Probing new physics at colliders via HEFT

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Based upon, arXiv: 2208.09334 , with Oliver Atkinson, Akanksha Bhardwaj, Christoph Englert, Panogiotis Stylianou

arXiv: 2402.06746 , with Christoph Englert, Roman Kogler, Michael Spannowsky

arXiv: 2405.05385 , with Daniel Domenech, Christoph Englert, Maria J. Herrero, Roberto A. Morales

EFTs and Beyond

December 4th , 2024

Outline

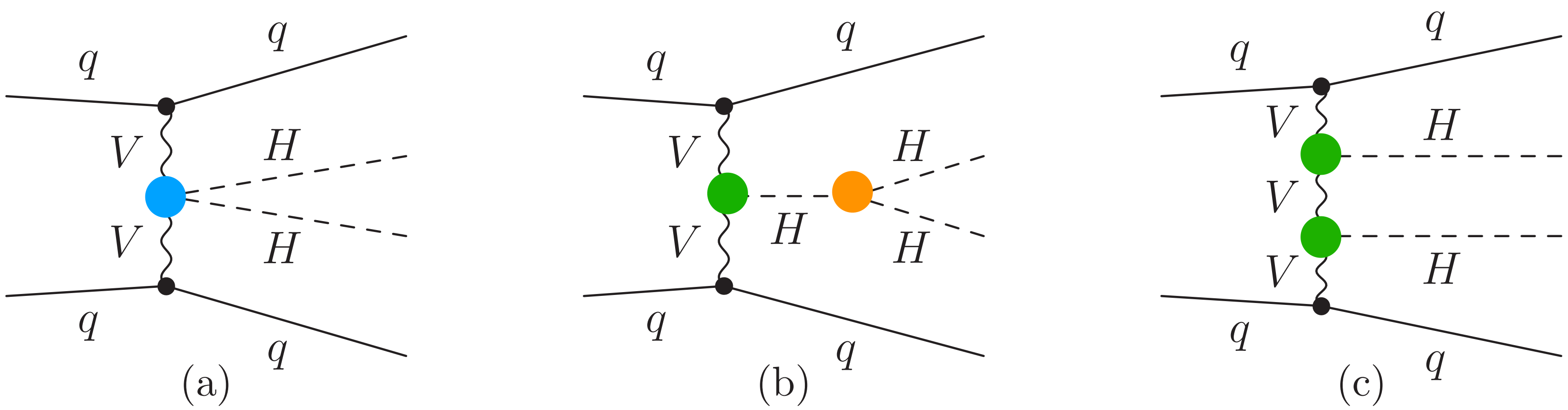
- Starting with the Quartic Higgs Gauge Couplings, I will discuss why we need a different framework.
- Then I will introduce the framework of the HEFT.
- Discuss the constraints of HHVV interactions using the one-loop effects on single Higgs data.
- Using Higgs boson off-shell measurements, probing the sensitivity of HEFT interactions.
- Effects of HEFT radiative corrections to multi-Higgs processes.

Quartic Gauge-Higgs couplings
&
Motivation for HEFT framework

A, Oliver Atkinson, Akanksha Bhardwaj, Christoph Englert, Panogiotis Stylianou 2208.09334

Status of the Quartic Higgs couplings with Gauge Bosons

- Experimentally $HHVV$ couplings are probed in HH production via Weak Boson fusion.
- WBF is statistically limited at LHC as ggF has the largest cross-section.



- These couplings are very weakly constrained due to the small rate of HH production.
- To enhance HH, following κ framework, the couplings are modified away from SM

coupling modifiers $\kappa_V = \frac{g_{HVV}}{g^{\mathrm{SM}}_{HVV}}$ $\kappa_\lambda = \frac{g_{HHH}}{g^{\mathrm{SM}}_{HHH}}$ $\kappa_{2V} = \frac{g_{HHVV}}{g^{\mathrm{SM}}_{HHVV}}$

κ_V : Constrained from single Higgs decays $H \to WW^*/ZZ^*$

κ_λ : Better sensitivity from ggF

κ_{2V} : Unique sensitivity from WBF

Studying the deviations in $HHVV$ couplings away from SM predictions are important

$\Longrightarrow$ these can induce changes in the cross-sections and lead to enhanced HH rates.

$\Longrightarrow$ indicator of physics beyond SM

Baseline of κ_{2V} in SM

Considering only $HHVV$ couplings modifications and HVV modifiers to be SM like.

- **Electroweak precision constraints** Gfitter 1407.3792.

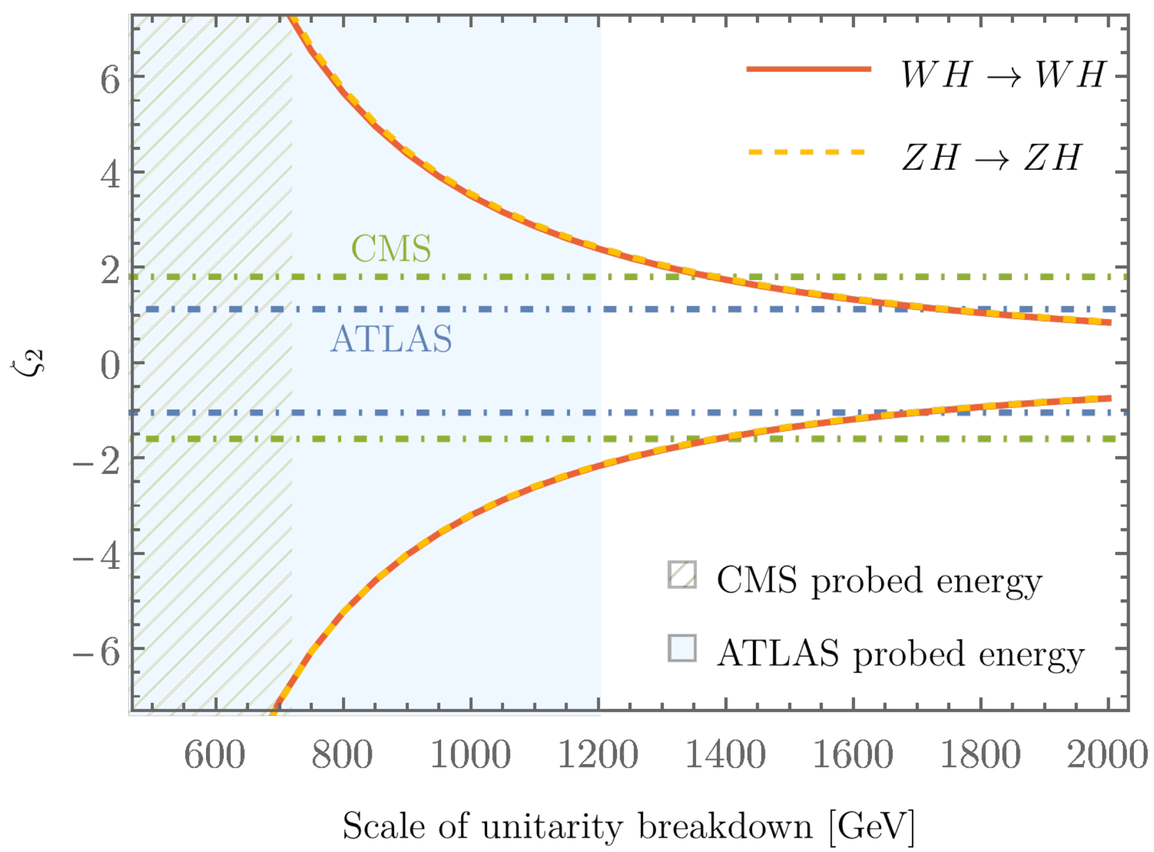
$$\Delta S = \Delta U = 0$$

$\Delta T \sim \kappa_{2Z}^2 - \kappa_{2W}^2$, by imposing $\kappa_{2W} = \kappa_{2Z} = \kappa_{2V}$ gives $\Delta T = 0 \Longrightarrow$ EWPO constraints not violated.

- **Unitarity constraints**

Considering longitudinal $HV_L \to HV_L$ scattering and $\kappa_{2V} = 1 + \zeta_2$

As per unitarity criterion, for same initial and final states i, $\text{Re}\,|a_{ii}^0| \leq \frac{1}{2}$



95 % CL experimental constraints

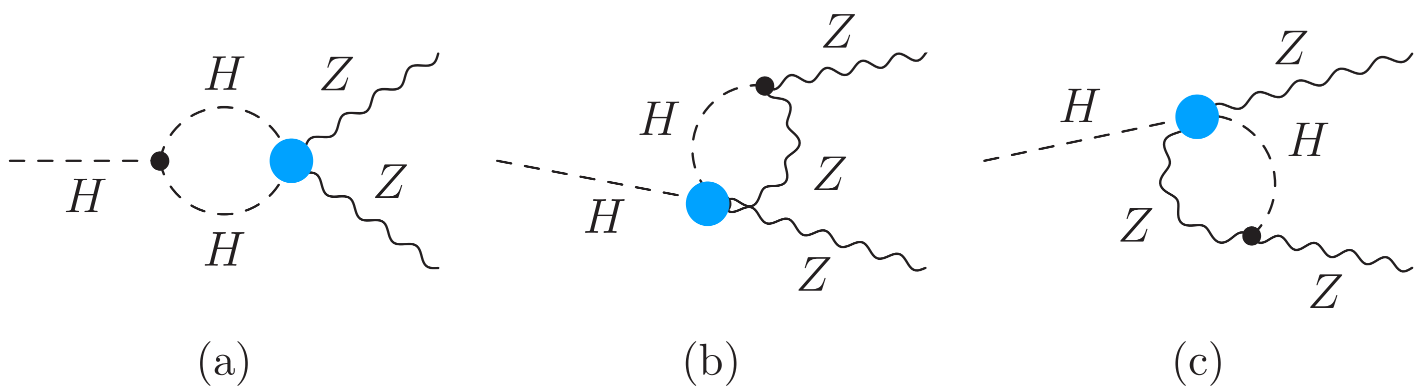
ATLAS $\kappa_{2V} \in [-0.05, 2.12]$

CMS $\kappa_{2V} \in [-0.6, 2.8]$

Loose unitarity constraints on ζ_2

At one loop order

- Radiative corrections to $H \to ZZ^*$ (neglecting fermions) in general R_ξ gauge



considering
$\kappa_{2V} = 1 + \zeta_2$

$$\mathcal{M}^{\rm Loop} + \mathcal{M}_{\rm CT}\Big|_{\Delta_{\rm UV}} = -\zeta_2 \frac{\alpha}{32\pi} \frac{e}{M_W s_W^5 c_W^2} \left(M_H^2 + 2M_Z^2 s_W^2 \{3 + \xi_Z\}\right) \times [\epsilon^\mu(Z_1)\epsilon_\mu(Z_2)]^*.$$

- For $\zeta_2 \neq 0$, the gauge invariance is broken due to non zero ξ_Z.

- This is mainly as the SM Φ is a doublet and due to gauge symmetry,

$$\begin{aligned} \mathcal{L}_{SM} &\supset D_\mu \Phi^\dagger D_\mu \Phi \\ &\supset \frac{e^2}{2\cos^2\theta_W \sin^2\theta_W} g^{\mu\nu}(v\, H Z_\mu Z_\nu + HH Z_\mu Z_\nu) + \frac{e^2}{2\sin^2\theta_W} g^{\mu\nu}(v\, H W_\mu W_\nu + HH W_\mu W_\nu) \end{aligned}$$

$HHVV$ couplings are correlated with HVV and modifying only one term spoils the gauge invariance.

In SM, weak unitarity constraints on κ_{2V} and broken gauge invariance $\Longrightarrow$ A better theoretical framework is needed in order to consider the model independent measurements of ATLAS and CMS.

Framework requirements

- ☑ Avoiding correlations inconsistencies between HZZ and HHZZ
- ☑ Considering $H^n VV$ as independent.

