Multiboson interactions: from HH searches to EFT SM measurements

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ÉCOLE POLYTECHNIQUE

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Séminaire

22 février 2024

CMS

Electro-Weak Interactions

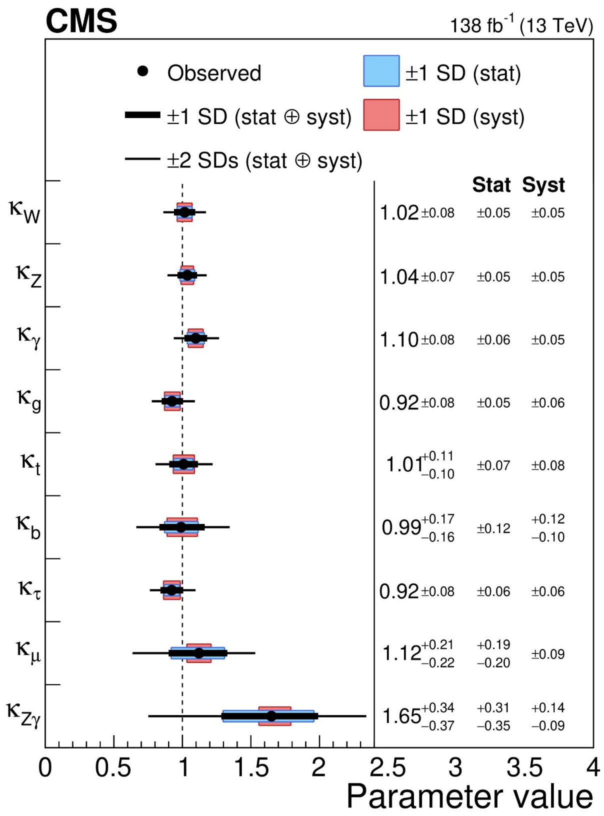
The **EW sector** of the SM is an extremely predictive and successful theory

Unified
$SU(2)_L \times U(1)_Y$

Perturbative
down to small energy scale

Few free parameters

Tested to high precision by last and next-to-last generation of HEP experiments



Nature 607 (2022) 60-68

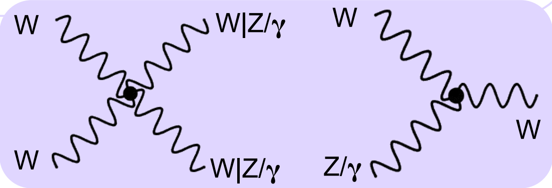
Multiboson Couplings

The SM predicts the existence of **multiboson** couplings

Multi-gauge

➢ From non-Abelian structure of SU(2)

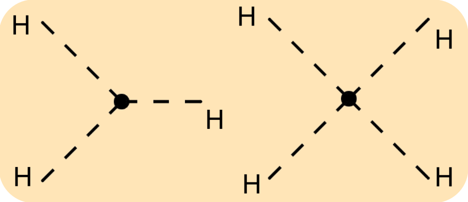
- Gauge invariance of vector boson kinetic terms enforces triple and quartic couplings
- No vertices with only Z/γ, since both stem from the same field W_3 after GWS mixing



Multi-Higgs

➢ From shape of Higgs potential (quartic)

➢ From field expansion around the VEV (triple), after symmetry breaking



In common:

- All **coupling strengths predicted exactly** in EW theory
- Very **hard to measure experimentally** since relevant processes also occur through competing (dominant) diagrams

Multiboson Couplings

In this talk

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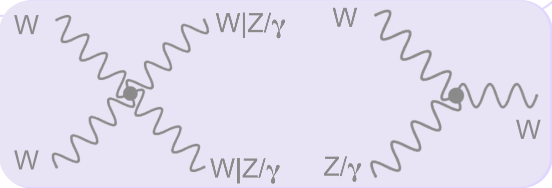

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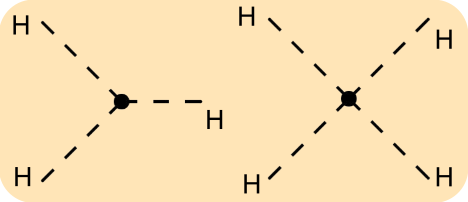

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EFT

Non-SM effects constrained using parameterization based on **Effective Field Theories**

→ Do not introduce SM modifications of arbitrary magnitude ❌

→ Makes sure that the dimensionality of the respective operators is suppressed by a corresponding power of the new physics scale (Λ) ✅

Standard Model EFT (SMEFT)

Consistent EFT **generalization of the SM** with a series of higher dimensional operators which are invariant under $SU_C(3) \times SU(2)_L \times U(1)_Y$, using **only SM fields**

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{i=1}^{n_d} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}, \; d > 4$$

Free parameters: Wilson coefficients

Gauge invariant operators

EFT

Non-SM effects constrained using parameterization based on **Effective Field Theories**
→ Do not introduce SM modifications of arbitrary magnitude
→ Makes sure that the dimensionality of the respective operators is suppressed by a corresponding power of the new physics scale (Λ)

Standard Model EFT (SMEFT)

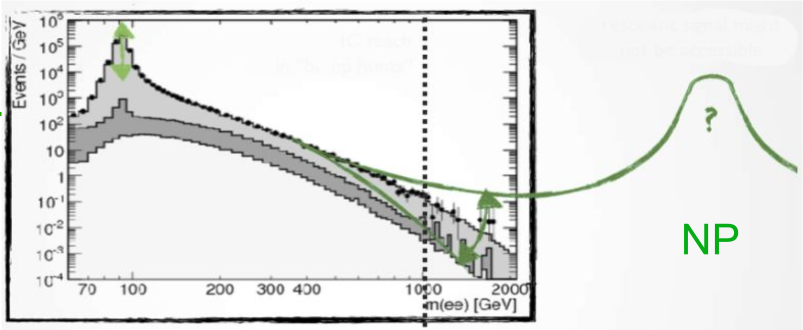
Pros

- **Model independent**
- different **measurements can be combined** leading to more stringent results

Cons

- Invalid at energies too close to Λ or above (**unitarity violation**)
- Power of data diluted by the large **freedom** in **choosing** which **operator** to consider
- no common agreement on **how to estimate uncertainties from missing higher orders**

EFT: bottom-up approach



New Physics — Λ

E<<Λ

SM — E

Energy

Knowledge of NP not required

Information on NP can be **inferred** by measuring c_i

SM with fields and symmetries $\xrightarrow{E/\Lambda}$ $\mathcal{L}^{(n)}_{EFT}$

- all allowed operators at $(E/\Lambda)^n$
- free parameters c_i

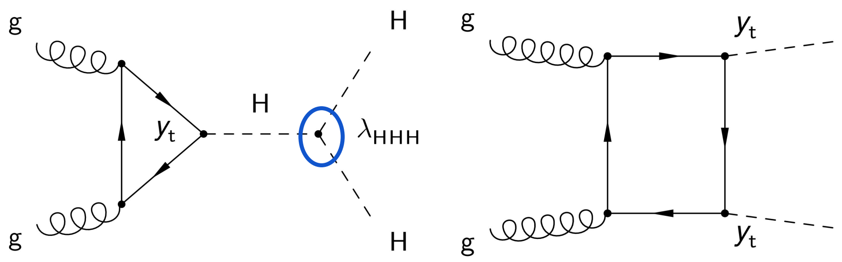
HH production (non-resonant)

