Quartic Gauge-Higgs couplings: Constraints and Future Directions

Anisha
anisha@glasgow.ac.uk

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O.Atkinson, A. Bhardwaj, C. Englert, P. Stylianou

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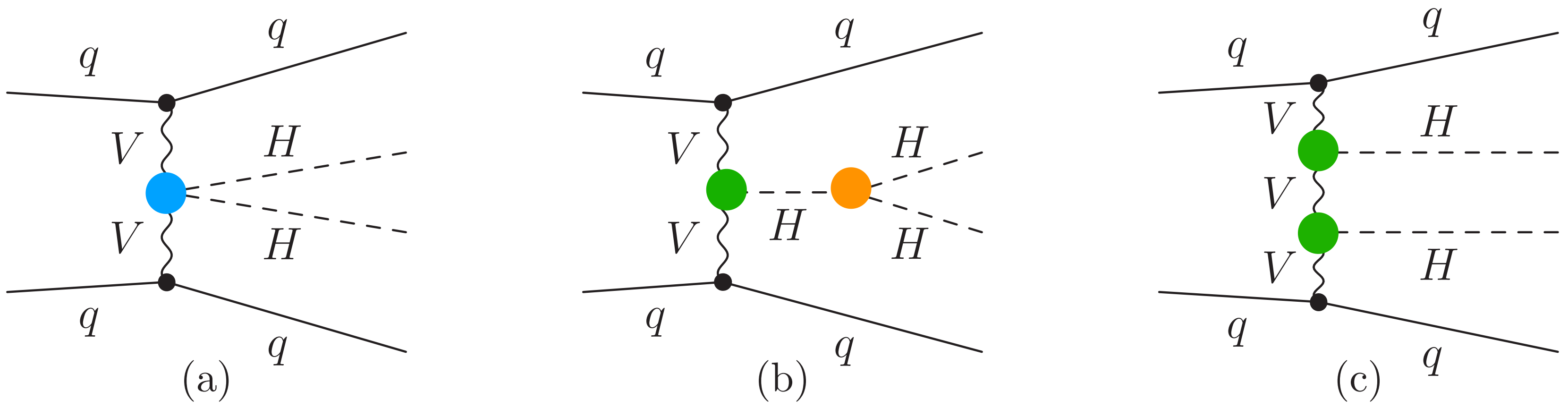
Status of the Quartic Higgs couplings with Gauge Bosons

Experimentally such quartic couplings are probed in Di-Higgs production via Weak Boson fusion.

WBF is statistically limited at LHC as GGF has the largest cross-section.



Despite the small rate of WBF scattering, modifying these couplings away from SM, following κ framework, and writing coupling modifiers

$$\kappa_V = \frac{g_{HVV}}{g^{\text{SM}}_{HVV}} \qquad \kappa_{2V} = \frac{g_{HHVV}}{g^{\text{SM}}_{HHVV}} \qquad \kappa_\lambda = \frac{g_{HHH}}{g^{\text{SM}}_{HHH}}$$

Modifying these couplings can induce changes in the cross-sections and lead to enhanced HH production. These anomalous couplings can shed light on the electroweak symmetry breaking.

Baseline of κ_{2V} in SM

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

- **Electroweak precision constraints**

$$\begin{aligned}\Delta S &= \Delta U = 0 \\ \Delta T &= \frac{\kappa_{2Z}^2 - \kappa_{2W}^2}{16\pi}\frac{M_H^2}{M_W^2 s_W^2}\log\frac{\Lambda^2}{M_H^2}\,,\end{aligned}$$

T-parameter $\Longrightarrow$ custodial isospin violation for $\kappa_{2W} \neq \kappa_{2Z}$

Current LHC constraints demand $\kappa_{2Z} \simeq \kappa_{2W}$ at the $1.5\,\%$ level for $\Lambda = 10$ TeV. Gfitter 1407.3792.

At one loop level, imposing custodial invariance, i.e. $\Delta T = 0$ for $\kappa_{2W} = \kappa_{2Z} = \kappa_{2V}$.

