DiHiggs Searches at CMS

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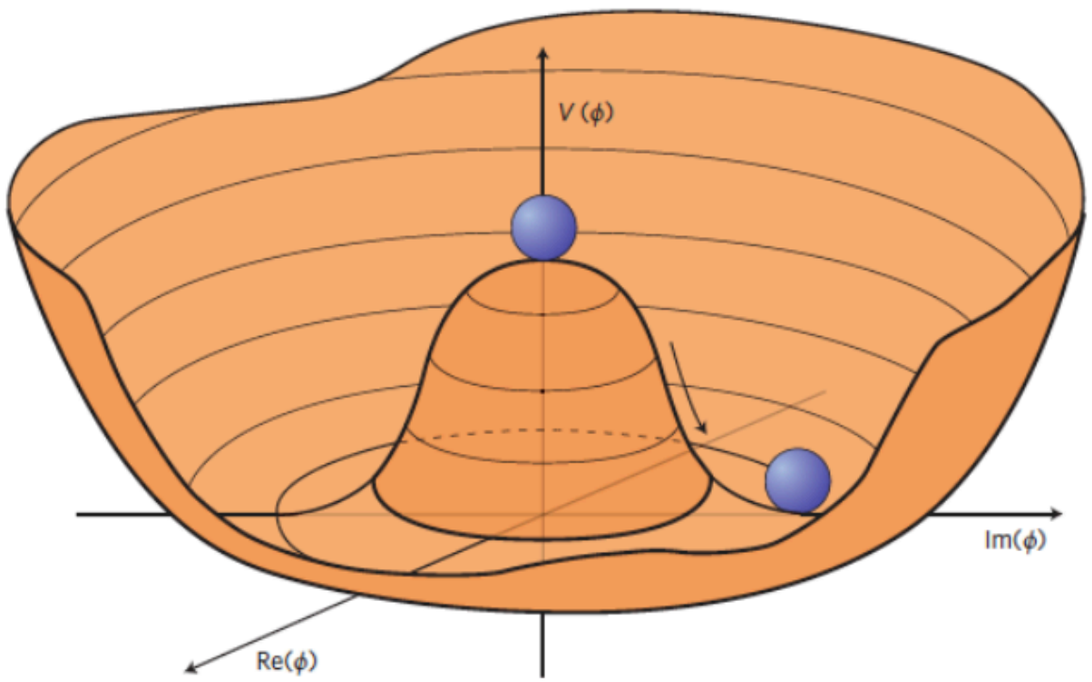
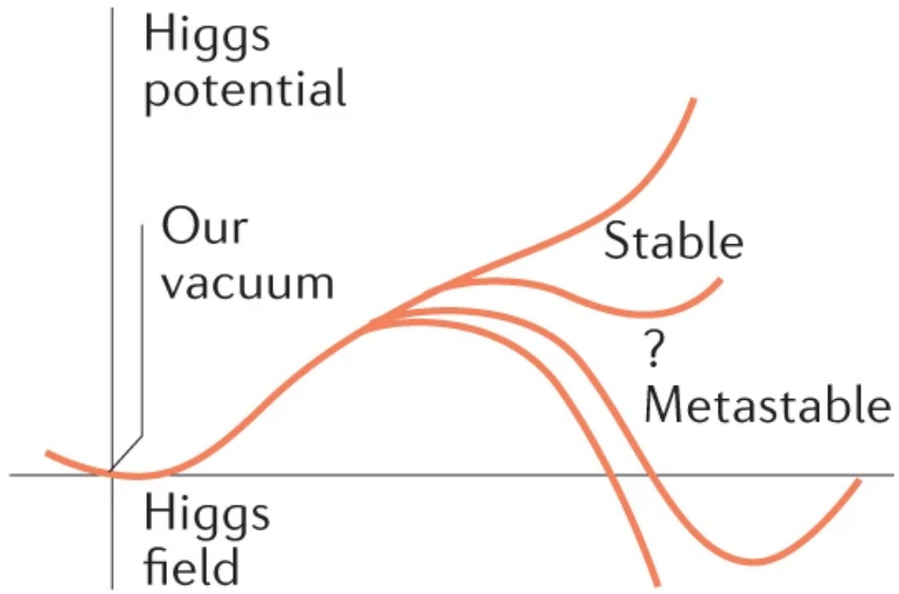
Motivation

- Trilinear coupling λ can probe the shape of the Higgs potential

$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_{hhh} v H^3 + \ldots$$

  - Directly probed via di-Higgs searches
- Higgs couplings are potential portals to new physics



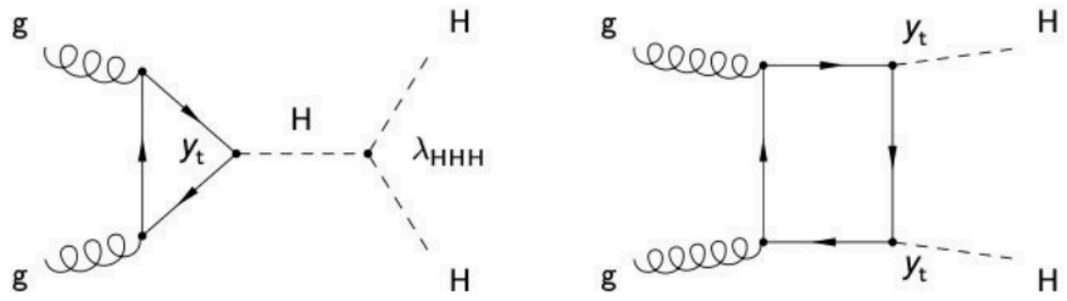


HH Production at LHC

- Small cross section: challenging to measure
  - Two major production modes: ggF, VBF
  - Additional modes: VHH, ttHH

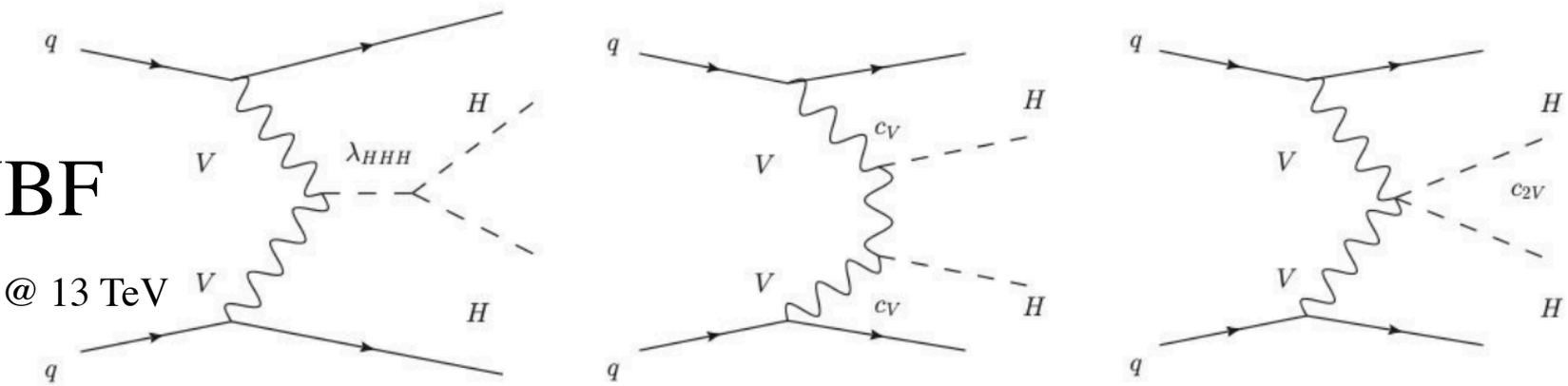
ggF

30.8 fb @ 13 TeV



VBF

1.69 fb @ 13 TeV



~11% increase in the cross section at 13.6 TeV

Overview of Searches

- Extensive searches performed during Run 2 in all major decay modes
  - Machine learning algorithms and optimizations widely used
- Most sensitive channels: bbbb, bbττ, bbγγ

