Institute of High Energy Physics
Chinese Academy of Sciences

HH Combination in CMS

Jin Wang[1]
On behalf of the CMS Collaboration

1. Institute of High Energy Physics, CAS

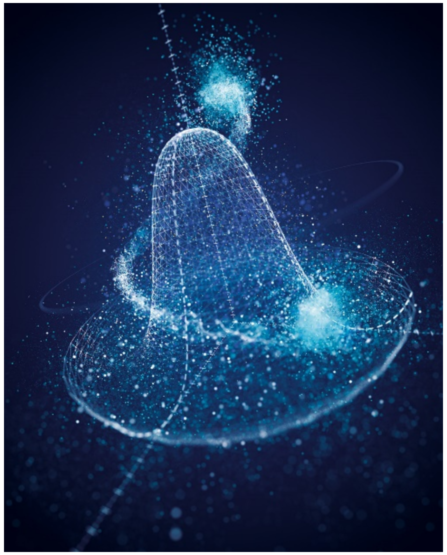
26th July 2022

Higgs Potential 2022

HH measurement

- HH measurement directly probes Higgs self-coupling
  - Crucial for understanding the Higgs field potential
    - Involved in early universe and defines its fate
  - $V = \mu^2 H^2 + \frac{\mu^2}{v} H^3 + \frac{\mu^2}{4v^2} H^4$

Beyond reach at accessible energies



- HH production sensitive to BSM effects
  - Modified couplings, $k_\lambda, k_{2V}, k_V, k_t$
    - $k_\lambda = \lambda/\lambda_{SM}$
  - Additional coupling, c_2, c_g, c_{2g}
  - Resonant production

nature

Explore content ⌄ About the journal ⌄ Publish with us ⌄

nature > articles > article

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

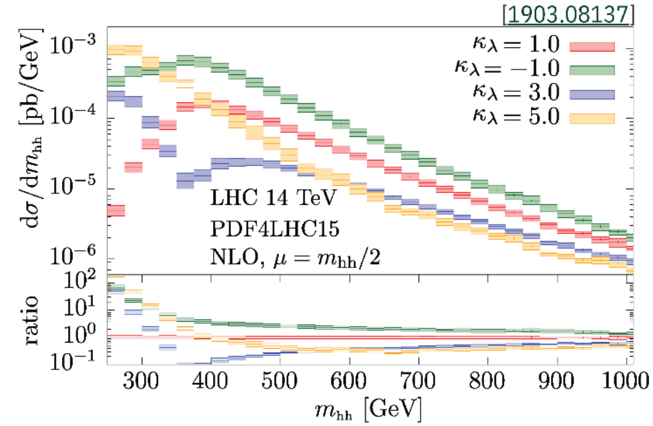
10k Accesses | **2** Citations | **401** Altmetric | Metrics

Focus on non-resonant HH production and SM interpretation based on Nature article July 4th 2022

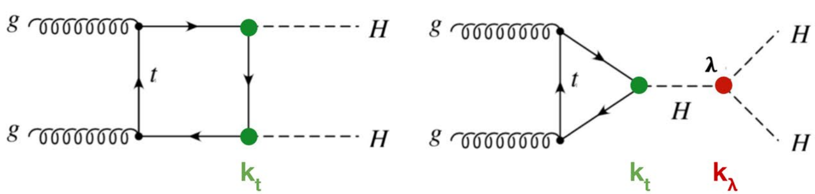
HH production modes

- 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
    - $\sigma_{ggF} = 31.05\, fb$ SM @13TeV
      - Dominant channel for studying self-coupling
      - Destructive interference
    - $\sigma_{VBF} = 1.73\, fb$ SM @13TeV
      - Only channel to access quartic VVHH coupling
- Spectrum of m_{HH} depends on k_λ
  - Softer for large $|k_\lambda|$

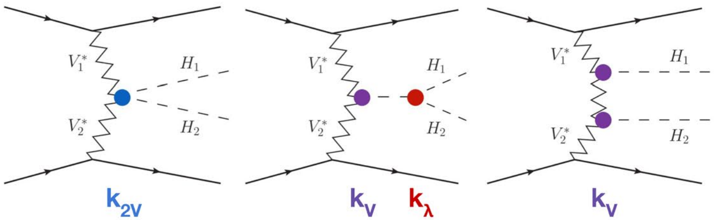
$\kappa_\lambda = \lambda/\lambda^{SM}$ also dictates signal kinematics:



Gluon-gluon fusion (**ggF**)



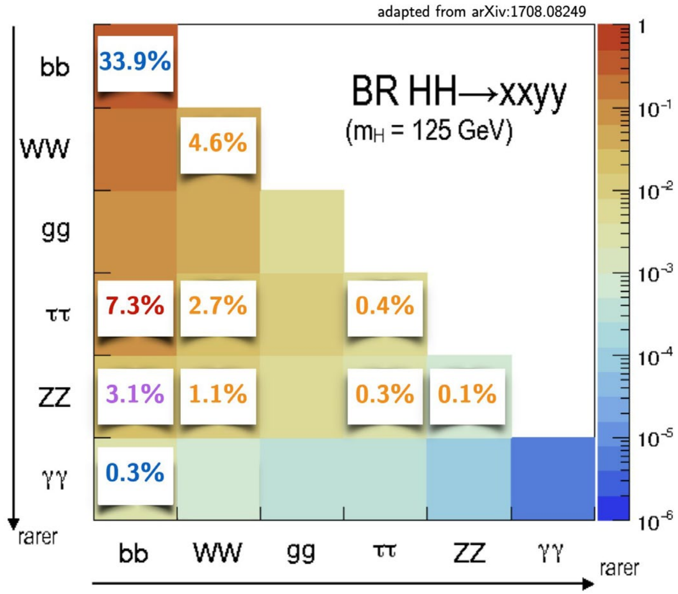
Vector-boson fusion (**VBF**)