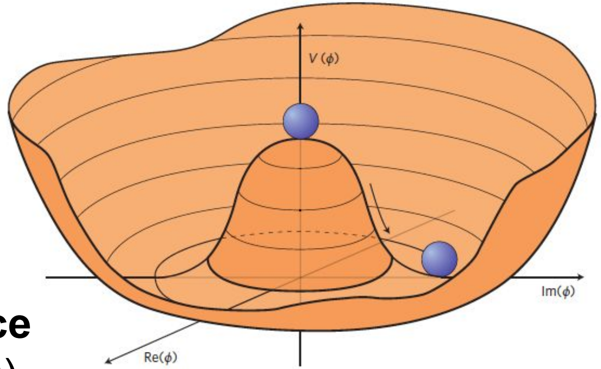
HH production can be used to directly study Higgs boson self-coupling and Higgs potential

arXiv:1312.5672

At LHC mainly produced through gluon fusion via fermion loop

ggHH





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

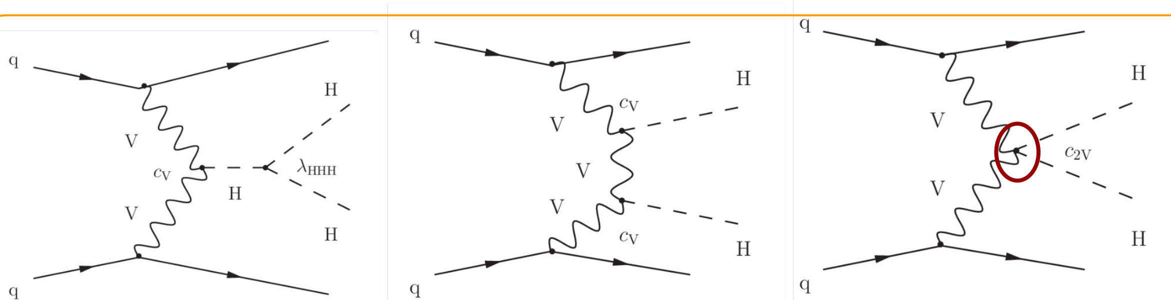
- In SM, amplitude from 2 contributions, **destructive interference**
  → Tiny cross-section, known with **high precision** (NNLO QCD)

  $\sigma_{13TeV} = 31.05^{+6\%}_{-23\%}$ 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)

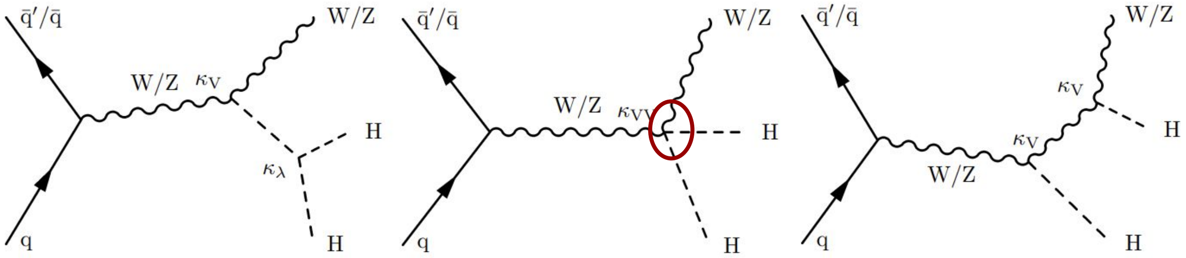
VBFHH and VHH

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

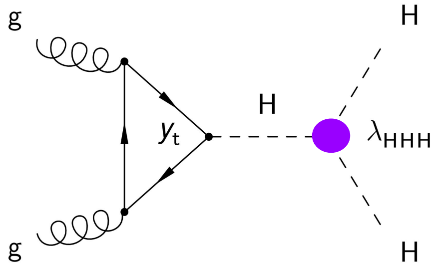
Exp. **observation very hard**, but small **modifications** to **VVHH** would lead to **big changes** in σ

HH beyond the SM: SMEFT

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

BSM effects parametrized as **multiplicative modifier** of the SM parameter λ: $\mathbf{k_\lambda}$

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

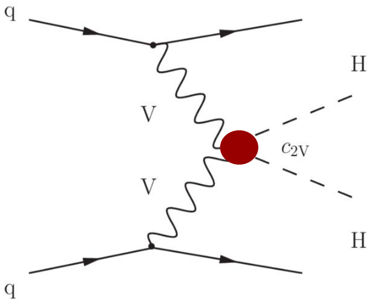


For **VVHH** BSM effects also parametrized as modifier of the SM coupling: $\mathbf{k_{2V}}$

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

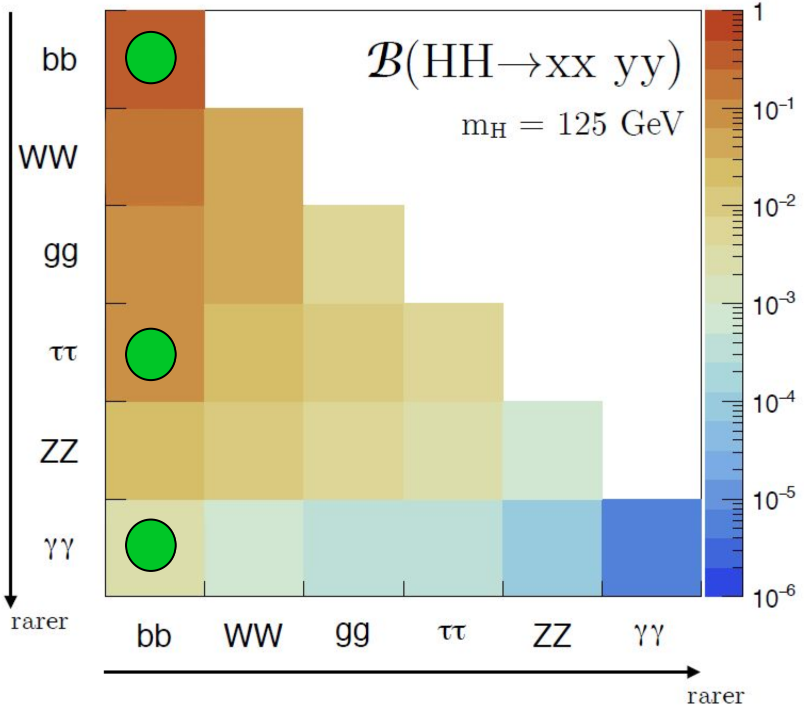
To combine with other anomalous quartic couplings, need proper dim-8 parametrization → JHEP 09 (2022) 038

more on this later



HH Experimental Searches

In Run 1

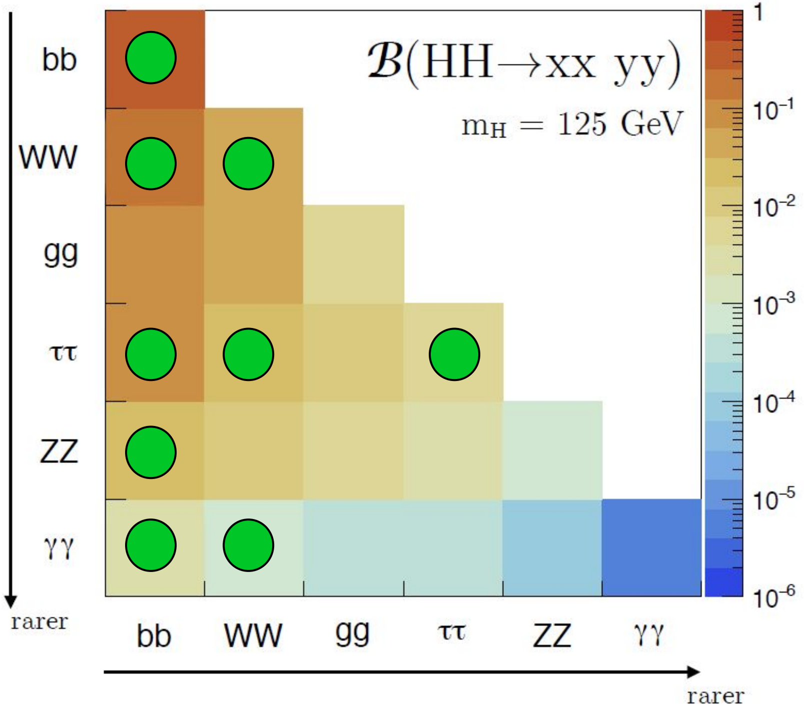


Experimental searches performed in many final states

"Higgs hunter's rule": larger BR corresponds to lower purity and vice versa

HH Experimental Searches

In Run 2: many **new final states** explored!



