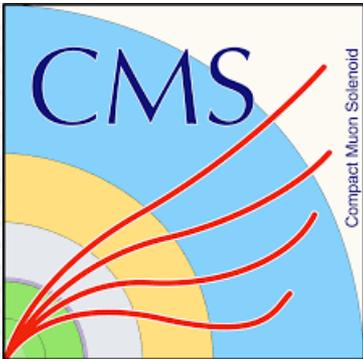


HH Combination from CMS



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On behalf of the CMS Collaboration

1. Institute of High Energy Physics, CAS

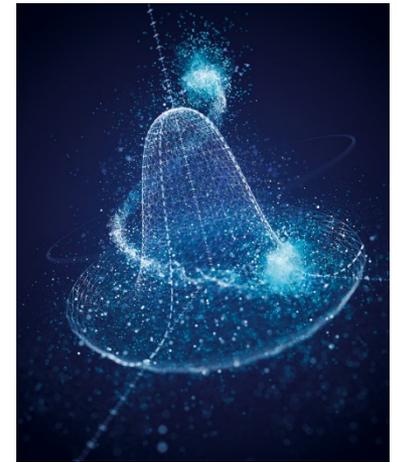
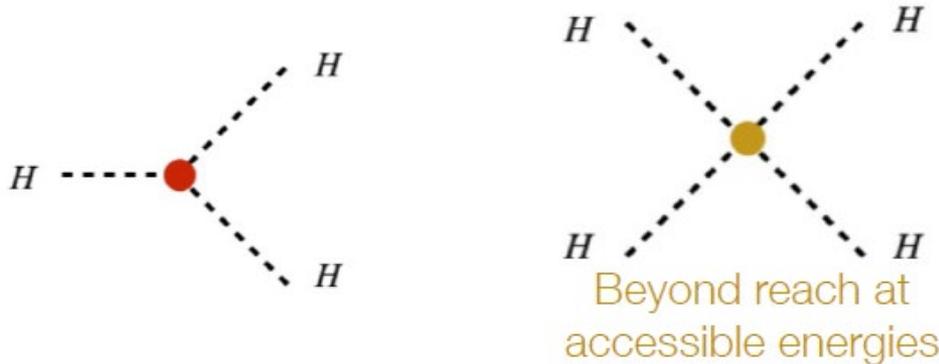
HH measurement

2

- HH measurement directly probes Higgs self-coupling λ

- Crucial for understanding the Higgs field potential

- $$V = \mu^2 H^2 + \frac{\mu^2}{v} H^3 + \frac{\mu^2}{4v^2} H^4$$



[CERN Courier](#)

- Tight correlation with the dynamics of the electroweak phase transition

- HH production sensitive to BSM effects

- Modified SM couplings
- Additional couplings in Effective Field Theory
- Resonant production

Focus on non-resonant HH production and SM interpretation based on [Nature article](#) July 2022

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Article | [Open Access](#) | [Published: 04 July 2022](#)

A portrait of the Higgs boson by the CMS experiment ten years after the discovery

[The CMS Collaboration](#)

[Nature](#) 607, 60–68 (2022) | [Cite this article](#)

10k Accesses | 2 Citations | 401 Altmetric | [Metrics](#)

[Nature 607 \(2022\) 60](#)

HH production modes

3

HH production challenging to measure due to its small cross section

$\sigma_{HH} \sim \frac{\sigma_H}{1000}$ in SM at 13 TeV

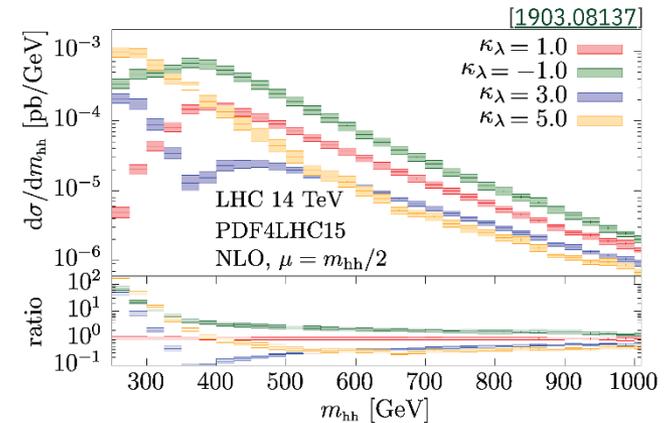
Two main production modes

- $\sigma_{ggF} = 31.05 \text{ fb}$ SM @13 TeV
 - Dominant channel for studying self-coupling
 - Destructive interference
- $\sigma_{VBF} = 1.73 \text{ fb}$ SM @13 TeV
 - Only channel to access quartic VVHH coupling

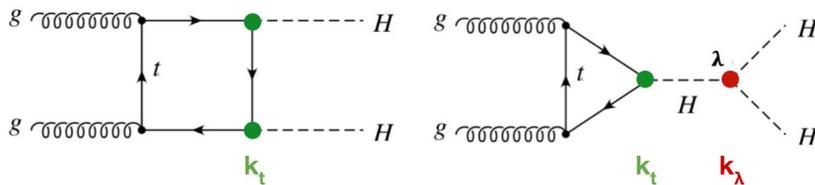
Spectrum of m_{HH} depends on k_λ

- $k_\lambda = \lambda/\lambda_{SM}$
- Softer for large $|k_\lambda|$

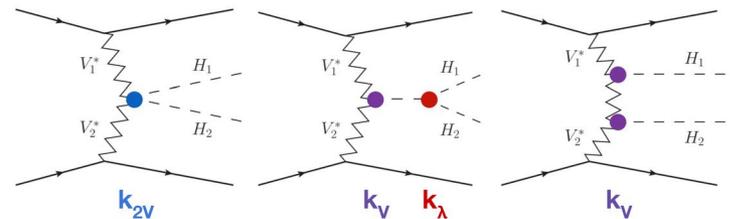
$\kappa_\lambda = \lambda/\lambda^{SM}$ also dictates signal kinematics:



Gluon-gluon fusion (**ggF**)



Vector-boson fusion (**VBF**)



Various Higgs coupling modifiers (coupling over SM prediction): $k_\lambda, k_{2V}, k_t, k_V$

HH signal modeling in CMS

4

- Continuous morphing between discrete ($\mathbf{k}_\lambda, \mathbf{k}_{2V}, \mathbf{k}_V, \mathbf{k}_t$) points
 - One MC per point

$$\text{ggF} \quad D_{gg hh}(k_\lambda, k_t) = r \cdot r_{gg hh} \cdot \sum_i^3 f_{gg hh}^i(k_\lambda, k_t) \cdot D_{gg hh}^i$$

$$\text{VBF} \quad D_{qq hh}(k_{2V}, k_V, k_\lambda) = r \cdot r_{qq hh} \cdot \sum_i^6 f_{qq hh}^i(k_{2V}, k_V, k_\lambda) \cdot D_{qq hh}^i$$

