Results on Higgs-pair production in CMS

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On behalf of the CMS collaboration

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Outline

- Di-Higgs motivation searches
- Survey of CMS results with 13 TeV data
- Run3 and HL-LHC prospects
- Summary

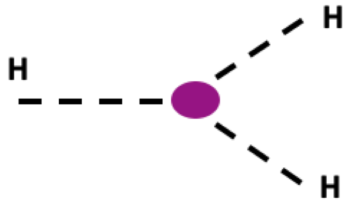
Higgs Pair Production

- The **precision measurement** of the Higgs boson properties is one of the **primary targets @LH**
- The SM description of the **Higgs potential** is encoded with two parameters: *mH*, *λ*
- The measurement of σ(HH) is the best way to extract the Higgs self-coupling **λ3**

$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 u H^3 + \frac{1}{4} \lambda_4 H^4$$

- $\frac{1}{2} m_H^2 H^2$: Higgs Discovery (2012)
- $\lambda_3 u H^3$: Trilinear self coupling λ3 Direct access via HH production
- $\frac{1}{4} \lambda_4 H^4$: Quartic self-coupling λ4 Responsible for HHH

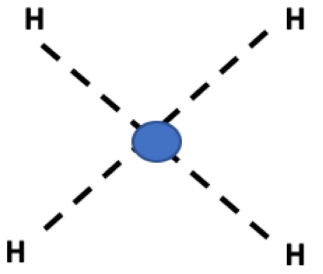
λ3 →



expect observation in HL-LHC

λ3=λ4 in the SM

λ4 →



out of reach at current colliders

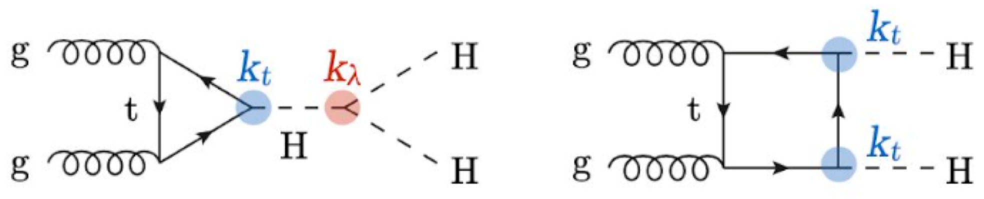
Kappa framework approach- Test accuracy and deviation from the SM

for every coupling c , $\boldsymbol{\kappa_c = c^{obs}/c^{SM}}$

Di-Higgs Pair Production

The di-Higgs cross section depends on the production mode, but it’s **~1000 times rarer than single-Higgs**

At the LHC HH pairs are mainly produced through **gluon gluon fusion** (ggF) via a fermionic loop

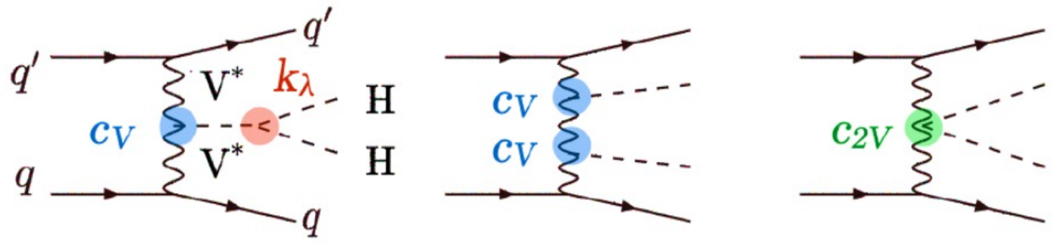


Destructive interference between square and triangle

σ_{ggF} =32.05 fb @NNLO

Direct access to κ_λ where $\kappa_\lambda = \lambda_3/\lambda_{3SM}$

Second leading production through **Vector Boson Fusion (VBF)**



Signature from high energy jets

σ_{VBF} = 1.73 fb @NNLO

Direct access to κ_λ, κ_V , κ_{2V}

Unique handle to study the quartic HHVV (κ_{2V}) coupling

HH production probe for BSM

Non-resonant signature

Low energy effect of new physics that modify the Higgs bosons' interactions:

κ framework approach: modify HHH vertices

deviations from the SM are modelled by couplings modifiers kappa

Non-SM modifications to ggHH

Higgs Effective Field Theory (HEFT) approach:

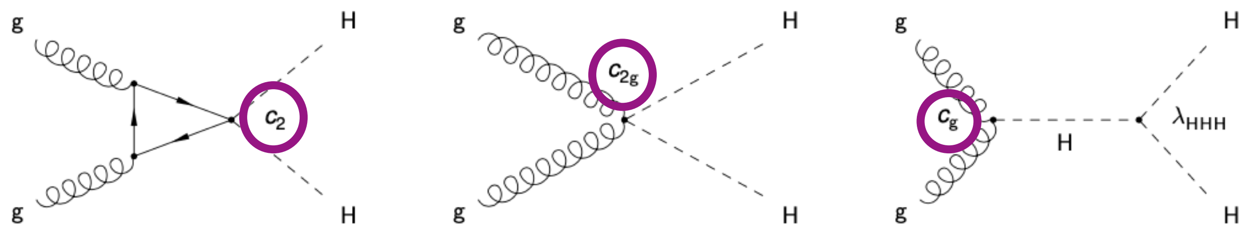
introduce operators with a strength

given by Wilson coefficient

explore sensitivity to BSM EFT couplings

with **20 shape benchmarks points** (JHEP03(2020)091, JHEP04(2016)126)

additional ggF couplings (c2,cg,c2g)

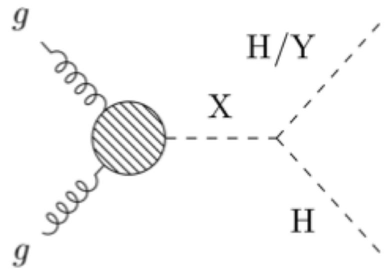


Resonant signatures

Direct production of a new state X→HH

Significance cross-section enhancement on resonance

Large set of BSM scenarios: various M_X hypothesis and search channels



Di-Higgs Final State

- Higgs boson decay branching ratios result in rich set of final states
- All decay channels are a compromise between Branching Ratio (BR) and final state signal purity (S/B) (no golden channel)

Final states that drive the sensitivity "silver channels":

H(bb)→good branching ratio

H(ττ), H(γγ)→good signal purity

Run1: a few channels

Run2: H->bb or multileptons

Full Run2: many new final states covered

	bb	$WW_{>=1l}$	WW_{4q}	ττ	ZZ	γγ
bb	34%					
$WW_{>=1l}$	13.4%	1.3%				
WW_{4q}	11.6%	1.1%	2.1%			
ττ	7.3%	1.4%	1.2%	0.39%		
ZZ	3.1%	0.6%	0.2%	0.33%	0.069%	
γγ	0.26%	0.06%	0.04%	0.028%	0.012%	0.0005%

Overview of Di Higgs CMS results

HH->bbbb (highest branching fraction, large multijet background)

- *Phys.Rev.Lett.129,081802* (*resolved*)
- *CMS-PAS-B2G-21-001* (*VBF boosted*)
- *Submitted to JHEP* (*VHH*)
- *Submitted to Eur. Phys. J. C* (*ZZ/ZH*)

HH → bb̄ ττ (relatively large branching fraction, cleaner final state)

- *Phys.Lett.B842(2023)137531*

HH→bb̄ γγ (small branching fraction, clean signal signature h → γγ mass peak)

- *JHEP03(2021)257*

***HH → bb̄ VV* / Multileptons** (low branching fraction, but clean leptonic final states)

- *JHEP07(2023)095*(4W/WWττ/4τ,≥2l)
- *JHEP 06 (2023) 130* (*bbZZ, 4l*)
- *CMS-PAS-HIG-21-005*(*bbWW,≥1l*)
- *CMS-PAS-B2G-21-001*(*γγWW*)
- *CMS-PAS-HIG-22-012* (γγττ)

More final states are covered

	bb	$WW_{>=1l}$	WW_{4q}	ττ	ZZ	γγ
bb	34%					
$WW_{>=1l}$	13.4%	1.3%				
WW_{4q}	11.6%	1.1%	2.1%			
ττ	7.3%	1.4%	1.2%	0.39%		
ZZ	3.1%	0.6%	0.2%	0.33%	0.069%	
γγ	0.26%	0.06%	0.04%	0.028%	0.012%	0.0005%

Limits on Di-Higgs Production

	bb	$WW_{>=1l}$	WW_{4q}	ττ	ZZ	γγ
bb	34%					
$WW_{>=1l}$	13.4%	1.3%				
WW_{4q}	11.6%	1.1%	2.1%			
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γγ	0.26%	0.06%	0.04%	0.028%	0.012%	0.0005%

Leave no phase-space unturned

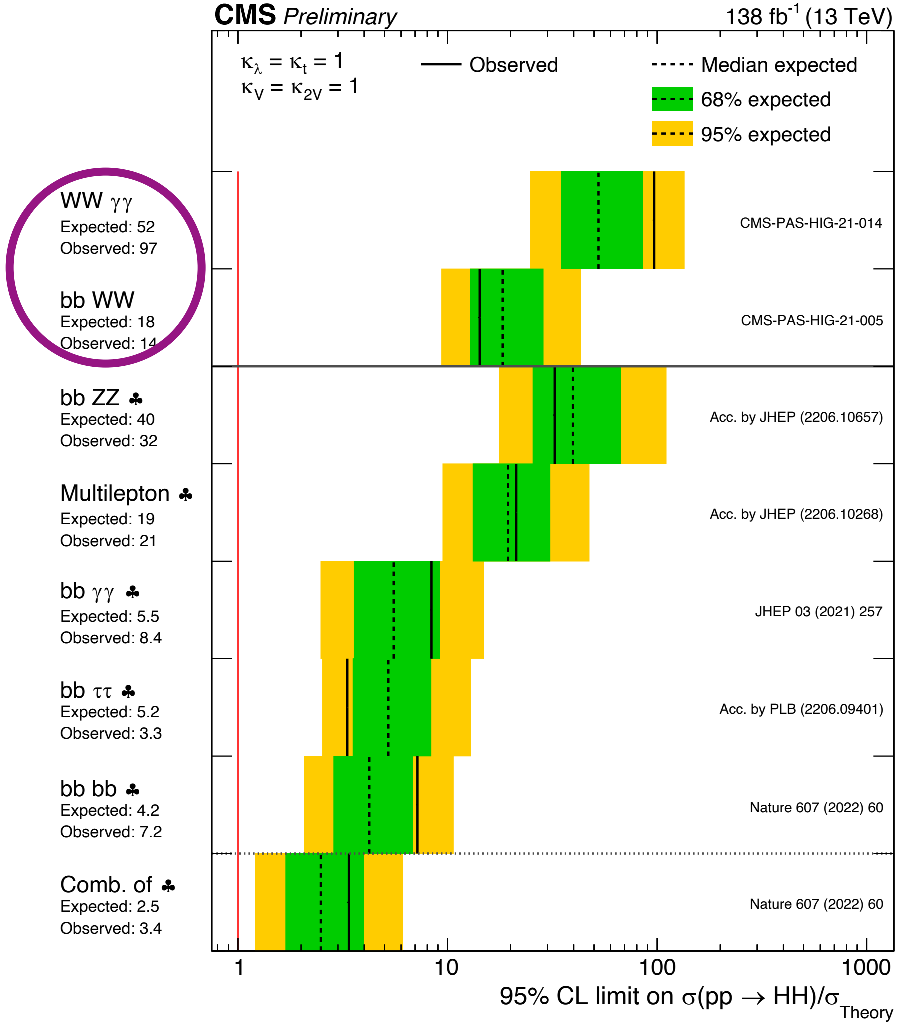
New additions since Nature paper: WWγγ, bbWW