CMS HH combination

- 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

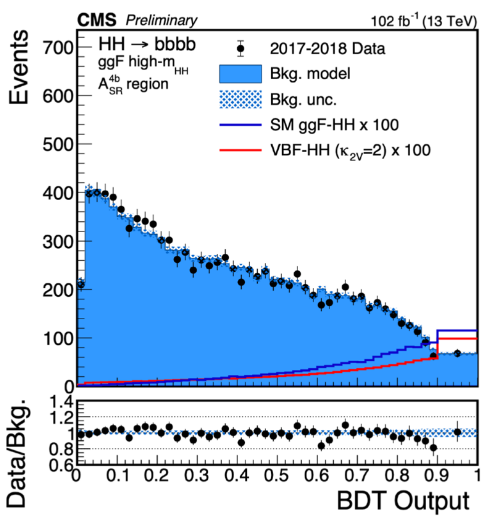
Channel	reference
$bbbb$ resolved	arXiv:2202.09617
$bbbb$ boosted	arXiv:2205.06667
$bb\tau\tau$	arXiv:2206.09401
$bb\gamma\gamma$	JHEP03(2021)257
$bbZZ$	arXiv:2206.10657
$multilepton$	arXiv:2206.10268

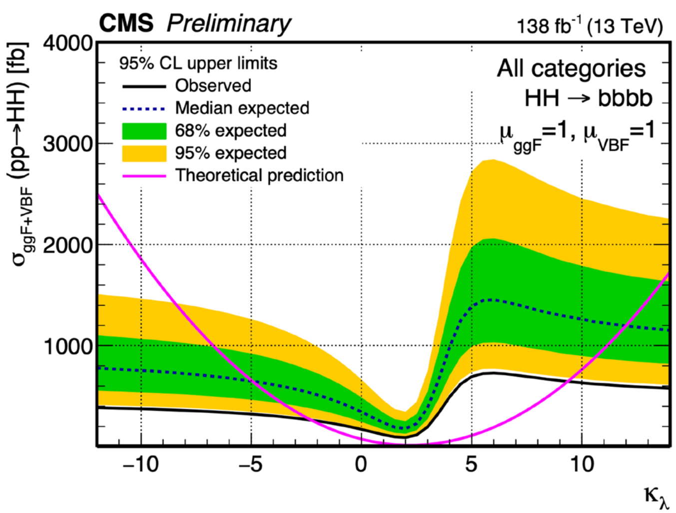


- HH searches evolution since 2016 besides more data
  - Selections targeting VBF HH production mechanism
  - Extensive usage of machine learning, selection/tagging optimization
  - Boosted topologies, additional final states

CMS $HH \rightarrow bbbb$ resolved

- Final state with four b-jets, plus extra jet pair for VBF HH signal
  - highest branching fraction, large multijet 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 multijet background estimated from data and fitted simultaneously in multiple signal regions





Observed (expected) results:

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

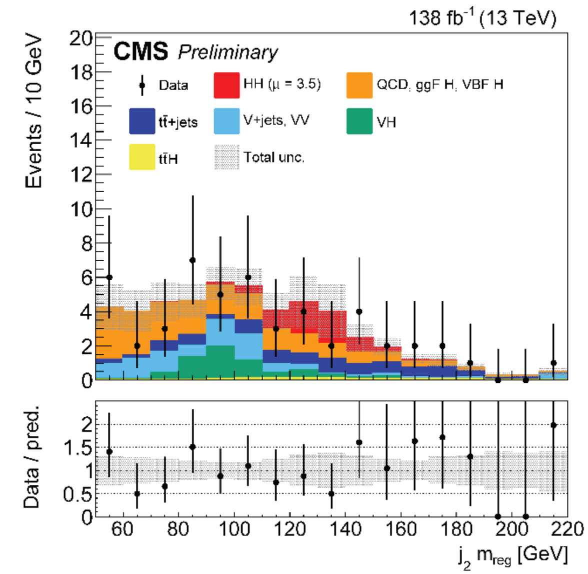
$$-2.3(-5.0) < k_{\lambda} < 9.4(12)$$

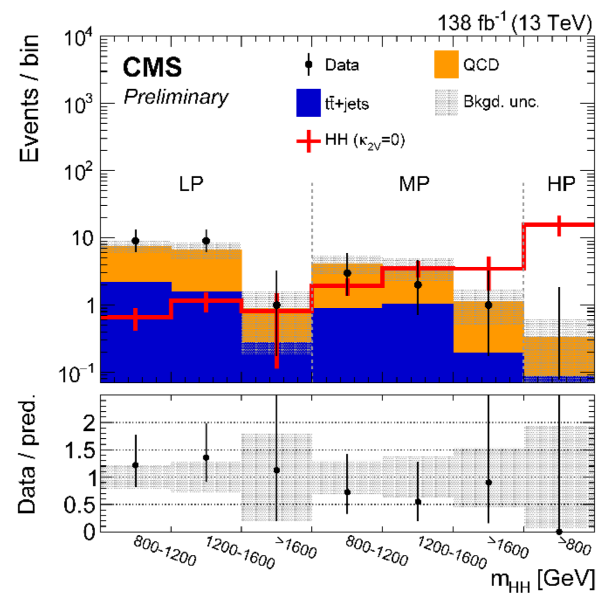
$$-0.1(-0.4) < k_{2V} < 2.2(2.5)$$

arXiv:2202.09617

CMS $HH \to bbbb$ boosted

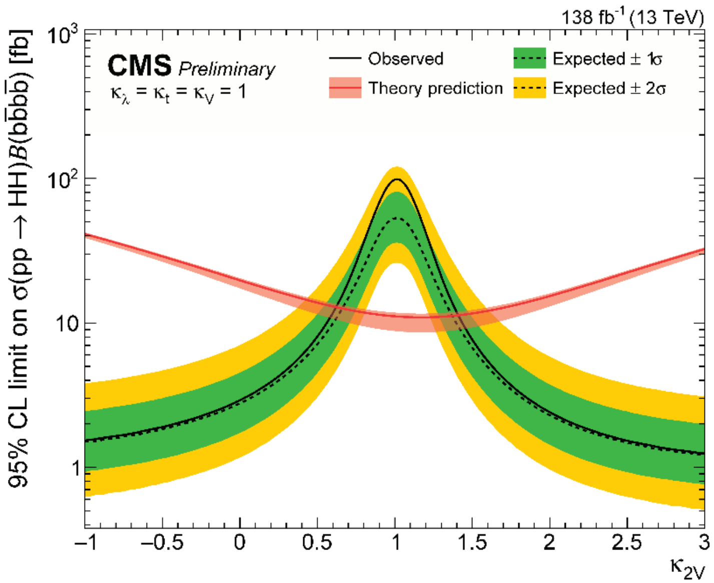
- Final state with two AK8 jets (+extra jet pair in VBF HH)
  - Boosted H→bb candidate(s) reconstructed as large radius jet(s)
  - Using jet substructure info “ParticleNet” tagger to identify boosted H decays
  - DNN b-jet energy regression to improve H→bb mass resolution
- Main backgrounds from QCD and tt
  - Fit/correction from control regions
- 3 ggHH enriches categories
  - BDT classifier to separation/categorization
  - Signal extraction: fit to subleading jet mass
- 3 VBFHH enriched categories
  - Classification on ParticleNet score
  - signal extraction from fit to m_{HH}

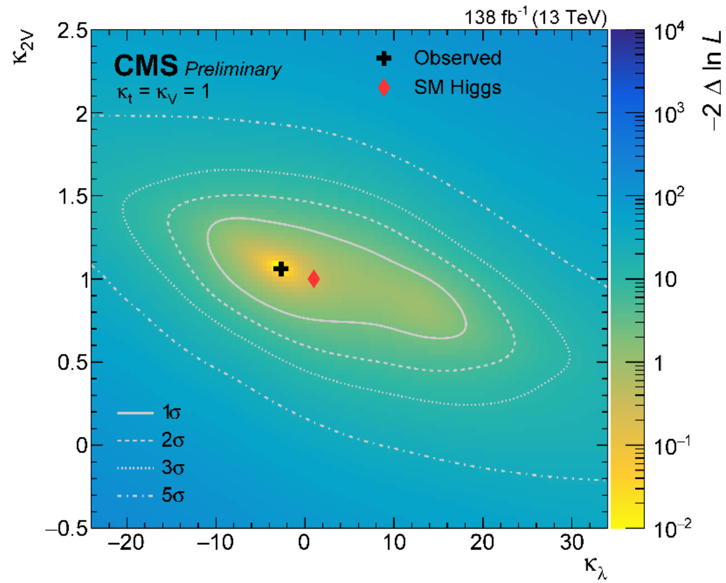




CMS $HH \to bbbb$ boosted results

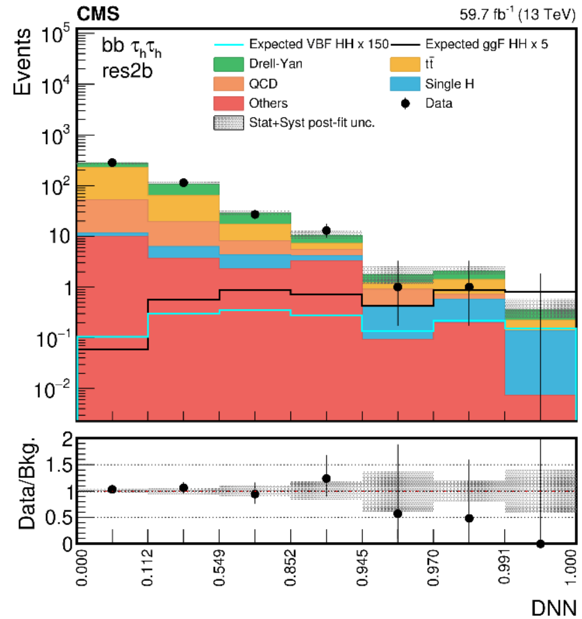
- Very good constraints on HH signal strength and k_λ
  - $\sigma^{HH}_{ggF+VBF} < 9.9(5.1) \times \sigma^{HH\,SM}_{ggF+VBF}$
  - $-9.9\ (-5.1) < k_\lambda < 16.9\ (12.2)$
- $k_{2V} = 0$ firstly excluded at >5σ assuming $k_\lambda = k_t = k_V = 1$
  - $0.62\ (0.66) < k_{2V} < 1.41\ (1.37)$





CMS $HH \to bb\tau\tau$

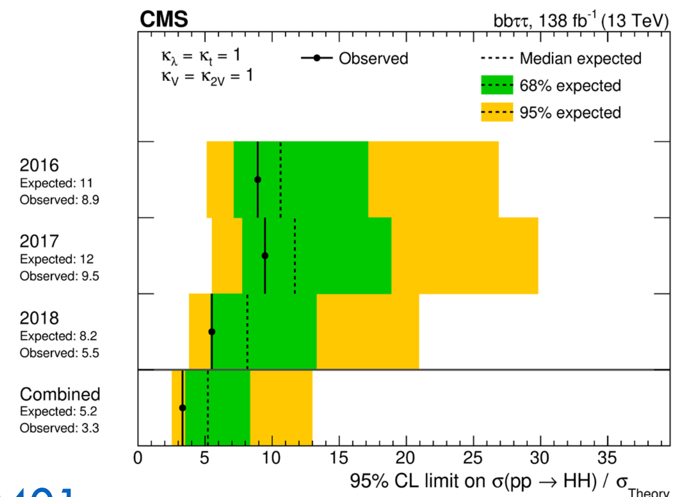
- Triggers based on leptons and hadronic taus
  - di-τ trigger with or without jets
  - Single-e, e-τ, single-mu and μ-τ triggers
- Leading background from QCD, ttbar and DY events
  - Estimated using data-driven or control regions
- Event categorization on production mode and final state
- DNN classifiers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



