Sensitivity to New Physics in final states with multiple gauge and Higgs bosons

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Final states with multiple gauge and Higgs bosons

- Final states suitable to investigate **VVHH interactions**
- Quartic couplings usually investigated in VBS or triboson processes
- But also final states with H bosons are useful → HH production!

In this work:

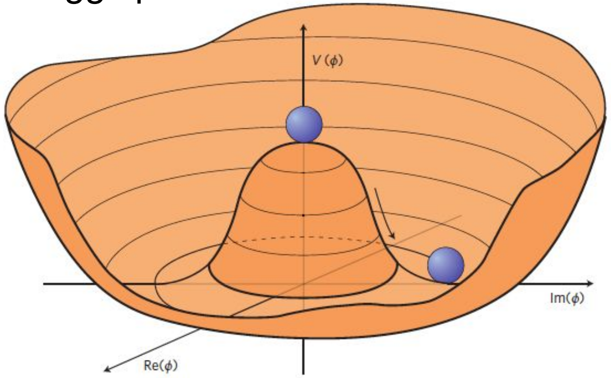
- Reinterpret HH experimental results in terms of **dim-8 EFT operators**, sensitive to VVHH interactions
- **Unitarity constraints** considered
  - dedicated technique adopted
  - mass-dependent constraints set

Results published in JHEP09(2022)038

HH PRODUCTION

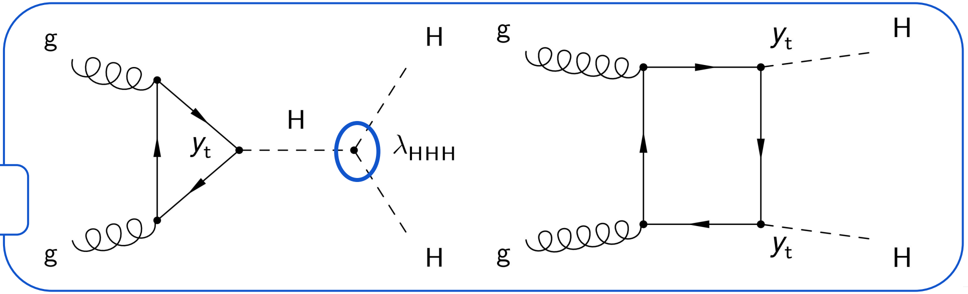
arXiv:1312.5672

- 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



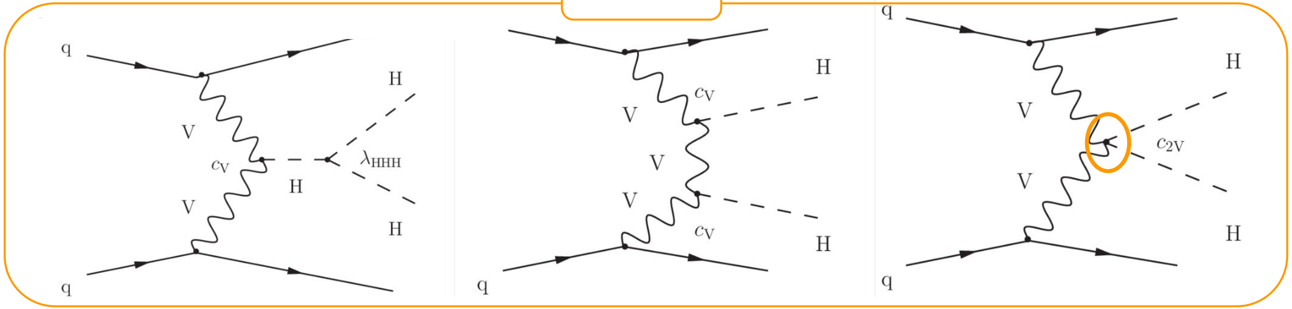
$$V\left(\phi^\dagger\phi\right) = \mu^2\phi^\dagger\phi + \lambda\left(\phi^\dagger\phi\right)^2$$