WWγγ: Clean γγ peak, leptonic final states or jets

bbWW: Second largest branching fraction

Large background. Final states with at least one lepton cleaner.

Key is in the combination



CMS Higgs results

Combined sensitivity on σ/σ_{SM}

CMS

$\sigma_{HH} < \mathbf{3.4}\ \sigma^{SM}_{HH}$

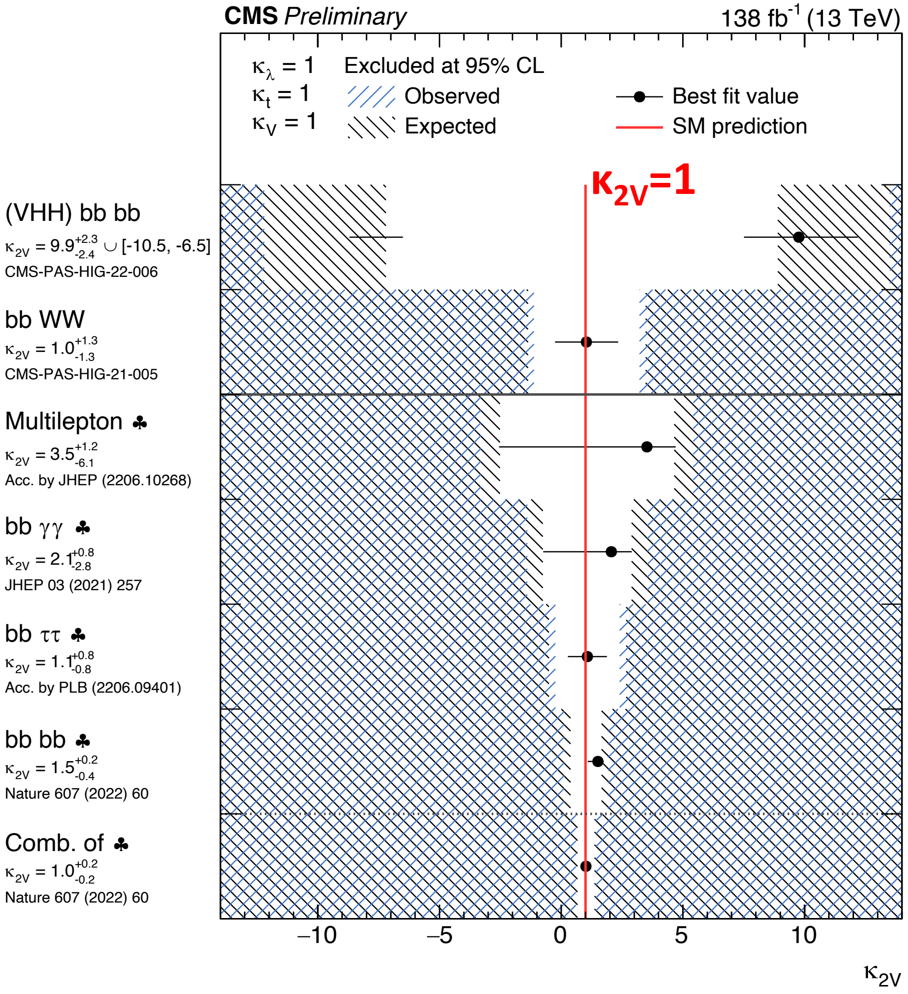
$\kappa_\lambda \in [-1.24, 6.49]$

$\kappa_{2V} \in [0.67, 1.38]$

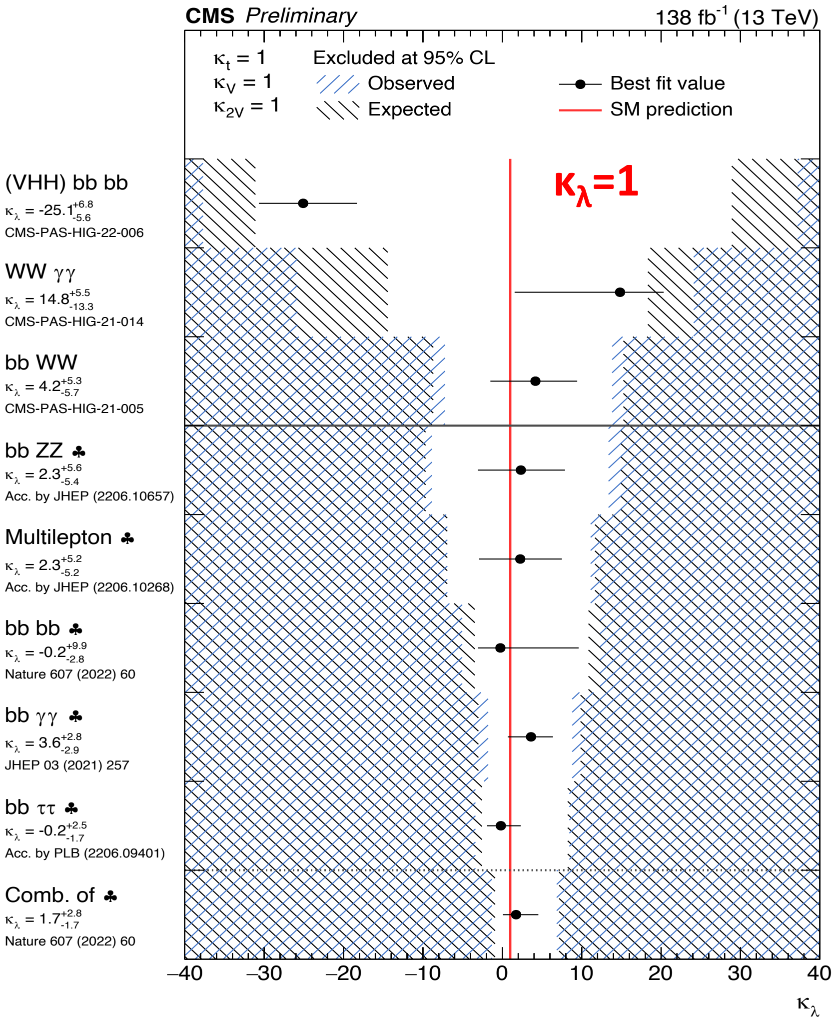
Run 2 Combination

[CMS Summary](#)

κ_{2V}= 0 is excluded at 6.6σ



$0.67 < \kappa_{2V} < 1.38$



$-1.24 < \kappa_{\lambda} < 6.49$

Overview of Di-Higgs CMS results

Newest results

bbVV fully hadronic

CMS-PAS-HIG-23-012

γγττ
CMS-PAS-HIG-22-012

H + HH combination
CMS-HIG-23-006

WWγγ
CMS-PAS-HIG-21-014

bbWW
JHEP 07 (2024) 293

More final states are covered

	bb	$WW_{>=1l}$	WW_{4q}	ττ	ZZ	γγ
bb	34%					
$WW_{>=1l}$	13.4%	1.3%				
WW_{4q}	11.6%	1.1%	2.1%			
ττ	7.3%	1.4%	1.2%	0.39%		
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γγ	0.26%	0.06%	0.04%	0.028%	0.012%	0.0005%

results on Di-Higgs Production will be presented today

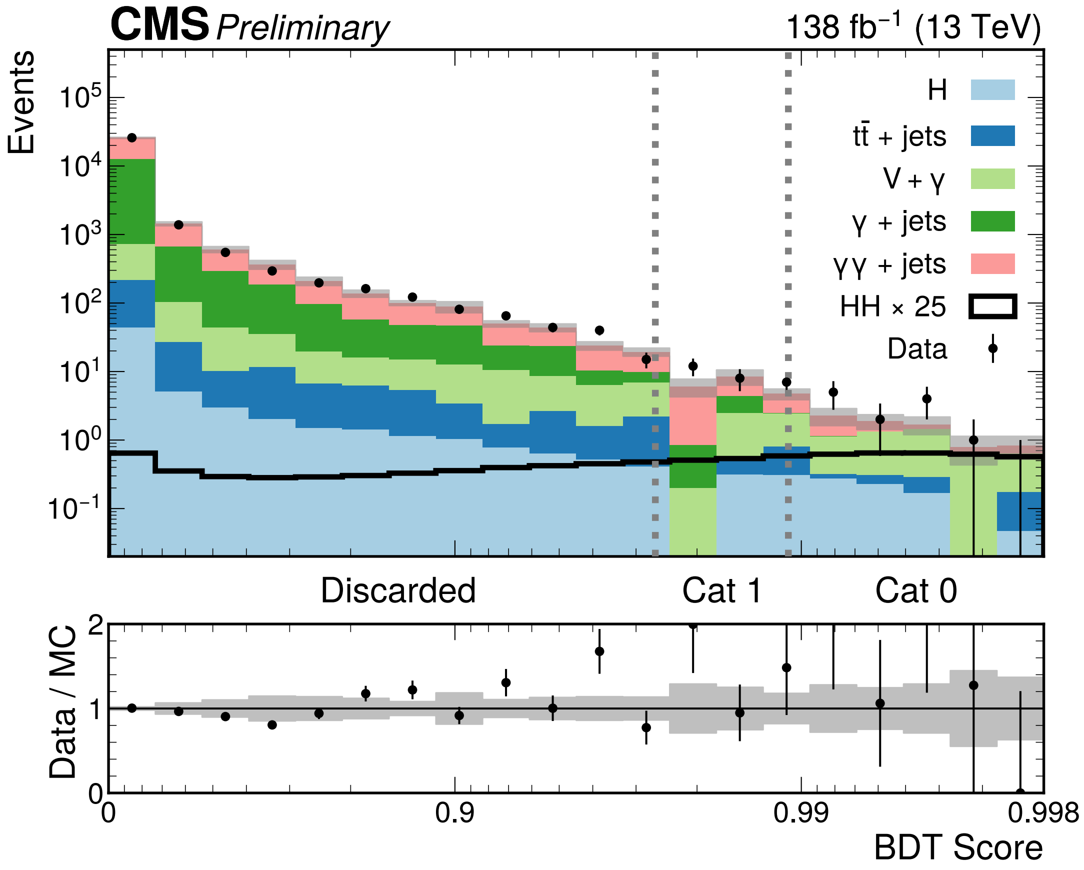
HH->γγττ

CMS-PAS-HIG-22-012

NEW

- **New final state, ggF production mode**
- Standard H→γγ triggers; hadronic + leptonic τ decay modes
- Dominant backgrounds are irreducible γγ+jets and reducible γ+jets

