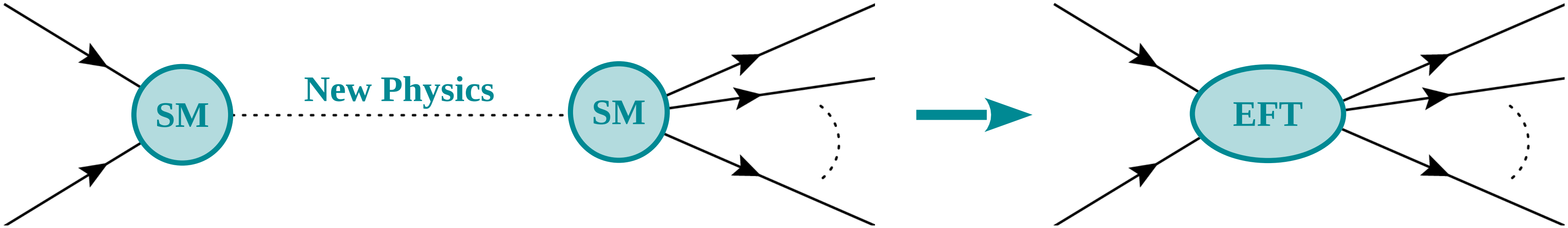
Universität Regensburg

The $e^+e^- \to ZH$ process in the Standard Model Effective Field Theory beyond Leading Order

Konstantin Asteriadis | University of Regensburg | 11.06.2024

FCC Week 2024 – San Francisco

Effective theories (EFT) as tools for BSM searches

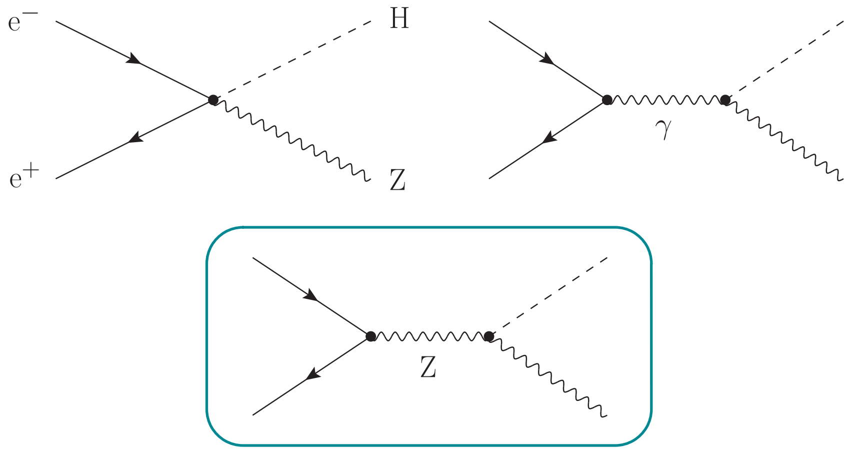


- Ideal case, detect new particles directly …
- Otherwise detect "heavy" new physics indirectly
- EFT's and the Standard Model Effective Theory (SMEFT) in particular can be a great tool to parametrize such heavy effects systematically

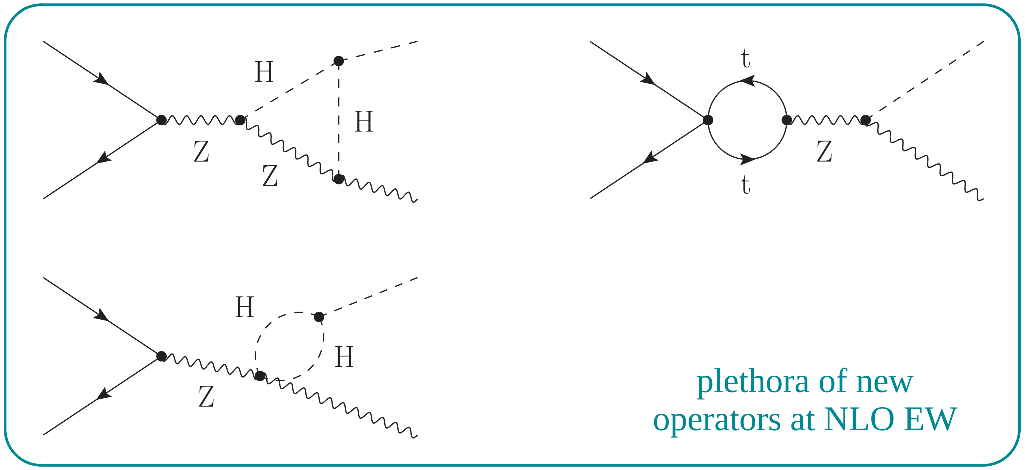
$$L_{\text{SMEFT}} = L_{\text{SM}} + \sum_i \frac{C_i^6 O_i^6}{\Lambda^2} + \sum_i \frac{C_i^8 O_i^8}{\Lambda^4} + \mathcal{O}\left(\frac{1}{\Lambda^6}\right)$$

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

Higgstrahlung in the SM and SMEFT



leading order Standard Model



- 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]

- SMEFT at LO extensively studied using LEP data → precision of future lepton collider might allow the indirect study of operators not present at LO

- **Next step: SMEFT at NLO in the electro-weak expansion** (first studies published KA, Dawson, Giardino, Szafron, arXiv:2406.03557 ... more to come soon)

SMEFT at NLO in the electro-weak expansion

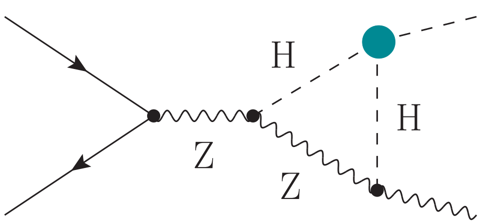
- Fully differential NLO EW calculation including ...