↓ for the indirect reach of κ_{2V} in light of constraining single Higgs measurements

Higgs Effective Field Theory

Buchalla et al.1307.5017 Brivio et al.1604.06801 Herrero, Morales 2107.07890

- SM Higgs H is not part of the Φ doublet and is a singlet field.
  - No limitations on its interaction with other SM fields.
  - The interactions are given via generic polynomial in powers of $(h/v)^n$
- Goldstones π^a are written non-linearly using U matrix where

$$U(\pi^a) = \exp\left(i\pi^a\tau^a/v\right) = \mathbb{1}_2 + i\frac{\pi^a}{v}\tau^a - \frac{2G^+G^- + G^0G^0}{2v^2}\mathbb{1}_2 + \dots$$

$$G^{\pm} = (\pi^2 \pm i\pi^1)/\sqrt{2}$$
$$G^0 = -\pi^3$$

- Gauge Bosons are given

$$D_\mu U = \partial_\mu U + ig_W\left(W_\mu^a\tau^a/2\right)U - ig'UB_\mu\tau^3/2$$

HEFT Lagrangian

Buchalla et al.1307.5017

Brivio et al.1604.06801

Herrero, Morales 2107.07890

Leading order Lagrangian

$$\mathcal{L} = -\frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{v^2}{4}\mathcal{F}_H \,\mathrm{Tr}[D_\mu U^\dagger D^\mu U] + \frac{1}{2}\partial_\mu H \partial^\mu H - V(H) + \mathcal{L}_{\rm ferm} + \mathcal{L}_{\rm Yuk}$$

Interactions of Higgs with SM fields is given by the **Flare function**

Salas-Bernardez et al 2211.09605

$$\mathcal{F}_H = \left(1 + 2(1+\zeta_1)\frac{H}{v} + (1+\zeta_2)\left(\frac{H}{v}\right)^2 + \ldots\right)$$

In case of SM, $\zeta_1 = \zeta_2 = 0$

$$\zeta_1 = \kappa_V - 1 \equiv \frac{g_{HVV}}{g^{\rm SM}_{HVV}} - 1 \qquad \zeta_2 = \kappa_{2V} - 1 \equiv \frac{g_{HHVV}}{g^{\rm SM}_{HHVV}} - 1$$

Potential $$V(H) = \frac{1}{2}M_H^2 H^2 + \kappa_3 \frac{M_H^2}{2v} H^3 + \kappa_4 \frac{M_H^2}{8v^2} H^4$$

In this analysis, $\kappa_{3,4} = 1$

Yukawa Lagrangian $$\mathcal{L}_{\rm Yuk} = -\frac{v}{\sqrt{2}} \left(\bar{u}^i_L \quad \bar{d}^i_L\right) U \begin{pmatrix} \mathcal{Y}^u_{ij} u^j_R \\ \mathcal{Y}^d_{ij} d^j_R \end{pmatrix} + \mathrm{h.c.}$$

$$\mathcal{Y}^f_{ij} = y^f_{ij}\left(1 + (1+a_{1f})\frac{H}{v} + \ldots\right)$$

assuming $a_{1f} = 0$

Neglected the light quark flavour and lepton masses throughout this work

Looking into the loop order effects

To achieve a consistent correlation of different Higgs legs, we study the radiative corrections to Higgs decay channels.

$$\mathcal{L}_{HEFT} = \mathcal{L} + \sum_i a_i \mathcal{O}_i \longrightarrow$$

HEFT operators contribute to the total counter-term

Appelquist-Longhitano-Feruglio (ALF) basis extended with a singlet Higgs.

$\mathcal{O}_0$	$a_0(M_Z^2 - M_W^2)\mathrm{Tr}\left[U\tau^3U^\dagger\mathcal{V}_\mu\right]\mathrm{Tr}\left[U\tau^3U^\dagger\mathcal{V}_\mu\right]$	$\mathcal{O}_1$	$a_1\, g' g_W \mathrm{Tr}\left[UB_{\mu\nu}\frac{\tau^3}{2}U^\dagger W^a_{\mu\nu}\frac{\tau^a}{2}\right]$
$\mathcal{O}_{HBB}$	$-a_{HBB}\, g'^2 \frac{H}{v}\mathrm{Tr}\left[(B_{\mu\nu}\frac{\tau^3}{2})(B^{\mu\nu}\frac{\tau^3}{2})\right]$	$\mathcal{O}_{HWW}$	$-a_{HWW}\, g_W^2 \frac{H}{v}\mathrm{Tr}\left[(W^a_{\mu\nu}\frac{\tau^a}{2})(W^{a\mu\nu}\frac{\tau^a}{2})\right]$
$\mathcal{O}_{H0}$	$a_{H0}(M_Z^2 - M_W^2)\frac{H}{v}\mathrm{Tr}\left[U\tau^3U^\dagger\mathcal{V}_\mu\right]\mathrm{Tr}\left[U\tau^3U^\dagger\mathcal{V}_\mu\right]$	$\mathcal{O}_{H1}$	$a_{H1}\, g' g_W \frac{H}{v}\mathrm{Tr}\left[UB_{\mu\nu}\frac{\tau^3}{2}U^\dagger W^a_{\mu\nu}\frac{\tau^a}{2}\right]$
$\mathcal{O}_{H8}$	$-\frac{a_{H8}}{4}\, g_W^2 \frac{H}{v}\mathrm{Tr}\left[U\tau^3U^\dagger W^a_{\mu\nu}\frac{\tau^a}{2}\right]\mathrm{Tr}\left[U\tau^3U^\dagger W^a_{\mu\nu}\frac{\tau^a}{2}\right]$	$\mathcal{O}_{H11}$	$a_{H11}\frac{H}{v}\mathrm{Tr}\left[\mathcal{D}_\mu\mathcal{V}^\mu\mathcal{D}_\nu\mathcal{V}^\nu\right]$
$\mathcal{O}_{H13}$	$-\frac{a_{H13}}{2}\,\frac{H}{v}\mathrm{Tr}\left[U\tau^3U^\dagger\mathcal{D}_\mu\mathcal{V}_\nu\right]\mathrm{Tr}\left[U\tau^3U^\dagger\mathcal{D}^\mu\mathcal{V}^\nu\right]$	$\mathcal{O}_{d1}$	$ia_{d1}\, g' \frac{\partial^\nu H}{v}\mathrm{Tr}\left[UB_{\mu\nu}\frac{\tau^3}{2}U^\dagger\mathcal{V}^\mu\right]$
$\mathcal{O}_{d2}$	$ia_{d2}\, g_W \frac{\partial^\nu H}{v}\mathrm{Tr}\left[W^a_{\mu\nu}\frac{\tau^a}{2}\mathcal{V}^\mu\right]$	$\mathcal{O}_{d3}$	$a_{d3}\frac{\partial^\nu H}{v}\mathrm{Tr}\left[\mathcal{V}^\mu\mathcal{D}_\mu\mathcal{V}^\mu\right]$
$\mathcal{O}_{d4}$	$a_{d4}\, g_W \frac{\partial^\nu H}{v}\mathrm{Tr}\left[U\tau^3U^\dagger W^a_{\mu\nu}\frac{\tau^a}{2}\right]\mathrm{Tr}\left[U\tau^3U^\dagger\mathcal{V}^\mu\right]$	$\mathcal{O}_{\Box\mathcal{V}\mathcal{V}}$	$a_{\Box\mathcal{V}\mathcal{V}}\frac{\Box H}{v}\mathrm{Tr}\left[\mathcal{V}_\mu\mathcal{V}^\mu\right]$
$\mathcal{O}_{\Box 0}$	$a_{\Box 0}\frac{(M_Z^2 - M_W^2)}{v^2}\frac{\Box H}{v}\mathrm{Tr}\left[U\tau^3U^\dagger\mathcal{V}_\mu\right]\mathrm{Tr}\left[U\tau^3U^\dagger\mathcal{V}_\mu\right]$	$\mathcal{O}_{\Box\Box}$	$a_{\Box\Box}\frac{\Box H\Box H}{v^2}$

$$\mathcal{V}_\mu = (D_\mu U)U^\dagger \qquad \mathcal{D}_\mu\mathcal{V}^\mu = \partial_\mu\mathcal{V}^\mu + i[g_W W^a_\mu\frac{\tau^a}{2}, \mathcal{V}^\mu]$$

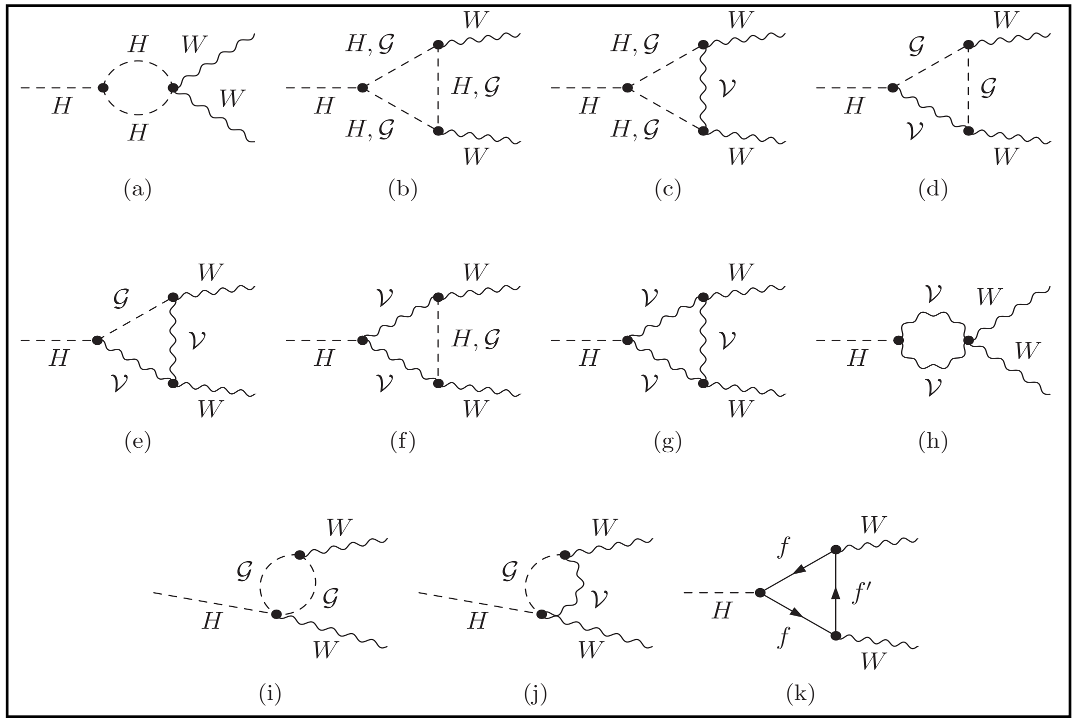
Alonso et al 1304.5937
Brivio et al 1604.06801
Herrero, Morales 2107.07890

Example explaining the HEFT Loop order effects

- Taking example of $H \to WW$

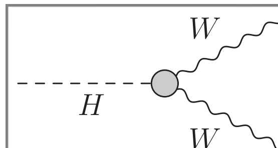
For details about loop computations, refer Herrero, Morales 2107.07890

One loop diagrams with leading order Lagrangian



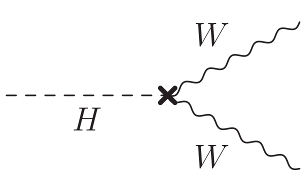
Amplitude with Higher dimensional operators

$\mathcal{O}_{HWW}$	$-a_{HWW}\; g_W^2 \frac{H}{v} \mathrm{Tr}\left[W^a_{\mu\nu} W^{a\mu\nu}\right]$
$\mathcal{O}_{\square\mathcal{V}\mathcal{V}}$	$a_{\square\mathcal{V}\mathcal{V}} \frac{\square H}{v} \mathrm{Tr}\left[\mathcal{V}_\mu \mathcal{V}^\mu\right]$
$\mathcal{O}_{d2}$	$i a_{d2}\; g_W \frac{\partial^\nu H}{v} \mathrm{Tr}\left[W^a_{\mu\nu} \frac{\tau^a}{2} \mathcal{V}^\mu\right]$

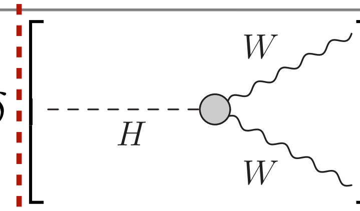


$$= \frac{e^2}{2\, v\, s_W^2} \left[\left(-2a_{HWW}(k_1^2 + k_2^2 - q^2) + 2a_{\square\mathcal{V}\mathcal{V}}\, q^2 + a_{d2} q^2\right) g^{\mu\nu} - 2\left(a_{d2} + 2a_{HWW}\right) k_2^\mu k_1^\nu\right]$$

Complete Counter Term

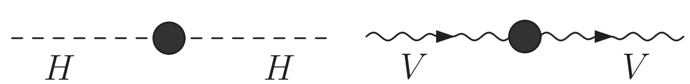


$$= \frac{e M_W (1+\zeta_1)}{s_W} \left(\delta Z_e + \frac{\delta M_W^2}{2M_W^2} - \frac{\delta s_W}{s_W} + \frac{\delta\zeta_1}{1+\zeta_1} + \frac{\delta Z_H}{2} + \delta Z_W\right) g^{\mu\nu} + \delta \left[\; \right]$$



Renormalisation of HEFT operators and fixed looking into the divergent structures

