Summary of CMS Higgs EFT results

Alessandro Calandri - ETH Zürich

LHC Higgs Working Group workshop - Nov 15, 2023

Introduction & outline of the talk

- **No evidence of New Physics at the LHC - direct searches of BSM effects continue but focus is shifting to indirect exploration of Higgs sector**
  - increasing number of Higgs EFT measurements in CMS and ATLAS
- **EFT results focus in interpretation of unfolded spectrum in presence of EFT effects or extract coefficients with dedicated analyses using optimal observables**

- Kappa parametrisation on effective couplings and extension to Wilson coefficients
- EFT interpretations of Higgs STXS measurements
- Highlights on recent Higgs EFT results in CMS
  - $H \to ZZ \to 4l$ and off-shell analysis
  - $H \to WW$ results
  - $H \to \tau\tau$ EFT analysis in CMS and combination with on-shell $H \to ZZ$ and $H \to \gamma\gamma$
  - CP violation in ttH multilepton final states
  - a quick glimpse on double Higgs EFT results
- Wrapping-up and conclusions

Kappa parametrisation and Wilson coefficients

➡ **Experimental profile of the Higgs boson with Run 1/ 2 data becoming very precise**

- large set of precision measurements performed with Run 2 data

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

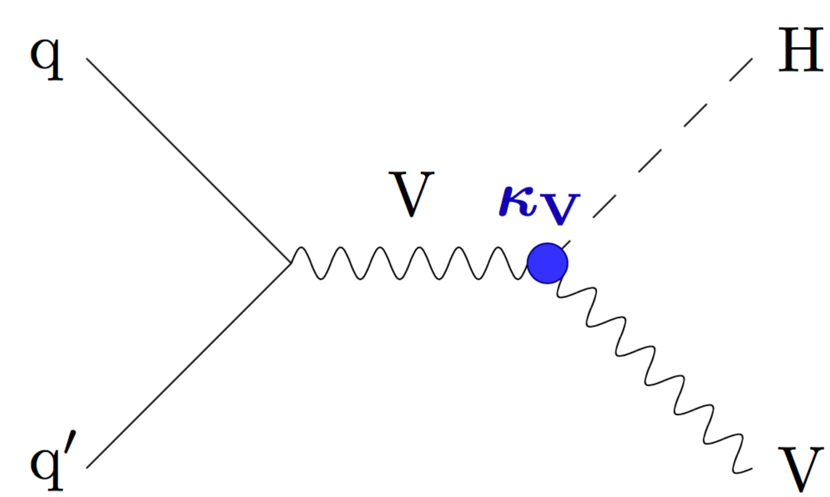
Wilson coefficients (if c=0 → SM)

$$\mathscr{L}_{SMEFT} = \mathscr{L}^4_{SM} + \sum_i \frac{c_i^{(5)}}{\Lambda}\mathscr{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathscr{O}_i^{(6)} + \sum_i \frac{c_i^{(7)}}{\Lambda^3}\mathscr{O}_i^{(7)} + \mathscr{O}(8) + \ldots$$

Tensor structure of EFT terms

➡ **Kappa parametrisation scale effective couplings**

- BSM effect may not rescale just couplings in Higgs production and decay
- need for dedicated probe of additional operators in tensor structure scaled by Wilson coefficients and suppressed by Λ^{d-4} (Λ represent the energy scale of the NP process)

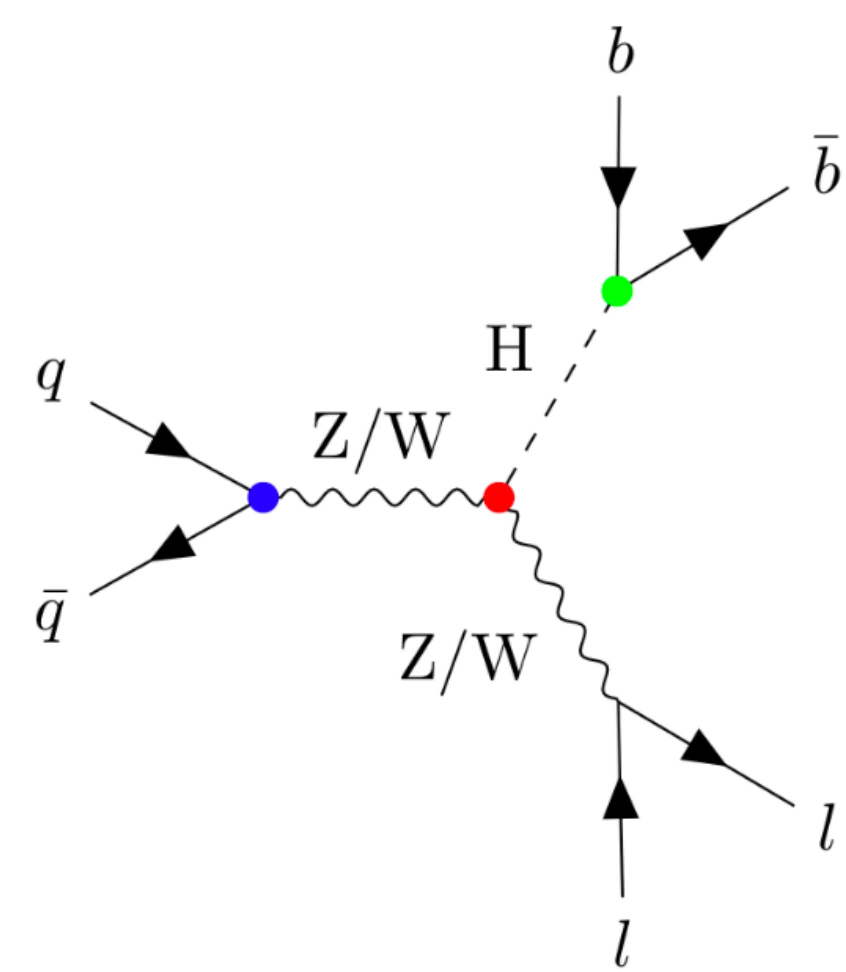


Wilson coefficients & EFT Lagrangian expansion

- **Expansion of SM lagrangian in 1/Λ: observables EFT effects are parametrised**
  - with linear term in WC's and a linear+quadratic term in WC's (both are dim-6 operators)
  - difference between linear and linear+quadratic used to get hints of components beyond $1/\Lambda^2$
- **SMEFT [link] is a popular model for EFT interpretation using dim-6 operators**
  - with linear term in WC's and a linear+quadratic term in WC's
- **Some EFT contributions are CP-odd operators: access on those operators is relevant as non vanishing components indicate CP violation**

Example of VH→bb channel

Operator	Wilson coefficient	Lagrangian modification	Channels
$\mathcal{O}_{Hq}^{(1)} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{q}\gamma^\mu q$	cHj1	qqV vertex, HVqq contact term	Zll
$\mathcal{O}_{Hq}^{(3)} = iH^\dagger \sigma^i \overleftrightarrow{D}_\mu H \bar{q}\sigma^i\gamma^\mu q$	cHj3	qqV vertex, HVqq contact term	Zll, Wlv
$\mathcal{O}_{Hu} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{u}_R\gamma^\mu u_R$	cHu	qqV vertex, HVqq contact term	Zll
$\mathcal{O}_{Hd} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{d}_R\gamma^\mu d_R$	cHd	qqV vertex, HVqq contact term	Zll
$\mathcal{O}_{HW} = H^\dagger H W^i_{\mu\nu} W^{i\mu\nu}$	cHW	HVV vertex	Zll, Wlv
$\mathcal{O}_{H\tilde{W}} = H^\dagger H \tilde{W}^i_{\mu\nu} W^{i\mu\nu}$	cHWtil	HVV vertex	Zll, Wlv
$\mathcal{O}_{HB} = H^\dagger H B_{\mu\nu} B^{\mu\nu}$	cHB	HVV vertex	Zll
$\mathcal{O}_{H\tilde{B}} = H^\dagger H \tilde{B}_{\mu\nu} B^{\mu\nu}$	cHBtil	HVV vertex	Zll
$\mathcal{O}_{HWB} = H^\dagger \sigma^i H W^i_{\mu\nu} B^{\mu\nu}$	cHWB	HVV vertex, Wlv vertex	Zll
$\mathcal{O}_{H\tilde{W}B} = H^\dagger \sigma^i H \tilde{W}^i_{\mu\nu} B^{\mu\nu}$	cHWBtil	HVV vertex, Wlv vertex	Zll
$\mathcal{O}_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$	cHbox	HVV vertex, hbb coupling	Zll, Wlv
$\mathcal{O}_{HD} = (D^\mu H^\dagger H)(H^\dagger D_\mu H)$	cHDD	HVV vertex, hbb coupling, qqV vertex	Zll, Wlv
$\mathcal{O}_{bH} = (H^\dagger H)(\bar{q} b H)$	cbHRe + cbHIm	hbb coupling	Zll, Wlv