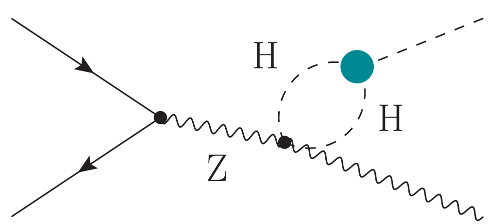
    ... potentially polarized beams

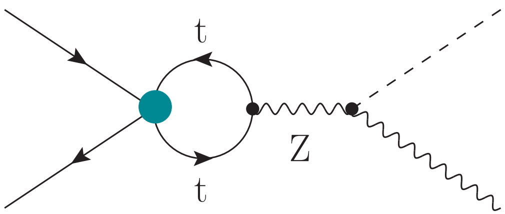
    ... all dimension-6 SMEFT operators

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

- $\mathcal{O}(10)$ Operators at LO $\rightarrow$ ~ 80 contribute to this process at NLO
- At NLO sensitive to poorly constrained interactions





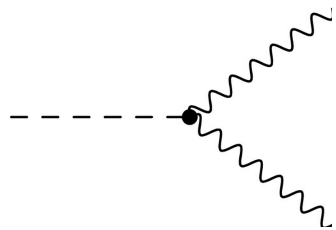


Higgs tri-linear coupling C_ϕ

4-fermion operators $C_{eu}[1,1,3,3]$

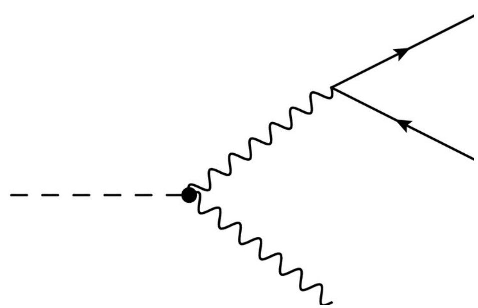
- New mechanism for CP violation in Higgsstrahlung at NLO EW (first at $\mathcal{O}(1/\Lambda^2)$)

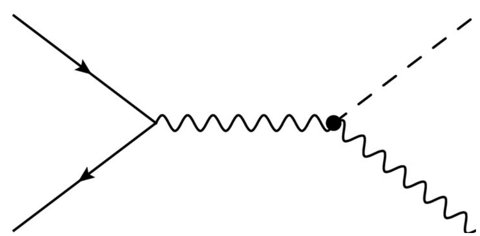
CP Violation in Higgstrahlung / Higgs decay



$$\sim (g^{\mu\nu} - p^\mu p^\nu) + \frac{O_{\mathrm{CP}}}{\Lambda^2}\epsilon^{\mu\nu\rho\sigma}p_\rho p_\sigma + \mathcal{O}(1/\Lambda^4)$$

- SM symmetric, CP violating contributions anti-symmetric → no interference
- **CP violation in higher orders of EFT expansion** $\sim 1/\Lambda^4$

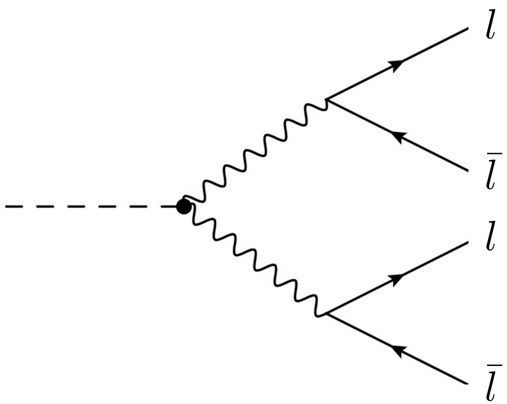


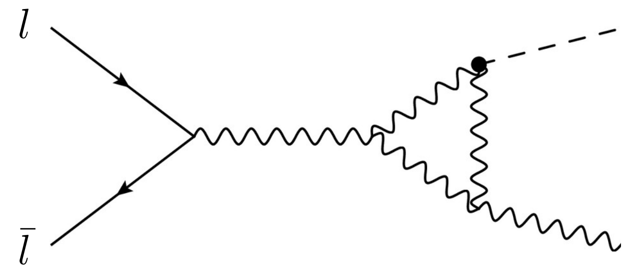


$$\sim 1 + i\frac{O_{\mathrm{CP}}}{\Lambda^2} + \mathcal{O}(1/\Lambda^4)$$

- CP violating contributions imaginary but SM is real at tree level → no interference
- **CP violation in higher orders of perturbation theory where virtual corrections can develop imaginary contributions**

CP Violation in Higgstrahlung / Higgs decay





Plethora of studies of H $\to$ 4 leptons at LHC both from ATLAS and CMS both in SM and SMEFT

Recent: CP violation in SMEFT at $\mathcal{O}(1/\Lambda^4)$ at a potential future lepton collider in JHEP 03, 050 (2016)

Requires complicated angular analysis of the 4 lepton final state

CP violation from virtual corrections studied in arXiv:2406.03557 [KA, Dawson, Giardino, Szafron]

Simpler analysis since only reconstructed Higgs (or Z) momenta enough to define asymmetry based on "total" NLO cross sections