RCs from 2point functions



$\delta a_{d2}\big|_\Delta = 2\delta a_{HWW}\big|_\Delta$

q^2 dependent part fixes $\delta a_{\square\mathcal{V}\mathcal{V}}$, δa_{HWW}

q^2 independent part fixes $\delta\zeta_1$

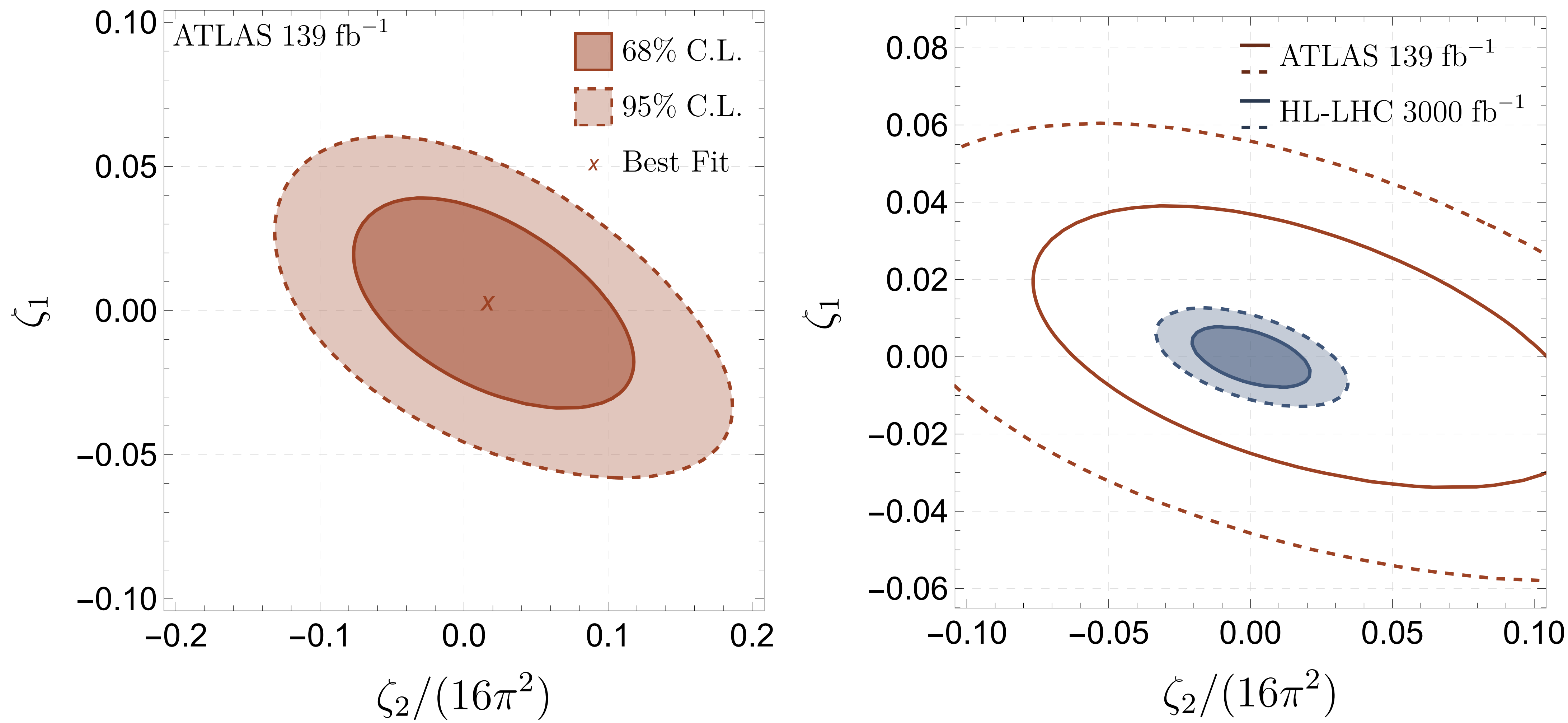
- Using $H \to \gamma\gamma, \gamma Z, WW^*, ZZ^*$,

$$\mathcal{M}^2 = |\mathcal{M}_{\rm LO}|^2 + 2\,\mathrm{Re}\left\{\mathcal{M}_{\rm LO}\mathcal{M}^*_{\text{1-loop}}\right\} \longrightarrow \text{decay widths}$$

Dawson, Giardino 1801.01136 Dawson, Giardino 1807.11504

Single Higgs data constraints for $\zeta_2 - \zeta_1$ correlations

Using single Higgs κ data fit ATLAS 2022



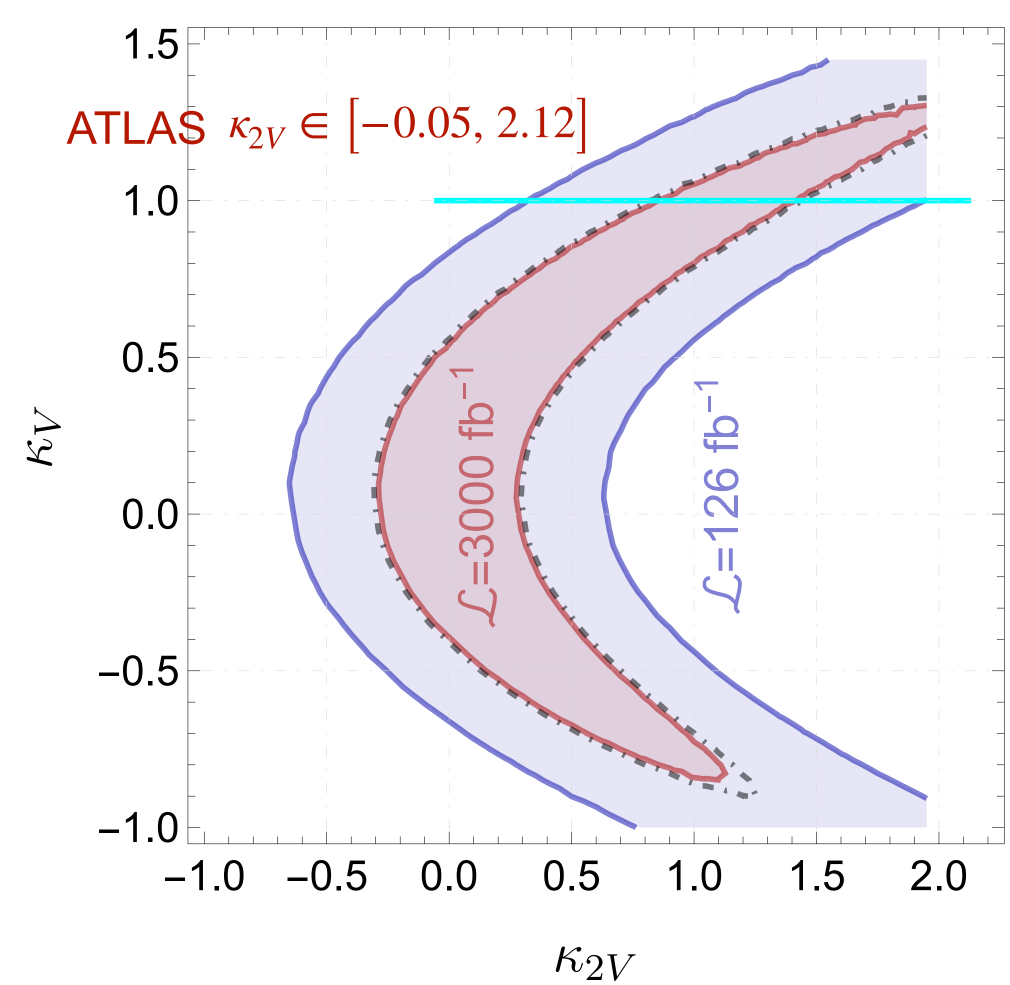
- The bounds on $\kappa_{2V} = 1 + \zeta_2$ from single Higgs data are loose.
- With HL-LHC projected data, single Higgs data greatly constraints ζ_1 and the constraints on ζ_2 reduced by a factor of 4.
- These plots indicate that κ_{2V} and κ_V are independent parameters at the LHC.
- There is a further need to increase the sensitivity coverage to ζ_2 through direct searches.

Comparison with the direct search limits

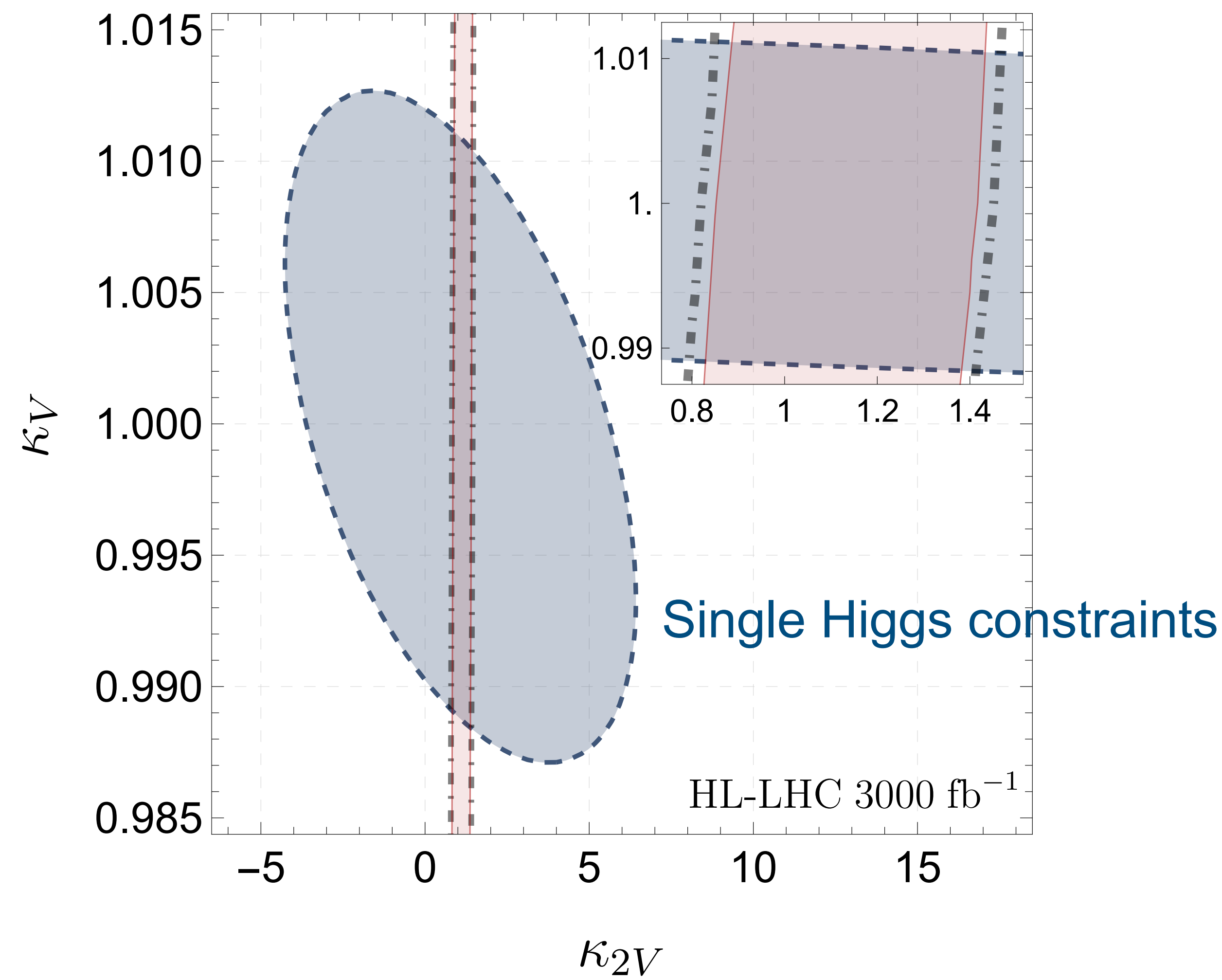
For the direct search: process considered: $pp \to HH \to b\bar{b}b\bar{b} + 2j$

To obtain direct search limits, employed Graph neural network analysis → to discriminate QCD multijet background from signal

95% Exclusion contours using GNN



HL-LHC projections



Direct sensitivity on κ_{2V} are better than the limits obtained from single Higgs data.

Study of Higgs off-shell effects in HEFT

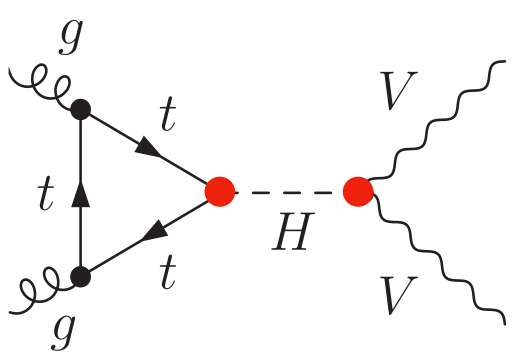
A, Christoph Englert, Roman Kogler, Michael Spannowsky 2402.06746

Higgs off-shell vs on shell effects

- Off-shell measurements in the $pp \to VV$ have a long history in determining the model-independent bound on the Higgs width.

Caola, Melnikov 1307.4935
Kauer, Passarino 1206.4803

  - with the dominant production channel i.e. $gg \to H^* \to VV$



$$\mu_{VV}^{\text{on-shell}} = \frac{\sigma_H \, \text{BR}(H \to VV)]}{\sigma_H \, \text{BR}(H \to VV)]^{\text{SM}}} \propto \frac{\kappa_{ggF}^{2,\text{on-shell}} \; \kappa_{VV}^{2,\text{on-shell}}}{\Gamma_H / \Gamma_H^{SM}}$$

$$\mu_{VV}^{\text{off-shell}} \propto \kappa_{ggF}^{2,\text{off-shell}} \; \kappa_{hVV}^{2,\text{off-shell}} \qquad \text{for } M_{VV} >> M_H$$

  - Higgs width is obtained assuming that these couplings remain the same over a large range of energies.

- These off-shell Higgs measurements have the potential to probe new physics/BSM effects.

Englert, Spannowsky 1405.0285

- In the context of SMEFT framework, a lot of literature is available discussing the off-shell effects.
  - to constrain top-Yukawa couplings and effective Higgs gluon interactions.
  - to break the degeneracies from on-shell data.

For details refer, Englert, Spannowsky 1410.5440, Azatov et al 1406.6338, Azatov et al 1608.00977, Azatov et al 2203.02418, Rossia et al 2306.09963

- Revisiting off-shell $gg \to H^* \to VV$ in the HEFT framework.
  - via operator inducing high momentum effects in the off-shell propagating Higgs.

