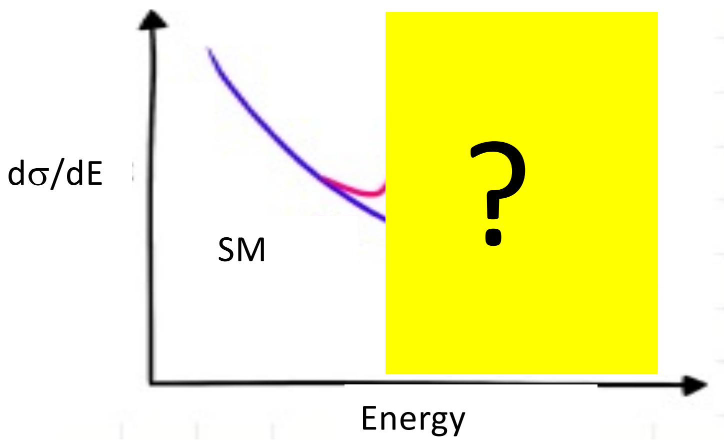
ZH @ 1-loop in SMEFT



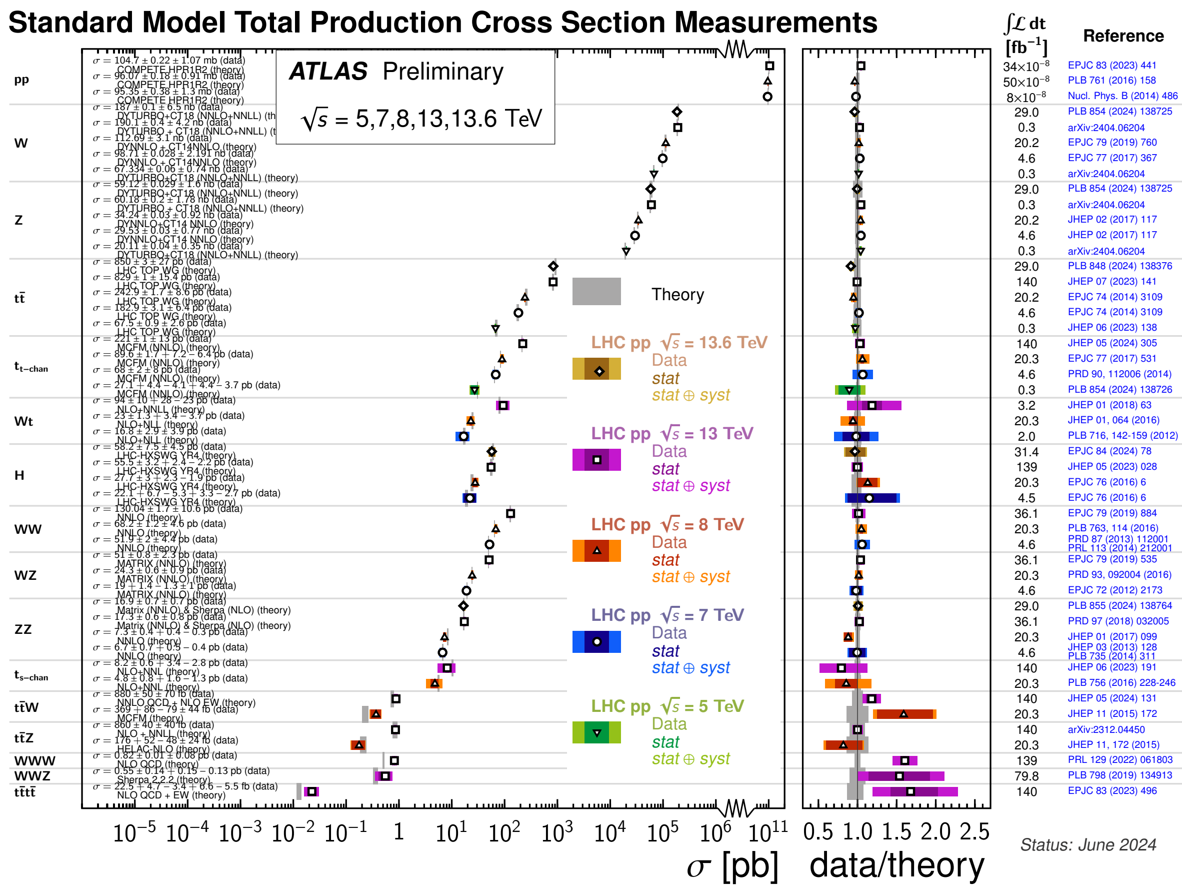
S. Dawson, BNL

Jan 14, 2025

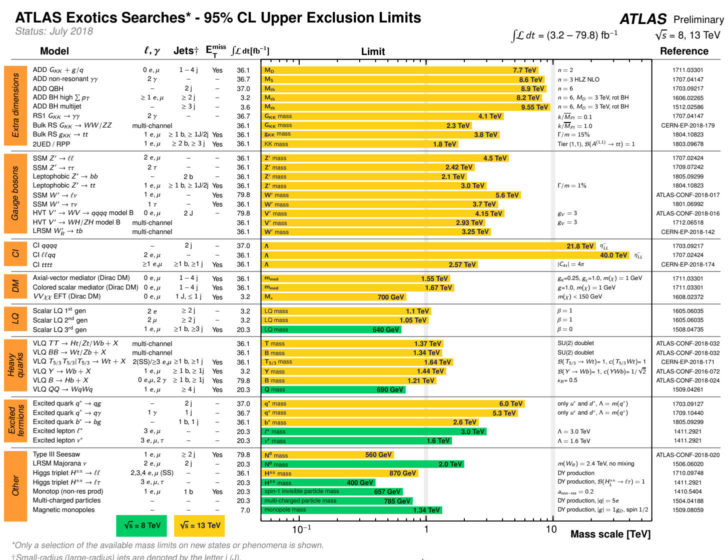
K. Asteriadis, S. Dawson, P.P. Giardino, R.Szafron, 2409.11466 , 2406.03557
S. Dawson, P.P. Giardino, M. Forslund, 2411.08952

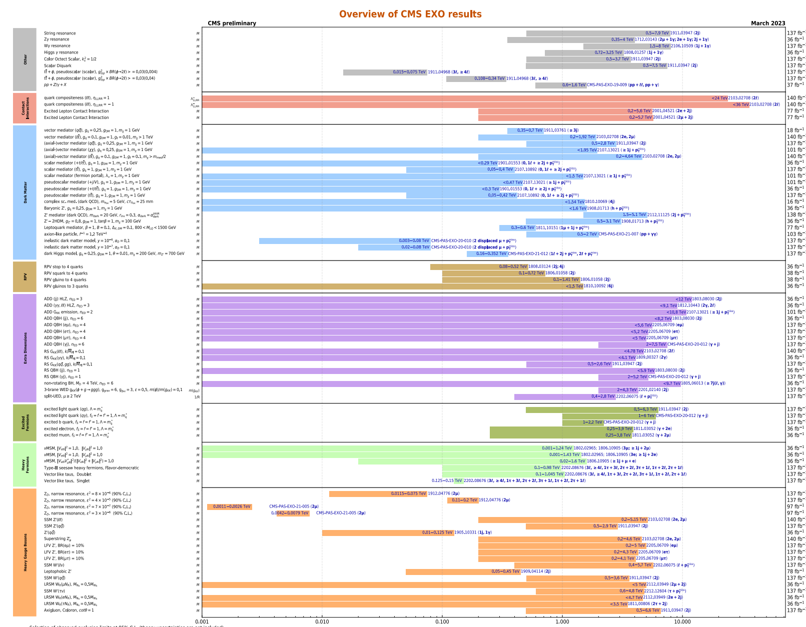
LHC measurements look "SM-like"

Theory/experiment agreement over many orders of magnitude and for many different processes



No new particles discovered *(yet?)*





Many limits exceed 1 TeV

Assume New Physics is very heavy

$\Lambda \gg M_W$ where complete theory exists

- Any new particles or symmetries are at this scale
- Expect effects of heavy particles at low scales to be suppressed *(decoupling!)*

This is sad scenario where there is no intermediate scale physics

M_W Only SM particles in theory at low scales

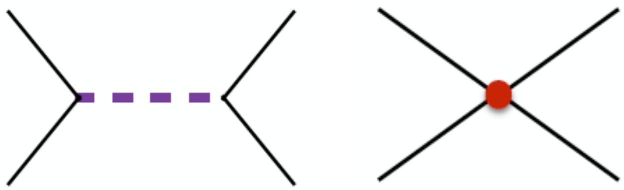
- Learn about high scale physics by measuring interactions of effective low energy theory
- ***We don't need to know the complete theory***

Effective Theories are tools for BSM searches

- Use SM effective field theory $L_{SMEFT} = L_{SM} + \frac{L_5}{\Lambda} + \frac{L_6}{\Lambda^2} + \frac{L_7}{\Lambda^3} + \frac{L_8}{\Lambda^4}$

$$L_n = \Sigma_i C_i^n O_i^n$$

- Consistent approach that can be systematically improved
  - New physics effects contained in coefficients C
  - Λ is generically scale of new physics
- Expansion in $1/\Lambda^2$ and in $1/(16\pi^2)$
  - Theory is renormalizable order-by-order in $1/\Lambda$
- What can we learn about BSM physics in this framework?

