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**

In this work:

- Reinterpret HH experimental results in terms of **dim-8 EFT operators**
- Focus on **genuine** SMEFT anomalous quartic operators
- **Unitarity constraints** considered
  - dedicated technique adopted
  - mass-dependent constraints set

Study published in JHEP09(2022)038

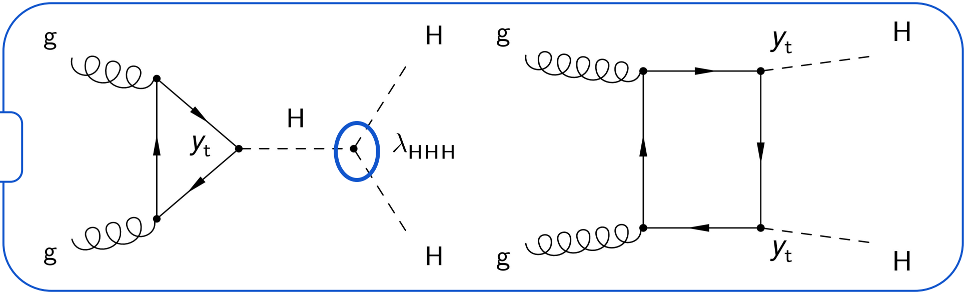
HH production (non-resonant)

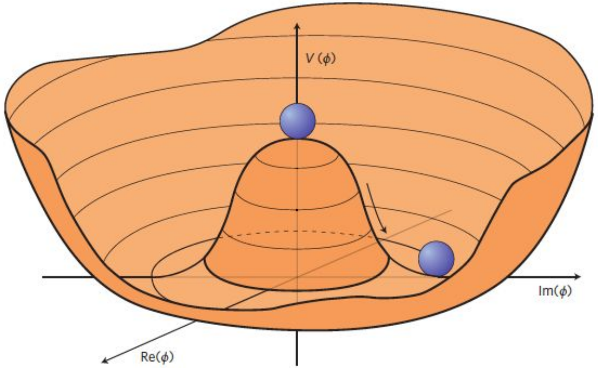
HH production can be used to directly study Higgs boson self-coupling and Higgs potential

arXiv:1312.5672

At LHC mainly produced through gluon fusion via fermion loop

ggHH





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

- In SM, amplitude from 2 contributions, **destructive interferenc**
  → Tiny cross-section, known with **high precision** (NNLO QCD)

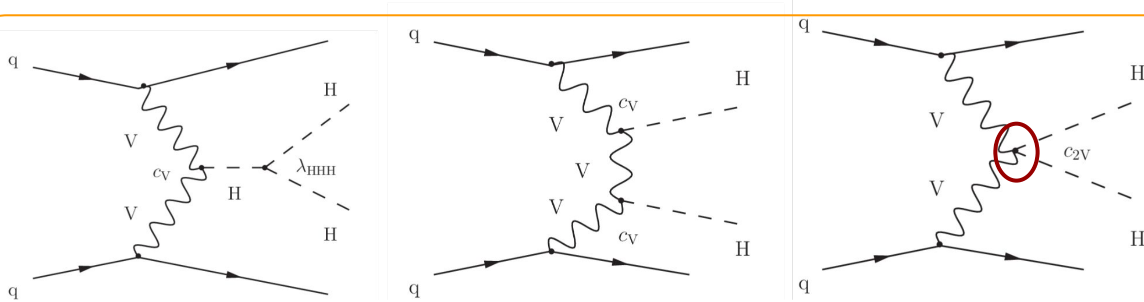
  $\sigma_{13\mathrm{TeV}} = 31.05^{+6\%}_{-23\%}$ fb (scale + m_t)

- Beyond SM, only **triangle diagram** sensitive to new physics in the Higgs potential (λ) (anomalous Yukawa **Htt** couplings would modify both)

VBFHH and VHH

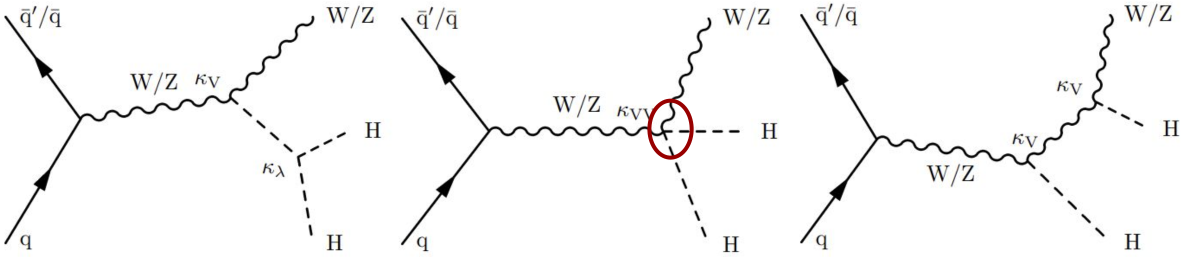
With full Run 2, possible to target also **subdominant** production modes: VBFHH, VHH