HEFT operator off-shell effects

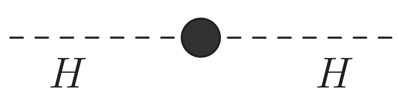
[Brivio et al. 1405.5412.](#)

In HEFT chiral dimension-4 lagrangian,

$$\mathcal{O}_{\Box\Box} = a_{\Box\Box} \frac{\Box H \Box H}{v^2}$$

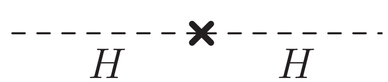
Induces two fold effects

- Modifies the Higgs self energy which also affects the Higgs propagator.



$$= -i\Sigma(q^2) = i(q^2 - m_H^2) + i\frac{2a_{\Box\Box}}{v^2} q^4$$

- Higgs field get redefined for the residue to 1



$$= \delta Z_H (q^2 - M_H^2) + \delta M_H^2$$

In SMEFT such momentum-dependent effects cancel

↓

SMEFT vs HEFT via $a_{\Box\Box}$

After solving the on shell renormalisation conditions

$$\delta Z_H = \frac{d\Sigma(q^2)}{dq^2}\Bigg|_{q^2=m_H^2} = -\frac{4a_{\Box\Box}}{v^2} m_H^2 \longrightarrow \boxed{H \to H\left(1 - \frac{2a_{\Box\Box}}{v^2} m_H^2\right)}$$

Uniform coupling rescaling

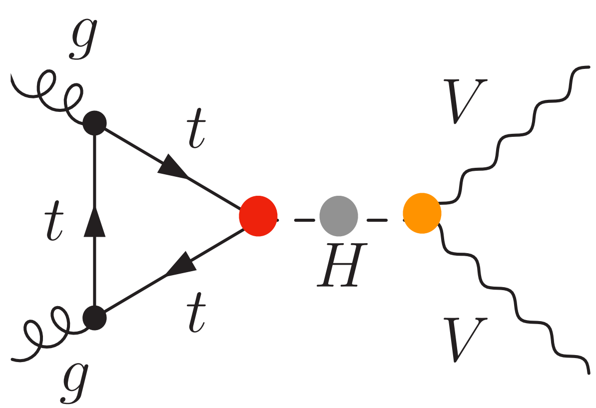
These combined give the modified propagator

Higgs propagator

$$\boxed{\Delta_H(q^2) = \frac{1}{q^2 - m_H^2}\left(1 - \frac{2a_{\Box\Box}}{v^2}(q^2 - m_H^2)\right)}$$

non-trivial momentum dependency

HEFT effects on Higgs off-shell amplitudes



To implement EFT corrections to off-shell $H(q) \to V(p_1)V(p_2)$,

- Include Yukawa coupling modification a_{1t} by considering $t\bar{t} \to H(q)$
- Propagator corrections from $a_{\square\square}$
- Tree level corrections to vertex HVV

No contact ggH interactions are considered.

$$i\widetilde{\Gamma}_{HVV} = -\frac{e^2 m_t}{2c_W^2 s_W^2}\frac{1}{q^2 - M_H^2 + i\Gamma_H M_H}$$

$$\left\{\left[(1+\mathcal{F}_1) + \frac{\mathcal{F}_2}{v^2}(q^2 - p_1^2 - p_2^2) + \frac{\mathcal{F}_3}{v^2}q^2 + \frac{\mathcal{F}_5}{v^2}\frac{M_H^2}{q^2 - M_H^2 + i\Gamma_H M_H}\right][\varepsilon^*(p_1)\cdot\varepsilon^*(p_2)] + \frac{\mathcal{F}_4}{v^2}[\varepsilon^*(p_1)\cdot p_2][\varepsilon^*(p_2)\cdot p_1]\right\}$$

For, $H \to ZZ$

$$\mathcal{F}_1 = a_{1t} + 2a_{\square\square}\frac{M_H^2}{v^2} + \zeta_1$$

$$\mathcal{F}_2 = a_{H13} + 2a_{HBB}s_W^4 + 2a_{HWW}c_W^4$$

$$\mathcal{F}_3 = a_{\square BB} - 2a_{\square\square} + a_{d2} + 2a_{d4} + \frac{e^2}{c_W^2}a_{\square 0} - (a_{d1} - a_{d2} - 2a_{d4})s_W^2$$

$$\mathcal{F}_5 = 2a_{\square\square}$$

$$\frac{\mathcal{F}_4}{2} = (a_{d1} + 4a_{HWW})s_W^2 - 2a_{HWW} - (a_{d2} + 2a_{d4})c_W^2 - 2(a_{HBB} + a_{HWW})s_W^4$$

Linear order of HEFT corrections $\propto a_i$

EWPO constraints are not violated

$S \propto a_{H1},\ T \propto a_{H0},\ U \propto a_{H8}$

Higgs off-shell effects

- These modifications to the $H \to ZZ/WW$ amplitudes are implemented in `Vbfnlo`.

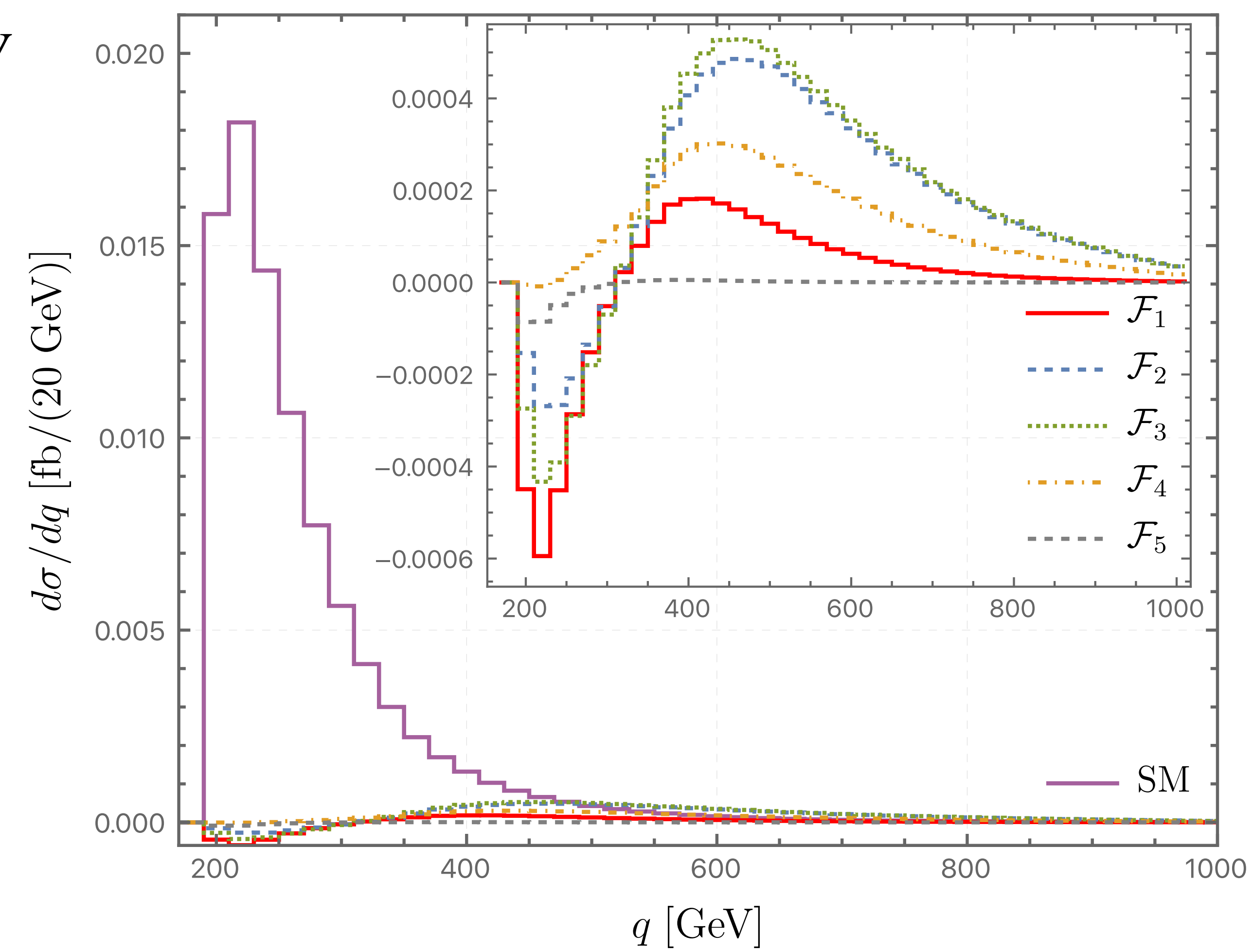
  Baglio et al 1404.3940

- Cross-checks are done.

  Campbell et al 1311.3589

- Differential cross-sections are obtained.

- Off-shell Higgs momentum distributions for $H \to ZZ$ with effects of the different HEFT insertions for $q > 350$ GeV.



- To obtain quantitative estimate of the sensitivity of the off-shell measurements, we included these binned differential data as

Binned χ^2 test statistic $$\chi^2 = \sum_i \frac{(N_i - N_i^{\rm SM})^2}{\sigma^2_{i,\rm syst} + \sigma^2_{i,\rm stat}}$$

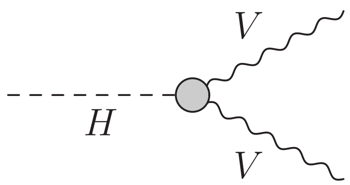
N_i denotes the ith bin entry and $N_i^{\rm SM}$ denotes the SM expectation.

HEFT effects on Higgs on-shell amplitudes

For on-shell effects, include the corrections on the Higgs branching fractions for $H \to VV^*, \gamma\gamma, Z\gamma, gg$

consider only a_{1t} → no correction in $b\bar{b}$

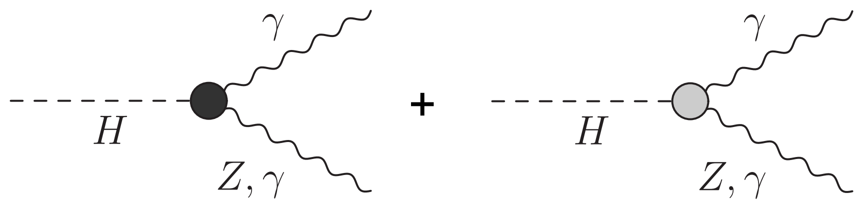
$H \to VV^*$



Tree-level corrections to the HVV vertex

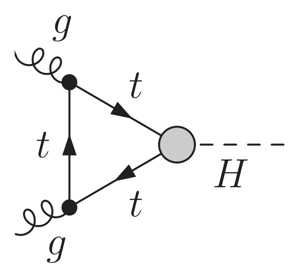
Dawson, Giardino 1801.01136, Dawson, Giardino 1807.11504

$H \to \gamma\gamma, Z\gamma$



$$\mathcal{M} = |\mathcal{M}_{\text{1-loop}}|^2 + 2\,\text{Re}\big(\mathcal{M}^*_{\text{HEFT}}\mathcal{M}_{\text{1-loop}}\big)$$

$H \to gg$ similar to ggF



Corrections to $t\bar{t}H$ + Higgs field redefinition factor

Using these, we obtain the partial decay widths and the corrections to the total H width Γ_H^{HEFT}

Modified Higgs Branching Ratios

$$\frac{\text{BR}^{\text{HEFT}}(H \to X)}{\text{BR}^{\text{SM}}(H \to X)} = \frac{\Gamma^{\text{HEFT}}(H \to X)}{\Gamma^{\text{SM}}(H \to X)}\,\frac{\Gamma_H^{\text{SM}}}{\Gamma_H^{\text{HEFT}}}$$

$X = \gamma\gamma, VV^*, Z\gamma$

Signal Strengths

$$\mu^X_{\text{ggF}} = \frac{[\sigma_{\text{ggF}}\ \text{BR}(H \to X)]^{\text{HEFT}}}{[\sigma_{\text{ggF}}\ \text{BR}(H \to X)]^{\text{SM}}}$$

assuming narrow width approximation

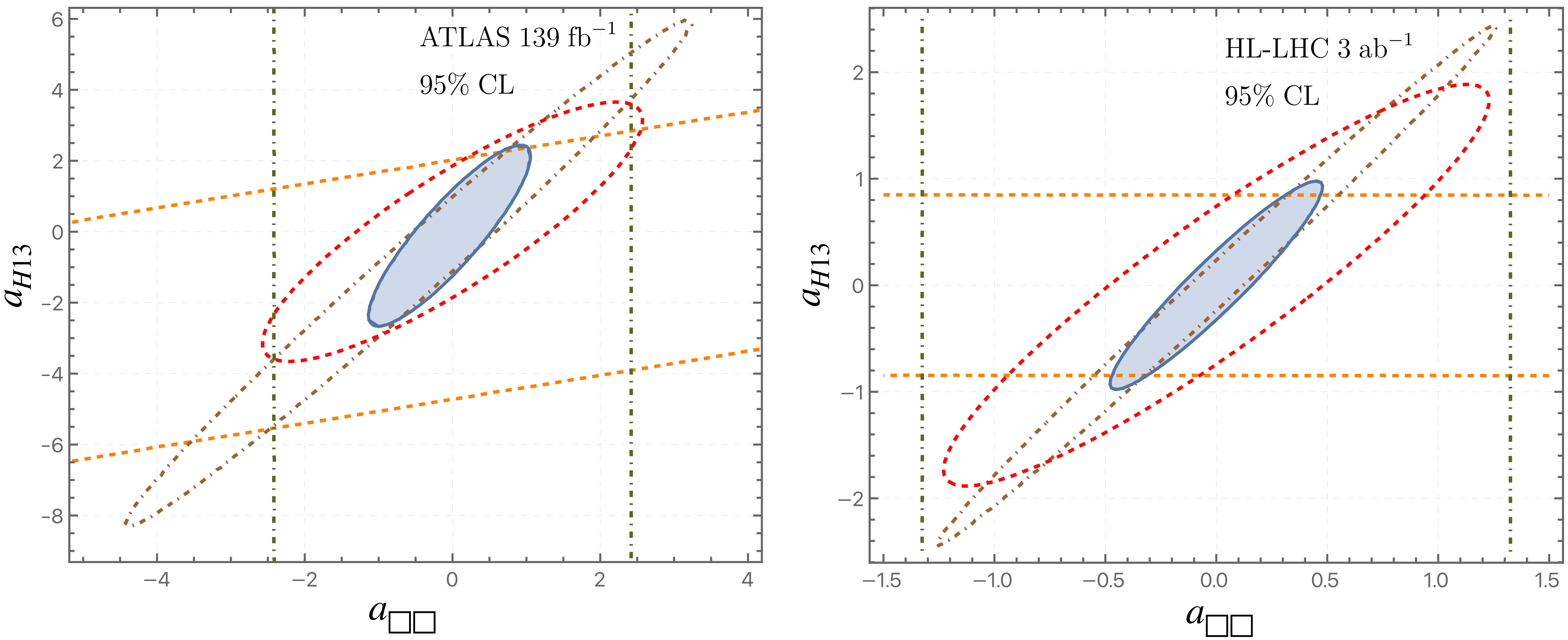
Observables	ATLAS Run 2 data				HL-LHC uncertainties
	Measurements	Correlations			
$\mu^{\gamma\gamma}_{ggF}$	$1.02^{+0.11}_{-0.11}$	1	0.05	0.09	± 0.36
μ^{ZZ}_{ggF}	$0.95^{+0.11}_{-0.11}$		1	0.1	± 0.039
μ^{WW}_{ggF}	$1.13^{+0.13}_{-0.12}$			1	± 0.043
$\mu^{Z\gamma}_{ggF}$					± 0.33

$$\chi^2_{\text{on-shell}} = \sum_{i,j=1}^{\text{data}} \big(\mu_{i,\text{exp}} - \mu_{i,\text{th}}\big)(V_{ij})^{-1}\big(\mu_{j,\text{exp}} - \mu_{j,\text{th}}\big)$$

