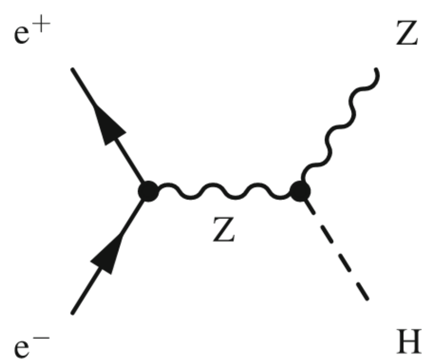
SMEFT contributions to Higgstrahlung at NLO



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Based on: K. Asteriadis, S. Dawson, P. P. Giardino, R. Szafron: 2406.03557 , arXiv:2406.xxxxx

New Physics and SMEFT@NLO

- Study deviations from SM in terms of SMEFT expansion

$$L_{SMEFT} = L_{SM} + \Sigma_i \frac{C_i^6}{\Lambda^2} O_i^6 + \Sigma_i \frac{C_i^8}{\Lambda^4} O_i^8 + ...$$

- Expansions in $1/\Lambda^2$ and in loops $1/(16\pi^2)$
- Compute cross sections consistently to $O(1/\Lambda^2)$ and $O(1/16\pi^2)$ including all electroweak corrections to NLO
- At NLO, typically gain information about many operators that do not contribute at tree level
- RGE running of dimension-6 operators from Λ to weak scales known, so logarithmic corrections come for free

NLO Electroweak SMEFT

- Broad program of computing Higgs decays at NLO in SMEFT, Z decays at NLO in dimension-6 SMEFT
  - $H \to \gamma\gamma$, $H \to \gamma Z$, $H \to VV$, $H \to bb$, $Z \to ff$
- Results can be expressed similarly to (plus tree level EFT if applicable):

$$A_{\mu\nu}(H \to \gamma Z) = \mathcal{A}\left(g_{\mu\nu} - \frac{p^\nu q^\mu}{p \cdot q}\right)$$

$$\mathcal{A} \sim \frac{a_{sm}}{16\pi^2} + \Sigma_i \frac{C_i}{\Lambda^2}\left[A_{EFT,i} + \frac{B_{EFT,i}}{16\pi^2} + \frac{C_{EFT,i}}{16\pi^2}\log(\frac{\Lambda^2}{M_Z^2})\right] + ...$$

- C_{EFT} can be found from RGE running
- B_{EFT} requires complete NLO calculation
- For $H \to \gamma\gamma$ and $H \to \gamma Z$, B_{EFT} and C_{EFT} are of similar numerical size

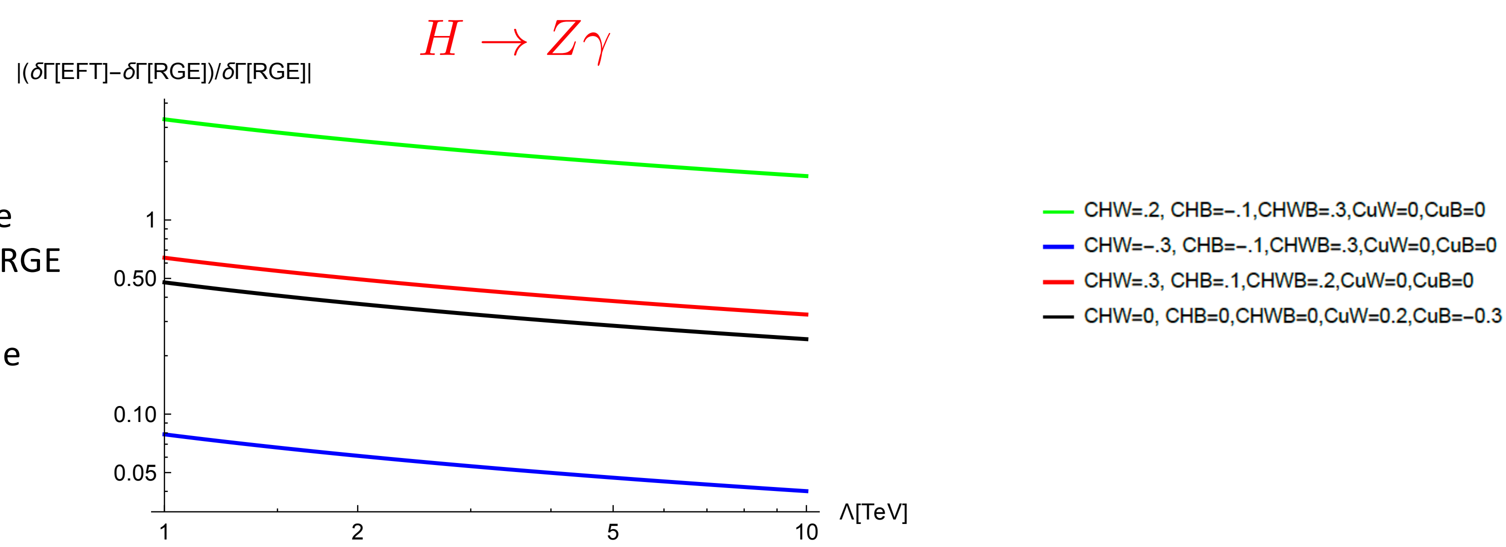
$\gamma\gamma$: 1807.11504, 1805.00302 γZ: 1801.01136, 1903.12046 $Z \to ff$: 1909.02000 $H \to bb$: 2007.15238, 1904.06358