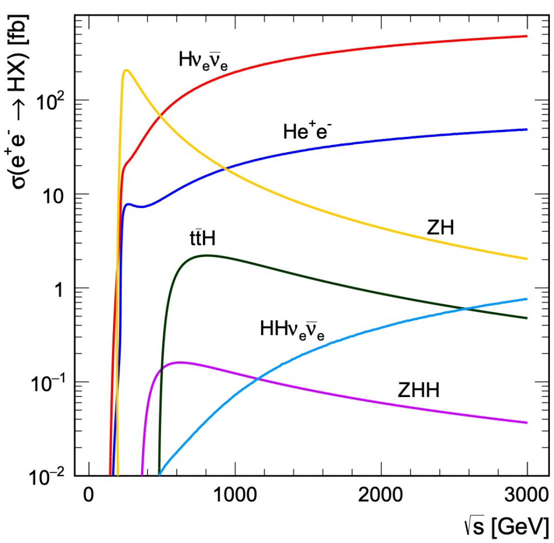


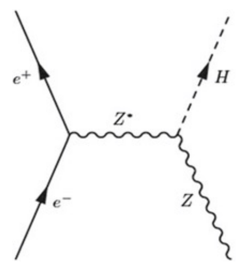
$$\frac{1}{s - M^2} \longrightarrow -\frac{1}{M^2}$$

We will consider a dimension-6 SMEFT expansion

Lepton colliders offer new opportunities

- Running at √s=240 GeV enhances the ZH rate





- Rate measured to O(.5%) accuracy at √s =240 GeV
- Sensitive to modifications of eeZ and ZZH vertices, along with Higgs couplings

New Interactions in SMEFT

- Note 4-point interaction enhanced by (energy)^2 relative to SM: $\frac{A}{A_{SM}} \sim \frac{s}{\Lambda^2} C_i$
- At tree level, depends on $C_{\phi D}, \; C_{\phi \Box}, \; C_{\phi e}, \; C_{\phi l}^1, \; C_{\phi l}^3, \; C_{ll}$

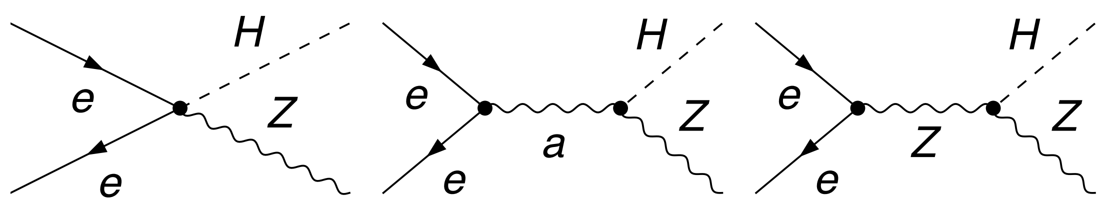
Linear rescaling of ZZH vertex ($C_{\phi D}$, $C_{\phi \Box}$)

eeZ vertex ($C_{\phi e}$)

4-pt vertex, eeZ vertex ($C_{\phi l}^1$, $C_{\phi l}^3$)

Relationship between v and G_F (C_{ll})

- At tree level, ZZH and ZHγ vertices also have dependence on momentum sensitive operators $C_{\phi WB}, \; C_{\phi W}, \; C_{\phi B}$