And many **new measurements** performed!

- k_λ
- k_{2V}
- VBFHH and VHH production modes

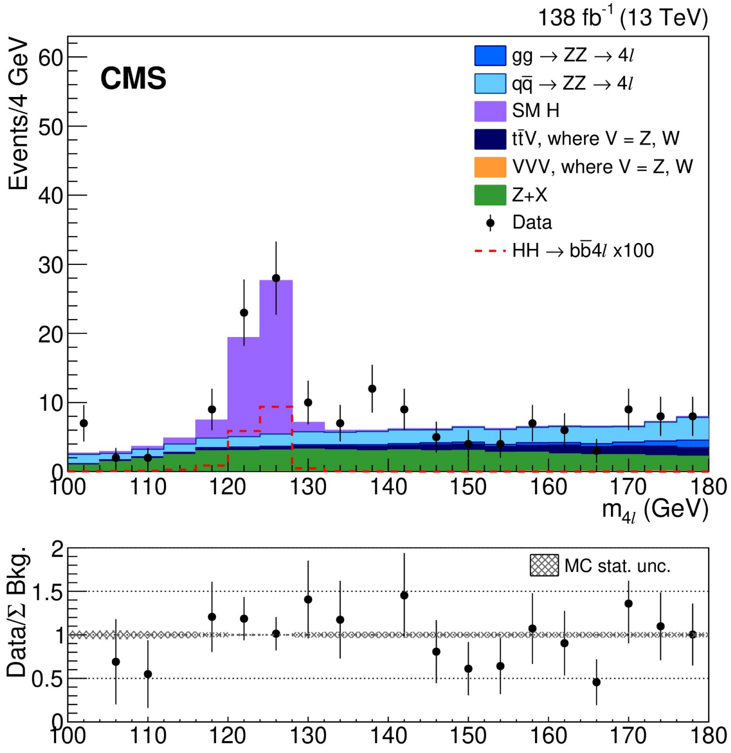
HH Search in Rare Channels: bb4l

First result in this channel!

→ **Clear signature** thanks to 4l decay, but **tiny BR = 0.014%** @mH=125GeV

- Triggers: single/double/triple and cross *e*, μ
- Selection:
  2 pairs of OS SF leptons (e,μ) forming ZZ cand + **at least 2** AK4 **jets** with pT>20GeV and **|η|<2.4**
- If >2 jets in event, those with higher btag score (deepCSV) selected
- **Signal region**: 115<m4l<135

To veto VBFH(4l) events



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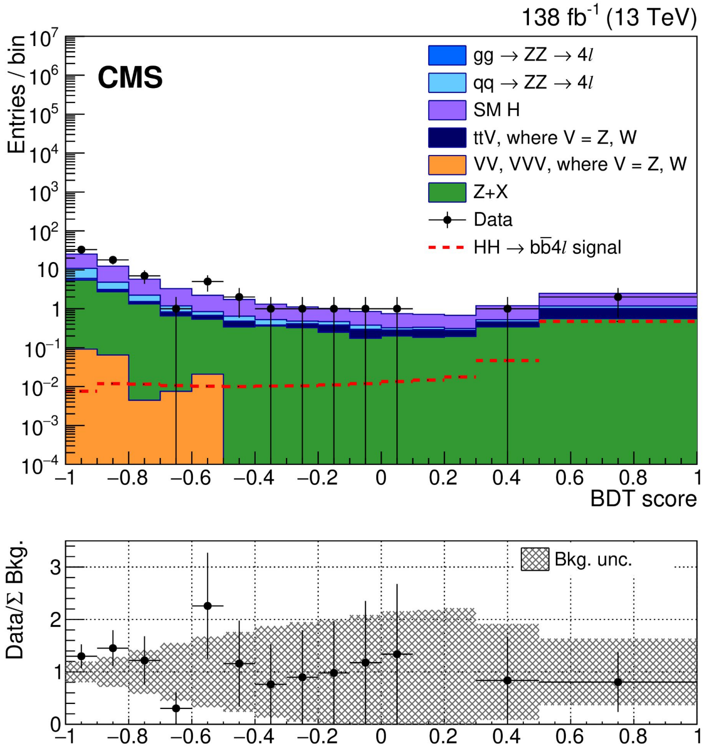
HH Search in Rare Channels: bb4l

- backgrounds: single H and ZZ production (from MC), reducible background (from data)
- **BDT** to separate signal from background
- Results extracted fitting BDT discriminant

Observed (expected) limits @95% CL:

- σ(HH→bb4l) < **32.4** (39.6) σ_{SM}
- **-8.8 < k_λ < 13.4** (-9.8 < k_λ < 15.0)



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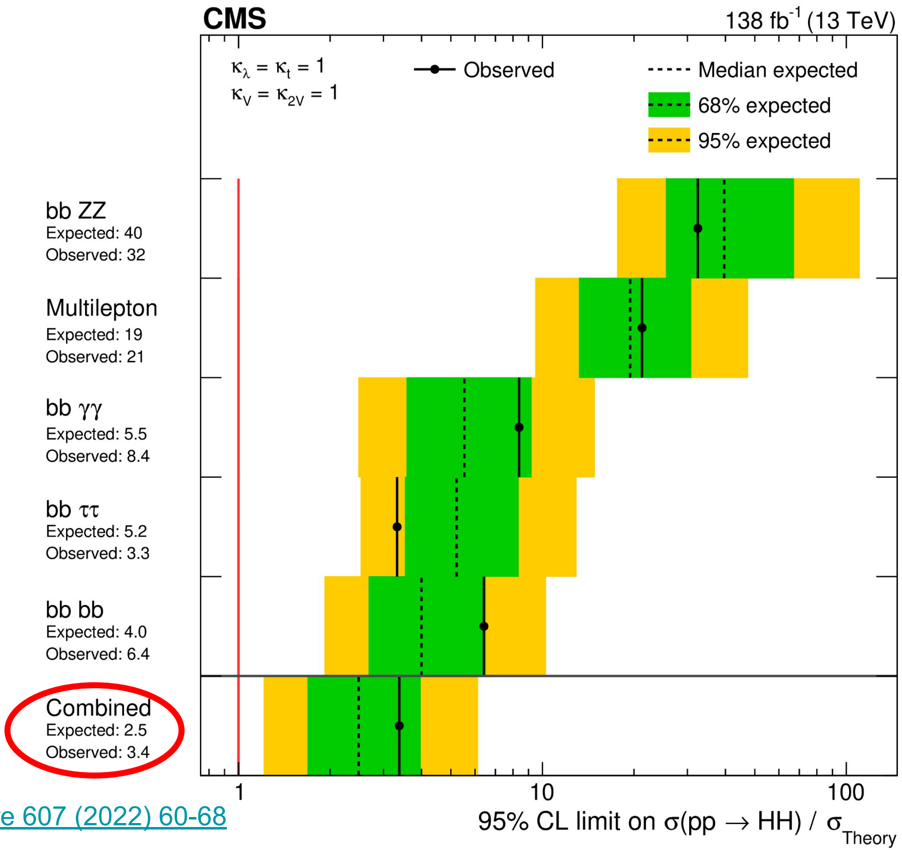
Full Run 2 Combination