NLO Electroweak SMEFT: Constants matter

- Example: H→Zγ
  - Λ~ 1 TeV, constants can give large effects (very dependent on specific values of coefficients)

δΓ[EFT]=Include loop constant +RGE

δΓ[RGE]=Include only RGE



1801.01136, 1903.12046

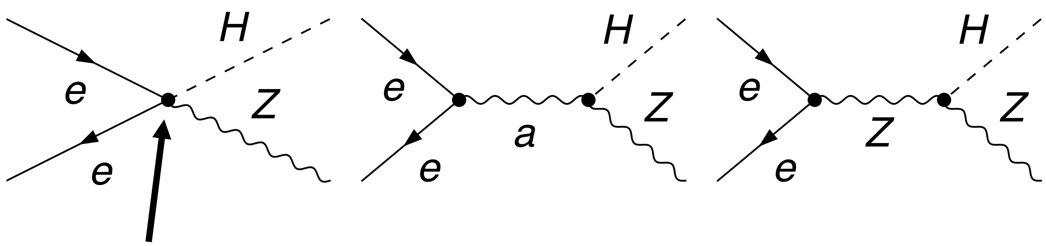
* Similar conclusions for H→γγ

New Physics and Higgstrahlung

Higgstrahlung in the SMEFT:

- New interactions, plus rescaling of SM couplings
- At tree level, dependence on 7 SMEFT coefficients

$$C_{\phi D}\,, C_{\phi\Box}\,, C_{\phi WB}\,, C_{\phi W}\,, C_{\phi B}\,, C_{\phi e}[1,1]\,, C^{+}_{\phi l}[1,1] \equiv C^{(1)}_{\phi l}[1,1] + C^{3)}_{\phi l}[1,1]$$



- Enhanced by s/Λ^2 relative to propagator diagrams
- Expect 4-fermion operators to be important at higher energies

New Physics and Higgstrahlung

$$C_{\phi D}\,,C_{\phi\Box}\,,C_{\phi WB}\,,C_{\phi W}\,,C_{\phi B}\,,C_{\phi e}[1,1]\,,C^{+}_{\phi l}[1,1]\equiv C^{(1)}_{\phi l}[1,1]+C^{(3)}_{\phi l}[1,1]$$

