SMEFT in final states with multiple Higgs and gauge bosons

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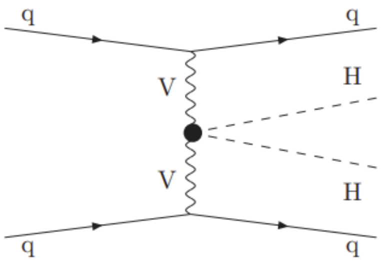
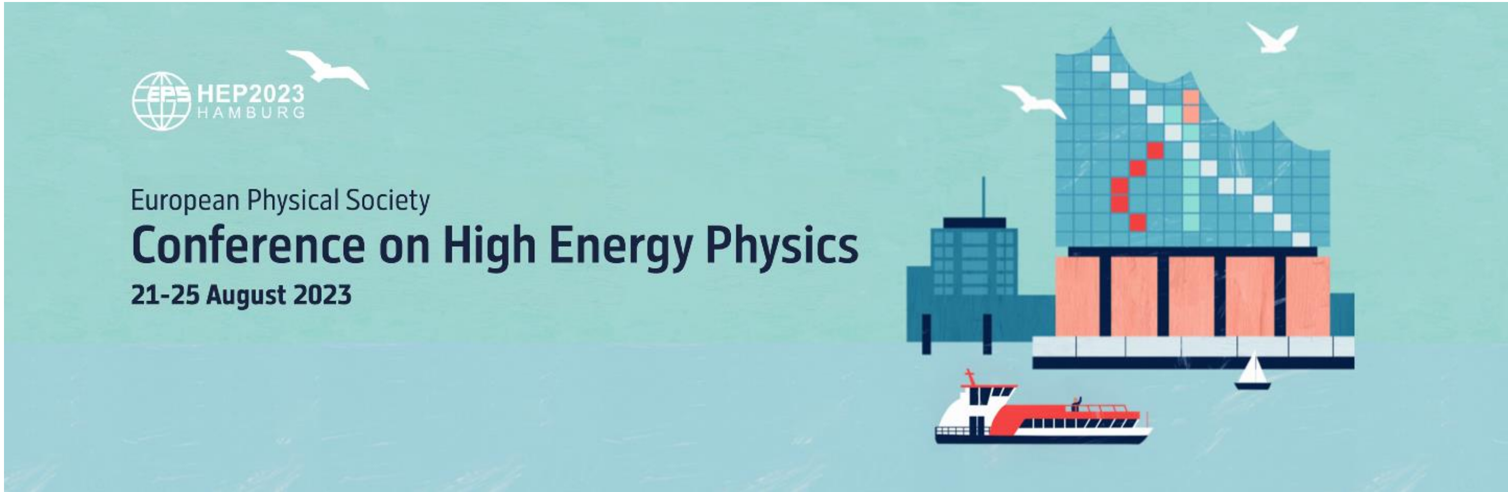
A. Cappati, R.C., P. Torrielli, and M. Zaro, [JHEP09 (2022) 038]



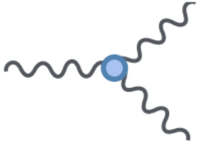


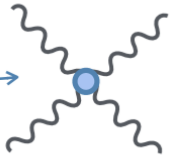
VVHH interactions and SMEFT

- **VVHH interaction vertices predicted by the SM…**
  - with identical strength as VVH couplings (modulo powers of v)
- **… but very difficult to investigate**
  - Processes where they contribute significantly have very small cross-sections
  - The only relevant experimental data is LHC Run-2

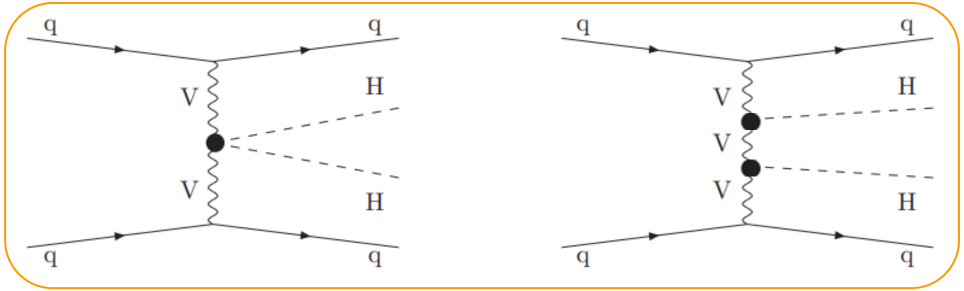
- How to parameterise possible beyond-SM effects in VVHH interactions?
  - We adopt a **Standard-Model Effective Field Theory (SMEFT)** approach

$$L_{EFT} = L_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_{i,\text{dim-6}} + \sum_j \frac{c_j}{\Lambda^4} O_{j,\text{dim-8}}$$





Choice of SMEFT dimensionality



A typical final state at the LHC:

- Production of Higgs-boson pairs from Vector Boson Fusion (VBF HH)

EFT effects quite complex:

- Dimension-6 SMEFT effects may modify triple couplings (VVH, HHH)
  - At dimension-6, **modifications of VVH and VVHH vertices are necessarily the same** (as in the SM) → best constrained by single-Higgs-boson production and decay data
  - **Only one genuine** ($\propto h^6$) **HHH-modifying operator** → best constrained by HH production in gluon-fusion
- Dimension-8 SMEFT operators include operators generating **genuine anomalous-Quartic-Couplings (aQC,** i.e. leaving triple couplings unchanged)
  - We focus on these, as the investigated final states have unique sensitivity

Dimension-8 basis and unitarity constraints

- Eboli et al. (Phys. Rev. D74 (2006) 073005)

$$\mathcal{O}_{S,0} = [(D_\mu\Phi)^\dagger D_\nu\Phi] \times [(D^\mu\Phi)^\dagger D^\nu\Phi]$$
$$\mathcal{O}_{S,1} = [(D_\mu\Phi)^\dagger D^\mu\Phi] \times [(D_\nu\Phi)^\dagger D^\nu\Phi]$$
$$\mathcal{O}_{S,2} = [(D_\mu\Phi)^\dagger D_\nu\Phi] \times [(D^\nu\Phi)^\dagger D^\mu\Phi]$$

SCALAR

$$\mathcal{O}_{M,0} = \mathrm{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] \times [(D_\beta\Phi)^\dagger D^\beta\Phi] \qquad \mathcal{O}_{M,4} = [(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi] \times B^{\beta\nu}$$
$$\mathcal{O}_{M,1} = \mathrm{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}] \times [(D_\beta\Phi)^\dagger D^\mu\Phi] \qquad \mathcal{O}_{M,5} = [(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi] \times B^{\beta\mu} + \mathrm{H.c.}$$
$$\mathcal{O}_{M,2} = [B_{\mu\nu}B^{\mu\nu}] \times [(D_\beta\Phi)^\dagger D^\beta\Phi] \qquad \mathcal{O}_{M,7} = [(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi]$$
$$\mathcal{O}_{M,3} = [B_{\mu\nu}B^{\nu\beta}] \times [(D_\beta\Phi)^\dagger D^\mu\Phi]$$