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

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

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

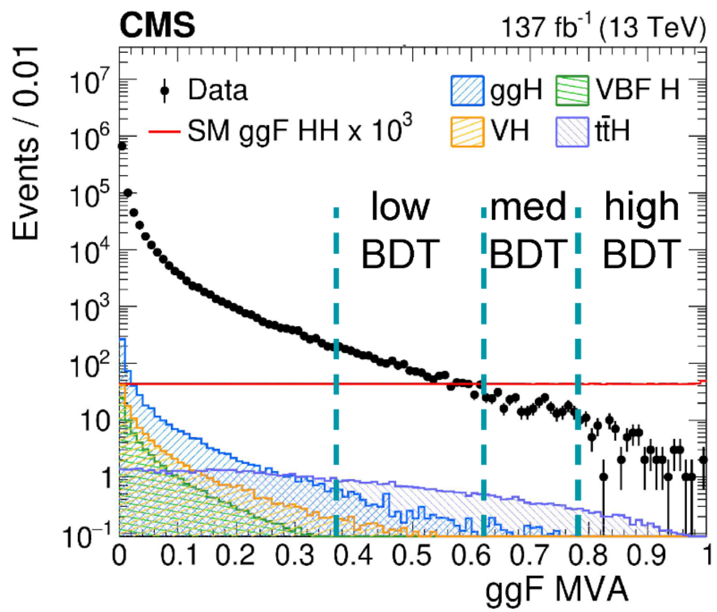


arXiv:2206.09401

CMS $HH \to bb\gamma\gamma$

- Final states: 2 photons and 2 b-jets
  - very small BR, clean signal extraction due to the narrow $h \to \gamma\gamma$ mass peak
- Main backgrounds: $\gamma\gamma + jets$, $\gamma + jets$, ttH
- Besides ggF production mode, VBF production is also studied
- Two Boosted Decision Trees (BDTs) are trained to separate HH signal and backgrounds
  - 1 for ggF, 1 for VBF
- To reduce ttH background contamination, a dedicated Deep Neural Network (DNN) was developed
- Category optimized to enhance sensitivity to SM and anomalous couplings
  - 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.

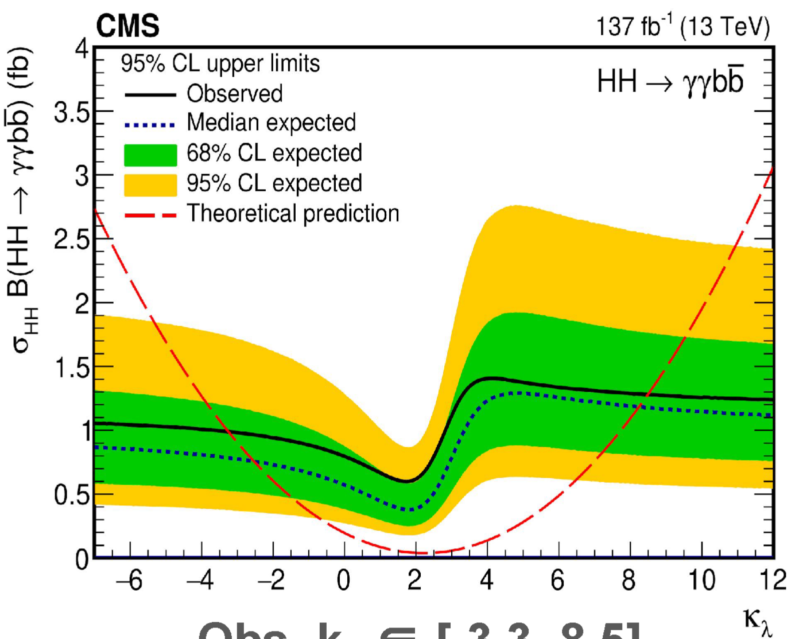


JHEP 03 (2021) 257

CMS $HH \to bb\gamma\gamma$ results

- No deviations from SM observed
- Obs.(exp.) upper limit on HH signal strength 7.7(5.2)×SM

