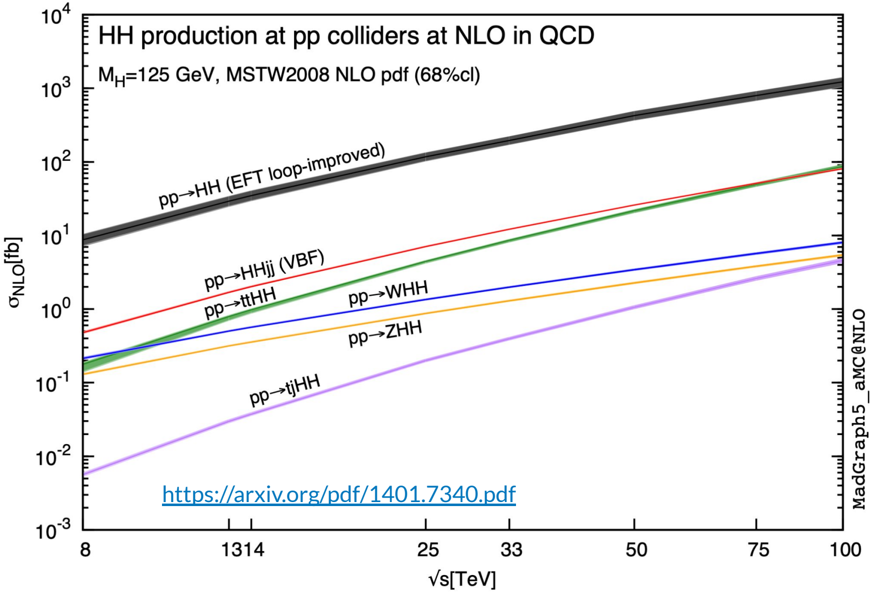
VVh/Vhh in ATLAS and CMS

Rare multi-boson production at the LHC and beyond

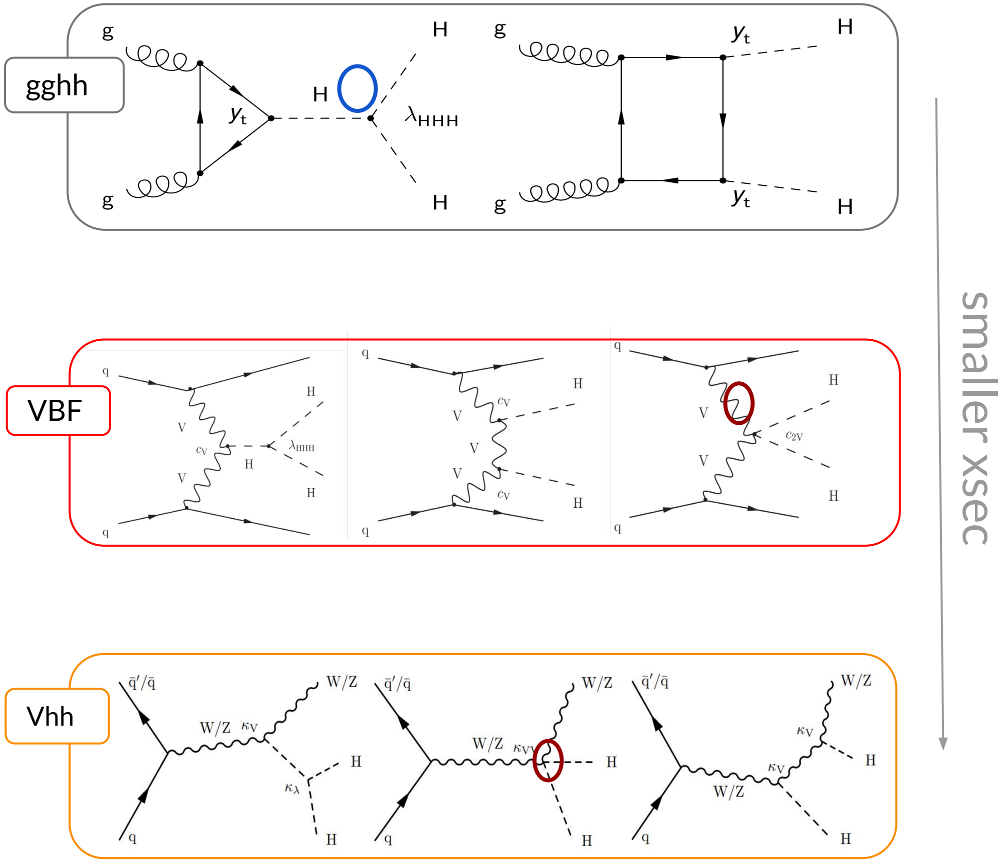
Alessandra Cappati (LLR)* *from zoom*,
Matteo Presilla (KIT)

1st COMETA General Meeting, Izmir

hh production modes



https://arxiv.org/pdf/1401.7340.pdf

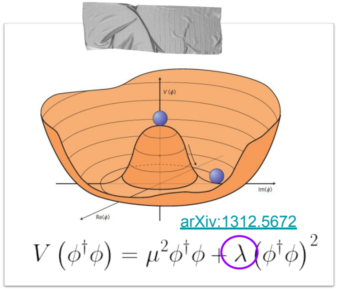


With full Run 2, possible to target also **subdominant** production modes

→ Diagrams also involve a different couplings

Exp. **observation very hard**, but small **modifications** to **VVhh** would lead to **big changes** in σ

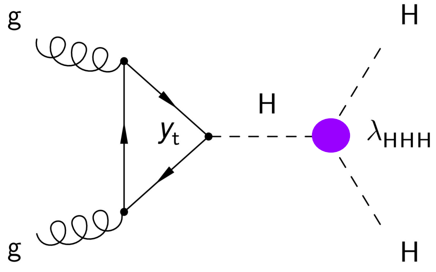
hh beyond the SM



arXiv:1312.5672

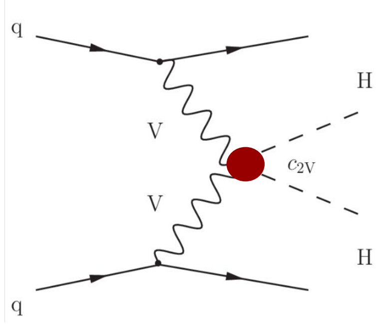
$$V\left(\phi^\dagger\phi\right) = \mu^2\phi^\dagger\phi + \lambda\left(\phi^\dagger\phi\right)^2$$

BSM processes can **modify cross-section** and **kinematic properties**



BSM effects parametrized as **multiplicative modifier** of the SM parameter λ: **k_λ**

→ For **purely scalar operators**, description in terms of Wilson coefficients or modifiers are **equivalent**



For **VVhh** BSM effects also parametrized as modifier of the SM coupling: **k_{2V}**

→ Not equivalent to the SMEFT approach (only true for some models)

To combine with other anomalous quartic couplings, need proper EFT parametrization → JHEP 09 (2022) 038

more on this later

Outline:

- Vhh production: non-resonant & resonant
- Anomalous VVh couplings
- VBF-hh dim-8 EFT, and new signatures