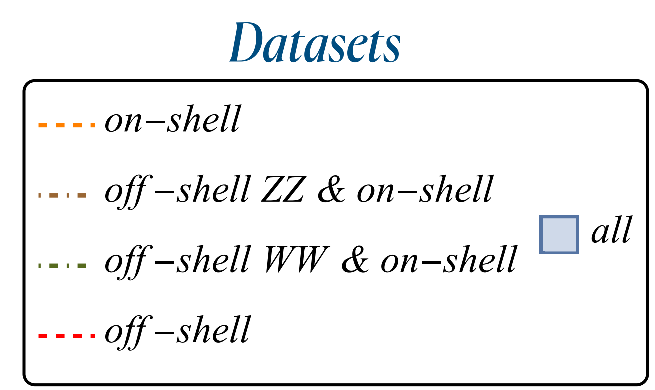
Linear order of HEFT corrections $\propto a_i$

Correlating off-shell and on-shell effects

- To get the allowed bounds, we ***profile*** over the SMEFT directions using HEFT-SMEFT translations
- $a_{\Box\Box}, a_{H13}, a_{\Box VV}, a_{d4}$ yield the strongest single parameter bounds.



- $a_{\Box\Box}$ gets strongly bounded with off-shell measurements.
- The most stringent impact from the off-shell measurements, predominantly $H \to ZZ$.
- Improvements expected at HL-LHC.



HEFT Bosonic corrections to multi-Higgs

A, Daniel Domenech, Christoph Englert, M. J. Herrero, Roberto Morales 2405.05385

HEFT modifications to Higgs self couplings

Higgs self couplings are important to determine the shape of potential.

$$V(H) = \frac{1}{2}M_H^2 H^2 + \kappa_3 \frac{M_H^2}{2v} H^3 + \kappa_4 \frac{M_H^2}{8v^2} H^4$$

in SM, $\kappa_3 = \kappa_4 = 1$

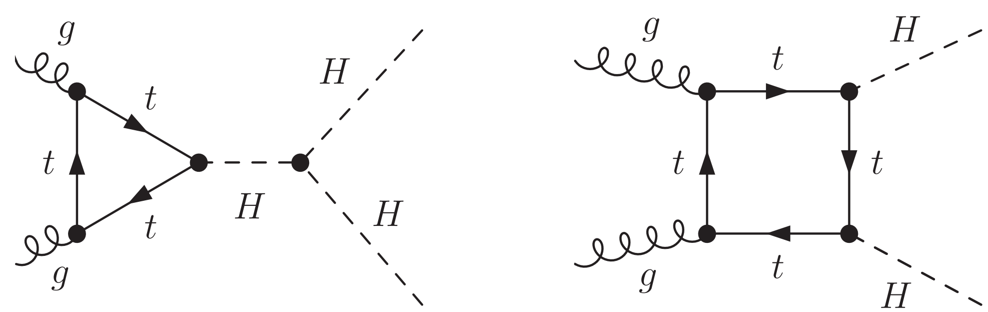
Direct probes of the κ_3 and κ_4 are multi-Higgs production.

modifications to coupling modifiers κ_3 and κ_4 away from SM values via HEFT → Enhancements in multi-Higgs production cross-sections

Considering only gluon gluon fusion

$gg \to HH$

$\sigma_{HH}^{ggF} \sim 31$ fb

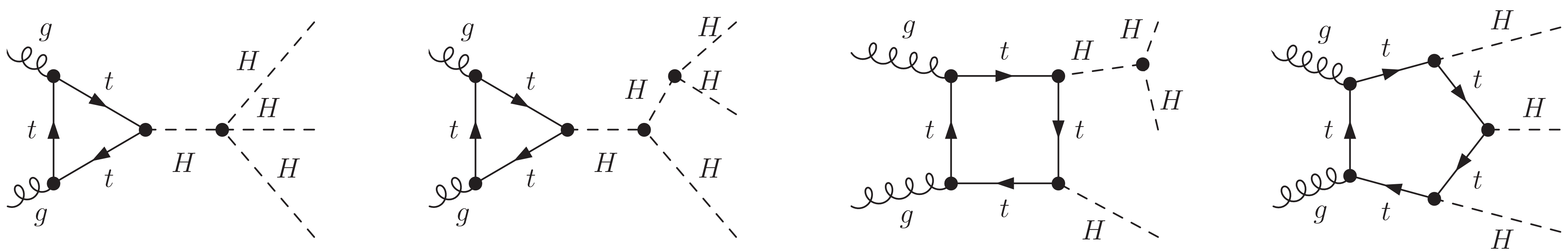


Borowka et al 1608.04798   Grazzini et al 1803.02463

Baglio et al 1811.05692   CMS 2023   ATLAS 2023

$gg \to HHH$

$\sigma_{HHH}^{ggF} \sim 50$ ab



Papaefstathiou et al 1508.06524   Chen et al 1510.04013   Fuks et al 1510.07697   Fuks et al 1704.04298

Papaefstathiou et al 1909.09166   Florian et al 1912.02760   Abdughani et al 2005.11086   Stylianou et al 2312.04646

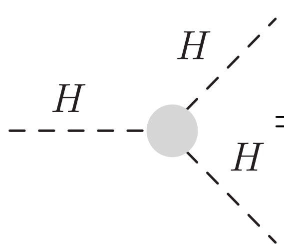
Included one-loop radiative HEFT corrections and assumed SM-like top-Higgs and top-gauge couplings.

Relevant HEFT higher dimensional operators

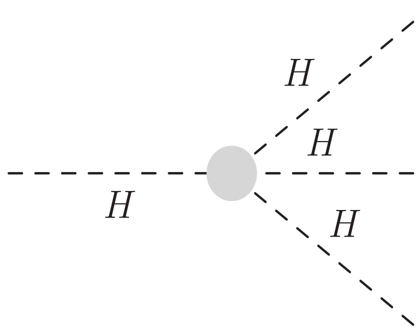
Brivio et al 1604.06801
Alonso et al 1304.5937
Herrero, Morales 2208.05900

$\mathcal{O}_{\Box\Box}$	$a_{\Box\Box}\,\frac{\Box H \Box H}{v^2}$	$\mathcal{O}_{H\Box\Box}$	$a_{H\Box\Box}\,\left(\frac{H}{v}\right)\,\frac{\Box H \Box H}{v^2}$
$\mathcal{O}_{Hdd}$	$a_{Hdd}\,\frac{m_{\rm H}^2}{v^2}\left(\frac{H}{v}\right)\,\partial^\mu H \partial_\mu H$	$\mathcal{O}_{HHdd}$	$a_{HHdd}\,\frac{m_{\rm H}^2}{v^2}\left(\frac{H^2}{v^2}\right)\,\partial^\mu H \partial_\mu H$
$\mathcal{O}_{ddW}$	$a_{ddW}\,\frac{m_{\rm W}^2}{v^2}\left(\frac{H}{v}\right)\,\partial^\mu H \partial_\mu H$	$\mathcal{O}_{HddW}$	$a_{HddW}\,\frac{m_{\rm W}^2}{v^2}\left(\frac{H^2}{v^2}\right)\,\partial^\mu H \partial_\mu H$
$\mathcal{O}_{ddZ}$	$a_{ddZ}\,\frac{m_{\rm Z}^2}{v^2}\left(\frac{H}{v}\right)\,\partial^\mu H \partial_\mu H$	$\mathcal{O}_{HddZ}$	$a_{HddZ}\,\frac{m_{\rm Z}^2}{v^2}\left(\frac{H^2}{v^2}\right)\,\partial^\mu H \partial_\mu H$
$\mathcal{O}_{dd\Box}$	$a_{dd\Box}\,\frac{1}{v^3}\,\partial^\mu H\,\partial_\mu H\,\Box H$	$\mathcal{O}_{Hdd\Box}$	$a_{Hdd\Box}\,\frac{1}{v^3}\left(\frac{H}{v}\right)\,\partial^\mu H\,\partial_\mu H\,\Box H$
$\mathcal{O}_{HH\Box\Box}$	$a_{HH\Box\Box}\,\left(\frac{H^2}{v^2}\right)\frac{\Box H \Box H}{v^2}$	$\mathcal{O}_{dddd}$	$a_{dddd}\,\frac{1}{v^4}\partial^\mu H\,\partial_\mu H\,\partial^\nu H\,\partial_\nu H$

- Operators contribute $\mathcal{O}(p^4)$ corrections at tree level.
  - non standard coupling modifications and momentum dependencies.



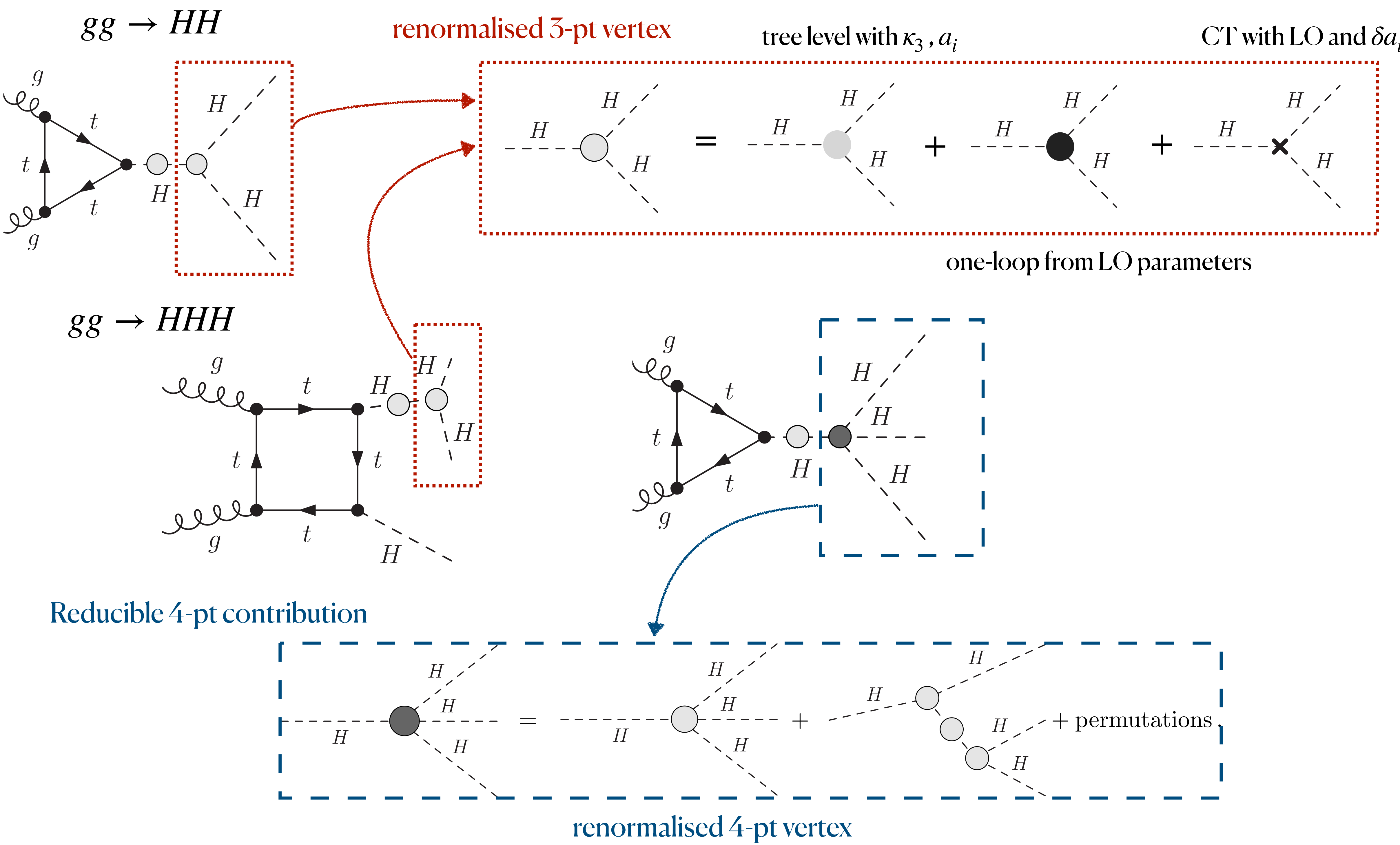
$$= -3i\kappa_3\frac{m_{\rm H}^2}{v} + \frac{i}{v^3}\left(a_{dd\Box}(p_1^4+p_2^4+p_3^4) + 2(a_{H\Box\Box}-a_{dd\Box})(p_1^2p_2^2+p_2^2p_3^2+p_3^2p_1^2)\right.$$
$$\left. + (a_{Hdd}\,m_{\rm H}^2 + a_{ddW}\,m_{\rm W}^2 + a_{ddZ}\,m_{\rm Z}^2)(p_1^2+p_2^2+p_3^2)\right)$$



