Search for Higgs boson pair production at CMS

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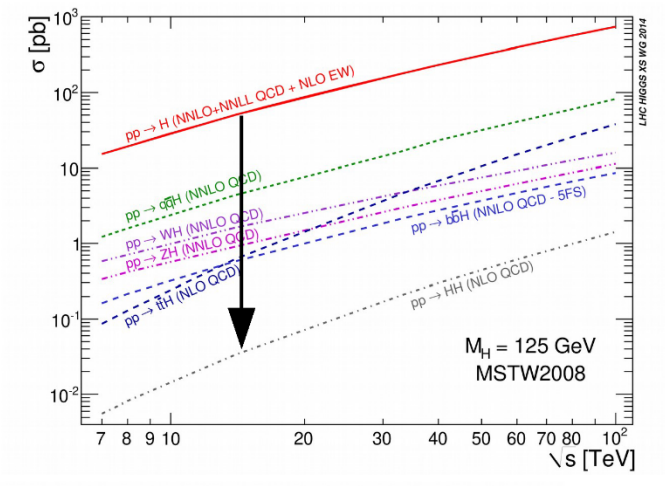
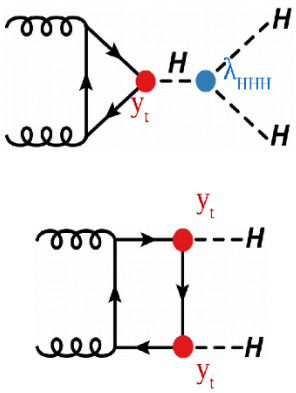
Higgs self-coupling and HH production

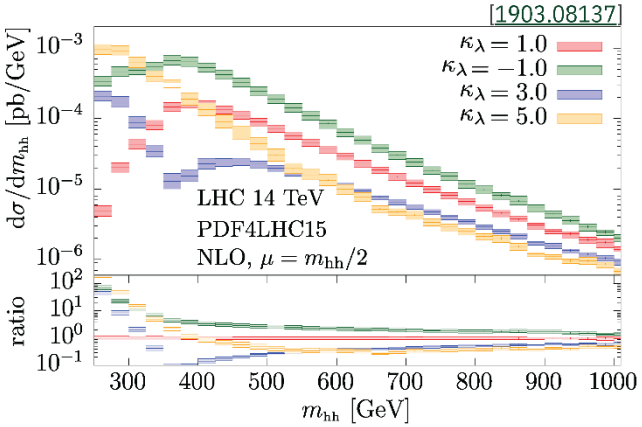
- Higgs self-coupling could be directly accessed by the SM HH production
  - crucial to understand the EW symmetry breaking mechanism

- Non-resonant production: rare process of the SM
  - destructive interference
  - $\sigma(gg \to HH) \approx 0.1\% * \sigma(gg \to H)$





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



- BSM contributions can modify the Higgs boson coupling parameters and modify the HH cross section: define $\kappa_\lambda = c_{hhh} = \lambda_{HHH}/\lambda^{SM}_{HHH}$

- BSM resonances Heavy scalar/graviton could also decay to a HH pair

HH decays

- HH decay branching ratio fraction

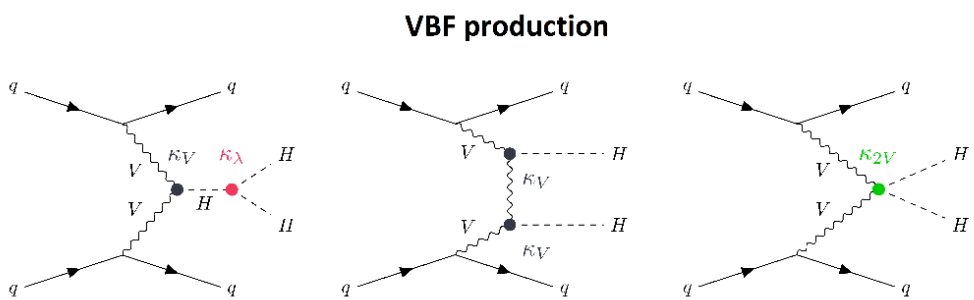
%	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	33				
WW	25	4.6			
$\tau\tau$	7.4	2.5	0.39		
ZZ	3.1	1.2	0.34	0.08	
$\gamma\gamma$	0.26	0.1	0.03	0.01	-

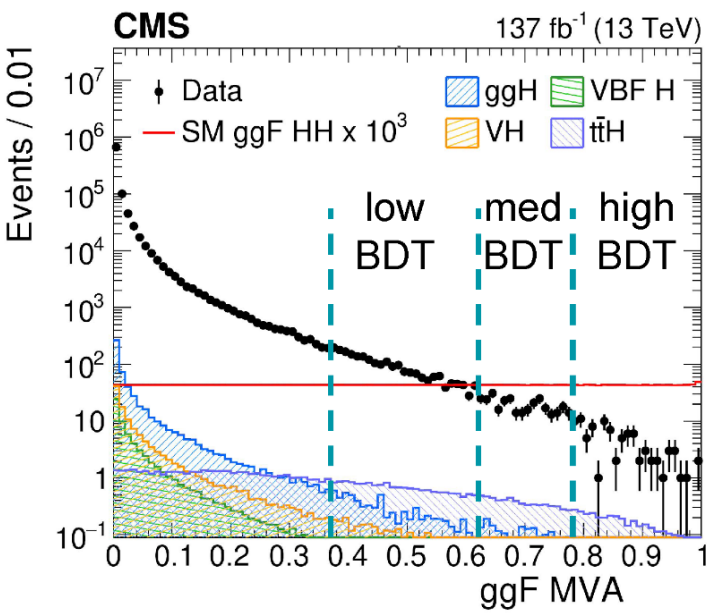
- bb$\gamma\gamma$: very small BR, clean signal extraction due to the narrow $h \rightarrow \gamma\gamma$ mass peak
- bbbb: highest branching fraction, large multijet background
- bbWW, bb$\tau\tau$, bbZZ: smaller BR, exploring lepton final states to reject backgrounds
- multilepton(WW+$\tau\tau$+ZZ) and WW$\gamma\gamma$: important complementary channels

