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Higgs boson off-shell measurements probe non-linearities

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in collaboration with Christoph Englert, Roman Kogler, Michael Spannowsky

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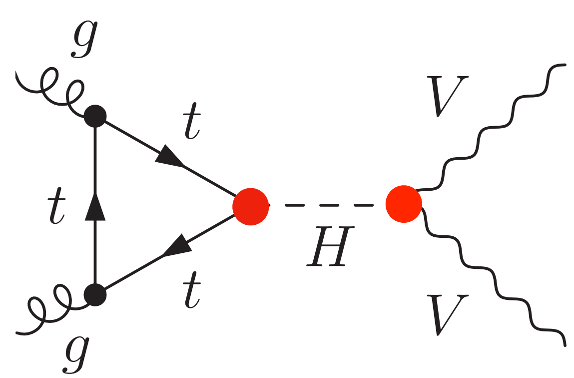
Higgs off-shell vs on shell effects

In process $pp \to VV$, the cross-section obtained in the region away from Higgs mass when correlated with the on-shell cross-section determines the model independent bound on the Higgs width.

Caola, Melnikov 1307.4935

Considering ggF as the dominant production channel i.e. $gg \to H^* \to VV$

For the on-shell region, assuming narrow width approximation



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

For the off-shell region away from the Higgs peak $M_{VV} >> M_H$, Higgs width parameter decouples and it does not contribute

$$\mu_{VV}^{\text{off-shell}} \propto \kappa_{ggF}^{2,\text{off-shell}} \ \kappa_{hVV}^{2,\text{off-shell}}$$

Kauer, Passarino 1206.4803

Using these, Higgs width is determined under the assumption that the 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

We revisit this measurement in the EFT framework.

Recap of Effective Field Theory

- Describe new physics using Higher Dimensional Operators (HDO) each supplemented with coefficients by comparing theoretical predictions with experimental data.
- No need to know the UV theory → Model independent way
- Efficient way to probe NP indirectly which is hidden from the current collider searches.
- For Higgs sector two different types of EFT are possible.

SM EFT

- Higgs field and Goldstone bosons are encoded in $SU(2)_L$ Higgs doublet
- The effective SMEFT lagrangian is written before SSB with SM lagrangian.

HEFT

- Higgs and Goldstone bosons are treated separately.
  - Higgs is a singlet and GBs are written as bi-doublet of $SU(2)_L \times U(1)_Y$.
  - No limitations on the interactions of Higgs with other SM fields.
- The effective HEFT lagrangian is written as EW chiral lagrangian with extra Higgs singlet.

For review, refer Brivio,Trott 1706.08945

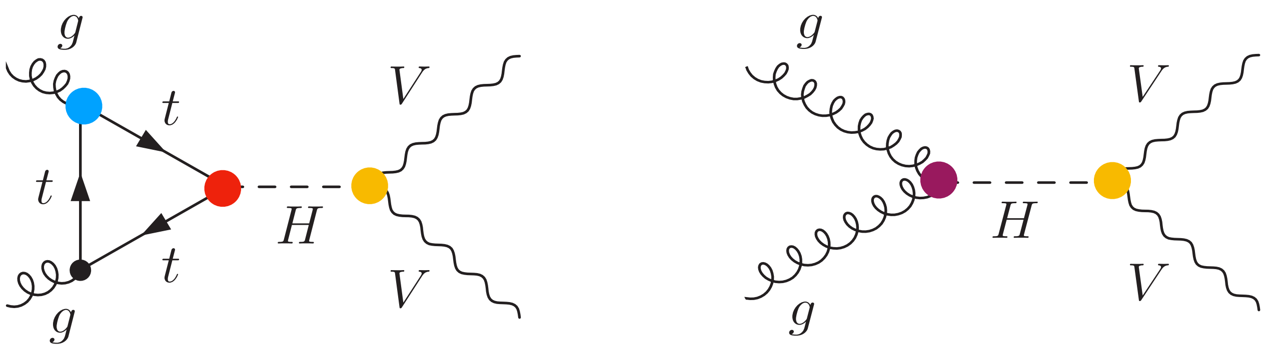
A lot of works have been done to distinguish SMEFT and HEFT considering both bottom up and top down approach.