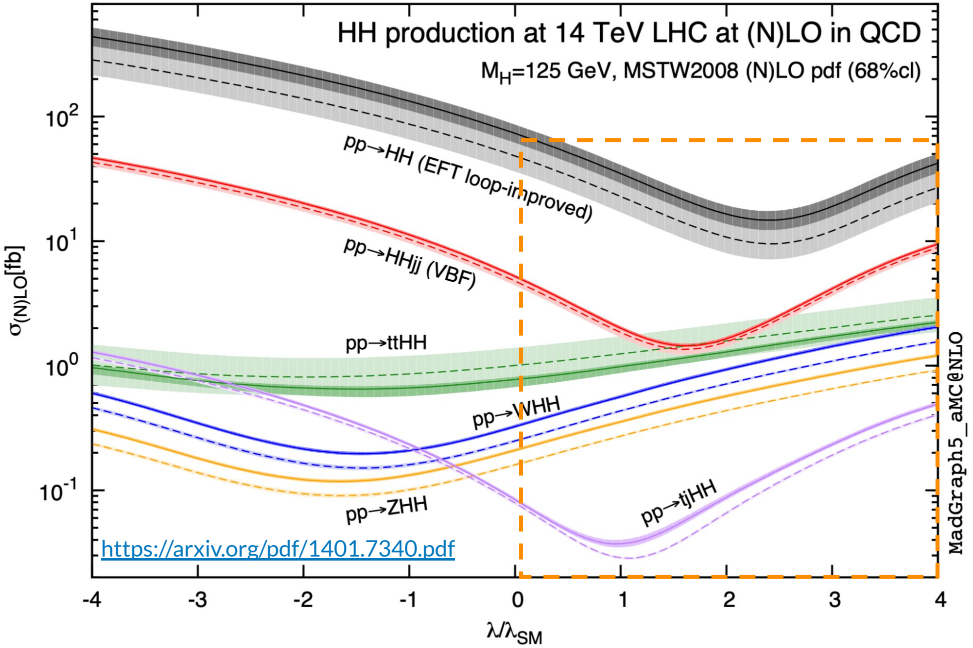
Vhh production:

non-resonant production.

(ATLAS: EPJC 83(2023)519, CMS-PAS-HIG-22-006)

Vhh production

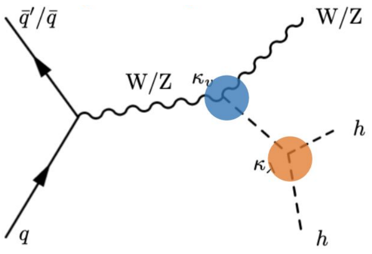
Complimentary to ggF and VBF channels, with cleaner signal when choosing V-leptonic decay



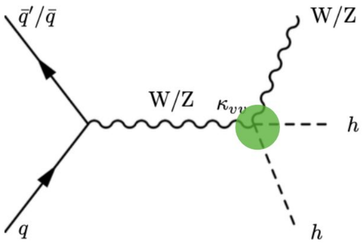
https://arxiv.org/pdf/1401.7340.pdf

Constructive interference yields an increasing Vhh cross section as k_λ increases ($0<k_\lambda<4$), while ggF and VBF channels are near their minimum

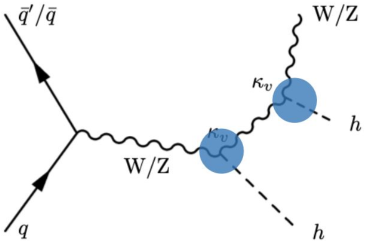
Vhh search in CMS



Higgs self-coupling



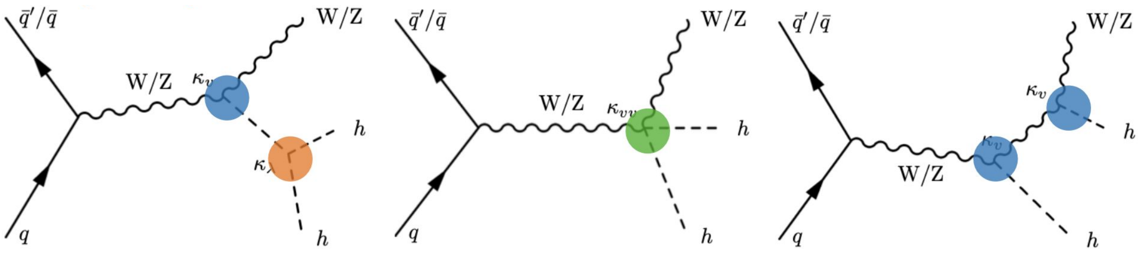
VVhh coupling



VVh coupling

- Focus on hh → 4b final states (~34%) with both leptonic and hadronic decays of the V boson
- Nearly all V-decay channels: 2L, 1L, MET, Fully hadronic
- **Very low sensitivity to SM process**: only 110 events would have been produced without any selection applied!

Vhh search in CMS



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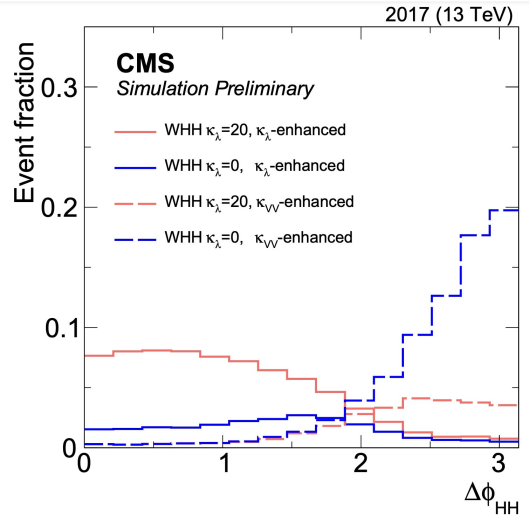
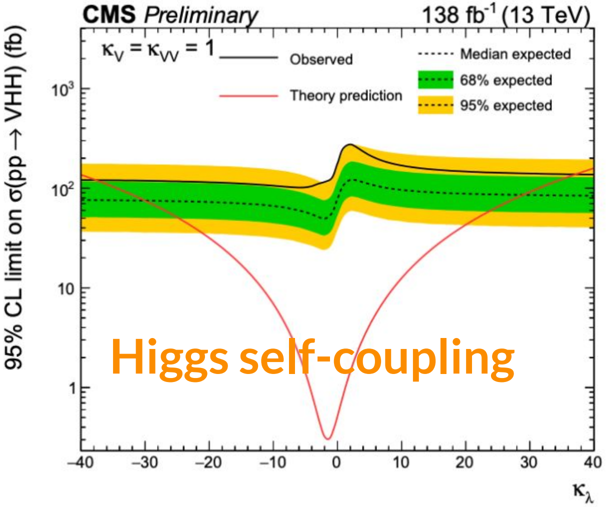
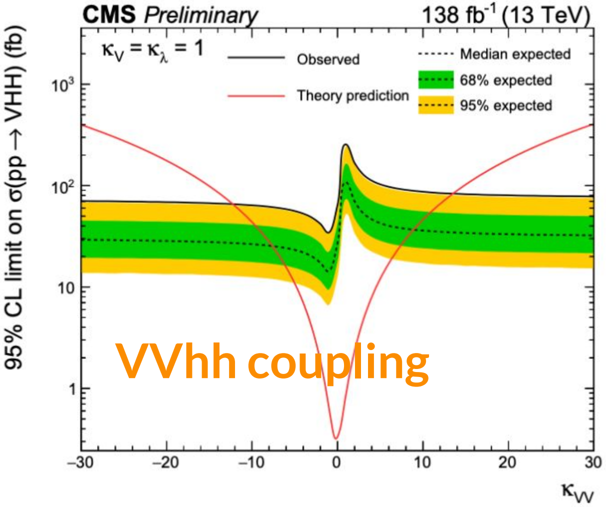
➔ Striking **difference of some kinematics distribution** when the coupling constants vary

