Di-Higgs searches at CMS

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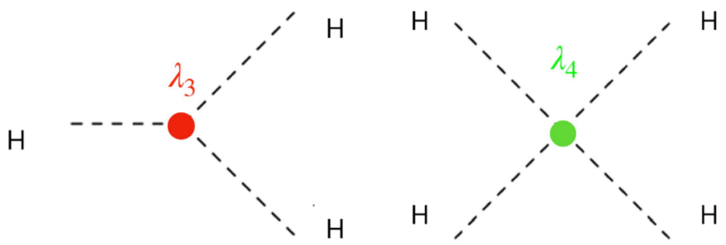
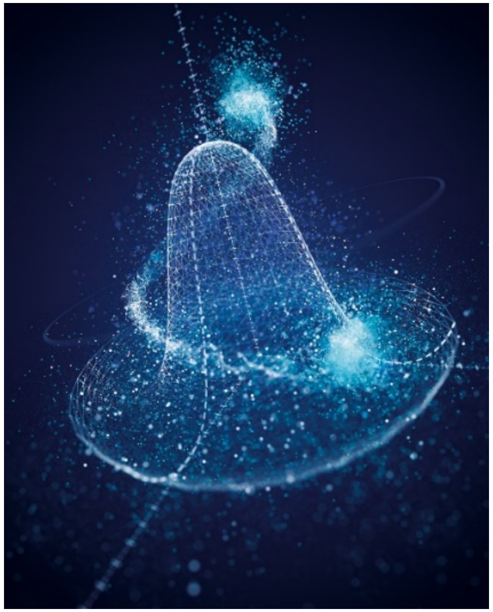
Introduction

- HH measurement directly probes Higgs self-coupling λ
  - Crucial for understanding the Higgs field potential
    - $V(H) = \frac{1}{2}{m_H}^2 H^2 + \lambda_3 H^3 + \lambda_4 H^4$



  - Tight correlation with the dynamics of the electroweak phase transition



[CERN Courier](#)

- HH production also sensitive to Beyond Standard Model (BSM) effects
  - Modified SM couplings
  - Additional couplings in Effective Field Theory
  - Resonant production

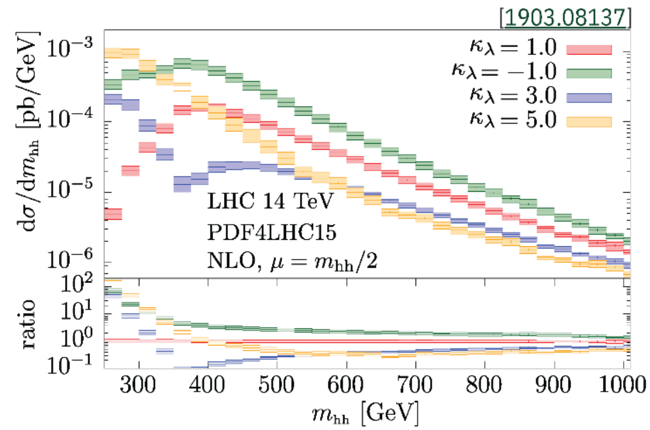
This talk focuses on non-resonant HH measurements at CMS

See also the [talk of resonance searches](#) by Ilias Zisopoulos

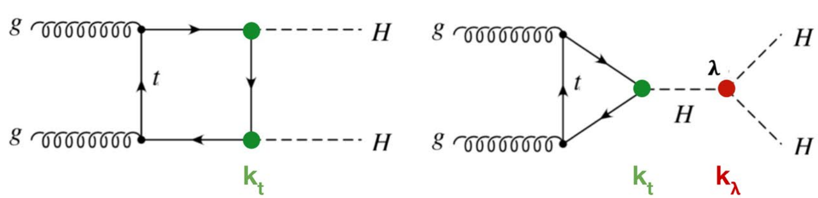
HH production

- HH production challenging to measure due to it small cross section
  - $\sigma_{HH} \sim \frac{\sigma_H}{1000}$ in SM at 13TeV
  - Two main production modes
    - $\sigma_{ggF} = 31.1\ fb$ SM @13TeV
      - Dominant channel for studying self-coupling
      - Destructive interference
    - $\sigma_{VBF} = 1.73\ fb$ SM @13TeV
      - Only channel to access quartic VVHH coupling
    - ~11% increase in the cross section at 13.6 TeV
  - Test deviation from the SM couplings with κ-framework: : $k_X = X/X_{SM}$

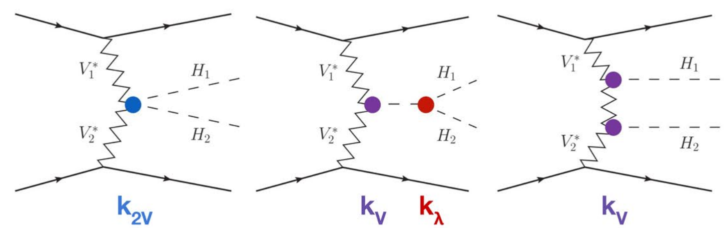
$\kappa_\lambda = \lambda/\lambda^{SM}$ also dictates signal kinematics:



Gluon-gluon fusion (**ggF**)



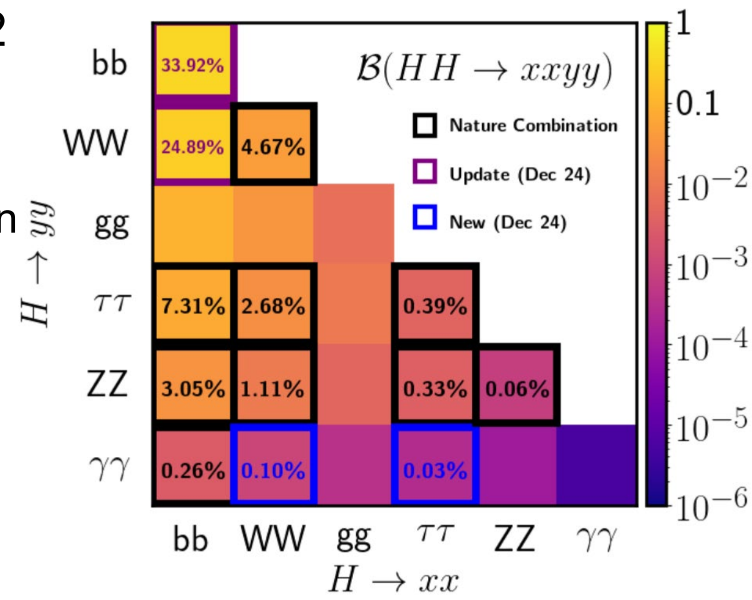
Vector-boson fusion (**VBF**)



- Additional production modes including VHH, ttHH

Overview of HH measurement at CMS

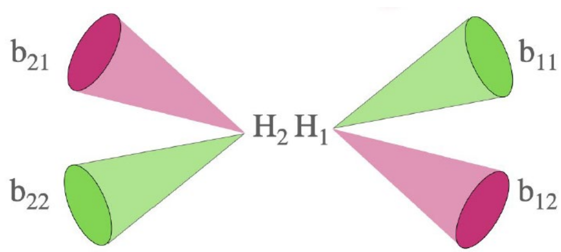
- HH searches have been evolving since early Run 2
  - More HH production modes and decay channels, boosted topologies
  - Extensive usage of machine learning, trigger, selection and tagging optimization
- Best HH sensitivity via combination of all channels
  - Run2 Legacy Combination : CMS-PAS-HIG-20-011
  - Using full Run 2 data with 138 fb^{-1}
  - All final states defined to be mutually exclusive



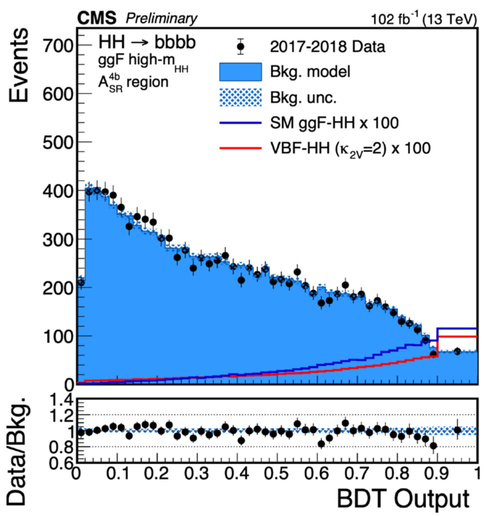
HH Combination Nature 607 (2022) 60		New additions in Run2 Legacy Combination	
$bbbb$ resolved	Phys. Rev. Lett. 129 (2022) 081802	$VHH\ bbbb$	JHEP 10 (2024) 061
$bbbb$ boosted	Phys. Rev. Lett. 131 (2023) 041803	$bbWW(leptonic)$	JHEP 07 (2024) 293
$bb\tau\tau$	Phys. Lett. B 842 (2023) 137531	$bbVV(hadronic)$	CMS-PAS-HIG-23-012
$bb\gamma\gamma$	JHEP03(2021)257	$WW\gamma\gamma$	CMS-PAS-HIG-21-014
$bbZZ(4l)$	JHEP 06 (2023) 130	$\tau\tau\gamma\gamma$	CMS-PAS-HIG-22-012
$Multilepton$	JHEP 07 (2023) 095		

