Effect of anomalous HHH and $ZZHH$ couplings on the decay width of $H \to Z^*Z^* \to 4l$

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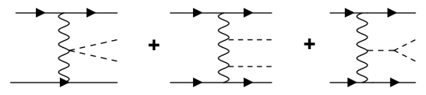
Overview

Motivation : $H \to Z^* Z^* \to 4l$

- Higgs sector in SM is not well explored, in particular HHH, $HHHH$ and $VVHH$ couplings are still not well measured.
- Few processes can probe these coupling.
  - VBF mechanism for HH production



The obtained bound are $-5.4 < \kappa_{HHH} < 11.4$ and $-0.1 < \kappa_{V_2H_2} < 2.1$ at 95% confidence level [1]. The bound comes from both the couplings $WWHH$ and $ZZHH$.

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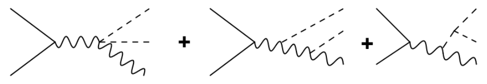
[1] ATLAS Col.,PRD 108, 052003(23)

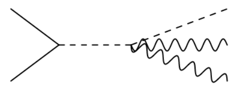
Motivation : $H \rightarrow Z^* Z^* \rightarrow 4l$

- Higgs-strahlung : HHV (V=W, Z) production



At the HL-LHC the bound will be quite weak $-9 < \kappa_{V_2 H_2} < 11$ [2].

- VVH (V=W, Z) production



We can probe two $VVHH$ couplings separately.

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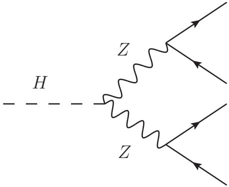
[2] Eur. Phys. J. Plus (2019) 134: 288

Motivation : $H \to Z^* Z^* \to 4l$

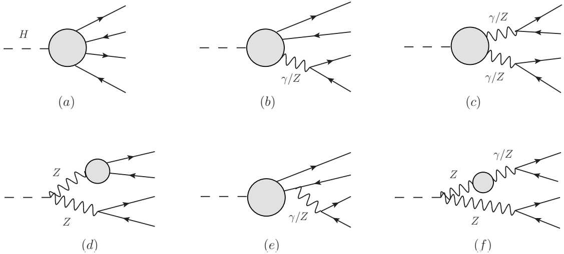
- One loop EW correction to Higgs partial decay widths.
- These processes are sensitive to HHH and $VVHH$ couplings beyond LO.
- Effect of anomalous HHH and $ZZHH$ coupling on the Higgs decay width.
- Effect of scaling of $ZZWW$ coupling on Higgs decay width.

LO and NLO diagrams

Tree level diagram :



One loop level generic diagrams :



(a) (b) (c)

(d) (e) (f)

Feynman Diagrams

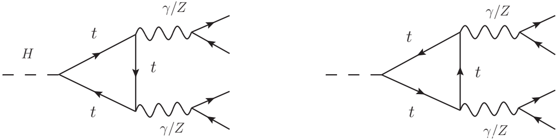
- Total number of diagrams :
  - LO : 1 diagram
  - NLO virtual : Pentagon + Box + Triangle + Self Energy diagrams.
    - Total 118 diagrams for $H \to \nu_e \bar{\nu}_e \nu_\mu \bar{\nu}_\mu$.
    - Total 256 diagrams for $H \to e^+ e^- \mu^+ \mu^-$.
  - NLO real emission :
    - No diagrams for $H \to \nu_e \bar{\nu}_e \nu_\mu \bar{\nu}_\mu$.
    - 4 diagrams for $H \to e^+ e^- \mu^+ \mu^-$.

- Loop-level prototype generic diagrams are 20.

Techniques to compute amplitudes :

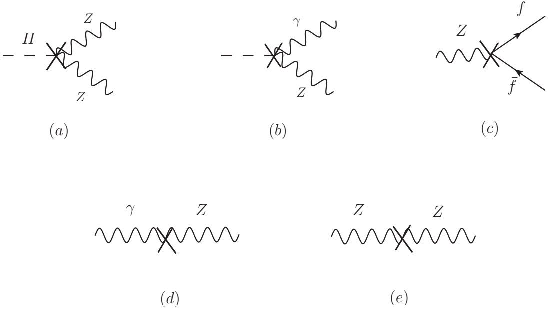
- We compute helicity amplitudes by using spinor helicity formalism at the matrix element level.
- The helicity amplitudes have been computed using our `FORM` routines.
- We adopt t'Hooft-Veltman (HV) dimensional scheme to compute the amplitudes.
- We use the package 'OneLOop' for scalar integrals computation.
- We use an in-house routine *OVReduce*, based on Oldenborgh-Vermaseren reduction techniques to reduce tensor integrals in terms of scalar integrals.
- For final state phase space integral, we use a Monte Carlo integration package called `AMCI`. The `AMCI` has been implemented via a parallel virtual machine called `PVM`.