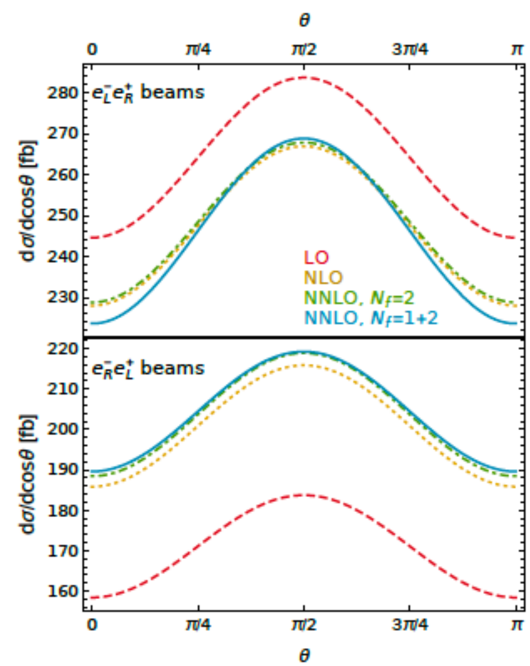
No contribution from Higgs tri-linear at tree level

SM NLO, NNLO

- SM NLO EW ✅
- SM NNLO mixed EW/QCD ✅
- State of the art: SM NNLO EW

- We are contributing to a piece of this program: SMEFT NLO EW
- Compute contributions ~ $\frac{C_i}{\Lambda^2 16\pi^2}$

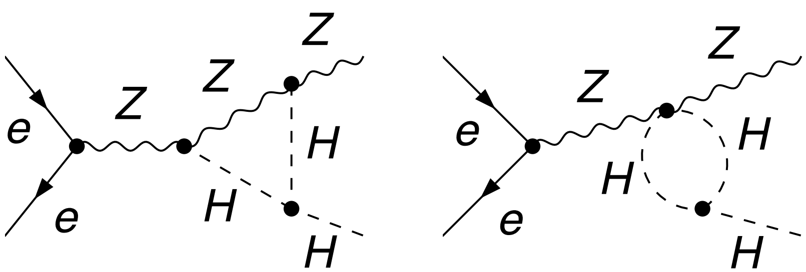
SM, $e^+e^- \to$ -ZH @ √s=240 GeV



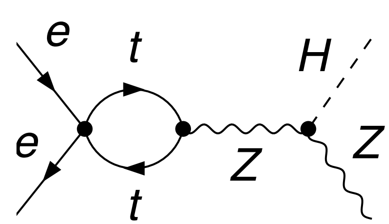
2305.16547

Higgstrahlung at NLO EW SMEFT

- Complete NLO calculation including all dimension-6 operators
  - (~70 SMEFT operators contribute in ~ 35 combinations)
- Sensitive to poorly constrained interactions that first arise at NLO
- 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, $C_i(\mu)$



Higgs tri-linear coupling, C_ϕ



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

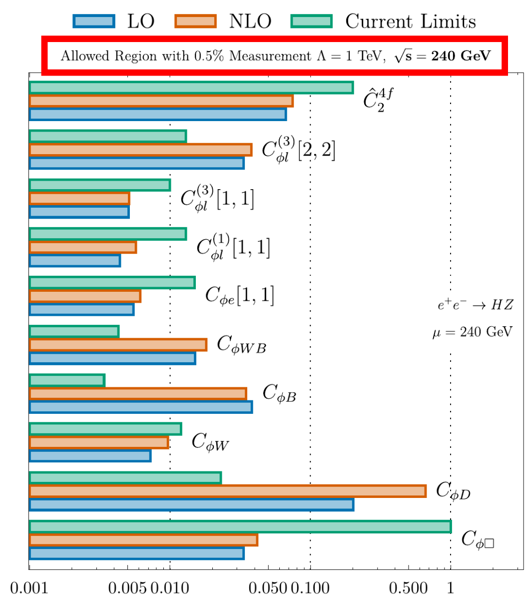
+ many more

* Complete results at https://gitlab.com/smeft/eehz

SMEFT Operators Present at LO

- Consider future measurements at:
  - √s=240 GeV with a precision of 0.5% on total rate
  - √s=365 and 500 GeV with a precision of 1%
- For both polarized and unpolarized beams
- Single parameter bounds in general very similar at LO and NLO with no significant energy dependence
- For most operators, FCC-ee significantly improves bounds