Off-shell Higgs measurements in EFT

A lot of literature is available discussing the off-shell Higgs in $gg \to H^* \to VV$ in the context of SMEFT framework.

Including higher dimension SMEFT operators which induce changes in the Higgs couplings

- top-Higgs, gluon-Higgs, gauge-Higgs, top-gluon interactions



Studying the sensitivity of the relevant Higgs operators modifying these couplings

- Primarily 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

In our work, our aim is to revisit the off-shell $gg \to H^* \to VV$ in the HEFT framework

- Via the operator which induces high momentum effects in the off-shell propagating Higgs.
- To discuss HEFT vs SMEFT effects.
- To set the constraints on the HEFT interactions.

HEFT Framework

- SM Higgs H is not part of the Φ doublet. H 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

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

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

U leads to multiple Goldstone interactions with themselves and other fields.

- Gauge Bosons is given via the covariant derivative of U matrix

$$D_\mu U = \partial_\mu U + ig_W(W^a_\mu\tau^a/2)\,U - ig'UB_\mu\tau^3/2$$
$$W^{\pm}_\mu = \frac{1}{\sqrt{2}}(W^1_\mu \mp W^2_\mu)\,, \quad \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix} = \begin{pmatrix} c_W & s_W \\ -s_W & c_W \end{pmatrix}\begin{pmatrix} W^3_\mu \\ B_\mu \end{pmatrix}\,.$$

- Using the above relevant pieces, HEFT Lagrangian is written.

HEFT Lagrangian

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

Leading order Lagrangian

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

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

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

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

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

Anisha et al 2208.09334
Davila et al 2312.03877

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

Yukawa Lagrangian

$$\mathcal{L}_{\mathrm{Yuk}} = -\frac{v}{\sqrt{2}} \begin{pmatrix} \bar{u}^i_L & \bar{d}^i_L \end{pmatrix} U \begin{pmatrix} \mathcal{Y}^u_{ij} u^j_R \\ \mathcal{Y}^d_{ij} d^j_R \end{pmatrix} + \mathrm{h.c.}$$

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

Neglected the light quark flavour and lepton masses throughout this work

In our analysis, we have taken a_{1t}.

No contact ggH interactions are considered.

HEFT higher dimensional operators used in the work

Herrero, Morales 2107.07890

Brivio et al 1604.06801

Alonso et al 1212.3305

Included only bosonic operators

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

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

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

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

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

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

EWPO constraints are not violated

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

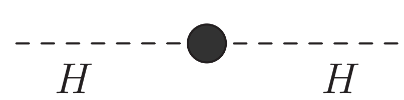
HEFT operator effects absent in SMEFT

In HEFT chiral dimension-4 lagrangian, Brivio et al. 1405.5412.

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

Induces two fold effects

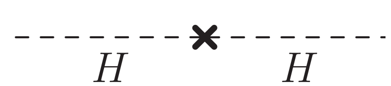
- Modifies the Higgs self energy which also affects the Higgs propagator.



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

In SMEFT no such effects

- Higgs field get redefined for the residue to 1



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

After solving the on shell renormalisation conditions

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

Uniform coupling rescaling

These combined give the modified propagator

Higgs propagator

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

non-trivial momentum dependency

HEFT operator effects absent in SMEFT

In HEFT chiral dimension-4 lagrangian,

Brivio et al. 1405.5412.

