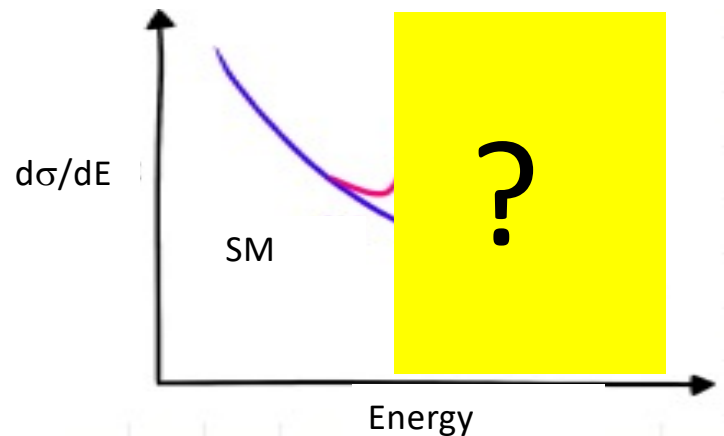


# ZH @ 1-loop in SMEFT



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. Forsslund, [2411.08952](#)

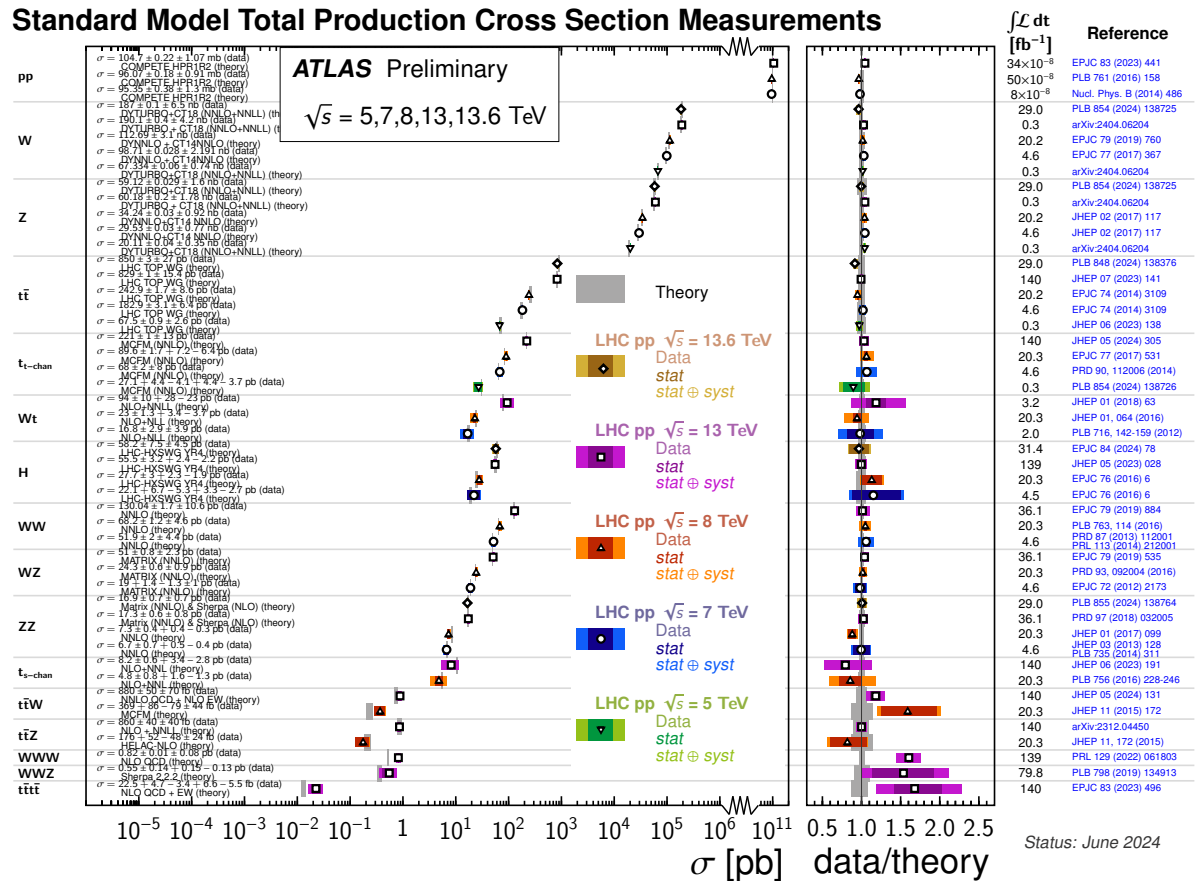
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# LHC measurements look "SM-like"

