Higgs Differential and STXS cross section measurements at CMS, combination and EFT interpretation

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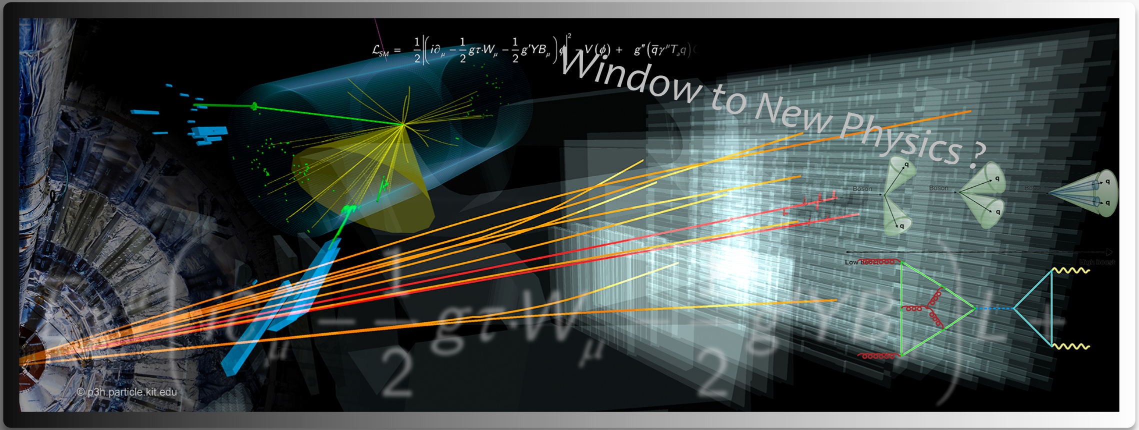


EPS-HEP 2025

Marseille, France 7 – 11 July 2025

In this talk

- Latest precision measurements of **Higgs boson cross section production** performed with the **CMS detector:**
  - ***Fiducial, differential Cross Sections***
  - ***Simplified Template Cross Sections (STXS)***

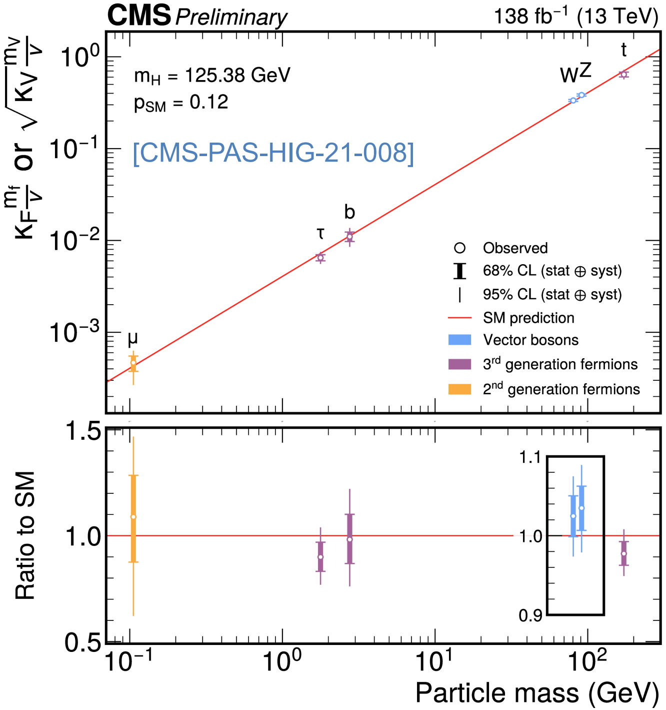
in *bosonic and fermionic* decay channels with data collected during Run-2 of the LHC and the early data collected in Run-3

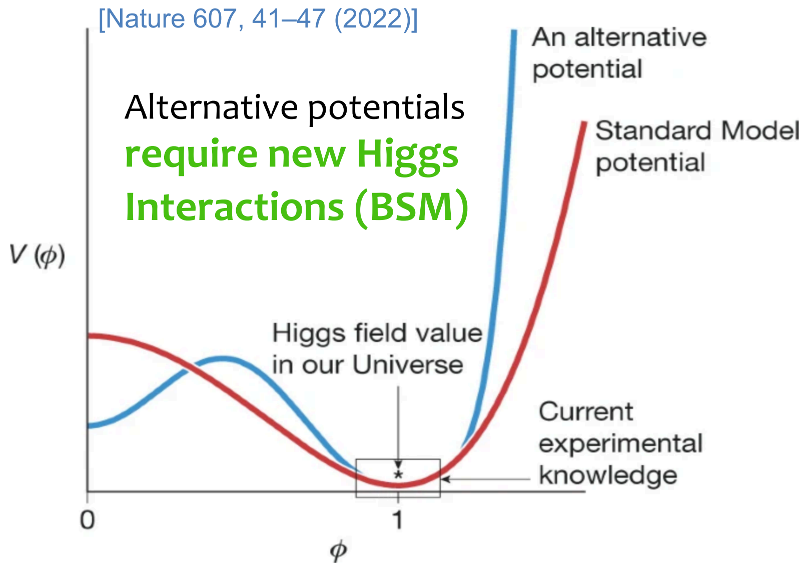
- **Combination of Run-2 cross section measurements** and their
- **interpretations** as constraints on Wilson coefficients of beyond Standard Model operators in the framework of ***SM Effective Field Theories (SMEFT)***

- ATLAS+CMS input to the European Particle Physics Strategy Update 2026

Portrait of the Higgs Boson

- Discovery of the Higgs boson by ATLAS and CMS (2012) completed the Standard Model particle spectrum
- The Higgs boson's properties (mass, spin, parity, couplings) are consistent with SM predictions so far, but:





our current knowledge of the Higgs potential is limited

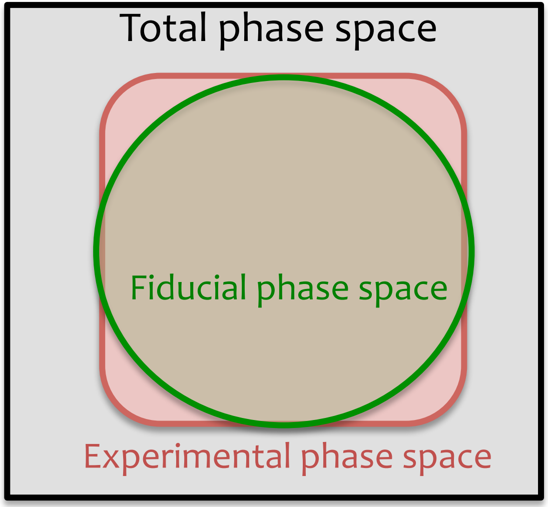
- With large data set of LHC Run-2 (+ Run-3) **precise measurements** are enabled

Fiducial differential cross-sections

- A method to study the Higgs properties in a **more** model independent way

- **Differential:** the cross section is measured in bins of some observables (p_T^H, #jets, …)
  - Provides **more information than inclusive measurements**

- **Fiducial**: the extrapolation of the result is limited to a restricted phase space defined close as possible to the **experimental phase space** (selection)
  - Easy comparison with different theories

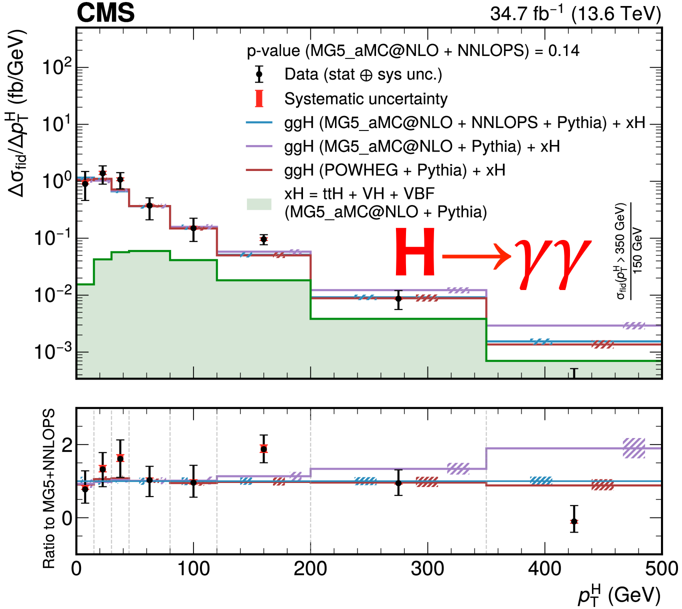


- **Fiducial, differential** measurements are:
  - **The most model-independent** way to measure Higgs boson production cross section
  - Sensitive to **BSM** effects

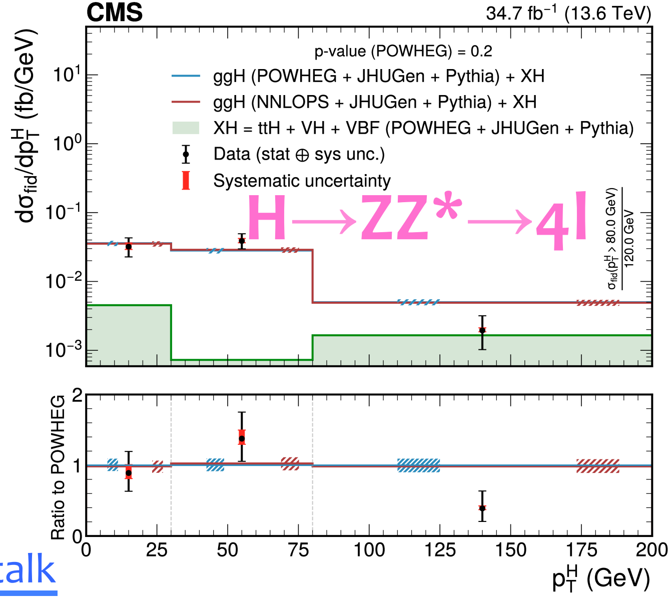
Recent Higgs Xs measurements

- **Fiducial, differential cross section** measurement:

[CMS-PAS-HIG-23-014, Sub. to JHEP]



[CMS-PAS-HIG-24-013, Accp. in JHEP]



Early Run-3 @ 13.6 TeV

Within the uncertainties, the fiducial, differential cross sections agree with the SM predictions

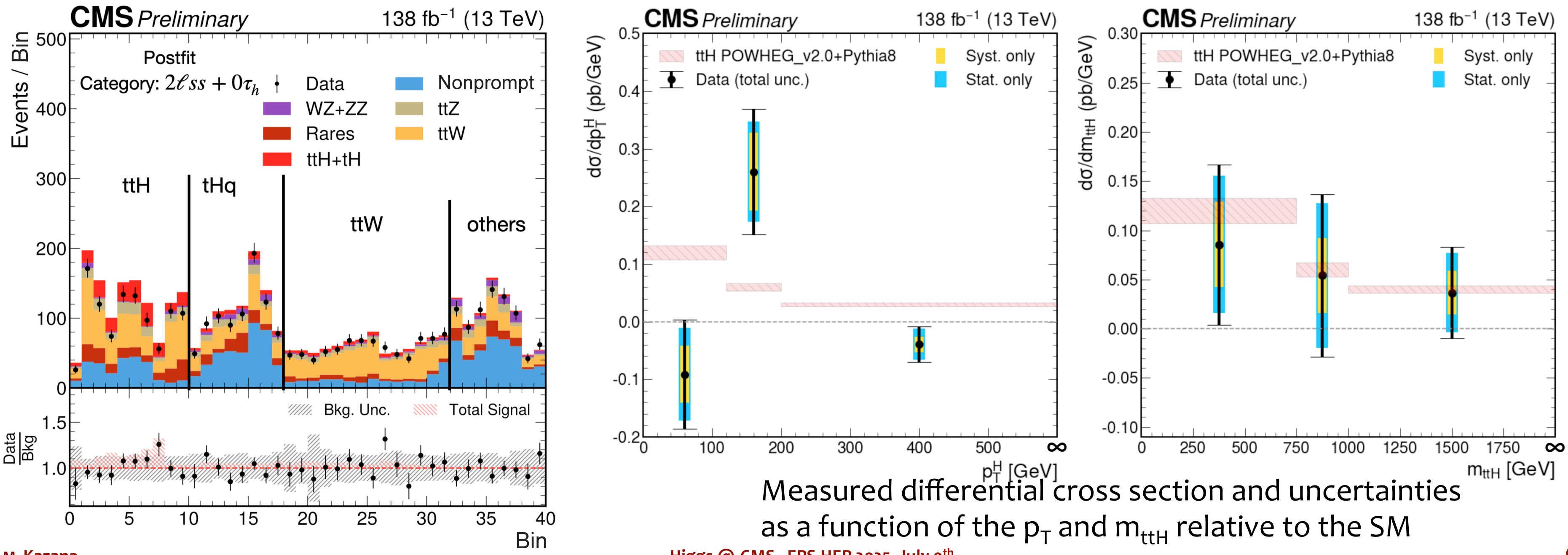
→ see Ralf Schmieder'talk

Inclusive σ_{fid} = **74 ± 11** (stat) $^{+5}_{-4}$ (syst) fb
SM expectation **67.8 ± 3.8** fb

σ_{fid} = **2.89** $^{+0.53}_{-0.48}$ (stat) $^{+0.29}_{-0.21}$ (syst) fb
σ_{SM} = **3.09** $^{+0.27}_{-0.24}$ fb

Recent Higgs Xs measurements

- First **differential** measurement for **ttH multilepton + jets** channel using full **Run-2**
- Top Yukawa coupling **sensitive to BSM effects**
- Target Higgs decay modes **H→ WW → lνlν / lνqq** and **H→ ττ → hadrons/leptons+ν's**
- Machine-learning techniques (DNN) used for the separation sig./bkg.