Limit on **production cross-section** from full Run 2 combination of many channels

σ(HH) < **3.4** (2.5) σ_{SM}

Improvements w.r.t previous combinations (2016 results: σ(HH) < 22 (12) σ_{SM}) thanks to:

- analyses improvement/optimization
- object tagging improvement and trigger development
- addition of new channels



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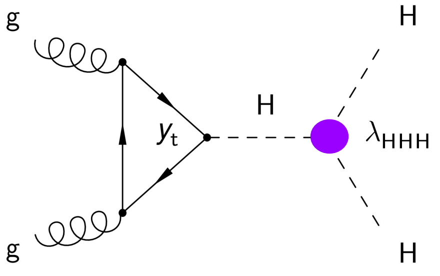
Limits on trilinear coupling

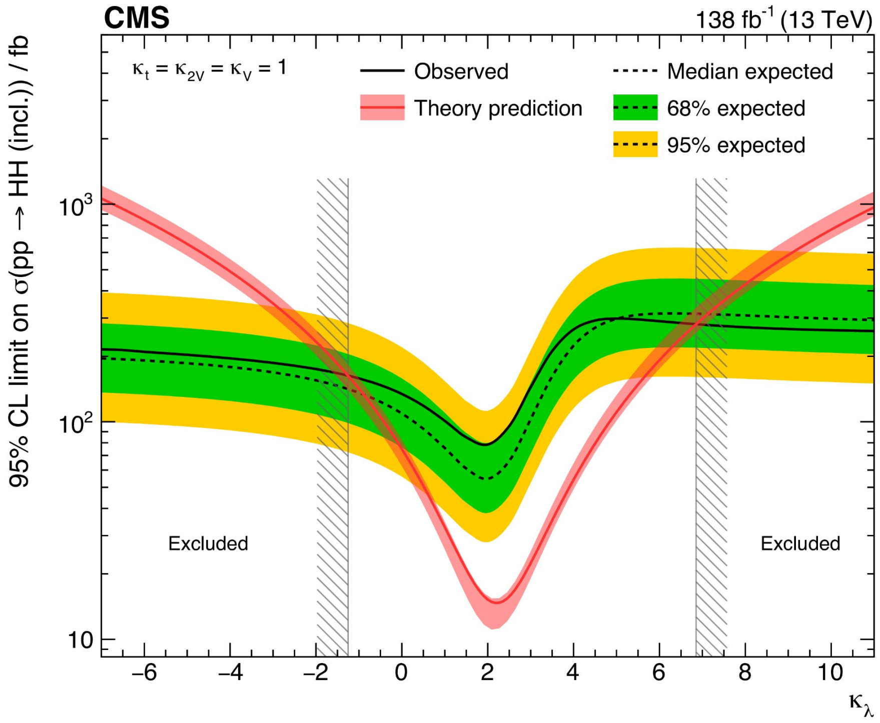
Nature 607 (2022) 60-68



Observed (expected) limits at 95% CL:

-1.24 (-2.28) < $\boldsymbol{k_\lambda}$ < **6.49** (7.94)

Assuming SM values for all other ks



Limits on quartic coupling

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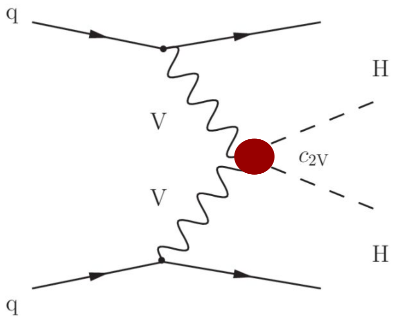
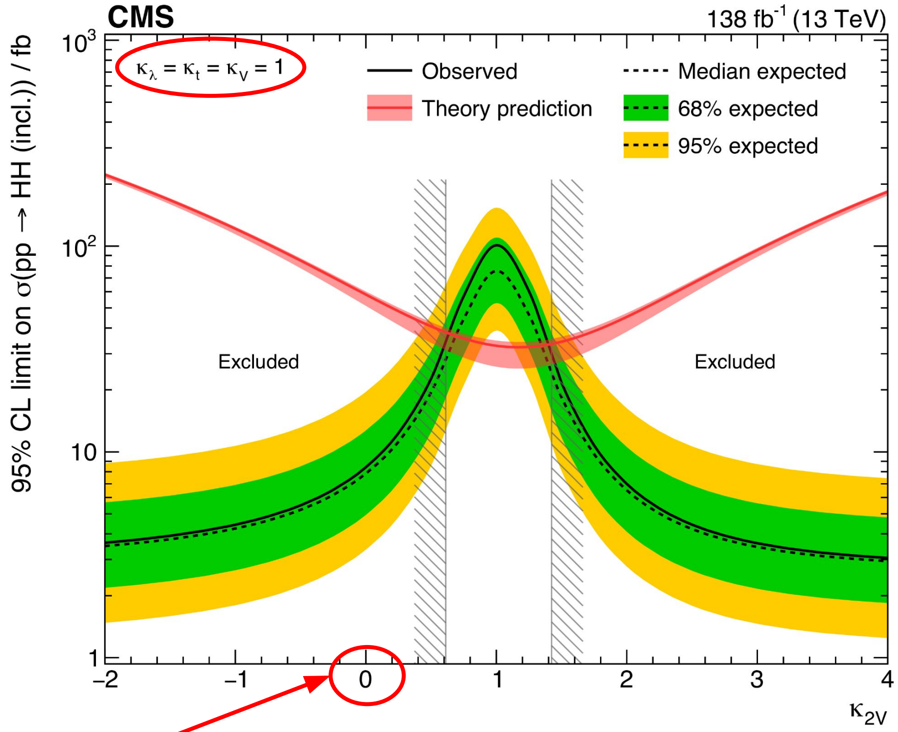


Observed (expected) limits at 95% CL:

0.67 (0.61) < k_{2V} < **1.38** (1.42)

Assuming SM values for all other ks



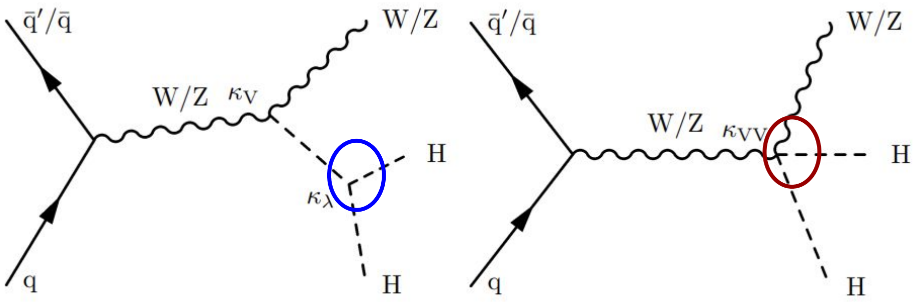
k_{2V} = 0 excluded!

