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

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3rd ECFA Workshop on e^+e^-
Higgs, Top, Electroweak Factories

10/10/2024

Based on: K. Asteriadis, S. Dawson, PPG, R. Szafron: arXiv:2406.03557 and arXiv: 2409.11466

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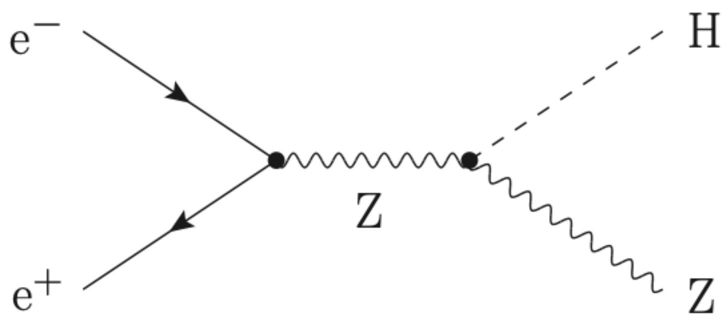
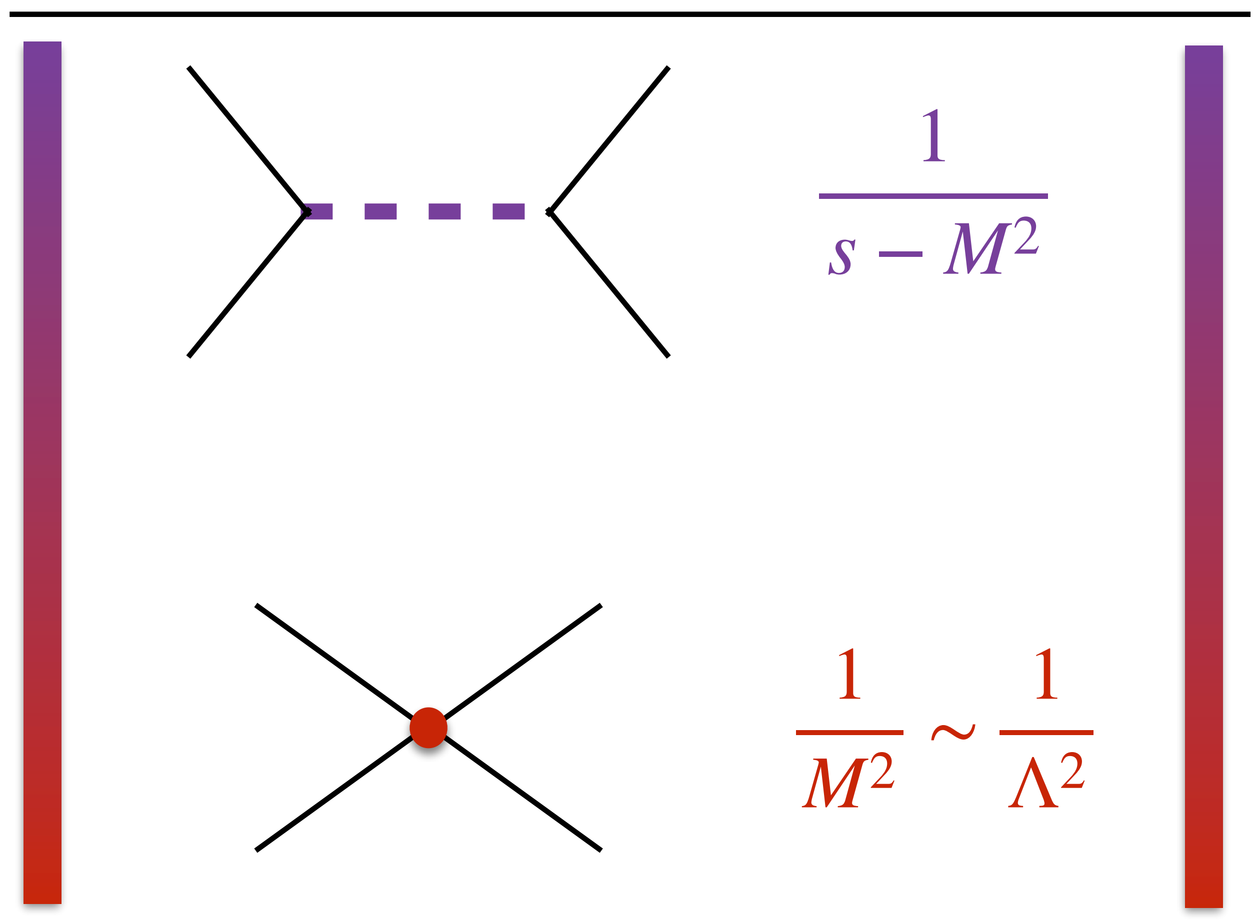


The measurement of $\sigma(e^+e^- \to HZ)$ at future accellerators can be an important source of information on New Physics (NP)

If we assume that NP exists at scales $\Lambda \gtrsim 1\,\mathrm{TeV}$, we can use Effective Field Theories (EFT) to describe the effects of NP on precise searches.

