CMS non-resonant HH combination at Run-2

Chengjun Yu[1], Xinyue Geng[2], Jin Wang[3]

1.University of Science and Technology of China

2.Peking University

3.Institute of High Energy Physics of the Chinese Academy of Sciences

On behalf of the CMS collaboration

2024.12.21

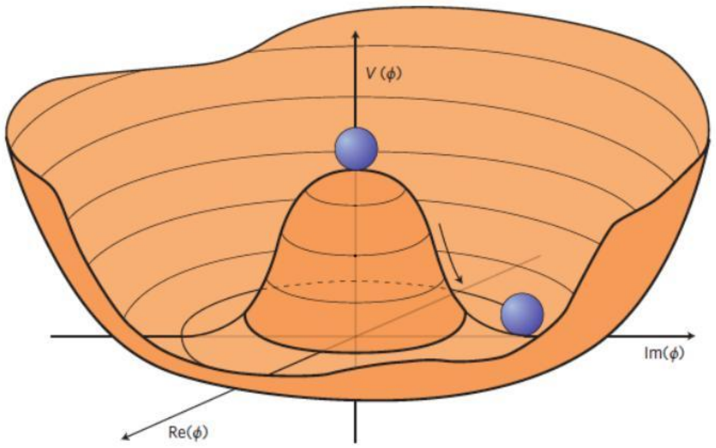
Introduction

- Higgs discovery already 12 years ago and many corners of the Higgs sector already explored

- Higgs self coupling remains.

- Higgs self coupling(s) directly linked to the Higgs potential of crucial importance of the SM.

- But thats not all: qqHH/VHH, C2V and BSM



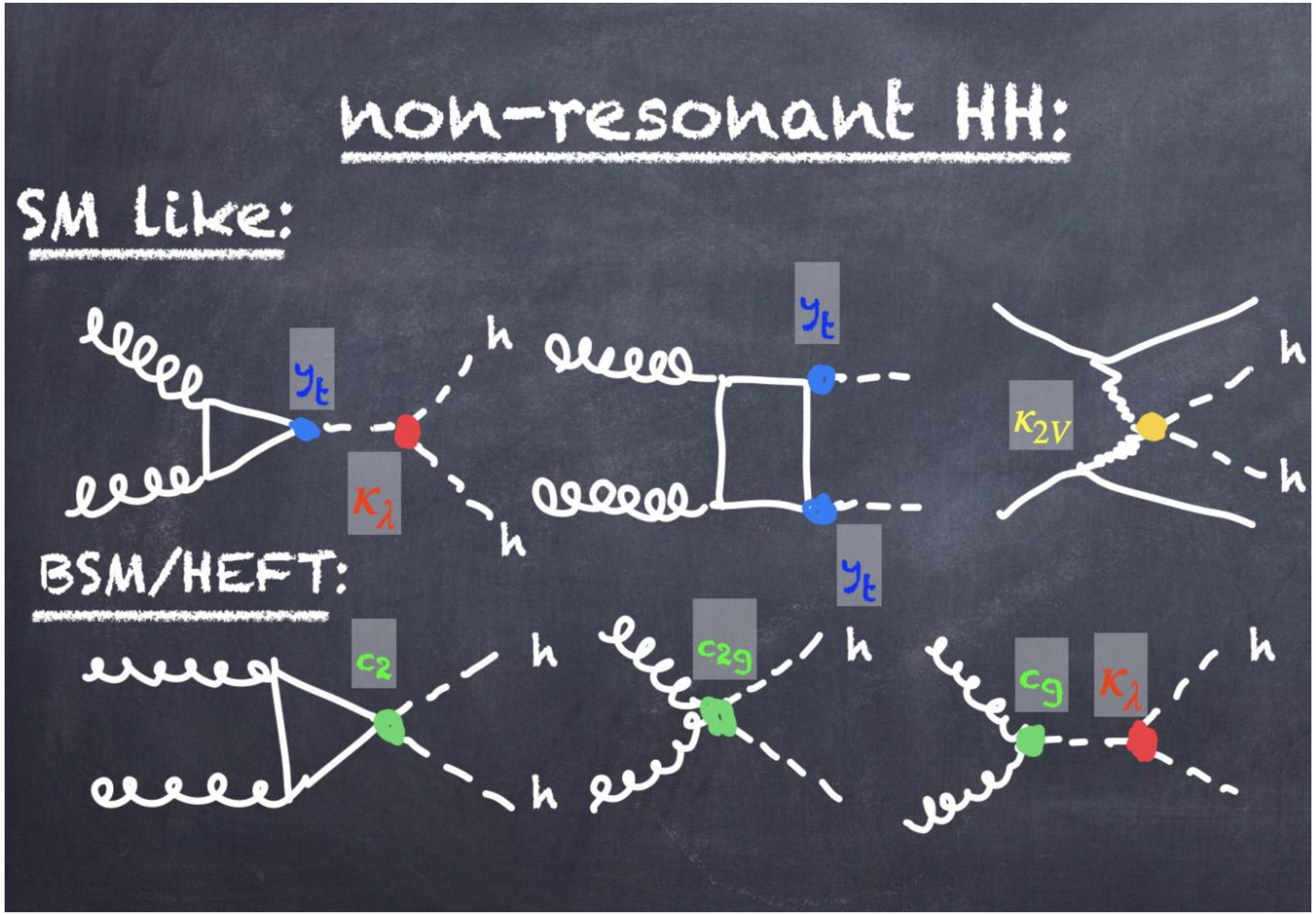
$$V(\phi) = \mu^2\phi\phi^\dagger - \lambda(\phi\phi^\dagger)^2 \; ; \; \phi = \frac{\nu + h}{\sqrt{2}}$$

$$= -\lambda\nu h^3 - \frac{1}{4}\lambda h^4 + \ldots$$

$$\lambda_{SM} = \frac{m_H^2}{\nu^2}; \; \nu = 246\,\text{GeV}; \; m_H = 125\,\text{GeV}$$

Introduction

- The results presented in this talk are based on the PAS https://cds.cern.ch/record/2917252/files/HIG-20-011-pas.pdf .
- The data set is from proton-proton collisions at 13 TeV collected by the CMS experiment from 2016 to 2018 (Run 2),
- SM like production in ggHH/ qqHH/VHH: κ_λ,κ_t, κ_V,κ_{2V} Limits/Likelihoods and constraints
- BSM/HEFT: Focussed on ggHH, Benchmarks (c2, cg, c2g, κλ, κt) and Limits/Likelihoods and constraints in c2, κλ, κt



Introduction

Shape benchmarks

To tackle the complex 5-parameters parameter space the approach of defining couple of **shape benchmarks** to **exemplify the most common shapes** in large scans of these parameters was suggested in [1] (defined from LO scans)

- The procedure was extended based in NLO scans in [2]
- and the definition of shape benchmarks is now being maintained by the LHC WG4 (HH), including experimental constraints in the scans, with the latest result on [3]