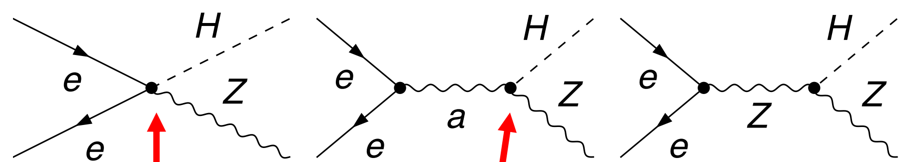
Renormalizes vev

ΔT

Needed to get canonical kinetic energy for Higgs

ΔS

Contribute to gauge boson 2-point functions

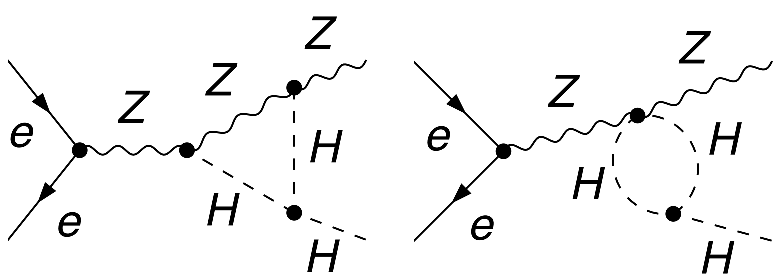


$C_{\phi e}[1,1],\ C^{+}_{\phi l}[1,1]$

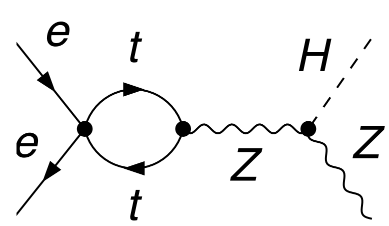
$C_{\phi W},\ C_{\phi B},\ C_{\phi WB}$

Higgstrahlung at NLO EW SMEFT

- Complete NLO calculation including all dimension-6 operators for polarized e^-, e^+
  - (~80 SMEFT operators contribute)
- One-loop virtual + tree level real photon emission
  - Generate with FeynArts → FeynCalc → Package-X
  - Renormalize on-shell for M_W, M_Z, $\overline{\mathrm{MS}}$ for Wilson Coefficients, $C_i(\mu)$
- Sensitive to poorly constrained interactions that first arise at NLO



Higgs tri-linear coupling, C_ϕ



4-fermion operators, $C_{eu}[1133]$

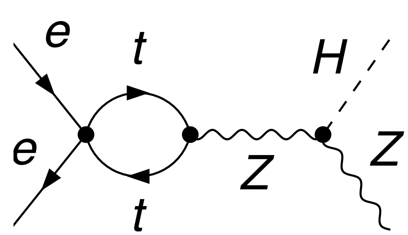
+ many more

$e^+e^- \rightarrow ZH$ is window to many new interactions

- Sensitivity to Higgs tri-linear correlated with other contributions
  - Calculate cross section to $1/\Lambda^2$ so results are linear bands
- How do future constraints compare with existing information?
  - Assume .5% accuracy on total cross section measurement at $\sqrt{s}$=240 GeV, 1% at $\sqrt{s}$=365 GeV
- Compare with limits from LEP Z-pole observables and predictions for Tera-Z
  - Compare with global fits using MFV and $U(3)^5$ flavor assumptions
  - Compare with FCC-ee Z projections

Top-loop mediated new physics

- Top mass enhances contribution



- Top contributions that contribute at NLO:
  - Dipole: $C_{uW}[3,3],\ C_{uB}[3,3]$
  - Top-Yukawa: $C_{u\phi}[3,3]$
  - Top-Z coupling:

$C_{\phi q}^{(1)}[3,3],\ C_{\phi q}^{(3)}[3,3], C_{\phi u}[3,3]$

  - 4-fermion electron-top interactions

$C_{eu}[1,1,3,3], C_{lu}[1,1,3,3],$

$C_{lq}^{(1)}[1,1,3,3], C_{lq}^{(3)}[1,1,3,3], C_{qe}[3,3,1,1]$

Results for top quark related operators

- Polarized and unpolarized results

$$\frac{\sigma^{L,R}_{NLO}}{\sigma^{L,R}_{SM,NLO}} = 1 + \Sigma \frac{C_i}{\Lambda^2}\left(\Delta_i^{L,R}(s) + \bar{\Delta}_i^{L,R}(s)\log\frac{\mu^2}{s}\right)$$