New Physics $\sim 1\,\mathrm{TeV}$



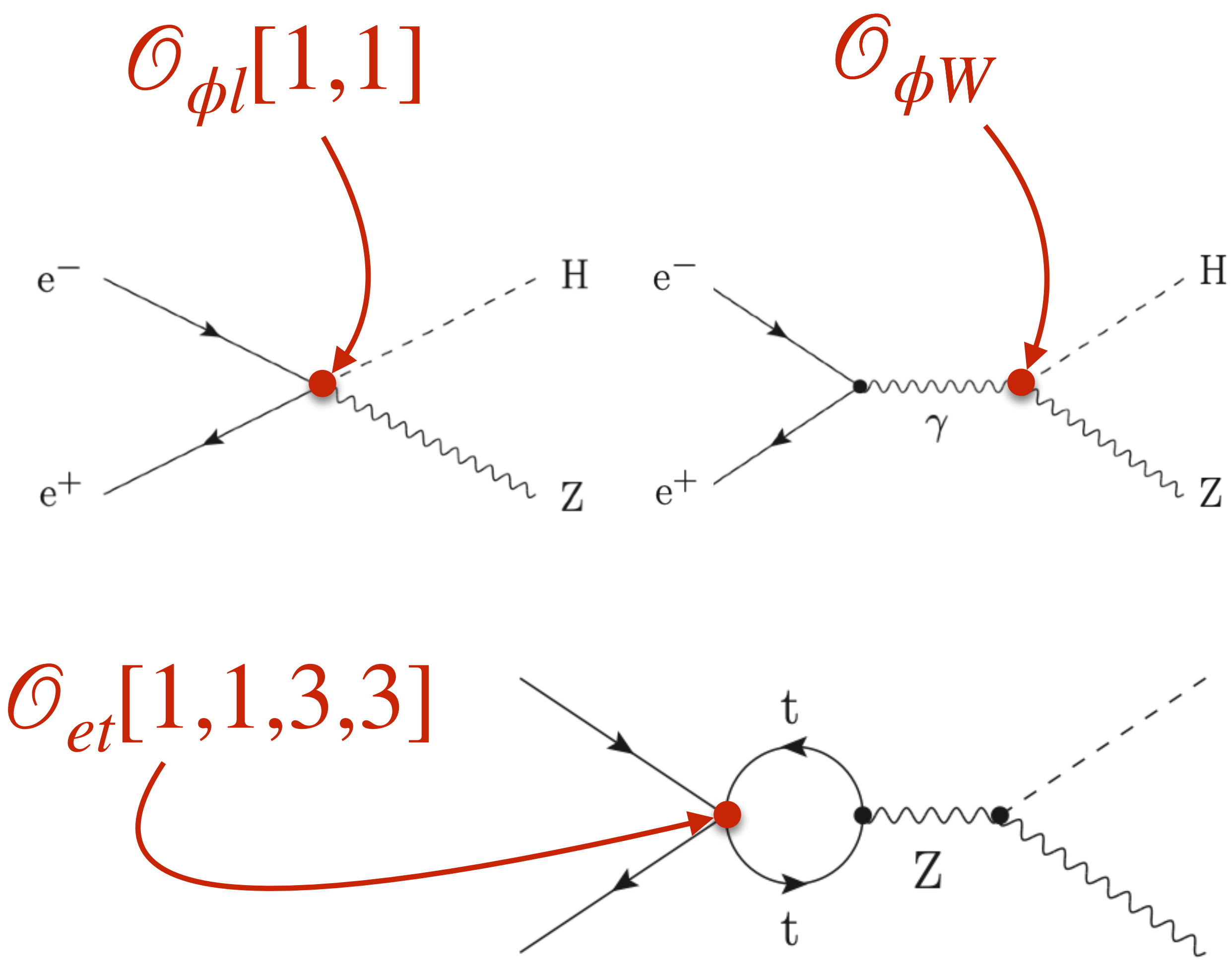
Standard Model

Operators respect SM gauge symmetries

We parametrize the effect of NP on $e^+e^- \to HZ$ using the SMEFT

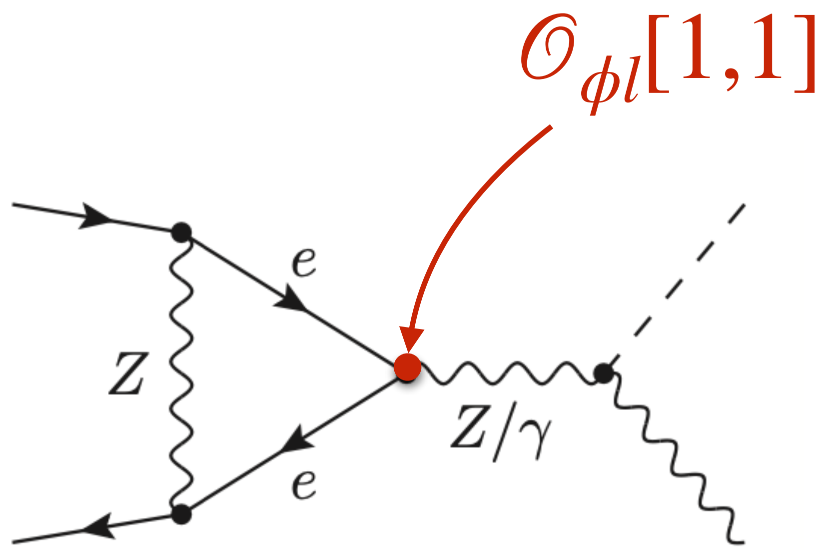
$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_{k=5} \sum_{i} \frac{\mathscr{C}_i^k}{\boxed{\Lambda^{k-4}}} \boxed{\mathscr{O}_i^k}$$

Scale of new physics

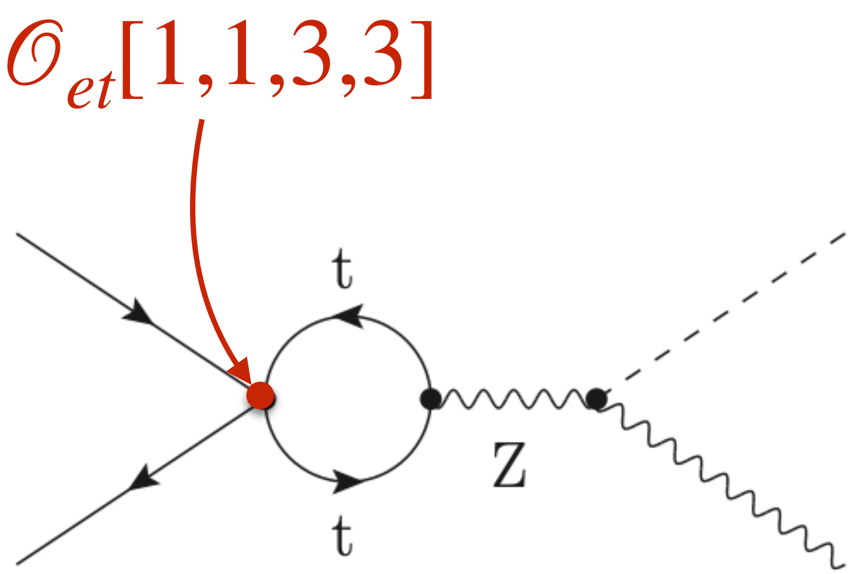


We considered the inclusion of all operators that contribute to $e^+e^- \to HZ$ at Leading Order (LO) and (electro-weak) Next-to-Leading Order (NLO)

There are 2 reasons to calculate the NLO corrections.



Higher precisions bounds on operators that are already present at LO



Possible bounds on operators that do not enter at LO

Our calculation

SM results, including LO and virtual NLO, excluding QED contributions

SM virtual and real QED contributions

$$\boxed{\sigma_{\rm NLO}} = \boxed{\sigma^{W}_{\rm SM,NLO}} \left(1 + \boxed{\delta_{SM,QED}} + \frac{1}{\Lambda^2}\sum_i \mathscr{C}_i(\mu)\left\{\boxed{\Delta^{\rm (NLO)}_{i,\rm weak}} + \boxed{\bar{\Delta}_i \log\frac{\mu^2}{s}} + \boxed{\Delta_{i,\rm QED}}\right\}\right)$$

EFT results, including LO and virtual NLO, excluding IR divergent contributions

EFT - RGE contributions

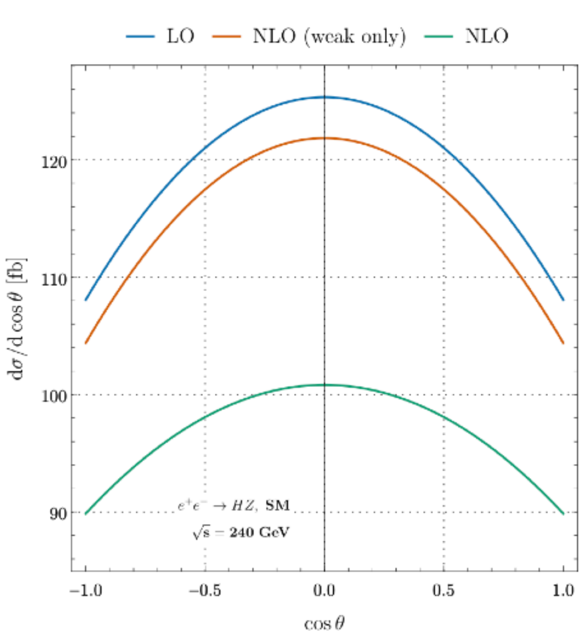
EFT virtual and real QED (IR divergent) contributions