Morphed shape

Morphing coeff.
for point i

MC shape for
point i

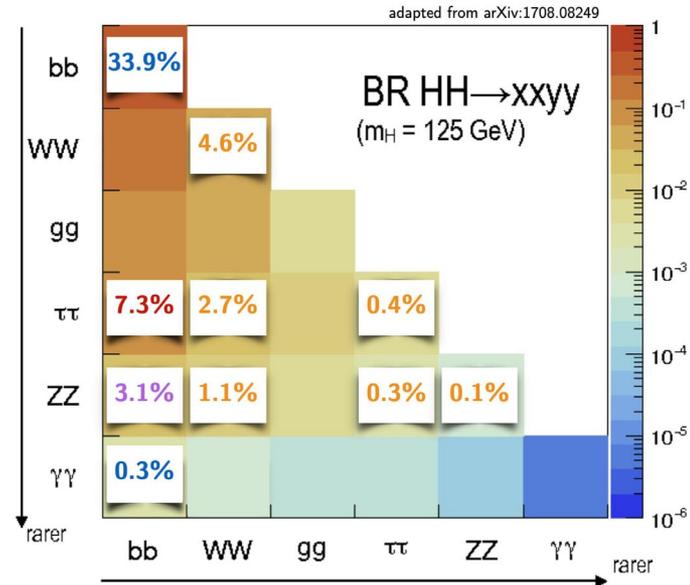
- Also take into account additional model/systematic dependence
 - \mathbf{k}_λ dependent QCD scale + m_{top} signal uncertainty
 - Scaling of single H background cross sections with \mathbf{k} 's
 - Scaling of H branching fractions with \mathbf{k} 's for signal and single H background

CMS HH combination with full Run 2 data

5

- Best HH sensitivity via combination of all available decay channels
 - Using full Run 2 data with 138 fb^{-1}
 - Included the most sensitive channels
 - All final states defined to be mutually exclusive

Channel	reference
<i>bbbb</i> resolved	PRL 129(2022)081802
<i>bbbb</i> boosted	arXiv:2205.06667
<i>bb</i> $\tau\tau$	arXiv:2206.09401
<i>bb</i> $\gamma\gamma$	JHEP03(2021)257
<i>bbZZ</i>	arXiv:2206.10657
<i>multilepton</i>	arXiv:2206.10268



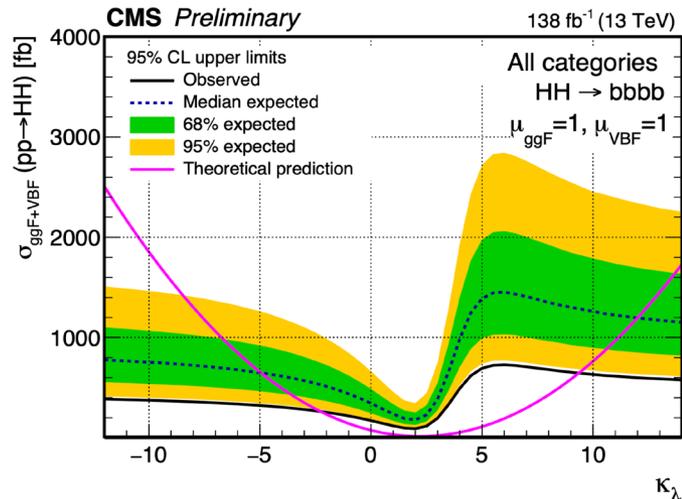
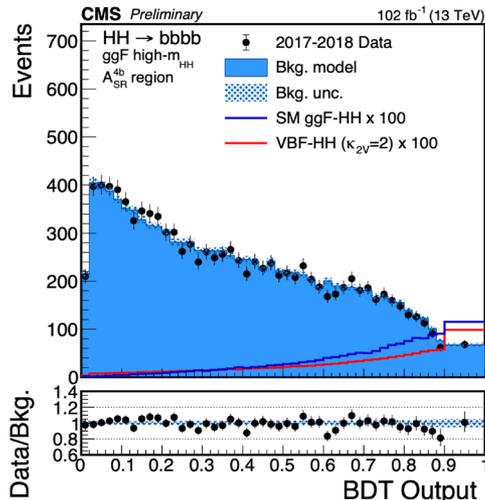
- HH search evolution since early Run 2 ([Phys. Rev. Lett. 122, 121803 2019](#)) besides more data
 - Selections targeting VBF HH production mechanism
 - Extensive usage of machine learning, selection/tagging optimization
 - Boosted topologies, additional final states

CMS $HH \rightarrow bbbb$ resolved

6

- Final state with four b-jets, plus extra jet pair for VBF HH signal
 - highest branching fraction, large multi-jet background
 - Measuring both ggF and VBF production of HH
 - reconstruct HH candidate using 4 jets for ggF
 - require additional 2 jets for VBF events
 - use dedicated BDTs to separate different signals and backgrounds
 - large multi-jet background estimated from data and fitted simultaneously in multiple signal regions

[PRL 129\(2022\)081802](#)



Observed (expected) results:

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

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

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

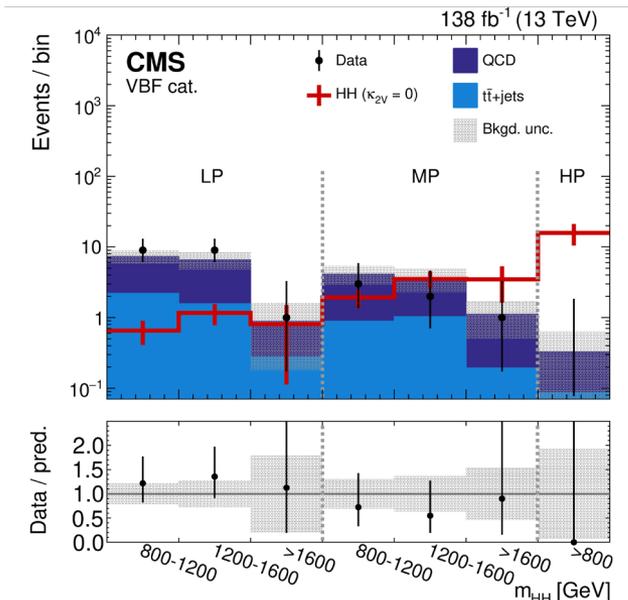
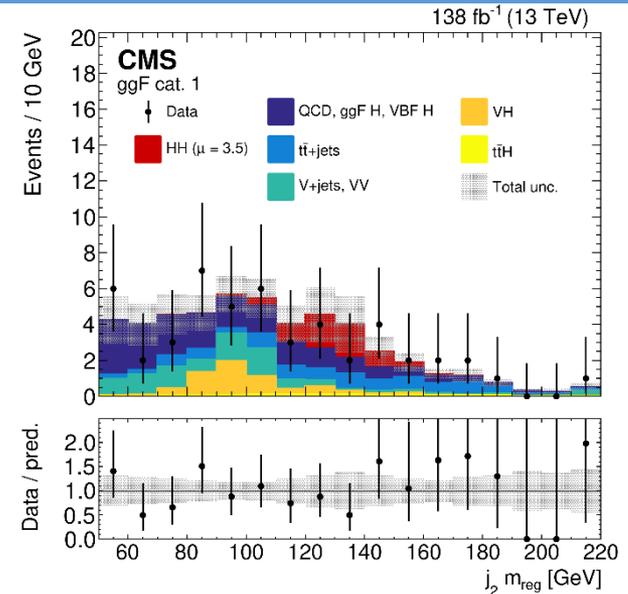
More details in Nicolas's [talk](#)