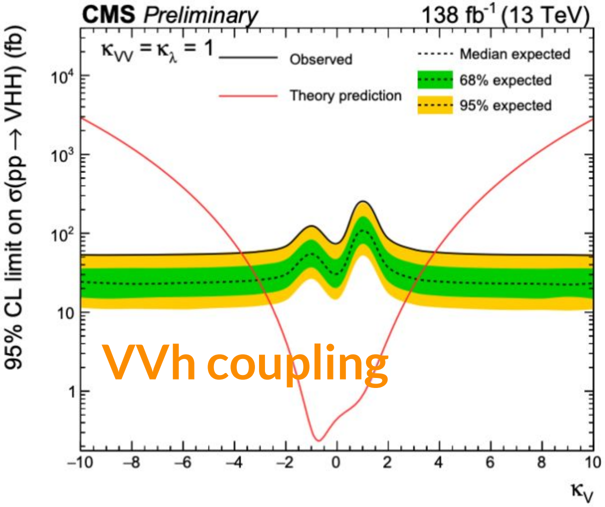
➔ Utilizing this feature with BDTs; we can create some **regions that are sensitive to high $k_\lambda(k_{VV})$ coupling**



non-resonant Vhh results





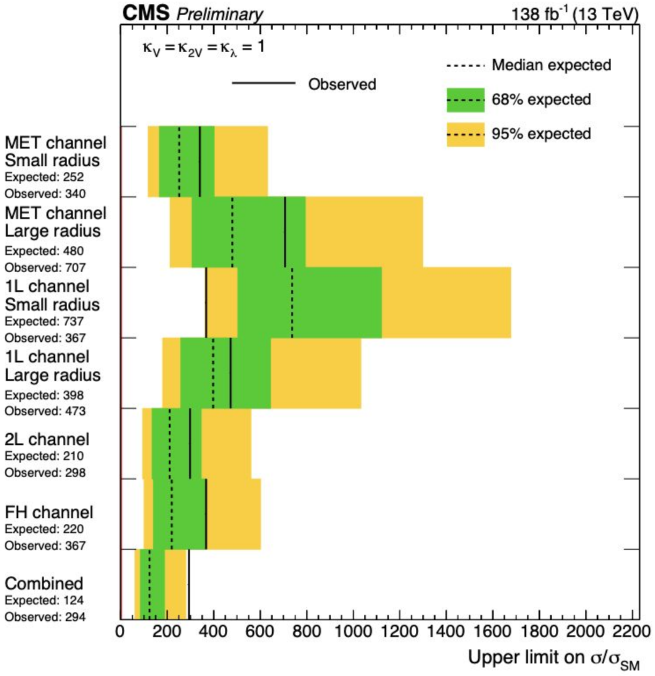


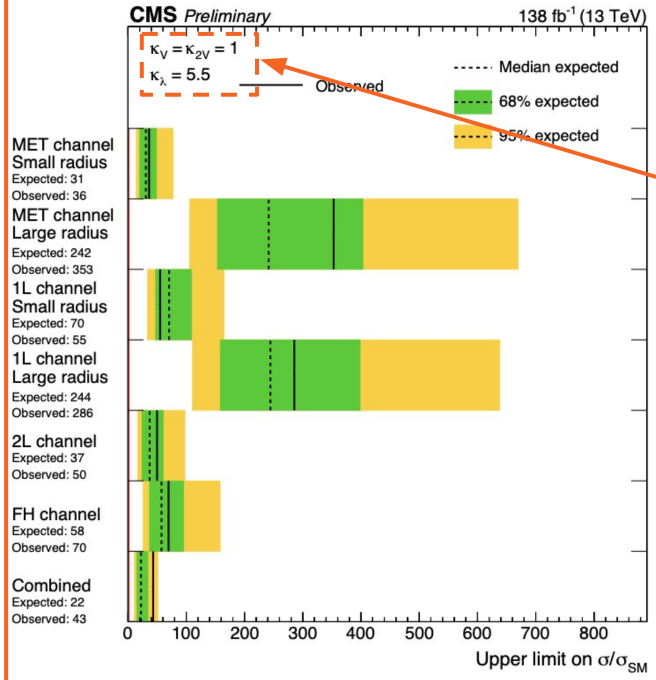
- Unique feature to decompose k_{WW} and k_{ZZ} couplings separately
- Constraints similar for CMS and ATLAS

$-12.2\ (\mathbf{-7.2}) < \kappa_{2V} < 13.5\ (\mathbf{8.9})$
$-14.0\ (\mathbf{-10.2}) < \kappa_{WW} < 15.4\ (\mathbf{11.6})$
$-17.4\ (\mathbf{-10.5}) < \kappa_{ZZ} < 18.5\ (\mathbf{11.6})$

$-37.7\ (\mathbf{-30.1}) < \kappa_\lambda < 37.2\ (\mathbf{28.9})$
$\mu^{VHH} \equiv \sigma_{VHH}/\sigma_{VHH}^{SM} < 294\ (\mathbf{124})$

Vhh cross-section upper limits





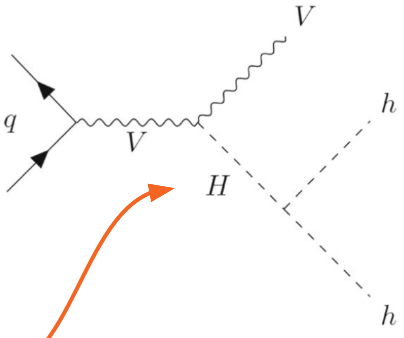
For the **sensitive region for VHH**, where the primary HH production cross sections are near minimal because of destructive interference

Vhh production:
resonant production.

(ATLAS: EPJC 83(2023)519)

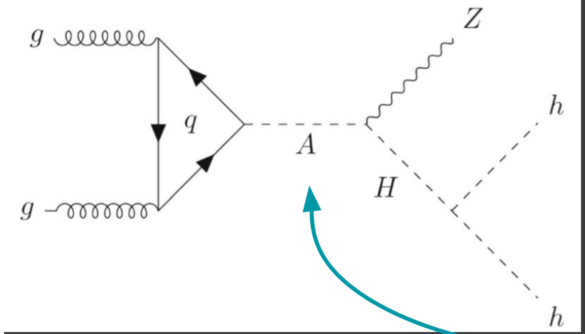
Resonant mediators

VH, Higgstrahlung



CP-even heavy scalar from off-shell V decay

- Masses from 260 to 1000 GeV
- Narrow resonance (~3%)
- EW singlet/typeII 2HDM

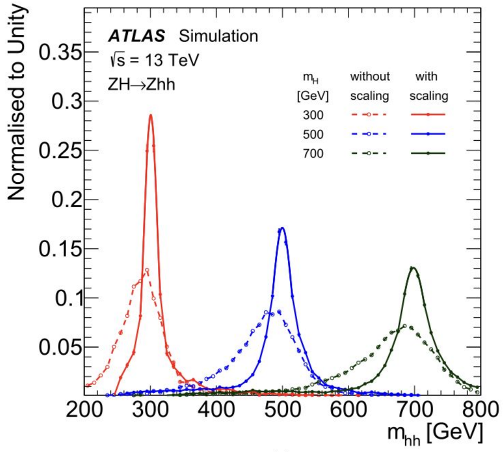


typical 2HDM signature

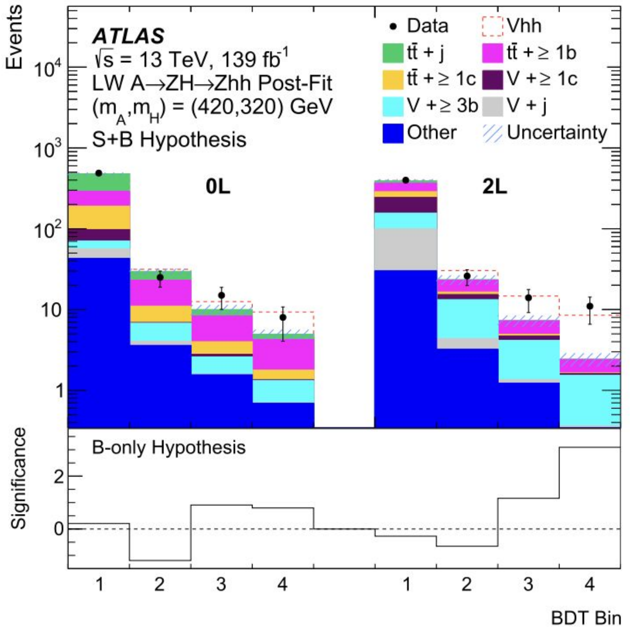
neutral heavy pseudoscalar

- A is CP-odd, with widths up to 20% of its mass
- A mass range 360-800 GeV

Vhh resonant search



(a)