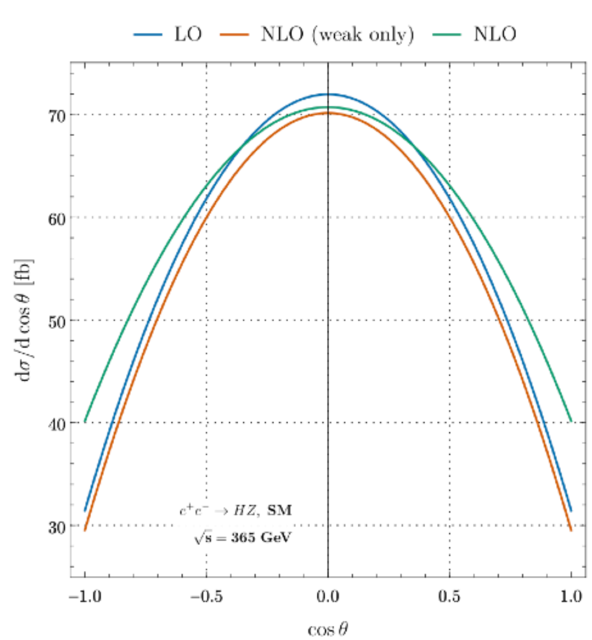
SM results agree with literature: A. Freitas and Q. Song Phys. Rev. Lett. 130 no. 3, (2023) 031801

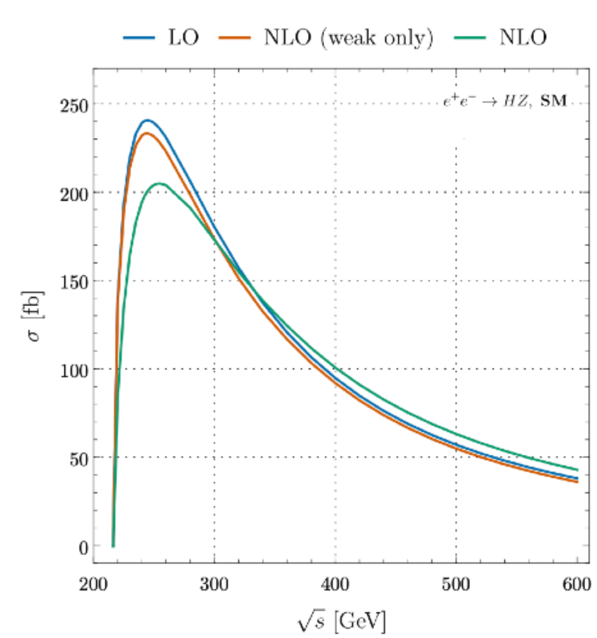
We calculated in a mixed renormalization scheme, with On-Shell SM parameters and $\overline{\mathrm{MS}}$ for EFT operators. We used a $\{G_\mu, M_Z, M_W\}$ input scheme

$$
\begin{aligned}
G_\mu &= 1.16638 \times 10^{-5}\ \mathrm{GeV}^{-2}\,, \\
M_W^{\mathrm{exp}} &= 80.379\ \mathrm{GeV}\,, \\
M_Z^{\mathrm{exp}} &= 91.1876\ \mathrm{GeV}\,, \\
M_H &= 125.1\ \mathrm{GeV}\,, \\
m_t &= 172.76\ \mathrm{GeV}\,, \\
m_e &= 0.511\ \mathrm{MeV}\,.
\end{aligned}
$$

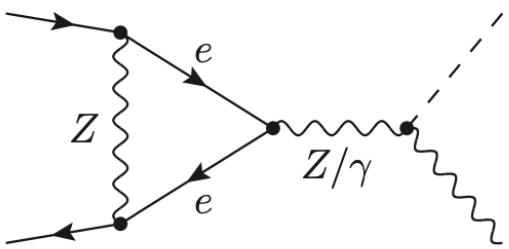
We considered possible future measurements at
$\sim 240\ \mathrm{GeV}, 365\ \mathrm{GeV}\ \&\ 500\ \mathrm{GeV}$
(assuming $0.5\ \%$, $1\ \%$ & $1\ \%$ accuracy respectively)





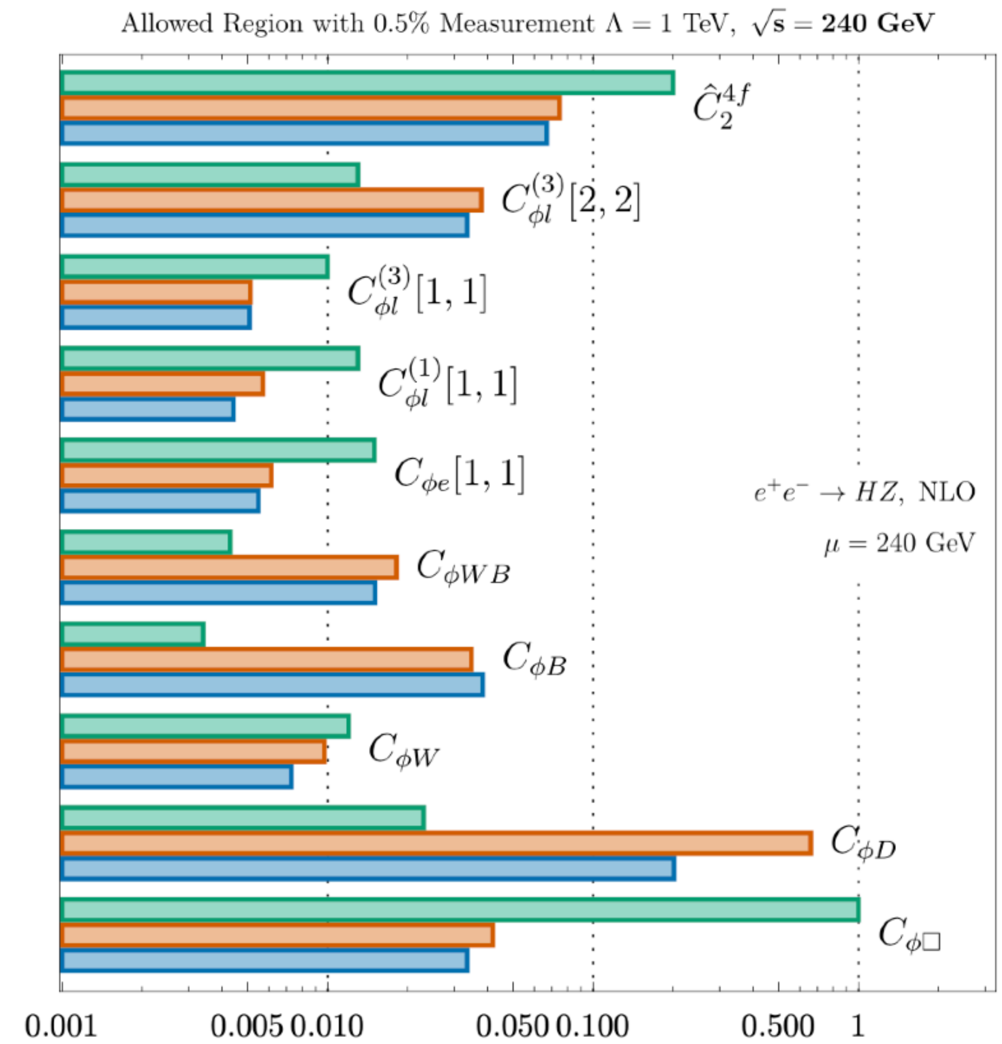


Furthermore we consider both polarized and unpolarized beams



Single fit limits on operators that appear at LO, vs. limits from the global fit.