- Logs and constants frequently of the same size

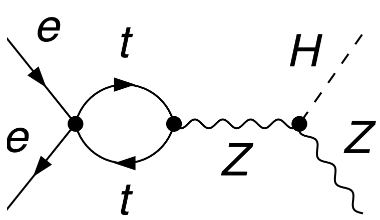
		Δ_i^L/Λ^2	Δ_i^L/Λ^2	Δ_i^R/Λ^2	Δ_i^R/Λ^2	Δ_i/Λ^2	Δ_i/Λ^2
	$\sqrt{s} = 240\,\text{GeV}$			$2.81 \cdot 10^{-5}$	$-3.06 \cdot 10^{-2}$	$1.28 \cdot 10^{-5}$	$-1.39 \cdot 10^{-2}$
$C_{eu}[1,1,3,3]$	$\sqrt{s} = 365\,\text{GeV}$			$-8.23 \cdot 10^{-2}$	$-7.11 \cdot 10^{-2}$	$-3.73 \cdot 10^{-2}$	$-3.23 \cdot 10^{-2}$
	$\sqrt{s} = 500\,\text{GeV}$			$-2.76 \cdot 10^{-1}$	$-1.32 \cdot 10^{-1}$	$-1.27 \cdot 10^{-1}$	$-6.07 \cdot 10^{-2}$
	$\sqrt{s} = 240\,\text{GeV}$	$-2.90 \cdot 10^{-5}$	$3.15 \cdot 10^{-2}$			$-1.59 \cdot 10^{-5}$	$1.73 \cdot 10^{-2}$
$C_{lu}[1,1,3,3]$	$\sqrt{s} = 365\,\text{GeV}$	$8.45 \cdot 10^{-2}$	$7.31 \cdot 10^{-2}$			$4.64 \cdot 10^{-2}$	$4.01 \cdot 10^{-2}$
	$\sqrt{s} = 500\,\text{GeV}$	$2.91 \cdot 10^{-1}$	$1.39 \cdot 10^{-1}$			$1.58 \cdot 10^{-1}$	$7.54 \cdot 10^{-2}$
	$\sqrt{s} = 240\,\text{GeV}$	$-6.70 \cdot 10^{-3}$	$-3.29 \cdot 10^{-3}$			$-3.67 \cdot 10^{-3}$	$-1.80 \cdot 10^{-2}$
$C_{lq}^{(1)}[1,1,3,3]$	$\sqrt{s} = 365\,\text{GeV}$	$-1.11 \cdot 10^{-1}$	$-7.62 \cdot 10^{-2}$			$-6.09 \cdot 10^{-2}$	$-4.18 \cdot 10^{-2}$
	$\sqrt{s} = 500\,\text{GeV}$	$-3.07 \cdot 10^{-1}$	$-1.45 \cdot 10^{-1}$			$-1.66 \cdot 10^{-1}$	$-7.86 \cdot 10^{-2}$
	$\sqrt{s} = 240\,\text{GeV}$	$-4.84 \cdot 10^{-3}$	$2.52 \cdot 10^{-2}$	$-2.34 \cdot 10^{-3}$	$-2.03 \cdot 10^{-3}$	$-3.71 \cdot 10^{-3}$	$1.29 \cdot 10^{-2}$
$C_{lq}^{(3)}[1,1,3,3]$	$\sqrt{s} = 365\,\text{GeV}$	$8.61 \cdot 10^{-2}$	$6.17 \cdot 10^{-2}$	$-4.06 \cdot 10^{-3}$	$-2.03 \cdot 10^{-3}$	$4.54 \cdot 10^{-2}$	$3.29 \cdot 10^{-2}$
	$\sqrt{s} = 500\,\text{GeV}$	$2.62 \cdot 10^{-1}$	$1.20 \cdot 10^{-1}$	$-5.29 \cdot 10^{-3}$	$-2.01 \cdot 10^{-3}$	$1.39 \cdot 10^{-1}$	$6.40 \cdot 10^{-2}$
	$\sqrt{s} = 240\,\text{GeV}$			$6.51 \cdot 10^{-3}$	$3.19 \cdot 10^{-2}$	$2.95 \cdot 10^{-3}$	$1.45 \cdot 10^{-2}$
$C_{qe}[3,3,1,1]$	$\sqrt{s} = 365\,\text{GeV}$			$1.08 \cdot 10^{-1}$	$7.41 \cdot 10^{-2}$	$4.90 \cdot 10^{-2}$	$3.36 \cdot 10^{-2}$
	$\sqrt{s} = 500\,\text{GeV}$			$2.91 \cdot 10^{-1}$	$1.38 \cdot 10^{-1}$	$1.34 \cdot 10^{-1}$	$6.33 \cdot 10^{-2}$