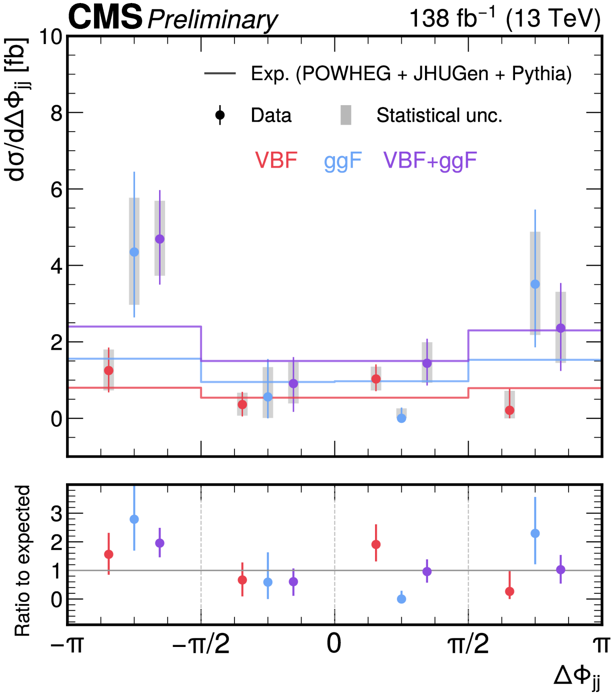


Measured differential cross section and uncertainties as a function of the p_T and m_{ttH} relative to the SM

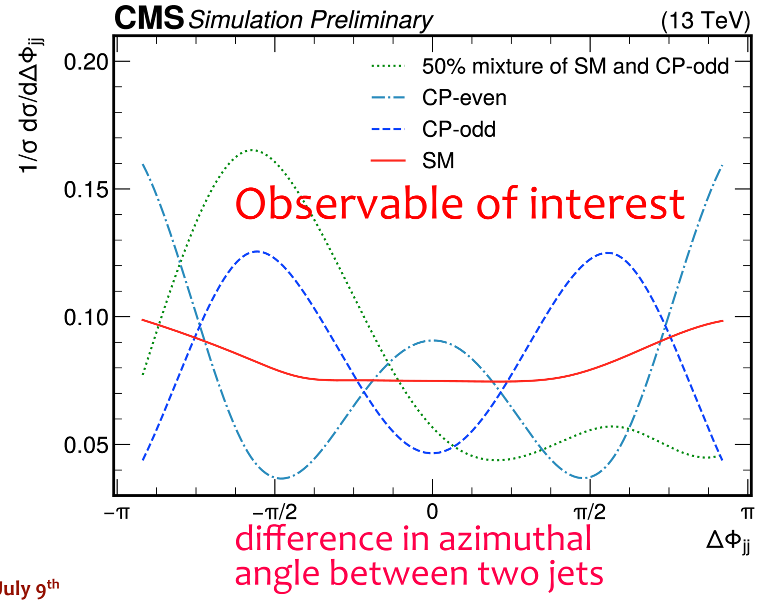
Recent Higgs Xs measurements

[CMS-PAS-HIG-24-004, April 2025]

- The **fiducial differential** cross section in VBF and ggF for **H(WW) + 2 jets** using full **Run-2**
- Target Higgs decay modes **H→ WW → lνlν**
- Model independent measurement to be easily re-interpreted
- Fit variable that discriminates signal from backgrounds but agnostic with respect to the signal hypothesis
  → Adversarial deep neural network (ADNN)



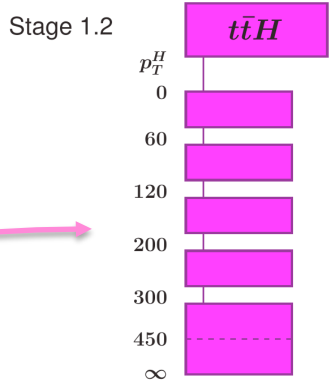
Measured fiducial cross section of the VBF and ggF production modes



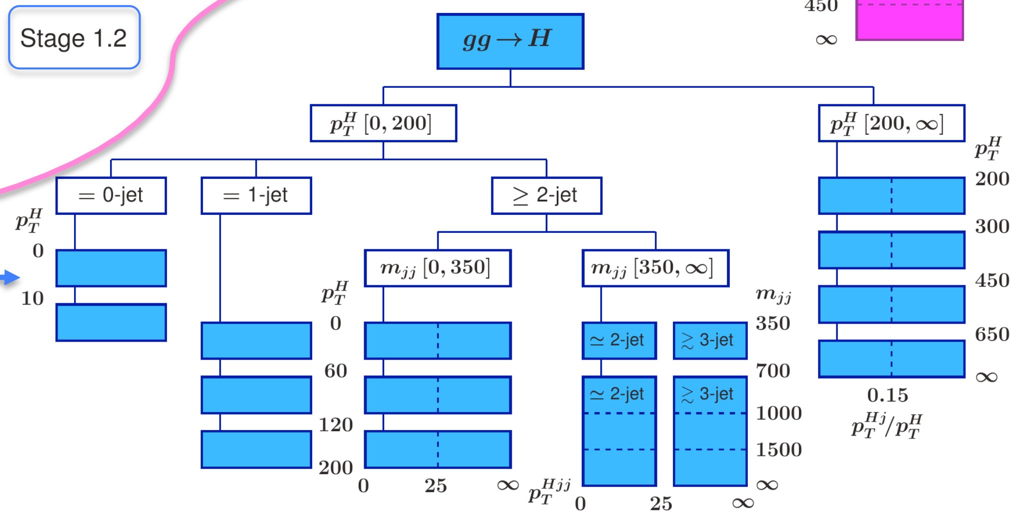
STXS cross-sections

- A method to study the Higgs properties in a **more** model independent way

- Simplified Template Cross Sections (STXS) framework
  - Complementary to differential measurements
  - Updated classification to stage 1.2 agreed between ATLAS and CMS



- The cross section is measured in pre-defined kinematical template bins **per production mode**, eg.:
  - No fiducial phase space defined
  - Reduces theoretical uncertainties
  - Isolating production modes
  - Combining multiple decay channels
  - Input for EFT / κ / λ_3 fits
  - High sensitivity to **BSM effects**



Combined measurements

- The **most comprehensive study** of Higgs boson production and decay performed by the CMS experiment to-date → **Run-2 Legacy combination STXS measurement**

  [CMS-PAS-HIG-21-018, April 2025]

  - Ultimate precision via statistical combinations
    - Evolution of [Nature 607, 60–68 (2022)]
    - New/updated channels + many more interpretations
- Each decay channel targets multiple production modes:
  - **H→γγ, H→ZZ*→4l, H→WW*→lνlν, H→ττ, H→bb, H→μμ, H→Zγ**
- Extremely complex likelihood

$$L(\vec{x};\vec{\alpha},\vec{\theta}) = \prod_r L_r(\vec{x};\vec{\alpha},\vec{\theta}) \prod_l p_l(y_l;\theta_l)$$

Analysis regions:
Signal and control regions (>1K)

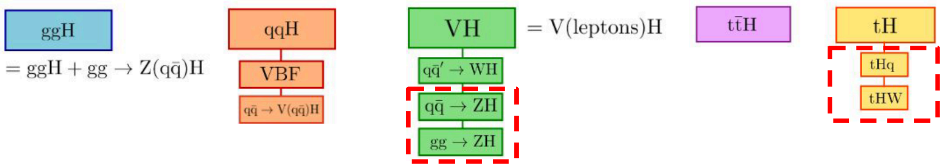
Nuisance parameters
Common sources correlated (>10K)

- The best-fit inclusive signal yield is measured to be

$$\mu = 1.014^{+0.055}_{-0.053}$$

STXS stage 0 combination

- Combination of **13 POI (7 prod. channels)** and **6 decay channels**

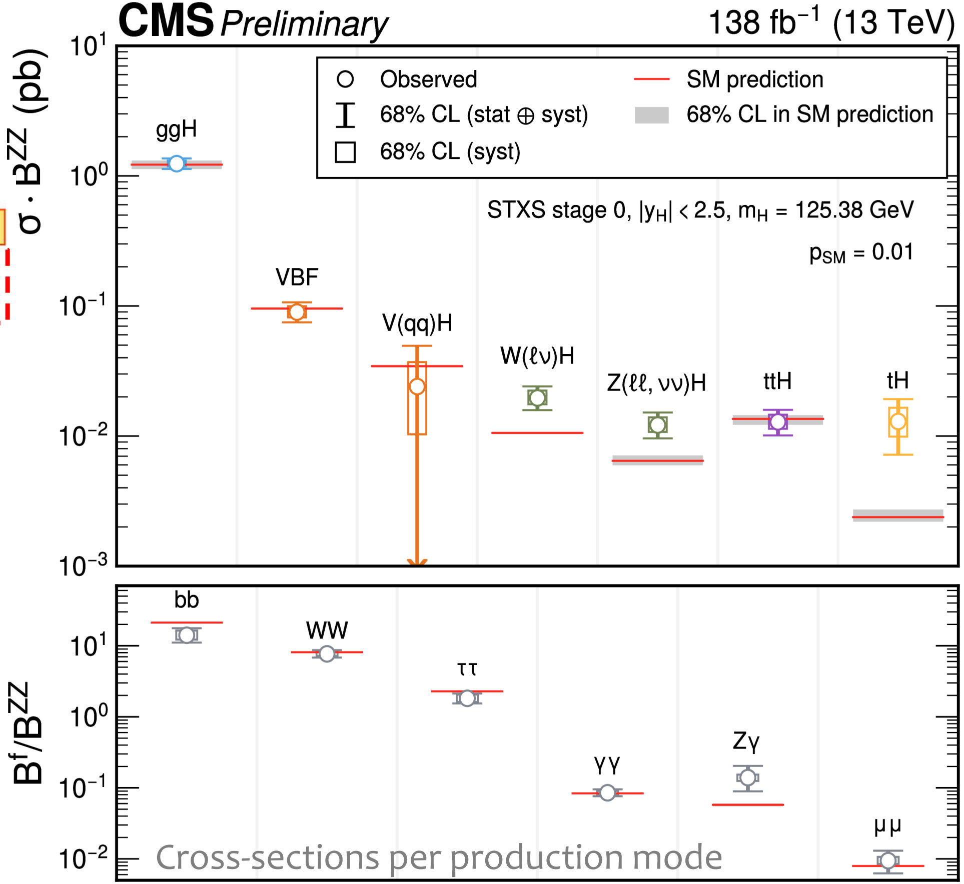


- Fit floating ratios of branching fractions
  [maximum likelihood fit in which the ratios between signal strengths of different processes are not fixed]