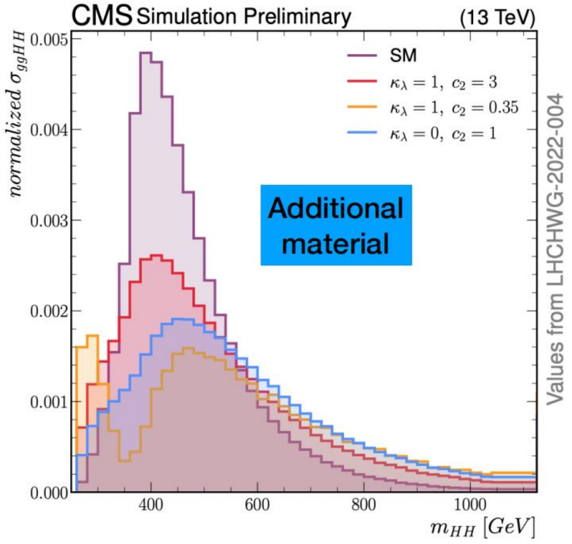
We consider the shape benchmarks defined on [1] (frozen vanilla case) and [3], that evolves with experimental bounds on parameters

[1] A.C, M.Dall'Osso, T.Dorigo, F. Goertz, C.Gottardo, M.Tosi JHEP 04 (2016) 126
[2] M. Capozi and G. Heinrich JHEP 03 (2020) 091 [3] LHCHWG-2022-004
[4] *JHEP* 02 (2021) 049 — A.C., F.Goertz, K.Mimasu, M.Gouzevitch, A.Aggarwal

Scans including modeling of c2

If the new physics is a low energy effect of heavy scalars considered in models are color neutral, the cg and egg effective interactions are in fact induced at the one-loop level [1]

We focus HEFT-like scans in (κλ , κt, c2)



If c2 deviates from the SM-value (=0) ➔ harder Higgs bosons

Introduction

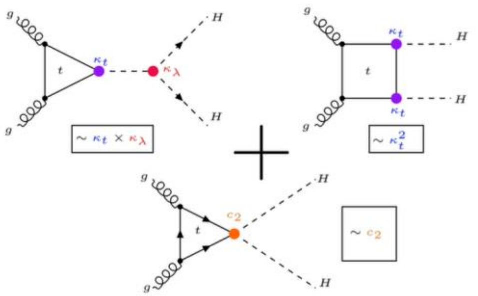
- Input channels

Analysis	CADI	Production modes	Results types	Comments
$bb\gamma\gamma$	HIG-19-019	ggHH+qqHH	SMLike/BM/HEFT+UV	
$bb\tau\tau$	HIG-20-010	ggHH+qqHH	SMLike/BM/HEFT+UV	
$bbbb\,(resolved)$	HIG-20-005	ggHH+qqHH	SMLike/BM/HEFT+UV	
$bbbb\,(boosted)$	B2G-22-001	ggHH+qqHH	SMLike/BM/HEFT+UV	
$bbbb\,(VHH)$	HIG-22-006	VHH	SMLike	New since Nature
$multilepton$	HIG-21-002	ggHH+qqHH	SMLike/BM/HEFT+UV	
$bbWW\,(resolved)$	HIG-21-005	ggHH+qqHH	SMLike/BM/HEFT+UV	New since Nature
$bbWW\,(boosted)$	HIG-23-012	ggHH+qqHH	SMLike	New since Preap
$bbZZ\,(4\ell)$	HIG-20-004	ggHH	SMLike	
$WW\gamma\gamma$	HIG-21-014	ggHH+qqHH	SMLike/BM/HEFT+UV	New since Nature
$\tau\tau\gamma\gamma$	HIG-22-012	ggHH	SMLike/BM	New since Nature, only JHEP04 Benchmarks

New analyses added compared to the Nature Pub:
bbWW(resolved + boosted), bbbb(VHH), ττγγ, WWγγ

Signal nodelling

$$|\mathbf{A}|^2 = \left| \quad \right|^2$$



$$|A|^2 = \kappa_\lambda^2 \cdot \kappa_t^2 \cdot |\triangle|^2 + \kappa_t^4 \cdot |\square|^2 + c_2^2 \cdot |X|^2 + \kappa_\lambda \cdot \kappa_t \cdot c_2 \cdot |\triangle^* X + X^* \triangle| + \kappa_t^2 \cdot c_2 \cdot |\square^* X + X^* \square| + \kappa_t^3 \cdot \kappa_\lambda \cdot |\triangle^* \square + \square^* \triangle|$$

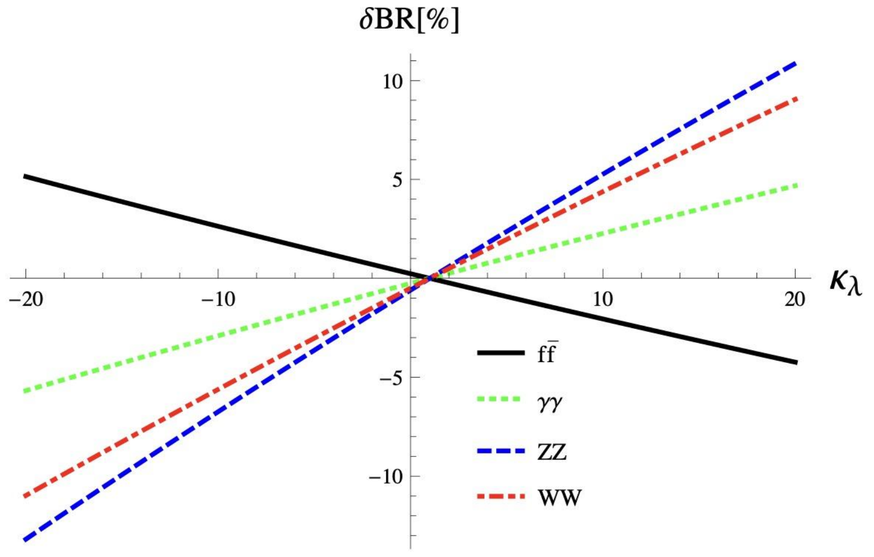
$$\boldsymbol{\sigma}(\kappa_\lambda, \kappa_\mathrm{t}, c_2) = \mathbf{c}^T(\kappa_\lambda, \kappa_\mathrm{t}, c_2) \cdot \mathbf{v}$$

$$\vec{\sigma} = \begin{pmatrix} \sigma^a \\ \sigma^b \\ \sigma^c \end{pmatrix} = \begin{pmatrix} c_1^a & c_2^a & c_3^a \\ c_1^b & c_2^b & c_3^b \\ c_1^c & c_2^c & c_3^c \end{pmatrix} \cdot \begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix} = \mathbf{C} \cdot \mathbf{v} \longrightarrow \mathbf{v} = \mathbf{C}^{-1} \cdot \vec{\sigma}$$

$$\boldsymbol{\sigma}(\kappa_\lambda, \kappa_\mathrm{t}, c_2) = \mathbf{c}^T(\kappa_\lambda, \kappa_\mathrm{t}, c_2) \cdot \mathbf{C}^{-1} \cdot \vec{\sigma}$$