PRELIMINARY

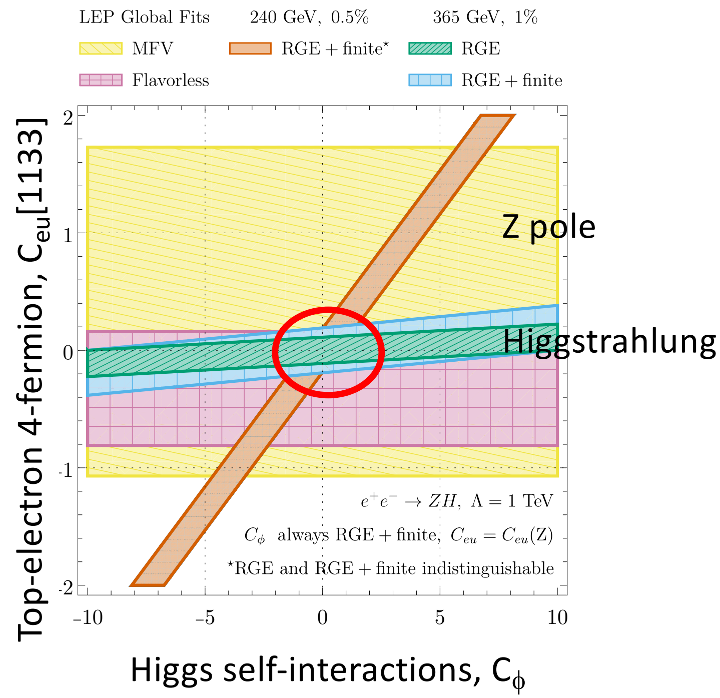
In preparation: Tables for all operators that contribute for various energies

*QED corrections considered separately

$e^+e^- \rightarrow ZH$ is window to many new interactions



Observables at different scales: Z pole observables at M_Z, Higgstrahlung at $\sqrt{s}$



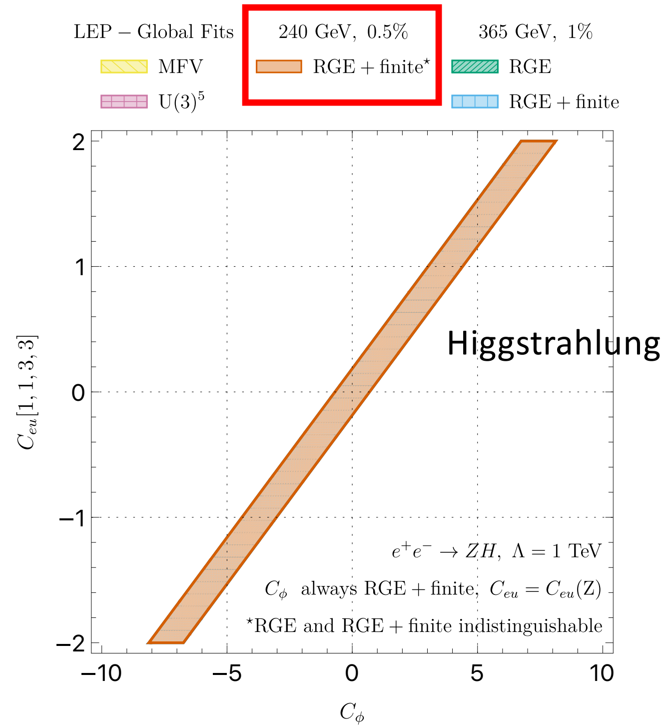
Power of measurement at 2 different energies

2406.03557

* C's in plots evaluated at $\mu=M_Z$

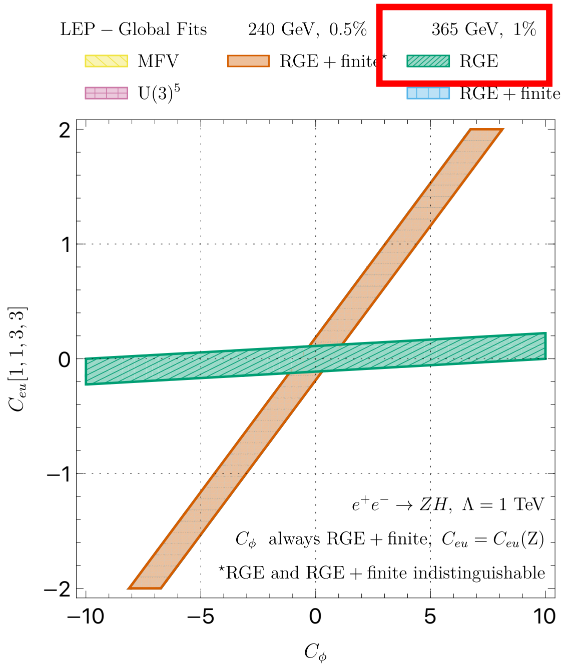
Go through plot slowly

- Λ= 1 TeV
- Assume accuracy of 0.5% for √s=240 GeV
- At √s=240 GeV most of the information from Log terms
- C_ϕ does not have log dependence