- CMS are exploring all these final states in LHC Run2

CMS $HH \to bb\gamma\gamma$

- Final states: 2 photons and 2 b-jets
- 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





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CMS $HH \to bb\gamma\gamma$

- Also studied 12 BSM benchmarks with various combinations of values for the coupling modifiers
  - k_λ, C_{2V}, C_V, C_2, C_{2g}, C_g
- $\widetilde{M_X}$ creates signal regions sensitive to multiple theoretical scenarios.
  - $\widetilde{M_X} = m_{\gamma\gamma jj} - (m_{jj} - m_H) - (m_{\gamma\gamma} - m_H)$

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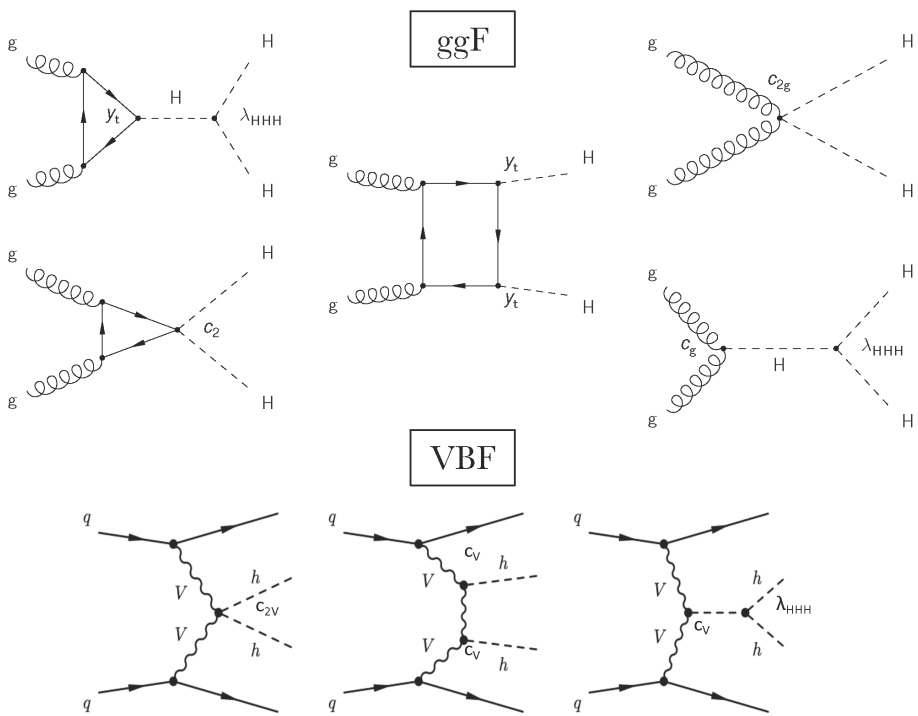

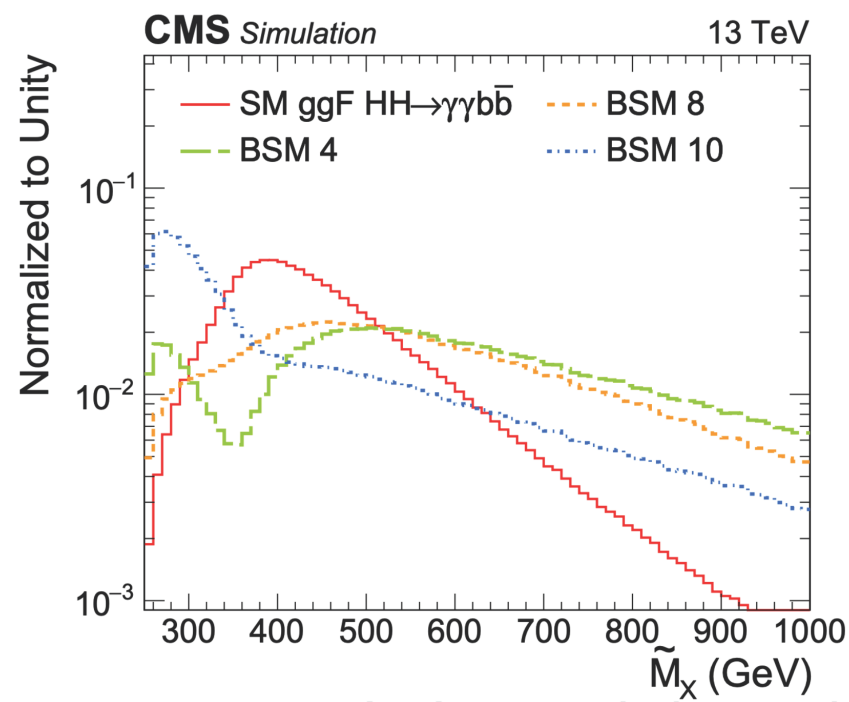

CMS $HH \to bb\gamma\gamma$

- 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.

Category	MVA	$\widetilde{M}_X$ (GeV)
VBF CAT 0	0.52-1.00	>500
VBF CAT 1	0.86-1.00	250-500
ggF CAT 0	0.78-1.00	>600
ggF CAT 1		510-600
ggF CAT 2		385-510
ggF CAT 3		250-385
ggF CAT 4	0.62-0.78	>540
ggF CAT 5		360-540
ggF CAT 6		330-360
ggF CAT 7		250-315
ggF CAT 8	0.37-0.62	>585
ggF CAT 9		375-585
ggF CAT 10		330-375
ggF CAT 11		250-330