MIXED

$$\mathcal{O}_{T,0} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\widehat{W}_{\alpha\beta}\widehat{W}^{\alpha\beta}\right], \quad \mathcal{O}_{T,1} = \mathrm{Tr}\left[\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\widehat{W}_{\mu\beta}\widehat{W}^{\alpha\nu}\right]$$
$$\mathcal{O}_{T,2} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\widehat{W}_{\beta\nu}\widehat{W}^{\nu\alpha}\right], \quad \mathcal{O}_{T,3} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}_{\alpha\beta}\right] \times \mathrm{Tr}\left[\widehat{W}^{\alpha\nu}\widehat{W}^{\mu\beta}\right]$$
$$\mathcal{O}_{T,4} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}_{\alpha\beta}\right] \times B^{\alpha\nu}B^{\mu\beta}, \quad \mathcal{O}_{T,5} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{O}_{T,6} = \mathrm{Tr}\left[\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu}, \quad \mathcal{O}_{T,7} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}$$
$$\mathcal{O}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}, \quad \mathcal{O}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}\,.$$

TRANSVERSE

- Using this basis, **unitarity bounds** are estimated from optical theorem (partial wave expansion, up to P-wave), valid for all VV → VV transitions (Phys. Rev. D 101 (2020) 113003)
  - they are function of the c.o.m. energy of the partonic system considered

Wilson Coefficient	1 operator	
		For $\sqrt{s} < 1.5\,(3)$ TeV
$\left\lvert \frac{f_{S,0}}{\Lambda^4} \right\rvert$	$32\,\pi\, s^{-2}$	20 (1.2) TeV^{-4}
$\left\lvert \frac{f_{S,1}}{\Lambda^4} \right\rvert$	$\frac{96}{7}\,\pi\, s^{-2}$	8.5 (0.53) TeV^{-4}
$\left\lvert \frac{f_{S,2}}{\Lambda^4} \right\rvert$	$\frac{96}{5}\,\pi\, s^{-2}$	8.5 (0.53) TeV^{-4}

Relevant final states at the LHC

NOTE: as all processes are very rare, we only consider the H → bbbar decay mode

$$\mathcal{O}_{S,0} = [(D_\mu\Phi)^\dagger D_\nu\Phi] \times [(D^\mu\Phi)^\dagger D^\nu\Phi]$$
$$\mathcal{O}_{S,1} = [(D_\mu\Phi)^\dagger D^\mu\Phi] \times [(D_\nu\Phi)^\dagger D^\nu\Phi]$$
$$\mathcal{O}_{S,2} = [(D_\mu\Phi)^\dagger D_\nu\Phi] \times [(D^\nu\Phi)^\dagger D^\mu\Phi]$$

$$\mathcal{O}_{M,0} = \mathrm{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] \times [(D_\beta\Phi)^\dagger D^\beta\Phi]$$
$$\mathcal{O}_{M,1} = \mathrm{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}] \times [(D_\beta\Phi)^\dagger D^\mu\Phi]$$
$$\mathcal{O}_{M,2} = [B_{\mu\nu}B^{\mu\nu}] \times [(D_\beta\Phi)^\dagger D^\beta\Phi]$$
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$$\mathcal{O}_{M,4} = [(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi] \times B^{\beta\nu}$$
$$\mathcal{O}_{M,5} = [(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi] \times B^{\beta\mu} + \mathrm{H.c.}$$
$$\mathcal{O}_{M,7} = [(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi]$$

$$\mathcal{O}_{T,0} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\widehat{W}_{\alpha\beta}\widehat{W}^{\alpha\beta}\right], \quad \mathcal{O}_{T,1} = \mathrm{Tr}\left[\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\widehat{W}_{\mu\beta}\widehat{W}^{\alpha\nu}\right]$$
$$\mathcal{O}_{T,2} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\widehat{W}_{\beta\nu}\widehat{W}^{\nu\alpha}\right], \quad \mathcal{O}_{T,3} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}_{\alpha\beta}\right] \times \mathrm{Tr}\left[\widehat{W}^{\alpha\nu}\widehat{W}^{\mu\beta}\right]$$
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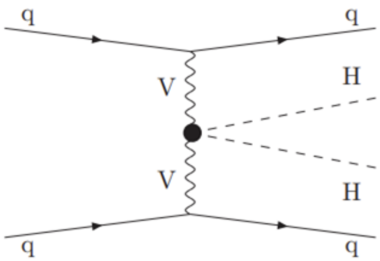
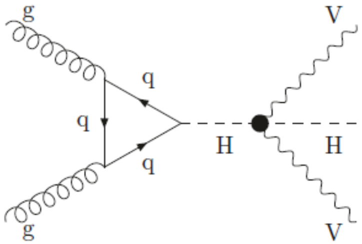
$$\mathcal{O}_{T,6} = \mathrm{Tr}\left[\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu}, \quad \mathcal{O}_{T,7} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}$$
$$\mathcal{O}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}, \quad \mathcal{O}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}.$$

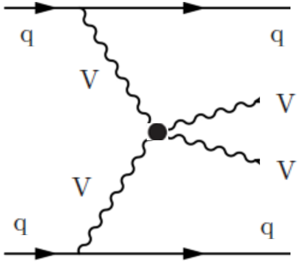
- **VBF HH** (S and M operators)



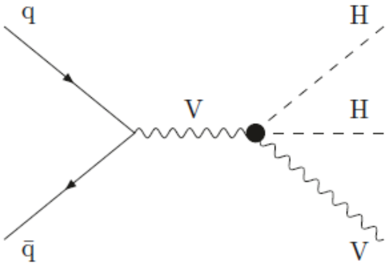
- **gg → VVH production** (S, M)
  - N.B. sub-dominant vs. qqbar production



- **Vector boson-scattering (VBS) final states** (T, but also S, M via covariant-derivative terms)



- **qqbar → VHH production** (S, M)

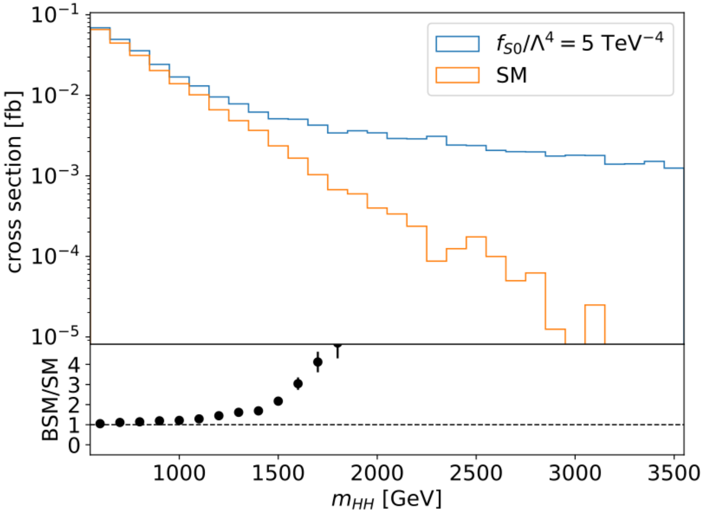


Simulation setup

VBF-HH

- MC generator: **MadGraph5_aMC@NLO** v2.7
- Generator-level selections applied:
  - p_T, η, m_{jj}, $\Delta\eta_{jj}$ of tagging jets, for VBS and VBF final states (1-4)
  - m_{bb} close to m_H for candidate b-jet pairs (7)

