Institute of High Energy Physics
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Higgs self-coupling measurements in LHC

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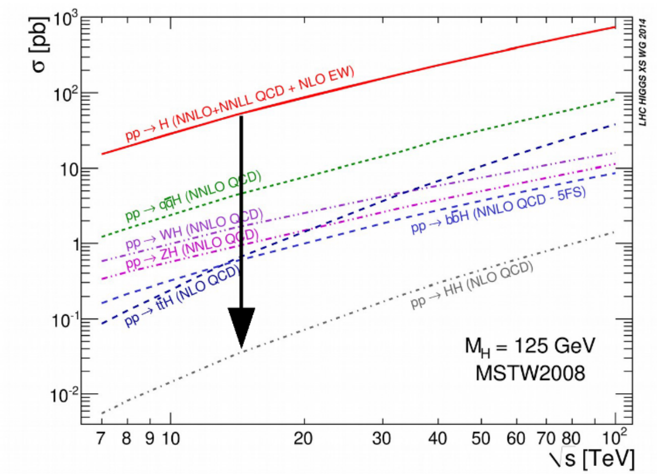
Higgs self-coupling and HH production

- 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

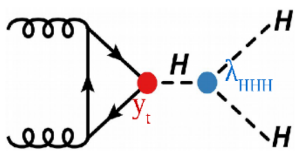
– destructive interference

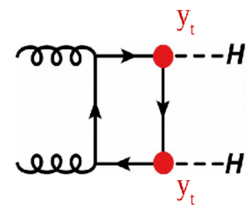
– $\sigma(gg \to HH) \approx 0.1\% * \sigma(gg \to H)$



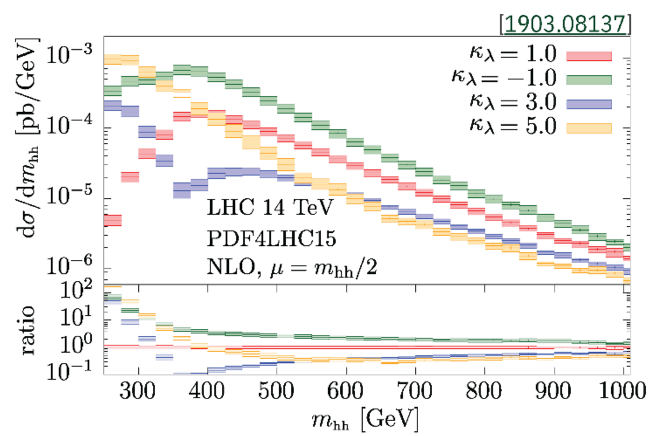
– BSM contributions can modify the Higgs boson coupling parameters and modify the HH cross section: define $\kappa_\lambda = c_{hhh} = \lambda_{HHH} / \lambda_{HHH}^{SM}$

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





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



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	-

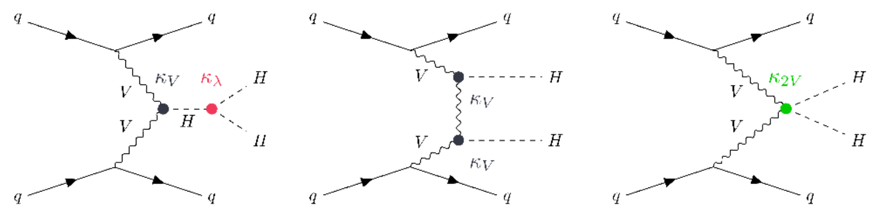
- bbbb: highest branching fraction, large multijet background
- bbWW, bb$\tau\tau$, bbZZ: smaller BR, exploring lepton final states to reject backgrounds
- bb$\gamma\gamma$: very small BR, clean signal extraction due to the narrow $h \to \gamma\gamma$ mass peak
- multilepton(WW+$\tau\tau$+ZZ) and WW$\gamma\gamma$: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

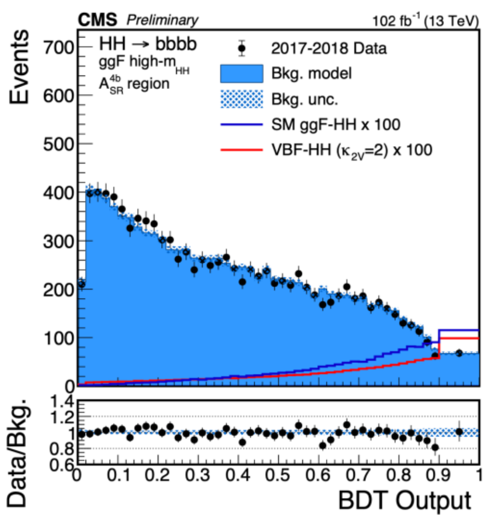
- ATLAS and CMS are exploring all these final states in LHC Run2