ggHH



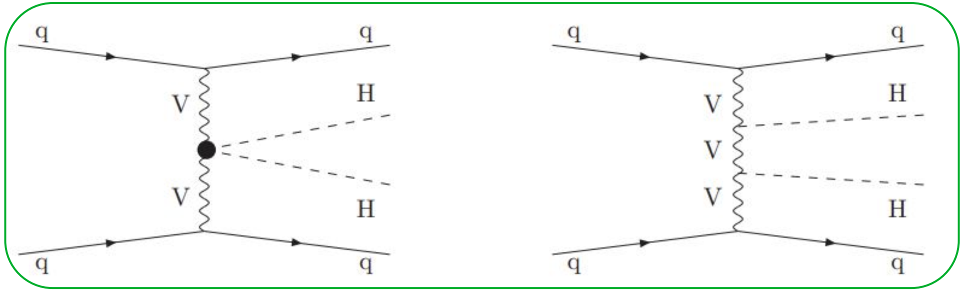
- With full Run2, possible to target also vector boson fusion production mode (1.72 fb)
  → **sensitive to VVHH coupling**

VBFHH

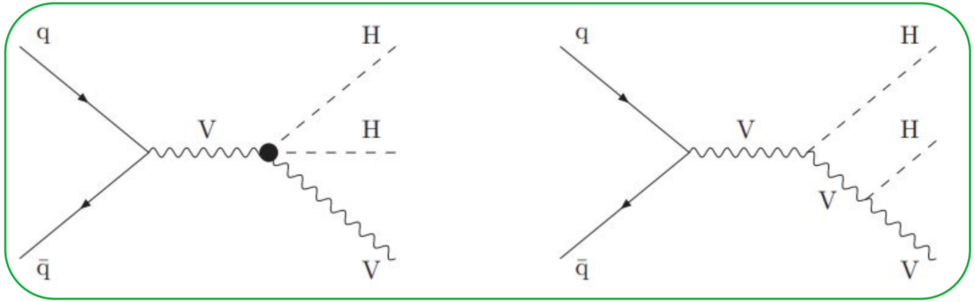


Processes Studied

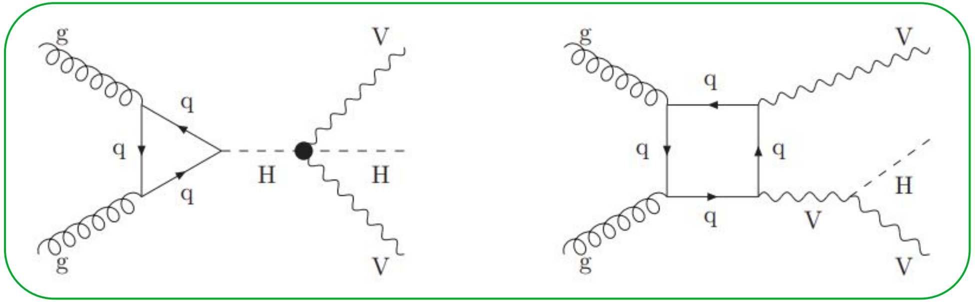
VBF-HH



ZHH

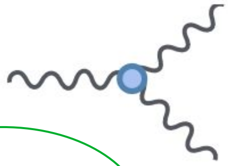


gg→ZZH

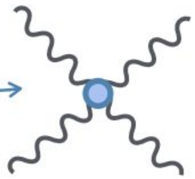


EFT framework

Triple gauge couplings



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



Quartic gauge couplings

- Complete operator basis considered:

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

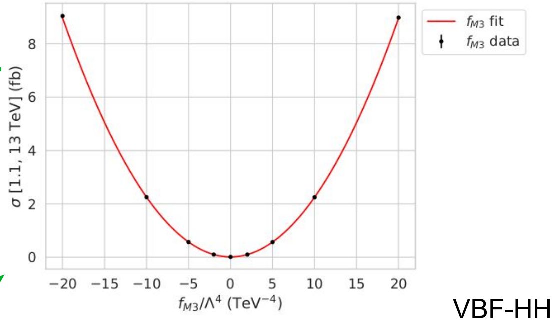
Scalar

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

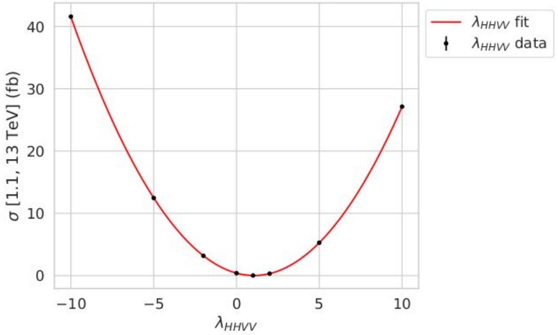
Mixed

Simulation Setup

- 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:
  - **σ[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} = $\sqrt{s}$

