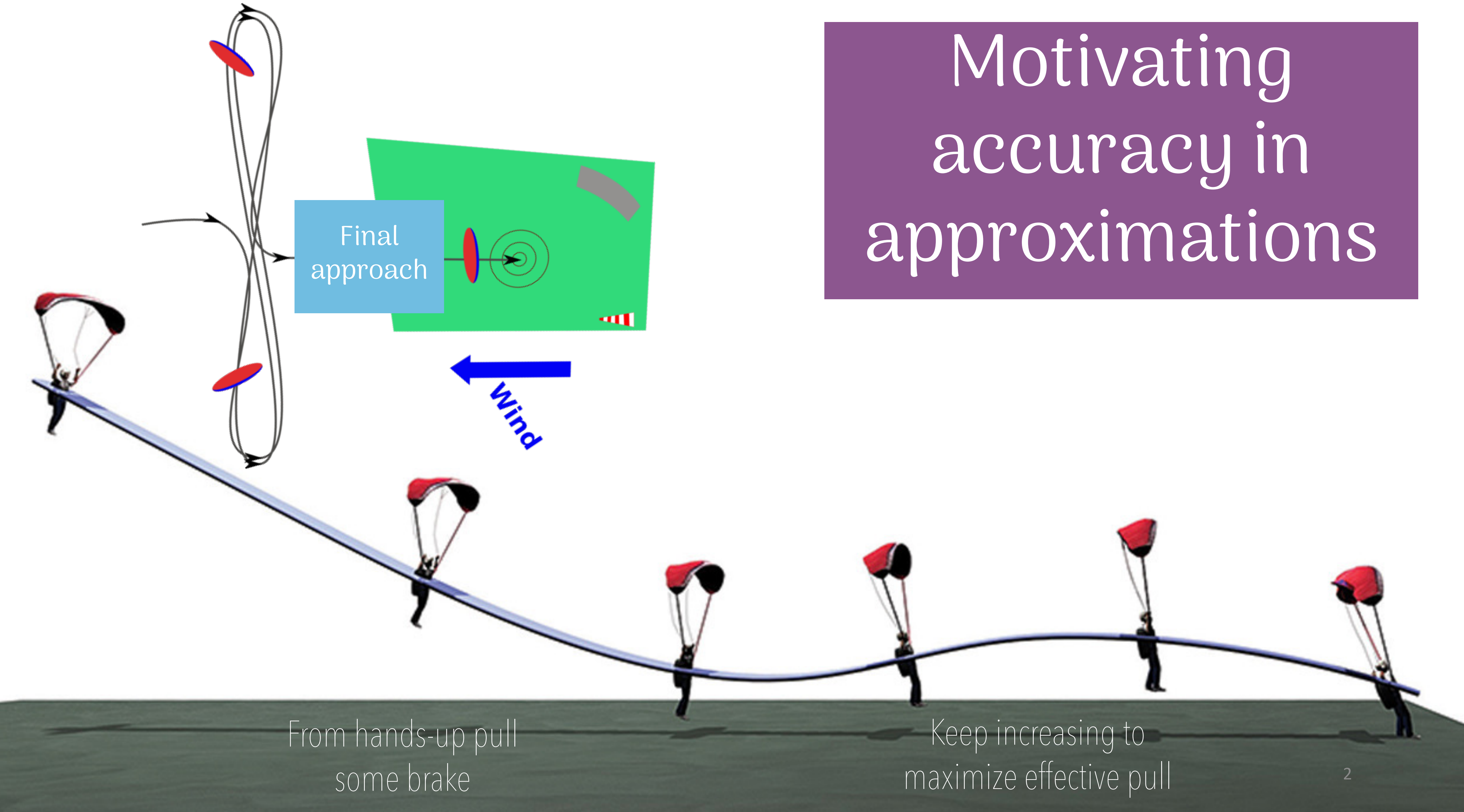
Lourdes Urda

Effective Field Theory Results from the CMS experiment

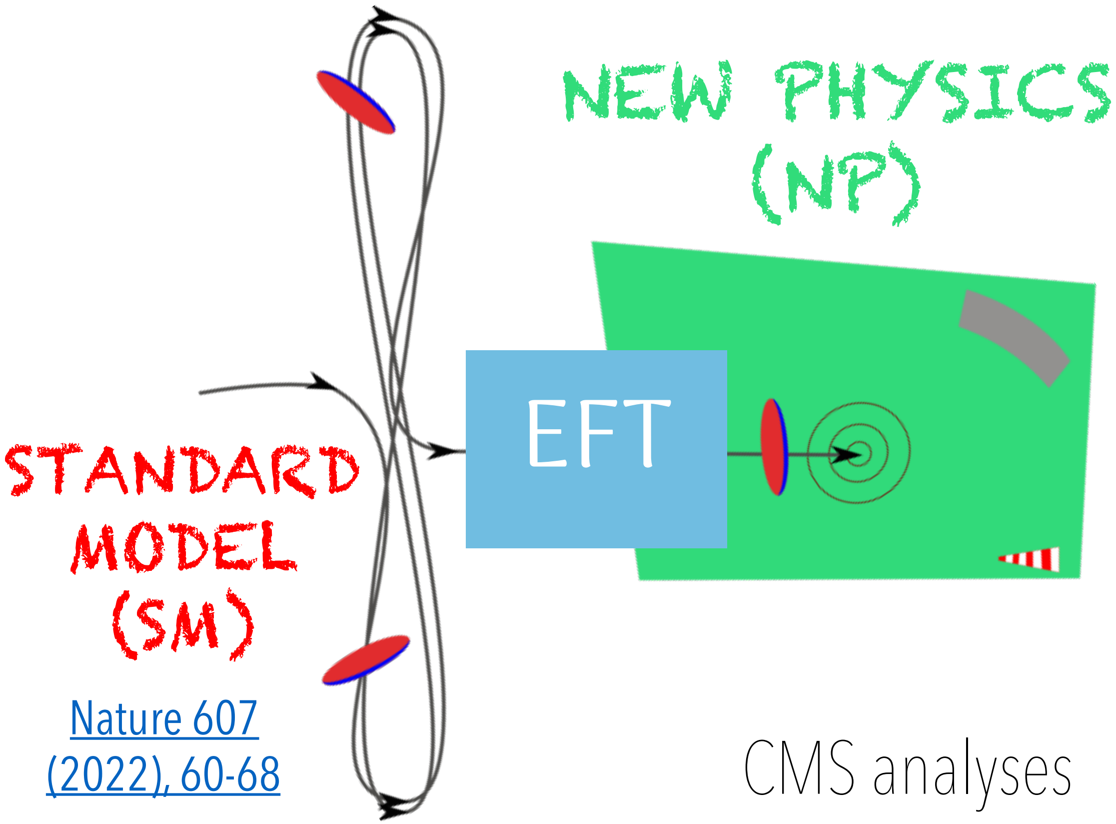
Higgs Hunting 2024

24/09/24

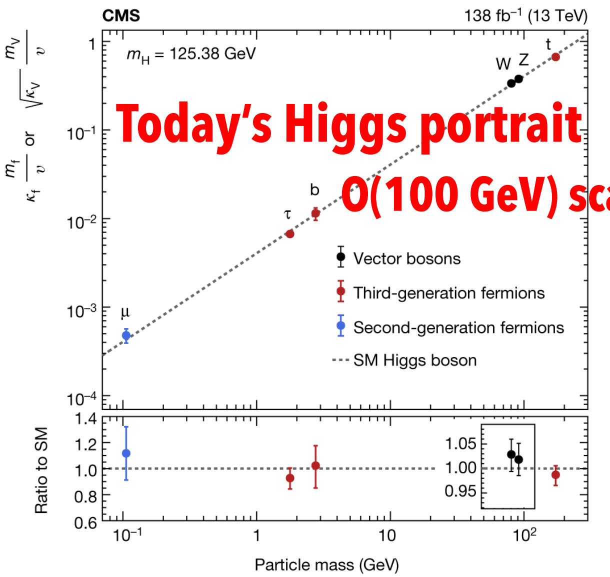
Motivating accuracy in approximations



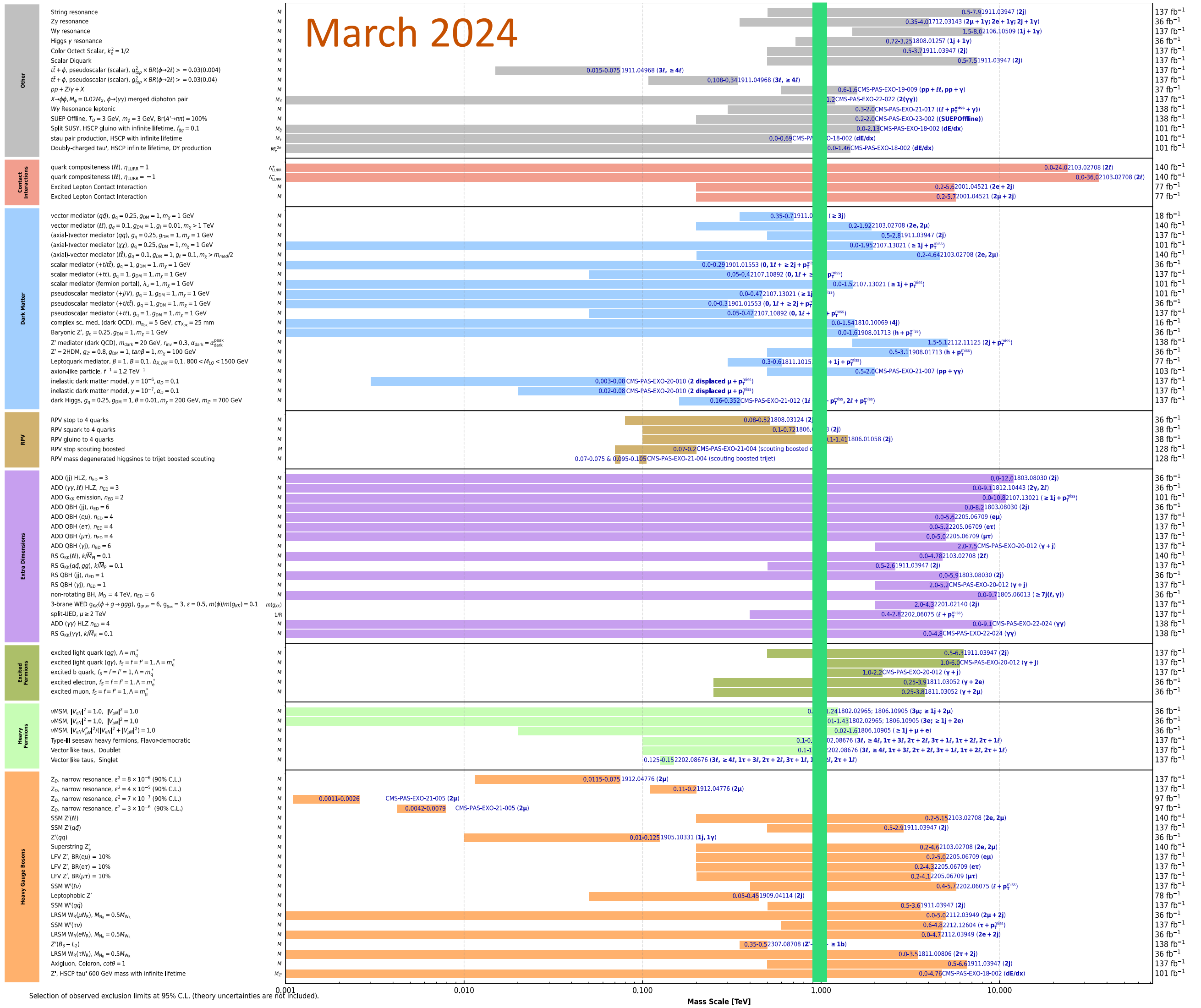
Overview of CMS EXO results



Nature 607 (2022), 60-68



CMS analyses indicating an **energy gap** between SM physics and NP



EFT links phenomena across different energy scales

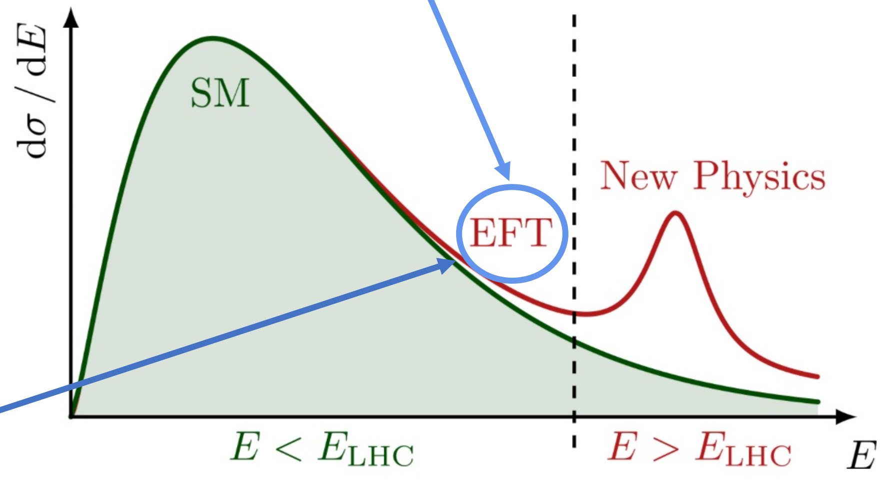
~1 TeV

SM Effective Field Theory (SMEFT)

$$\mathcal{L}_{eff} = \mathcal{L}^{SM} + \mathcal{L}^{D=6}, \qquad \mathcal{L}^{D=6} = \frac{1}{\Lambda^2}\sum_i c_i^{(6)} \mathcal{O}_i^{(6)}$$

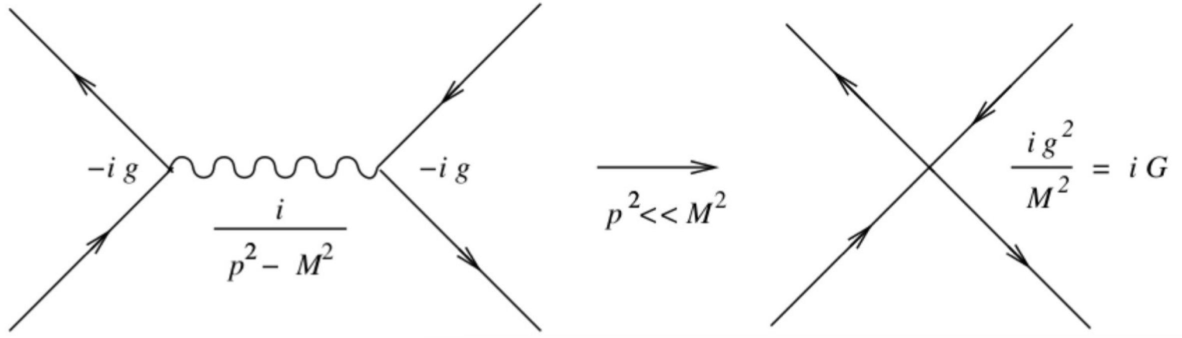
- ✓ c_i specify the strength of the new interactions
- ✓ EFT only valid at $E < \Lambda$

Deformations in SM described by $\mathcal{O}_i^{(6)}$ effective interaction



Full theory (*New Physics*)

Effective interaction (*EFT*)



Cross section (xs) also affected as:

SM xs + SM-BSM interference xs + BSM xs

CMS analyses enable us to accurately place limits on Wilson Coefficients (c_i)

CMS Run 2 EFT-related analyses

Individual channels

$H \to WW \to e\mu\nu\nu$

Eur. Phys. J. C 84 (2024) 779

New! $VH \to bb$

CMS-PAS-HIG-23-016

New! $HZ\gamma$ and $H\gamma\gamma$

CMS-PAS-HIG-23-011

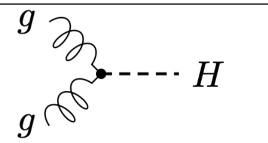
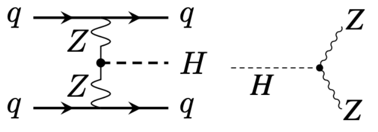
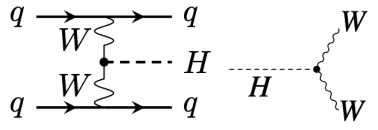
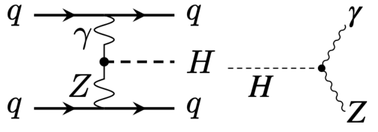
Combination of channels

EFT interpretation of Higgs diff. fid. measurements

CMS-PAS-HIG-23-013

New! EFT interpretation of SM measurements

CMS-PAS-SMP-24-003

Operator	Wilson coefficient	Example process
$H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}$	c_{HG}	
$H^\dagger H \tilde{G}^a_{\mu\nu} G^{a\mu\nu}$	$\tilde{c}_{HG}$	
$H^\dagger H B_{\mu\nu} B^{\mu\nu}$	c_{HB}	
$H^\dagger H \tilde{B}_{\mu\nu} B^{\mu\nu}$	$\tilde{c}_{HB}$	
$H^\dagger H W^i_{\mu\nu} W^{i\mu\nu}$	c_{HW}	
$H^\dagger H \tilde{W}^i_{\mu\nu} W^{i\mu\nu}$	$\tilde{c}_{HW}$	
$H^\dagger \sigma^i H W^i_{\mu\nu} B^{i\mu\nu}$	c_{HWB}	
$H^\dagger \sigma^i H \tilde{W}^i_{\mu\nu} B^{i\mu\nu}$	$\tilde{c}_{HWB}$	

Global EFT data analyses are highly motivated

A single operator can influence many processes, and multiple operators can affect one single process.

$H \to WW \to e\mu\nu\nu$

Eur. Phys. J. C 84 (2024) 779

Based on likelihood ratios

$$\mathcal{D}_{\rm BSM} = \frac{\mathcal{P}_{\rm BSM}(\vec{\Omega})}{\mathcal{P}_{\rm BSM}(\vec{\Omega}) + \mathcal{P}_{\rm SM}(\vec{\Omega})}$$

Reconstruction at detector-level

MELA-based kinematic discriminants (KD) sensitive to production vertex:

Production mode (D_{VBF})

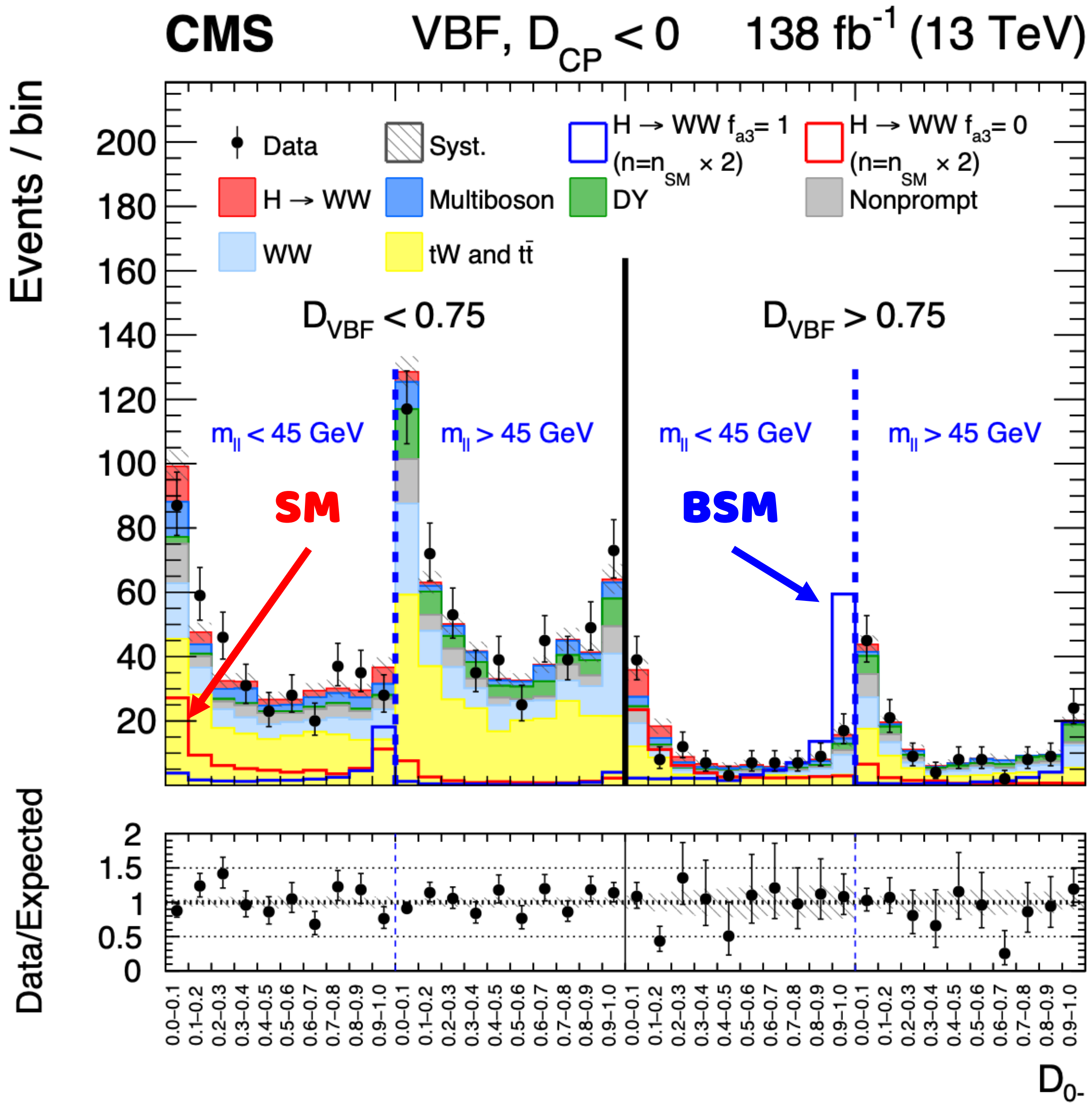
Pure BSM contribution (D_{0-})