- ➔ Similar strategy to the non-resonant search
- ➔ signal m_{hh} are expected to peak at $\sim m_H$
- ➔ **m_{hh} resolution improved by constraining the measured masses of the two Higgs** boson candidates to the exp value

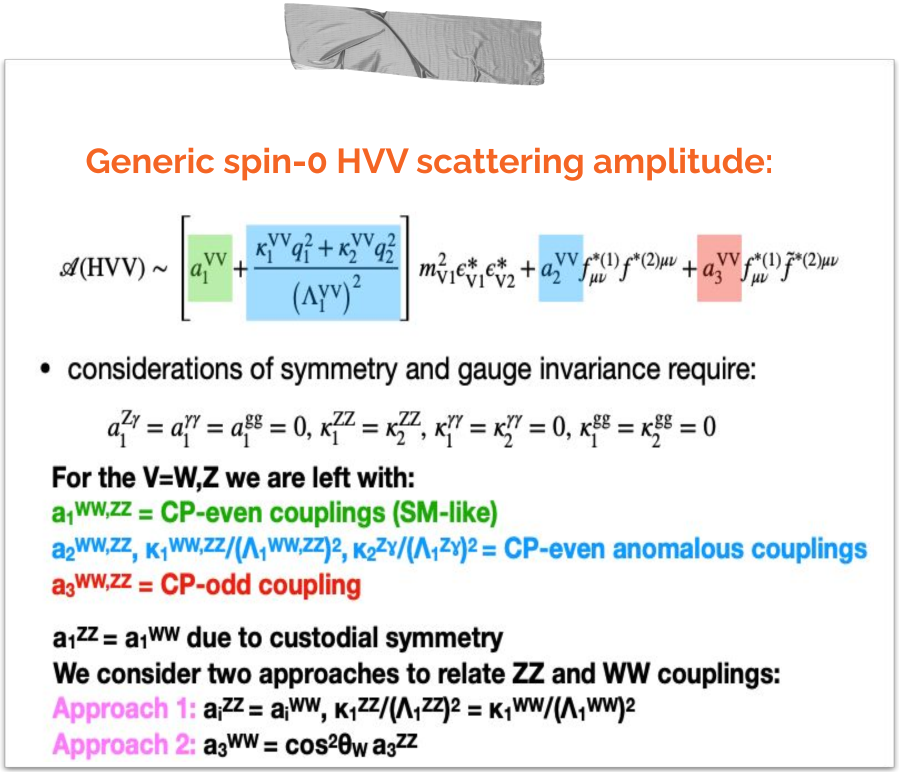
- ➔ Significant excesses at $(m_A, m_H) = (420,320)$GeV with a **local (global) significance of 3.8σ (2.8σ) in the LW scenario**
- ➔ Competitive upper limits on models parameters

VVh:

anomalous couplings.

(Phys. Rev. D 104, 052004,
Phys. Rev. D 108, 032013,
CMS-PAS-HIG-22-008)

AC formalism



Generic spin-0 HVV scattering amplitude:

$$\mathscr{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

- considerations of symmetry and gauge invariance require:

$$a_1^{Z\gamma} = a_1^{\gamma\gamma} = a_1^{gg} = 0,\ \kappa_1^{ZZ} = \kappa_2^{ZZ},\ \kappa_1^{\gamma\gamma} = \kappa_2^{\gamma\gamma} = 0,\ \kappa_1^{gg} = \kappa_2^{gg} = 0$$

For the V=W,Z we are left with:

$a_1^{WW,ZZ}$ = CP-even couplings (SM-like)

$a_2^{WW,ZZ}$, $\kappa_1^{WW,ZZ}/(\Lambda_1^{WW,ZZ})^2$, $\kappa_2^{Z\gamma}/(\Lambda_1^{Z\gamma})^2$ = CP-even anomalous couplings

$a_3^{WW,ZZ}$ = CP-odd coupling

$a_1^{ZZ} = a_1^{WW}$ due to custodial symmetry

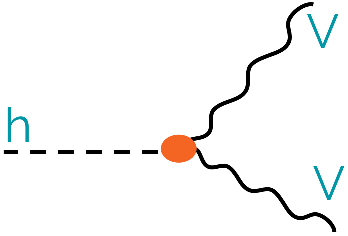
We consider two approaches to relate ZZ and WW couplings:

Approach 1: $a_i^{ZZ} = a_i^{WW}$, $\kappa_1^{ZZ}/(\Lambda_1^{ZZ})^2 = \kappa_1^{WW}/(\Lambda_1^{WW})^2$

Approach 2: $a_3^{WW} = \cos^2\theta_W\, a_3^{ZZ}$

Are there any anomalous interactions between a Higgs boson and two gauge bosons?

Current precision allows small anomalous CP-even and/or CP-odd couplings.



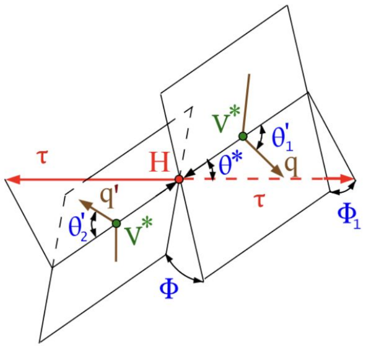
Convenient to parameterise ACs in terms of effective cross-sections (most of the uncertainties cancel in the ratio):

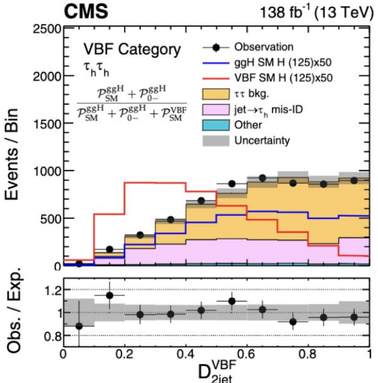
$$f_{a_i} = \frac{|\,a_i\,|^2\,\sigma_i}{\sum_{j=1,2,3\ldots} |\,a_j\,|^2\,\sigma_j}\,\mathrm{sign}\left(\frac{a_i}{a_1}\right)$$

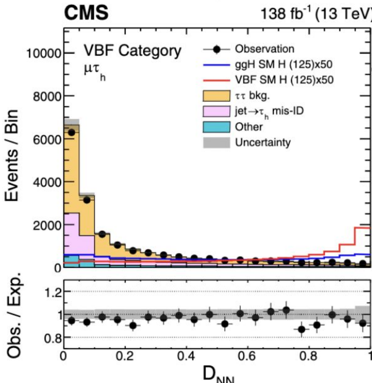
How do we measure AC?