- **Unitarity constraints**

Considering longitudinal $HV_L \to HV_L$ scattering

As per unitarity criterion, for same initial and final states i,

$$\text{Re}\,|a_{ii}^0| \leq \frac{1}{2}$$

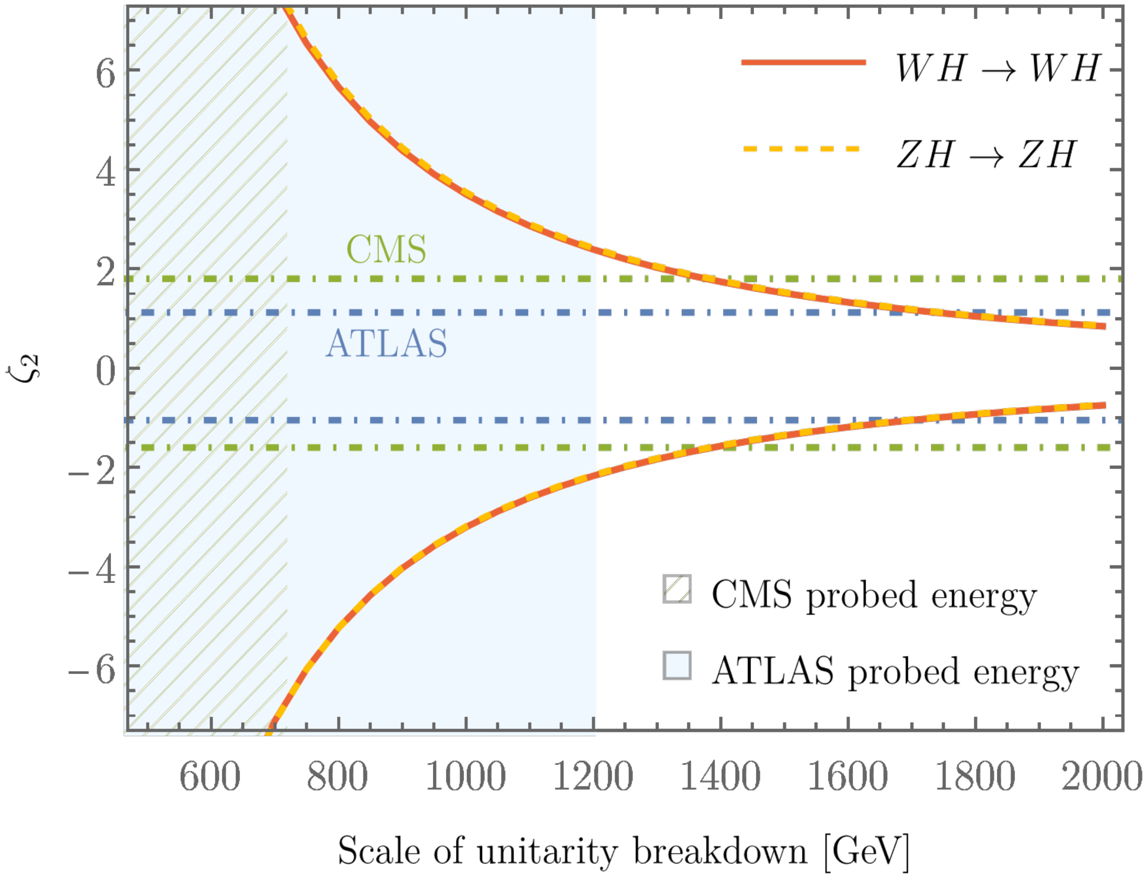
Jacob, Wick, 1959

For $\kappa_{2V} = 1 + \zeta_2$, these constraints are shown.