SM-BSM interferences (D_{CP})

Sensitive to decay vertex:

$m_{\ell\ell}$

Fit to multidimensional KD



SMEFT Higgs basis

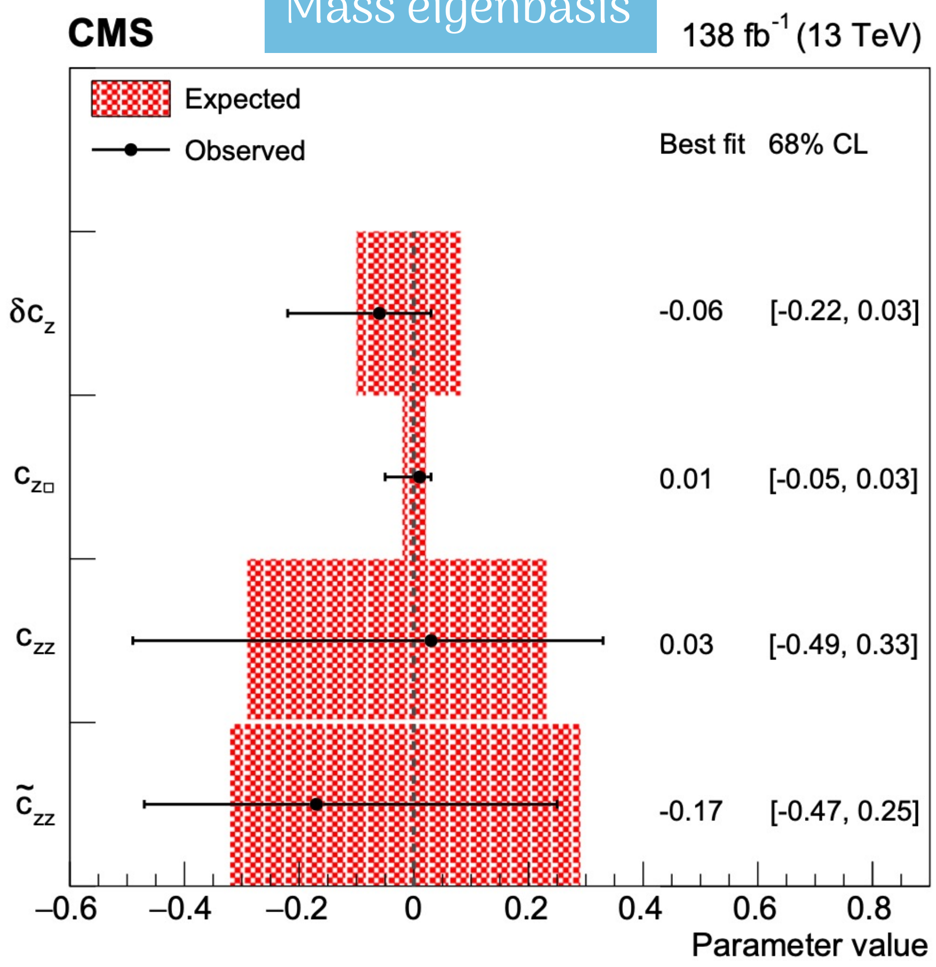
Linear+Quadratic

SMEFT Warsaw basis

Useful for analyses combination

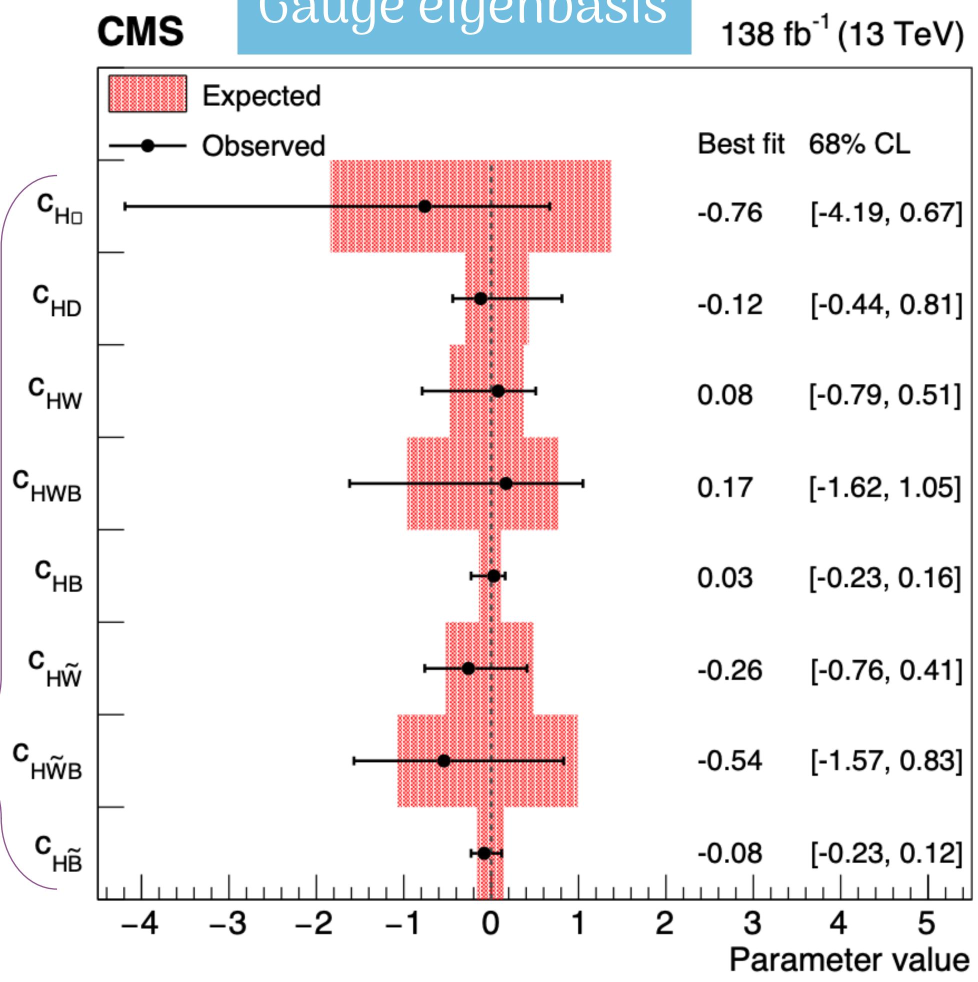
Useful for the theoretician community

Mass eigenbasis



Surpassing results of Run 1 analysis in precision and coverage.

Gauge eigenbasis



Wilson Coefficients

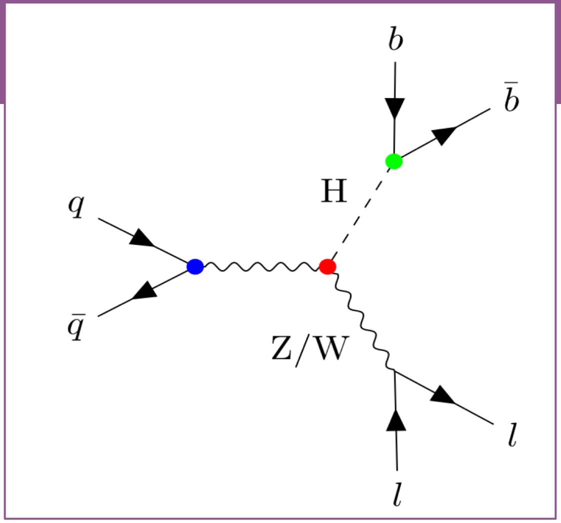
(3 independent fits to the data)

Results in terms of cross section fraction contribution available.

CMS-PAS-HIG-23-016

VH → bb

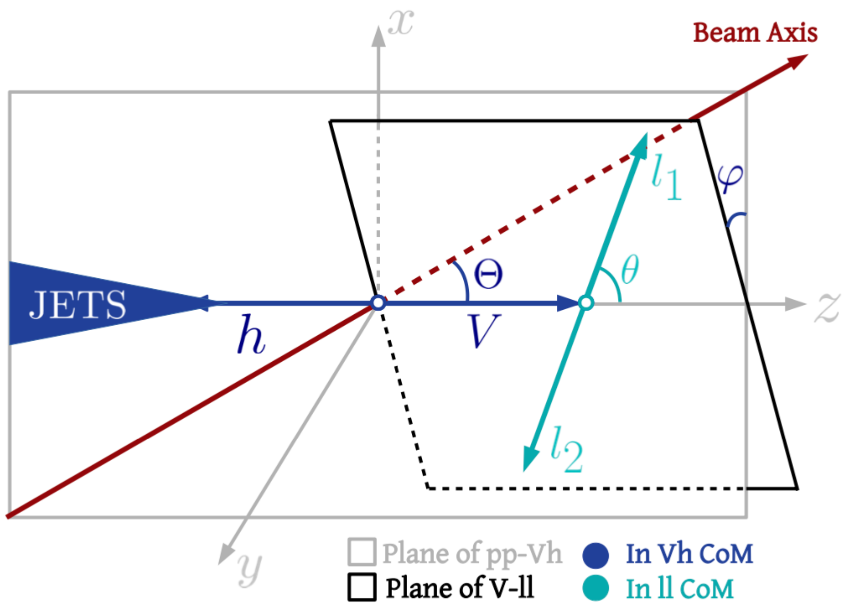
Higgs anomalous couplings on production and decay vertex

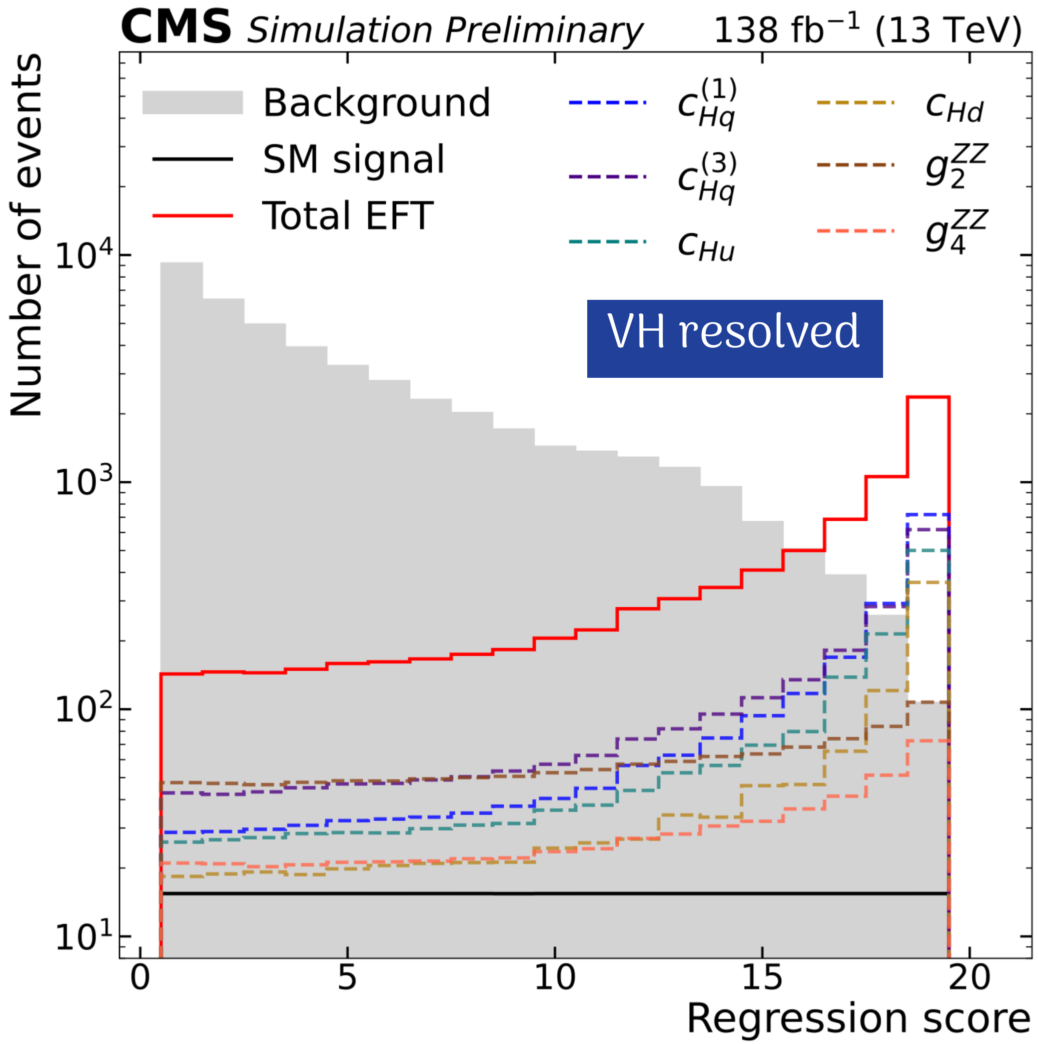


Also based on likelihood ratios

but with reconstructed objects

after detector smearing





Decay Channels:

- 0 leptons: $Z \rightarrow \upsilon\upsilon$
- 1 lepton: $W \rightarrow \ell\nu$
- 2 leptons: $Z \rightarrow \ell\ell$

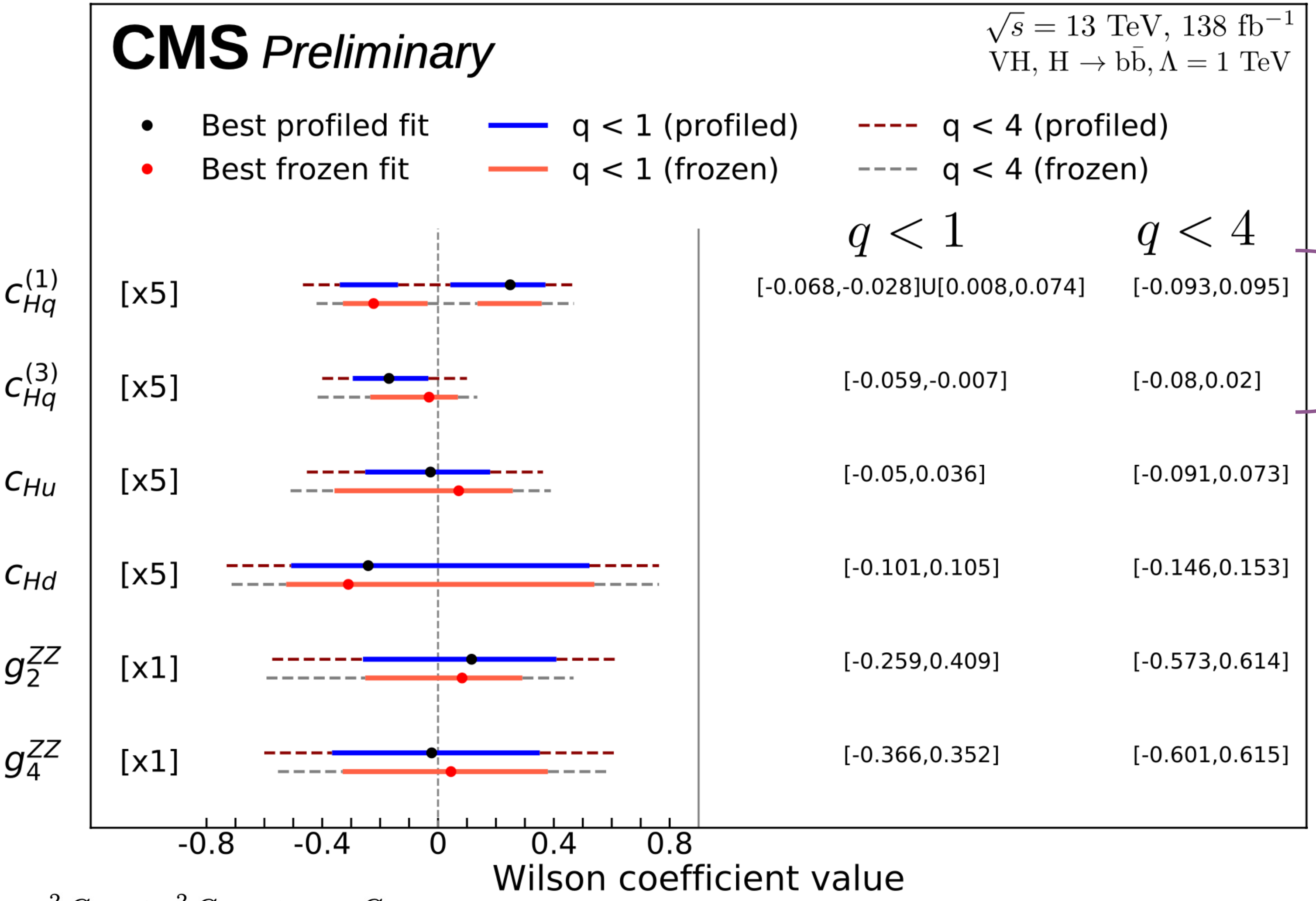
Fit to observables:

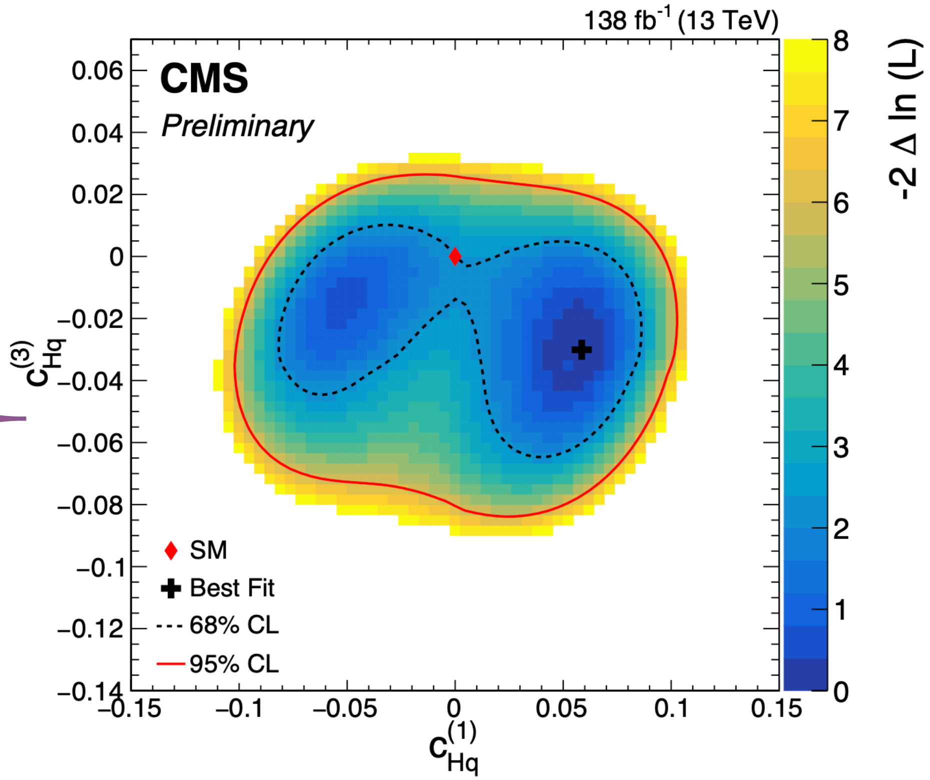
Boosted information Trees (BIT)

Observables optimized for the EFT effects

Data/MC plots for reference

Constraints on Wilson Coefficients





$g_2^{ZZ} \propto s_w^2 C_{HB} + c_w^2 C_{HW} + s_w c_w C_{HWB}$

$g_4^{ZZ} \propto s_w^2 C_{H\tilde{B}} + c_w^2 C_{H\tilde{W}} + s_w c_w C_{H\tilde{W}B}$