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

## Standard Model Total Production Cross Section Measurements



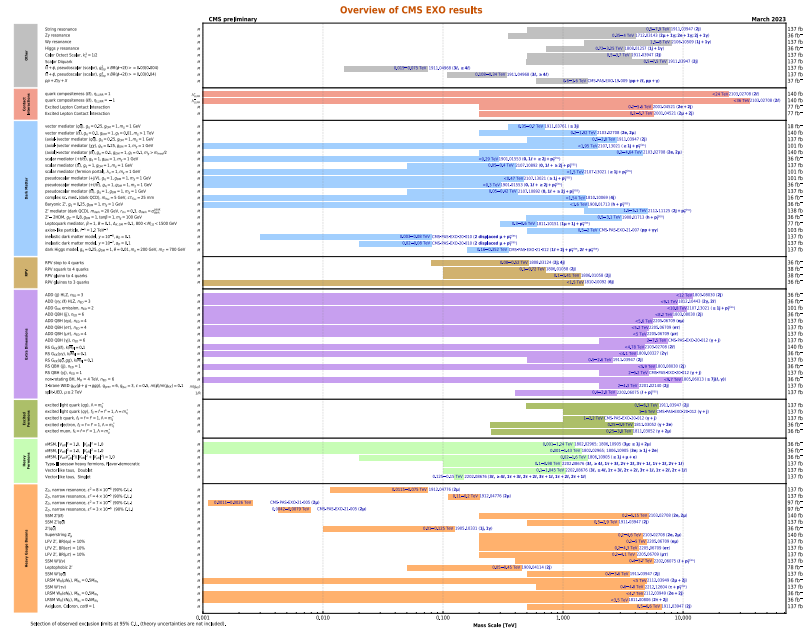
# No new particles discovered (yet?)

**ATLAS Exotics Searches\* - 95% CL Upper Exclusion Limits**  
 Status: July 2018

**ATLAS Preliminary**  
 $\int \mathcal{L} dt = (3.2 - 79.8) \text{ fb}^{-1}$   $\sqrt{s} = 8, 13 \text{ TeV}$

Model	$\ell, \gamma$	Jets <sup>†</sup>	$E_{miss}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
<b>Extra dimensions</b>	ADD $G_{\mu\nu} + g/\ell$	0, $\mu$	1-4	Yes	36.1	1711.0301
ADD non-resonant $\gamma\gamma$	2, $\gamma$	-	-	-	56.7	1707.0447
ADD graviton	2, $\gamma$	-	-	-	27.0	1707.0207
ADD BH high $2\gamma$	2, $\mu$	2-3	-	-	3.2	1606.0285
ADD BH single <sup>†</sup>	-	2, 3	-	-	3.6	1612.0286
RSI $G_{\mu\nu} + \gamma\gamma$	2, $\gamma$	-	-	-	36.7	1707.0447
Bulk RS $G_{\mu\nu} + WW/ZZ$	multi-channel	-	-	-	36.1	1707.0447
Bulk RS $G_{\mu\nu} + \ell\ell$	1, $\mu, \tau$	2-3, 2-3	Yes	36.1	1604.1622	
ZUED / PPP	1, $\mu, \tau$	2-3, 2-3	Yes	36.1	1603.0676	
<b>Gravitons</b>	SSM $Z' \rightarrow \ell\ell$	2, $\mu, \tau$	-	-	36.1	1707.0248
SSM $Z' \rightarrow \gamma\gamma$	2, $\gamma$	-	-	-	36.1	1707.0248
Leptophobic $Z' \rightarrow bb$	2, $b, \tau$	-	-	-	2.1	1605.0299
Leptophobic $Z' \rightarrow \ell\ell$	2, $\mu, \tau$	2-3, 2-3	Yes	36.1	1604.1622	
SSM $W' \rightarrow \ell\nu$	1, $\mu, \tau$	-	Yes	79.8	1607.0248	
SSM $W' \rightarrow \ell\ell$	1, $\mu, \tau$	-	Yes	36.1	1607.0248	
HVT $V' \rightarrow WW \rightarrow e\mu\mu$ model B	0, $\mu, \tau$	2, J	-	-	79.8	1607.0248
HVT $V' \rightarrow WW/ZZ$ model B	multi-channel	-	-	-	36.1	1712.0518
LRSM $W_2 \rightarrow \ell\nu$	multi-channel	-	-	-	36.1	1604.1622
<b>CI</b>	CI open	2, $\gamma$	-	-	37.0	1703.0217
CI / Reg	2, $\mu, \tau$	-	-	-	36.1	1707.0248
CI mix	2, $\mu, \tau$	2-3, 2-3	Yes	36.1	1707.0248	
<b>DM</b>	Axial-vector mediator (Disc DM)	0, $\mu, \tau$	1-4	Yes	36.1	1711.0301
Colored scalar mediator (Disc DM)	0, $\mu, \tau$	1-4	Yes	36.1	1711.0301	
VV or EFT (Disc DM)	0, $\mu, \tau$	1, 2, 3	Yes	3.2	1606.0285	
<b>LO</b>	Scalar LO 1 <sup>st</sup> gen	2, $\mu, \tau$	2-3	-	3.2	1606.0285
Scalar LO 2 <sup>nd</sup> gen	2, $\mu, \tau$	2-3	-	-	3.2	1606.0285
Scalar LO 3 <sup>rd</sup> gen	1, $\mu, \tau$	2-3, 2-3	Yes	20.3	1606.0285	
<b>Heavy quarks</b>	VLD $77 \rightarrow \mu\mu/Z/\nu\nu + X$	multi-channel	-	-	36.1	1707.0248
VLD $88 \rightarrow WW/Z\nu + X$	multi-channel	-	-	-	36.1	1707.0248
VLD $T_{\mu\nu} T_{\mu\nu} \rightarrow WW + X$	20/50/30 $\mu, \tau$	2, 3	Yes	36.1	1606.0285	
VLD $V \rightarrow \mu\mu + X$	1, $\mu, \tau$	2-3, 2-3	Yes	3.2	1606.0285	
VLD $V \rightarrow \mu\mu + X$	0, $\mu, \tau$	2-3, 2-3	Yes	79.8	1606.0285	
VLD $QQ \rightarrow \mu\mu W\gamma$	1, $\mu, \tau$	2-3	Yes	20.3	1606.0285	
<b>Exotic fermions</b>	Excluded quark $q' \rightarrow q\gamma$	-	2	-	37.0	1703.0217
Excluded quark $q' \rightarrow q\gamma$	1, $\gamma$	1	-	-	36.7	1708.1040
Excluded quark $q' \rightarrow q\gamma$	-	1, 3	-	-	36.1	1605.0299
Excluded lepton $\ell'$	2, $\mu, \tau$	-	-	-	20.3	1411.2801
Excluded lepton $\ell'$	2, $\mu, \tau$	-	-	-	20.3	1411.2801
<b>Other</b>	Type III Seesaw	1, $\mu, \tau$	2-3	Yes	79.8	1607.0248
LRSM Majorana $\nu$	2, $\mu, \tau$	2	-	-	20.3	1606.0285
Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2, 3, $\mu, \tau$ (BS)	-	-	-	36.1	1712.0518
Higgs triplet $H^{\pm\pm} \rightarrow \ell\nu$	2, 3, $\mu, \tau$	-	-	-	20.3	1411.2801
Mixing (non-res prod)	1, $\mu, \tau$	1, 3	Yes	20.3	1412.0424	
Multi-charged particles	-	-	-	-	20.3	1604.1622
Magnetic monopoles	-	-	-	-	7.0	1609.0859