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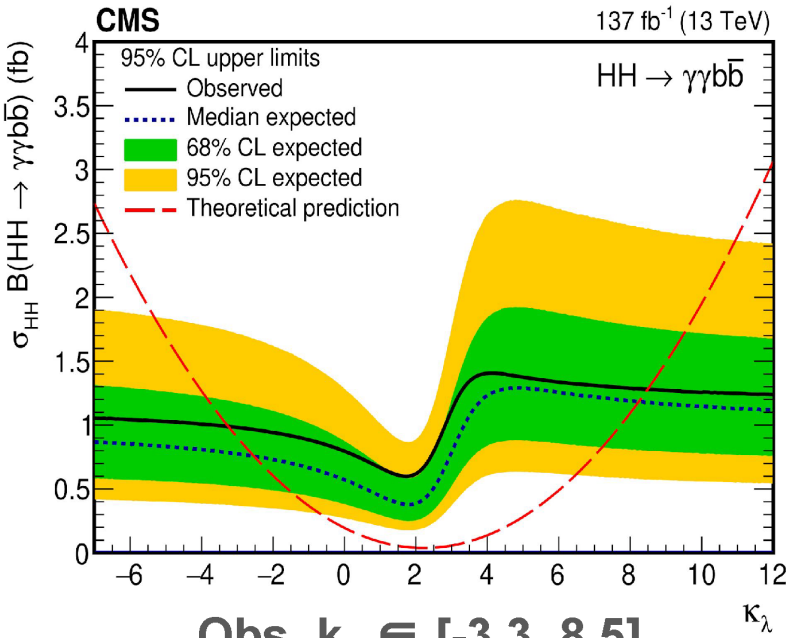
CMS $HH \to bb\gamma\gamma$ results

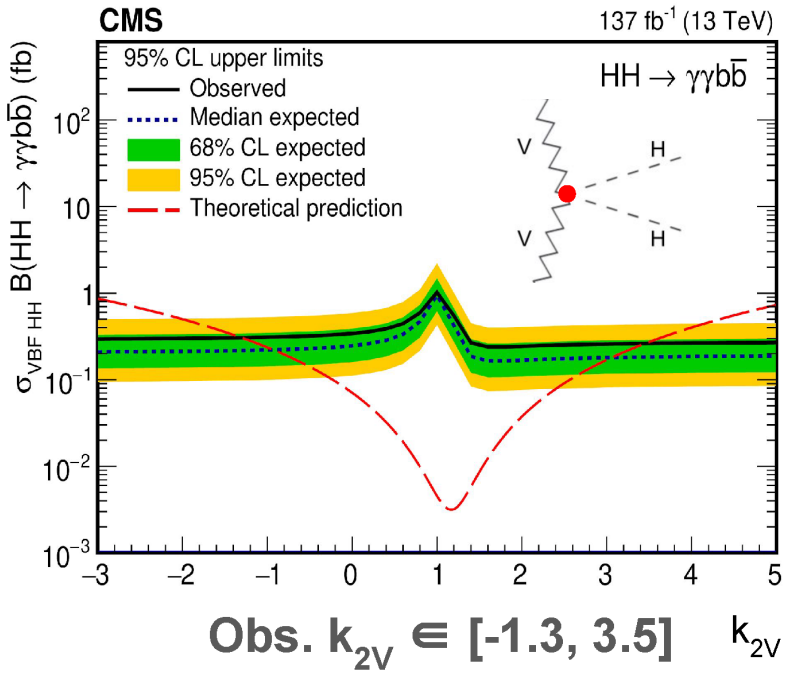
- No deviations from SM observed
- Obs.(exp.) upper limit on HH signal strength 7.7(5.2)×SM

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]

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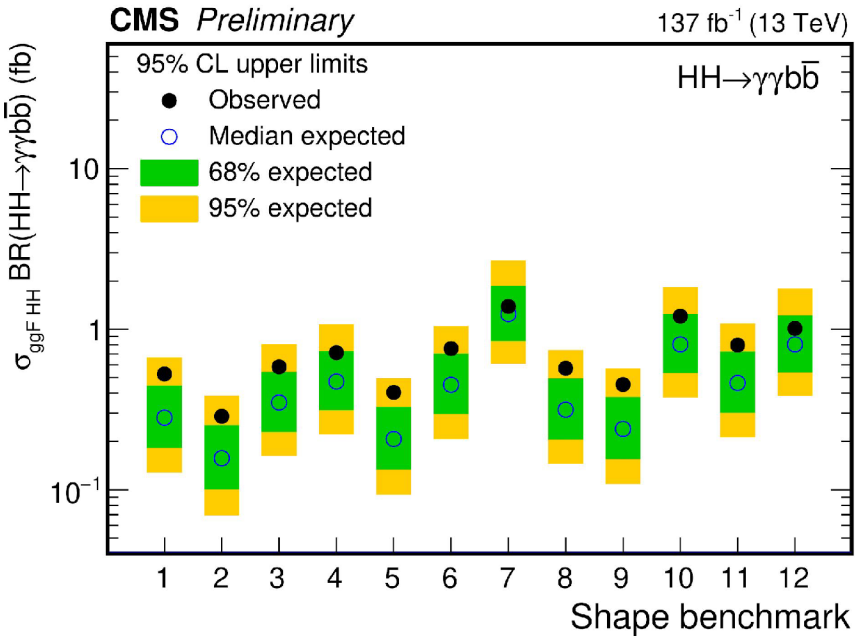
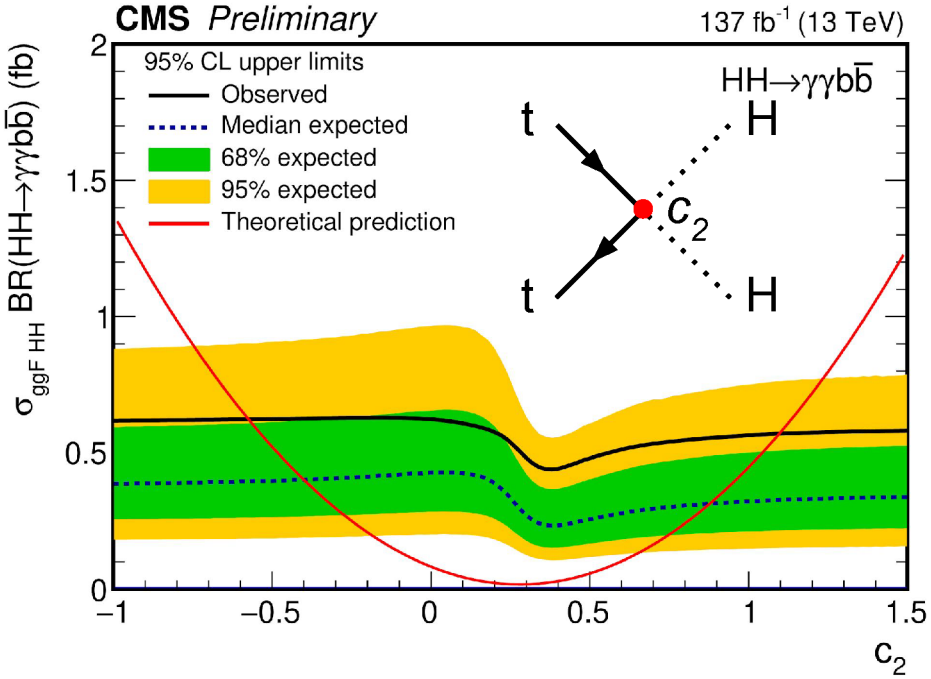
CMS $HH \to bb\gamma\gamma$ EFT results