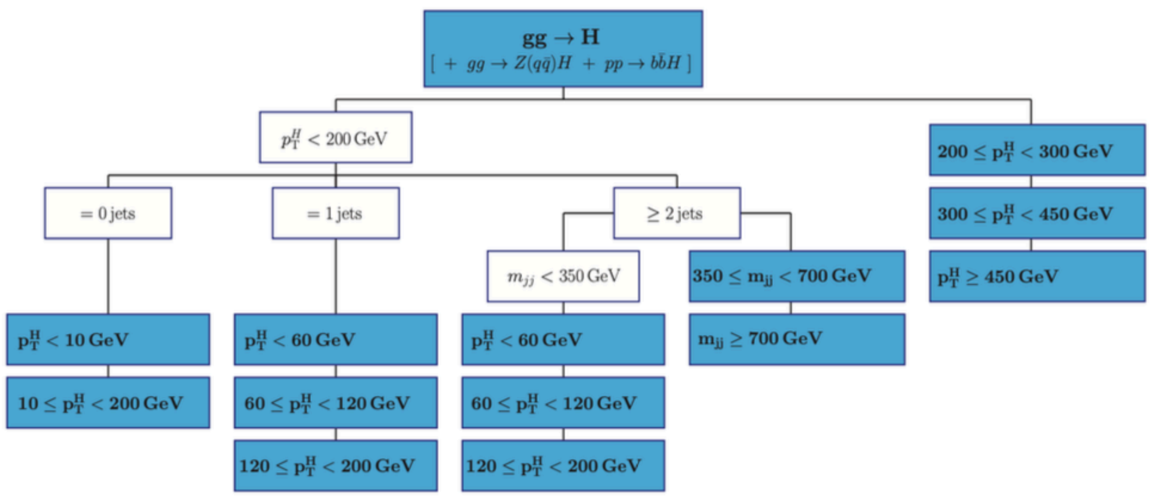


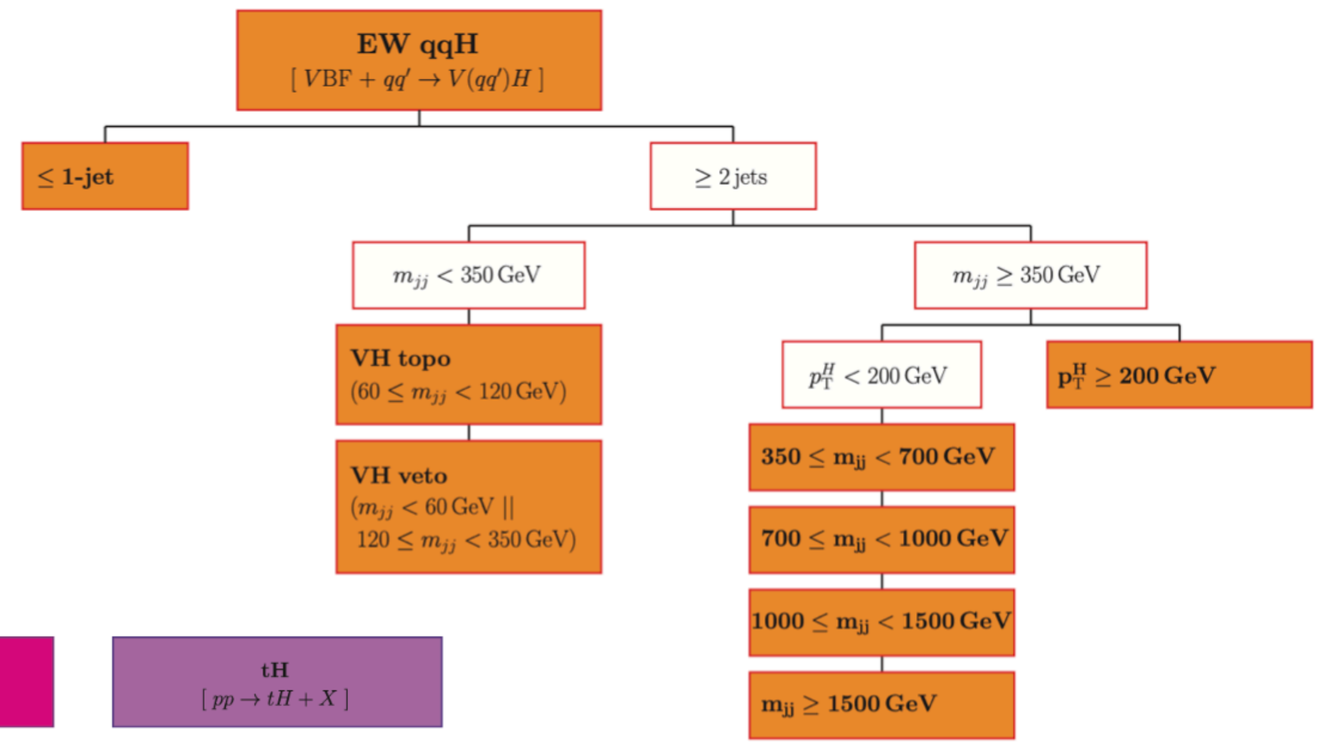
EFT interpretation using STXS

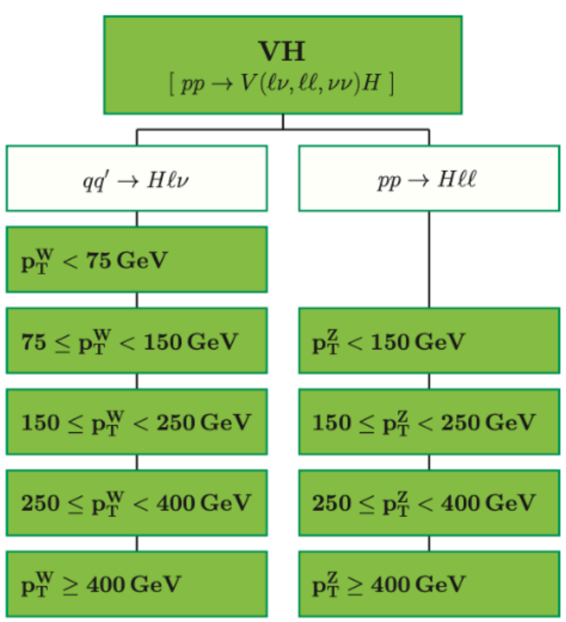
➡ **Fundamental to keep all operators in interpretation due to correlation effects**

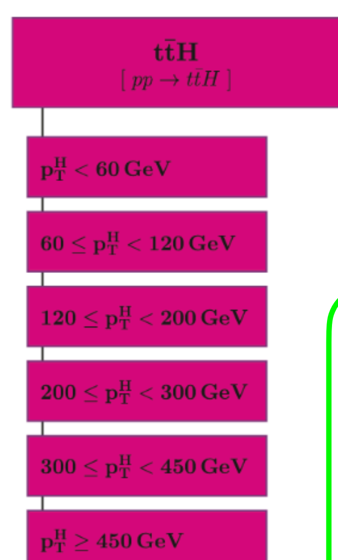
➡ **No single measurement constraints all operators - need for global approach**

- EFT interpretation of STXS fit using STXS categorisation for Higgs production modes - no sensitivity to CP given lack of dedicated CP-sensitive observables (ΔΦ(jj) for VBF production)









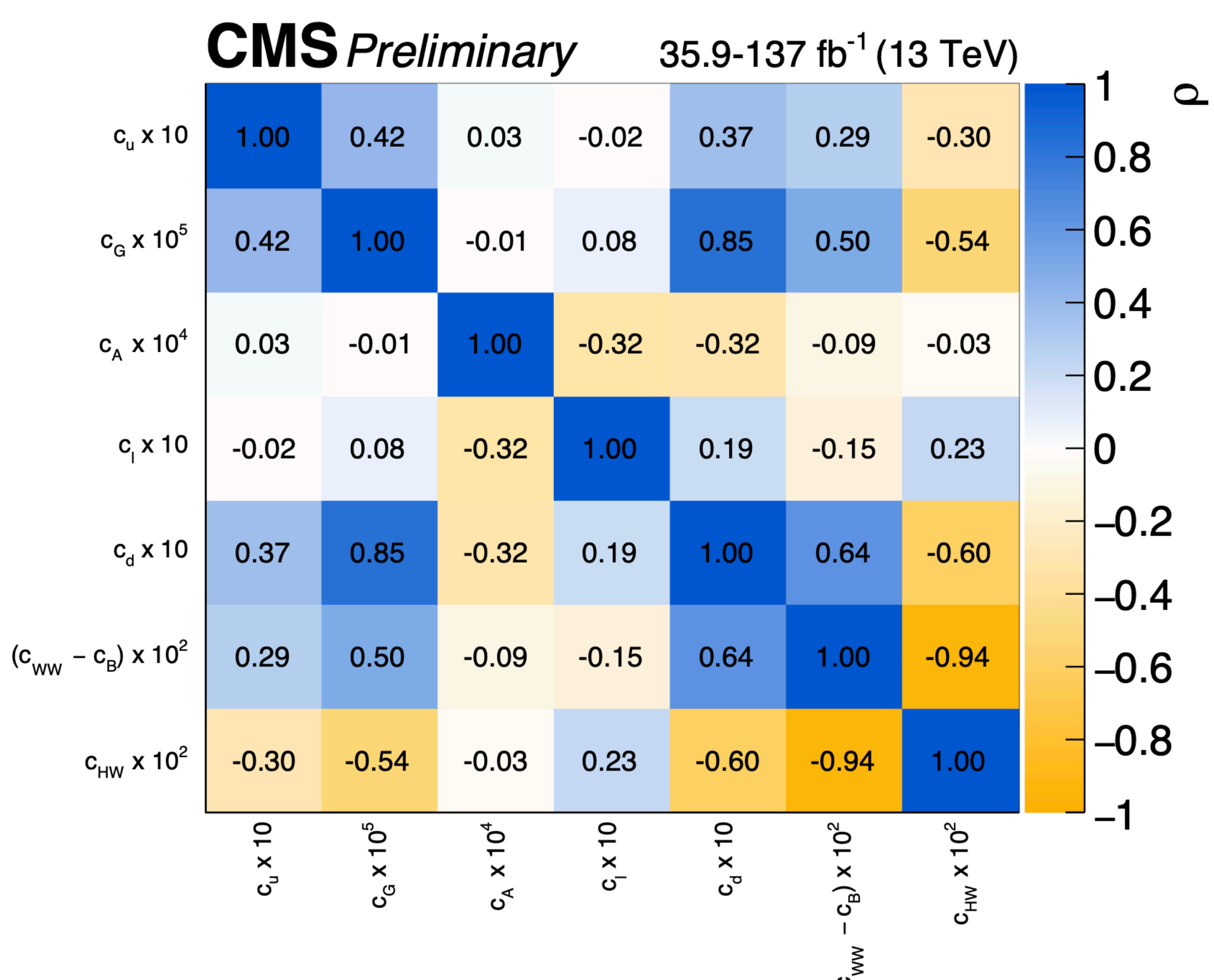
➡ Main channels included or about to be included with full Run 2 statistics