rarer →

	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

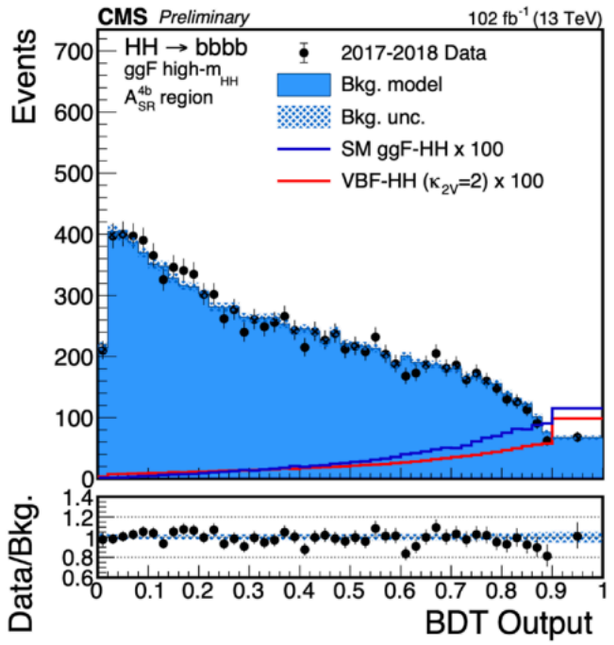
↓ rarer

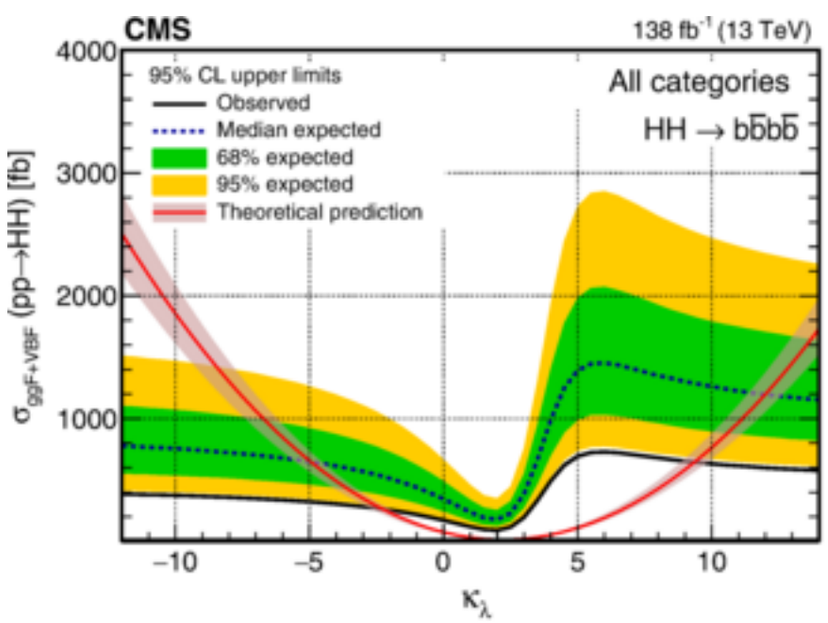
Channel	Reference
bbbb resolved	Phys. Rev. Lett. 129,
bbbb boosted	Phys. Rev. Lett. 131,
bbγγ	JHEP03(2021)257
bbττ	Phys. Let. B 842, 37531
VH bbbb	JHEP10(2024)061

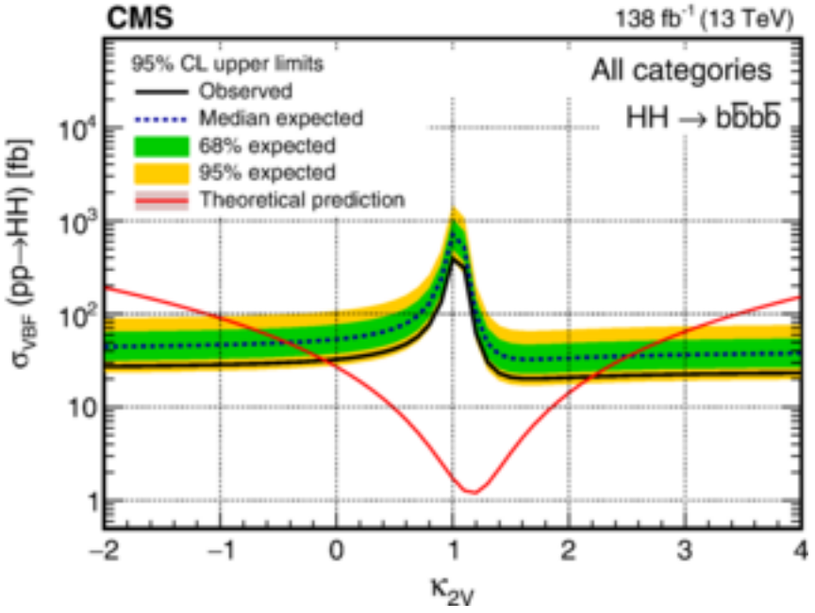
Channel	Reference
bbZZ(4l)	JHEP06(2023)130
WWWW, WWττ, tttt	JHEP07(2023)095
bbWW	JHEP07(2024)293
WWγγ	CMS-PAS-HIG-21-014
γγττ	CMS-PAS-HIG-22-012

HH→bb̄bb̄ resolved

- Event selection: ≥ 4 jets, with ≥ 3 b-tagged
  - H products are reconstructed as individual small radius jets
- Data driven method to estimate multi-jet background
  - Using the 3 b-tagged and 4 b-tagged Control Regions
- BDT used to separate ggF and VBF, and to further separate ggF and background
- Observed (expected) results:
  - $\sigma_{HH} < 3.9\ (7.8) \times \sigma^{SM}$
  - $-2.3(-5.0) < \kappa_\lambda < 9.4(12)$
  - $-0.1(-0.4) < \kappa_{2V} < 2.2(2.5)$



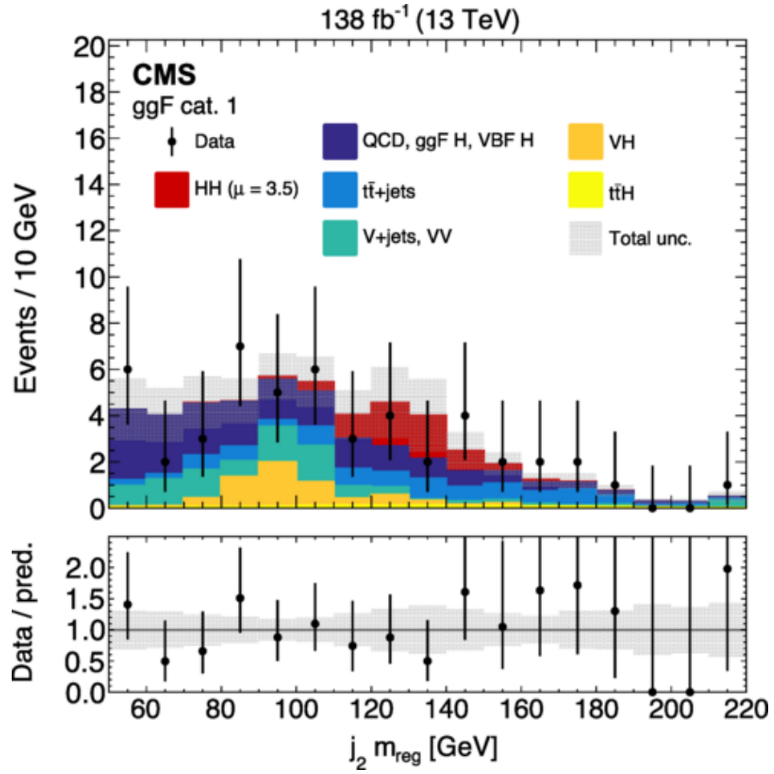


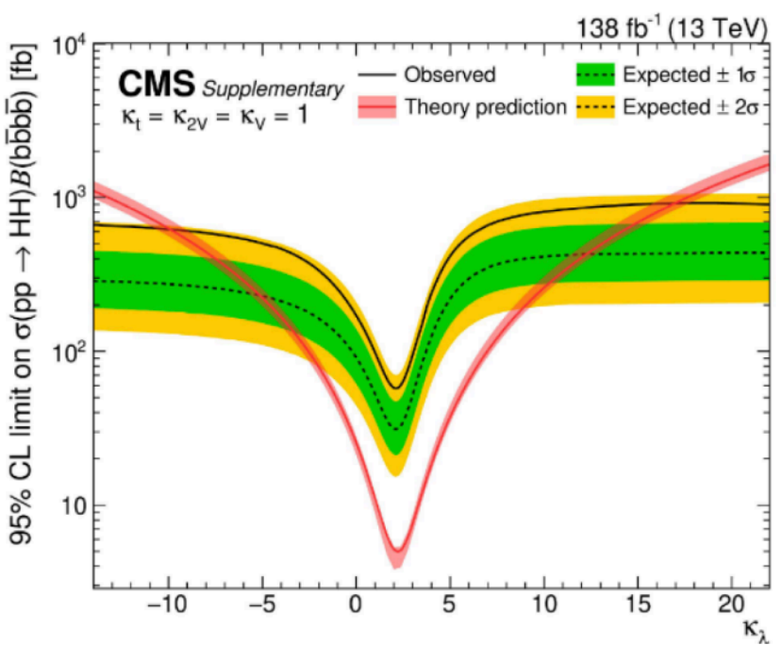


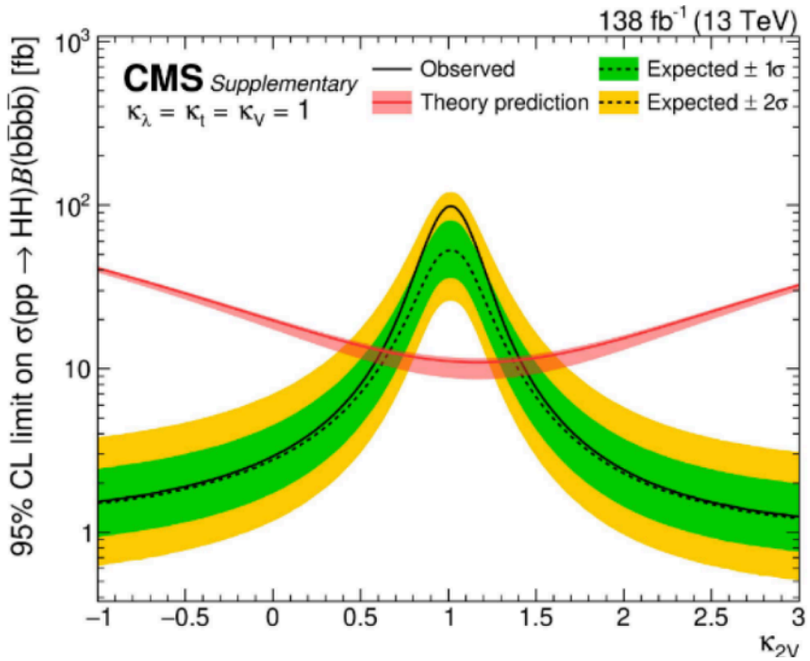
Phys. Rev. Lett. 129, 081802

HH→bb̄bb̄ boosted

- Event selection: >= 2 large-cone jets with $p_T \geq 300$ GeV
  - H products boosted into two merged jets
- ParticleNet algorithm used to identify H decays vs QCD background
  - GNN algorithm tagging 2-prong resonance in a large cone jet
- DNN bjet energy regression used to improve mass resolution
- Observed (expected) results:
  - $\sigma_{HH} < 9.9\ (5.1) \times \sigma^{SM}$
  - $-9.9\ (-5.1) < \kappa_\lambda < 16.9\ (12.2)$
  - $0.62\ (0.66) < \kappa_{2V} < 1.41\ (1.37)$
    - More sensitive to deviations in κ_{2V}.