- Limits on HH cross section for different benchmarks
  - observed limits ranging from 0.3 to 1 fb
- Limits on HH cross section vs. C_2
  - Obs. $C_2 \in$ [-0.6, 1.1], Exp. $C_2 \in$ [-0.4, 0.9]





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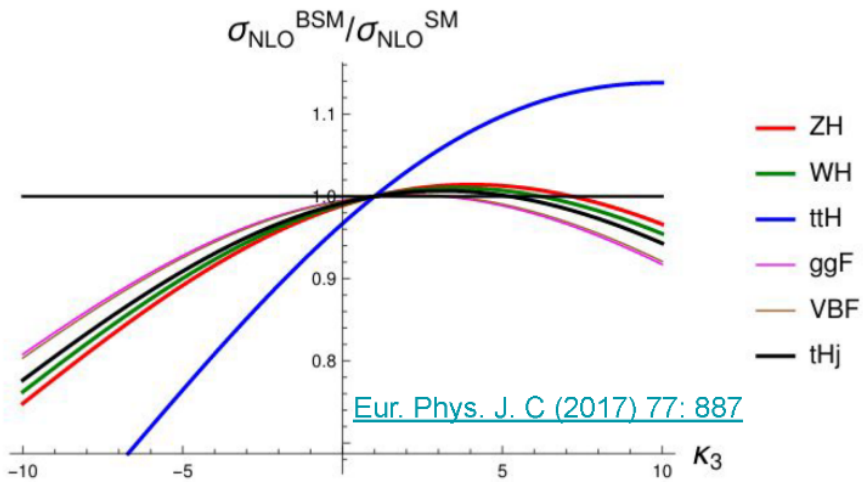
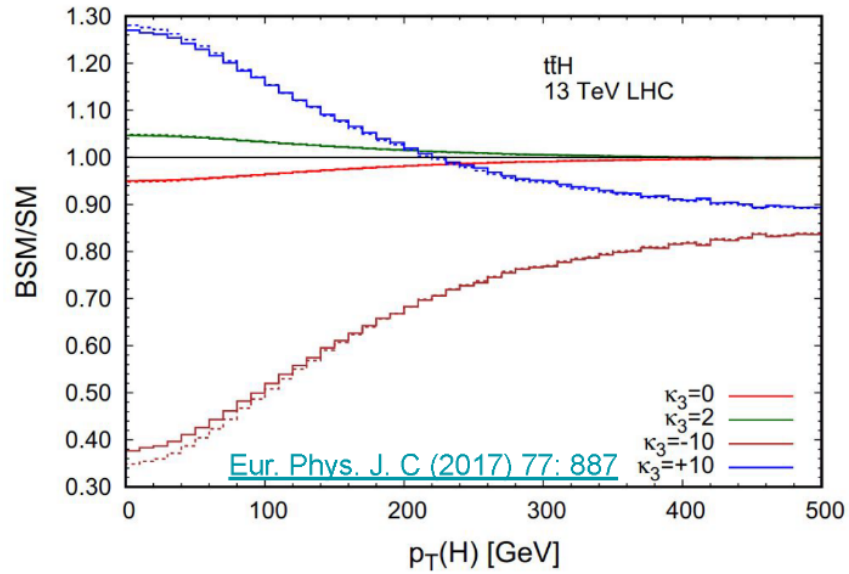
Higgs self-coupling with single Higgs processes

- Higgs self-coupling k_λ also affect the single Higgs NLO electroweak corrections