→ Diagrams also involve a different coupling: **VVHH**



VBFHH

σ_{13TeV} = 1.73 fb



VHH

σ_{13TeV} = 0.87 fb

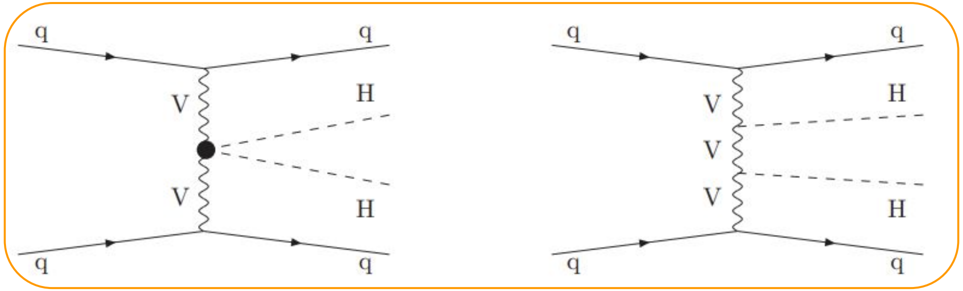
Exp. **observation very hard**, but small **modifications** to **VVHH** would lead to **big changes** in $\boldsymbol{\sigma}$

Processes Considered

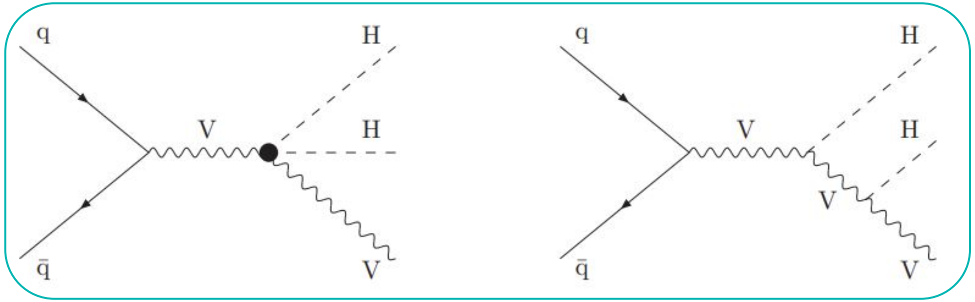
Typical lowest order diagrams for the processes considered

- with BSM contribution (left)
- without BSM (right)