CMS $HH \rightarrow bbbb$ boosted

7

- Final state with two AK8 jets (+extra jet pair in VBF HH)
 - Boosted $H \rightarrow bb$ candidate(s) reconstructed as large radius jet(s)
 - Exploring jet substructure with novel machine learning method "[ParticleNet](#)"
 - to identify boosted H decays
 - b-jet energy regression to improve $H \rightarrow bb$ mass resolution
- Main backgrounds from QCD and $t\bar{t}$
 - Fit/correction from control regions
- 3 ggHH enriches categories
 - BDT classifier to separation/categorization
 - Signal extraction: fit to sub-leading jet mass
- 3 VBFHH enriched categories
 - Classification on ParticleNet score
 - signal extraction from fit to m_{HH}

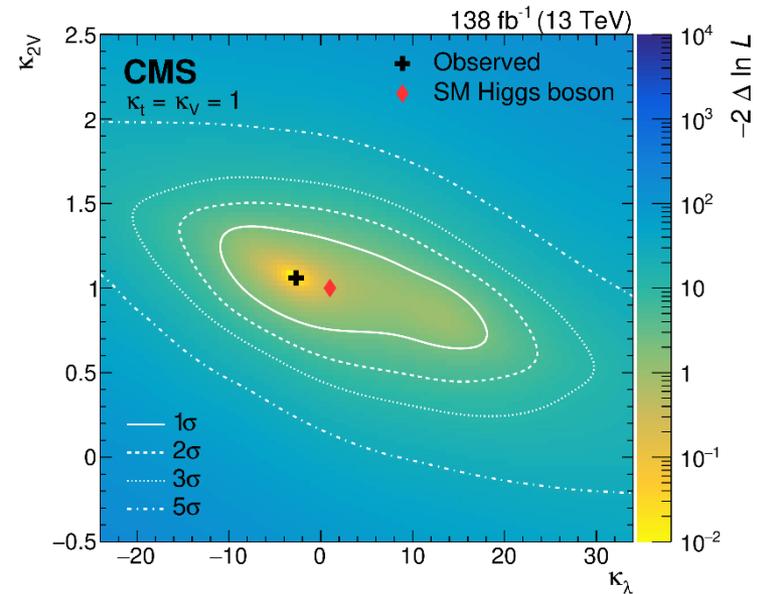
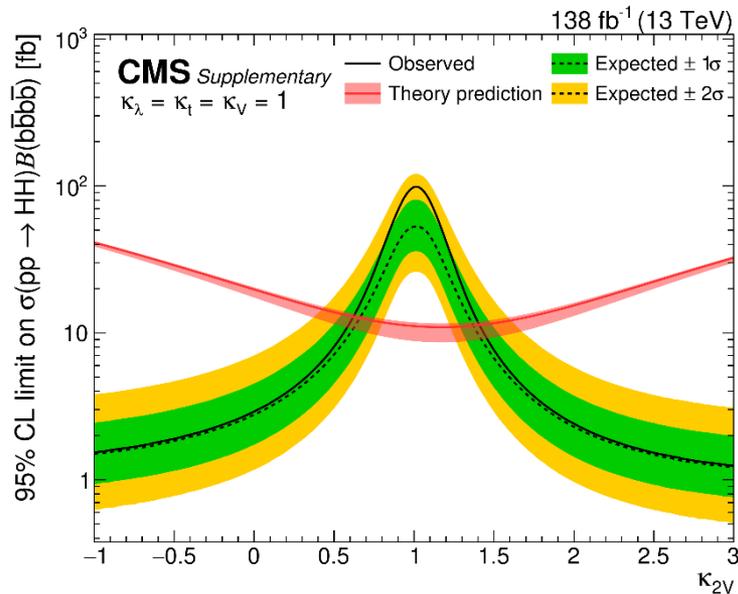
[arXiv:2205.06667](https://arxiv.org/abs/2205.06667)



CMS $HH \rightarrow b\bar{b}b\bar{b}$ boosted results

8

- Very good constraints on HH signal strength and k_λ
 - $\sigma_{ggF+VBF}^{HH} < 9.9(5.1) \times \sigma_{ggF+VBF}^{HH SM}$
 - $-9.9 (-5.1) < k_\lambda < 16.9 (12.2)$
- $k_{2V} = 0$ firstly excluded at $>5\sigma$ assuming $k_\lambda = k_t = k_V = 1$
 - $0.62 (0.66) < k_{2V} < 1.41 (1.37)$



[arXiv:2205.06667](https://arxiv.org/abs/2205.06667)

More details in Nicolas's [talk](#)

CMS $HH \rightarrow b\bar{b}\tau\tau$

9

- 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, $t\bar{t}$ 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

[arXiv:2206.09401](https://arxiv.org/abs/2206.09401)

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

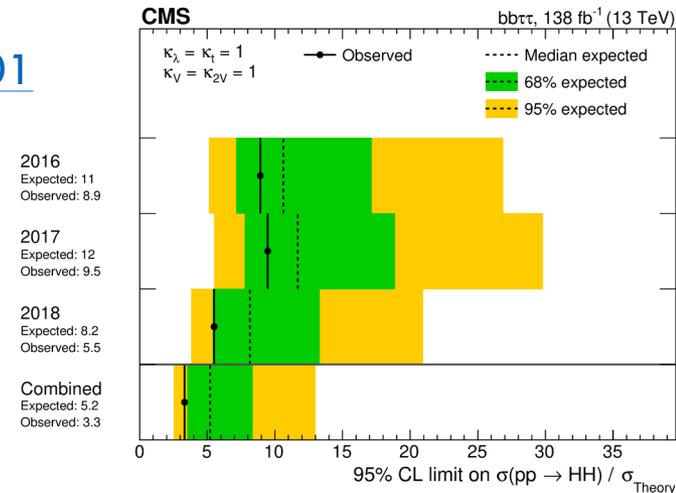
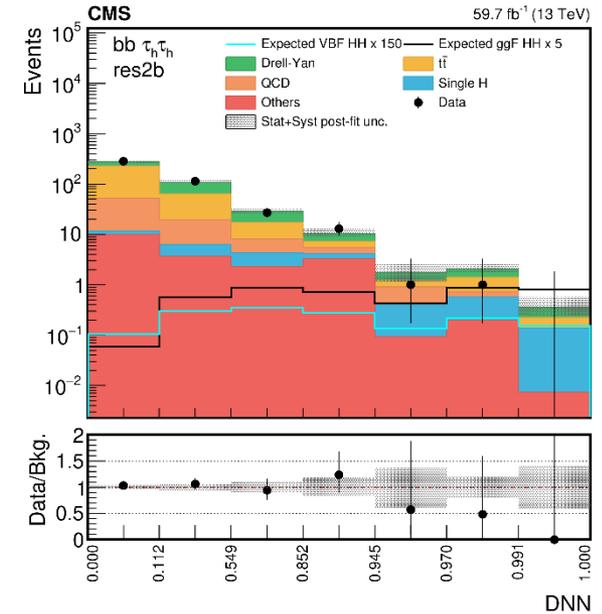
$$\sigma_{ggF+VBF}^{HH} < 3.3(5.2) \times \sigma_{ggF+VBF}^{HH SM},$$