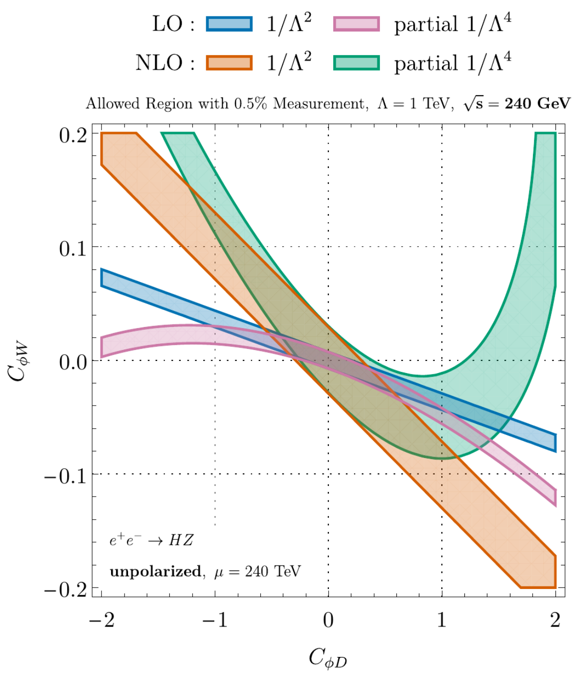
Single Parameter Fits



Global single parameter fit limits from [2012.02779](2012.02779)

SMEFT Operators Present at LO

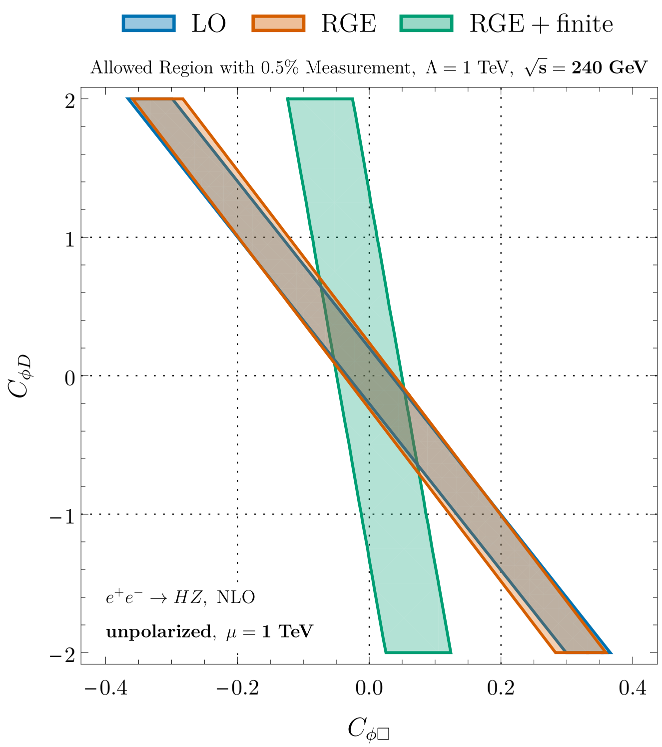
- Differences between LO and NLO limits in correlated fits can be large
- We have done consistent calculation including terms of order: $\frac{C_i}{\Lambda^2 16\pi^2}$
- Assuming (LO SMEFT)^2 contribution is dominant gives idea of uncertainties of results
- (We don't have full $1/\Lambda^4$ results. This requires dimension-8, along with double insertions in loops)



* Partial $1/\Lambda^4$ includes squaring $1/\Lambda^2$ amplitudes and using $1/\Lambda^4$ relations for redefinitions of coupling constants

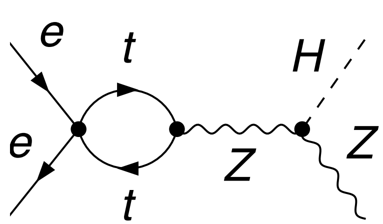
Finite Contributions Matter

- Logarithmic contributions can be found from renormalization group evolution (RGE)
- Finite contributions require complete NLO calculation
- Finite pieces sometimes larger than logarithms
- *A priori*, we don't know if finite pieces or logs will dominate