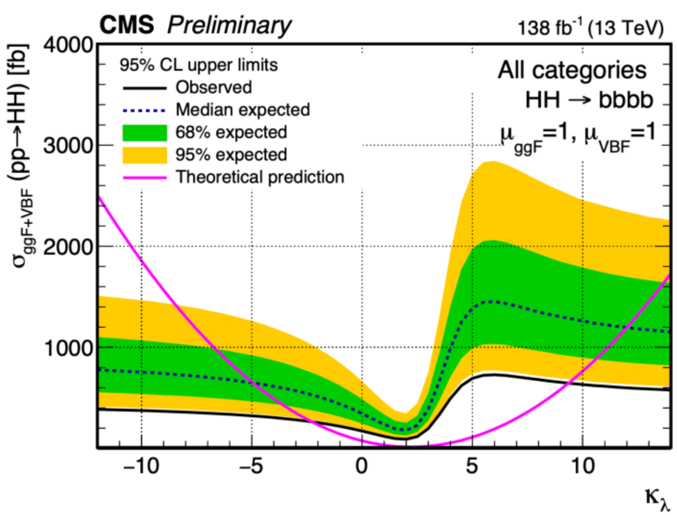
CMS $HH \to bbbb$ with Run 2 data

- 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

VBF production







observed (expected) results

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

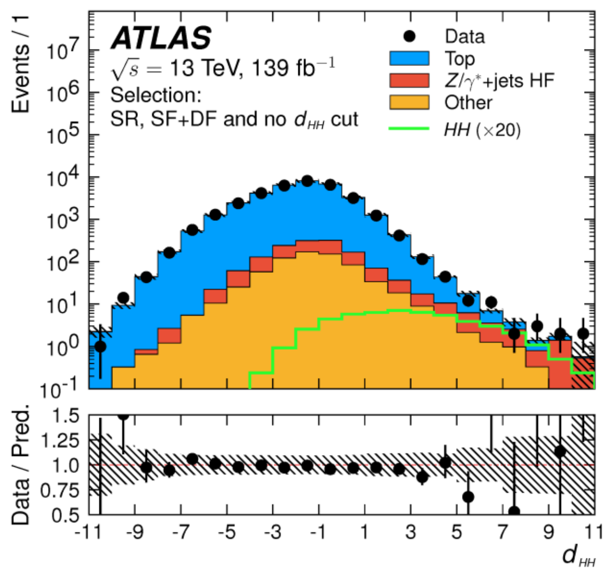
$$-2.3\ (-5.0) < \kappa_\lambda < 9.4\ (12.0)$$

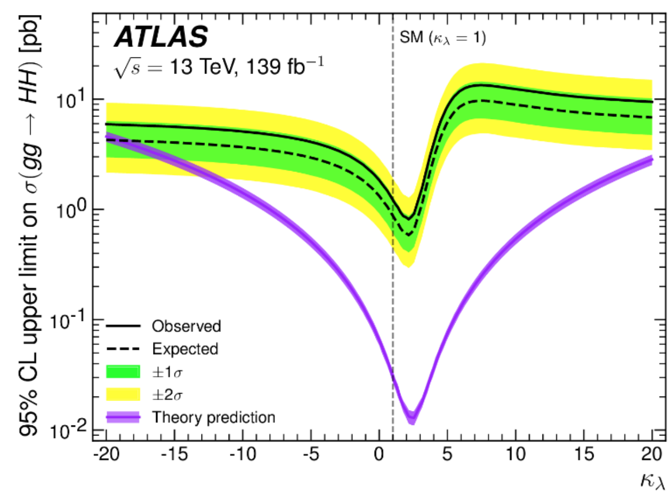
$$-0.1\ (-0.4) < \kappa_{2V} < 2.2\ (2.5)$$

CMS-PAS-HIG-20-005

ATLAS $HH \to bbWW$ with Run2 data

- ATLAS analysis of two b-jets, two leptons and missing transverse energy using 139 fb^{-1} data
  - [Phys. Lett. B 801 (2020) 135145]
  - targeting mainly ggF $HH \to bbWW$ but also contains $bb\tau\tau, bbZZ$ signals
  - use multi-class Neural Network(NN) to separate the main signal and backgrounds
    - define discriminant $d_{HH} = \ln(\frac{p_{HH}}{p_{top}} + p_{Zll} + p_{Z\tau\tau})$ with p_i as the probability of events belong to class I in the mult-class NN output



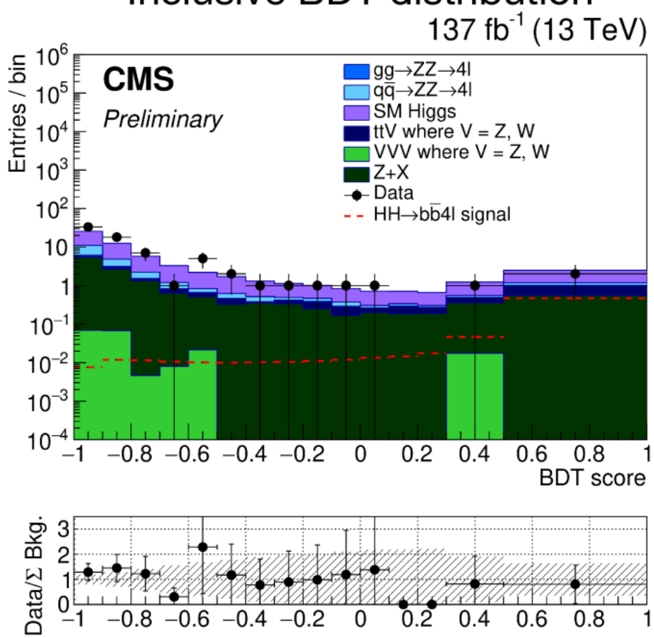


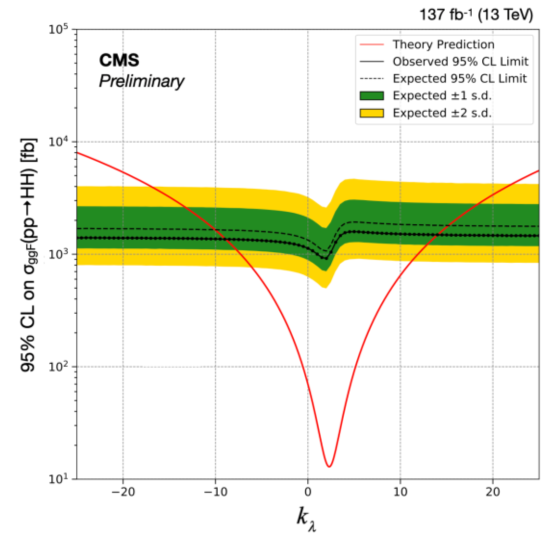
- $\sigma_{ggF}^{HH} < 40\ (29) \times \sigma_{ggF}^{HH\ SM}$

