Higgs Combined Measurements at CMS

Massimiliano Galli (ETH Zürich, IPA) on behalf of the CMS Collaboration

Higgs 2024

November 5th 2024

ETH zürich

Introduction

CMS ETH zürich

- Higgs boson features became clearer over the past 12 years
- Still several puzzles: naturalness of Higgs mass, stability of the universe, matter-antimatter asymmetry, etc.
- Higgs boson measurements are a natural probe for new physics (can affect number of signal events, shapes, production, decay, etc.)
- **Combinations of its measurements allow to reach ultimate level of precision**
- This talk: **latest CMS Higgs combinations** for couplings measurements

Nature 607, 60-68 (2022)

Article

A portrait of the Higgs boson by the CMS experiment ten years after the discovery

https://doi.org/10.1038/s41586-022-04892-x The

- 14 single-H analyses, 9 decay channels
- 6 HH analyses, 5 decay channel
- **Signal strength** and **coupling modifiers (κ)**

Submitted to Phys. Lett. B

Constraints on the Higgs boson self-coupling from the combination of single and double Higgs boson production in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

- 11 single-H analyses, 7 HH analyses
- Inclusive and **STXS bins**
- **Coupling modifiers (κ)**

CMS-PAS-HIG-23-013

Combination and interpretation of fiducial differential Higgs boson production cross sections at $\sqrt{s} = 13$ TeV

- 5 single-H analyses
- **Fiducial differential XS** measurements in bins of Higgs-related observables
- Interpretation with **coupling modifiers (κ)** and **effective field theories**

Latest HH combination in J. Motta's and R. Gerosa's talks

Types of Higgs Coupling Measurements Combined

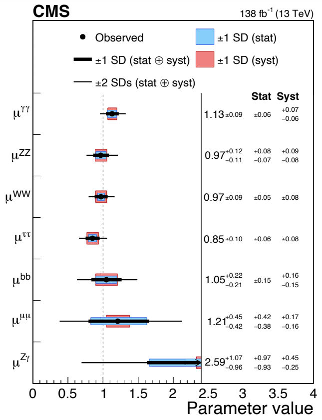
CMS ETH zürich

Run 1 → **Run 2 (+ Run 3, HL-HLC)**

Signal strength modifiers

- Scale the observed yield with respect to SM prediction
- Can hide compensations from different effects

$$\mu = \frac{\sigma \cdot \mathrm{BR}}{\sigma^{SM} \cdot \mathrm{BR}^{SM}}$$



κ-Framework

- Simple parametrization of deviations from SM derived at amplitude level
  - Assume only one underlying state at 125 GeV
  - Narrow width approximation
- Sensitive to interference effects
- Only modify couplings strengths, same tensor structure as SM

$$\sigma_i \sim \kappa_i^2 \sigma_i^{SM}$$

$$\Gamma_f \sim \kappa_f^2 \Gamma_f^{SM}$$

$$\sigma_i \cdot \mathrm{BR}^f = \left(\frac{\sigma_i \Gamma_f}{\Gamma_H}\right)_{SM} \cdot \frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2}$$

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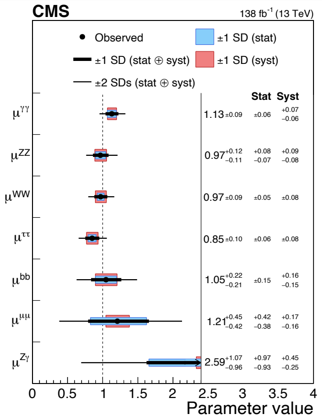
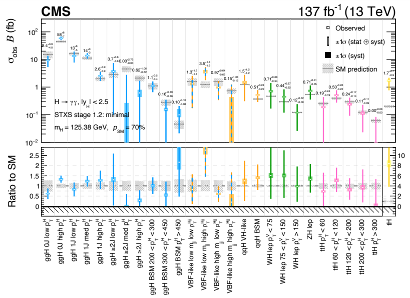


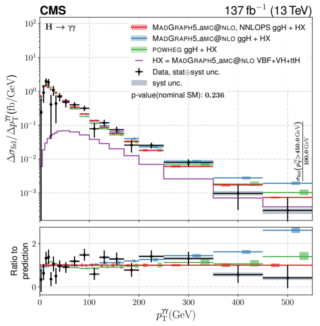
STXS



Bins defined to minimize theoretical uncertainties

Fiducial diff. cross sections

- Measurements performed in a fiducial phase space close to detector acceptance
- Minimize model dependence



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Types of Higgs Coupling Measurements Combined

CMS ETHzürich

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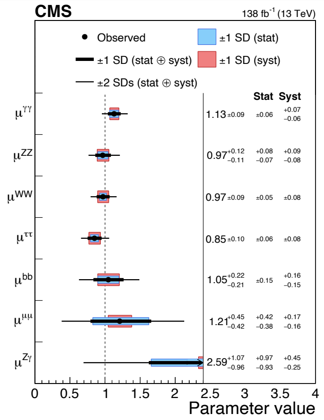
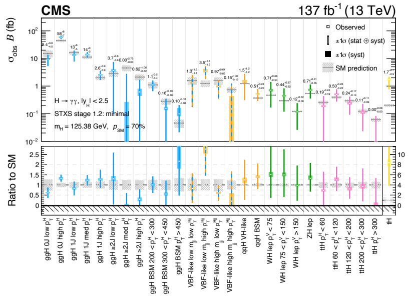


STXS



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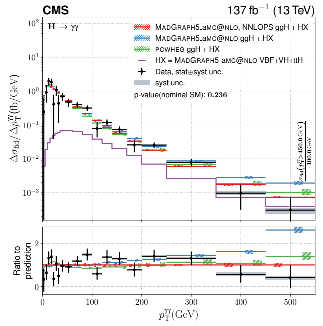

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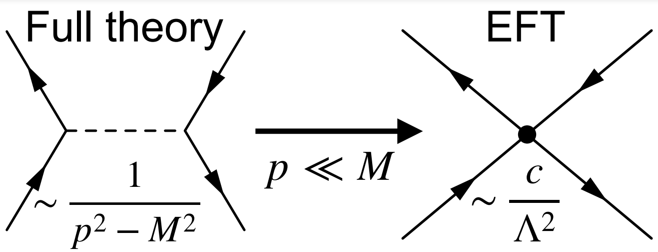
Effective field theories (EFT)



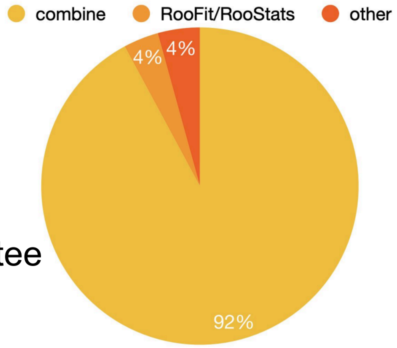
$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_{i=5}^{\infty} \sum_{j=0}^{N_i} \frac{c_j^{(i)}}{\Lambda^{i-4}} O_j^{(i)}$$

- More general than κ -formalism
- Operators can induce couplings with different Lorentz structure than SM → modification of Higgs kinematics
- Set constraints on Wilson coefficients (WC) associated to the operators

The Combination Procedure

- Standard combination strategy:
  - **Likelihood multiplication** of different input channels
  - Fully account for **correlation** of nuisance parameters across channels
- **Combine tool** developed for the discovery
  - Used by >90% CMS analyses (not only Higgs!)
  - Accounts for the increasing complexity of the analyses
  - **Paper + full 2012 combined likelihoods were published this year!**

arXiv:2404.06614



From CMS Statistics Committee Questionaires 2021-2022

Physics Model

$$\mu \;\; \mu(\vec{\kappa}) \;\; \mu(\vec{c}) \cdots$$

Data+MC

Counting experiment

Parametric shape analysis

Template-based shape analysis

Likelihood

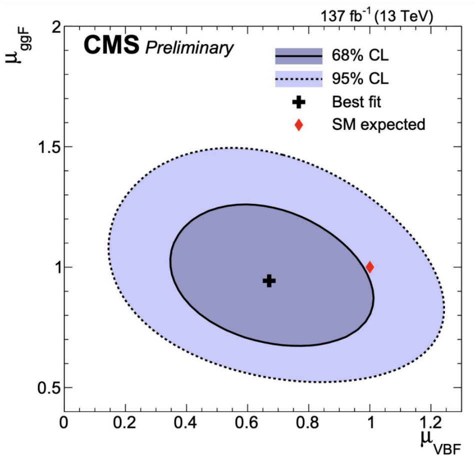
$$\mathscr{L}(\vec{\mu},\vec{\nu}) = \prod_d p\left(\vec{x}_d;\vec{\mu},\vec{\nu}\right) \prod_k p_k\left(y_k;\nu_k\right)$$

Build test statistics

Minimization

- $\vec{\mu}$: parameters of interest
- $\vec{\nu}$: nuisance parameters
- $\vec{y}$: auxiliary variables
- $\vec{x}_d$: channels

Results



Differential Cross Sections

- **Full Run2 combination of (single) Higgs production differential cross section measurements**
- Combined measurements provided for: p_T^H, N_{jets}, $|y_H|$, $p_T^{j_1}$, m_{jj}, $|\Delta\eta_{jj}|$, τ_C^j

$$n_i^{\mathrm{sig},km}(\vec{\mu} \mid \vec{\nu}) = \sum_{j=1}^{n_{\mathrm{bins},k}^{\mathrm{gen}}} \mu_j \sigma_j^{\mathrm{SM}} A_j^{km} \varepsilon_{ji}^{km}(\vec{\nu}) L(\vec{\nu}) \mathscr{B}^m$$

Fiducial acceptance

$$\mu = \frac{\sigma \cdot \mathrm{BR} \cdot A}{\sigma^{\mathrm{SM}} \cdot \mathrm{BR}^{\mathrm{SM}} \cdot A^{\mathrm{SM}}}$$

Individual channel

Extrapolation to inclusive phase space 4π (introduces **unavoidable model dependence**)

$$\mu = \frac{\sigma}{\sigma^{\mathrm{SM}}}$$

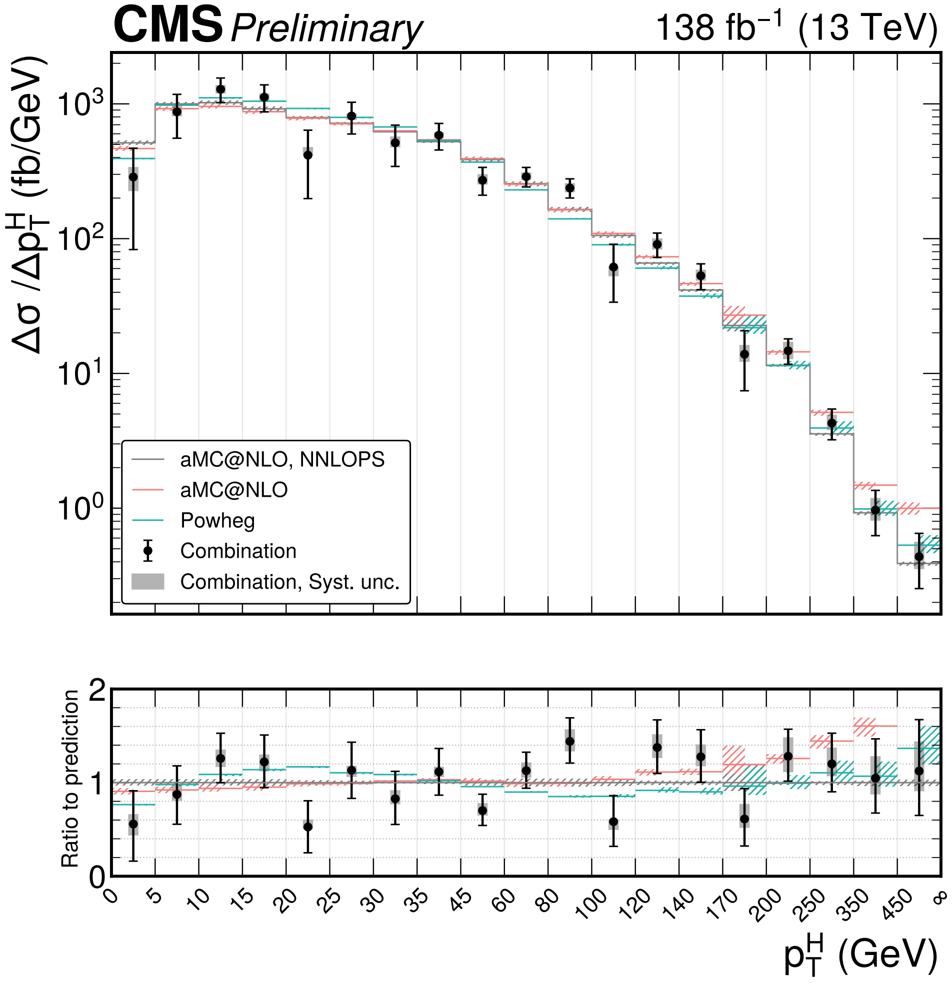
Combination

CMS-PAS-HIG-23-013

Analysis	Reference
$\mathrm{H} \rightarrow \gamma\gamma$	JHEP 07 (2023) 091
$\mathrm{H} \rightarrow \mathrm{ZZ}^{(*)} \rightarrow 4l$	JHEP 08 (2023) 040
$\mathrm{H} \rightarrow \mathrm{W}^+\mathrm{W}^{-(*)} \rightarrow \mathrm{e}^{\pm}\mu^{\mp}\nu_1\bar{\nu}_1$	JHEP 03 (2021) 003
$\mathrm{H} \rightarrow \tau^+\tau^-$	Phys. Rev. Lett. 128 (2022) 081805
$\mathrm{H} \rightarrow \tau^+\tau^-$ (boosted)	Phys. Lett. B 857 (2024) 138964

Differential Cross Sections

Fiducial diff. cross sections



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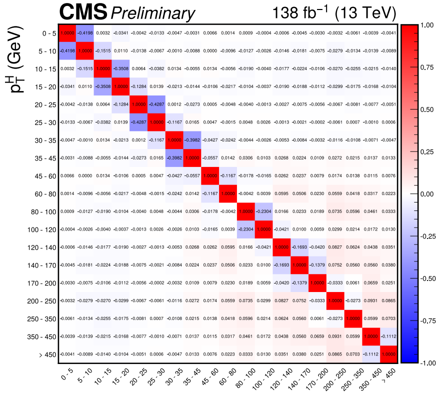
- No relevant discrepancies with the SM
- p_T^H measurement at ultimate level of precision