\*Only a selection of the available mass limits on new states or phenomena is shown.  
 † Small-radius (large-radius) jets are denoted by the letter J (L).



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***

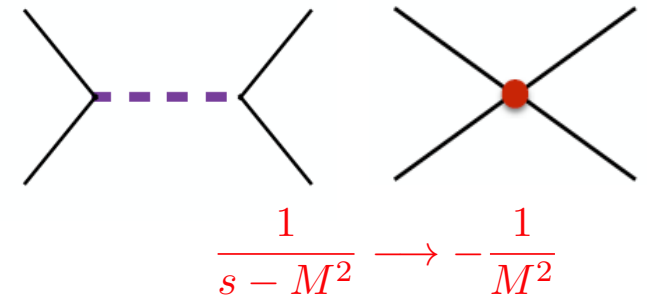
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# Effective Theories are tools for BSM searches

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

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

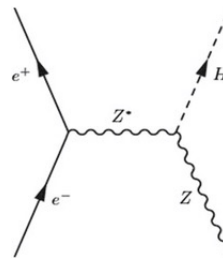
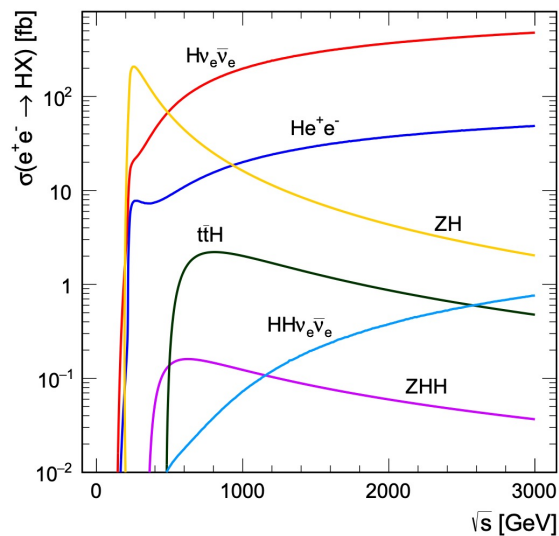
- Consistent approach that can be systematically improved
  - New physics effects contained in coefficients C
  - $\Lambda$  is generically scale of new physics
- Expansion in  $1/\Lambda^2$  and in  $1/(16\pi^2)$ 
  - Theory is renormalizable order-by-order in  $1/\Lambda$
- What can we learn about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