Different approaches employed to achieve good AC sensitivity:

- ➔ **“Optimal observables” approach:** reduce phase space dimensionality by combining observables
- ➔ **Matrix element methods (MEM):** build Neymann-Pearson-like discriminants based on parton-level information
- ➔ **Machine learning techniques:** build NN classifiers to exploit correlations and boost the sensitivity

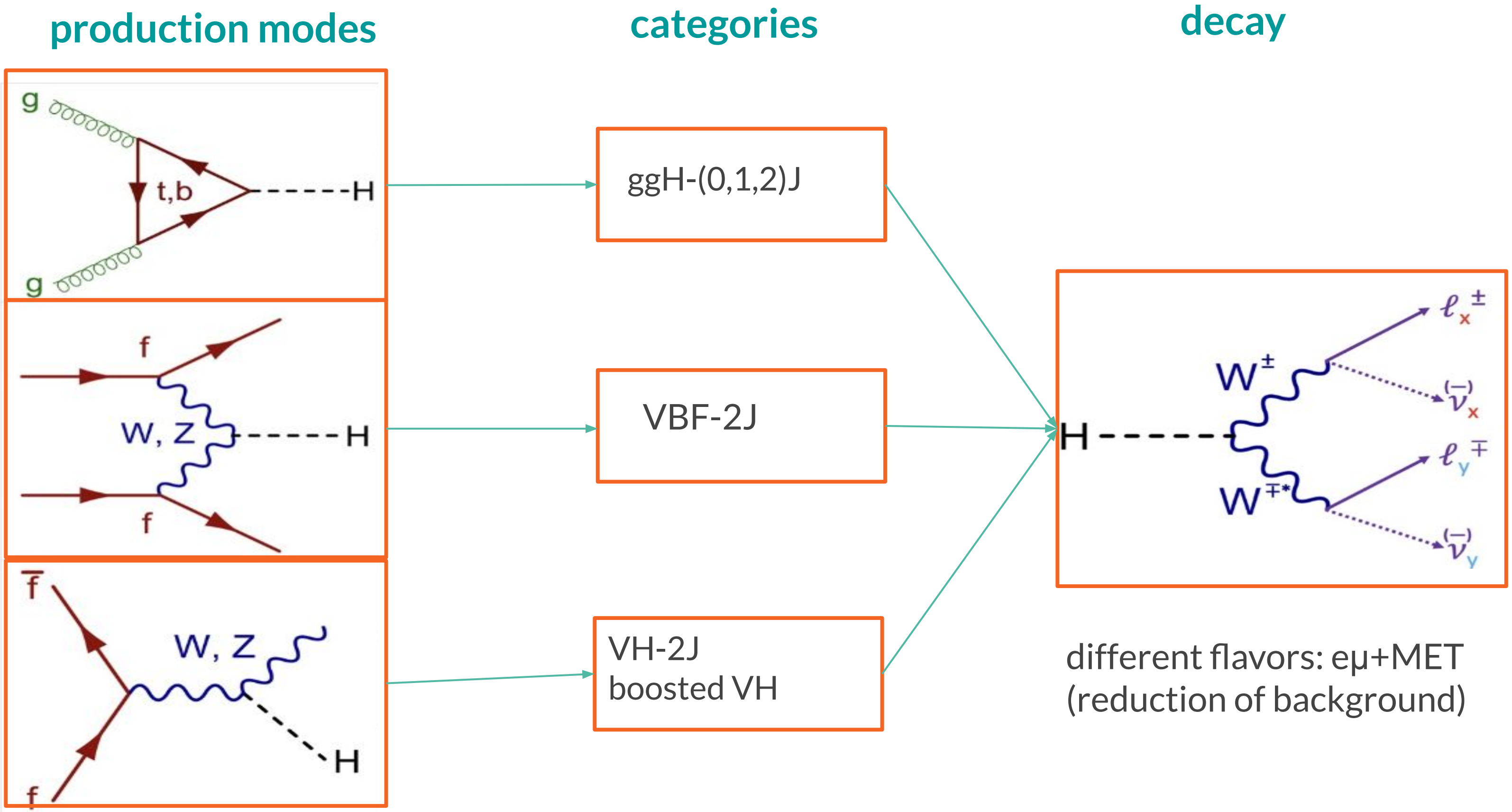






Phys. Rev. D 108, 032013

A recent CMS example



production modes

categories

decay

ggH-(0,1,2)J

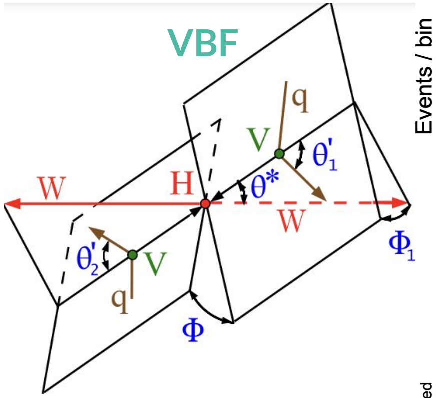
VBF-2J

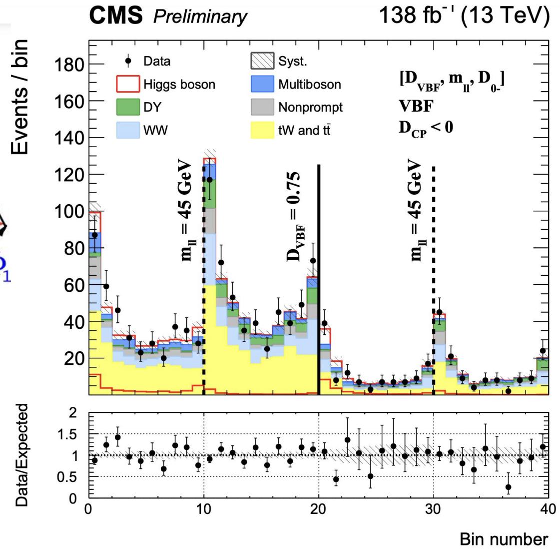
VH-2J
boosted VH

different flavors: eμ+MET
(reduction of background)

CMS-PAS-HIG-22-008

HWW analysis





From the 5 observables (Ω) that fully describe the topology
(3 angles+2 four-momenta)

MELA reduction to 3 types of discriminant:

ggH signal vs VBF/VH signal =>

$$\mathcal{D}_{\mathrm{sig}} = \frac{\mathcal{P}_{\mathrm{sig}}(\vec{\Omega})}{\mathcal{P}_{\mathrm{sig}}(\vec{\Omega}) + \mathcal{P}_{\mathrm{bkg}}(\vec{\Omega})}$$

SM vs BSM =>

$$\mathcal{D}_{\mathrm{BSM}} = \frac{\mathcal{P}_{\mathrm{BSM}}(\vec{\Omega})}{\mathcal{P}_{\mathrm{BSM}}(\vec{\Omega}) + \mathcal{P}_{\mathrm{SM}}(\vec{\Omega})}$$

Interference vs pure SM/BSM signal =>

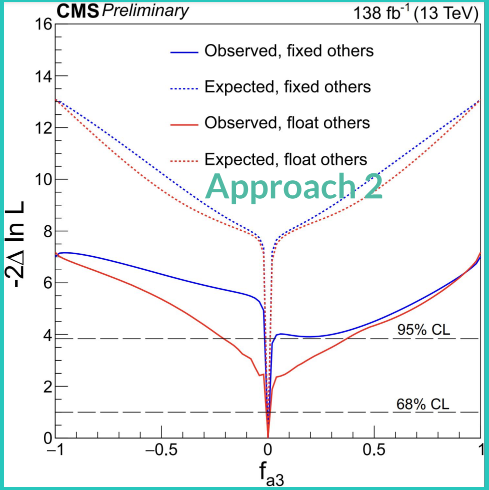
$$\mathcal{D}_{\mathrm{int}} = \frac{\mathcal{P}^{\mathrm{int}}_{\mathrm{SM-BSM}}(\vec{\Omega})}{\mathcal{P}_{\mathrm{SM}}(\vec{\Omega}) + \mathcal{P}_{\mathrm{BSM}}(\vec{\Omega})}$$

- ★ $\mathscr{P}_i$ is the probability for the process (i=SM, BSM).
- ★ $\mathscr{P}_{\mathrm{SM-BSM}}$ is the interference part of the probability distribution with a mixture of SM and BSM.