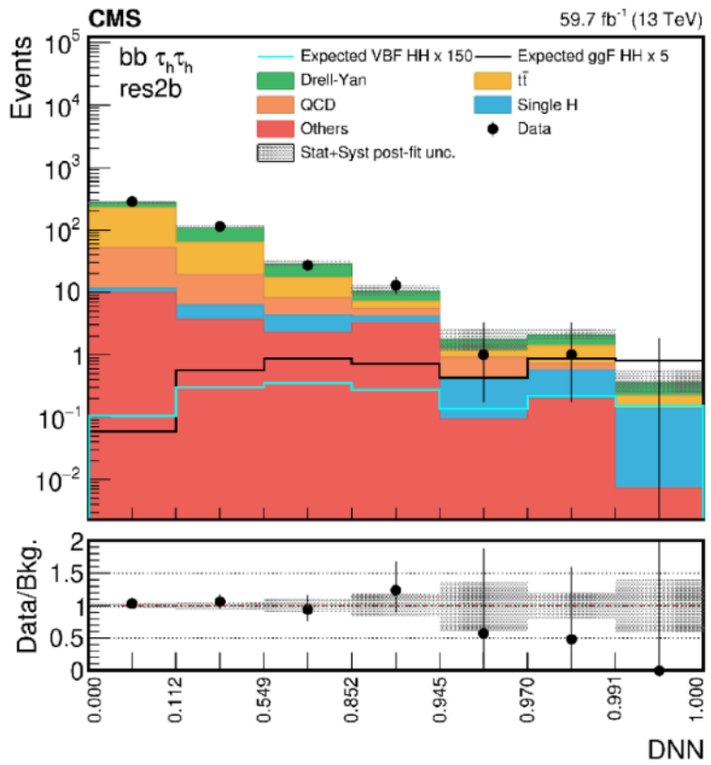


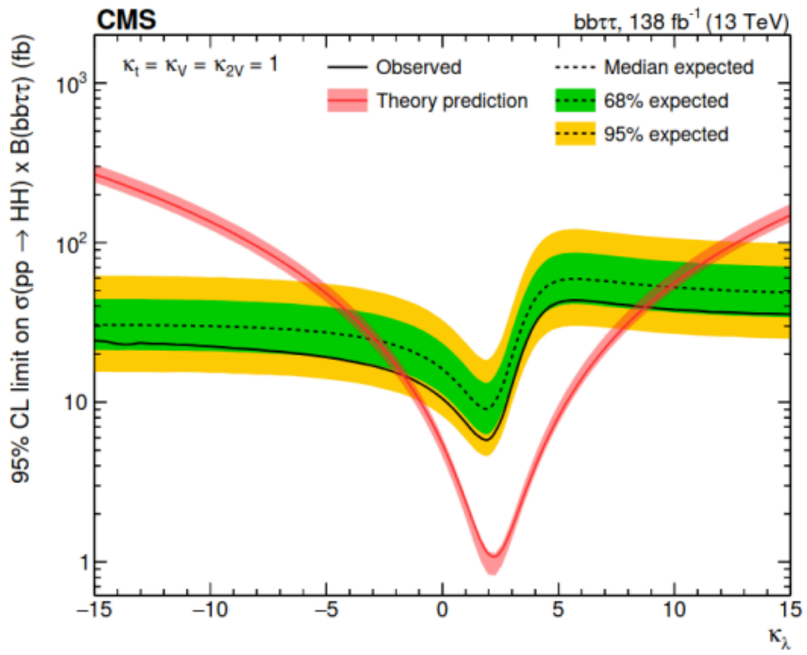


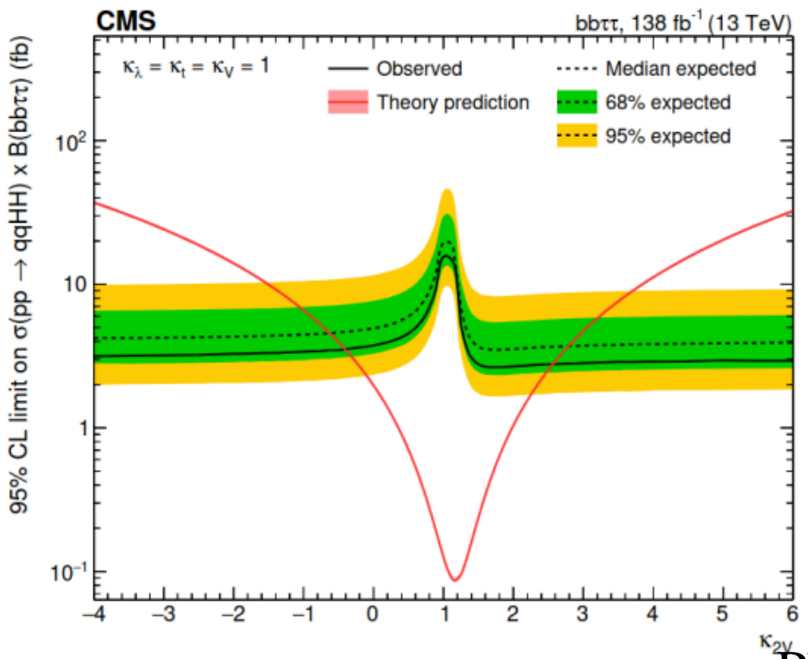
Phys. Rev. Lett. 131, 041803

HH→ bb̄ττ

- 1 τ_h + 1 τ (hadronic or leptonic) + ≥ 2 jets
- Event categorized based on production modes and final state particles
- DNNs used to distinguish signal from background in each category
- Observed (expected) results:
  - $\sigma_{HH} < 3.3\ (5.2) \times \sigma^{SM}$
  - $-1.8\ (-3.0) < \kappa_\lambda < 8.8\ (9.9)$
  - $-0.4(-0.6) < \kappa_{2V} < < 2.6\ (2.8)$