We will consider a dimension-6 SMEFT expansion

# Lepton colliders offer new opportunities

- Running at  $\sqrt{s}=240$  GeV enhances the ZH rate

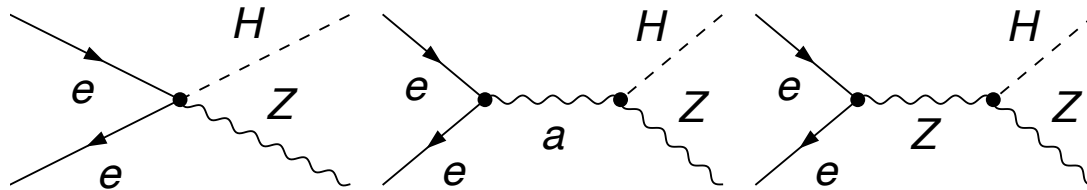


- Rate measured to  $O(.5\%)$  accuracy at  $\sqrt{s} = 240$  GeV
- Sensitive to modifications of  $eeZ$  and  $ZZH$  vertices, along with Higgs couplings

# New Interactions in SMEFT



- Note 4-point interaction enhanced by  $(\text{energy})^2$  relative to SM:  $\frac{A}{A_{SM}} \sim \frac{s}{\Lambda^2} C_i$
- At tree level, depends on  $C_{\phi D}, C_{\phi \square}, C_{\phi e}, C_{\phi l}^1, C_{\phi l}^3, C_{ll}$ 
  - Linear rescaling of ZZH vertex
  - eeZ vertex
  - 4-pt vertex, eeZ vertex
  - Relationship between  $v$  and  $G_F$

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



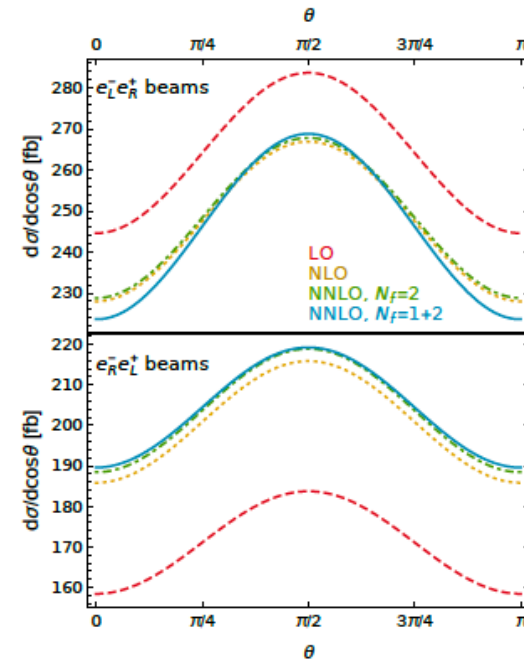
No contribution from Higgs tri-linear at tree level

# 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  $\sim \frac{C_i}{\Lambda^2 16\pi^2}$

SM,  $e^+e^- \rightarrow ZH$  @  $\sqrt{s}=240$  GeV

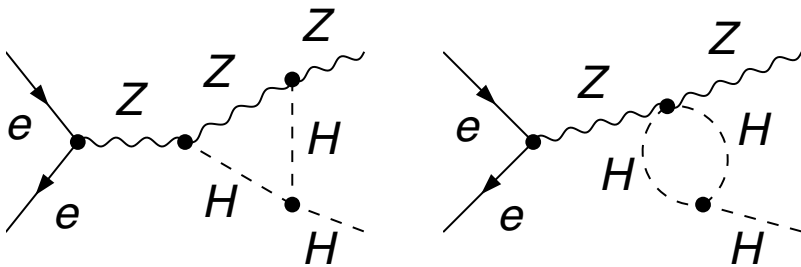


[2305.16547](https://arxiv.org/abs/2305.16547)

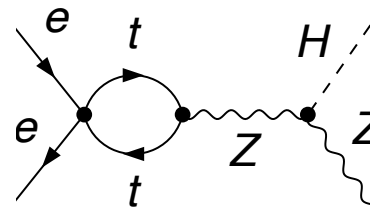


# Higgstrahlung at NLO EW SMEFT

- Complete NLO calculation including all dimension-6 operators
  - ( $\sim 70$  SMEFT operators contribute in  $\sim 35$  combinations)
- Sensitive to poorly constrained interactions that first arise at NLO
- One-loop virtual + tree level real photon emission
  - Generate with FeynArts  $\rightarrow$  FeynCalc  $\rightarrow$  Package-X
  - Renormalize on-shell for  $M_W, M_Z, \overline{MS}$  for Wilson Coefficients,  $C_i(\mu)$