$$\sigma_{VBF}^{HH} < 124(154) \times \sigma_{VBF}^{HH SM},$$

$$-1.8(-3.0) < k_\lambda < 8.8(9.9)$$

$$-0.4(-0.6) < k_{2V} < 2.6(2.8)$$

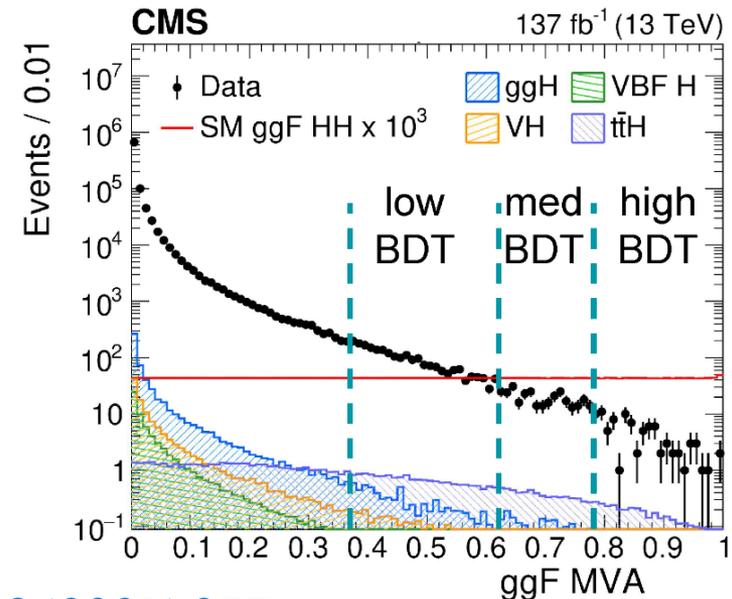
More details in Jaime's [talk](#)



CMS $HH \rightarrow b\bar{b}\gamma\gamma$

10

- Final states: 2 photons and 2 b-jets
 - very small BR, clean signal extraction due to the narrow $h \rightarrow \gamma\gamma$ mass peak
- Main backgrounds: $\gamma\gamma + jets$, $\gamma + jets$, ttH
- Besides ggF production mode, VBF production is also studied
- MVA methods (Boosted Decision Trees) are trained to separate HH signal and backgrounds
- To reduce ttH background contamination, a dedicated Deep Neural Network (DNN) was developed
- Event categorized based on MVA score and \widetilde{M}_X
 - $\widetilde{M}_X = m_{\gamma\gamma jj} - (m_{jj} - m_H) - (m_{\gamma\gamma} - m_H)$
 - 2 VBF categories, 12 ggF categories
- The HH signal is extracted from a 2D fit to the invariant mass of the two Higgs bosons ($m_{\gamma\gamma}$, m_{bb}) in the final state simultaneously in all categories.



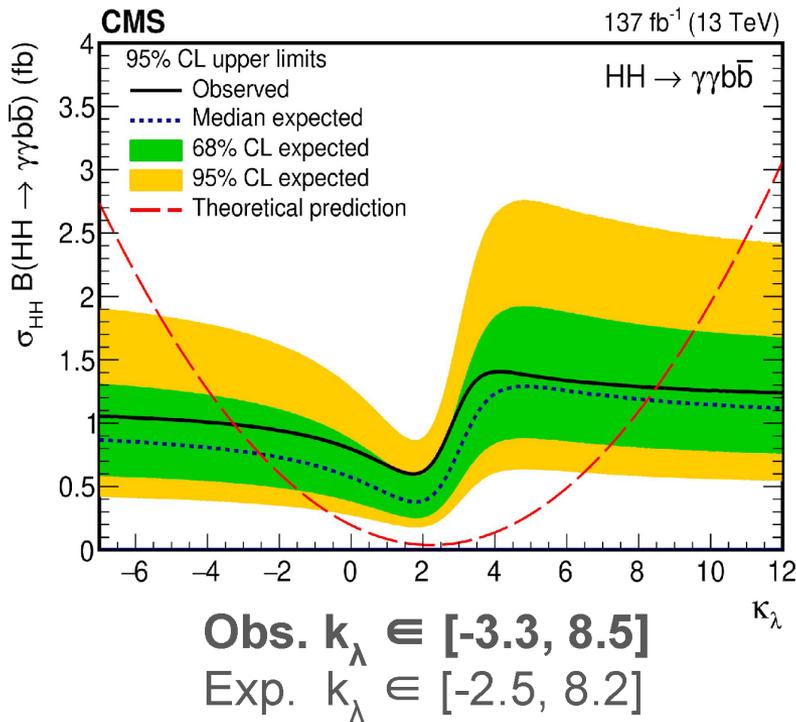
[JHEP 03 \(2021\) 257](#)