Search for VHH

CMS-PAS-HIG-22-006

Search for **VHH non-resonant**, in HH→bbbb
→ compensate small σ with large BR (33%)
→ V=W, Z, both leptonic and hadronic decays considered

- Events divided in categories according to the decay of V
- BDT/NN for bkg-signal separation

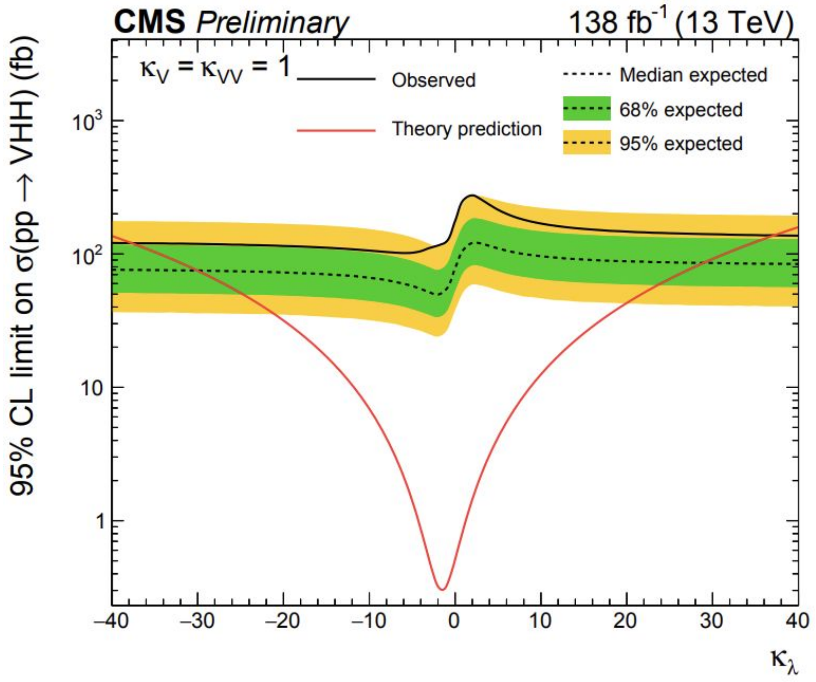


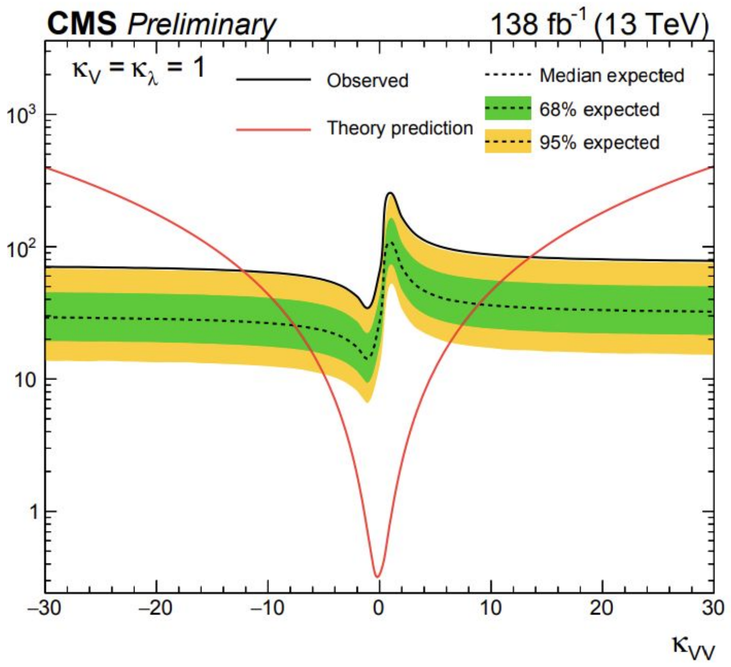
Observed (expected) limits at 95% CL:

σ(VHH) < **294** (124) σ_{SM}

Search for VHH

CMS-PAS-HIG-22-006





-37.7 (-30.1) < $\boldsymbol{k_\lambda}$ < **37.2** (28.9)

-12.2 (-7.2) < $\boldsymbol{k_{VV}}$ < **13.5** (8.9)

Final states with multiple Gauge and Higgs Bosons

Final states suitable to investigate **VVHH interactions**

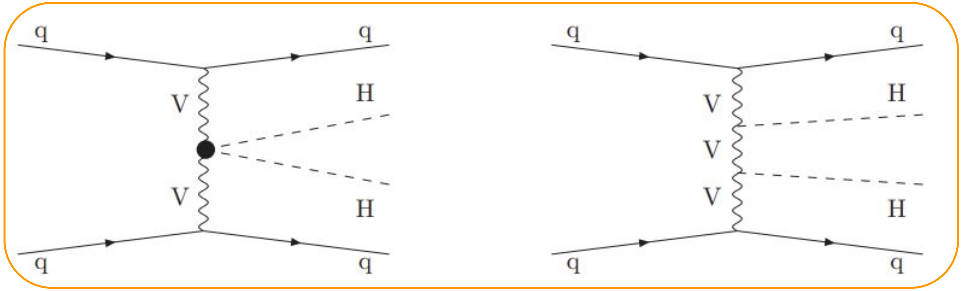
In this work:

- 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

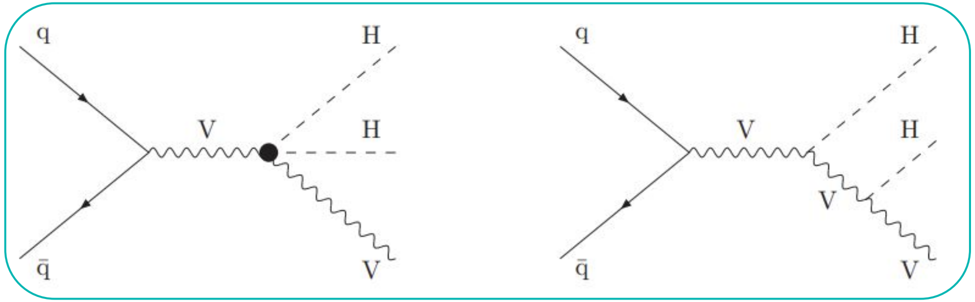
Results in JHEP09(2022)038

Processes Considered

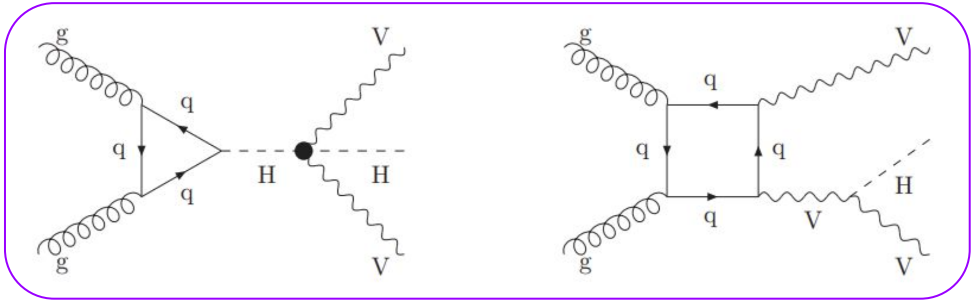
VBF-HH



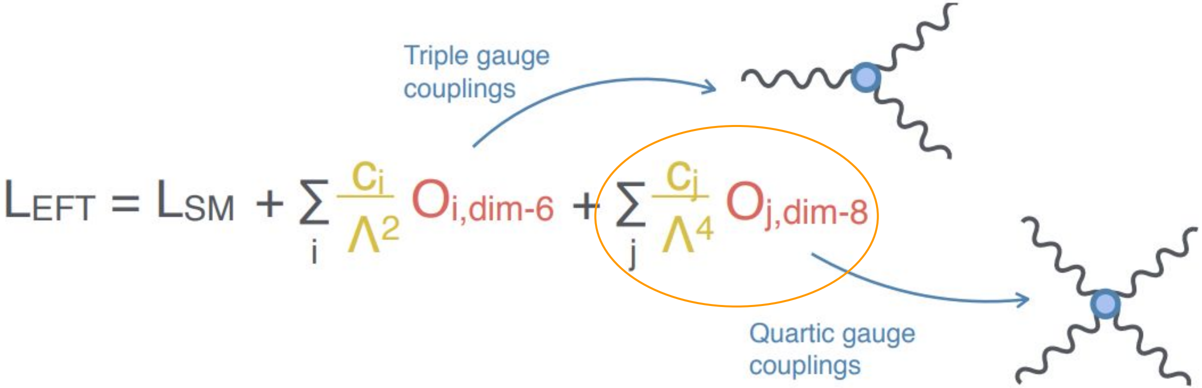
ZHH



gg→ZZH



EFT Framework



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

- 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

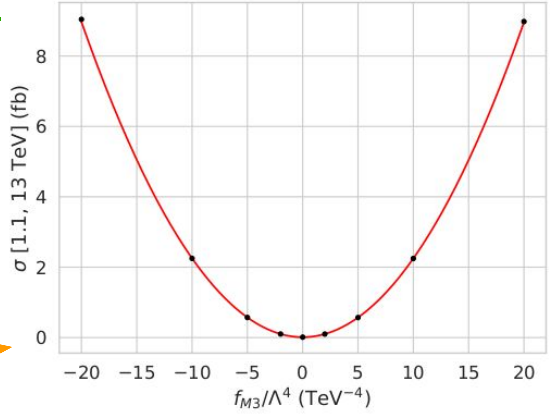
$$\mathcal{O}_{M,0} = \text{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] \times [(D_\beta\Phi)^\dagger D^\beta\Phi]$$
$$\mathcal{O}_{M,1} = \text{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}] \times [(D_\beta\Phi)^\dagger D^\mu\Phi]$$
$$\mathcal{O}_{M,2} = [B_{\mu\nu}B^{\mu\nu}] \times [(D_\beta\Phi)^\dagger D^\beta\Phi]$$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

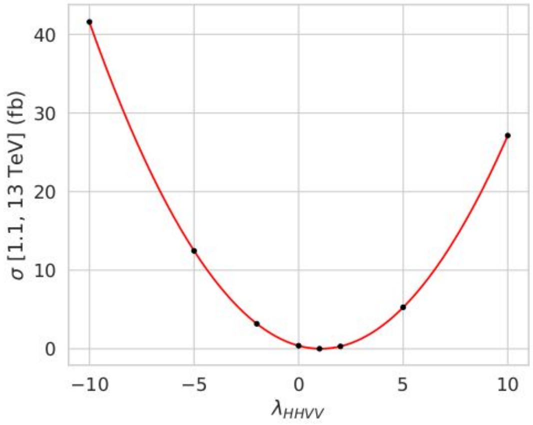
Mixed

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 **k_{2V} variations** (k_{2v} = {0, 1, ±2, ±5, ±10})



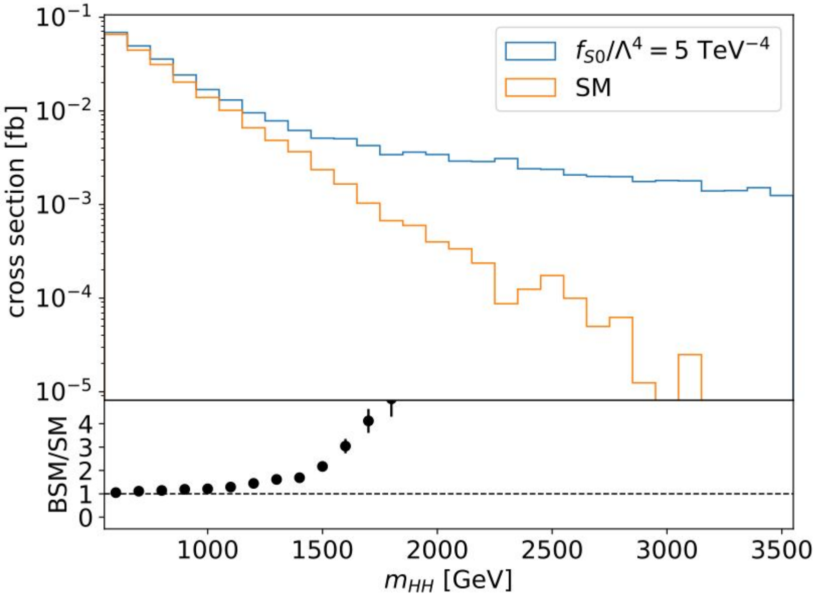


Observable used to estimate the EFT sensitivity:

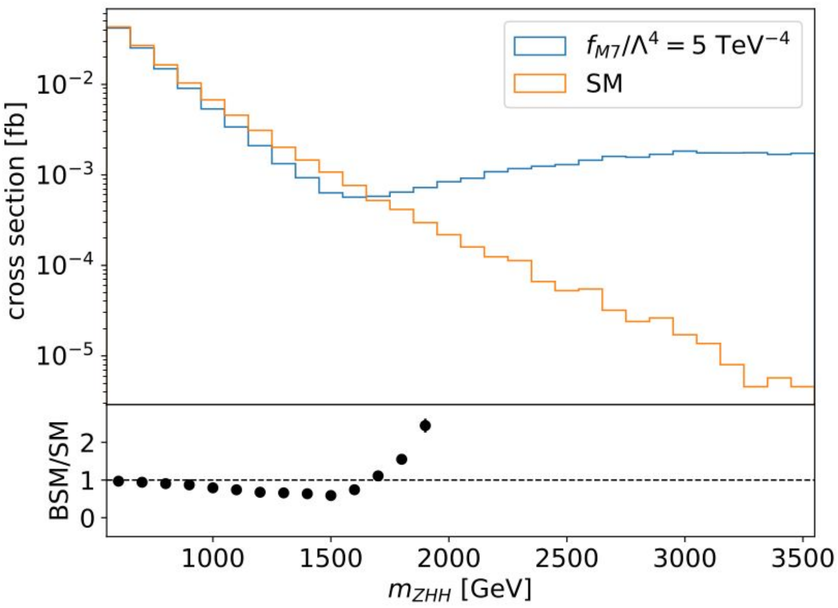
- **$\sigma[m_{min}, m_{max}]$** (cross-section in mass interval)
  m = invariant mass of the di- or tri- boson states
  m_{min} = 1.1TeV, m_{max} = $\sqrt{s}$