Higgs tri-linear coupling,  $C_\phi$



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

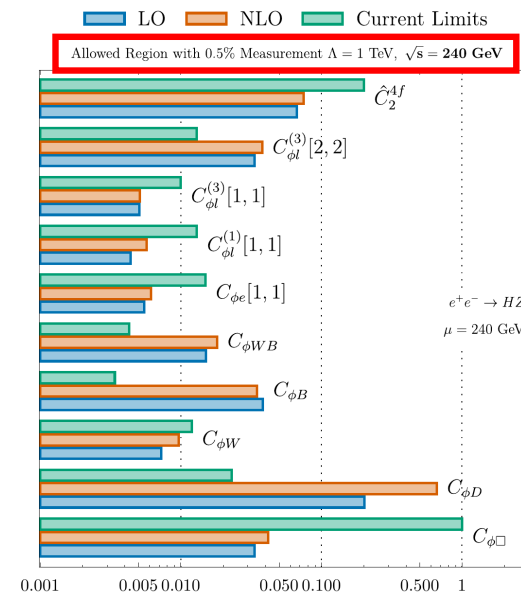
+ many more

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

# SMEFT Operators Present at LO

- Consider future measurements at:
  - $\sqrt{s}=240$  GeV with a precision of 0.5% on total rate
  - $\sqrt{s}=365$  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

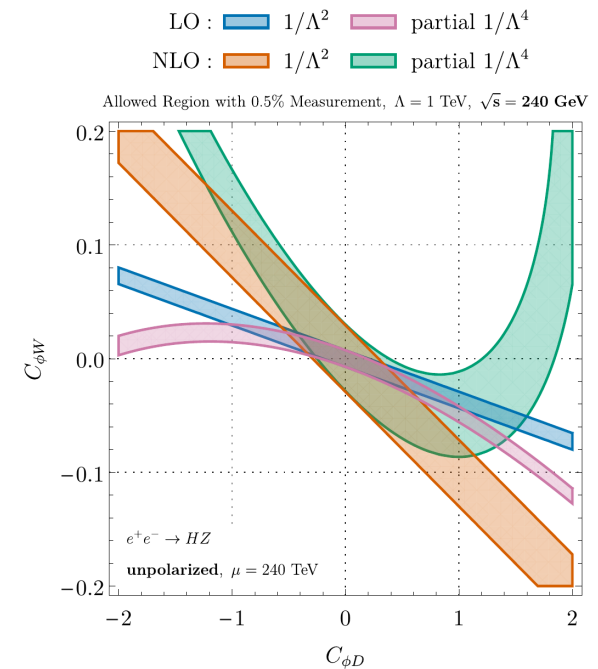


Global single parameter fit limits from [2012.02779](https://arxiv.org/abs/2012.02779)

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# SMEFT Operators Present at LO

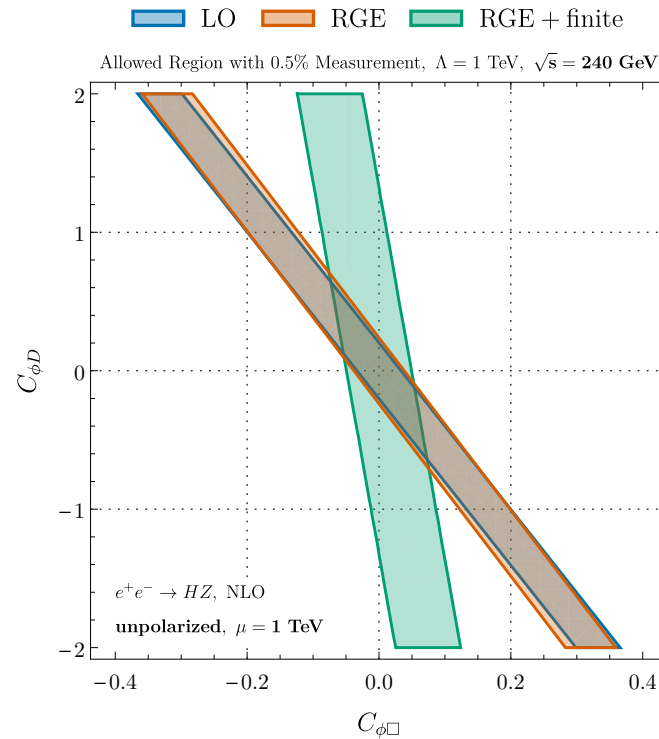
- Differences between LO and NLO limits in correlated fits can be large
- We have done consistent calculation including terms of order:  $\frac{C_i}{\Lambda^2 16\pi^2}$
- Assuming (LO SMEFT)<sup>2</sup> contribution is dominant gives idea of uncertainties of results
- (We don't have full  $1/\Lambda^4$  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