- Global p-value of the fit

  p_{SM} = 0.01

- **Tensions at ~ 2σ**
  observed over SM expectations in:
  → **tH**
  → **WH and ZH**

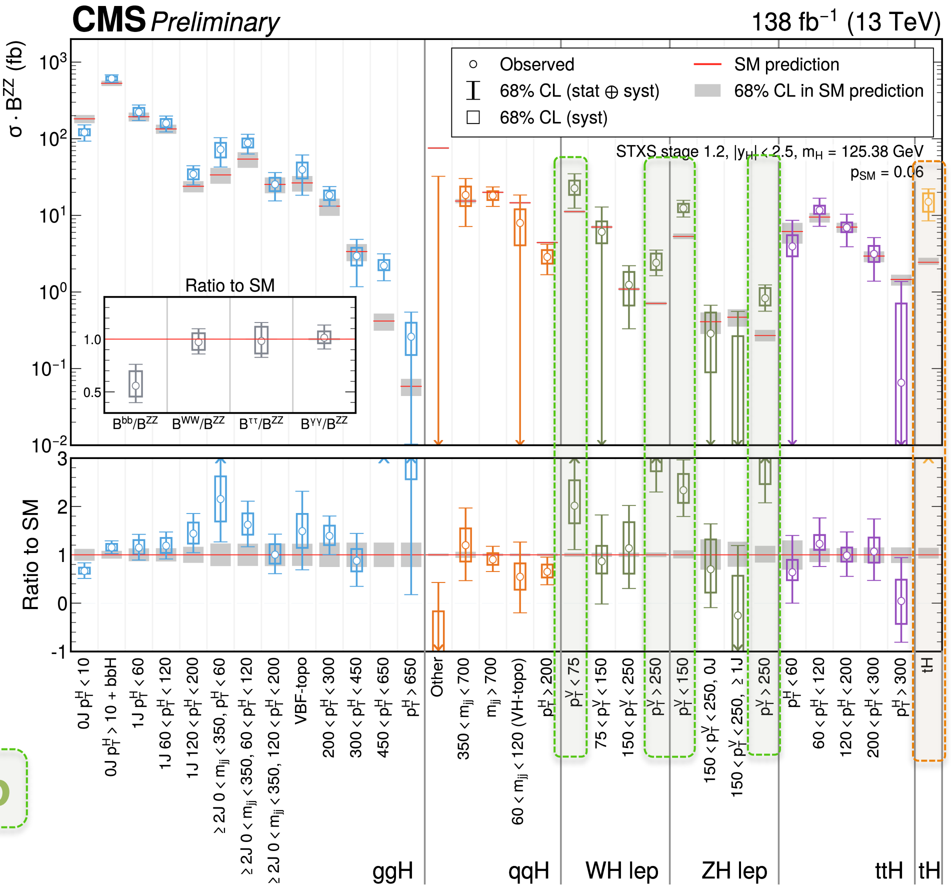


Cross-sections per production mode as products with the H→ZZ branching fractions

STXS stage 1.2 combination

[CMS-PAS-HIG-21-018, April 2025]

- First combined STXS (1.2, see p.8) **$\sigma * B^{ZZ}$** measurement
- Good sensitivity to many kinematic regions [32 + 4 BF ratios]
- **Fine agreement with SM**
- **About 2σ deviations** in high **p_T^V** bins for **WH lep, ZH lep** and **tH**



κ–framework interpretation

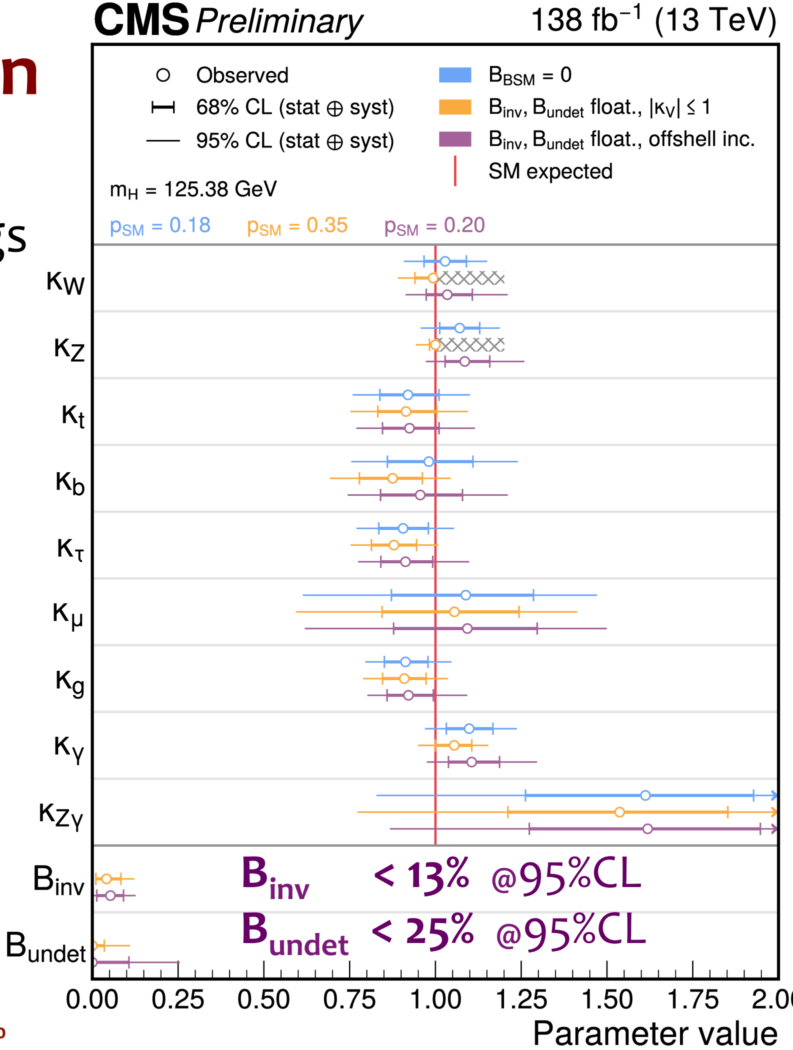
The effective coupling modifier configuration is fit with 3 different assumptions on the Higgs boson total decay width (Γ^{TOT})

- no additional BSM contributions to Γ^{TOT}
- B_{inv} and B_{undet} as additional parameters, if $|\kappa_W| \leq 1$ and $|\kappa_Z| \leq 1$

[CMS-PAS-HIG-21-018, April 2025]

- **Offshell H→ ZZ→4l input** channel is introduced into the combination to constrain Γ^{TOT} directly from data

→ for the first time width is included therefore no assumption on κ_Z is made



κ–framework interpretation

- Also **fit ratios of coupling modifiers:**

$$\lambda_{ij} = \kappa_i / \kappa_j$$

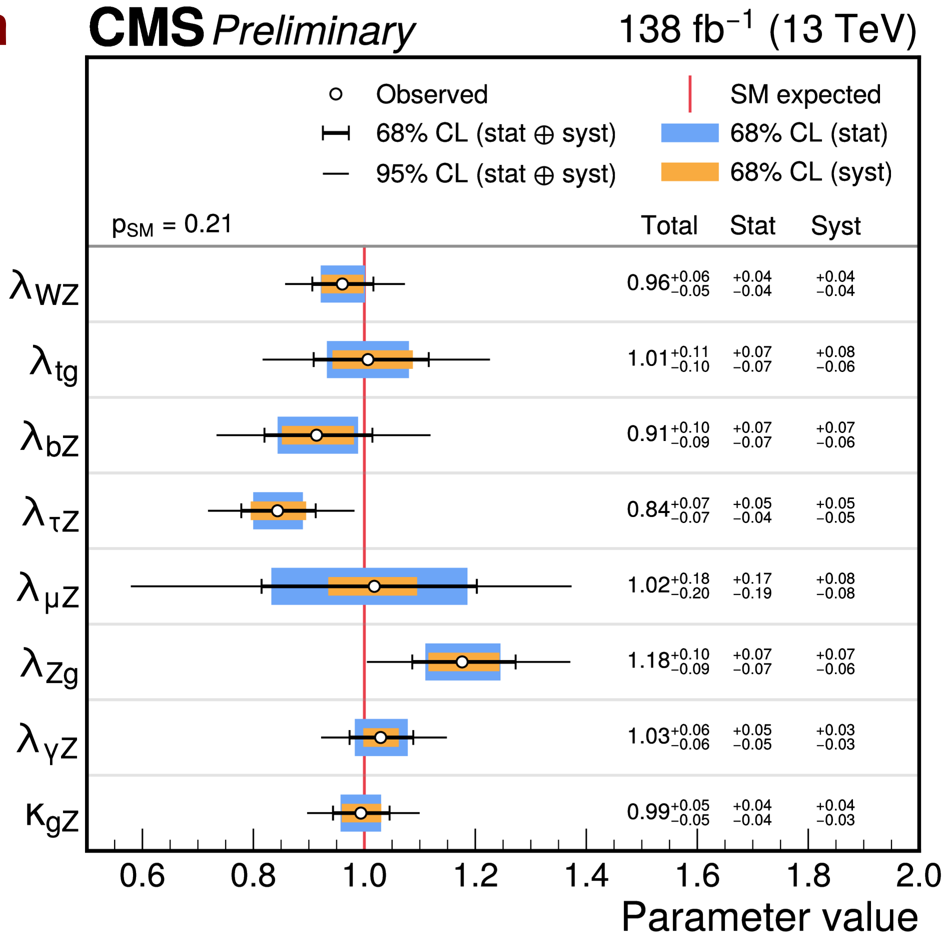
avoids need for assumptions on Γ^{TOT}

- Requires **reference coupling modifier**:

$$\kappa_{gZ} = \kappa_g \kappa_Z / \kappa_H$$

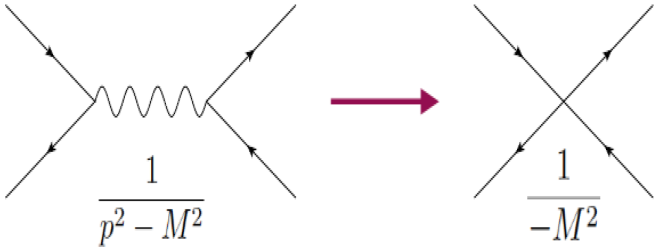
- **Fit** includes all channels except $H \rightarrow$inv and offshell

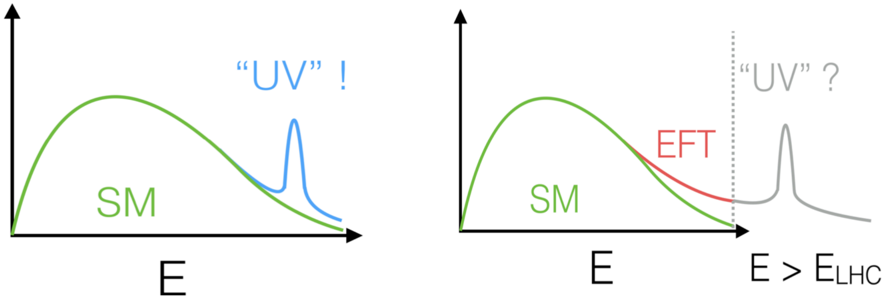
- **Largest value for:** λ_{Zg} $1.18^{+0.10}_{-0.09} \left(^{+0.09}_{-0.08}\right)$



Effective Field Theory (EFT)

- BSM phenomenology at energy scale Λ in the limit E≪Λ





- **Precision measurement** is **key to look for deviations** of SM couplings: achieved using **low-energy approximation EFT** to fundamental Ultraviolet (UV) complete theory

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda}\mathcal{O}_{5,i} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_{6,i} + \sum_i \frac{c_i^{(7)}}{\Lambda^3}\mathcal{O}_{7,i} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_{8,i} + \dots .$$

Lepton number violation

Lepton & Baryon number violation

- Under assumption that the theory cut-off is much larger than the energy, **SMEFT** series can be truncated at **dimension 6** (dim-5 violates L number conservation, dim-7 L and B)
  - dim-8 often neglected and contributing as $1/\Lambda^4$