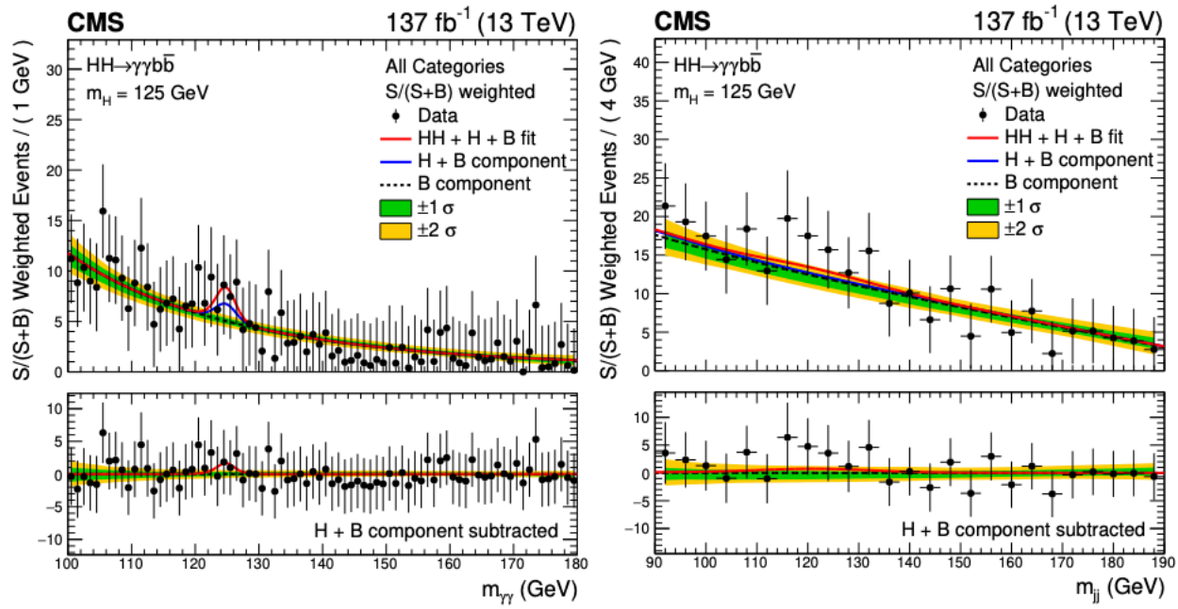




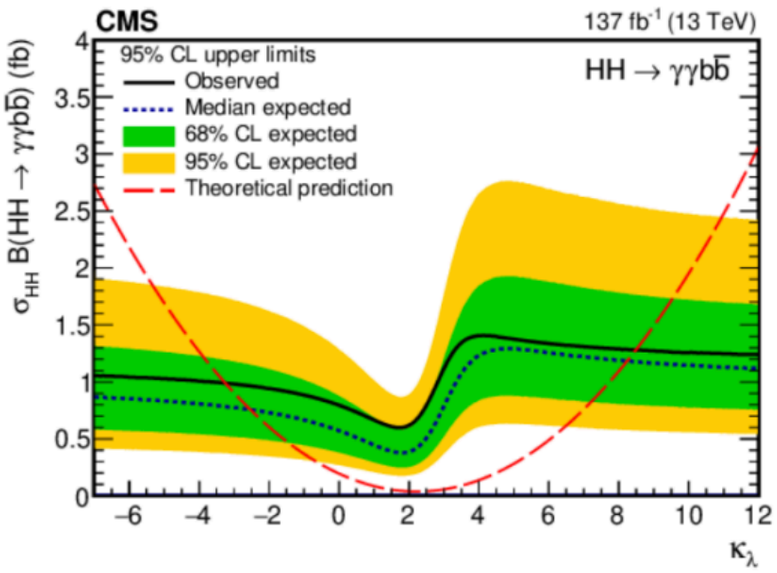
Phys. Let. B 842, 37531

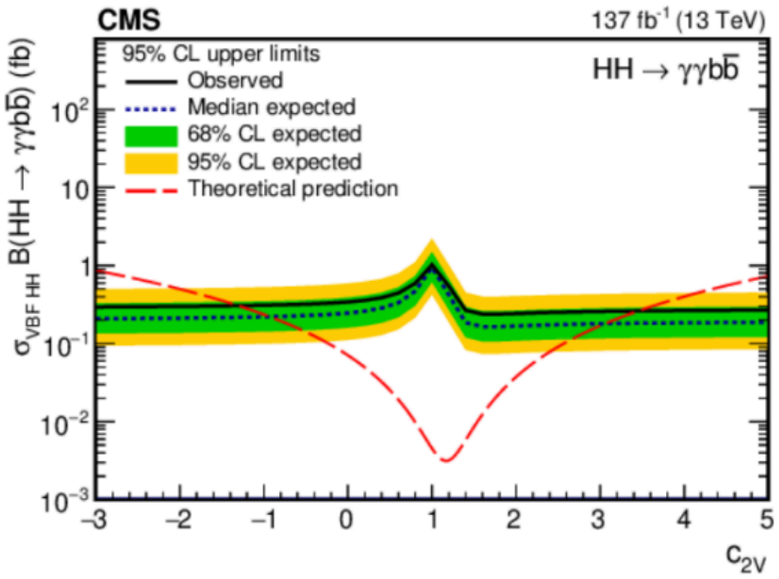
HH→ $b\bar{b}\gamma\gamma$

- More statistics limited, but clean signal due to the narrow $\gamma\gamma$ mass shape
- Major background:
  - Non resonant: $\gamma\gamma$+jets, γ+jets: train BDT to reduce
  - Single Higgs peaking background: ttH (H→ $\gamma\gamma$)
    - Very similar to signal. Much more challenging
    - Trained DNN to tag and reject
- BDT used to distinguish ggF and VBF
- DNN regression to improve m_{bb} resolution
- 2D fit to $m_{\gamma\gamma}$, m_{bb}
- Observed (expected) results:
  - $\sigma_{HH} < 7.7\ (5.2) \times \sigma^{SM}$
  - $-3.3\ (-2.5) < \kappa_\lambda < 8.5\ (8.2)$
  - $-1.3(-0.9) < \kappa_{2V} < 3.5\ (3.1)$



$m_{\gamma\gamma}$ m_{jj}





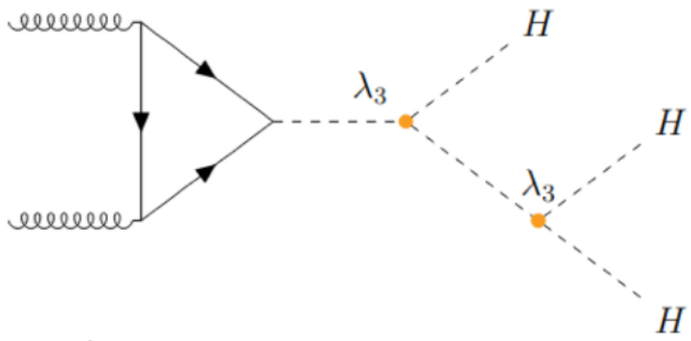
JHEP03(2021)257

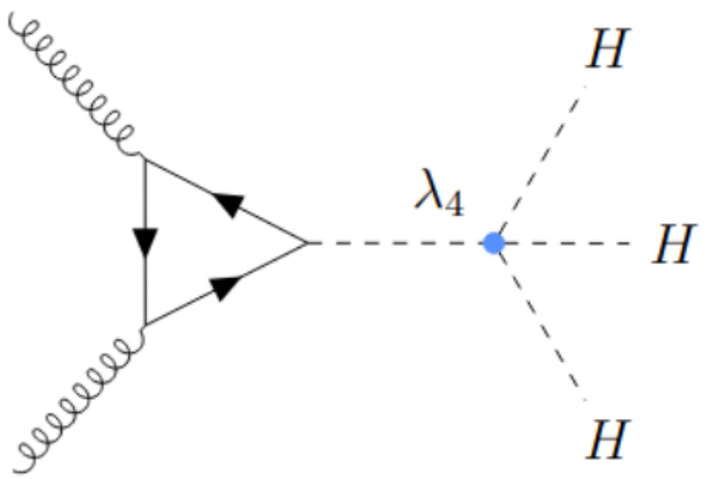
HHH→ 4b2γ

CMS-PAS-HIG-24-015

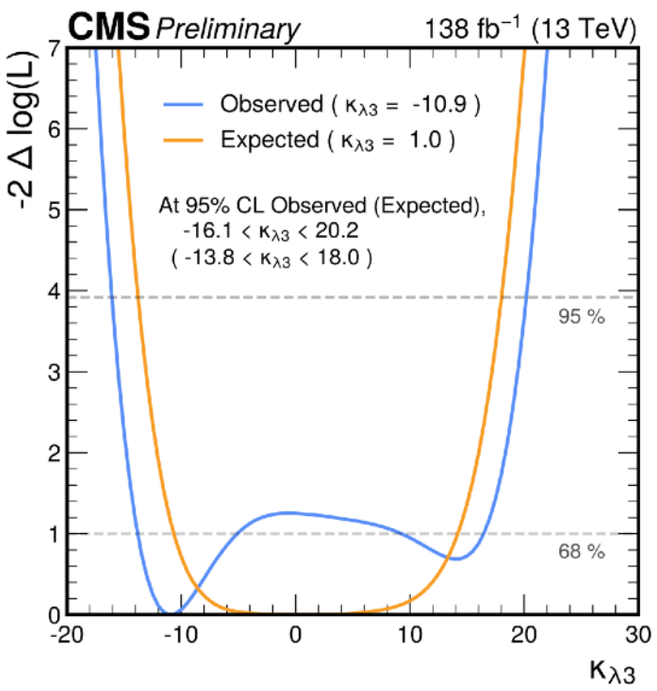
- Probes λ_3 and λ_4 simultaneously
  - Provides unique insight to Higgs potential

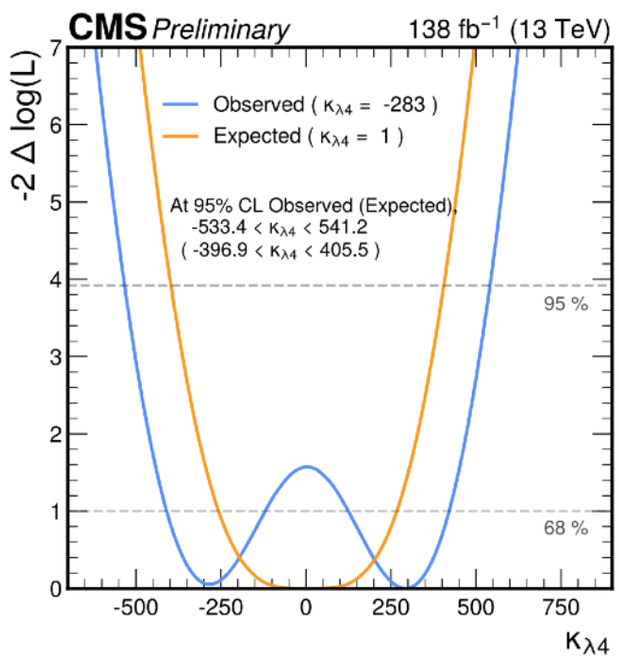
$$V(h) = \frac{1}{2}m_h^2h^2 + \lambda_3 vh^3 + \frac{1}{4}\lambda_4 h^4$$