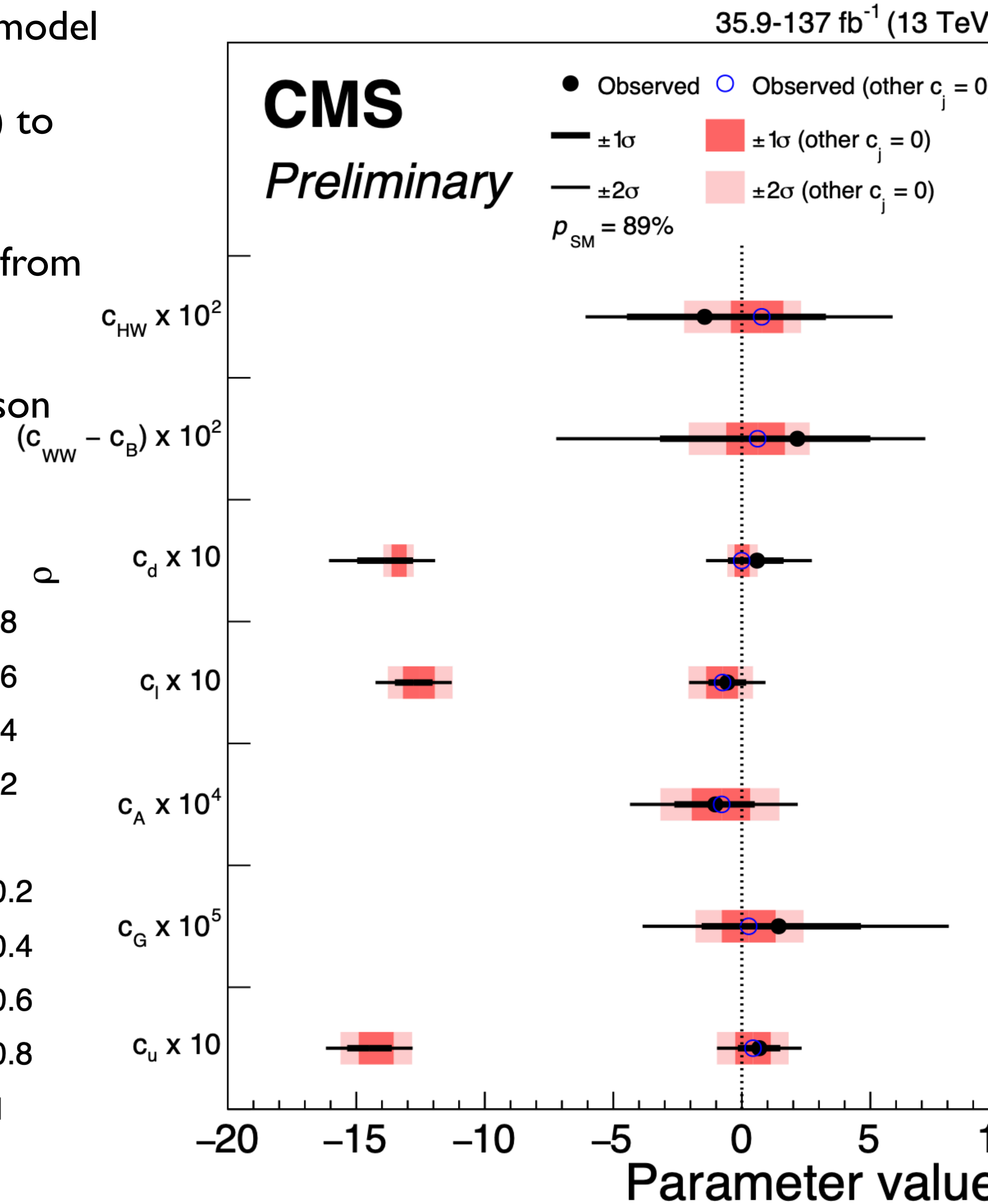
➡ Targeting all production modes in STXS bins

EFT interpretation using STXS (3)

CMS PAS HIG-19-005

- **Assumption of EFT interpretation in STXS bins: no EFT effects on background components - acceptance corrections in STXS bins to account for EFT effects**
  - EFT coupling constraints extracted in HEL model
  - No optimal observables (angles, kinematics) to enhance analysis sensitivity to EFT effects
  - c(WW) and c(B) fit together - constrained from EWK data
  - Results provided with all freely-floating Wilson coefficients and profiling one at a time

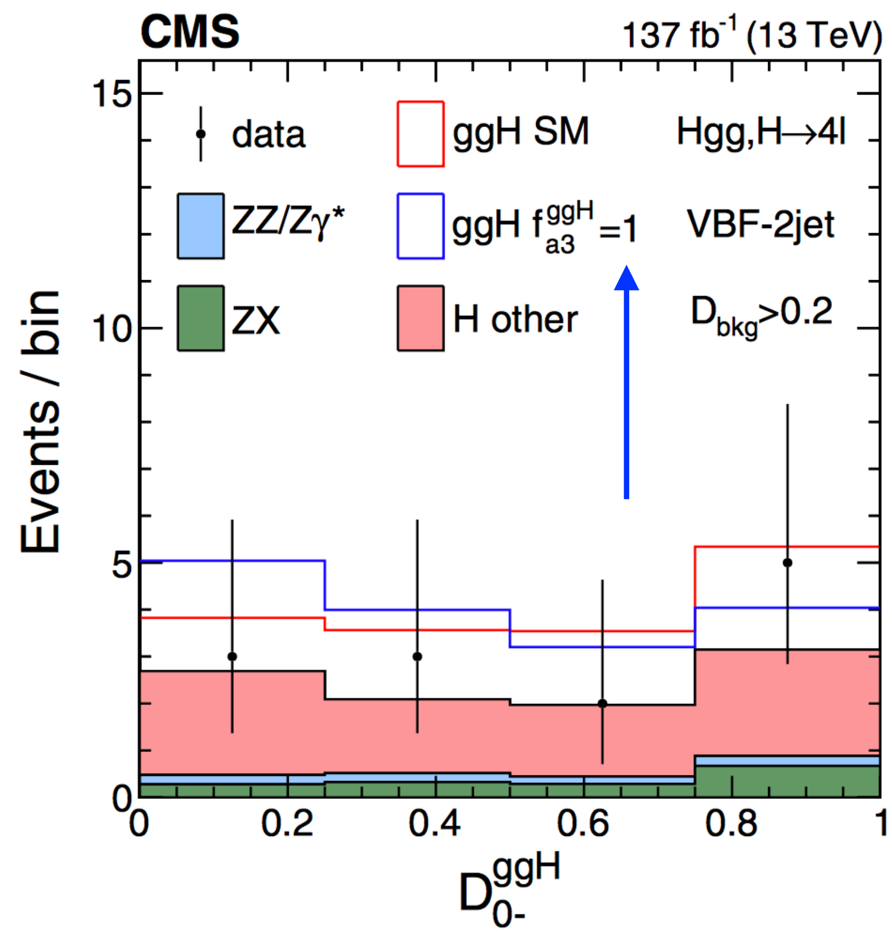


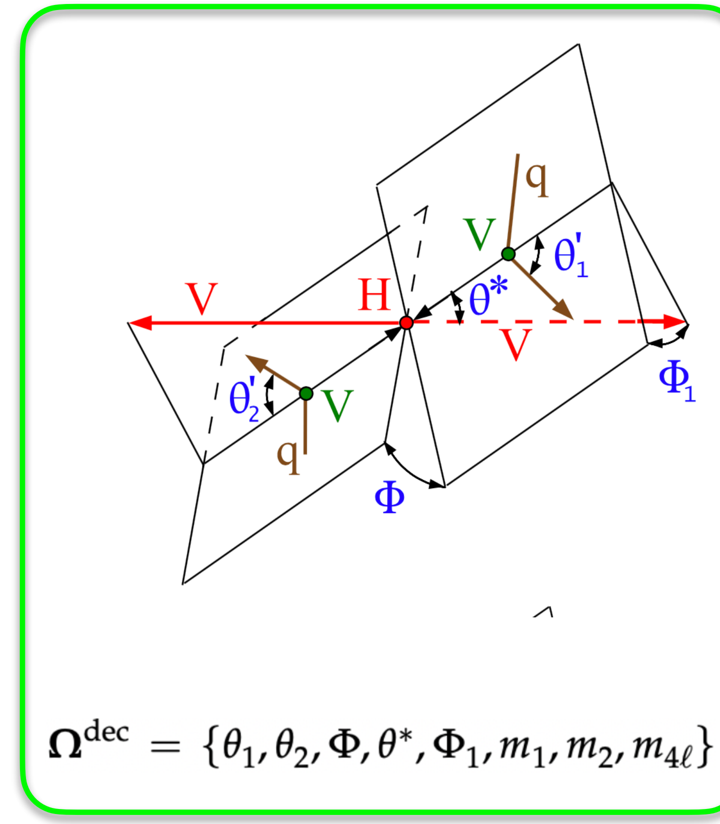


On-shell H->ZZ->4l

Phys. Rev. D 104 (2021) 052004

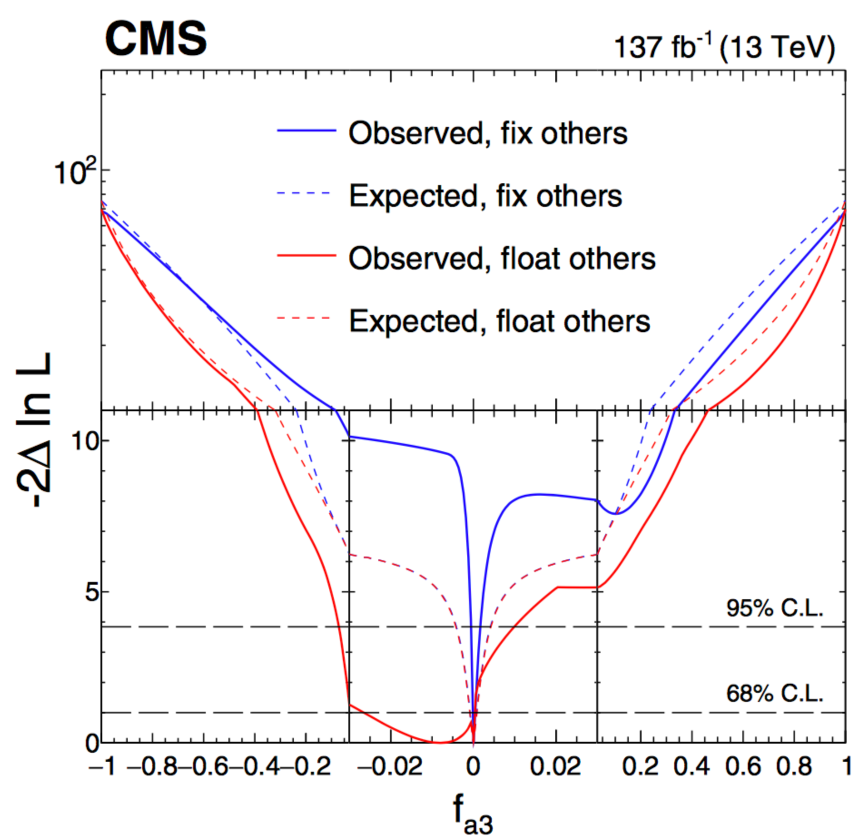
- **Full production and decay kinematic to constrain Wilson coefficients**
  - MEM (MELA) employed to separate production modes/ discriminate signal vs backgrounds
  - using optimal observables included in MELA to tackle EFT tensor structure