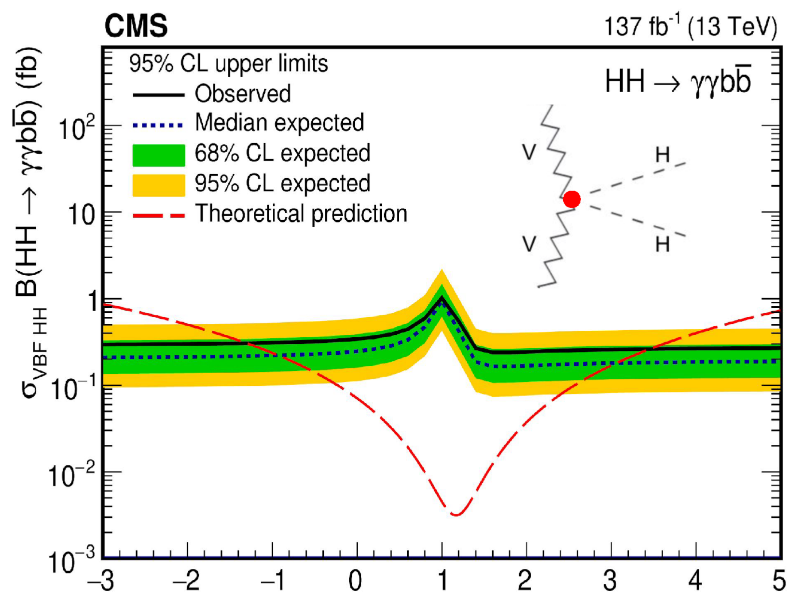
Limit on HH XS×BR vs k_λ



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

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

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



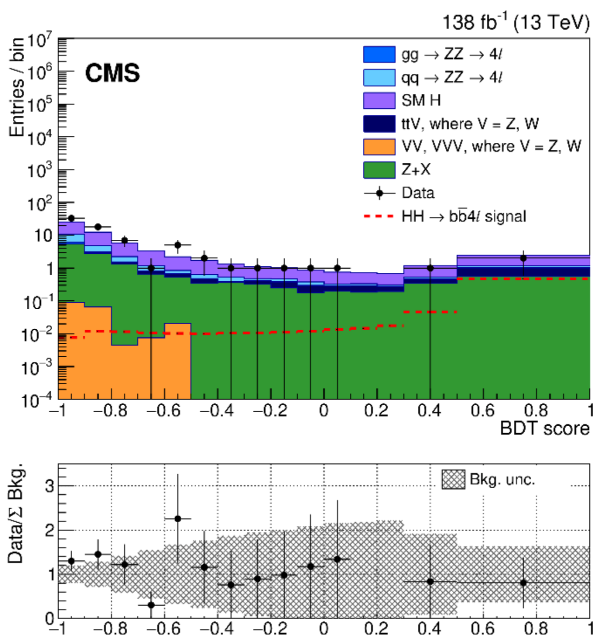
Obs. $k_{2V} \in [-1.3, 3.5]$

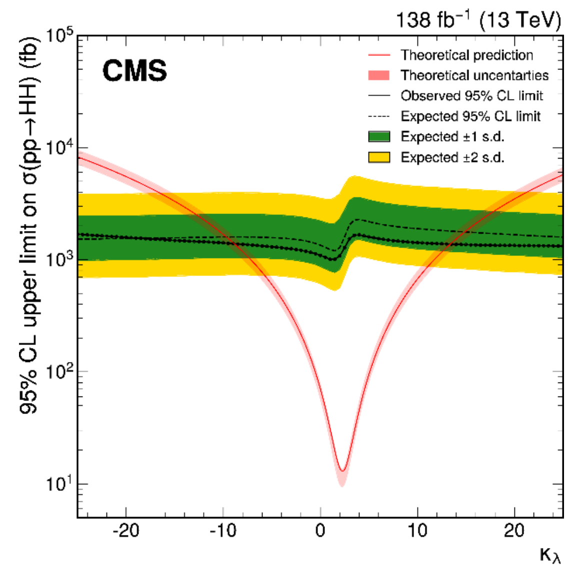
Exp. $k_{2V} \in [-0.9, 3.0]$

[JHEP 03 (2021) 257]

CMS $HH \rightarrow bbZZ$ with Run2 data

- ggF $HH \rightarrow bbZZ$ channel with final states of two b-jets and two pairs of opposite-charge leptons $(4\mu, 4e, 2\mu 2e)$: arXiv:2206.10657
  - 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





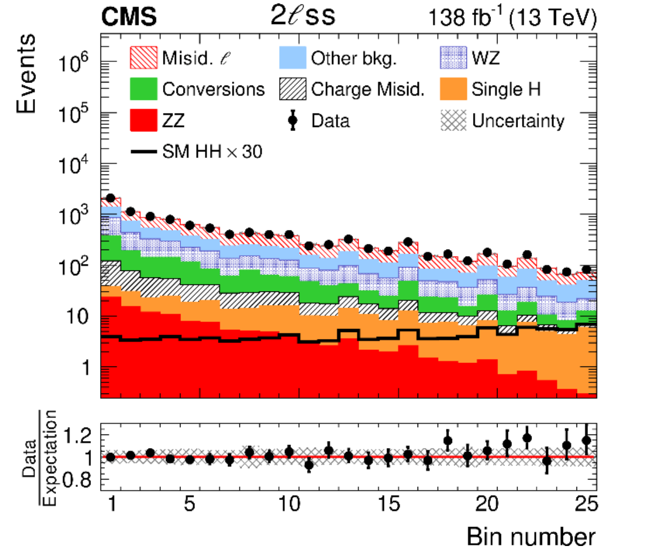
Observed (expected) limits at 95% CL:

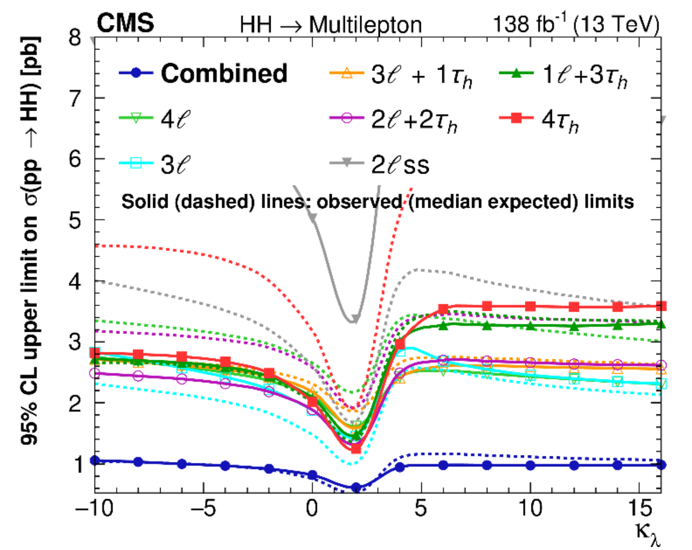
$$\sigma_{ggF}^{HH} < 30(37) \times \sigma_{ggF}^{HH\,SM}$$

HH→Multilepton (WWWW, WWττ, ττττ)

- HH->WWWW, WWττ, and ττττ final states with μ, e, or τ_h
  - 7 event categories with final states of 2lss, 3l, 4l, 3l+1τ_h, 2l+2τ_h, 1l+3τ_h, 0l+4τ_h
  - AK4/AK8 jets requirements in 2lss and 3l categories
  - Selections on m(l+l-) 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