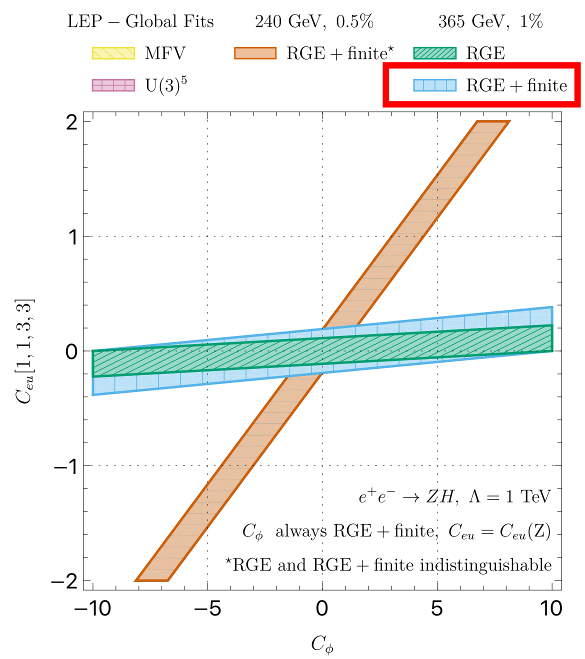
Results have different energy dependence

- Assume accuracy of 1% for √s=365 GeV
- Result at √s=365 GeV much less sensitive than at √s=240 GeV



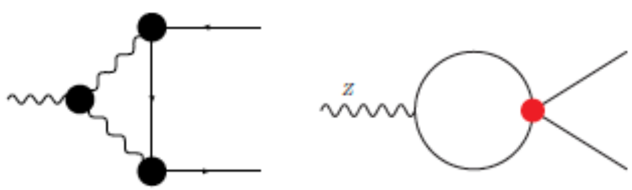
Now add constant pieces

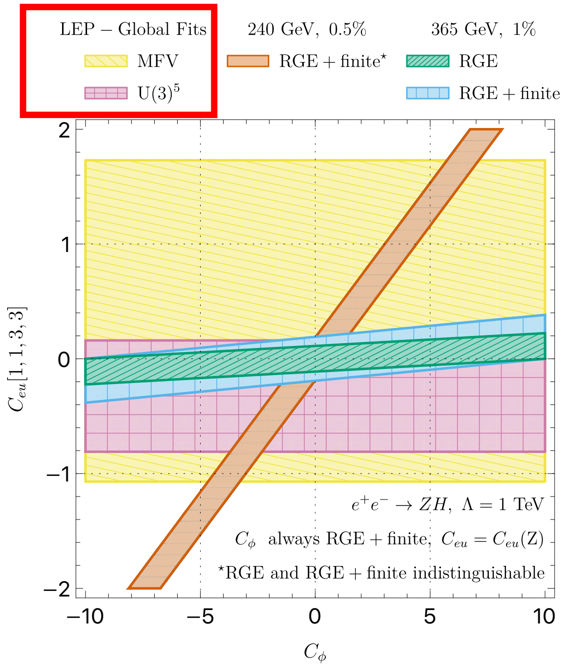
- At √s=365 GeV, both constant pieces and log terms matter



Add limits from Z-pole data

- Z-pole data has no C_ϕ dependence
- Consider new physics only in top quark interactions (MFV) or with a $U(3)^5$ flavor symmetry