CMS-PAS-HIG-22-008

Results:

f_{a3} scan



EFT Higgs basis

Coupling	Observed	Expected
δc_z	$-0.06^{+0.09}_{-0.16}$	$0.00^{+0.08}_{-0.10}$
$c_{z\Box}$	$0.01^{+0.02}_{-0.06}$	$0.00^{+0.02}_{-0.02}$
c_{zz}	$0.03^{+0.30}_{-0.52}$	$0.00^{+0.23}_{-0.29}$
$\tilde{c}_{zz}$	$-0.17^{+0.42}_{-0.30}$	$0.00^{+0.29}_{-0.32}$

SMEFT Warsaw basis

Coupling	Observed	Expected
$c_{H\Box}$	$-0.76^{+1.43}_{-3.43}$	$0.0^{+1.37}_{-1.84}$
c_{HD}	$-0.12^{+0.93}_{-0.32}$	$0.0^{+0.43}_{-0.30}$
c_{HW}	$0.08^{+0.43}_{-0.87}$	$0.0^{+0.37}_{-0.48}$
c_{HWB}	$0.17^{+0.88}_{-1.79}$	$0.0^{+0.77}_{-0.96}$
c_{HB}	$0.03^{+0.13}_{-0.26}$	$0.0^{+0.11}_{-0.14}$
$c_{H\tilde{W}}$	$-0.26^{+0.67}_{-0.50}$	$0.0^{+0.48}_{-0.52}$
$c_{H\tilde{W}B}$	$-0.54^{+1.37}_{-1.03}$	$0.0^{+0.99}_{-1.07}$
$c_{H\tilde{B}}$	$-0.08^{+0.20}_{-0.15}$	$0.0^{+0.15}_{-0.16}$

All f_{ai} consistent with 0, the SM value. Limits translated to SMEFT in two bases.

VBF-hh dim-8 EFT & new signatures

(R. Covarelli, A. Cappati, P. Torrielli, M. Zaro - JHEP09 (2022) 038)

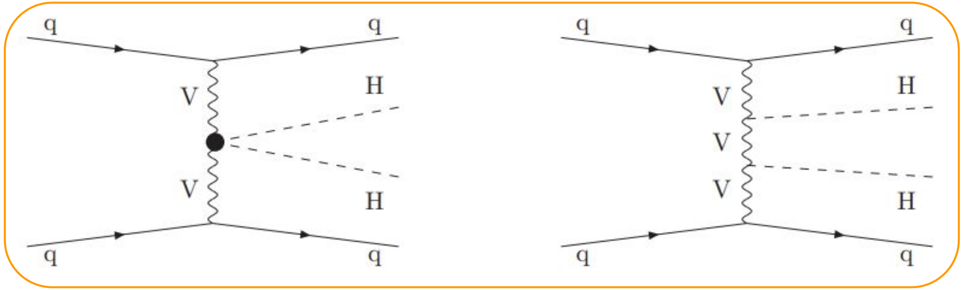
A different proposal from VVhh phenomenology

RC, A. Cappati, P. Torrielli, M. Zaro
JHEP09 (2022) 038

- Paper investigates **VVhh interactions**
- In EFT terms, only investigated in (gauge) VBS or triboson processes

In this work:

- Reinterpretation of **VBF hh experimental results** in terms of **dim-8 EFT operators**, sensitive to VVHH interactions
- Focus on **genuine** SMEFT aQGC-generating operators (dimension 8 Eboli's basis)
- **Unitarity constraints** considered
  - dedicated technique adopted
    → **mass-dependent constraints**



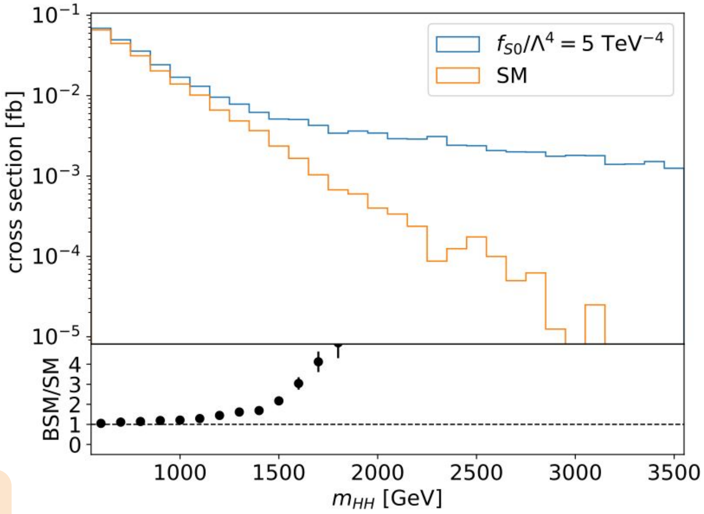
Simulation setup

- Simplified phenomenology analysis
- Generator: **MadGraph5_aMC@NLO**
- Processes:
  - VBF-hh
  - VBS ($W^\pm W^\pm$, $W^\pm Z$, W^+W^-) (for comparison)

- Typical experimental selections applied on tagging jets

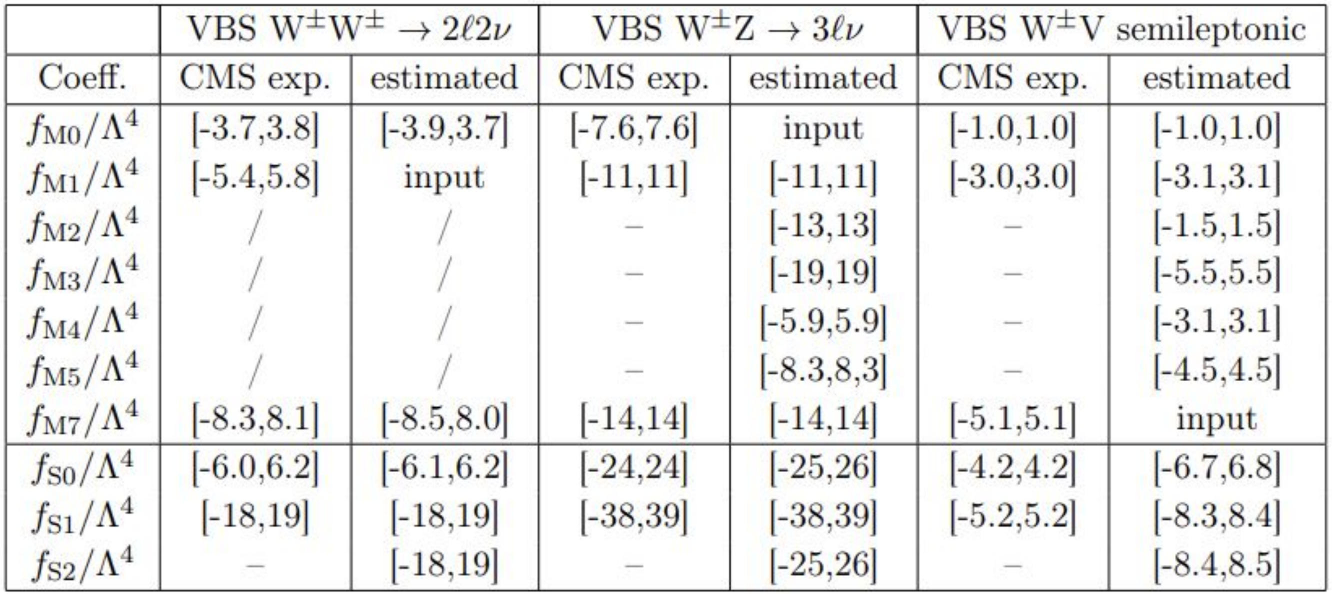
- Observable used to estimate the EFT sensitivity:
  - **σ[m_{min}, m_{max}]** (integrated cross section in mass interval)
  - m = invariant mass of the di-boson states produced
    - m_{min} = 1.1 TeV,
    - m_{max} = **various values between 1.1 TeV and √s (the latter corresponding to no unitarity bound)**