In general NLO bounds are not much different from LO bounds.
Only noteworthy execption is $\mathscr{C}_{\phi D}$:
~ 0.2 at LO vs ~ 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	$2.09 \cdot 10^{-2}$	$-1.65 \cdot 10^{-2}$	$4.18 \cdot 10^{-3}$	$8.66 \cdot 10^{-3}$	$-1.25 \cdot 10^{-3}$

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

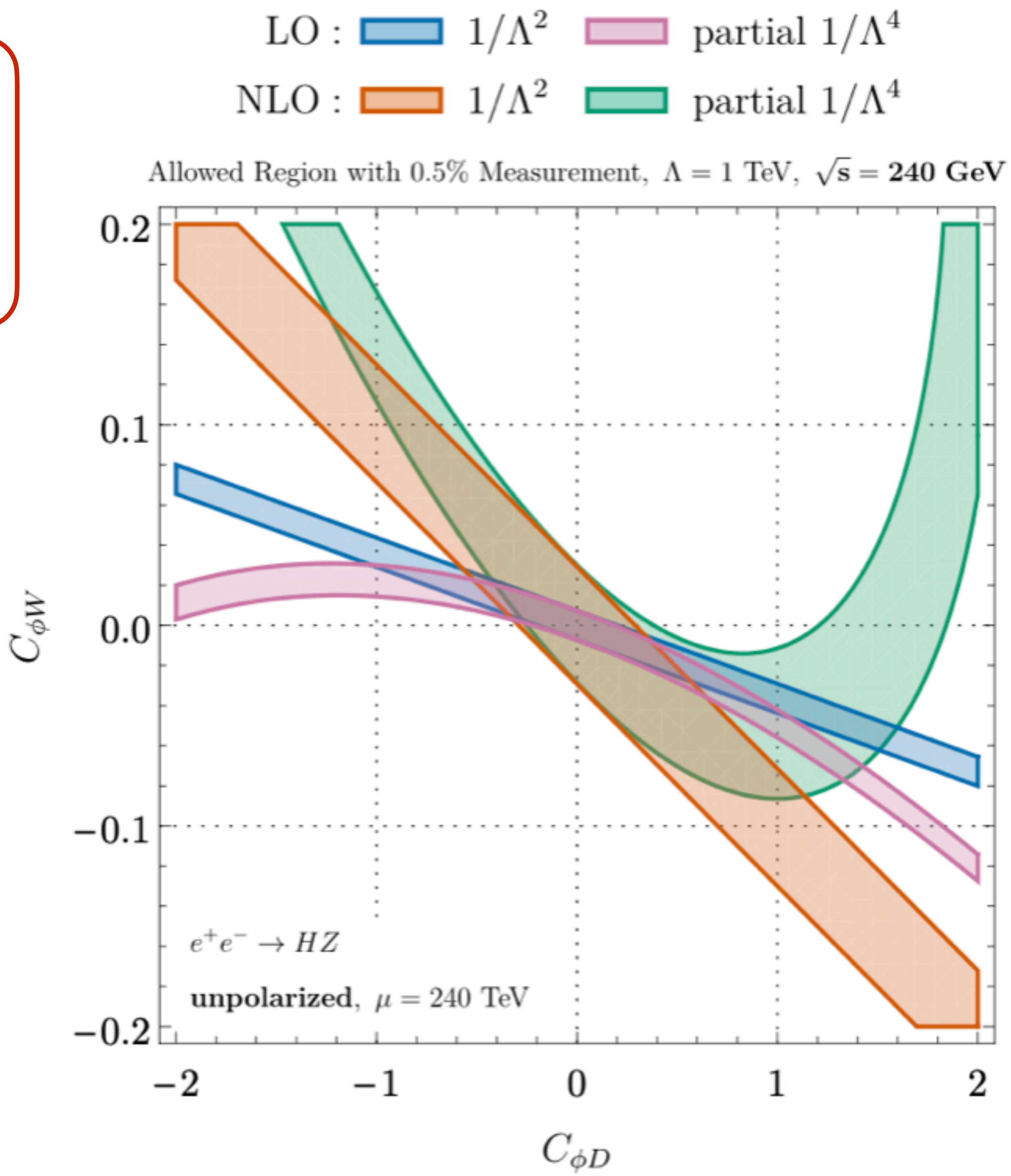
Large cancellation between LO and NLO contribution (in actuality cancellation between Right and Left polarization)

Global fit: J. Ellis, M. Madigan, K. Mimasu, V. Sanz, and T. You JHEP 04 (2021) 279

When multiple operators are conisdered at the same time, the resulting limits could be quite different.