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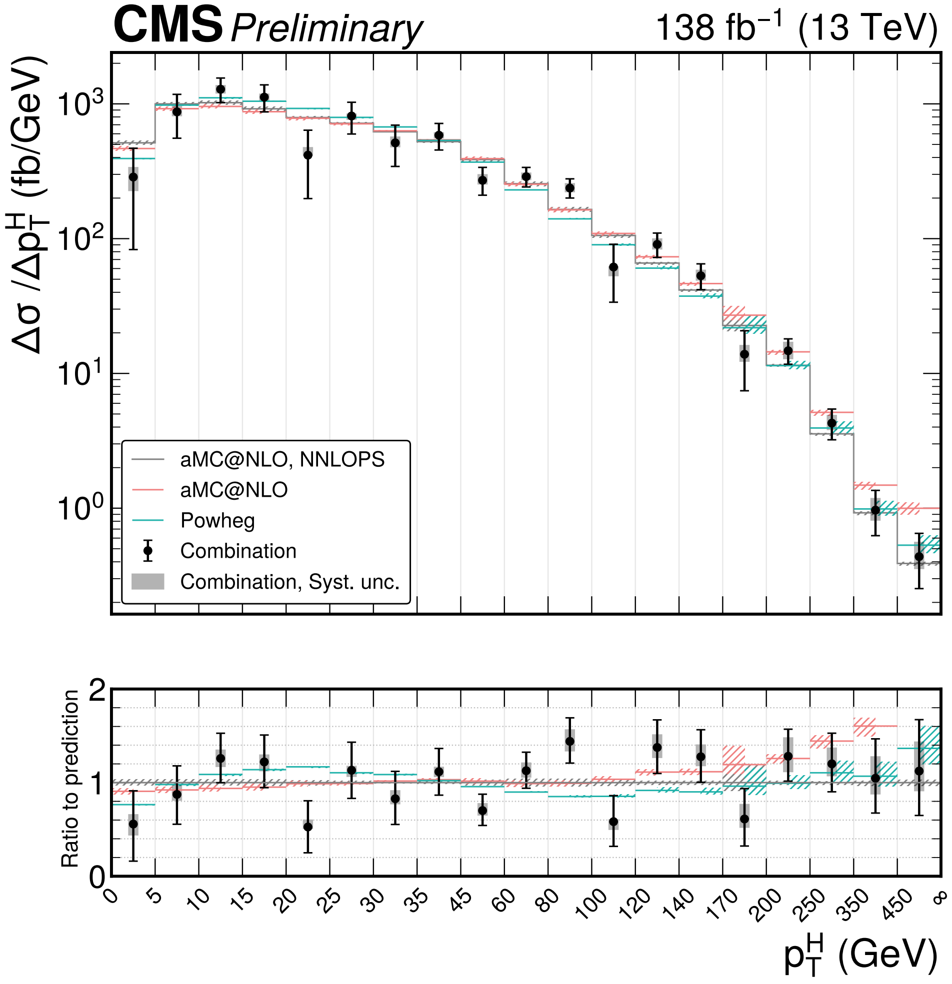

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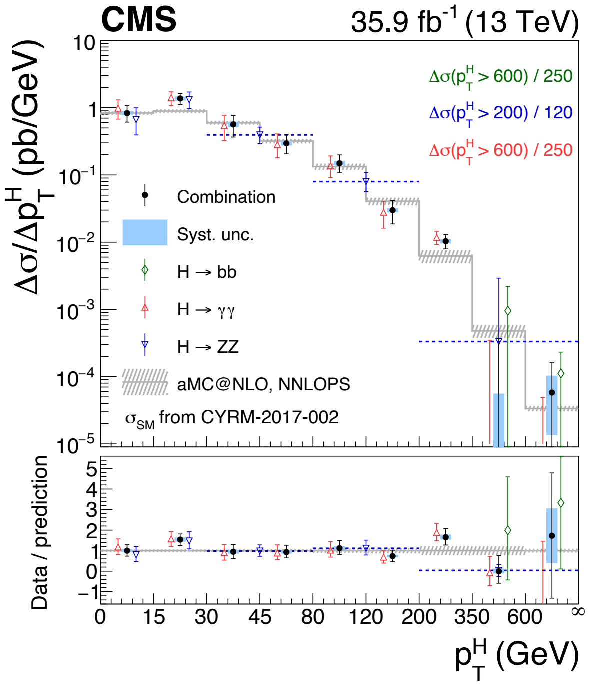


Compared to 2016-only combination, we are able to measure XS in **finer bins** whith a **comparable level of precision**!

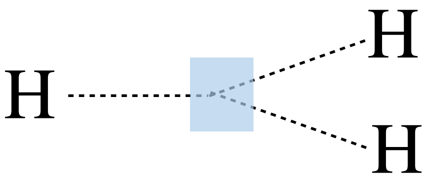
Phys. Lett. B 792 (2019) 369

H+HH

Single-H | **HH**

- Higgs self-coupling probes the nature of the Higgs potential

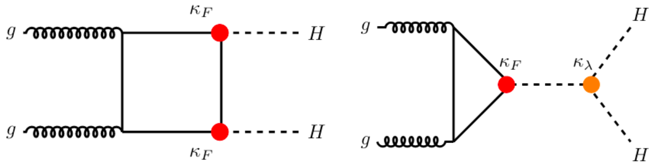
$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4$$



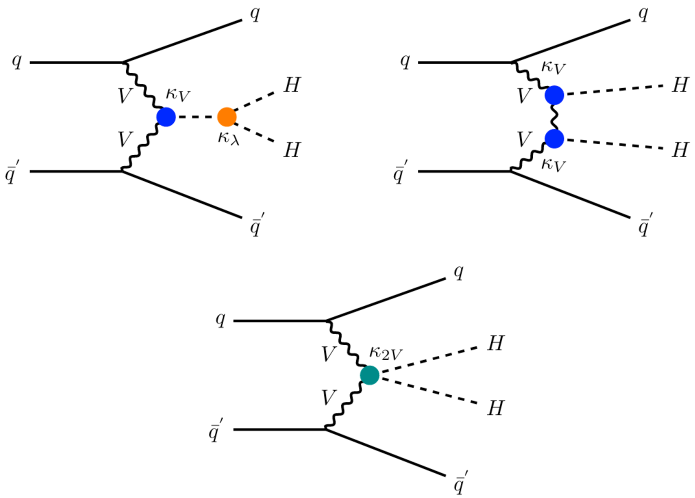
$$\kappa_\lambda = \lambda_3 / \lambda_{SM}$$

- κ_λ can be determined from **HH** cross section measurements
- **Single-H** also sensitive to κ_λ both in inclusive and differential measurements
- (VBF)HH also sensitive to κ_{2V}
- **Combination good as constraints from H and HH are complementary**
  - Single H - stringent constraints on coupling to fermions and vector bosons, mild to κ_λ
  - HH searches - tighter constraints to κ_λ

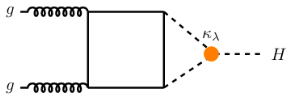
LO HH ggH



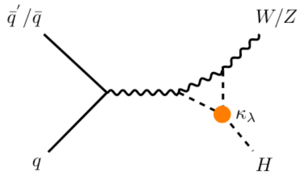
LO HH VBF



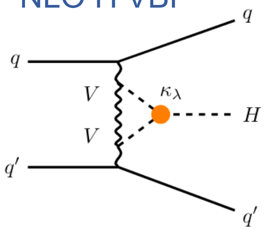
NLO H ggH



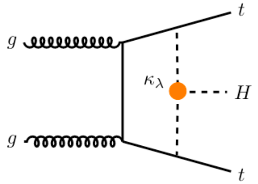
NLO H VH



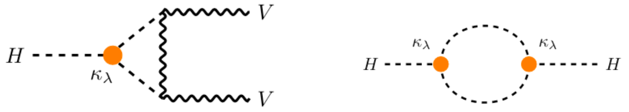
NLO H VBF



NLO H ttH



H propagator



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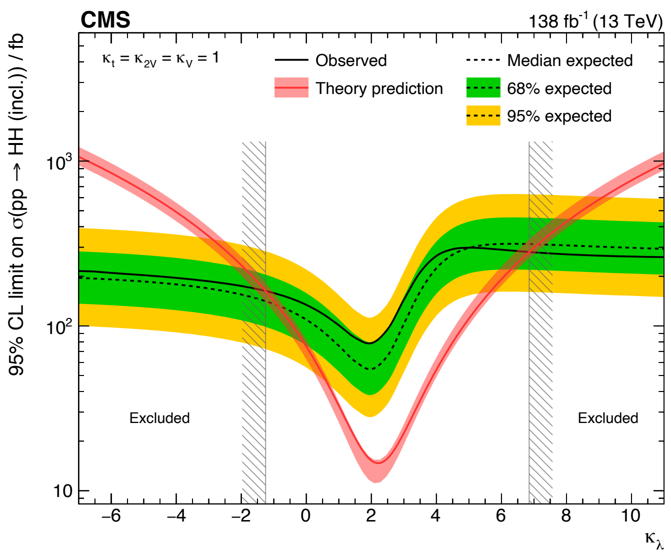
H+HH: κ_λ constraints

STXS
κ-Framework
ETH zürich

- Assuming BSM only affects κ_λ, while all other Higgs couplings set to SM values
- Sensitivity driven by HH categories
- **Confidence interval from H+HH ~1.1 times larger than HH** because of single-H shifting interval towards higher values
- Individual results consistent with previous combination [Nature 607, 60-68 (2022)]

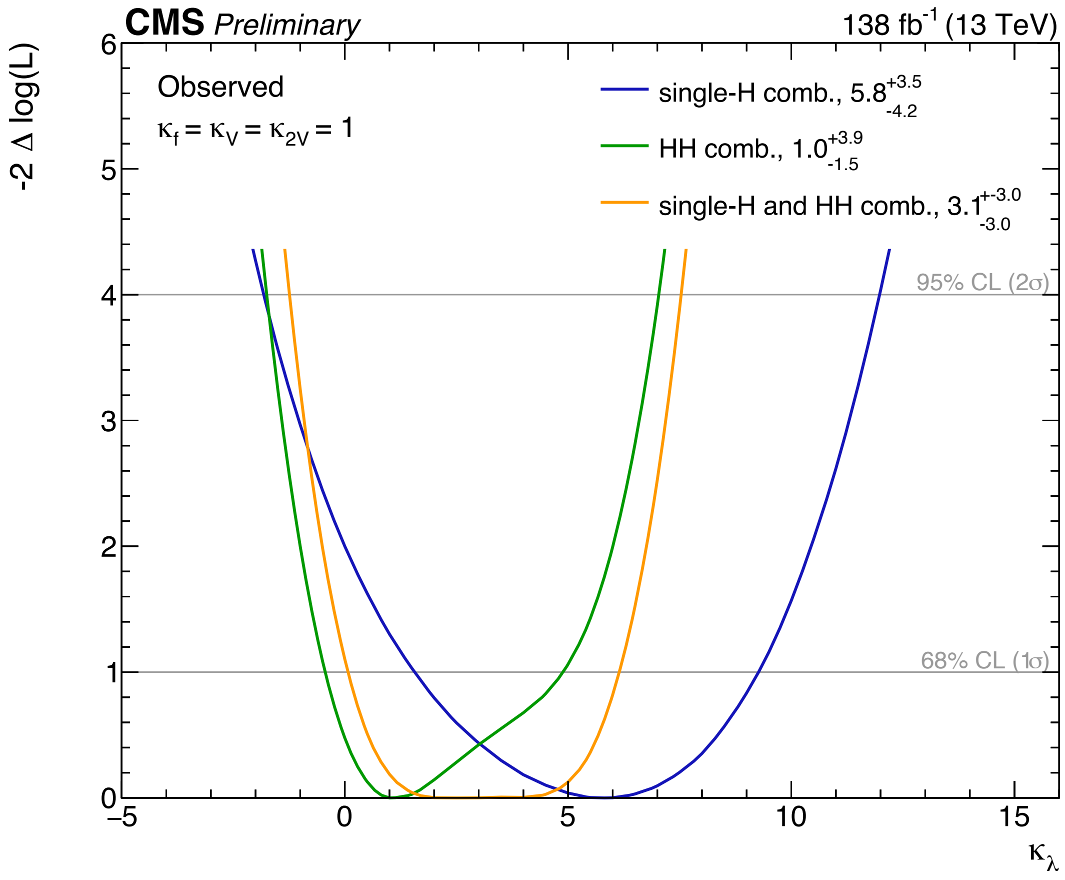


95% CL limit on $\sigma(\mathrm{HH})$ vs κ_λ

κ_λ: [-1.24, 6.49]

Value of
Observed 95% C.L.: $-1.4 < \kappa_\lambda < 7.8$
obtained when allowing other couplings to flow (compatible with ATLAS H+HH combination)

Observed 95% C.L.: $-1.2 < \kappa_\lambda < 7.5$
Expected 95% C.L.: $-2.0 < \kappa_\lambda < 7.7$



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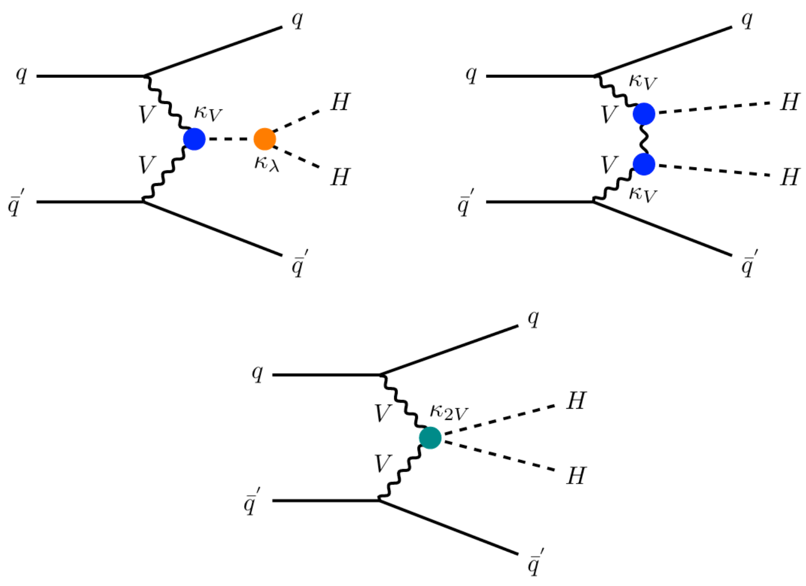
H+HH: 2D Likelihood Scan (κ_V, κ_{2V})

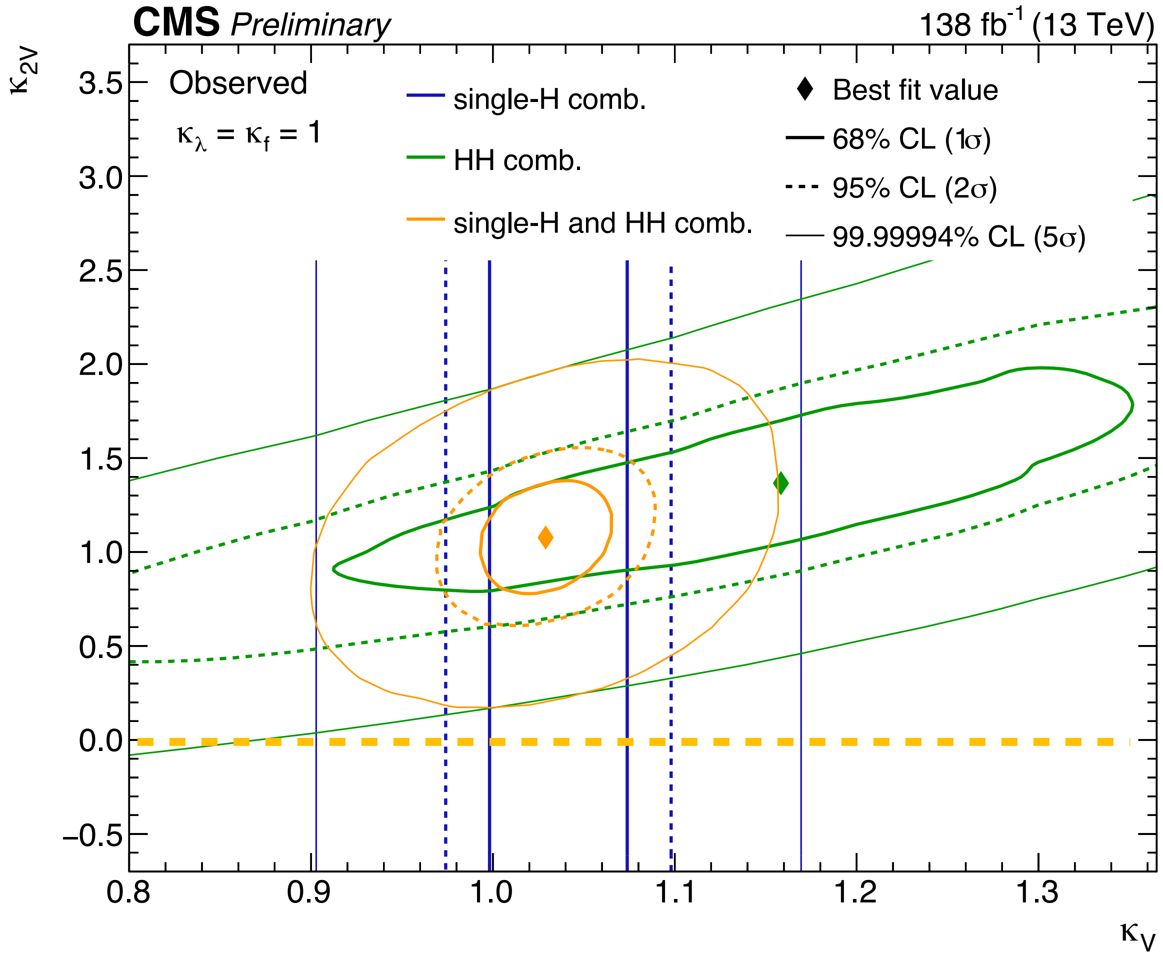
STXS
κ-Framework
CMS
ETH zürich

- Constraint on κ_{2V} driven by HH categories enriched in VBF HH events
- VBF HH XS has large degeneracy with respect to κ_V and κ_{2V}
- Single-H has no sensitivity on κ_{2V} but provides stringent constraint on κ_V
- **First exclusion of $\kappa_{2V} = 0$ <u>for any value of κ_V</u> at 5σ**