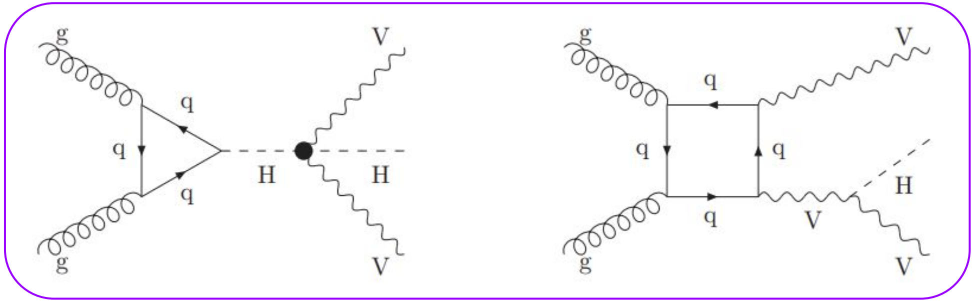
VBF-HH



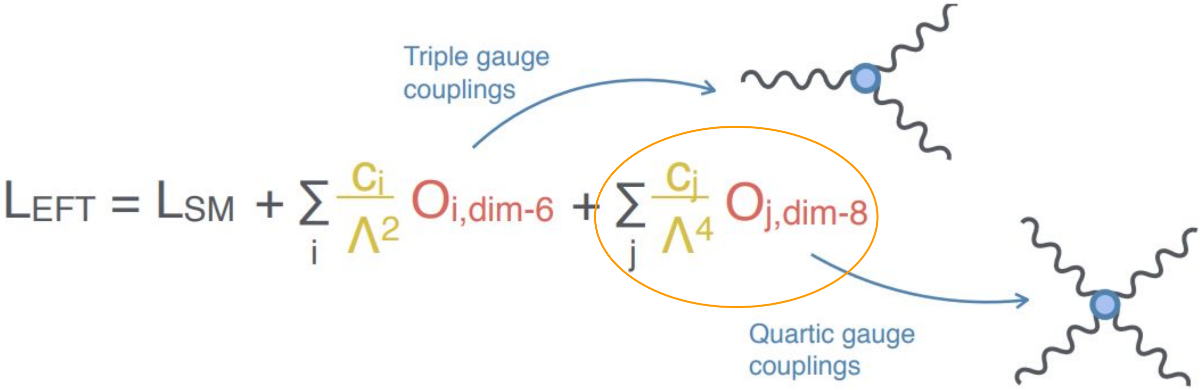
ZHH



gg→ZZH



EFT Framework



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

Triple gauge couplings

Quartic gauge couplings

- Complete operator basis considered:

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

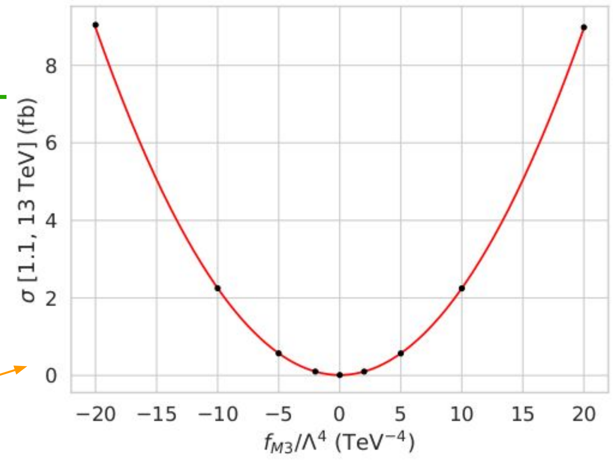
Scalar

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

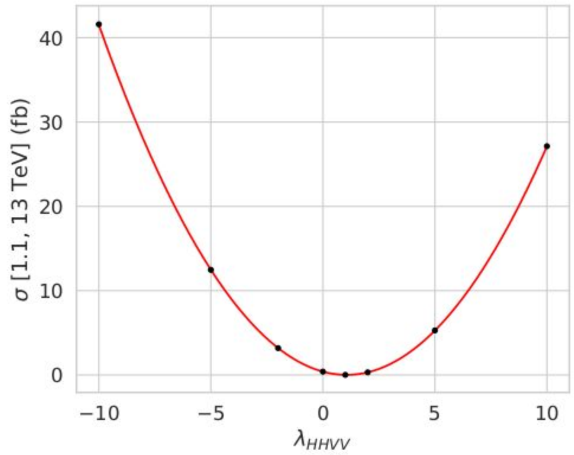
Mixed

Simulation Setup

- Generator: **MadGraph5_aMC@NLO v2.7.3**
- Processes:
    - VBF-HH, ZHH, gg→ZZH,
    - VBS ($W^\pm W^\pm$, $W^\pm Z$, W^+W^-) (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 **k_{2V} variations** (k_{2v} = {0, 1, ±2, ±5, ±10})



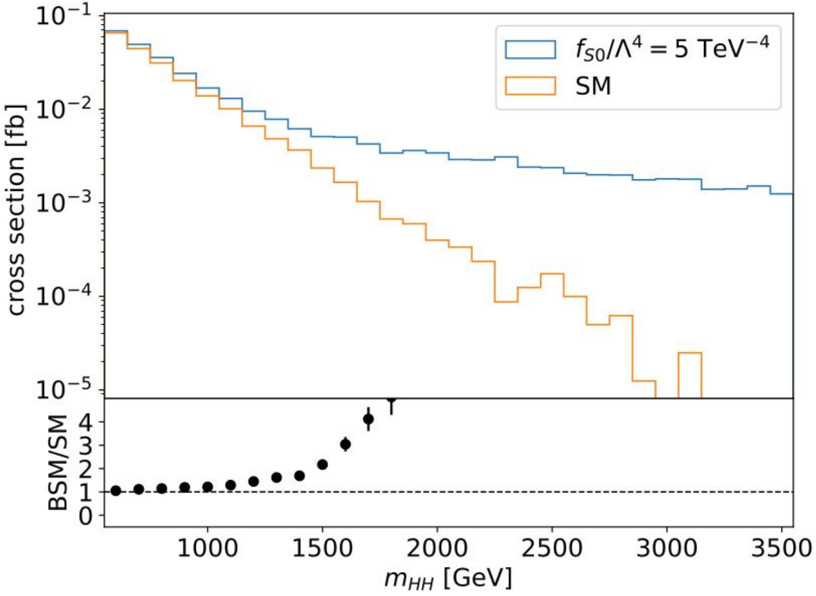
Observable used to estimate the EFT sensitivity:

- **$\sigma[m_{min}, m_{max}]$** (cross-section in mass interval)
  m = invariant mass of the di- or tri- boson states
  m_{min} = 1.1TeV

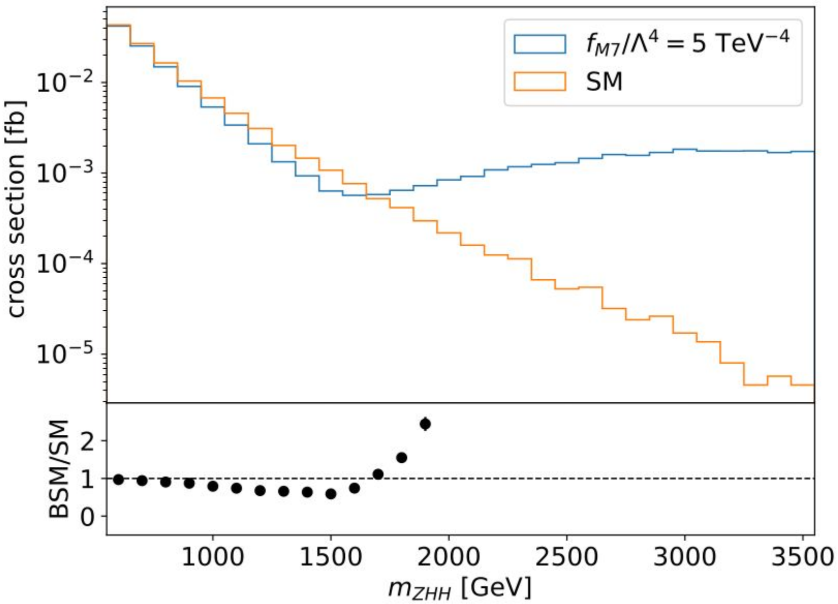
The effect of SMEFT

Quartic couplings modifications **distort the differential spectra**, primarily the invariant mass distribution → **enhanced rates** in the high energy **tails**

VBF-HH



ZHH



Methodology validation on VBS

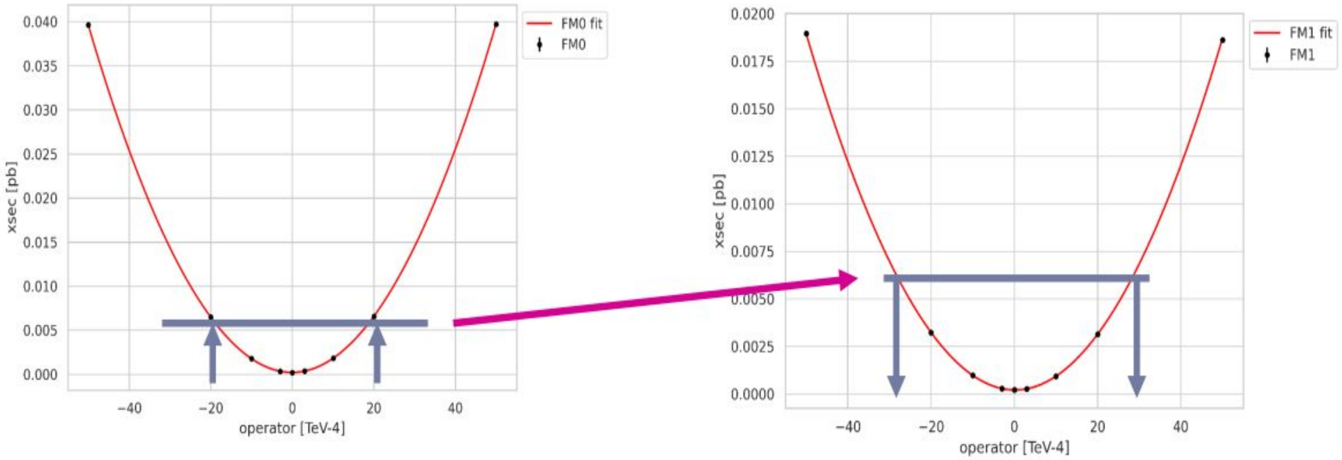
- Try to **reproduce CMS results**, for multiple processes
- σ computed as function of $f_x/\Lambda^4 \rightarrow$ quadratic fits performed

in this case, $m_{max}=\sqrt{s}$ (no upper bound on inv. mass)

1. Take experimental limit on one operator from CMS publication
2. Superimpose on the parabola the limit on the operator to extrapolate 95% CL exclusion limit on σ
3. Derive limits on all other operators
4. Compare obtained limits with the published ones