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

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

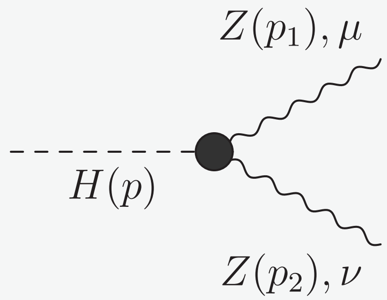
$$H \to H\left(1 - \frac{C_{\Box\Phi}}{\Lambda^2}m_H^2\right)$$

Higgs propagator

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

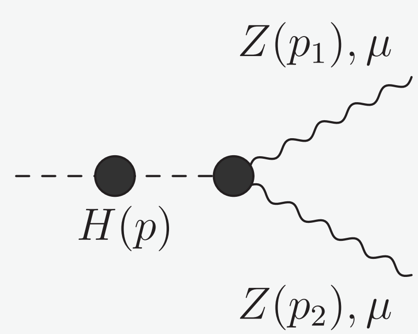
In addition,

Vertex effects



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

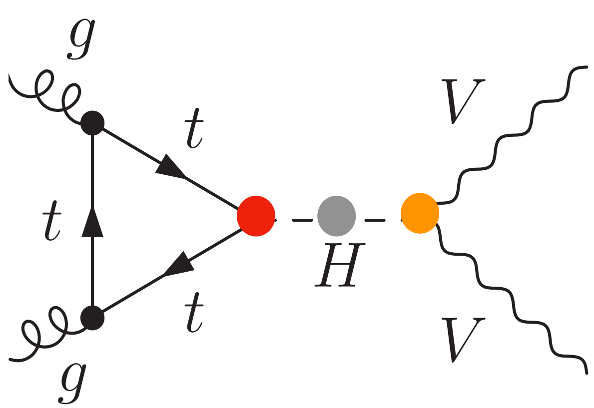
Including these Higgs propagator, field redefinition and HZZ vertex effects



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

Momentum dependent corrections cancel.

HEFT effects on Higgs off-shell amplitudes