$\to$ in the following

CP Violation in Higgstrahlung

- Four CP violating operators

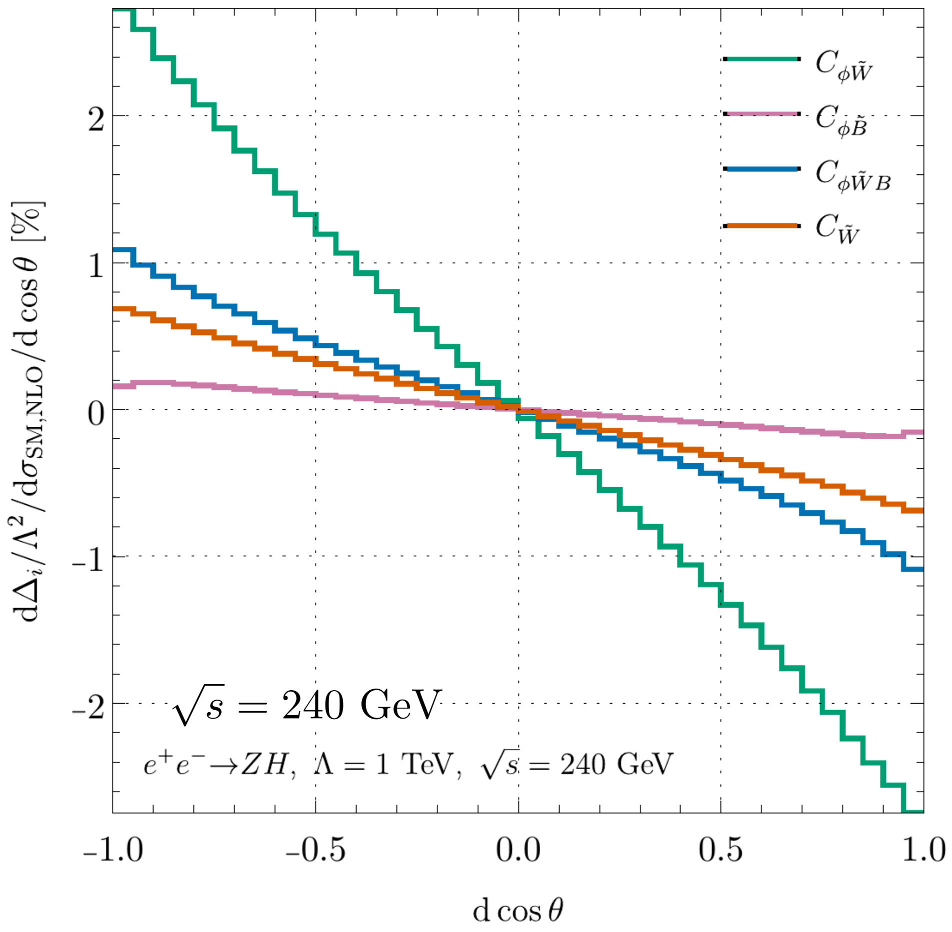
$$O_{\tilde{W}} = \epsilon_{abc} \tilde{W}_{\mu}^{a\nu} W_{\nu}^{b\rho} W_{\rho}^{c,\mu}$$
$$O_{\phi\tilde{W}} = \tilde{W}_{\mu\nu}^{a} W^{\mu\nu b} (\phi^\dagger \phi)$$
$$O_{\phi\tilde{B}} = \tilde{B}_{\mu\nu} B^{\mu\nu} (\phi^\dagger \phi)$$
$$O_{\phi\tilde{W}B} = \tilde{W}_{\mu\nu}^{a} B^{\mu\nu} (\phi^\dagger \sigma^a \phi)$$

- Assuming $\Lambda = 1$ TeV, $C_i = 1$ and $\sqrt{s} = 240$ GeV (FCC-ee)

$$\frac{\sigma_{\text{NLO}}}{\sigma_{\text{SM,NLO}}} = 1 + \sum_i \frac{C_i(\mu)}{\Lambda^2} \left\{ \Delta_i + \bar{\Delta}_i \log \frac{\mu^2}{s} \right\}$$

- 2 – 3% differences close to the beam line
- Biggest difference from $O_{\phi\tilde{W}}$
- Variations in shape

[KA, Dawson, Giardino, Szafron, arXiv:2406.03557]