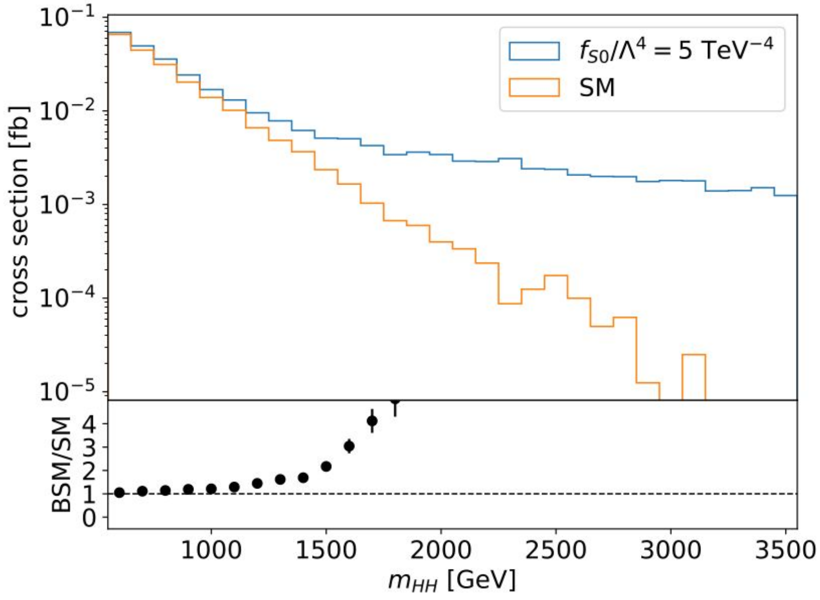
Cuts:

- 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

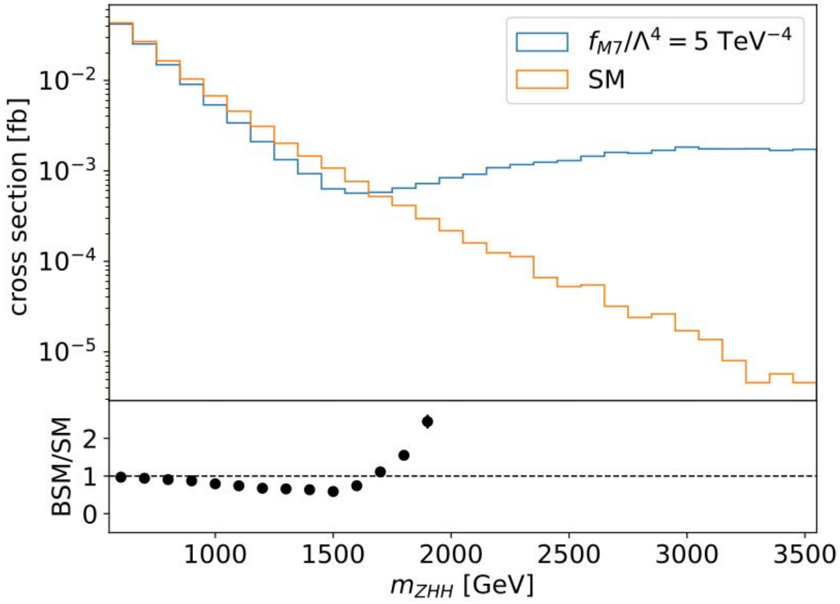
Process number	MadGraph5_aMC@NLO syntax	QCD order	Max. jet flav.	CMS result	$\overline{\sigma}$[1.1, 13 TeV] SM (fb)
Signal (including EFT effects)					
1	p p > w+ w+ j j QCD=0 p p > w- w- j j QCD=0	LO	4	[27, 28]	4.514(9)
2	p p > w+ z j j QCD=0 p p > w- z j j QCD=0	LO	4	[27, 28]	8.55(2)
3	p p > w+ w- 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