Process number	MadGraph5_aMC@NLO syntax	QCD order	Max. jet flav.	CMS result	$\overline{\sigma}$[1.1, 13 TeV] SM (fb)
Signal (including EFT effects)					
1	`p p > w+ w+ j j QCD=0` `p p > w- w- j j QCD=0`	LO	4	[29, 30]	4.514(9)
2	`p p > w+ z j j QCD=0` `p p > w- z j j QCD=0`	LO	4	[29, 30]	8.55(2)
3	`p p > w+ w- j j QCD=0`	LO	4	[30]	9.97(2)
4	`p p > h h j j QCD=0`	LO	5	[40]	0.0329(7)
5	`p p > z h h QED=3`	LO	5	-	0.01295(5)
6	`g g > z z h [noborn=QCD]`	LI (LO)	5	—	$3.493(7) \times 10^{-3}$
Background (SM only)					
7	`p p > z b b~ b b~`	LO	4	—	0.729(3)

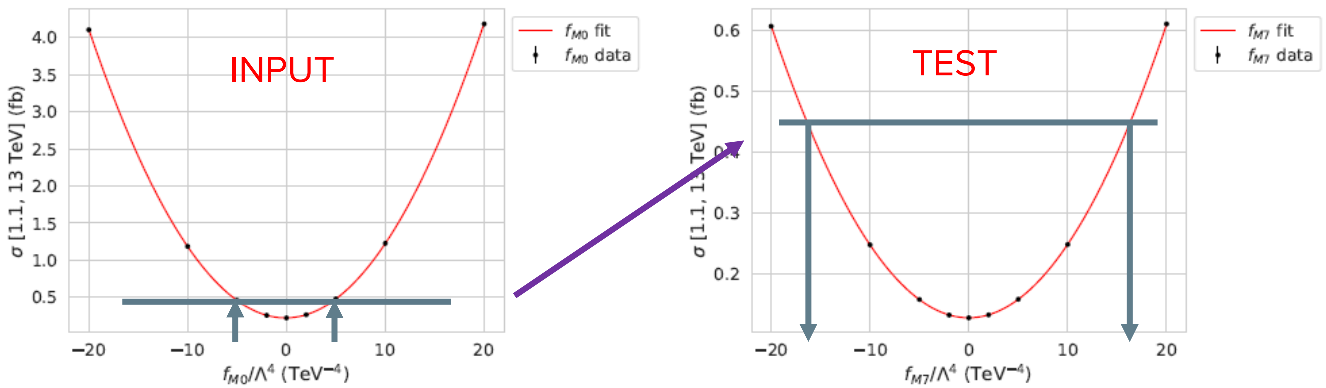


- BSM effects simulated:
  1. either varying the VVHH coupling by hand
  2. or for various values of the EFT Wilson coefficients

Validation: reproducing CMS VBS results

- In order to estimate EFT sensitivity, real experimental analyses use signal MC templates of the invariant mass of the di-/tri-boson states produced (m) - or proxies of m, in case of undetected particles
- Our **simplified observable**: $\boldsymbol{\sigma[m_{min}, m_{max}]}$ (integrated cross section in invariant-mass interval)
    - m_{min} fixed to 1.1 TeV ($\sigma_{SM} \approx \sigma_{EFT}$)
    - m_{max} assuming **various values** between **m_{min} + 0.1 TeV and √s (the latter corresponding to no unitarity bound)**

Validation method (no unitarity bound)



Validation: reproducing CMS VBS results

- Assume integrated cross-section in BSM fiducial region is the observable determining experimental sensitivity
    1. Run simulation scans for a given bosonic final state and all operators (3xS + 7xM)
    2. Compute all cross-sections and interpolate with quadratic function
    3. Take the experimental limit on one operator from CMS publications (w/o unitarity)
    4. Extrapolate corresponding 95%-CL excluded cross-section
    5. Derive limits on all other operators and compare with published ones

- Managed to reproduce CMS results w/o unitarity bounds using simplified observable **– except in one case**
- Also filled in missing results

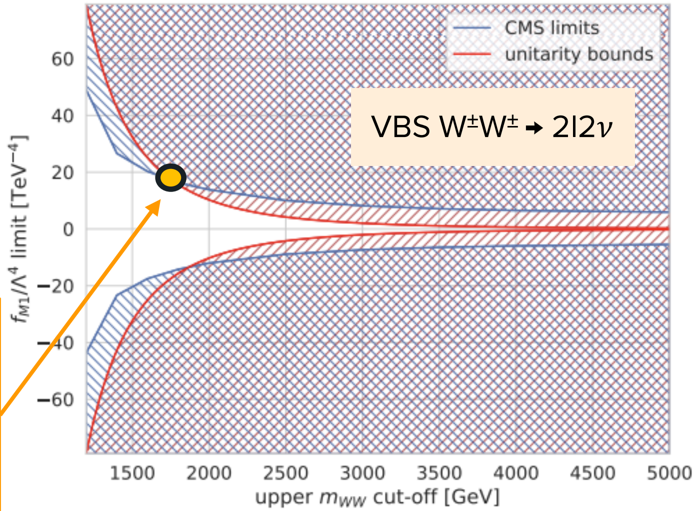
	VBS $W^{\pm}W^{\pm} \to 2\ell 2\nu$		VBS $W^{\pm}Z \to 3\ell\nu$		VBS $W^{\pm}V$ semileptonic	
Coeff.	CMS exp.	estimated	CMS exp.	estimated	CMS exp.	estimated
f_{M0}/Λ^4	[-3.7,3.8]	[-3.9,3.7]	[-7.6,7.6]	input	[-1.0,1.0]	[-1.0,1.0]
f_{M1}/Λ^4	[-5.4,5.8]	input	[-11,11]	[-11,11]	[-3.0,3.0]	[-3.1,3.1]
f_{M2}/Λ^4	/	/	–	[-13,13]	–	[-1.5,1.5]
f_{M3}/Λ^4	/	/	–	[-19,19]	–	[-5.5,5.5]
f_{M4}/Λ^4	/	/	–	[-5.9,5.9]	–	[-3.1,3.1]
f_{M5}/Λ^4	/	/	–	[-8.3,8,3]	–	[-4.5,4.5]
f_{M7}/Λ^4	[-8.3,8.1]	[-8.5,8.0]	[-14,14]	[-14,14]	[-5.1,5.1]	input
f_{S0}/Λ^4	[-6.0,6.2]	[-6.1,6.2]	[-24,24]	[-25,26]	[-4.2,4.2]	[-6.7,6.8]
f_{S1}/Λ^4	[-18,19]	[-18,19]	[-38,39]	[-38,39]	[-5.2,5.2]	[-8.3,8.4]
f_{S2}/Λ^4	–	[-18,19]	–	[-25,26]	–	[-8.4,8.5]