Results are consistent with the SM expectation

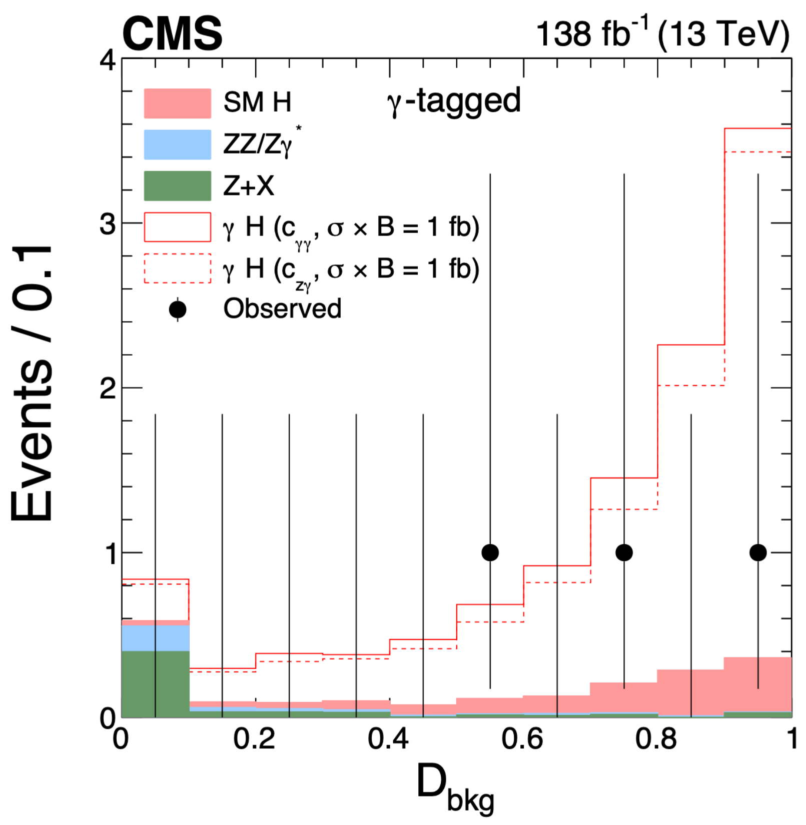
EFT in HZγ and H$\gamma\gamma$

CMS-PAS-HIG-23-011

Targeting the production vertex involving the Higgs and an associated photon, these AC can impact the production rate

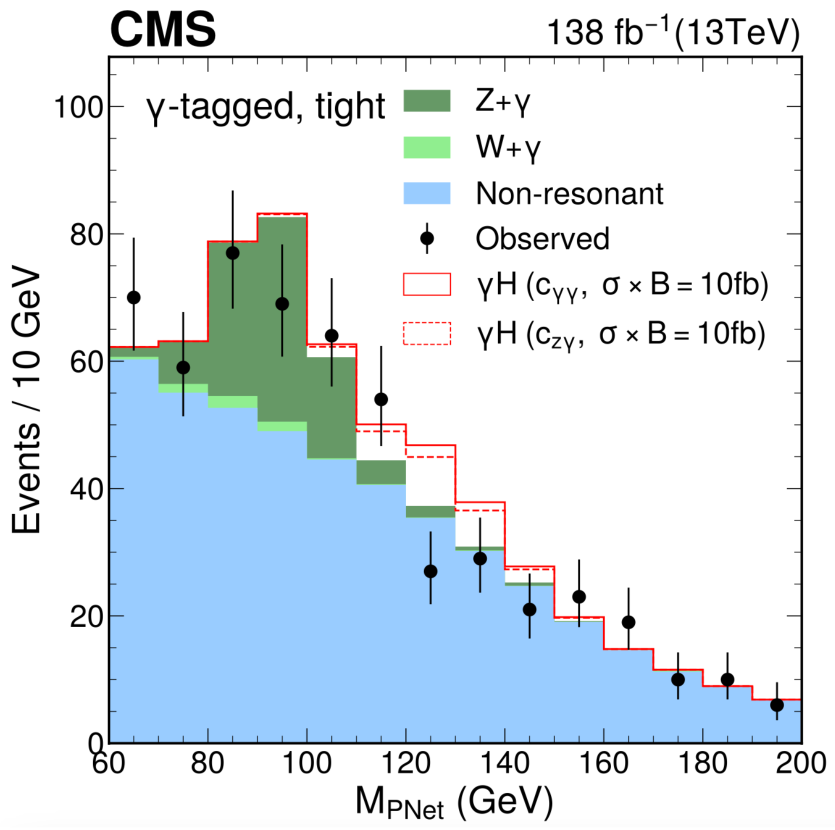
H → ZZ → 4ℓ

MELA-based discriminants



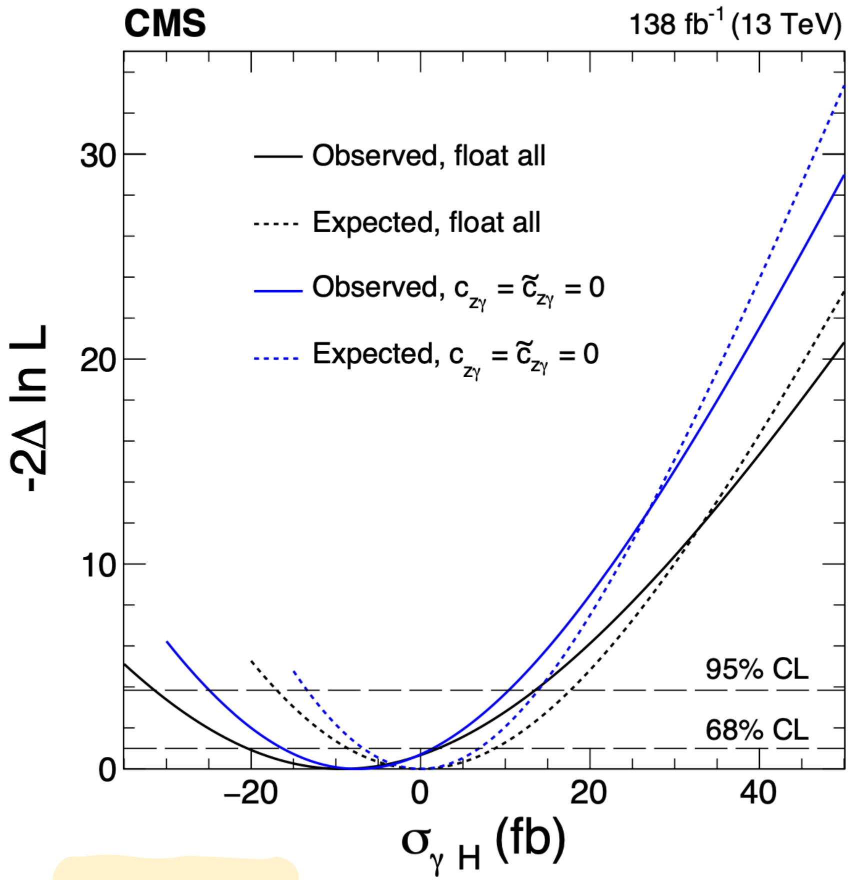
H → bb

Mass of Higgs candidate



Fitted observables

Cross-section measurement from the combination of channels



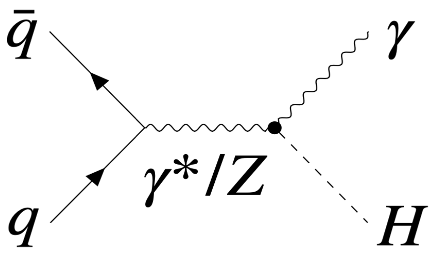
Result

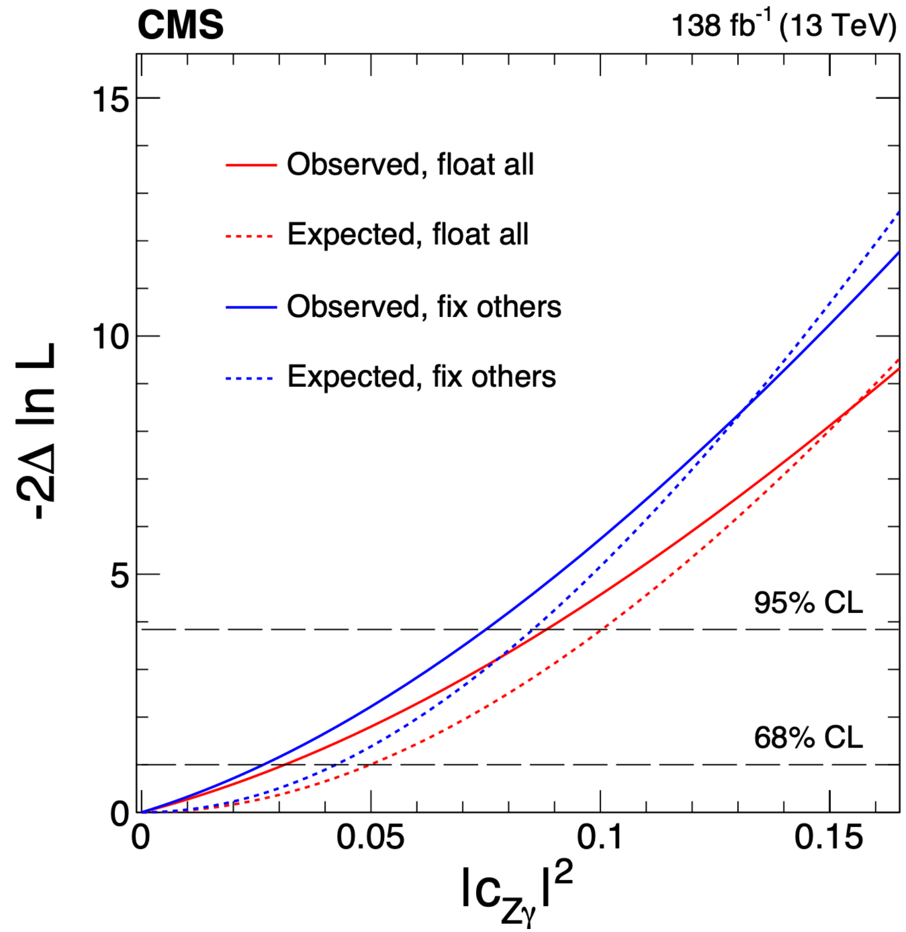
HVV couplings scans

SMEFT Higgs basis

$c_{\gamma\gamma}$, $c_{z\gamma}$, $\tilde{c}_{\gamma\gamma}$, $\tilde{c}_{z\gamma}$

H → bb dominated



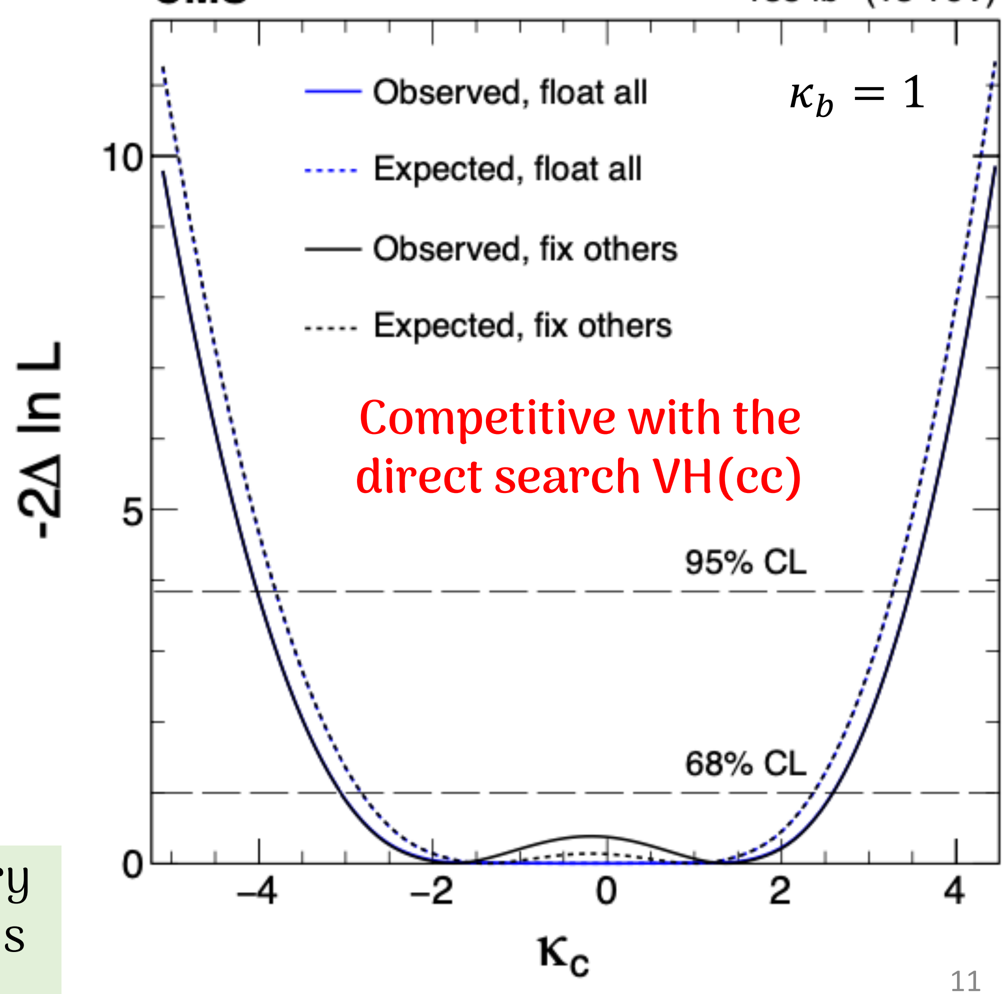


Supplementary result on Higgs Width Γ^H_{BSM}

Yukawa couplings scans

Hff vertex parametrization κ_u, κ_d, κ_s, and κ_c

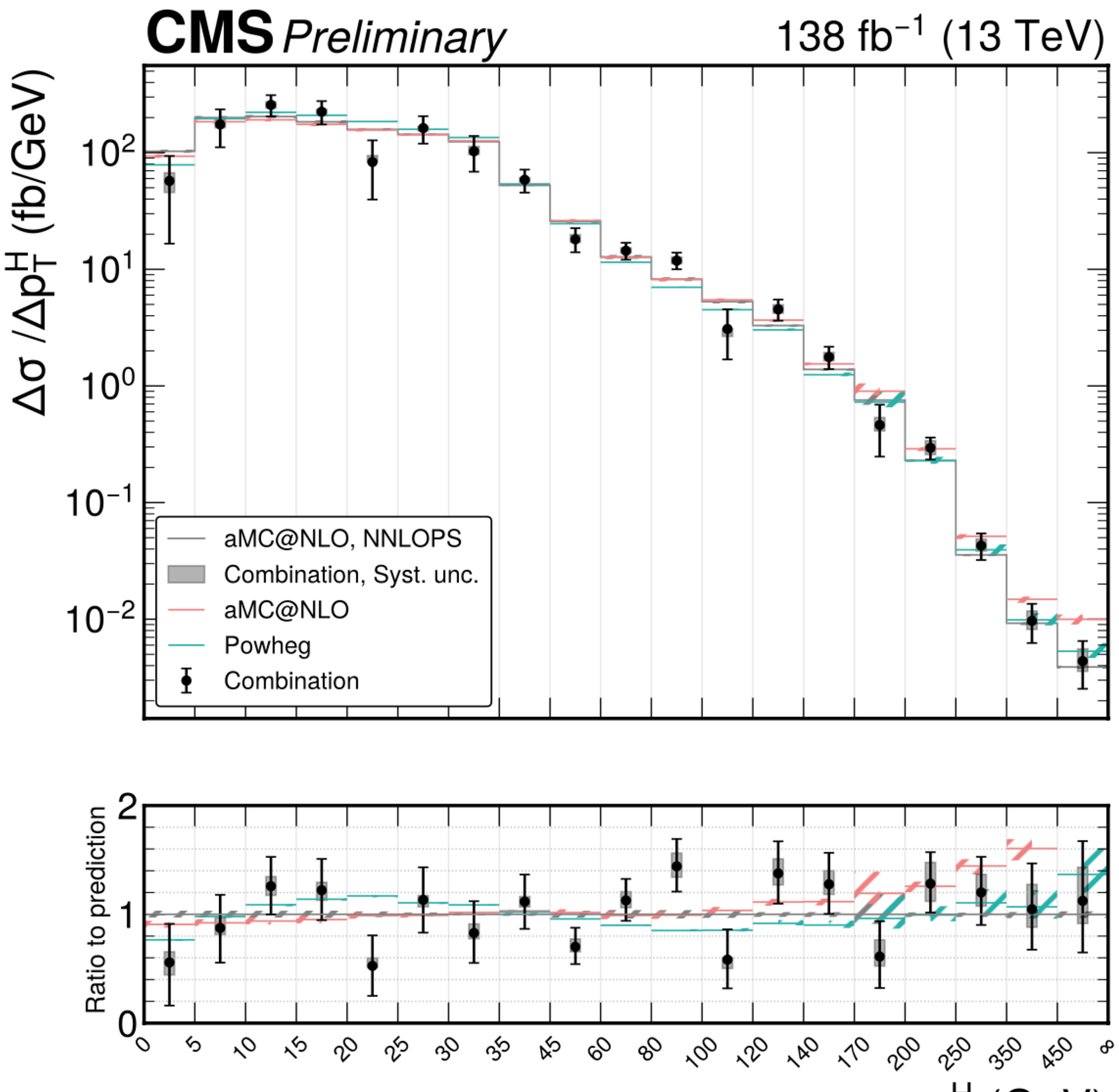
H → ZZ → 4ℓ only



Combination and EFT interpretation of Higgs differential fiducial measurements

CMS-PAS-HIG-23-013

$H \to \gamma\gamma$ JHEP 07 (2023) 091
$H \to ZZ \to 4\ell$ JHEP 08 (2023) 040
$H \to WW \to e\mu\nu\nu$ 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



OBSERVABLE → p_T^H (GeV)

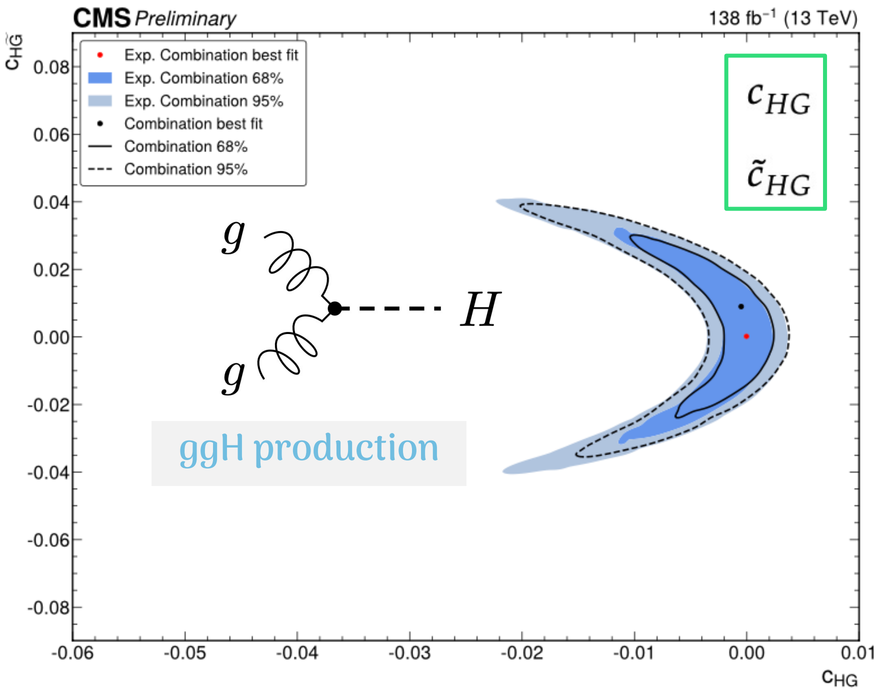
Analysis strategy:

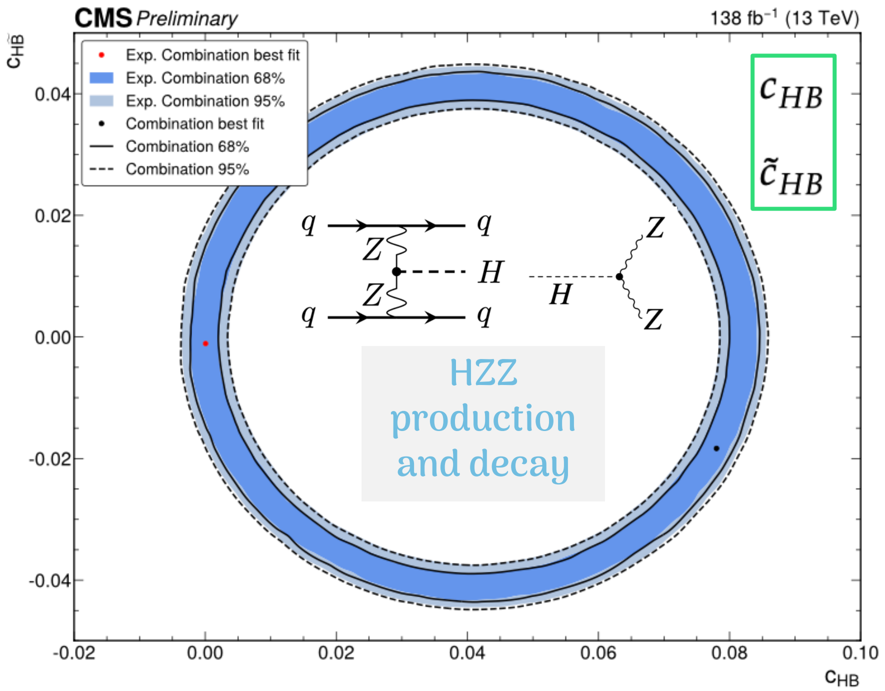
Differential distributions are sensitive to Higgs couplings through distortions in the predicted SM cross-section spectra.