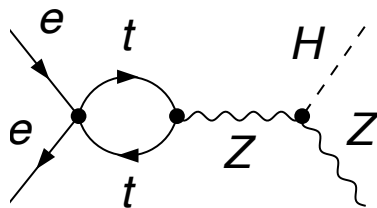
# Finite Contributions Matter

- 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

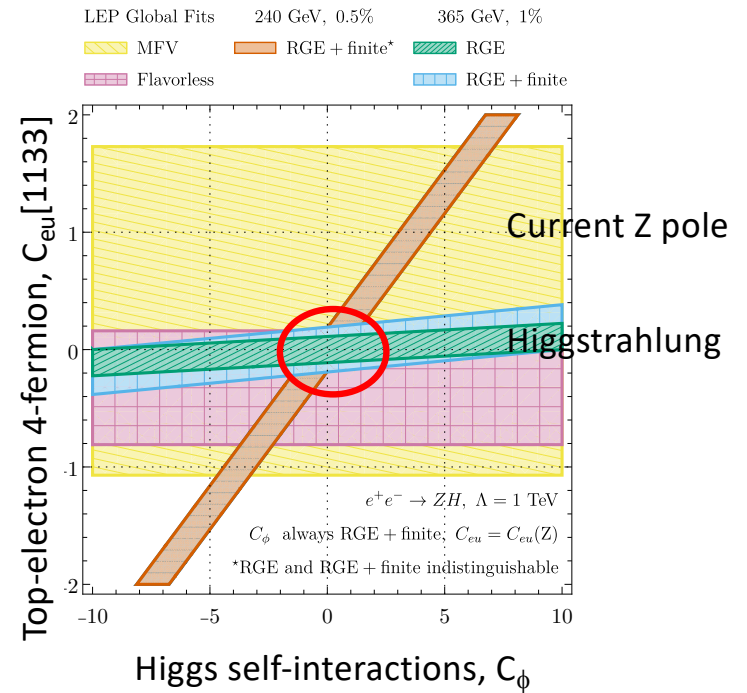
- Sensitivity to Higgs tri-linear correlated with other contributions
  - Calculate to  $1/\Lambda^2$  so results are linear bands
- How do future constraints compare with existing information?
  - Assume .5% accuracy on total cross section measurement at  $\sqrt{s}=240$  GeV, 1% at  $\sqrt{s}=365$  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  $\sqrt{s}$

[2406.03557](#)

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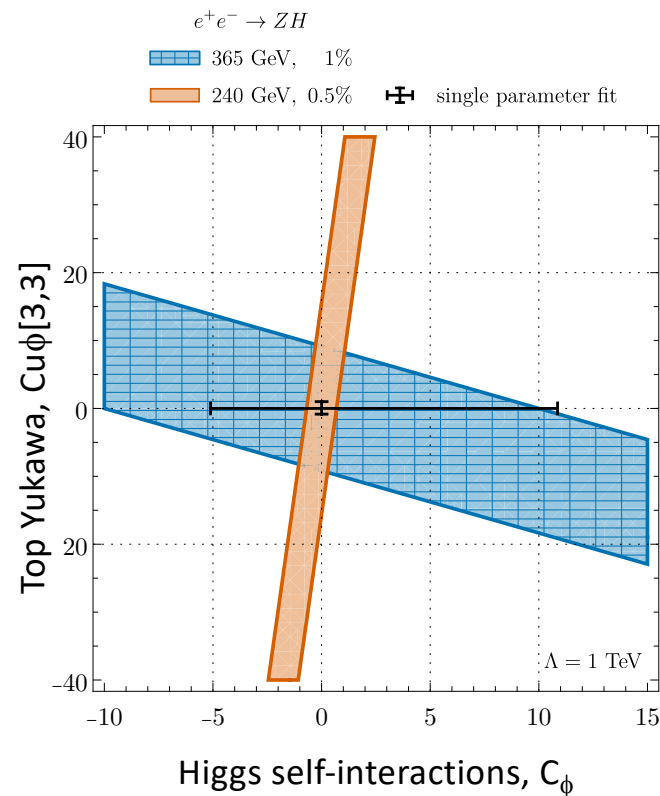
Power of measurement at 2 different energies

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

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

- 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  $C_{\phi \square}$  contribute to many processes other than modification of ZZH vertex

"pheno L":