VBF-hh



Reproducing CMS VBS results

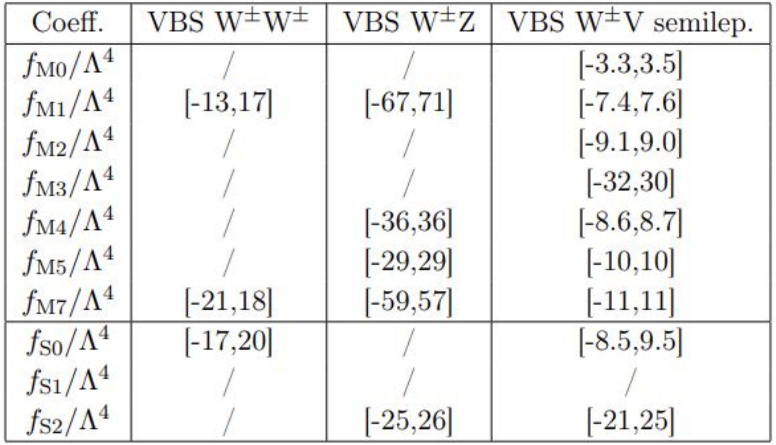
- Managed to reproduce CMS VBS results (w/o unitarity bounds) with simplified observable
- Also filled in missing results



	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]

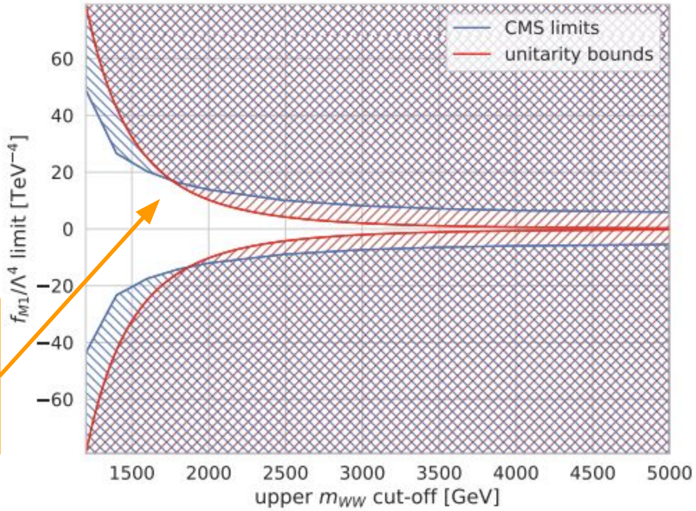
Implementation of unitarity bounds

1. Evaluate **σ[m$_{min}$, m$_{max}$]** for several **m$_{max}$**
2. For each σ, obtain **m$_{max}$-dependent limits** on operator coefficients with same procedure used for validation



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]

VBS $W^\pm W^\pm \rightarrow 2l2\nu$



intersection: max m to set limits not violating unitarity

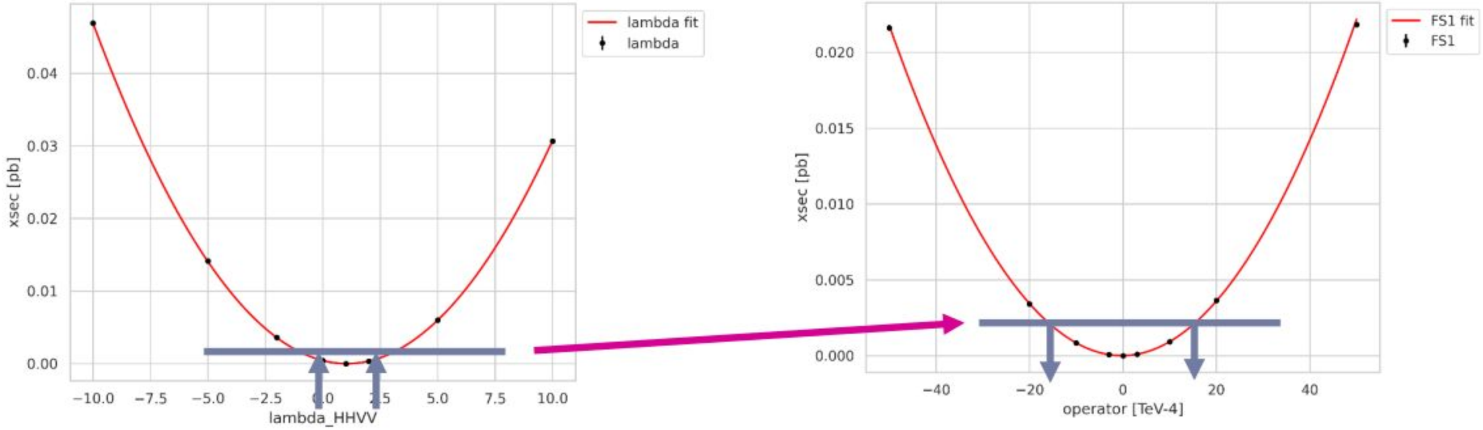
- **Limits obtained w/ unitarity much less stringent than those w/o**
- If curves do not cross, available data are not enough to set more stringent limits than those imposed by unitarity

VBF-hh limit setting

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

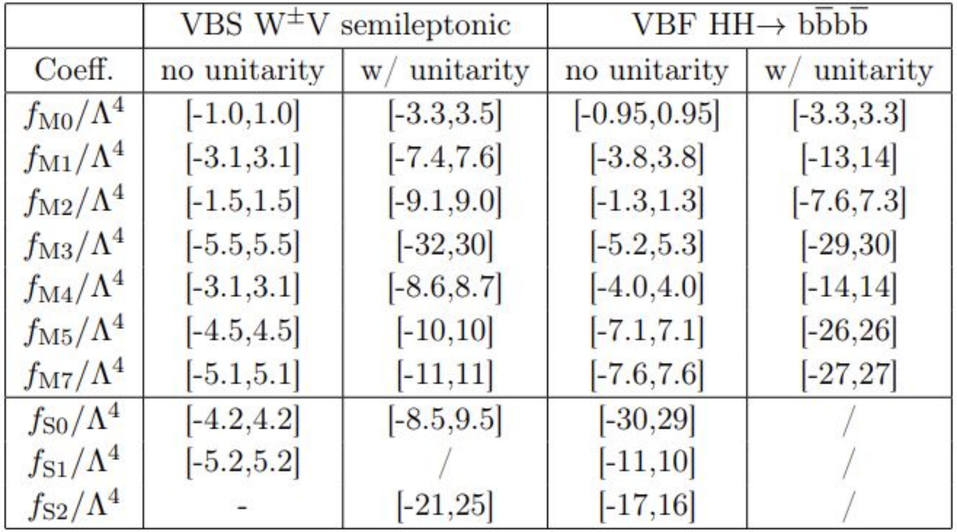
1. Consider public VBF hh → 4b 95% CL limit (CMS only) on k_{2V}
2. Use a VBF-hh simulation as function of k_{2V} to fit a parabola and obtain limit on σ
3. From limit on σ, extract limits on corresponding dim-8 Wilson coefficient from simulation