$$= -3i\kappa_4\frac{m_{\rm H}^2}{v^2} + \frac{i}{v^4}\left(a_{Hdd\Box}(p_1^4+p_2^4+p_3^4+p_4^4 - 2(p_1^2p_2^2+p_1^2p_3^2+p_1^2p_4^2+p_2^2p_3^2+p_2^2p_4^2+p_3^2p_4^2))\right.$$
$$+4a_{HH\Box\Box}(p_1^2p_2^2+p_1^2p_3^2+p_1^2p_4^2+p_2^2p_3^2+p_2^2p_4^2+p_3^2p_4^2)$$
$$+2(a_{HHdd}\,m_{\rm H}^2 + a_{HddW}\,m_{\rm W}^2 + a_{HddZ}\,m_{\rm Z}^2)(p_1^2+p_2^2+p_3^2+p_4^2)$$
$$+4a_{dddd}\left((p_1+p_2)^2(p_1+p_3)^2 + (p_1+p_2)^2(p_2+p_3)^2 + (p_1+p_3)^2(p_2+p_3)^2\right.$$
$$\left.\left. -(p_1^2p_2^2+p_1^2p_3^2+p_1^2p_4^2+p_2^2p_3^2+p_2^2p_4^2+p_3^2p_4^2)\right)\right)$$

- To obtain renormalised vertices, these operators also act as counter terms.

HEFT radiative corrections for HH/HHH

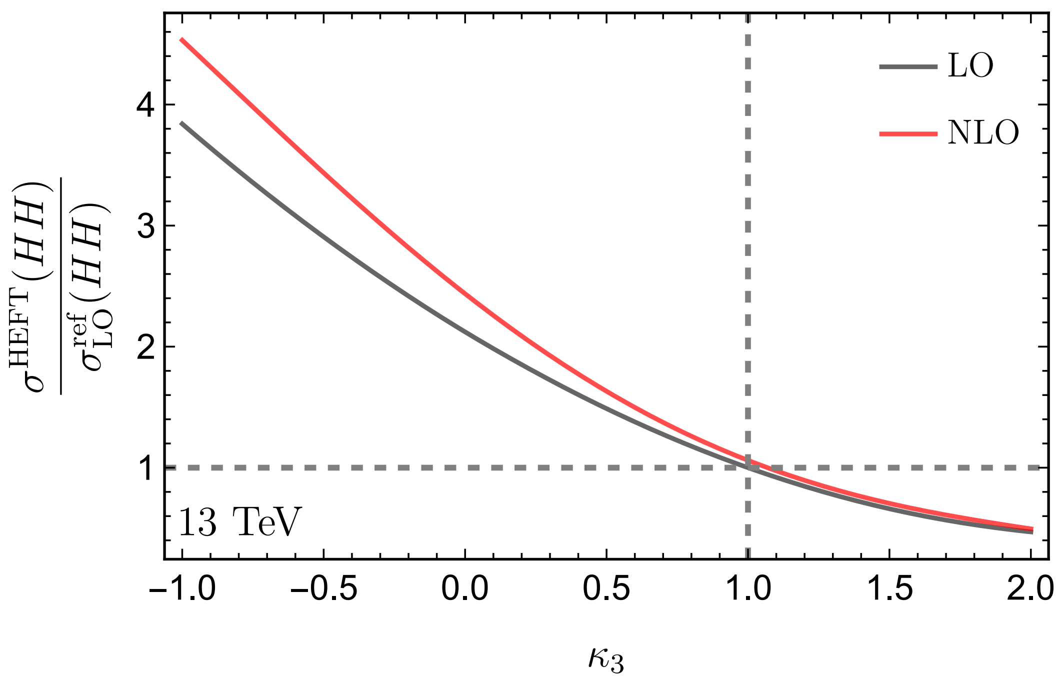


these corrections are implemented in `Vbfnlo`

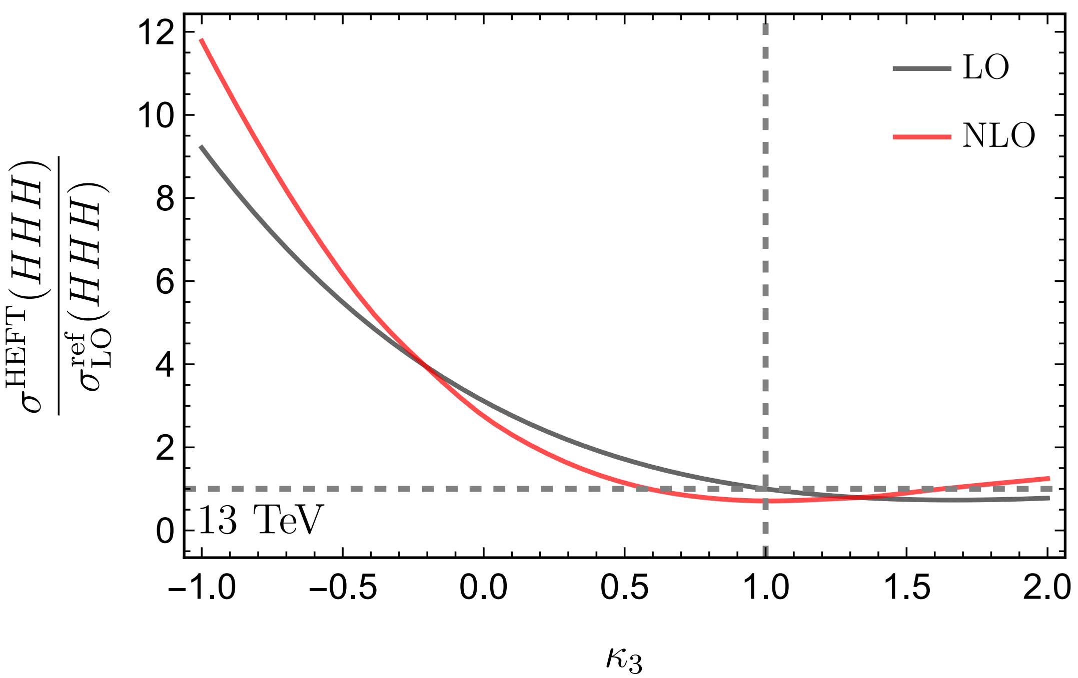
Arnold et al 0811.4559

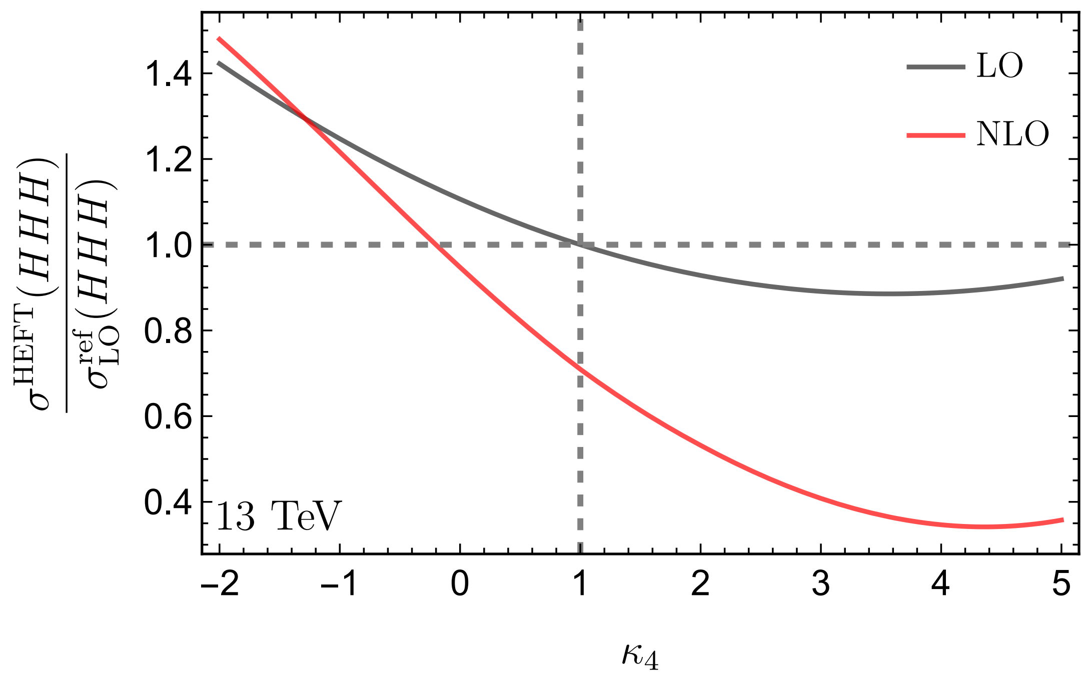
Effects of radiative corrections

Cross-sections relative to LO expectation without HEFT operators



- radiative corrections become more relevant away from the $\kappa_3 = \kappa_4 = 1$.
- size of the corrections change in HEFT
  - due to non-linearity, highly sensitive to off-shell Higgs momentum.
- radiative corrections in $\kappa_3 < 0$ leads to enhancement.
- κ_4 is mildly sensitive.
  - no enhancements possible in HHH production via κ_4.

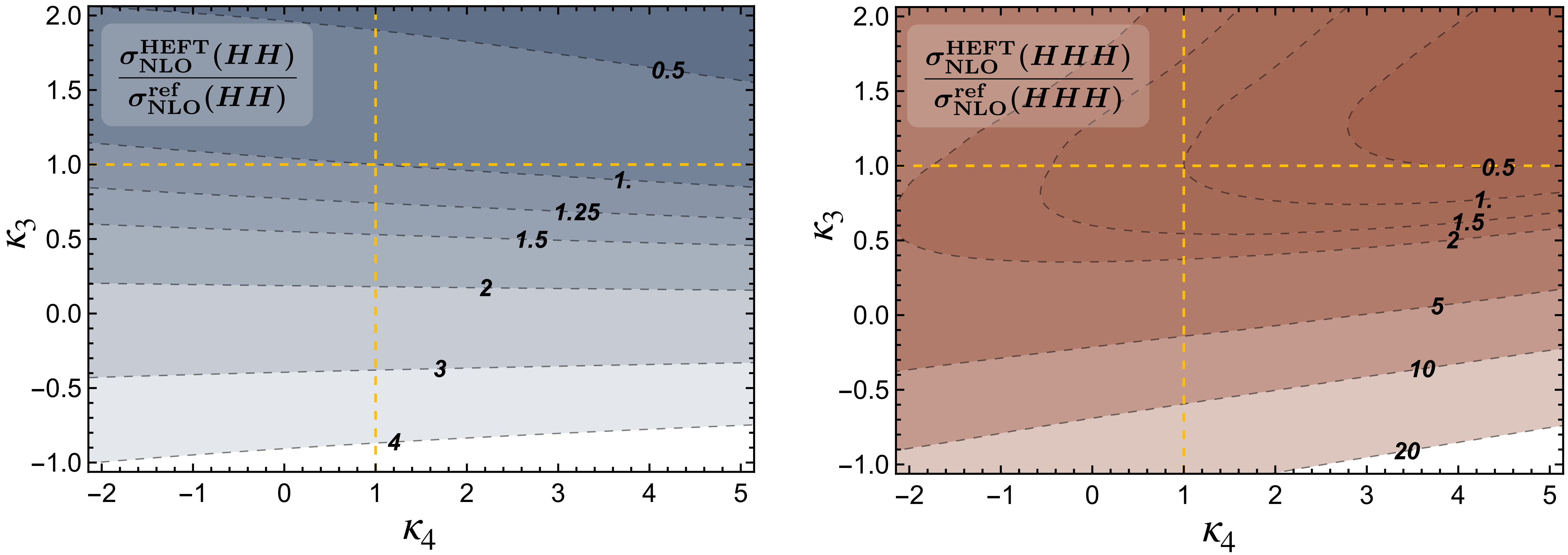




$\sigma^{\mathrm{ref}}_{\mathrm{LO}}(HH) = 17.40\,\mathrm{fb}$ $\sigma^{\mathrm{ref}}_{\mathrm{LO}}(HHH) = 0.041\,\mathrm{fb}$