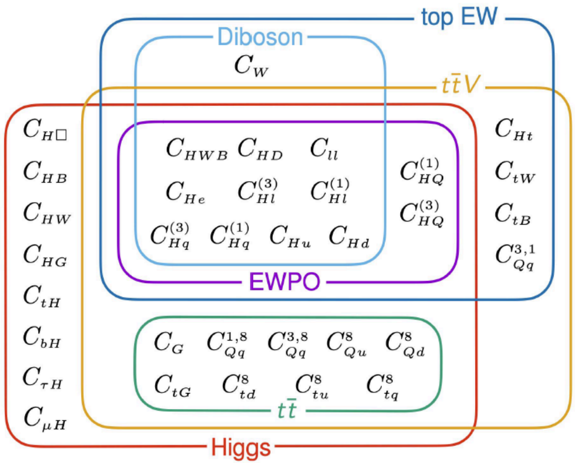
Wilson coefficients c_i & SMEFT parametrization

- Expansion of SM lagrangian in 1/Λ: observables EFT effects are parameterized with a linear and linear+quadratic in c_i s

$$\sigma = |\mathcal{A}_{\mathrm{SM}}|^2 + \sum_i \frac{c_i^{(6)}}{\Lambda^2} 2\mathrm{Re}\left(\mathcal{A}_i^{(6)}\mathcal{A}_{\mathrm{SM}}^*\right) + \sum_i \frac{\left(c_i^{(6)}\right)^2}{\Lambda^4}\left|\mathcal{A}_i^{(6)}\right|^2 + \sum_{i<j}\frac{c_i^{(6)}c_j^{(6)}}{\Lambda^4} 2\mathrm{Re}\left(\mathcal{A}_i^{(6)}\mathcal{A}_j^{(6)*}\right)$$

SM — Interference of SM and NP — Pure NP

$$\sigma = \sigma_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} p_i + \sum_i \frac{c_i^2}{\Lambda^4} p_{2,i} + \sum_{i<j} \frac{c_i c_j}{\Lambda^4} p_{ij}$$

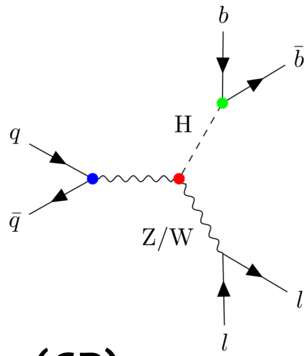


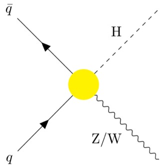
- **SMEFT** is a popular model for EFT interpretation using **dim-6 operators**
  - Easier technical implementation (many available tools at LO and NLO)
  - Covers a wide range of UV complete theories
- Different SM sectors are affected by different EFT operators
- **Global fits** allow us to enhance sensitivity and constrain more directions in the EFT parameter space

SMEFT effects in VH

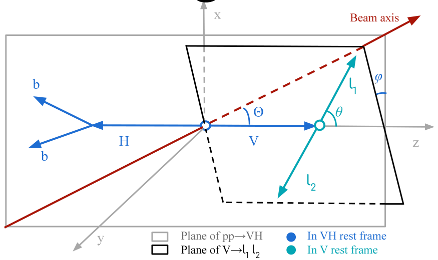
[CMS-PAS-HIG-2023-16, JHEP 03(2025)114]

- **VH(bb)**: Z→ll/νν, W→ lν & H→bb
- qqV, HVV, Hbb vertices as well and new contacts terms HVqq affected by Wilson coefficients

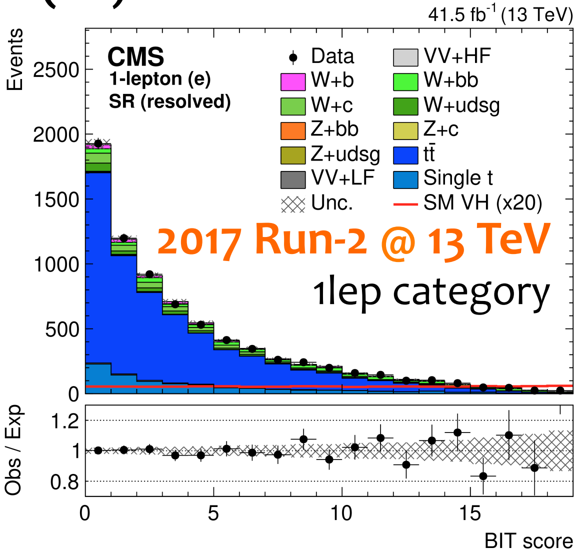




- SMEFT effects probed using
  - cross section(yields), kinematic variables and **angular structure (CP)**



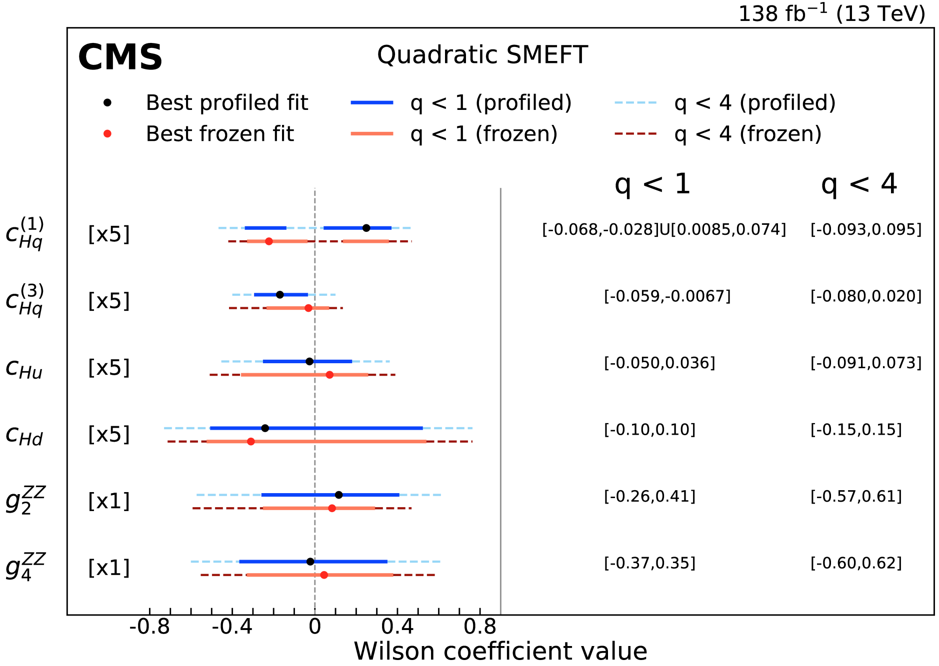
- **Boosted Information Tree (BIT)** regressions to construct likelihood ratio R(x|c) from reco-level quantities x
  - Optimal observable for a given **Wilson coefficients hypothesis c**
- **Fix c = c* and use R(x|c*)** as variable for signal extraction from binned fit
  - c* optimized to provide best sensitivity to simultaneous measurements of all Wilson coefficients

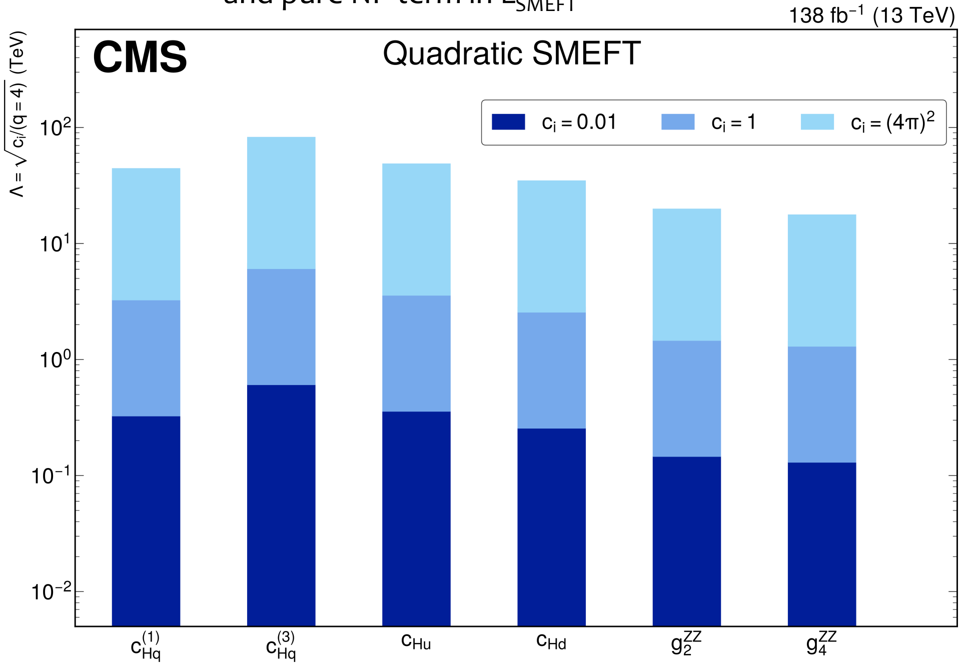


[CMS-PAS-HIG-2023-16, JHEP 03(2025)114]

SMEFT constraints in VH

- For all Wilson coefficients but $c_{Hq(3)}$, $c_{c\,i}$ **quadratic component** dominates over linear
- Constraints on $c_{Hq(1)}$ has two interval in quadratic SMEFT: two minima due to interplay between interference and pure NP term in L_{SMEFT}





- P-value compatibility to SM expectations 84% (quadratic SMEFT)
- Profiled limits on the energy scale Λ
  - Upper limits on the Wil c_i's corresponding to q= 4 used for translating the constraints to Λ

SMEFT constraints in H(WW)

- The **fiducial differential** cross section in VBF and ggF for **H(WW) + 2 jets**

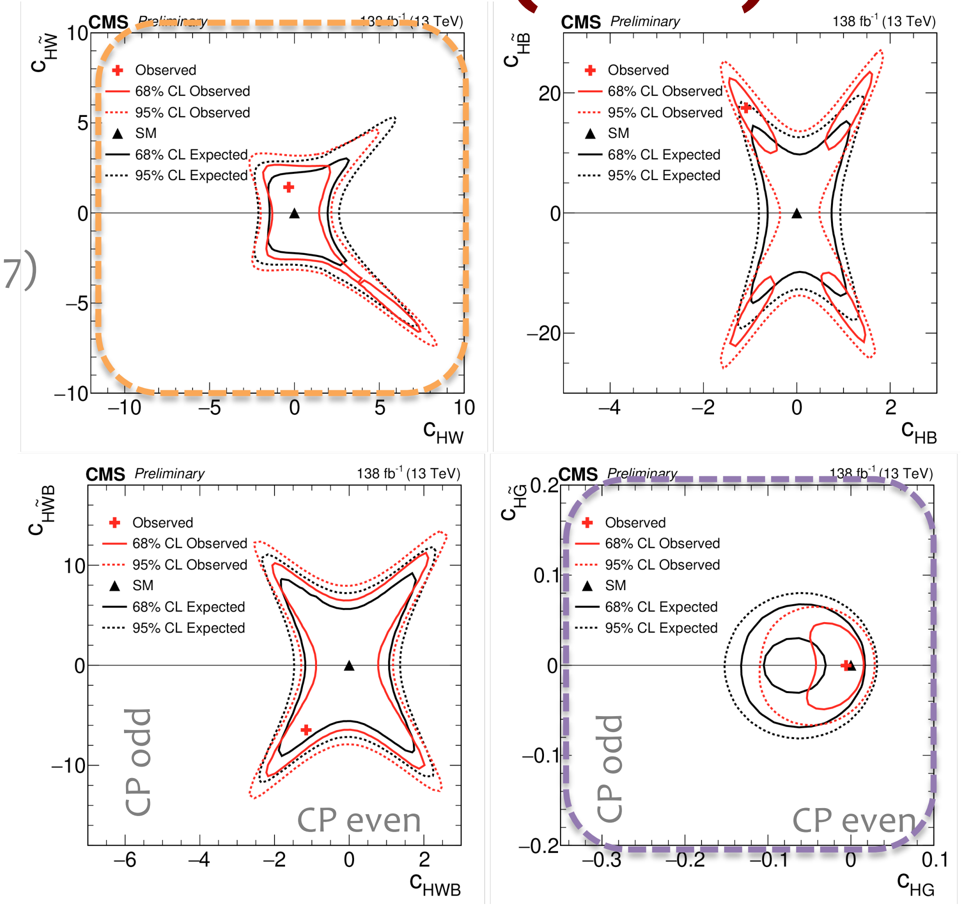
- Differential cross section measurements (see p. 7) used to constrain Wilson coefficients SMEFT