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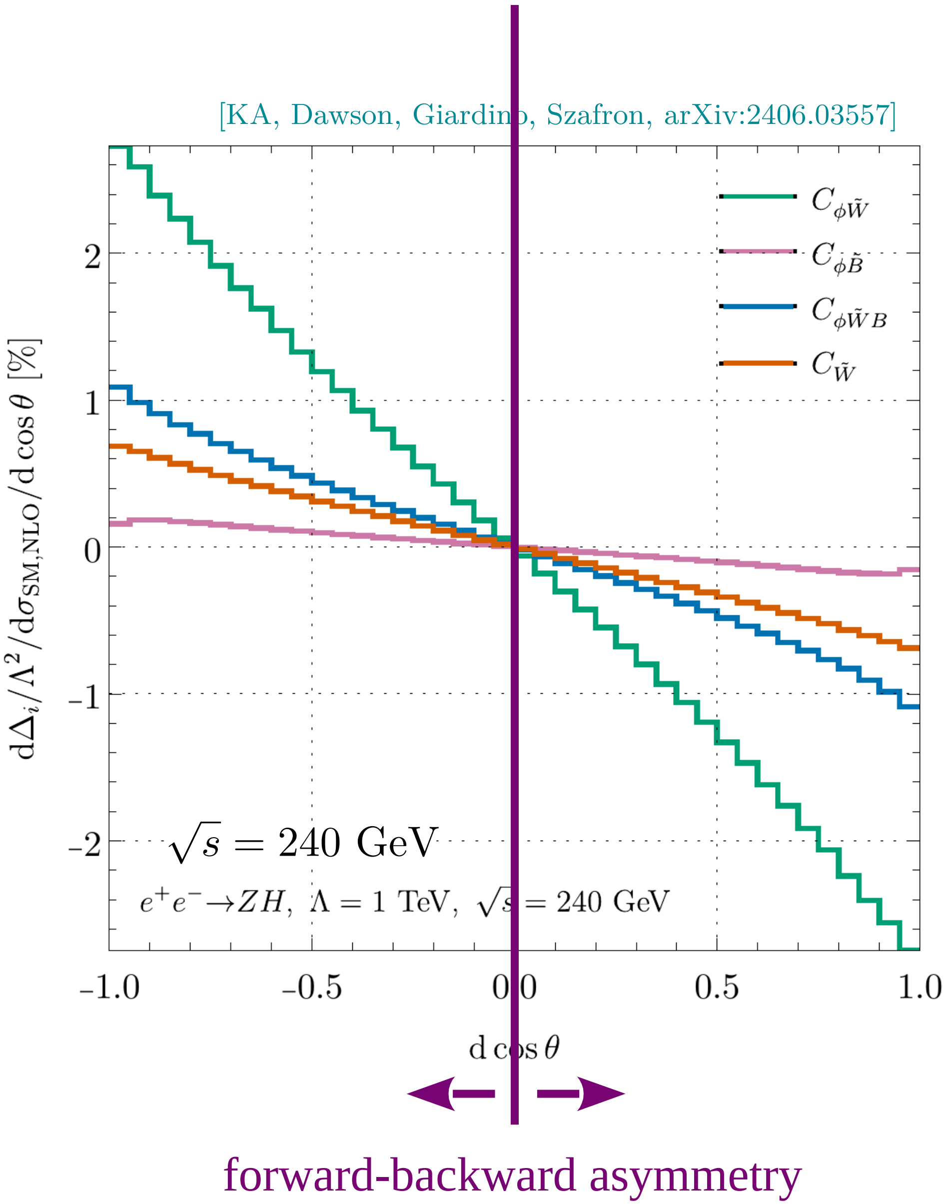
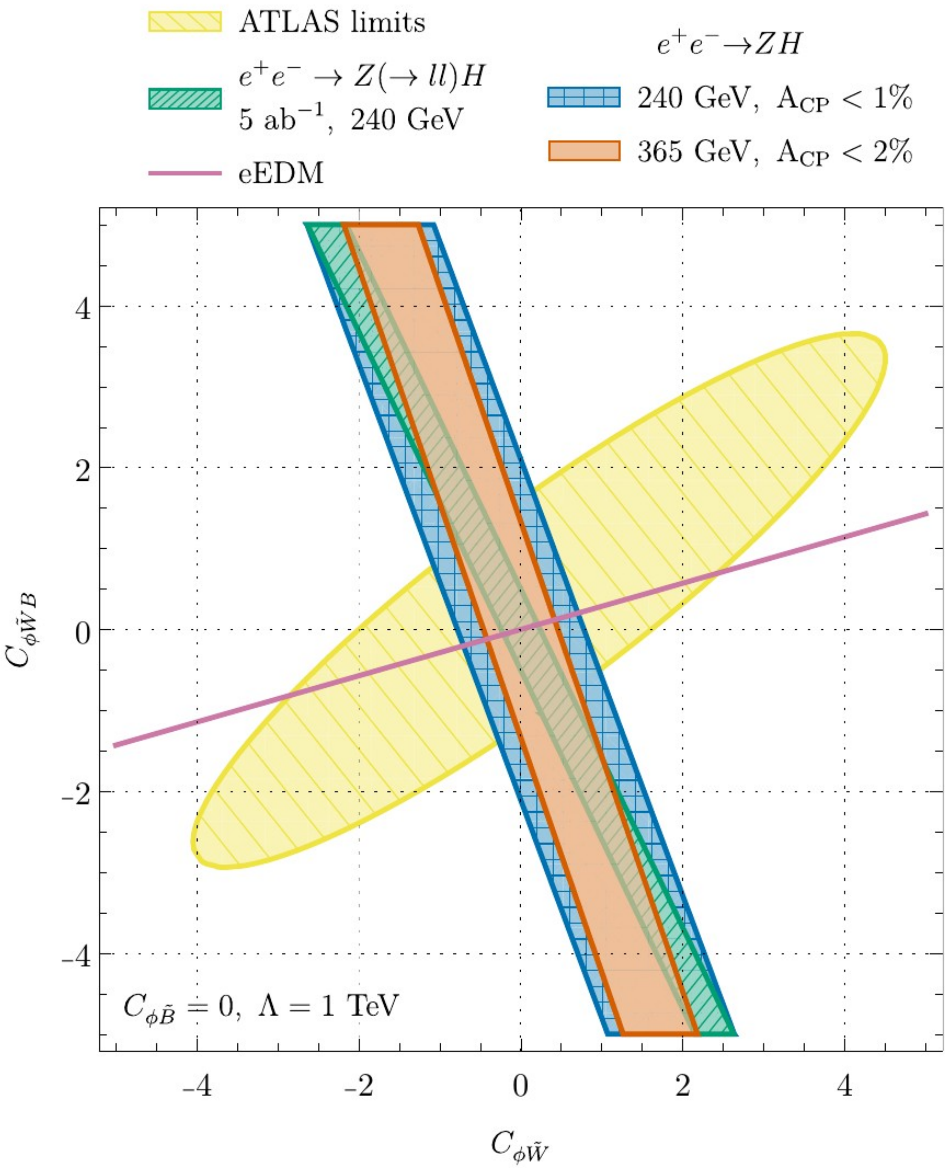