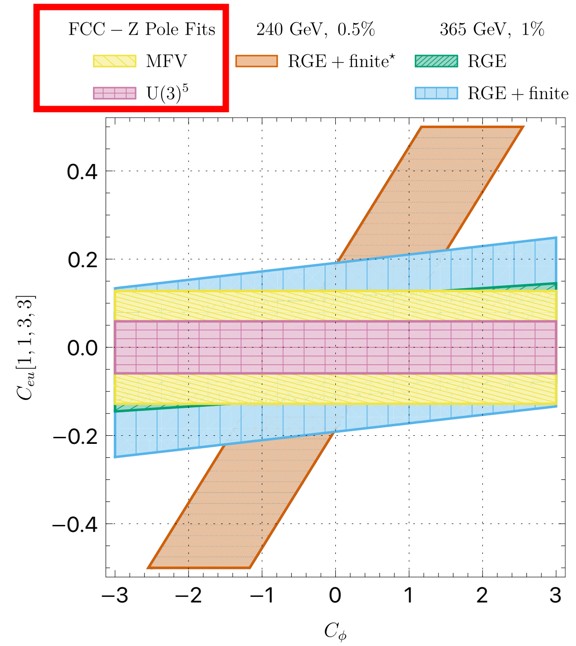




Z pole SMEFT NLO: [2304.00029](), [2201.09887]()

Limits will be improved with future Z-pole running

- Z pole running and Higgstrahlung give complementary information
- (Note y-axis scale)

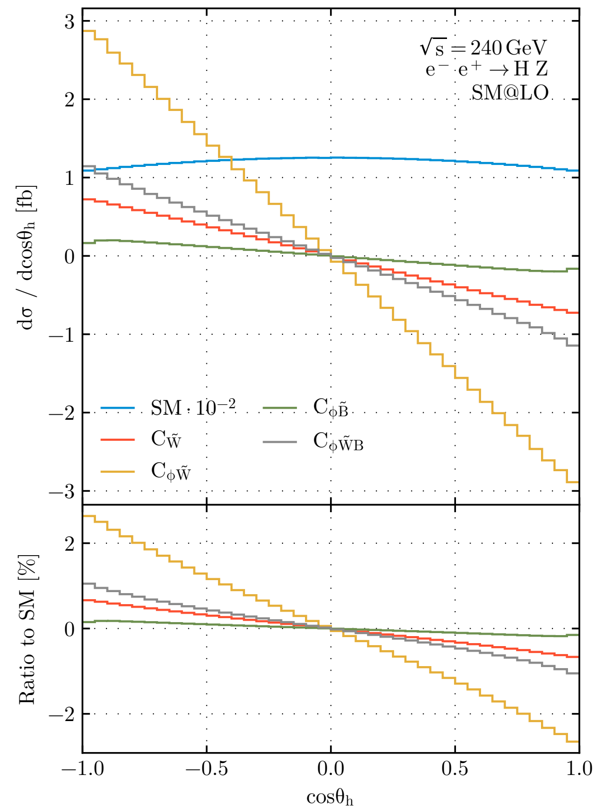


Sensitivity to CP violation

- Higgstrahlung at e^+e^- colliders is sensitive to CP violation in the gauge sector at NLO
- At tree level and to $O(1/\Lambda^2)$, CP violating dimension-6 operators do not interfere with the SM contribution from $e^+e^- \to ZH$ (since SM contribution is real and CP violating piece is imaginary)
- At one-loop, there is a contribution from imaginary part of loop integrals

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

* These operators contribute at tree level to $e^+e^- \to W^+W^-$



CP violation at future e^+e^- colliders

- Define CP violating asymmetry

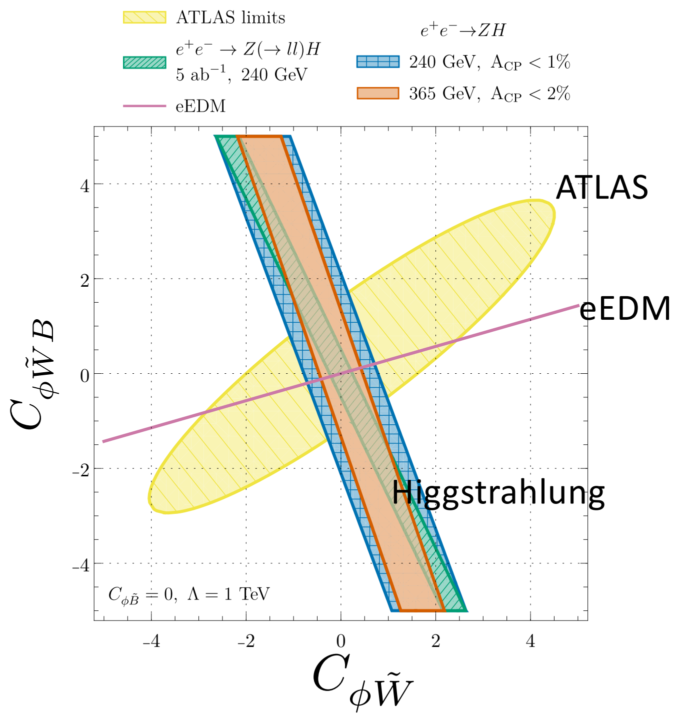
$$A_{CP} = \frac{\sigma(\cos\theta > 0) - \sigma(\cos\theta < 0)}{\sigma(\cos\theta > 0) + \sigma(\cos\theta < 0)}$$