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



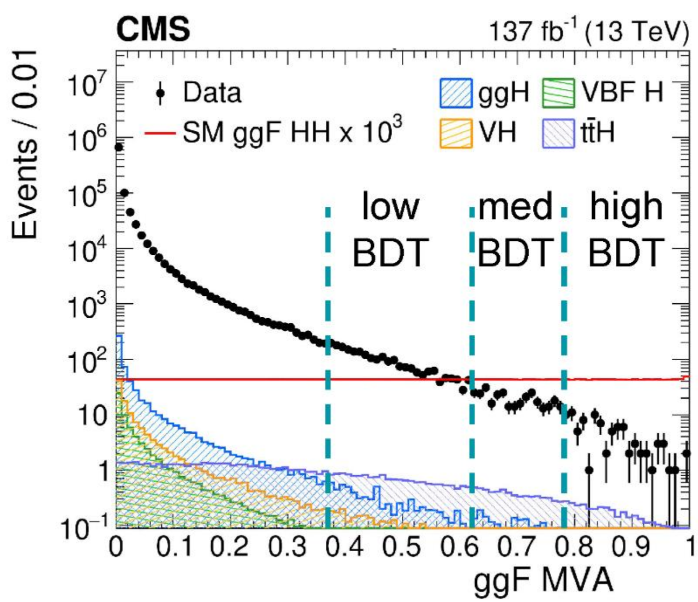


Observed (expected) limits at 95% CL:

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

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

- Targeting both ggF and VBF production of $HH \to bb\gamma\gamma$ events
  - MVA strategy to optimize signal and background separation
    - BDT to separate ggF or VBF HH from ɣ(ɣ)+jets events
      - optimized category to maximum Higgs self-coupling sensitivity
    - Deep Neural Network (DNN) to separate HH from ttH(ɣɣ) events
  - signal extraction from simultaneous fit of $m_{\gamma\gamma}$ and m_{bb}
- Obs.(exp.) upper limit on HH signal strength 7.7(5.2)×SM



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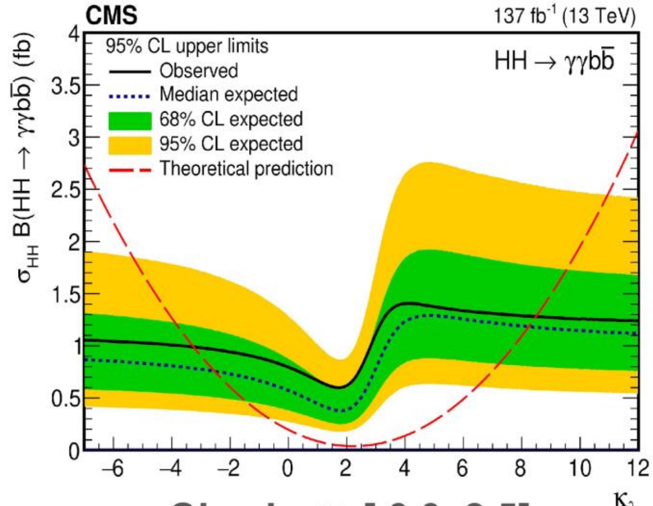
Limit on HH XS×BR vs k_λ



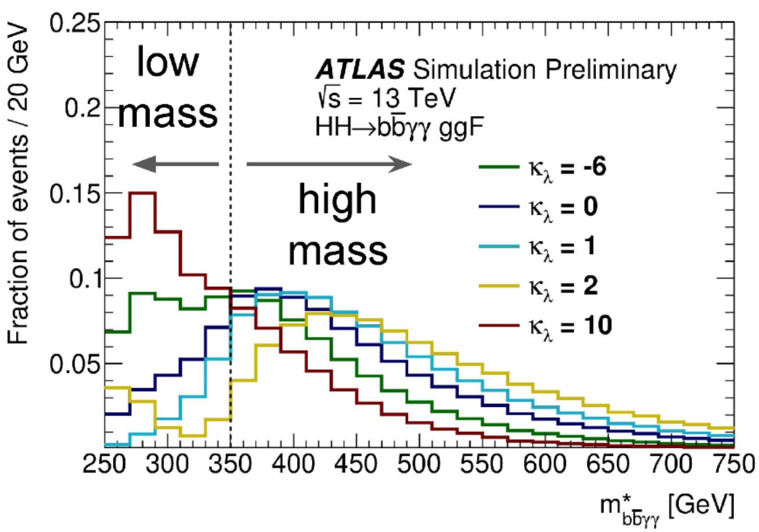
Obs. $k_\lambda \in [-3.3, 8.5]$

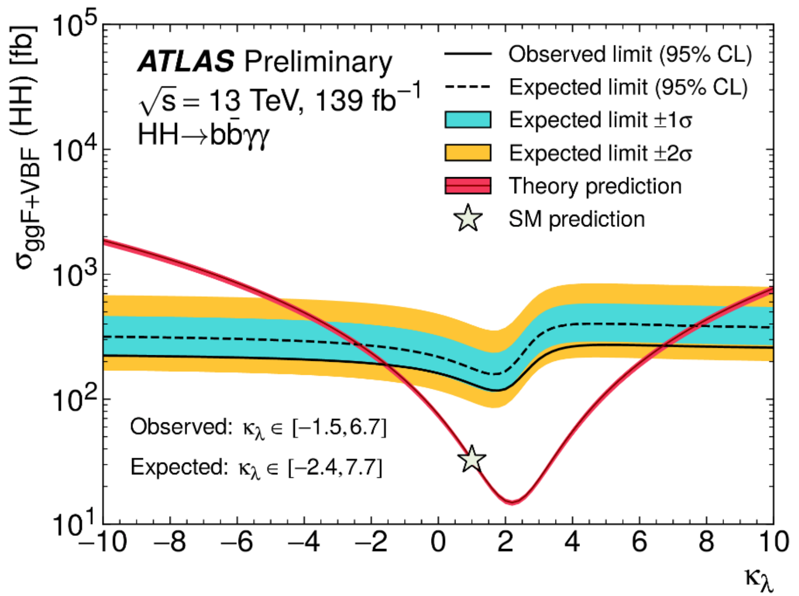
Exp. $k_\lambda \in [-2.5, 8.2]$

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

$m^*_{bb\gamma\gamma} = m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250$ GeV