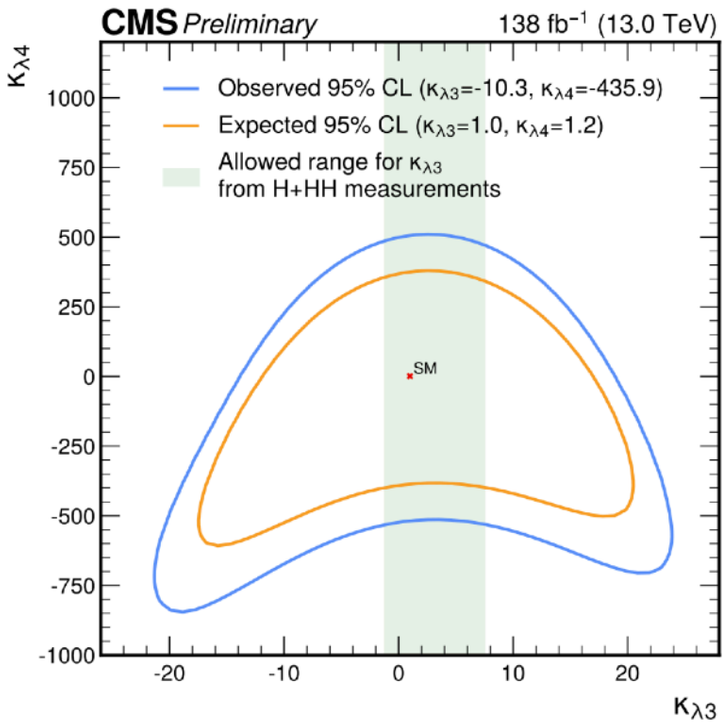




- Train BDTs to reject resonant and non-resonant backgrounds
- Data driven method to estimate fake photon background
- Observed (expected) results:
  - -16.1(-13.8) < $\kappa_{\lambda 3}$ < 20.2(18), -533(-397) < $\kappa_{\lambda 4}$ < 541(406)

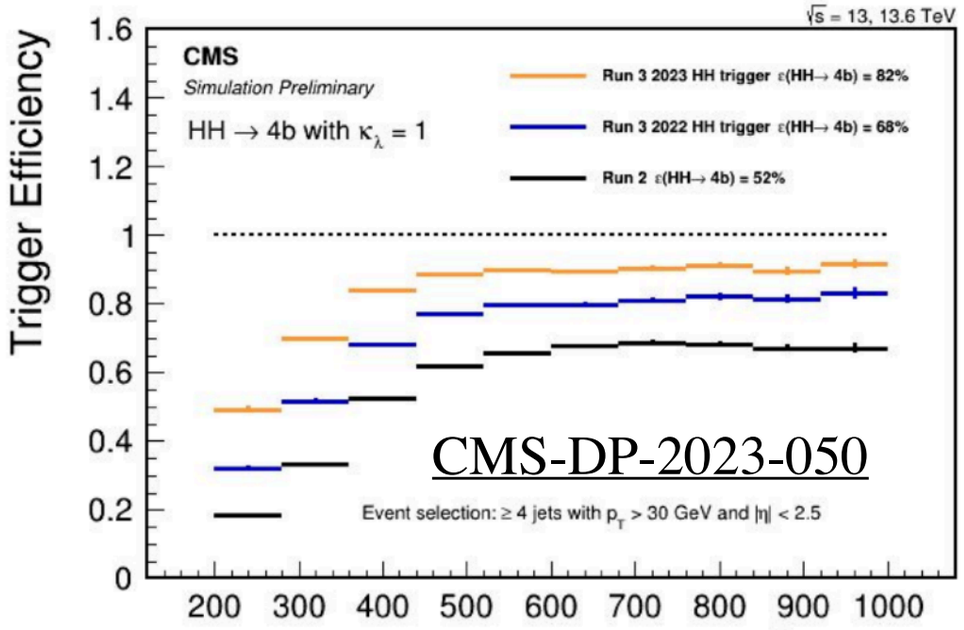






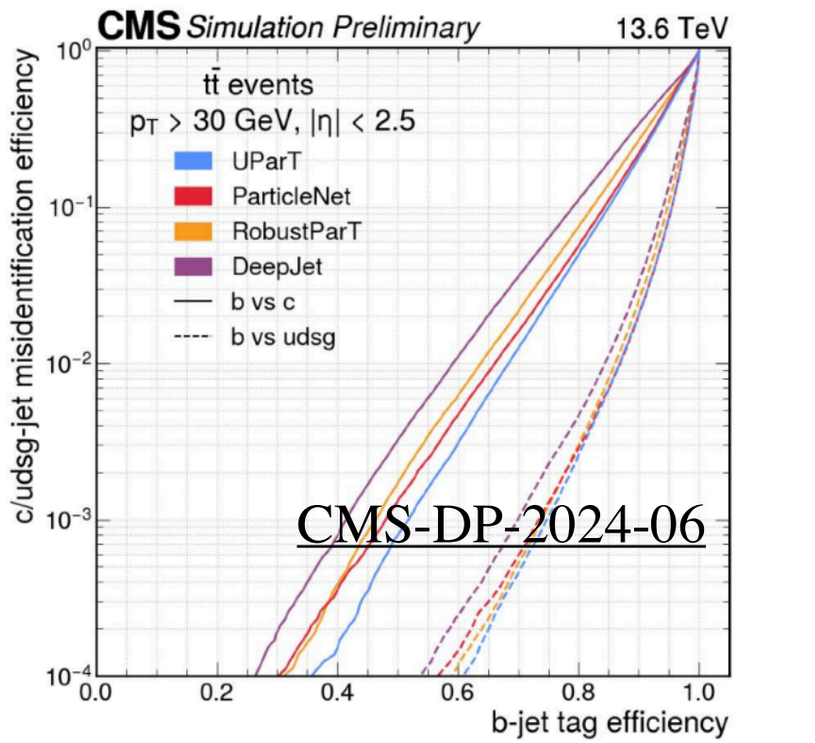
How will we improve in Run 3?

- HH parking triggers:
  - ParticleNet tagger
  - Directly improves signal efficiency
  - Allows for better data driven background estimation



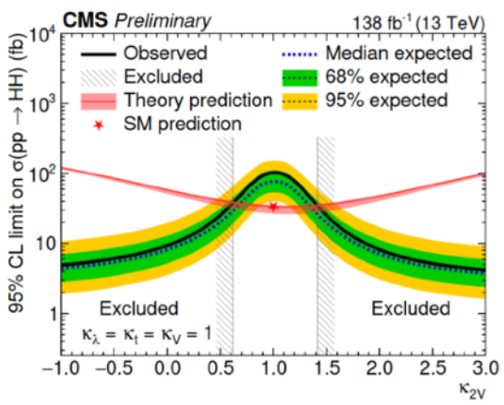
- Machine learning algorithm for b-jet tagging and energy regression
  - ParticleNet and ParticleTransformer
  - Better tagging efficiency
  - Better resolution for jet pT and mjj

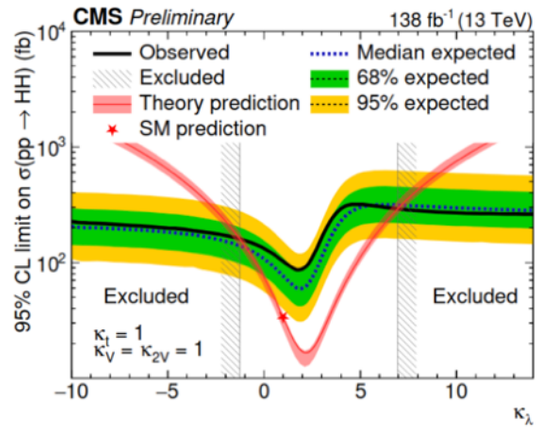
- Improved background estimation techniques
- And more!