Also overlaid $95\,\%$ CL constraints from ATLAS and CMS

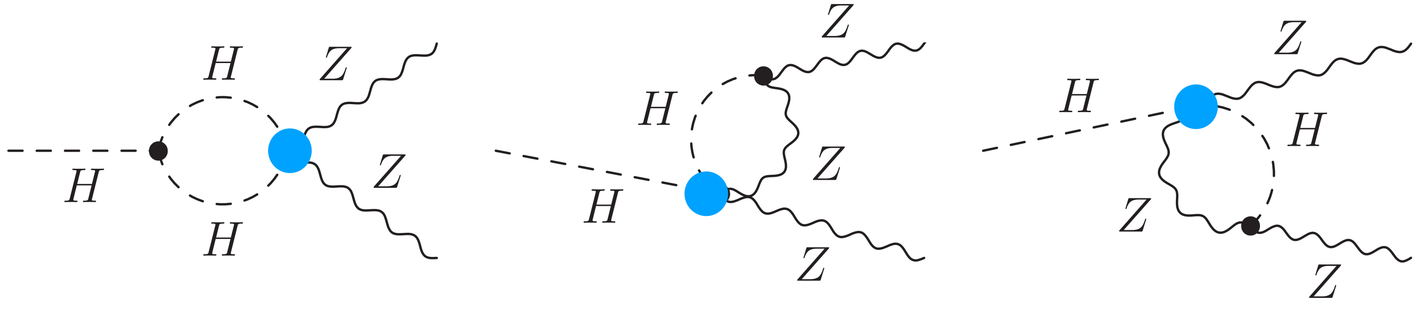
$\kappa_{2V} \in [-0.05, 2.12]$ $\kappa_{2V} \in [-0.6, 2.8]$

The unitarity constraints on ζ_2 are relatively quite loose.



At one loop order

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



(a) (b) (c)

Considering

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

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

- 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,

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

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.

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. H is a singlet field. No limitations on its interaction with other SM fields.
- Goldstones π^a are written non-linearly using U matrix which is parameterised as

$$\begin{aligned} U(\pi^a) \quad &= \quad \exp\left(i\pi^a\tau^a/v\right) \qquad v = 246 \text{ GeV} \\ &= \quad \mathbb{1}_2 + i\frac{\pi^a}{v}\tau^a - \frac{2G^+G^- + G^0G^0}{2v^2}\mathbb{1}_2 + \ldots \end{aligned}$$

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

$$G^0 = -\pi^3$$

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

$$D_\mu U = \partial_\mu U + i g_W (W_\mu^a \tau^a/2)\, U - i g' U B_\mu \tau^3/2$$

$$W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp W_\mu^2)\,, \quad \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix} = \begin{pmatrix} c_W & s_W \\ -s_W & c_W \end{pmatrix} \begin{pmatrix} W_\mu^3 \\ B_\mu \end{pmatrix} .$$

HEFT Framework

Buchalla et al.1307.5017

Brivio et al.1604.06801

Herrero, Morales 2107.07890

Leading order Lagrangian

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

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

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

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

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

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 $$\mathcal{L}_{\mathrm{Yuk}} = -\frac{v}{\sqrt{2}}\left(\bar{u}^i_L \quad \bar{d}^i_L\right) U \left(1 + c\,\frac{h}{v} + \ldots\right) \begin{pmatrix} y^u_{ij} u^j_R \\ y^d_{ij} d^j_R \end{pmatrix} + \mathrm{h.c.}$$

$c = 1$

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 channel

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 their renormalisation is required for a consistent final one-loop result.

HEFT operators

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

Expansion in loops!!

Contribute to the total Counter-term

- 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.