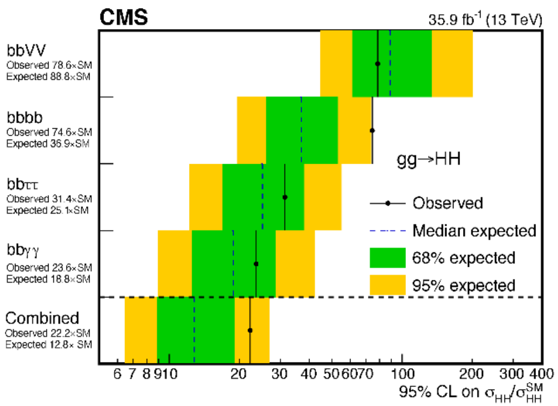


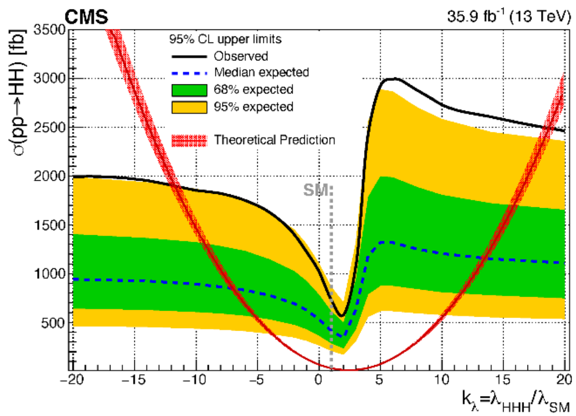
ATLAS-CONF-2021-016

the most stringent limits to k_λ to date

HH combination

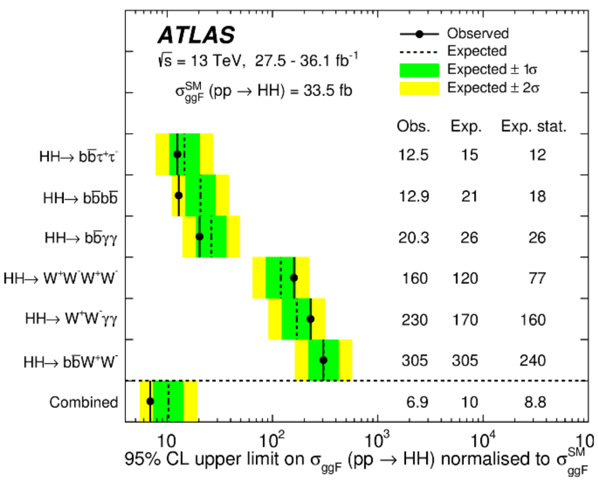
- Both ATLAS and CMS have performed HH combination with partial Run2 data
  - 27.5-36.1 fb^{-1} data for ATLAS, 35.9 fb^{-1} data for CMS
  - only consider ggF HH production

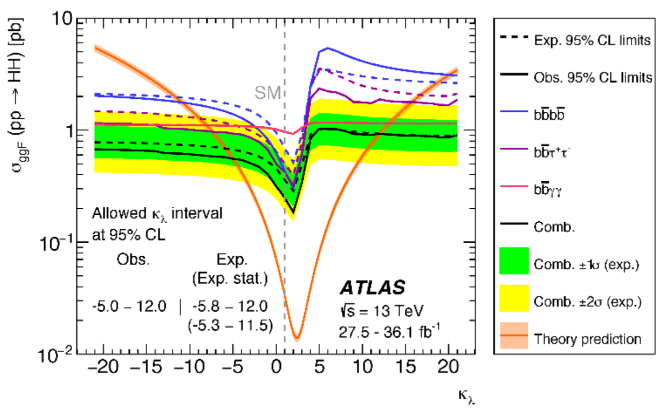




Observed (expected) limits at 95% CL:

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

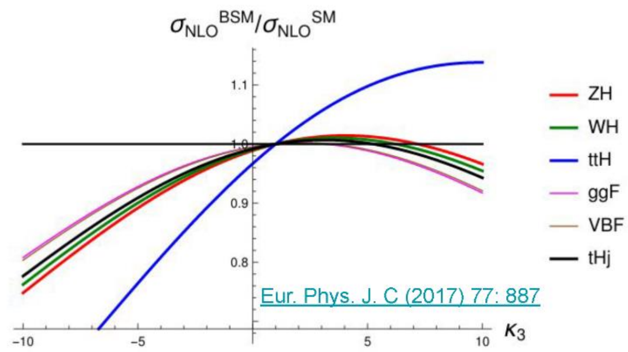




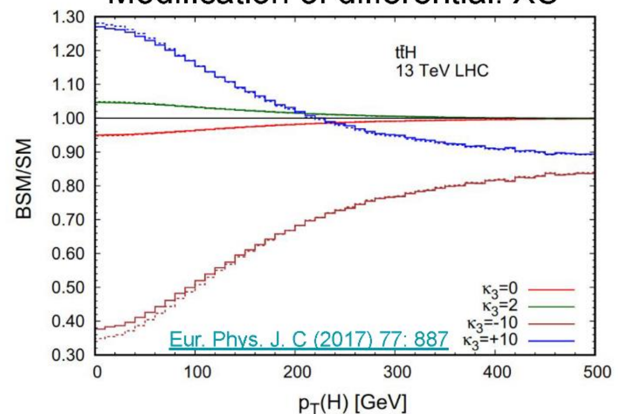
Higgs self-coupling with single Higgs processes