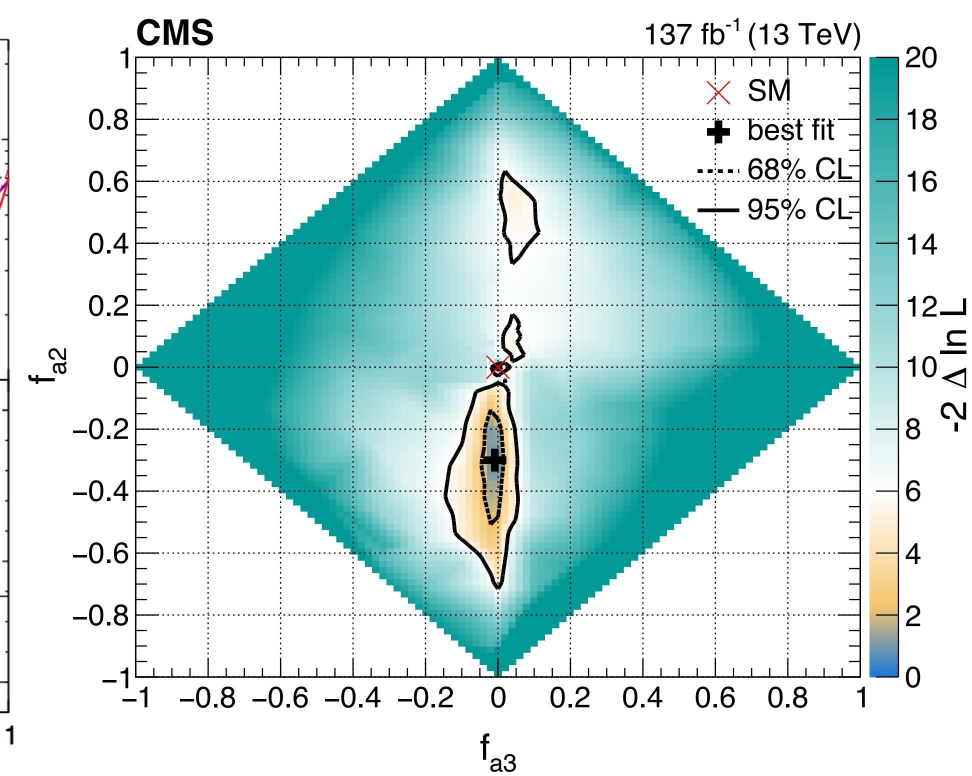




Constraints HVV using Anomalous Coupling: extended to WC constraints (SMEFT)

- **Various hypotheses on combined AC fit**
  - fixing all couplings but one to SM expectations or all couplings profiled
  - access sensitivity to CP structure in HZZ decay



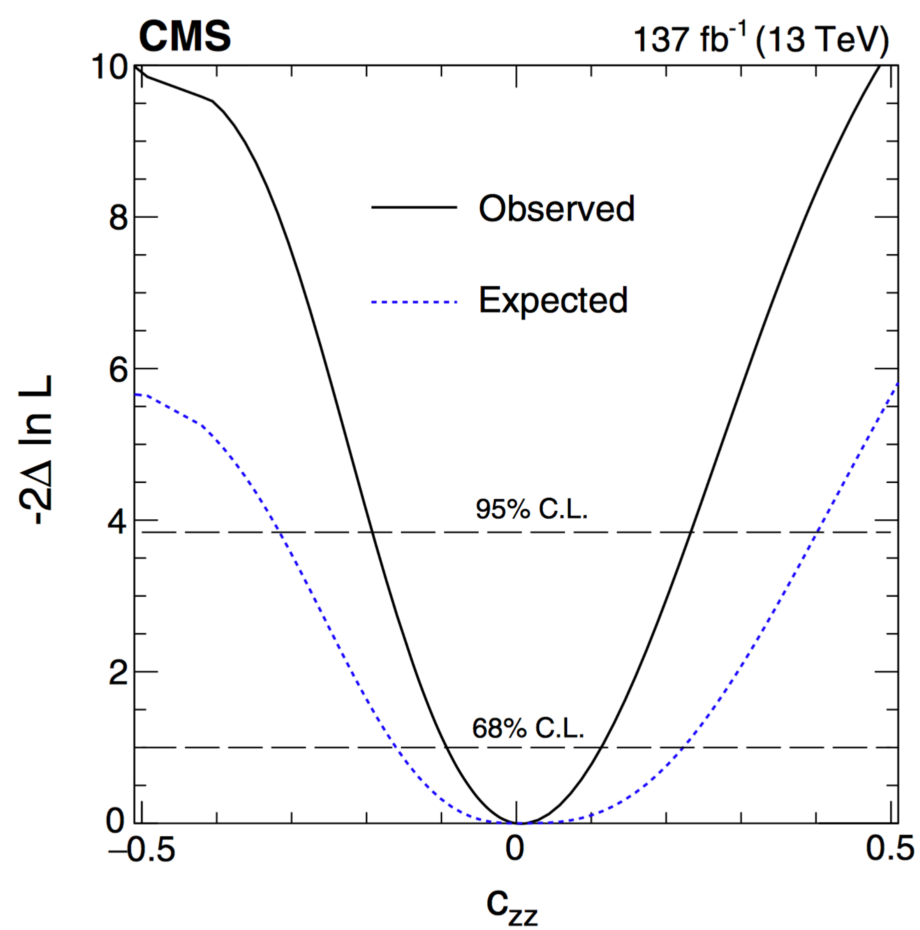


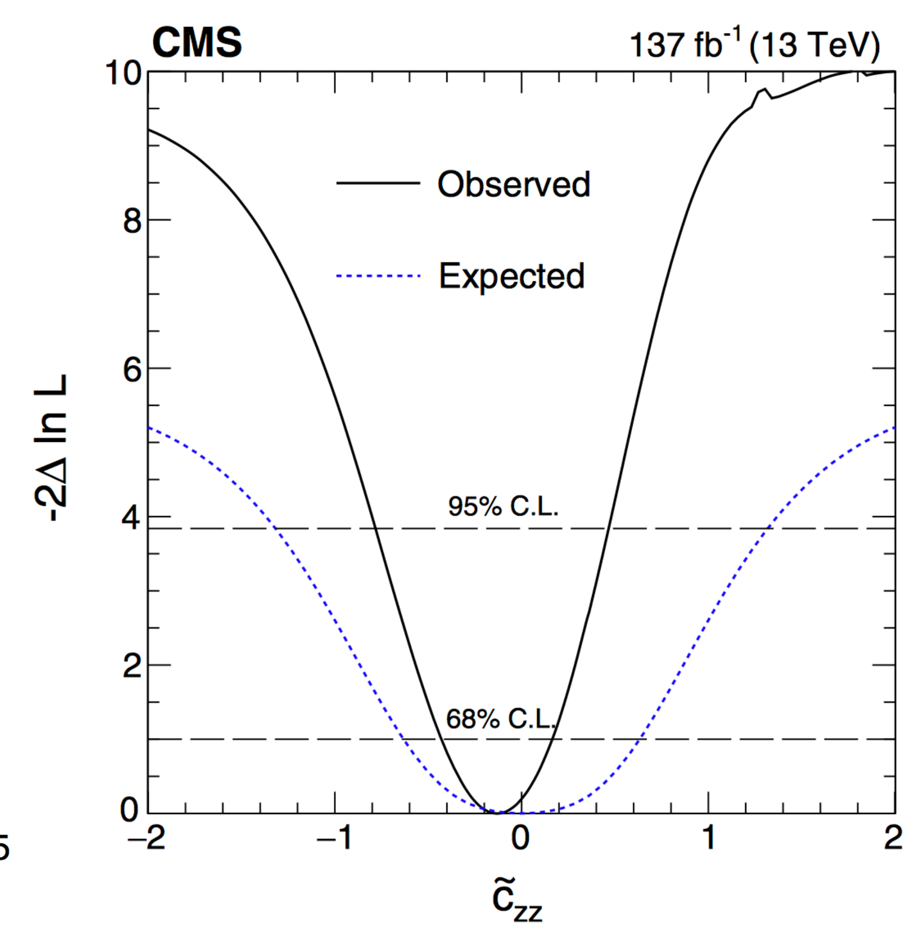
- **Performing simultaneous fit to all Wilson coefficients: targeting HZZ couplings using VBF and VH modes**
  - both linear and quadratic terms considered
  - largest precision for c(HW), also access with good precision on CP-odd EFT WC

Coupling	Observed	Expected
$c_{H\Box}$	$0.04^{+0.43}_{-0.45}$	$0.00^{+0.75}_{-0.93}$
c_{HD}	$-0.73^{+0.97}_{-4.21}$	$0.00^{+1.06}_{-4.60}$
c_{HW}	$0.01^{+0.18}_{-0.17}$	$0.00^{+0.39}_{-0.28}$
c_{HWB}	$0.01^{+0.20}_{-0.18}$	$0.00^{+0.42}_{-0.31}$
c_{HB}	$0.00^{+0.05}_{-0.05}$	$0.00^{+0.03}_{-0.08}$
$c_{H\tilde{W}}$	$-0.23^{+0.51}_{-0.52}$	$0.00^{+1.11}_{-1.11}$
$c_{H\tilde{W}B}$	$-0.25^{+0.56}_{-0.57}$	$0.00^{+1.21}_{-1.21}$
$c_{H\tilde{B}}$	$-0.06^{+0.15}_{-0.16}$	$0.00^{+0.33}_{-0.33}$

CP-odd

- Also provided constraints for c(ZZ) and CP-odd c(ZZ) coupling components using results on Warsaw basis