Contours for κ_3 vs κ_4

Cross-sections relative to NLO cross-sections without HEFT operators

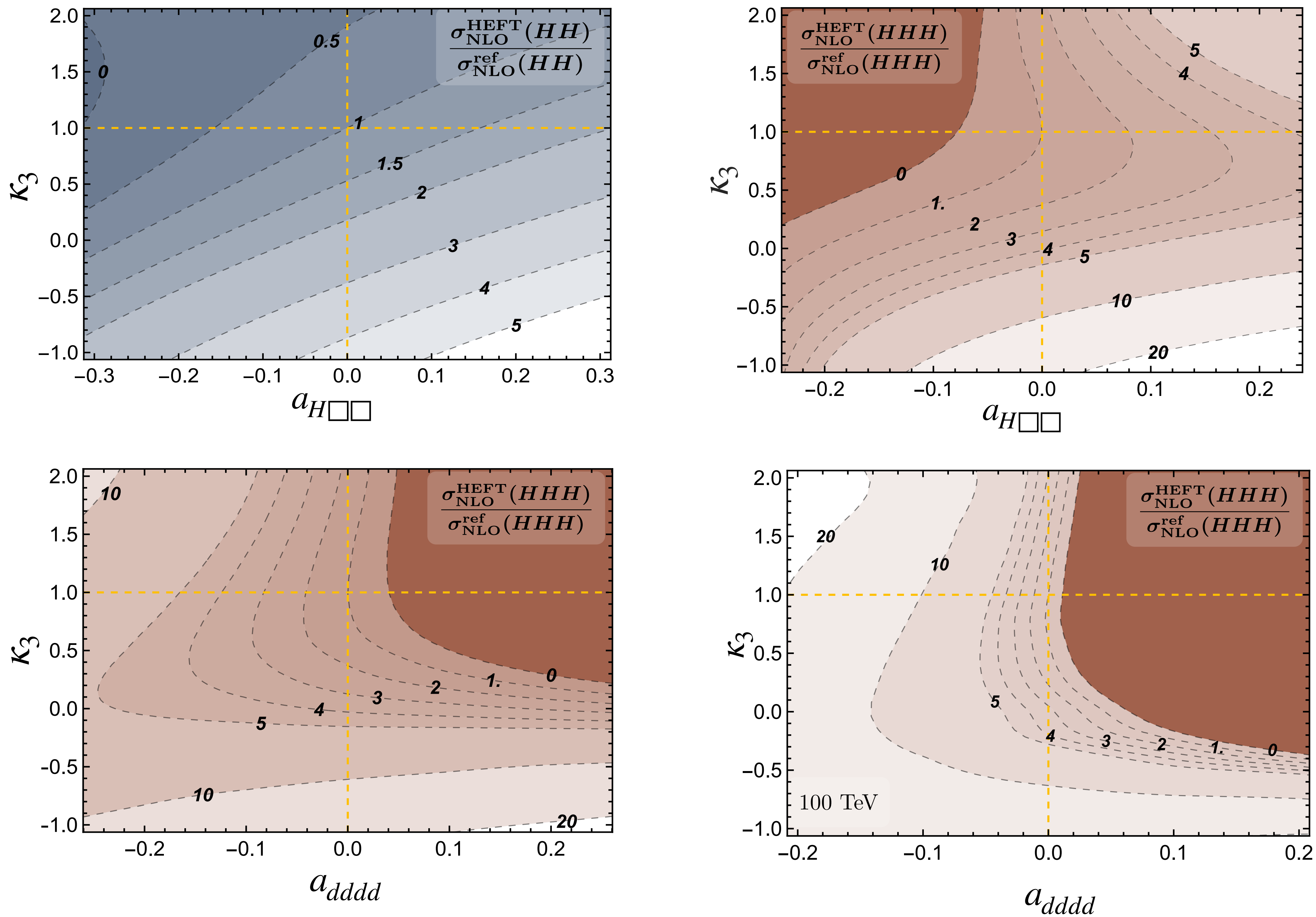


- κ_4 is relatively insensitive for both HH and HHH production.
- κ_3 is a relevant parameter as its modifications affects both HH and HHH production.
- $\kappa_3 \gtrsim -0.5$ is the motivated range to be explored at HL-LHC for which we obtain a significant departure of the HHH production.

$\sigma^{\mathrm{ref}}_{\mathrm{NLO}}(HH) = 18.45\,\mathrm{fb}$ $\sigma^{\mathrm{ref}}_{\mathrm{NLO}}(HHH) = 0.029\,\mathrm{fb}$

Effects with HEFT operators

- Several combinations can lead to enhancement of cross-sections.
- With HEFT $\mathcal{O}(p^4)$ operators due to non trivial momentum dependencies, the cross-sections are altered.



- a_{dddd} imparts momentum dependent departure from SM leading to enhanced HHH cross-section even for $\kappa_3 \simeq 1$.

Conclusions

- In Higgs Effective Field Theory framework, $\kappa_V - \kappa_{2V}$ are uncorrelated.
  - Considering HHVV couplings independent of the HVV interactions, κ_{2V} effects are studied as weak radiative corrections.
  - The κ_{2V} limits obtained from single Higgs measurements are quite weak when compared to the LHC sensitivity to κ_{2V}.
- Used the off-shell measurements to set the constraints on the HEFT interactions.
  - Main focus is $a_{\Box\Box}$ which modifies Higgs propagator with q^4 dependence.
- HEFT operators offer non-trivial momentum dependencies that can affect the phenomenology of multiHiggs final states.
  - Including one-loop radiative correction upto $\mathcal{O}(p^4)$ lead to cross-section enhancements for $gg \to HH(H)$.
  - HHH still remains difficult due to very small rate.
  - This HEFT analysis motivates HH physics at the HL-LHC phase if the TeV scale contains aspects of non-linearity, they will show up in pronounced ways in di-Higgs production
- To enhance further sensitivity to HEFT parameters, these all measurements when combined can offer promising prospects for a global fit.

Thank you for the attention !

Back up

Looking into the Loop order effects

- To achieve a consistent correlation of different Higgs legs, we study the radiative corrections to Higgs decay channels.

Comments about Renormalisation in HEFT

The 1-loop amplitudes generate UV divergences with new structures that requires to add higher dimensional HEFT operators to the LO Lagrangian.
In HEFT all relevant operators are included from the start as these are required for a consistent final one-loop result.

$$\Longrightarrow \quad \mathcal{L}_{HEFT} = \mathcal{L} + \sum_i a_i \mathcal{O}_i$$

HEFT operators

Contribute to the total Counter-term

For the one- loop computations

- Validated the gauge independence in the loop results in the R_ξ gauge.
- On-shell (OS) renormalisation conditions for the Electroweak parameters and for the field and mass renormalisation constants using the relevant 2-point functions.
- HEFT parameters (ζ_1, a_i) are renormalised in $\overline{\text{MS}}$ scheme using the UV divergences obtained in the 2-point and 3-point functions.

} Both handled simultaneously

For details, refer Herrero, Morales 2107.07890

Single Higgs data analysis for $\kappa_V - \kappa_{2V}$ correlations

- Using $H \to \gamma\gamma, \gamma Z, WW^*, ZZ^*$,

$$\mathcal{M}^2 = |\mathcal{M}_{\rm LO}|^2 + 2\,{\rm Re}\left\{\mathcal{M}_{\rm LO}\mathcal{M}^*_{\text{1-loop}}\right\}$$

Dawson, Giardino 1801.01136

Dawson, Giardino 1807.11504

the corresponding decay widths are obtained in terms of ζ_1, ζ_2 & ζ_2 is loop induced.

χ^2 **fit using κ-data from ATLAS 139 fb^{-1}**

χ^2 statistic $\chi^2(\zeta_1,\zeta_2) = \sum_{i,j=1}^{\rm data} \left(\kappa_{i,\rm exp} - \kappa_{i,\rm th}(\zeta_1,\zeta_2)\right)(V_{ij})^{-1}\left(\kappa_{j,\rm exp} - \kappa_{j,\rm th}(\zeta_1,\zeta_2)\right)$

Parameters	ATLAS Run 2 data 139 fb^{-1}	HL-LHC uncertainties 3000 fb^{-1}	Correlation Matrix			
κ_Z	$0.99^{+0.06}_{-0.06}$	±0.012	1	0.40	0.44	0.09
κ_W	$1.05^{+0.06}_{-0.06}$	±0.013		1	0.47	0.08
κ_γ	$1.01^{+0.06}_{-0.06}$	±0.013			1	0.12
$\kappa_{Z\gamma}$	$1.38^{+0.31}_{-0.37}$	±0.073				1

Scaling factor for HL-LHC uncertainties*

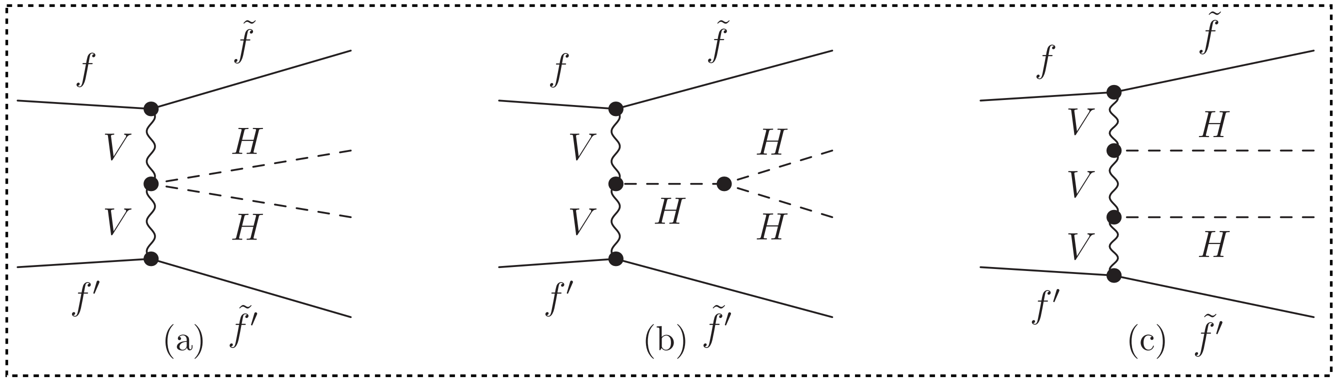
$$\sigma_{\rm HL} = \frac{1}{\sqrt{3000/139}}\sigma_{\rm ATLAS}$$

*Ignored the individual scaling factors of the statistical and systematic uncertainties

Direct searches for κ_{2V}

Process considered: $pp \rightarrow HH \rightarrow b\bar{b}b\bar{b} + 2j$

Representative Feynman diagrams



Considered only κ_{2V} and κ_V coupling modifiers

Pre-selections cuts for WBF topology

- two forwarded jets in opposite detector hemispheres (with opposite signs of pseudorapidity) and $m_{jj} \geq 500$ GeV
- For WBF jets, $p_T \geq 50$
- Four central b-jets have $|\eta_{b\text{-jets}}| < 2.5$ with $p_T \geq 20$ GeV.

Events are simulated with $\kappa_{2V} = 2$ & $\kappa_V = 1$

Dominant Background process

- Dominant SM background is QCD multijet production.
- QCD multijet background cross-section is 4.41 pb and the signal cross-section is 0.086 fb

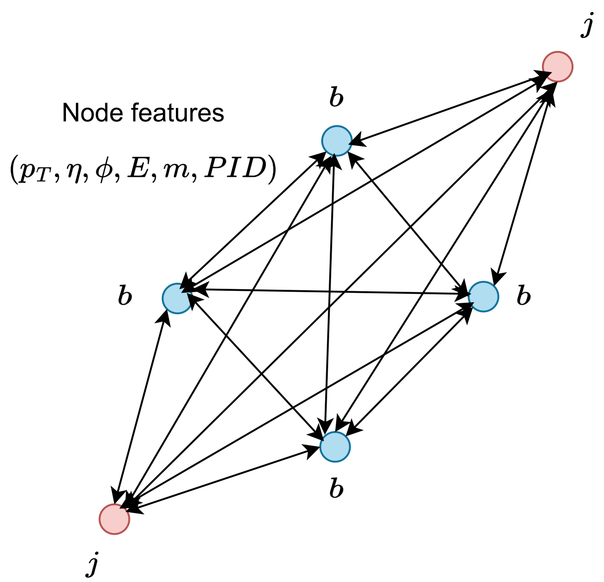
Thus, we need to work to reduce the background and increase signal sensitivity.

Enhancing the signal sensitivity

To discriminate signal from background, Graph Neural network(GNN) is employed.

Overview of GNN implementation

Fully-connected bi-directional graph



Final states are denoted as nodes with input features

Edge Convolution

Nodes features are updated using single message passing layer.

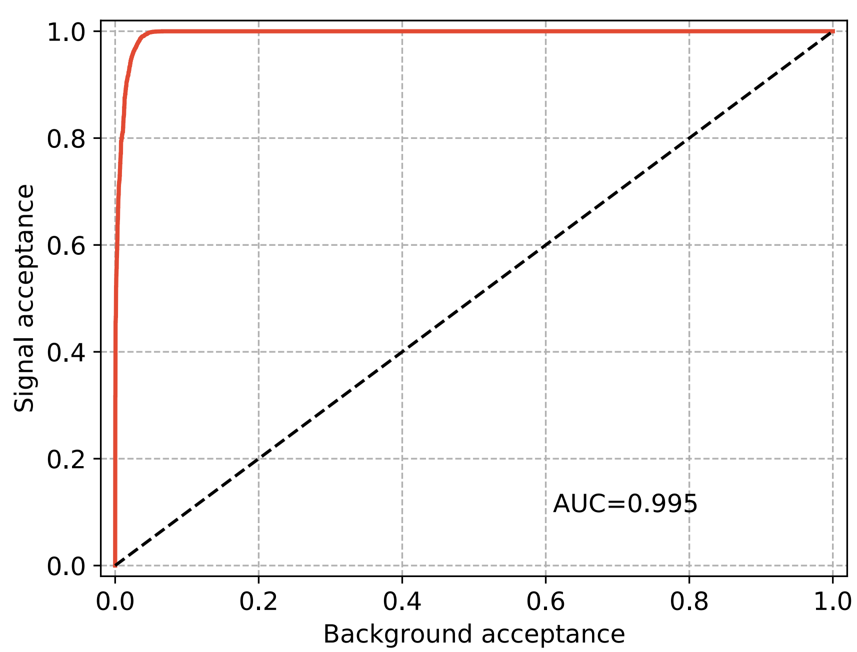
$$\vec{x}_i^{(l+1)} = \frac{1}{|\mathcal{N}(i)|} \sum_{j \in \mathcal{N}(i)} \mathrm{ReLU}\left(\Theta \cdot (\vec{x}_j^{(l)} - \vec{x}_i^{(l)}) + \Phi \cdot (\vec{x}_i^{(l)})\right)$$

Mean

All the features are processed and probability of signal and background are obtained as output.