Modification of total XS



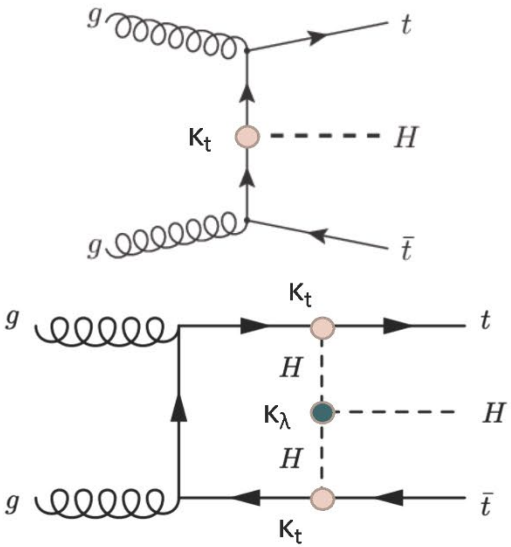
Modification of differential. XS

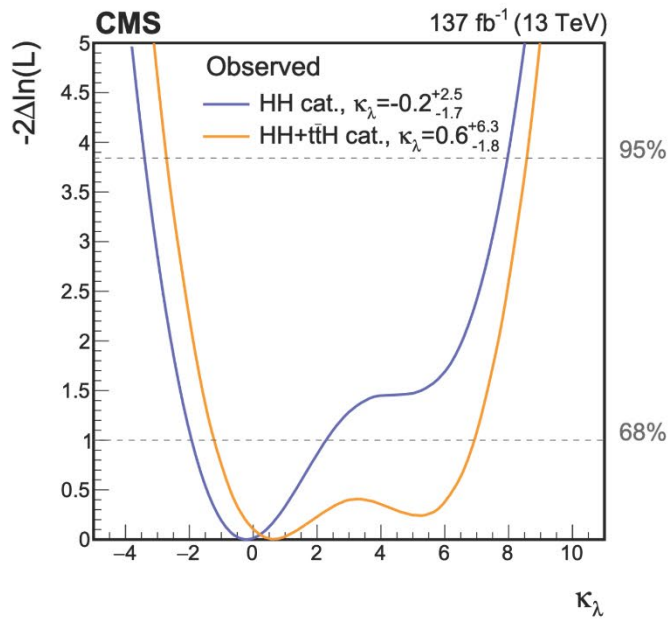


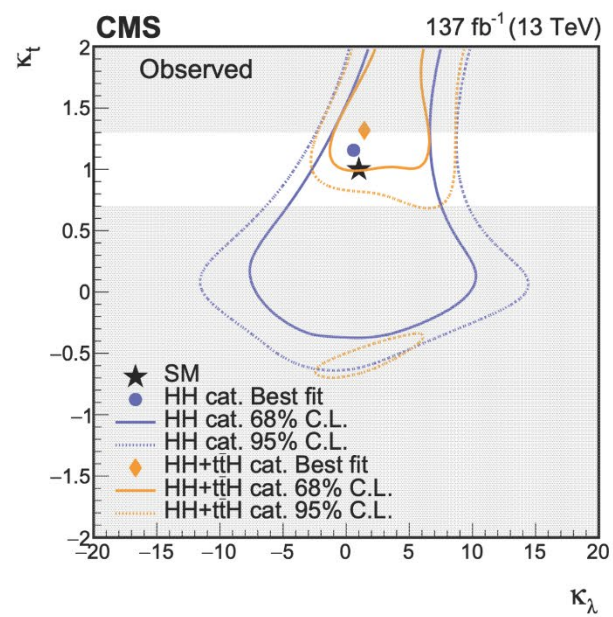
- Could use single Higgs processes indirectly probe k_λ

CMS $HH \to bb\gamma\gamma$ combined with ttH

- $HH \to bb\gamma\gamma$ signal was combined with the single H production ttH mode
  - provides an improved constraint on the k_λ and k_t parameters.







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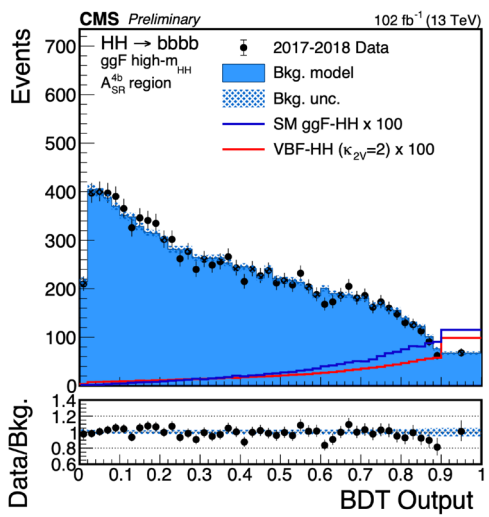
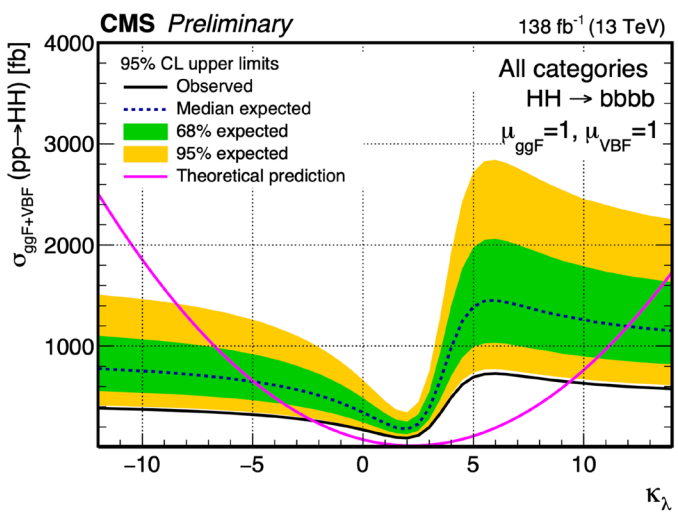
CMS $HH \to bbbb$ with Run 2 data

- Recently published results with $HH \to bbbb$ from CMS (June 2021)
  - measuring both ggF and VBF production of HH
  - reconstruct HH candidate using 4 jets
  - with 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

$$\sigma^{HH}_{ggF+VBF} < 3.6\ (7.3) \times \sigma^{HH\ SM}_{ggF+VBF}$$

$$-2.3\ (-5.0) < \kappa_\lambda < 9.4\ (12.0)$$

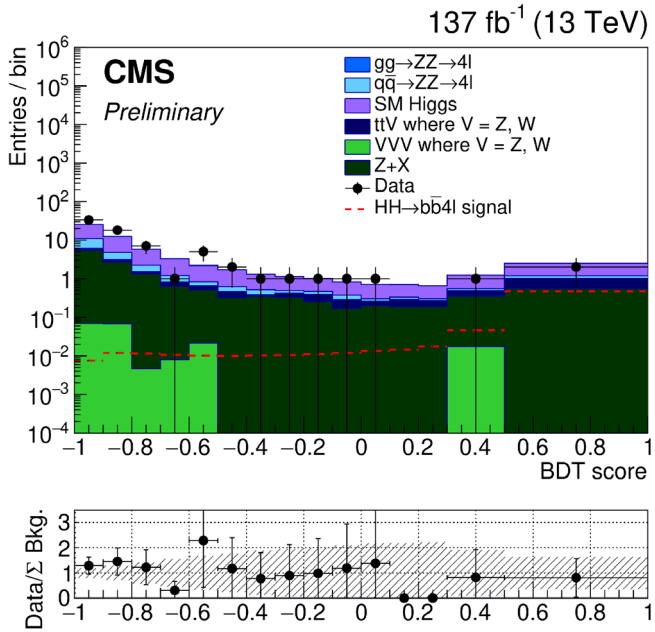
$$-0.1\ (-0.4) < \kappa_{2V} < 2.2\ (2.5)$$