EFT combination across channels & operators

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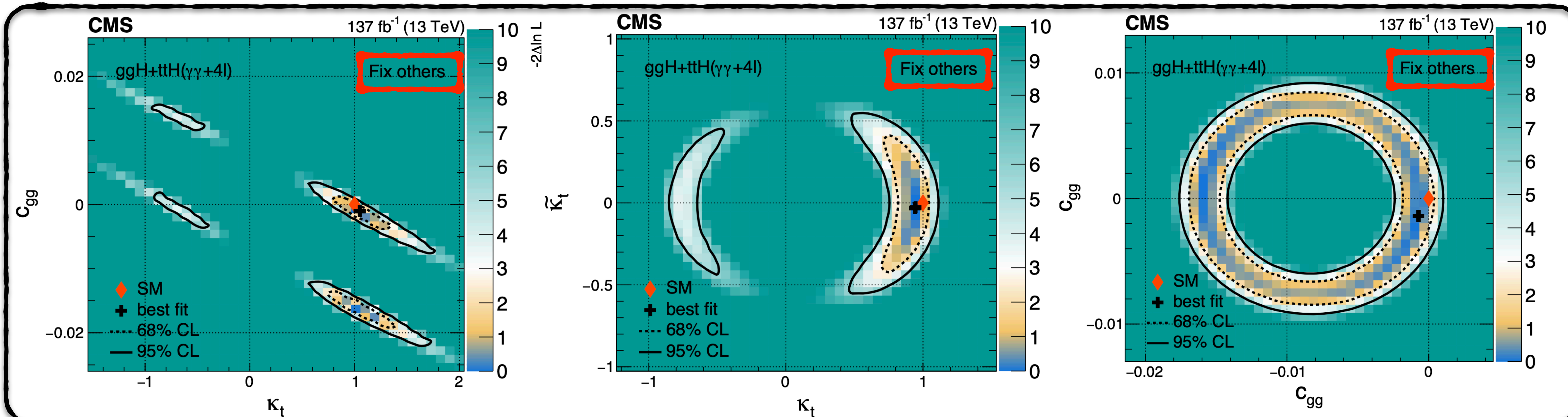
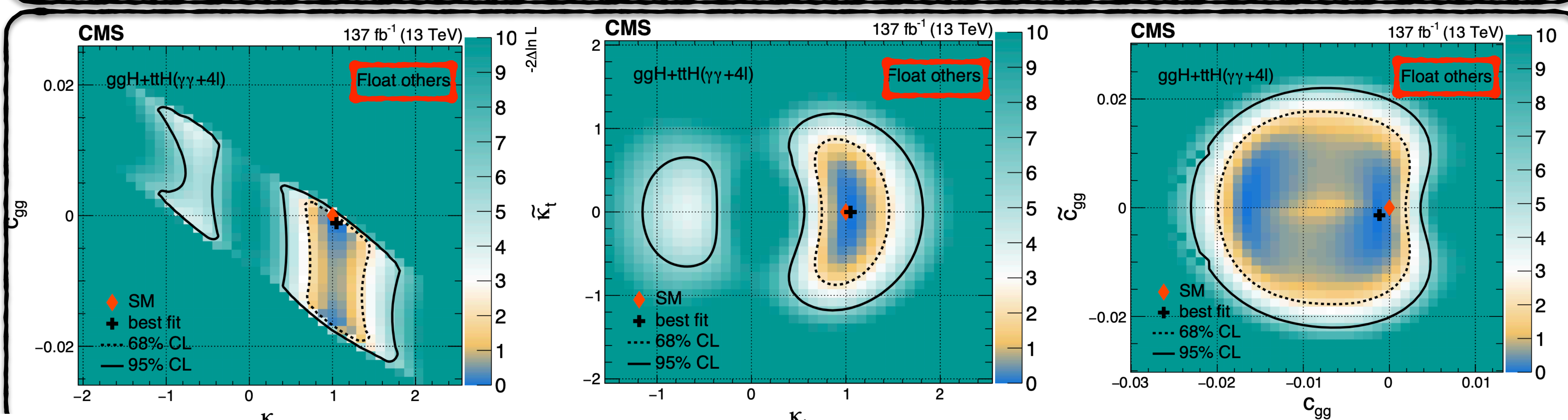
➡ **Simultaneous measurement of EFT operators, c(gg),~c(gg), kt,~kt impacting gluon-fusion loop - common EFT approach for several channels with additional sensitivity to CP odd operators**

- gluon fusion in addition to ttH/tH (→γγ/ZZ) used to constrain EFT top couplings





H->ZZ using off-shell

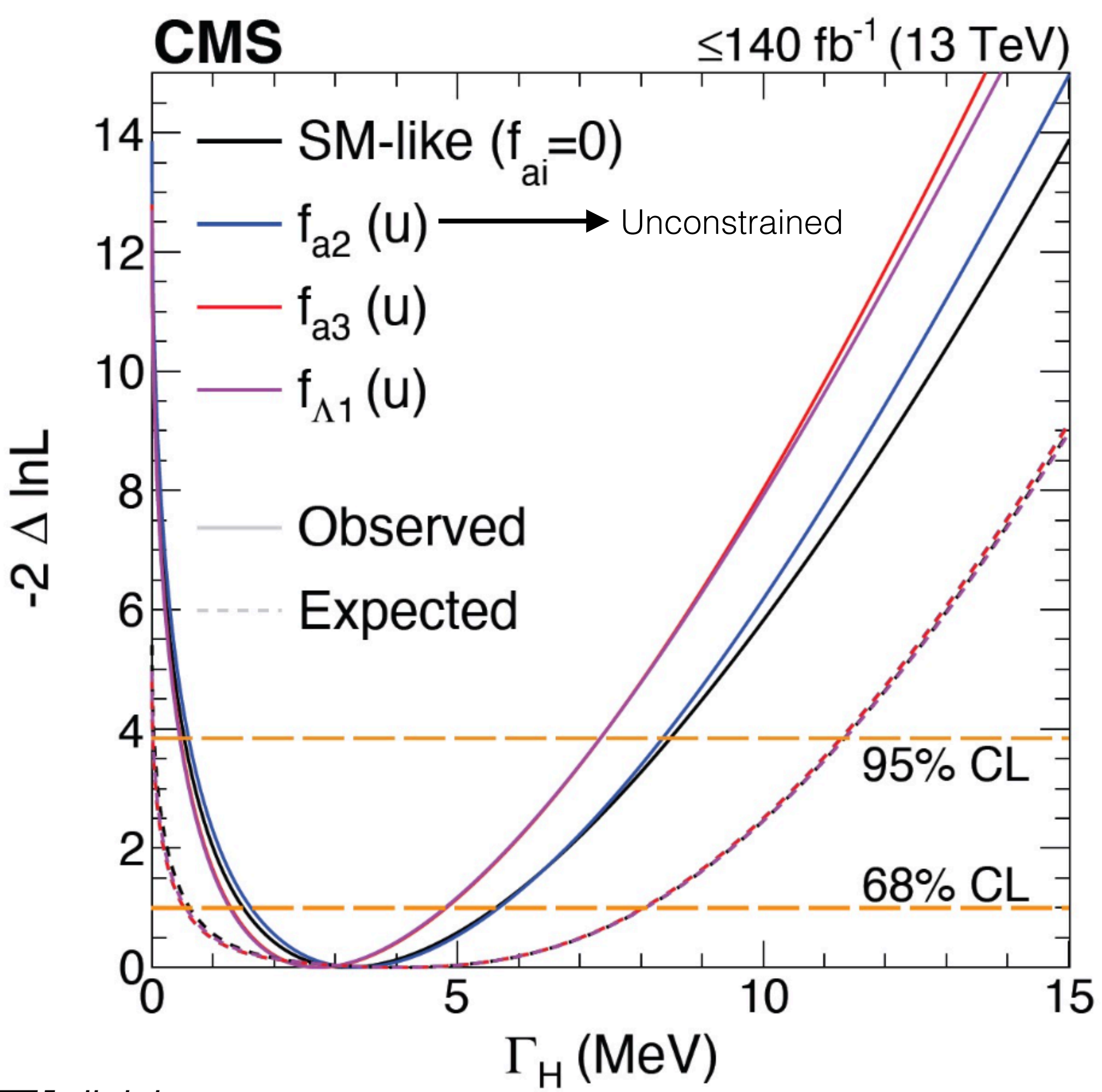
Nat. Phys. 18 (2022) 1329

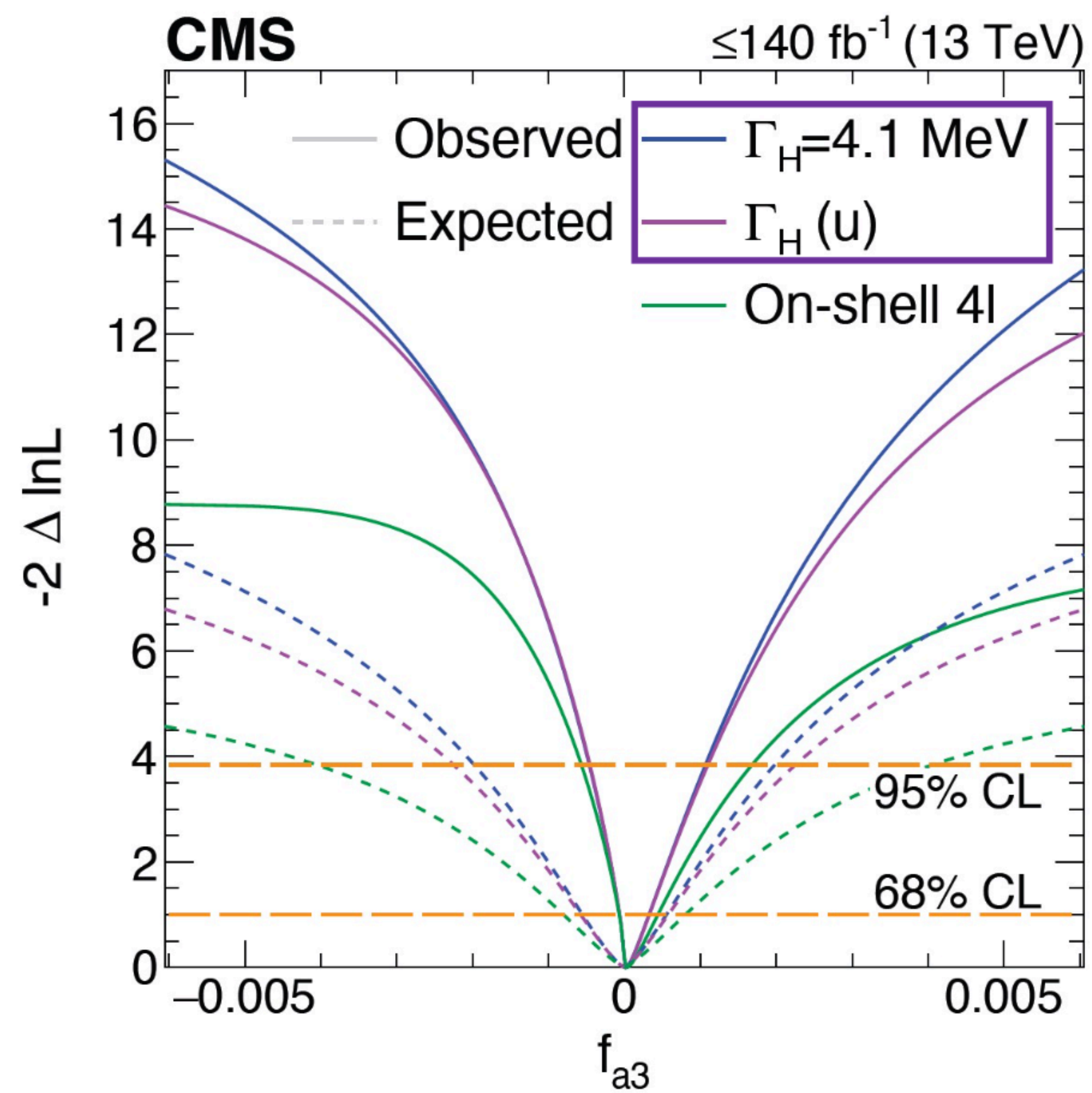
➡ **Working assumption in off-shell coupling no BSM modifying running coupling in combination of on- and off-shell production → interpretation for Higgs width**

- EFT analysis to test assumption for Higgs off-shell/width analysis - MELA sensitive to AC HVV
- combination with HZZ off-shell analysis to reach sensitivity on Γ(H)

$$\sigma^{\text{off-Shell}} \propto \sigma^{\text{on-Shell}}\,\Gamma_{\text{Higgs}}$$

➡ **No significant dependence on BSM effects in Γ(H) when AC included on HVV vertex**





Extending AC HVV constraints to HWW

New for Higgs Hunting 2023!