Signal nodelling

- Linear combination of input samples used in all of our parameter scans (combine physics model)
- Principle the same for ggHH/qqHH and VHH
- Additionally scaling of SH backgrounds and BRs as function of included in same physics model
- Also adds dependent theory uncertainty for ggHH

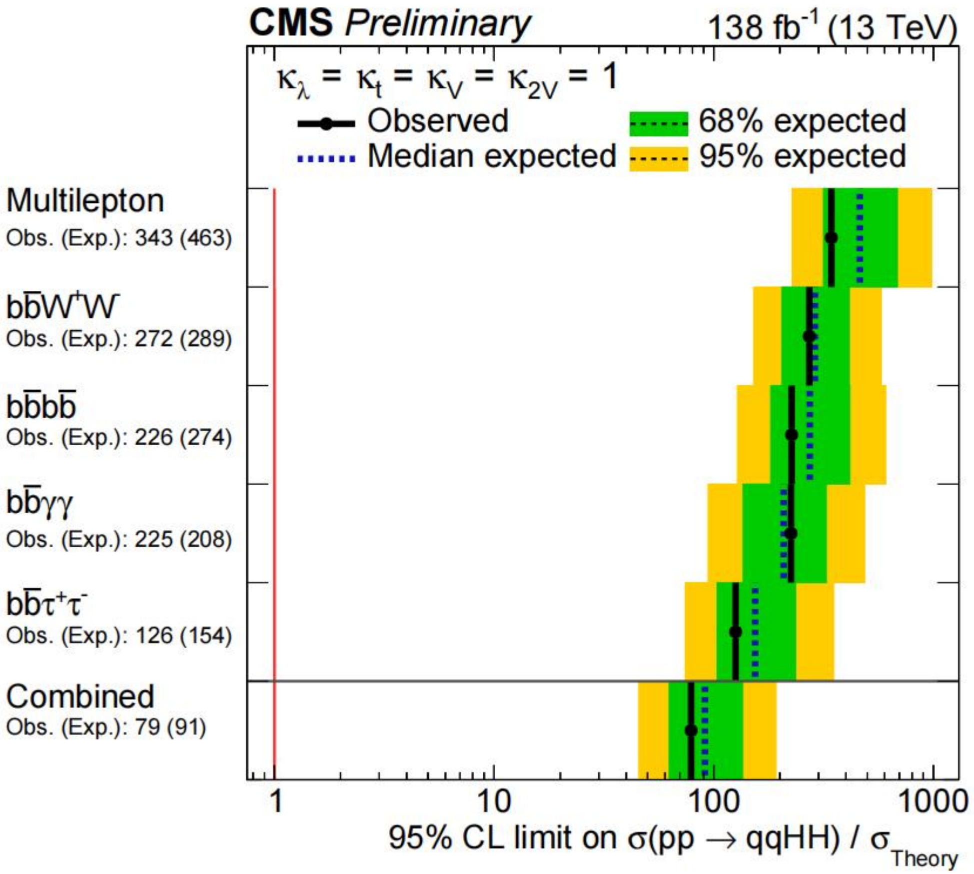


Defination of BRs from:
https://arxiv.org/pdf/1607.04251

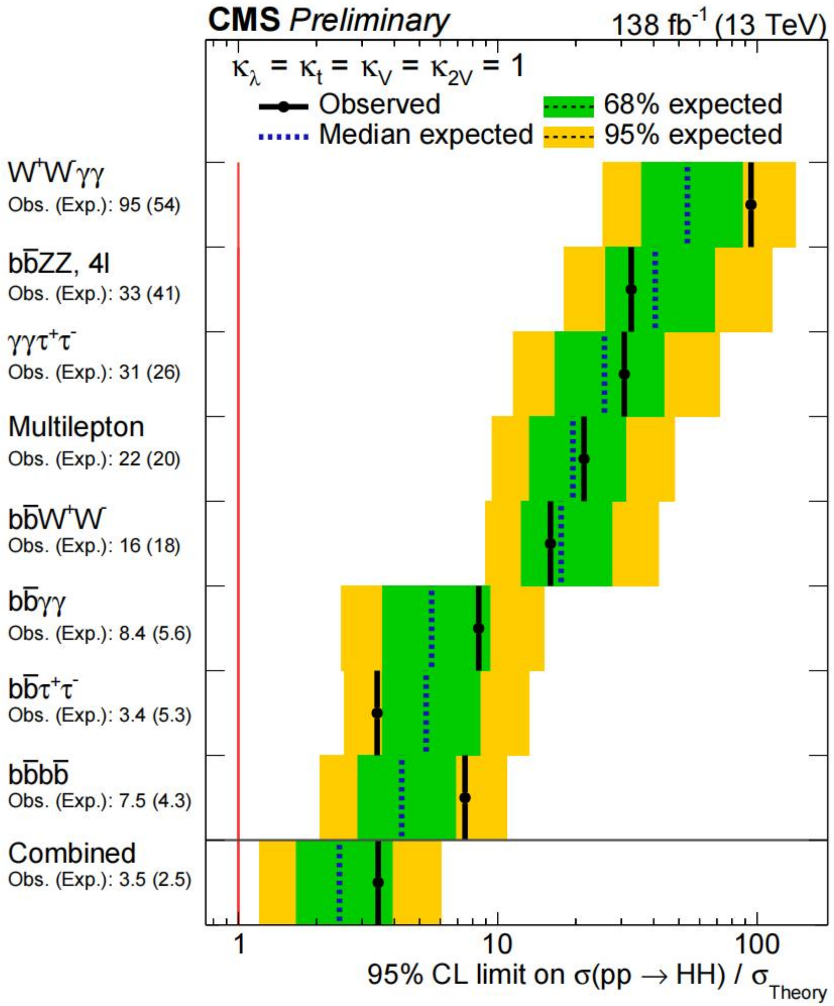
SM-like results

- 95% CL Upper limits on r/rqqHH at SM per channel and combination
- 95% CL Upper limits scans on HH inclusive cross section (κ_λ and c_{2V})
- 1D NLL scans in (κ_λ and c_{2V})
- 2D NLL scans in (κ_λ ,c_{2V}), (κ_λ ,κ_t) and (c_V,c_{2V})