CP Violation in Higgstrahlung

- Define CP violating asymmetry

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

- Expected precision for the total cross section at FCC-ee might be as low as ~ 0.5% at 240 GeV (365 GeV ~ 1%) $\rightarrow$ Assume half the precision
- Consider $C_{\phi\tilde{W}}$ and $C_{\phi\tilde{W}B}$ (other Wilson coefficients set to 0)
- Limits from H $\rightarrow$ 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)]



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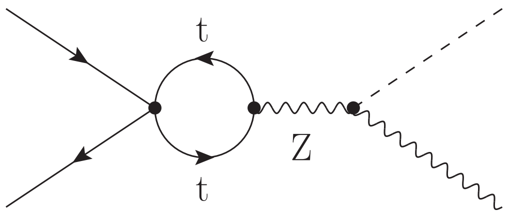
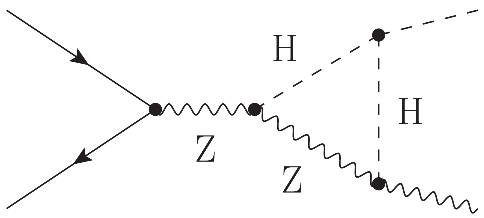
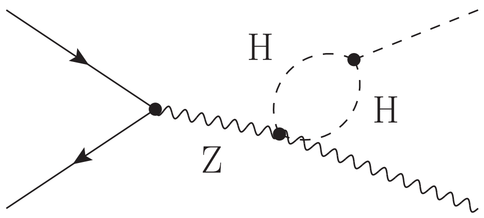
Higgs Tri-linear and Top Quark Couplings

- At NLO EW sensitive to Higgs tri-linear coupling and anomalous top-quark couplings through quantum corrections
- Well motivated by many models such as Higgs doublet or complex singlet models
- **First: Higgs tri-linear and 4-fermion coupling**
- Existing limits: Z-pole using LEP data
  [JHEP 05, 208 (2023)]
  - dependent on flavour assumptions:
    - Minimal flavour violation
    - Flavour-independent operators







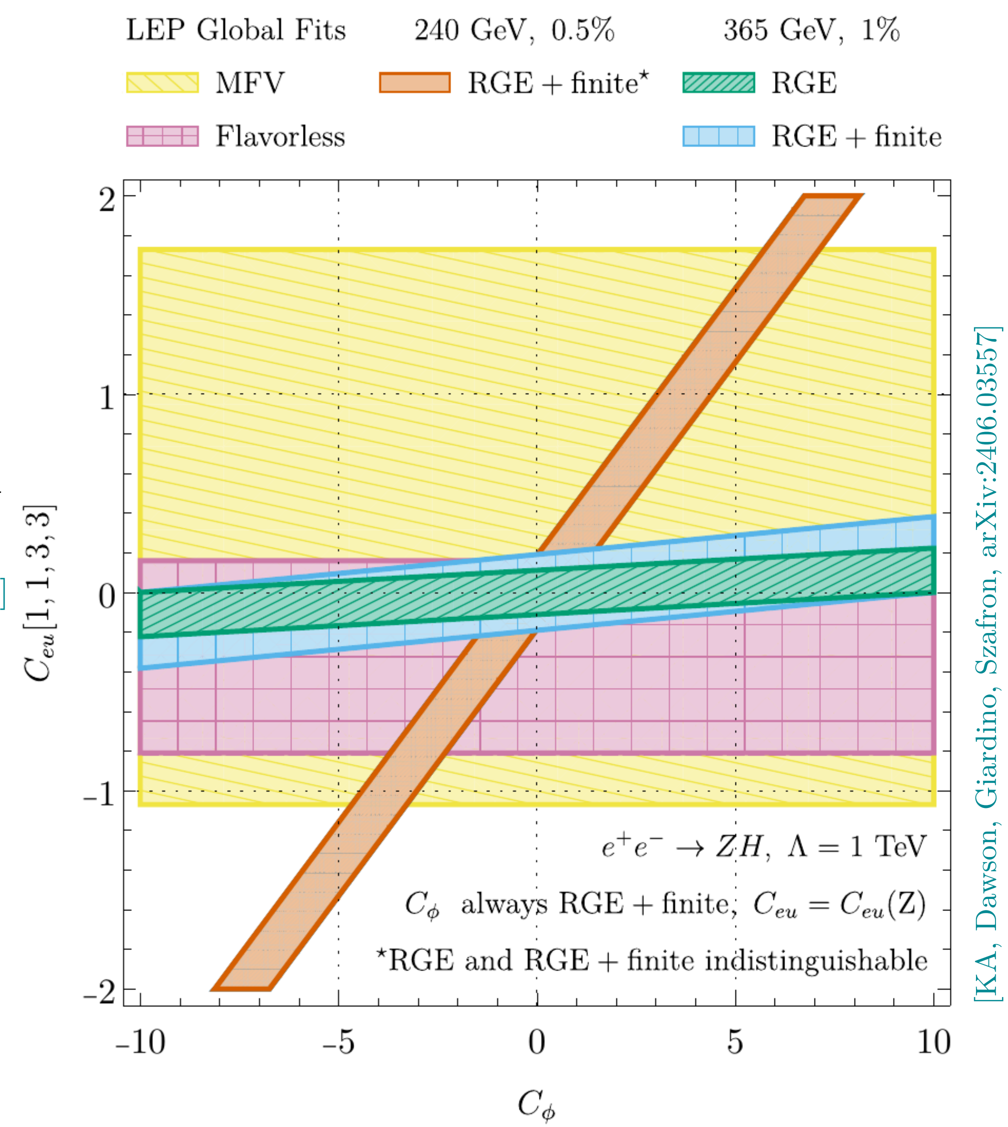
Higgs Tri-linear and Top Quark Couplings