➡ **Expanding investigation on AC constraints in HWW channel**

➡ **Constraints on anomalous effects at the HVV and Hgg vertices following AC and SMEFT interpretations**

- analysis split in categories targeting gluon fusion, VBF-like and VH-like topologies
- MELA kinematic discriminant: output nodes for Higgs mode discriminator, SM couplings vs BSM, interference vs SM/BSM

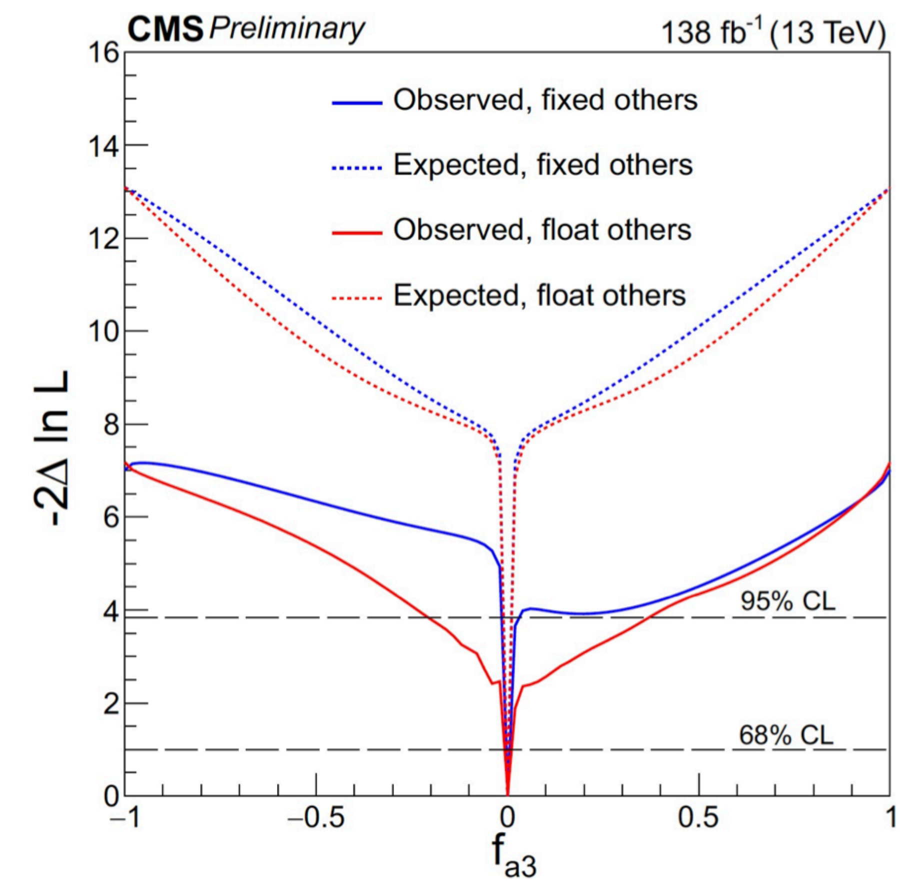
➡ **Results provided under two fitting hypotheses**

- POI's are fixed/floating

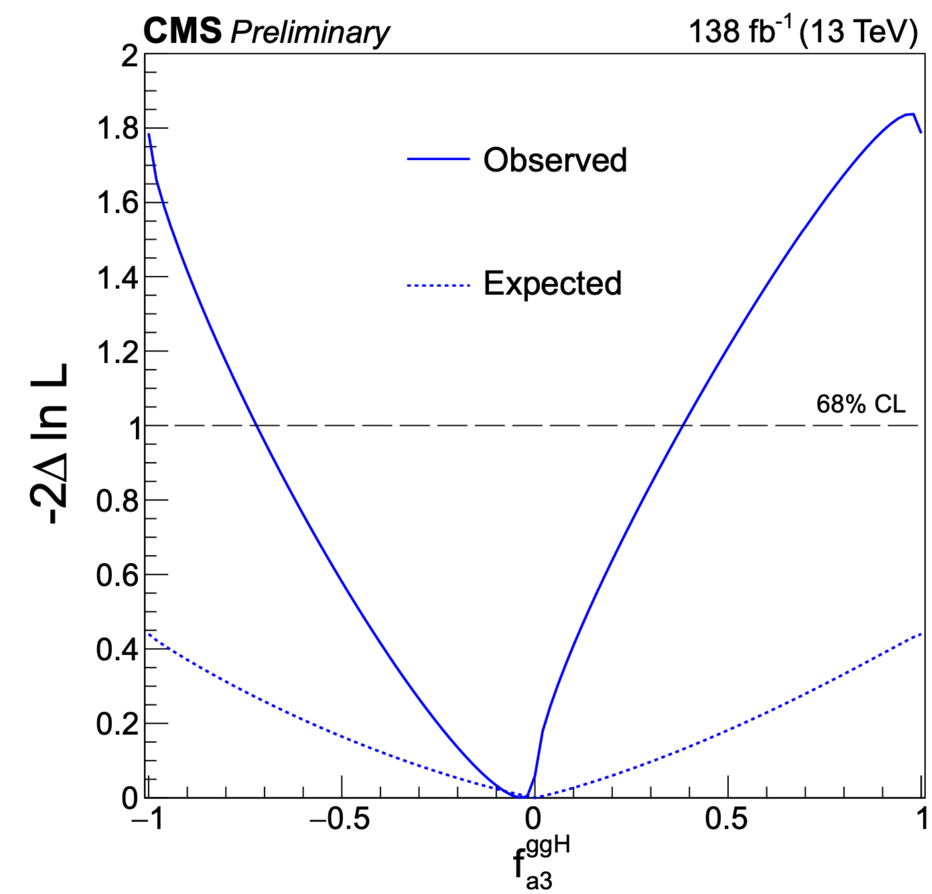
➡ **AC and Higgs SMEFT Warsaw basis**

➡ **Significant improvement in sensitivity/analysis coverage compared to full Run I analysis**

Coupling	Observed	Expected
$c_{H\Box}$	$-0.76^{+1.43}_{-3.43}$	$0.0^{+1.37}_{-1.84}$
c_{HD}	$-0.12^{+0.93}_{-0.32}$	$0.0^{+0.43}_{-0.30}$
c_{HW}	$0.08^{+0.43}_{-0.87}$	$0.0^{+0.37}_{-0.48}$
c_{HWB}	$0.17^{+0.88}_{-1.79}$	$0.0^{+0.77}_{-0.96}$
c_{HB}	$0.03^{+0.13}_{-0.26}$	$0.0^{+0.11}_{-0.14}$
$c_{H\tilde{W}}$	$-0.26^{+0.67}_{-0.50}$	$0.0^{+0.48}_{-0.52}$
$c_{H\tilde{W}B}$	$-0.54^{+1.37}_{-1.03}$	$0.0^{+0.99}_{-1.07}$
$c_{H\tilde{B}}$	$-0.08^{+0.20}_{-0.15}$	$0.0^{+0.15}_{-0.16}$