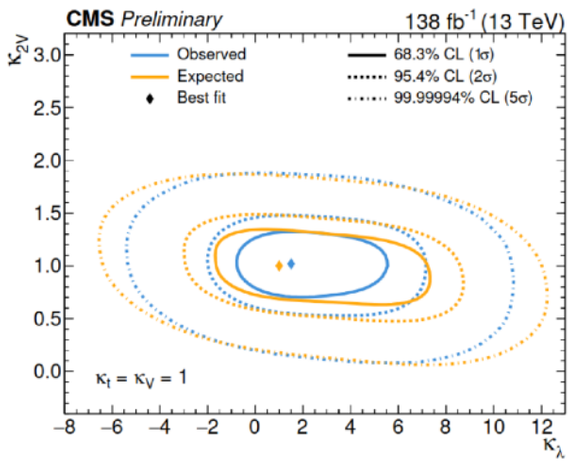


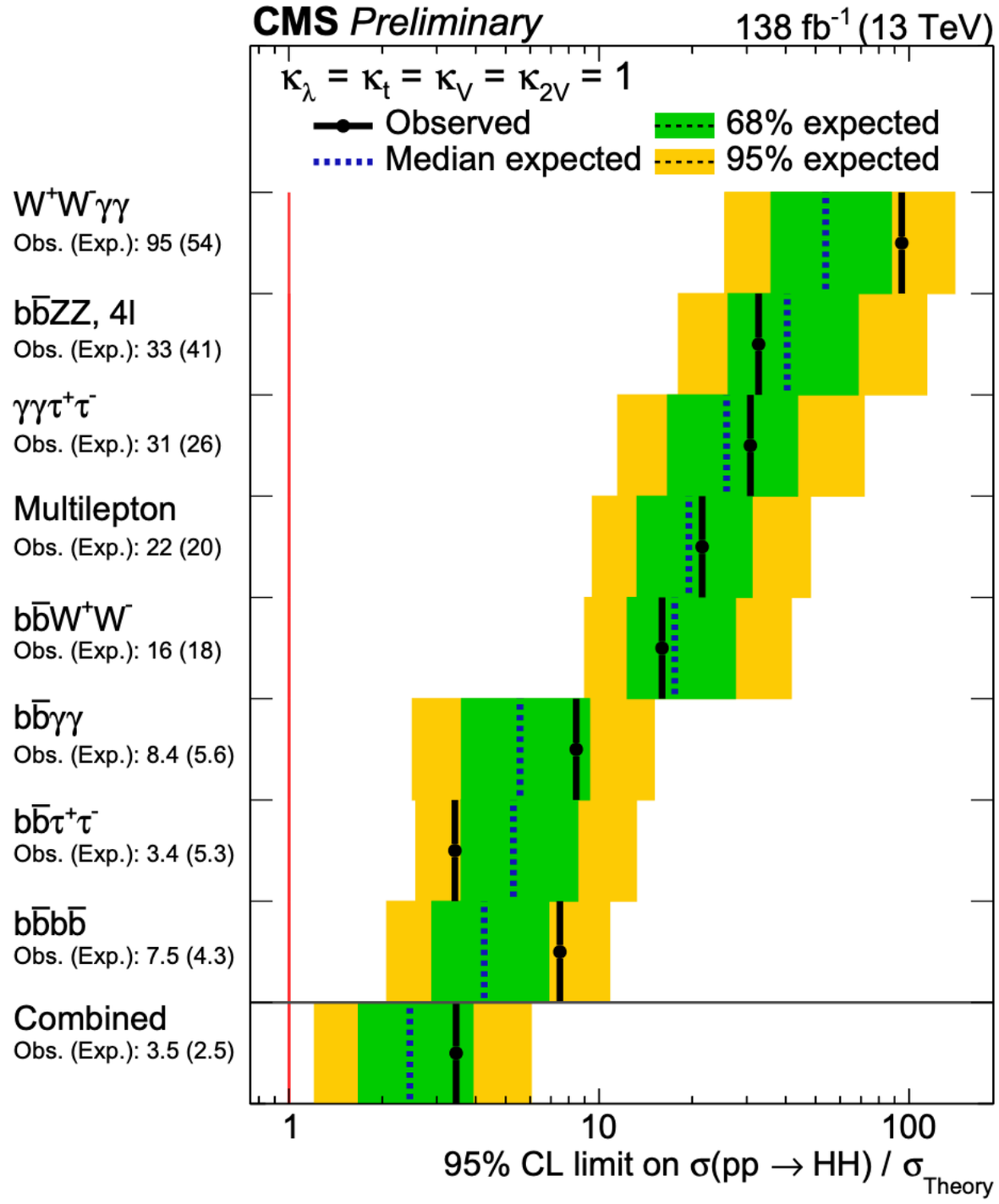
Run 2 HH Combination

- Combining all available channels in Run 2
  - Overlap removal resulted in slight shifts in individual channels
  - Updated uncertainties and signal cross section
- Combined sensitivity observed (expected):
  - $\sigma_{HH} < 3.5\ (2.5) \times \sigma^{SM}$
  - $-1.4\ (-2.29) < \kappa_\lambda < 6.43\ (7.95)$
  - $0.63\ (0.62) < \kappa_{2V} < 1.4\ (1.41)$
    - $\kappa_{2V} = 0$ scenario is excluded for all κ_λ





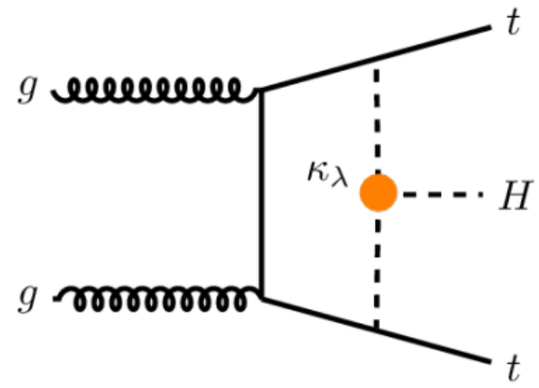


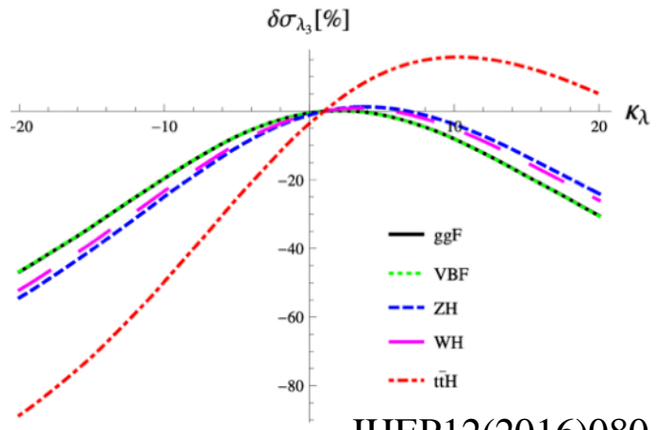


CMS-PAS-HIG-20-011

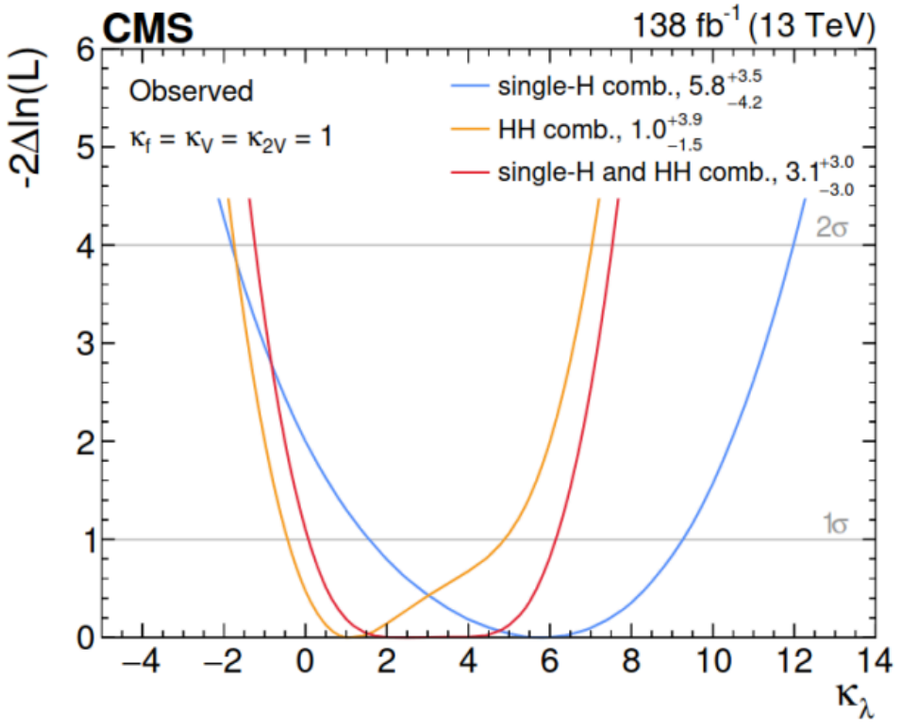
H+HH Combination

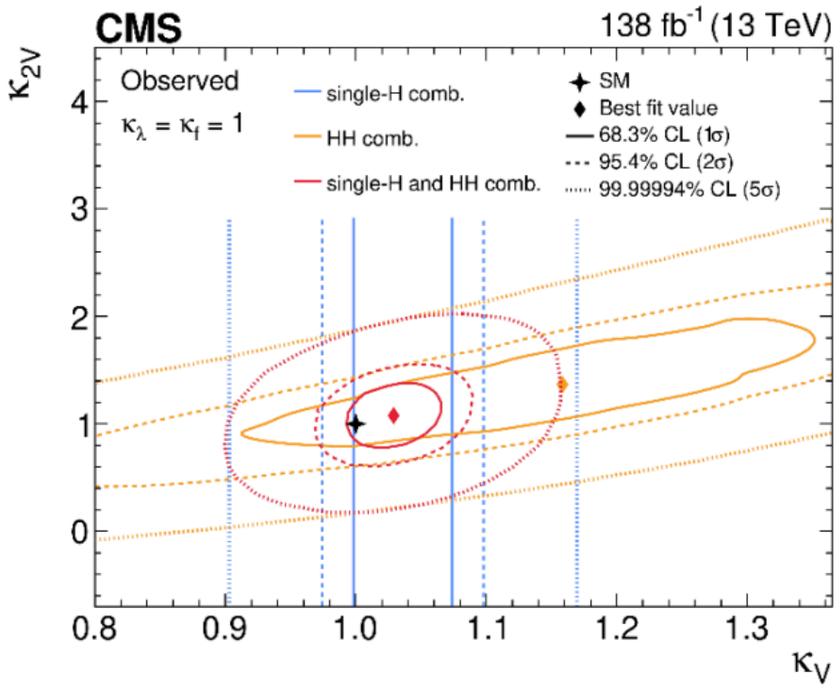
- Single Higgs boson processes are sensitive to κ_λ through EW corrections
  - Example: differential ttH analysis probing κ_λ (CMS-PAS-HIG-23-015)
- Combine with constraints from single Higgs channels:
  - -1.2 (−2.0) $< \kappa_\lambda <$ 7.5 (7.7). Other H coupling fixed
  - −1.4 (−2.3) $< \kappa_\lambda <$ 7.8 (7.8). Other H coupling floated
- The 2D exclusion plot significantly constrained by single H