HH signal modeling in combination

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

ggF

$$D_{gghh}(k_\lambda, k_t) = r \cdot r_{gghh} \cdot \sum_i^3 f^i_{gghh}(k_\lambda, k_t) \cdot D^i_{gghh}$$

VBF

$$D_{qqhh}(k_{2V}, k_V, k_\lambda) = r \cdot r_{qqhh} \cdot \sum_i^6 f^i_{qqhh}(k_{2V}, k_V, k_\lambda) \cdot D^i_{qqhh}$$

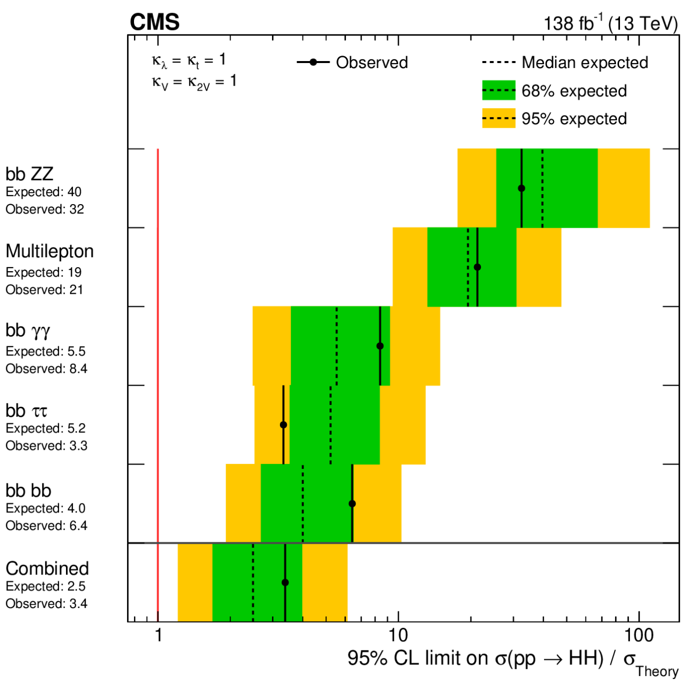
Morphed shape — Morphing coeff. for point i — MC shape for point i

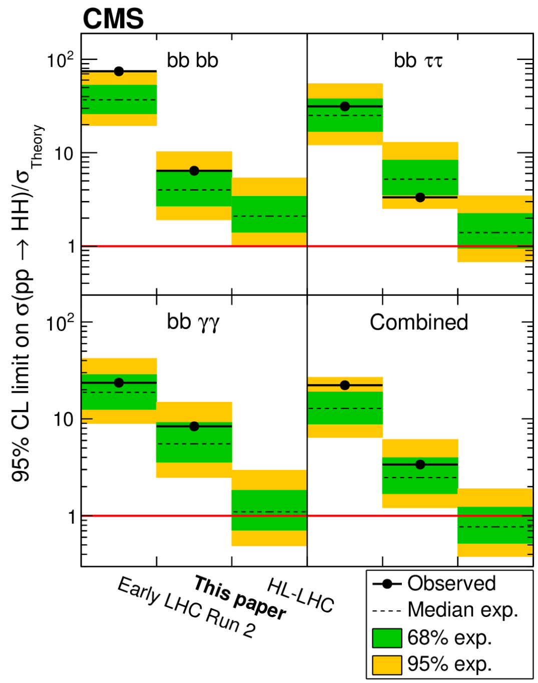
- Also take into account additional model/systematic dependence
  - $\mathbf{k}_\lambda$ dependent QCD scale + m_{top} signal uncertainty
  - Scaling of single H background cross sections with **k**'s
  - Scaling of H branching fractions with **k**'s for signal and single H background

Systematic uncertainties

- 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}, kλ dependent
    - Shower modelling
  - Backgrounds
    - Higgs branching ratios for single H
    - PDF, α_s, QCD scale
    - EWK corrections
    - modeling of ISR/FSR etc.