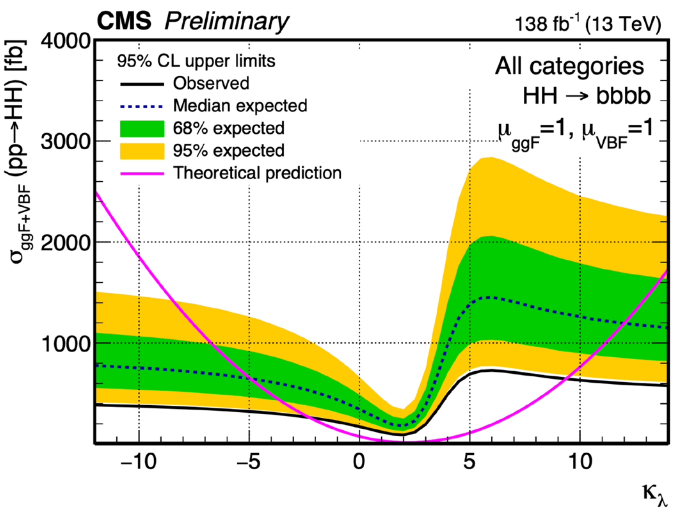
$HH \rightarrow bbbb$ resolved

- Targeting HH decay resolved into 4 b-jets
- Large multi-jet background estimated from data and fitted simultaneously in multiple signal regions
- Use dedicated BDTs to separate different signals and backgrounds
- Simultaneous fit of MVA for ggF and mHH for VBF categories



Phys. Rev. Lett. 129 (2022) 081802





Observed (expected) results:

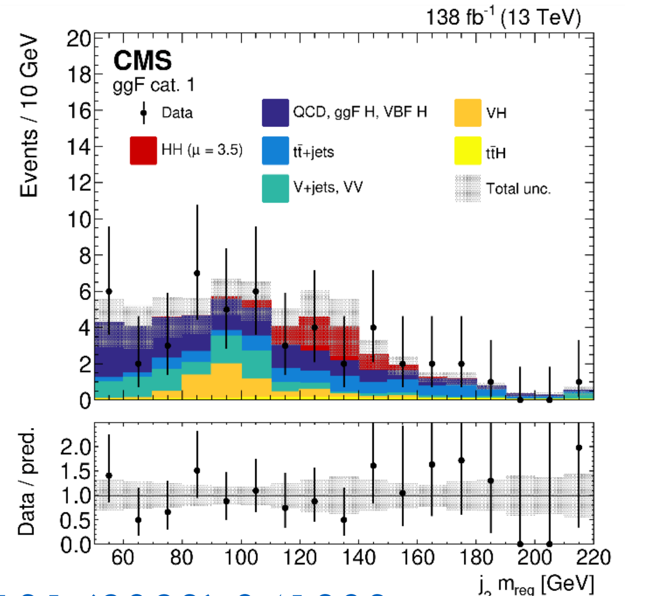
$$\sigma^{HH}_{ggF+VBF} < 3.9(7.8) \times \sigma^{HH\,SM}_{ggF+VBF}$$

$$-2.3(-5.0) < k_\lambda < 9.4(12)$$

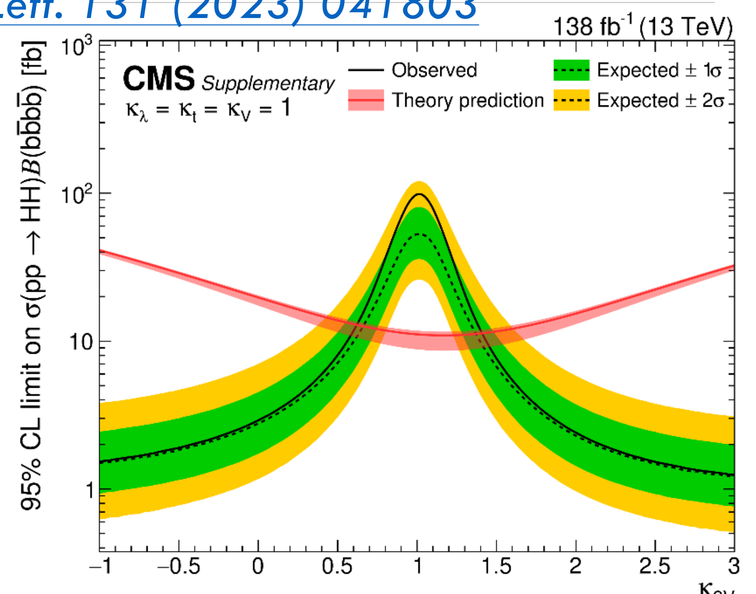
$$-0.1(-0.4) < k_{2V} < 2.2(2.5)$$

$HH \rightarrow bbbb$ boosted

- HH decay boosted into two merged jets
  - Boosted H→bb candidate(s) reconstructed as large radius jet(s)
    - "ParticleNet" tagger (arXiv:1902.08570) to identify boosted H decays
  - DNN b-jet energy regression to improve H→bb mass resolution
- Main backgrounds from QCD and tt
  - Fit/correction from control regions
- ggF and VBF signal extracted with
  - Fit to sub-leading jet mass for ggF
  - Fit to m_{HH} for VBF
- Observed (expected) results:
  - $\sigma^{HH}_{ggF+VBF} < 9.9(5.1) \times \sigma^{HH\,SM}_{ggF+VBF}$
  - $-9.9\ (-5.1) < k_\lambda < 16.9\ (12.2)$
- k_{2V} = 0 firstly excluded at >5σ assuming $k_\lambda = k_t = k_V = 1$
  - $0.62\ (0.66) < k_{2V} < 1.41\ (1.37)$

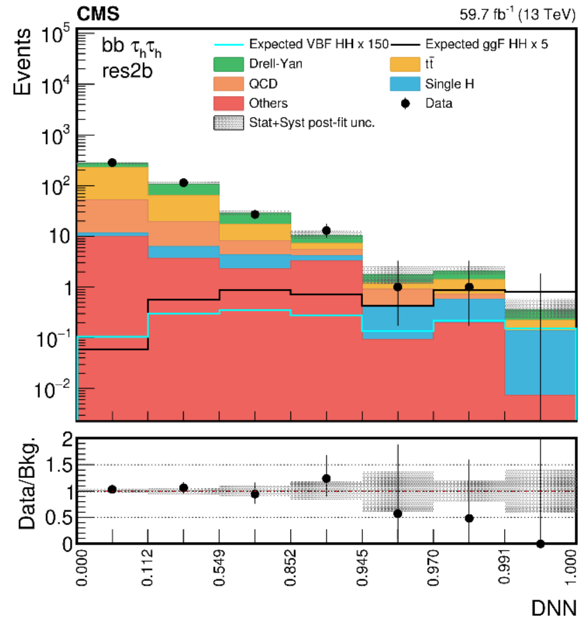


Phys. Rev. Lett. 131 (2023) 041803



$HH \to bb\tau\tau$

- Targeting HH decays in $\tau_h\tau_h, \mu\tau_h$ and $e\tau_h$
  - Triggers based on leptons and hadronic taus
  - Di-τ trigger with or without jets
  - Single-e, e-τ, single-mu and μ-τ triggers
- Leading background from QCD, ttbar and DY events
  - Estimated using data-driven or control regions
- Event categorization on production mode and final state
- DNN classifiers to separate signal and backgrounds
- Signal extraction from fit to DNN score

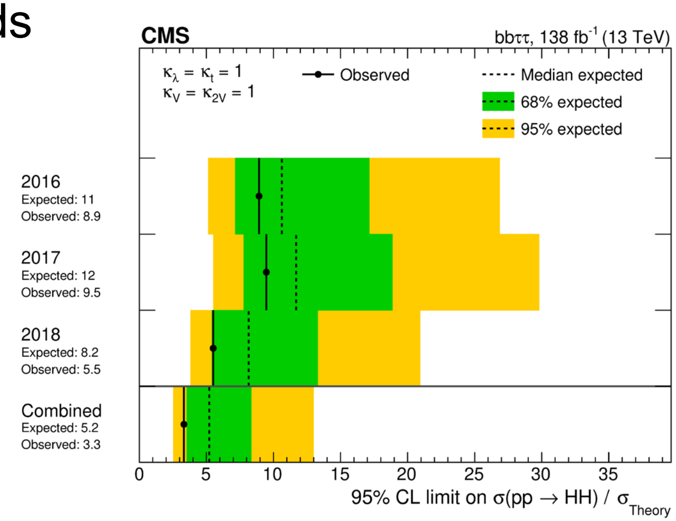


Most stringent limits on inclusive HH (observed) and VBFHH:

$$\sigma^{HH}_{ggF+VBF} < 3.3(5.2) \times \sigma^{HH\,SM}_{ggF+VBF},$$
$$\sigma^{HH}_{VBF} < 124(154) \times \sigma^{HH\,SM}_{VBF},$$