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

Modification of total XS



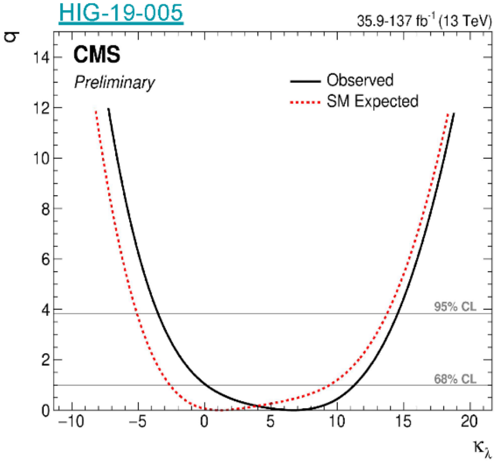
Modification of differential. XS



Constrain k_λ from single-H in partial Run 2 comb @ CMS

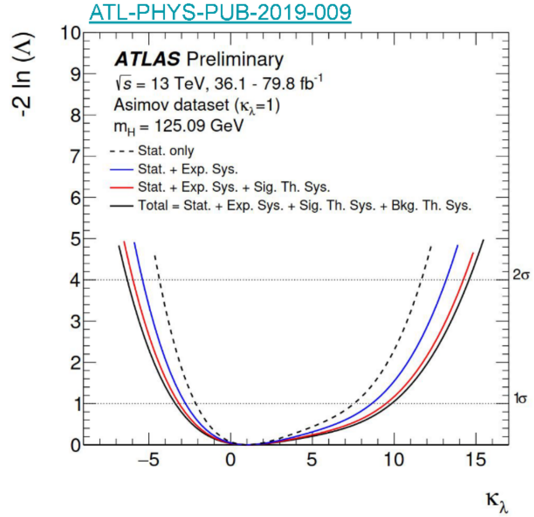
- Neglected differential effects

HIG-19-005



ATLAS partially considered the differential info

ATL-PHYS-PUB-2019-009



Constraints on k_λ with single Higgs production:

ATLAS HH+H combination:
-2.3 (-5.1)< k_λ<10.3 (11.2)

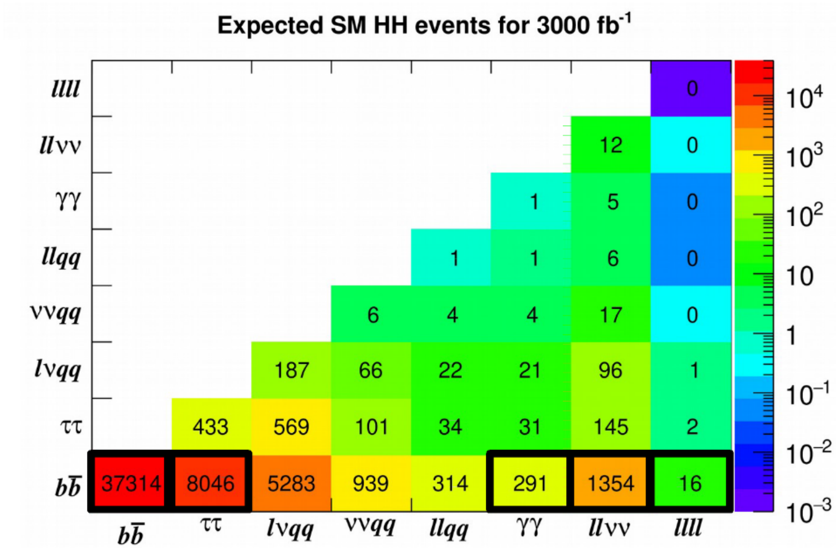
CMS single Higgs combination;
-3.5 (-5.1) < k_λ<14.5 (13.5)

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

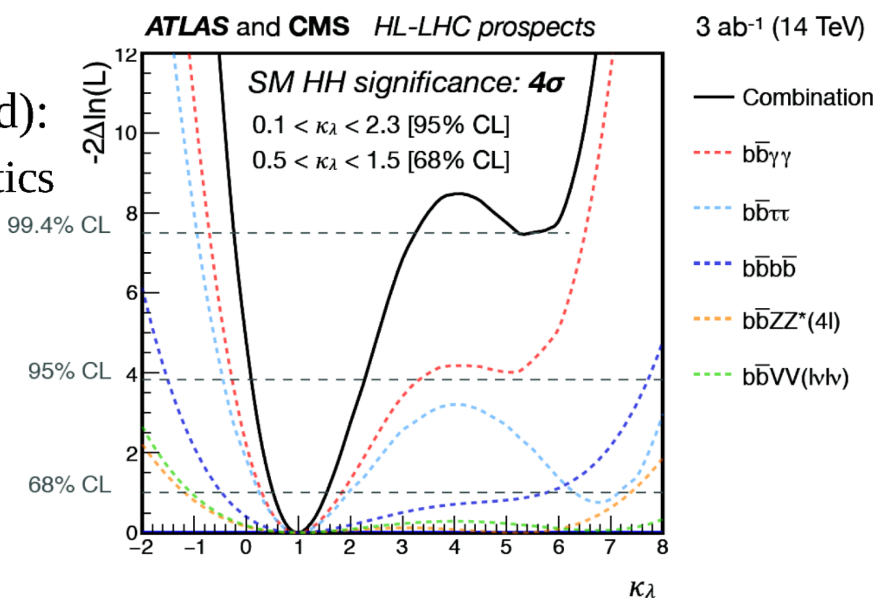
	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6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

arxiv:1902.00134

  - 4σ expected with ATLAS+CMS!

- Measurement of μ (SM signal injected):
  - ~25% (30%) without (with) systematics
  - $\mu = 0$ (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

- Both ATLAS and CMS are finalizing a range of HH measurements that probe the Higgs self-coupling with full Run2 data
  - some of the main channels have their results with full Run2 datasets
    - $bbbb$,$bbWW$, $bbZZ$ and $bb\gamma\gamma$ channels
  - the most stringent limits to k_λ at 95% CL. to date correspond to:
    - $-1.5\ (-2.4) < k_\lambda < 6.7\ (7.7)$ from ATLAS $bb\gamma\gamma$ channel
  - limits would be improved by the combination of different HH channels and introducing constraints from single Higgs production
    - stay tuned for the full Run2 results !