Steps repeated for different choices of initial input

Validation successful: managed to reproduce results from CMS ✅



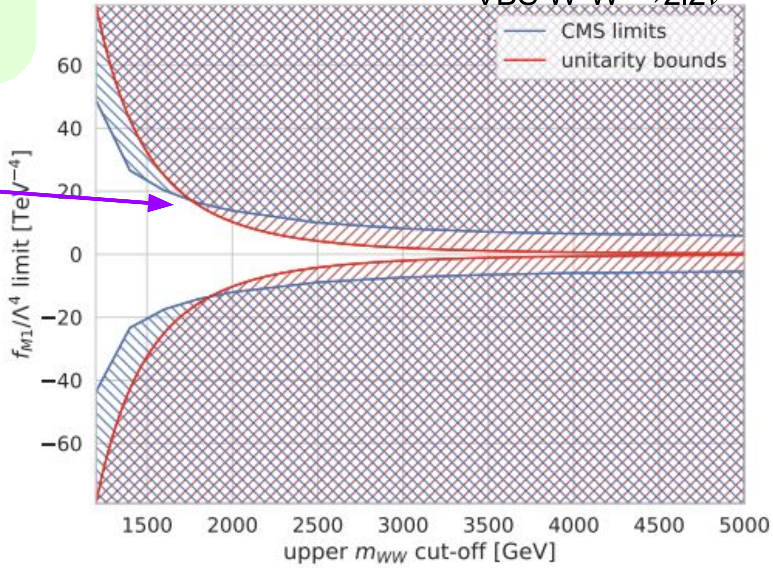
Implementation of unitarity in VBS

1. Evaluate **σ[m$_{min}$, m$_{max}$]** for several **m$_{max}$** (in exp analysis, would mean not to use data above m$_{max}$)
2. For each σ, obtain **m$_{max}$-dependent limits** on operator coefficients with same procedure used for validation (limits rescaled since only part of exp. data fall in [m$_{min}$, m$_{max}$])

m$_{max}$ → from m$_{min}$+100GeV to max kinematically allowed mass

Intersection: max m to set limits not violating unitarity

VBS W$^{\pm}$W$^{\pm}$→2l2ν



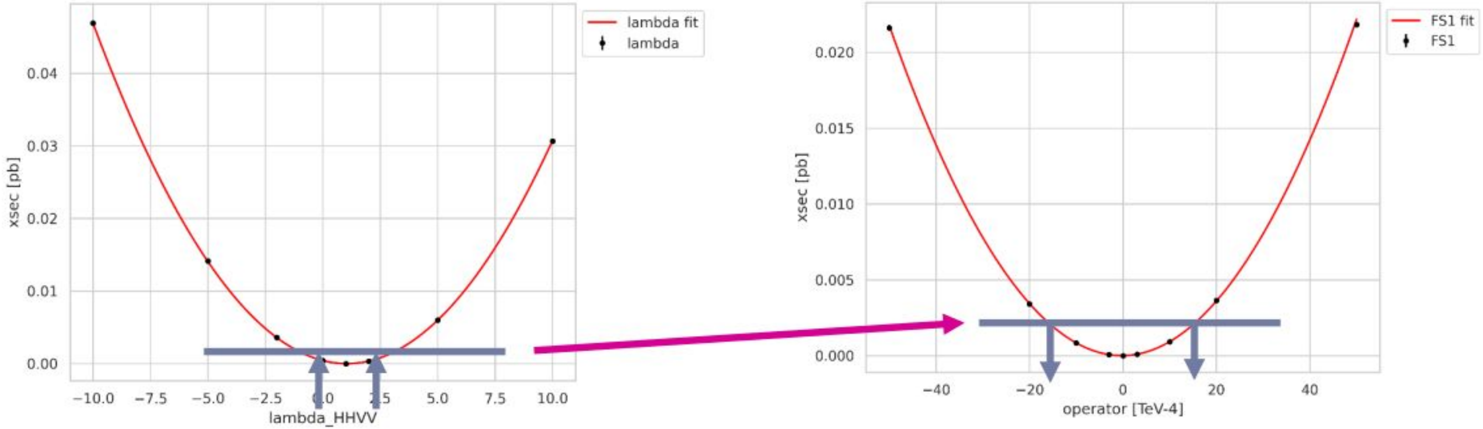
- Limits obtained w/ unitarity less stringent than those w/o (especially at low m$_{max}$ because of reduced statistics in [m$_{min}$, m$_{max}$])
- If curves don't cross, available data are not enough to set limits more stringent than those from unitarity alone

