Non-resonant Di-Higgs searches at CMS

Higgs 2023, Nov 27 - Dec 2, 2023
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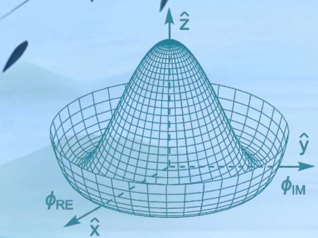

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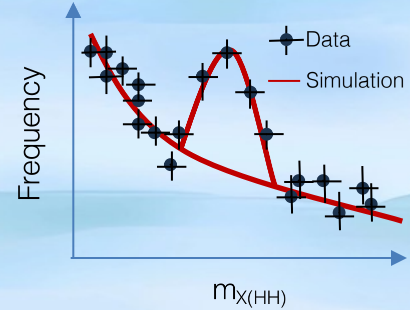
Conference Indico

Motivations



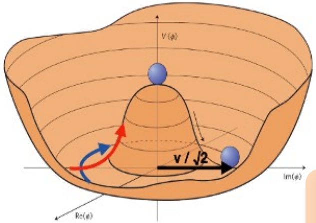
Resonant HH searches:
covered in the talk by
T. Kramer and
J. Steggemann

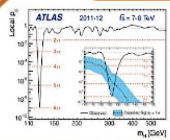
arXiv:1312.5672

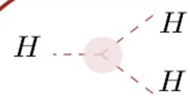
Standard Model (SM)

- The measurement of σ(HH) is the best way to extract the **Higgs self-coupling λ_3**

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







Higgs discovery (2012)

Trilinear self-coupling λ_3: direct access via HH production (expect evidences at HL-LHC) (*)

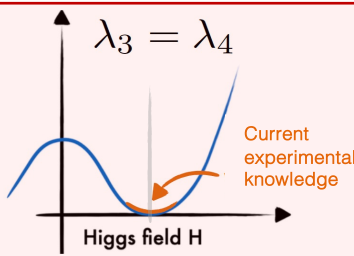
Quartic self-coupling λ_4 : responsible for HHH production (20??)

- This parameter determines the shape of the Higgs potential V(H) together with m_H and the vacuum expectation value ν → big consequences for the Universe

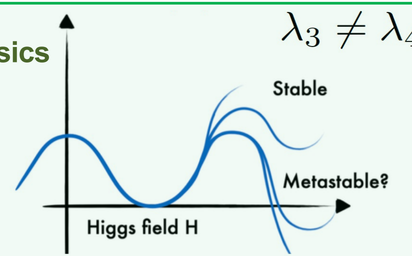
Standard Model

$$\lambda_3 = \frac{m_H^2}{2v^2} \sim 0.13$$

m_H, v measured very precisely



New physics

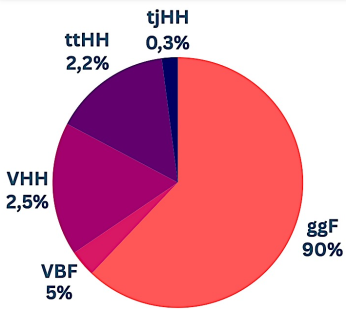


(*) λ_3, λ_4 can be also constrained indirectly from NLO contributions to the single Higgs production cross section

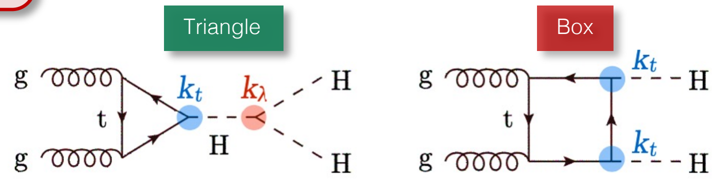
Standard Model (SM)

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

SM HH production mechanisms



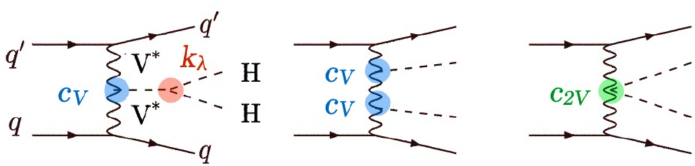
ggF



Destructive interference: tiny cross section $\sigma^{ggF}{}_{SM}$ (HH) (31.05 fb @ 13 TeV) → ~1000x smaller than the single Higgs one $\sigma^{ggF}{}_{SM}$(H) (~48 pb @ 13 TeV) → Experimentally very challenging!

VBF

Unique handle to probe VVHH c_{2V}



- At CMS we also study other production mechanisms:

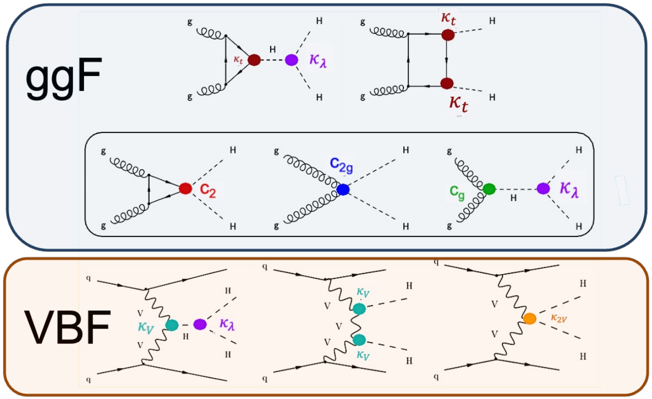
→ Vector Bosons Fusion (VBF,1.72 fb @ 13 TeV)

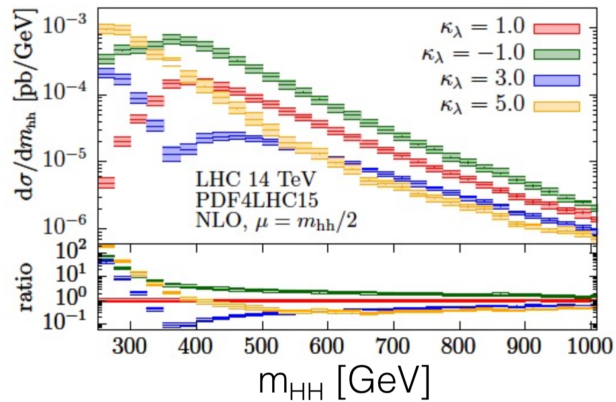
→ Associated with Single Vector boson (VHH, 0.86 fb @ 13 TeV)

Beyond Standard Model (BSM)

Physics Letters B (2014) 142-149
JHEP03(2020)091

- BSM processes can modify **HH production rates** and **kinematics**
- In the **Higgs Effective Field Theory (HEFT)** approach, deviations from the SM are modelled by **couplings modifiers** kappa ($\kappa_\lambda \equiv \lambda_3/\lambda_3^{SM}$, κ_{2V}, κ_t, κ_V)



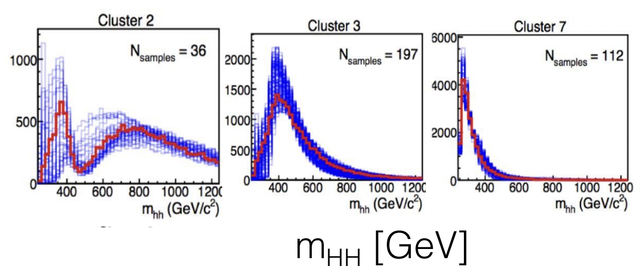


JHEP(2019)066

- Additional **ggF couplings** (c_2, c_g, c_{2g})
- Explore sensitivity to BSM EFT couplings with **20 shape benchmarks points**:

→ based on test statistic measuring kinematics' similarity

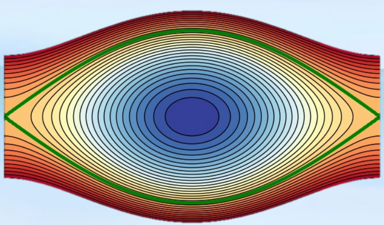
→ allow extrapolation between different points

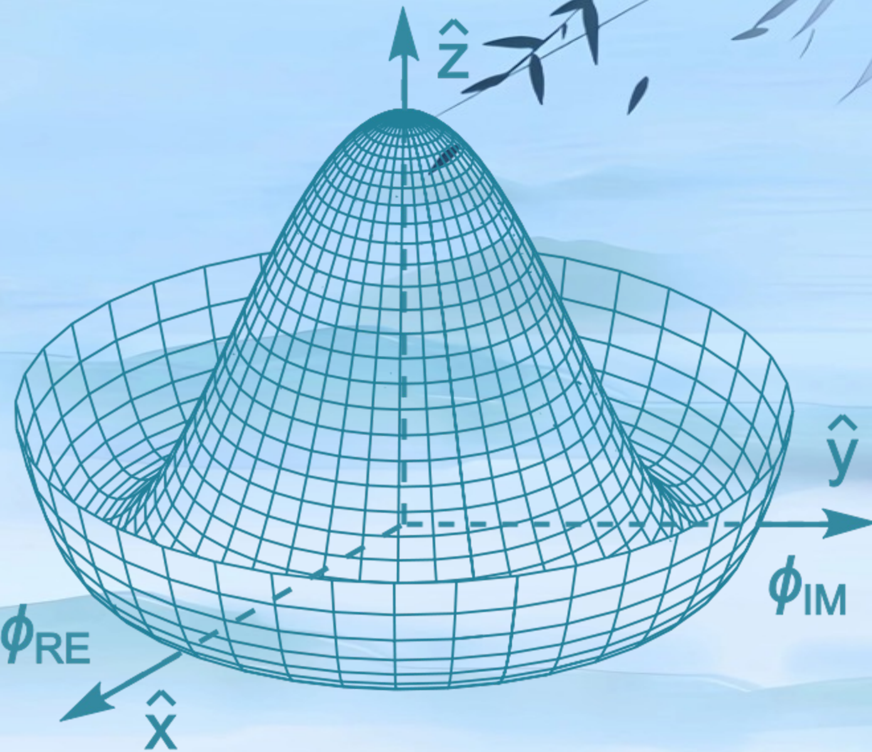


JHEP04(2016)126

Outline

Which is the HH phase space available?



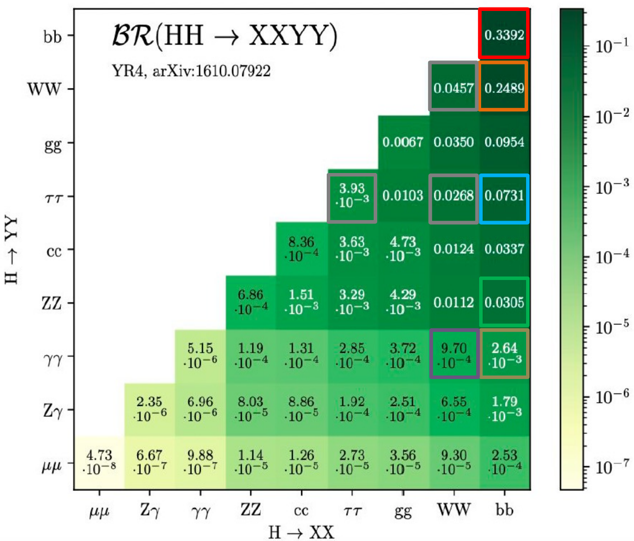


Di-Higgs decay channels

See also Marco Valente talk

- A **rich phenomenology** with many final states accessible at LHC

→ All decay channels are a **compromise** between Branching Ratio (BR) and final state signal purity (S/B) → There is **no a single golden** channel!



- Searches complementarity in different decay channels ⟺ **complementary sensitivity** to coupling variations

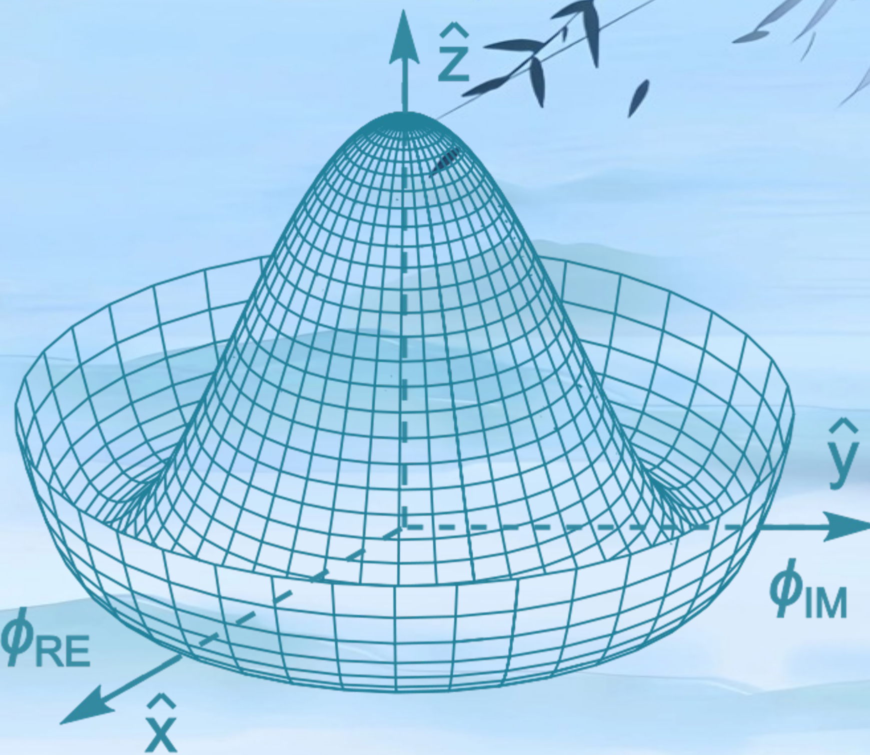
CMS full Run II (2016+2017+2018) results

● nonres VBF ● nonres ggF

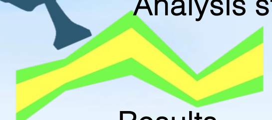
	nonres ggF	nonres VBF	
HH→4b, resolved	●	●	Phys. Rev. Lett. 129 (2022) 081802
HH→4b, boosted	●	●	Phys. Rev. Lett. 131, 041803
VHH → 4b			CMS PAS HIG-22-006 (New since Higgs2022)
HH→bbWW*	●	●	CMS PAS HIG-21-005 (New since Higgs2022)
HH→bbττ	●	●	Phys. Lett. B 842 (2023) 137531
HH→WWW*W*, WWττ, ττττ (multilepton)	●	●	JHEP 07 (2023) 095
HH→bbZZ(4l)	●		JHEP 06 (2023) 130
HH→bbγγ	●	●	JHEP 03 (2021) 257
HH→WW*γγ	●		CMS PAS HIG-21-014

HH(4b)

Largest BR **(34%)** provides opportunity to explore **several production mechanisms** and **kinematic regimes**