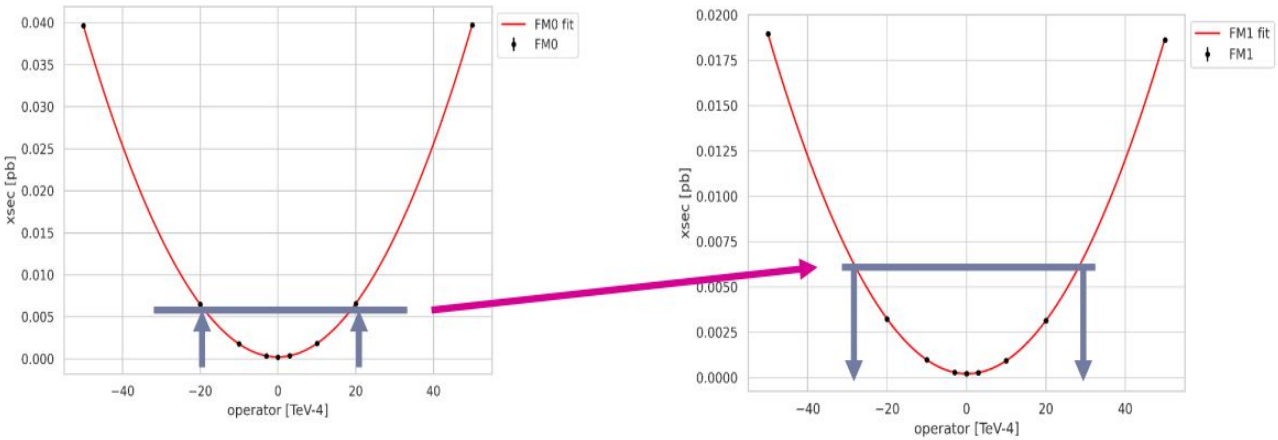
ZHH



Validation on VBS

- Try to reproduce CMS results
- At first without unitarity regularization, since most CMS result don't have it
- σ values computed for each process, then multiplied by BR of gauge or H boson involved to obtain value in dedicated final state
- σ computed as function of f_x/Λ^4, and quadratic fits performed

1. Take experimental limit on one operator from CMS publication
2. Extrapolate 95% CL exclusion limit on σ, superimposing on the parabola the limit on the operator
3. From this, derive limits on all other operators
4. Compare obtained limits with the published ones
5. Steps 1-4 repeated for different choices of initial input



Validation on VBS - Results

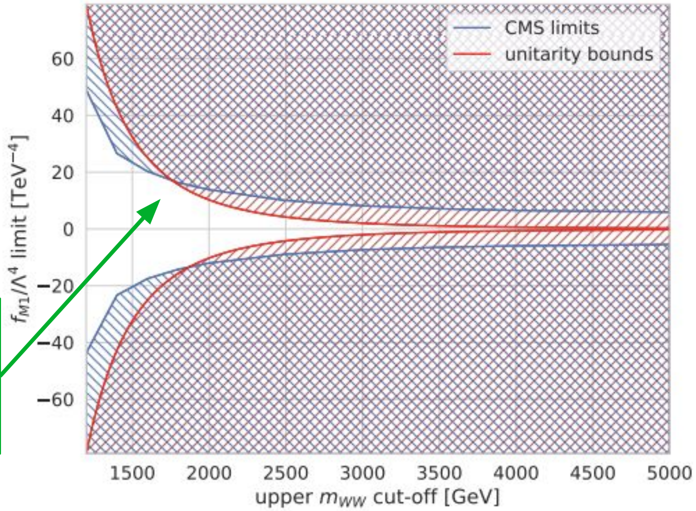
- CMS results incomplete, several operators not examined
- **Validation successful**: manage to reproduce results (apart from WV semileptonic for S0-2 operators, where we keep CMS results)

	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 in VBS

1. Evaluate $\sigma[m_{min}, m_{max}]$ for several m_{max}
2. For each σ, obtain m_{max}-dependent limits on operator coefficients with same procedure used for validation
3. Since only part of experimental data fall into $[m_{min}, m_{max}]$, limits on σ obtained at step 2 are rescaled in each test, assuming poissonian errors