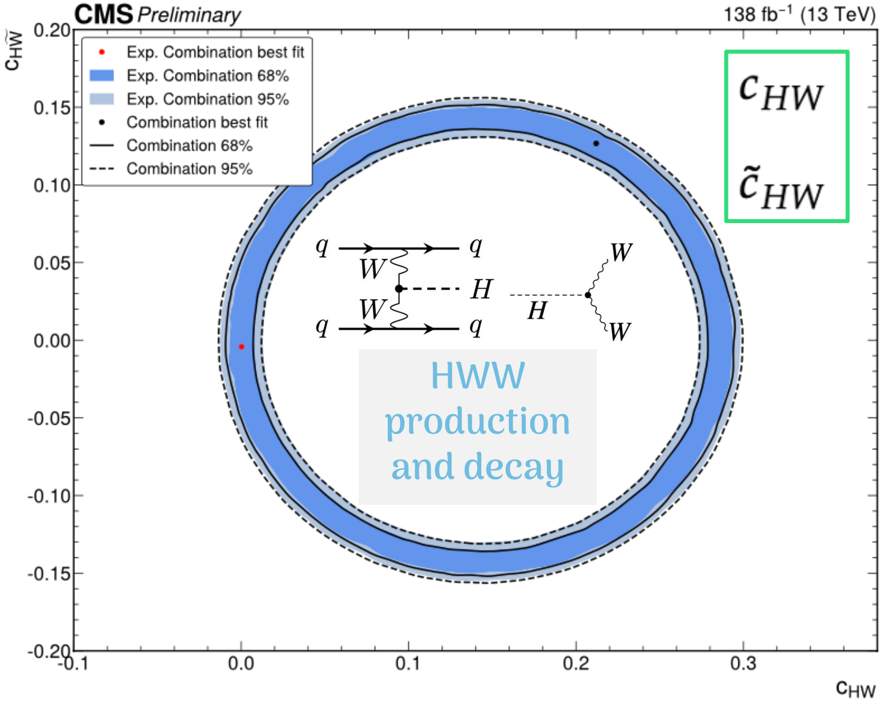
Used parametrizations:

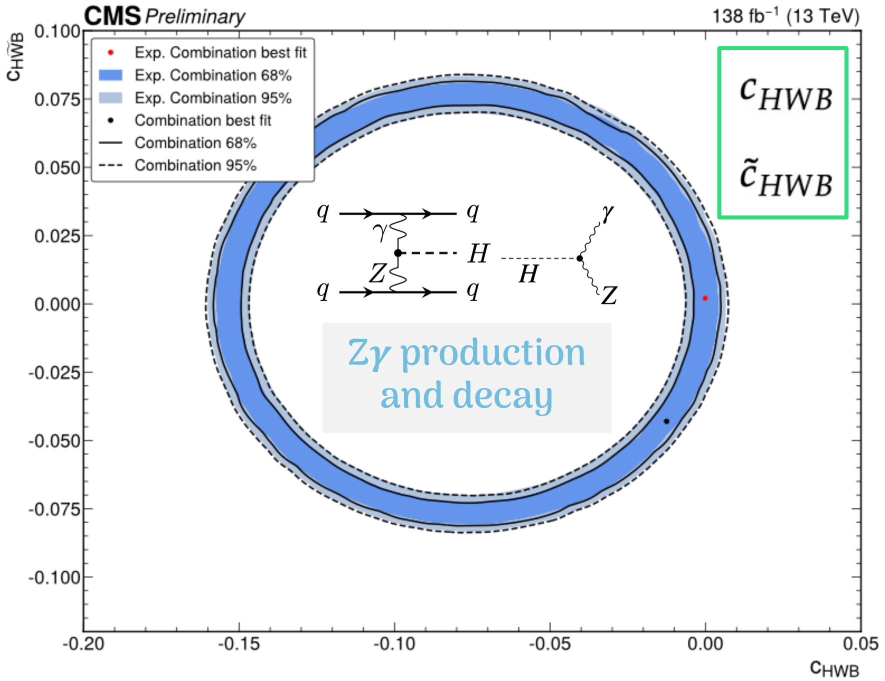
κ-framework and SMEFT

p_T^H 2D scans of Wilson coefficients





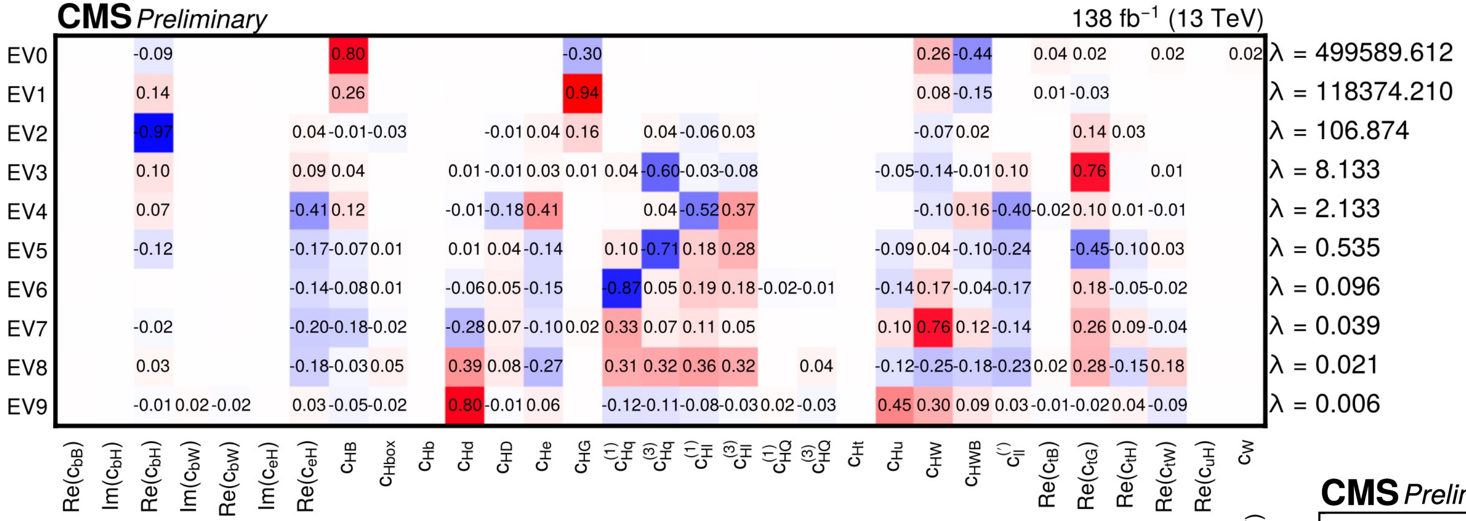




Fit pairs of CP-even and CP-odd Wilson coefficients to assess their impact on Higgs production and decay, with all other coefficients set to their SM values of zero.

But there are more...!

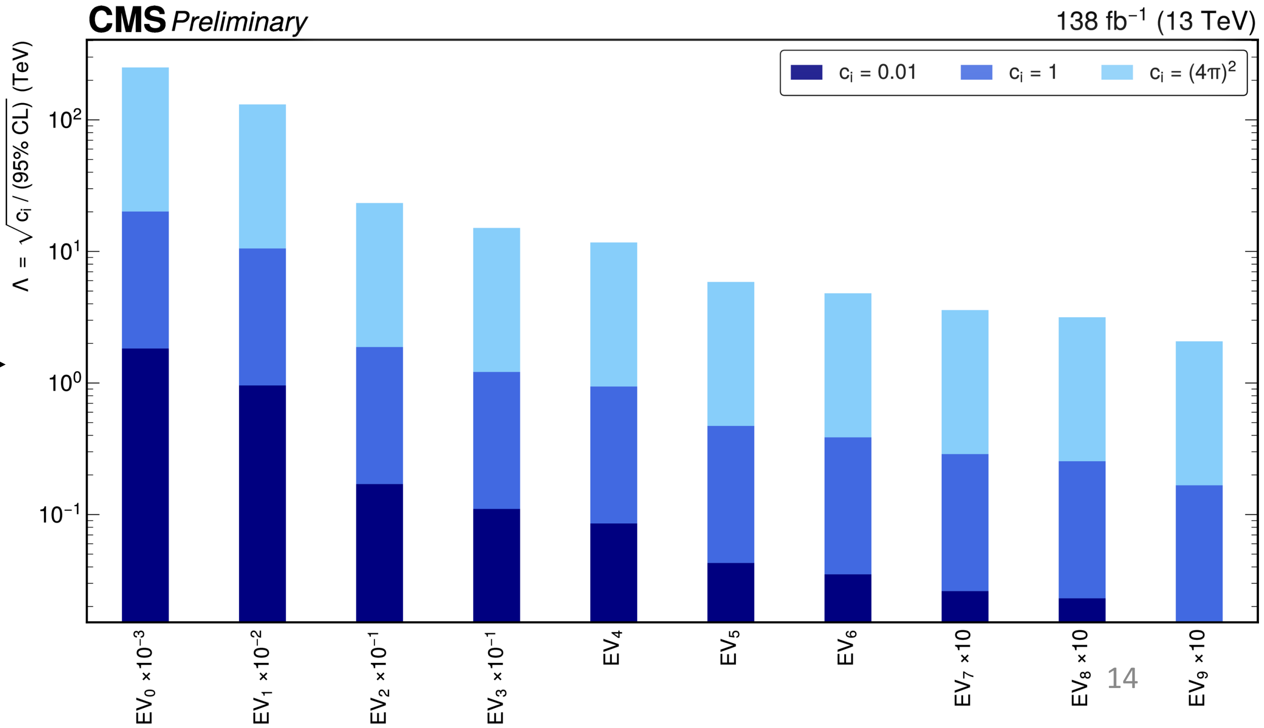
Interpretation of the entire phase space



Determine orthogonal linear combinations of the most constrained Wilson coefficients from the data to simultaneously constrain 10 directions (EV) in parameter space.

Limits on the NP energy scale

95% CL lower limits for different values of Wilson coefficients →



Combined EFT interpretation of SM measurements

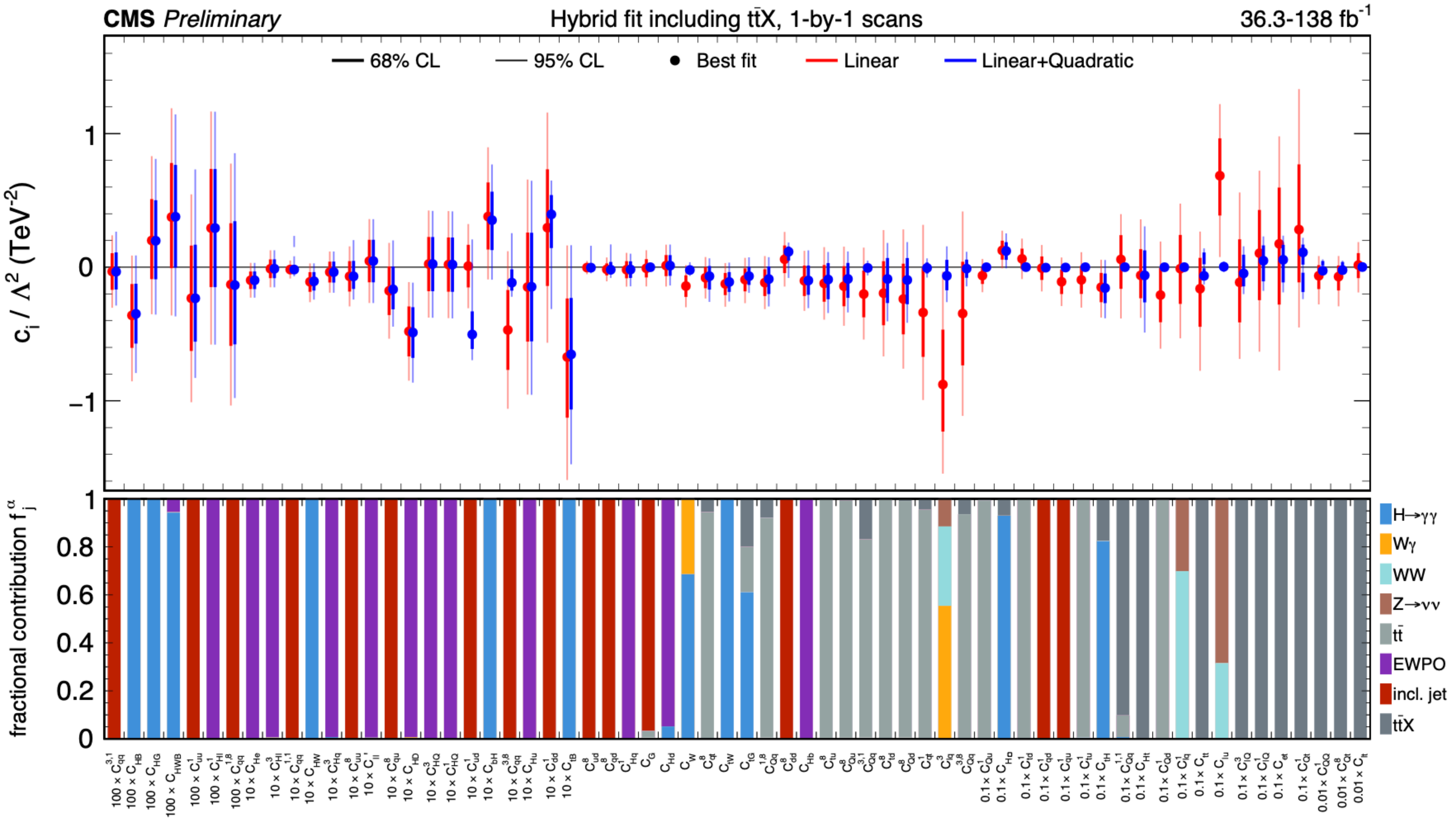
CMS-PAS-SMP-24-003

First combination from an experiment including top, Higgs, vector boson and jet measurements in an EFT interpretation!

Analysis	Type of measurement	Observables used	Experimental likelihood
$\mathrm{H} \to \gamma\gamma$	Diff. cross sections	STXS bins [40]	✓
$\mathrm{W}\gamma$	Fid. diff. cross sections	$p_{\mathrm{T}}^{\gamma} \times \lvert\phi_f\rvert$	✓
WW	Fid. diff. cross sections	$m_{\ell\ell}$	✓
$\mathrm{Z} \to \nu\nu$	Fid. diff. cross sections	$p_{\mathrm{T}}^{\mathrm{Z}}$	✓
$\mathrm{t\bar{t}}$	Fid. diff. cross sections	$M_{\mathrm{t\bar{t}}}$	×
EWPO	Pseudo-observables	$\Gamma_Z,\ \sigma^0_{\mathrm{had}},\ R_\ell,\ R_c,\ R_b,\ A^{0,\ell}_{FB},\ A^{0,c}_{FB},\ A^{0,b}_{FB}$	×
Inclusive jets	Fid. diff. cross sections	$p_{\mathrm{T}}^{\mathrm{jet}} \times \lvert y^{\mathrm{jet}}\rvert$	×
$\mathrm{t\bar{t}X}$	Direct EFT	Yields in regions of interest	✓

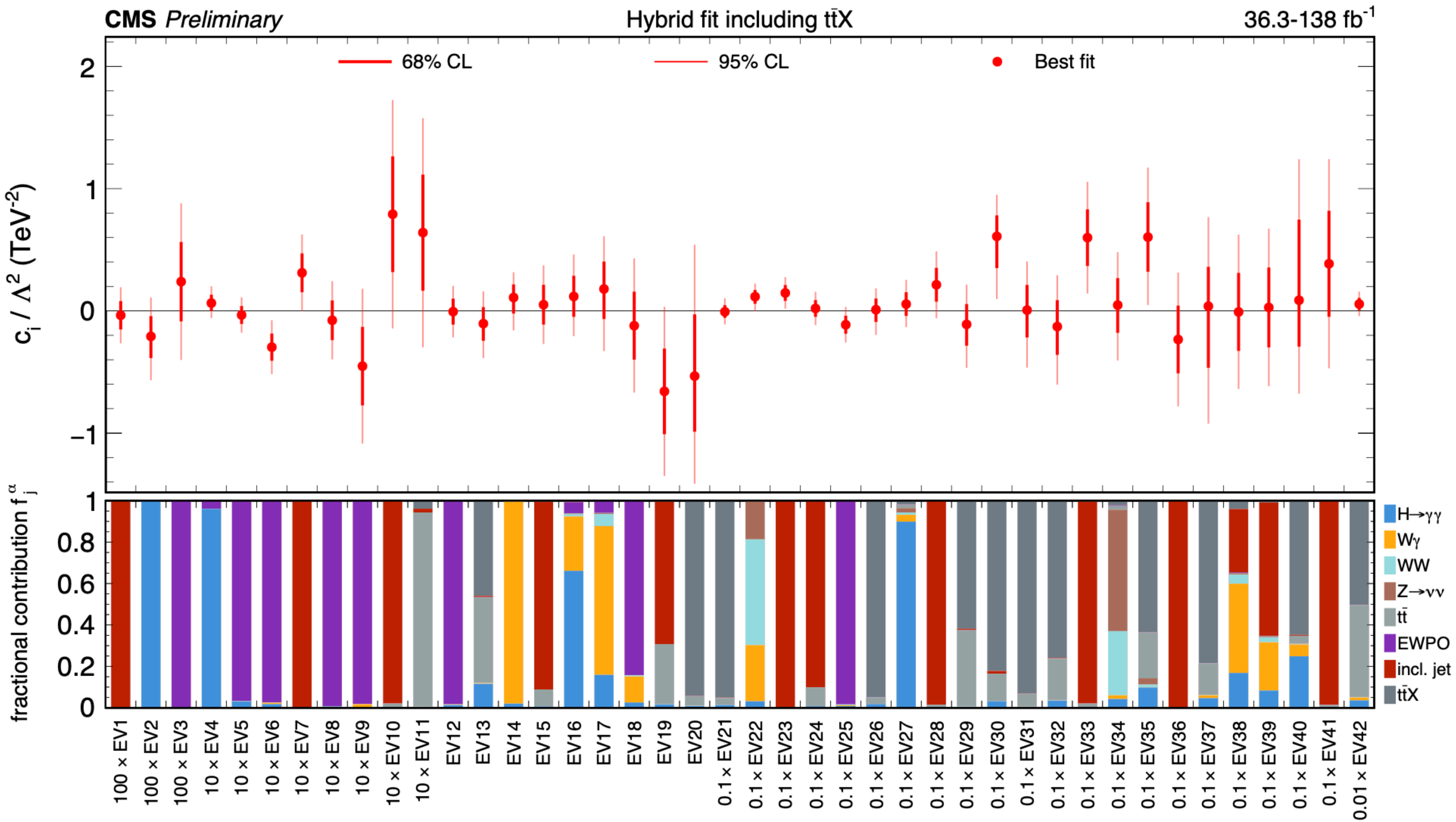
✓ LEP and SLC electroweak precision measurements included.

Constraints on Wilson Coefficients



Individually : 64, with confidence intervals ranging from ±0.003 to ±20.

Flash of the EV fit



42 directions are constrained simultaneously… The most so far!

Supplementary result on 95% CL lower limits on the scales Λ of NP ~ TeV

Conclusions

- EFT serves as a connection to the fundamental nature of interactions, bridging different energy scales.
- 5 indirect searches of BSM effects in the context of SMEFT have been presented across:
  - 3 individual channels, refining our understanding of Higgs couplings to particles and the EWSB mechanism.
  - Two combined EFT interpretation analyses on the Higgs and SM demonstrate that global EFT data analyses are crucial.
- EFT Run 2 analyses are statistically limited but show promise for future Higgs physics in Run 3 and beyond.
- For now, everything is consistent with the SM within uncertainties.
- Precision is key — accurate approximations are essential to staying safe and sound!