Analysis strategy

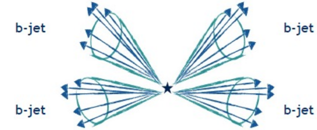


Results

HH→4b resolved

nonres VBF — nonres ggF

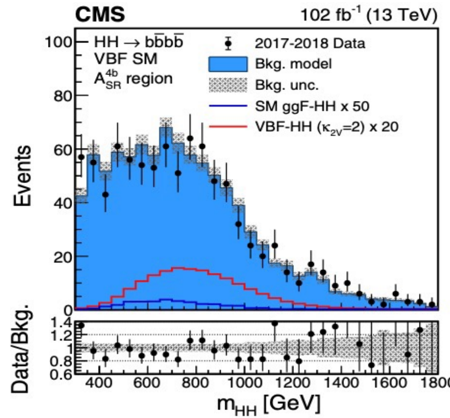
Phys. Rev. Lett. 129 (2022) 081802

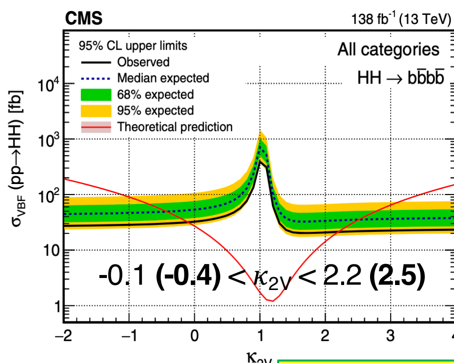


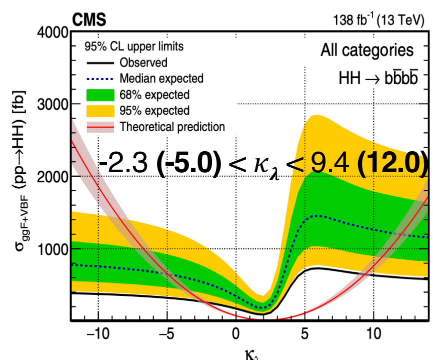
Sensitive for VBF production and κ_{2V} variations:

✗ Multi-jet background (QCD 85%, tt 15%)

- Events with at least **four jets** (anti-k_t, ΔR=0.4, DeepJet b-tagger), large **jet pairing** combinatorial
- QCD bkg estimated from data with CR **3b**
  See talk by M. Roguljic
- Subcategories (**2 ggF**, **2 VBF**) to increase signal purity based on **m_{HH}** (ggF) or **BDT to remove ggF** (VBF)
- Fit BDT (**m_{HH}**) in ggF (**VBF**) categories







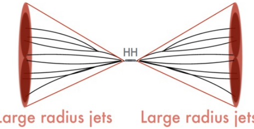
$\mu^{HH} \equiv \sigma/\sigma^{HH}_{MS} < 3.9$ **(7.8)**

$\mu^{VBF} \equiv \sigma/\sigma^{VBF}_{MS} < 226$ **(412)**

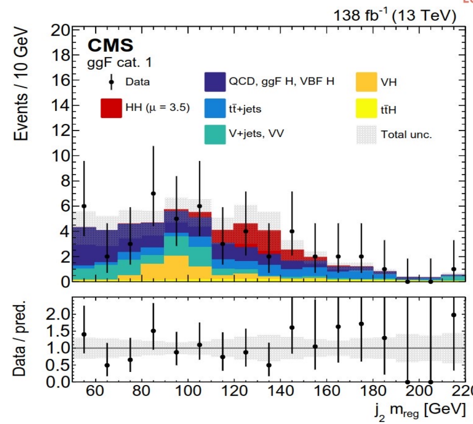
nonres VBF nonres ggF

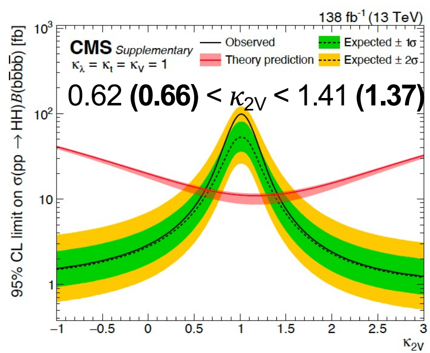
HH→4b boosted

Phys. Rev. Lett. 131, 041803

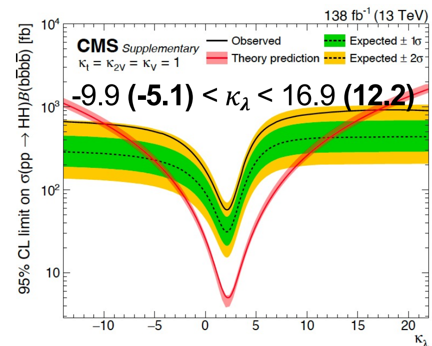


- HH pairs reconstructed in **two AK8 (large radius) jets** having $p_T(H) \sim 2m/R > 300$ GeV
- Jets tagged with ParticleNet for bt-tagging: **4x better bkg rejection** than previous algorithm
- **ParticleNet-based** ggF and VBF categories; **BDT** for ggF; m_{HH} as discriminating variable





0.62 **(0.66)** $< \kappa_{2V} < 1.41$ **(1.37)**

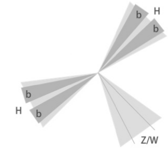


-9.9 **(-5.1)** $< \kappa_\lambda < 16.9$ **(12.2)**

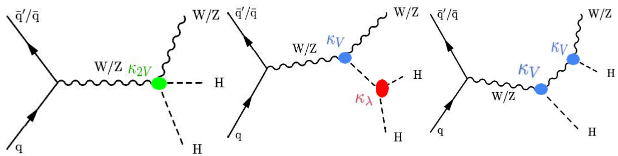
$\mu^{HH} < 9.9$ **(5.1)**

VHH→4b

CMS PAS HIG-22-006

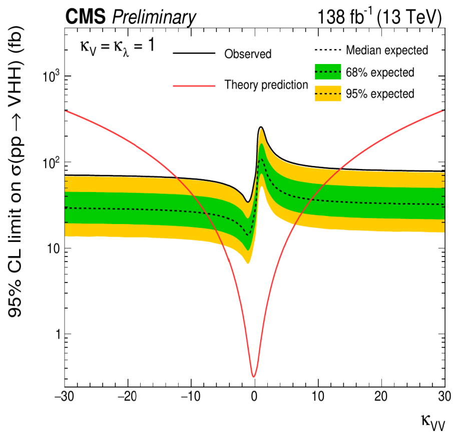


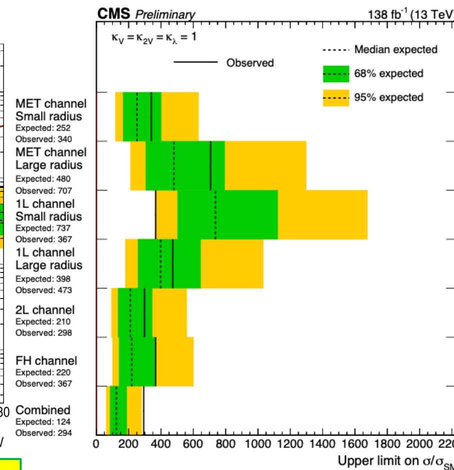
- ✗ Low $\sigma \cdot$BR @ SM
- ✗ Large background



Diagrams @ LO

- VHH for the **first time** at CMS
- 4 channels ($W\to l\nu$, $Z\to\nu\nu$, $Z\to ll$, $W/Z\to qq$) and 59 categories (resolved , boosted, m_{HH}, number of b-jets, signal- and tt- enhancement)
- BDT and DNN classifiers to improve S/B ratio + BDT defining regions sensitive to anomalous values for κ_λ or κ_{2V}



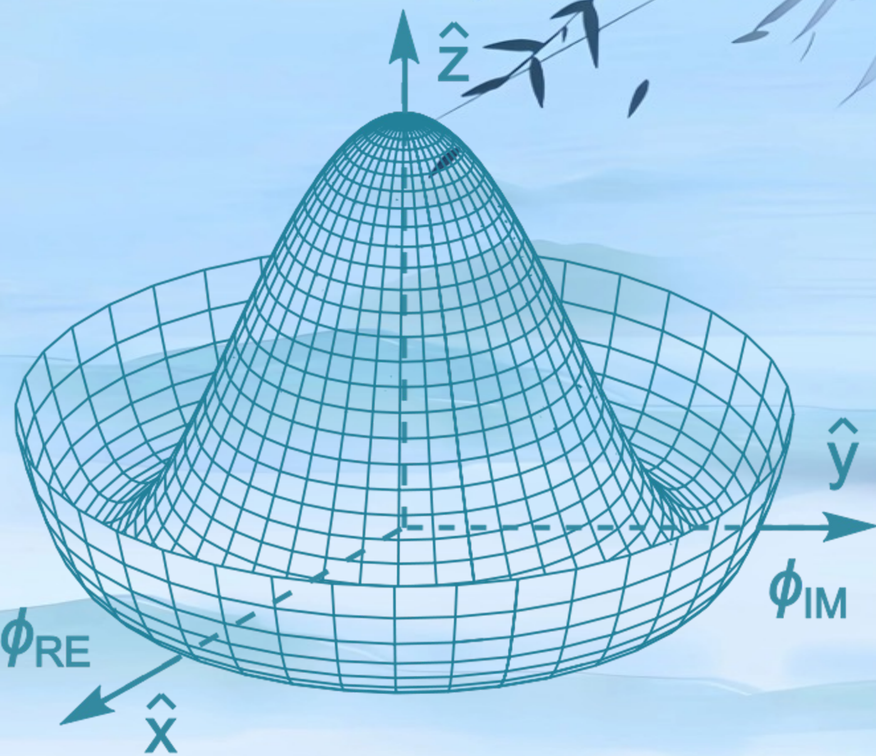


-12.2 **(-7.2)** $< \kappa_{2V} <$ 13.5 **(8.9)**
-14.0 **(-10.2)** $< \kappa_{WW} <$ 15.4 **(11.6)**
-17.4 **(-10.5)** $< \kappa_{ZZ} <$ 18.5 **(11.6)**

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

$HH(bb\gamma\gamma)$

Limited BR **(0.26%)**



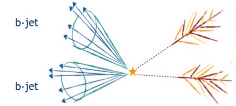
Analysis strategy

Results

nonres VBF nonres ggF

HH→bbγγ

JHEP 03 (2021) 257

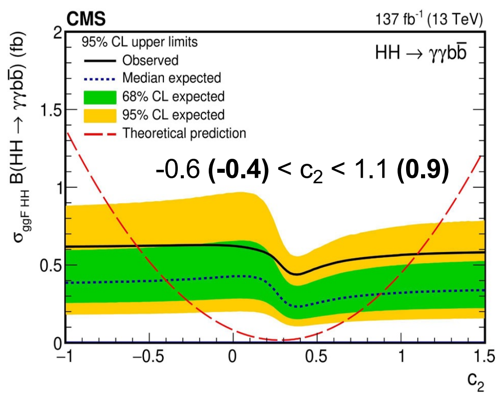


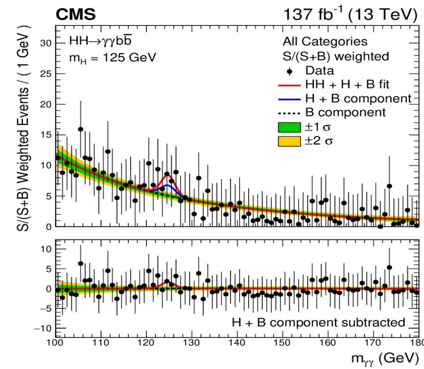
Sensitive to big variations of κ_λ :
- ✓ Very clean final state
- ✓ Excellent mass resolution $m_{\gamma\gamma}$ (1-2%)

- Events with at least two b-jets and 2γ
- Background: continuous $\gamma\gamma$+jet and single Higgs
- Dedicated DNN to remove ttH bkg
- Optimized categories based on (BDT, $\widetilde{M}_X$): 12 ggF, 2 VBF

$$\widetilde{M}_X = m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 2m_H$$

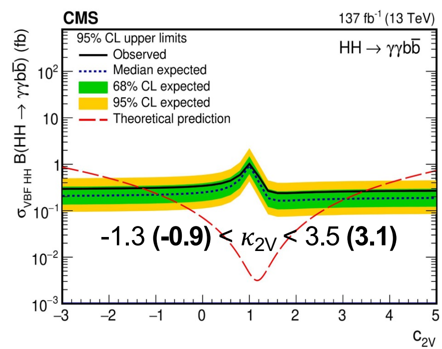
- Signal extracted from unbinned 2D parametric fit ($m_{\gamma\gamma}$, m_{bb}) in all categories





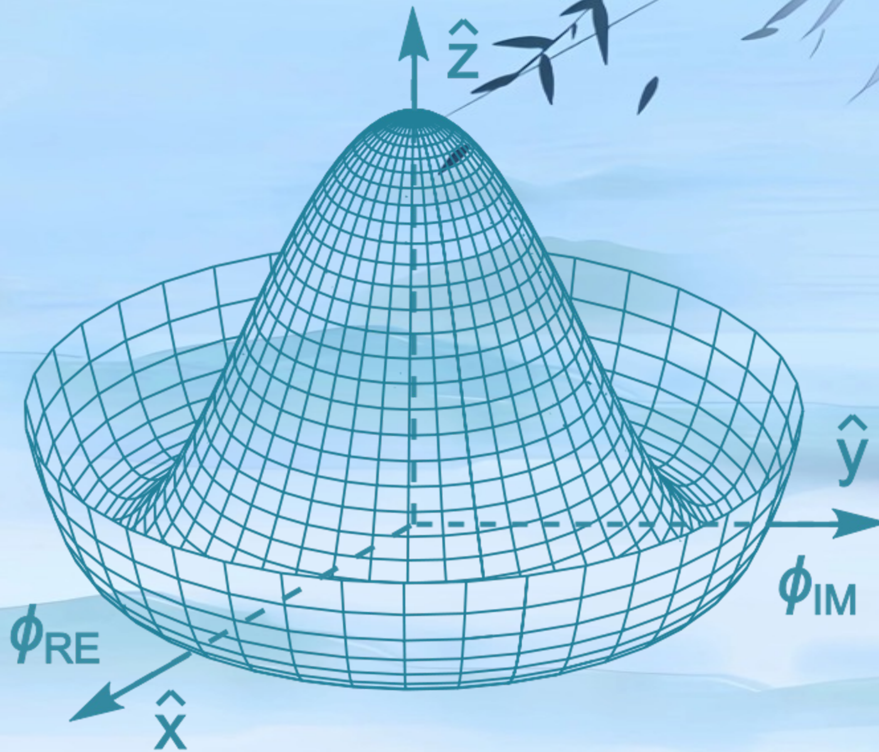
3.3 (-2.5) < κ_λ < 8.5 (8.2)
μ^{HH} < 7.7 **(5.2)**
μ^{VBF} < 225 **(208)**

Factor 4 of improvement wrt. 2016 analysis results (35.9 fb-1) arXiv:1806.00408



HH($bb\tau\tau$)

Still large BR **(7.3%)** provides opportunity to explore **several production mechanisms**