The strongest constraints for:

- the VBF cross section measurement under the assumption of the **CP-even C_{HW}** coefficient

- the ggF cross section measurement sensitive to the **CP-even c_{HG}** coefficient

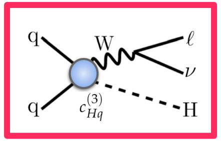
- All results consistent with the SM expectations



[CMS-PAS-HIG-21-018, April 2025]

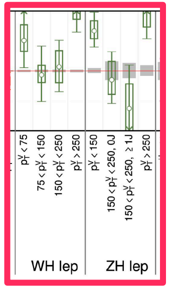
SMEFT interpretation using STXS

- Several interpretations including SMEFT of full Run-2 CMS Higgs combination performed
  - Using STXS phase-space for EFT extraction
  - Linear ($1/\Lambda^2$) and linear+quadratic ($1/\Lambda^4$) parametrization in EFT coupling expansion
  - SMEFT@NLO with propagator corrections included
- **Constraints on one Wilson coefficient at a time** while fixing others to SM
  - probed 43 SMEFT coefficients

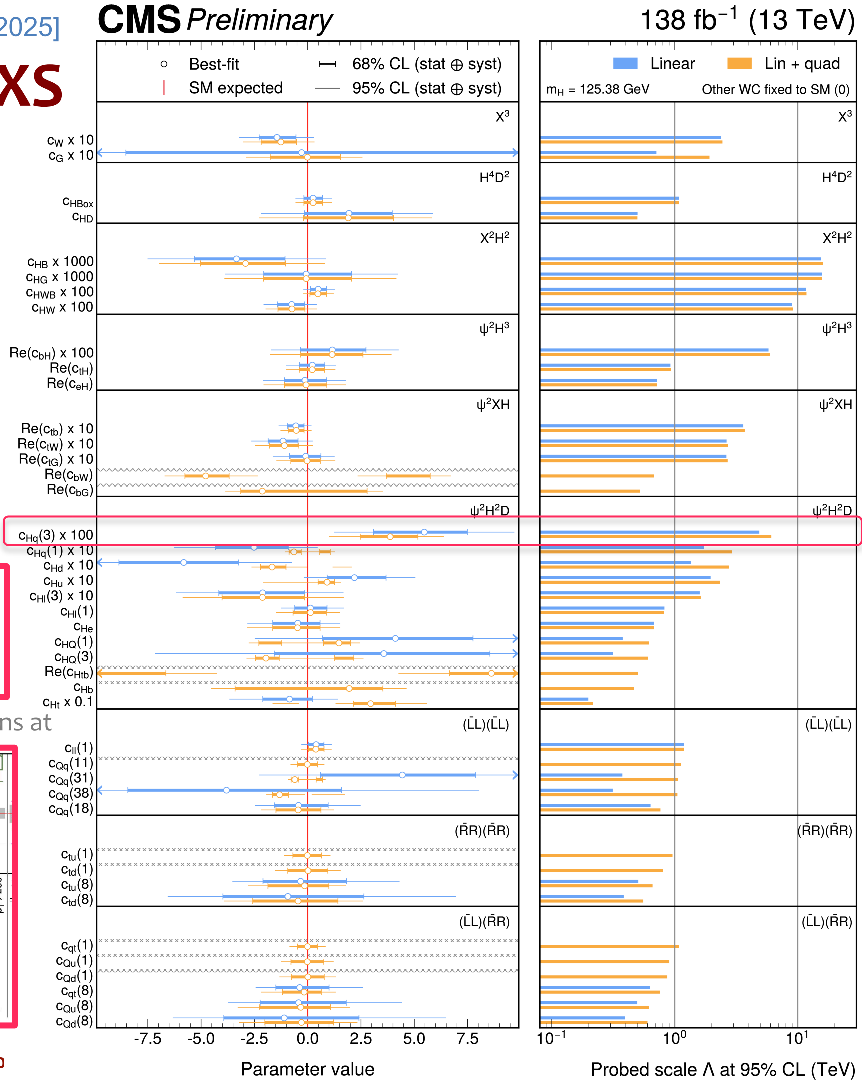


- In the right panel, the results translated into a 95% lower limit on the new Λ scale

Consistent with deviations at high p_T in WH, ZH leptonic regions p. 10



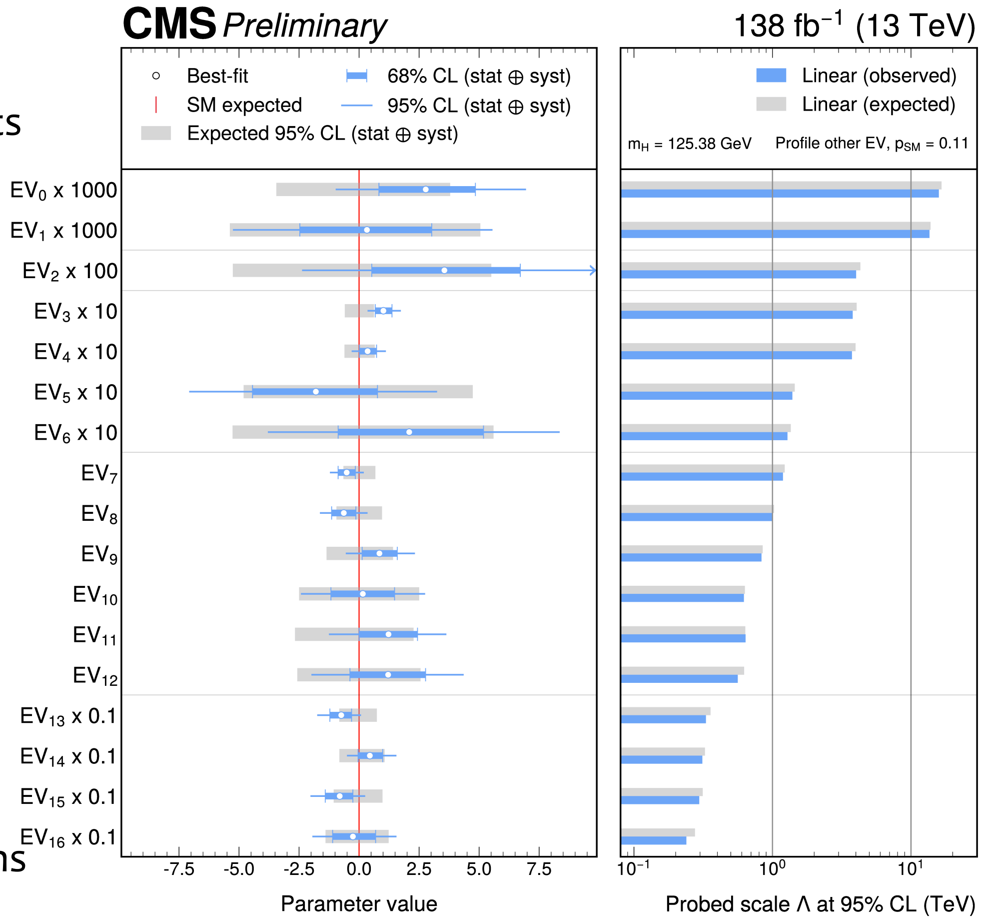
- Very granular combination ensures full coverage of SMEFT phase-space
  - Results overall consistent to SM expectations



SMEFT interpretation using PCA

[CMS_PAS-HIG-21-018, April 2025]

- Removing flat directions will lead to **Principal Component Analysis (PCA)** constraints
- Constraints on the **linear combinations** Wilson c_i extracted with the PCA procedure
  - PCA procedure on 97 POI covariance matrix to identify sensitive directions
  - simultaneous fit to 17 combination of c_i for linear parameterization with terms up to $O(EV/\Lambda^2)$
- In the right panel, the results translated into a 95% lower limit on the **new physics energy scale Λ**, assuming $Ev_j = 1$
- Good overall compatibility with SM expectations (11% p-value)

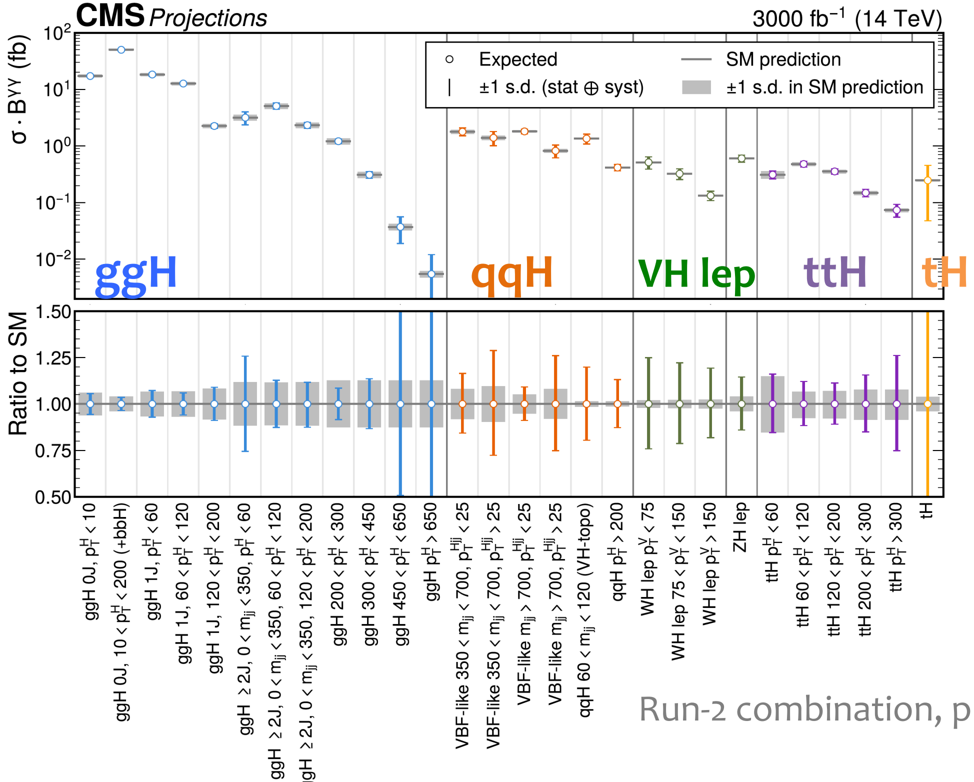


Future High-Luminosity LHC projections

- The HL-LHC physics programme will be **crucial for** deepening the understanding of fundamental physics, enabling in particular **precision studies of the Higgs sector** and enhancing sensitivity to rare processes and **potential new physics**

$\mathcal{L}$		$\delta\mu$ [%] $H \to Z\gamma$	$\delta\mu$ [%] $H \to \mu\mu$
2 ab^{-1}	ATLAS	21	13
	CMS	23	8.4
	ATLAS+CMS	15	7.1
3 ab^{-1}	ATLAS	17	11
	CMS	19	7.0
	ATLAS+CMS	14	5.9

Projected uncertainties in % on signal strengths (μ)



Run-2 combination, p.11

Higgs STXS and EFT – Summary

- **Run-2** data has **enabled** significantly **more granular measurements**
- CMS released **fiducial differential** and many **STXS cross section** measurements
- CMS provided the **legacy combination** of all channels with a full Run 2 data, including an extended **SMEFT interpretation**
- **Run-3** might give a hint to new physics
  - If DATA/SM predictions increase…
  - Run-3 statistics will help to improve SMEFT constraints
- More results in the near future

Discovery through the precision?!

- https://cms-results.web.cern.ch/cms-results/public-results/publications/HIG/
- https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG/

Thank you!