CMS $HH \rightarrow b\bar{b}\gamma\gamma$ results

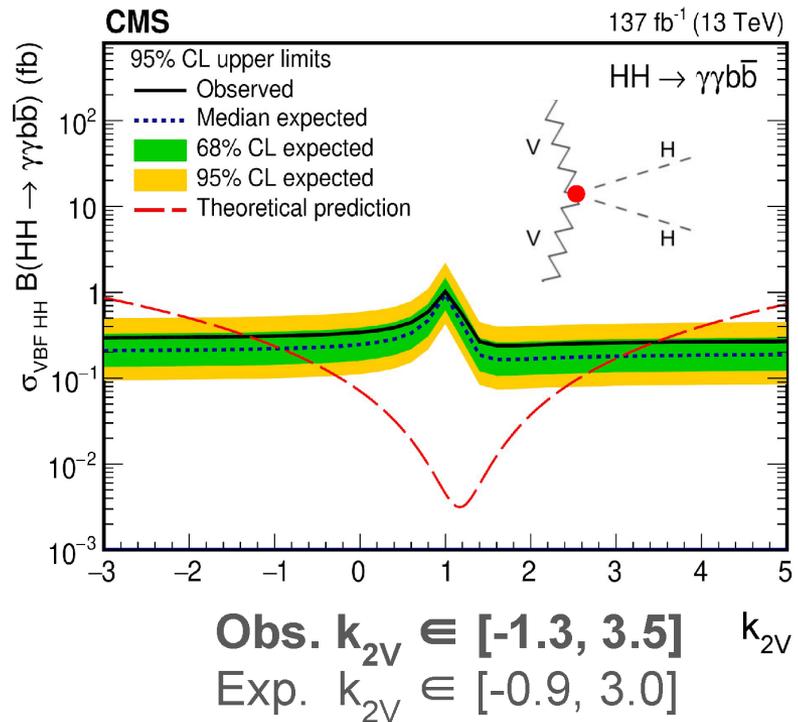
11

- No deviations from SM observed
- Obs.(exp.) upper limit on HH signal strength $7.7(5.2)\times\text{SM}$

Limit on HH XS×BR vs k_λ



Limit on VBF HH XS×BR vs $k_{2V} = c_{2V} / c_{2V}^{\text{SM}}$



[JHEP 03 \(2021\) 257](#)

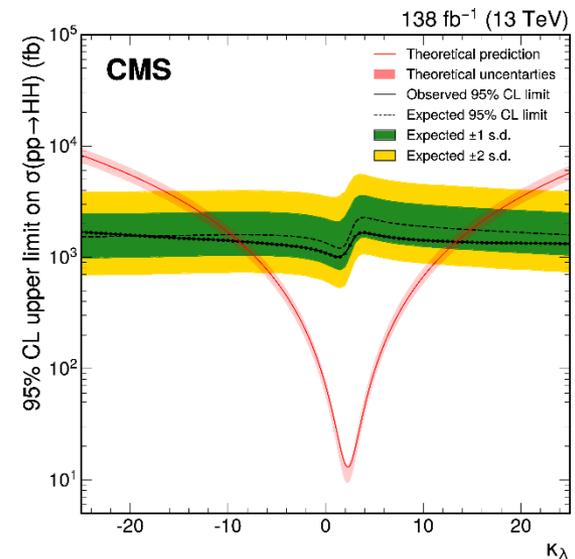
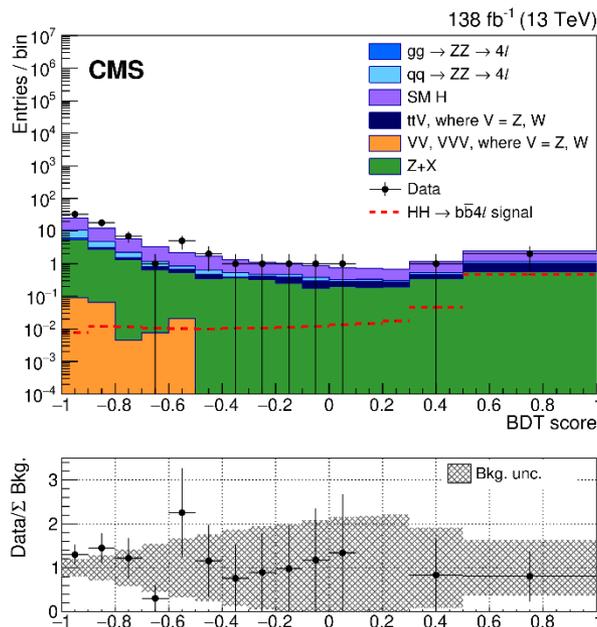
More details in Chu's [talk](#)

CMS $HH \rightarrow bbZZ$ with Run2 data

12

- ggF $HH \rightarrow bbZZ$ channel with final states of two b-jets and two pairs of opposite-charge leptons ($4\mu, 4e, 2\mu 2e$):
 - 9 BDTs are trained for each data-taken year and each final state channels to separate signal and backgrounds
 - signal region is defined with $m_{4l} \sim m_H$
 - multi-dimensional binned fit to the BDT distribution in data is performed to extract the signal

[arXiv:2206.10657](https://arxiv.org/abs/2206.10657)



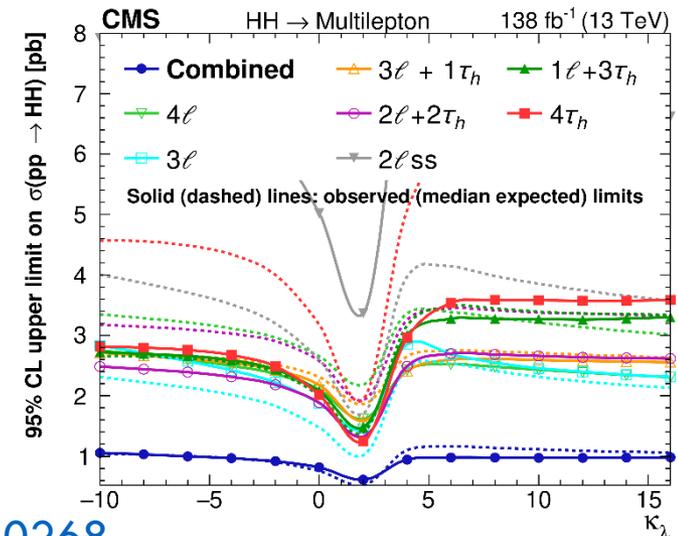
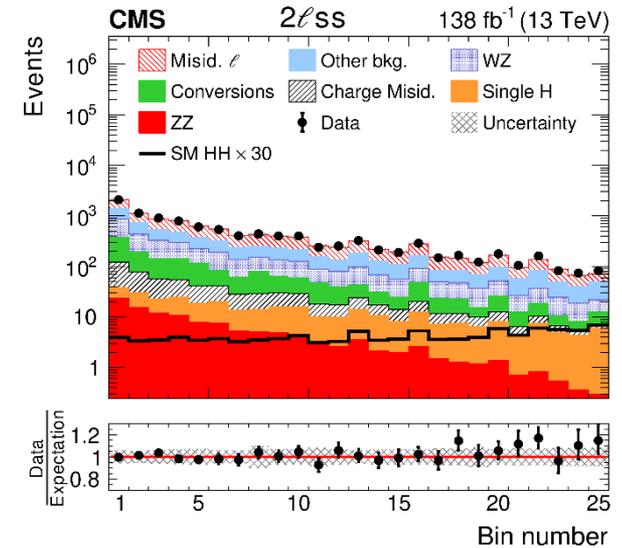
Observed (expected) limits at 95% CL:

$$\sigma_{ggF}^{HH} < 30(37) \times \sigma_{ggF}^{HH SM}$$

$HH \rightarrow$ multilepton ($WWWW, WW\tau\tau, \tau\tau\tau\tau$)