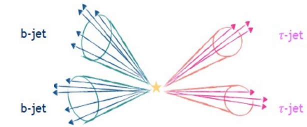
Analysis strategy

Results

nonres VBF nonres ggF

$HH \rightarrow bb\tau\tau$

Phys. Lett. B 842 (2023) 137531

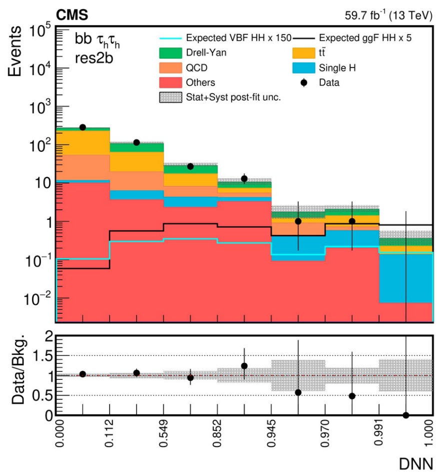


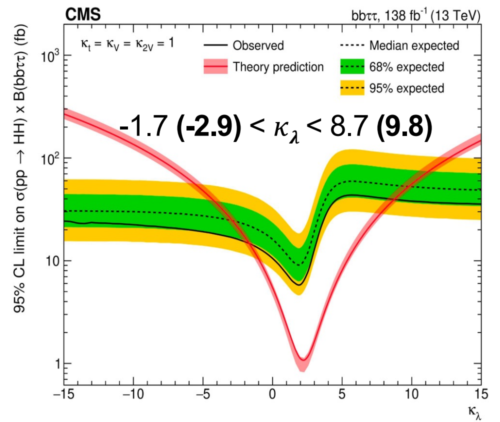
More sensitive for κ_λ and κ_{2V} close to SM

✓ Good compromise BR/final state reconstruction

✗ Electroweak bkg and top quark mimic signal

- Events with at least two b-tagged (DeepJet-tagged) jets and 2 (DeepTau tagged) taus ($e\tau_{had}$, $\mu\tau_{had}$, $\tau_{had}\tau_{had}$)
- 8 categories: resolved, boosted VBF- and ggF-like
- Fit DNN multi-classificator score (ggF, VBF, ttH, DY, TT)



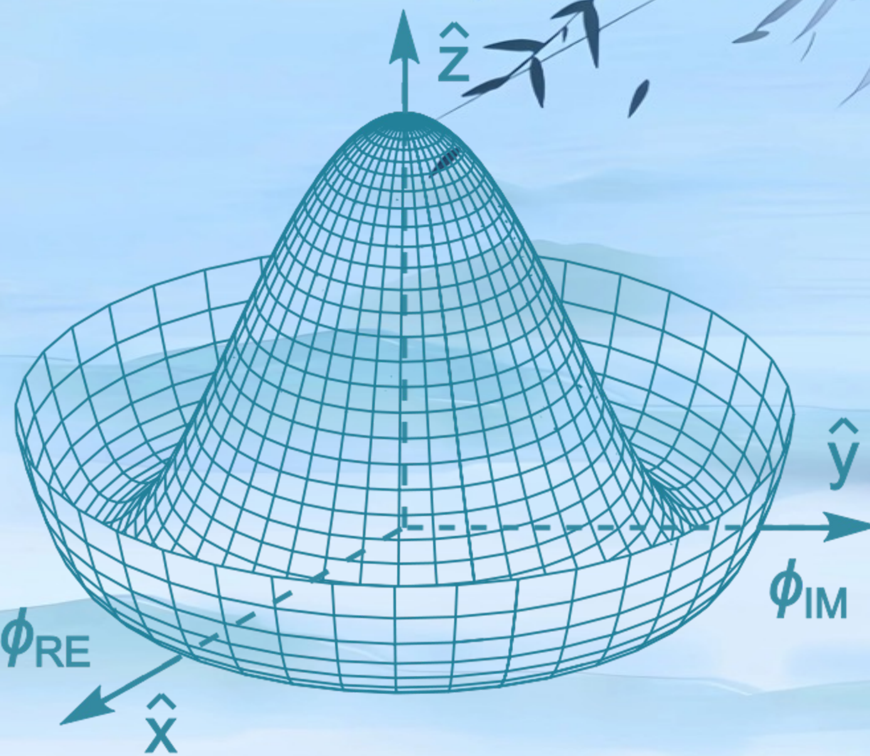


Factor 4.5 better on μ^{HH} wrt previous result @ 35.9 fb^{-1} arXiv:1808.00336

-0.4 **(-0.6)** < κ_{2V} < 2.6 **(2.8)**
μ^{HH} < 3.3 **(5.2)**
μ^{VBF} < 124 **(154)**

HH(bbWW)

Large BR **(25%)** provides opportunity to explore **several production mechanisms** and **kinematic regimes**



Analysis strategy

Results

HH→bbWW*

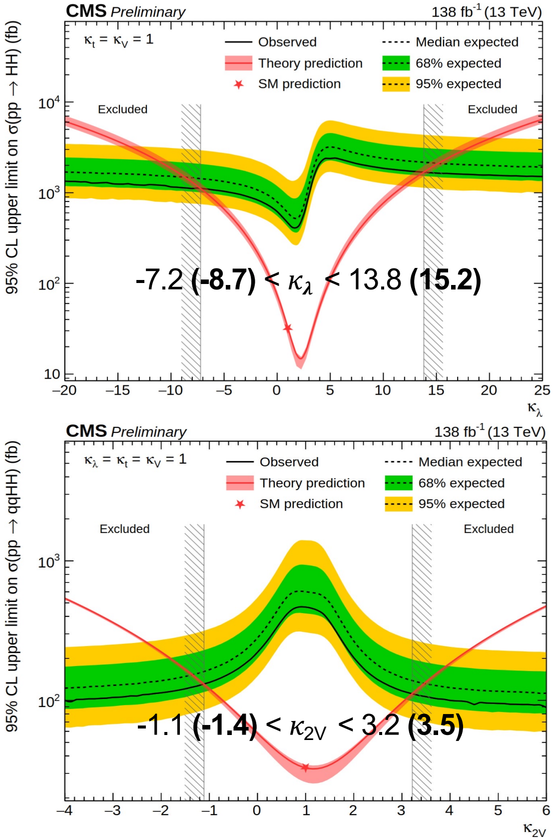
nonres VBF nonres ggF

CMS PAS HIG-21-005

✗ Large background

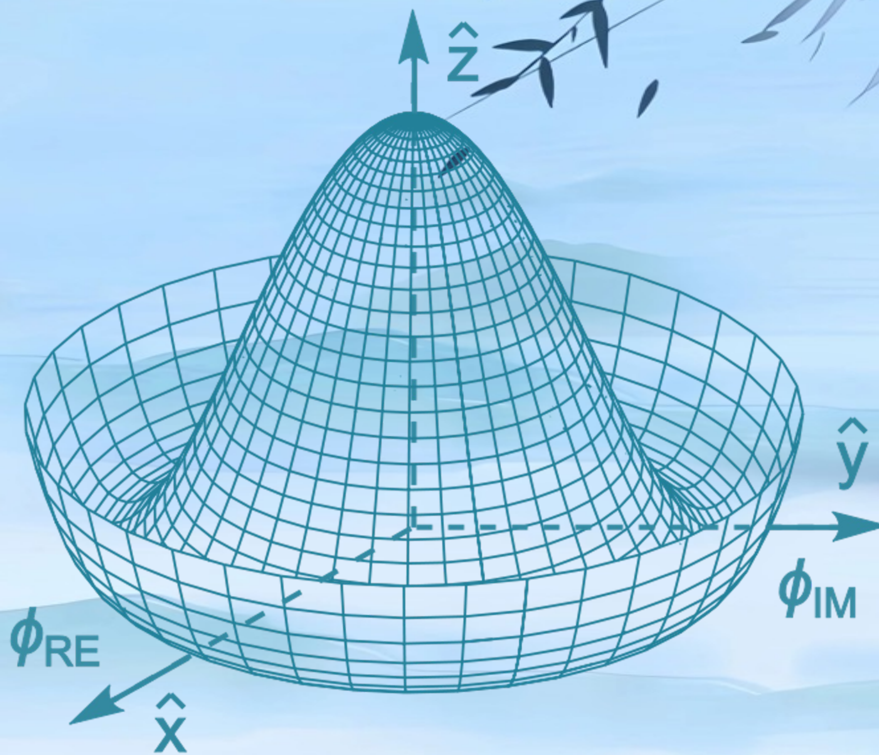
- Events with at least one W decaying into leptons and an AK4 (AK8) b-tagged jet if resolved (boosted)
- Tau veto: orthogonality wrt bb$\tau\tau$
- 2 channels based on H→WW* decay: Di-Lepton (WW*→lνlν), Single-Lepton (WW*→lνqq)
- Backgrounds: W+jets, t, tt from MC and normalized by ML fit, data-driven DY estimation with dedicated CRs
- DNN multi-classifier to separate signal vs bkgs (main W+jets, ttbar) : 9(x2) categorie
- Signal extraction for ggF and VBF from 1D fit of DNN score distributions

μ^{HH} < 14 **(18)**
μ^{VBF} < 277 **(301)**
-0.8 **(-1.0)** < c_2 < 1.3 **(1.4)**



HH(Multilepton)

Small BR **(7.7% in total)**



Analysis strategy

Results

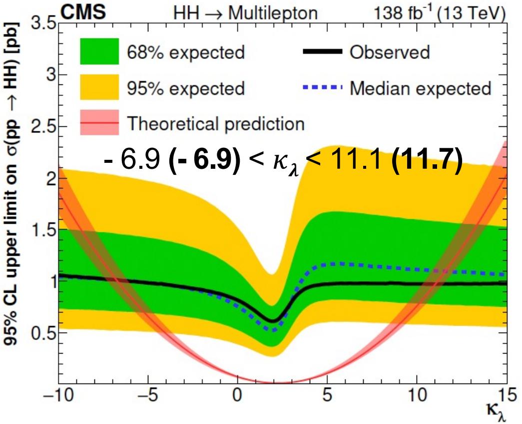
nonres ggF

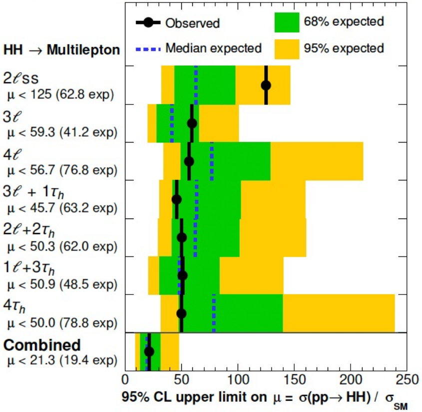
Multilepton (4V, 2V2τ, 4τ)

JHEP 07 (2023) 095

✓ Small background

- 7 channels distinguished by the leptons' multiplicity :
  - 4l +0τ_h , 3l +0τ_h, 2lss +0τ_h,
  - 3l +1τ_h, 1l +3τ_h, 2l+2τ_h, 0l + 4τ_h
- Resolved category (all channels) and boosted (3l, 2lss)
- Dedicated BDT trained to separate prompt leptons from nonprompt or misidentified leptons
- Signal extraction from simultaneous fit of output BDTs per channel + 2 CRs (WZ(3l), ZZ(4l))

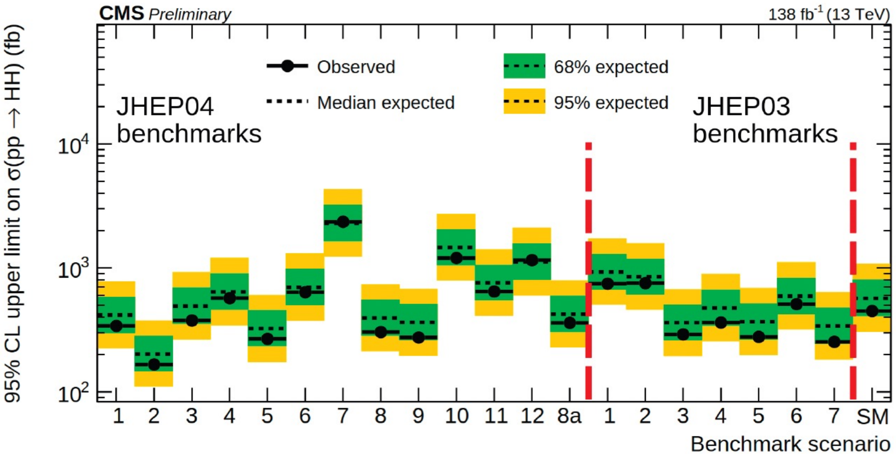




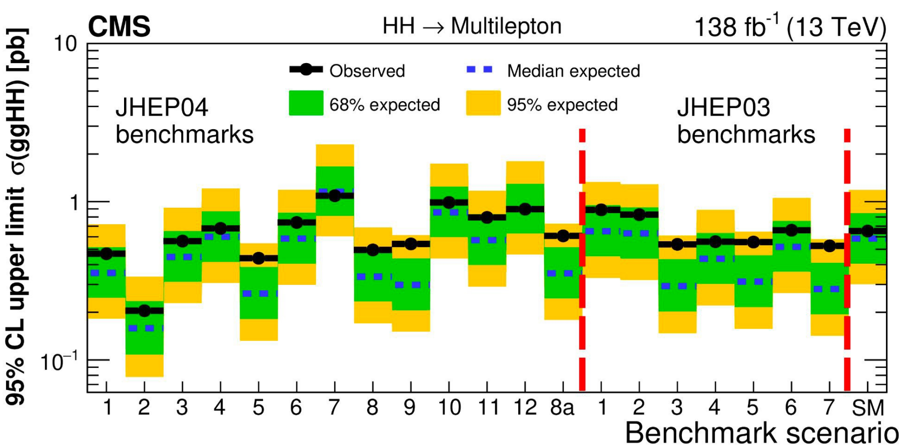
μ^{HH} < 21.3 **(19.4)**

EFT interpretation examples

bbWW

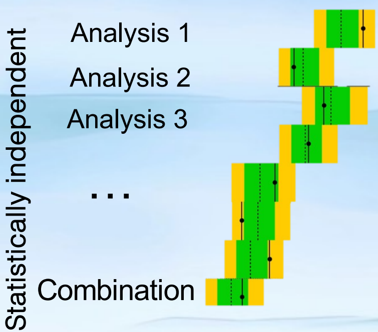


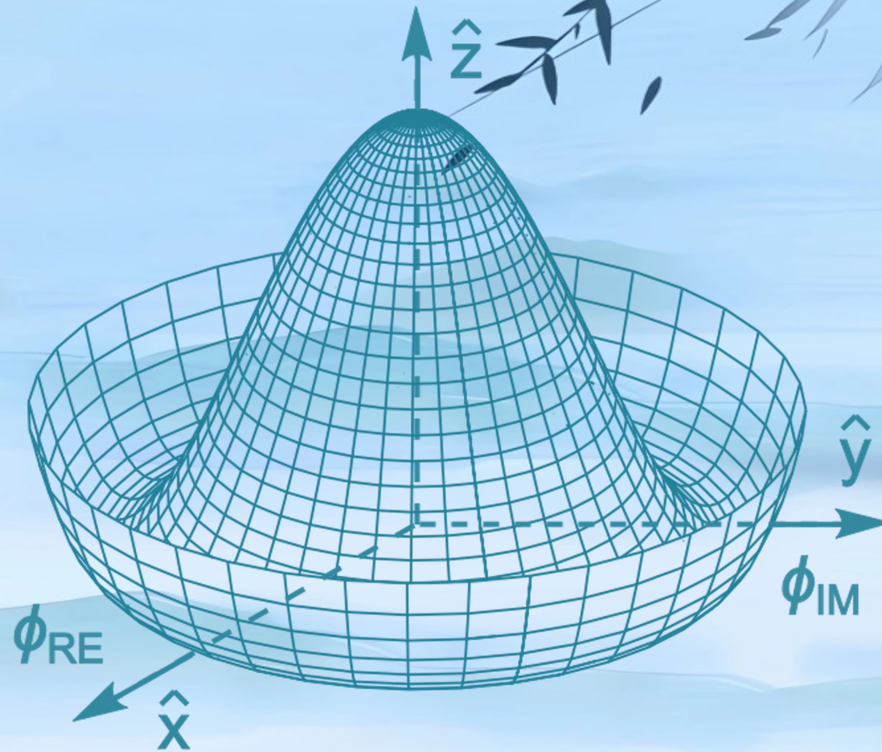
Multilepton



Combinations

Statistical combinations (xsec, constraints for self-couplings) to enhance evidence chance