BACK UP SLIDES

EFT H → WW → $e\mu\nu\nu$ analysis

Targeting HVV anomalous couplings in production and decay vertexes

Analysis strategy:

MELA-based kinematic discriminants (KD)

Production channels:

ggH, VBF, VH, and boosted VH

Used approaches:

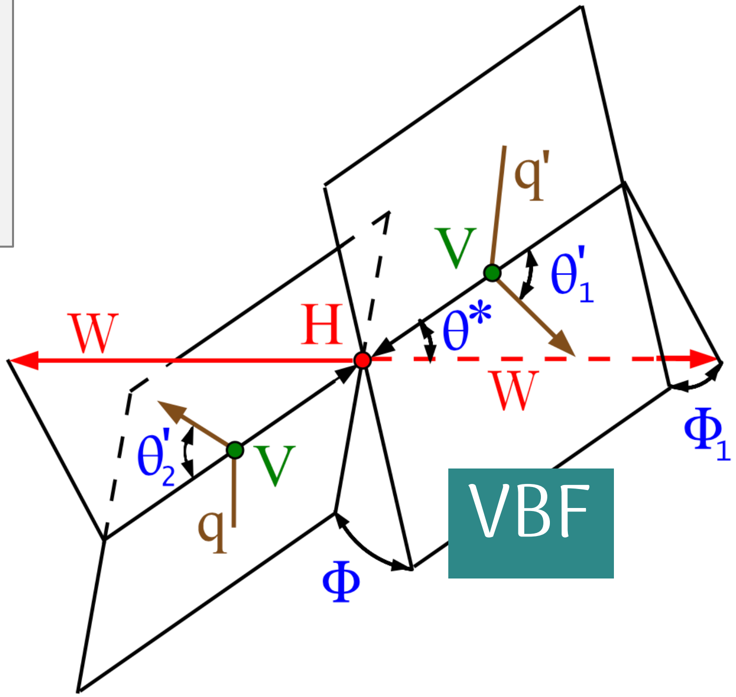
AC and SMEFT

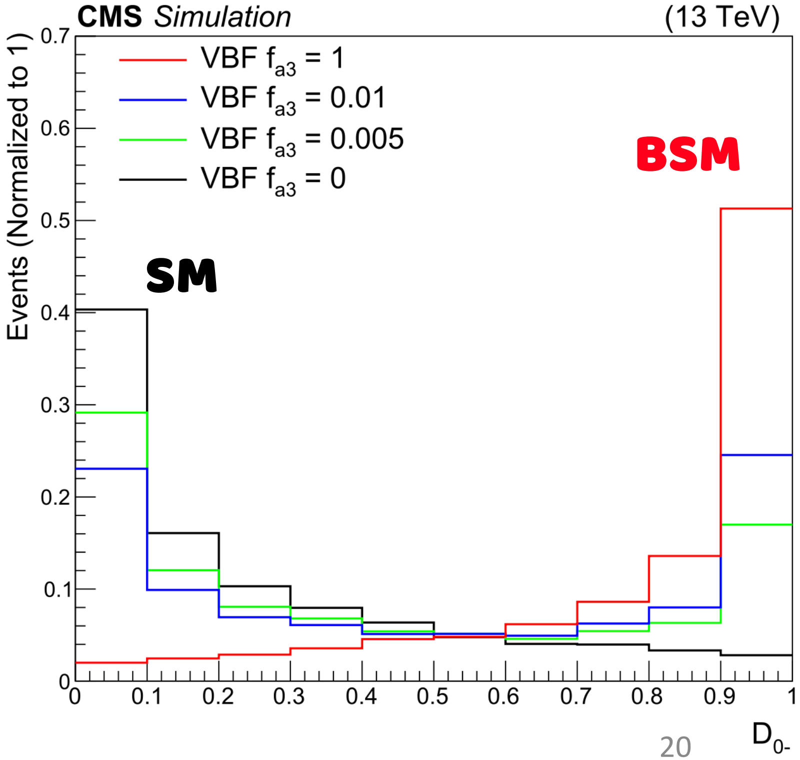
Matrix Element Likelihood Approach (MELA)

Reconstructed event

Theoretical hypothesis

Probability that the event **matches** the hypothesis

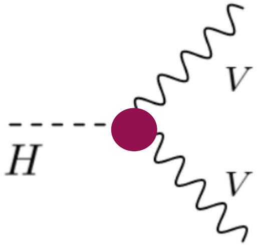




HVV vertex parametrization

Scattering amplitude :

Higher-order SM loop or BSM contributions (anomalous couplings)



$$A(\mathrm{HV_1V_2}) \sim \left[\underbrace{a_1^{VV}}_{\text{SM}} + \frac{\kappa_1^{VV} q_{V1}^2 + \kappa_2^{VV} q_{V2}^2}{\left(\Lambda_1^{VV}\right)^2} \right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + \frac{1}{v} a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

Anomalous Couplings (AC) approach — $a^{WW} = a^{ZZ}$

SMEFT approach

SU(2)xU(1) — $a^{WW} \neq a^{ZZ}$

Simultaneously studied: a_1 , a_2 , a_3 (CP-odd) and $a_{\Lambda 1}$

Results can be given in terms of:

1. Cross-section fraction f_{ai} (+μ on signal model):

$$f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_j |a_j|^2 \sigma_j} \mathrm{sign}\left(\frac{a_i}{a_1}\right)$$

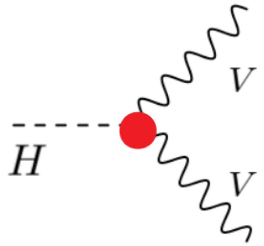
2. SMEFT Mass eigen (Higgs) basis
3. SMEFT Gauge eigen (Warsaw) basis

On this talk!

HVV vertex parametrization

Scattering amplitude :

Higher-order SM loop or BSM contributions (anomalous couplings)



SM

$$A(\mathrm{HV_1V_2}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + \frac{1}{v} a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

SU(2)xU(1)

Relationships between a^{WW} and a^{ZZ}

$$a_1^{WW} = a_1^{ZZ}$$

$$a_2^{WW} = c_w^2 a_2^{ZZ}$$

$$a_3^{WW} = c_w^2 a_3^{ZZ}$$

$$\frac{\kappa_1^{WW}}{(\Lambda_1^{WW})^2} = \frac{1}{c_w^2 - s_w^2}\left(\frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2} - 2s_w^2 \frac{a_2^{ZZ}}{M_Z^2}\right)$$

$$\frac{\kappa_2^{Z\gamma}}{(\Lambda_1^{Z\gamma})^2} = \frac{2s_w c_w}{c_w^2 - s_w^2}\left(\frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2} - \frac{a_2^{ZZ}}{M_Z^2}\right)$$

SMEFT approach

Simultaneously studied: a_1 , a_2 , a_3 (CP-odd) and $a_{\Lambda 1}$

Results can be given in terms of:

1. Cross-section fraction f_{ai} (+μ on signal model):

$$f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_j |a_j|^2 \sigma_j} \operatorname{sign}\left(\frac{a_i}{a_1}\right)$$

On this talk!

2. SMEFT Mass eigen (Higgs) basis
3. SMEFT Gauge eigen (Warsaw) basis

$H \to WW \to e\mu\nu\nu$

Eur. Phys. J. C 84 (2024) 779

MELA-based kinematic discriminants (KD) sensitive to production vertex:

Production mode (D_{VBF})

Pure AC contribution (D_{0-})

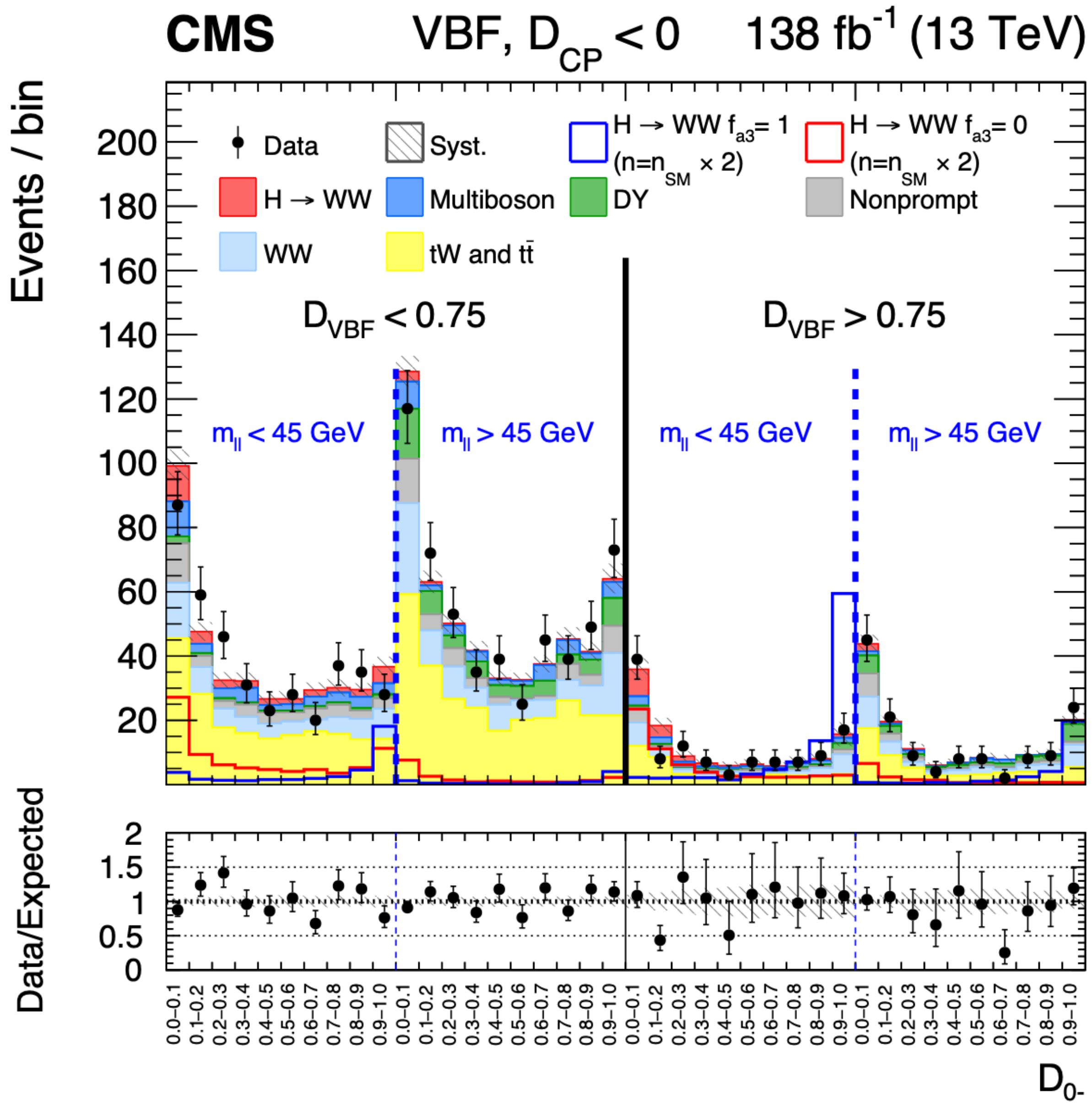
Interference AC contribution (D_{CP})

Sensitive to decay vertex:

$m_{\ell\ell}$

Fit to multidimensional KD

$[D_{VBF}, D_{0-}, m_{\ell\ell}]$
+
D_{CP} categorization

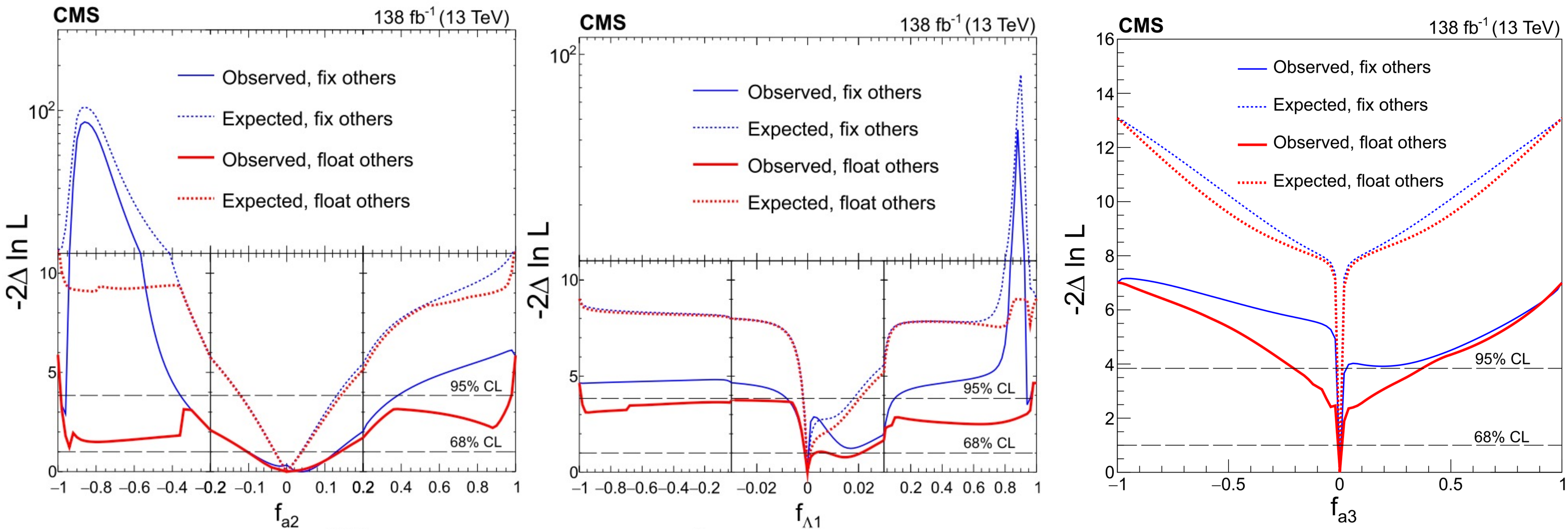


f_{ai} scans

SU(2)xU(1)
3 independent parameters

Results in terms of cross-section fraction

$$f_{ai} = \frac{|a_i|^2\sigma_i}{\sum_j |a_j|^2\sigma_j} \,\mathrm{sign}\left(\frac{a_i}{a_1}\right)$$



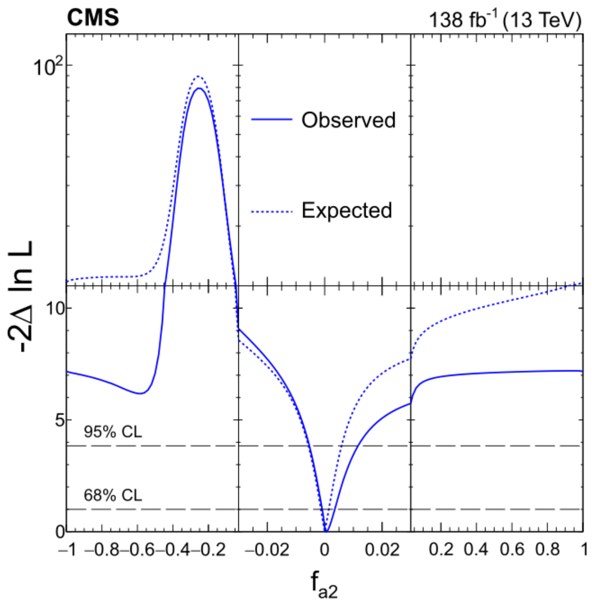
Translation into SMEFT bases possible

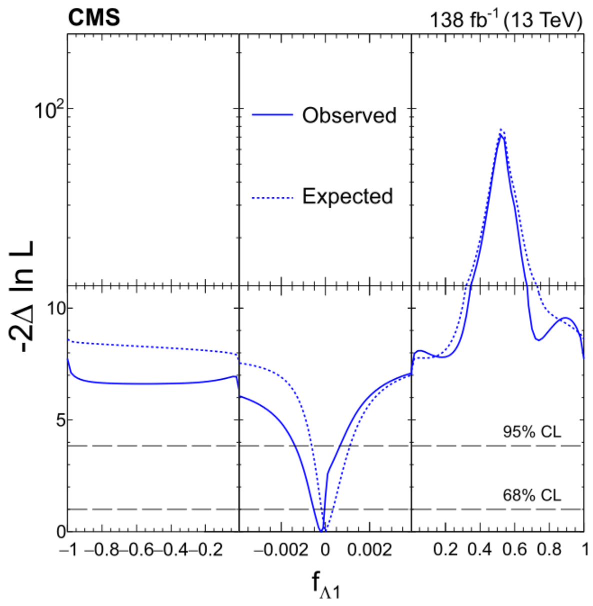
AC SCANS

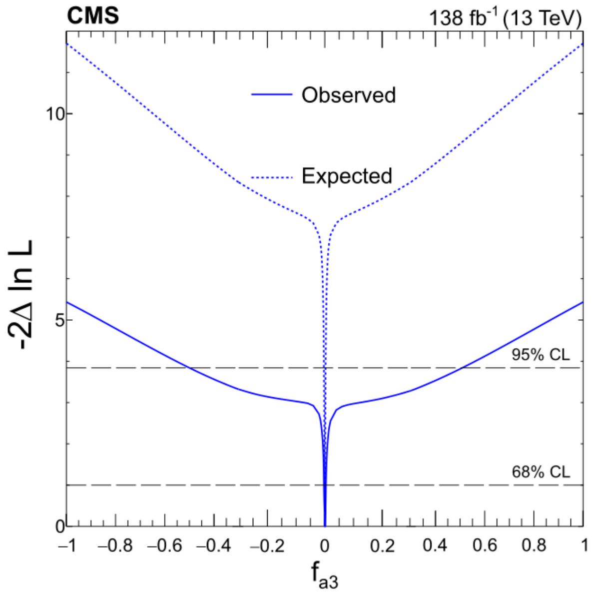
Results in terms of cross-section fraction f_{ai}

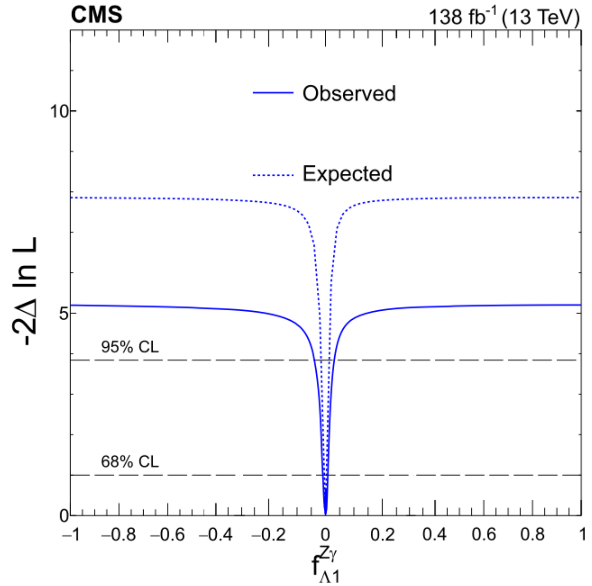
SMEFT SCANS

4 independent parameters



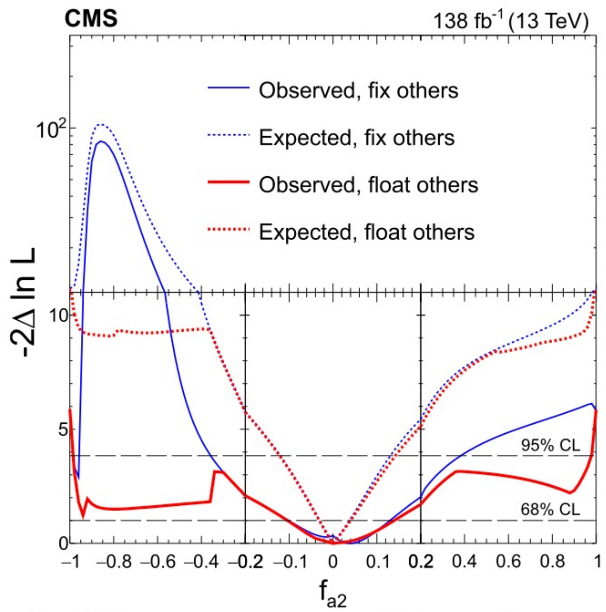


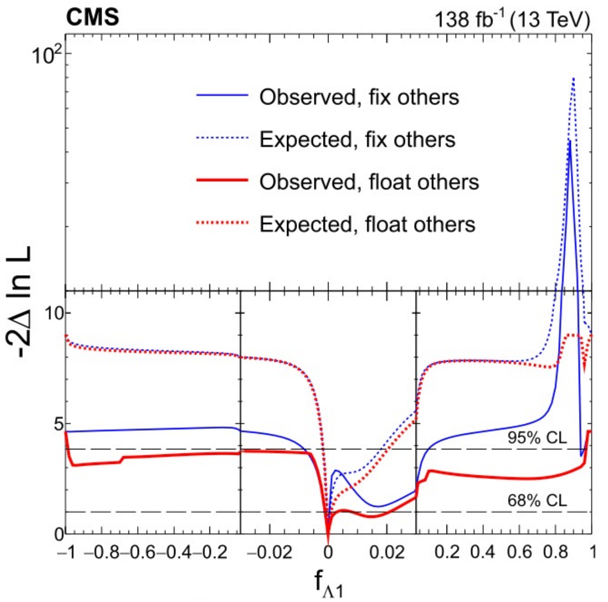


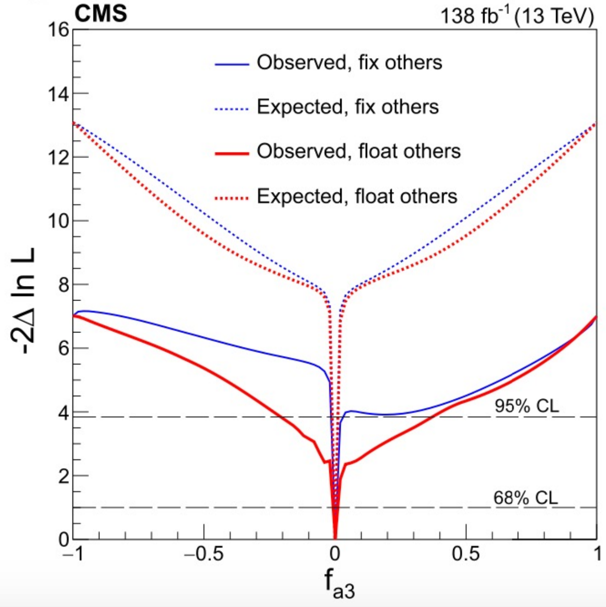


3 independent parameters

SU(3)xU(1)