13

- $HH \rightarrow WWWW, WW\tau\tau, \tau\tau\tau\tau$ final states with μ , e , or τ_h
 - 7 event categories with final states of $2\ell ss$, 3ℓ , 4ℓ , $3\ell+1\tau_h$, $2\ell+2\tau_h$, $1\ell+3\tau_h$, $0\ell+4\tau_h$
 - AK4/AK8 jets requirements in $2\ell ss$ and 3ℓ categories
 - Selections on $m(\ell+\ell^-)$ to reduce DY and ZZ bkg
- Background dominated by di-boson and events with mis-identified ℓ or τ_h
 - Data-driven modelling for fakes and MC modelling for others
- BDT classifiers to separate signal from background
 - Optimized separately for SM and BSM models
- Observed (expected) results:
 - $\sigma_{HH} < 21.3(19.4) \times \sigma_{HH}^{SM}$
 - $-6.9 (-6.9) < k_\lambda < 11.1 (11.7)$



[arXiv:2206.10268](https://arxiv.org/abs/2206.10268)

Systematic scheme in HH combination

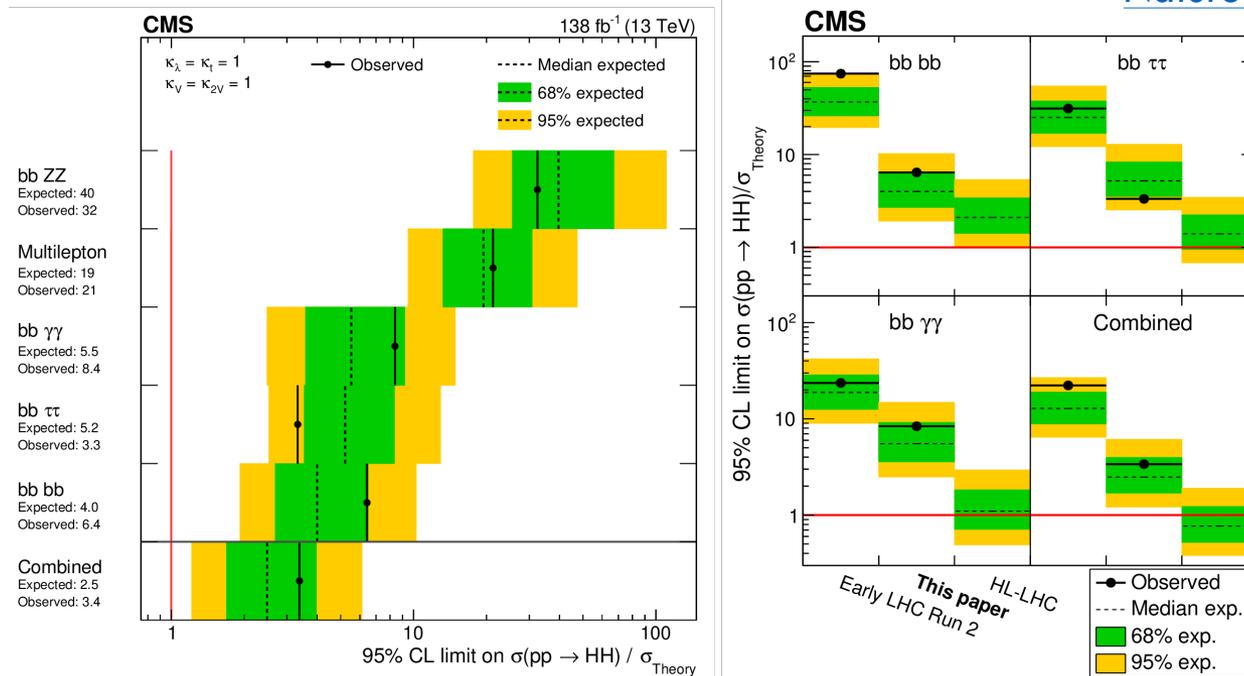
14

- ⊙ Experimental uncertainties
 - ⊙ Common with all channels
 - ⊙ luminosity, Jet resolution and scales, b-tagging, missing ET, tau/lepton identification, trigger, pile up, MC statistics etc.
 - ⊙ Channel specific
 - ⊙ mostly background estimation uncertainties, scales or constrained from control regions
- ⊙ Theoretical uncertainties
 - ⊙ HH Signal
 - ⊙ Higgs branching ratios in HH
 - ⊙ PDF + α_s
 - ⊙ QCD scale + m_{top} , $k\lambda$ dependent
 - ⊙ Shower modelling
 - ⊙ Backgrounds
 - ⊙ Higgs branching ratios for single H
 - ⊙ PDF, α_s , QCD scale
 - ⊙ EWK corrections
 - ⊙ modeling of ISR/FSR etc.
 - ⊙ Common to same processes

Limits on the HH production and their time evolution

15

[Nature 607 \(2022\) 60](#)

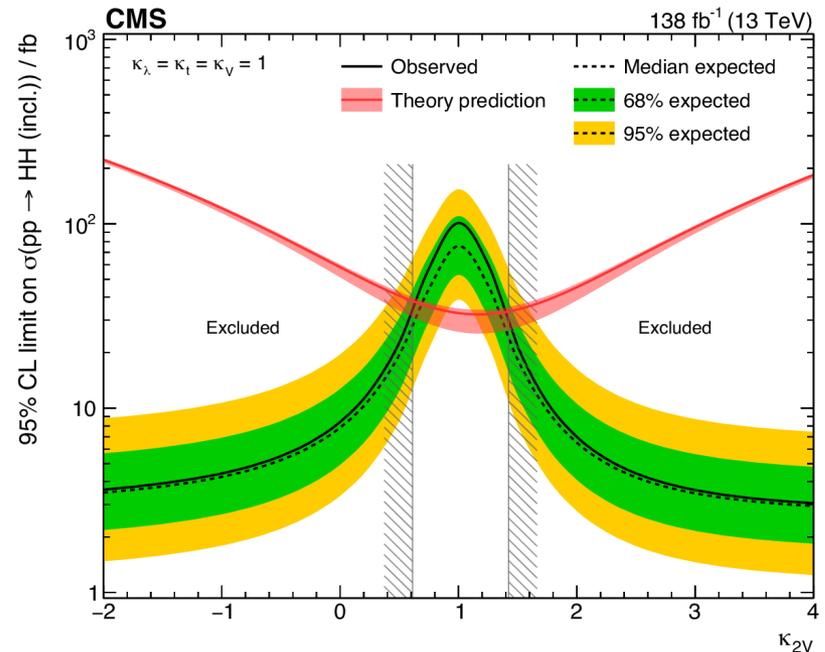
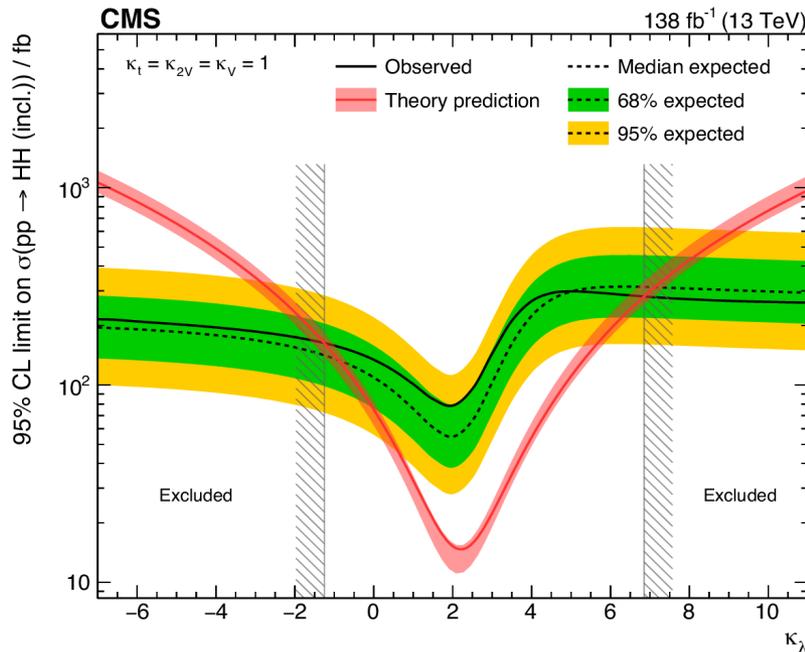