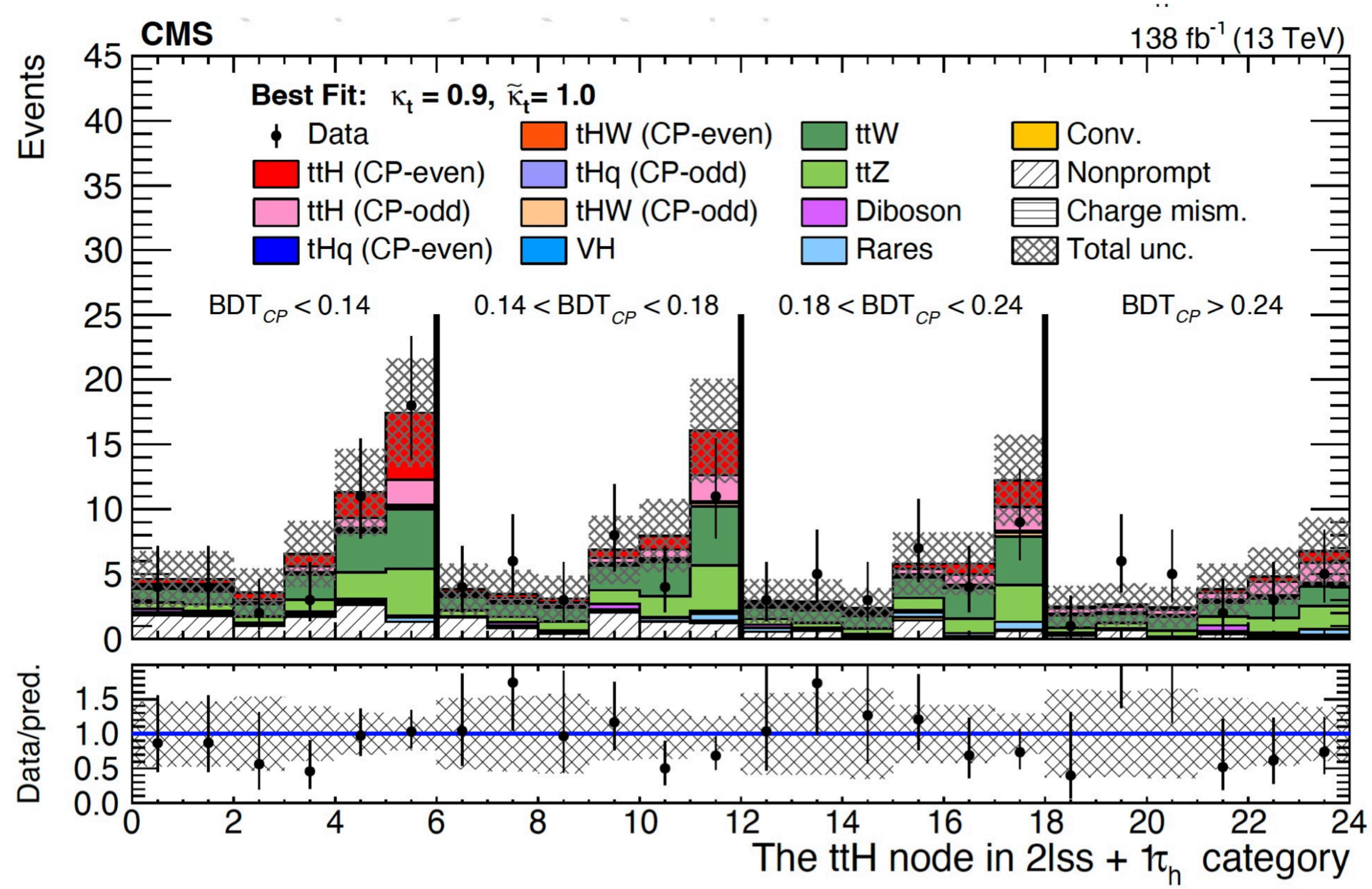
CMS PAS HIG-22-008

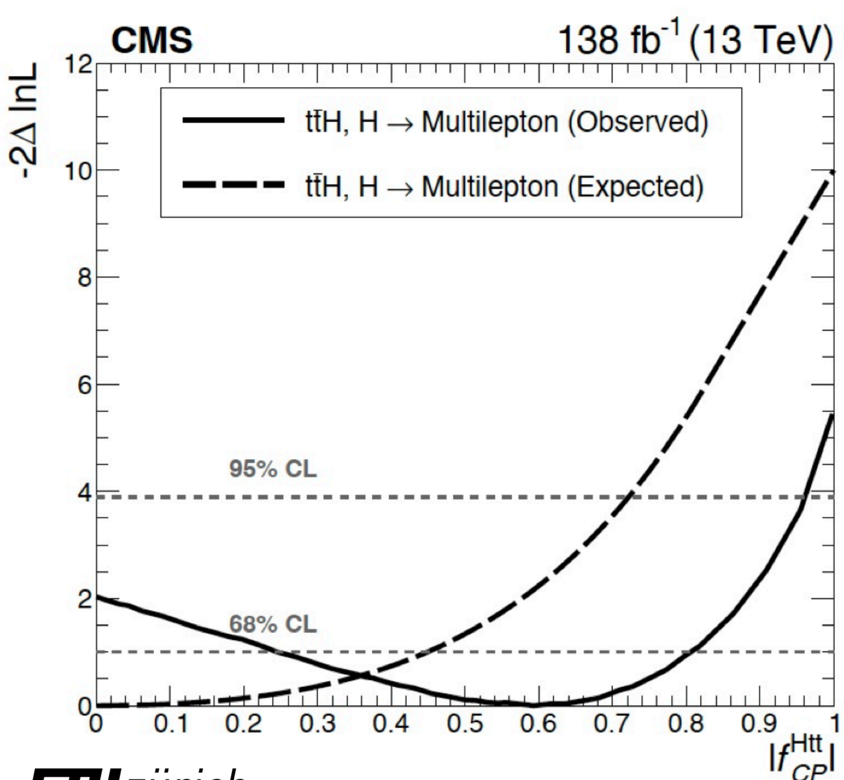


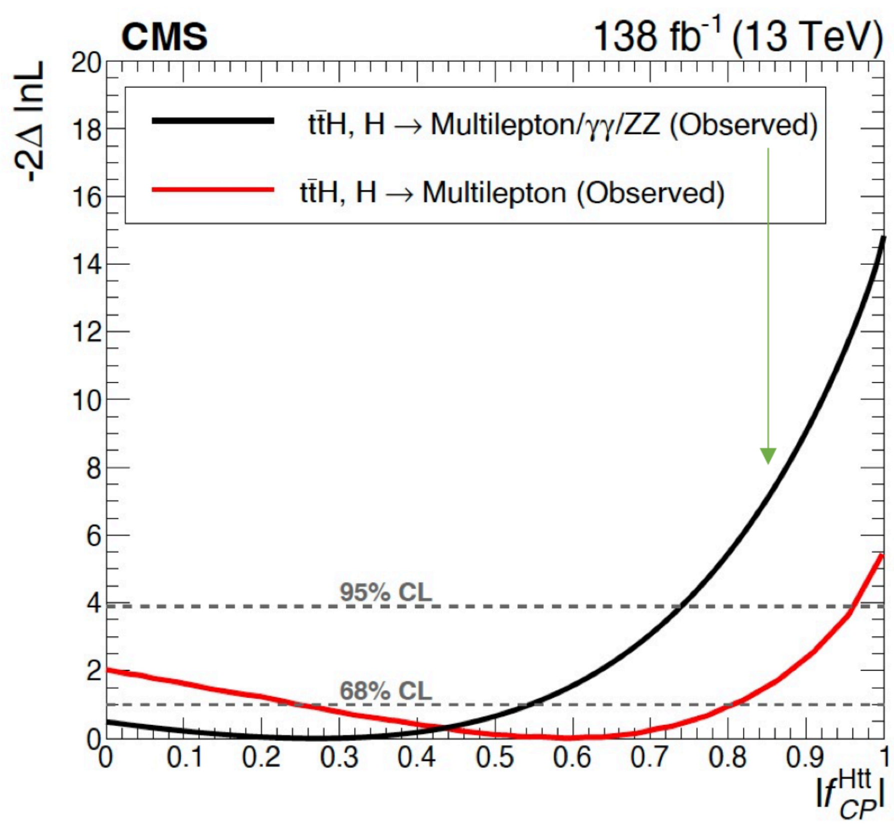
CP violation in ttH/tH

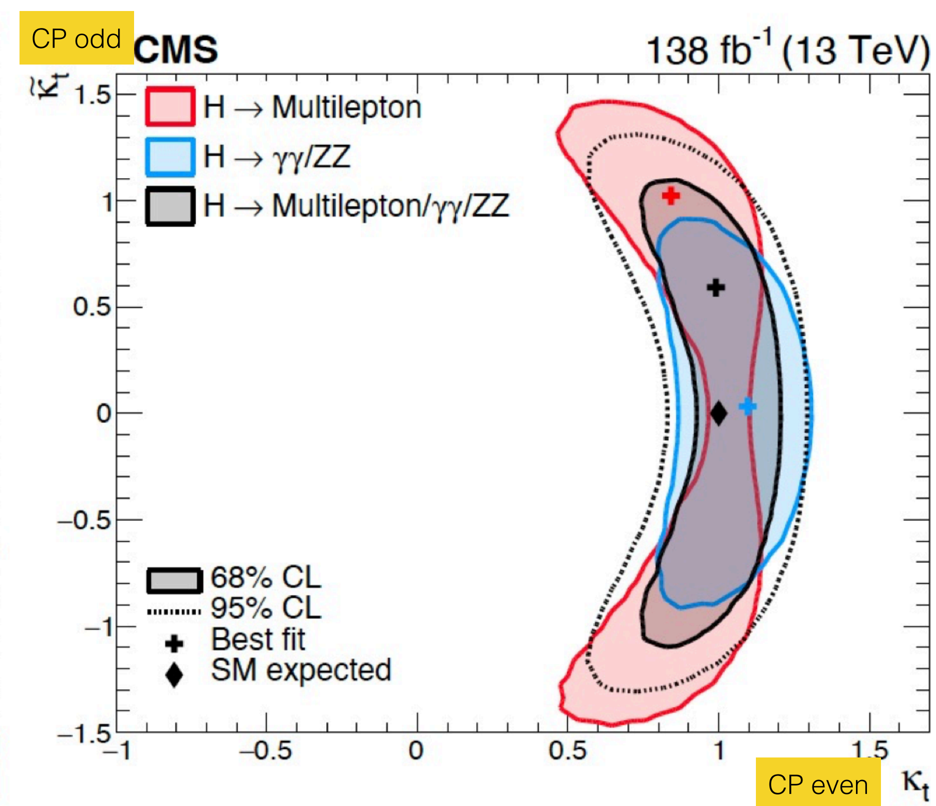
JHEP 07 (2023) 092

- **Targeting HWW and Hττ final states - CP even/odd operators**
  - BDT sensitive to CP observables (ΔRjj, Δηjj, …)
- **Results including combination of multi-lepton and γγ/ZZ**
  - f(CP)=0 SM expectation; f(CP)=0.28; <0.55 at 68% CL interval
    - results compatible to CP even scenario: CP odd contribution not favoured at 3.7σ