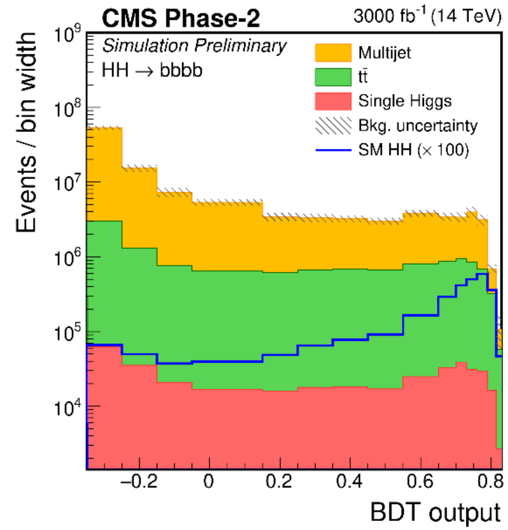
- With HL-LHC the Higgs self-coupling 68% C.L intervals could be constrained at 50% level
  - exclude k_λ= 0 at 95% C.L.
  - expect the observation of the HH SM production

Back Up

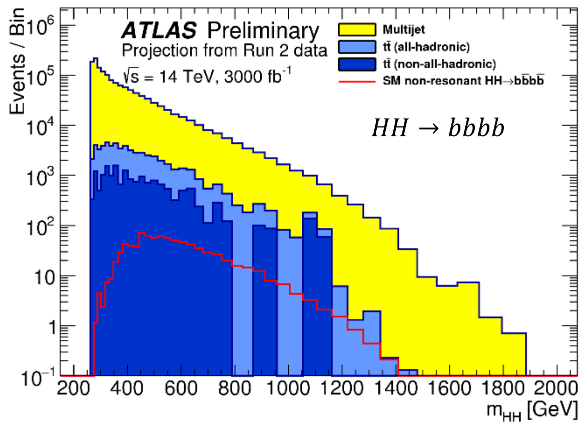
General HH analysis strategy

- Analysis strategy
  - develop MVA method to reject background
  - explore m_{HH} and SM Higgs spectrum

CMS-PAS-FTR-18-019



fit discriminants



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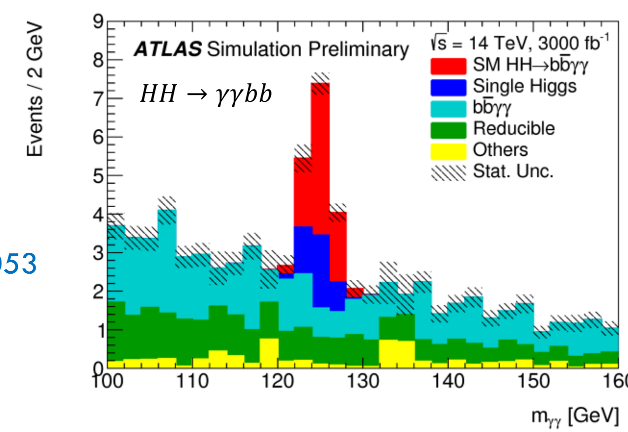
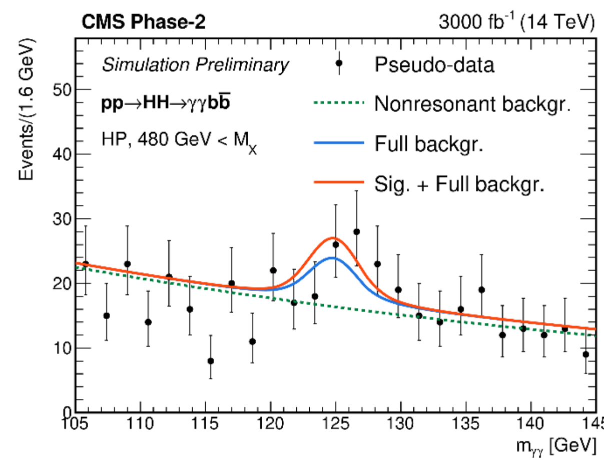
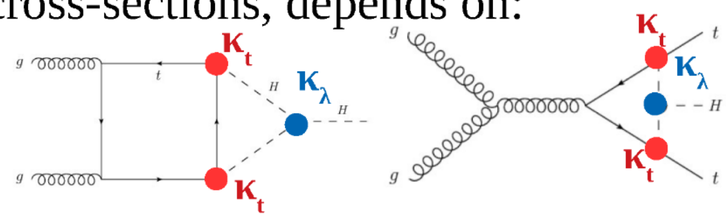