Non resonant Run 2 Combination

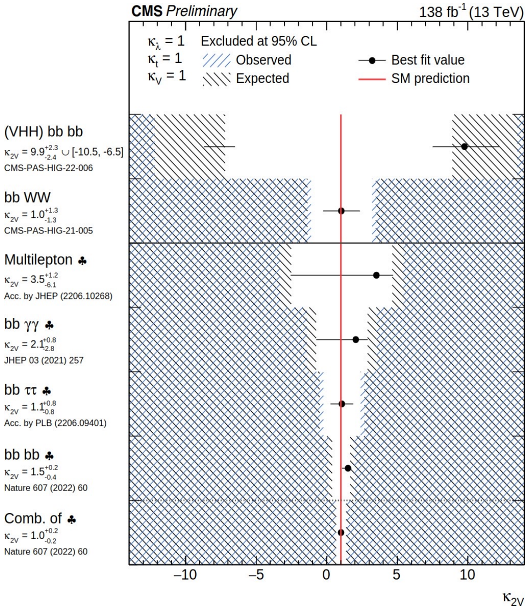
Nature 607 (2022) 60-68

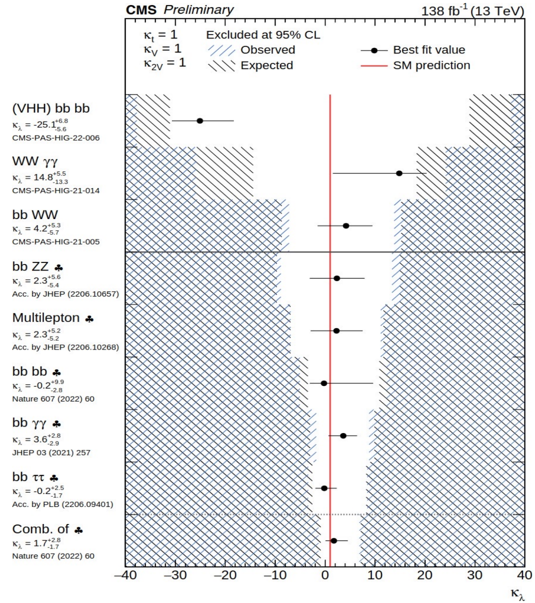
Improved result wrt previous analysis (35.9 fb^{-1}, 3 analyses + bbVV) of a factor > 2 on κ_λ

Tightest limit on κ_{2V} at LHC ($\kappa_{2V} = 0$ excluded, > 5σ)

Previous result:
-11.8 (-7.1) < κ_λ < 18.8 (13.6)

-1.24 **(-2.28)** < κ_λ < 6.49 **(7.94)**
0.67 **(0.61)** < κ_{2V} < 1.38 **(1.42)**





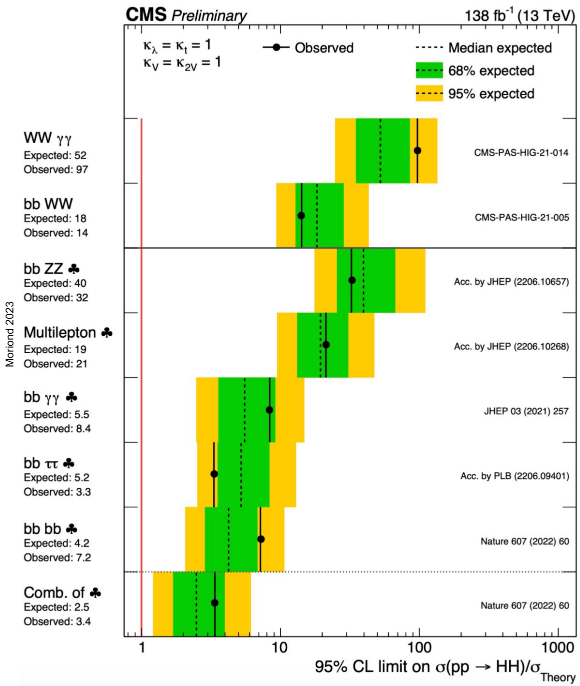
Non-resonant Run 2 Combination (1)

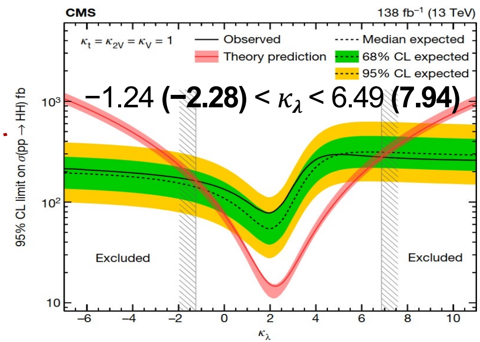
Nature 607 (2022) 60-68

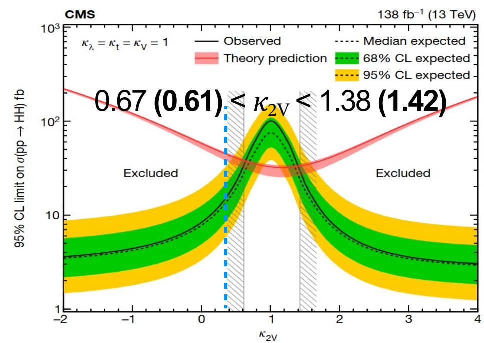
Improved result wrt previous analysis (35.9 fb^{-1}, 3 analyses+ bbVV) of a factor > 5 on μ^{HH}

Previous result on μ^{HH} : 22.2 (12.8)

μ^{HH} < 3.4 **(2.5)**



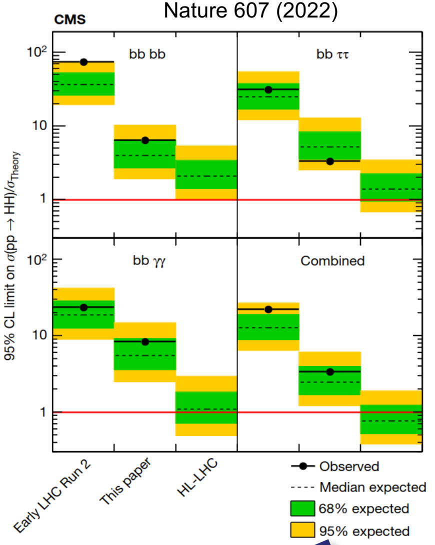




Conclusions and perspectives

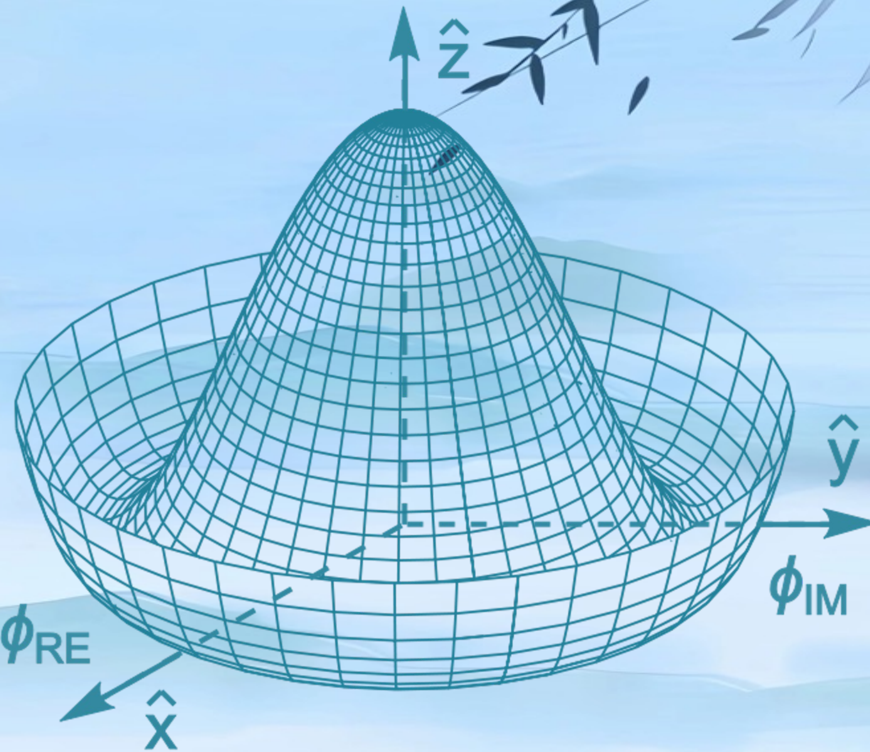
- HH searches are fundamental to know scalar sector in SM and BSM scenarios
- Promising results from Run 2, expected to improve in the future:
  → new HH decay channels
  → consider H+HH combinations
  → stats are still a limiting factor but ggF theory uncertainty may become important in the future
- Close to SM HH sensitivity and k_{2V} = 0 was excluded
- Run 3 : an opportunity to improve before the HL-LHC → improved trigger strategy will boost HH searches

Nature 607 (2022)



Stay TUNED

Backup



Summary

HH→4b resolved
Phys. Rev. Lett. 129 (2022) 081802

-2.3 **(-5.0)** < κ_λ < 9.4 **(12.0)**
-0.1 **(-0.4)** < κ_{2V} < 2.2 **(2.5)**
σ/σ^{HH}_{MS} < 3.9 **(7.8)**
σ/σ^{VBF}_{MS} < 226 **(412)**

HH→bb$\tau\tau$
Phys. Lett. B 842 (2023) 137531

-1.7 **(-2.9)** < κ_λ < 8.7 **(9.8)**
-0.4 **(-0.6)** < κ_{2V} < 2.6 **(2.8)**
σ/σ^{HH}_{MS} < 3.3 **(5.2)**
σ/σ^{VBF}_{MS} < 124 **(154)**

HH→WW*$\gamma\gamma$
CMS PAS HIG-21-014

σ/σ^{HH}_{MS} < 97 **(53)**
-25.8 **(-14.4)** < κ_λ < 24.1 **(18.3)**
-2.4 **(-1.7)** < c_2 < 2.9 **(2.2)**

HH→4b boosted
Phys. Rev. Lett. 131, 041803

-9.9 **(-5.1)** < κ_λ < 16.9 **(12.2)**
0.62 **(0.66)** < κ_{2V} < 1.41 **(1.37)**
σ/σ^{HH}_{MS} < 9.9 **(5.1)**

HH→bb$\gamma\gamma$
JHEP 03 (2021) 257

-3.3 **(-2.5)** < κ_λ < 8.5 **(8.2)**
-1.3 **(-0.9)** < κ_{2V} < 3.5 **(3.1)**
σ/σ^{HH}_{MS} < 7.7 **(5.2)**
σ/σ^{VBF}_{MS} < 225 **(208)**
-0.6 **(-0.4)** < c_2 < 1.1 **(0.9)**

VHH → 4b
CMS PAS HIG-22-006

- 37.7 **(- 30.1)** < κ_λ < 37.2 **(28.9)**
−12.2 **(-7.2)** < κ_{2V} < 13.5 **(8.9)**
−14.0 **(-10.2)** < κ_{2W} < 15.4 **(11.6)**
−17.4 **(-10.5)** < κ_{2Z} < 18.5 **(11.6)**
σ/σ^{VHH}_{MS} < 294 **(124)**

HH→bbWW*
CMS PAS HIG-21-005

σ/σ^{HH}_{SM} < 14 **(18)**
σ/σ^{VBF}_{SM} < 277 **(301)**
-7.2 **(-8.7)** < κ_λ < 13.8 **(15.2)**
-1.1 **(-1.4)** < κ_{2V} < 3.2 **(3.5)**
-0.8 **(-1.0)** < c_2 < 1.3 **(1.4)**

Multilepton
JHEP 07 (2023) 095

- 6.9 **(- 6.9)** < κ_λ < 11.1 **(11.7)**
σ/σ^{HH}_{SM} < 21.3 **(19.4)**

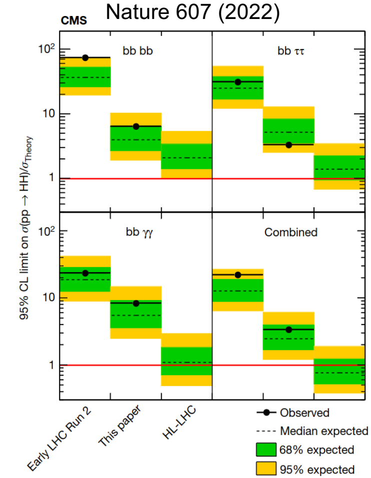
HH→bbZZ(4l)
JHEP 06 (2023) 130

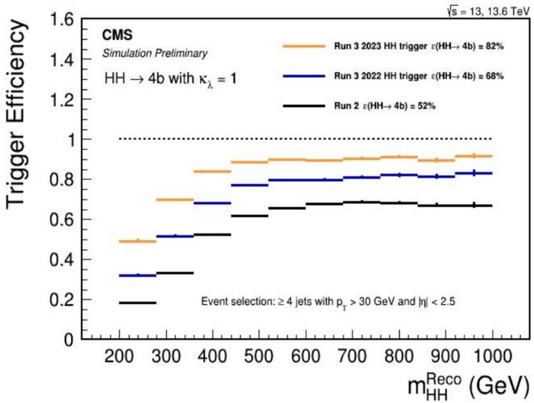
σ/σ^{HH}_{MS} < 32.4 **(39.6)**
-8.8 **(-9.8)** < $k\lambda$ < 13.4 **(15.0)**