SM Point Limits

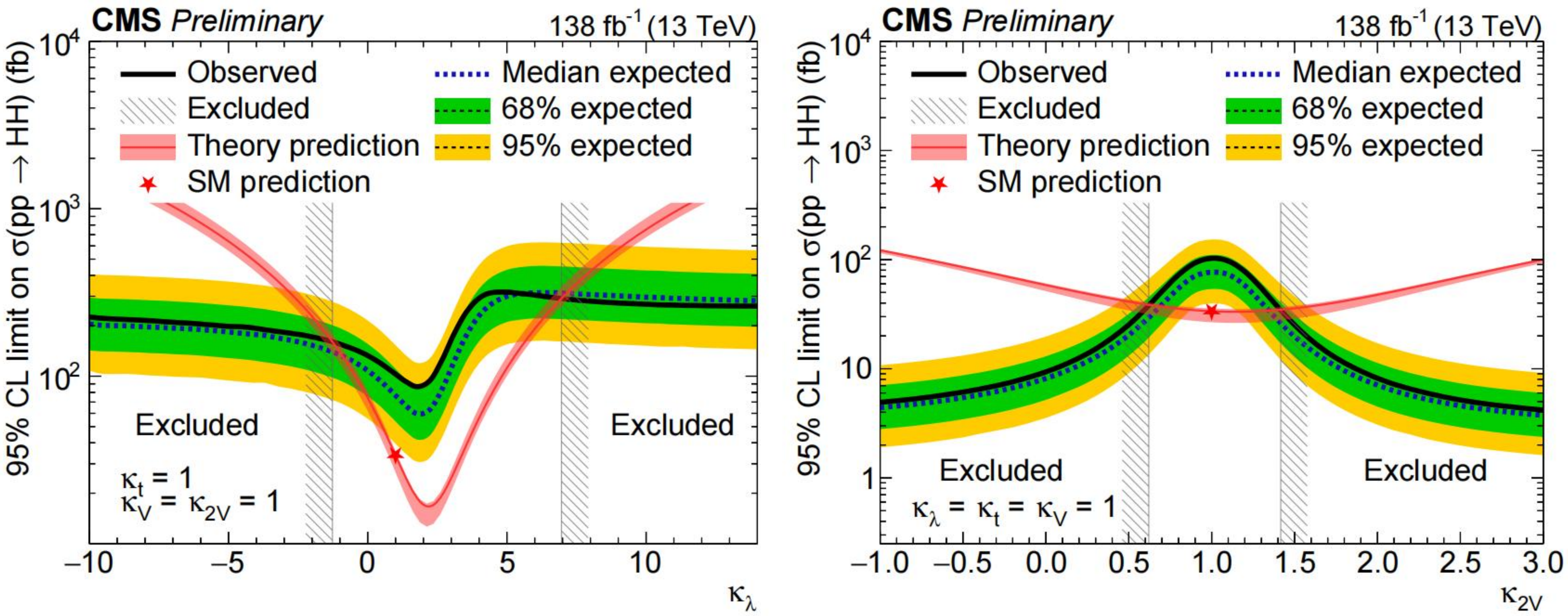


The 95% CL upper limits on the VBF signal strength for each channel and their combination. The equivalent upper limit for the VBF alone is observed (expected) to be 79 (91) times the SM prediction



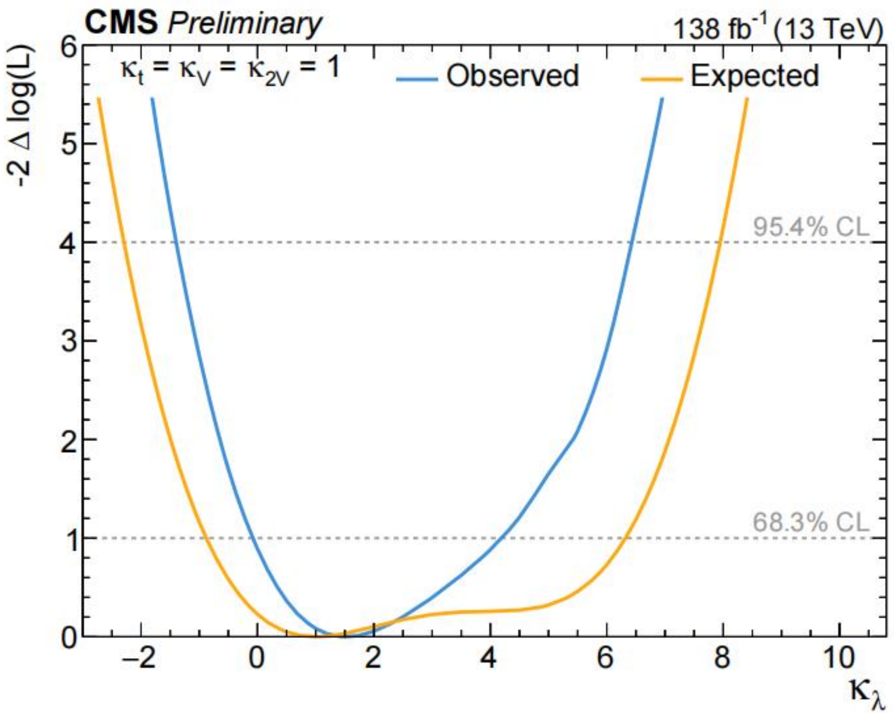
The 95% CL upper limits on the inclusive signal strength for each channel and their combination. The limit is observed (expected) to be 3.5 (2.5) times the SM prediction

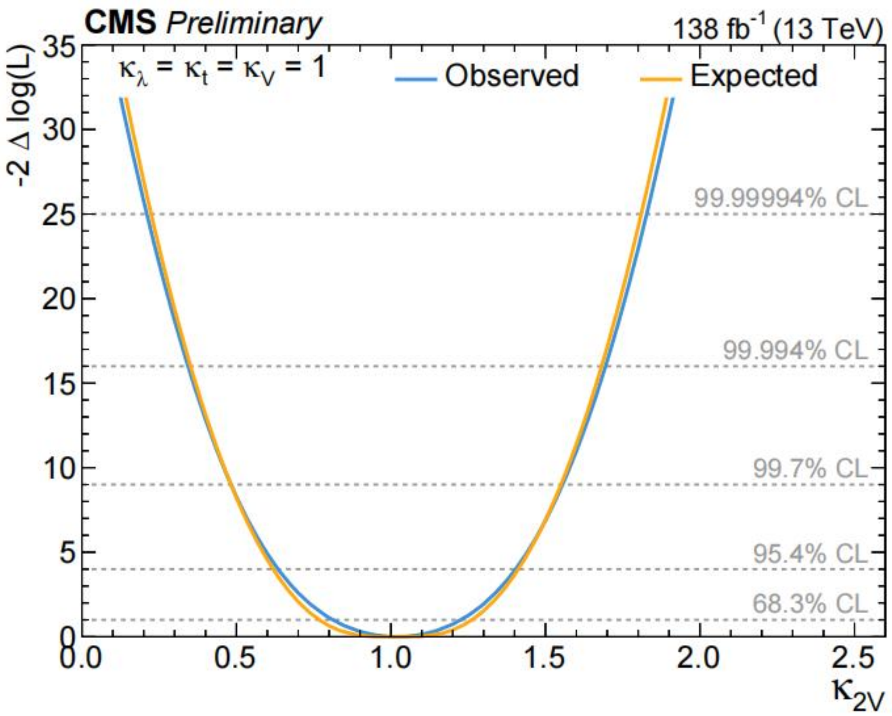
Constraints on κλ and κ2V



κ_λ at 95% Cl.: -1.39 and 7.02 (expected -1.02 and 7.19), κ_{2V} at 95% Cl.: 0.62 and 1.42 (expected 0.69 and 1.35)