To implement HEFT 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 $a_{\Box\Box}$
- Tree level corrections to vertex HVV

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

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

For, $H \to ZZ$

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

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

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

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

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

Linear order of HEFT corrections $\propto a_i$

Higgs off-shell effects

These modification to the amplitudes are implemented in VBFNLO.

Baglio et al 1404.3940

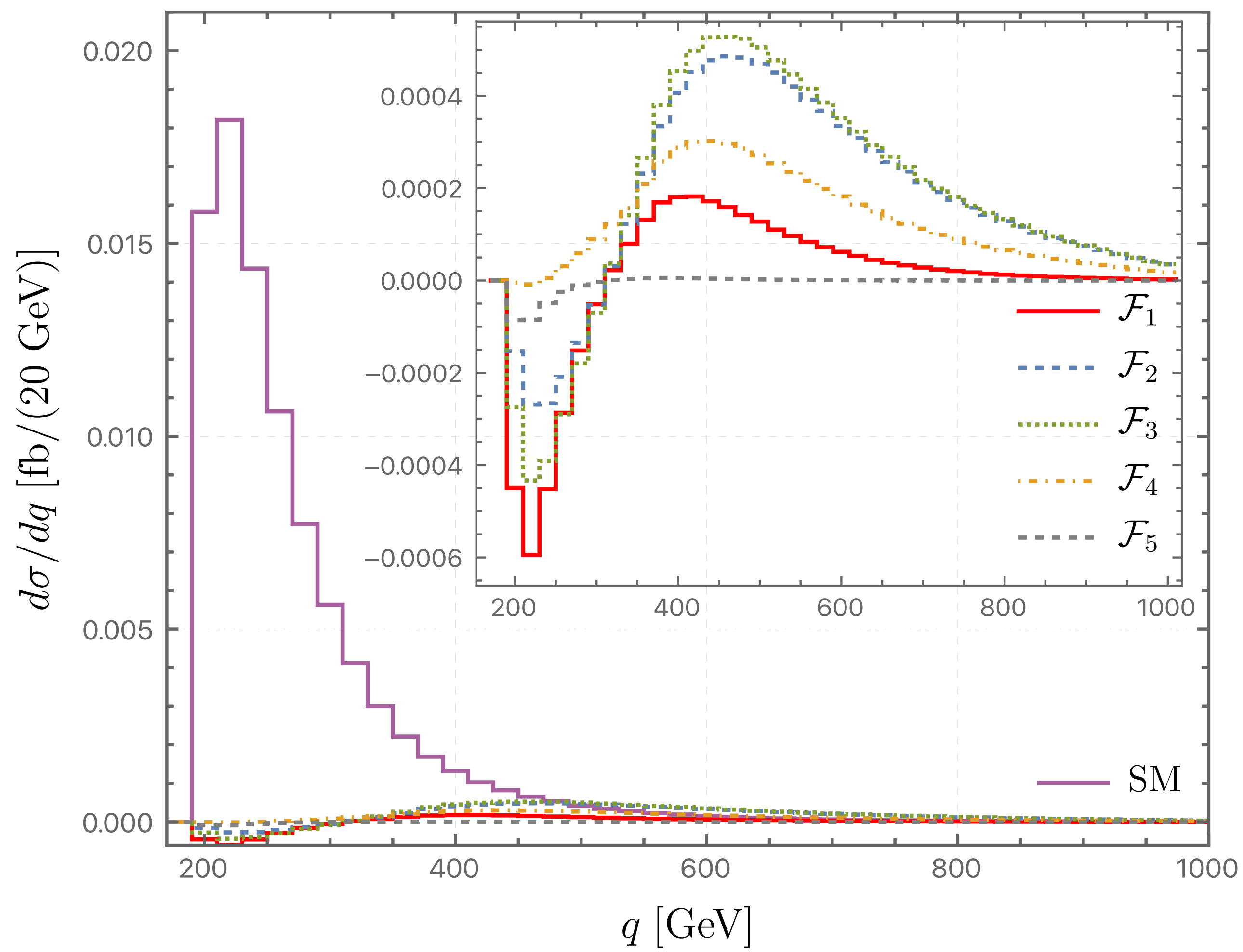
Cross-checks are done.