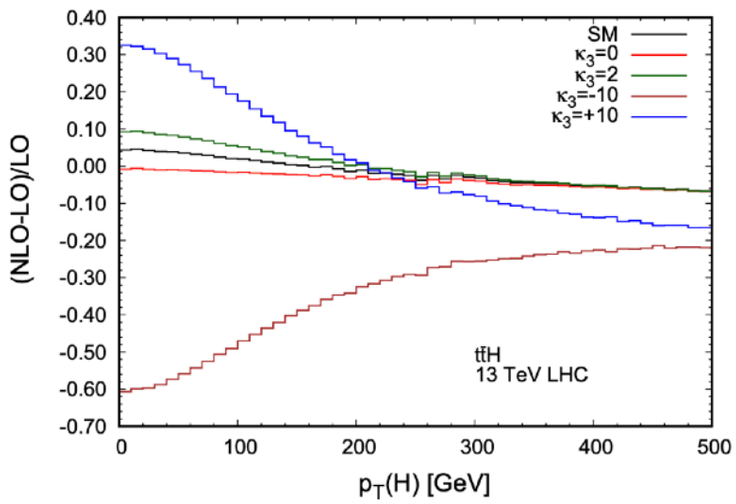




JHEP12(2016)080





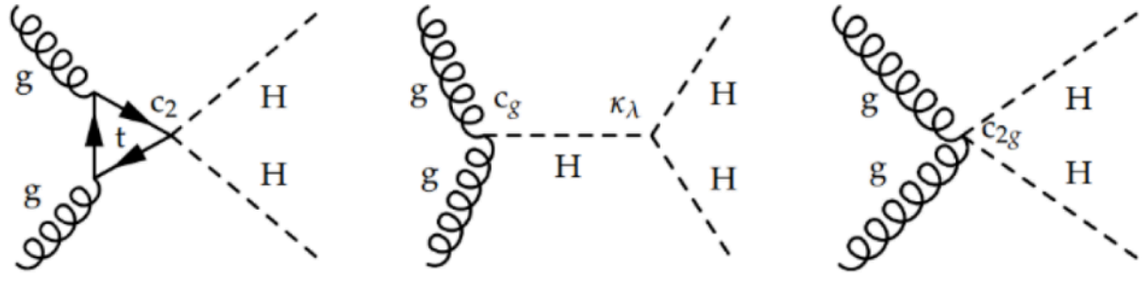


Phys. Lett. B 861 (2025) 139210

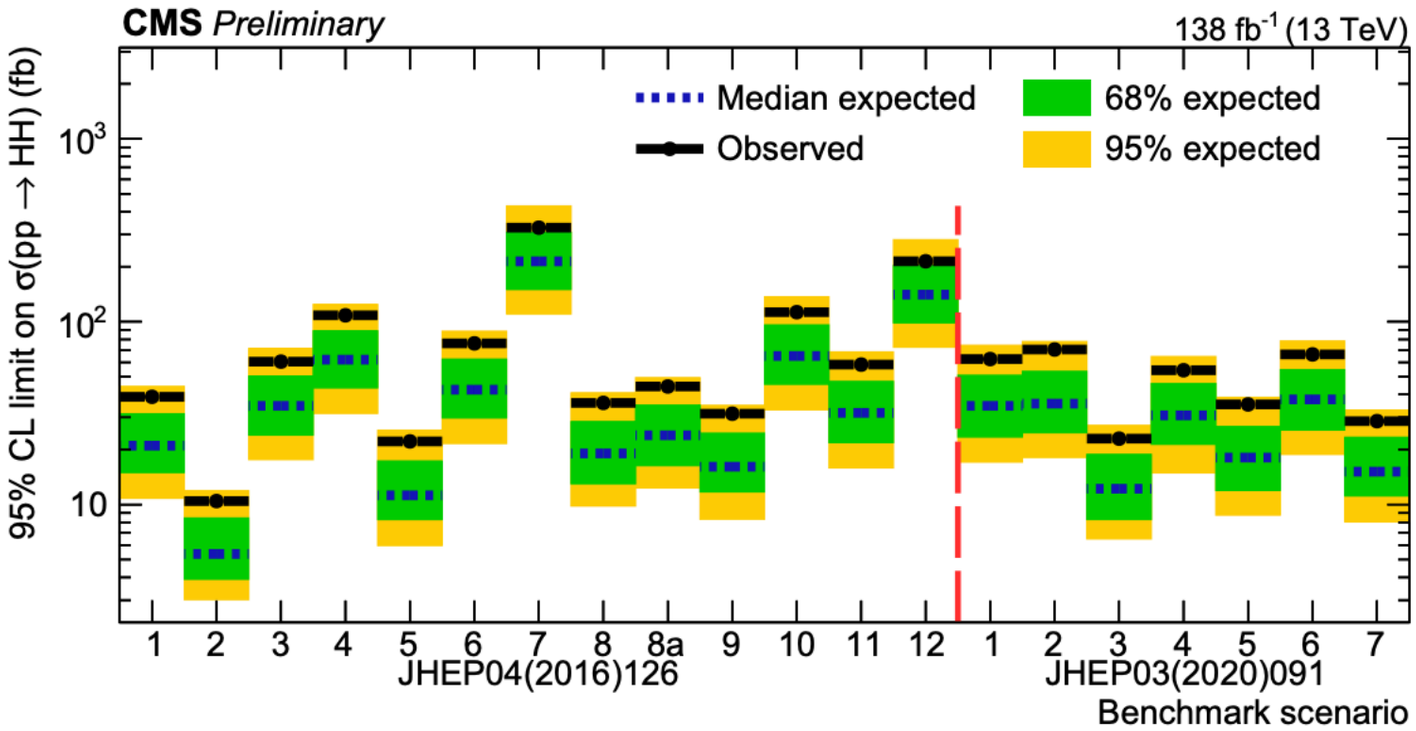
Eur. Phys. J. C (2017) 77: 887

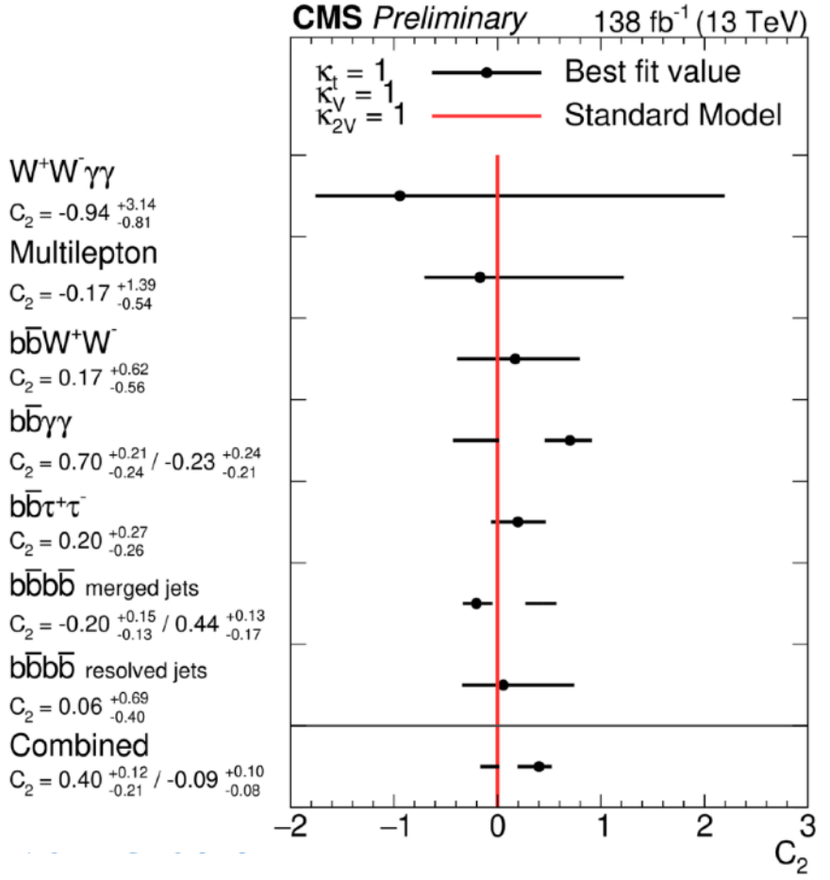
EFT Interpretations

- Studied the cross section 2 HEFT benchmark sets of coupling modifier combinations (κ_λ, κ_t, c_2, c_g , c_{2g}) and c_2 coupling modifier alone



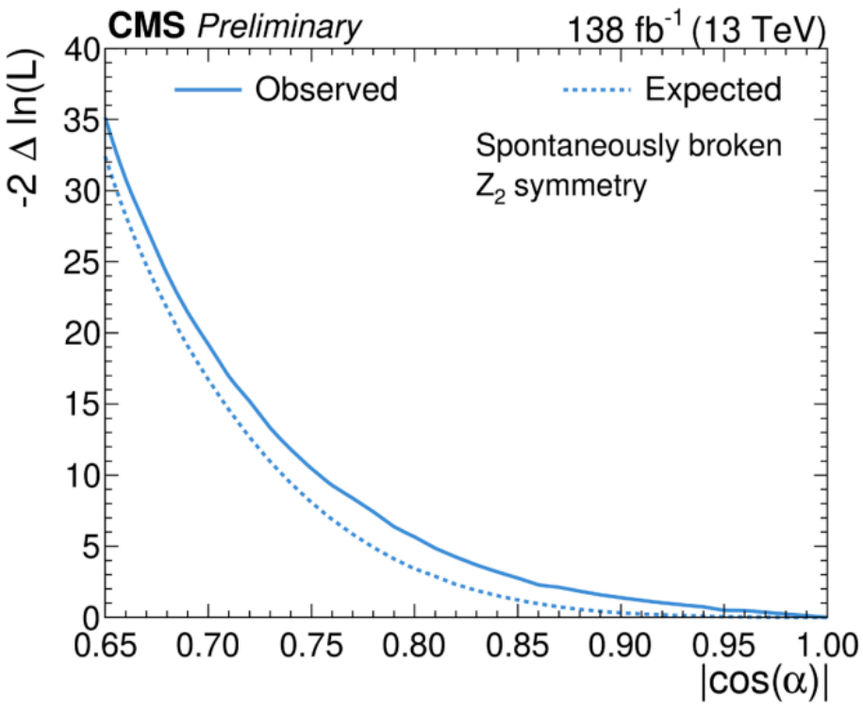
- No significant deviations observed
  - Small excess in all benchmarks