VBFHH Process

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

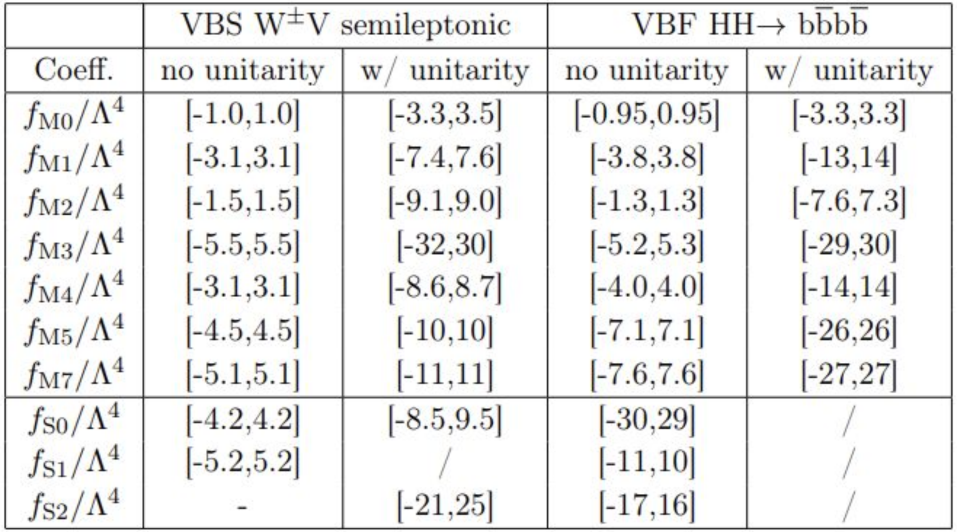
1. Consider public HH→4b 95% CL limit on k_{2V}
2. Use the VBF-HH simulation as function of k_{2V} to set limit on the parabola and obtain limit on σ
3. From limit on σ, extract limits on corresponding coefficient

Validation: use limits on f_x as input and reproduce CMS limits on k_{2V}

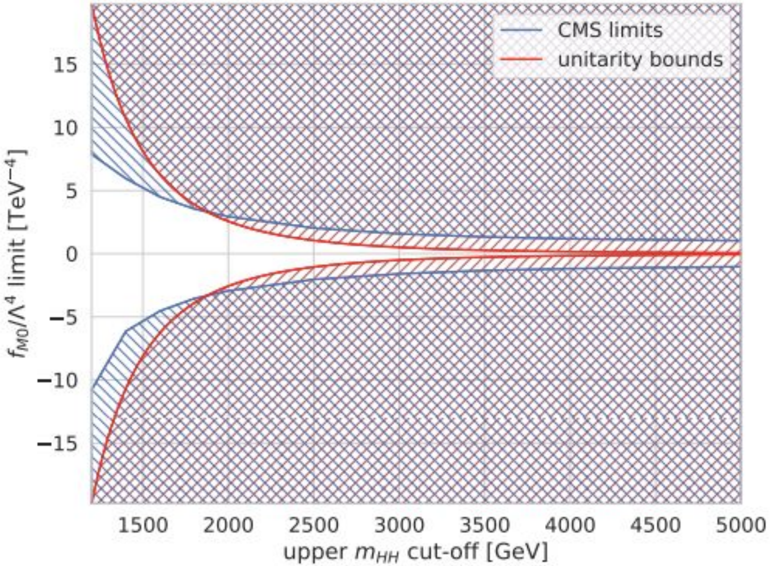


VBFHH Results

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



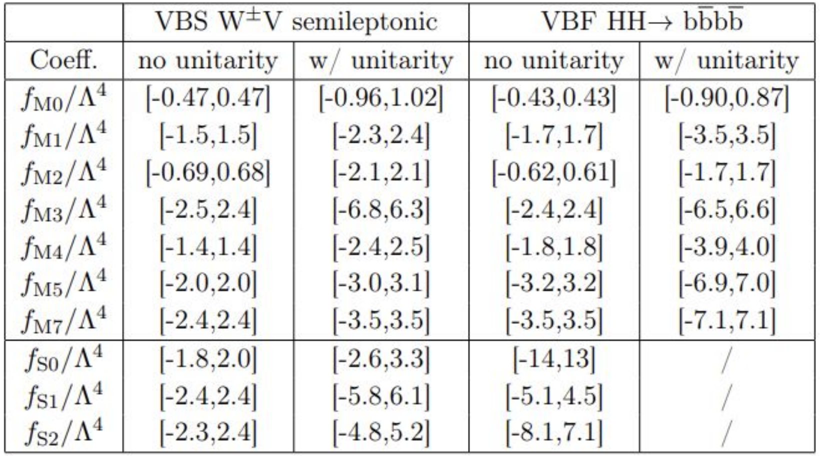
	VBS $W^{\pm}V$ semileptonic		VBF $HH \rightarrow b\bar{b}b\bar{b}$	
Coeff.	no unitarity	w/ unitarity	no unitarity	w/ unitarity
f_{M0}/Λ^4	[-1.0,1.0]	[-3.3,3.5]	[-0.95,0.95]	[-3.3,3.3]
f_{M1}/Λ^4	[-3.1,3.1]	[-7.4,7.6]	[-3.8,3.8]	[-13,14]
f_{M2}/Λ^4	[-1.5,1.5]	[-9.1,9.0]	[-1.3,1.3]	[-7.6,7.3]
f_{M3}/Λ^4	[-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]	/