LO HH VBF

Observed



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(κ_b, κ_c) from Differential XS Combination

Fiducial diff. cross sections
κ-Framework

CMS ETHzürich

CMS-HIG-PAS-23-013

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$H \to \gamma\gamma$	JHEP 07 (2023) 091
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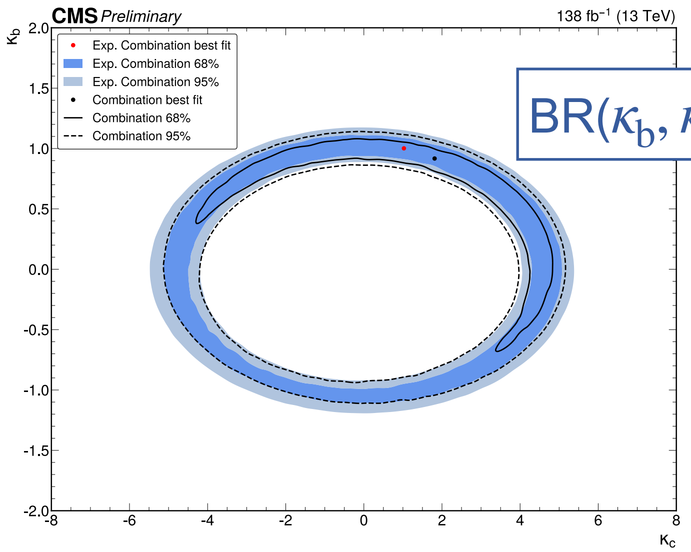
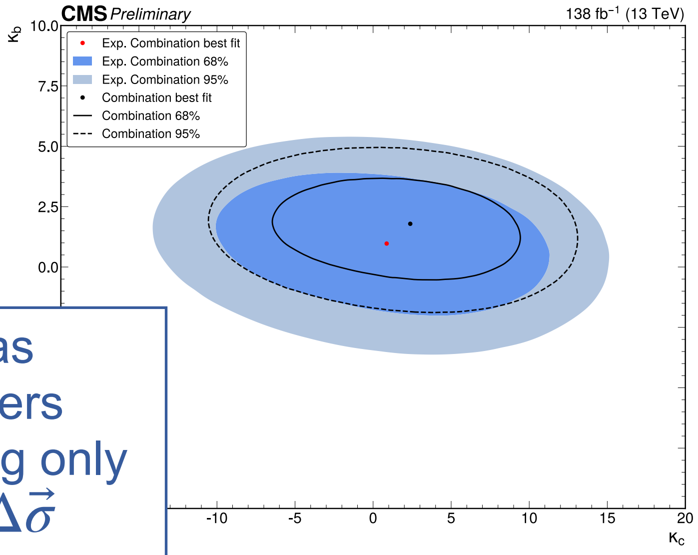
- In ggH production, variations of the couplings manifest through **distortions of the p_T^H spectrum**
- Use model developed in Phys. Rev. Lett. 118, 121801 to probe light Yukawa couplings
- Parametrize ggH contribution of $\mu = \dfrac{\sigma \cdot BR}{\sigma^{SM} \cdot BR^{SM}}$ in p_T^H up to 120 GeV
- Shapes similar to the ones produced in Phys. Lett. B 792 (2019) 369 and in agreement with the SM within 1 sigma

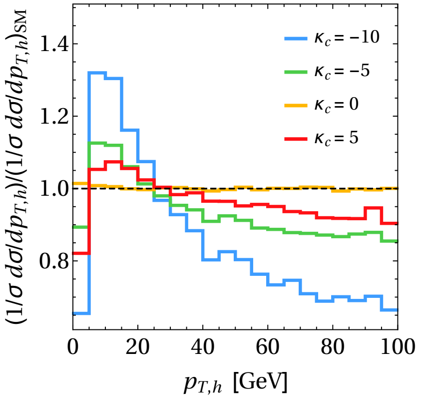
Phys. Rev. Lett. 118, 121801



BR(κ_b, κ_c)



- BR implemented as nuisance parameters
- Constraints coming only from shape $\vec{s} = \dfrac{\Delta\vec{\sigma}}{\sigma_{incl}}$

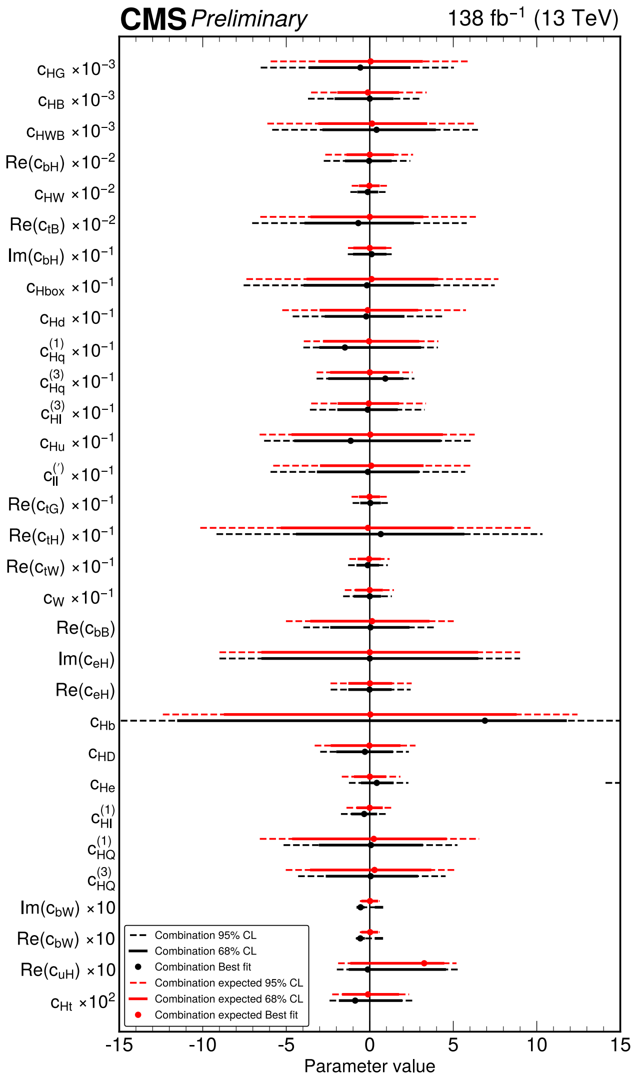


$$\kappa_i = \frac{y_i}{y_i^{SM}}$$

EFT Interpretation of Differential XS

Fiducial diff. cross sections
Effective field theories

[CMS-HIG-PAS-23-013]



Lin. + quad.

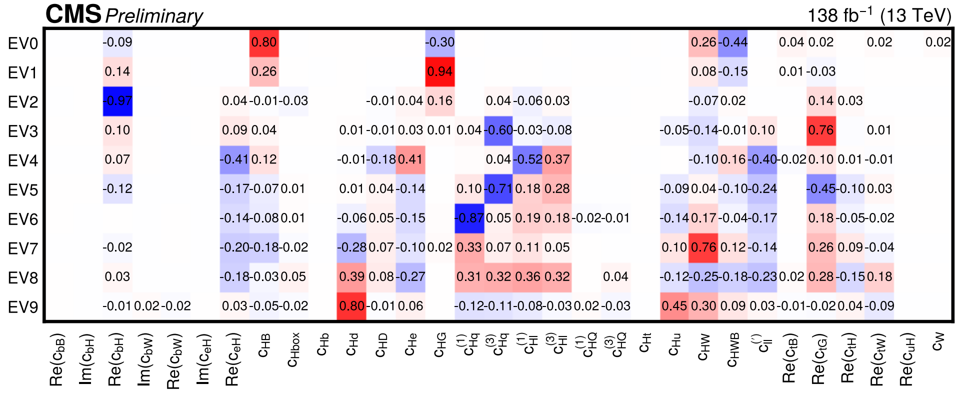
Parametrize

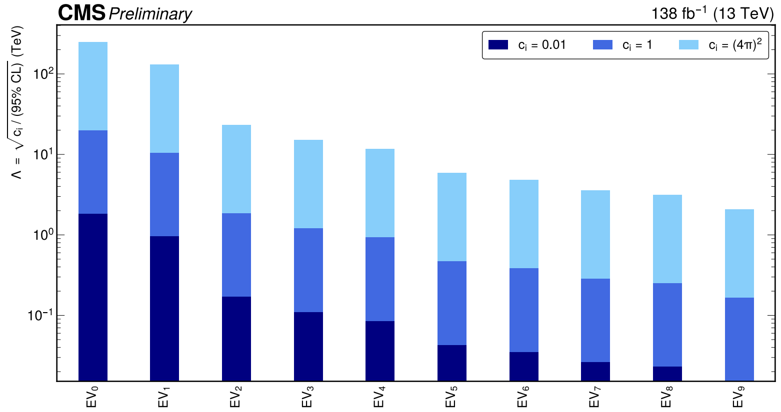
$$\mu = \frac{\sigma \cdot \mathrm{BR} \cdot A}{\sigma^{\mathrm{SM}} \cdot \mathrm{BR}^{\mathrm{SM}} \cdot A^{\mathrm{SM}}}$$

(no extrapolation to 4π)

Analysis
$\mathrm{H} \rightarrow \gamma\gamma$
$\mathrm{H} \rightarrow \mathrm{ZZ}^{(*)} \rightarrow 4l$
$\mathrm{H} \rightarrow \mathrm{W}^{+}\mathrm{W}^{-(*)} \rightarrow e^{\pm}\mu^{\mp}\nu_1\bar{\nu}_1$
$\mathrm{H} \rightarrow \tau^{+}\tau^{-}$
$\mathrm{H} \rightarrow \tau^{+}\tau^{-}$ (boosted)

68% and 95 CL intervals for 31 WCs, set while setting others to their SM value





Linear only

- Define linear combinations of WCs to simultaneously constrain **10 directions** in the parameter space while setting others to SM value (choice driven by sensitivity of data to WCs, not SM assumptions)
- Absolute value means importance of WC in linear combination
- Results expressed as **lower limits on new physics scale**

Summary

- Combinations of experimental measurements are a powerful tool to probe the Higgs sector
- Several **combined measurements of Higgs couplings with Run 2** data at CMS using:
    - Signal strength measurements
    - STXS and fiducial differential cross section measurements
    - Coupling measurements with κ-framework
    - Wilson coefficients (effective field theories)
- Overall good agreement with SM
- **Future combinations**:
    - Legacy single-H combination (new channels, extensive interpretation of STXS measurements with EFTs and κ-formalism)
    - Early Run 3 (+ Run 2) differential XS combination (same idea as CMS-PAS-HIG-23-013)

Backup

List of Analyses

Nature 607, 60-68 (2022)

Analysis	Decay tags	Production tags
Single Higgs boson production		
$H \to \gamma\gamma$ [42]	$\gamma\gamma$	ggH, $p_T(H) \times N_j$ bins VBF/VH hadronic, $p_T(Hjj)$ bins WH leptonic, $p_T(V)$ bins ZH leptonic ttH $p_T(H)$ bins, tH
$H \to ZZ \to 4\ell$ [43]	4μ, $2e2\mu$, $4e$	ggH, $p_T(H) \times N_j$ bins VBF, m_{jj} bins VH hadronic VH leptonic, $p_T(V)$ bins ttH
$H \to WW \to \ell\nu\ell\nu$ [44]	$e\mu/ee/\mu\mu$	ggH $\leq$ 2-jets
	$\mu\mu$+jj/ee+jj/$e\mu$+jj	VBF VH hadronic
	3ℓ	WH leptonic
	4ℓ	ZH leptonic
$H \to Z\gamma$ [45]	$Z\gamma$	ggH VBF
$H \to \tau\tau$ [46]	$e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$	ggH, $p_T(H) \times N_j$ bins VH hadronic VBF VH, high-$p_T(V)$
$H \to bb$ [47–51]	$W(\ell\nu)H(bb)$	WH leptonic
	$Z(\nu\nu)H(bb)$, $Z(\ell\ell)H(bb)$	ZH leptonic ttH, $\to 0, 1, 2\ell +$ jets
	bb	ggH, high-$p_T(H)$ bins
$H \to \mu\mu$ [52]	$\mu\mu$	ggH VBF
ttH production with $H \to$ leptons [53]	2ℓSS, 3ℓ, 4ℓ, $1\ell + \tau_h$, 2ℓSS+$1\tau_h$, $3\ell + 1\tau_h$	ttH
$H \to$ Inv. [71, 72]	p_T^{miss}	ggH VBF VH hadronic ZH leptonic
Higgs boson pair production		
$HH \to bbbb$ [57, 58]	H(bb)H(bb)	ggHH, VBFHH (resolved, boosted)
$HH \to bb\tau\tau$ [59]	$H(bb)H(\tau\tau)$	ggHH, VBFHH
$HH \to$ leptons [60]	H(WW)H(WW), $H(WW)H(\tau\tau)$, $H(\tau\tau)H(\tau\tau)$	ggHH, VBFHH
$HH \to bb\gamma\gamma$ [61]	$H(bb)H(\gamma\gamma)$	ggHH, VBFHH
$HH \to bbZZ$ [62]	H(bb)H(ZZ)	ggHH

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Analysis	Integrated luminosity (fb^{-1})	Targeted H production modes	Maximum granularity	References
$H \to 4l$	138	ggF, VBF, VH, $t\bar{t}H$	STXS 1.2	[43]
$H \to \gamma\gamma$	138	ggF, VBF, VH, $t\bar{t}H$, tH	STXS 1.2	[44, 45]
$H \to WW$	138	ggF, VBF, VH	STXS 1.2	[46]
$H \to$ leptons ($t\bar{t}H$)	138	$t\bar{t}H$	Inclusive	[47]
$H \to b\bar{b}$ (ggF)	138	ggF	Inclusive	[48]
$H \to b\bar{b}$ (VH)	77	VH	Inclusive	[49, 50]
$H \to b\bar{b}$ ($t\bar{t}H$)	36	$t\bar{t}H$	Inclusive	[51]
$H \to \tau\tau$	138	ggF, VBF, VH	STXS 1.2	[52]
$H \to \mu\mu$	138	ggF, VBF	Inclusive	[53]

Analysis	Int. luminosity (fb^{-1})	Targeted HH production modes	References
$HH \to \gamma\gamma b\bar{b}$	138	ggF and VBF	[45]
$HH \to \tau\tau b\bar{b}$	138	ggF and VBF	[54]
$HH \to b\bar{b}b\bar{b}$	138	ggF, VBF, and VHH	[55–57]
$HH \to$ leptons	138	ggF	[58]
$HH \to WWb\bar{b}$	138	ggF and VBF	[59]