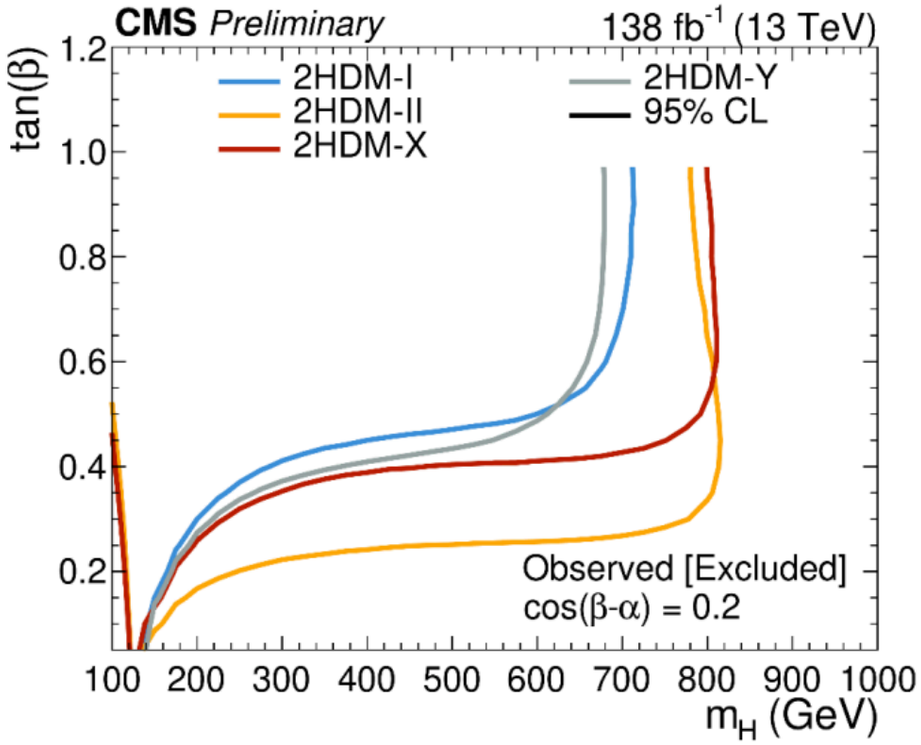




UV Model

- Mapping between κ_λ, $\varkappa t$ and c2 and the parameters of each model, to extract constraint
- Complementary to EFT interpretation and resonant searches

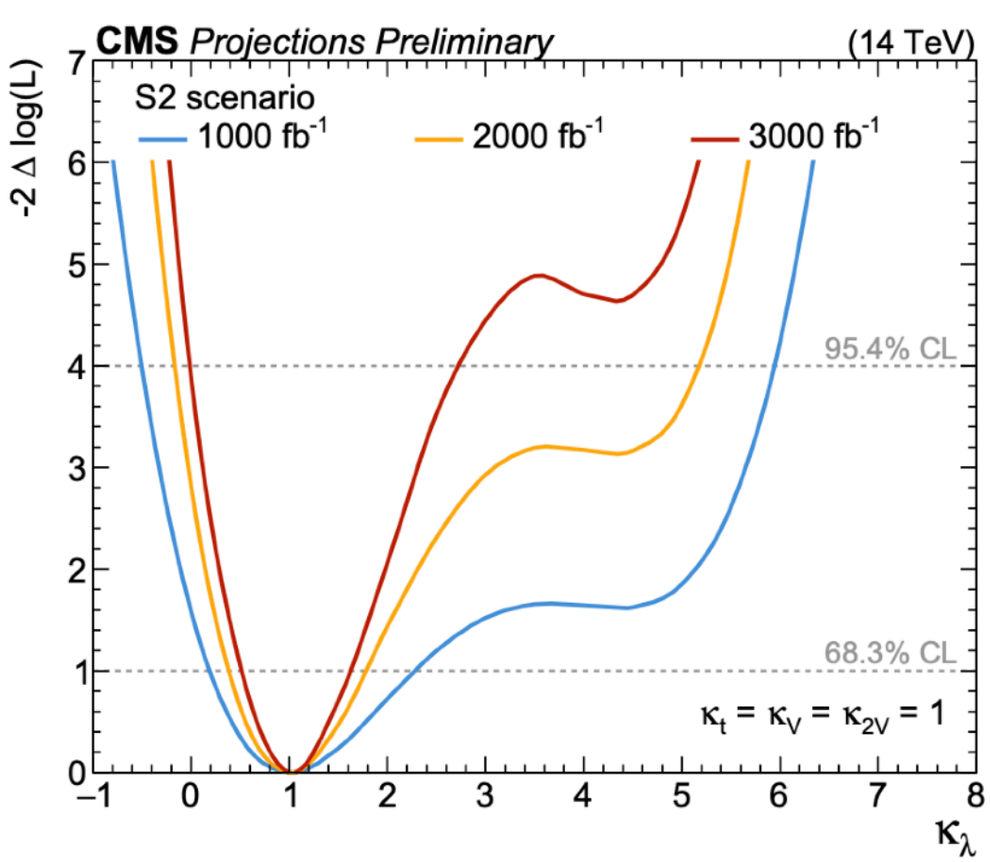


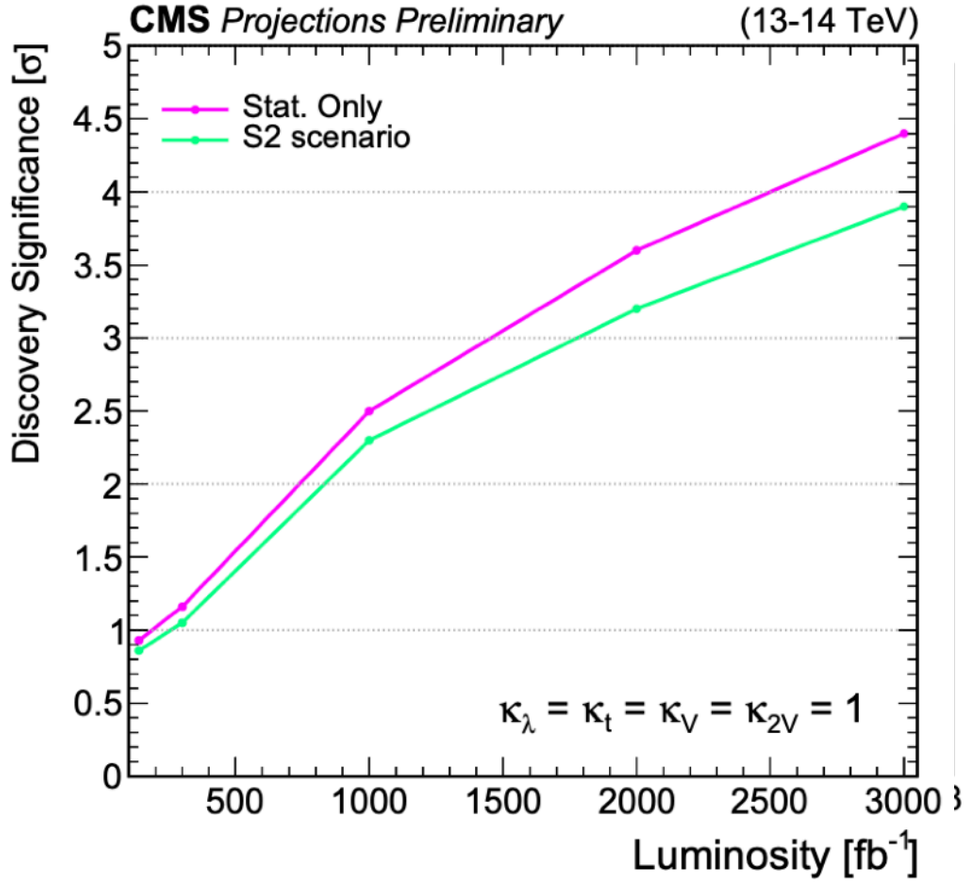


HL-LHC Projection

- Several scenarios studied for projection
  - S1: standard systematics for legacy Run 2 with statistical errors scaled with $\sqrt{L}$
  - S2: S1 with reduced systematic uncertainties + halved theory uncertainties + zero MC stat
  - S3: S2 + additional impact of improvements in specific object reconstruction (5% improvement in b-jet and new τhad performance)

- Evidence for HH production by ~2000 fb^{-1} in CMS at the HL-LHC in S2
- Combination with ATLAS: shown in Shin-Shan Yu 's talk





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Summary

- HH signatures well covered with full Run 2 datasets
  - Directly probes Higgs potential and Higgs quartic gauge coupling
  - Strong constraints obtained on the HH cross section and κ_{2V}
  - HHH search offers insights to both λ_3 and λ_4
- CMS expects to see evidence around 2000 fb^{-1} in HL-LHC projection
- Searches with early Run 3 data to be expected in the near future
  - Expected improvements in trigger, object reconstruction, etc

Backup

VBF Cross section Combined