signal enriched categories



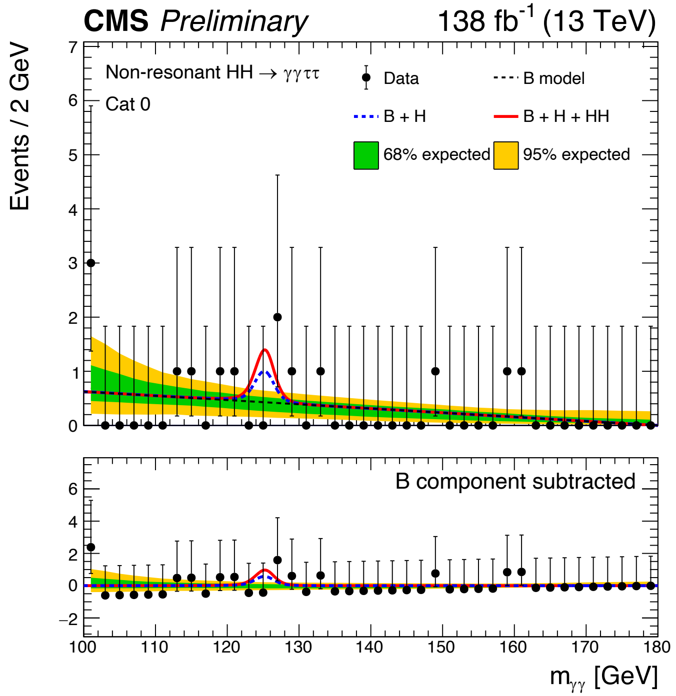
Analysis strategy

- BDT is trained using kinematic features
- Fit mγγ in signal-enriched categories
- Signal models derived from fits to the MC with a Double Crystal Ball (DCB)
- signal and H→γγ background are taken from simulation.

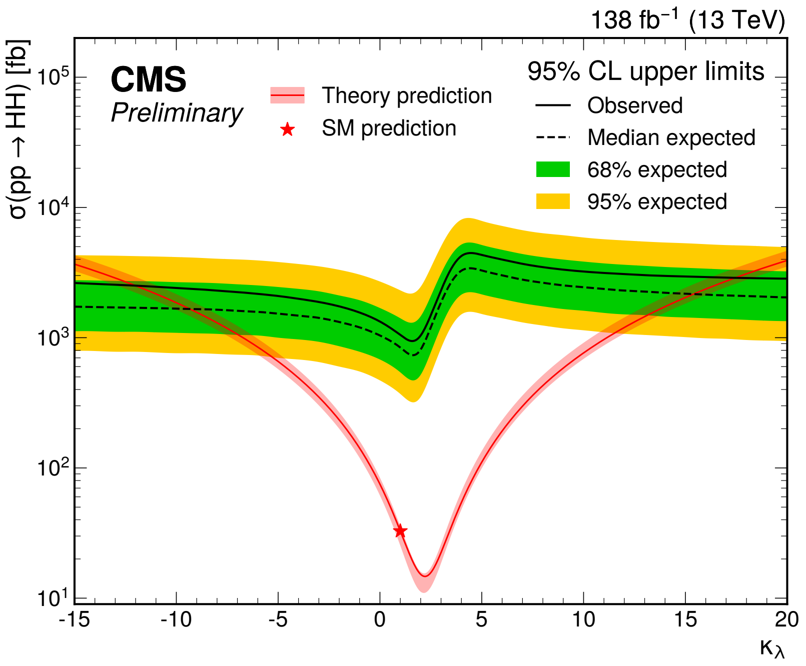
HH->γγττ

Results are expected to add in sensitivity on HH future combination

Observed (expected) 95% CL limit on $\sigma(HH)$ of 930 (740) fb, or 33 (26) × SM

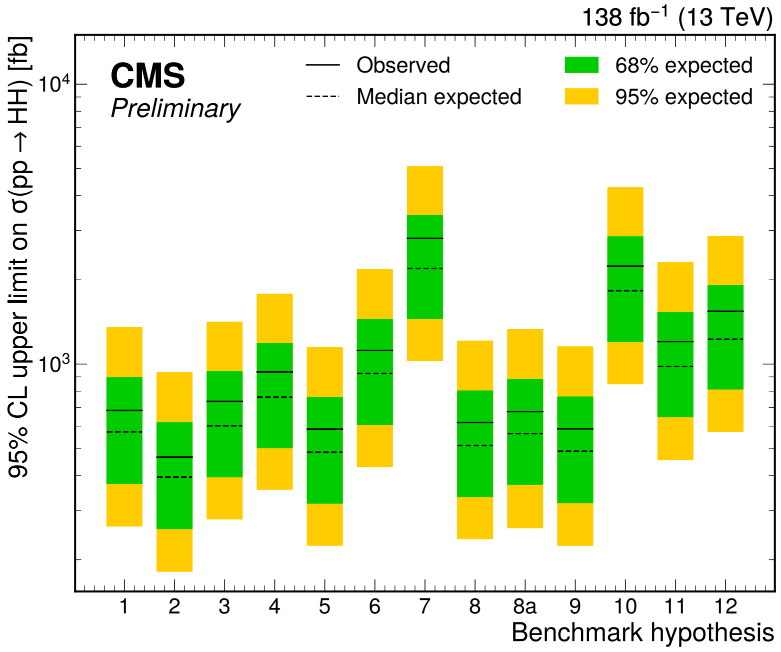


Unblinded mγγ distribution



Assuming other H couplings are SM-like constraints on κ_λ:

κ_λ [−13, 18] ([−11, 16])



Observed and expected 95% CL limits on **EFT benchmarks**

H + HH combination

CMS-HIG-23-006

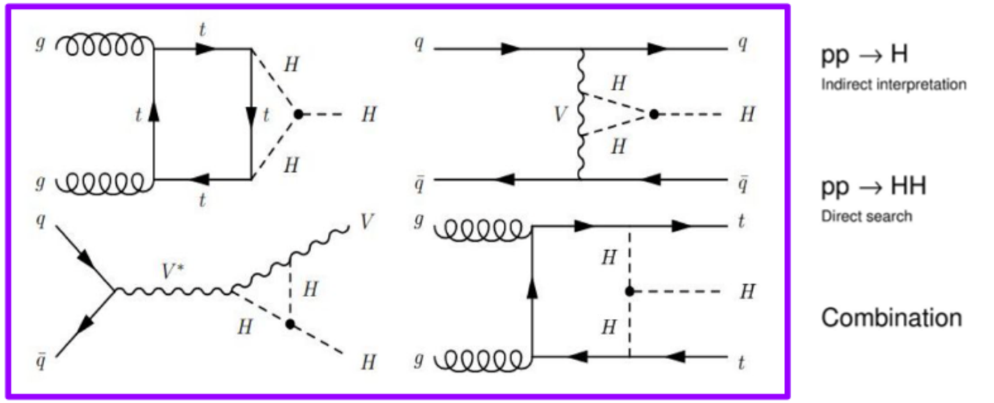
both SH / HH sensitive to -> Combination improves constraints on with Run 2 data

combine all available single H and HH analyses from CMS

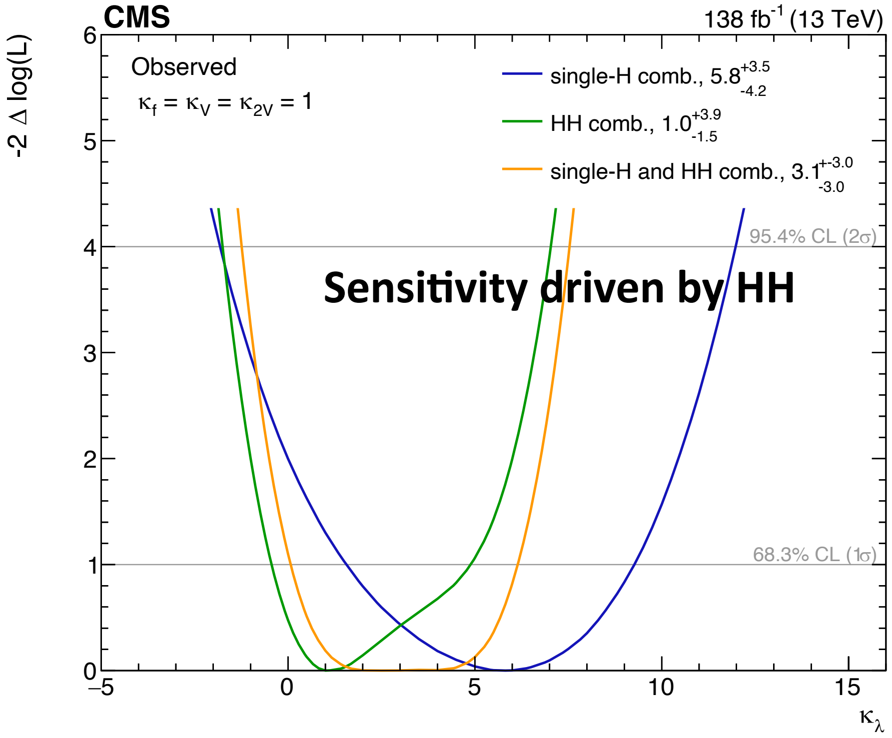
Complementary:

- **HH** more sensitive to κ_λ
- **Single Higgs**: provides stronger constrains on H couplings to fermions and vector bosons

Indirect κ_λ access through NLO contributions to single Higgs production and decay



$\sigma_H > \sigma_{HH}$ Sensitivity to smaller variations



1D likelihood scan of κλ with other couplings fixed to 1

H + HH combination

Analysis	Integrated luminosity (fb^{-1})	Maximum granularity	References
$H \to 4l$	138	STXS 1.2	[34]
$H \to \gamma\gamma$	138	STXS 1.2	[35,none]
$H \to WW$	138	STXS 1.2	[37]
$H \to$ leptons ($t\bar{t}H$)	138	Inclusive	[38]
$H \to b\bar{b}$ (ggH)	138	Inclusive	[39]
$H \to b\bar{b}$ (VH)	77	Inclusive	[40,41]
$H \to b\bar{b}$ ($t\bar{t}H$)	36	Inclusive	[42]
$H \to \tau\tau$	138	STXS 1.2	[43]
$H \to \mu\mu$	138	Inclusive	[44]

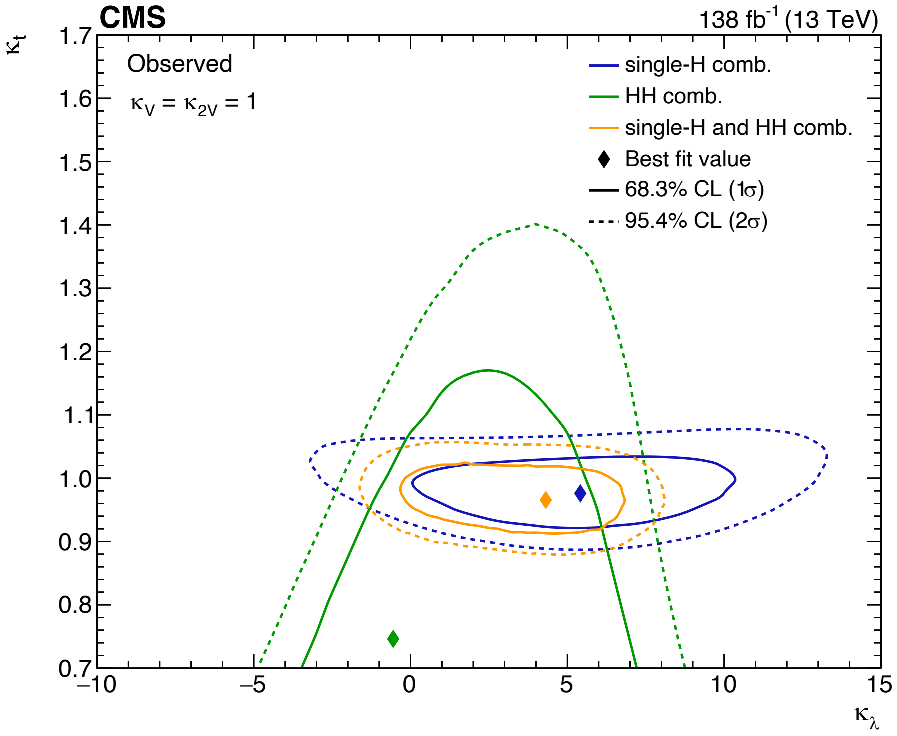
Analysis	Int. luminosity (fb^{-1})	Targeted production modes
$HH \to \gamma\gamma b\bar{b}$	138	ggHH and qqHH
$HH \to \tau\tau b\bar{b}$	138	ggHH and qqHH
$HH \to 4b$	138	ggHH, qqHH and VHH
$HH \to$ leptons	138	ggHH
$HH \to WWb\bar{b}$	138	ggHH and qqHH

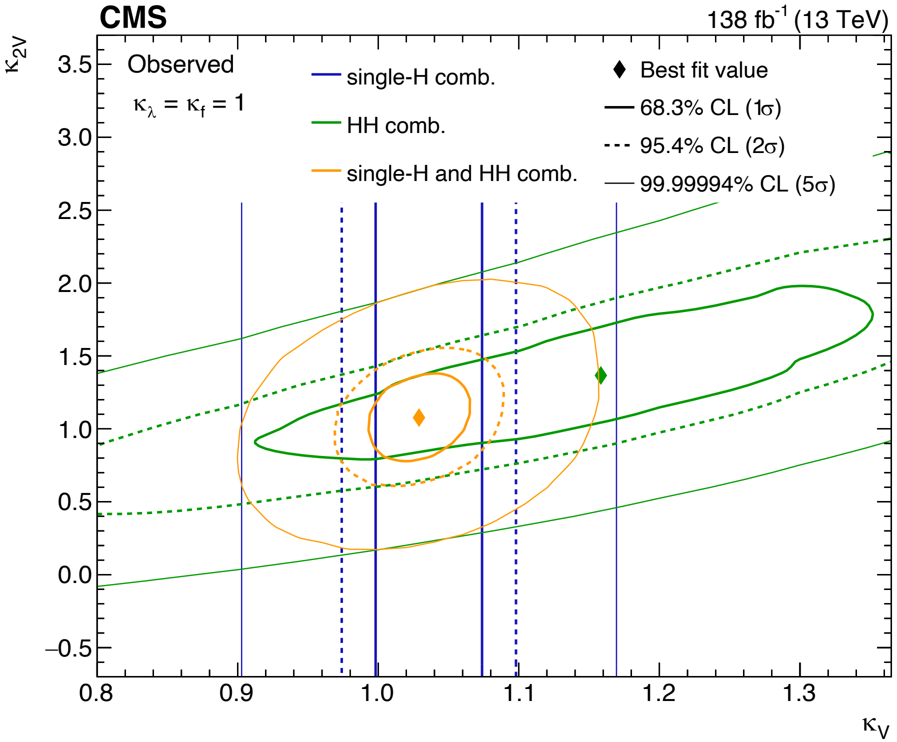
Main challenge: estimate and efficiently remove overlaps between signal region of different analyses

- additional selections are applied and/or
- the least sensitive category/analysis is removed

H + HH combination

Parameters are constrained in 2D





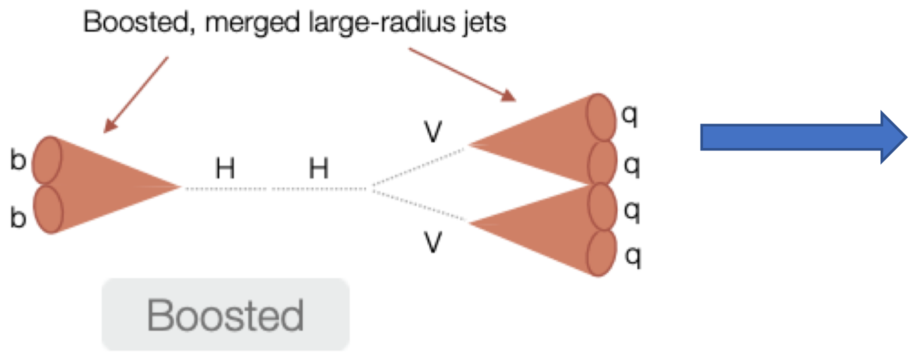
Constrain with single Higgs

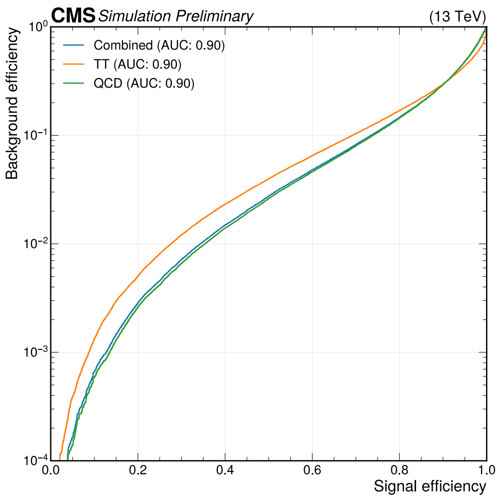
Constrain with HH

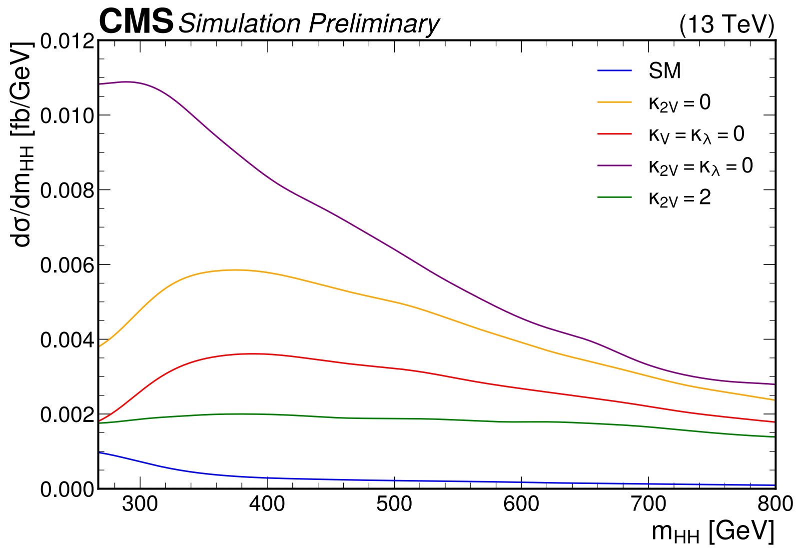
HH → bbVV(4q)

CMS-PAS-HIG-23-012 **NEW**

- Uncovered phase space with high branching fraction
- Focus on high-m_{HH} Lorentz boosted regime → sensitive to κ_{2V}
- Boosted jets → lower QCD background