- Consider Higgs self-interaction C_ϕ and electron-top 4-fermion operator $C_{eu}[1,1,3,3]$

- SMEFT Wilson coefficients are regulated in $\overline{\text{MS}}$ $\rightarrow$ Scale dependent contributions $\bar{\Delta}_i$ can be obtained from RGE evolution [Jenkins, Manohar, Trott '13 '14; Alonso, Jenkins, Manohar, Trott '14]

$$\frac{\sigma_{\text{NLO}}}{\sigma_{\text{SM,NLO}}} = 1 + \sum_i \frac{C_i(\mu)}{\Lambda^2}\left\{\Delta_i + \bar{\Delta}_i \log\frac{\mu^2}{s}\right\}$$

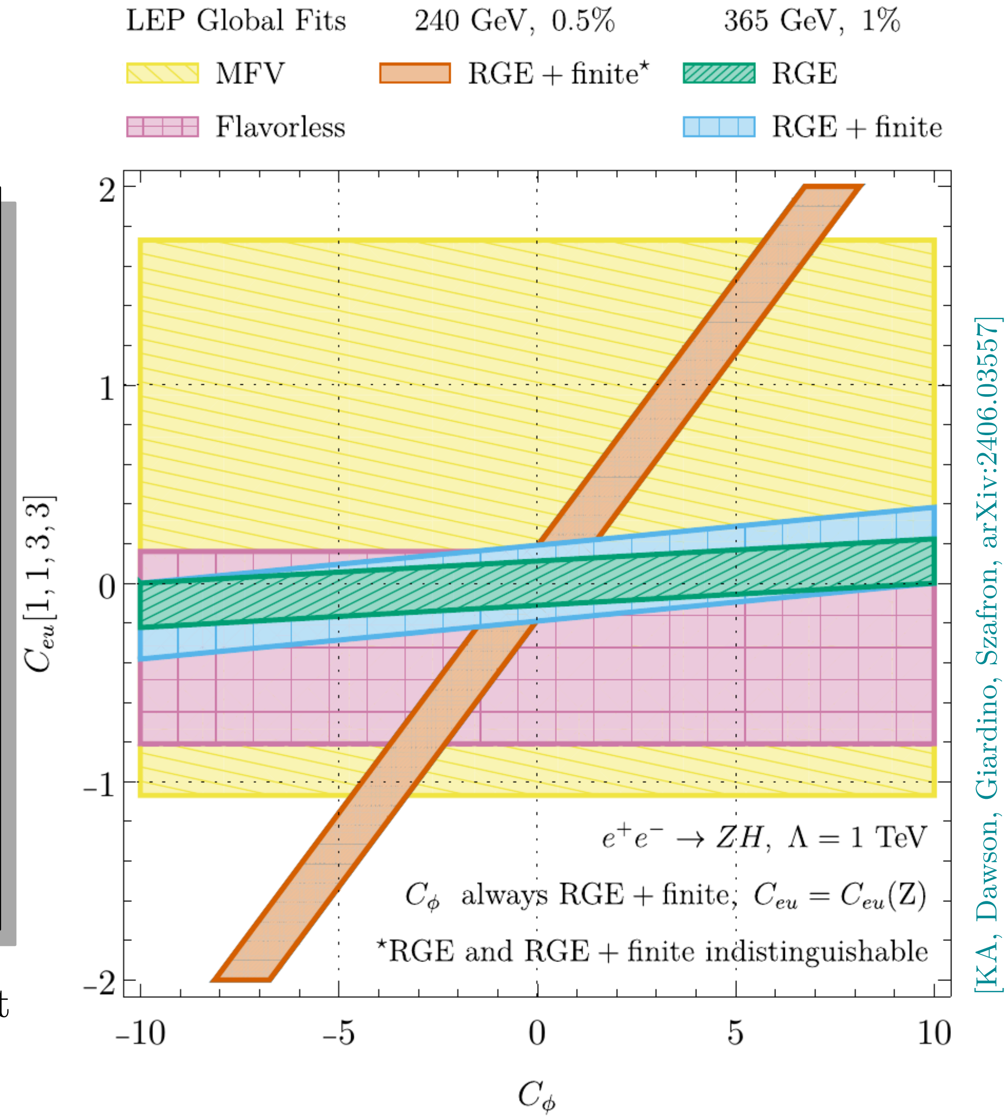
- Finite contributions Δ_i only from exact higher order computations



Importance of finite contributions

$$\frac{\sigma_{\mathrm{NLO}}}{\sigma_{\mathrm{SM,NLO}}} = 1 + \sum_i \frac{C_i(\mu)}{\Lambda^2} \left\{ \Delta_i + \bar{\Delta}_i \log \frac{\mu^2}{s} \right\}$$