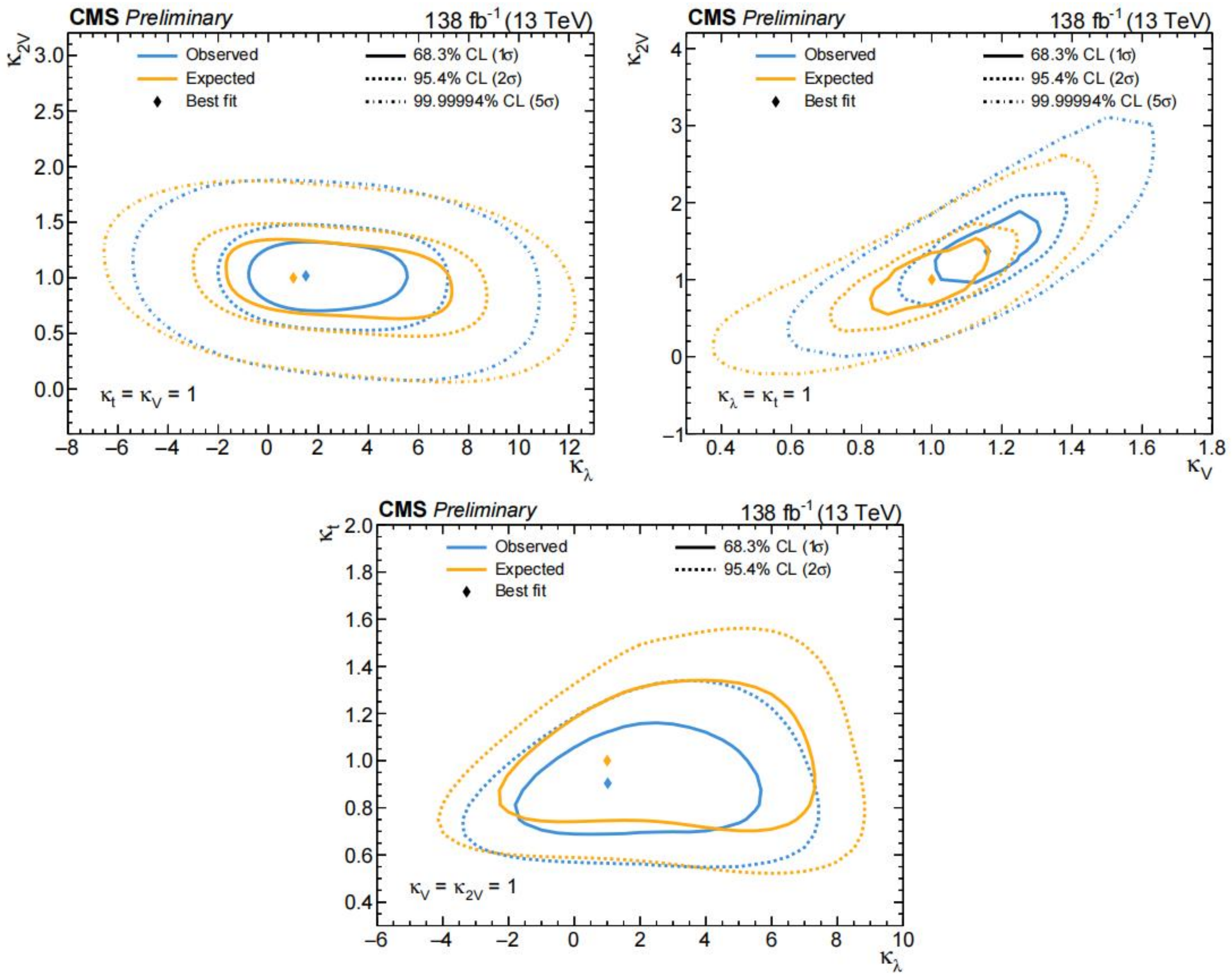
1D Likelihood scan





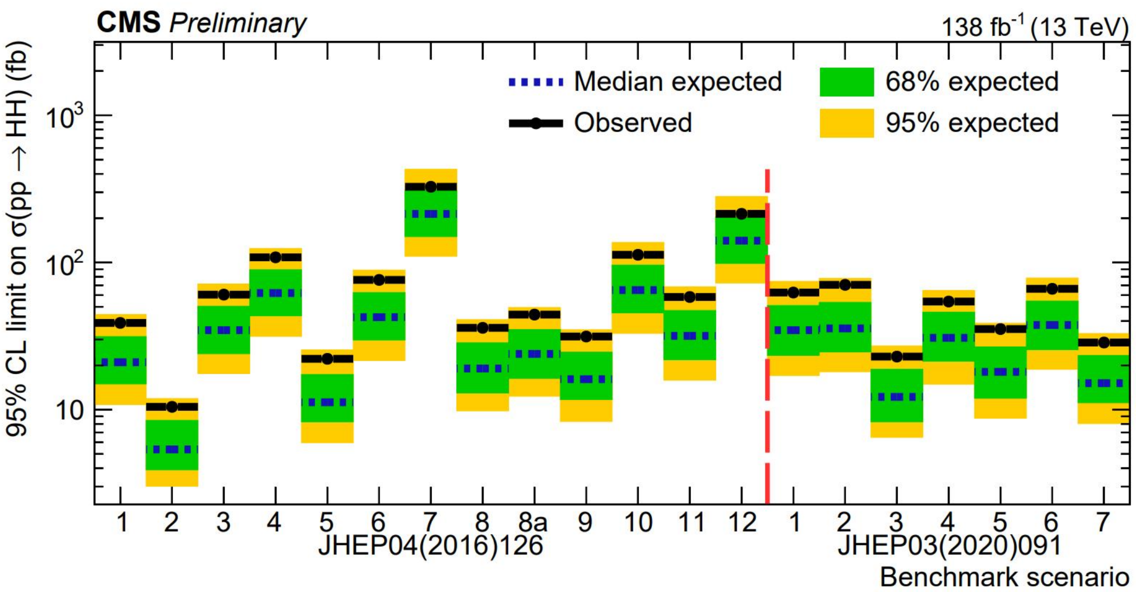
−2Δ log(L) as a function of coupling modifiers κλ (left) and κ2V (right) for the combination of all channels.