Validation: use limits on f_x as input and re-produce CMS limits on k_{2V}

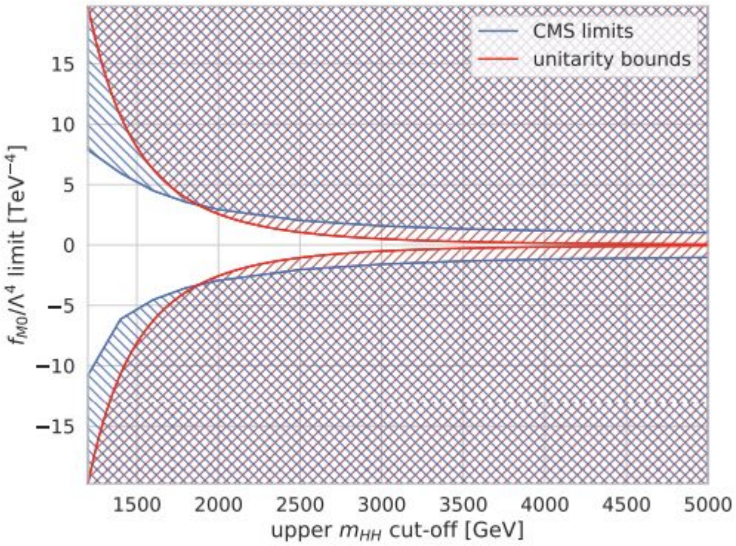


VBF-hh results

- **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$\to$ b$\bar{\text{b}}$b$\bar{\text{b}}$	
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]	/

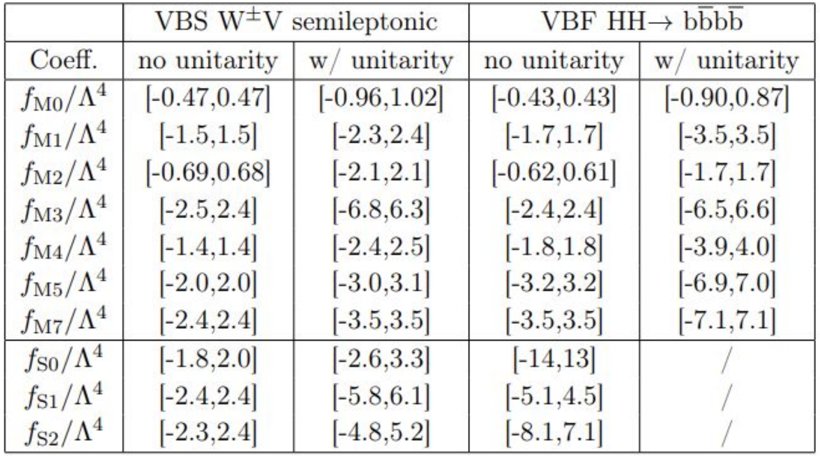


Perspectives for HL-LHC

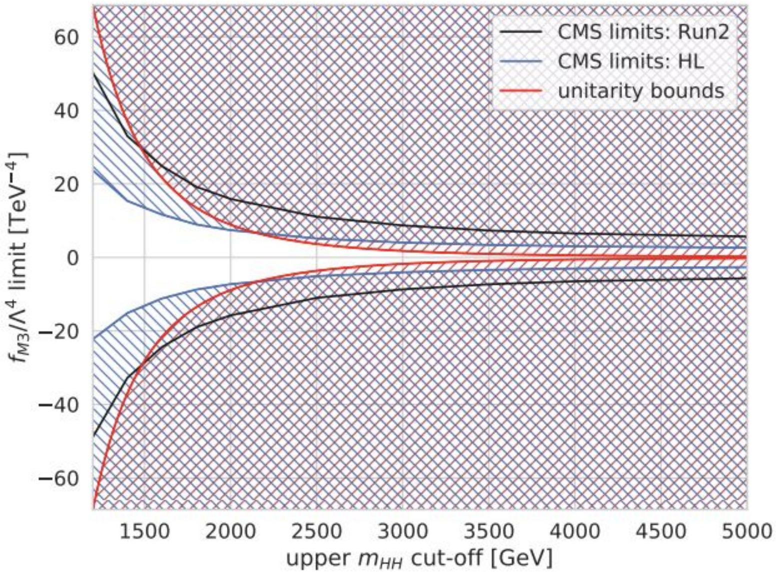
- Limits w/o unitarity obtained rescaling the excluded σ by $L^{-½}$ (L = 3 ab^{-1}, 13 TeV)
- Limits w/ unitarity present significant additional gain since m_{max} moves to larger values, allowing inclusion of more data in the sensitivity estimate

→ limits improve by factor 4-5

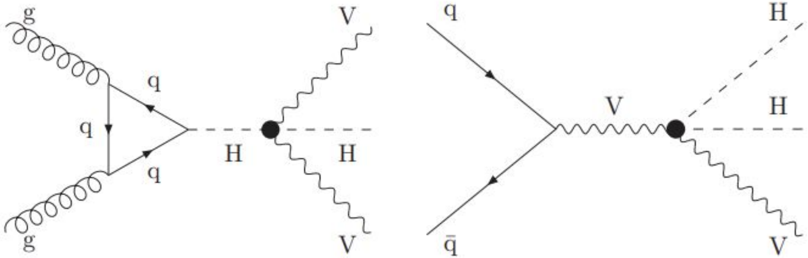
→ first physical limit on f_{S1}



	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 final states



gg→VVH and **qq→VHH**

→ for both, V=Z, since final states with W bosons would suffer from large top-induced bkg and would require a real experimental analysis

1. **gg→VVH**

   Considering EFT effects with similar magnitude as those induced in VBS and VBF HH, the **cross-section remains too small**, even at HL-LHC

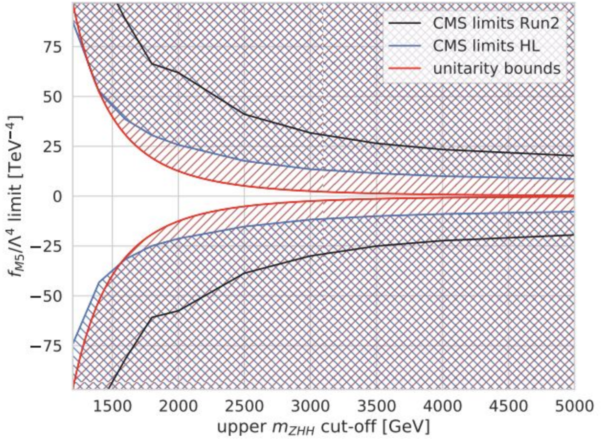
2. **qq→VHH**

   Performed simple analysis (since no available exp. results at the time)

   - *Assume only 1 SM bkg (Z+4 b jets)*
   - *Enhance signal by requiring m_{bb} close to m_H for b jet pair candidates*
   - *Estimate $\sigma[m_{min}, m_{max}]$ for signal+EFT and bkg*
   - *Compute S and B with LHC Run 2 luminosity, and limits with Feldman-Cousins approach*

   Sensitivity smaller than other final states

   But promising results with HL-LHC prospects: **limits w/ unitarity on some M-type operators!**



Summary.

- Rare Vhh production
  - non-resonant => SM and k-framework
  - resonant => sensitivity to specific BSM scenarios
- Search for anomalous effects, in the tensor structure of the H interactions with electroweak bosons (HVV):
  - matrix element likelihood approach &/or a neural network to optimize the measurement of anomalous couplings, as well as interpretation in terms of EFT scenarios
- Novel approach to aQGC from VVhh
  - competitive to traditional VBS probes
  - new possibile signatures to explore

BACKUP

Recent ATLAS and CMS results

recent Vhh measurements

EPJC83(2023)519 **Search for Higgs boson pair production in association with a vector boson.**

HIG-22-006 **Search for vector-boson associated di-Higgs production with HH->4b and with leptonic vector boson decays.**

Anomalous Couplings in VVh

HIG-22-008 **Anomalous Higgs couplings in HWW.**

PRD 108 (2023) 032013 **AC to vector bosons/fermions in production in h->ττ.**

PRD 99, 112003 **Off-shell Higgs production and AC in four-lepton final state.**