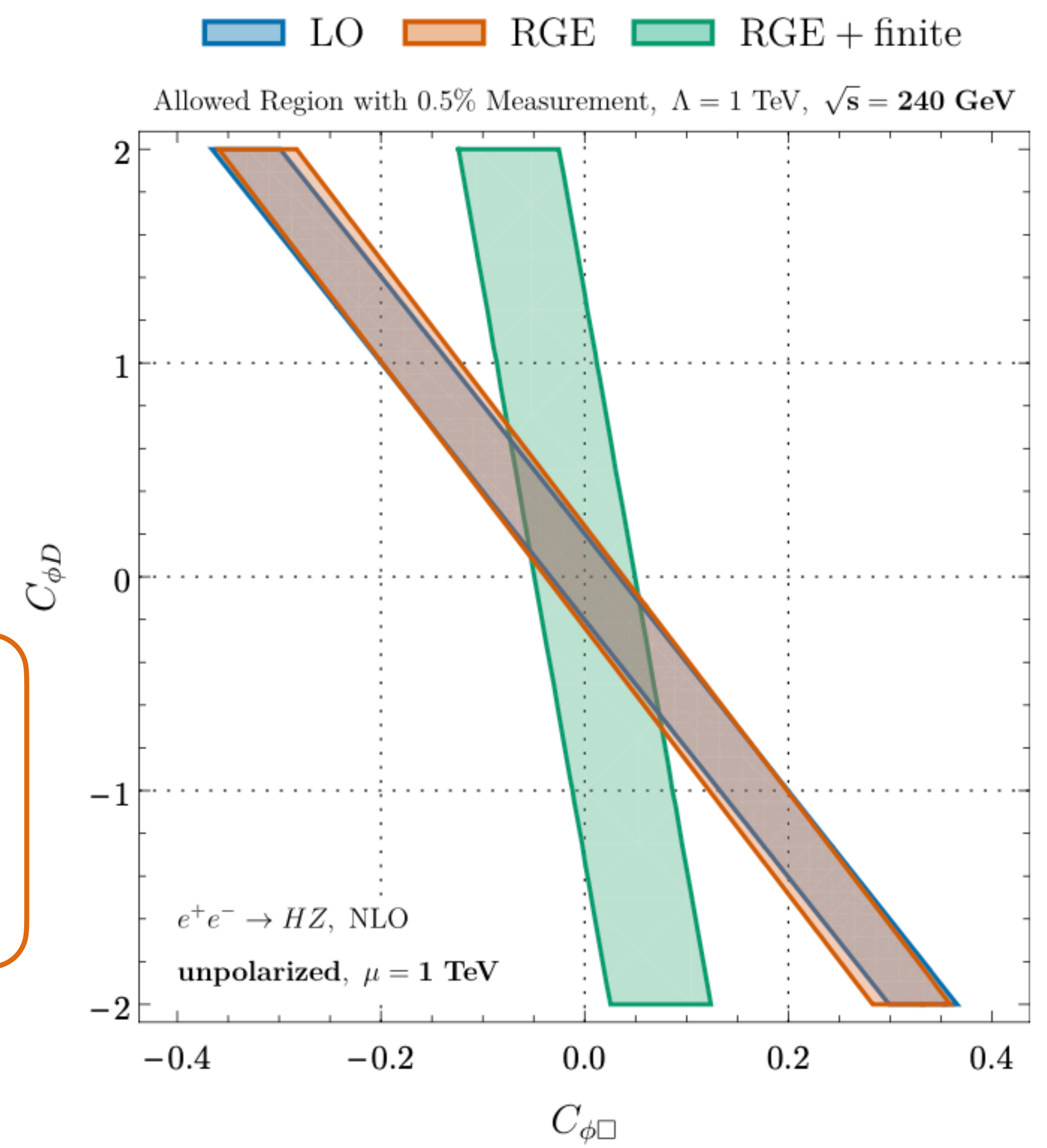
Small changes to the flat direction in the $\mathscr{C}_{\phi W} - \mathscr{C}_{\phi D}$ plane leads to large change in the bounds

Effects of NLO corrections in global fits are relevant



The inclusion of $1/\Lambda^4$ can also have a large effect, but this is not a well-definied procedure at NLO (without dim-8 operators). One can interpret the $1/\Lambda^2$-$1/\Lambda^4$ overlap region as the region of "validity".

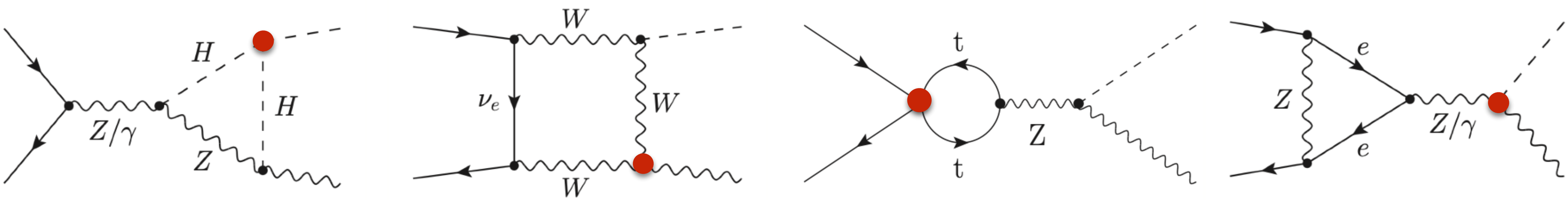
In our calculations we included not only RGE effects, but also finite (i.e. not log dependent) contributions.



We see that in many cases the effect of the finite contributions are much larger than those of the RGE contributions

This is of course a "scale-dependent" statement. At high enough scale the RGE contributions will surpass the finite contributions. However if the scale is too high the EFT contribution to SM processes will become negligible and the point is moot.

At NLO other operators contribute.