The effect of SMEFT

VBF-HH



ZHH

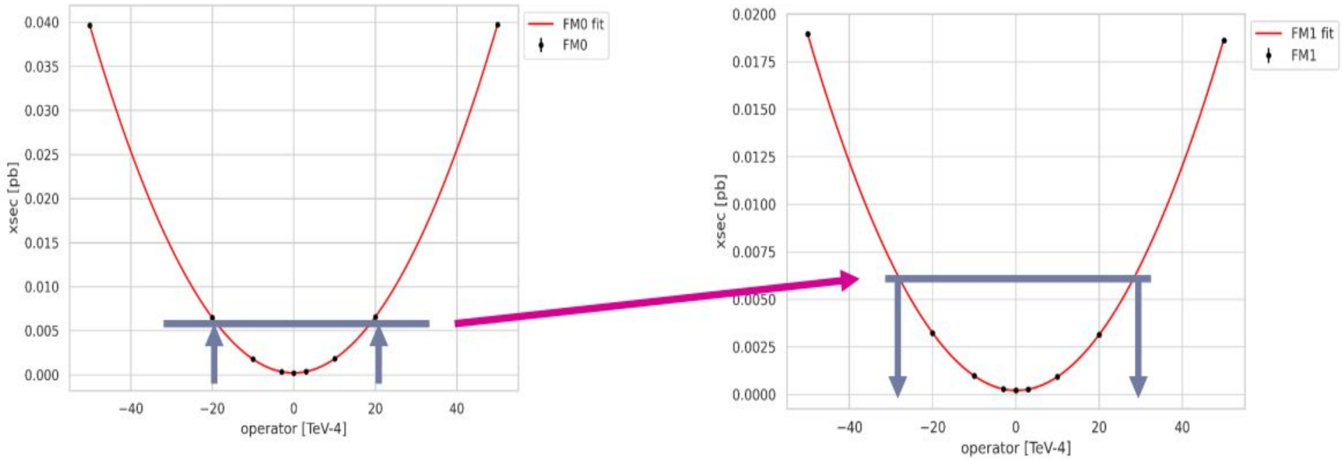


Validation on VBS

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

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 on VBS

- CMS results found to be incomplete, several operators not examined
- **Validation successful**: manage to reproduce results ✅

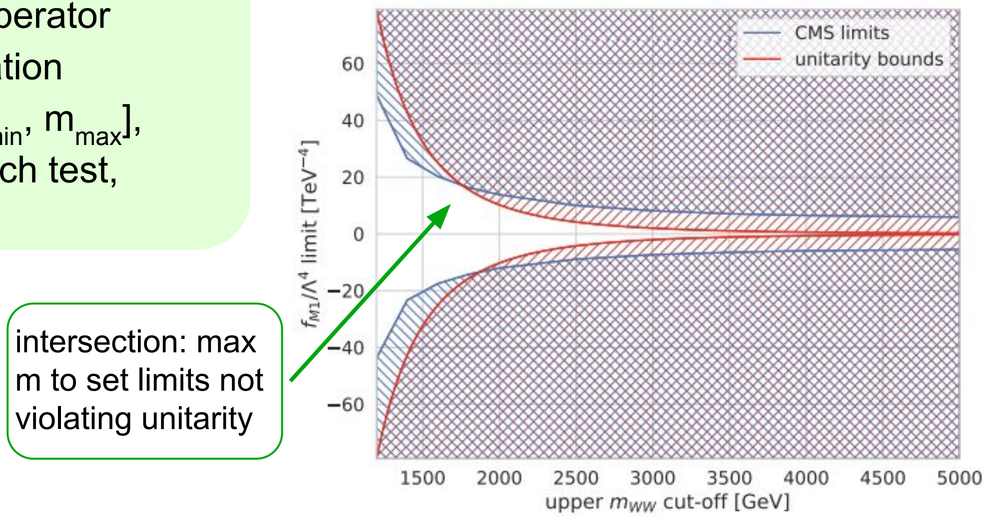
	VBS $W^{\pm}W^{\pm} \to 2\ell 2\nu$		VBS $W^{\pm}Z \to 3\ell\nu$		VBS $W^{\pm}V$ semileptonic	
Coeff.	CMS exp.	estimated	CMS exp.	estimated	CMS exp.	estimated
f_{M0}/Λ^4	[-3.7,3.8]	[-3.9,3.7]	[-7.6,7.6]	input	[-1.0,1.0]	[-1.0,1.0]
f_{M1}/Λ^4	[-5.4,5.8]	input	[-11,11]	[-11,11]	[-3.0,3.0]	[-3.1,3.1]
f_{M2}/Λ^4	/	/	–	[-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 **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
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

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 $W^{\pm}W^{\pm}\rightarrow 2l2\nu$



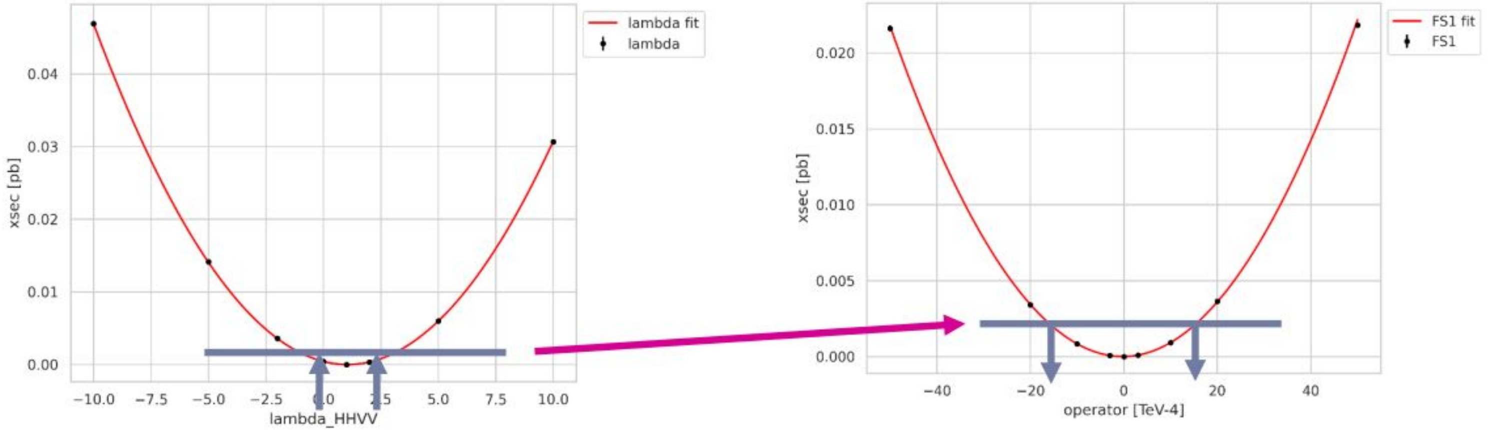
- Limits obtained w/ unitarity less stringent than those w/o
- If curves do not cross, available data are not enough to set more stringent limits than those imposed by unitarity

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

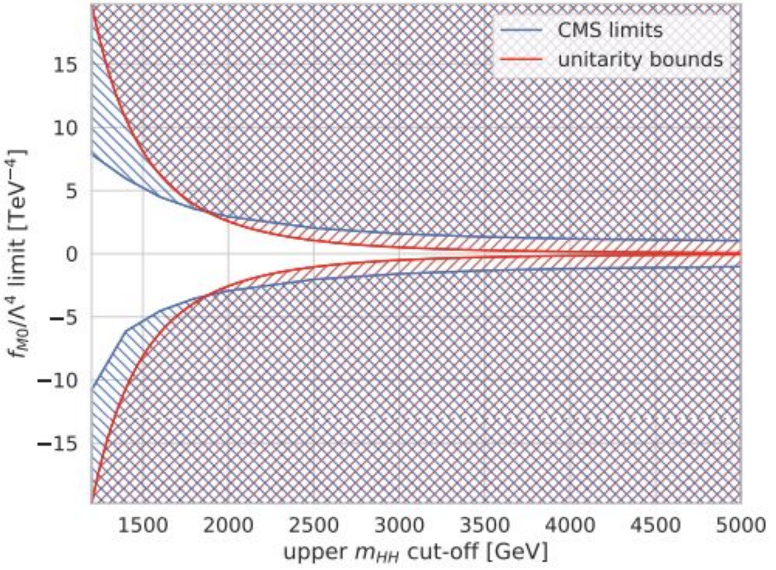
Validation: use limits on f_x as input and re-produce CMS limits on k_{2V}