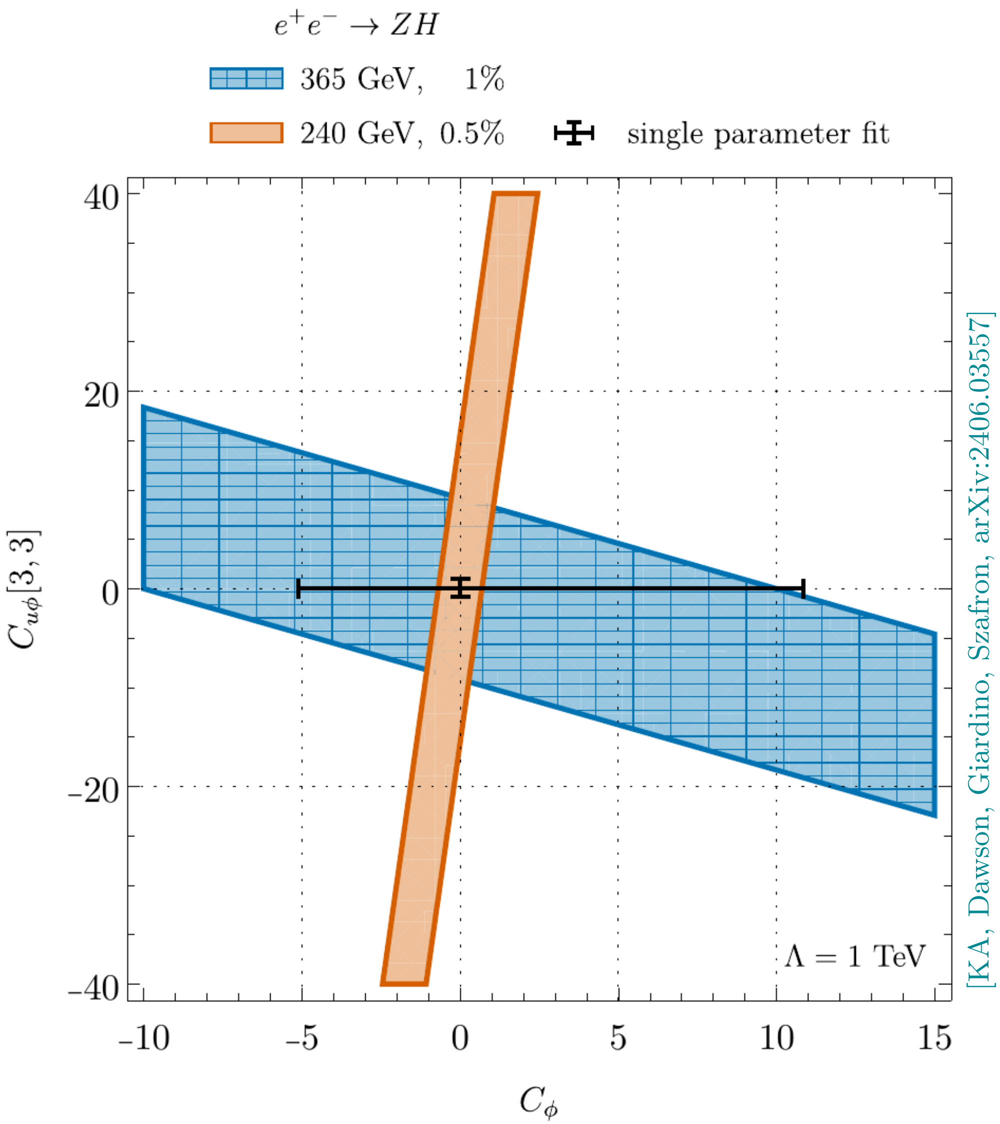
	$\sqrt{s} = 240$ GeV		$\sqrt{s} = 365$ GeV	
	Δ_i/Λ^2	$\bar{\Delta}_i/\Lambda^2$	Δ_i/Λ^2	$\bar{\Delta}_i/\Lambda^2$
C_ϕ	$-7.22\cdot10^{-3}$	0	$-1.00\cdot10^{-3}$	0
$C_{uW}[3,3]$	$-1.63\cdot10^{-3}$	$4.01\cdot10^{-3}$	$3.36\cdot10^{-3}$	$6.25\cdot10^{-3}$
$C_{uB}[3,3]$	$0.15\cdot10^{-3}$	$-2.22\cdot10^{-3}$	$-2.96\cdot10^{-3}$	$-3.20\cdot10^{-3}$
$C_{u\phi}[3,3]$	$0.32\cdot10^{-3}$	0	$-1.09\cdot10^{-3}$	0
$C_{\phi q}^{(1)}[3,3]$	$-1.34\cdot10^{-3}$	$-4.10\cdot10^{-3}$	$-4.39\cdot10^{-3}$	$-4.31\cdot10^{-3}$
$C_{\phi q}^{(3)}[3,3]$	$0.51\cdot10^{-3}$	$4.12\cdot10^{-3}$	$4.15\cdot10^{-4}$	$7.58\cdot10^{-4}$
$C_{\phi u}[3,3]$	$-0.54\cdot10^{-3}$	$3.49\cdot10^{-3}$	$5.37\cdot10^{-3}$	$3.11\cdot10^{-3}$
$C_{eu}[1,1,3,3]$	$0.01\cdot10^{-3}$	$-1.39\cdot10^{-2}$	$-3.73\cdot10^{-2}$	$-3.23\cdot10^{-2}$
$C_{lu}[1,1,3,3]$	$-0.02\cdot10^{-3}$	$1.73\cdot10^{-2}$	$4.64\cdot10^{-2}$	$4.01\cdot10^{-2}$
$C_{lq}^{(1)}[1,1,3,3]$	$-0.37\cdot10^{-2}$	$-1.80\cdot10^{-2}$	$-6.09\cdot10^{-2}$	$-4.18\cdot10^{-2}$
$C_{lq}^{(3)}[1,1,3,3]$	$-0.37\cdot10^{-2}$	$1.29\cdot10^{-2}$	$4.54\cdot10^{-2}$	$3.29\cdot10^{-2}$
$C_{qe}[3,3,1,1]$	$0.30\cdot10^{-2}$	$1.45\cdot10^{-2}$	$4.90\cdot10^{-2}$	$3.36\cdot10^{-2}$