VBS $W^{\pm}W^{\pm} \to 2l2\nu$



intersection: max m to set limits not violating unitarity

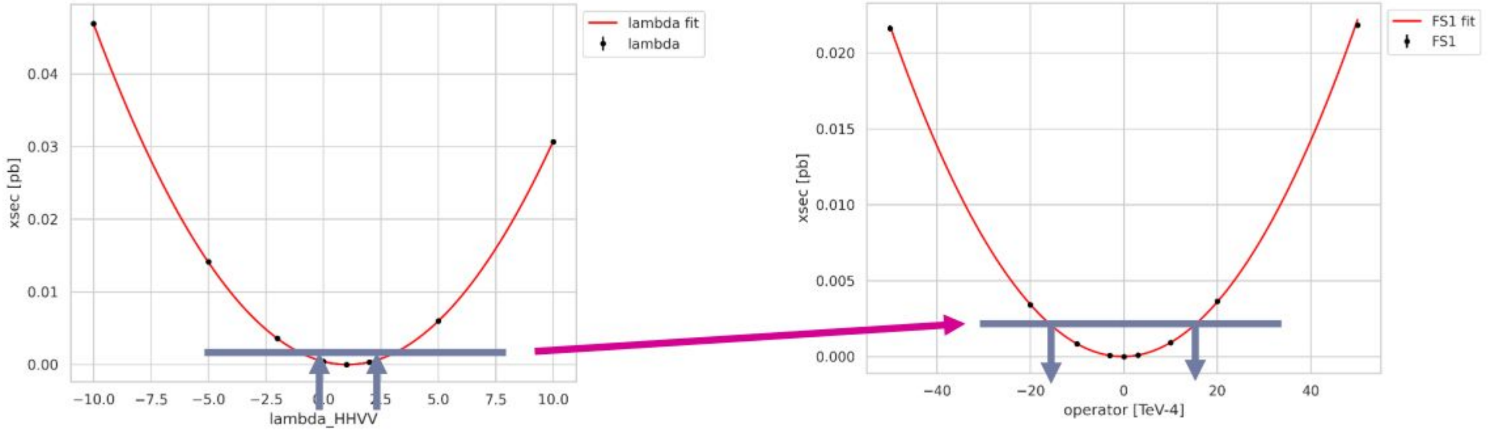
Coeff.	VBS $W^{\pm}W^{\pm}$	VBS $W^{\pm}Z$	VBS $W^{\pm}V$ semilep.
f_{M0}/Λ^4	/	/	[-3.3,3.5]
f_{M1}/Λ^4	[-13,17]	[-67,71]	[-7.4,7.6]
f_{M2}/Λ^4	/	/	[-9.1,9.0]
f_{M3}/Λ^4	/	/	[-32,30]
f_{M4}/Λ^4	/	[-36,36]	[-8.6,8.7]
f_{M5}/Λ^4	/	[-29,29]	[-10,10]
f_{M7}/Λ^4	[-21,18]	[-59,57]	[-11,11]
f_{S0}/Λ^4	[-17,20]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

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

VBF-HH process

Similar to VBS, but experimental results in terms of k_{2V}

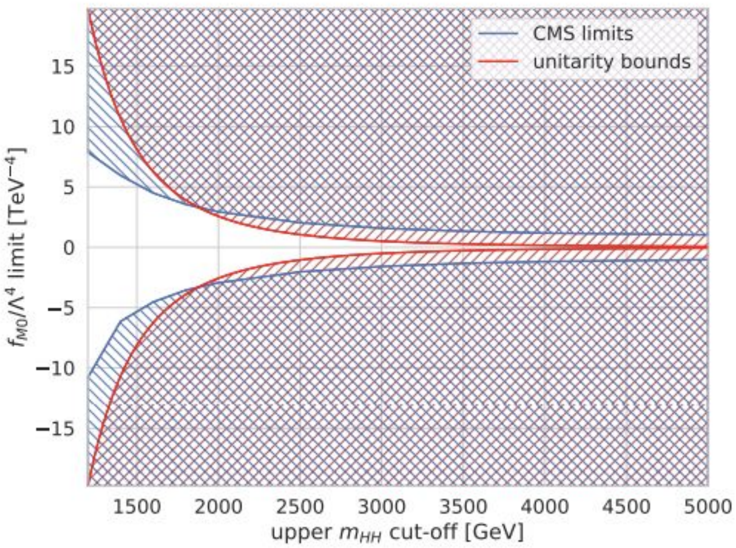
1. Consider public HH→4b 95% CL limit on k_{2V}
2. Use the VBF-HH simulation as function of k_{2V} to set limit on the parabola and obtain limit on σ
3. From limit on σ, extract limits on corresponding coefficient
4. Validation: use limits on f_x as input and re-produce CMS limits on k_{2V}