Granted *by the Polish Ministry of Science,* ***2022/WK/14***

References

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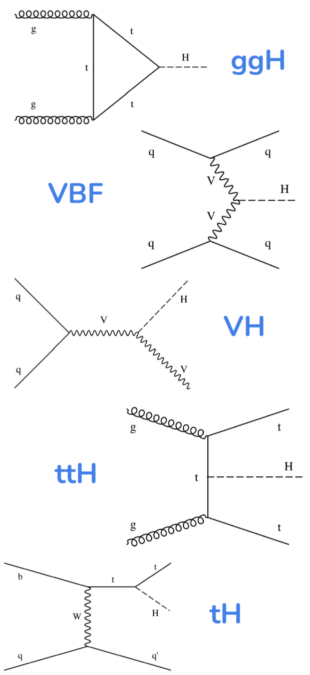
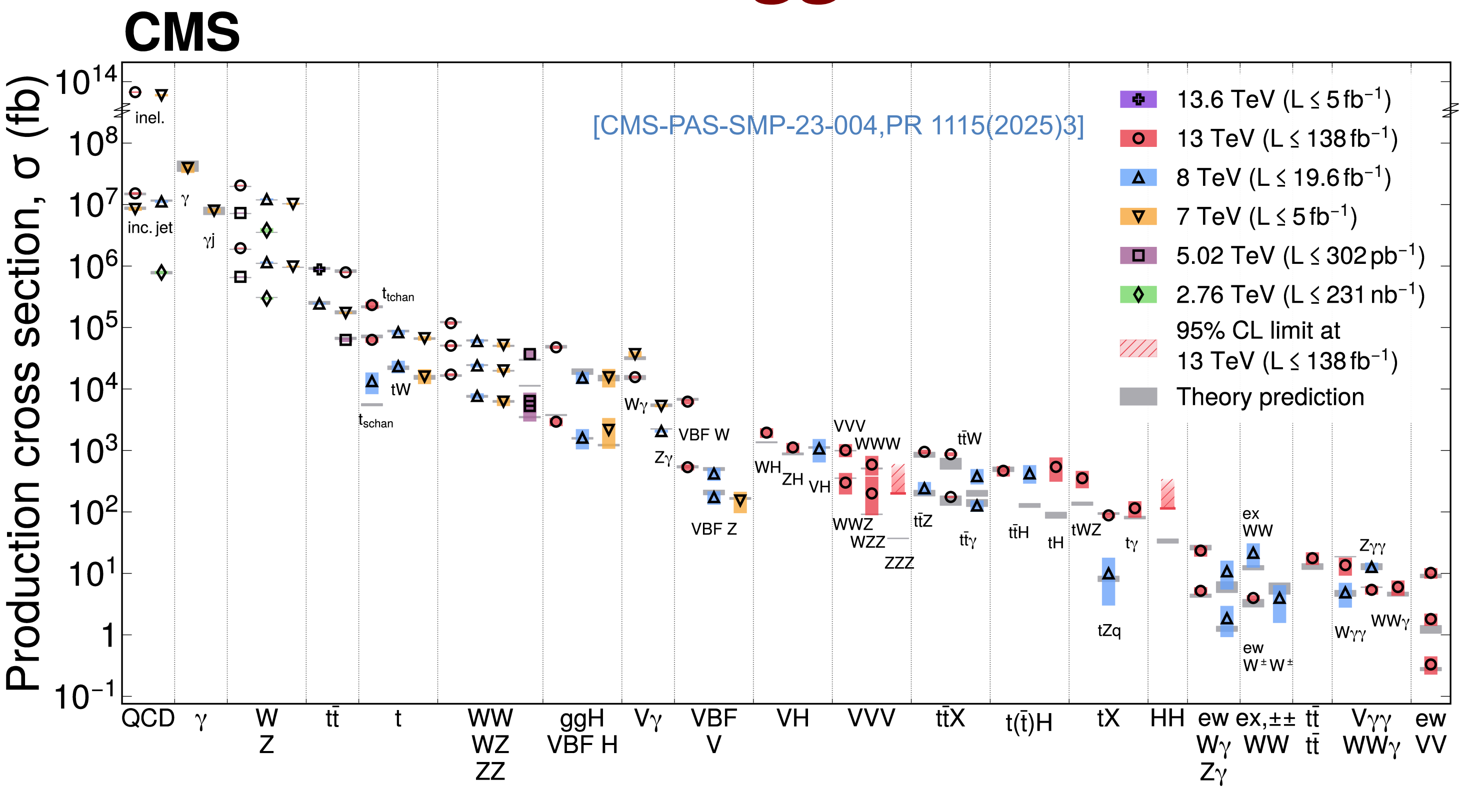
- CMS-NOTE-25-007, HL-LHC projections for single Higgs boson measurements at the CMS experiment; March 2025

Production of Higgs Boson



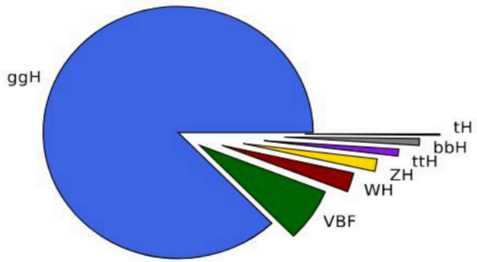


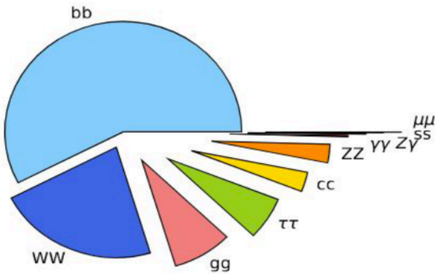
- Explore Higgs interactions to **uncover deviations** that could hint at BSM physics

Cross sections of Higgs Boson

Production mode	Cross section (pb)
ggH	48.31 ± 2.44
VBF	3.771 ± 0.807
WH	1.359 ± 0.028
ZH	0.877 ± 0.036
ttH	0.503 ± 0.035
bbH	0.482 ± 0.097
tH	0.092 ± 0.008

Decay channel	Branching fraction (%)
bb	57.63 ± 0.70
WW	22.00 ± 0.33
gg	8.15 ± 0.42
$\tau\tau$	6.21 ± 0.09
cc	2.86 ± 0.09
ZZ	2.71 ± 0.04
$\gamma\gamma$	0.227 ± 0.005
$Z\gamma$	0.157 ± 0.009
ss	0.025 ± 0.001
$\mu\mu$	0.0216 ± 0.0004

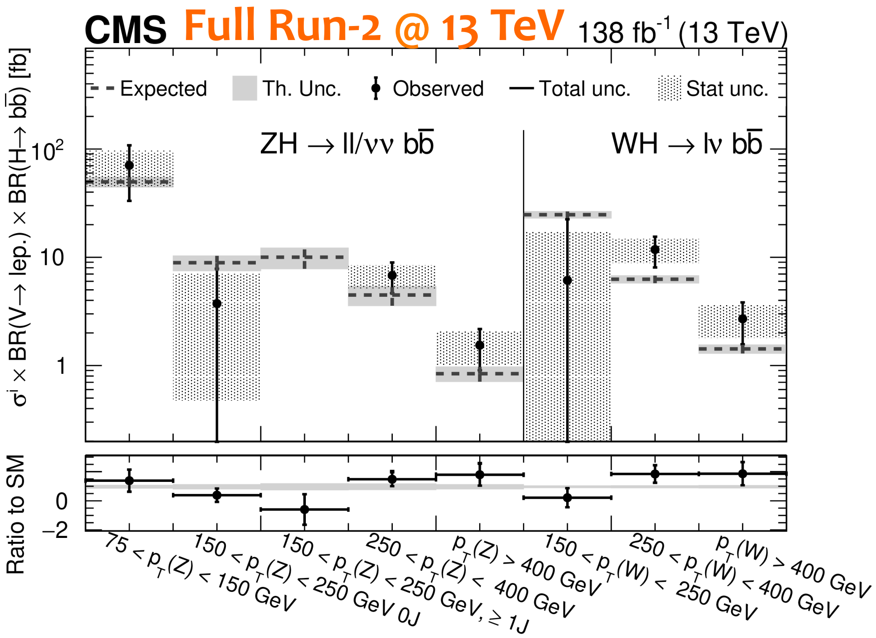




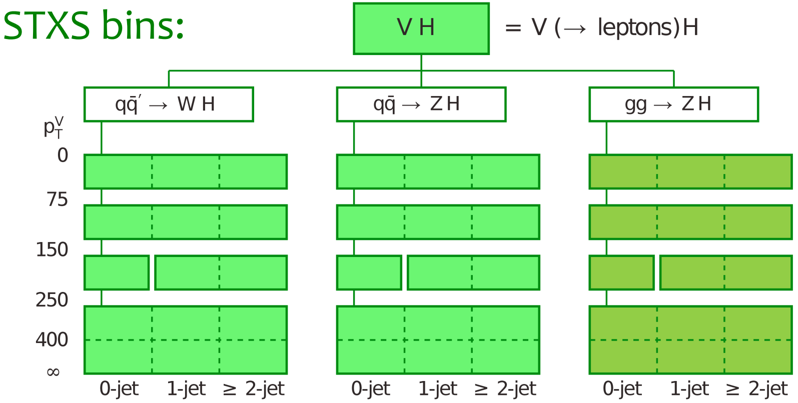
SM predictions @ 13 TeV

STXS measurements with VH

- STXS measurements for VH(bb): Z→ll/νν, W→ lν & H→bb



[Phys.Rev.D 109(2024)092011,HIG-21-001]



A subcategorization in p_T is applied to maximize the sensitivity of different STXS bins

- Within the uncertainties, the differential cross sections agree with the SM predictions
- The overall signal strength, combining all analysis categories, is $\mu = 1.15^{+0.22}_{-0.20}$