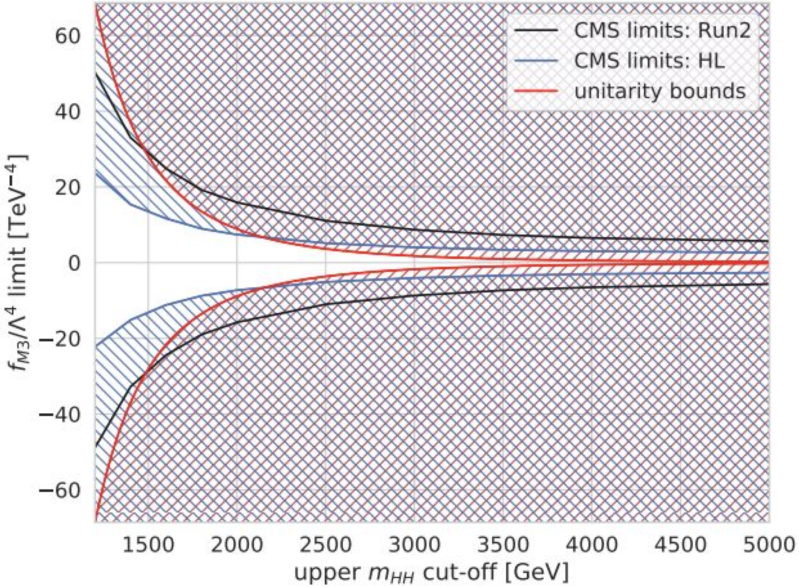
VBFHH: perspectives for HL-LHC

- 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}



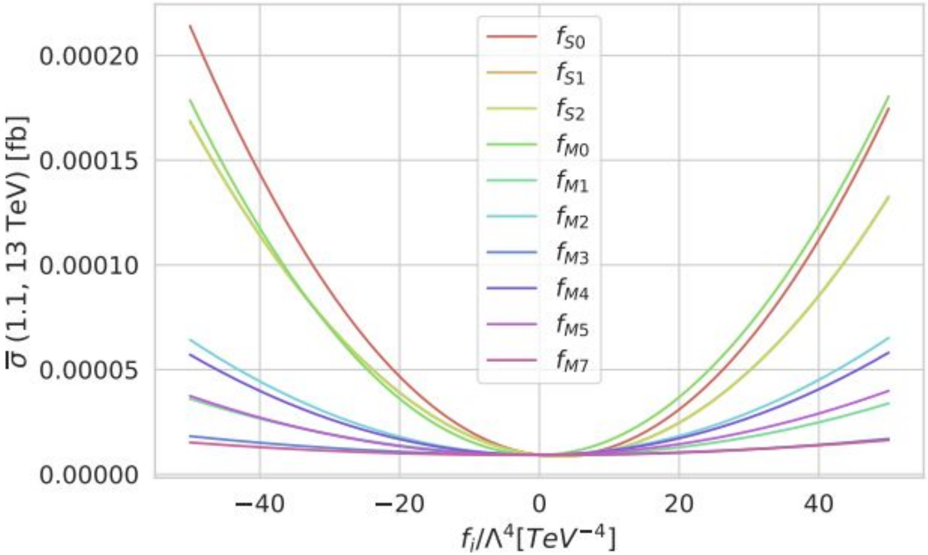
	VBS $W^{\pm}V$ semileptonic		VBF HH→ $b\bar{b}b\bar{b}$	
Coeff.	no unitarity	w/ unitarity	no unitarity	w/ unitarity
f_{M0}/Λ^4	[-0.47,0.47]	[-0.96,1.02]	[-0.43,0.43]	[-0.90,0.87]
f_{M1}/Λ^4	[-1.5,1.5]	[-2.3,2.4]	[-1.7,1.7]	[-3.5,3.5]
f_{M2}/Λ^4	[-0.69,0.68]	[-2.1,2.1]	[-0.62,0.61]	[-1.7,1.7]
f_{M3}/Λ^4	[-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]	/