- Whether RGE contribution is sufficient or not hugely depends on energy
- **Measurement at two energy scales complementary**

Higgs Tri-linear and Top Quark Couplings

- Consider Higgs self-interaction C_ϕ and anomalous top-Yukawa coupling $C_{u\phi}[3,3]$
- Single parameter limits from global fit to LHC Higgs data [JHEP 04, 279 (2021)] and HH searches [ATLAS, arXiv:2404.05498]
- **Measurement at two energy scales complementary**



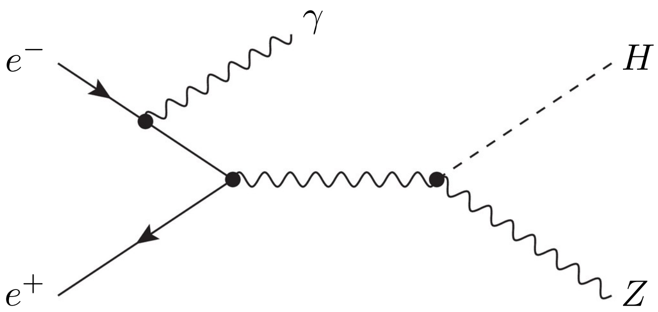
Conclusion

- First complete SMEFT computation at NLO EW
- Studied the potential of a future lepton collider (specifically FCC-ee) to measures potential BSM effects in
  - CP violation
  - Higgs self-interactions
  - Anomalous top-quark interactions

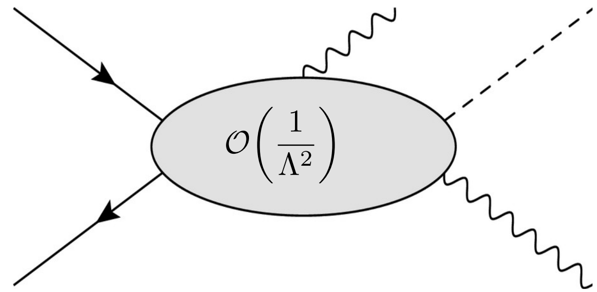
- Although these appear first at NLO EW Higgstrahlung can be a sensitive probe for new physics scenarios
- There is a particularly huge potential in the combination of measurements at different energies

Outlook: Real corrections in the SM and SMEFT (future study)

- In the SM collinear regions logarithmically enhanced
  - No huge effect e.g. for azimuthal angle between H and Z largely different then π (in COM frame of hard collision)



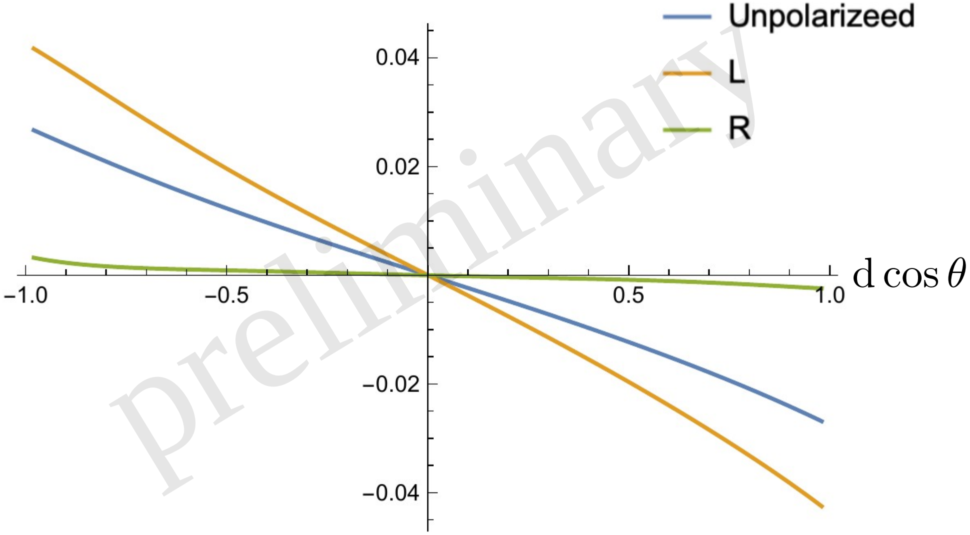
- In SMEFT additional scales cancel collinear enhancement
  - Higher order SMEFT corrections might be more homogeneous in phase space of radiation?



Outlook: More to come ...

- Closer look at operators already present at LO
- Investigate potential of polarized beams
- ...

$\mathrm{d}\Delta_{\phi\tilde{\mathrm{W}}}/\Lambda^2/\mathrm{d}\sigma_{\mathrm{SM,NLO}}/\mathrm{d}\cos\theta$ [%]



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