Differential Cross Sections

$$n_i^{\text{sig},km}(\vec{\mu}\mid\vec{\nu}) = \sum_{j=1}^{n^{\text{gen}}_{\text{bins},k}} \mu_j \sigma_j^{\text{SM}} A_j^{km} \varepsilon_{ji}^{km}(\vec{\nu}) L(\vec{\nu}) \mathscr{B}^m$$

Fiducial acceptance

$$\mu = \frac{\sigma \cdot \text{BR} \cdot A}{\sigma^{\text{SM}} \cdot \text{BR}^{\text{SM}} \cdot A^{\text{SM}}}$$ Individual channel

Extrapolation to inclusive phase space 4π
(introduces **unavoidable model dependence**)

$$\mu = \frac{\sigma}{\sigma^{\text{SM}}}$$ Combination

Channel	$H \to \gamma\gamma$	$H \to ZZ^{(*)} \to 4\ell$	$H \to W^+W^{-(*)} \to e^\pm\mu^\mp\nu_1\bar{\nu}_1$	$H \to \tau^+\tau^-$	$H \to \tau^+\tau^-$ boosted
p_T^H bin boundaries (GeV)	0 - 5	0 - 10	0 - 30	0 - 45	
	5 - 10				
	10 - 15	10 - 20			
	15 - 20				
	20 - 25	20 - 30			
	25 - 30				
	30 - 35	30 - 45	30 - 45		
	35 - 45				
	45 - 60	45- 60	45 - 80	45 - 80	
	60 - 80	60 - 80			
	80 - 100	80 - 120	80 - 120	80 - 120	
	100 - 120				
	120 - 140	120 - 200	120 - 200	120 - 140	
	140 - 170			140 - 170	
	170 - 200			170 - 200	
	200 - 250	200 - ∞	200 - ∞	200 - 350	
	250 - 350				
	350 - 450			350 - 450	
	450 - ∞			450 - ∞	450 - 600
					600 - ∞

- **Full Run2 combination of (single) Higgs production differential cross section measurements**
- Mostly **sensitive to ggH**
- Implements procedure to combine bins with different level of granularity at generator level
- Combined measurements provided for: p_T^H, N_{jets}, $|y_H|$, $p_T^{j_1}$, m_{jj}, $|\Delta\eta_{jj}|$, τ_C^j

CMS-PAS-HIG-23-013

Analysis	Reference
$H \to \gamma\gamma$	JHEP 07 (2023) 091
$H \to ZZ^{(*)} \to 4l$	JHEP 08 (2023) 040
$H \to W^+W^{-(*)} \to e^\pm\mu^\mp\nu_1\bar{\nu}_1$	JHEP 03 (2021) 003
$H \to \tau^+\tau^-$	Phys. Rev. Lett. 128 (2022) 081805
$H \to \tau^+\tau^-$ (boosted)	Phys. Lett. B 857 (2024) 138964

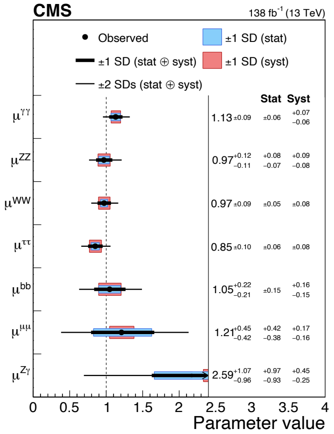
Types and Evolution of Higgs Couplings Measurements

Run 1

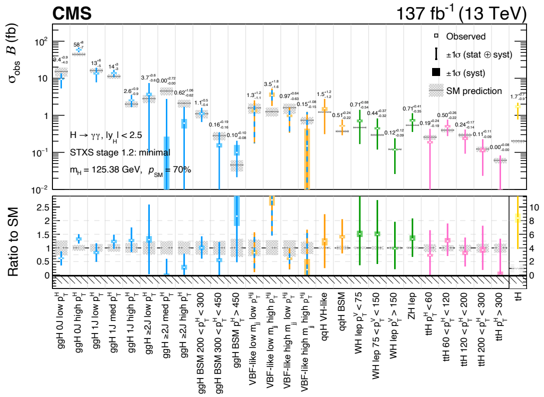
Run 2 (+ Run 3, HL-HLC)

Signal strength modifiers

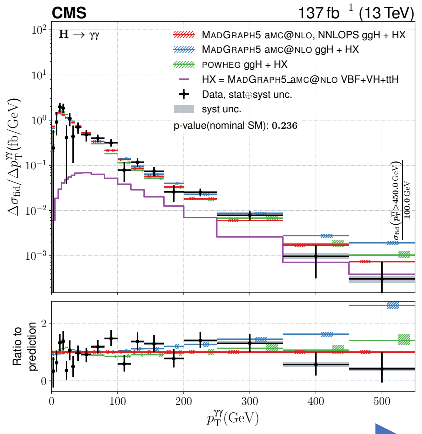
$$\mu = \frac{\sigma \cdot \mathrm{BR}}{\sigma^{SM} \cdot \mathrm{BR}^{SM}}$$



STXS



Fiducial cross sections



Experimental sensitivity

Model independence

κ-Framework

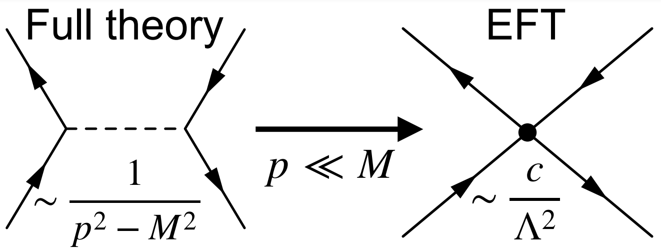
Simple parametrization of deviations from SM

- Assume only one underlying state at 125 GeV
- Narrow width approximation
- Easy reinterpretation on other models

$$\sigma_i \sim \kappa_i^2 \sigma_i^{SM} \qquad \Gamma_f \sim \kappa_f^2 \Gamma_f^{SM}$$

$$\sigma_i \cdot \mathrm{BR}^f = \left(\frac{\sigma_i \Gamma_f}{\Gamma_H}\right)_{SM} \cdot \kappa_i^2 \kappa_f^2 / \kappa_H^2$$

Effective field theories (EFT)



$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_{i=5}^{\infty} \sum_{j=0}^{N_i} \frac{c_j^{(i)}}{\Lambda^{i-4}} O_j^{(i)}$$

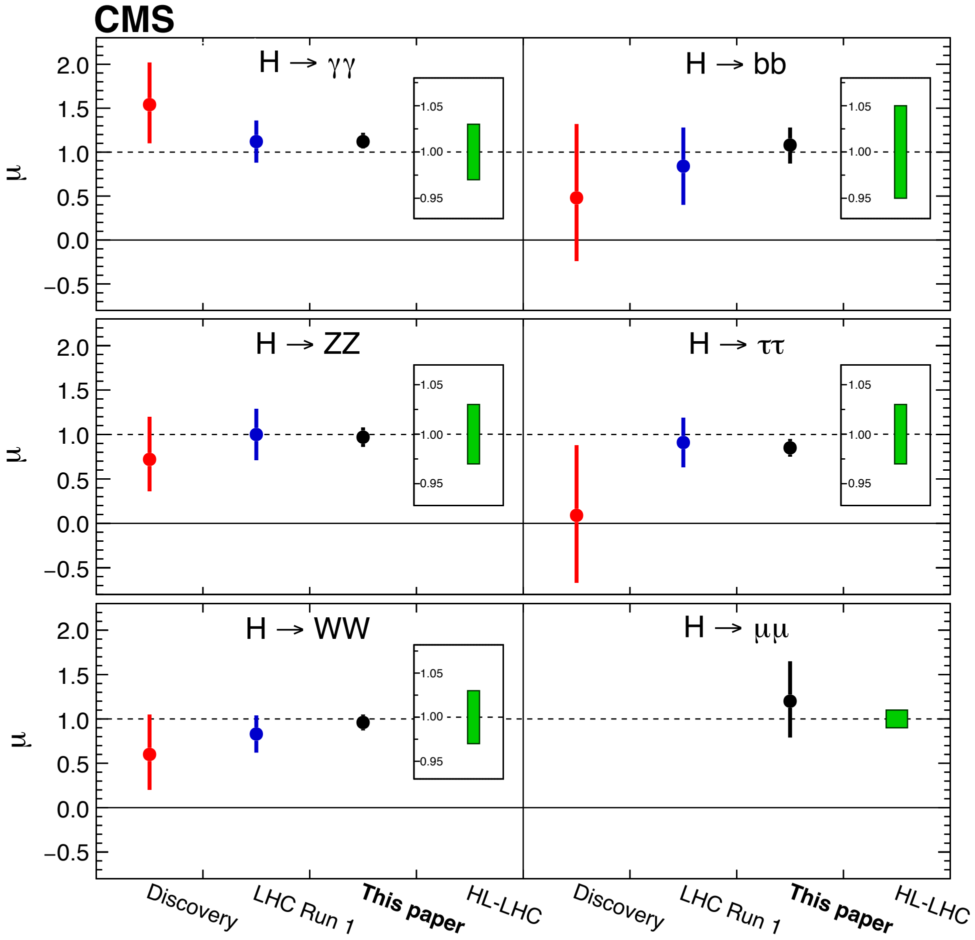
- More general than κ-formalism
- Operators can induce couplings with different Lorentz structure than SM → modification of Higgs kinematics
- Parametrizations can be derived inside specific fiducial phase spaces

Combined Measurements of μ

Signal strength modifiers

Nature 607, 60-68 (2022)

- Overall signal strength measurement: fit all data from production modes and decay channels with common μ (can hide compensations of different effects)
- **Higgs discovery**
  - $5.1\ \mathrm{fb}^{-1}$ at 7 TeV and $5.3\ \mathrm{fb}^{-1}$ at 8 TeV
  - $\mu = 0.87 \pm 0.23$ (dominated by statistical uncertainty)
- **Run 1 combination**
  - $5.1\ \mathrm{fb}^{-1}$ at 7 TeV and $19.7\ \mathrm{fb}^{-1}$ at 8 TeV
  - $\mu = 1.00 \pm 0.13\ \left[{}^{+0.08}_{-0.07}(\text{theory}) \pm 0.07(\text{exp.}) \pm 0.09(\text{stat})\right]$
- **Run 2 combination**
  - $138\ \mathrm{fb}^{-1}$ at 13 TeV
  - $\mu = 1.002 \pm 0.057[\pm 0.037\ (\text{theory})\ \pm 0.033\ (\text{expt.})\ \pm 0.029\ (\text{stat.})\ ]$
- **Statistical uncertainty now comparable to systematic and theory**
  - Need new approaches to reduce systmatics
  - Improved precision on theory production



Signal strength parameters in different datasets

Combined Measurements of μ

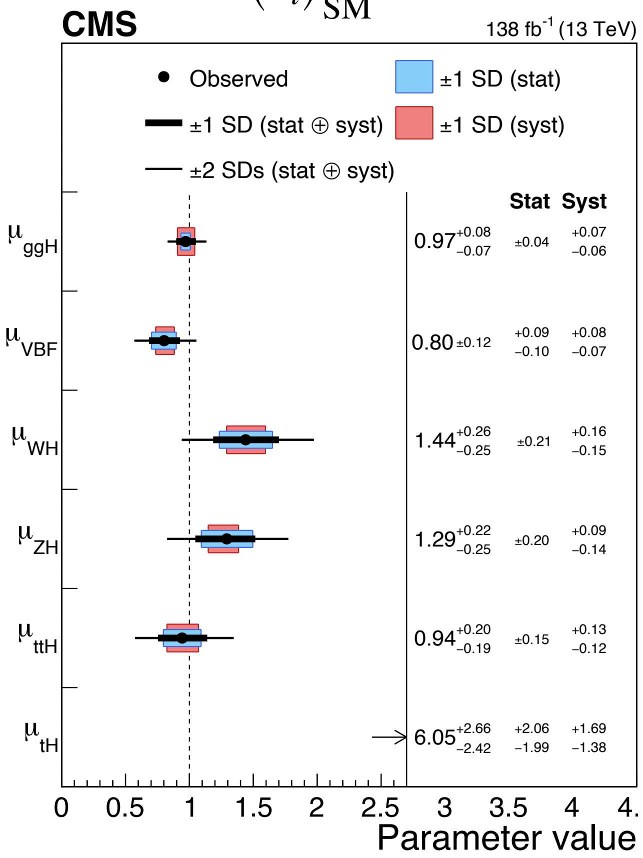
CMS

ETH zürich

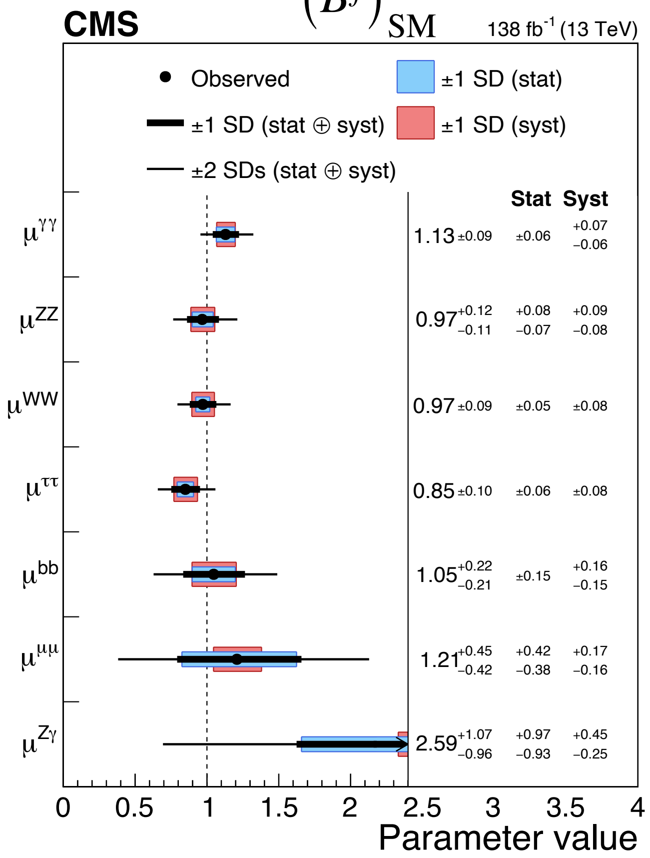
- **Good agreement with the SM**

- CMS combination matrix
- **Good compatibility with SM** in most channels
- Discrepancies in channels with limited statistical precision