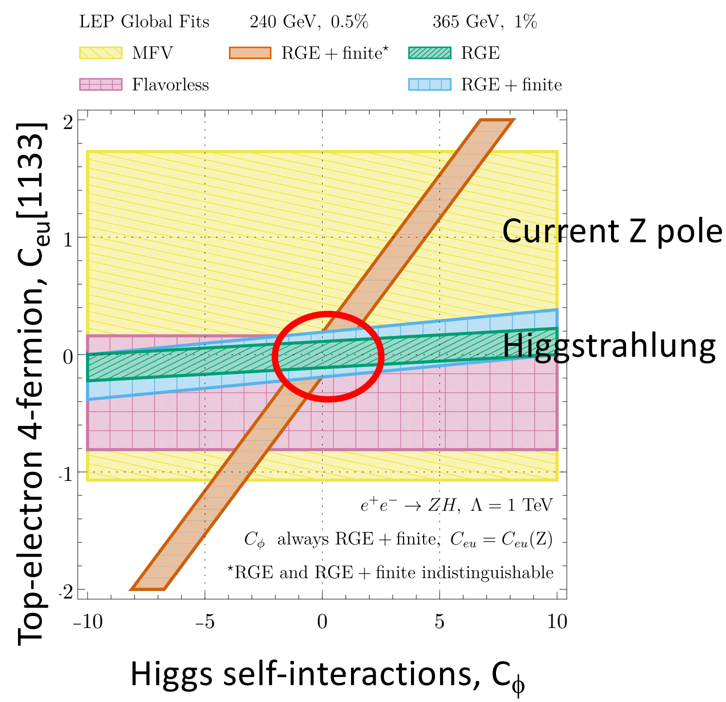


$e^+e^- \rightarrow ZH$ is window to many new interactions

- Sensitivity to Higgs tri-linear correlated with other contributions
    - Calculate 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
- Limits from Z-pole depend on flavor assumptions
    - Compare with global fits using MFV and flavor-blind operators



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



Power of measurement at 2 different energies

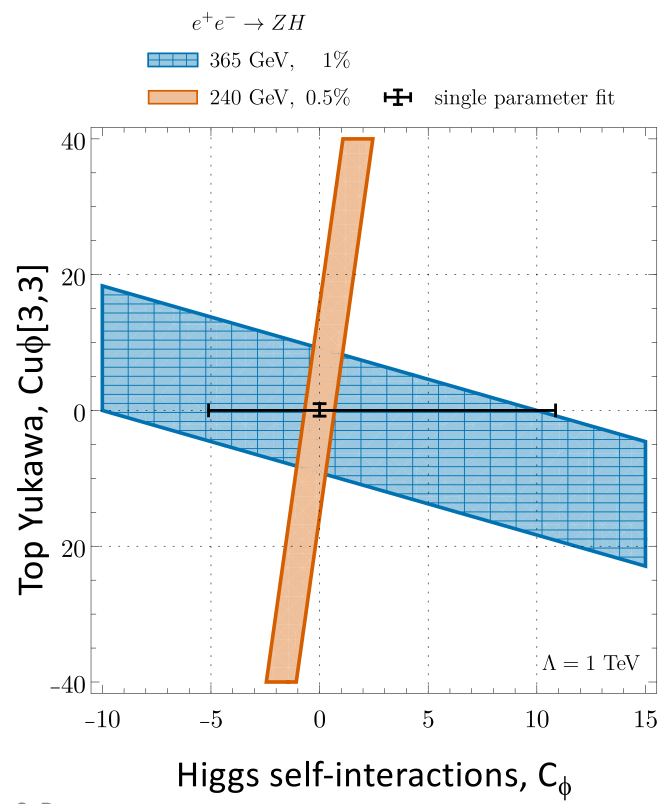
2406.03557

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

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

- Example of a case where correlation can be ignored
- Excellent current limits on top quark Yukawa from LHC Higgs measurements

$$\frac{y_t}{y_t^{SM}} = \frac{v^2}{\Lambda^2}\left(\frac{v}{2m_t}C_{u\phi}[3,3]\right)$$



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

Sensitivity to Higgs tri-linear

- Correlations can have large energy/ polarization dependence
- In SMEFT, $C_{\phi D}$ and $C_{\phi\Box}$ contribute to many processes other than modification of ZZH vertex

"pheno L":

$$L \sim \frac{2M_Z^2}{v}(1+\delta_Z)HZ_\mu Z^\mu$$

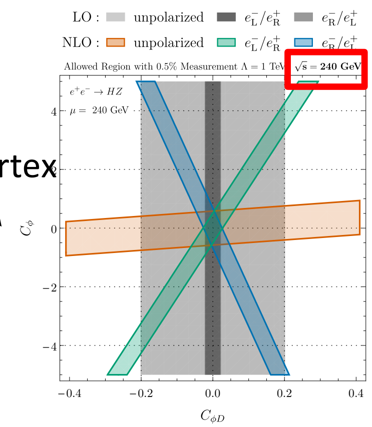
$$\delta_Z \rightarrow \frac{v^2}{4\Lambda^2}(4C_{\phi\Box}+C_{\phi D})$$