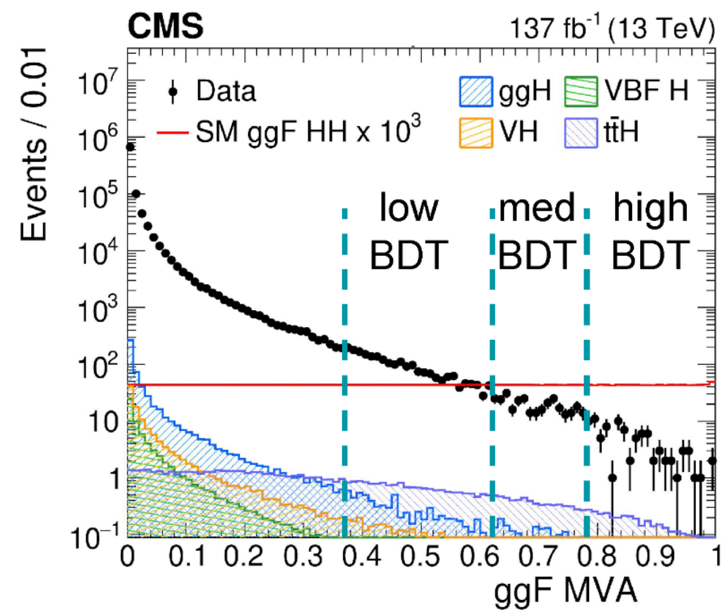
$$-1.8(-3.0) < k_\lambda < 8.8(9.9)$$
$$-0.4(-0.6) < k_{2V} < 2.6(2.8)$$

Phys. Lett. B 842 (2023) 137531

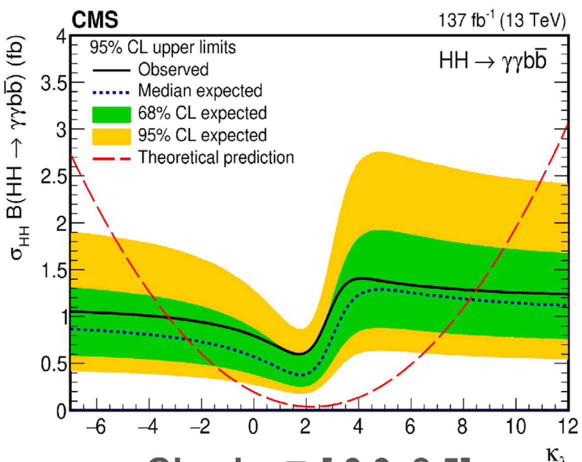


$HH \rightarrow bb\gamma\gamma$

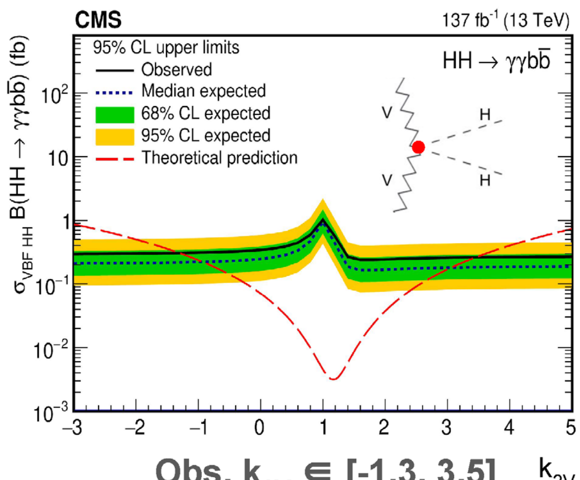
- Targeting $HH \rightarrow bb\gamma\gamma$ final state analysis
  - very small BR, clean signal extraction due to the narrow $h \rightarrow \gamma\gamma$ mass peak
- Main backgrounds: $\gamma\gamma + jets$, $\gamma + jets$, ttH
  - Boosted Decision Trees trained to separate signal and backgrounds
  - Deep Neural Network (DNN) to reduce ttH background
    - ttH: the dominant resonant background, similar final-state topology and can reconstruct a diphoton mass peak resembling the signal
- Category for ggF and VBF based on the MVA output
- Signal extracted from a 2D fit to $(m_{\gamma\gamma}, m_{bb})$



Limit on HH XS×BR vs k_λ



Limit on VBF HH XS×BR vs k_{2V} = c_{2V}, c_{2V}



Obs. $k_\lambda \in [-3.3, 8.5]$
Exp. $k_\lambda \in [-2.5, 8.2]$

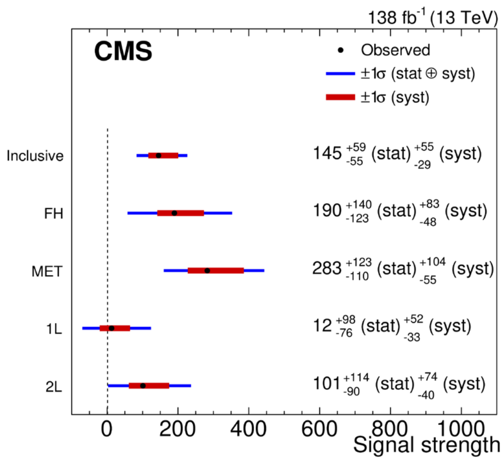
Obs. $k_{2V} \in [-1.3, 3.5]$
Exp. $k_{2V} \in [-0.9, 3.0]$