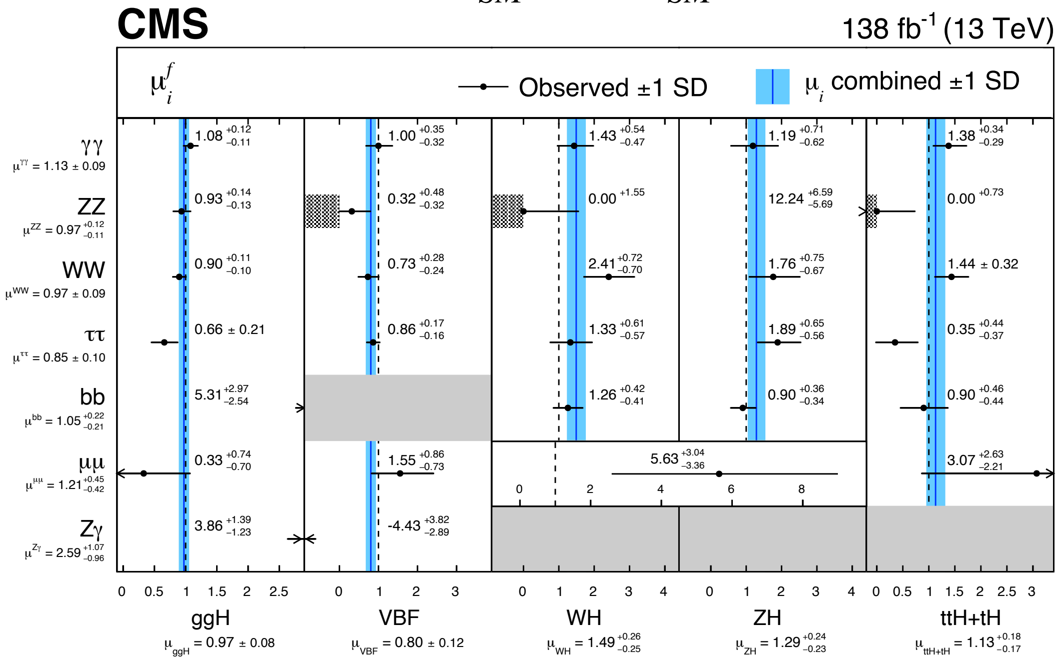
$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{SM}}$$



$$\mu^f = \frac{B^f}{(B^f)_{SM}}$$



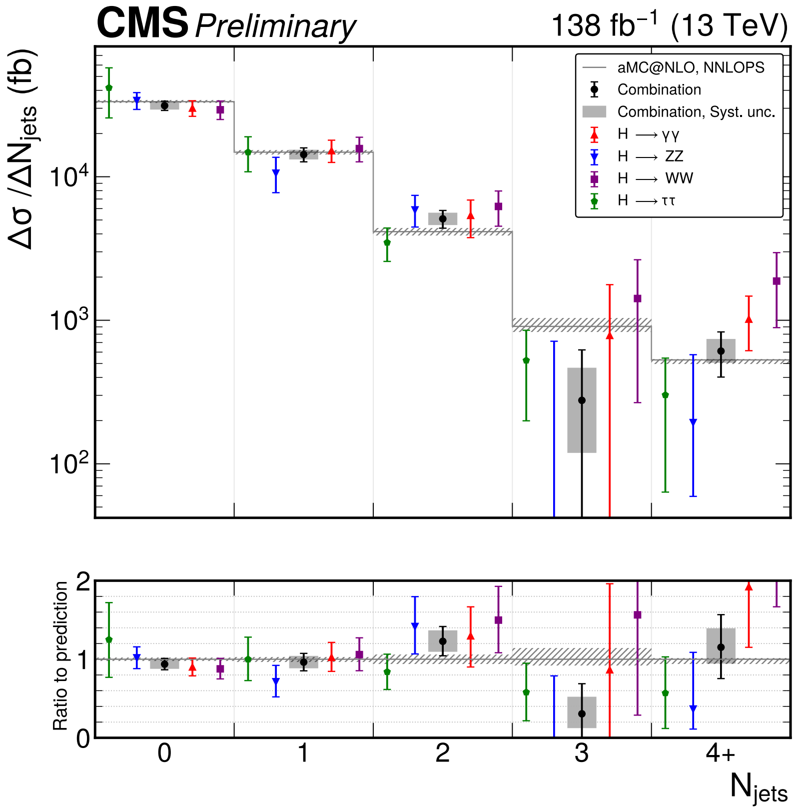
$$\mu_i^f = \frac{\sigma_i \times B^f}{(\sigma_i)_{SM} \times (B^f)_{SM}} = \mu_i \times \mu^f$$

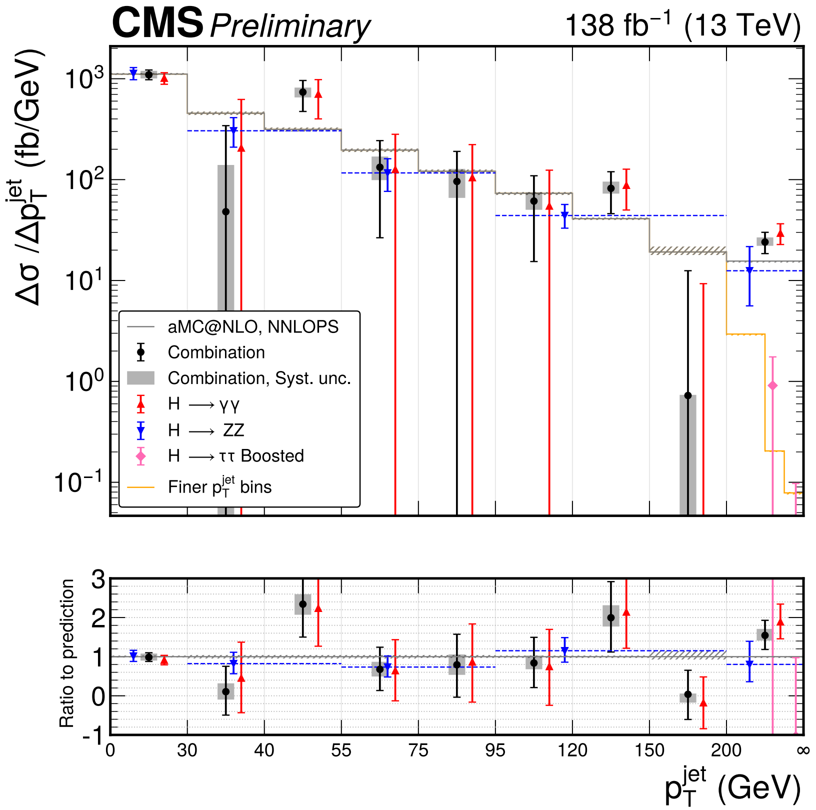


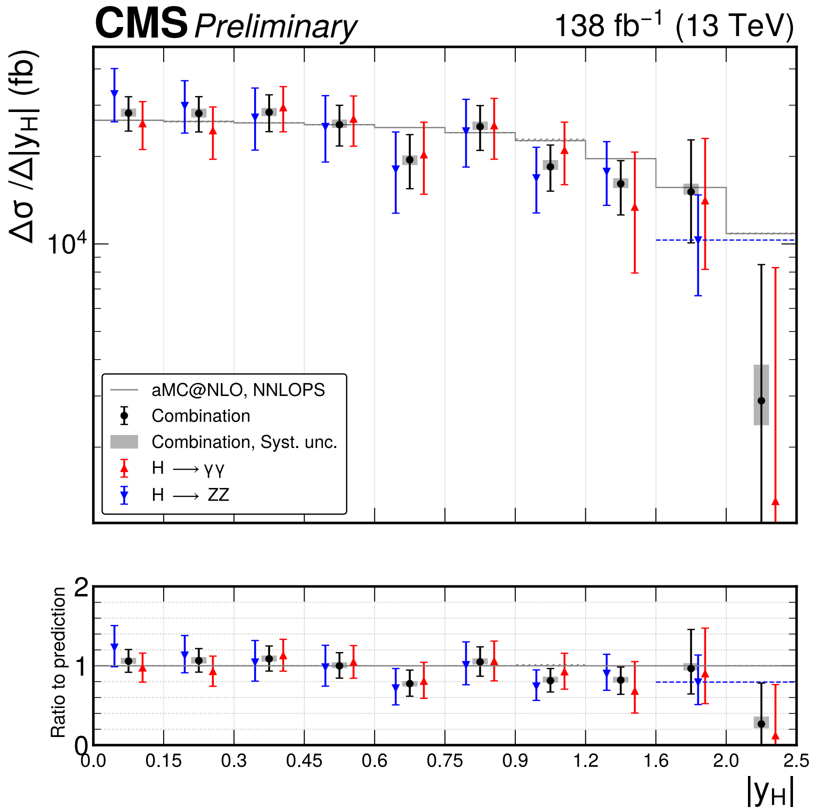
[Nature 607, 60-68 (2022)]

Differential Cross Sections

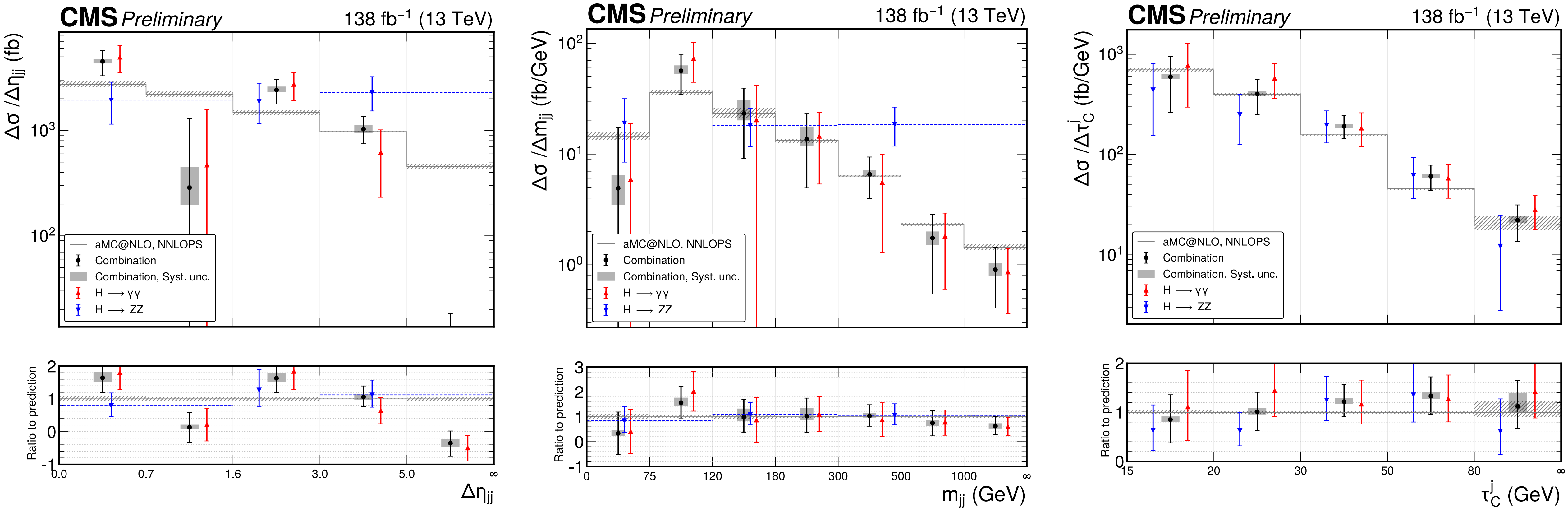
Fiducial cross sections







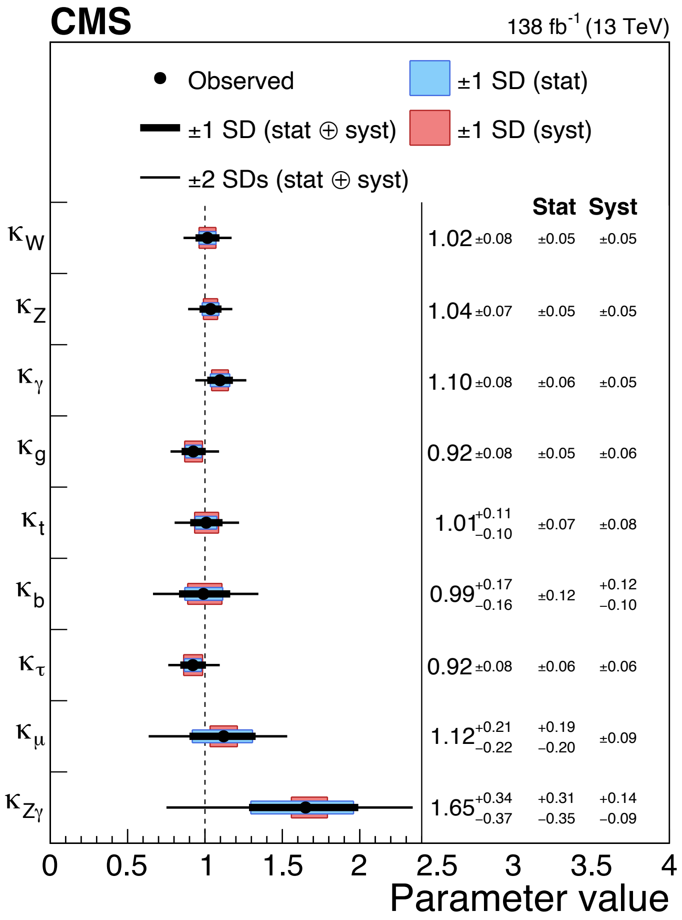
Differential Cross Sections



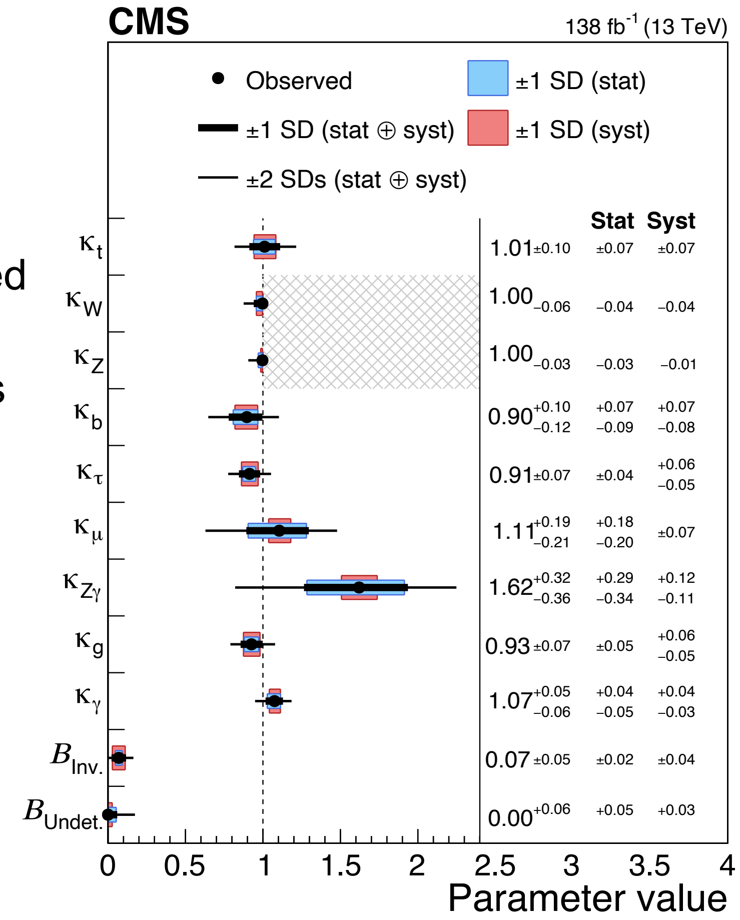
Higgs Couplings with Different Assumptions

κ-Framework

- Assumption: no invisible and undetected decays
- No new physics in loops (gg→H, H → $\gamma\gamma$, H → $Z\gamma$)
- Same level of systematic and statistical contribution to uncertainty in all measurements except for κ_μ and $\kappa_{Z\gamma}$



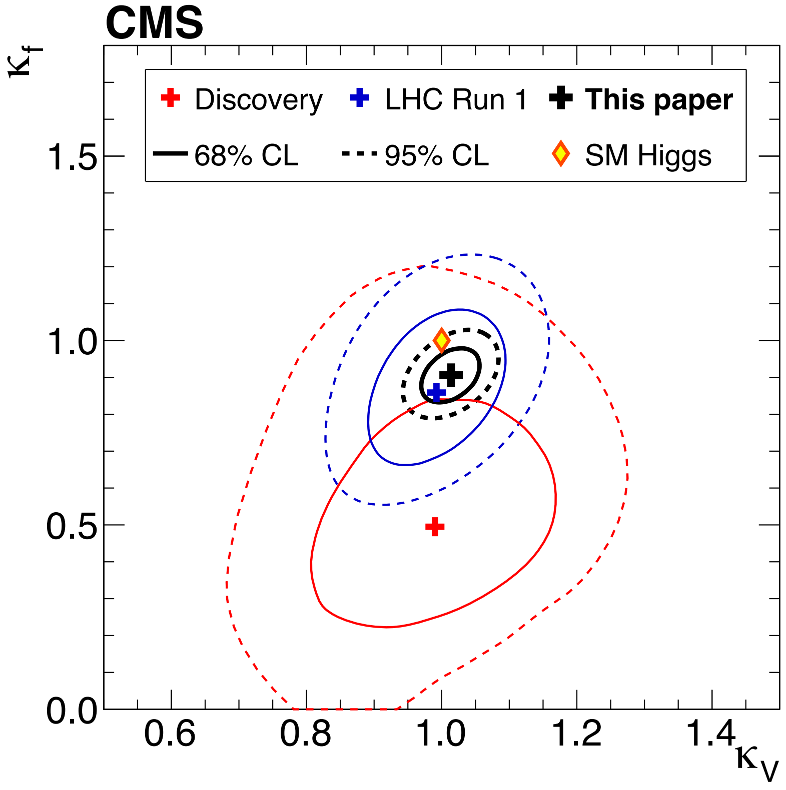
- Assumption: allow invisible and undetected decays
- Imposed upper bounds on κ_W and κ_Z
- Both invisible and undetected decays compatible with zero