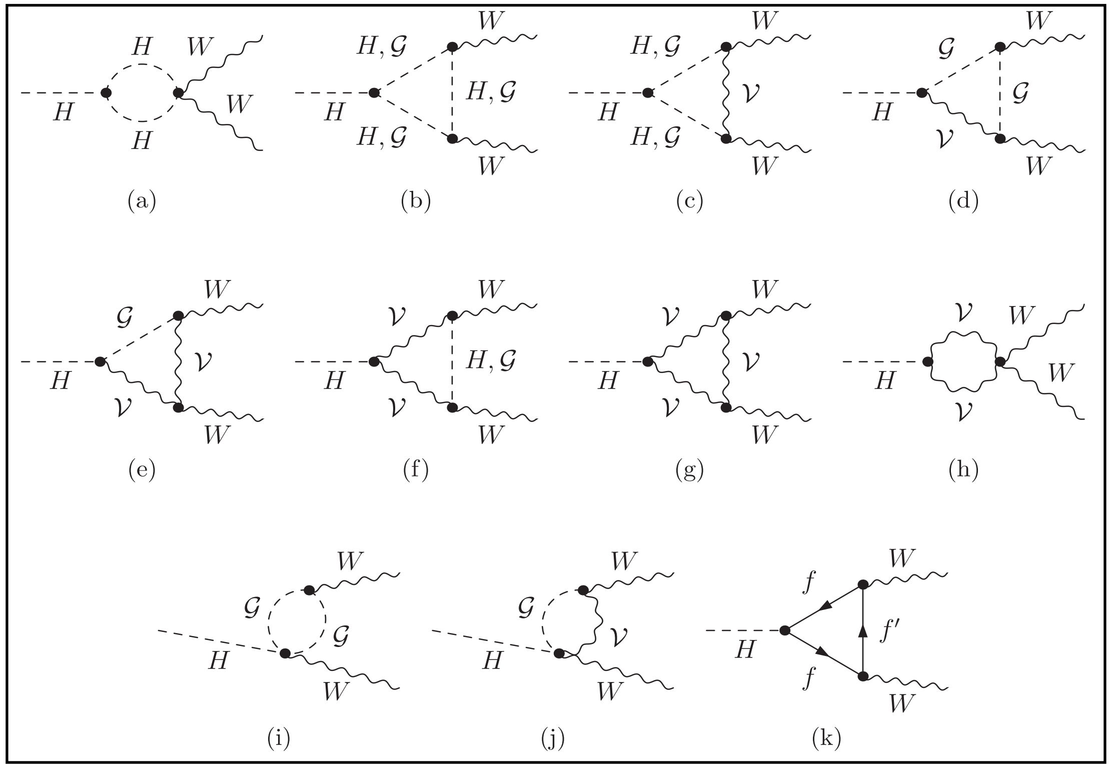
Both handled simultaneously

For details, refer Herrero, Morales 2107.07890

Example explaining the HEFT Loop order effects

Taking example of $H \to WW$

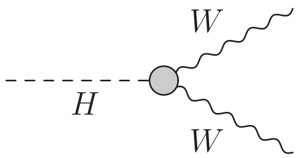
One loop diagrams with leading order Lagrangian



Amplitude with Higher dimensional operators

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

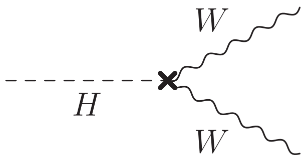
$$\boldsymbol{\mathcal{V}}_\mu = (D_\mu U)U^\dagger$$



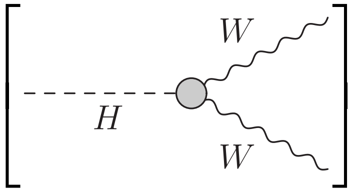
$$= \frac{e^2}{2\, v\, s_W^2}$$

$$\left[\Big(-2a_{HWW}(k_1^2 + k_2^2 - q^2) + 2a_{\square\boldsymbol{\mathcal{V}}\boldsymbol{\mathcal{V}}}\, q^2 + a_{d2} q^2\Big) g^{\mu\nu} - 2\big(a_{d2} + 2a_{HWW}\big) k_2^\mu k_1^\nu\right]$$

Complete Counter Term

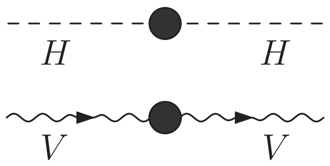


$$= \frac{e M_W (1+\zeta_1)}{s_W} \left(\boxed{\delta Z_e + \frac{\delta M_W^2}{2M_W^2} - \frac{\delta s_W}{s_W} + \frac{\delta\zeta_1}{1+\zeta_1} + \frac{\delta Z_H}{2} + \delta Z_W}\right) g^{\mu\nu} + \delta\, \boxed{\left[\quad\right]}$$



Renormalisation of HEFT operators and fixed looking into the divergent structures

RCs from 2point functions



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

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

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

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

Using $H \to \gamma\gamma, \gamma Z, WW^*, ZZ^*$, we obtain the corresponding decay widths in terms of ζ_1, ζ_2 & ζ_2 is loop induced.