Translation into other SMEFT bases possible

SMEFT Higgs basis

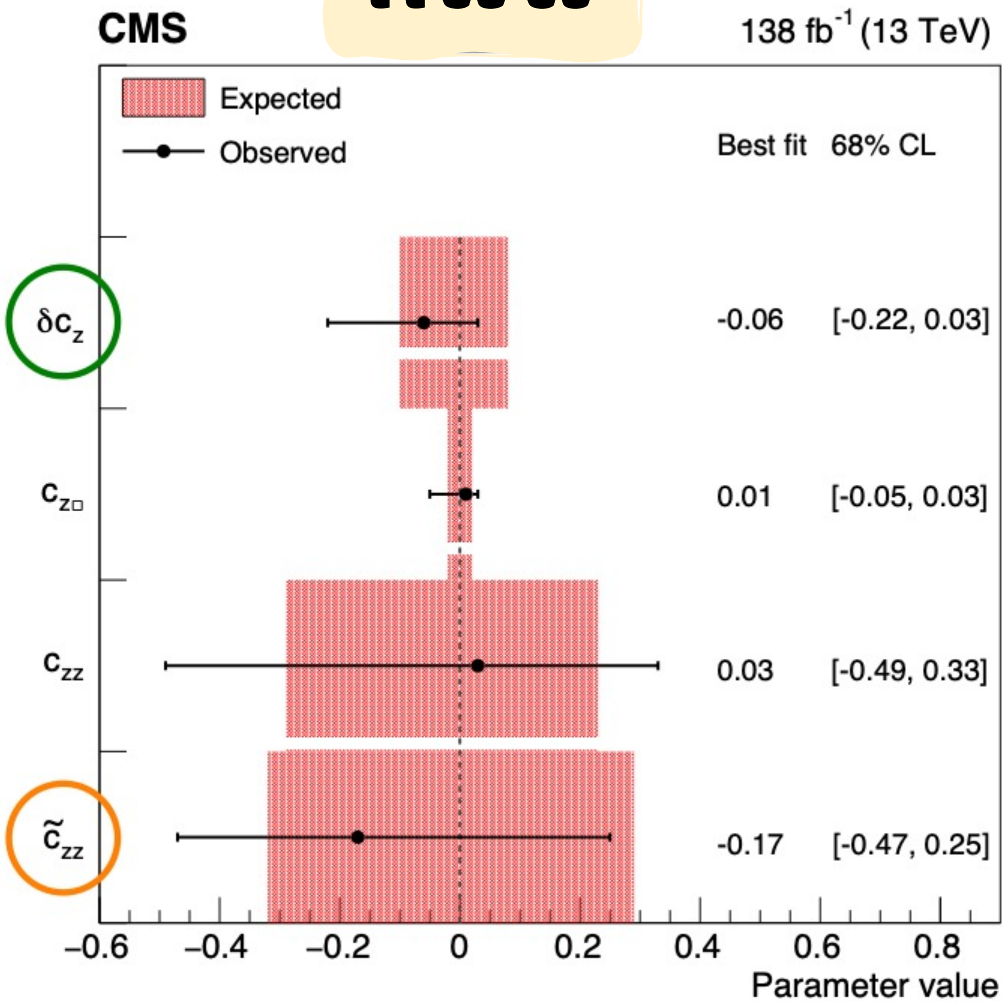
Useful for analyses combination

$$\delta c_z = \frac{1}{2} a_1^{ZZ} - 1$$
$$c_{zz} = -\frac{2 s_w^2 c_w^2}{e^2} a_2^{ZZ}$$
$$\tilde{c}_{zz} = -\frac{2 s_w^2 c_w^2}{e^2} a_3^{ZZ}$$
$$c_{z\Box} = \frac{m_Z^2 s_w^2}{e^2} \frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2}$$

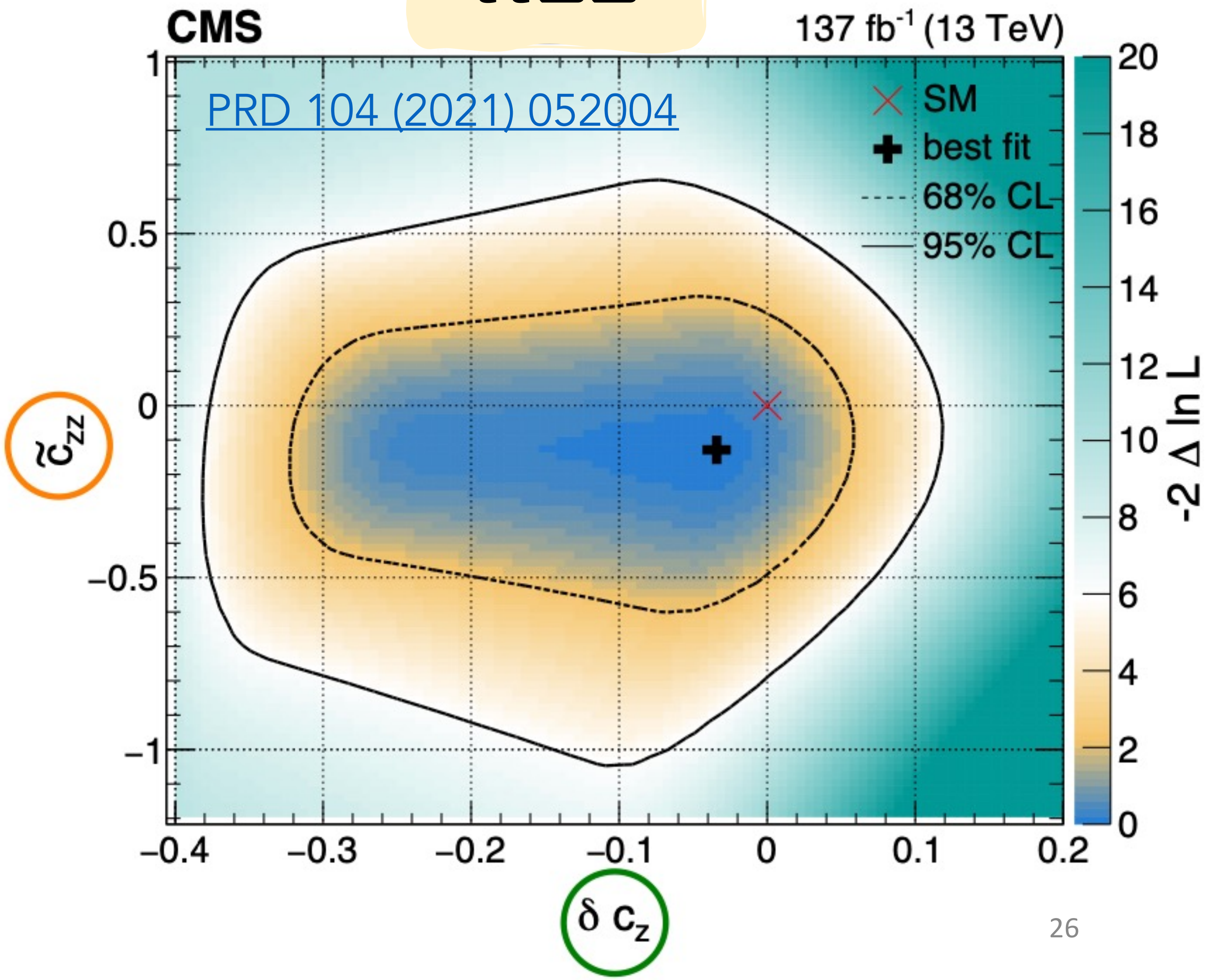
Mass eigenbasis

Results compatible with HZZ analysis

HWW

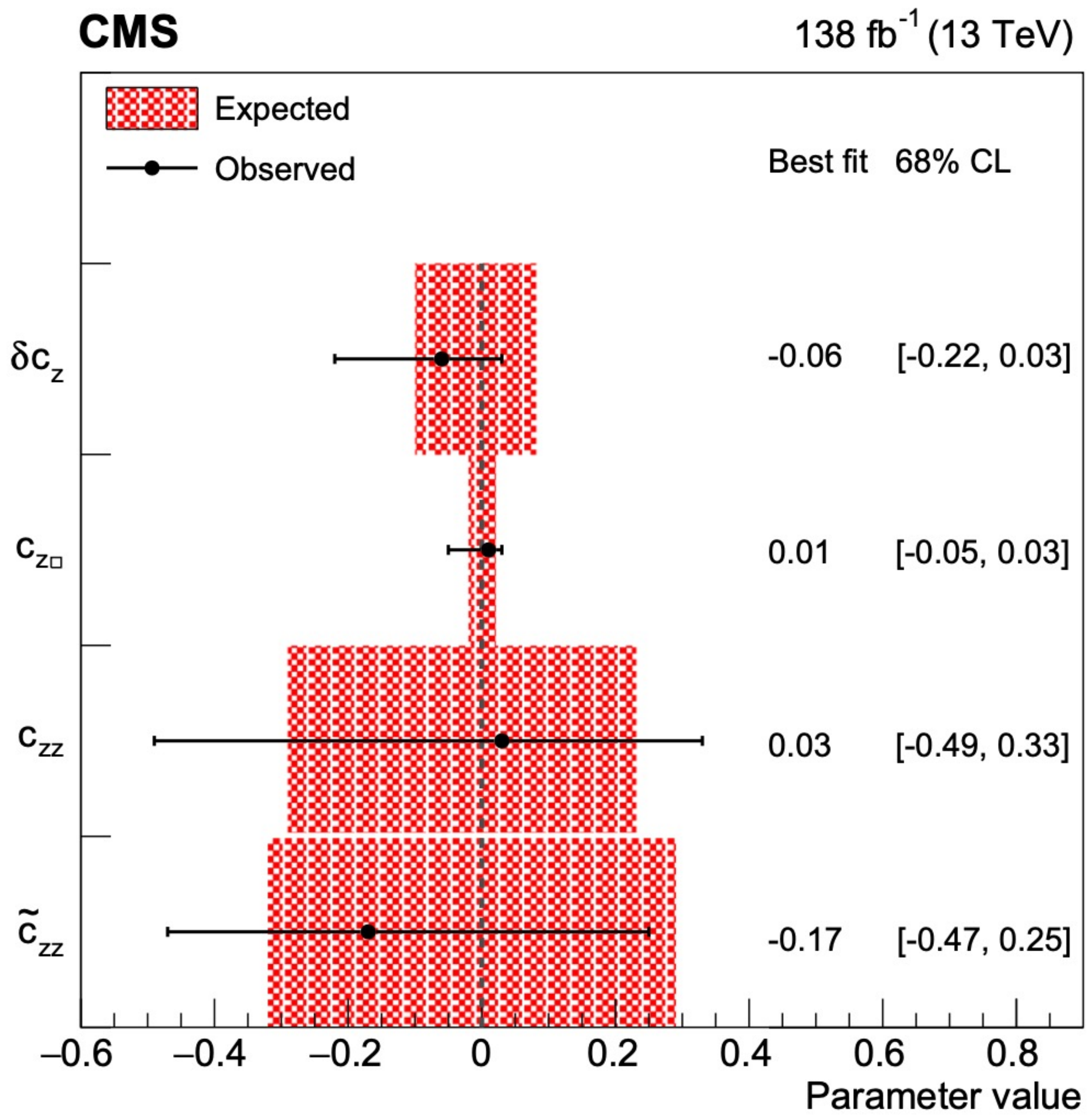


HZZ



SMEFT Higgs basis

Mass eigenbasis



Useful for analyses combination

$$\delta c_z = \frac{1}{2} a_1^{ZZ} - 1$$

$$c_{zz} = -\frac{2 s_w^2 c_w^2}{e^2} a_2^{ZZ}$$

$$\tilde{c}_{zz} = -\frac{2 s_w^2 c_w^2}{e^2} a_3^{ZZ}$$

$$c_{z\Box} = \frac{m_Z^2 s_w^2}{e^2} \frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2}$$

Comparable sensitivity with full Run 2 analyses:

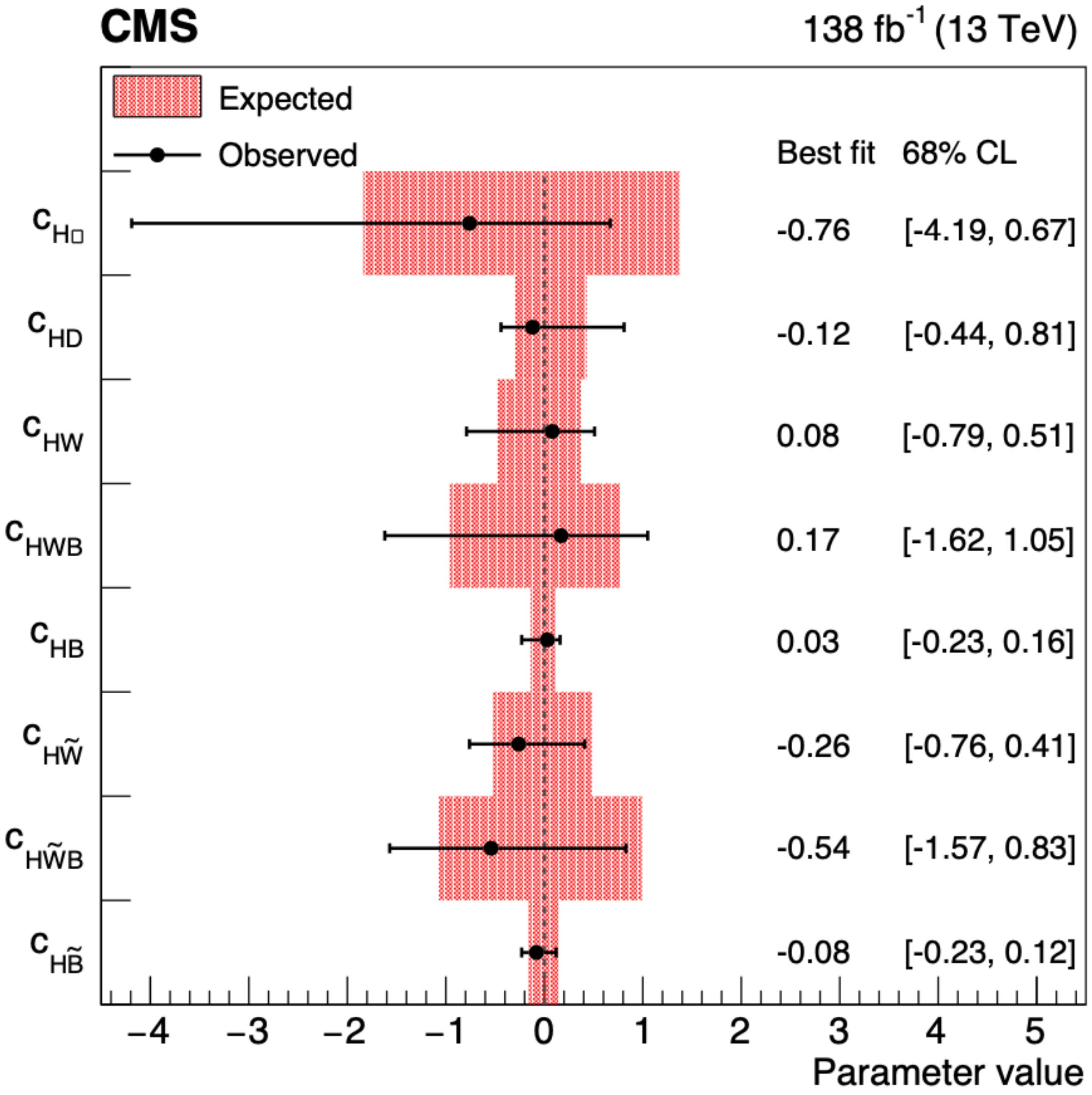
HZZ PRD 104 (2021) 052004

$H\tau\tau$ JHEP 06 (2022) 012, PRD 108 (2023) 032013

ttH analyses JHEP 07 (2023) 092

SMEFT Warsaw basis

Gauge eigenbasis



Useful for the theoretician community

$$\delta a_1^{ZZ} = \frac{v^2}{\Lambda^2}\left(2c_{H\Box} + \frac{6e^2}{s_w^2}c_{HWB} + \left(\frac{3c_w^2}{2s_w^2} - \frac{1}{2}\right)c_{HD}\right)$$

$$\kappa_1^{ZZ} = \frac{v^2}{\Lambda^2}\left(-\frac{2e^2}{s_w^2}c_{HWB} + \left(1 - \frac{1}{2s_w^2}\right)c_{HD}\right)$$

$$a_2^{ZZ} = -2\frac{v^2}{\Lambda^2}\left(s_w^2 c_{HB} + c_w^2 c_{HW} + s_w c_w c_{HWB}\right)$$

$$a_3^{ZZ} = -2\frac{v^2}{\Lambda^2}\left(s_w^2 c_{H\tilde{B}} + c_w^2 c_{H\tilde{W}} + s_w c_w c_{H\tilde{W}B}\right)$$

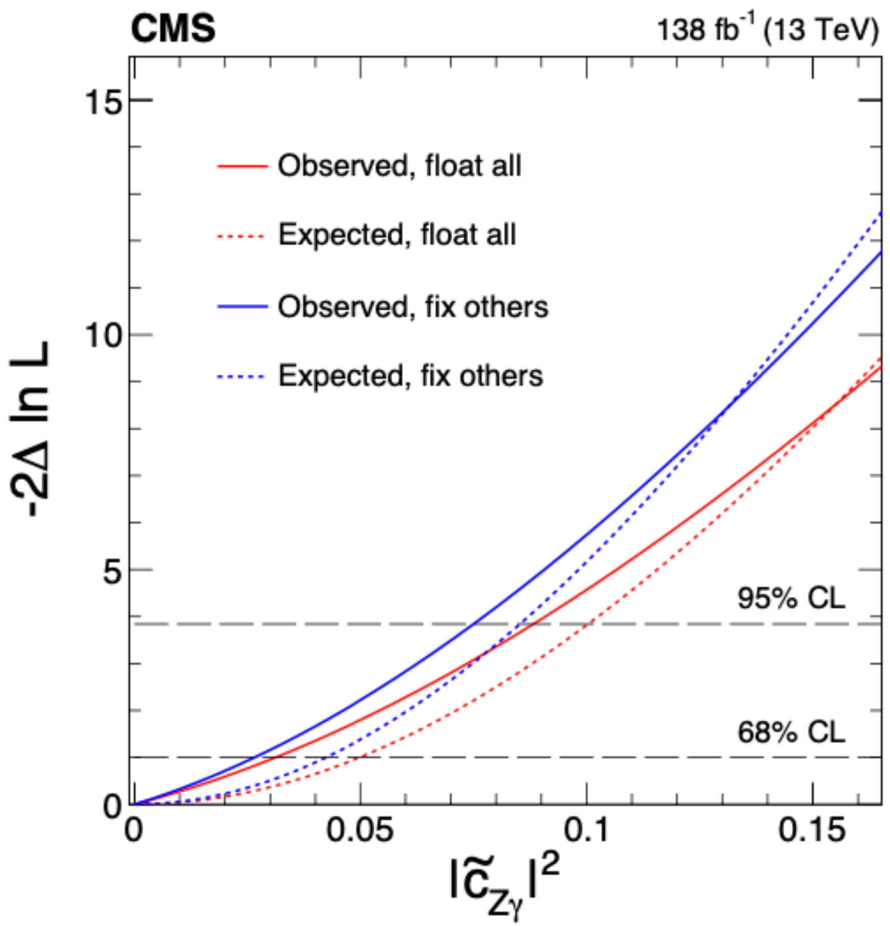
The results massively surpass that of the Run 1 analysis from the CMS experiment in both precision and coverage.