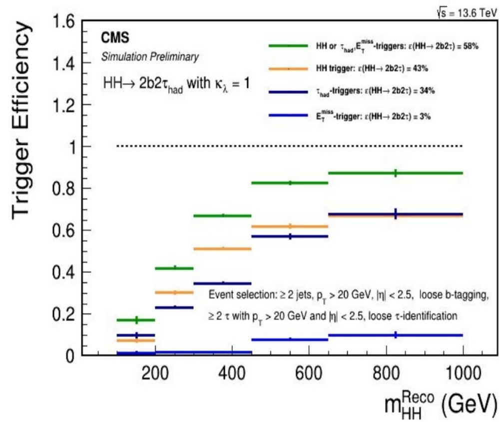
Run 3 and beyond

- Run 3 is an opportunity for improvement before the HL-LHC

→ improved trigger strategy will boost HH searches



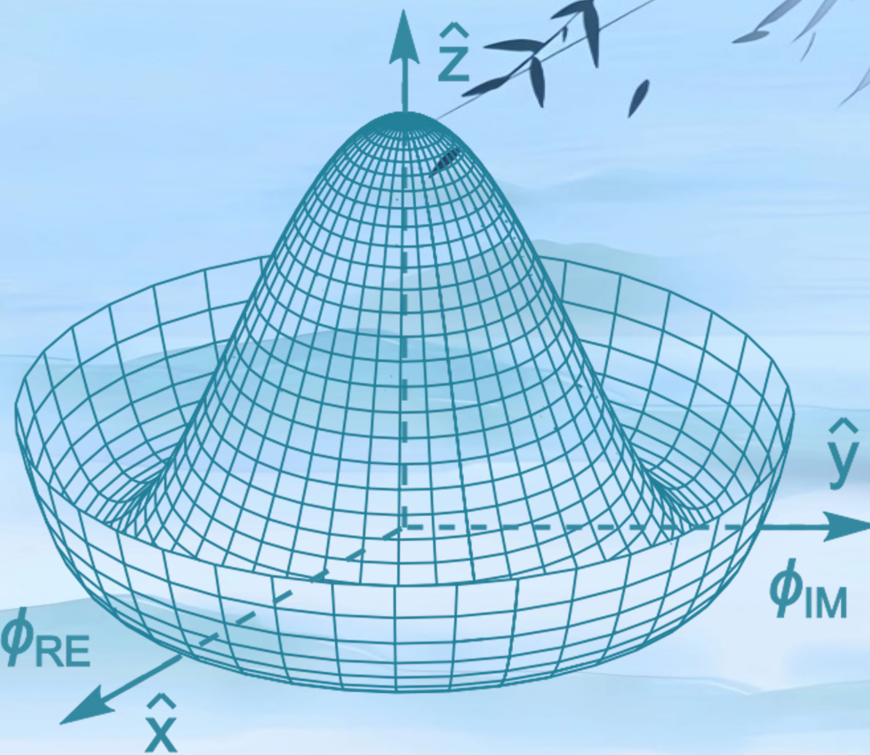




CERN-CMS-DP-2023-050

HH(WW$\gamma\gamma$)

Tiny BR (< 0.1%)



Analysis strategy

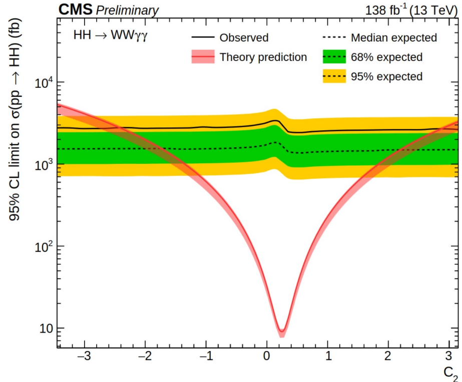
Results

HH→WW*γγ

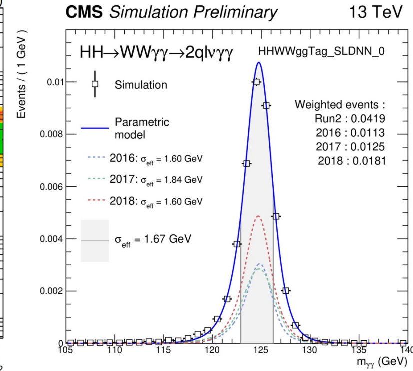
nonres ggF

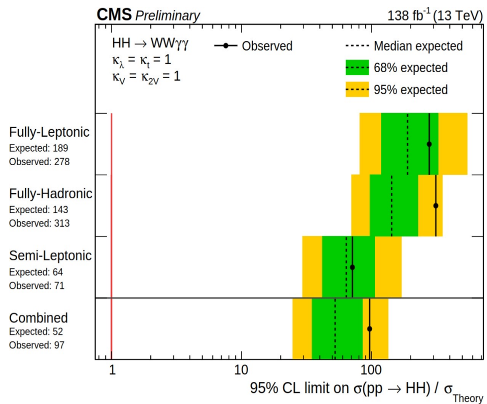
✔ **Excellent mass resolution $m_{\gamma\gamma}$ (1-2%)**

- 3 channels based on number of leptons: (WW*→4q, WW*→lνlν, WW*→lνqq)
  → 0: multiclass DNN to remove H and jets/γ bkgs
  → 1: binary DNNs
  → 2: cut-based
- Signal, background from single Higgs are modelled fitting $m_{\gamma\gamma}$ distribution (simulation).
- Continuous bkg: modelled from data
- Parametric fit on $m_{\gamma\gamma}$ in all categories to extract signal (100 - 180 GeV)

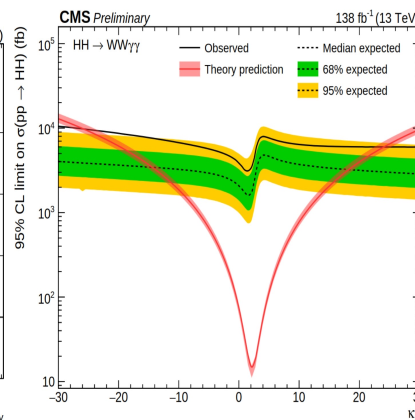


-2.4 (-1.7) < c_2 < 2.9 (2.2)
σ_{EFT} < 1.7 – 6.2 (1.0 – 3.9) pb





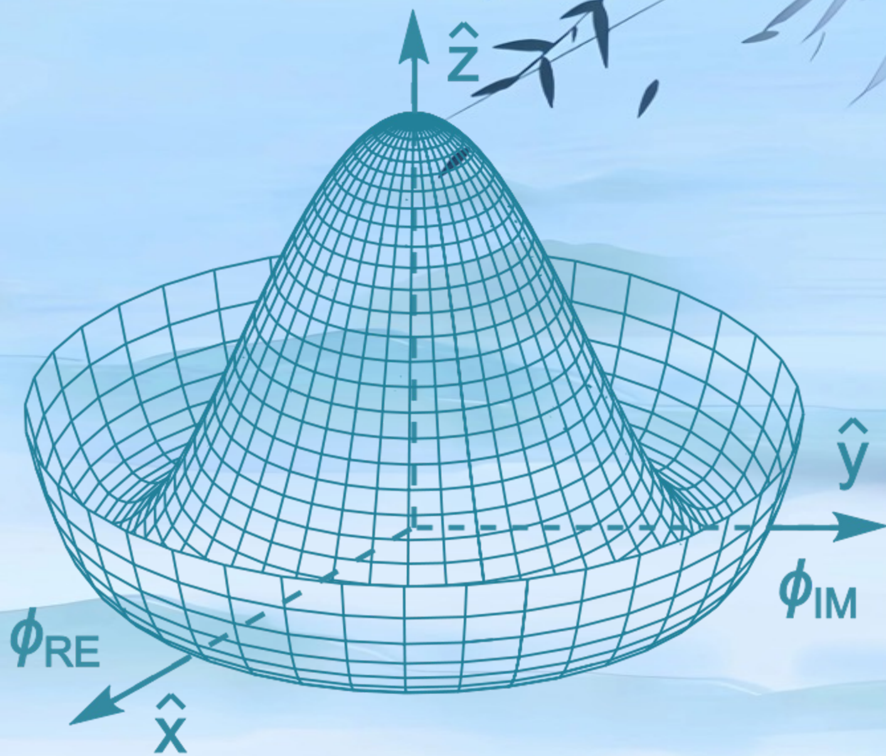
μ^{HH} < 97 (53)



-25.8 (-14.4) < κ_λ < 24.1 (18.3)

HH(bbZZ)

Low BR **(3%)**



Analysis strategy

Results

JHEP 06 (2023) 130

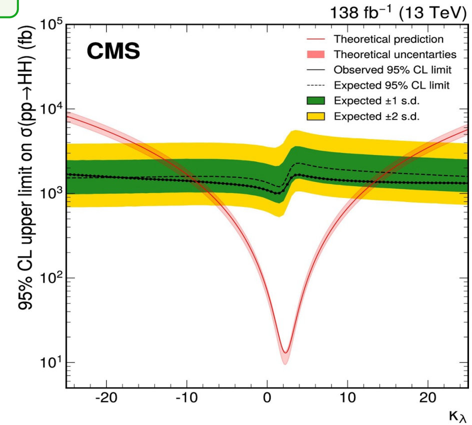
nonres ggF

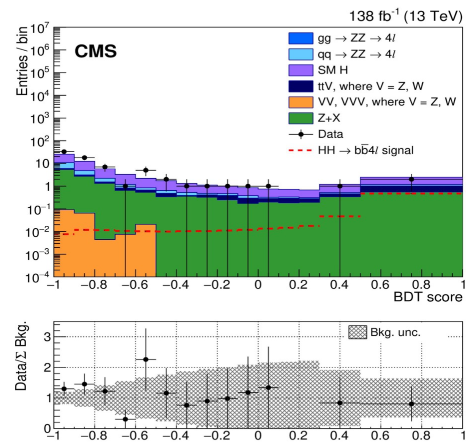
HH→bbZZ(4l)

✔ Clean signature of final state

- Events with four identified leptons (4mu, 4e, 2e2mu) + selection of 2 extra jets with highest DeepCSV score
- Reconstruction strategy for H(ZZ) candidate taken from single Higgs analysis
- Fake non-prompt leptons ($e \rightarrow \gamma$ conversion, misreconstructed jets, HF decays) estimated from data in Z+1L+2 jets and applied to Z+2L+2 jets region
- Backgrounds: single Higgs and ZZ production (MC), Z+X (from data)
- Signal vs bkg discrimination with BDT being fed full b-tagger distribution jets → year and channel-dependent training to get results from BDT score fitting

$\mu^{HH}_{MS} < 32.4$ **(39.6)**
-8.8 **(-9.8)** $< \kappa_\lambda <$ 13.4 **(15.0)**





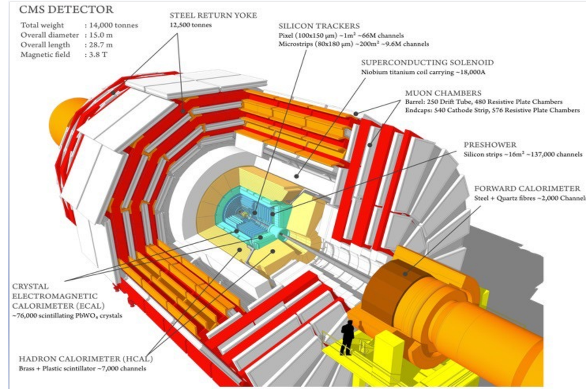
The CMS detector

JINST 3 (2008) S08004

CMS consists of a series of detectors arranged in an onion shape around the collision point:

- Solenoid magnet : B = 3.8 T

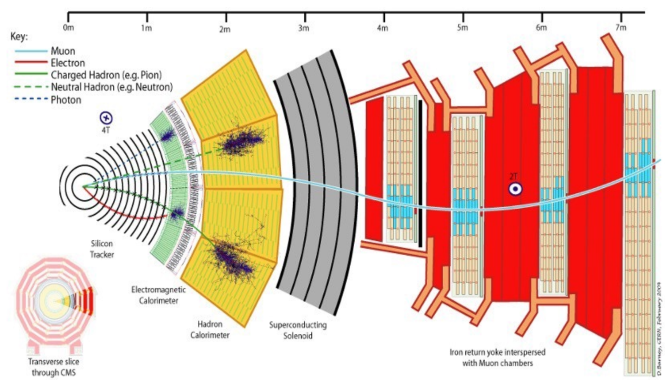
- The Tracker, a silicon device (15148 strip+1856 pixel), is the most internal sub-system of CMS, used to detect the passage of charged particles (η < 3.0) providing position measurements ($\sigma(d_{xy})$~20 – 75 μm) and momentum ($\sigma(p_T)$ ~ 1.5%) up to 100 GeV



- The Electromagnetic Calorimeter, a homogeneous calorimeter with $PbWO_4$ crystals ($\sigma(p_T)$ ~1.6 – 5%), measures the energy of electrons, positrons and photons

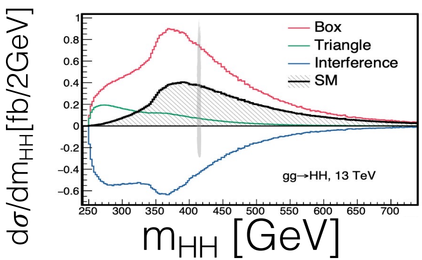
- The Hadron Calorimeter is located inside the magnet (most powerful solenoid ever made – 3.8 T) and measures the energy of the hadrons

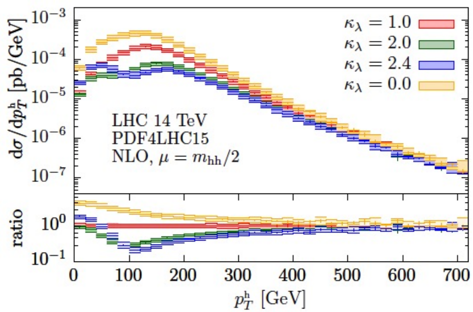
- The muon system consists of 1400 muon chambers
  → CMS is designed to detect muons very accurately

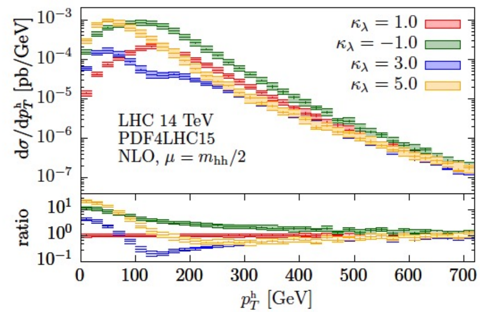


JHEP(2019)066
Symmetry 2022, 14(7), 1467
Physics Letters B (2014) 142-149

Experimental challenge







Experimental sensitivity depends on HH kinematics

→ Low m_{HH}: higher background contamination from QCD / ttbar

→ Results in lower sensitivity

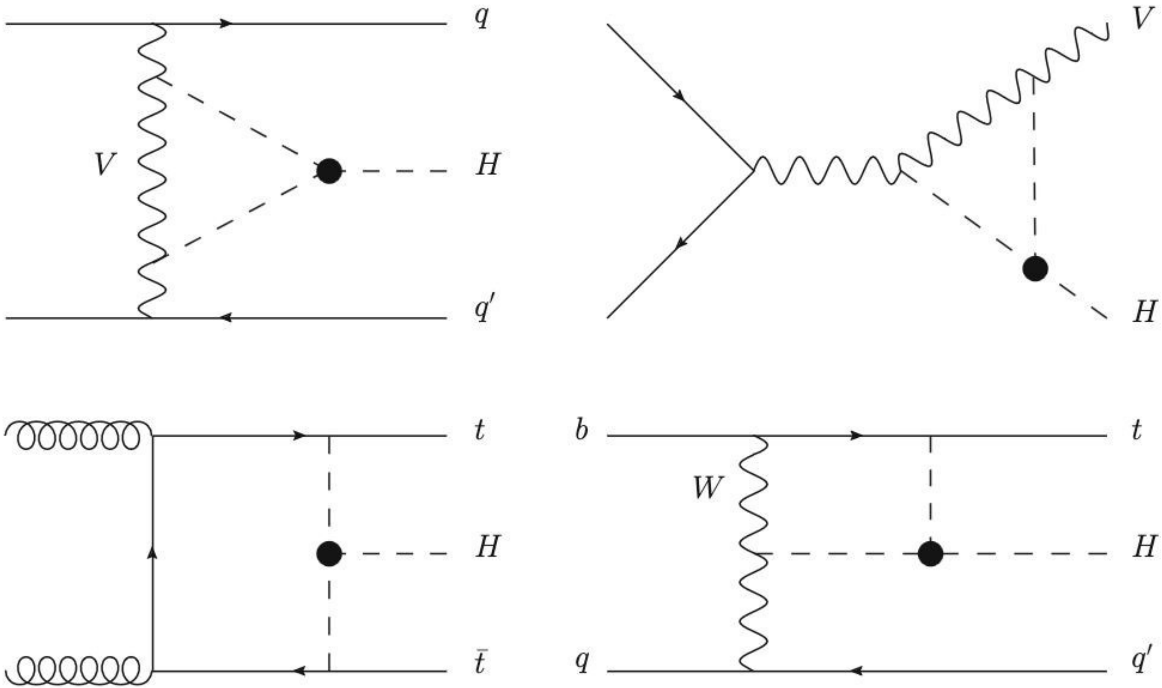
→ In addition, finite rate available at the trigger → challenging to record produced events!