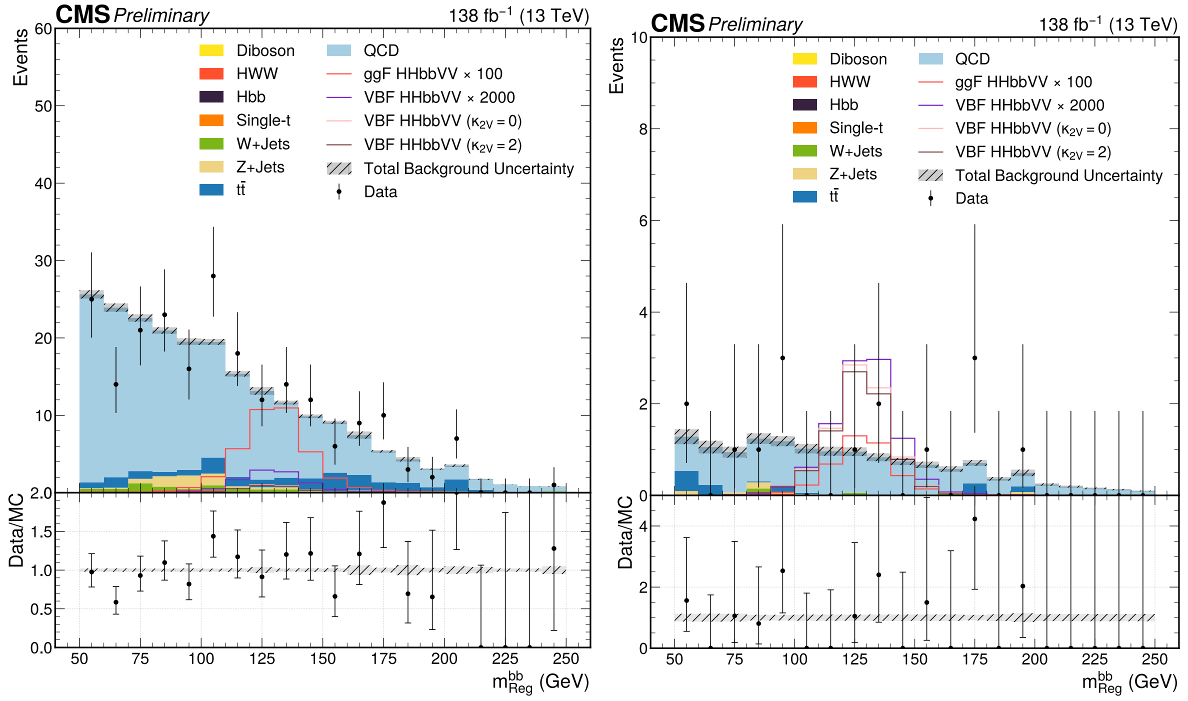


- New H->VV tagger developed based on a transformer-based model
- Study **ggF and VBF** production: target κ_{2V} modifications at high m_{HH}

HH → bbVV(4q)

Selection:

- events selected using H(bb) ParticleNet tagger
- HVV tagger scores
- VBF-jet features (large invariant masses and pseudorapidity separation)
- BDT on AK8 jet kinematics



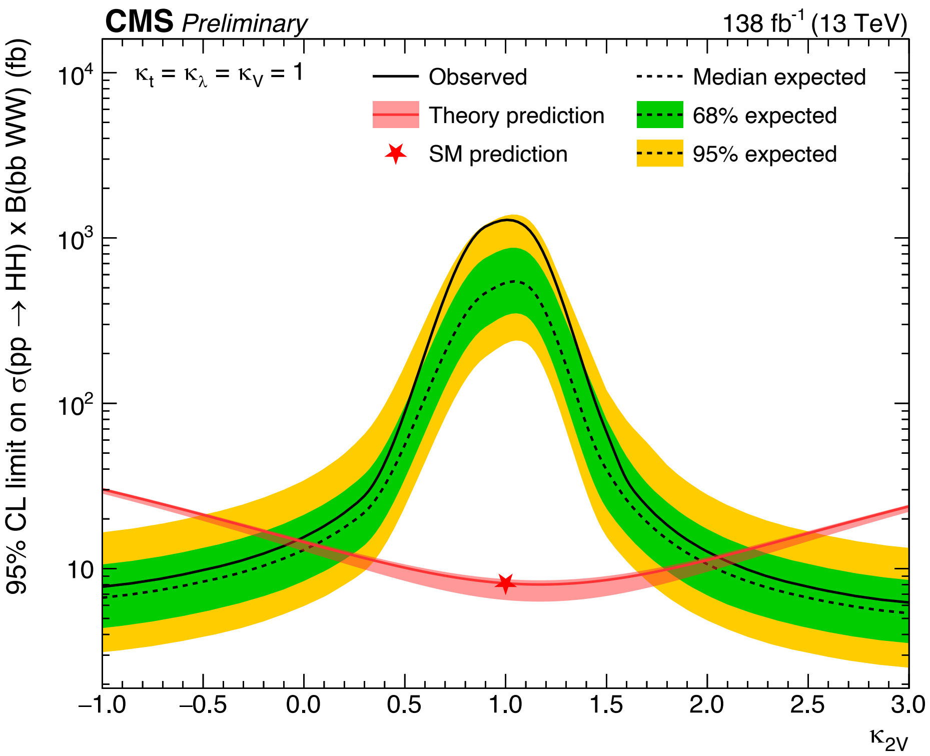
Backgrounds:

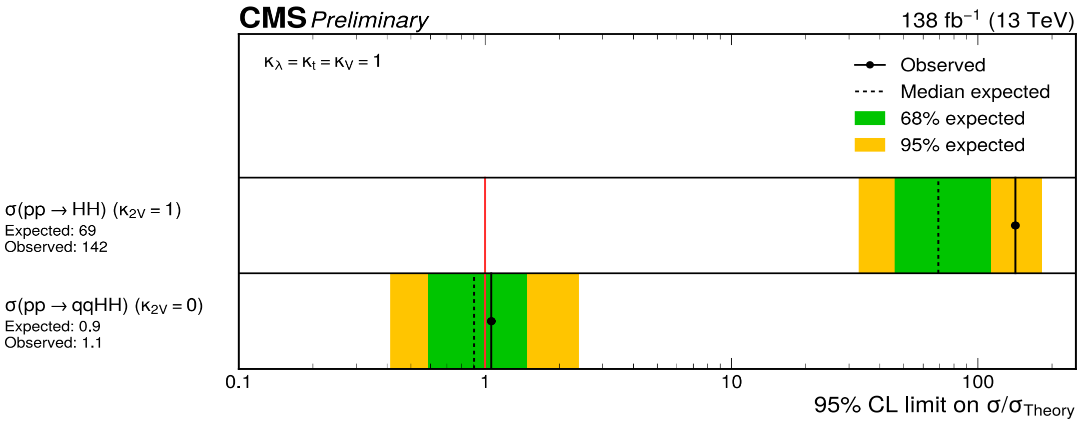
- QCD is estimated with a data driven method
- parametric transfer factor from a control region
- tt and V+jets are taken form simulation
- **Fit on H(bb) regressed mass (m_{bb})**

HH → bbVV(4q)

no relevant constraint on κ_λ, but
Powerful constrain on κ_{2V}

Observed constraint on κ_{2V}@ 95%CL:
[-0.04,2.05]





HH->bbWW

CMS PAS HIG-21-005
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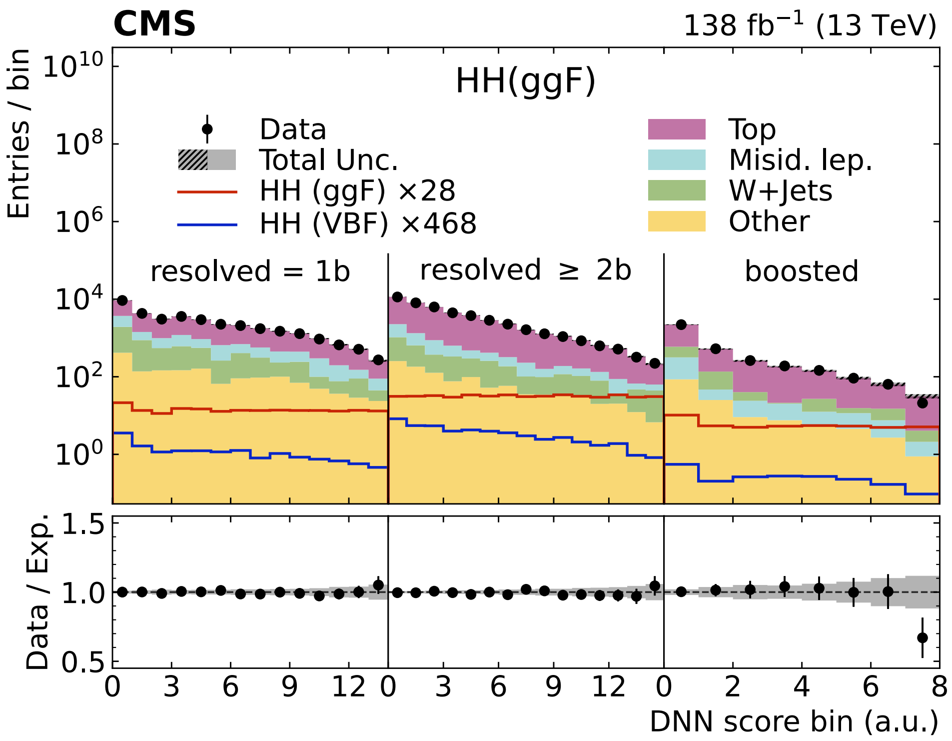
- **ggF and VBF** production is studied
- events with **at least one W decaying into leptons** and a b-tagged jet
- both resolved and boosted jets
- tau veto (orthogonal to bbττ)
- 2 channels based on H->WW* decay: **dilepton and single lepton**

backgrounds:

- W+jets, t, tt, taken from MC
- DY taken form the data

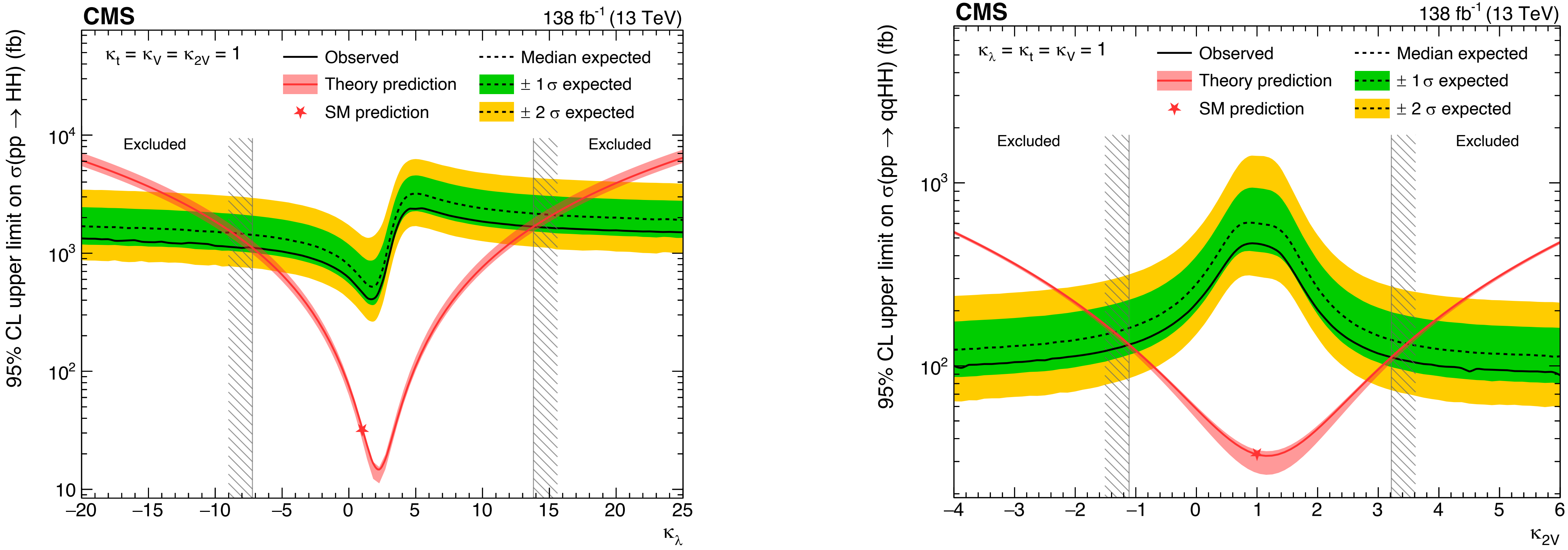


DNN multi-classifier trained to separate signal vs background

Signal extraction: a profile binned likelihood fit is performed to the DNN discriminants for each event category

HH->bbWW

Signal extraction for ggF and VBF from 1D fit of DNN score distributions



$-7.2(-8.7) < \kappa_\lambda < 13.8(15.2)$ **$-1.1(-1.4) < \kappa_{2V} < 3.2(3.5)$**

HH->WWγγ

CMS-PAS-HIG-21-014

ggF production

three channels based on lepton multiplicity

- **0 lepton**: 2 Binary DNNs (**WWγγ DNN + bbγγ killer DNN**)

WWγγ DNN is trained to separate HH from all backgrounds (H + continuum background)

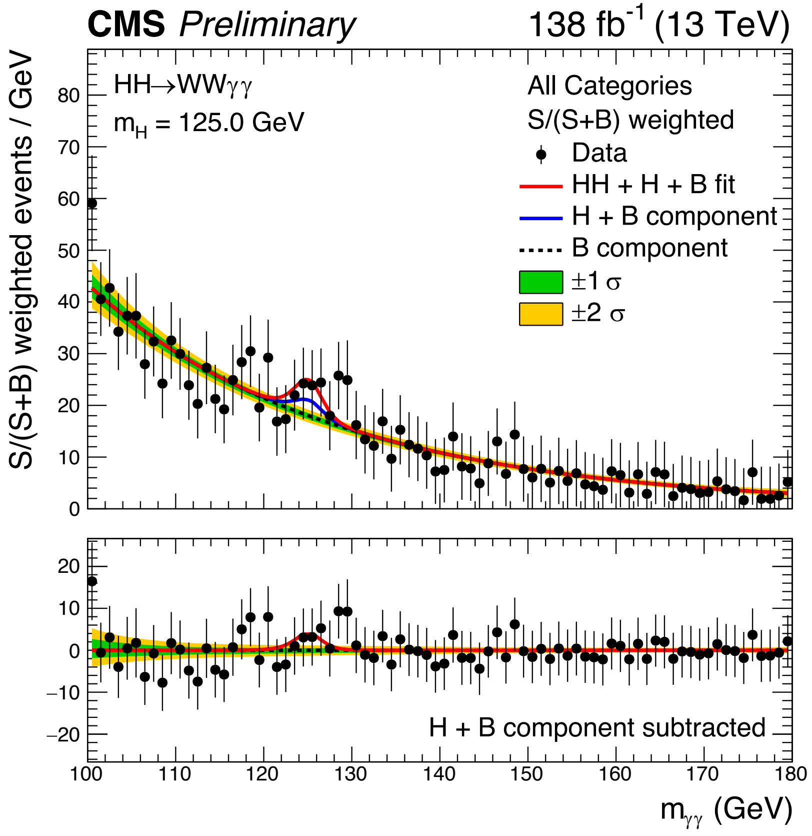
bbγγ DNN trained to reject HH bb events

- **1 lepton**: **Multi-Class DNN**

-Trained a multi-classed DNN to separate HH , H and continuum background

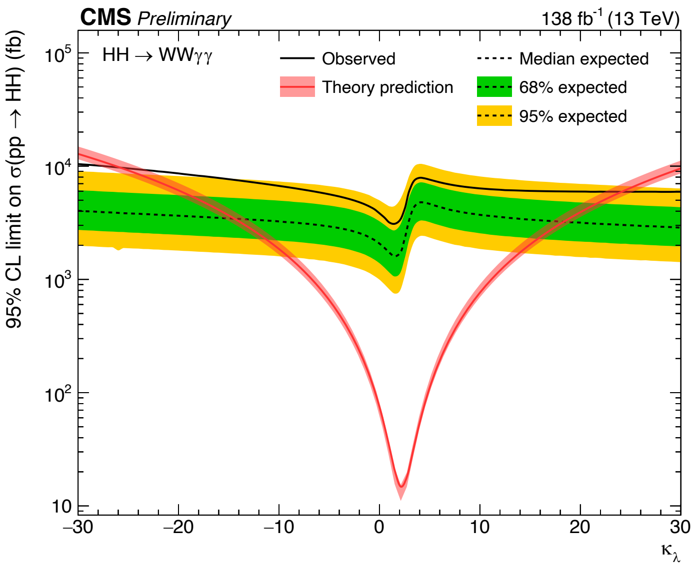
- **2 lepton: Cut based**: - clean final state and low statistics

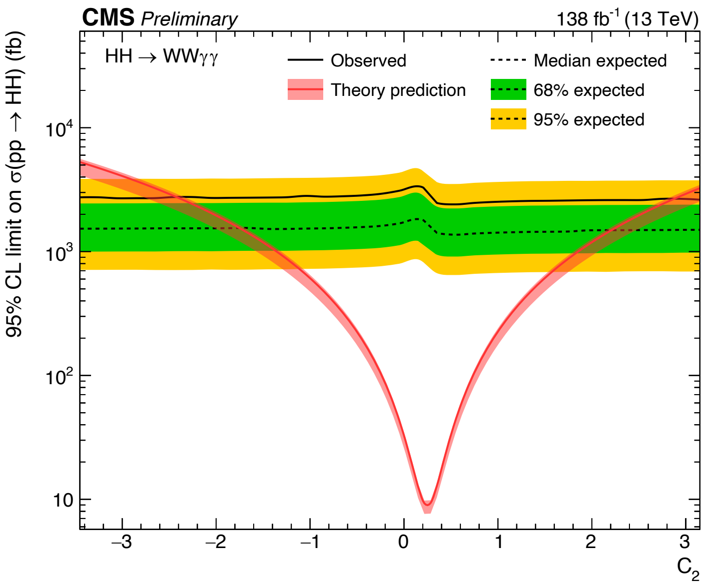
Signal extracted from mγγ parametric fit

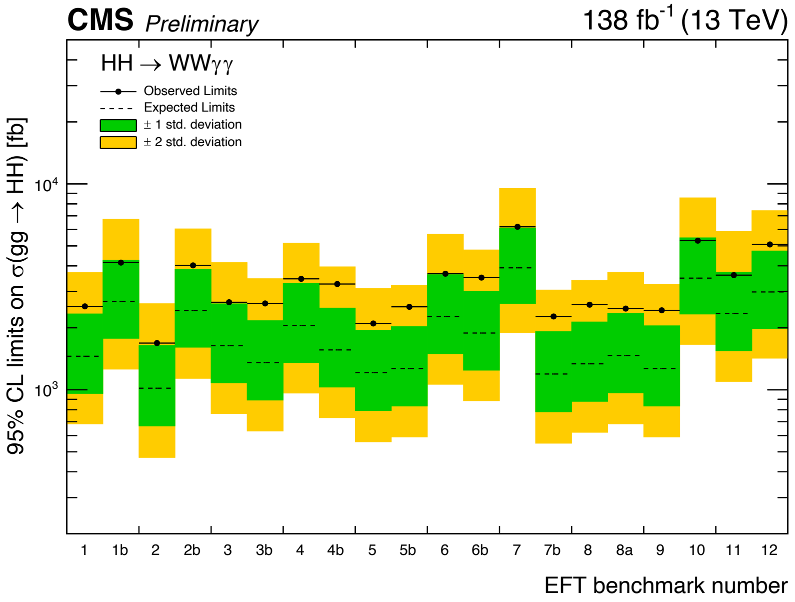


HH->WWγγ

CMS-PAS-HIG-21-014







$-25.8(14.4) < \kappa_\lambda < 24.1(18.3)$

coupling of two Higgs bosons to two top quarks c_2

$-2.4(-1.7) < c_2 < 2.9(2.2)$

upper limits are placed on twenty EFT benchmark scenarios ranging from

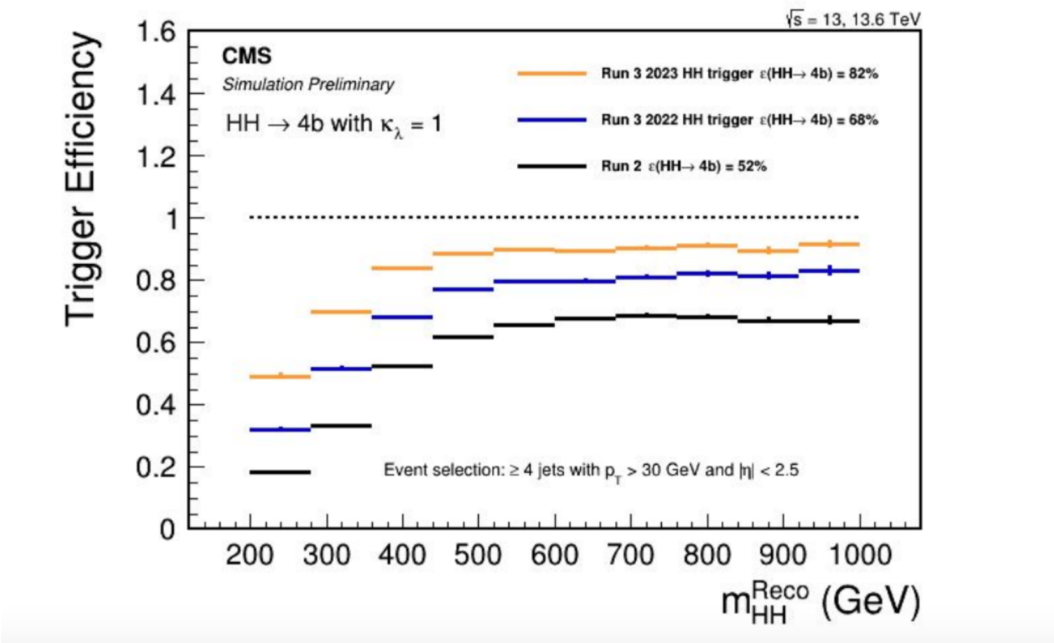
$\sigma^{EFT} < 1.7\text{-}6.2(1.0\text{-}3.9)$