Obs.(exp.) upper limit on HH signal strength
7.7(5.2)×SM

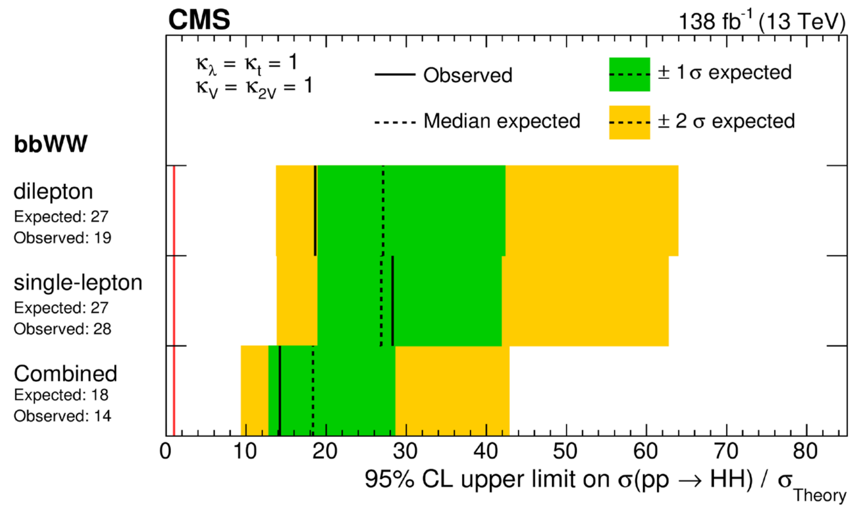
JHEP 03 (2021) 257

Results from other channels

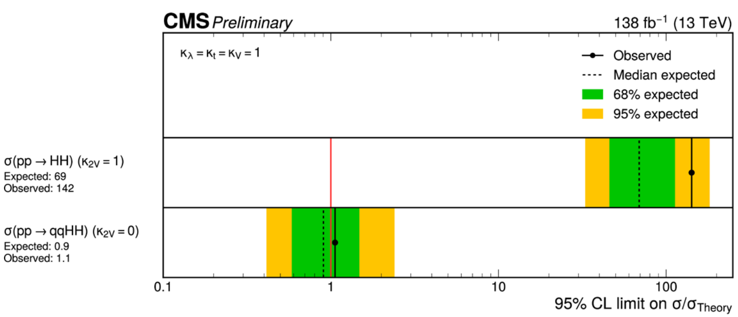
$VHH\ bbbb$ JHEP 10 (2024) 061



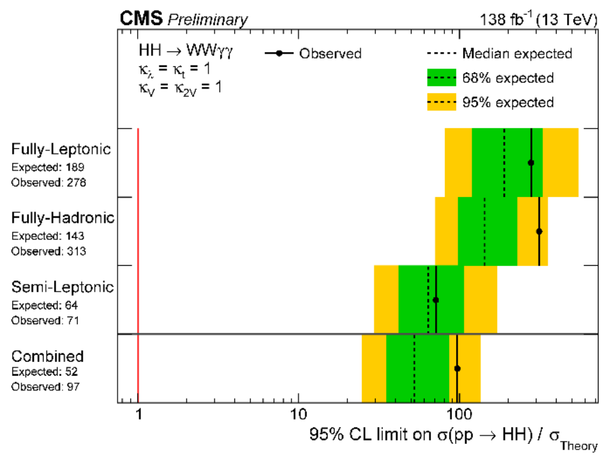
$bbWW(leptonic)$ JHEP 07 (2024) 293



$bbVV(hadronic)$ CMS-PAS-HIG-23-012



$WW\gamma\gamma$ CMS-PAS-HIG-21-014



$\tau\tau\gamma\gamma$ CMS-PAS-HIG-22-012

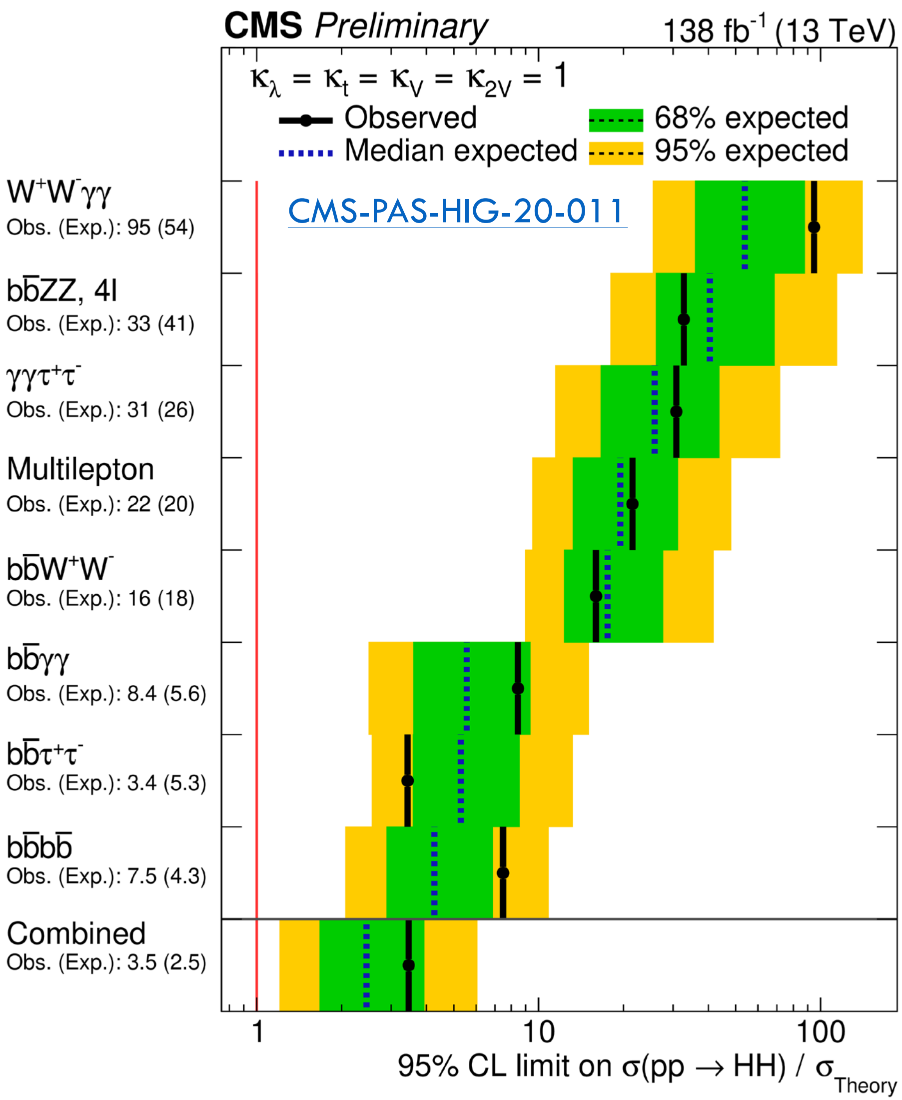
Observed (expected) HH upper limit at the 95% CL: $33(26) \times \sigma_{ggF+VBF}^{HH\ SM}$

Complementary HH searches, with results compatible with SM predictions

Legacy Run2 combination

- The most complete CMS combination to date
  - Using full Run 2 data with 138 fb^{-1}
  - All available channels in Run2
    - Overlap removal between channels leading to slight shifts in the upper limit compared to individual results
  - Updated uncertainties and signal cross section
  - New EFT interpretations
  - Updated Projections

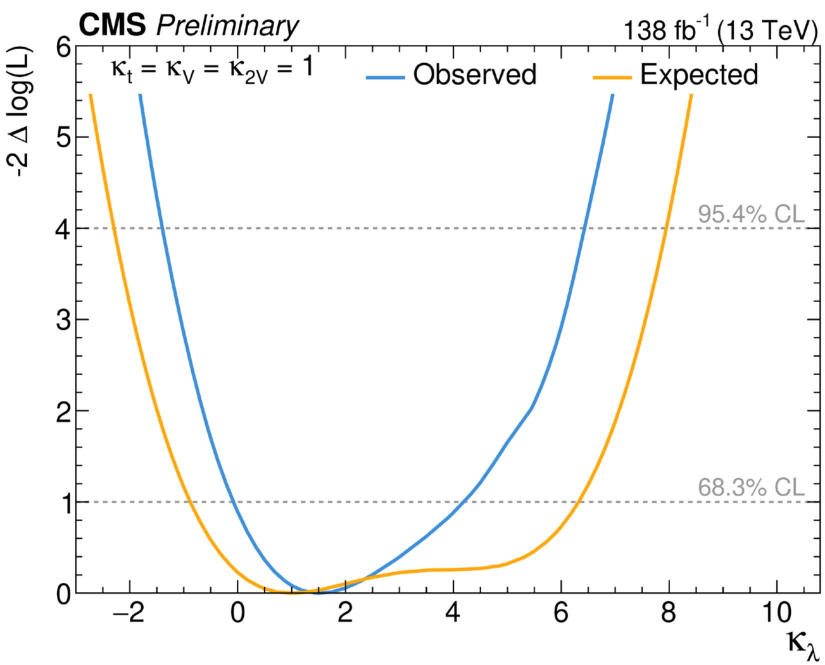
- Obs.(exp.) upper limit on HH signal strength : $3.5\ (2.5)\ \times \sigma_{ggF+VBF}^{HH\ SM}$
  - Significant improvement comparing to early Run 2 results
    - ~5× improvement, far beyond the ~2× gain expected from luminosity scaling alone.

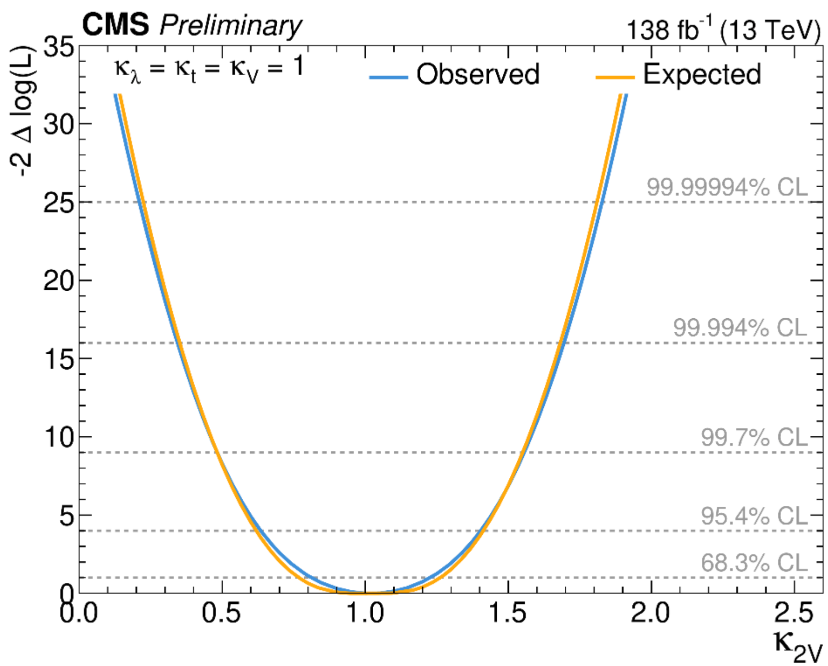


Limits extracted under the background-only hypothesis

Constraints on coupling modifiers

- Constrain Higgs boson self-interaction coupling modifier κ_λ @ 95.4% C.L.
  - Observed (expected) k_λ range: $-1.40\ (-2.29) < k_\lambda < 6.43\ (7.95)$
- Constrain quartic VVHH coupling modifier κ_{2V} @ 95.4% C.L.
  - Observed (expected) k_{2V} range: $0.63\ (0.62) < k_{2V} < 1.40\ (1.41)$
- $k_{2V} = 0$ is excluded with a significance of 6σ, assuming $k_\lambda = k_V = k_t = 1$