→ Sensitivity driven by high m_{HH} with lower background and better object reconstruction

Access to self-couplings: single Higgs production

Eur. Phys. J. C **77**, 887 (2017)

$\boldsymbol{\lambda}$ can be constrained indirectly thorugh single Higgs production at NLO.



Diagrams NLO contributing to Higgs self-couplings

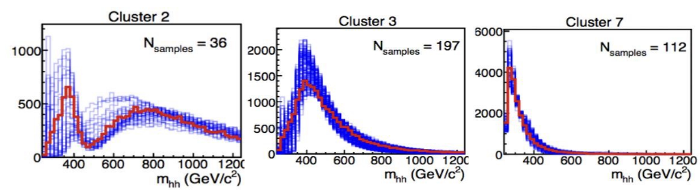
Benchmarks

- Group different coupling values in 5D space (κ_λ, κ_t, c_2, c_g, c_{2g}): benchmark point.

- JHEP04: Grouping is done based on log-likelihood ratio for observables m_{HH} and $\cos\theta^*$ at LO .
  - 12 points in 5D space.

$\cos\theta^*$: Angle between one of the Higgses and beam direction in HH frame.

	1	2	3	4	5	6	7	8	9	10	11	12	8a
kl	7.5	1.0	1.0	-3.5	1.0	2.4	5.0	15.0	1.0	10.0	2.4	15.0	1.0
kt	1.0	1.0	1.0	1.5	1.0	1.0	1.0	1.0	1.0	1.5	1.0	1.0	1.0
c2	-1.0	0.5	-1.5	-3.0	0.0	0.0	0.0	0.0	1.0	-1.0	0.0	1.0	0.5
cg	0.0	-0.8	0.0	0.0	0.8	0.2	0.2	-1.0	-0.6	0.0	1.0	0.0	0.8/3
c2g	0.0	0.6	-0.8	0.0	-1.0	-0.2	-0.2	1.0	0.6	0.0	-1.0	0.0	0.0

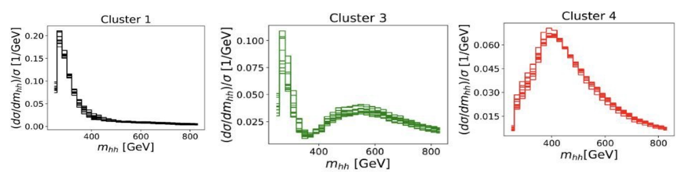


- JHEP03: Grouping is done using unsupervised learning algorithm to identify different shapes in m_{HH} .
  - 7 points in 5D space.

Benchmarks

		κ_λ	κ_t	c_2	c_g	c_{2g}
	SM	1.0	1.0	0.0	0.0	0.0
JHEP04	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
JHEP03	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

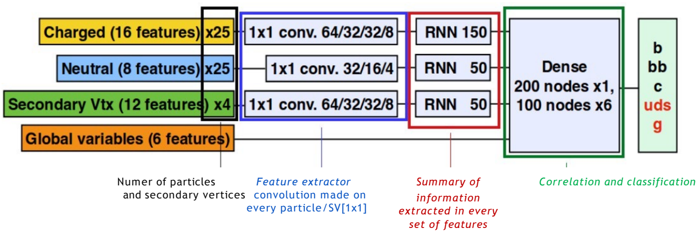
	1	2	3	4	5	6	7
kl	3.94	6.84	2.21	2.79	3.95	5.68	-0.10
kt	0.94	0.61	1.05	0.61	1.17	0.83	0.94
c2	-1./3.	1./3.	-1./3.	1./3.	-1./3.	1./3.	1.
cg	0.5*1.5	0.0*1.5	0.5*1.5	-0.5*1.5	1./6.*1.5	-0.5*1.5	1./6.*1.5
c2g	1./3.*(-3.)	-1./3.*(-3.)	0.5 *(-3.)	1./6.*(-3.)	-0.5 *(-3.)	1./3.*(-3.)	-1./6.*(-3.)

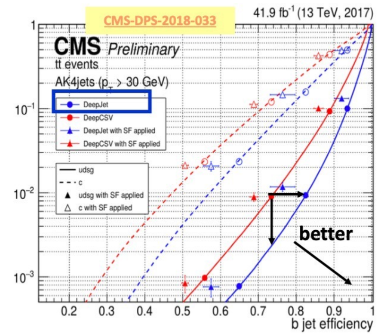


B-Tag algorithms CMS

DeepJet (small R, AK4)

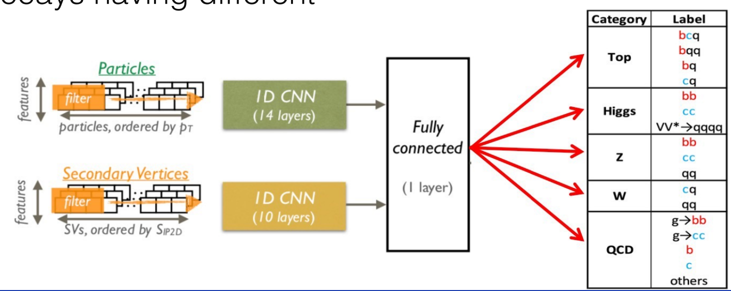
- Low-level information directly in a DNN to tag jets
- Jet as a list of particles lista di particelle (CNN-1D)
- Tagging heavy quarks and separate quark-gluons in one go





DeepAK8 (grande R - boosted)

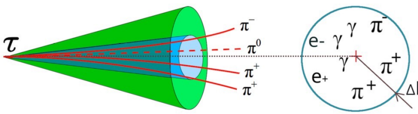
- Jet as a sequence of particles
- Very versatile ➔ different decays having different content in flavour

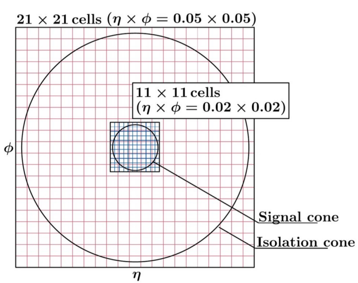


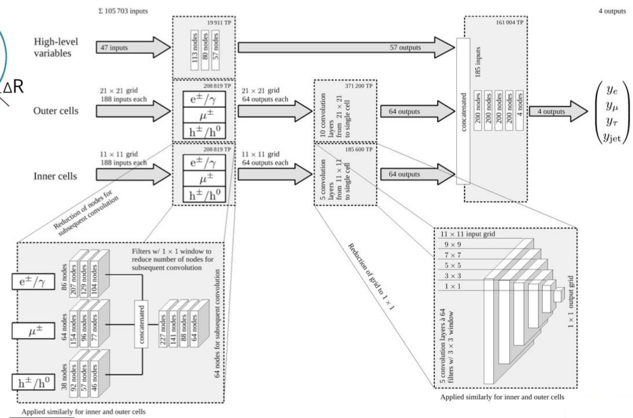
B-Tag algorithms CMS

DeepTau

- Convolutional Deep Neural Network to discriminate τs from jets, electrons and muons
- Information on τ high-level and event properties are combined with those on low-level ParticleFlow candidates, fully reconstructed electrons and muons and used as input
- Each candidate is inserted into a grid (η, ϕ), divided into three blocks (hadron, muon, e-gamma)
- Signal cone: $\Delta R < 0.1$ (11x11) ; insulation cone: $\Delta R < 0.5$ (21x21)



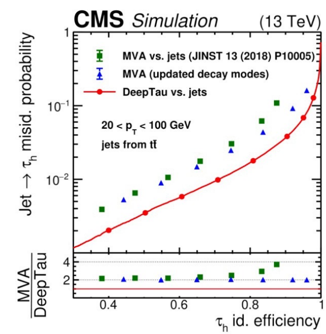




- Tre discriminatori finali

$$D_\tau^\alpha(p) = \frac{p_\tau}{p_\tau + p_\alpha}$$

Dove $\alpha = e, \mu, jet$

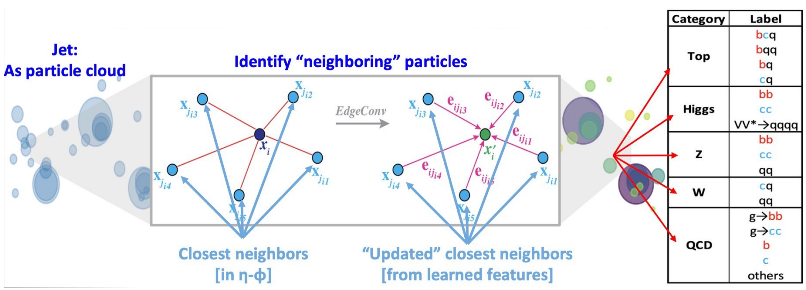


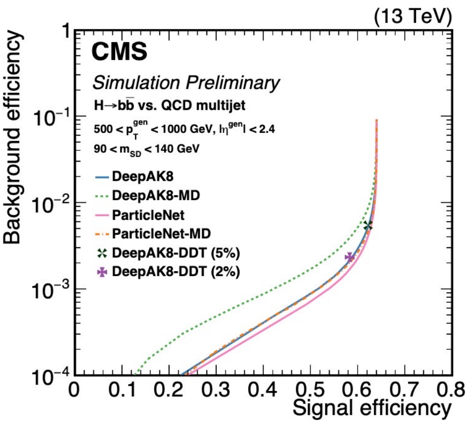
B-Tag algorithms CMS

ParticleNet

- Graph Neural Network to classify jets
- Jets as non-ordered sets of particles in the space
- Input: ParticleFlow candidates and secondary vertices
- Multiclassifier with several output nodes: W/Z/H/top/QCD+decays

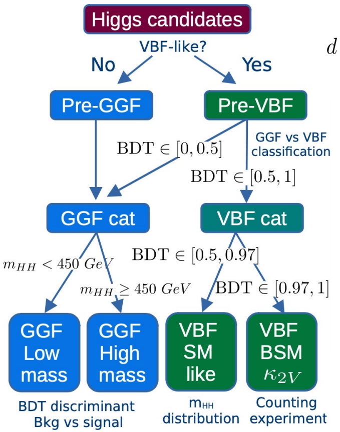
  Example: discriminante bb $D_{bb} = \frac{P[X\rightarrow bb]}{P[X\rightarrow bb]+P[QCD]}$
- Learn in a gerarchical way: first local structures then the global ones
- Significant improvement in performance wrt previous algorithms (like AK8) ➔ factor $\frac{Z[[\rightarrow YY]}{Z[[\rightarrow YY]]Z[\_`a]}$) 2 per jet S/B



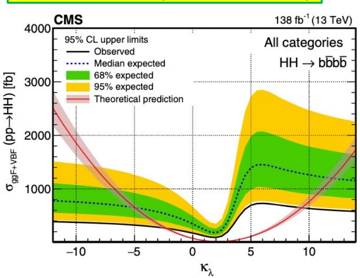


HH→4b

Resolved



$\sigma/\sigma_{SM} < 3.7$ (7.3)
$-2.5 < k_\lambda < 9.5$ ($-5.0 < k_\lambda < 12.0$)

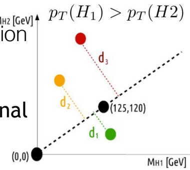


Jet pairing for the Higgs reconstruction based on:

$$d = \frac{|M_{H_1} - kM_{H_2}|}{\sqrt{1+k^2}}$$

Closer to the diagonal (M_{H_1}, M_{H_2})

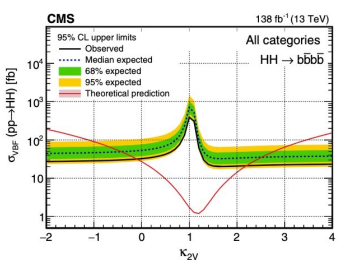
$k = 125/120 = 1.04$



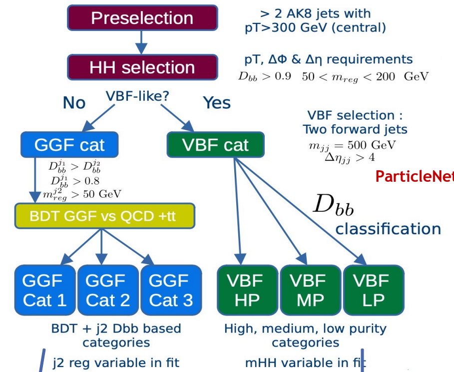
96% pairing correctness ggF HH

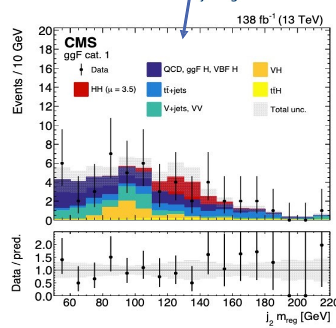
Background estimation: both SR and CR divided into regions 3b e 4b

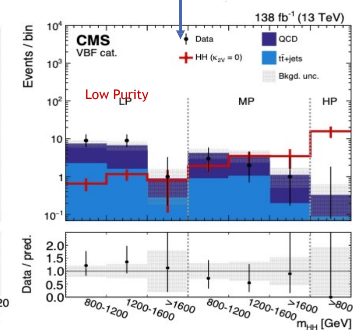
- Bkg events in SR_{4b} modelled by events in SR_{3b}
- Events in SR_{3b} are scaled by the ratio of the number of events in CR_{4b} and CR_{3b}
- Reweighting with BDT trained in CR_{4b} e CR_{3b}, applied to SR_{3b} to model SR_{4b}
  - Minimize problems related to the statistical uncertainties derived by the number of limited events in the two SR regions



Boosted







HH→bbττ

Phys. Lett. B 842 (2023) 137531

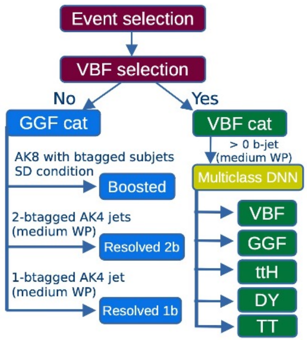
- Cuts on the masses m_{bb} e $m_{\tau\tau}$ for ggF
  - Minimize bkg and signal eff. > 90%