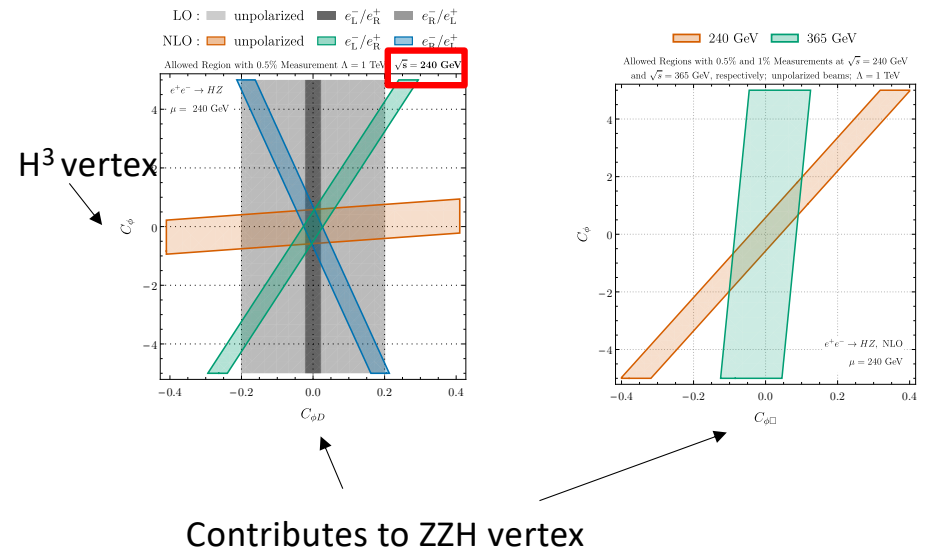
$$L \sim \frac{2M_Z^2}{v} (1 + \delta_Z) H Z_\mu Z^\mu$$

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

- In SMEFT,  $C_\phi$  is correlated with many operators

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

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



# Sensitivity to CP violation

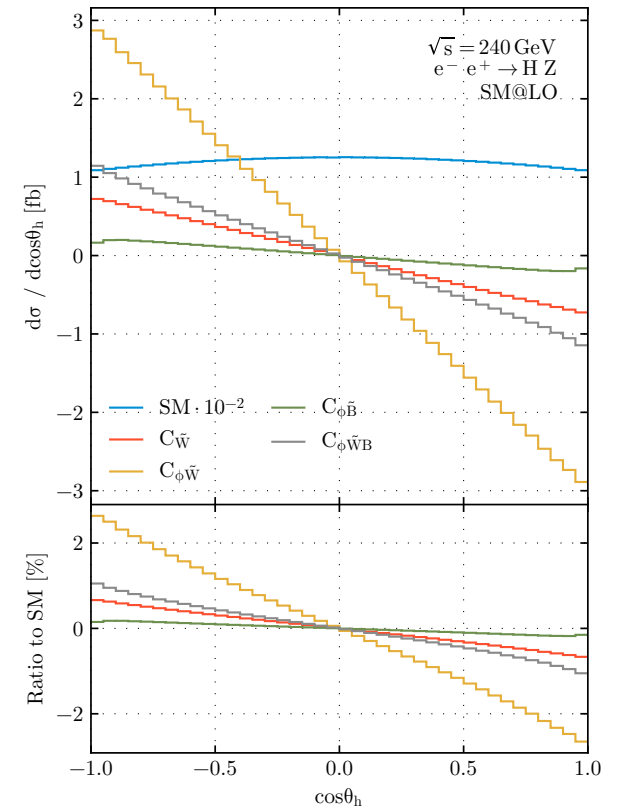
- Higgstrahlung at  $e^+e^-$  colliders is sensitive to **CP violation in the gauge sector at NLO**
- At tree level and to  $O(1/\Lambda^2)$ , CP violating dimension-6 operators do not interfere with the SM contribution from  $e^+e^- \rightarrow ZH$  (since SM contribution is real and CP violating piece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

$$O_{\tilde{W}} = \epsilon_{abc} \tilde{W}_\mu^{a\nu} W_\nu^{b\rho} W_\rho^{c,\mu}$$

$$O_{\phi\tilde{W}} = \tilde{W}_{\mu\nu}^a W^{\mu\nu b} (\phi^\dagger \phi)$$

$$O_{\phi\tilde{B}} = \tilde{B}_{\mu\nu} B^{\mu\nu} (\phi^\dagger \phi)$$

$$O_{\phi\tilde{W}B} = \tilde{W}_{\mu\nu}^a B^{\mu\nu} (\phi^\dagger \sigma^a \phi)$$