Dawson, Giardino 1801.01136

Dawson, Giardino 1807.11504

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

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

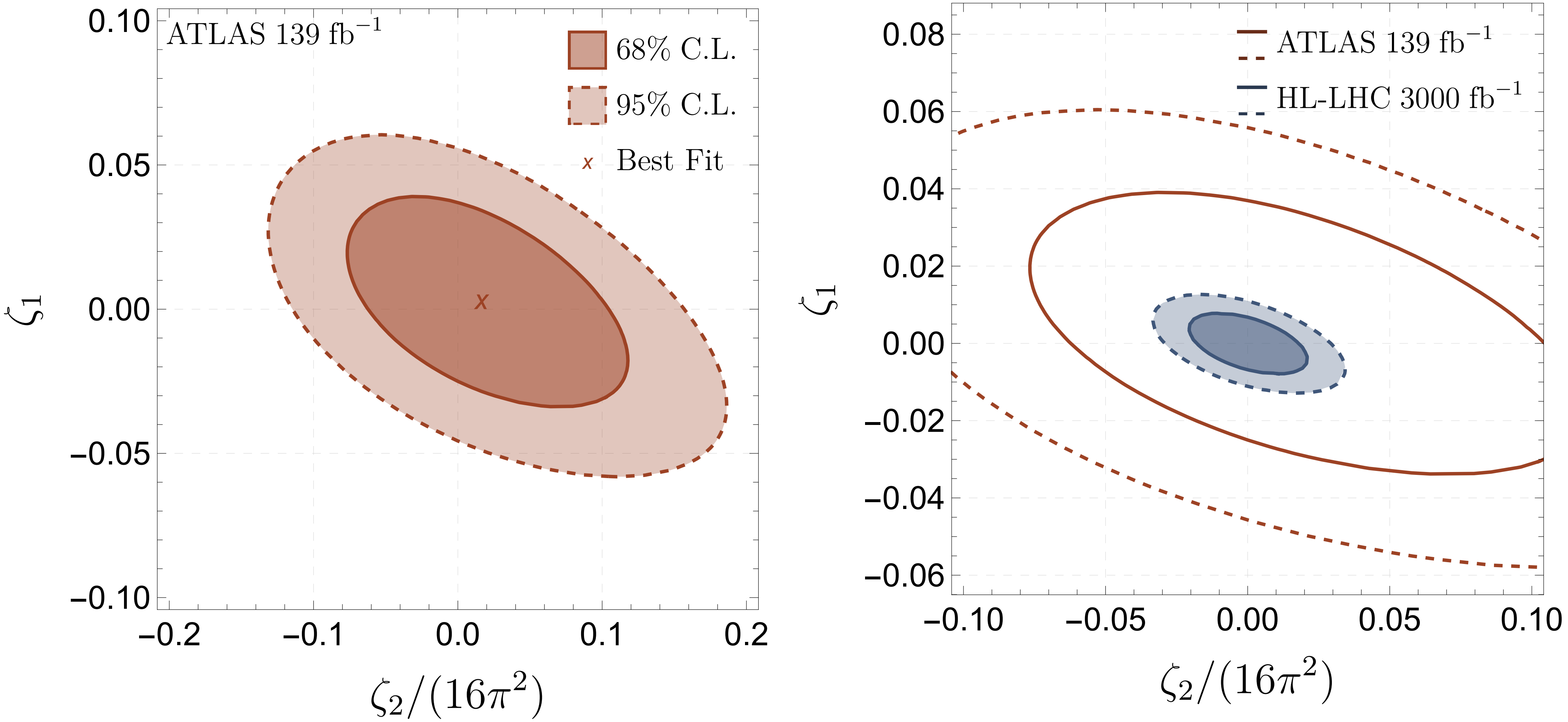
Parameters	ATLAS Run 2 data 139 fb^{-1}	HL-LHC uncertainties 3000 fb^{-1}	Correlation Matrix			
κ_Z	$0.99^{+0.06}_{-0.06}$	±0.012	1	0.40	0.44	0.09
κ_W	$1.05^{+0.06}_{-0.06}$	±0.013		1	0.47	0.08
κ_γ	$1.01^{+0.06}_{-0.06}$	±0.013			1	0.12
$\kappa_{Z\gamma}$	$1.38^{+0.31}_{-0.37}$	±0.073				1