- ⦿ Expected and observed upper limits of HH production cross section
 - ⦿ Presented as ratios of measured HH cross section and the expectation from the SM
 - ⦿ Observed (expected) 95% CL Upper limits: $3.4 (2.5) \times SM$
 - ⦿ Compared to early Run 2 results (35.9 fb⁻¹) and HL-LHC expectation (3000 fb⁻¹)
 - ⦿ Significant improvement comparing to early Run 2 results
 - ⦿ Sensitivity in HL-LHC sufficient to establish the existence of the SM HH production

HH production cross-section limits with k_λ , k_{2V}

16

- 95% CL interval for Higgs boson self-interaction coupling modifier k_λ
 - $[-1.24, 6.49]$
- 95% CL interval for k_{2V}
 - $[0.67, 1.38]$
- $k_{2V}=0$ is excluded with a significance of 6.6σ , assuming $k_\lambda = k_V = k_t = 1$



[Nature 607 \(2022\) 60](#)

Summary

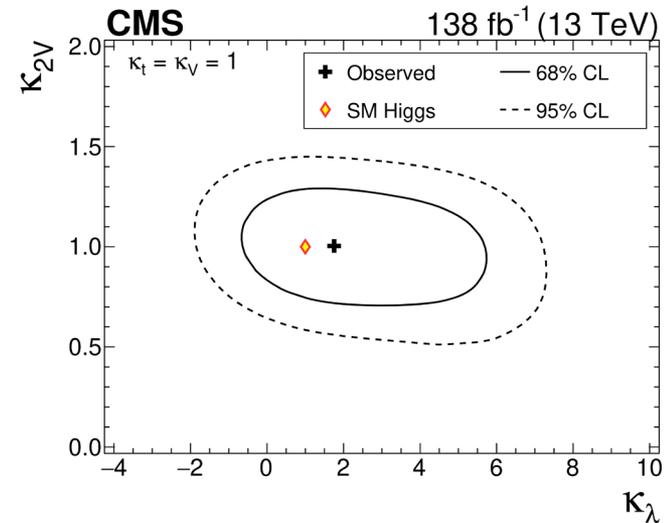
17

Non-resonant HH combination results in CMS with 138 fb⁻¹ data

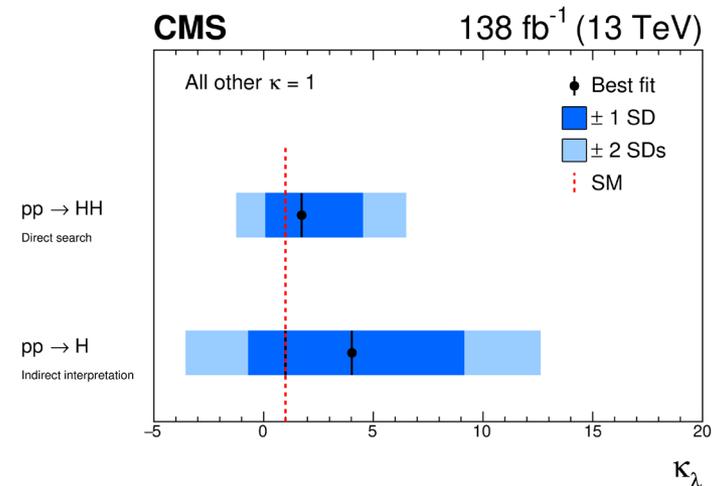
- Include leading channel inputs
 - bbbb (resolved+boosted), bb $\tau\tau$, bb $\gamma\gamma$, bbZZ(4l), multilepton
- All results agree with SM prediction
- Best sensitivity on HH production limits with the combination:
 - Observed $\sigma_{HH} < 3.4 \times \sigma_{HH SM}$ (2.4 expected) @ 95% CL
- Constraints on k_λ with 95% CL interval
 - $k_\lambda \in [-1.24, 6.49]$
- Constraints on k_{2V} with 95% CL interval
 - $k_{2V} \in [0.67, 1.38]$
- Exclusion of the $k_{2V} = 0$
 - With 6.6σ assuming $k_\lambda = k_V = k_t = 1$

More impressive results expected in future with Run 2 data

- Additional channels and interpretation
- Combination with single Higgs to constrain k_λ



[Nature 607 \(2022\) 60](#)



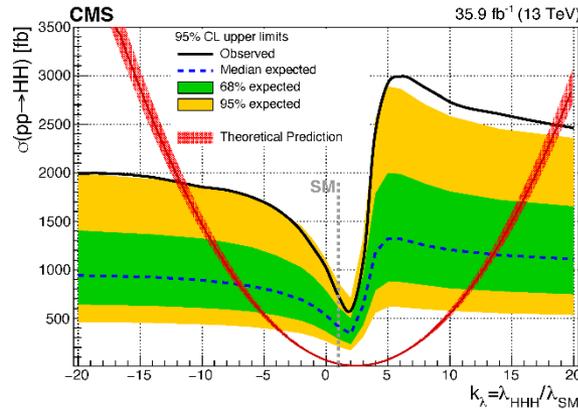
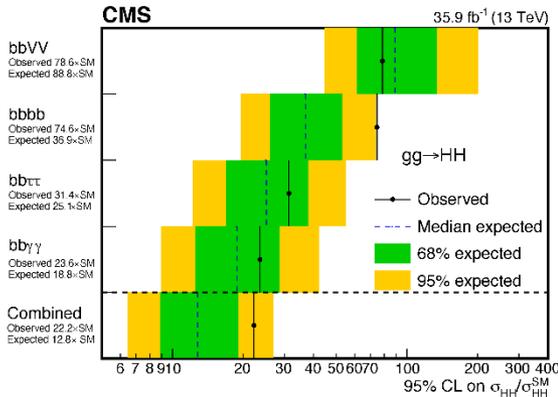
Back Up