[Nature 607, 60-68 (2022)]

Higgs Couplings to Fermions and Vector Bosons

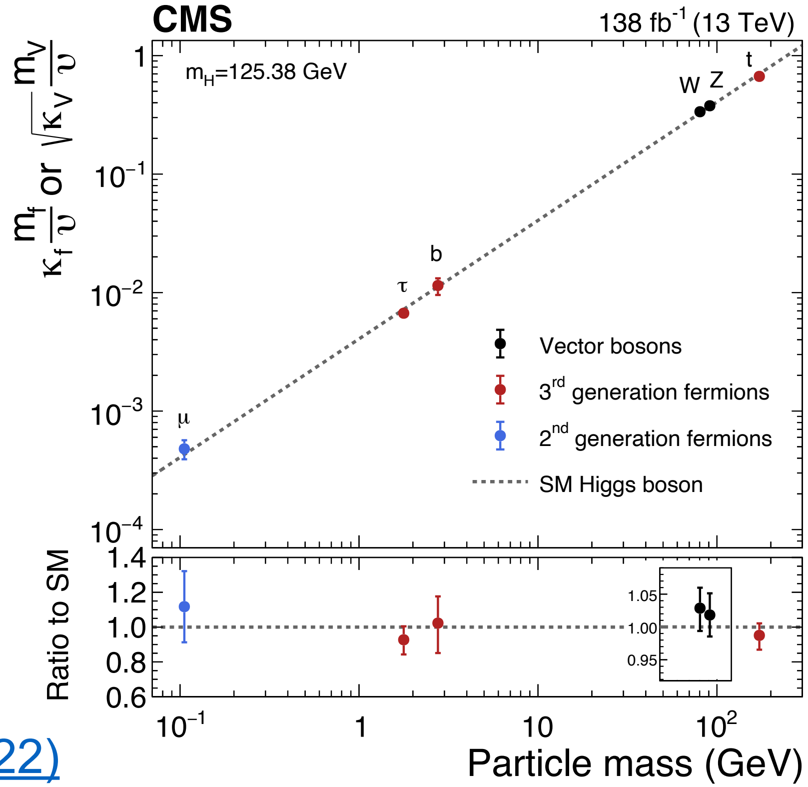
- Run 1: first indications of existance of κ_V and κ_f
- Run 2: 10% uncertainty
- Agreement with SM



[Nature 607, 60-68 (2022)]

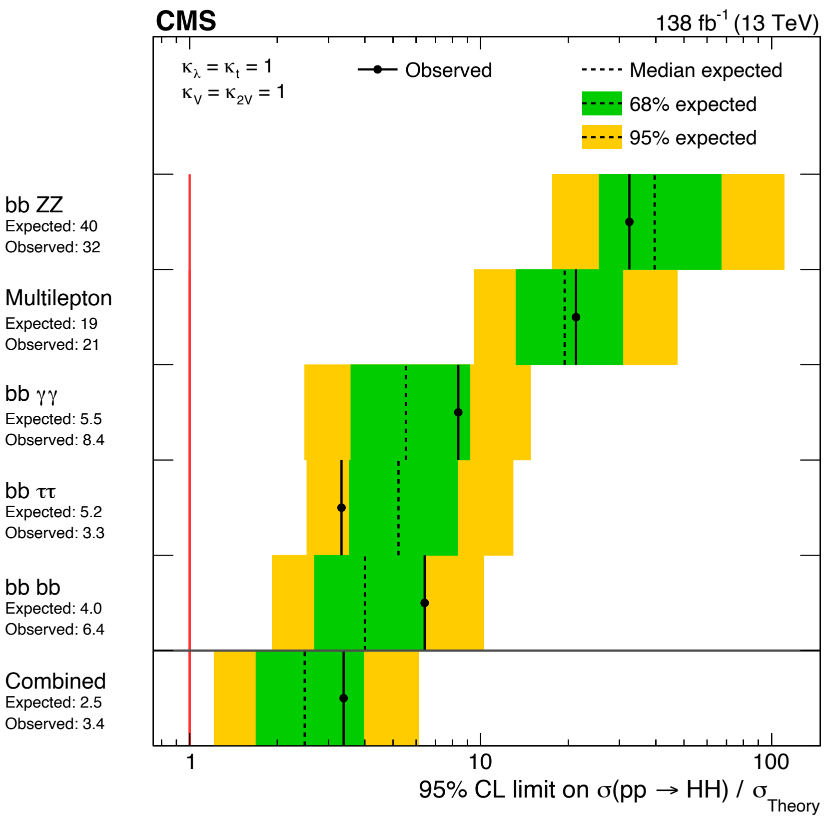
- Test Higgs couplings across three orders of magnitude in particle mass
- Agreement with SM
- Start testing second generation
- Same contribution of statistical and systematic uncertainties

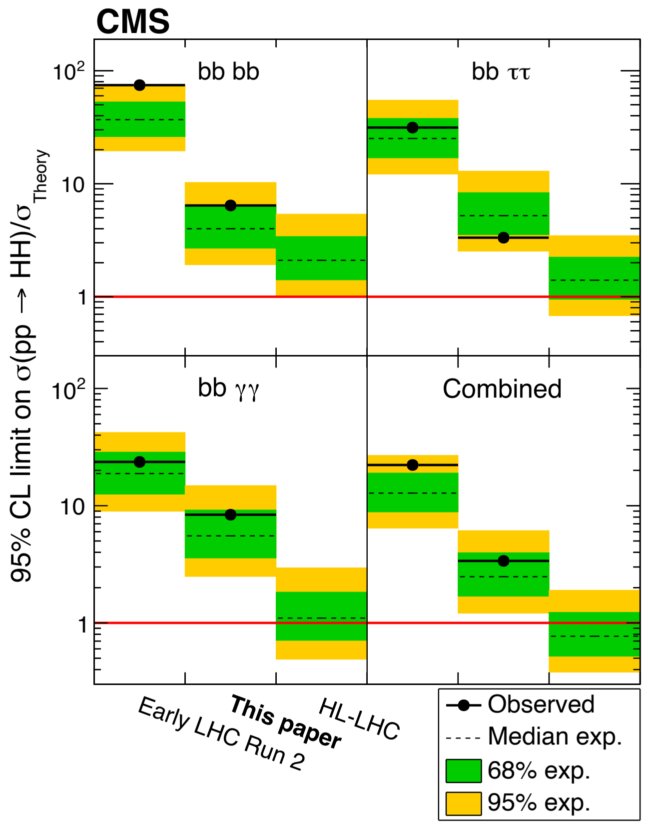
κ-**Framework**



Inclusive HH Searches

- Expected and observed limits (expressed as ratios wrt SM prediciton) using different final states and their combination
- Combined (expected) 95% CL upper limits: 3.4 (2.5)
- Significant improvement compared to early Run 2 results (35.9 fb^{-1})
- Sufficient sensitivity in HL-LHC (3000 fb^{-1} to establish existance of SM HH production





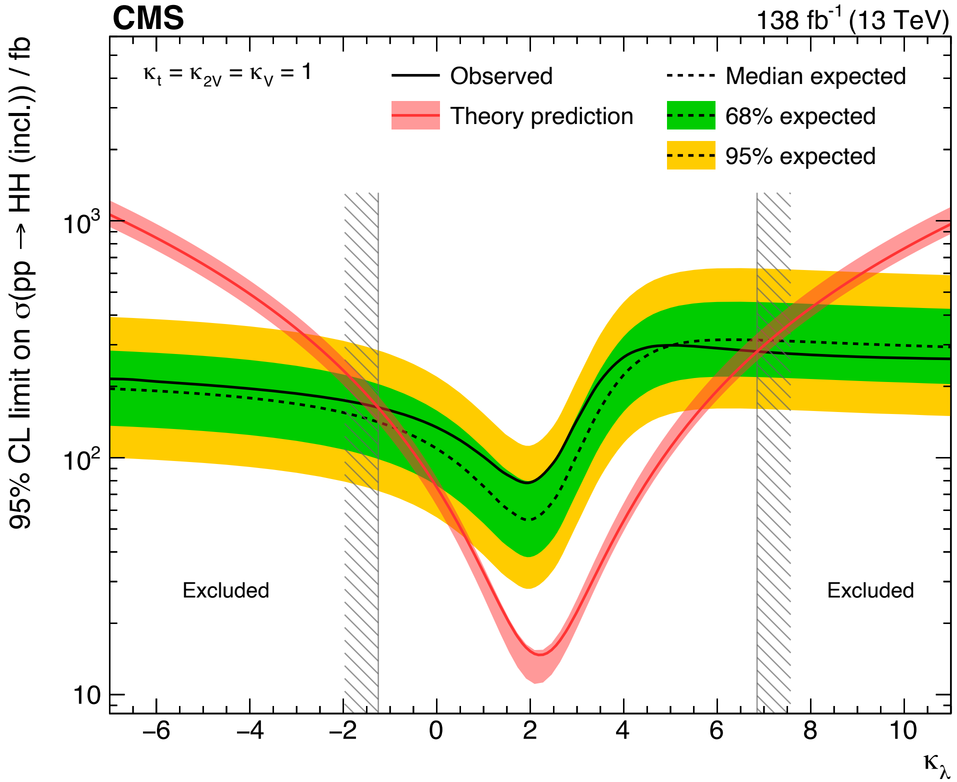
[Nature 607, 60-68 (2022)]

Inclusive HH Searches

κ-Framework

95% CL limit on $\sigma(\text{HH})$ vs κ_λ

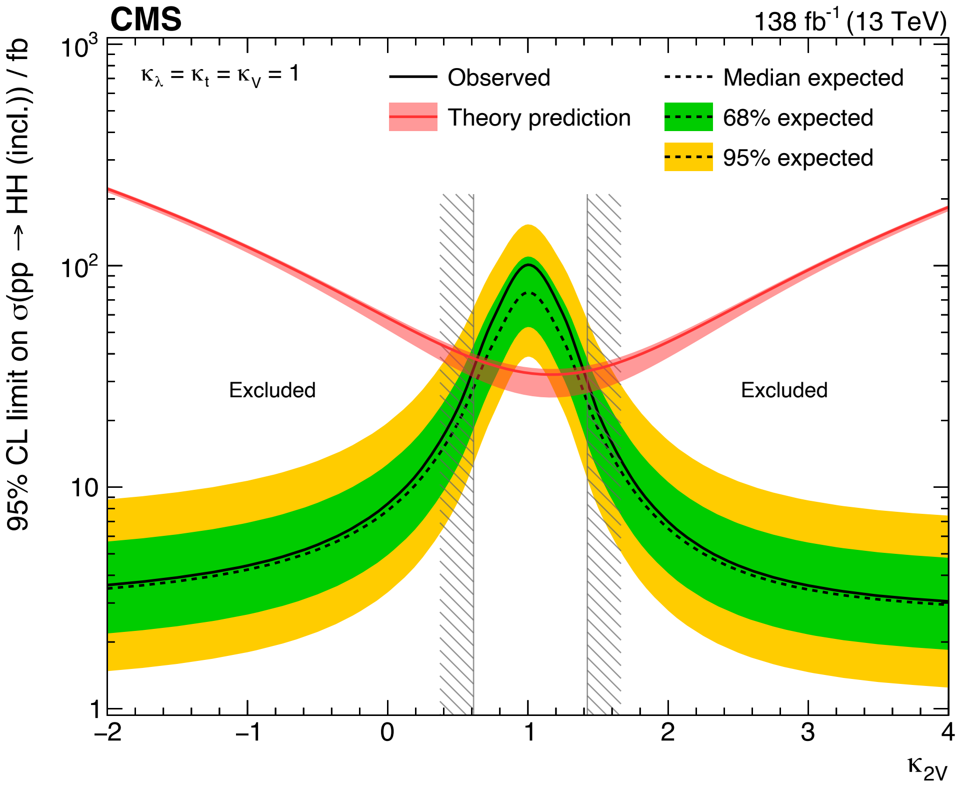
κ_λ: [-1.24, 6.49]



95% CL limit on $\sigma(\text{HH})$ vs κ_{2V}

κ_{2V}: [0.67, 1.38]

$\kappa_{2V} = 0$ excluded with significance 6.6σ assuming $\kappa_\lambda = \kappa_V = \kappa_t = 1$, establishing existance of VVHH

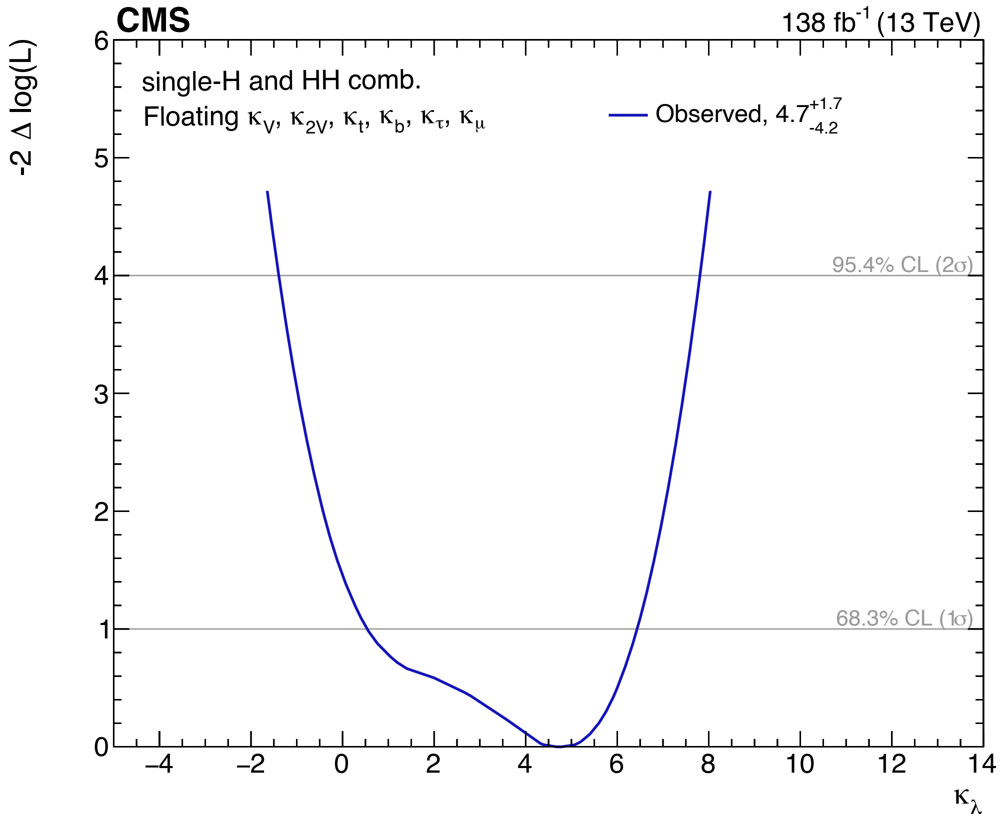


[Nature 607, 60-68 (2022)]

H+HH: κ_λ generic constraint

STXS κ-Framework

Observed 95% C.L.: $-1.4 < \kappa_\lambda < 7.8$



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- Other Higgs coupling modifiers left floating in the fit
- Constraint on κ_λ still strong
- **Consistent with ATLAS combination** results