HVV couplings scans

Constraints on mass eigen basis

$$c_{\gamma\gamma},\ c_{Z\gamma},\ \tilde{c}_{\gamma\gamma},\ \tilde{c}_{Z\gamma}$$

H → bb dominated

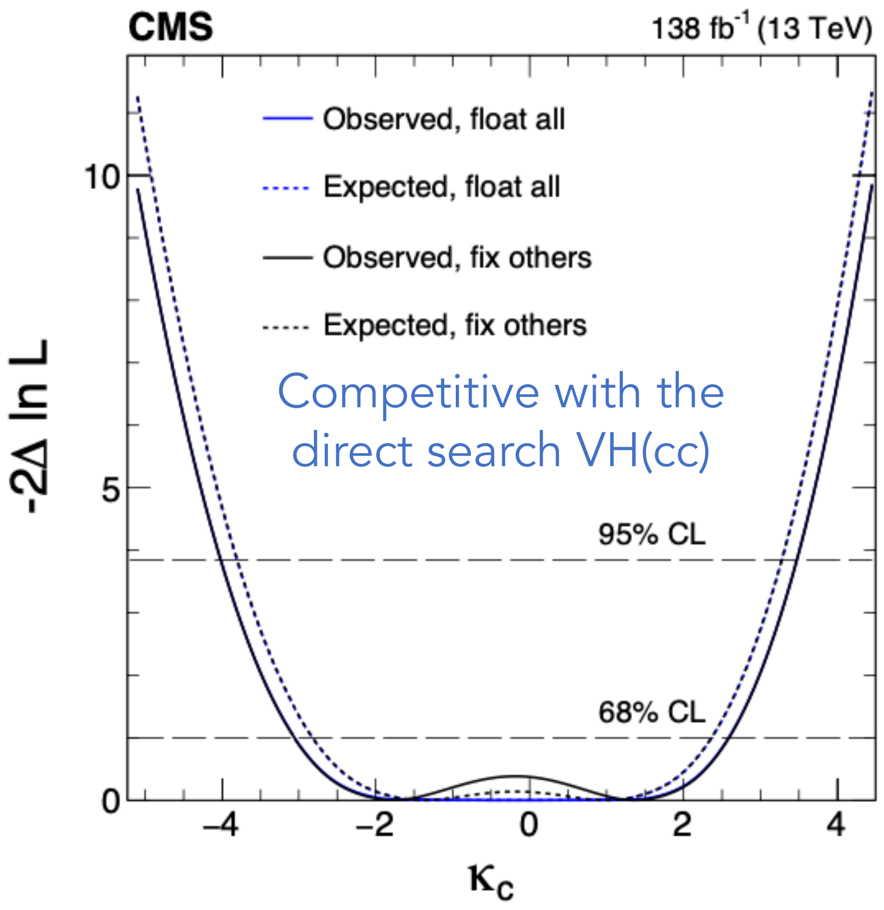


Yukawa couplings

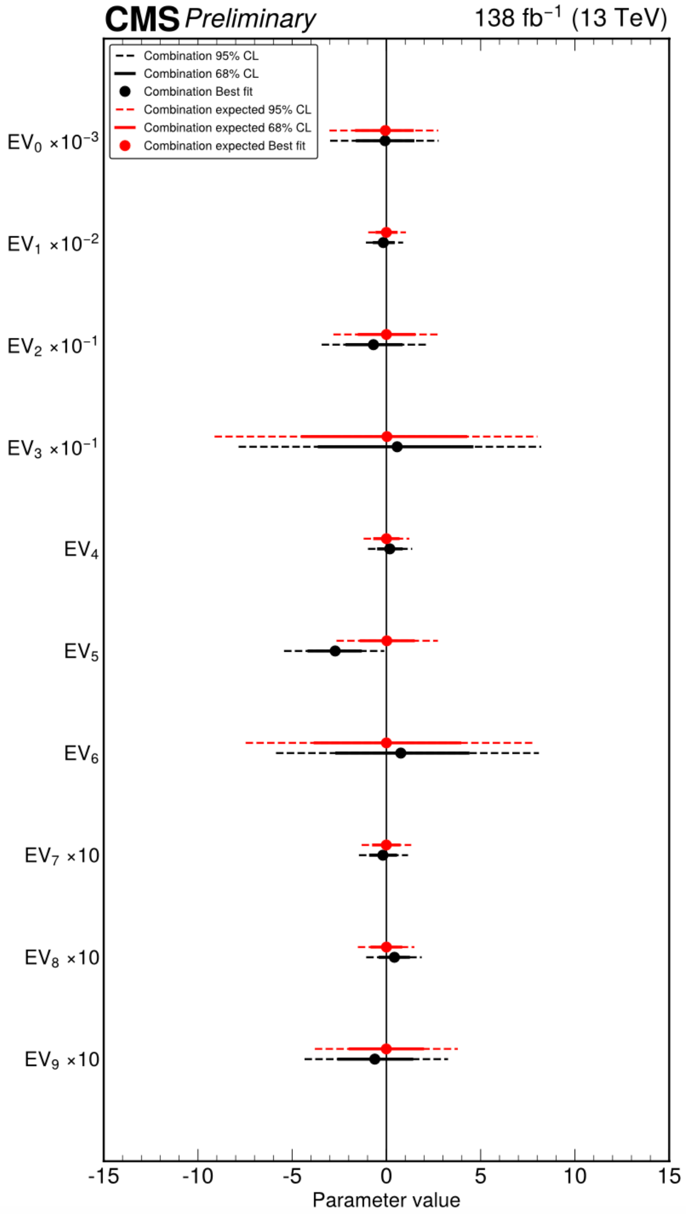
Hff vertex parametrization

$$\kappa_{\mathrm{u}},\ \kappa_{\mathrm{d}},\ \kappa_{\mathrm{s}},\ \text{and}\ \kappa_{\mathrm{c}}$$

H → ZZ → 4ℓ only

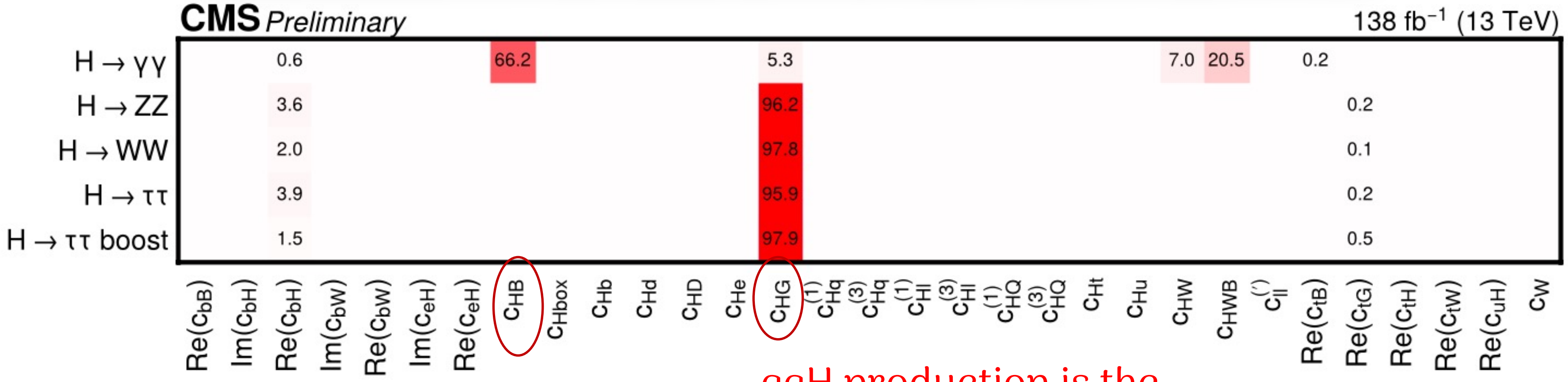


Interpretation of the entire phase space



Determine linear combinations of the most constrained Wilson coefficients from the data to simultaneously constrain 10 directions in parameter space.

Results are consistent with the SM within 1σ.



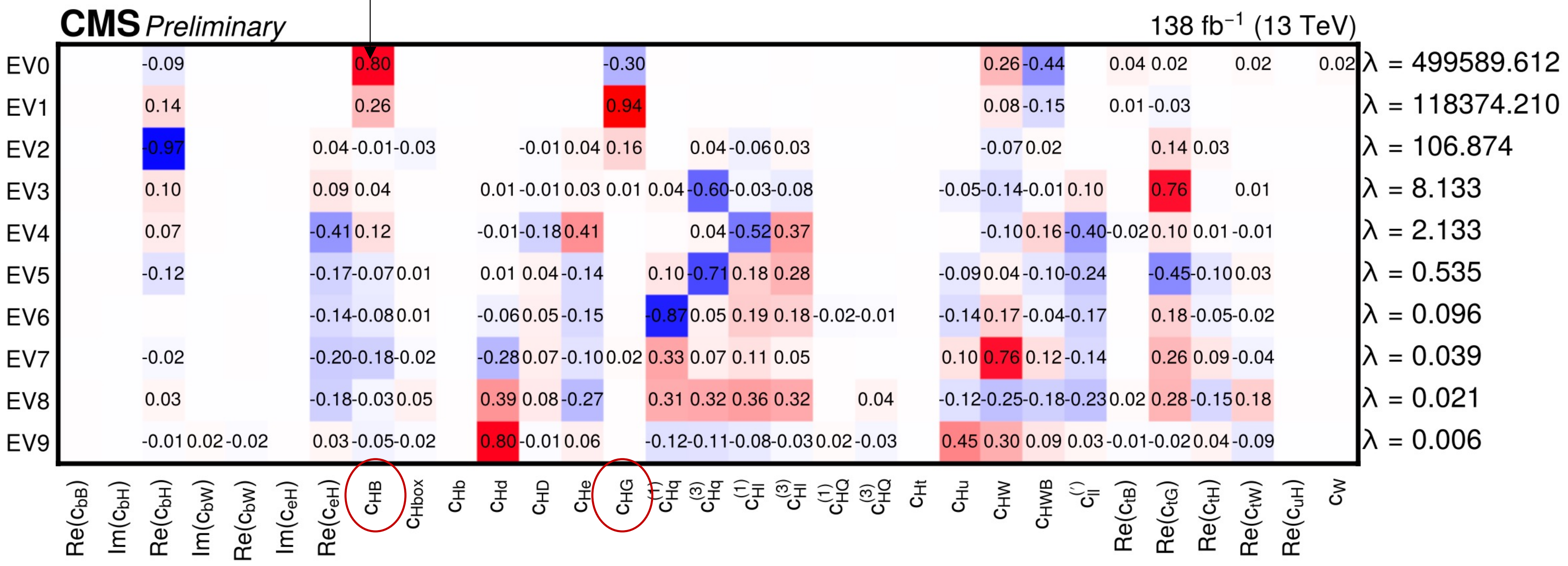
ggH production is the most sensitive in the majority of channels

Principal Component analysis (PCA)

HIG-23-013

Identify non-flat directions of the likelihood ⇢ greatest impact on the data.

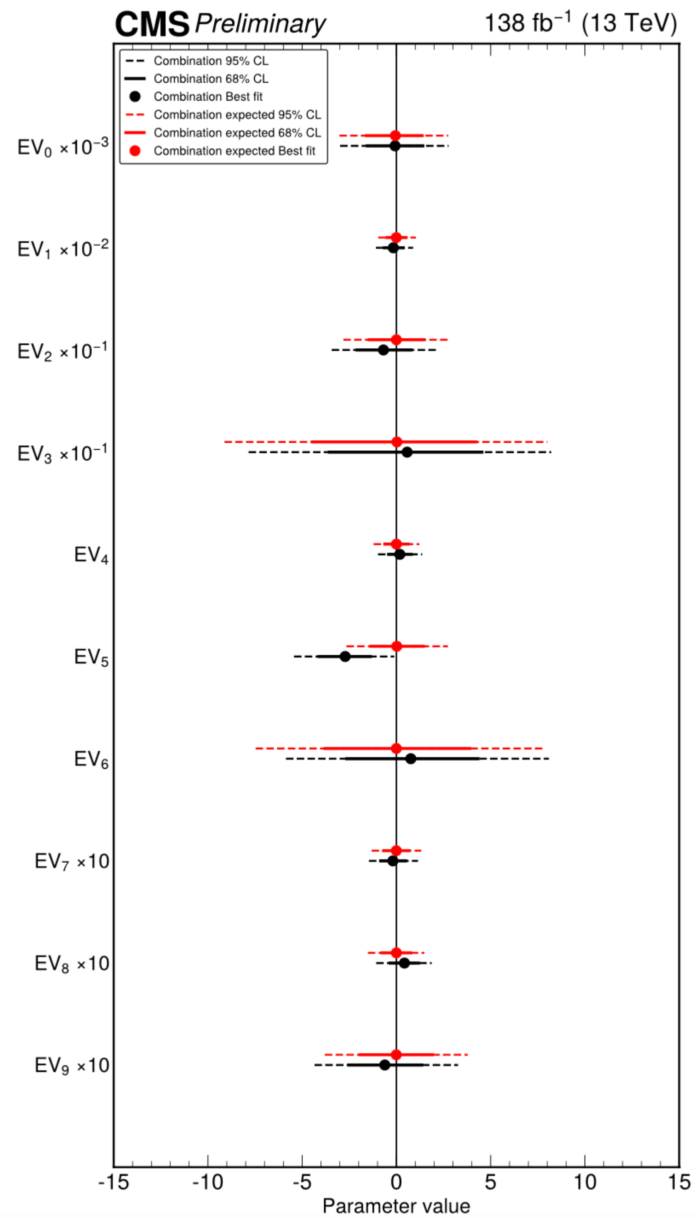
TO OVERCOME : Available data lacking sufficient information to constrain all Wilson coefficients (59!)

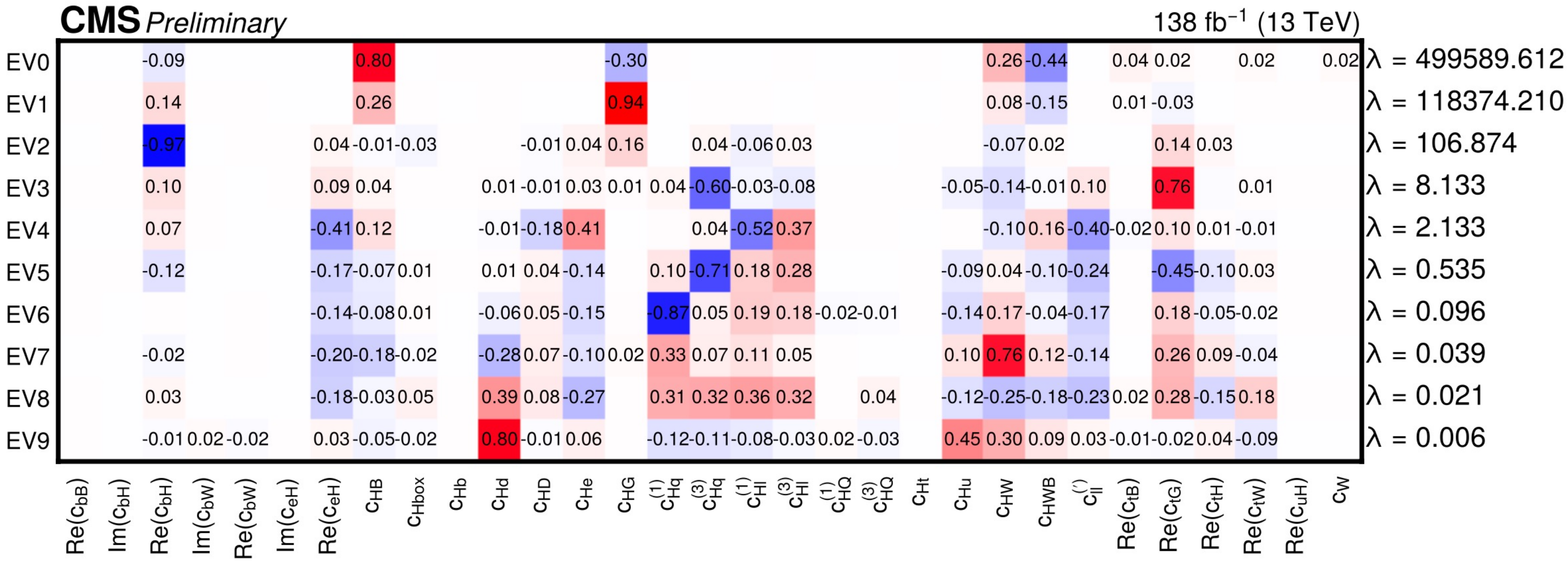


✓ The absolute values of the WC indicate the weight their in the linear combination.

✓ Higher weights in combinations with large eigenvalues (EV) signify that the coefficient is more constrained by the data.

Interpretation of the entire phase space





Determine linear combinations of the most constrained Wilson coefficients from the data to simultaneously constrain 10 directions in parameter space.

Results are consistent with the SM within 1σ.

Fit to observables

Boosted Information Tree (BIT)

Input Features:

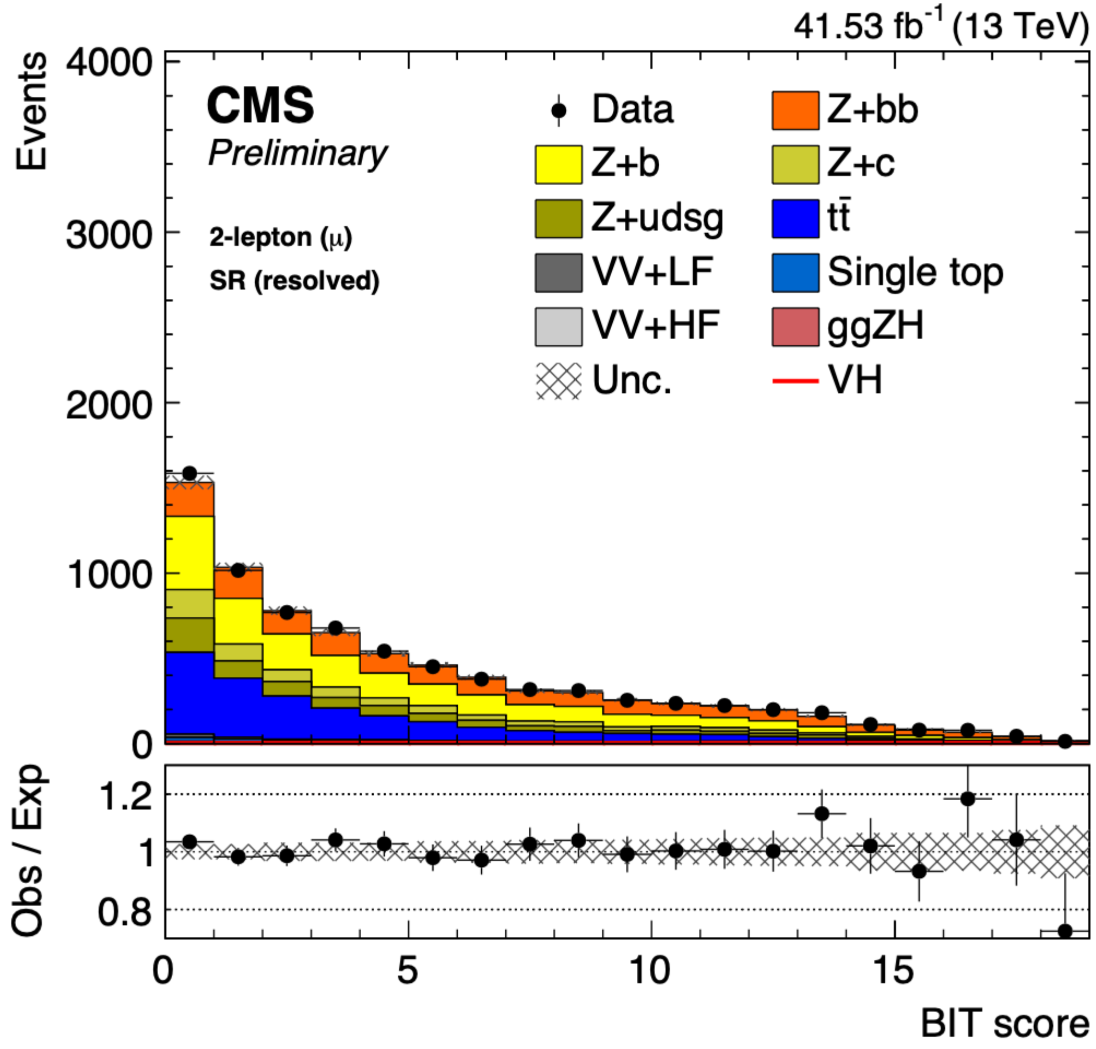
- **1- and 2-Lepton States:** Angular and kinematic variables.
- **0-Lepton State:** Energy-sensitive kinematic variables.