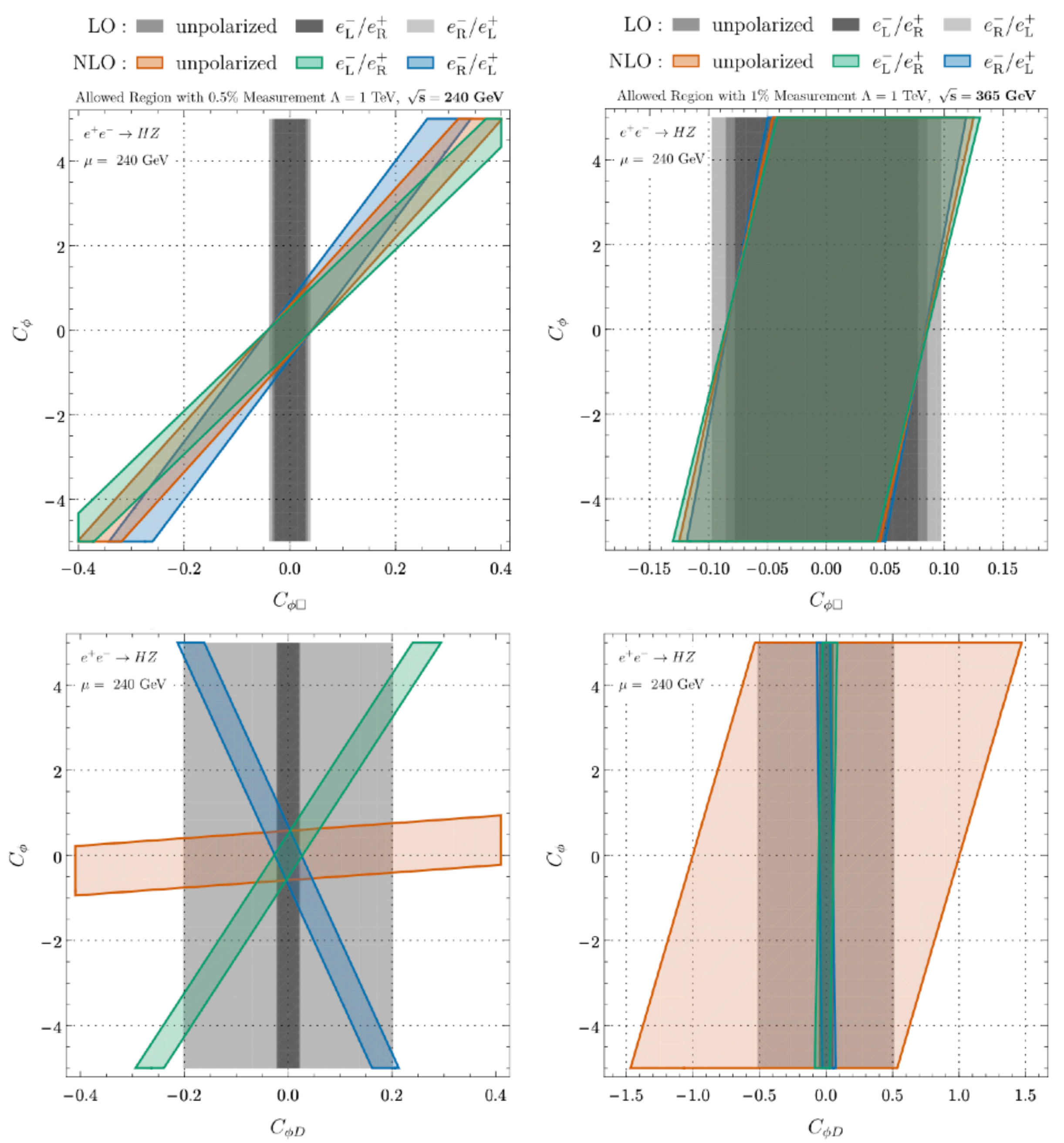


Modifications of the Higgs trilinear: $\mathscr{C}_{\phi}$

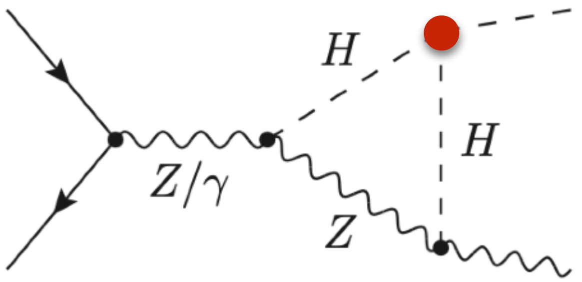
Modifications of the gauge triple-coupling: $\mathscr{C}_{W}$

Operators involving a top quark, e.g. $\mathscr{C}_{et}(1,1,3,3)$

Operators that induce a violation of CP, e.g. $\mathscr{C}_{\phi\tilde{W}}$



$e^+e^- \to HZ$ can give us information on the trilinear,

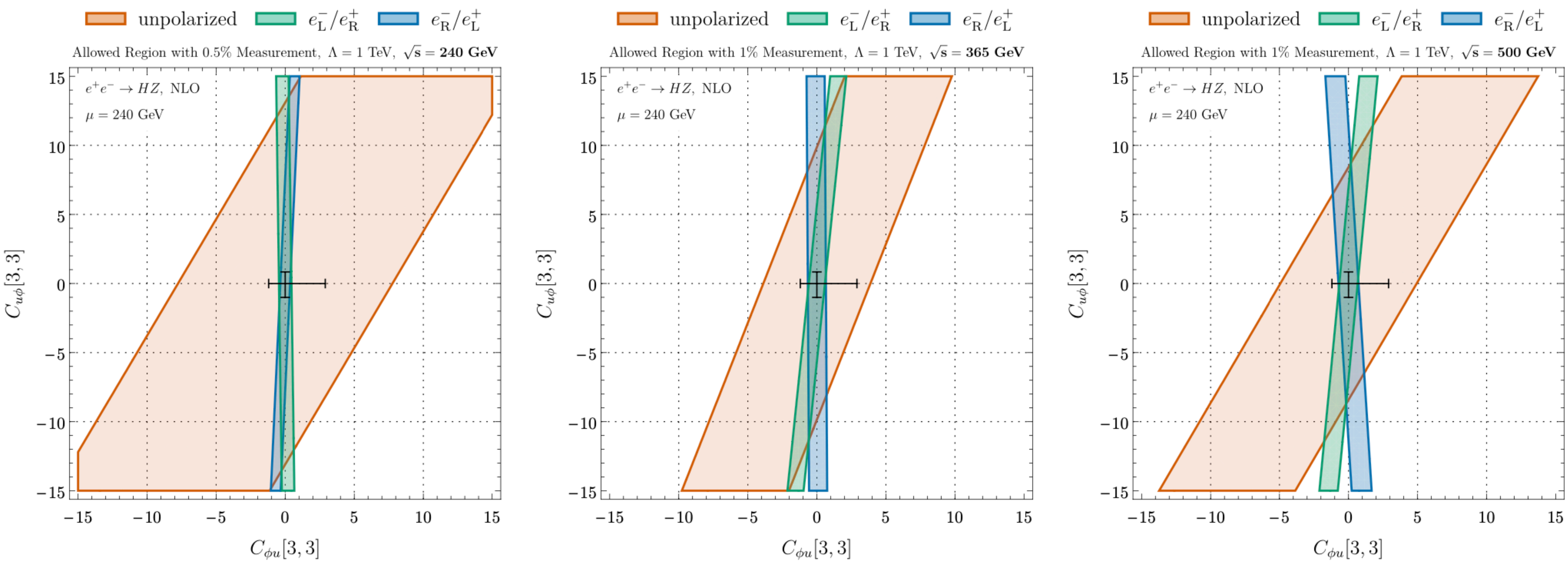


but including or excluding contributions from different operators significantly impacts the size of the constraints and the interpretation of the results.

The correlation between operators can have a large dependence over the energy

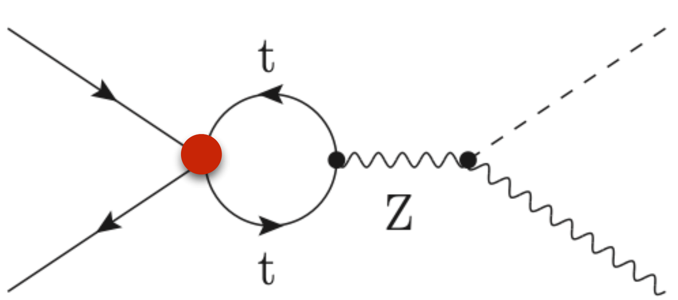
Depending on the operators, and the energy, considering different polarizations may or may not have an inpact