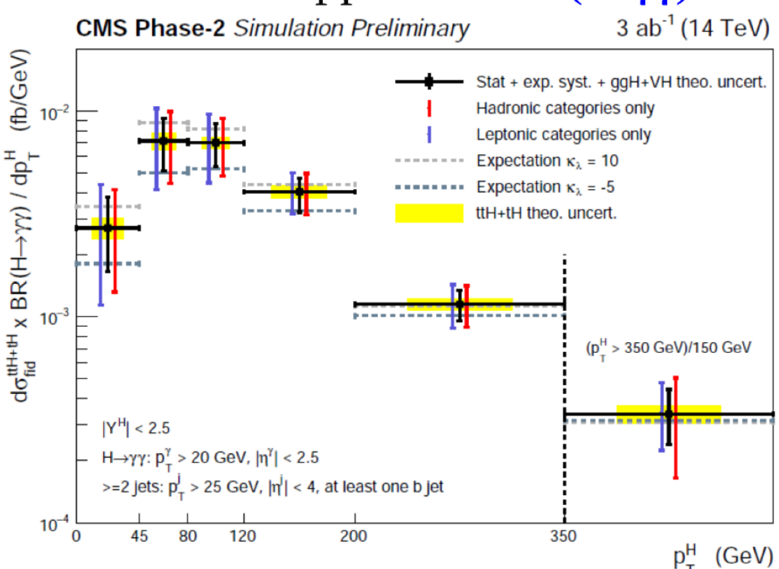


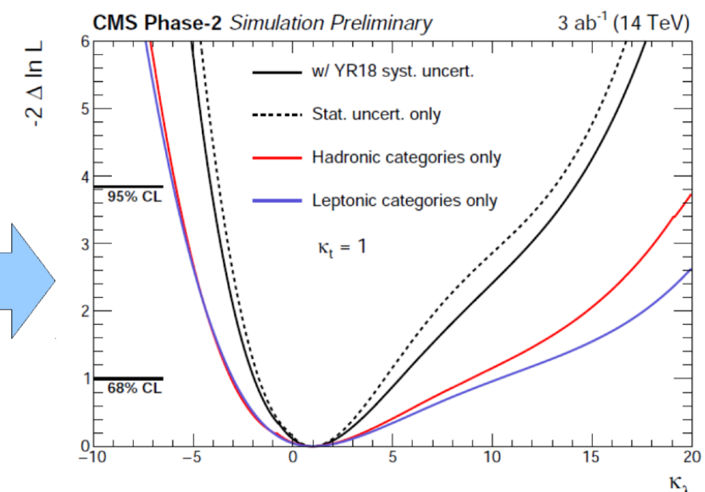
Indirect k_λ probes with single Higgs process

- Single-Higgs production: Higgs self-interaction only via one-loop corrections (ie two loop-level for ggF)
- κ_λ-dependent corrections to the tree-level cross-sections, depends on:
  - production mode → mainly $t\bar{t}H$, tH, VH
  - kinematics properties of the event



- Method applied to $t\bar{t}H(\rightarrow\gamma\gamma)$ differential cross-section measurement:





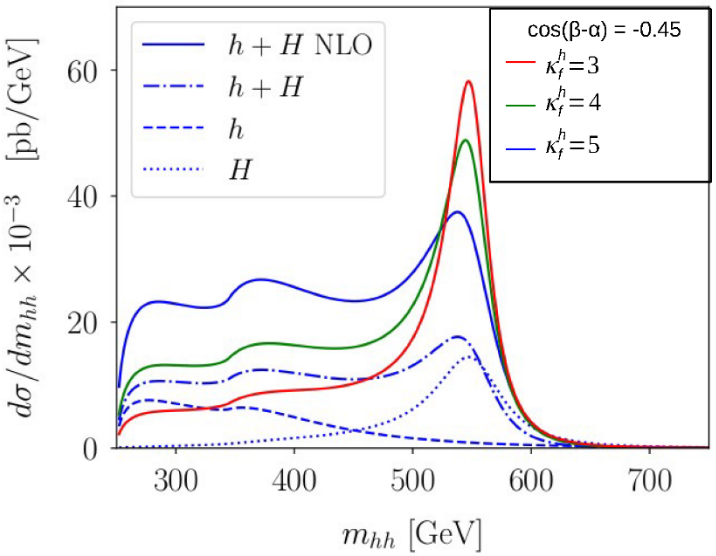
- 68% CI: $-1.9 < \kappa_\lambda < 5.3$ if only κ_λ varied

arxiv:1902.00134

- First test with experimental "data", more channels to be added

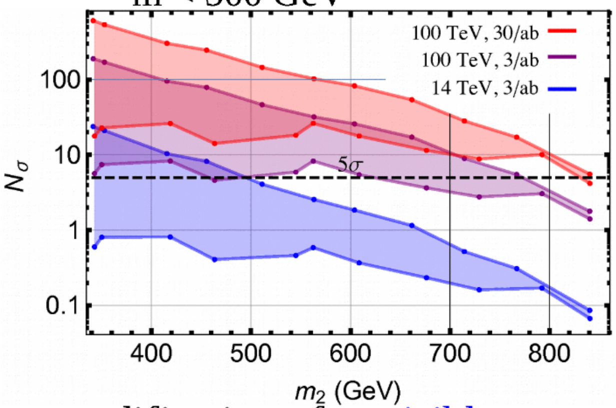
Implications of the HH measurements

- **Flavour physics: 2HDM model** where flavor symmetry broken at the electroweak scale
  - κ_f^h = enhancement of Higgs Yukawa couplings to fermions

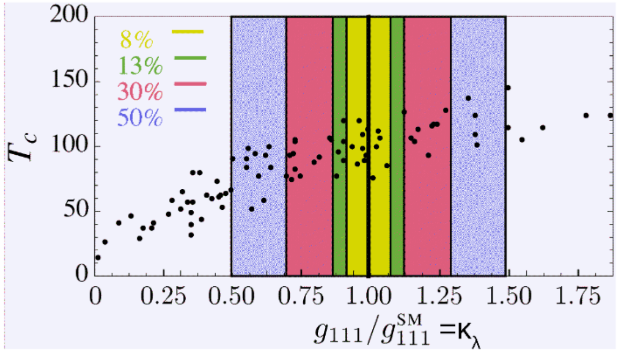


- Enhancement of the di-Higgs production + change of m_{HH} shape with interference

- **EWK phase transition:**
  - 1[st] order possible with additional bosons interacting with the Higgs
    - discovery possible at HL-LHC for m < 500 GeV