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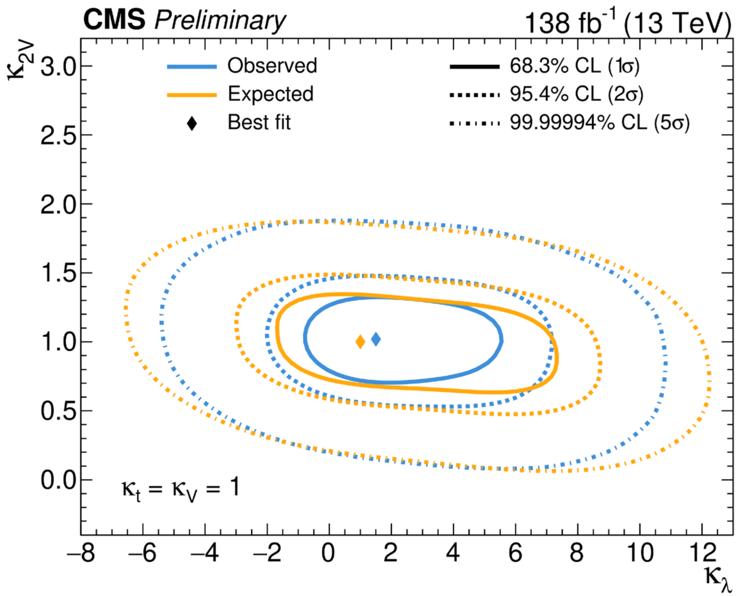
2D coupling constraints



- Two-dimensional constraints in the $(k_\lambda, k_{2V}), (k_\lambda, k_t), (k_V, k_{2V})$ planes
- No significant deviation from the SM is observed

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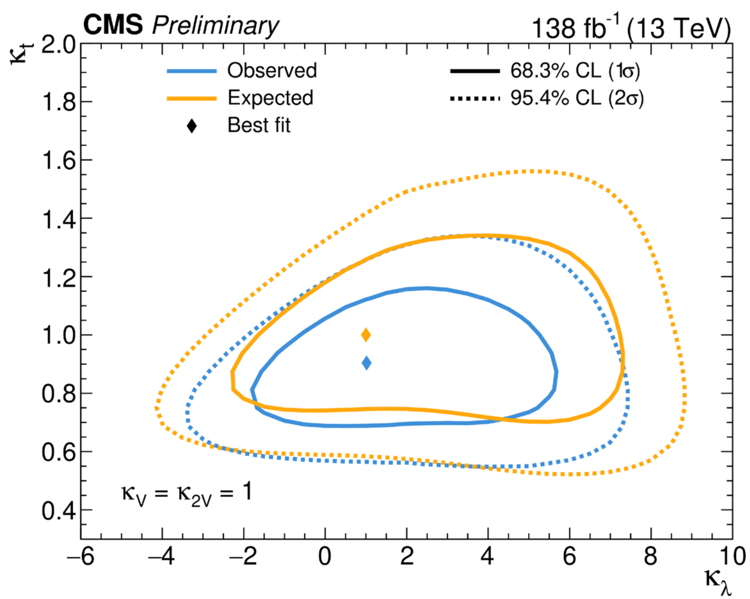
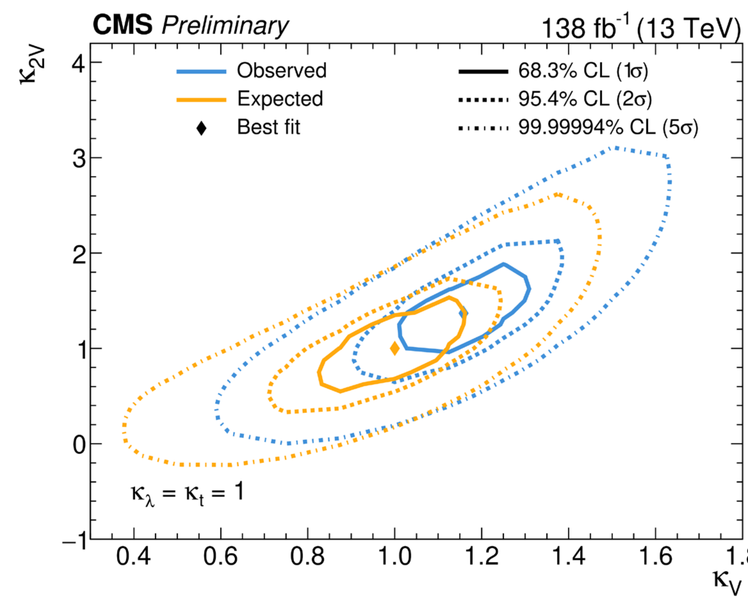
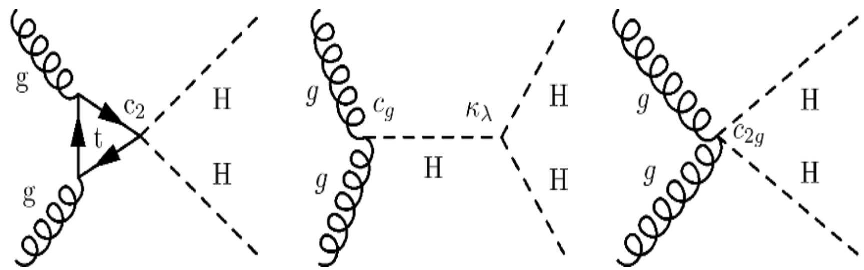




The HEFT modeling in CMS

- New symmetries and/or new heavy particles induces additional effective terms into the H potential

- Studied in the Higgs EFT (HEFT) scenario
  - linear variation of couplings ($k_{\lambda}, k_t , c_2 , c_g , c_{2g}$)



$$|A|^2 = \kappa_\lambda^2 \cdot \kappa_t^2 \cdot |\triangle|^2 + \kappa_t^4 \cdot |\square|^2 + c_2^2 \cdot |X|^2 + \kappa_\lambda \cdot \kappa_t \cdot c_2 \cdot |\triangle^* X + X^* \triangle| + \kappa_t^2 \cdot c_2 \cdot |\square^* X + X^* \square| + \kappa_t^3 \cdot \kappa_\lambda \cdot |\triangle^* \square + \square^* \triangle|$$

HH production amplitude expression including EFT contact term c_2

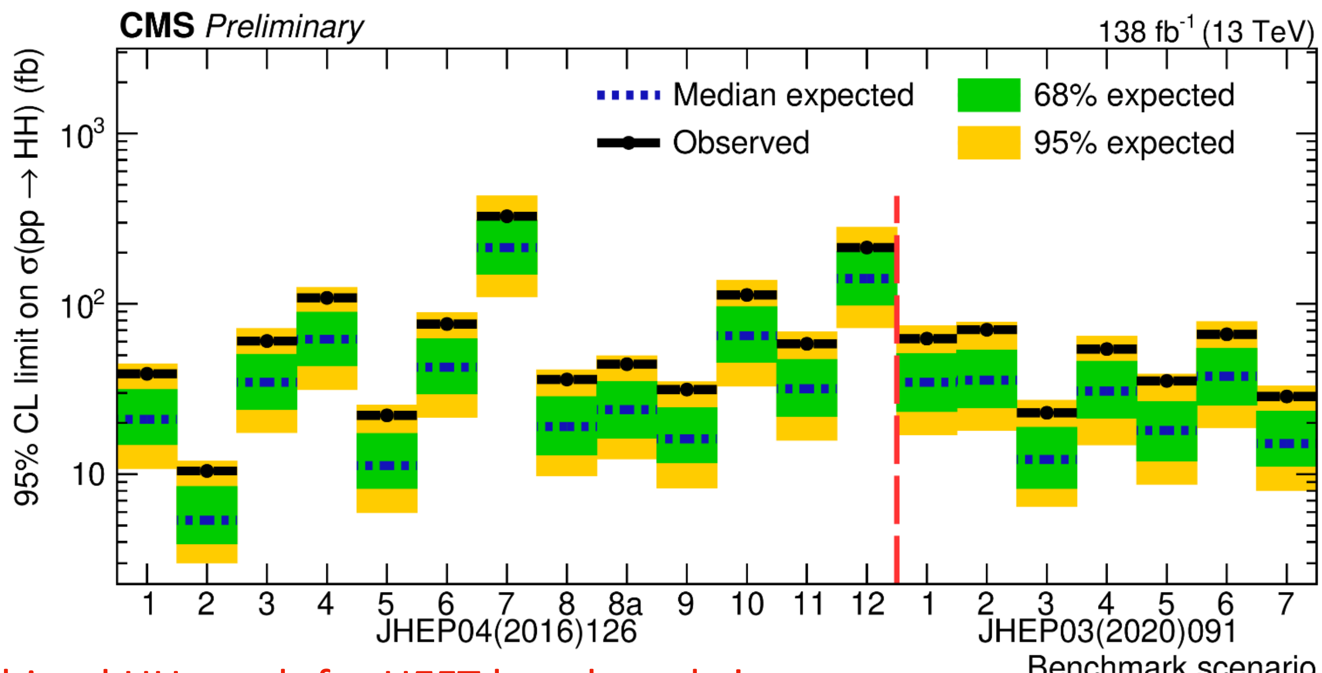
$\triangle$: triangle diagram contribution