Scaling factor for HL-LHC uncertainties*

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

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

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

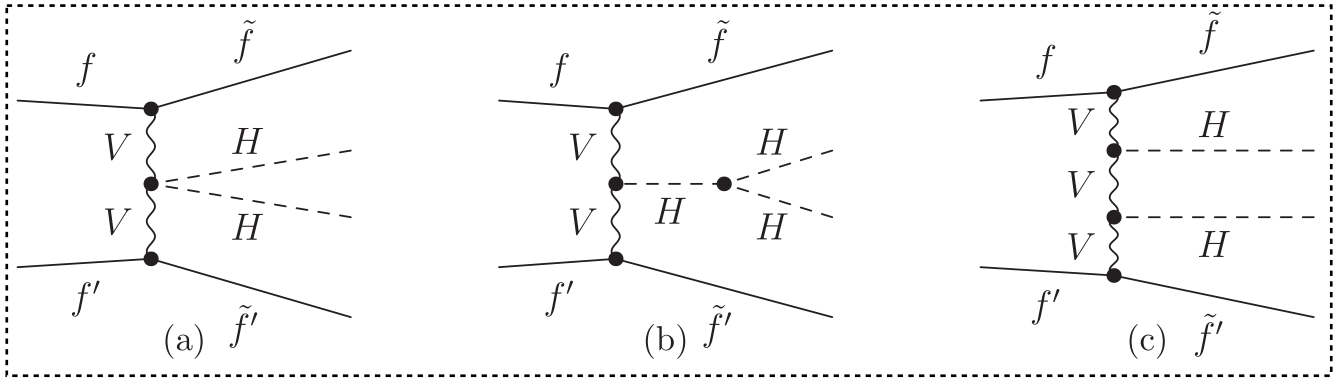


- The bounds on $\kappa_{2V} = 1 + \zeta_2$ from single Higgs data are loose.
- With HL-LHC projected data, single Higgs data greatly constraints ζ_1 and the constraints on ζ_2 reduced by a factor of 4.
- These plots indicate that κ_{2V} and κ_V are independent parameters at the LHC.
- There is a further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

Direct searches

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

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

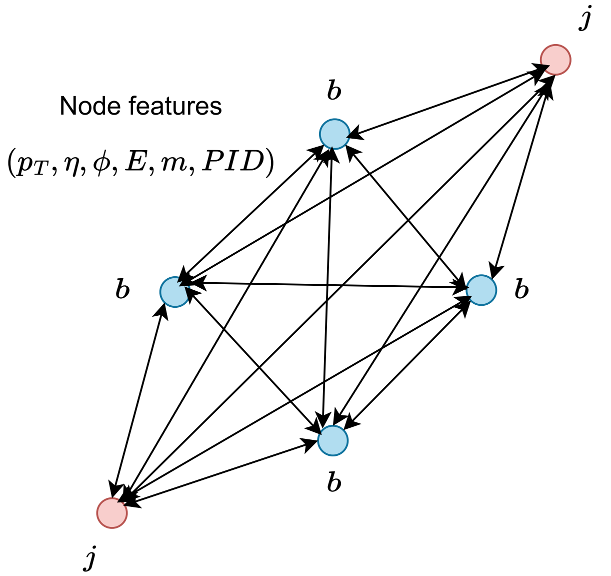
Thus, we need to work to reduce the background and increase signal sensitivity.