2D likelihood scan



−2Δ log(L) as a function of pairs of coupling modifiers (κλ, κ2V) (top left), (κV, κ2V) (top right), and (κλ, κt) (bottom) for the combination of all channels when all the other parameters are fixed to their SM value.

HEFT Benchmark results

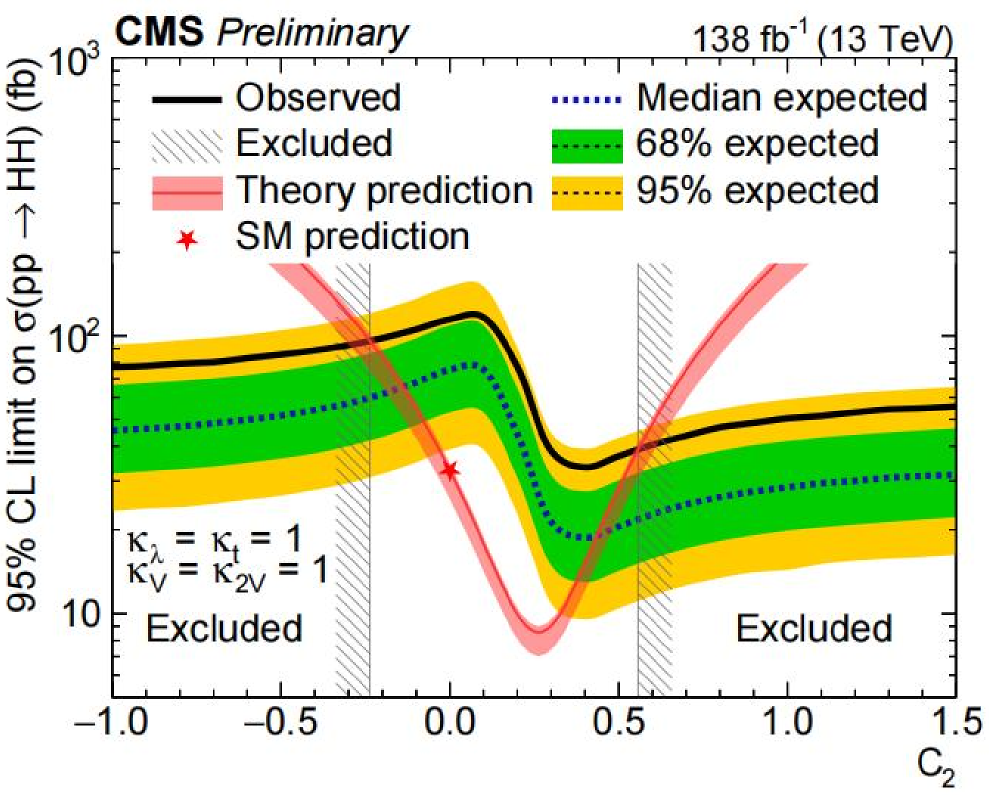


Limits on the HH production production cross-section for the 2 sets of HEFT benchmarks

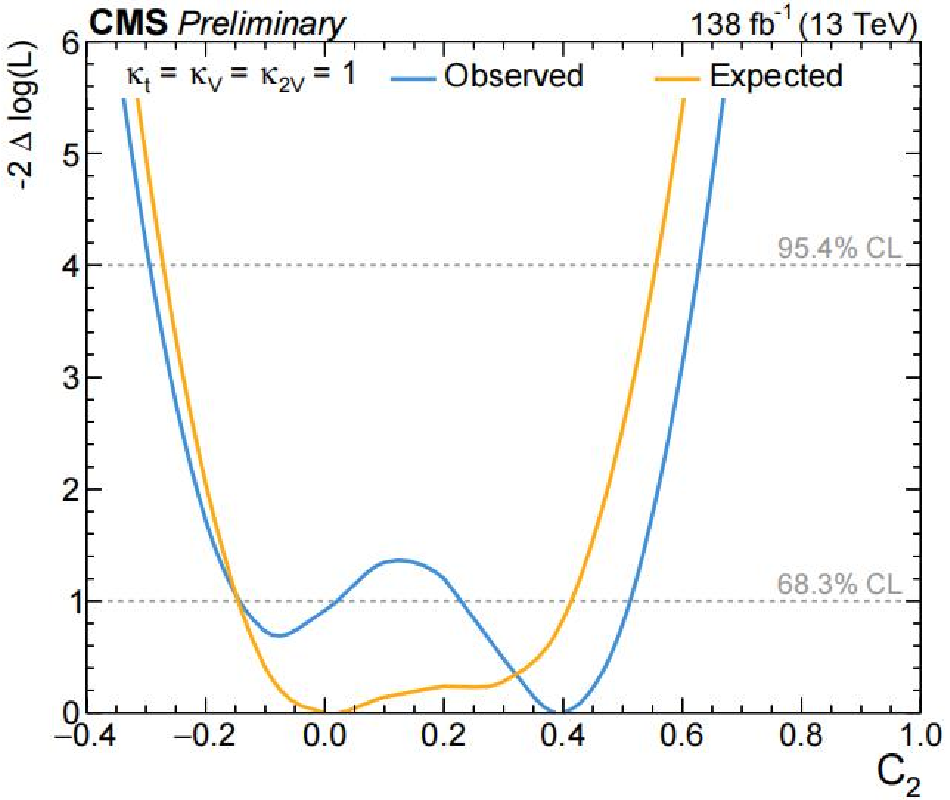
Scenario	expected 95% CL limit on σ_{HH} [fb]	observed 95% CL limit on σ_{HH} [fb]
JHEP03(2020)91 BM1	34.67	62.48
JHEP03(2020)91 BM2	35.64	70.48
JHEP03(2020)91 BM3	12.21	22.94
JHEP03(2020)91 BM4	30.76	54.28
JHEP03(2020)91 BM5	18.07	35.3
JHEP03(2020)91 BM6	37.6	66.25
JHEP03(2020)91 BM7	15.14	28.59
JHEP04(2016)01 BM1	21.0	38.85
JHEP04(2016)01 BM2	5.37	10.45
JHEP04(2016)01 BM3	34.67	60.49
JHEP04(2016)01 BM4	62.01	108.41
JHEP04(2016)01 BM5	11.23	22.15
JHEP04(2016)01 BM6	42.48	76.13
JHEP04(2016)01 BM7	213.87	326.77
JHEP04(2016)01 BM8	19.04	35.98
JHEP04(2016)01 BM8a	23.93	44.25
JHEP04(2016)01 BM9	16.11	31.4
JHEP04(2016)01 BM10	64.94	112.78
JHEP04(2016)01 BM11	31.74	58.28
JHEP04(2016)01 BM12	140.62	214.08

Table 4: Expected and observed 95% CL limits on the HH for the two sets HEFT benchmarks.