M. McCullough Phys. Rev. D 90 no. 1, (2014) 015001



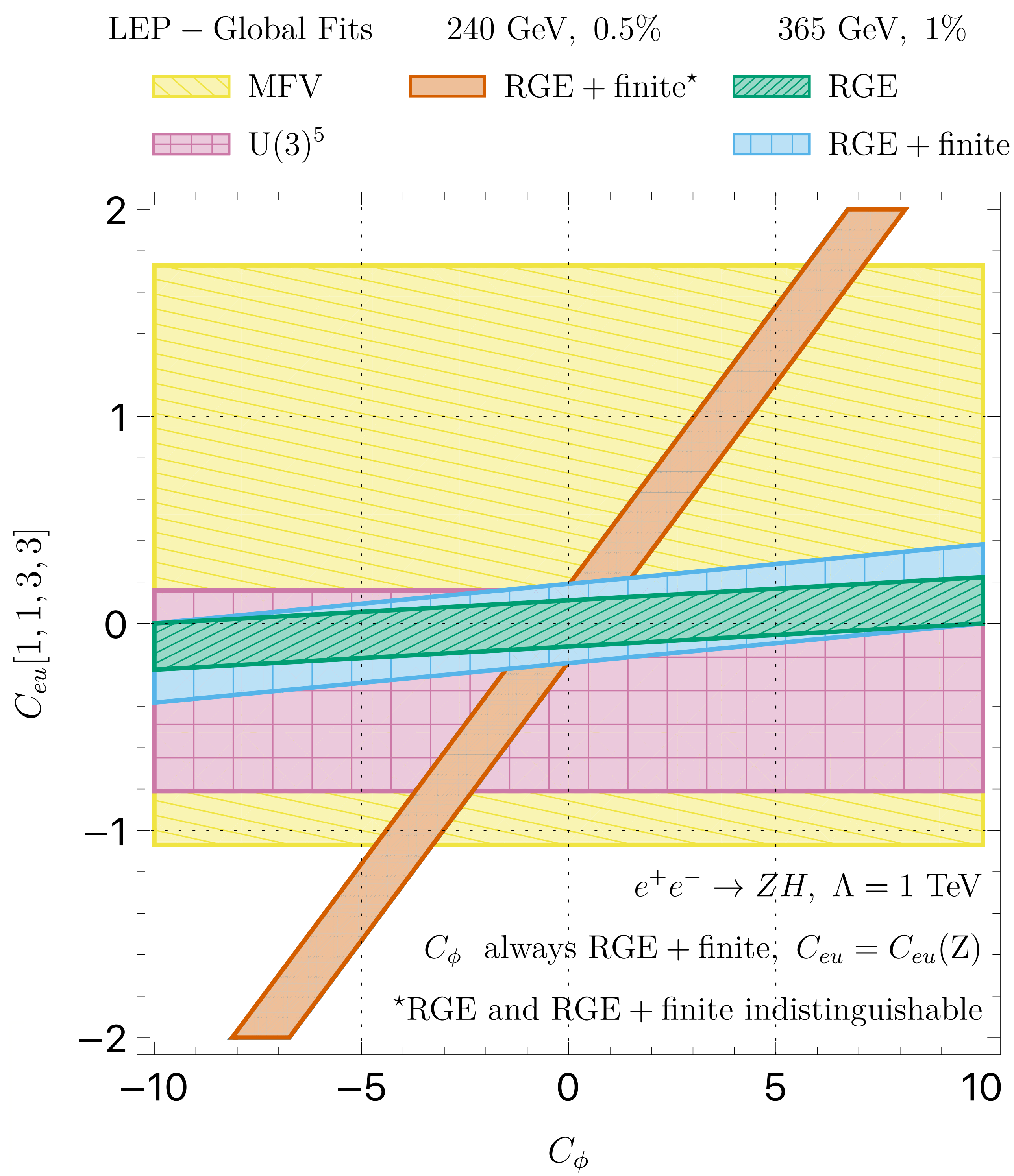
We observe a similar dependence also for top-induced NLO operators (e.g. modifications of the top-Yukawa, and top-Z coupling).

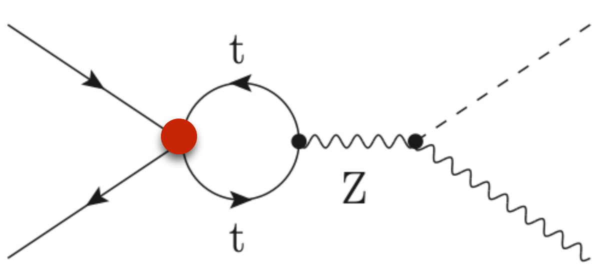
For the top-operators we observe a clear enhancement around the 2-top threshold $\sim 365\,\mathrm{GeV}$

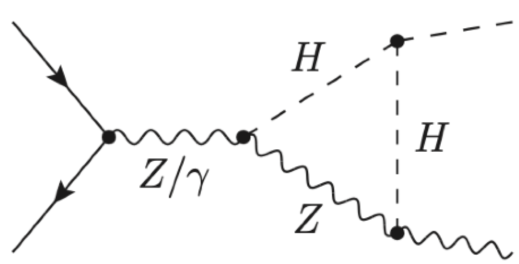


Plotting together top-induced and Higgs-induced operators shows an interesting dependence on the energy.

Nice complementarity between 240 GeV and 365 GeV



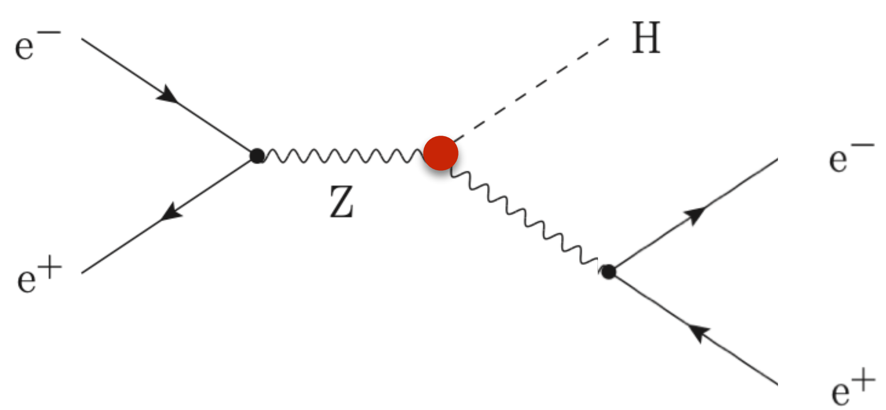




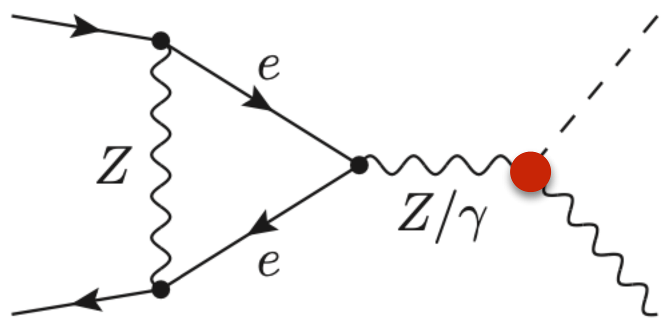
CP-odd operators do appear at LO

$$\boxed{\mathscr{A}(e^+e^- \to HZ) \propto \mathscr{A}_{CP-even} + i\mathscr{A}_{CP-odd}}$$