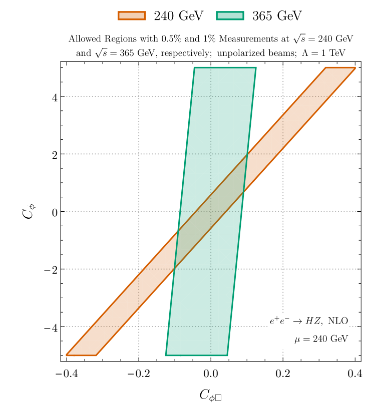
- In SMEFT, C_ϕ is correlated with many operators

$$1-\kappa_\lambda \rightarrow \frac{v^2}{\Lambda^2}\left[\frac{2v^2}{M_H^2\Lambda^2}C_\phi + 3(C_{\phi\Box} - \frac{C_{\phi D}}{4})\right]$$

- Eventually, our results will contribute to global NLO EW SMEFT fit

H[3] vertex



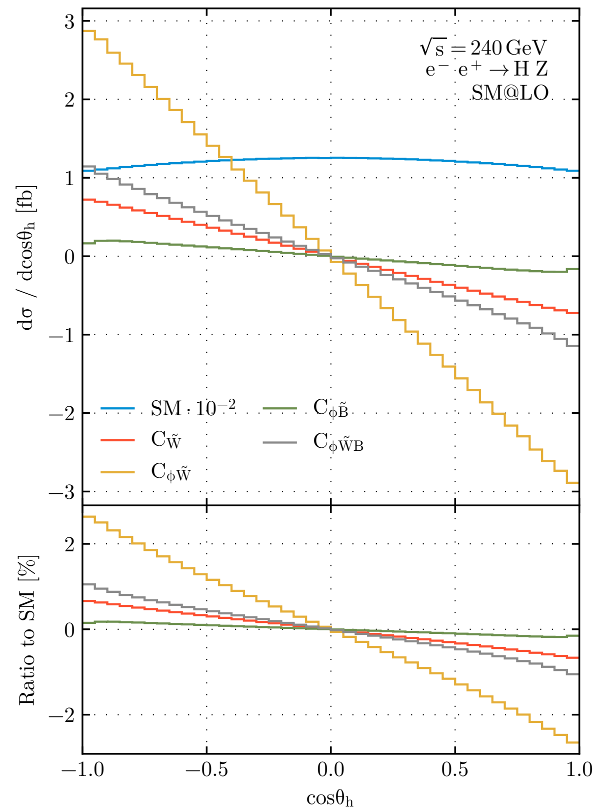


Contributes to ZZH vertex

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 $e^+e^- \rightarrow ZH$ (since SM contribution is real and CP violating piece is imaginary)
- At one-loop, there is a contribution from imaginary part of loop integrals

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



CP violation at future e^+e^- colliders

- Define CP violating asymmetry

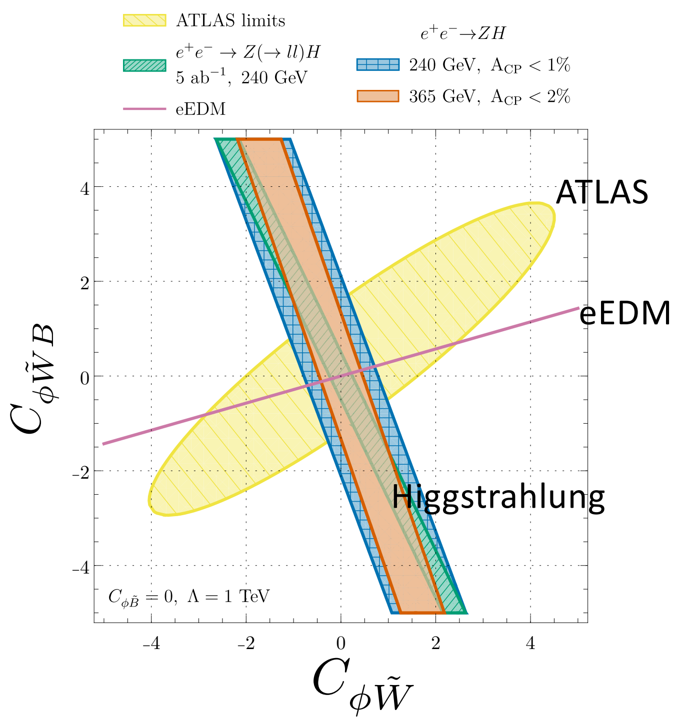
$$A_{CP} = \frac{\sigma(\cos\theta > 0) - \sigma(\cos\theta < 0)}{\sigma(\cos\theta > 0) + \sigma(\cos\theta < 0)}$$