Constraints on c2



c_2 at 95% Cl.: -0.28 to 0.59 (expected -0.17 to 0.47)



c_2 (1σ): 0.23 to 0.51 (expected -0.15 to 0.41)

c_2 (2σ): -0.29 to 0.63 (expected -0.27 to 0.56)

Projections to HL-LHC

We include projections of the currency highest sensitivity channels according to three established scenarios:

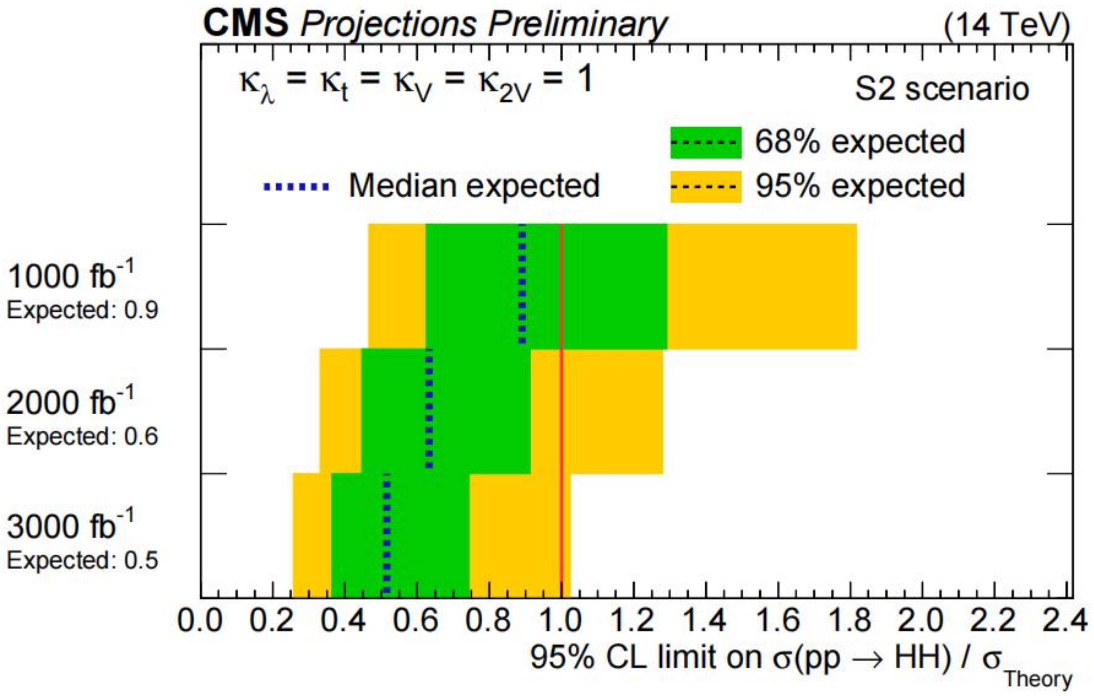
- The systematic uncertainties are assumed at the same level of Run 2.

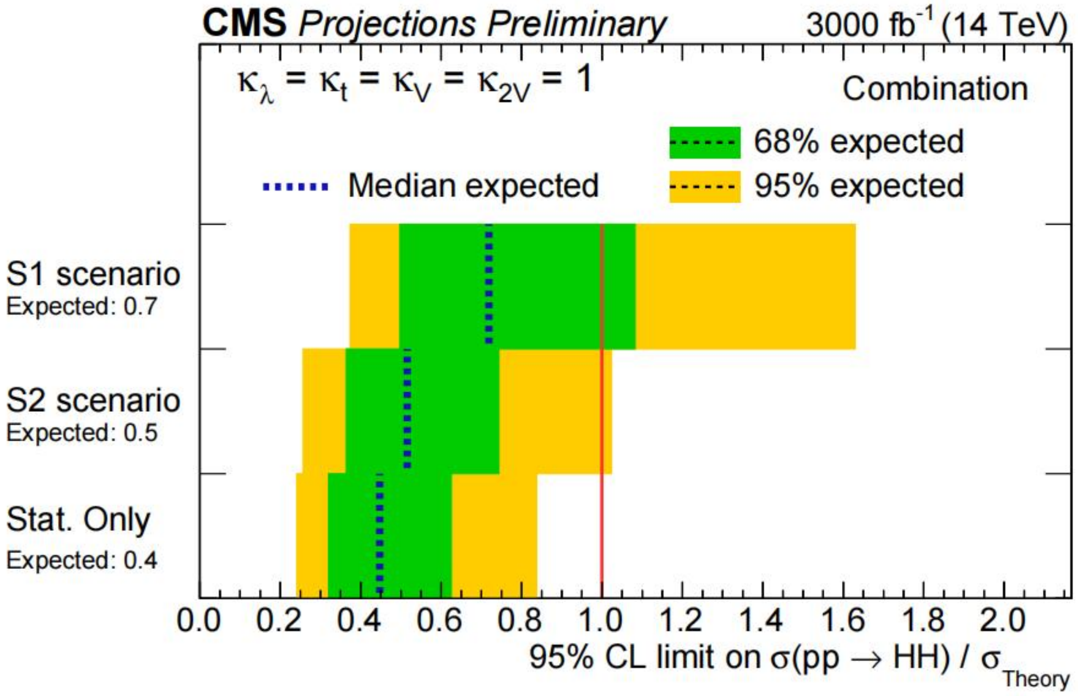
- The systematic uncertainties with a statistical origin

- “stat. only”: All the constrained nuisance parameters are assumed to be remain unchanged in the fit.

- For datadriven background estimation the statistical uncertainty on the background prediction is kept but scaled according to luminosity