VBF-HH Results

- **VBF-HH** estimated limits **supersede** those obtained with VBS for f_{M0}, f_{M2}, f_{M3}
- Unitarity boundaries added as described for VBS

	VBS $W^{\pm}V$ semileptonic		VBF HH$\rightarrow b\bar{b}b\bar{b}$	
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]	/



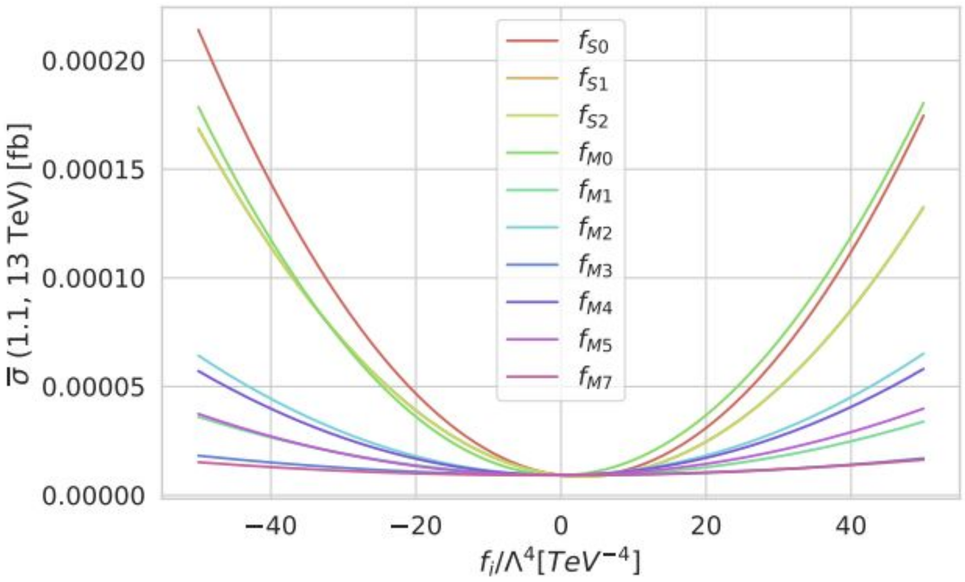
New experimental final states: ZHH

- Perform simple analysis
- Estimate the number of detectable events: $N = \sigma \cdot L \cdot \varepsilon \cdot A$
  - $H \to bb$ and $Z \to ll$ ($l = e, \mu$) considered
  - Acceptance (A) requirements, typical LHC requirements:
    - $p_T(b) > 30$ GeV, $p_T(e, \mu) > 20$ GeV
    - $|\eta(b)| < 2.5$, $|\eta(e, \mu)| < 2.4$
  - Efficiency (ε) for identification and selection taken from experimental papers
- Zbbbb bkg process simulated with $115 < m_{bb} < 135$ GeV
- Estimate upper limits on σ with Feldman-Cousins
- Similar procedure as before to estimate limits on Wilson coefficients
- With Run2 luminosity (L = 140 fb^{-1}) no limits w/ unitarity

	$ZHH \to \ell^+\ell^- b\bar{b}b\bar{b}$
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]