Implementation of unitarity bounds

1. Evaluate σ[m_{min}, m_{max}] for several m_{max} values
2. For each σ, obtain **m_{max}-dependent limits** on operator coefficients, the same procedure used for validation
3. **Intersect limit curve** with **unitarity bound curve** from Eboli's paper

Coeff.	VBS $W^{\pm}W^{\pm}$	VBS $W^{\pm}Z$	VBS $W^{\pm}V$ semilep.
f_{M0}/Λ^4	/	/	[-3.3,3.5]
f_{M1}/Λ^4	[-13,17]	[-67,71]	[-7.4,7.6]
f_{M2}/Λ^4	/	/	[-9.1,9.0]
f_{M3}/Λ^4	/	/	[-32,30]
f_{M4}/Λ^4	/	[-36,36]	[-8.6,8.7]
f_{M5}/Λ^4	/	[-29,29]	[-10,10]
f_{M7}/Λ^4	[-21,18]	[-59,57]	[-11,11]
f_{S0}/Λ^4	[-17,20]	/	[-8.5,9.5]
f_{S1}/Λ^4	/	/	/
f_{S2}/Λ^4	/	[-25,26]	[-21,25]

Curve intersection: maximum m which can be used to set limits not violating unitarity

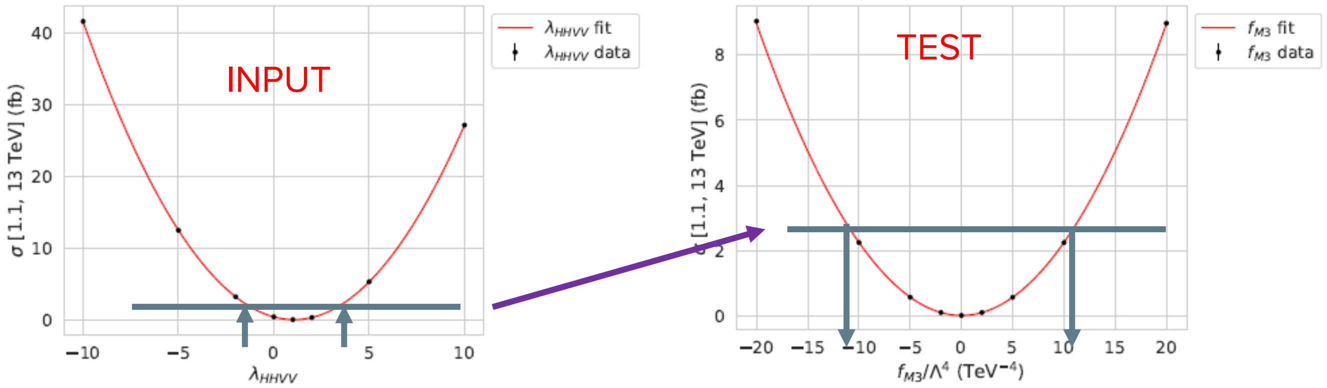


- **Limits obtained w/ unitarity bounds much less stringent than those obtained w/o**
- If curves do not cross, available data are not sufficient to set more stringent limits than those imposed by unitarity

VBF-HH limits from CMS results

LHC experimental results are given in terms of coupling modifier k_{2V}

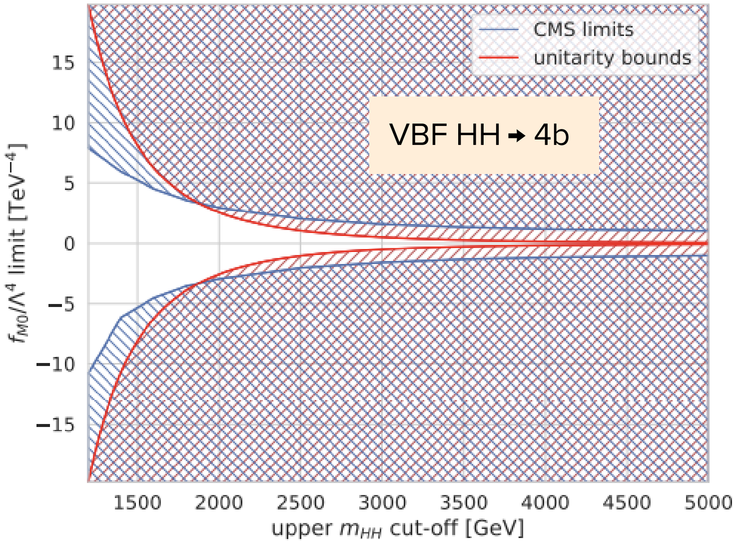
1. Consider published VBF HH ➔ 2 bbbar 95% CL limit (**N.B. from 2021 - CMS only**) on k_{2V}
2. Use VBF-HH simulation as a function of k_{2V} to fit parabola and obtain limit on σ
3. From limit on σ, extract limits on corresponding Wilson coefficients



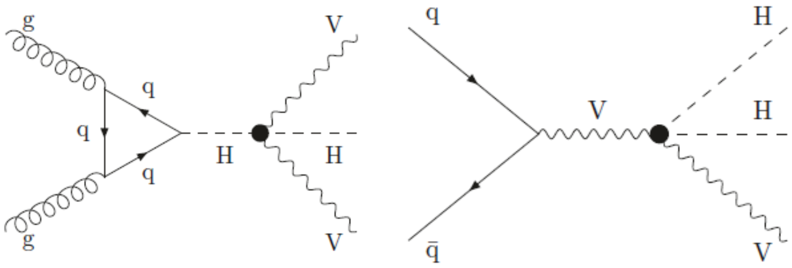
VBF-HH results

- **VBF-HH** estimated limits are **competitive** and **supersede** those obtained with VBS for f_{M0}, f_{M2}, f_{M3}
- When unitarity boundaries are added, limits worsen and/or become irrelevant in the expected way, but the above result stays true

	VBS $W^{\pm}V$ semileptonic		VBF $HH \to b\bar{b}b\bar{b}$	
Coeff.	no unitarity	w/ unitarity	no unitarity	w/ unitarity
f_{M0}/Λ^4	[-1.0,1.0]	[-3.3,3.5]	[-0.95,0.95]	[-3.3,3.3]
f_{M1}/Λ^4	[-3.1,3.1]	[-7.4,7.6]	[-3.8,3.8]	[-13,14]
f_{M2}/Λ^4	[-1.5,1.5]	[-9.1,9.0]	[-1.3,1.3]	[-7.6,7.3]
f_{M3}/Λ^4	[-5.5,5.5]	[-32,30]	[-5.2,5.3]	[-29,30]
f_{M4}/Λ^4	[-3.1,3.1]	[-8.6,8.7]	[-4.0,4.0]	[-14,14]
f_{M5}/Λ^4	[-4.5,4.5]	[-10,10]	[-7.1,7.1]	[-26,26]
f_{M7}/Λ^4	[-5.1,5.1]	[-11,11]	[-7.6,7.6]	[-27,27]
f_{S0}/Λ^4	[-4.2,4.2]	[-8.5,9.5]	[-30,29]	/
f_{S1}/Λ^4	[-5.2,5.2]	/	[-11,10]	/
f_{S2}/Λ^4	-	[-21,25]	[-17,16]	/