VBFHH Results

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

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

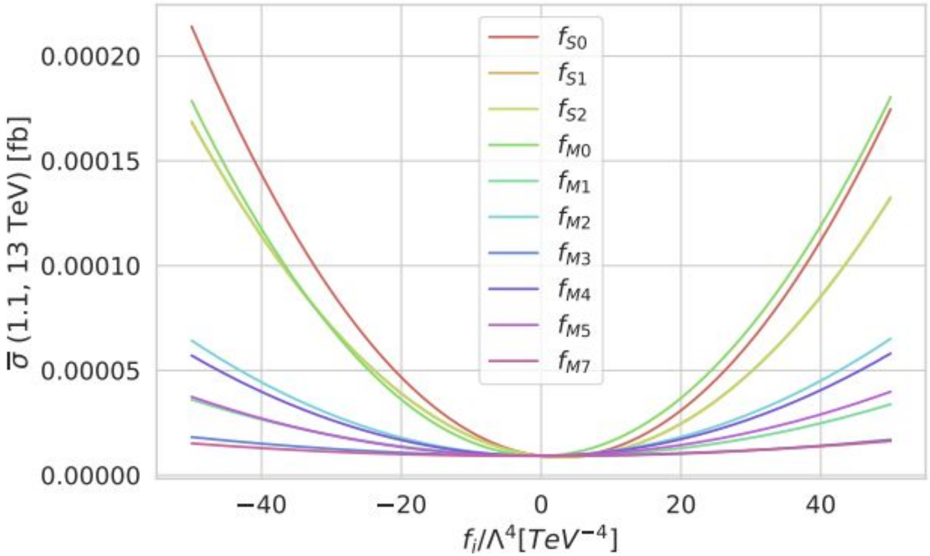
- Estimate the **number of detectable events**: $N = \sigma \cdot L \cdot \varepsilon \cdot A$
    - Decays: H→bb and Z→ll (l=e, μ)
    - Acceptance (A) requirements, typical LHC requirements:
      $p_T(b) > 30$ GeV, $p_T(e, \mu) > 20$ GeV
      $|\eta(b)| < 2.5$, $|\eta(e, \mu)| < 2.4$
    - Efficiency (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**

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: $gg \to ZZH$

- Loop Induced process
- Very low σ
- $H \to bb$ and $Z \to ll$ ($l = e, \mu$) considered
- Even with large variations of Wilson coefficients σ remains small
  $\to$ 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

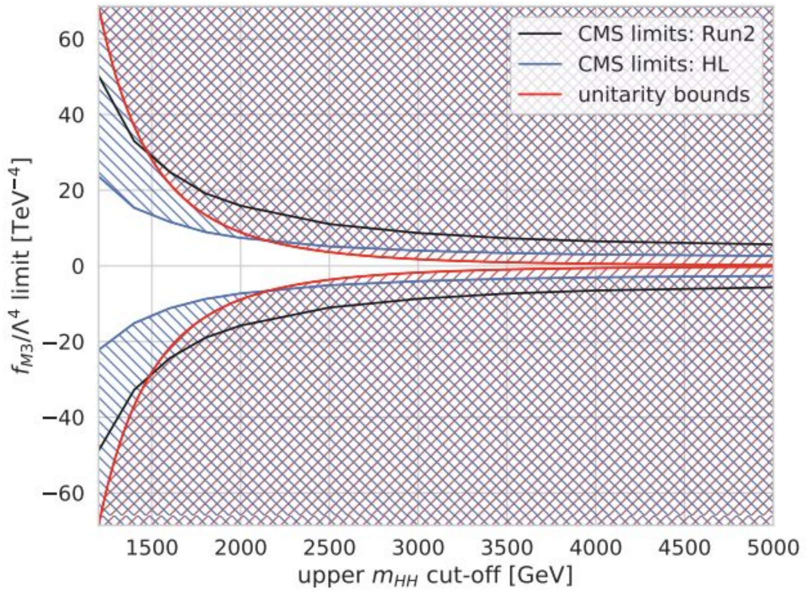


Perspectives for HL-LHC: VBFHH

- Limits w/o unitarity obtained rescaling the excluded σ by $L^{-1/2}$ (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

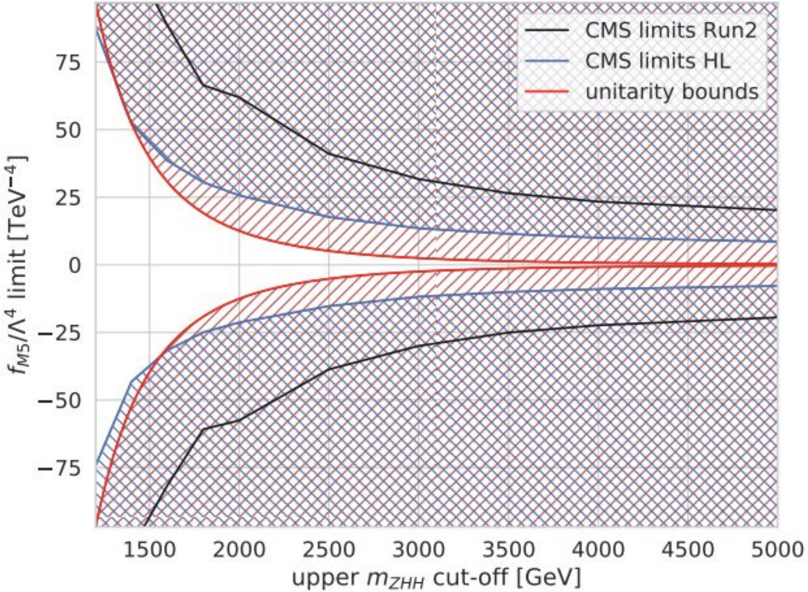
→ limits improve by factor 4-5
→ first physical limit on f_{S1}

	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**
- 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

Considered multiboson, in particular **multi-Higgs**, interactions

- limits from CMS experiment on HHH and VVHH couplings set on couplings modifiers from ggHH, VBFHH, VHH production
- for VVHH, not possible to directly combine with other anomalous couplings
  → reinterpretation in SMEFT needed

Presented study that reinterprets experimental results on k_{2V} limits in terms of constraints on Wilson Coefficients of **dim-8** SMEFT operators

- VBFHH can set limits comparable or even more stringent than those from VBS
  → this time, combination with results from VBS possible!

COMETA European COST Action

Comprehensive Multiboson Experiment-Theory Action (COMETA)

Aim: improve measurements and interpretation of **multiboson** processes at LHC

Involves experts from **theory** and **experimental** HEP, and **AI experts** within and outside academia

Foster **communication** between diverse research groups to develop advanced technology

Create an inclusive environment for **young** scientists, promote researchers in underfunded European countries

20+ EU countries involved
150+ members
~150k€/year for 4 years

More info:
COMETA website
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If interested, you can **join** via this page!

Next event: 1st COMETA General meeting next week!