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.

Similarly $H \to WW$ off-shell HEFT corrections are obtained and effects are studied.



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

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

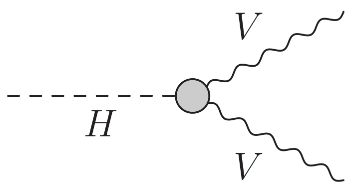
N_i denotes the ith bin entry and $N_i^{\rm SM}$ denotes the SM expectation.

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 $b\bar{b}$

$H \to VV^*$

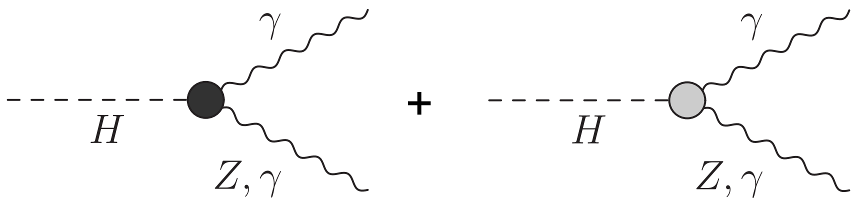


Tree-level corrections to the HVV vertex

Dawson, Giardino 1801.01136

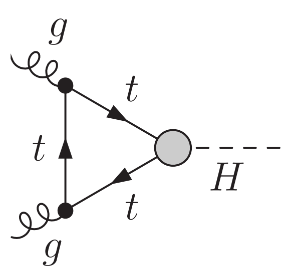
Dawson, Giardino 1807.11504

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



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

$H \to gg$ 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

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

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

Signal Strengths

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

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

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

Linear order of HEFT corrections $\propto a_i$

SMEFT - HEFT correspondence

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

HEFT

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

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

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

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

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

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

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

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

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

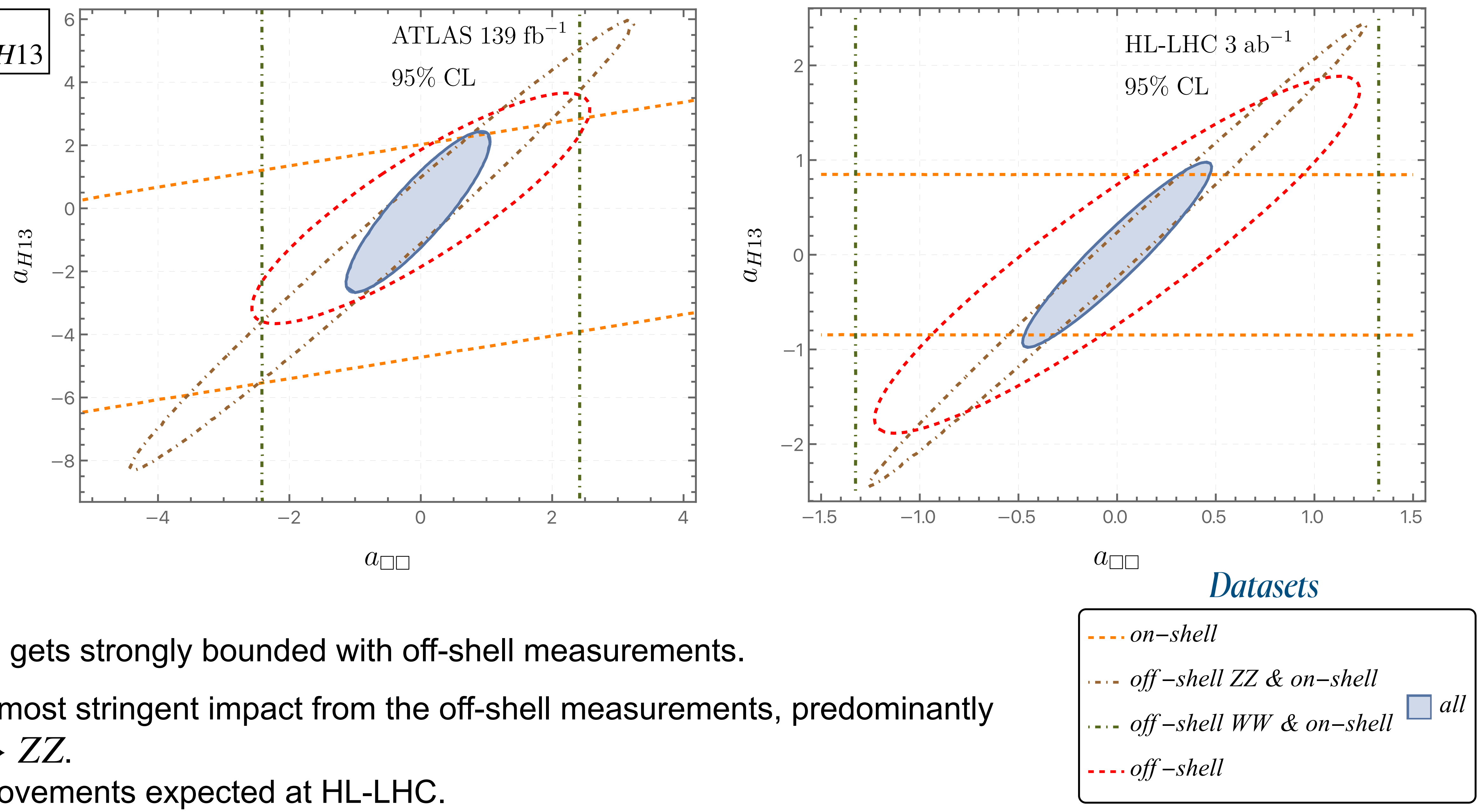
Grzadkowski et al 1008.4884

- 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

- Using the total χ^2, we ***profile*** over the SMEFT directions and obtained the parameter spaces.
- After profiling, for *all* dataset, $a_{\square\square}$, a_{H13}, $a_{\square VV}$, a_{d4} yield the strongest single parameter bounds.
- $95\ \%$ CL parameter regions are obtained with the $\Delta\chi^2$ constraints.