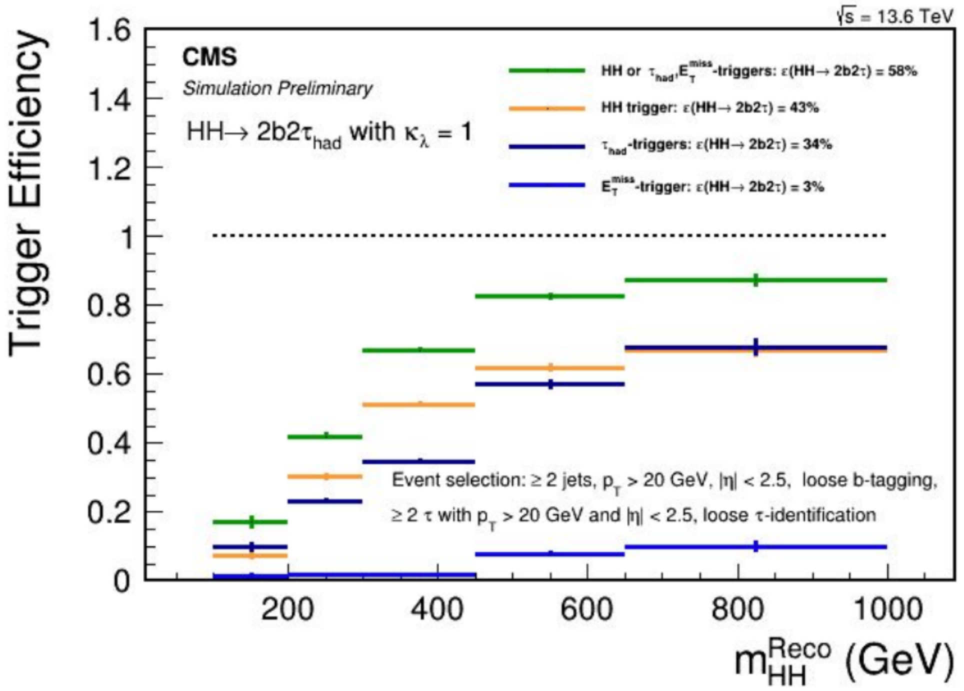
Improvements for Run3

CMS_DP_23_050

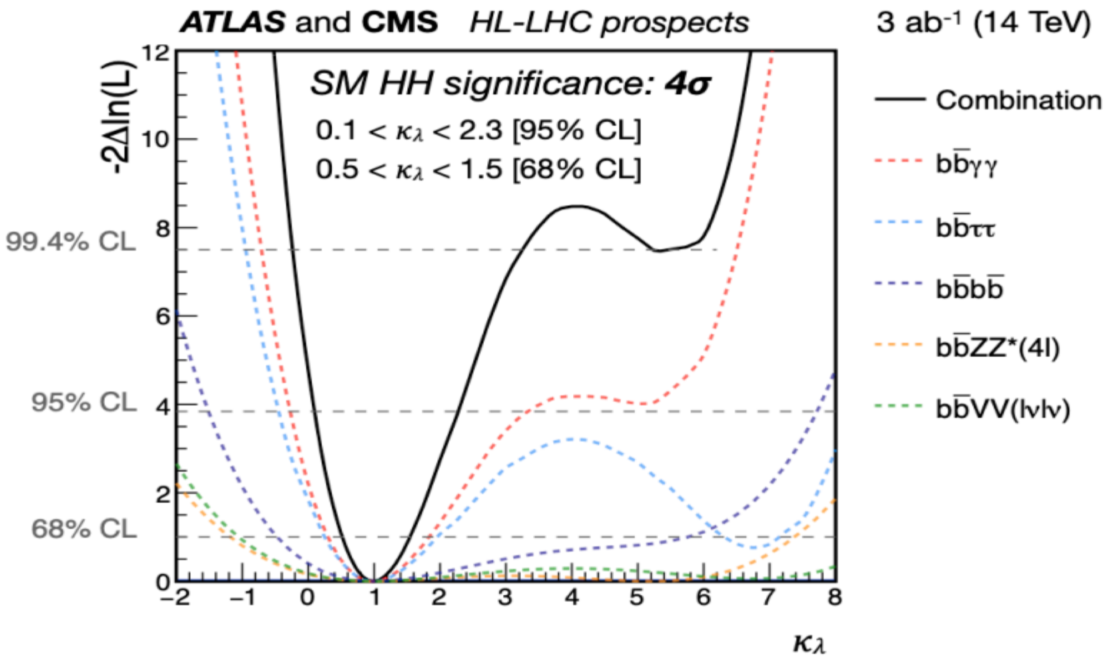
New online triggering strategies for Run 3 based on **ParticleNet for b-tagging** and **DeepTau for τ tagging** show great improvements over Run 2 baseline

Lower p_T threshold for bbbb, bb$\tau\tau$





Prospects for HL-LHC



Data taking period	Luminosity (fb^{-1})	HH projection	Reference
Run2	137	2.5 x SM	*Nature* **607**(2022)
HL-LHC (including upgrades)	**3000**	**4σ (ATLAS and CMS)**	**CERN yellow report**

expect for ATLAS+CMS combined: at least 4σ signal significance and 50% precision

ongoing developments *(triggers, machine learning based taggers, new decay channels, novel detectors ..)* have the **potential to observe HH at 5σ at HL-LHC**

Summary

- The **HH process is crucial** for understanding the shape of the Higgs potential
- Extensive study of HH production with Run-2 data
- Large **improvements** not only due to increased luminosity in Run 2, but also constantly improved analysis and reconstruction techniques
- **Exploring new HH channels**
- **H + HH combination**
- Run 3 will bring new opportunities (improved trigger strategies etc.)
- At HL-LHC, 5σ **discovery well accessible** combining ATLAS and CMS.

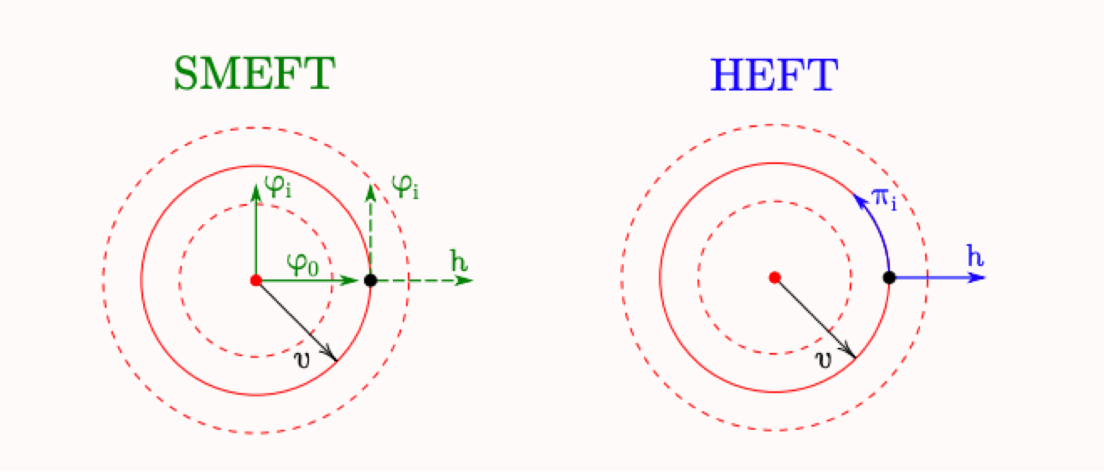
BACK UP

The Higgs Effective field theory

SMEFT expands around EW-symmetric point, HEFT expands around EW vacuum

rather than H doublet:
singlet h + Goldstones U

$$H \mapsto \frac{v + h}{\sqrt{2}} \mathbf{U}, \qquad \mathbf{U} = \exp\left(\frac{i\vec{\sigma}\cdot\vec{\pi}}{v}\right)$$



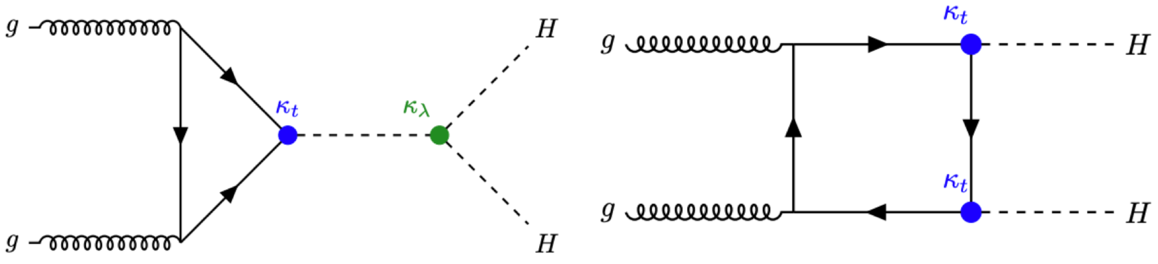
more general than SMEFT because implements weaker symmetry requirement there are UV scenarios that can be matched to HEFT but not SMEFT

in general more convergent than SMEFT: takes fewer orders to reproduce well UV model