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

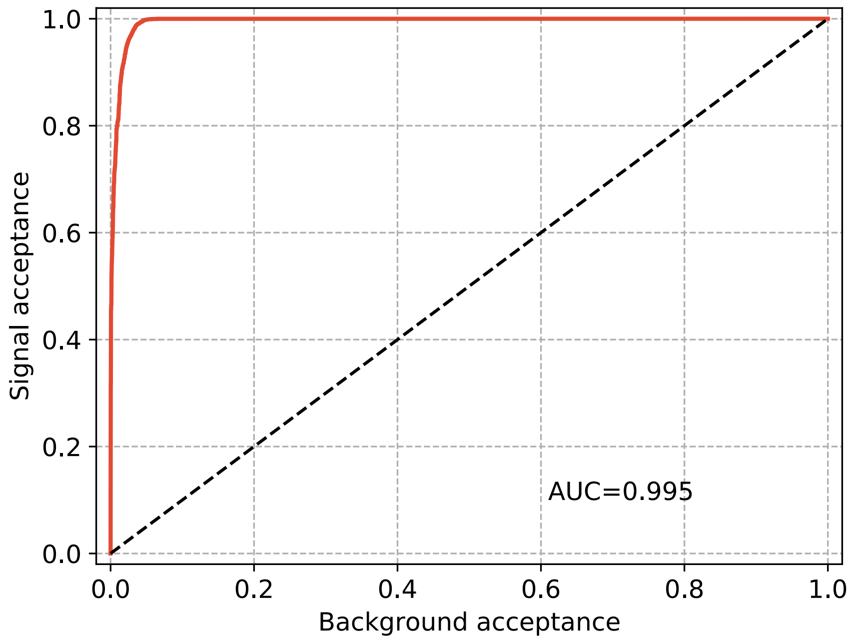
Nodes features are updated using single message passing layer.

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

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.