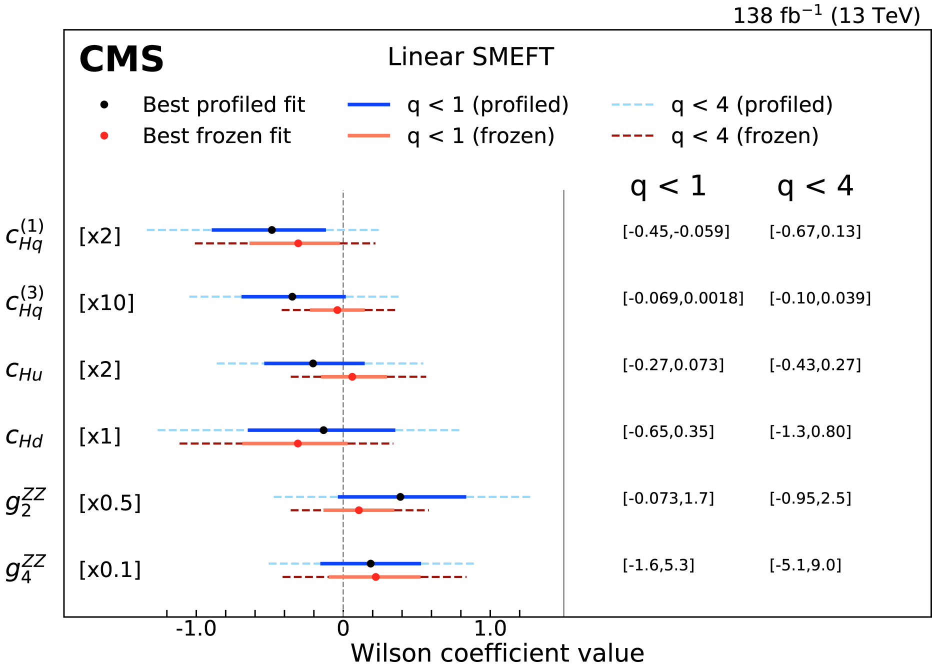
Recent Higgs Xs measurements

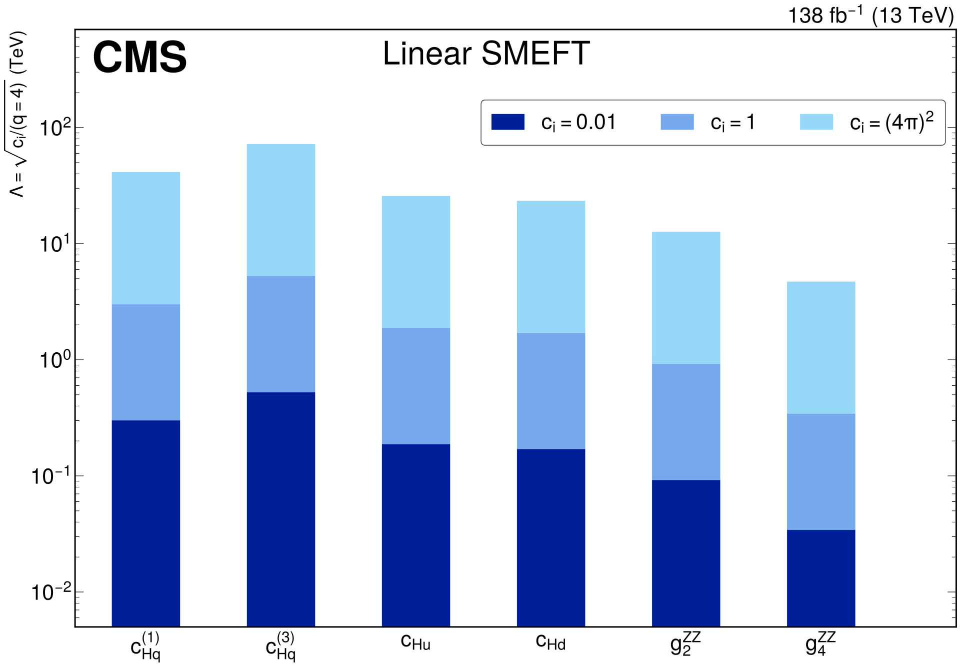
- First **differential** measurement for **ttH multilepton + jets** channel using full **Run-2**
- Top Yukawa coupling **sensitive to BSM effects**
- Target Higgs decay modes **H→ WW → lνlν / lνqq** and **H→ ττ → hadrons/leptons+ν's**
- Machine-learning techniques (DNN) used for the separation sig./bkg.

H boson p_T bin	Signal strength
$[0, 120)$ GeV	-0.78 ± 0.64 (stat) ± 0.48 (syst)
$[120, 200)$ GeV	4.36 ± 1.42 (stat) ± 0.80 (syst)
$[200, \infty)$ GeV	-1.32 ± 0.86 (stat) ± 0.46 (syst)
$m_{t\bar{t}H}$ **bin**	**Signal strength**
$[0, 750)$ GeV	0.71 ± 0.58 (stat) ± 0.36 (syst)
$[750, 1000)$ GeV	0.90 ± 1.23 (stat) ± 0.63 (syst)
$[1000, \infty)$ GeV	0.92 ± 1.02 (stat) ± 0.55 (syst)

[CMS-PAS-HIG-2023-16, JHEP 03(2025)114]

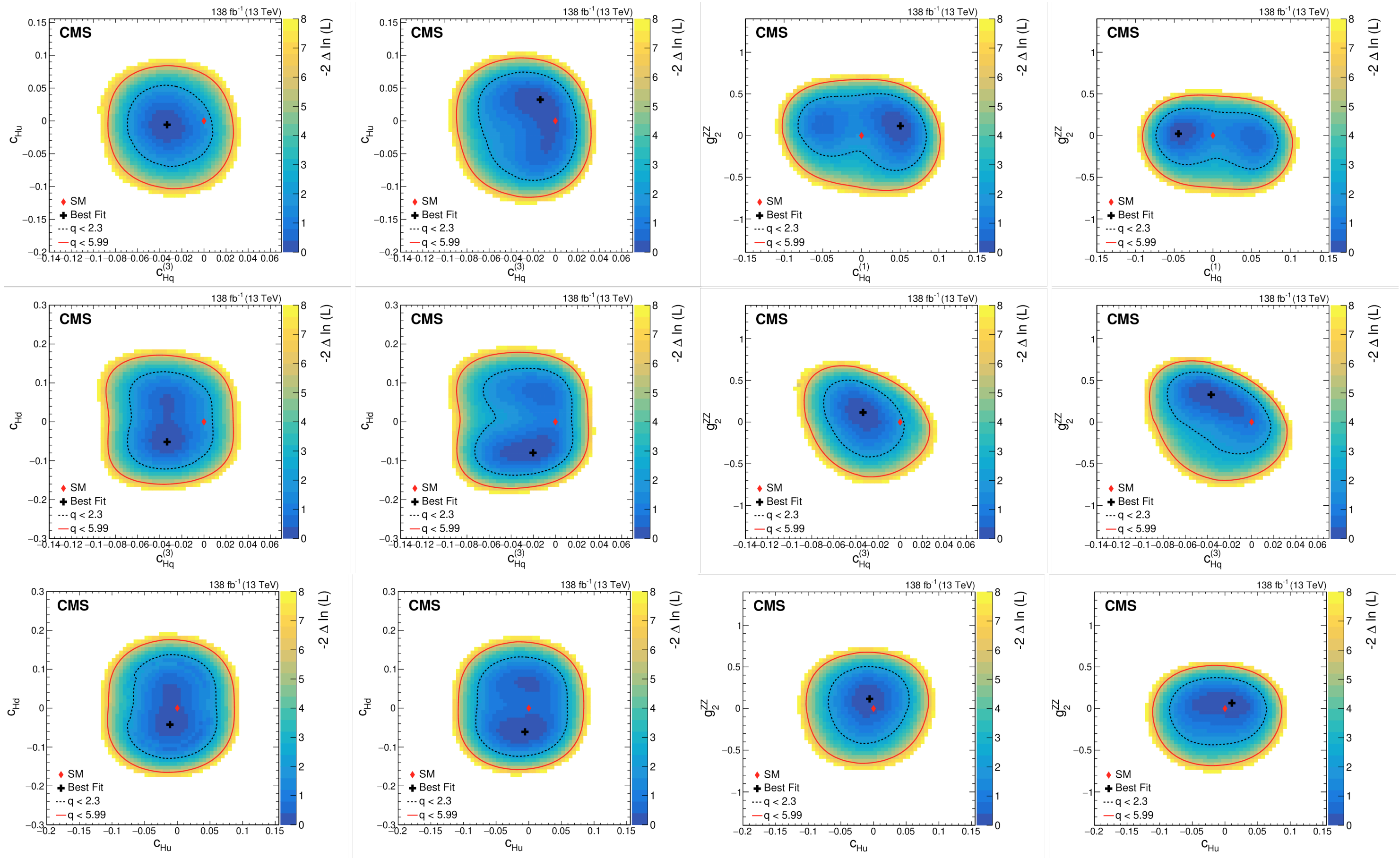
SMEFT effects in VH





- P-value compatibility to SM expectation is 73% (linear SMEFT)

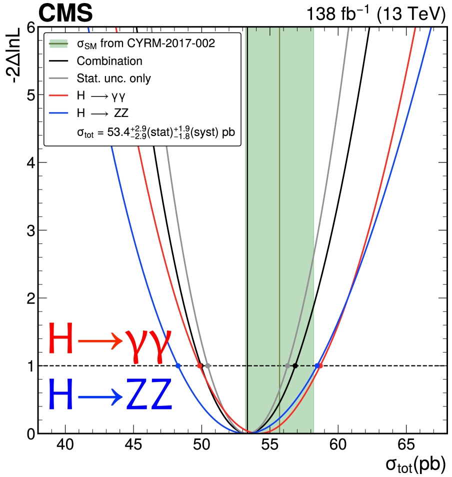
SMEFT effects in VH



SMEFT interpretation using differential Higgs combination

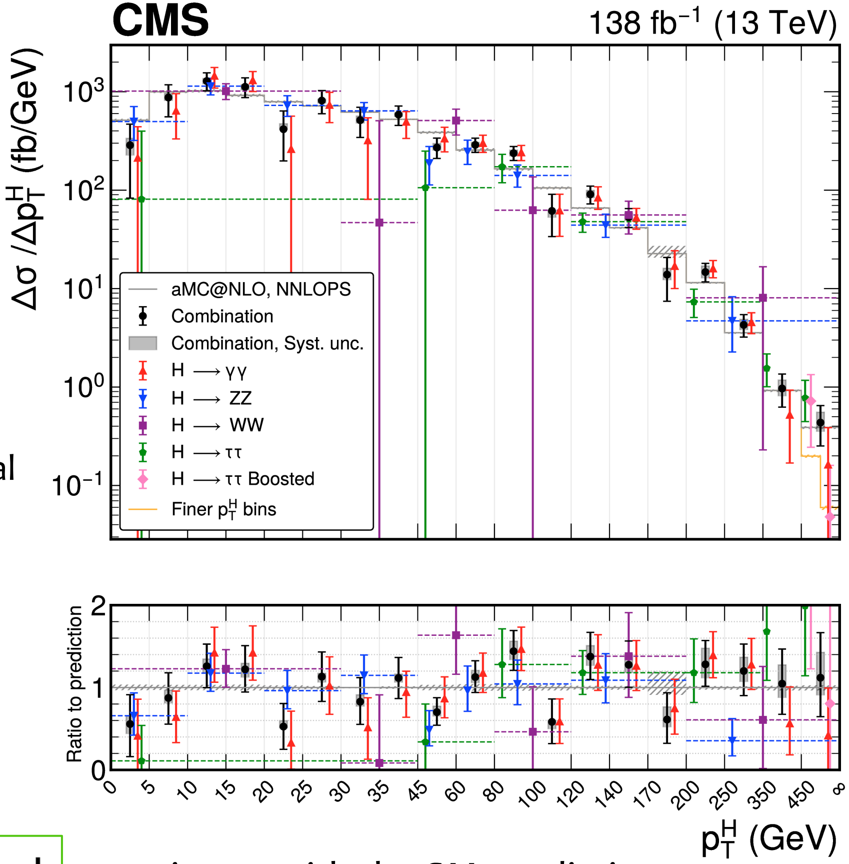
- Combined measurements of the **total** and **differential Higgs boson production cross sections** for different observables, eg.: p^H_T, N_{jets}, $|y_H|$

- The spectra are obtained with data from **4 decay channels:** $H\to\gamma\gamma$, $H\to ZZ(*)\to 4\ell$, $H\to WW(*)\to e\mu\nu_\ell\nu_\ell$, and $H\to\tau\tau$



The precision of the combined measurement of the p^H_T differential cross section is improved by about 20% w.r.t the $H\to\gamma\gamma$ alone

The improvement is particularly significant in the low- and high-p^H_T regions



$$53.4\ ^{+2.9}_{-2.9}\ \text{(stat)}\ ^{+1.9}_{-1.8}\ \text{(syst) pb}$$

consistent with the SM prediction

[CMS-PAS-HIG-23-013, July 2024]

SMEFT interpretation using differential Higgs combination

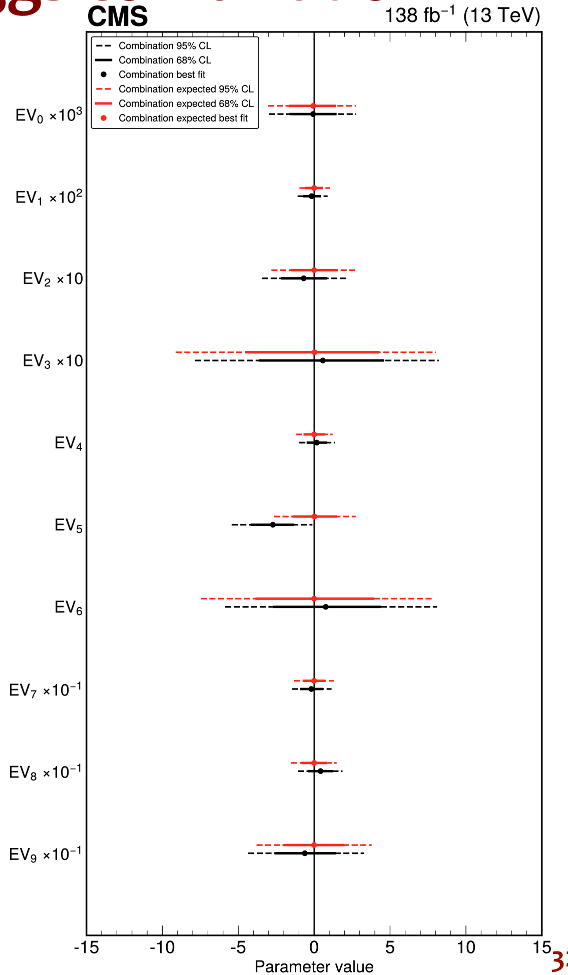
- **Principal Component Analysis (PCA)** applied to identify flat directions of combined EFT likelihood
  - 10 linear combinations of EV's that are constrained simultaneously
  - Results compatible with SM expectations