Early Run 2 HH combination

19

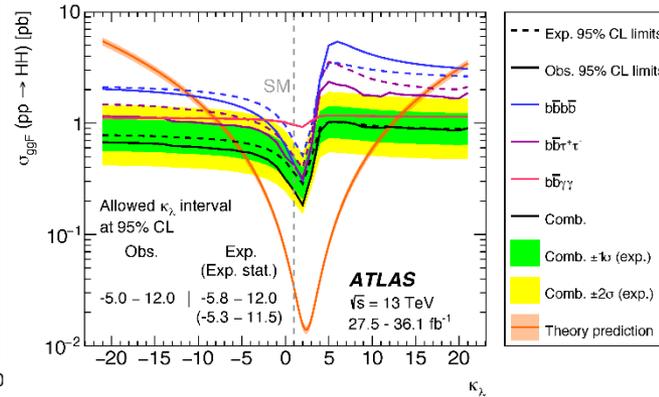
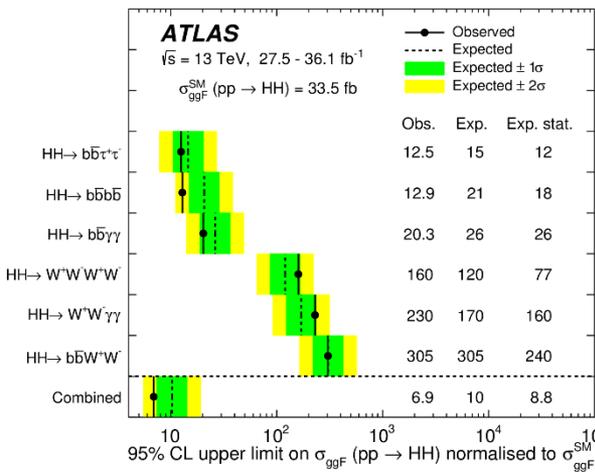
- Both ATLAS and CMS have performed HH combination with partial Run2 data
 - 27.5-36.1 fb⁻¹ data for ATLAS, 35.9 fb⁻¹ data for CMS
 - only consider ggF HH production

[Phys. Rev. Lett. 122, 121803 2019](#)



Observed (expected) limits at 95% CL:

- ATLAS: $\sigma_{ggF}^{HH} < 6.9 (10) \times \sigma_{ggF}^{HH SM}$
- CMS: $\sigma_{ggF}^{HH} < 12.8 (22.2) \times \sigma_{ggF}^{HH SM}$
- ATLAS: $-5 (-5.8) < \kappa_\lambda < 12 (12.0)$
- CMS: $-11.8 (-7.1) < \kappa_\lambda < 18.8 (13.6)$



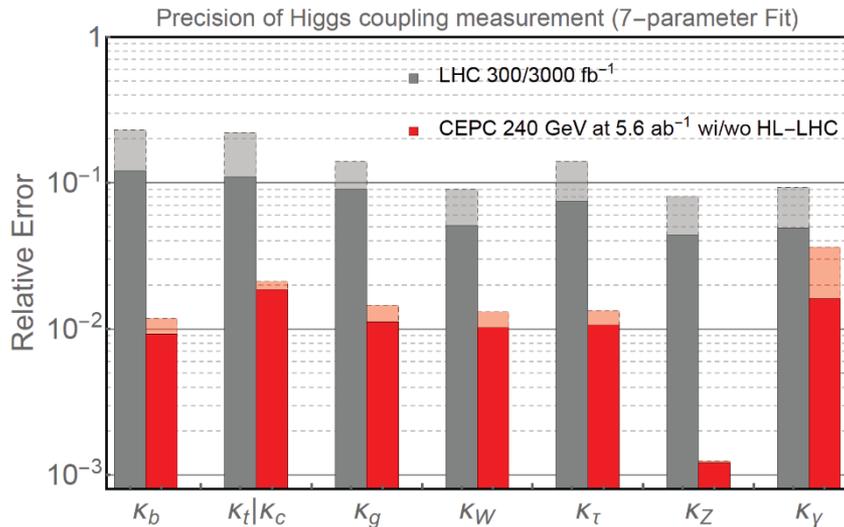
[Phys. Lett. B 800 \(2020\) 135103](#)

Lepton collider vs hadron collider

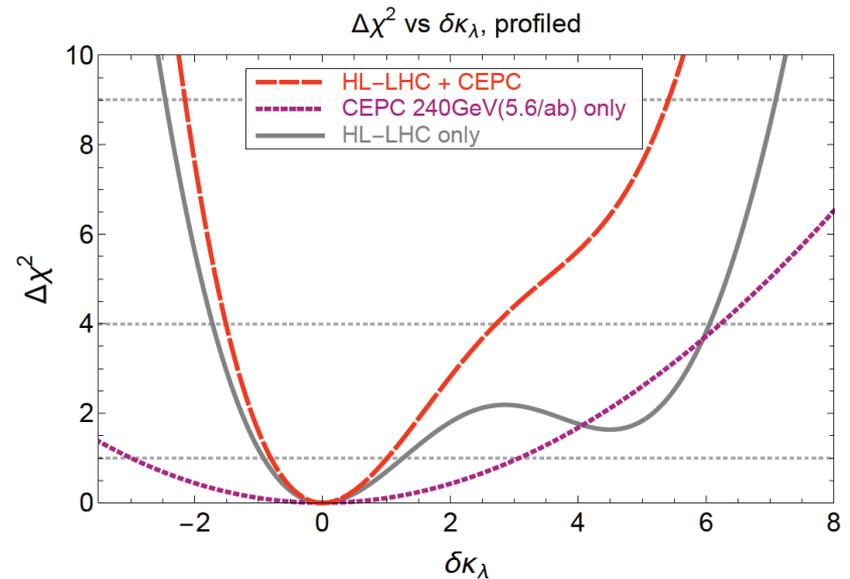
20

- Future lepton collider provides complementary results
 - Much smaller systematic uncertainties
 - An order of magnitude or more improvement in precision in most Higgs measurements and many electroweak observables
 - Search for potential unknown decay modes that are impractical at hadron colliders

[CEPC CDR Volume II \(Physics and Detector\)](#)



more precise coupling measurements



complementary k_λ constraints