Resolved

$$\frac{(m_{\tau\tau} - 129\ GeV)^2}{(53\ GeV)^2} + \frac{(m_{bb} - 169\ GeV)^2}{(145\ GeV)^2} < 1$$

Boosted

$$\frac{(m_{\tau\tau} - 128\ GeV)^2}{(60\ GeV)^2} + \frac{(m_{bb} - 159\ GeV)^2}{(94\ GeV)^2} < 1$$



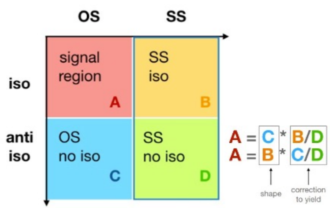
+ DNN bbττ vs background

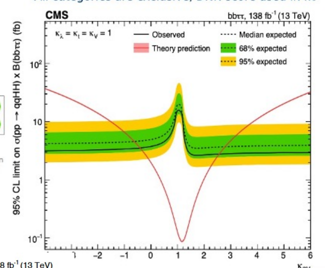
All categories are exclusive, DNN score used in fit

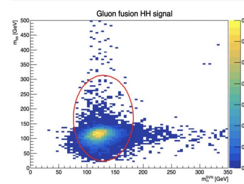
Online p_T trigger thresholds	single-e: $p_T > 25$ (32) GeV cross-e: electron $p_T > 24$ GeV, τ_h $p_T > 30$ GeV single-μ: $p_T > 22$ (24) GeV cross-μ: muon $p_T > 19$ (20) GeV, τ_h $p_T > 20$ (27) GeV ditau: $p_T > 35$ GeV, ditau VBF: $p_T > 20$ GeV
Offline p_T thresholds	online threshold +1 GeV (electrons and muons) online threshold +5 GeV (τ_h candidates)
η thresholds	electrons and muons: $\lvert\eta\rvert < 2.1$ tau: $\lvert\eta\rvert < 2.1$ (2.3) for ditau and cross (single) triggers
Lepton ID and isolation	tight electron BDT ID + isolation tight muon ID and isolation
τ_h ID ($\tau_e\tau_h$, $\tau_\mu\tau_h$ channels)	medium DeepTauVsJet tight DeepTauVsMu very-loose DeepTauVsEle
τ_h ID ($\tau_h\tau_h$ channel)	medium DeepTauVsJet very-loose DeepTauVsMu very-very-loose DeepTauVsEle
Distance to PV	$\lvert d_{xy}\rvert < 0.045$ cm (electrons and muons only) $\lvert d_z\rvert < 0.2$ cm
Pair selections	opposite-sign, $\Delta R > 0.5$

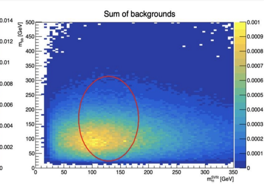
Background estimate:

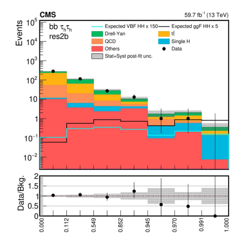
- tt, DY+jet from simulations (+normalization from CR)
- Multijet QCD from data using ABCD method
- Other processes from simulation

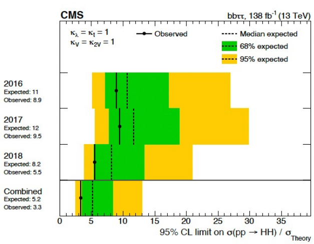


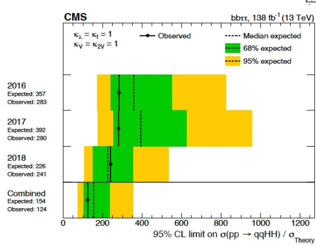












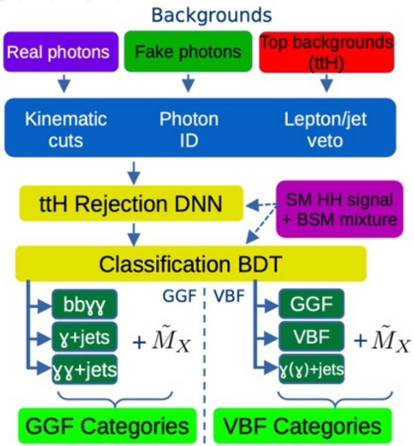
-1.7 **(-2.9)** $< \kappa_\lambda <$ 8.7 **(9.8)**

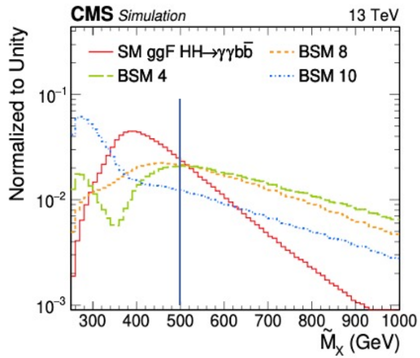
-0.4 **(-0.6)** $< \kappa_{2V} <$ 2.6 **(2.8)**

$\sigma/\sigma^{HH}_{MS} <$ 3.3 **(5.2)**

$\sigma/\sigma^{VBF}_{MS} <$ 124 **(154)**

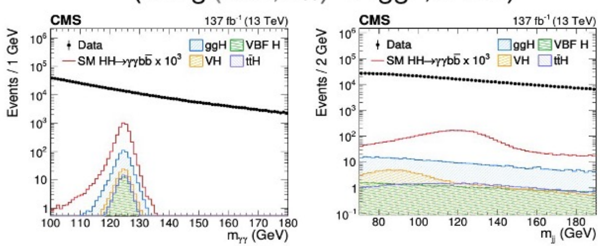
HH→bbγγ

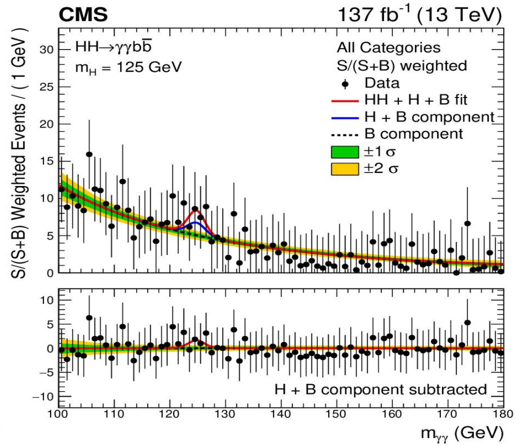


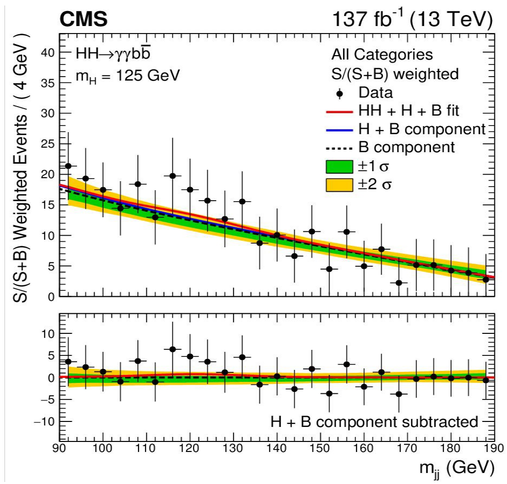


$$M_X = M_{2233} - M_{22} - M_{33} + 2M_6$$

- Fit 2D (m_{33}, m_{99}) to extract the signal il segnale (categ (BDT, M_X) 12 ggF, 2 VBF)

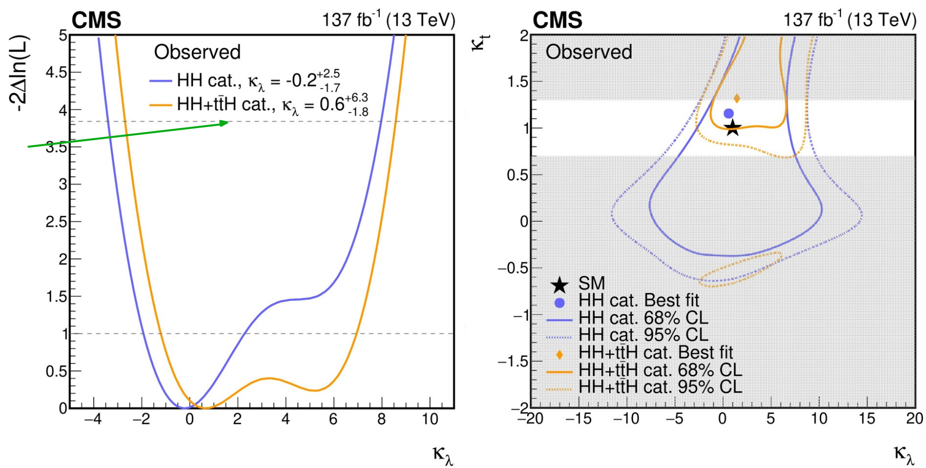






HH→bbγγ

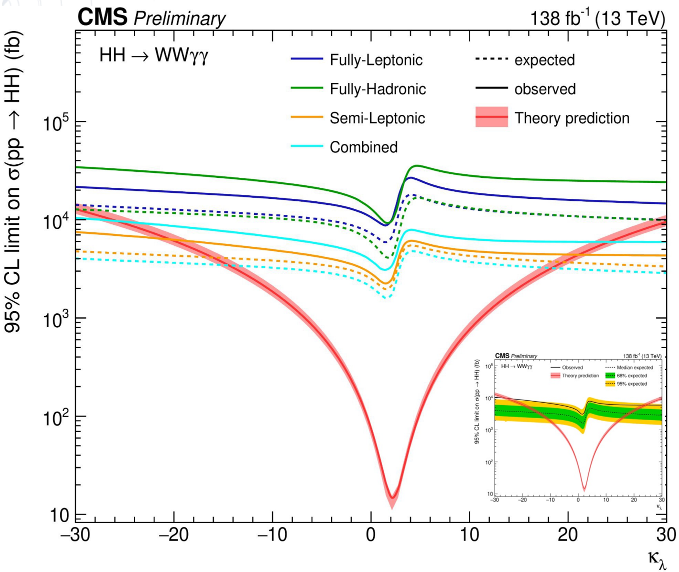
- **Combination** with **ttH(→γγ)** to improve constrain **kλ** and **kt**
- **Additional** orthogonal **categories** for events not passing HH selection to **target ttH**
- 2 minima likelihood due to cross section dependence on kλ and different acceptance of categories
- 2D scan (kλ,kt) to better constrain kλ and kt (valid only when |kt|~1)



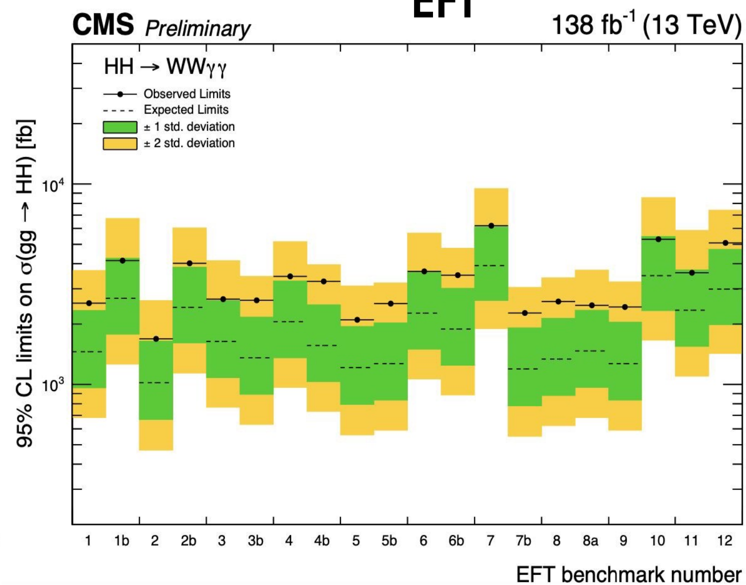
HH→WW*$\gamma\gamma$

CMS PAS HIG-21-014

k_λ



EFT



$\sigma / \sigma^{HH}_{MS}$ < 97 **(53)**
-25.8 **(-14.4)** < κ_λ < 24.1 **(18.3)**
-2.4 **(-1.7)** < c_2 < 2.9 **(2.2)**

Oss.**(Exp.):** 1.7 a 6.2 **(1.0 a 3.9) pb**

VHH→4b

CMS PAS HIG-22-006

Object selection

Channel	Vector boson decay products selection	Vector boson reconstruction and selection	Jet selection
MET small-radius		$\vec{p}_T^{Z} = \vec{p}_T^{miss}$ $p_T^Z > 150$ GeV	≥4 small-radius jets with $p_T > 35$ GeV
MET large-radius		$\vec{p}_T^{Z} = \vec{p}_T^{miss}$ $p_T^Z > 250$ GeV	≥2 large-radius jets with $p_T > 200$ GeV
1L	$p_T^e > 32(28)$ GeV 2018/2017 (2016) OR $p_T^\mu > 25$ GeV $\Delta\phi(\vec{p}_T^{\ell}, \vec{p}_T^{miss}) < 2.0$	$\vec{p}_T^{W} = \vec{p}_T^{\ell} + \vec{p}_T^{miss}$ $p_T^W > 125$ GeV	≥3 small-radius jets with $p_T > 25$ GeV and ≥4 small-radius jets with $p_T > 15$ GeV OR ≥2 large-radius jets with $p_T > 200$ GeV
2L	$p_T^{\mu_1} > 20$ GeV $p_T^{\mu_2} > 20$ GeV $p_T^{e_1} > 25$ GeV $p_T^{e_2} > 20$ GeV	$\vec{p}^{Z} = \vec{p}^{\ell_1} + \vec{p}^{\ell_2}$ $p_T^Z > 50$ GeV	≥4 small-radius jets with $p_T > 20$ GeV
FH	$p_T^{J_i} > 20$ GeV	$\vec{p}^{V} = \vec{p}^{J_1} + \vec{p}^{J_2}$ $65 < m_V < 105$ GeV	≥4 small-radius jets with $p_T > 40$ GeV and ≥6 small-radius jets with $p_T > 20$ GeV

Category definition based on the decay of W/Z

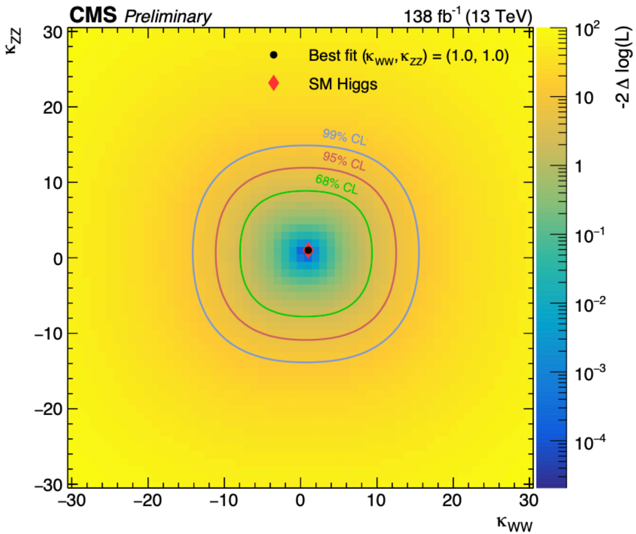
	MET small-radius	MET large-radius	1L small-radius	1L large-radius	2L	FH
Coupling enrichment	$\kappa_\lambda, \kappa_{VV}$	κ_{VV}	$\kappa_\lambda, \kappa_{VV}$	κ_{VV}	$\kappa_\lambda, \kappa_{VV}$	$\kappa_\lambda, \kappa_{VV}$
N_b	$N_b \geq 3$	—	$N_b \geq 3$	—	$N_b = 3$ $N_b = 4$	$N_b = 4$
$D_{b\bar{b},1} \times D_{b\bar{b},2}$	—	HP, LP	—	HP, LP	—	—
SR, CR	SR+CR	SR+CR	SR+CR	SR+CR	SR, CR	SR
SB	$\kappa_\lambda + \kappa_{VV}$	HP, LP	$\kappa_\lambda + \kappa_{VV}$	HP, LP	$N_b = 3$ $N_b = 4$	—
$t\bar{t}$ CR	—	—	—	—	One	—
Year split	Per year	Per year	Per year	Per year	Combined	Per year
Total regions	9	12	9	12	11	6