New final states (no LHC results yet)



- **gg → VVH** and **qqbar → VVH**
  - For both, choose **V = Z**, since final states with W bosons would suffer from large top-induced backgrounds, therefore would require a real experimental analysis

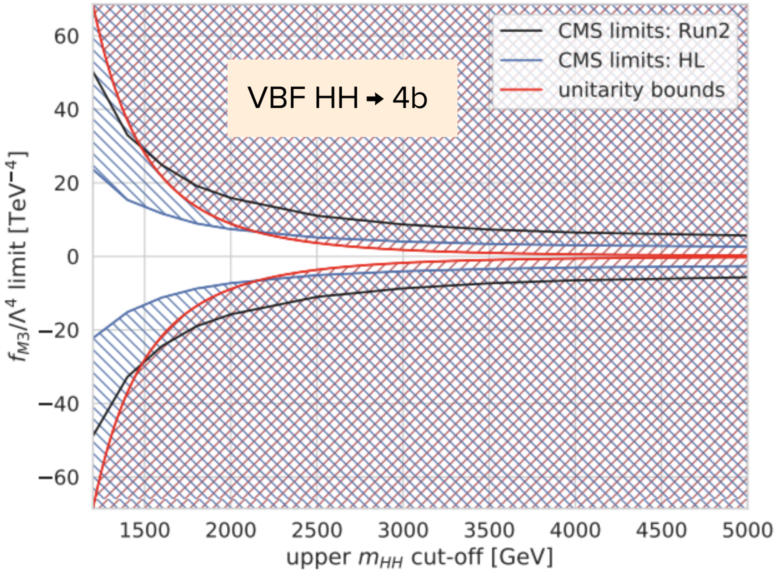
1. **gg → ZZH**
   - Considering EFT effects with similar size as those induced in VBS and VBF HH, cross-sections would be too small, even at HL-LHC
2. **qqbar → ZHH**
   - Perform a simplified analysis
     - Assume only one physical SM background (Z + 4 b-jets)
     - Enhance signal by requiring m_{bb} close to m_H for candidate b-jet pairs
     - Estimate : $\sigma[m_{min}, m_{max}]$ for signal+EFT and background
     - Compute S and B with LHC Run2 luminosity, and limits with a Feldman-Cousins approach
   - Sensitivity smaller than other final states

	$ZHH \to \ell^+\ell^- b\bar{b}b\bar{b}$
Coeff.	no unitarity
f_{M0}/Λ^4	[−8.4,8.7]
f_{M1}/Λ^4	[−15,15]
f_{M2}/Λ^4	[−12,12]
f_{M3}/Λ^4	[−20,20]
f_{M4}/Λ^4	[−20,21]
f_{M5}/Λ^4	[−18,18]
f_{M7}/Λ^4	[−29,30]
f_{S0}/Λ^4	[−210,200]
f_{S1}/Λ^4	[−350,380]
f_{S2}/Λ^4	[−350,380]

Perspectives for HL-LHC

- Assume that at high-mass statistical uncertainties dominate in experiments
- Limits w/o unitarity bounds obtained by rescaling the excluded σ by $L^{-1/2}$ (L = 3 ab^{-1})
  - ➜ limit improvement very mild (scales roughly as $L^{-1/4}$)
- Limits w/ unitarity bounds present significant additional gain since m_{max} moves to larger values, **allowing inclusion of higher-mass data in the analysis**
  - ➜ limits improve by a factor up to 4-5

	VBS $W^{\pm}V$ semileptonic		VBF HH→ $b\bar{b}b\bar{b}$	
Coeff.	no unitarity	w/ unitarity	no unitarity	w/ unitarity
f_{M0}/Λ^4	[-0.47,0.47]	[-0.96,1.02]	[-0.43,0.43]	[-0.90,0.87]
f_{M1}/Λ^4	[-1.5,1.5]	[-2.3,2.4]	[-1.7,1.7]	[-3.5,3.5]
f_{M2}/Λ^4	[-0.69,0.68]	[-2.1,2.1]	[-0.62,0.61]	[-1.7,1.7]
f_{M3}/Λ^4	[-2.5,2.4]	[-6.8,6.3]	[-2.4,2.4]	[-6.5,6.6]
f_{M4}/Λ^4	[-1.4,1.4]	[-2.4,2.5]	[-1.8,1.8]	[-3.9,4.0]
f_{M5}/Λ^4	[-2.0,2.0]	[-3.0,3.1]	[-3.2,3.2]	[-6.9,7.0]
f_{M7}/Λ^4	[-2.4,2.4]	[-3.5,3.5]	[-3.5,3.5]	[-7.1,7.1]
f_{S0}/Λ^4	[-1.8,2.0]	[-2.6,3.3]	[-14,13]	/
f_{S1}/Λ^4	[-2.4,2.4]	[-5.8,6.1]	[-5.1,4.5]	/
f_{S2}/Λ^4	[-2.3,2.4]	[-4.8,5.2]	[-8.1,7.1]	/



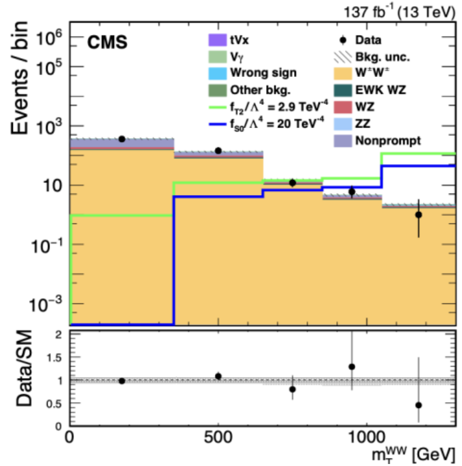
Conclusions

- Sensitivity of LHC processes involving rare VVHH interactions to BSM effects
  - Specific operators in a dimension-8 EFT extension of the SM are chosen, which introduce modifications to VVHH (and VVVV) vertices, without altering the better-constrained VVH and VVV interactions
- Examined current (up to 2020) **experimental results by the CMS Collaboration**
  - In spite of a much smaller SM cross-section, constraints from vector-boson fusion Higgs-pair production (VBF HH) on those operators are already comparable with or more stringent than those quoted in vector-boson-scattering (VBS) final states
- **We suggest a final-state-independent and experimentally-reproducible method to take into account unitarity bounds**
  - Constraints on Wilson coefficients weaken very significantly (in some cases become irrelevant)
- We investigated the potential of new experimental final states, such as ZHH associated production and we **show perspectives for the high-luminosity phase of the LHC**.