γ^5-anomaly



- The trace is inconsistent, as one can get different results depending on the different starting points of the trace.
- The formal treatment of $\gamma^5 = \frac{i}{4!}\epsilon_{\mu\nu\rho\sigma}\gamma^\mu\gamma^\nu\gamma^\rho\gamma^\sigma$ is not consistent in d-dimension as the anti-symmetric tensor $\epsilon_{\mu\nu\rho\sigma}$ lives in 4-dimension.
- We use KKS scheme (Korner-Kreimer-Schilcher) in which all γ^5-matrices has to be taken to a particular vertex ('reading point') by anti-commuting with other γ-matrices. Then one can do d-dimensional algebra and compute trace.
- Same prescription has been followed to calculate $Zf\bar{f}$-vertex correction where the current is with the d-dimensional γ-matrices and γ^5-matrices.

Renormalization and CT diagrams



- We do on-shell renormalization for the EW correction for these processes.

CMS and OL Renormalization

- The complex mass scheme (CMS) has been used to treat unstable particle in one loop electroweak correction. The unstable masses are defined with a complex part as

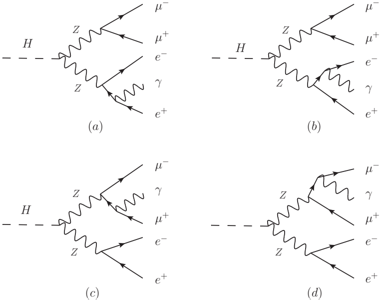
  $$m_V^2 \to \mu_V^2 = m_V^2 - i m_V \Gamma_V ,$$

  where $V = W, Z$ and Γ_V is the corresponding decay width. This treatment also makes Weinberg angle complex as $\cos^2 \theta_W = \mu_W^2 / \mu_Z^2$.
- The renormalization in CMS has been done in a modified version of the on-shell scheme where the renormalized mass is the pole of the corresponding propagator in the complex plane. When renormalized conditions being imposed, one need to perform the self energy computation with complex momenta.
- This computation can be done with Taylor expansion of self energies about the real mass and maintaining the one loop accuracy.

Input parameter scheme

- Different choice of α leads to different input parameter scheme.
- We calculate this process in $\alpha(M_Z)$ and G_F input parameter scheme.
- In $\alpha(M_Z)$ scheme, $\alpha(0)$ is evolved via renormalization-group equations from zero-momentum transfer to Z pole.
- In G_F scheme, the effective value of α is derived from the Fermi constant G_F in muon decay process.
- The charge renormalization constant contains mass singular terms like $\alpha \log m_f$ from each light fermion f which remain uncancelled in the EW corrections.
- Running of α absorbs these mass singular terms from the charge renormalization.

IR singularities and dipole subtraction ***I*** term



- Virtual diagrams are IR singular (not all) and the ***I*** term removes all IR singularities from virtual diagrams.
- Fermion split in to photon and fermion. Here both emitter and spectator are in the final state.
- The dipole terms $D_{ij,k}$ have similar behaviour as real emission diagrams in collinear and soft regime.

SM Results

Input parameter scheme	Γ^{LO} (10^{-9} GeV)	Γ^{NLO} (10^{-9} GeV)	RE
$H \to \nu_e \bar{\nu}_e \nu_\mu \bar{\nu}_\mu$			
G_F	930.7	959.7	3.11%
$\alpha(M_Z)$	1007.7	948.0	-5.92%
$H \to e^+ e^- \mu^+ \mu^-$			
G_F	238.04	241.03	1.26%
$\alpha(M_Z)$	256.82	237.69	-7.45%

We define relative enhancement as RE $= \frac{\Gamma^{NLO} - \Gamma^{LO}}{\Gamma^{LO}} \times 100$.