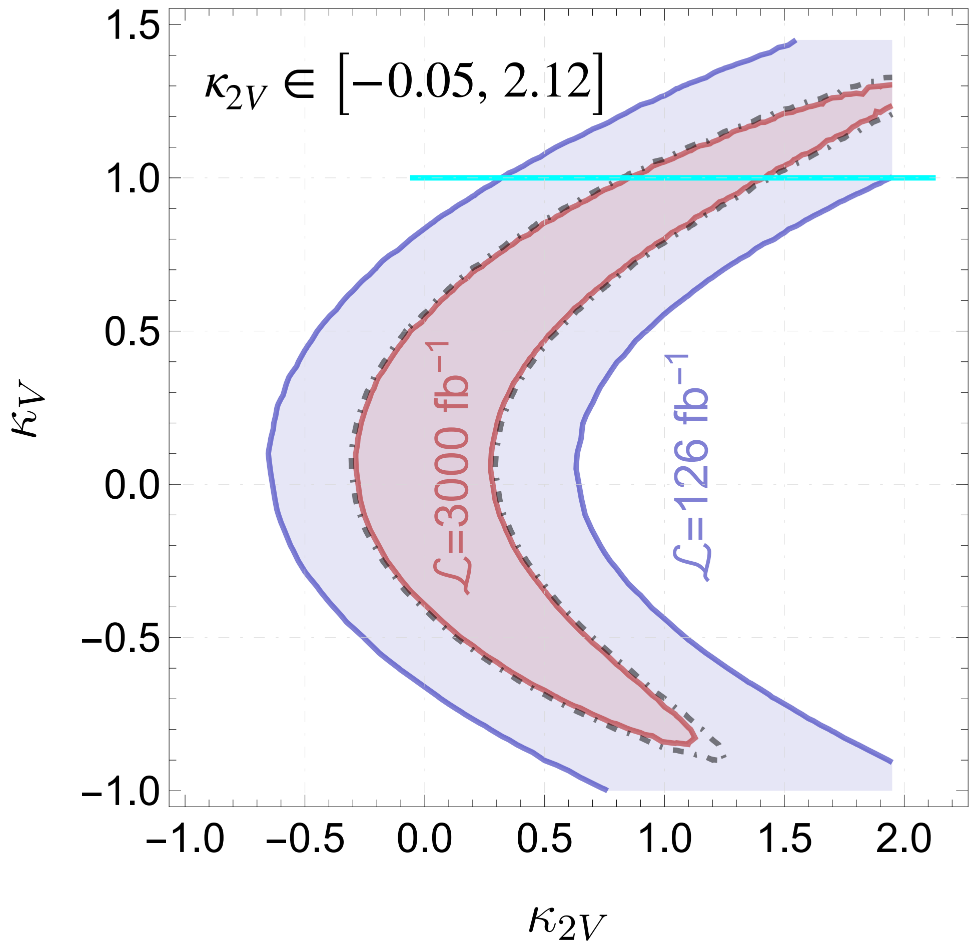
Network performance via ROC curve



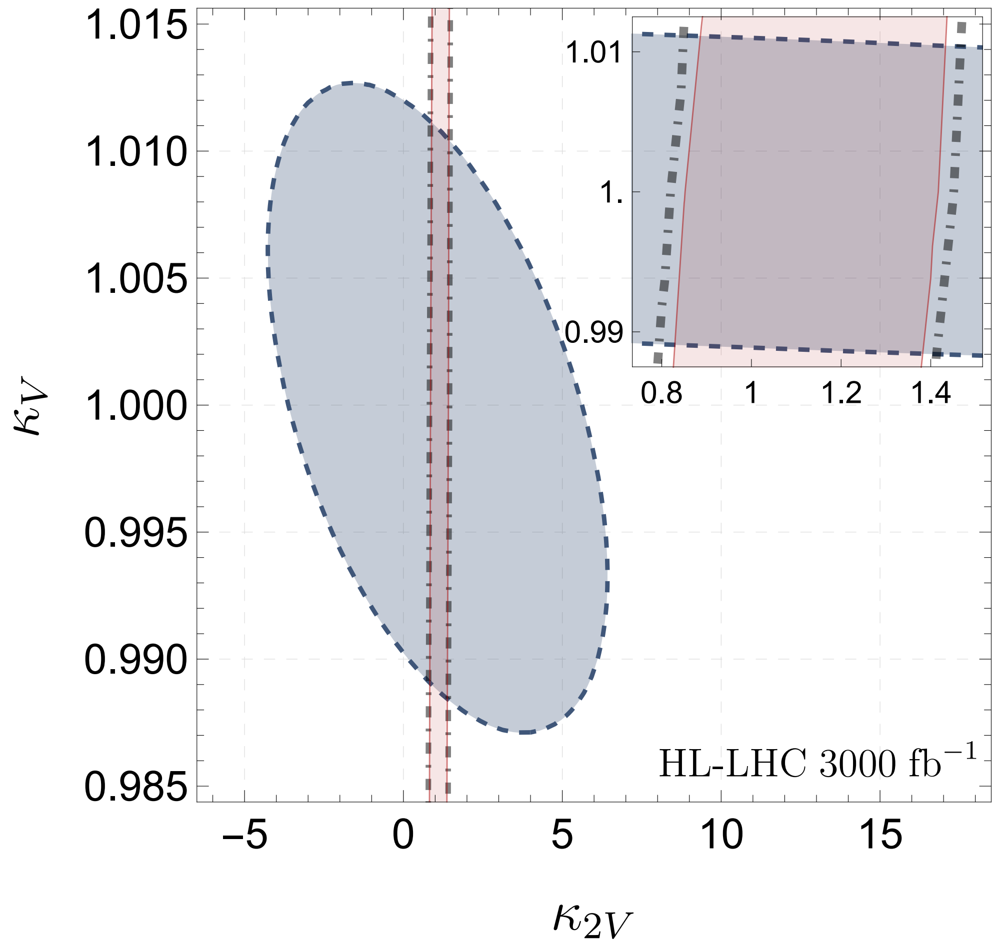
An optimal working point is chosen on this ROC.

Direct search limits

95% Exclusion contours given using the efficiencies obtained at the GNN optimal working point.



- ATLAS constraint shown in cyan shows a good agreement.
- Also $H \to b\bar{b}$ branching ratio as a function of κ_V is included.
- κ_{2V} sensitivity improved after including other sub-dominant backgrounds (25%).
- Overlaid HL-LHC projections with the single Higgs constraints obtained from the κ fit.



Conclusions

- Using Higgs Effective Field Theory framework, $\kappa_V - \kappa_{2V}$ correlations are explored.

- 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}.

- Graph Neural Network techniques increase the sensitivity to κ_{2V} through direct searches by discriminating $HHjj$ signal from QCD multijet background.

Thank you for the attention !

Back up

HEFT higher dimensional operators used in the work

Herrero, Morales 2107.07890

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

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