Training is done to get desired output: P(signal) →1, P(background)→ 0.

Network performance via ROC curve



An optimal working point is chosen on this ROC.

HEFT operator effects absent in SMEFT

Brivio et al. 1405.5412.

In HEFT chiral dimension-4 lagrangian,

$$\mathcal{O}_{\Box\Box} = a_{\Box\Box}\frac{\Box H \Box H}{v^2}$$

In SMEFT, similar quartic momentum dependence appear in a operator in SILH basis

$$Q_{\Box\Phi} = \frac{C_{\Box\Phi}}{\Lambda^2}|D^\mu D_\mu \Phi|^2 \qquad \Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+H \end{pmatrix}$$

Higgs field redefinition

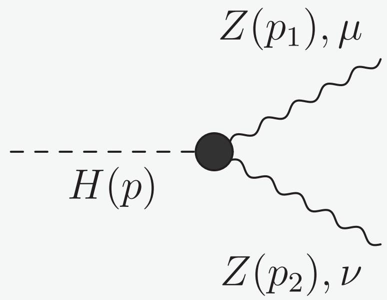
$$H \to H\left(1 - \frac{C_{\Box\Phi}}{\Lambda^2}m_H^2\right)$$

Higgs propagator

$$\Delta_H(p^2) = \frac{1}{q^2 - m_H^2}\left(1 - \frac{C_{\Box\Phi}}{\Lambda^2}(q^2 - m_H^2)\right)$$

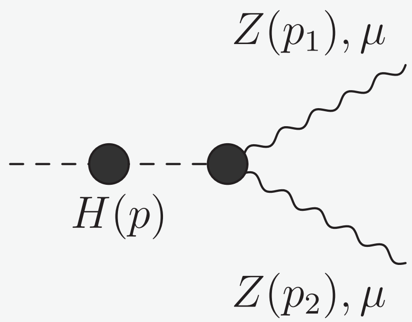
In addition,

Vertex effects



$$= \frac{ie^2 v}{2c_W^2 s_W^2}\left[g^{\mu\nu} + \left(q^2 g^{\mu\nu} - q^\nu q_2^\mu - q_1^\mu q_2^\nu - q^\mu q_2^\nu\right)\frac{C_{\Box\Phi}}{\Lambda^2}\right]$$

Including these Higgs propagator, field redefinition and HZZ vertex effects



$$= \frac{1}{q^2 - m_H^2}\frac{ie^2 v}{2c_W^2 s_W^2}$$

Momentum dependent corrections cancel.

HEFT higher dimensional operators used in the work

Included only bosonic operators

Herrero, Morales 2107.07890

Brivio et al 1604.06801

Alonso et al 1212.3305

$$\mathcal{V}_\mu = (D_\mu U)U^\dagger \qquad \mathcal{D}_\mu \mathcal{V}^\mu = \partial_\mu \mathcal{V}^\mu + i[g_W W^a_\mu \frac{\tau^a}{2}, \mathcal{V}^\mu]$$

$\mathcal{O}_{HBB}$	$-a_{HBB}\, g'^2 \frac{H}{v} \mathrm{Tr}\left[(B_{\mu\nu}\frac{\tau^3}{2})(B^{\mu\nu}\frac{\tau^3}{2})\right]$	$\mathcal{O}_{HWW}$	$-a_{HWW}\, g_W^2 \frac{H}{v} \mathrm{Tr}\left[(W^a_{\mu\nu}\frac{\tau^a}{2})(W^{a\mu\nu}\frac{\tau^a}{2})\right]$
$\mathcal{O}_{H0}$	$a_{H0}(M_Z^2 - M_W^2)\frac{H}{v}\mathrm{Tr}\left[U\tau^3U^\dagger\mathcal{V}_\mu\right]\mathrm{Tr}\left[U\tau^3U^\dagger\mathcal{V}_\mu\right]$	$\mathcal{O}_{H1}$	$a_{H1}\, g' g_W \frac{H}{v}\mathrm{Tr}\left[UB_{\mu\nu}\frac{\tau^3}{2}U^\dagger W^a_{\mu\nu}\frac{\tau^a}{2}\right]$
$\mathcal{O}_{H8}$	$-\frac{a_{H8}}{4}\, g_W^2 \frac{H}{v}\mathrm{Tr}\left[U\tau^3U^\dagger W^a_{\mu\nu}\frac{\tau^a}{2}\right]\mathrm{Tr}\left[U\tau^3U^\dagger W^a_{\mu\nu}\frac{\tau^a}{2}\right]$	$\mathcal{O}_{H11}$	$a_{H11}\frac{H}{v}\mathrm{Tr}\left[\mathcal{D}_\mu\mathcal{V}^\mu\mathcal{D}_\nu\mathcal{V}^\nu\right]$
$\mathcal{O}_{H13}$	$-\frac{a_{H13}}{2}\ \frac{H}{v}\mathrm{Tr}\left[U\tau^3U^\dagger\mathcal{D}_\mu\mathcal{V}_\nu\right]\mathrm{Tr}\left[U\tau^3U^\dagger\mathcal{D}^\mu\mathcal{V}^\nu\right]$	$\mathcal{O}_{d1}$	$ia_{d1}\, g'\frac{\partial^\nu H}{v}\mathrm{Tr}\left[UB_{\mu\nu}\frac{\tau^3}{2}U^\dagger\mathcal{V}^\mu\right]$
$\mathcal{O}_{d2}$	$ia_{d2}\, g_W\frac{\partial^\nu H}{v}\mathrm{Tr}\left[W^a_{\mu\nu}\frac{\tau^a}{2}\mathcal{V}^\mu\right]$	$\mathcal{O}_{d3}$	$a_{d3}\frac{\partial^\nu H}{v}\mathrm{Tr}\left[\mathcal{V}^\mu\mathcal{D}_\mu\mathcal{V}^\mu\right]$
$\mathcal{O}_{d4}$	$a_{d4}\, g_W\frac{\partial^\nu H}{v}\mathrm{Tr}\left[U\tau^3U^\dagger W^a_{\mu\nu}\frac{\tau^a}{2}\right]\mathrm{Tr}\left[U\tau^3U^\dagger\mathcal{V}^\mu\right]$	$\mathcal{O}_{\Box\mathcal{V}\mathcal{V}}$	$a_{\Box\mathcal{V}\mathcal{V}}\frac{\Box H}{v}\mathrm{Tr}\left[\mathcal{V}_\mu\mathcal{V}^\mu\right]$
$\mathcal{O}_{\Box 0}$	$a_{\Box 0}\frac{(M_Z^2-M_W^2)}{v^2}\frac{\Box H}{v}\mathrm{Tr}\left[U\tau^3U^\dagger\mathcal{V}_\mu\right]\mathrm{Tr}\left[U\tau^3U^\dagger\mathcal{V}_\mu\right]$	$\mathcal{O}_{\Box\Box}$	$a_{\Box\Box}\frac{\Box H\Box H}{v^2}$

EWPO constraints are not violated

$\mathbf{S} \propto a_{H1},\ \mathbf{T} \propto a_{H0},\ \mathbf{U} \propto a_{H8}$

SMEFT - HEFT correspondence

The correspondence between the HEFT operators considered in our analysis with SMEFT dim-6 operators

HEFT

$$\mathcal{O}_{HBB} = -a_{HBB}\, g'^2 \frac{H}{v} \mathrm{Tr}\left[B_{\mu\nu} B^{\mu\nu}\right]$$

$$\mathcal{O}_{HWW} = -a_{HWW}\, g_W^2 \frac{H}{v} \mathrm{Tr}\left[W^a_{\mu\nu} W^{a\mu\nu}\right]$$

$$\mathcal{L}_{\mathrm{Yuk}} = -\frac{v}{\sqrt{2}} \left(\bar{t}_L \quad \bar{b}_L\right) U \begin{pmatrix} \mathcal{Y}^t_{33}\, t_R \\ b_R \end{pmatrix} + \mathrm{h.c.}$$

$$\mathcal{Y}^t_{33} = y^t_{33}\left(1 + (1 + a_{1t})\frac{H}{v} + \ldots\right)$$

Translation rules

$$\Longleftrightarrow$$

$$a_{HBB} = -2\frac{v^2}{g'^2}\frac{C_{\Phi B}}{\Lambda^2}$$

$$a_{HWW} = -2\frac{v^2}{g_W^2}\frac{C_{\Phi W}}{\Lambda^2}$$

$$a_{1t} = -\frac{v^3}{\sqrt{2}M_t}\frac{C_{t\Phi}}{\Lambda^2}$$

SMEFT upto dim-6

$$Q_{\Phi B} = \frac{C_{\Phi B}}{\Lambda^2} \Phi^\dagger \Phi\, B_{\mu\nu} B^{\mu\nu}$$

$$Q_{\Phi W} = \frac{C_{\Phi W}}{\Lambda^2} \Phi^\dagger \Phi\, W^a_{\mu\nu} W^{a,\mu\nu}$$

$$Q_{t\Phi} = \frac{C_{t\Phi}}{\Lambda^2} \left(\Phi^\dagger \Phi\, (\bar{Q}\, t\, \tilde{\Phi}) + \mathrm{h.c.}\right)$$

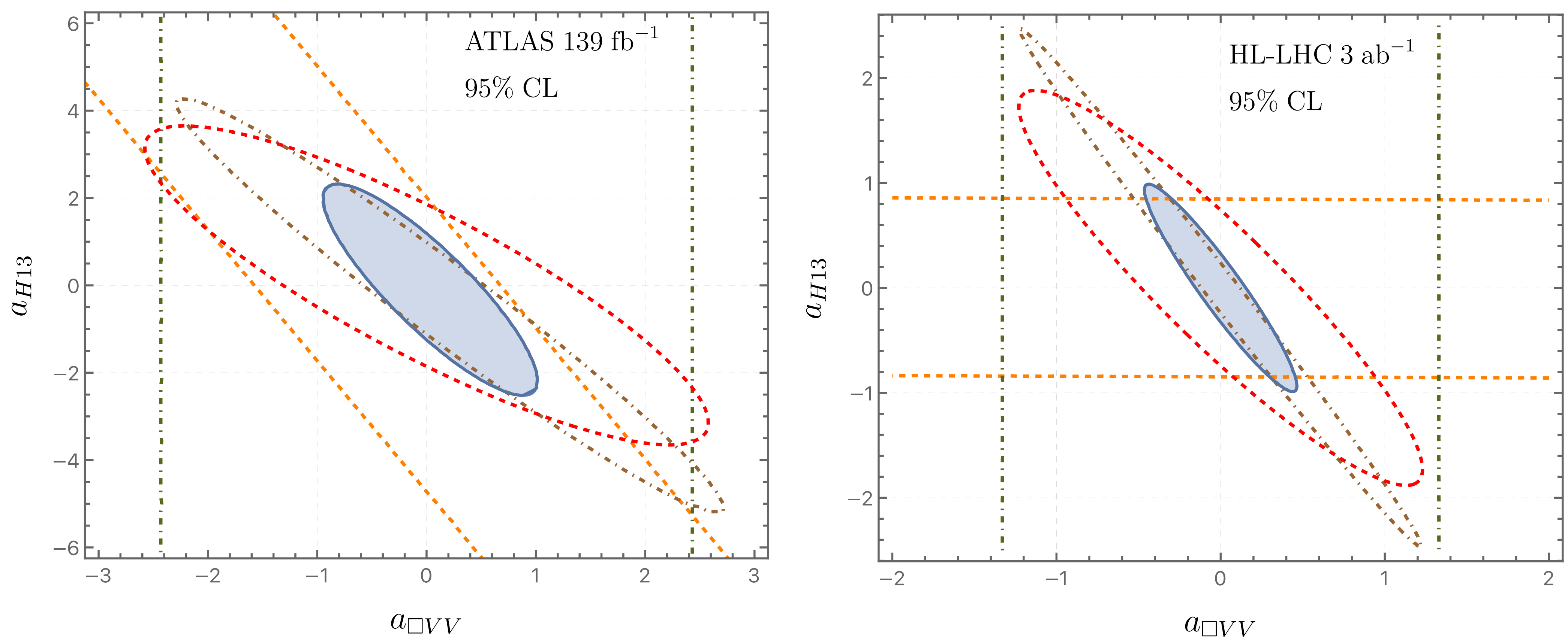
with $\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix}$

Grzadkowski et al 1008.4884

- To relate other HEFT operators, we need to go higher mass dimension in SMEFT.
- To further study the off-shell vs on-shell effects, we considered these HEFT-SMEFT correspondence.

Correlating off-shell and on-shell effects

$a_{\square VV}$ vs a_{H13}



Datasets	$\Delta\chi^2$ values	
	ATLAS 139 fb^{-1}	HL-LHC 3 ab^{-1}
on-shell	3.84	5.99
off-shell ZZ & on-shell	49.80	50.99
off-shell WW & on-shell	54.57	55.76
off-shell	90.53	90.53
all	93.95	95.08