- Depending on the input parameter scheme Γ^{LO} differ by $\sim 8\%$ and Γ^{NLO} differ by $\sim 1\%$.
- Our results differ by only $\sim 0.1\%$ with the package `Prophecy4f`[3].

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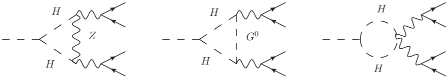
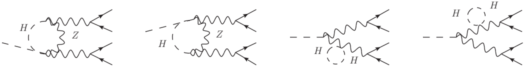
[3] Nucl. Phys. B 160, 131 (2006)

Anomalous coupling effect

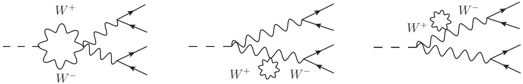
- NLO EW virtual diagrams with HHH and $ZZHH$ couplings.



- NLO EW virtual diagrams with $ZZHH$ couplings.



- NLO EW virtual diagrams with $ZZWW$ couplings.



- HHH, $ZZHH$ and $ZZWW$ couplings also appear in CT diagrams.

Anomalous HHH coupling effects

κ_{HHH}	RI (%)	
	G_F scheme	$\alpha(M_Z)$ scheme
$H \to \nu_e \bar{\nu}_e \nu_\mu \bar{\nu}_\mu$		
10	-7.54	-8.48
6	-1.22	-1.36
2	0.34	0.40
-2	-2.84	-3.20
-6	-10.6	-12.15
-10	-23.53	-26.48
$H \to e^+ e^- \mu^+ \mu^-$		
10	-7.65	-8.62
6	-1.23	-1.39
2	0.36	0.40
-2	-3.17	-3.25
-6	-10.95	-12.41
-10	-23.91	-26.72

We define relative increment (RI) as RI $= \frac{\Gamma_{\kappa}^{NLO} - \Gamma_{SM}^{NLO}}{\Gamma_{SM}^{NLO}} \times 100.$

Anomalous $ZZHH$ coupling effects

Effect of anomalous $ZZHH$ coupling :

κ_{ZZHH}	RI (%)	
	G_F scheme	$\alpha(M_Z)$ scheme
$H \to \nu_e \bar{\nu}_e \nu_\mu \bar{\nu}_\mu$		
10	5.73	0.28
6	3.17	0.16
2	0.64	0.03
-2	-1.92	-0.09
-6	-4.47	-0.22
-10	-7.01	-0.35
$H \to e^+ e^- \mu^+ \mu^-$		
10	5.13	-0.50
6	2.85	-0.28
2	0.57	-0.06
-2	-1.71	0.16
-6	-3.91	0.38
-10	-6.26	0.88

Anomalous $ZZWW$ coupling effects

Effect of anomalous $ZZWW$ coupling :

κ_{ZZWW}	RI (%)	
	G_F scheme	$\alpha(M_Z)$ scheme
	$H \to \nu_e \bar{\nu}_e \nu_\mu \bar{\nu}_\mu$	
10	10.45	-19.29
6	5.80	-10.72
2	1.16	-2.14
-2	-3.49	6.43
-6	-8.14	15.00
-10	-12.79	23.58
	$H \to e^+ e^- \mu^+ \mu^-$	
10	6.56	-23.68
6	3.95	-13.15
2	0.78	-2.79
-2	-2.35	7.85
-6	-5.48	18.38
-10	-8.59	28.90

Summary

- We have studied one loop EW correction to $H \rightarrow \nu_e \bar{\nu}_e \nu_\mu \bar{\nu}_\mu$ and $H \rightarrow e^+ e^- \mu^+ \mu^-$ processes.
- These processes have significant dependency on HHH coupling.
- The relative increment goes from $\sim 0.5\%$ to $\sim -27\%$ depending upon the allowed scaling of HHH coupling.
- The dependencies of $ZZHH$ coupling on partial decay width is marginal in $\alpha(M_Z)$ scheme but in G_F scheme, the RI goes from -7% to 5% depending on κ_{ZZHH}.
- The partial decay width also depends on $ZZWW$ coupling strongly.
- Gauge invariance is maintained with the scaling of HHH in this process, whereas the same is not maintained with the scaling of $ZZHH$ and $ZZWW$ couplings.
- A better theory is needed to vary $VVHH$ and $VVVV$ couplings with out disturbing the gauge invariance.

Thank You