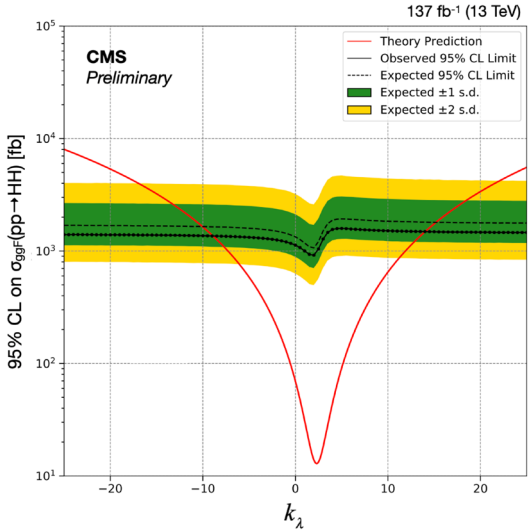
CMS-PAS-HIG-20-005

CMS $HH \to bbZZ$ with Run2 data

- ggF $HH \to bbZZ$ channel with final states of two b-jets and two pairs of opposite-charge leptons $(4\mu, 4e, 2\mu 2e)$: CMS-PAS-HIG-20-004
  - 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

Inclusive BDT distribution





Observed (expected) limits at 95% CL:

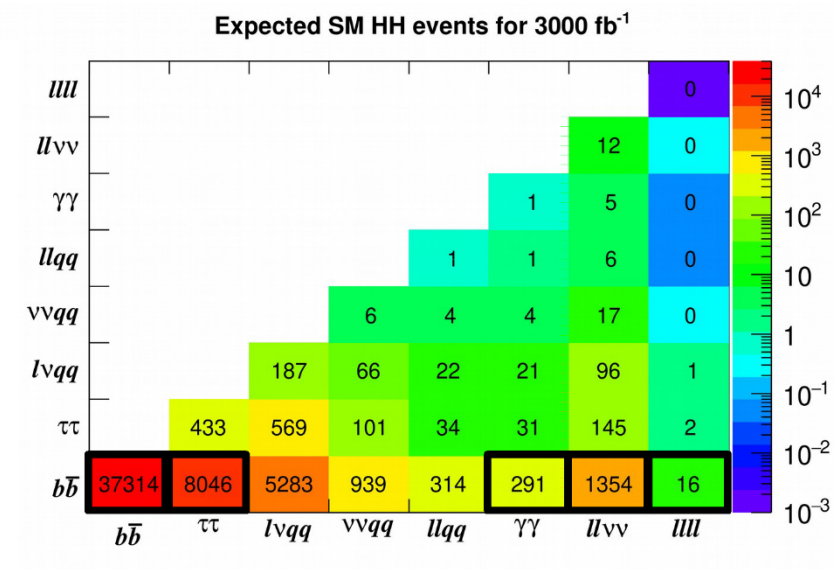
- $\sigma_{ggF}^{HH} < 30\ (37) \times \sigma_{ggF}^{HH\ SM}$
- $-9\ (-10.5) < \kappa_\lambda < 14\ (15.5)$

HL-LHC projection of HH

- Different channel are studied for HL-LHC with projection from Run-2 analyses
  - ~20% larger cross section, but much more difficult environment

– summary of channels/methods:

	ATLAS	CMS
bbbb	extrapolation	parametric
bbττ	extrapolation	parametric
bbγγ	smearing	parametric
bbVV (→lνlν)		parametric
bbZZ (→4l)		parametric



Combined HH results in HL-LHC

- Expected significance (SM) with and without systematics at HL-LHC

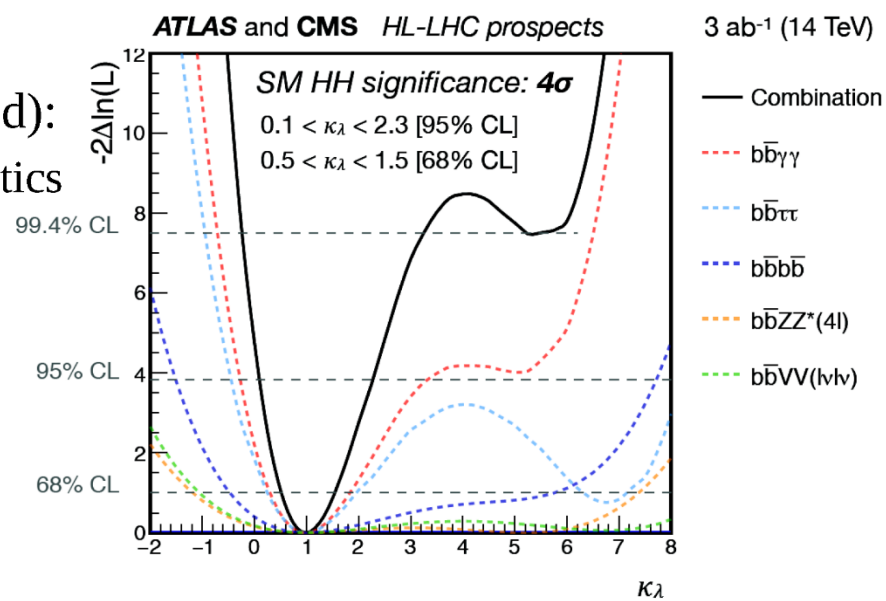
	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined		Combined	
	4.5		4.0	

arxiv:1902.00134

  - 4σ expected with ATLAS+CMS!