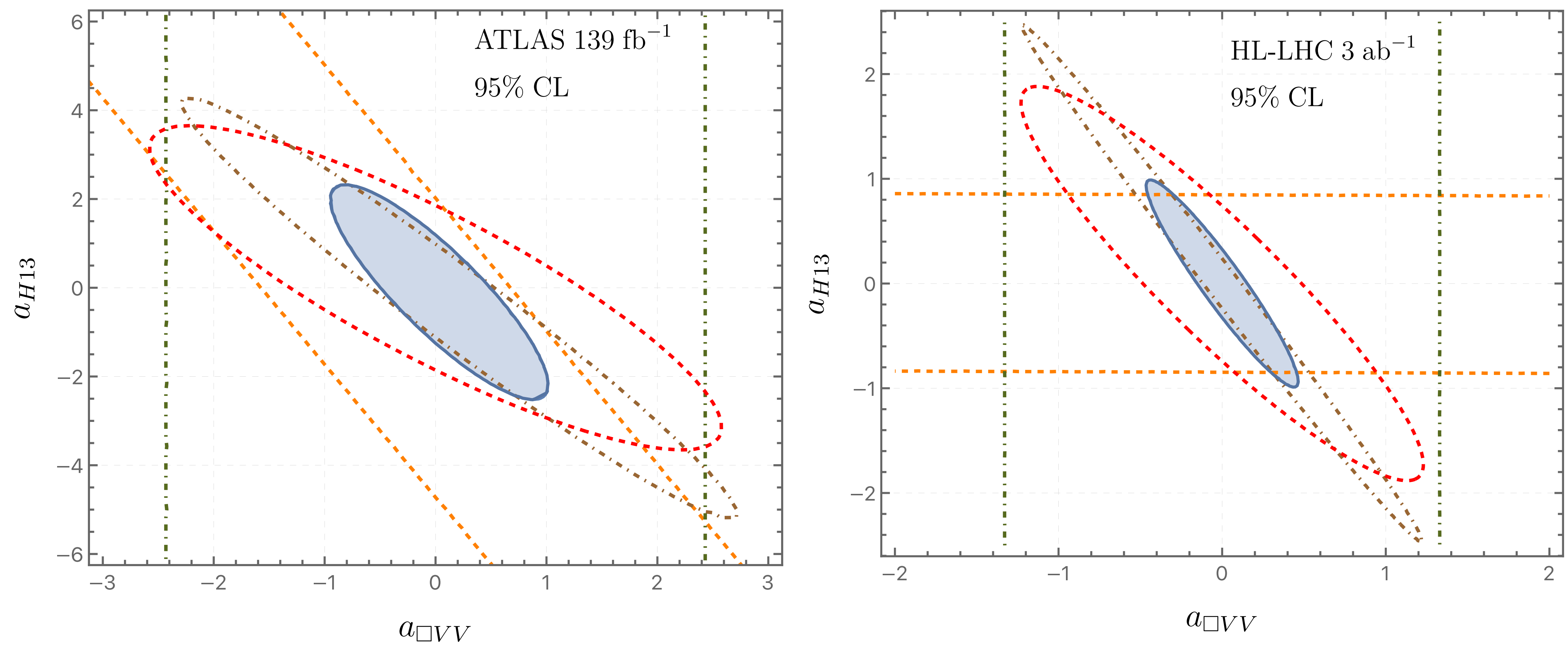
$a_{\square\square}$ *vs* a_{H13}



- $a_{\square\square}$ 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.

Correlating off-shell and on-shell effects

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



Similar observations

- The strongest impact is $H \to ZZ$ off-shell measurements.
- Improved constraints expected at HL-LHC.

Datasets

on−shell
off−shell ZZ & on−shell
off−shell WW & on−shell
off−shell
all

Conclusions

- We studied the off-shell measurements to set the constrain on the HEFT interactions.

- Main candidate is $a_{\square\square}$ which induces q^4 dependence in Higgs self energy and thus modifies Higgs propagator.

- Such effect being absent in SMEFT enables the HEFT vs SMEFT discrimination. Thus, this non-trivial momentum dependence brings in SMEFT vs HEFT effects.

- By correlating the off-shell with the on-shell data, the non-SMEFT interactions are constrained by profiling over SMEFTy directions.

- To enhance sensitivity to these HEFT parameters, off-shell measurements, when combined with VBF and multi-Higgs measurements, can offer promising prospects for a global fit.

Thank you for the attention !