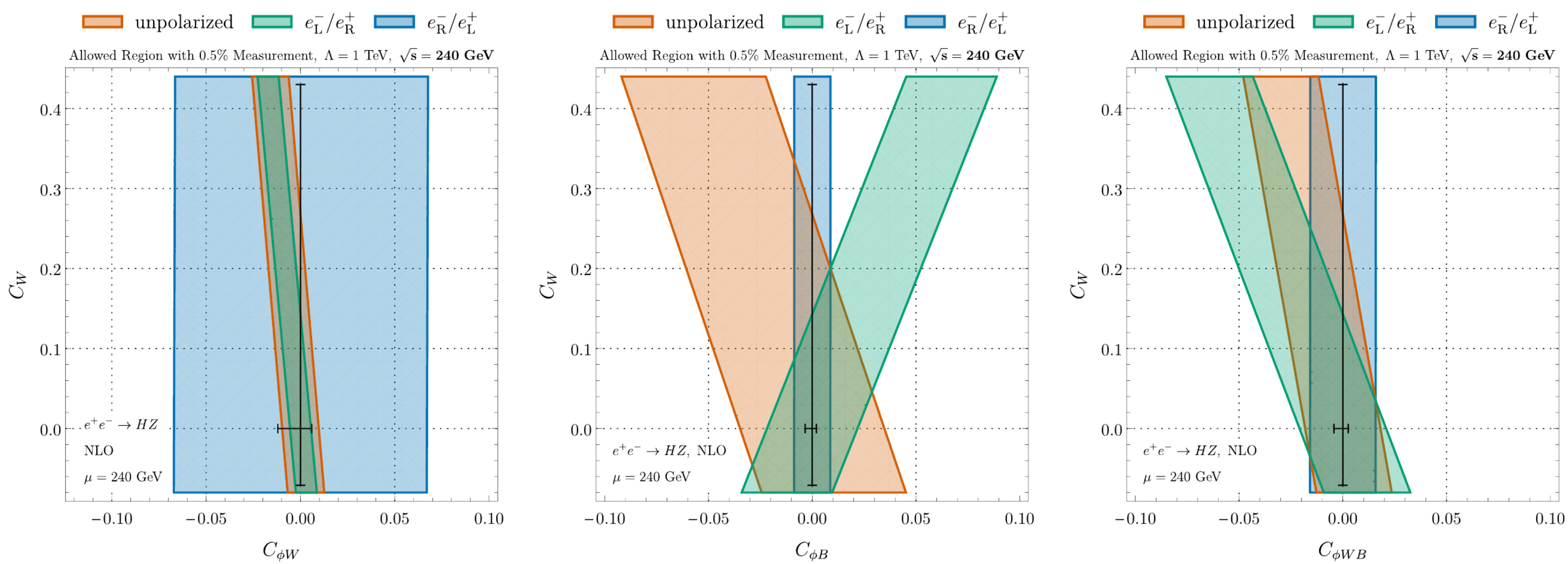
- Similar observations for top-induced NLO operators (e.g. modifications of the top-Yukawa, and top-Z coupling)
  - Spike in sensitivity around the 2-top threshold ~ 365 GeV



Modification of the gauge-triple coupling



- Consider various correlations with LO operators → we observe different degrees of correlation with LO operators
- No modification of the right-handed coupling → we observe different effects when averaging over polarizations and different sensitivities on the polarization in general



Conclusion

- SMEFT framework offers a systematic QFT-based framework that can replace the LEP-era pseudo-observables
- First complete SMEFT computation of a $2 \to 2$ process at NLO EW
- Studied impact of NLO corrections at $O(1/\Lambda^2)$
  - No huge change in single parameter limits
  - NLO corrections relevant in global fits
- Studied the potential of a potential future lepton collider (FCC-ee, ILC, ...) to measures potential BSM effects in CP violation, Higgs self-interactions and anomalous top-quark interactions
  - Although these appear first at NLO EW Higgstrahlung can be a sensitive probe for new physics scenarios
- There is a particularly huge potential in the combination of measurements at different energies
- Measurements of different polarizations can be complementary