Backup

Unitarity bounds - in CMS

- Non-homogeneous treatment among different analyses (not considered, bound only quoted a posteriori...)
- VBS ssWW and WZ: limits on aQGCs cited with and w/o unitarity bounds
    - "(Partial) clipping method" on signal samples ➜ the simulated aQGC distribution was clipped at the unitarity limits ($\Lambda = \sqrt{s}^U$) and replaced with SM above Λ_{max} , with a smoothing form-factor
    - Tool used for unitarity limits: VBFNLO



	Observed (W$^\pm$W$^\pm$) (TeV^{-4})	Expected (W$^\pm$W$^\pm$) (TeV^{-4})	Observed (WZ) (TeV^{-4})	Expected (WZ) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{T0}/Λ^4	[-0.28, 0.31]	[-0.36, 0.39]	[-0.62, 0.65]	[-0.82, 0.85]	[-0.25, 0.28]	[-0.35, 0.37]
f_{T1}/Λ^4	[-0.12, 0.15]	[-0.16, 0.19]	[-0.37, 0.41]	[-0.49, 0.55]	[-0.12, 0.14]	[-0.16, 0.19]
f_{T2}/Λ^4	[-0.38, 0.50]	[-0.50, 0.63]	[-1.0 , 1.3]	[-1.4, 1.7]	[-0.35, 0.48]	[-0.49, 0.63]
f_{M0}/Λ^4	[-3.0, 3.2]	[-3.7, 3.8]	[-5.8, 5.8]	[-7.6, 7.6]	[-2.7, 2.9]	[-3.6, 3.7]
f_{M1}/Λ^4	[-4.7, 4.7]	[-5.4, 5.8]	[-8.2, 8.3]	[-11, 11]	[-4.1, 4.2]	[-5.2, 5.5]
f_{M6}/Λ^4	[-6.0, 6.5]	[-7.5, 7.6]	[-12, 12]	[-15, 15]	[-5.4, 5.8]	[-7.2, 7.3]
f_{M7}/Λ^4	[-6.7, 7.0]	[-8.3, 8.1]	[-10, 10]	[-14, 14]	[-5.7, 6.0]	[-7.8, 7.6]
f_{S0}/Λ^4	[-6.0, 6.4]	[-6.0, 6.2]	[-19, 19]	[-24, 24]	[-5.7, 6.1]	[-5.9, 6.2]
f_{S1}/Λ^4	[-18, 19]	[-18, 19]	[-30, 30]	[-38, 39]	[-16, 17]	[-18, 18]

↓ Same limits, but cutting on unitarity violating phase space

	Observed (W$^\pm$W$^\pm$) (TeV^{-4})	Expected (W$^\pm$W$^\pm$) (TeV^{-4})	Observed (WZ) (TeV^{-4})	Expected (WZ) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{T0}/Λ^4	[-1.5, 2.3]	[-2.1, 2.7]	[-1.6, 1.9]	[-2.0, 2.2]	[-1.1, 1.6]	[-1.6, 2.0]
f_{T1}/Λ^4	[-0.81, 1.2]	[-0.98, 1.4]	[-1.3, 1.5]	[-1.6, 1.8]	[-0.69, 0.97]	[-0.94, 1.3]
f_{T2}/Λ^4	[-2.1, 4.4]	[-2.7, 5.3]	[-2.7, 3.4]	[-4.4, 5.5]	[-1.6, 3.1]	[-2.3, 3.8]
f_{M0}/Λ^4	[-13, 16]	[-19, 18]	[-16, 16]	[-19, 19]	[-11, 12]	[-15, 15]
f_{M1}/Λ^4	[-20, 19]	[-22, 25]	[-19, 20]	[-23, 24]	[-15, 14]	[-18, 20]
f_{M6}/Λ^4	[-27, 32]	[-37, 37]	[-34, 33]	[-39, 39]	[-22, 25]	[-31, 30]
f_{M7}/Λ^4	[-22, 24]	[-27, 25]	[-22, 22]	[-28, 28]	[-16, 18]	[-22, 21]
f_{S0}/Λ^4	[-35, 36]	[-31, 31]	[-83, 85]	[-88, 91]	[-34, 35]	[-31, 31]
f_{S1}/Λ^4	[-100, 120]	[-100, 110]	[-110, 110]	[-120, 130]	[-86, 99]	[-91, 97]

Events violating unitarity are rejected ~ 80% (WW) & 50% (WZ)

VBFNLO utility to calculate form factors, version 1.4.0:

This program belongs to the program package VBFNLO and can calculate input parameters needed for anomalous gauge boson coupling studies with VBFNLO.
As especially the pure operators for anomalous quartic gauge boson couplings lead to a violation of tree-level unitarity within the energy range of the LHC, special care has to be taken to avoid this unphysical behaviour. Within VBFNLO we have opted for the use of a dipole form factor and this tool can calculate the maximal form factor scale Lambda_FF which is allowed for a given input of coupling parameters, assuming the form factor shape

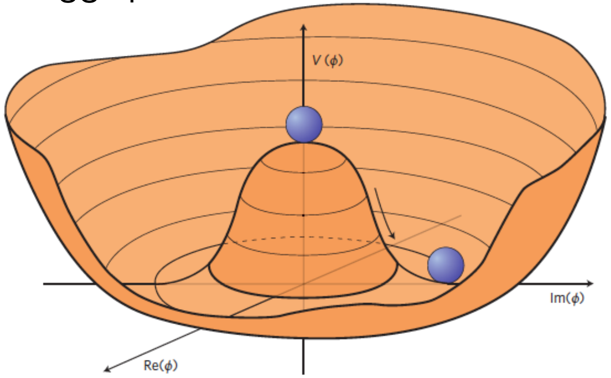
$$FF = \frac{1}{(1 + \frac{s}{\Lambda_{FF}^2})^{FFexp}}$$

The form factor is determined by calculating on-shell VV scattering and computing the zeroth partial wave of the amplitude. As unitarity criterion the absolute value of the real part of the zeroth partial wave has to be below 0.5 [1].

HH production

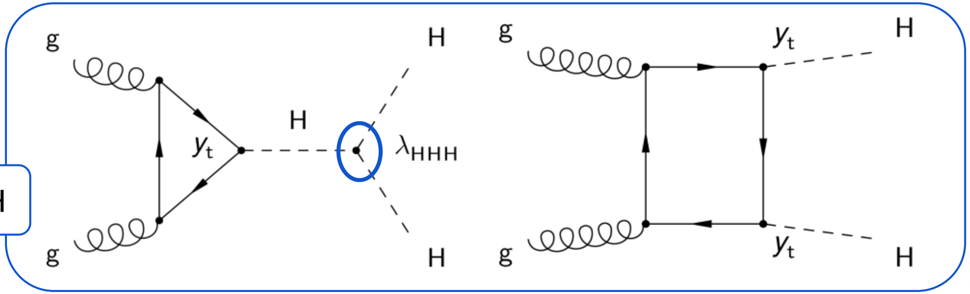
- HH production can be used to directly study Higgs boson self-coupling and Higgs potential
- At CERN LHC mainly produced through gluon fusion via fermion loop
- In SM destructive interference of triangle and box contributions
  ➔ Tiny cross section (31.05 fb) ➔ Experimentally very challenging