New experimental final states: gg→ZZH

Exploratory feasibility study to investigate the potential sensitivity

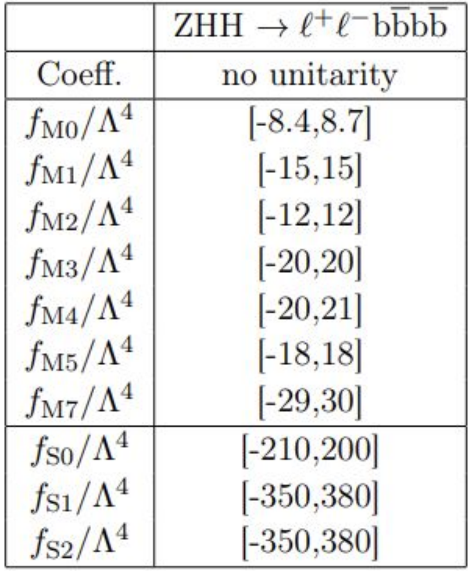
- Loop Induced process
- Very low σ
- H→bb and Z→ll (l=e,μ) considered
- Even with large variations of Wilson coefficients σ remains small → process **not sensitive enough** to be investigated at LHC
- But, it demonstrates that is **possible to simulate the process with new NLO UFO model** constructed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



New experimental final states: ZHH

No exp. result for ZHH available yet → Simple analysis performed

- Estimate the **number of detectable events**: $N = \sigma \cdot L \cdot \varepsilon \cdot A$
  - Decays: H→bb and Z→ll (l=e, μ)
  - 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
- **Background** Zbbbb 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**

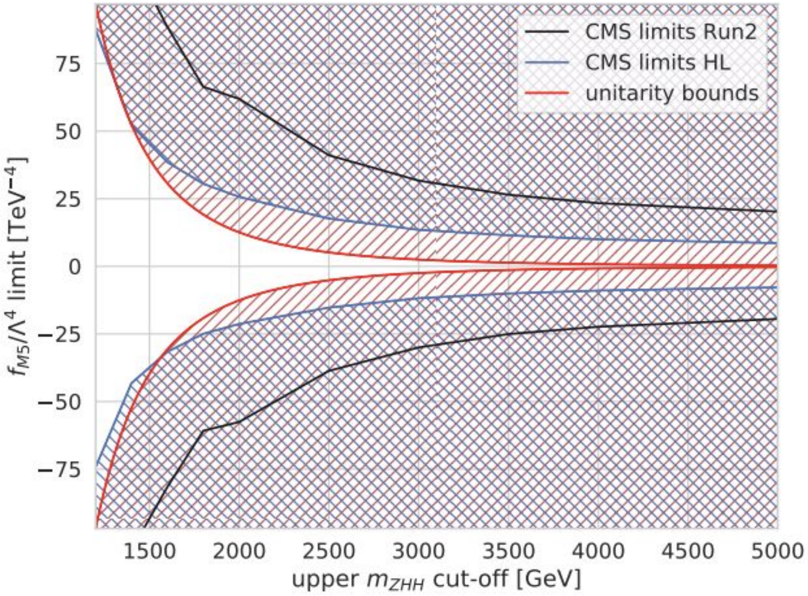


	$ZHH \to \ell^+\ell^- b\bar{b}b\bar{b}$
Coeff.	no unitarity
f_{M0}/Λ^4	[-8.4,8.7]
f_{M1}/Λ^4	[-15,15]
f_{M2}/Λ^4	[-12,12]
f_{M3}/Λ^4	[-20,20]
f_{M4}/Λ^4	[-20,21]
f_{M5}/Λ^4	[-18,18]
f_{M7}/Λ^4	[-29,30]
f_{S0}/Λ^4	[-210,200]
f_{S1}/Λ^4	[-350,380]
f_{S2}/Λ^4	[-350,380]

With Run2 luminosity (L = 140 fb^{-1}) no limits w/ unitarity

ZZH: perspectives for HL-LHC

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



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

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

- **Unitarity constraints**:
  - dedicated technique adopted
  - limits weakened by unitarity request, but **VBF-HH limits equally competitive with VBS** ones **even w/ unitarity**
- **HL-LHC** projections:
  → VBF-HH limits w/ unitarity can improve of 4-5 times w.r.t. Run2
  →ZHH final state can contribute in a combined exclusion of some coefficients