$\square$: box diagram contribution

X: contact interaction from EFT

Upper limits on HEFT benchmarks

- Upper limits in two representative HEFT benchmarks with different combinations of the coupling modifiers ($k_\lambda, k_t, c_2, c_g, c_{2g}$)
  - 1: Thirteen benchmark scenarios spanning a broad range of the coupling variations
  - 2: With NLO precision and considers direct and indirect constraints on couplings
- No significant deviations from expectations are observed
  - An overall small excess in all benchmarks, between 1σ and 2σ

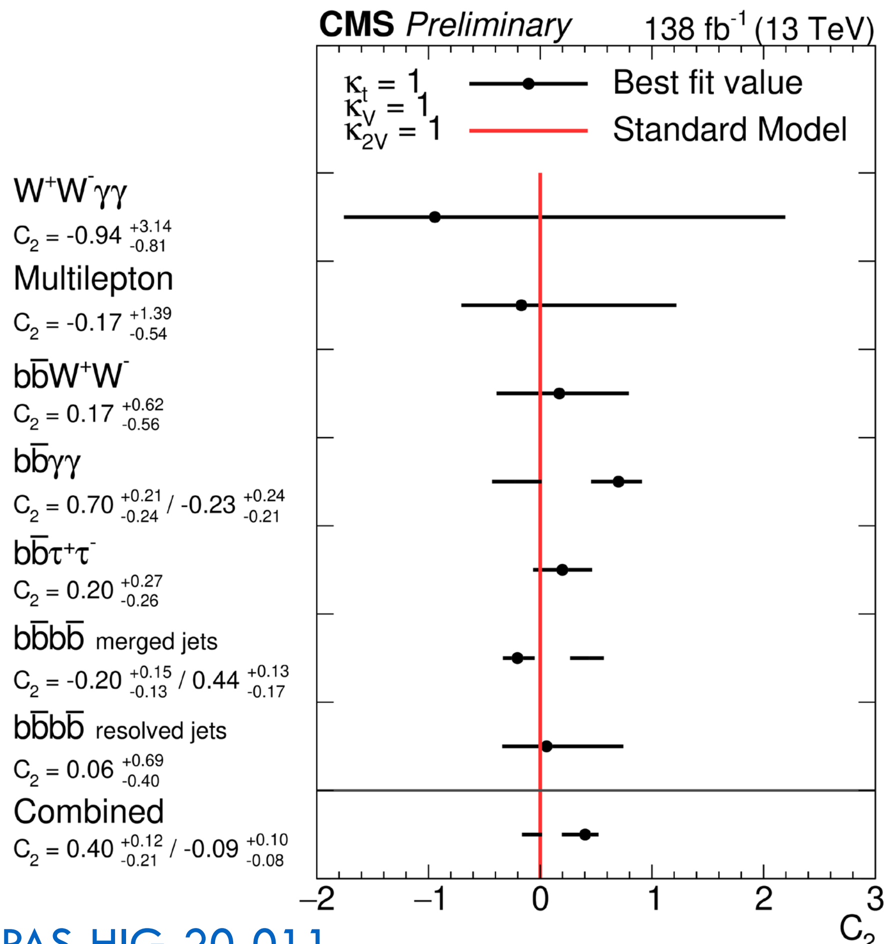


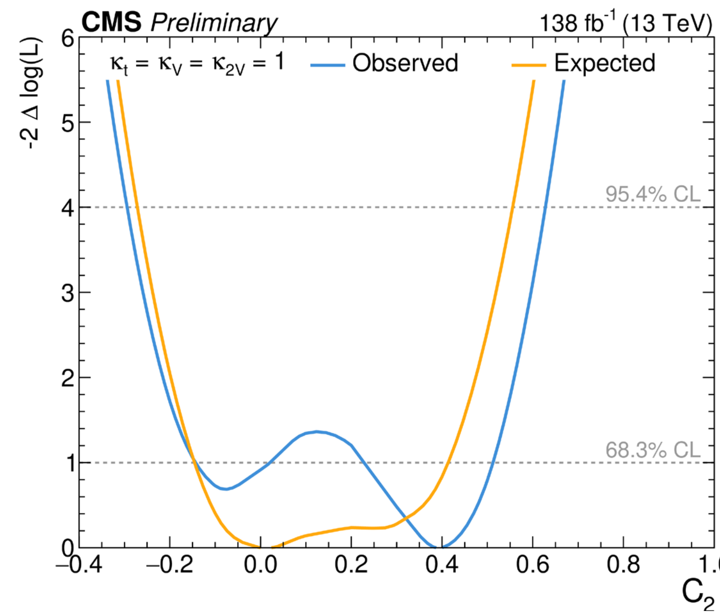
First combined HH result for HEFT benchmarks!

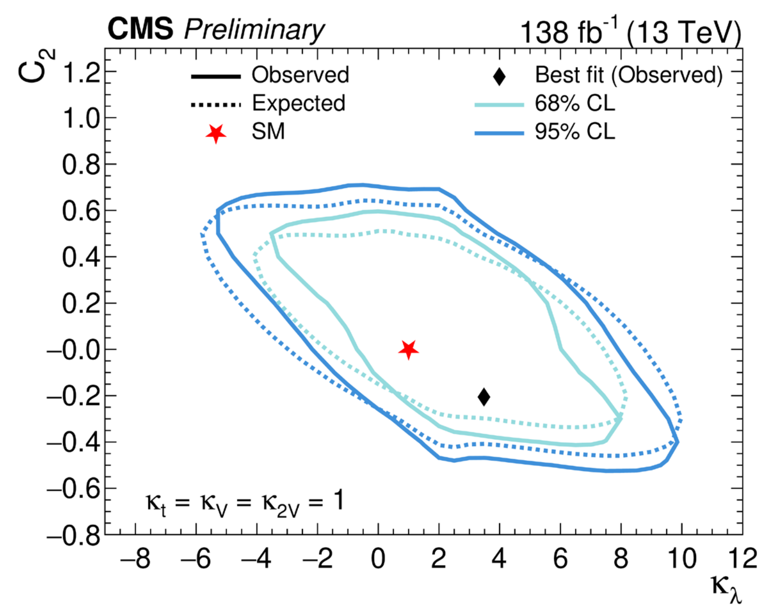
CMS-PAS-HIG-20-011

HEFT coupling scans

- Scan of C2 coupling modifier
  - In general compatible with the SM
  - The best fit slightly prefers $c_2 = 0.4$



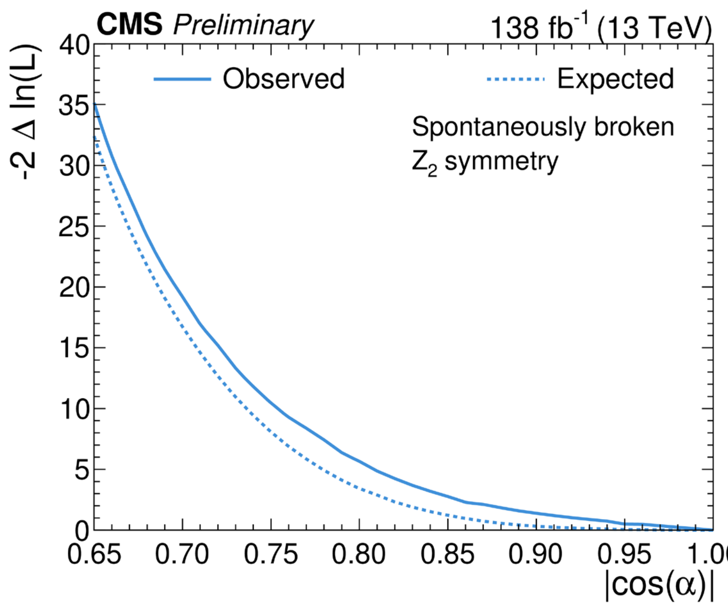




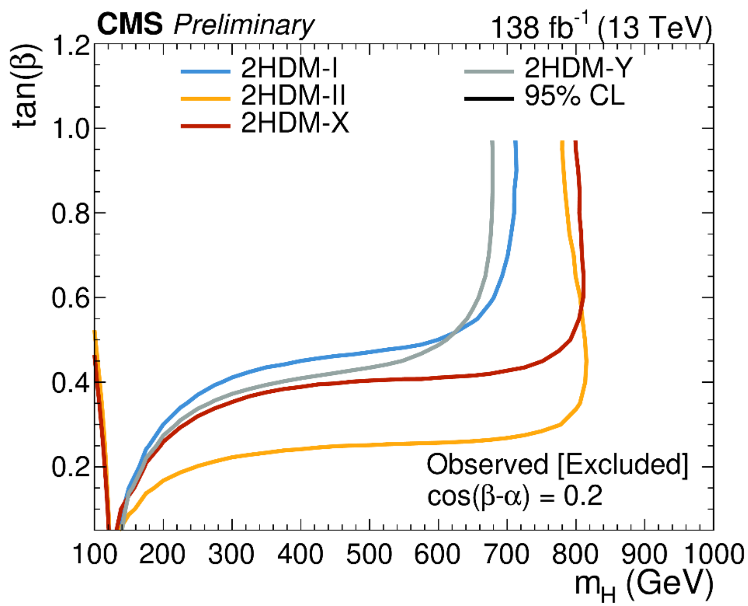
[CMS-PAS-HIG-20-011]