- 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

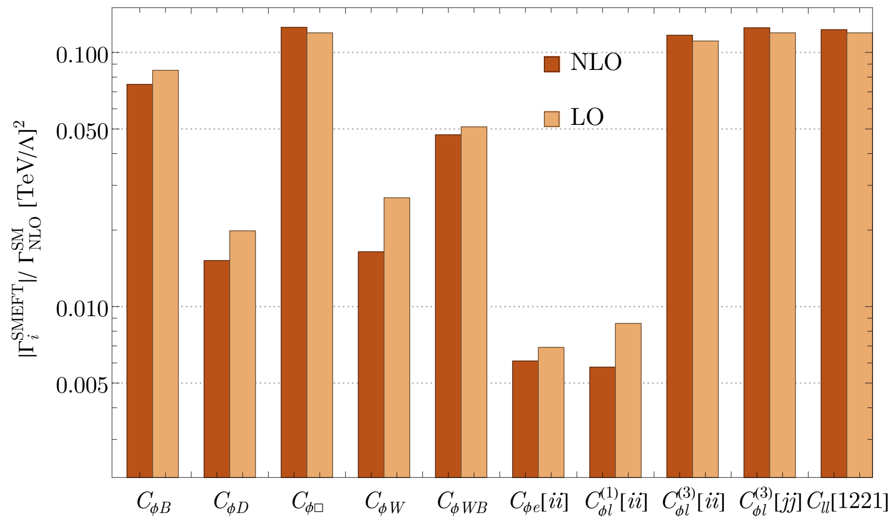


eEDM: 2109.15085, 1810.09413

2406.03557

H → l^+l^-Z at NLO EW in SMEFT

- Result follows from $e^+e^- \to ZH$ calculation
- Using narrow width approximation, can find dominant contributions to H → 4 leptons at NLO EW in dimension-6 SMEFT
  - Combine with previous NLO Z → l^+l^- results
- Virtual photon contributions have divergences that cancel against H → $l^+l^-Z\gamma$, which are treated with standard dipole subtraction

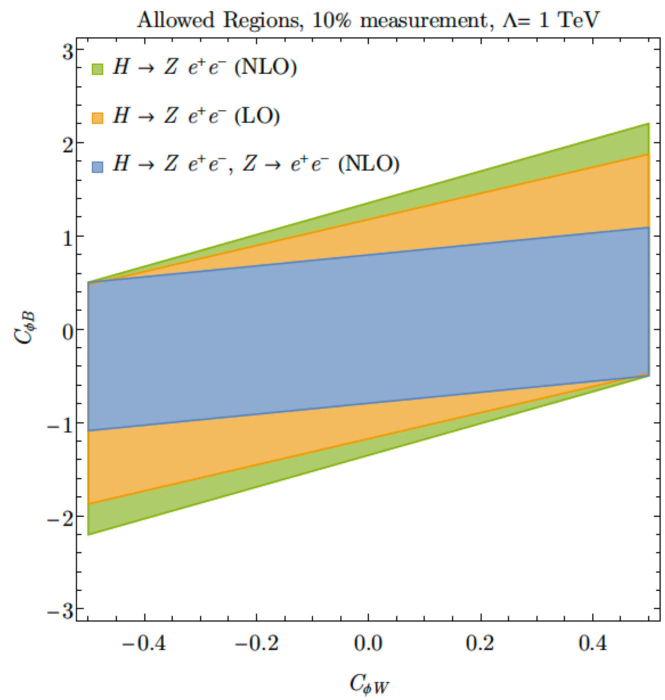


* C=1, Λ=1 TeV

2411.08952 , 2304.00029

H→ 4 lepton decays at EW NLO

- Consider a 10% measurement of H→ 4l
- Combine with known Z → l^+l^- at NLO SMEFT EW to find full H → 4l at NLO in NWA
- Correlations change shape at NLO



Conclusions

- Have completed NLO EW SMEFT calculation of $e^+e^- \rightarrow ZH$ with all contributions included
  - Results are available for public use
- Studied impact of NLO corrections on total rate
  - Small effects in single parameter fits
  - Significant correlations between effects of operators that first appear at NLO
  - Combination of measurements at different energies has potentially large impact
- Future:
  - Combine NLO EW Z pole calculations, complete NLO EW Higgs decay rates, and NLO EW $e^+e^- \rightarrow ZH$ rates for improved sensitivity
  - Working towards a global fit that is accurate at NLO EW order with dimension-6 SMEFT