arXiv:1312.5672



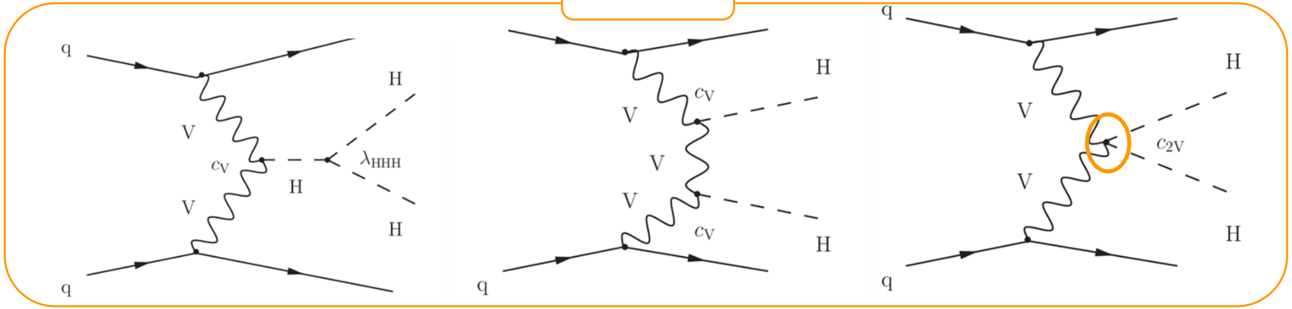
$$V\left(\phi^{\dagger}\phi\right) = \mu^2\phi^{\dagger}\phi + \lambda\left(\phi^{\dagger}\phi\right)^2$$

gg HH



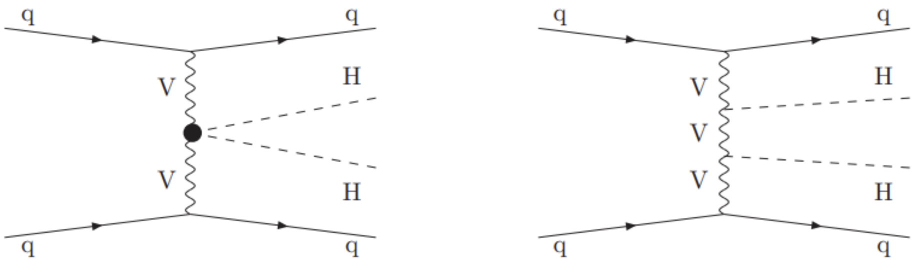
- With full Run2, possible to target also vector boson fusion production mode (1.72 fb)
  ➔ **sensitive to VVHH coupling**

VBF HH

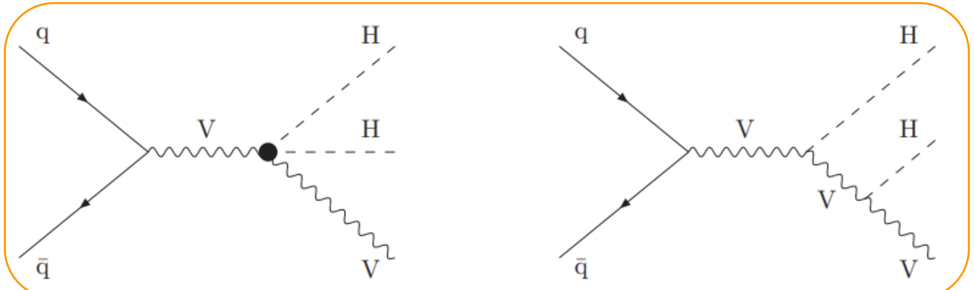


Processes Studied

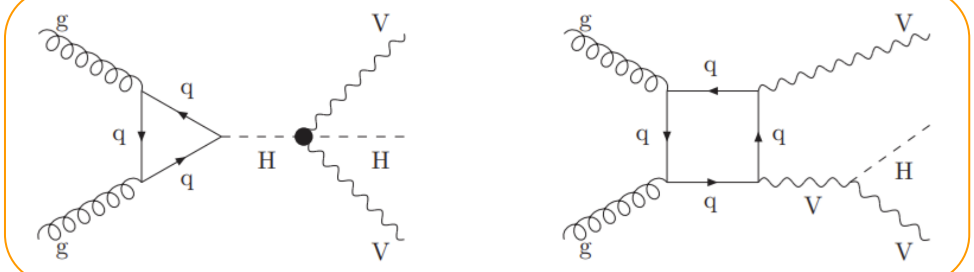
VBF-HH



ZHH

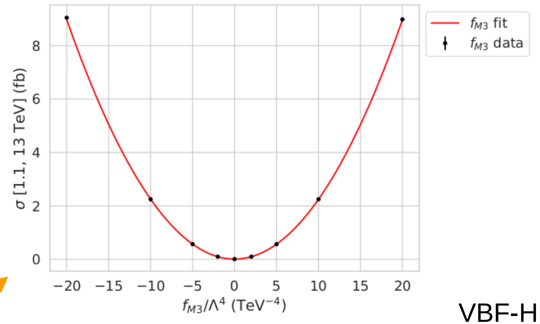


gg→ZZH

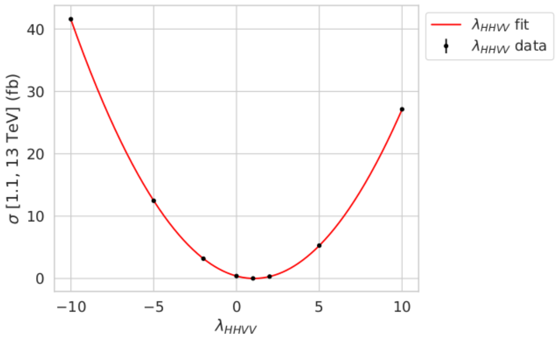


Simulation setup details

- Generator: **MadGraph5_aMC@NLO v2.7.3**
- Processes:
  - VBF-HH, ZHH, gg→ZZH,
  - VBS ($W^\pm W^\pm$ VBS, $W^\pm Z$ VBS, W^+W^- VBS) (for validation)
  - Zbbbb (main background for ZHH)
- **Wilson coefficients variations** f_x/Λ^4 = {0, ±2, ±5, ±10, ±20} TeV^{-4}
- for VBF-HH, also $\mathbf{k_{2V}}$ **variations** (k_{2V} = {0, 1, ±2, ±5, ±10})



VBF-HH



- Typical experimental selection applied on VBS and VBF processes
- Since EFT sensitive region at high energy
  - no parton shower applied
  - no selection applied to decay product of H and gauge bosons (exception for ZHH and Zbbbb processes, simple analysis performed)

Observable and Processes

- Observable used to estimate the EFT sensitivity:
  - $\sigma[m_{min}, m_{max}]$ (cross section in mass interval)
  - m = invariant mass of the di- or tri- boson states produced
  - m_{min} = 1.1TeV, $m_{max} = \sqrt{s}$