UV complete reinterpretations

- Probing UV complete models directly with available HH searches at CMS
  - Model dependent with more physical assumptions about interference, parameter values and correlations
  - A realistic testbed for assessing the reach and limitations of HH searches under explicit UV assumptions
  - Complementary to EFT interpretation and resonant searches
- Explored an example UV mappings for HH from [JHEP 02 (2021) 049]



Competitive singlet results



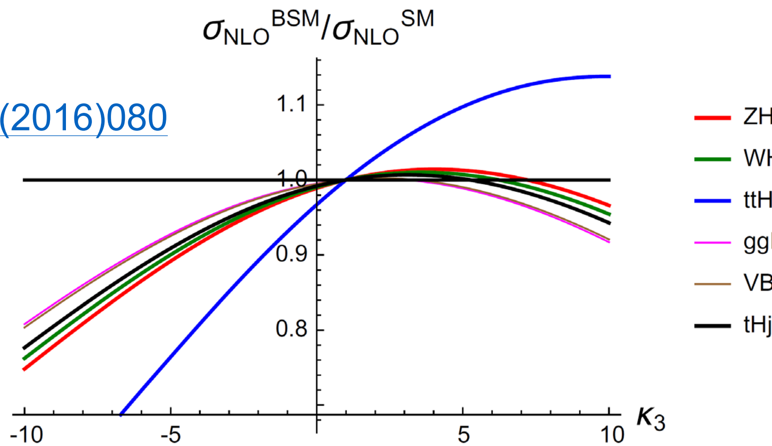
2HDM results: complementary coverage in the high-mass region

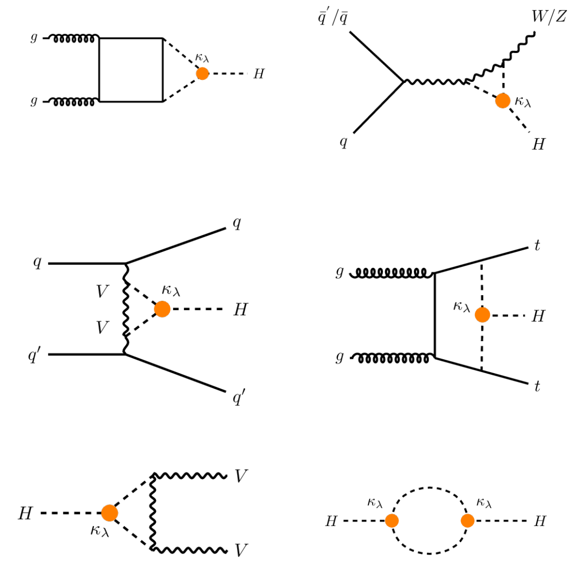
H+HH combination

- Single Higgs boson processes sensitive to Higgs self-coupling through EW corrections

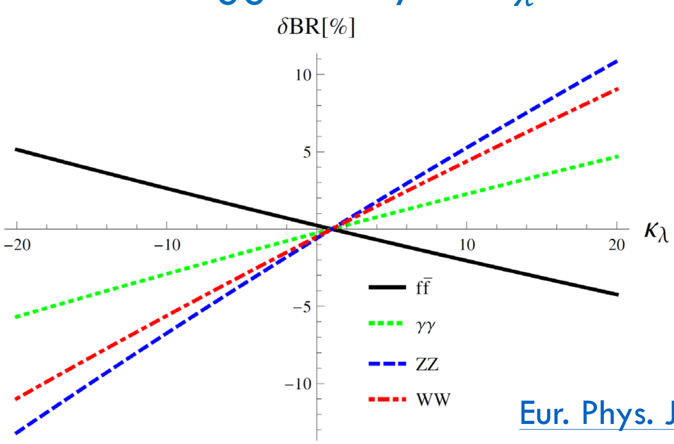
Single Higgs production vs. k_λ

JHEP12(2016)080





Higgs decay vs. k_λ



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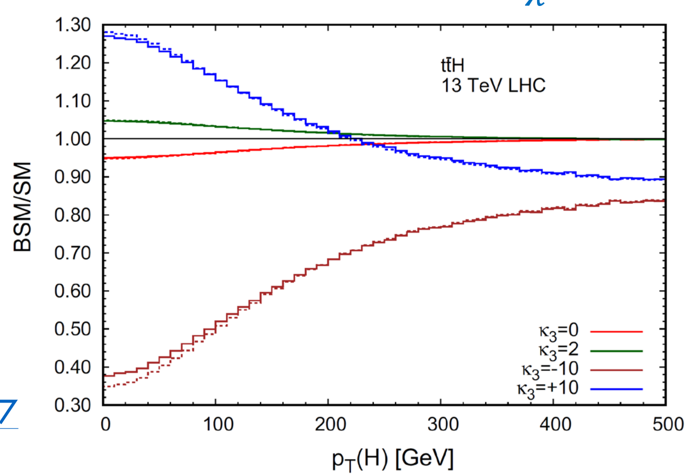
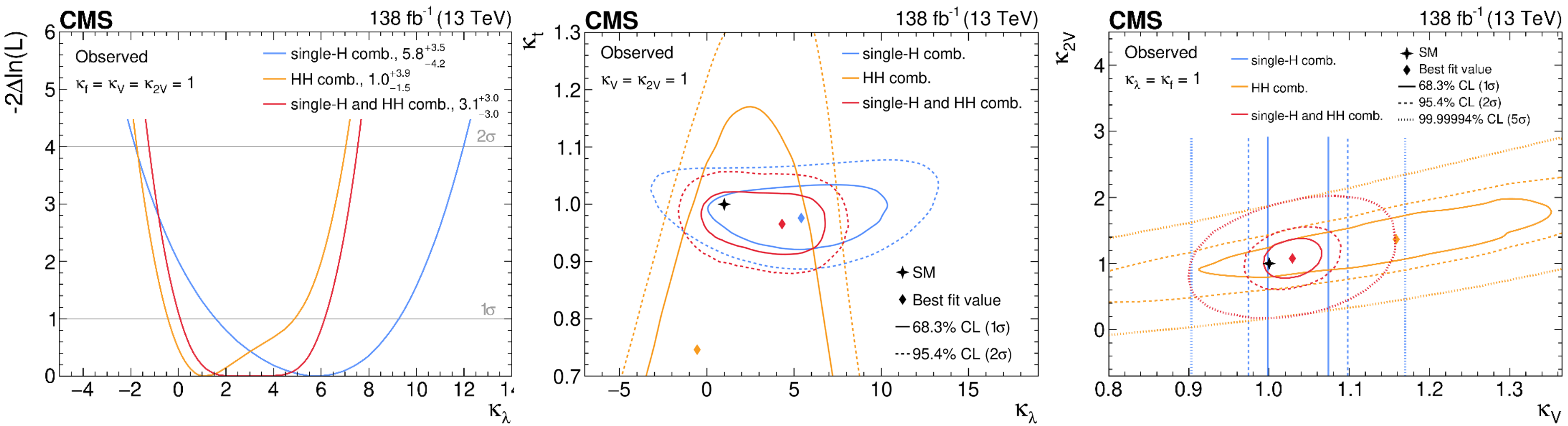
Kinematics vs. k_λ



H+HH combination

- Constrain k_λ with H+HH combination at 2 σ confidence level
  - Observed (expected) range fixing other H coupling: $-1.2\ (-2.0) < k_\lambda < 7.5\ (7.7)$
  - Observed (expected) range floating other H coupling: $-1.4\ (-2.3) < k_\lambda < 7.8\ (7.8)$