Limits on the HH production and their time evolution



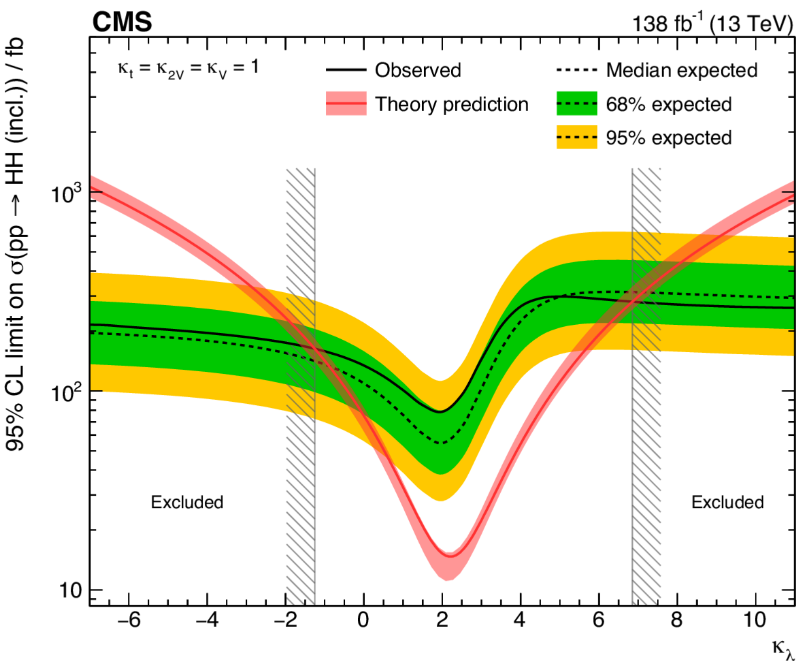


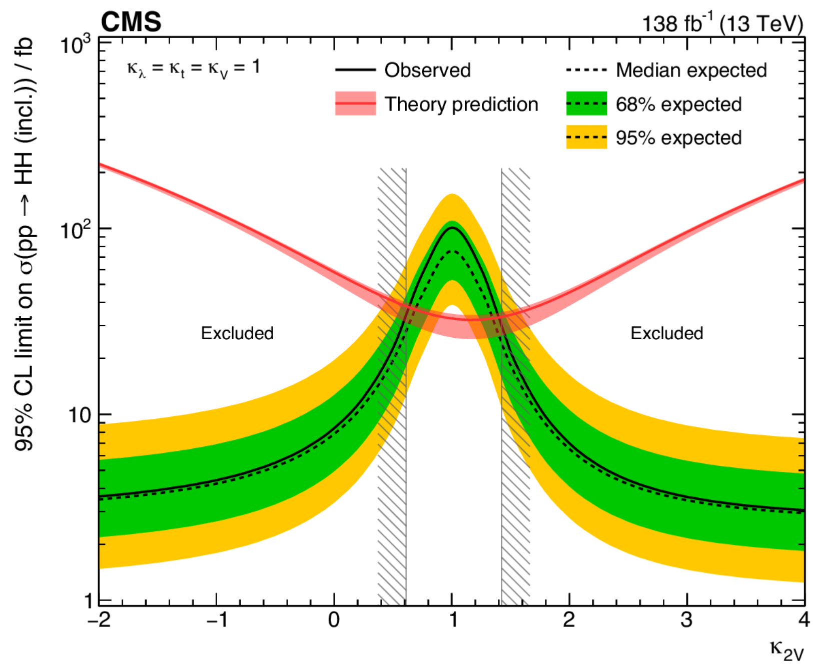
Nature article

- 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 kλ, k2V

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

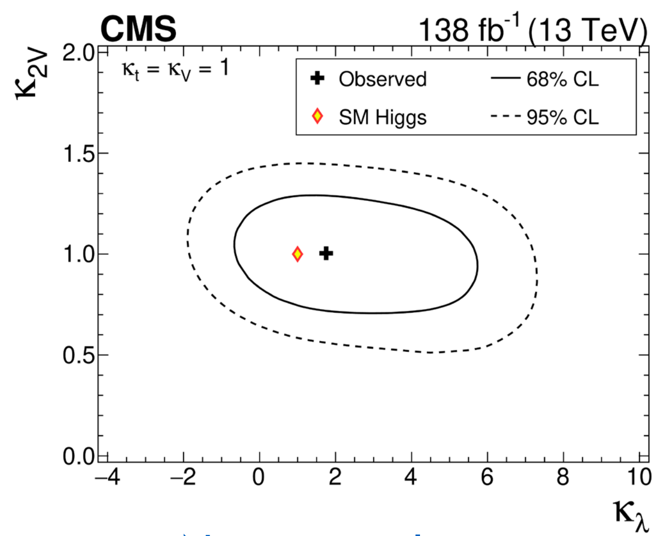




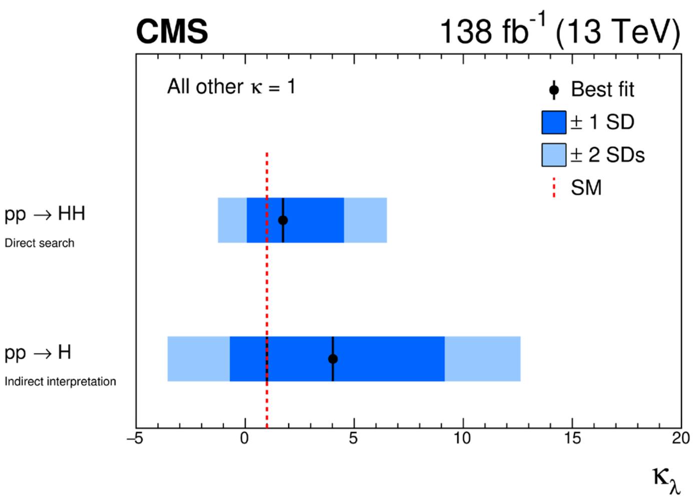
[Nature article]

Summary

- Non-resonant HH combination results in CMS with 138 fb^{-1} data
  - Contributing channels
    - 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 with addition channels in Run2 as well as the H+HH, ATLAS+CMS combination in future