⟶ The differential fiducial cross section measurements are sensitive to a limited set of operators and related Wilson coefficients, with the most constrained ones being **c_{HG}, c_{HB}, c_{HW} and c_{HWB}**

CMS   138 fb^{-1} (13 TeV)

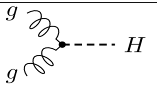
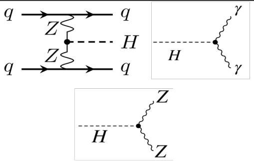
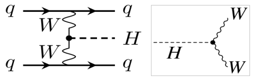
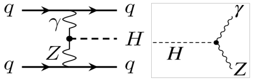
	Re(c_{bB})	Im(c_{bH})	Re(c_{bH})	Im(c_{bW})	Re(c_{bW})	Im(c_{eH})	Re(c_{eH})	c_{HB}	c_{Hbox}	c_{Hb}	c_{Hd}	c_{HD}	c_{He}	c_{HG}	$c_{Hq}^{(1)}$	$c_{Hq}^{(3)}$
EV0			-0.09					0.80						-0.30		
EV1			0.14					0.26						0.94		
EV2			-0.97				0.04	-0.01	-0.03			-0.01	0.04	0.16		0.04
EV3			0.10				0.09	0.04			0.01	-0.01	0.03	0.01	0.04	-0.60
EV4			0.07				-0.41	0.12			-0.01	-0.18	0.41			0.04
EV5			-0.12				-0.17	-0.07	0.01		0.01	0.04	-0.14		0.10	-0.71
EV6							-0.14	-0.08	0.01		-0.06	0.05	-0.15		-0.87	0.05
EV7			-0.02				-0.20	-0.18	-0.02		-0.28	0.07	-0.10	0.02	0.33	0.07
EV8			0.03				-0.18	-0.03	0.05		0.39	0.08	-0.27		0.31	0.32
EV9			-0.01	0.02	-0.02		0.03	-0.05	-0.02		0.80	-0.01	0.06		-0.12	-0.11

	$c_{Hl}^{(1)}$	$c_{Hl}^{(3)}$	$c_{HQ}^{(1)}$	$c_{HQ}^{(3)}$	c_{Ht}	c_{Hu}	c_{HW}	c_{HWB}	$c_{ll}^{(')}$	Re(c_{tB})	Re(c_{tG})	Re(c_{tH})	Re(c_{tW})	Re(c_{uH})	c_W	λ
EV0							0.26	-0.44		0.04	0.02		0.02		0.02	λ = 499589
EV1							0.08	-0.15		0.01	-0.03					λ = 118374
EV2	-0.06	0.03					-0.07	0.02			0.14	0.03				λ = 106
EV3	-0.03	-0.08				-0.05	-0.14	-0.01	0.10		0.76		0.01			λ = 8.133
EV4	-0.52	0.37					-0.10	0.16	-0.40	-0.02	0.10	0.01	-0.01			λ = 2.133
EV5	0.18	0.28				-0.09	0.04	-0.10	-0.24		-0.45	-0.10	0.03			λ = 0.535
EV6	0.19	0.18	-0.02	-0.01		-0.14	0.17	-0.04	-0.17		0.18	-0.05	-0.02			λ = 0.096
EV7	0.11	0.05				0.10	0.76	0.12	-0.14		0.26	0.09	-0.04			λ = 0.039
EV8	0.36	0.32		0.04		-0.12	-0.25	-0.18	-0.23	0.02	0.28	-0.15	0.18			λ = 0.021
EV9	-0.08	-0.03	0.02	-0.03		0.45	0.30	0.09	0.03	-0.01	-0.02	0.04	-0.09			λ = 0.006

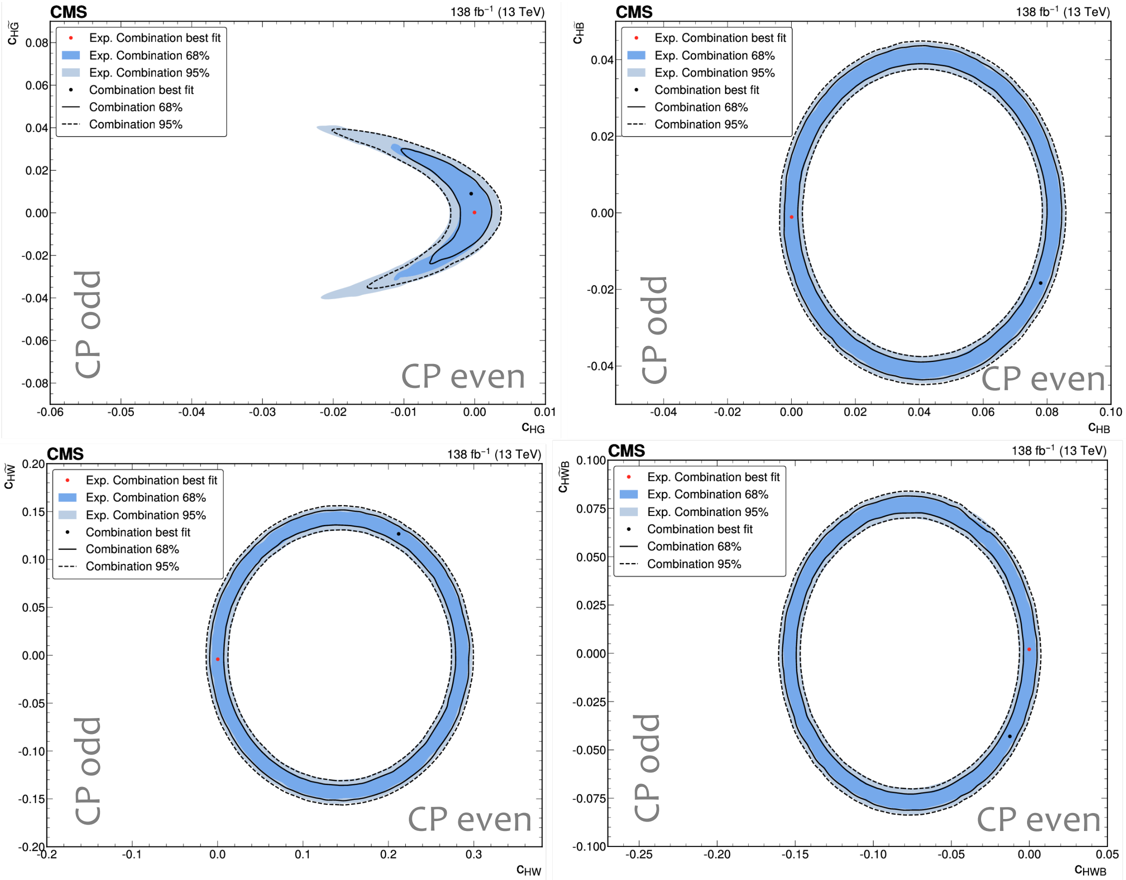


EFT interpretation using differential Higgs combination

- For X^2H^2 operators, those most constrained Wilson c_i: c_{HG}, c_{HB}, c_{HW}, c_{HWB} provide **2D limits on CP**

Wilson coefficient	Example process
c_{HG}, $\tilde{c}_{HG}$	
c_{HB}, $\tilde{c}_{HB}$	
c_{HW}, $\tilde{c}_{HW}$	
c_{HWB}, $\tilde{c}_{HWB}$	

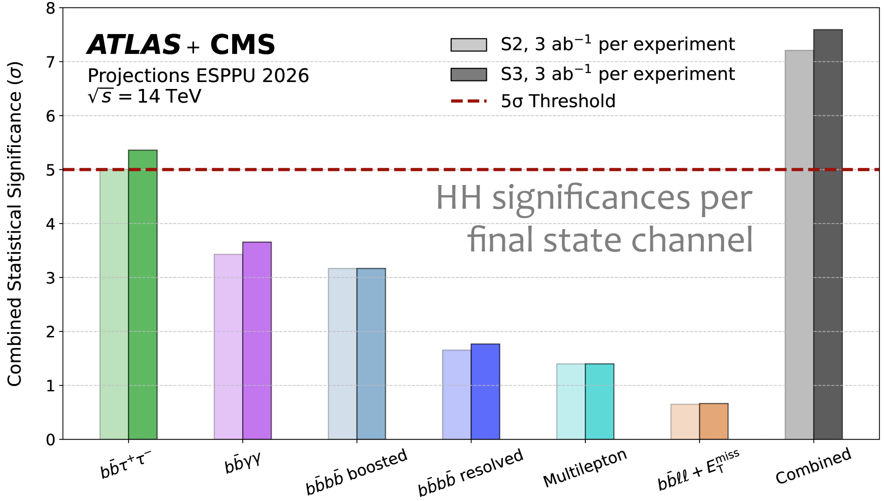
- Results are consistent with SM at 68% CL

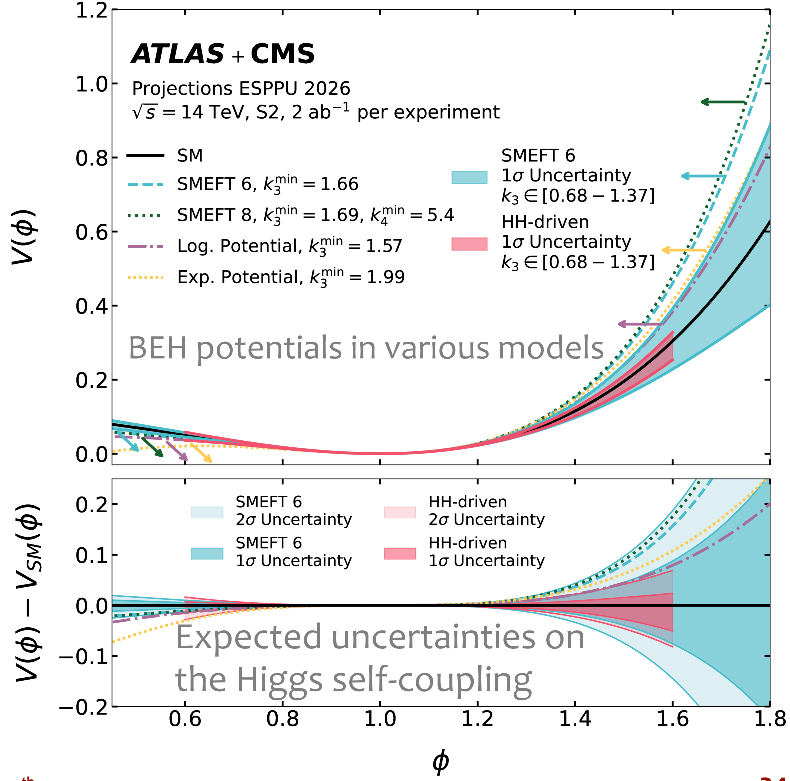


[CMS-PAS-HIG-25-002, CMS-NOTE-25-003]

Future High-Luminosity LHC projections

- The HL-LHC physics programme will be crucial for deepening the understanding of fundamental physics, enabling in particular **precision studies of the Higgs sector** and enhancing sensitivity to rare processes and potential new physics





The first Run-2 combination of single-H and HH boson production channels to constrain the Higgs self-coupling

Observed (expected) interval at 2σ CL

$-1.2 < \kappa_\lambda < 7.5$

$(-2.0 < \kappa_\lambda < 7.7)$

→ see Jin Wang talk