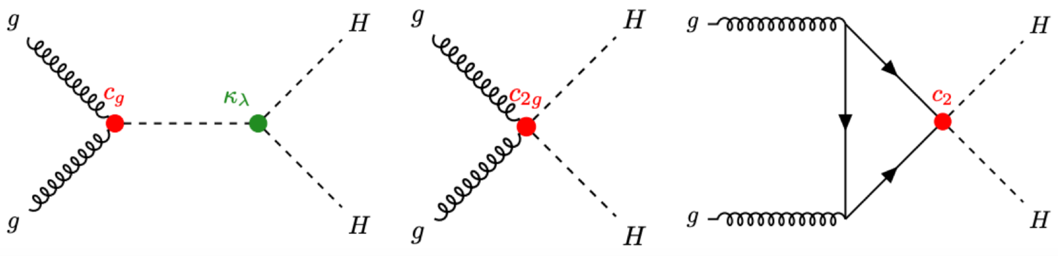
BSM Di-Higgs

$$\mathcal{L}_{BSM} = -\kappa_\lambda \lambda_{HHH}^{SM} v H^3 - \frac{m_t}{v}(\kappa_t H + \frac{c_2}{v} H^2)(\bar{t}_L t_R + h.c.) + \frac{\alpha_S}{12\pi v}(c_g H - \frac{c_{2g}}{2v} H^2) G^a_{\mu\nu} G^{a,\mu\nu}$$

$$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}, \quad \lambda_{HHH}^{SM} = \frac{m_H^2}{2v^2}, \quad \kappa_t = \frac{y_t}{y_t^{SM}}, \quad y_t^{SM} = \frac{\sqrt{2} m_t^2}{v}$$



(a) SM-like processes



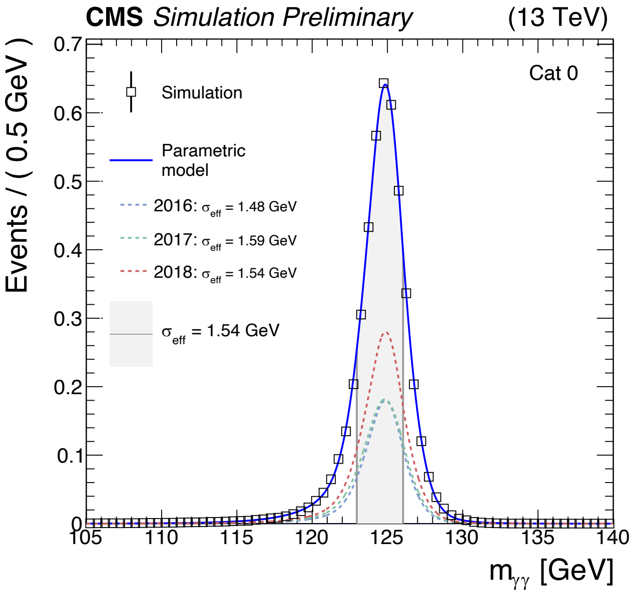
(b) Pure BSM processes

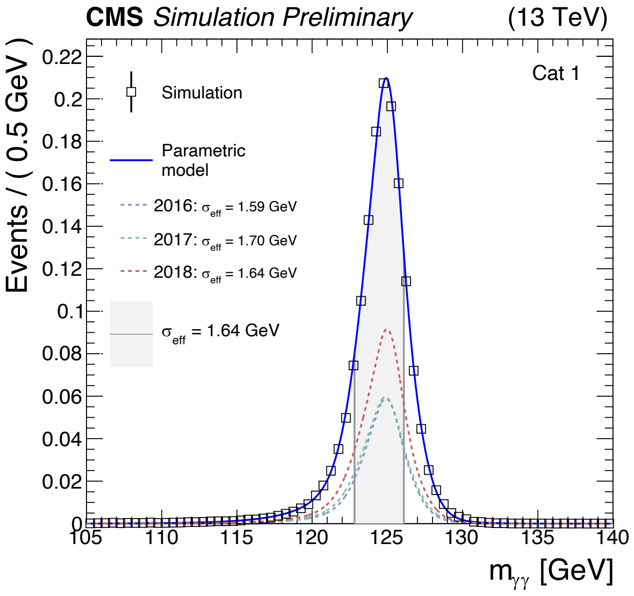
20 benchmark models

Benchmark	κ_λ	κ_t	c_2	c_g	c_{2g}
SM	1.0	1.0	0.0	0.0	0.0
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	-0.8	0.6
3	1.0	1.0	-1.5	0.0	-0.8
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	-1
6	2.4	1.0	0.0	0.2	-0.2
7	5.0	1.0	0.0	0.2	-0.2
8	15.0	1.0	0.0	-1	1
9	1.0	1.0	1.0	-0.6	0.6
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	1	-1
12	15.0	1.0	1.0	0.0	0.0
8a	1.0	1.0	0.5	$\frac{0.8}{3}$	0.0
1b	3.94	0.94	$\frac{-1}{3}$	0.75	-1
2b	6.84	0.61	$\frac{1}{3}$	0.0	1.0
3b	2.21	1.05	$\frac{-1}{3}$	0.75	-1.5
4b	2.79	0.61	$\frac{1}{3}$	-0.75	-0.5
5b	3.95	1.17	$\frac{-1}{3}$	0.25	1.5
6b	5.68	0.83	$\frac{1}{3}$	-0.75	-1.0
7b	-0.10	0.94	1.0	0.25	0.5

- There are 5 parameters in κλ, κt, c2g, c2, cg
- Points in the parameter phase space could be clustered in 20 benchmarks EFT
- MC samples could be reweighted by NLO ggHH samples using the analytic formula

HH->γγττ


CMS Simulation Preliminary
(13 TeV)
Cat 0
Simulation
Parametric model
2016: σ_eff = 1.48 GeV
2017: σ_eff = 1.59 GeV
2018: σ_eff = 1.54 GeV
σ_eff = 1.54 GeV
Events / (0.5 GeV)
m_γγ [GeV]


CMS Simulation Preliminary
(13 TeV)
Cat 1
Simulation
Parametric model
2016: σ_eff = 1.59 GeV
2017: σ_eff = 1.70 GeV
2018: σ_eff = 1.64 GeV
σ_eff = 1.64 GeV
Events / (0.5 GeV)
m_γγ [GeV]

H + HH combination

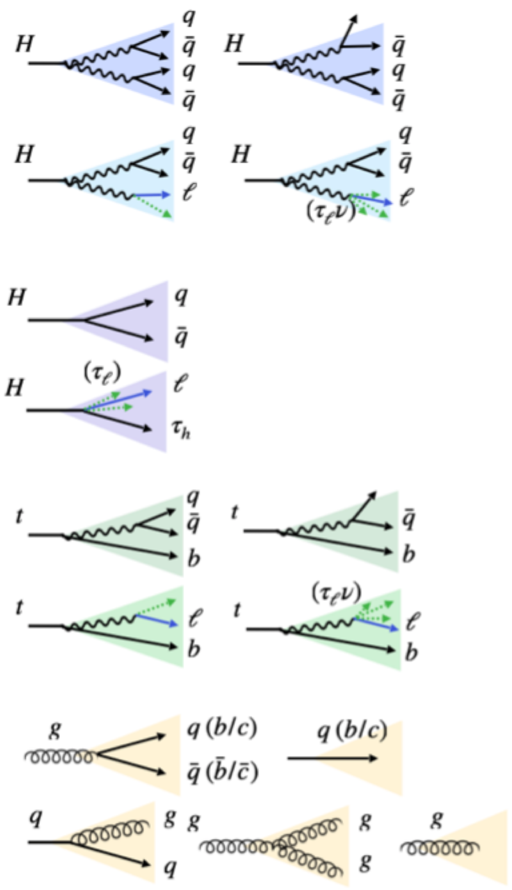
Hypothesis	Best fit κ_λ value $\pm 1\sigma$ Expected	Observed	2σ interval Expected	Observed
Other couplings fixed to the SM prediction	$1.0^{+4.6}_{-1.7}$	$3.1^{+3.0}_{-3.0}$	$[-2.0, 7.7]$	$[-1.2, 7.5]$
Floating $(\kappa_V, \kappa_{2V}, \kappa_f)$	$1.0^{+4.7}_{-1.8}$	$4.5^{+1.8}_{-4.7}$	$[-2.2, 7.8]$	$[-1.7, 7.7]$
Floating $(\kappa_V, \kappa_t, \kappa_b, \kappa_\tau)$	$1.0^{+4.8}_{-1.8}$	$4.7^{+1.7}_{-4.1}$	$[-2.3, 7.7]$	$[-1.4, 7.8]$
Floating $(\kappa_V, \kappa_{2V}, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu)$	$1.0^{+4.8}_{-1.8}$	$4.7^{+1.7}_{-4.2}$	$[-2.3, 7.8]$	$[-1.4, 7.8]$

Expected and observed constraints on $\kappa\lambda$ at 2σ and best fit values from the combination of the single-H and HH channels under different assumptions on the Higgs boson couplings to fermions and vector bosons.

HH → bbVV(4q)

GloParT

Process	Final state/ prongness	heavy flavour	# of classes
H→VV (full-hadronic)	qqqq	0c/1c/2c	3
	qqq		3
H→WW (semi-leptonic)	eνqq	0c/1c	2
	μνqq		2
	$\tau_e \nu qq$		2
	$\tau_\mu \nu qq$		2
	$\tau_h \nu qq$		2
H→qq		bb	1
		cc	1
		ss	1
		qq (q=u/d)	1
H→ττ	$\tau_e \tau_h$		1
	$\tau_\mu \tau_h$		1
	$\tau_h \tau_h$		1
t→bW (hadronic)	bqq	1b + 0c/1c	2
	bq		2
t→bW (leptonic)	beν	1b	1
	bμν		1
	$b\tau_e \nu$		1
	$b\tau_\mu \nu$		1
	$b\tau_h \nu$		1
QCD		b	1
		bb	1
		c	1
		cc	1
		others (light)	1



$$T_{\mathrm{HVV}} = \frac{P_{\mathrm{HVV4q}} + P_{\mathrm{HVV3q}}}{P_{\mathrm{QCD}} + P_{\mathrm{Top}} + P_{\mathrm{HVV4q}} + P_{\mathrm{HVV3q}}},$$