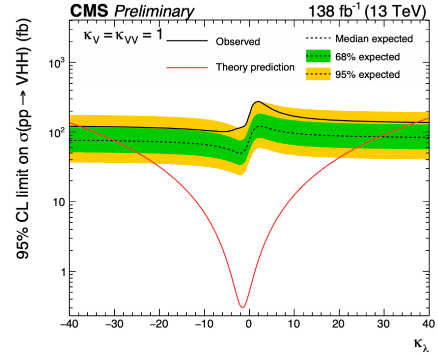
Variables used for the BDT training to separate enriched regions for κ_λ, κ_{2V}

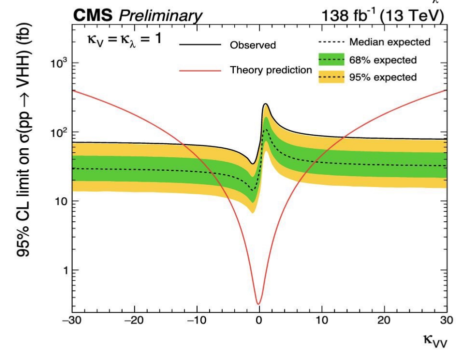
Input variable	MET	1L	2L	FH
m_{HH}	✓	✓	✓	✓
$p_T^{H_2}$	✓	✓		
p_T^{V}	✓	✓	✓	✓
$\Delta R(H_1, H_2)$	✓	✓	✓	✓
$\Delta\phi(\ell_1, \ell_2)$			✓	
$p_T^{H_1}$	✓	✓	✓	✓
$\Delta\eta(\ell_1, \ell_2)$			✓	
$\Delta R(J_{1,H_2}, J_{2,H_2})$			✓	
$\Delta R(J_{1,H_1}, J_{2,H_1})$			✓	
$p_T^{\ell_1}/m_V$			✓	
$\Delta\phi(V, H_2)$	✓	✓	✓	✓
m_{H_2}	✓	✓		
p_T^{HH}	✓	✓		
m_{H_1}	✓	✓		
$\Delta\eta(H_1, H_2)$	✓	✓		✓
$\Delta\phi(H_1, H_2)$	✓	✓		✓
Energy of H_1	✓	✓		✓
Energy of H_2	✓	✓		✓
Energy of HH	✓	✓		✓
η_{HH}	✓	✓		✓
η_{H_1}				✓
η_{H_2}				✓
$p_T^{H_2}/p_T^{H_1}$	✓	✓	✓	✓
$p_T^{\ell_2}/p_T^{\ell_1}$			✓	
$p_T^{\ell_1}$			✓	
Simulation year	✓	✓		

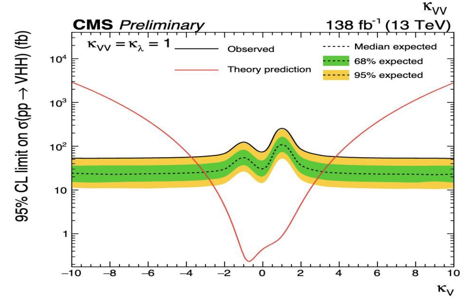
VHH→4b

[CMS PAS HIG-22-006]









- 37.7 **(- 30.1)** < κ_λ < 37.2 **(28.9)**

−12.2 **(-7.2)** < κ_{2V} < 13.5 **(8.9)**

−3.7 **(-3.1)** < κ_V < 3.8 **(3.1)**

−14.0 **(-10.2)** < κ_{2W} < 15.4 **(11.6)**

−17.4 **(-10.5)** < κ_{2Z} < 18.5 **(11.6)**

$\boldsymbol{\sigma / \sigma^{\mathrm{VHH}}_{\mathrm{MS}}}$ < 294 **(124)**

$HH \to bbWW^*$

CMS PAS HIG-21-005

Objects selection

- Small radius jets:
  - p_T > 25 GeV, $|\eta| < 2.4$
  - Medium working point on the DeepJet score
- Large radius Jets:
  - p_T > 200 GeV, $|\eta| < 2.4$,
  - $\tau_2 / \tau_1 < 0.75$
  - sub-jet p_T > 20 GeV
  - $30 < m_{SD} < 210$
  - m_{jj} > 12 GeV

Single Lepton Categories

Categories	Sub-Categories		
HH(GGF)	Resolved 1b	Resolved 2b	Boosted
HH(VBF)	Resolved 1b	Resolved 2b	Boosted
Top + Higgs	Resolved		Boosted
WJets + Other	Inclusive		

Di Lepton Categories

Categories	Sub-Categories		
HH(GGF)	Resolved 1b	Resolved 2b	Boosted
HH(VBF)	Resolved 1b	Resolved 2b	Boosted
Top + Other	Resolved		Boosted
DY + Multi-boson	Inclusive		

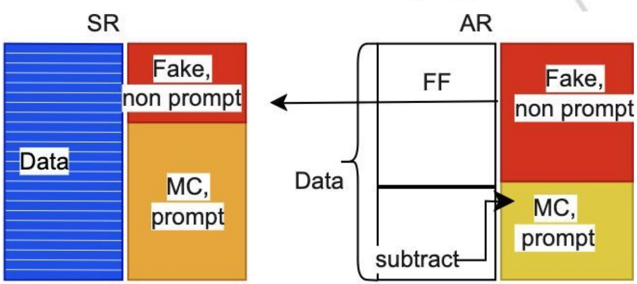
HH→bbWW*

CMS PAS HIG-21-005

QCD multijet, Fake lepton estimation:

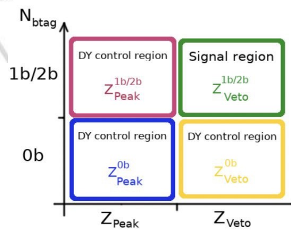
- SR → Signal region
- AR → Similar to signal region but lepton fails the tight selection
- Prompt → lepton matched with generator level lepton coming from W, Z, τ or Higgs
- FF → fake factor which is the probability to pass the fake to tight cut

$$w = (-1)^{n+1} \prod_{i=1}^{n} \frac{f_i}{1 - f_i},$$



DY estimation

- Calculate transfer weight from 0-bjet →1/2-bjet region in Z-peak region
- Weights are binned in HT (P_T sum of AK4 jets) for resolved and softdrop mass of leading AK8 jet for boosted category.
- Apply transfer weight in Z-veto region
- Non DY backgrounds are subtracted from data in both Z-peak and Z-veto region.



$$N\left(Z^{1b/2b}_{Veto}\right) = N\left(Z^{0b}_{Veto}\right) \frac{N\left(Z^{1b/2b}_{Peak}\right)}{N\left(Z^{0b}_{Peak}\right)}$$

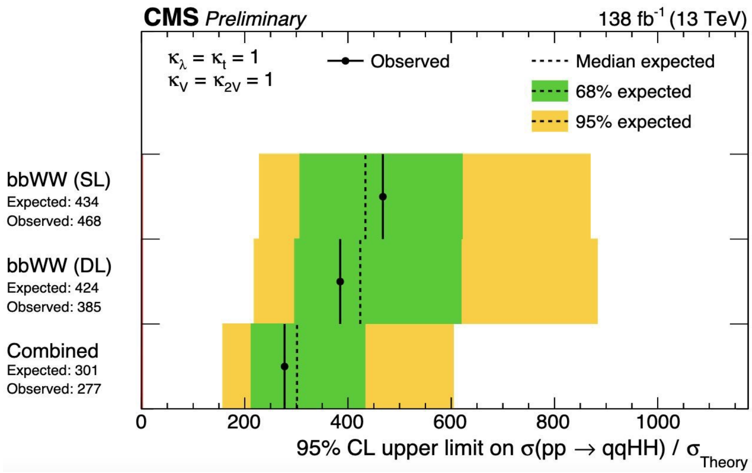
$Z_{veto} = | M_{ll} - M_Z | > 10$ GeV

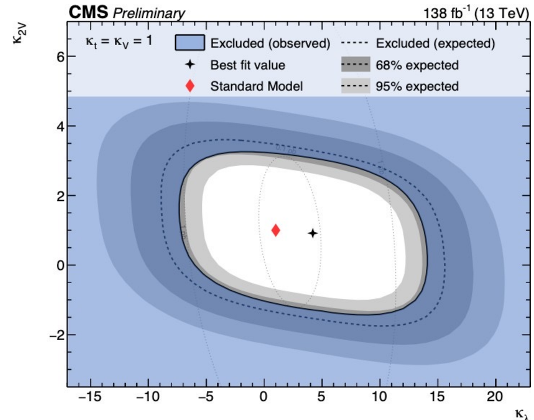
$Z_{peak} = | M_{ll} - M_Z | \leq 10$ GeV

0b/1b/2b = N(Ak4 bjets)

HH→bbWW*

CMS PAS HIG-21-005





σ/σ^{HH}_{SM} < 14 **(18)**
σ/σ^{VBF}_{SM} < 277 **(301)**
-7.2 **(-8.7)** < κ_λ < 13.8 **(15.2)**
-1.1 **(-1.4)** < κ_{2V} < 3.2 **(3.5)**
-0.8 **(-1.0)** < c_2 < 1.3 **(1.4)**

Multilepton

JHEP 07 (2023) 095

Category	2ℓss	3ℓ	4ℓ
Targeted HH decays	WW^*WW^*	WW^*WW^*	WW^*WW^*
Trigger	Single- and double-lepton	Single-, double- and triple-lepton	Single-, double- and triple-lepton
Lepton p_T	>25 / 15 GeV	>25 / 15 / 10 GeV	>25 / 15 / 15 / 10 GeV
Lepton charge sum	±2, with charge quality requirements applied	±1	0
Dilepton invariant mass	$\|m_{\ell\ell} - m_Z\| > 10$ GeV †	$\|m_{\ell\ell} - m_Z\| > 10$ GeV ‡	$\|m_{\ell\ell} - m_Z\| > 10$ GeV ‡
Jets	≥2 small-radius jets or ≥1 large-radius jet	≥1 small-radius jet or ≥1 large-radius jet	—
Missing p_T	$p_T^{miss,LD} > 30$ GeV §	$p_T^{miss,LD} > 30$ GeV ‖	—

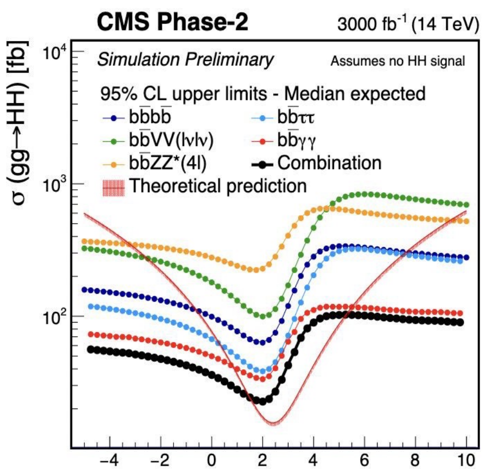
Category	$3\ell + 1\tau_h$	$2\ell + 2\tau_h$
Targeted HH decays	$WW^*\tau\tau$	$WW^*\tau\tau$, $\tau\tau\tau\tau$
Trigger	Single-, double-, and triple-lepton	Single- and double-lepton
Lepton p_T	>25 / 15 / 10 GeV	>25 / 15 GeV
τ_h p_T	>20 GeV	>20 GeV
Lepton and τ_h charge	ℓ and τ_h charges sum to 0	ℓ and τ_h charges sum to 0
Dilepton invariant mass	$\|m_{\ell\ell} - m_Z\| > 10$ GeV ‡	$\|m_{\ell\ell} - m_Z\| > 10$ GeV ‡

Category	$1\ell + 3\tau_h$	$4\tau_h$
Targeted HH decays	$\tau\tau\tau\tau$	$\tau\tau\tau\tau$
Trigger	Single-lepton, lepton+τ_h and double-τ_h	Double-τ_h
Lepton η	$\|\eta\| < 2.1$	—
Lepton p_T	>20 GeV (e) or >15 GeV (μ)	—
τ_h p_T	>40 / 30 / 20 GeV	>40 / 30 / 20 / 20 GeV
Lepton and τ_h charge	ℓ and τ_h charges sum to 0	τ_h charges sum to 0
$Z \to ee$ veto	$\|m_{e\tau_h} - 86$ GeV$\| > 15$ GeV ¶	—

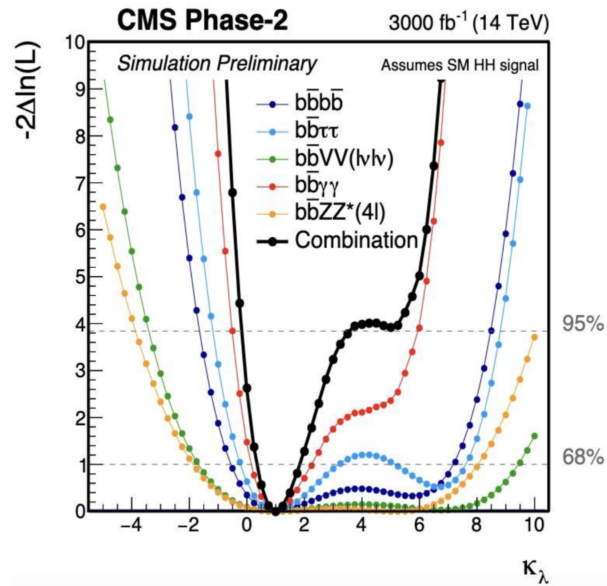
Results from projection study at HL-LHC

CERN Yellow Report

- HL-LHC projection is studied at 3000 fb^{-1} and center of mass energy 14 TeV.
- Five channels are considered: **bbbb, bb$\boldsymbol{\gamma\gamma}$, bb$\boldsymbol{\tau\tau}$, bbZZ(4ℓ), bbVV(ℓℓ)**.



Channel	bbbb	bb$\tau\tau$	bbWW$(\ell\nu\ell\nu)$	bb$\gamma\gamma$	bbZZ$(\ell\ell\ell\ell)$
$\mathcal{B}$ [%]	33.9	7.3	1.7	0.26	0.015
Number of events	37000	8000	1830	290	17



- Constraint on Higgs self-coupling:
  - 0.8 < $\boldsymbol{\kappa_\lambda}$ < 3.6 at 95% confidence level
- New channels have been added as well as improvement in analysis have been made after this study!