Specific Inputs

- **DEEPJET:** H candidate b-tagged jets
- **PARTICLENET:** H candidate AK8 jets

Training Procedure:

- **Data:** 50% for training, 50% for validation.

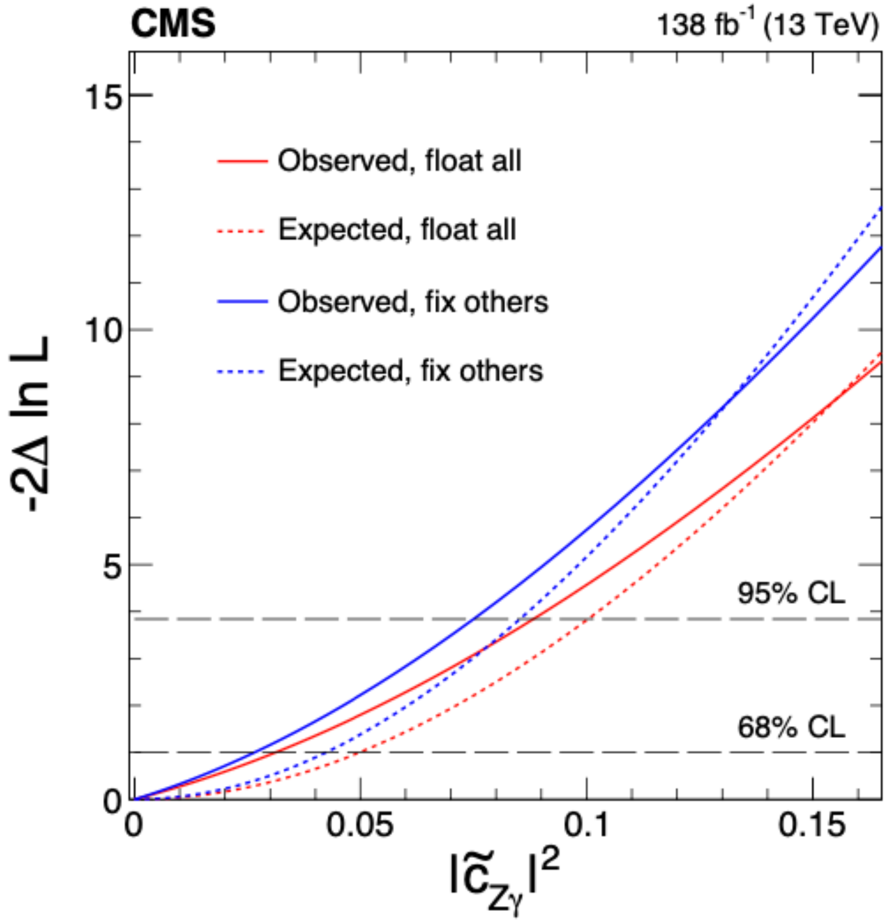


HVV couplings scans

Constraints on mass eigen basis

$c_{\gamma\gamma}, c_{Z\gamma}, \tilde{c}_{\gamma\gamma}, \tilde{c}_{Z\gamma}$

H → bb dominated

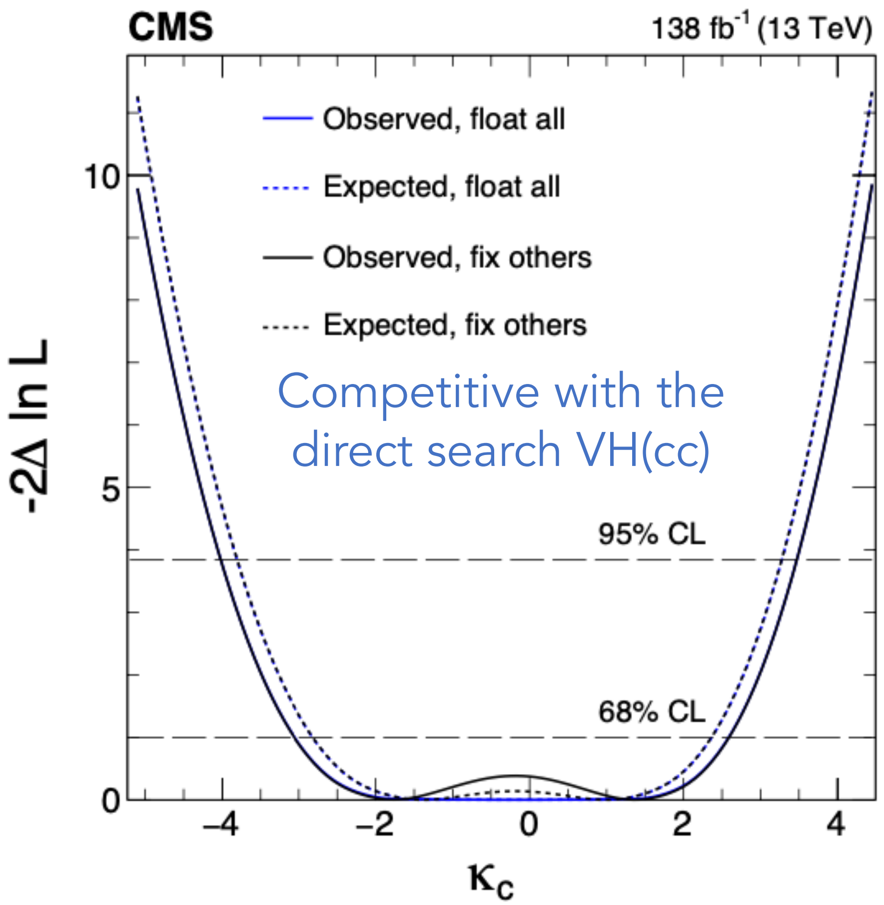


Yukawa couplings

Hff vertex parametrization

$\kappa_u, \kappa_d, \kappa_s$, and κ_c

H → ZZ → 4ℓ only



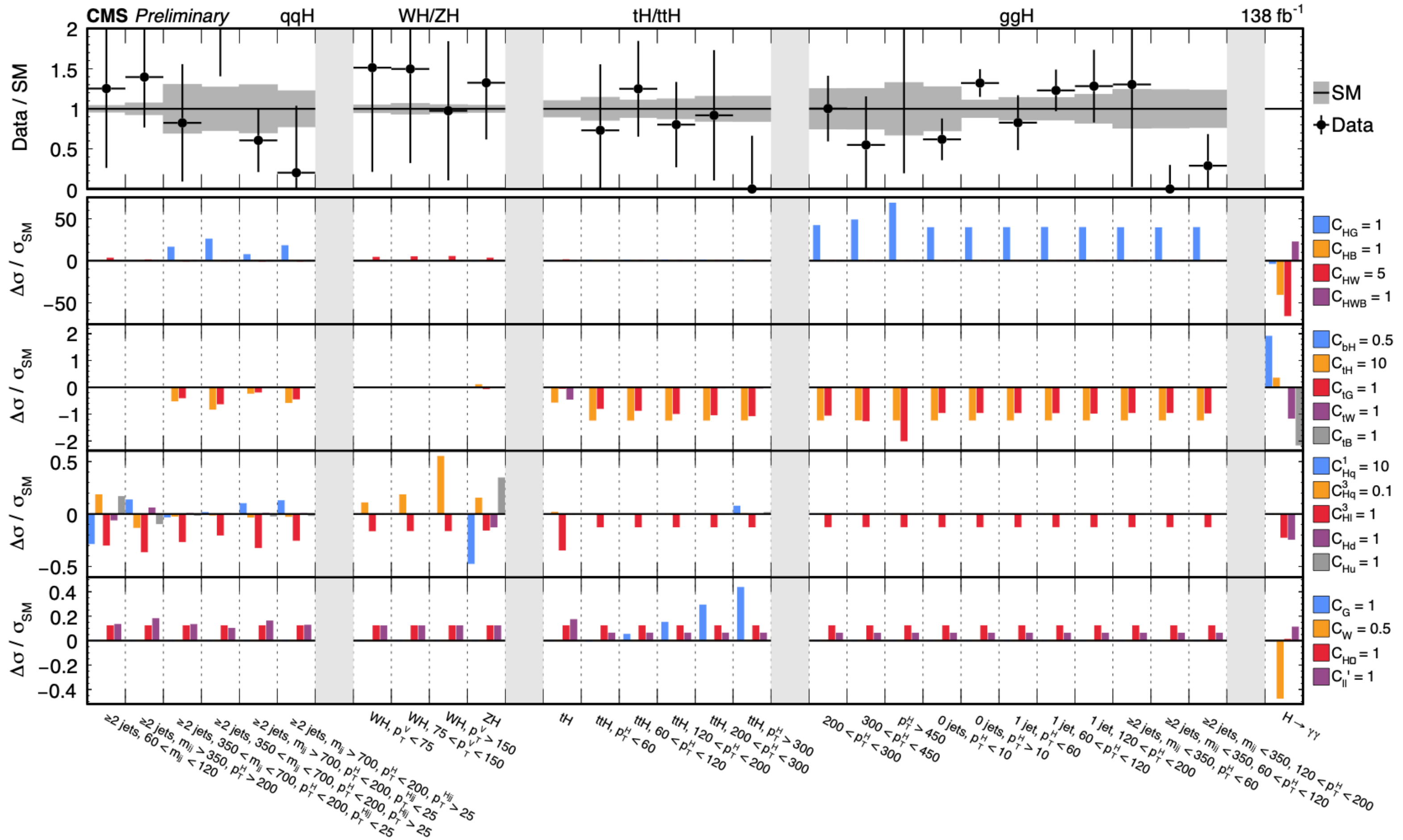
Parametrization

SMP-24-003

$$\sigma_{p,SMEFT} = \sigma_{p,SM}\left[1 + \sum \frac{A_{p,j}}{\Lambda^2} + \sum \frac{B_{p,jk}}{\Lambda^4}\right]$$

where $A_{p,j}$ and $B_{p,jk}$ represent linear and quadratic terms in the Wilson coefficients.

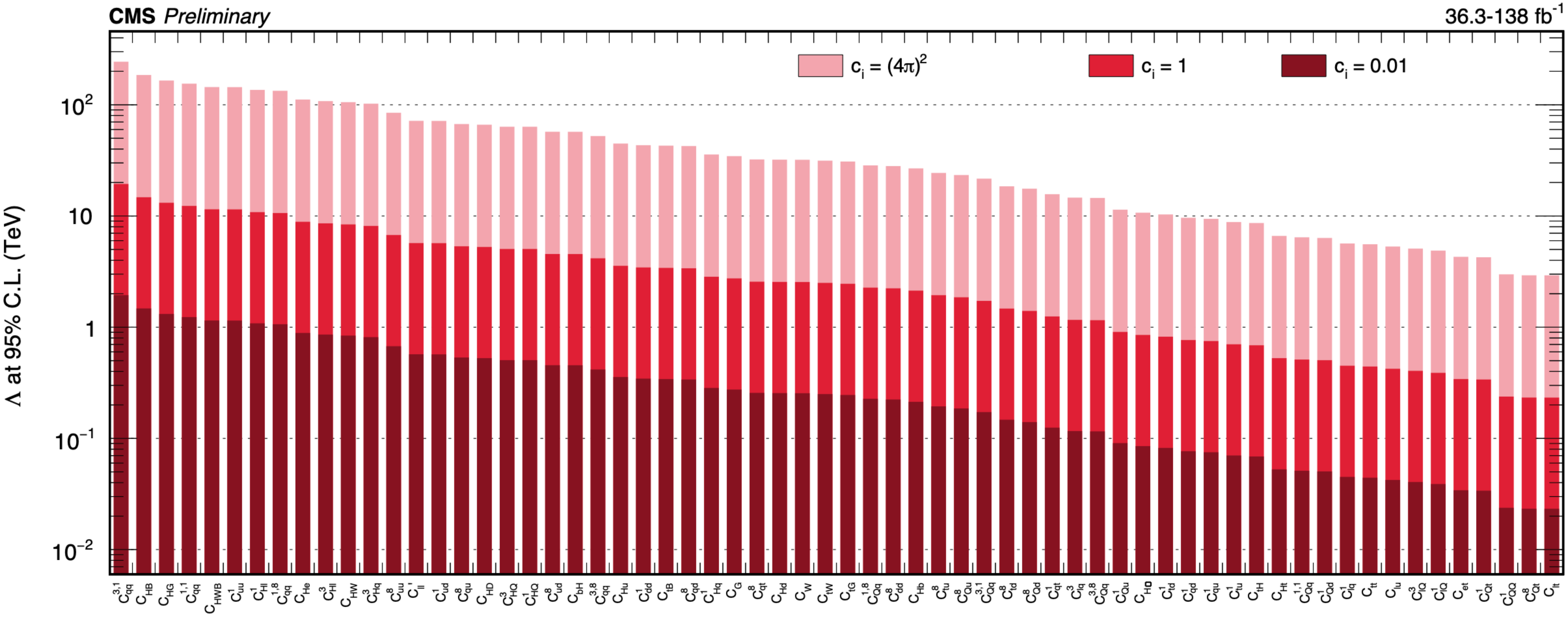
Impact of the linear part of parameterizations on cross sections, comparing with SM expectations.



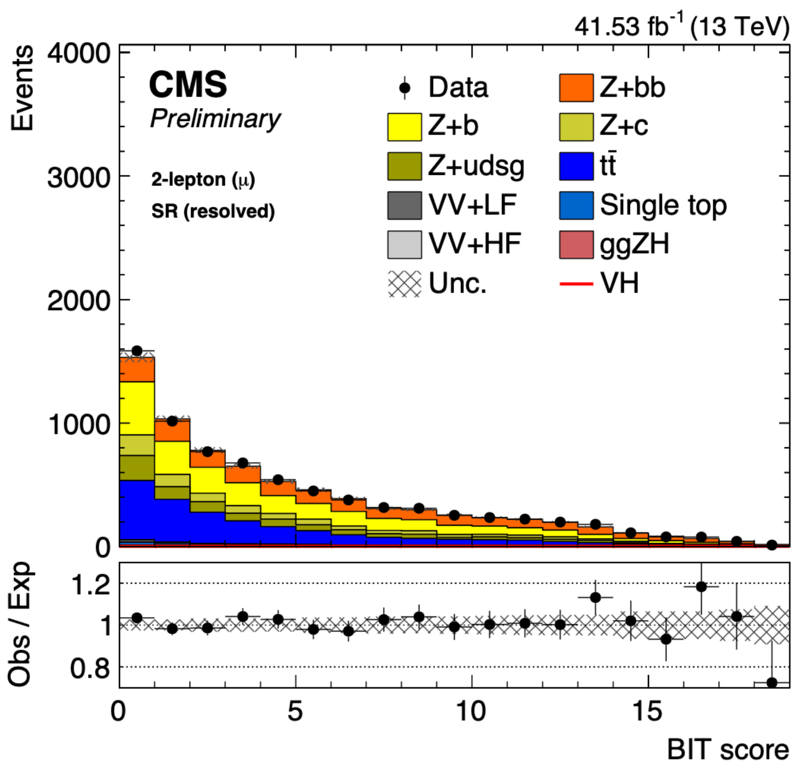
Worth Highlighting

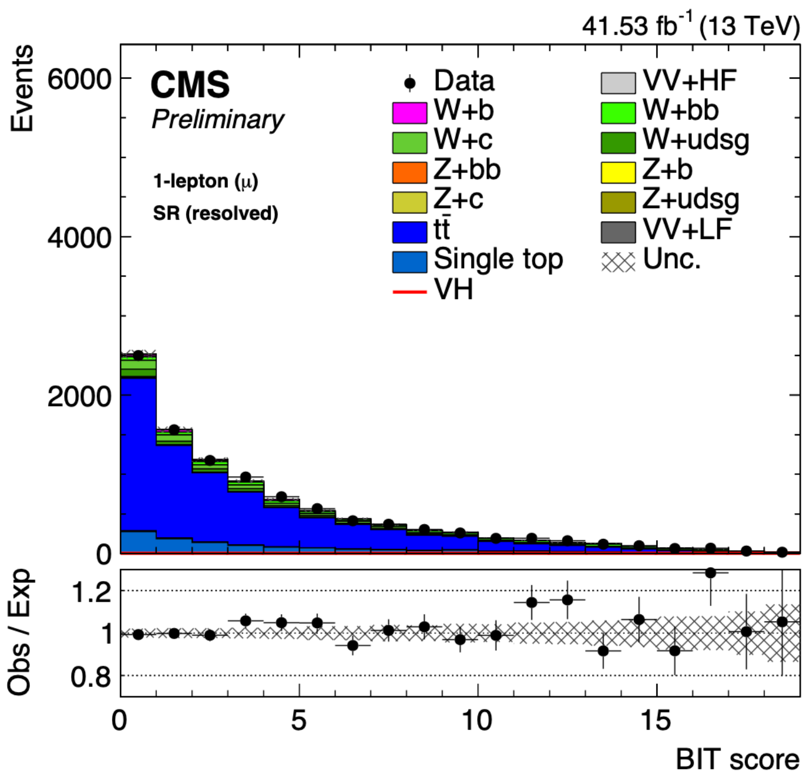
SMP-24-003

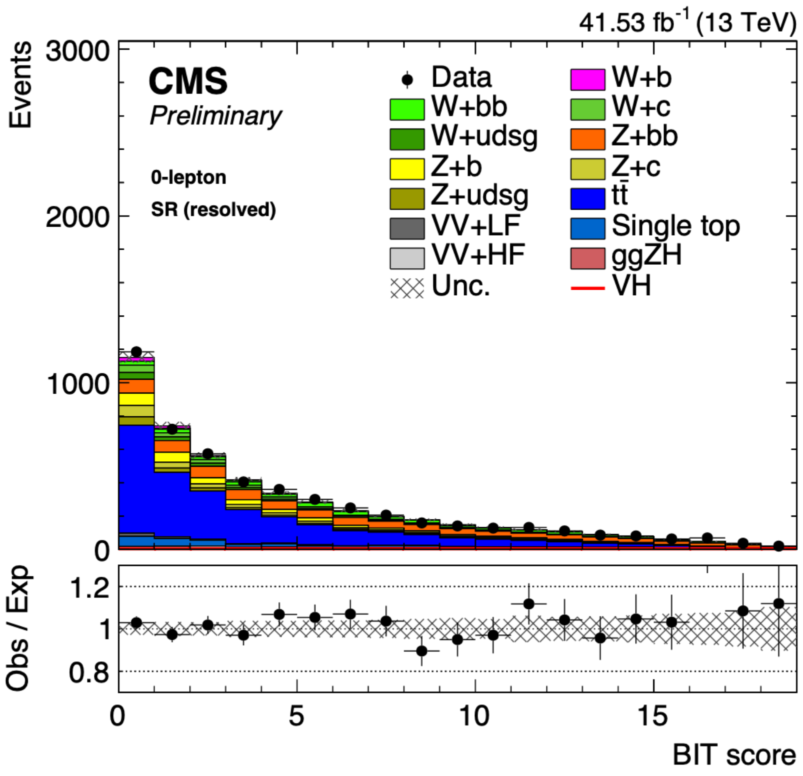
95% CL lower limits on the scales Λ



Data/MC plots







Other Full Run 2 CMS EFT-related analyses

Presented in HH23

CMS Analysis	Channel	Measurement	Combined with	REF
HIG-19-009	On Shell H→ZZ	HVV, Hgg, Htt	[Htt] H→$\gamma\gamma$ (HIG-19-013)	PRD 104 (2021) 052004
HIG-20-006	H→$\tau\tau$	H$\tau\tau$	-	JHEP 06 (2022) 012
HIG-20-007	H→$\tau\tau$	HVV, Hgg, Htt	on-Shell H→ZZ + H→$\gamma\gamma$	PRD 108 (2023) 032013
HIG-21-006	ttH and tH	Htt	on-Shell H→ZZ + H→$\gamma\gamma$	JHEP 07 (2023) 092
HIG-21-013	off-Shell H→ZZ	H Off-Shell evidence Γ_{Higgs}, HVV	on-Shell H→ZZ	Nat. Phys. 18 (2022) 1329