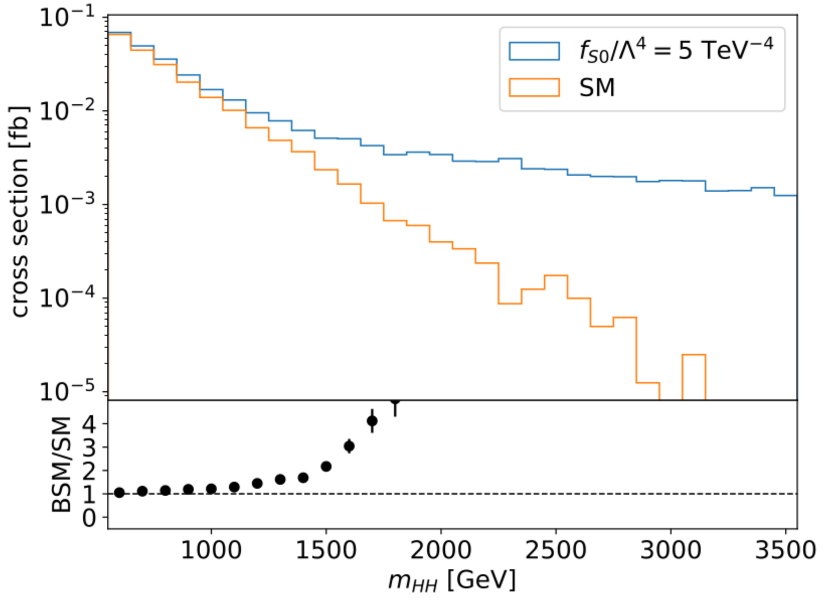
Cuts:

- For VBS and VBF processes
  - $p_T(j) > 40$ GeV
  - $m_{jj} > 500$ GeV
  - $|\eta(j)| < 4.7$
  - $|\Delta\eta_{jj}| > 2.5$
- For Zbbbb:
  - $115 < m_{bb} < 135$ GeV

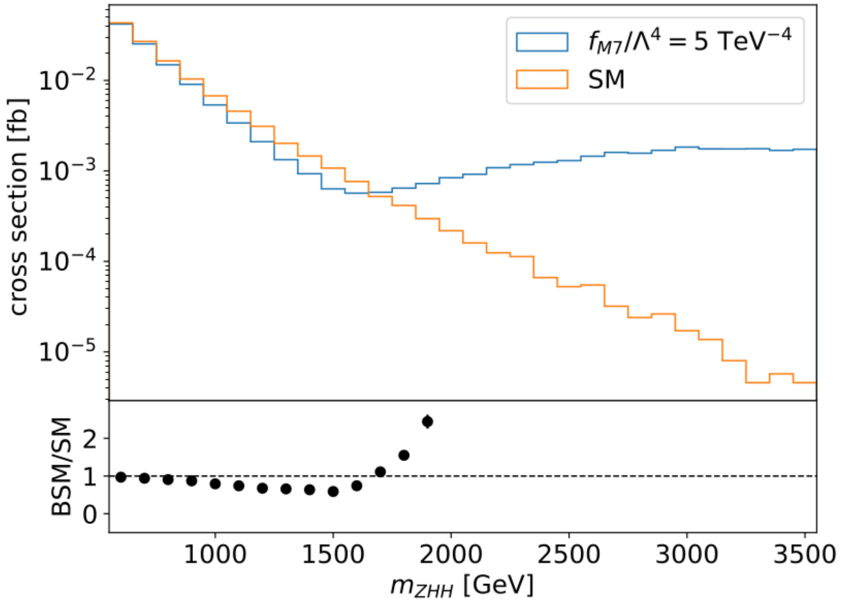
Process number	MadGraph5_aMC@NLO syntax	QCD order	Max. jet flav.	CMS result	$\overline{\sigma}[1.1, 13\ \text{TeV}]$ SM (fb)
Signal (including EFT effects)					
1	`p p > w+ w+ j j QCD=0` `p p > w- w- j j QCD=0`	LO	4	[27, 28]	4.514(9)
2	`p p > w+ z j j QCD=0` `p p > w- z j j QCD=0`	LO	4	[27, 28]	8.55(2)
3	`p p > w+ w- j j QCD=0`	LO	4	[28]	9.97(2)
4	`p p > h h j j QCD=0`	LO	5	[35]	0.0329(7)
5	`p p > z h h QED=3`	LO	5	-	0.01295(5)
6	`g g > z z h [noborn=QCD]`	LI (LO)	5	-	$3.493(7) \times 10^{-3}$
Background (SM only)					
7	`p p > z b b~ b b~`	LO	4	-	0.729(3)

EFT Modifications to Mass Distributions

VBF-HH

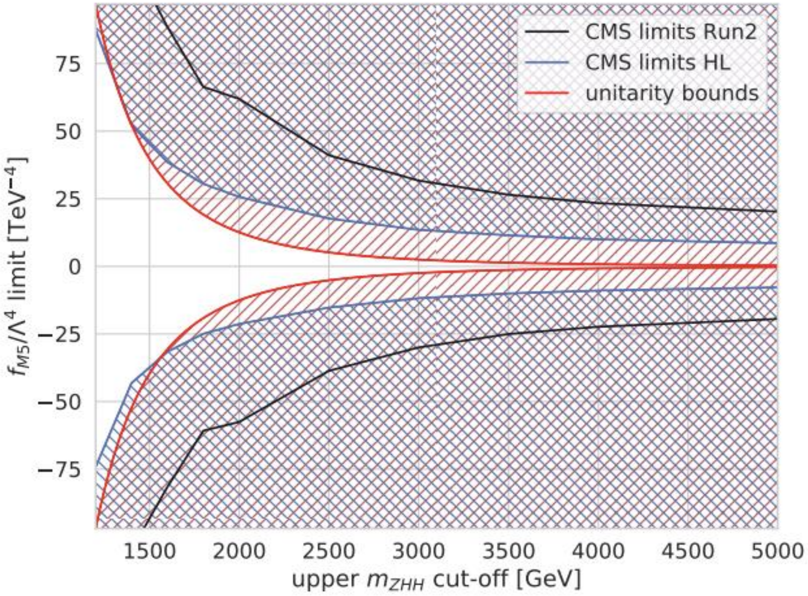


ZHH



Perspectives for HL-LHC: ZHH

- Exclusion limit on σ recomputed for L = 3 ab^{-1}, 13 TeV
- Possible to **set limits w/ unitarity** requirements **on some M-type operators**
- For future analyses: important to develop strategies to enhance signal w.r.t. bkg



	ZHH→ $\ell^+\ell^-$ $b\bar{b}b\bar{b}$	
Coeff.	no unitarity	w/ unitarity
f_{M0}/Λ^4	[-3.4,3.7]	/
f_{M1}/Λ^4	[-6.4,5.9]	[-66,31]
f_{M2}/Λ^4	[-4.7,4.8]	/
f_{M3}/Λ^4	[-8.4,8.2]	/
f_{M4}/Λ^4	[-8.2,8.9]	/
f_{M5}/Λ^4	[-7.1,7.7]	[-34,52]
f_{M7}/Λ^4	[-12,13]	[-91,160]
f_{S0}/Λ^4	[-90,83]	/
f_{S1}/Λ^4	[-140,160]	/
f_{S2}/Λ^4	[-140,160]	/