CMS constraint on κ_λ

Hypothesis	Best fit $\pm1\sigma$ Expected	Best fit $\pm1\sigma$ Observed	95.4% CL interval Expected	95.4% CL interval Observed
Other couplings fixed to SM	$1.0^{+4.6}_{-1.7}$	$3.1^{+3.0}_{-3.0}$	$[-2.0, 7.7]$	$[-1.2, 7.5]$
Floating $(\kappa_V, \kappa_{2V}, \kappa_f)$	$1.0^{+4.7}_{-1.8}$	$4.5^{+1.8}_{-4.7}$	$[-2.2, 7.8]$	$[-1.7, 7.7]$
Floating $(\kappa_V, \kappa_t, \kappa_b, \kappa_\tau)$	$1.0^{+4.8}_{-1.8}$	$4.7^{+1.7}_{-4.1}$	$[-2.3, 7.7]$	$[-1.4, 7.8]$
Floating $(\kappa_V, \kappa_{2V}, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu)$	$1.0^{+4.8}_{-1.8}$	$4.7^{+1.7}_{-4.2}$	$[-2.3, 7.8]$	$[-1.4, 7.8]$

ATLAS constraint on κ_λ

Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
HH+H combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.4 < \kappa_\lambda < 6.1$	$-2.2 < \kappa_\lambda < 7.7$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

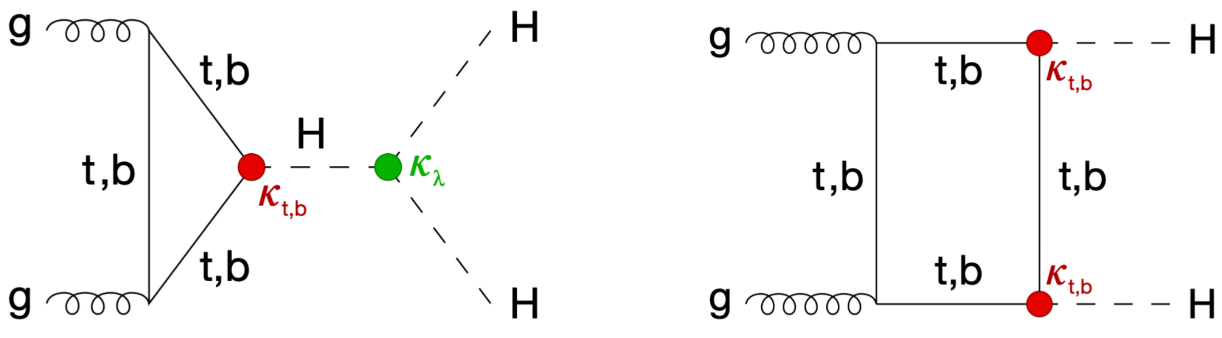
Phys. Lett. B 843 (2023) 137745

H+HH: 2D Likelihood Scan $(\kappa_\lambda, \kappa_t)$

κ-Framework

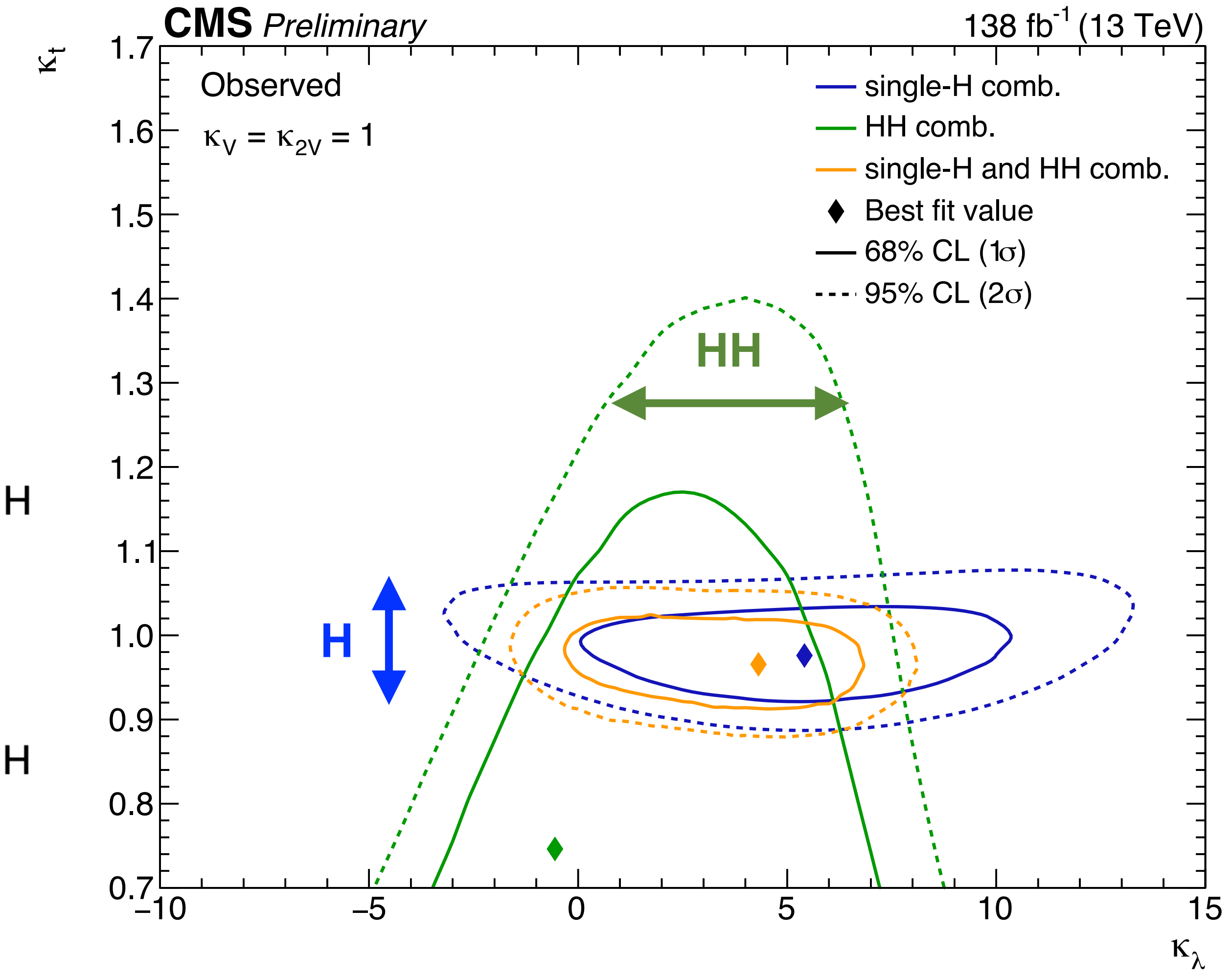
ETH zürich

- Large degeneracy of ggHH XS with respect to κ_λ, κ_t limits κ_λ sensitivity of the HH channels
- Excellent constraint on κ_t from single-H combination
- Complementarity of H and HH fully exploited



LO HH ggH

Observed



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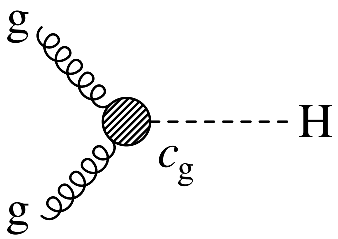
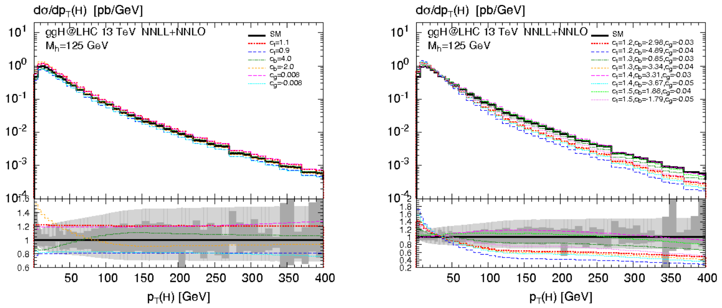
$(\kappa_b, \kappa_t, c_g)$ from Differential XS Combination

Fiducial cross sections
κ-Framework



- Use p_T^H distributions and model implemented in [JHEP03(2017)115] to set constraints on κ_b, κ_t and c_g (point-like Higgs coupling to gluons)
- Parametrizations up to 400 GeV in p_T^H
- Shapes similar to the ones produced in [Phys. Lett. B 792 (2019) 369] and in **agreement with the SM within 1 sigma**

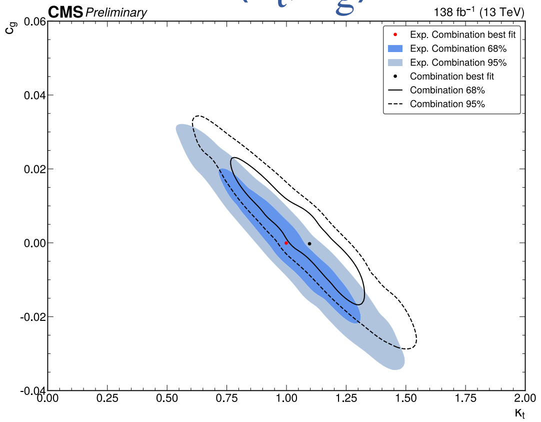


JHEP03(2017)115

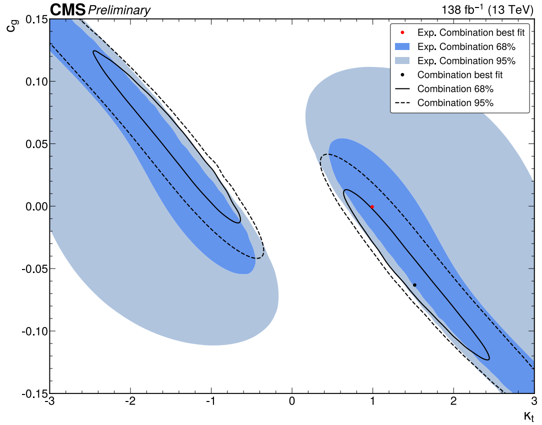
CMS-HIG-PAS-23-013

Analysis	Reference
$H \to \gamma\gamma$	JHEP 07 (2023) 091
$H \to ZZ^{(*)} \to 4l$	JHEP 08 (2023) 040
$H \to \tau^+\tau^-$	Phys. Rev. Lett. 128 (2022) 081805
$H \to \tau^+\tau^-$ (boosted)	Phys. Lett. B 857 (2024) 138964

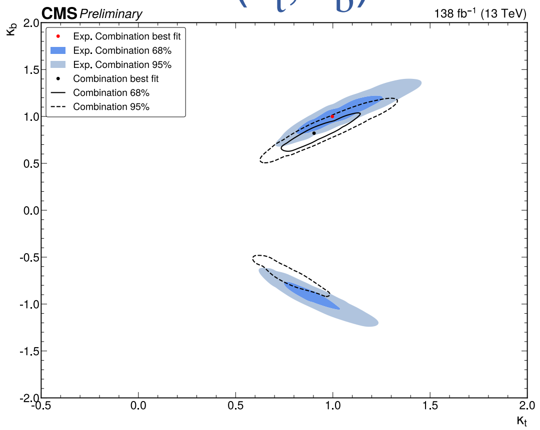
BR(κ_t, c_g)



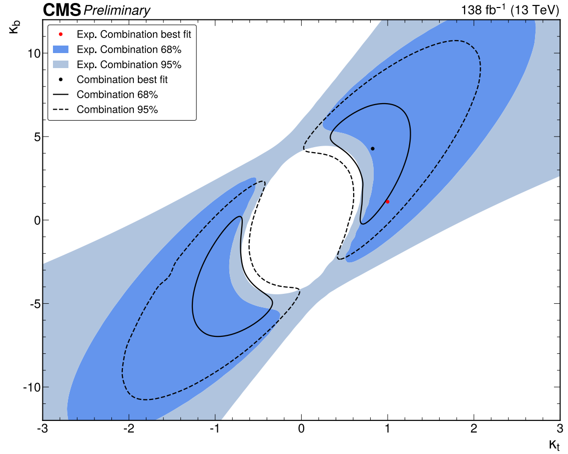
BR as nuisances



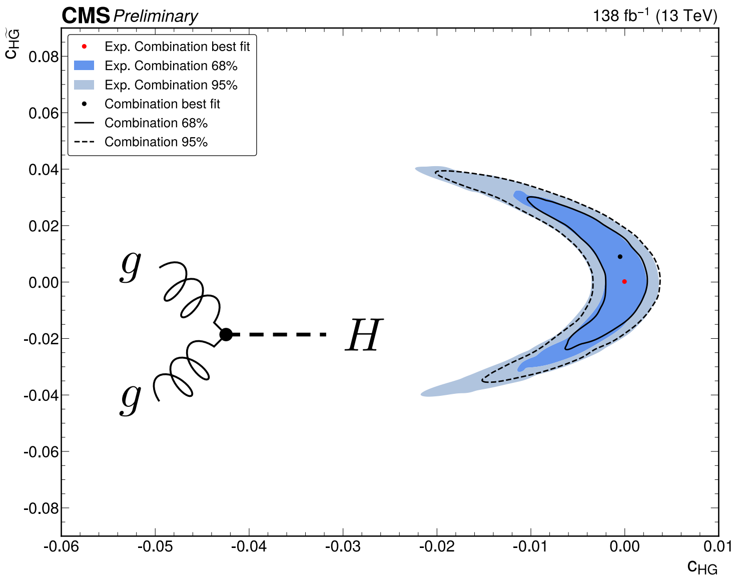
BR(κ_t, κ_b)