New experimental final states: gg→ZZH

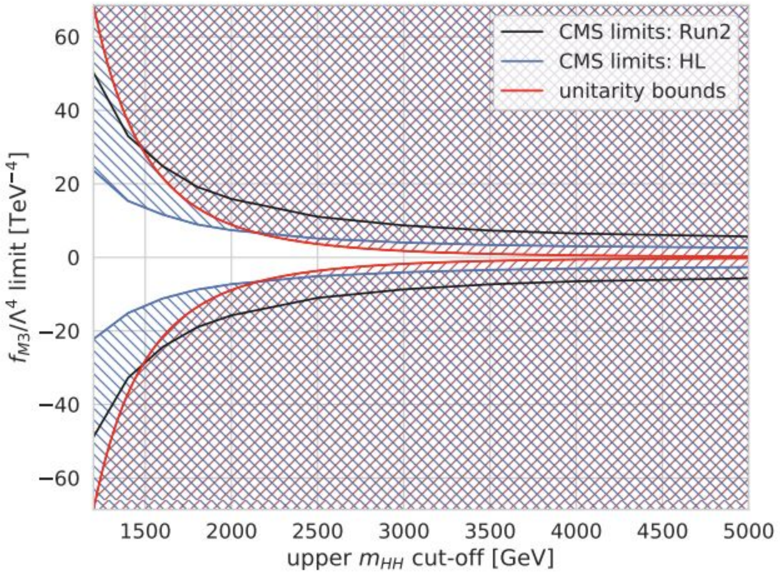
- Loop Induced process
- Very low σ
- H→bb and Z→ll (l=e,μ) considered
- Even with large variations of Wilson coefficients σ remains small → process **not sensitive enough** to be investigated at LHC
- However, it demonstrates that is **possible to simulate the process with new NLO UFO model** constructed including dim-8 operators



Perspectives for HL-LHC: VBF-HH

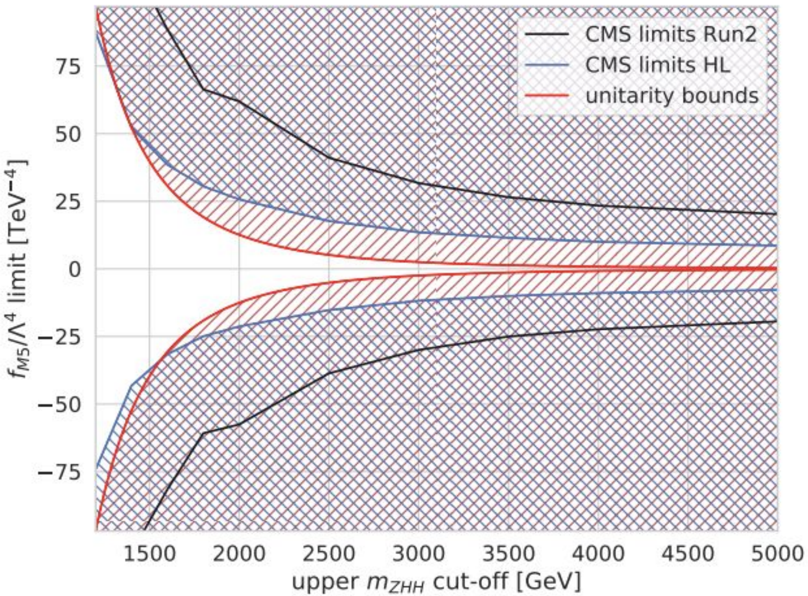
- Limits w/o unitarity obtained rescaling the excluded σ by $L^{-½}$ (L = 3 ab^{-1}, 13 TeV)
- Limits w/ unitarity present significant gain more since m_{max} moves to larger values, allowing inclusion of more data in the sensitivity estimate
  → **limits improve by factor 4-5**
  → **first physical limit on f_{S1}**

	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]	/



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]	/

Conclusions

- Studied sensitivity to BSM effects in **VVHH interactions** → dim-8 operators
- Processes considered in this study: VBF-HH, ZHH, gg→ZZH

- **VBF-HH can set limits comparable or even more stringent than those from VBS** on coefficients of dim-8 EFT operators
- ZHH and gg→ZZH have more limited constraining power

- **Unitarity constraints** considered
  - dedicated technique adopted to apply constraints consistently
  - limits weakened by unitarity request, but **VBF-HH limits equally competitive with VBS** ones **even w/ unitarity**
- **HL-LHC** projections considered
  → VBF-HH/VBS limits w/ unitarity can improve of 4-5 times w.r.t. Run2 (more than expected by simple luminosity scaling)
  →ZHH final state can contribute in a combined exclusion of some coefficients