Phys. Lett. B 861 (2025) 139210

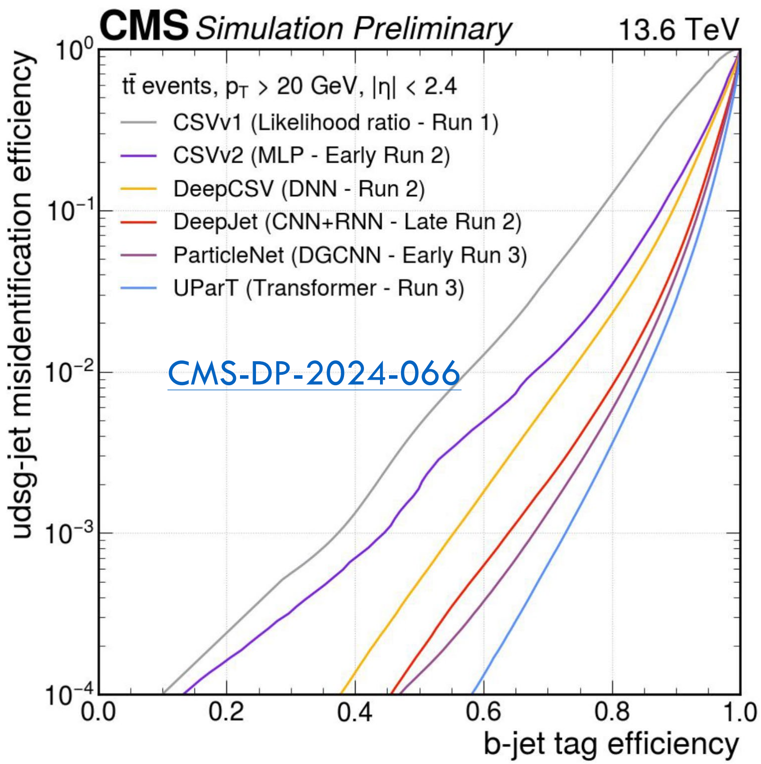


- The combination resolves the degeneracy in k_λ presented in HH-only fits.
- The 2D allowed regions in $(k_\lambda, k_t), (k_V, k_{2V})$ are significantly reduced by H+HH combination

Run 3: a new era of potential for HH

- New triggers designed in Run 3
  - Improves signal efficiency
  - Allows access to more phase spaces for background estimation
- More powerful b-tagging, jet p_T regression and di-jet mass regression methods
  - Heavy-flavour tagging improves ~5% per b-jet at the same mis-tag rate
  - Advanced machine learning methods for jet p_T regression and di-jet mass regression
- Optimization of signal/background classification and categorization
- Improved background estimation, validation, and assessment of systematic uncertainties

Much more to come from HH in Run 3



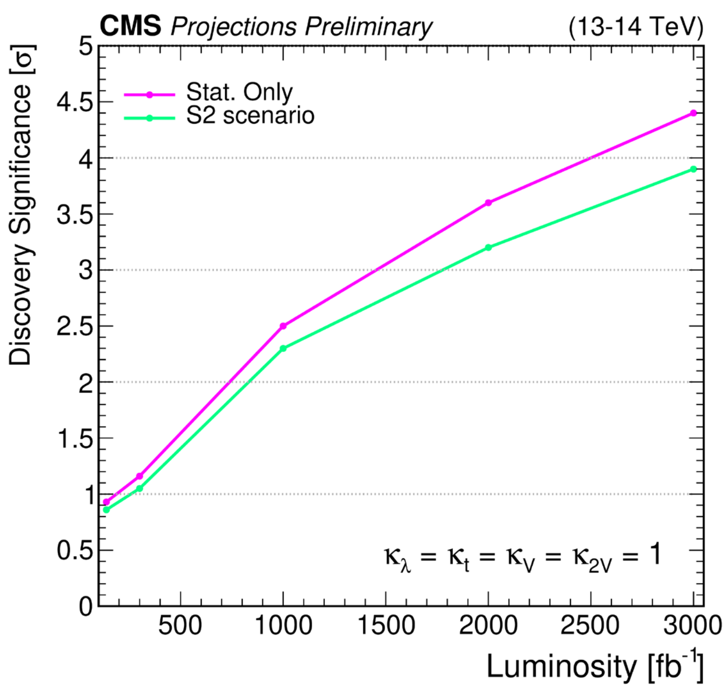
Evolution of the b-tagging performance for identification algorithms used in CMS from Run 1 to Run 3

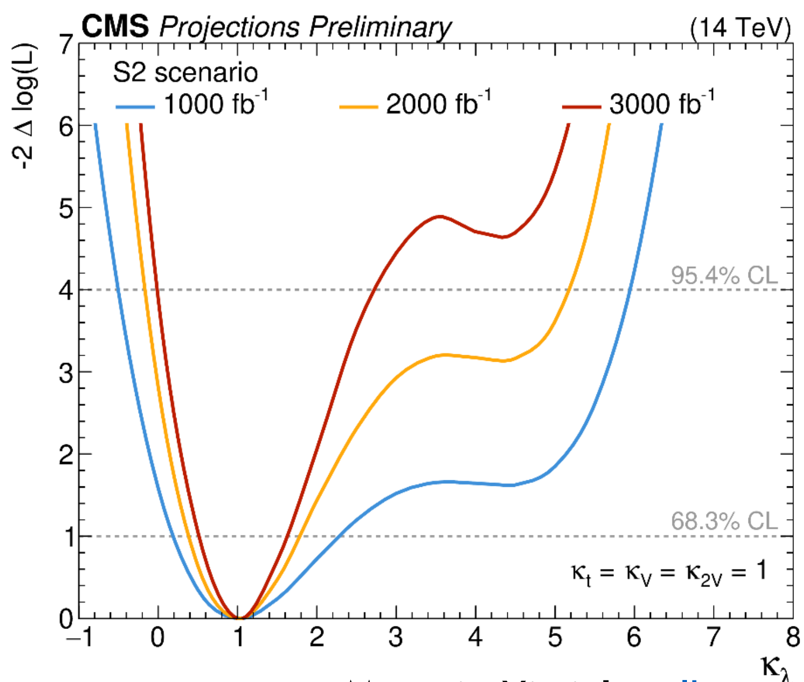
See also talks of
Trigger by Philipp Nattland
Jet tagging by Donato Troiano
Object performance by Raffaella Tramontano

HL-LHC projection

- Evidence for HH production by $\sim 2000\ fb^{-1}$ in CMS at the HL-LHC
  - "S2" : uncertainties with statistical origin scaled with luminosity, theory uncertainties halved
  - "S3": accounting for 5% improvements in b-jets tagging and hadronic taus identification efficiencies
- By the end of the HL-LHC, k_λ can be constrained within [0.5, 1.6] at 68% confidence level.

CMS-PAS-HIG-20-011





More in Yimin's talk

Summary

- Comprehensive HH searches using the full Run 2 dataset at CMS
  - Provide a direct probe of the Higgs potential and rare quartic gauge couplings

- Legacy results show significant sensitivity improvements over early Run 2
  - Expanded exploration of production modes and decay channels, including boosted topologies
  - Extensive application of machine learning for triggers, object tagging and event selection
  - Well-developed EFT interpretation within the HEFT framework
  - Combined analyses with single Higgs processes to constrain k_λ and Higgs couplings simultaneously

- **Looking ahead:** Run 3 holds great potential for further advancing HH searches!

Backup

H+HH combination

- H+HH combination
  - Ultimate precision on k_λ with less assumptions
  - Simultaneously constraining k_λ and modifiers of SM H couplings to fermions, and vector bosons
  - The main channels of single Higgs and HH are included

Analysis	Integrated luminosity (fb^{-1})	Targeted H production modes	Maximum granularity	References
$H \to 4l$	138	ggF, VBF, VH, $t\bar{t}H$	STXS 1.2	[51]
$H \to \gamma\gamma$	138	ggF, VBF, VH, $t\bar{t}H$, tH	STXS 1.2	[52,none]
$H \to WW$	138	ggF, VBF, VH	STXS 1.2	[54]
$H \to$ leptons ($t\bar{t}H$)	138	$t\bar{t}H$	Inclusive	[55]
$H \to b\bar{b}$ (ggF)	138	ggF	Inclusive	[56]
$H \to b\bar{b}$ (VH)	77	VH	Inclusive	[48]
$H \to b\bar{b}$ ($t\bar{t}H$)	36	$t\bar{t}H$	Inclusive	[57]
$H \to \tau\tau$	138	ggF, VBF, VH	STXS 1.2	[58]
$H \to \mu\mu$	138	ggF, VBF	Inclusive	[59]

Analysis	Int. luminosity (fb^{-1})	Targeted HH production modes	References
$HH \to \gamma\gamma b\bar{b}$	138	ggF and VBF	[53]
$HH \to \tau\tau b\bar{b}$	138	ggF and VBF	[60]
$HH \to b\bar{b}b\bar{b}$	138	ggF, VBF, and VHH	[61,62,none]
$HH \to$ leptons	138	ggF	[64]
$HH \to WWb\bar{b}$	138	ggF and VBF	[65]