- Measurement of μ (SM signal injected):
  - ~25% (30%) without (with) systematics
  - μ = 0 (no SM HH signal) excluded at 95% CL

- Measurement of κ_λ:
  - 68% CI of 50%
  - 2nd minimum excluded at 99.4% CL thanks to the m_{HH} shape information



Summary

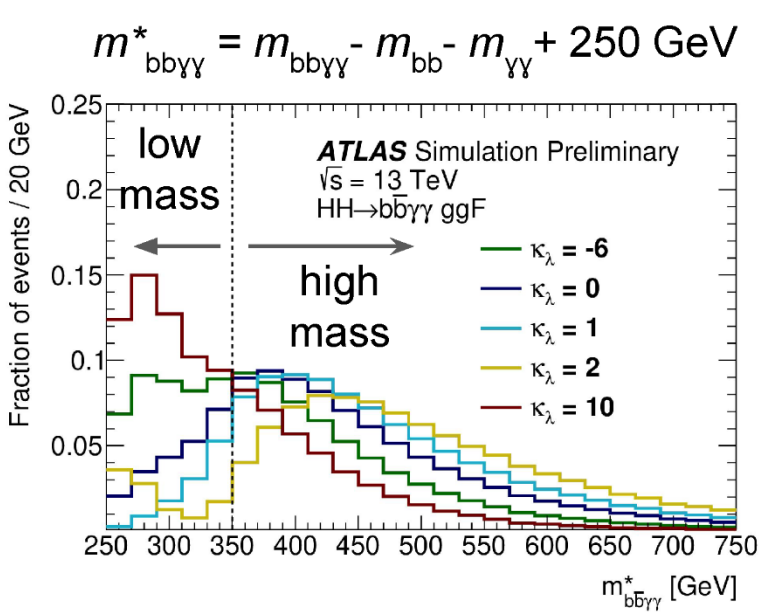
- CMS recently finalized a range of HH measurements
  - Some of the main channels have their results with full Run2 datasets
    - $bb\gamma\gamma$, $bbbb$, $bbZZ$ channels
  - Limits and constraints are extracted for HH cross section, k_λ, k_{2V} and BSM coupling modifiers
    - Observed 95% C.L. interval of k_λ from $bb\gamma\gamma$ channel
      - $-3.3 < k_\lambda < 8.5$
    - Observed 95% C.L. upper limits on HH cross section from $bbbb$ channel
      - 3.6*SM
    - Observed 95% C.L. interval of k_{2V} from $bbbb$ channel
      - $-0.1 < k_{2V} < 2.2$
  - Results would be further improved by the combination of different HH channels and introducing constraints from single Higgs production

- Stay tuned for the results from full Run2/Run3 and HL-LHC

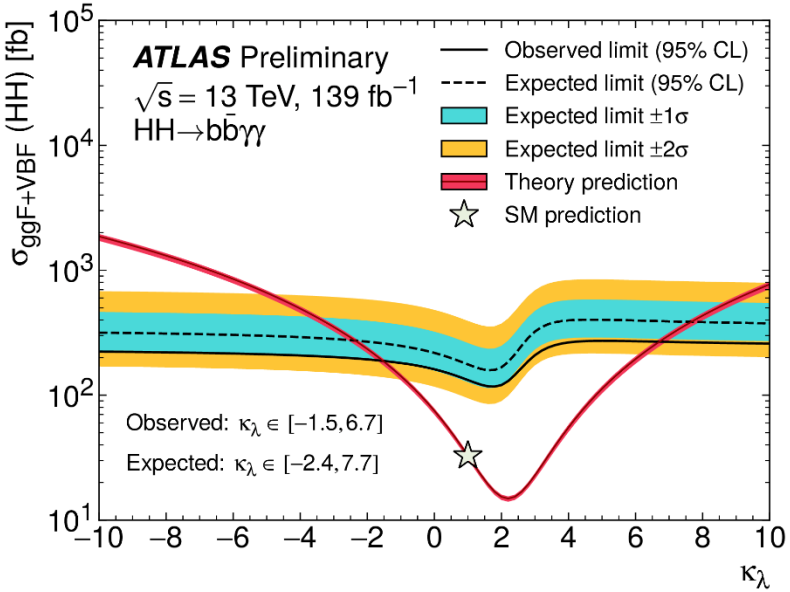
Back Up

ATLAS $HH \to bb\gamma\gamma$ with Run2 data

- Targeting mainly ggF production of $HH \to bb\gamma\gamma$ events but VBF events are also considered as signal
  - two different BDTs are trained for events with high/low 4 body mass $m^*(bb\gamma\gamma)$ to improve BSM sensitivity
  - Fit $m_{\gamma\gamma}$ distribution for signal extraction
- Upper limit on signal strength: obs.(exp.) = 4.1(5.5)×SM