# 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

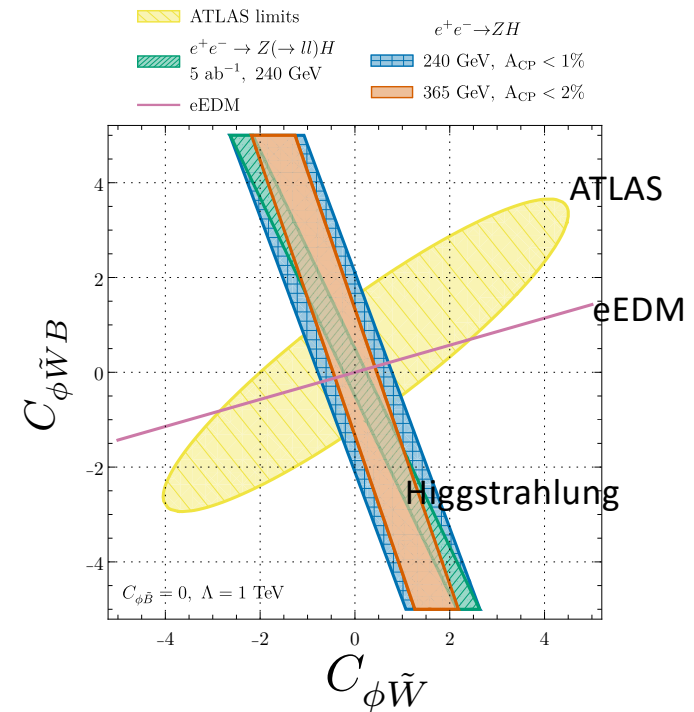
- eEDM depends on SMEFT coefficients

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

- RGE evolution generates  $C_{\phi\tilde{W}B}, C_{\phi\tilde{W}}, C_{\phi\tilde{B}}$

- Limits from angular observables at LHC from  $H \rightarrow 4$  lepton

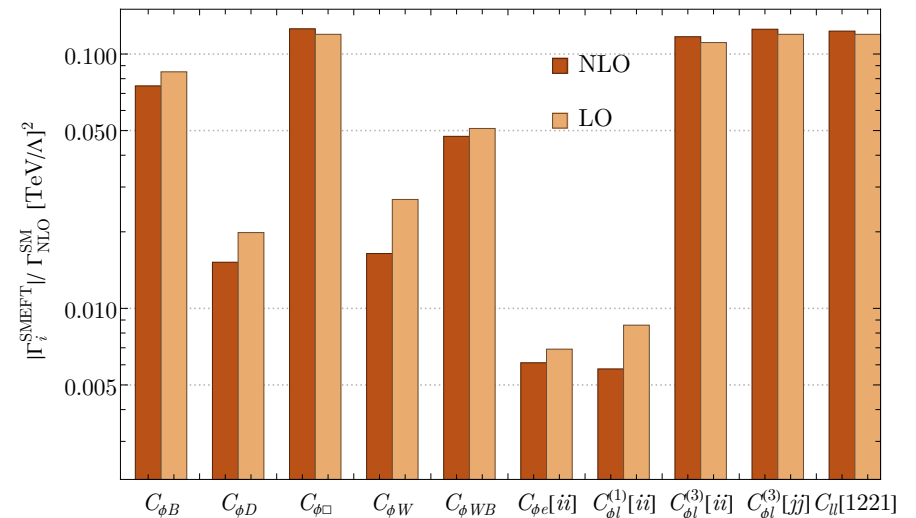
eEDM, LHC,  $e^+e^-$  probes of CP violation are complementary



eEDM: [2109.15085](#), [1810.09413](#)

# H $\rightarrow$ $l^+l^-Z$ at NLO EW in SMEFT

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

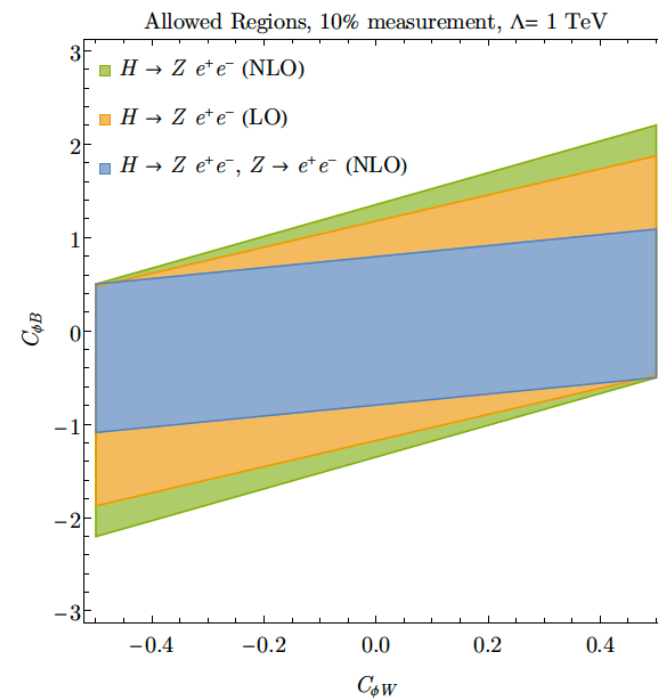


\*  $C=1, \Lambda=1$  TeV

[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