- CP violation in the gauge sector is strongly limited by eEDMs
  - eEDM depends on SMEFT coefficients

$$d_e = \sqrt{2} v Im \left\{ \sin\theta_W \frac{C_{eW}}{\Lambda^2} - \cos\theta_W \frac{C_{eB}}{\Lambda^2} \right\}$$

  - RGE evolution generates $C_{\phi\tilde{W}B}, C_{\phi\tilde{W}}, C_{\phi\tilde{B}}$
- Limits from angular observables at LHC from H-> 4 lepton

eEDM, LHC, e^+e^- probes of CP violation are complementary



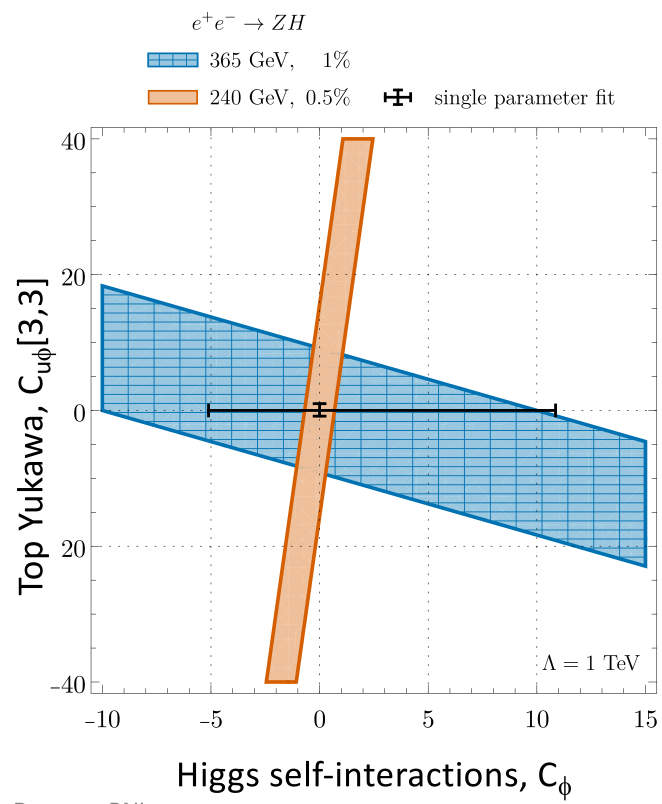
eEDM: 2109.15085, 1810.09413

2406.03557

Sensitivity to top operators in $e^+e^- \rightarrow ZH$

Combination of measurements at different energies can pin down coefficients very precisely

Example: 2HDMs generate $C_{u\phi}[3,3]$ and C_ϕ



Global fits: [2012.02779](2012.02779), [2404.12809](2404.12809)

Including QED

- QED treated separately from weak corrections to aid in including with Monte Carlos for ISR

$$\sigma = \sigma_{LO}(1 + \delta_{WEAK} + \delta_{QED})$$

$$\delta_{QED} \sim \frac{\alpha}{2\pi} \log\left(\frac{s}{m_e^2}\right)$$

- Effects at √s=240 GeV are large and negative

Conclusions

- We are happy to produce numbers for specific operators, polarizations and energies
- Eventually, results should be combined in global fits with NLO predictions to determine sensitivity to new operators
- Fits including only C_ϕ overestimate sensitivity
- Not all relevant NLO SMEFT calculations exist (Z pole and Higgstrahlung complete at NLO dimension-6 SMEFT)