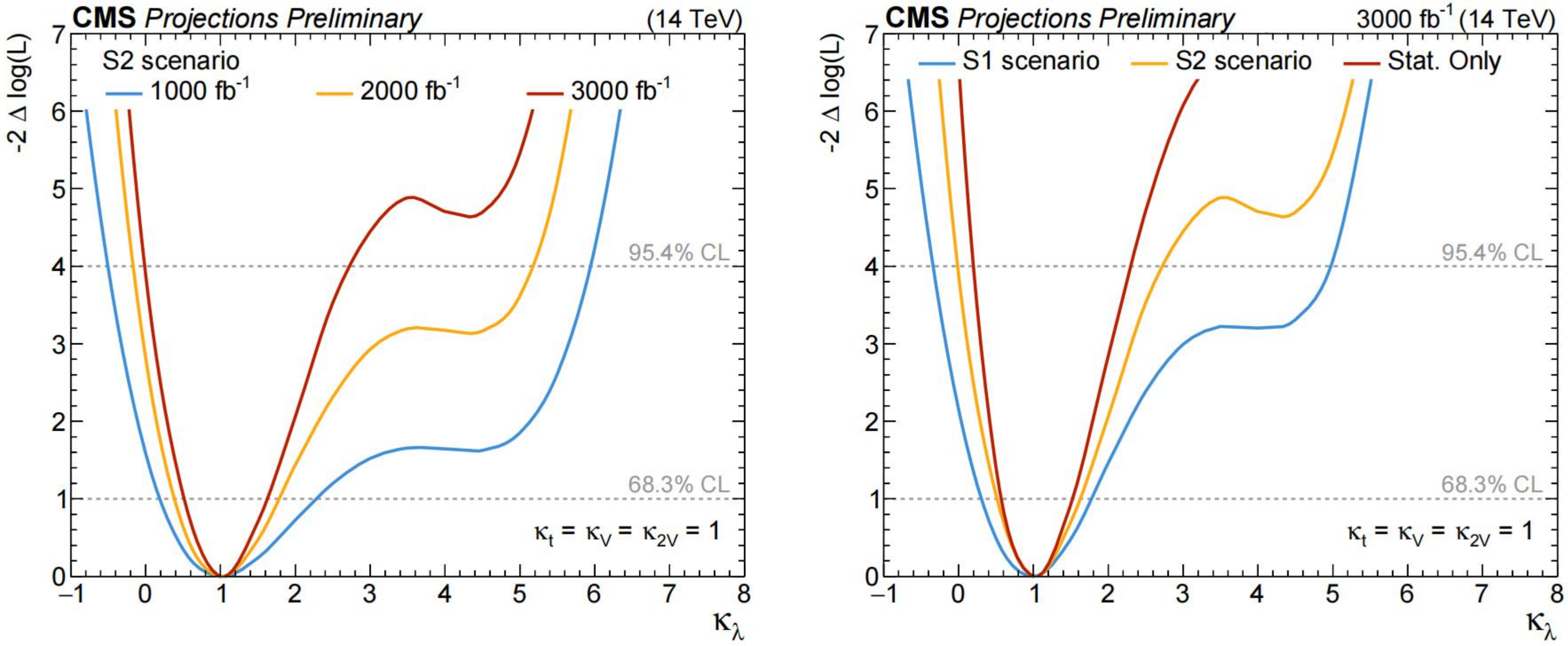
Projections to HL-LHC





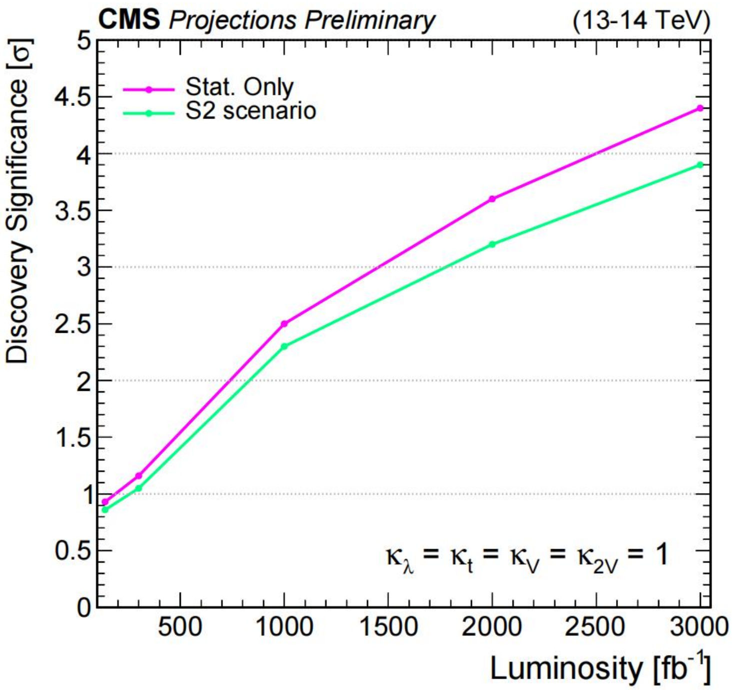
Expected upper limits on the HH signal strength from the combination of all the considered channels at different integrated luminosities (left), and under different assumptions on the systematic uncertainties for an integrated luminosity of 3000 fb−1(right).

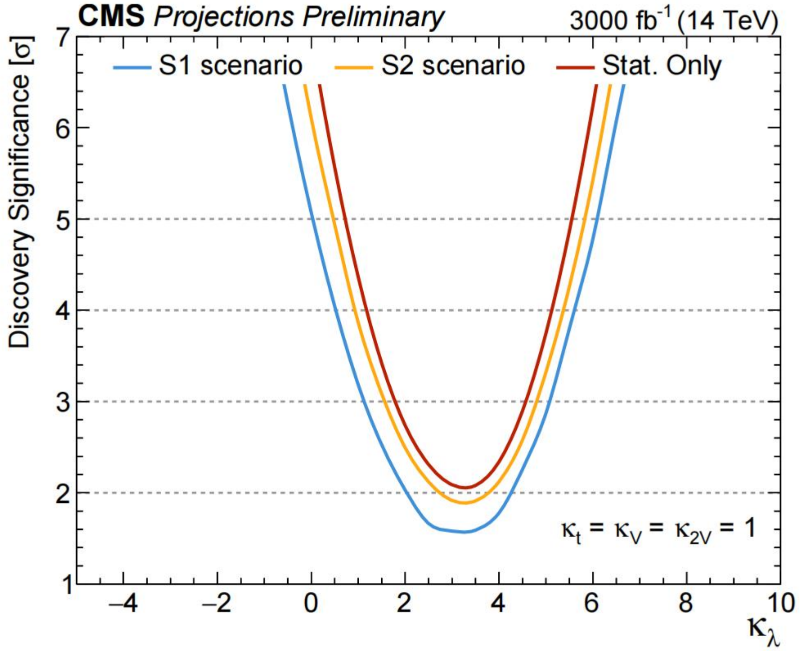
Projections to HL-LHC



Expected κλ likelihood scan from the combination of all the considered channels projected at different integrated luminosities (left), and under different assumptions on the systematic uncertainties for an integrated luminosity of 3000 fb−1(right).

Projections to HL-LHC





Evidence (3.2) expected for 2000 fb-1

Discovery in reach for 3000 fb−1

	Significance (σ) at 2000 fb^{-1}		Significance (σ) at 3000 fb^{-1}	
	S2	Stat. only	S2	Stat. only
$b\bar{b}b\bar{b}$ resolved jets	1.0	1.3	1.4	1.6
$b\bar{b}b\bar{b}$ merged jets	1.7	1.7	2.0	2.1
$b\bar{b}\tau\tau$	1.7	1.9	2.1	2.3
$b\bar{b}WW$	0.6	0.8	0.7	0.9
$b\bar{b}\gamma\gamma$	1.8	1.9	2.2	2.3
Combination	3.2	3.6	3.8	4.3

Summary

- A full set of results for the HH combination has been showen.
- These results present the most stringent limits and constraints using the LHC Run 2 data set collected by the CMS detector.
- Extrapolating our current results to the luminosity of HL-LHC it can be expected to see first evidence for Higgs boson pair production with ≈ 2000 fb^{-1} of data.

Back up