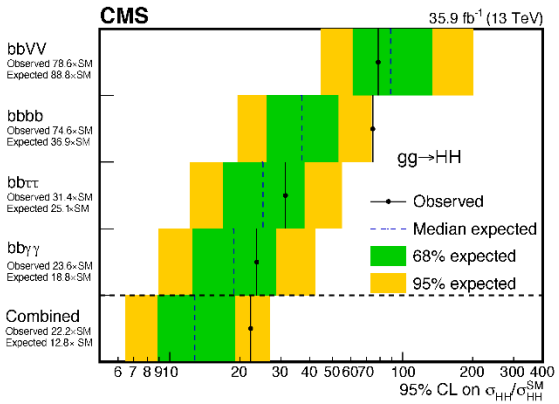
ATLAS-CONF-2021-016

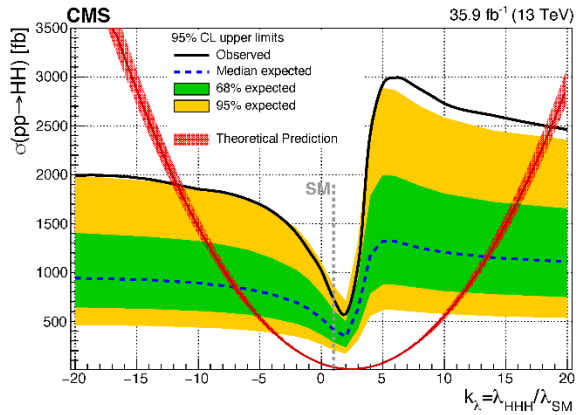


the most stringent limits to k_λ to date

HH combination

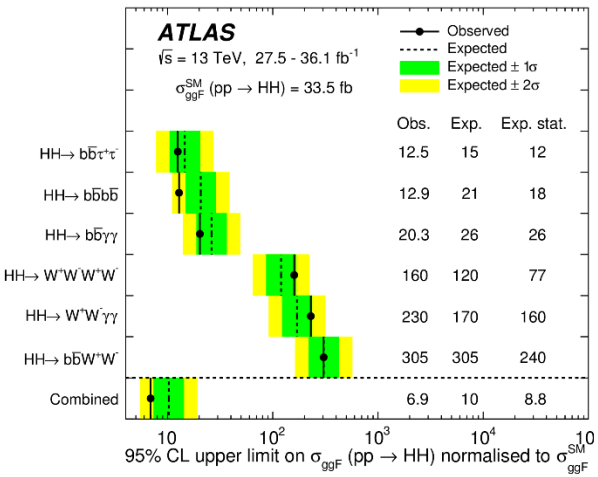
- Both ATLAS and CMS have performed HH combination with partial Run2 data
  - 27.5-36.1 fb^{-1} data for ATLAS, 35.9 fb^{-1} data for CMS
  - only consider ggF HH production

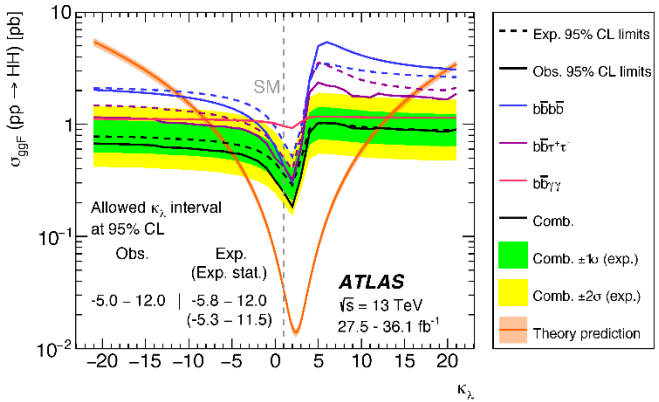




Observed (expected) limits at 95% CL:

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

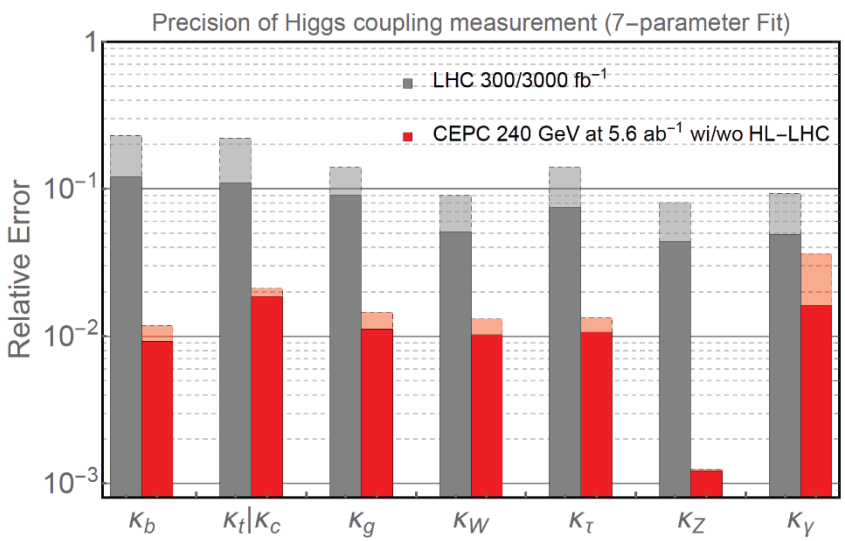


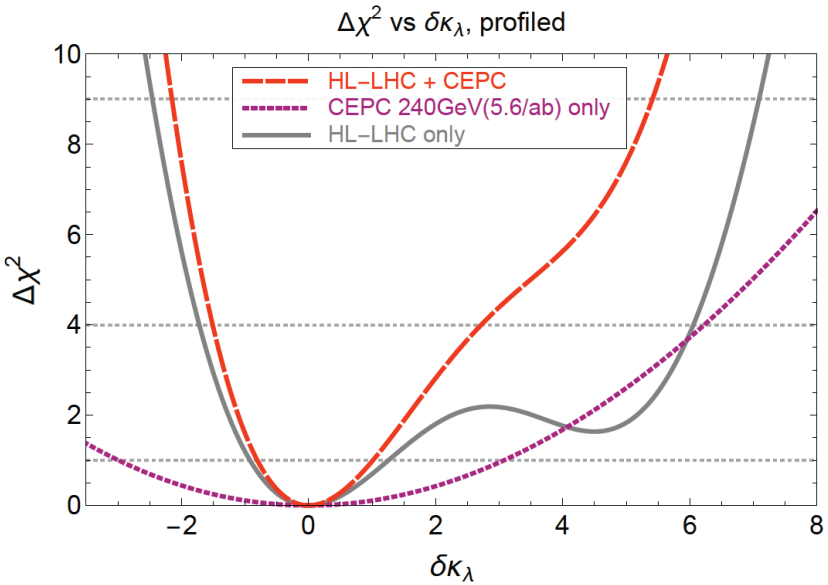


Lepton collider vs hadron collider

- 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