  - modification of κ_λ visible at HL-LHC or HE-LHC

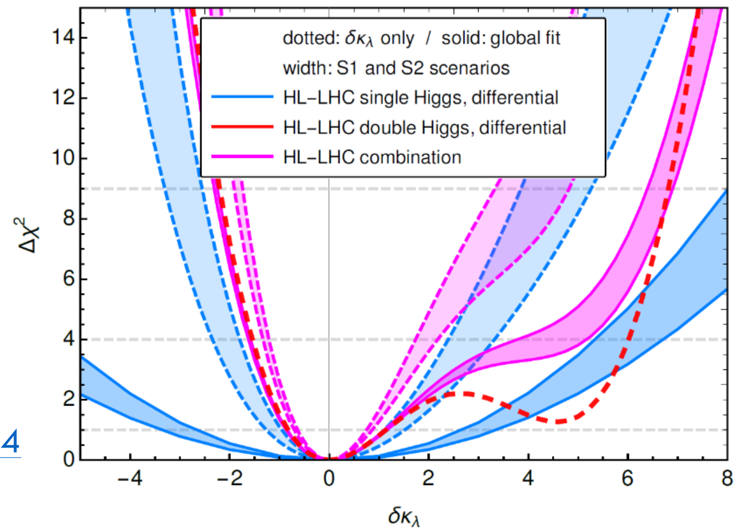


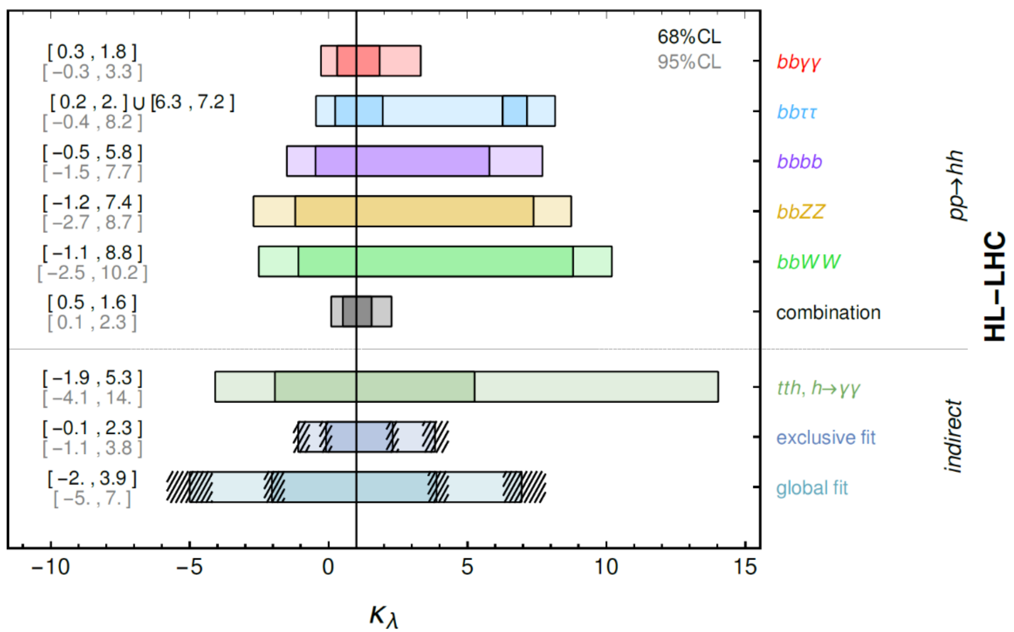
arxiv:1902.00134

Indirect k_λ probes with single Higgs process

- Global fits of single Higgs and double Higgs results
  - vary only k_λ (dash line)
  - EFT framework (solid line)

arxiv:1902.00134



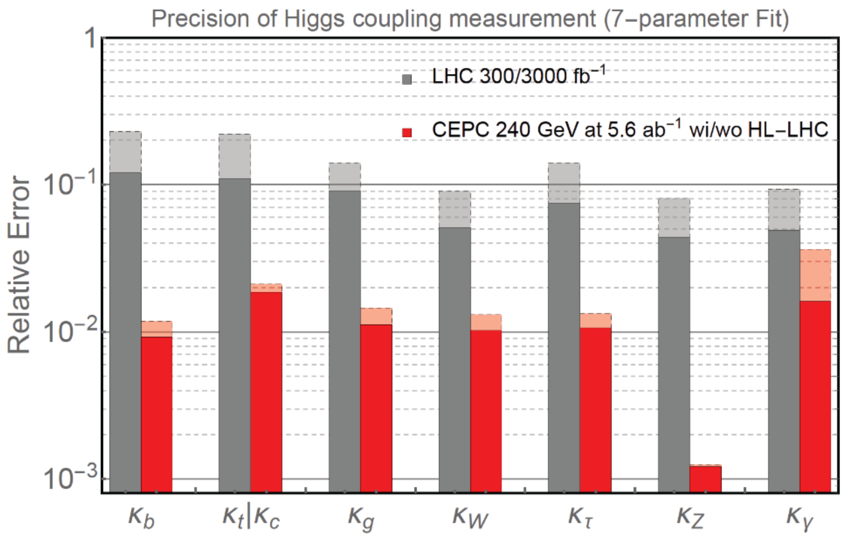


expected constraint on k_λ with HL-LHC

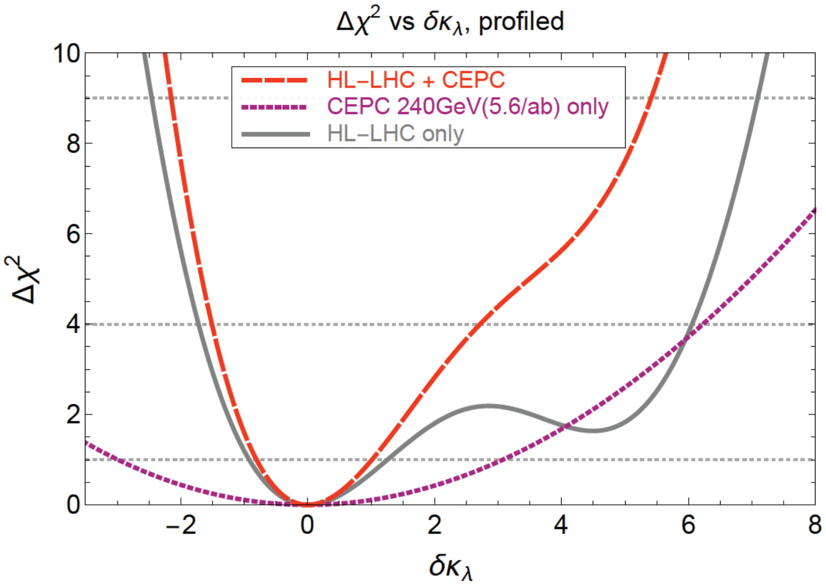
Lepton collider vs hadron collider

- 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