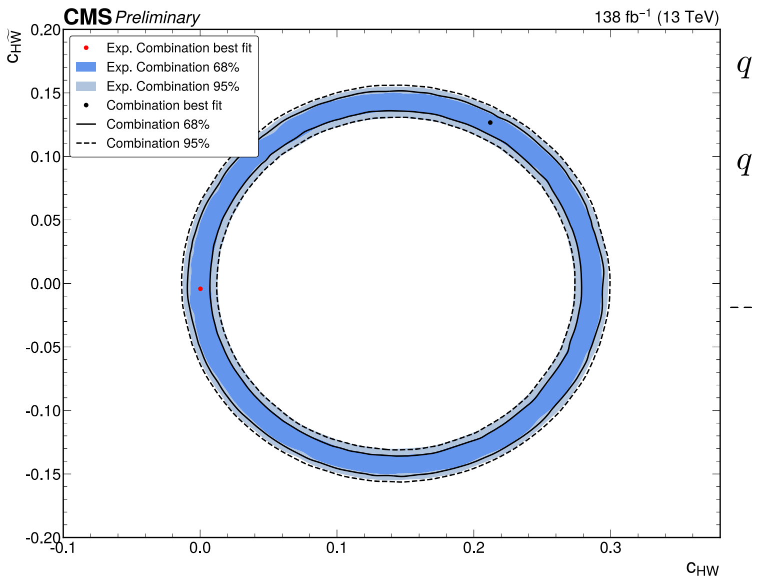


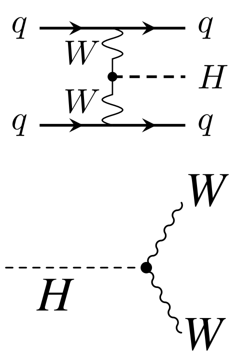
BR as nuisances



EFT Interpretation of Differential XS

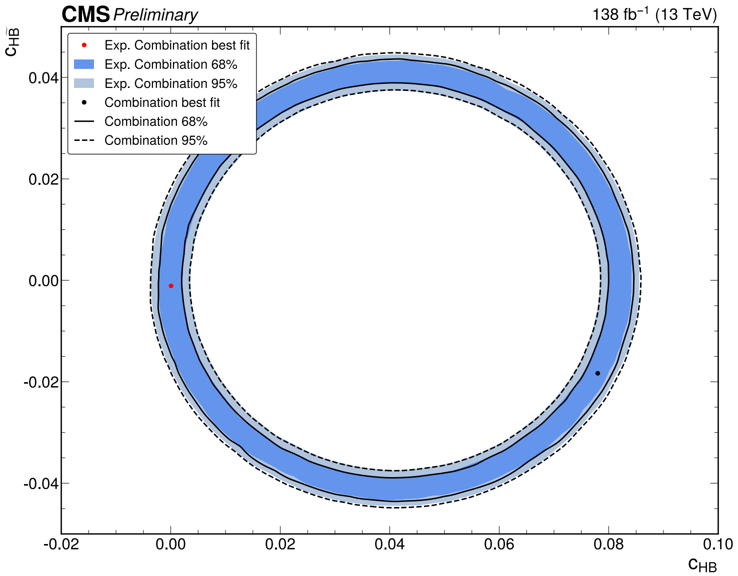


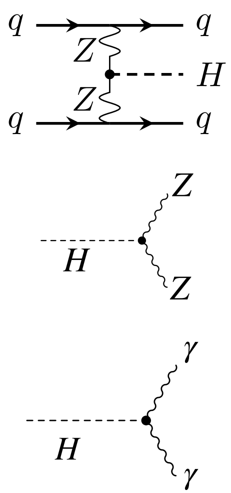


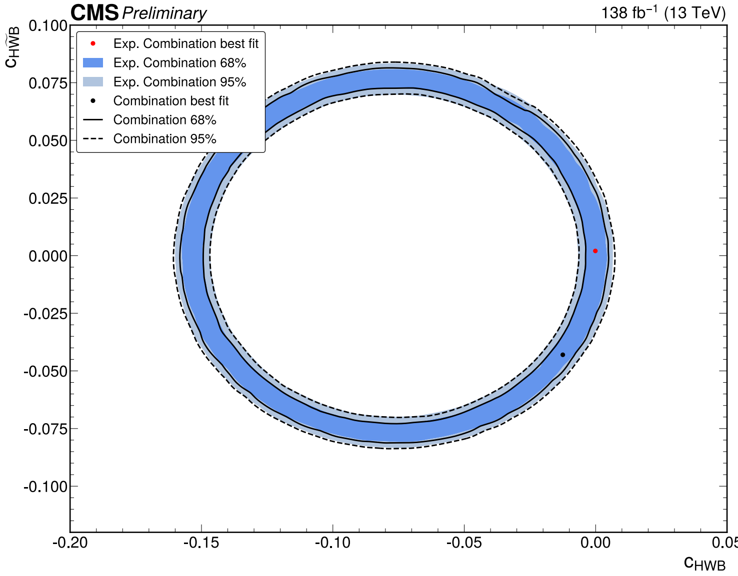


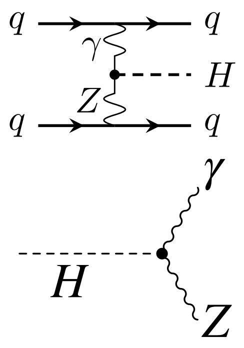
- Use p_T^H spectra to constraint pairs of CP-even, CP-odd WCs while setting all other to WC=0 (SM)
- **Agreement with SM prediction** and **JHEP 08 (2022) 027**
- Ring shapes centered around 0 for CP-odd WC comes from quadratic term in the expansion

$$\left|\mathcal{M}_{\mathrm{SMEFT}}\right|^2 = \left|\mathcal{M}_{\mathrm{SM}}\right|^2 + 2\,\mathrm{Re}\left\{\mathcal{M}_{\mathrm{SM}}\mathcal{M}^{+}_{\mathrm{BSM}}\right\} + \left|\mathcal{M}_{\mathrm{BSM}}\right|^2$$





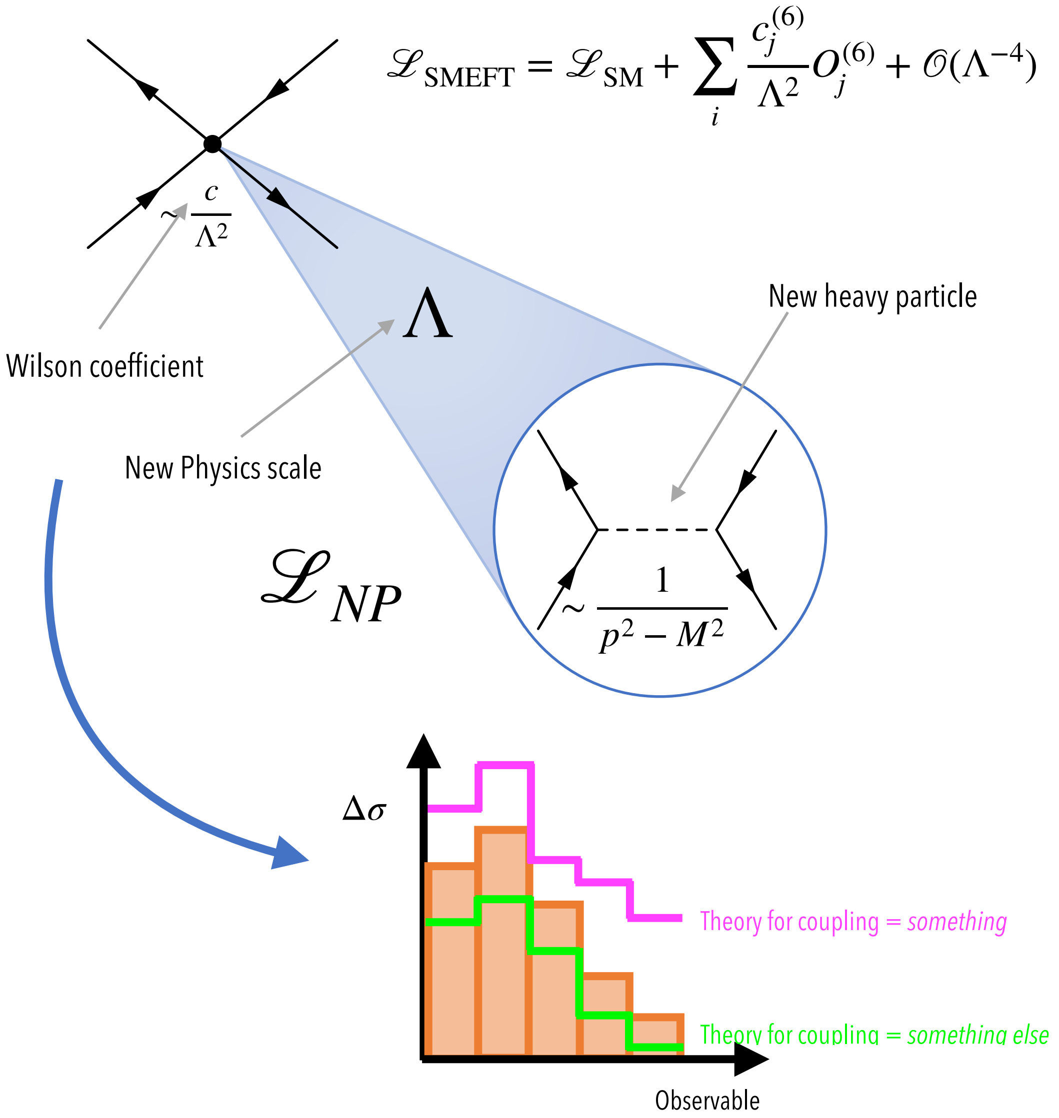




Analysis
$H \to \gamma\gamma$
$H \to ZZ^{(*)} \to 4l$
$H \to W^+W^{-(*)} \to e^{\pm}\mu^{\mp}\nu_1\bar{\nu}_1$
$H \to \tau^+\tau^-$
$H \to \tau^+\tau^-$ (boosted)

CMS-HIG-PAS-23-013

EFT Interpretation of Differential XS



- EFTs used to parametrize and study coupling variations
- Run 2 differential cross section measurements used to derive constraints on Wilson coefficients (WCs)
- Procedure:
  - Derive parametrization for $\mu = \frac{\sigma \cdot \mathrm{BR} \cdot A}{\sigma^{\mathrm{SM}} \cdot \mathrm{BR}^{\mathrm{SM}} \cdot A^{\mathrm{SM}}}$ for bins of $p_{\mathrm{T}}^{\mathrm{H}}$ spectra **inside fiducial phase space** (no extrapolation to 4π needed)
  - Pick subset of WCs to study
  - Set constraints

CMS-HIG-PAS-23-013

Analysis	Reference
$\mathrm{H} \to \gamma\gamma$	JHEP 07 (2023) 091
$\mathrm{H} \to \mathrm{ZZ}^{(*)} \to 4l$	JHEP 08 (2023) 040
$\mathrm{H} \to \mathrm{W}^+\mathrm{W}^{-(*)} \to e^{\pm}\mu^{\mp}\nu_1\bar{\nu}_1$	JHEP 03 (2021) 003
$\mathrm{H} \to \tau^+\tau^-$	Phys. Rev. Lett. 128 (2022) 081805
$\mathrm{H} \to \tau^+\tau^-$ (boosted)	Phys. Lett. B 857 (2024) 138964

EFT Interpretation of Differential XS

Fiducial diff. cross sections
Effective field theories

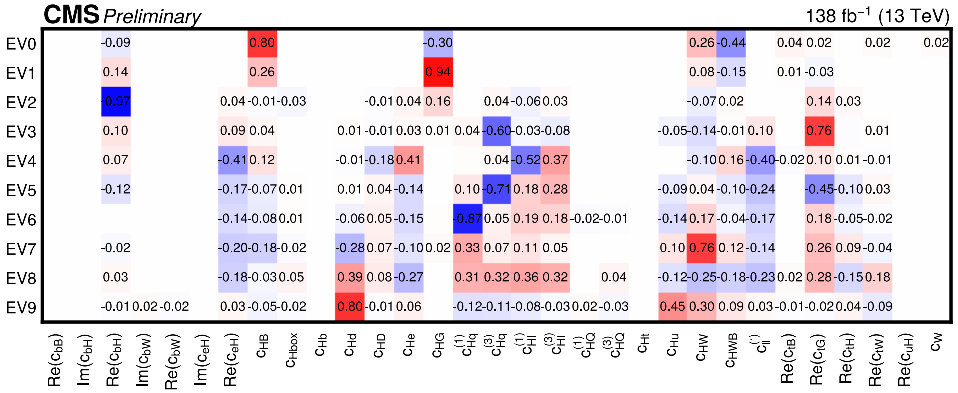
[CMS-HIG-PAS-23-013](CMS-HIG-PAS-23-013)

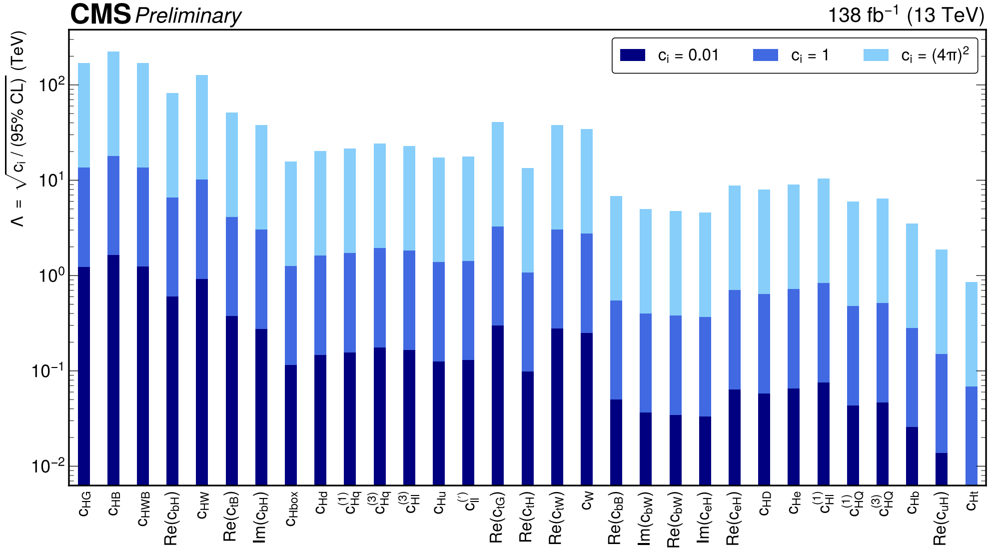
Analysis
$H \rightarrow \gamma\gamma$
$H \rightarrow ZZ^{(*)} \rightarrow 4l$
$H \rightarrow W^+W^{-(*)} \rightarrow e^{\pm}\mu^{\mp}\nu_1\bar{\nu}_1$
$H \rightarrow \tau^+\tau^-$
$H \rightarrow \tau^+\tau^-$ (boosted)

Parametrize

$$\mu = \frac{\sigma \cdot \mathrm{BR} \cdot A}{\sigma^{\mathrm{SM}} \cdot \mathrm{BR}^{\mathrm{SM}} \cdot A^{\mathrm{SM}}}$$

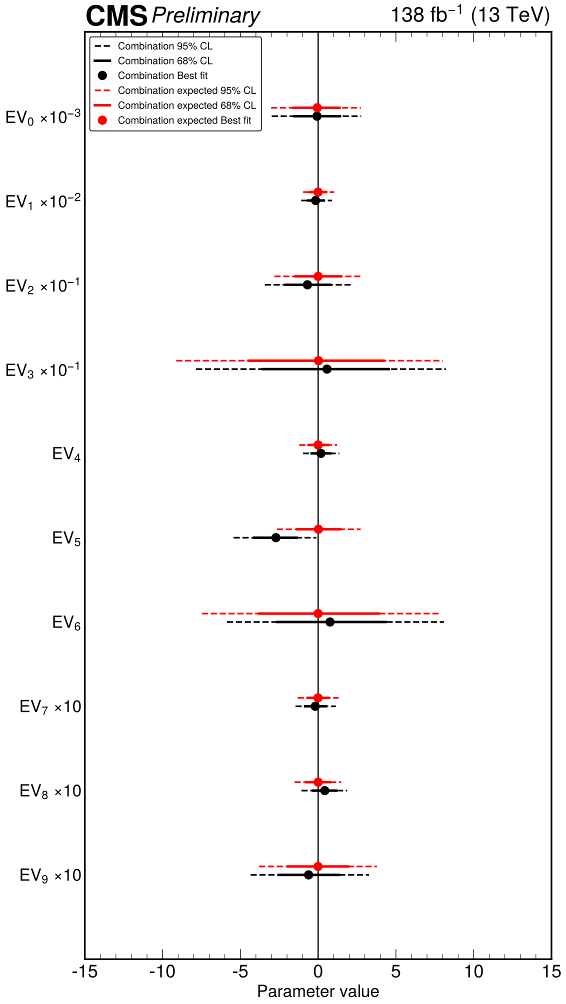
(no extrapolation to 4π)





Run fits for WCs one at a time to derive **lower limits on NP scale**

- Define linear combinations of WCs to simultaneously constrain **10 directions** in the parameter space while setting others to SM value (choise driven by sensitivity of data to WC, not SM assumptions)
- Absolute value means importance of WC in linear combination
- Results **agree with SM within 2σ**



Summary - Future Combinations

- **Legacy single-H combination (Run 2)**
  - Iteration of Nature 607, 60-68 (2022) with more analyses included (boosted H→bb, VBF H→bb, VH H→bb, ttH H→bb, H →inv.)
  - Extensive interpretation of STXS measurements with κ -framework and EFTs
- **Legacy HH combination (Run 2)**
  - Iteration of Nature 607, 60-68 (2022) with new channels (VHH4b, bbWW, WW$\gamma\gamma$, $\gamma\gamma\tau\tau$)
  - Planned results:
    - Upper limits on HH cross section
    - Probe SM couplings $\left(\kappa_\lambda, \kappa_t, \kappa_V, \kappa_{2V}\right)$
    - Scans and upper limits on (H)EFT framework $\left(\kappa_\lambda, \kappa_t, C_2, C_g, C_{2g}\right)$
- **Run 3 (+ Run 2) differential cross sections combination**
  - Same idea as CMS-PAS-HIG-23-013