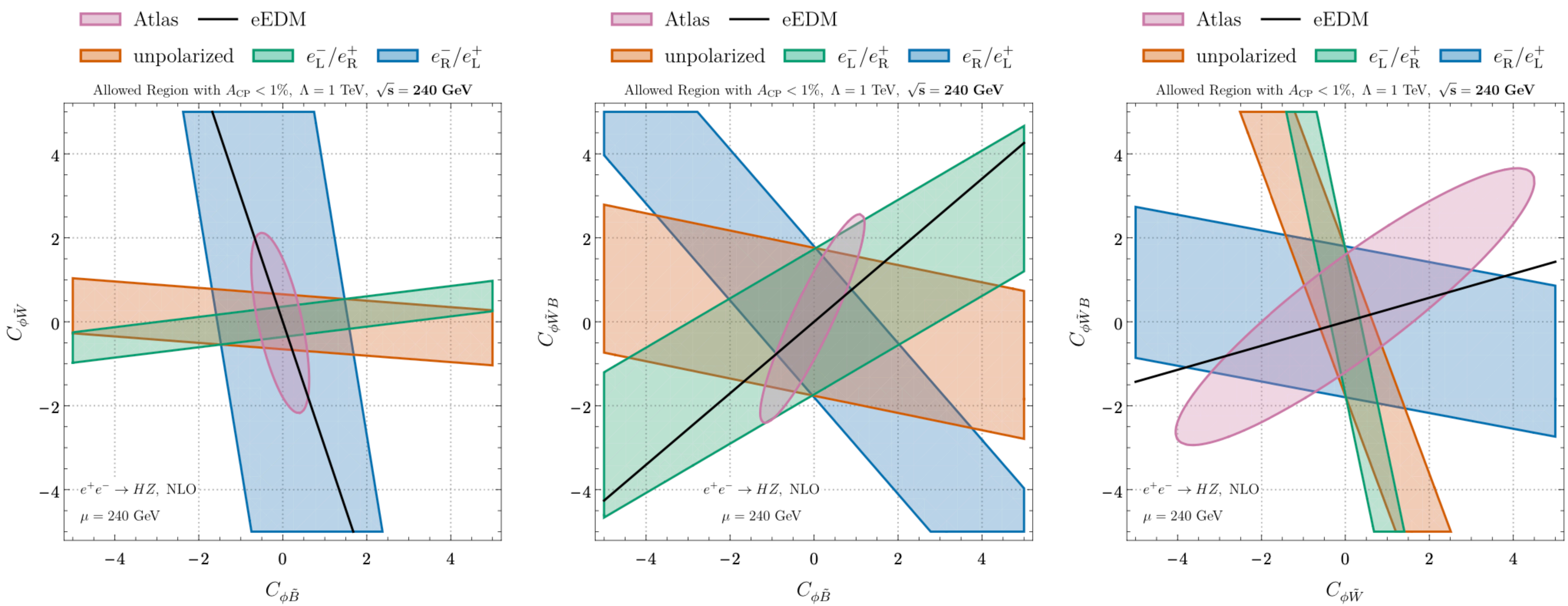
To access $\mathscr{A}_{CP-odd}$ it is possible to

1) 

Consider the Z decay and study the angular distribution of the final state vs. initial state leptons

2) 

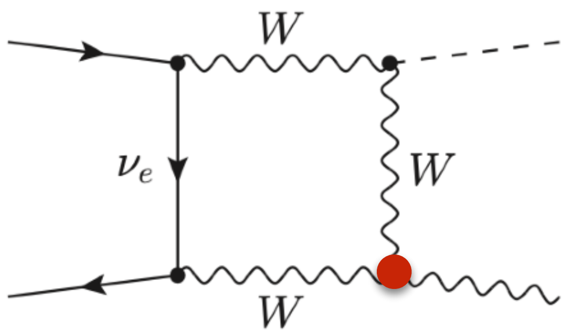
Use the fact that NLO integrals have imaginary parts, and study only the p_t distribution of the Z



We define a CP violating asymmetry to study the sensitivity to each operators.

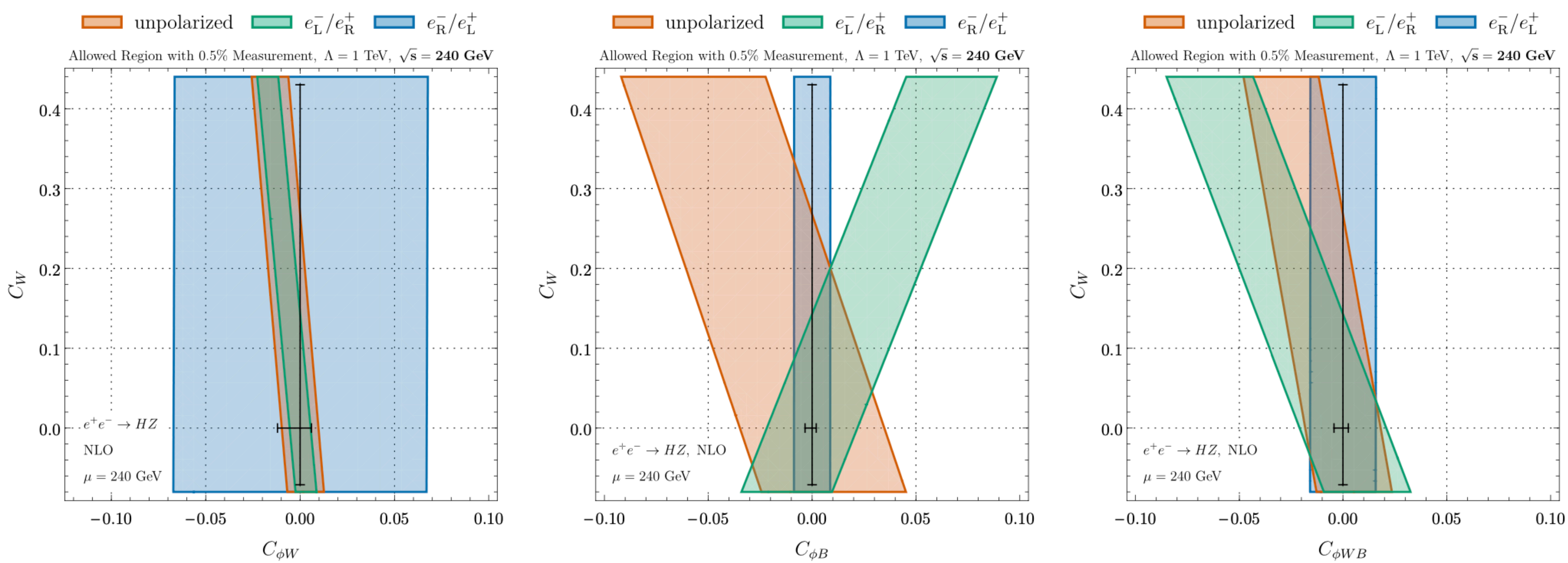
$$A_{\mathrm{CP},i} \equiv \frac{C_i(\mu)}{\Lambda^2} \frac{|\Delta^{(\mathrm{NLO})}_{i,\mathrm{weak}}(\cos\theta < 0) - \Delta^{(\mathrm{NLO})}_{i,\mathrm{weak}}(\cos\theta > 0)|}{\sigma^W_{\mathrm{SM,NLO}}}$$

CP studies at $e^+e^- \to HZ$ in general offer information that is nicely complementary to that of eEDM.



Another interesting operator is $\mathscr{C}_W$ which induces a modification of the gauge-triple coupling.

As before we notice different degrees of correlation with LO operators, and different sensitivity on the polarization.



- $\sigma(e^+e^- \to HZ)$ at future accelerators can inform us on N.P. around and above the $1\,\mathrm{TeV}$ scale
- The inclusion of loop corrections give us the possibility of obtaining information on a large variety of N.P. (Higgs self-coupling, top coupling, etc.)
- We observe that the correlations between operators can vary greatly depending on the energy and the polarization of the beam.
- $\sigma(e^+e^- \to HZ)$ depends on 7 SMEFT structures at LO and on 39 SMEFT structures at NLO: this is only a piece of a Global Fit.