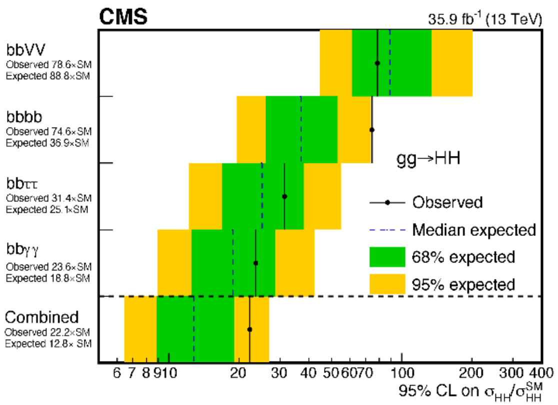
Nature article

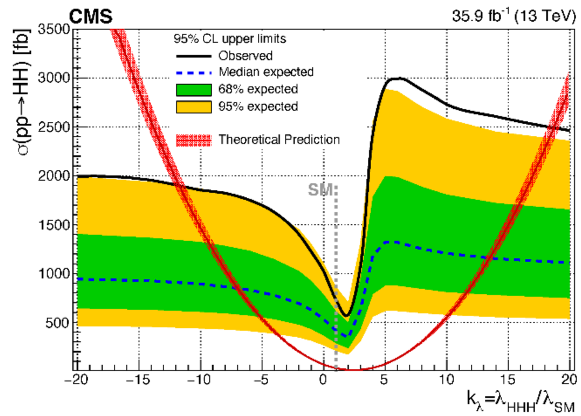


Back Up

Old HH combination

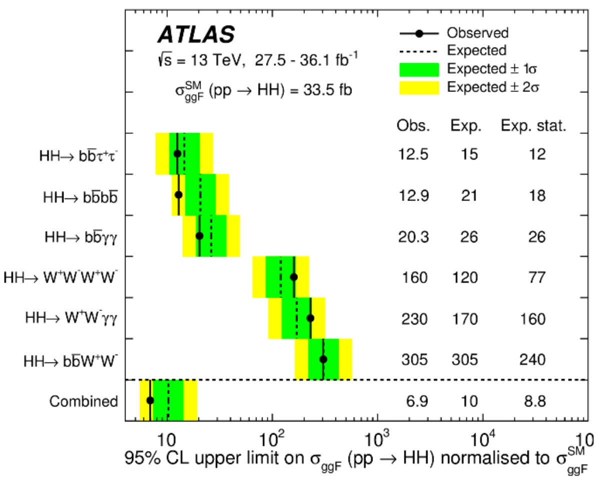
- Both ATLAS and CMS have performed HH combination with partial Run2 data
  - 27.5-36.1 fb^{-1} data for ATLAS, 35.9 fb^{-1} data for CMS
  - only consider ggF HH production

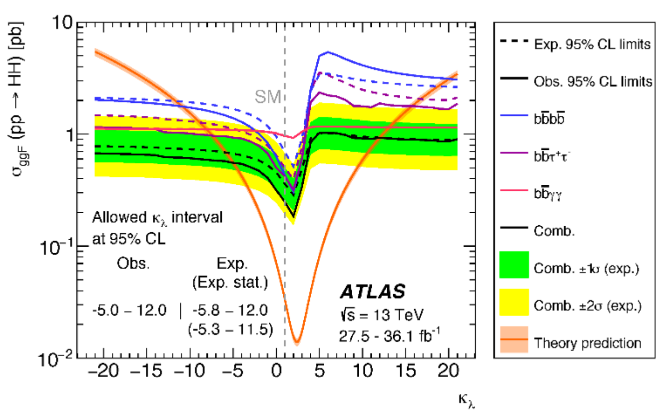




Observed (expected) limits at 95% CL:

- 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: $-11.8\ (-7.1) < \kappa_\lambda < 18.8\ (13.6)$

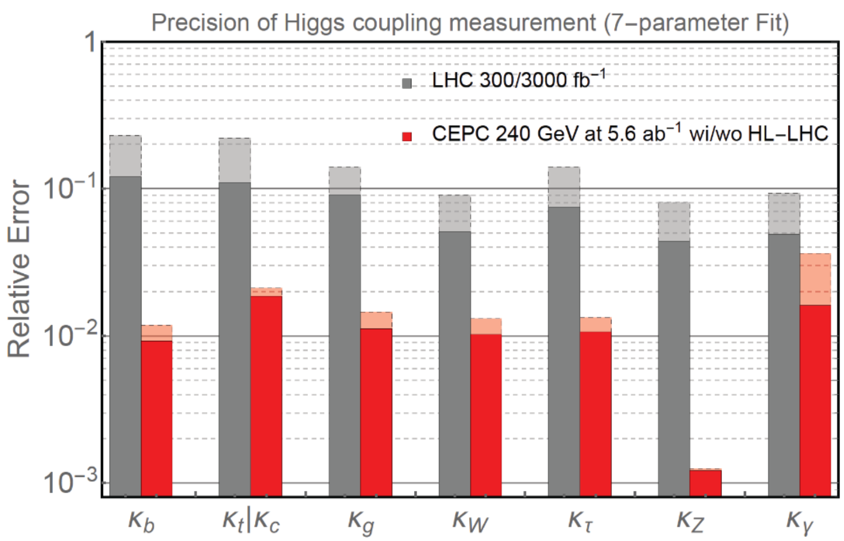




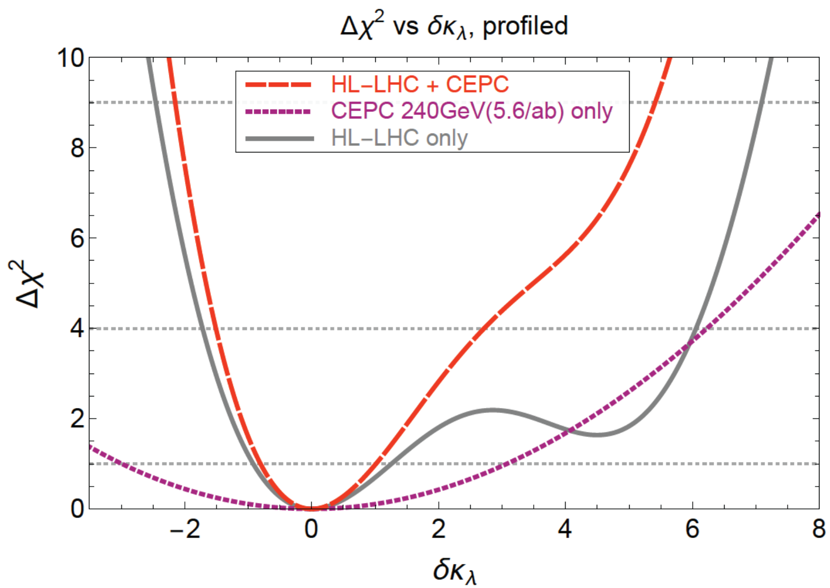
Lepton collider vs hadron collider

- Future lepton collider like CEPC will be practically free of systematic uncertainties
  - an order of magnitude or more improvement in precision in most Higgs measurements and many electroweak observables
  - search for potential unknow decay modes that are impractical at hadron colliders

CEPC CDR Volume II (Physics and Detector)



more precise coupling measurements



complementary k_λ constraints