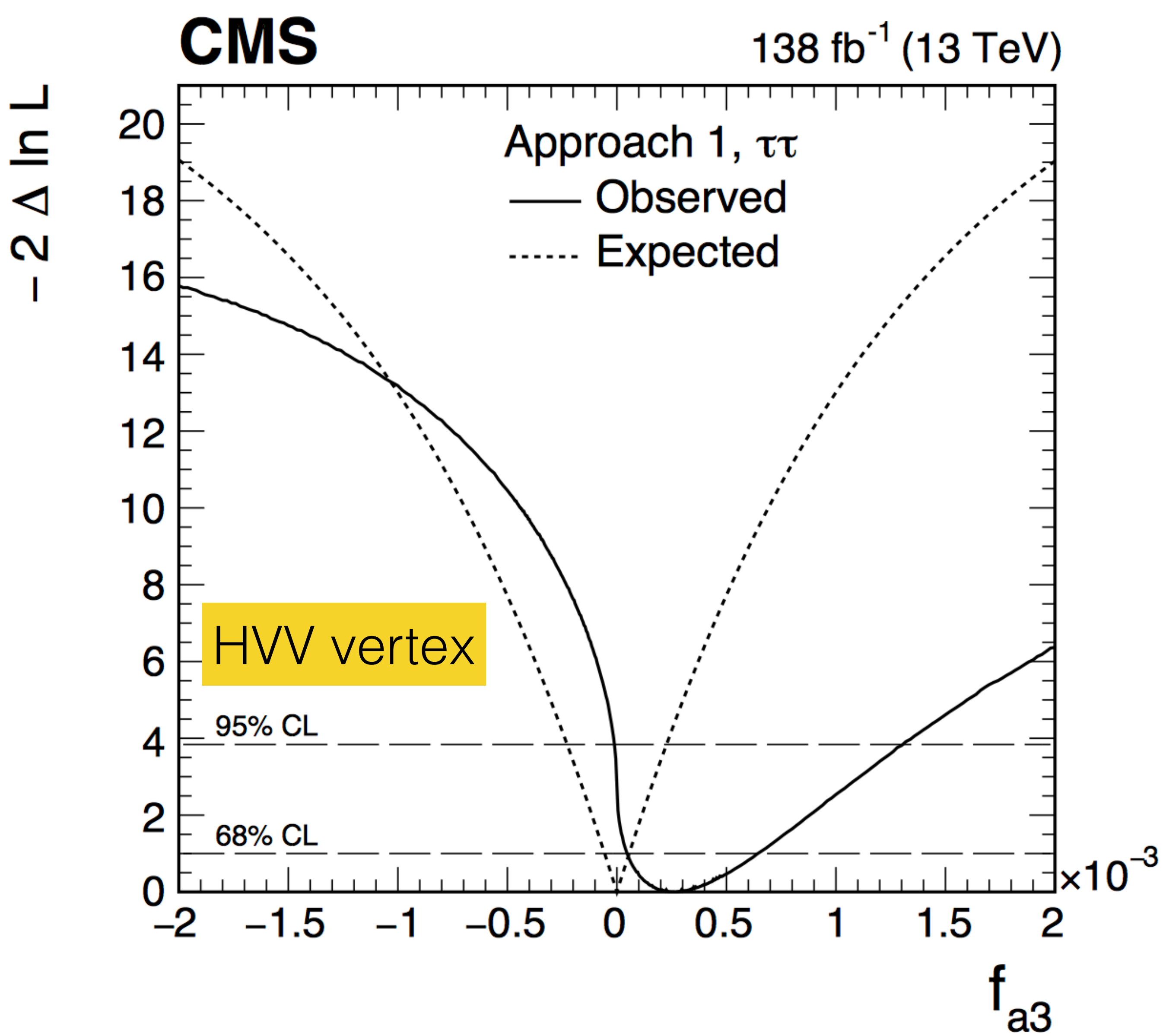


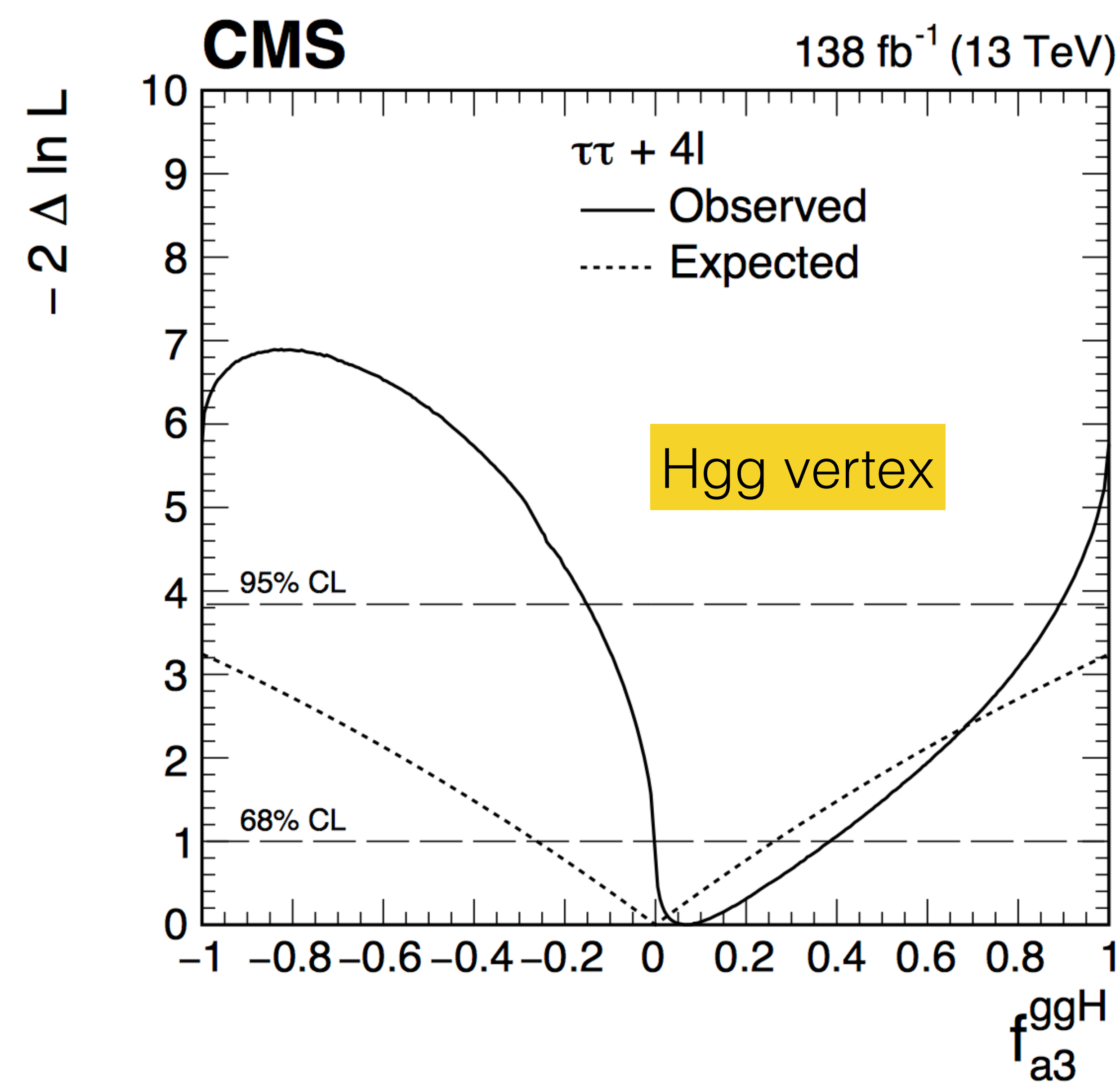


H->ττ analysis

➡ **Targeting measurement of several EFT vertices**

- VBF production analysis: HVV EFT vertex, ggH production analysis: Hgg EFT vertex
- HVV vertex constrained using H→ττ decay in VBF production while Hgg vertex uses combination of H→ττ and H→ZZ→4l (on-shell analysis)
- pure CP-odd hypothesis for Higgs couplings to gluons excluded at 2.4σ

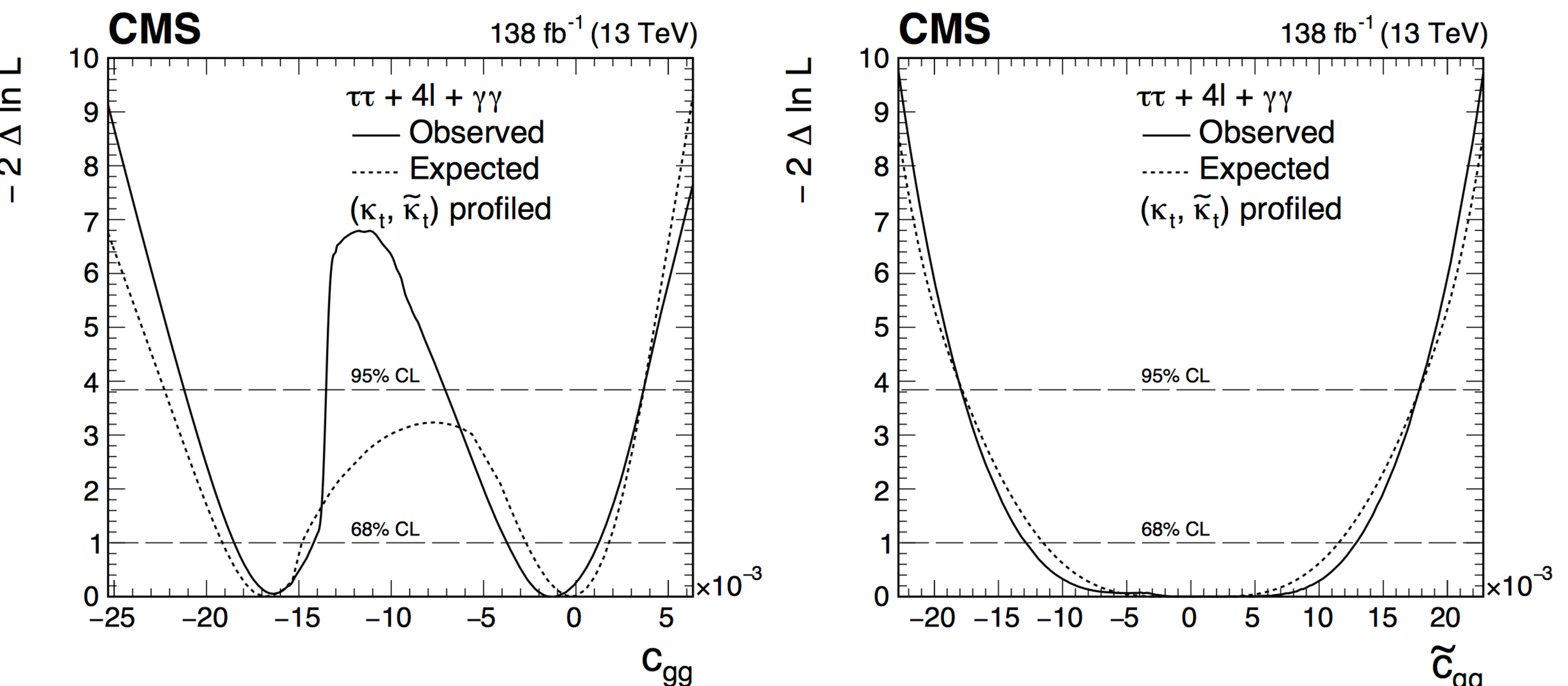




H->ττ analysis (2)

arXiv: 2205.05120 (sub to PRD)

- **Access Hff couplings with H→ZZ, ttH→γγ and H→ττ in gluon-fusion production mode - combination improves limits on anomalous couplings by around 25%**
  - achieved constraints on c(gg) and CP-odd c(gg) operators

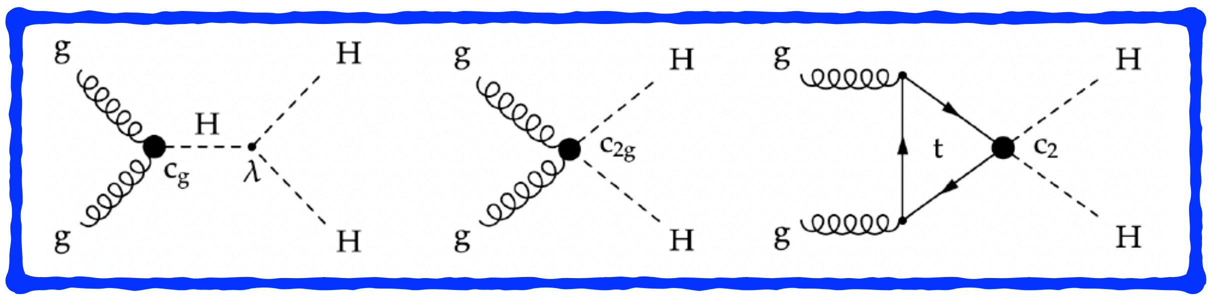


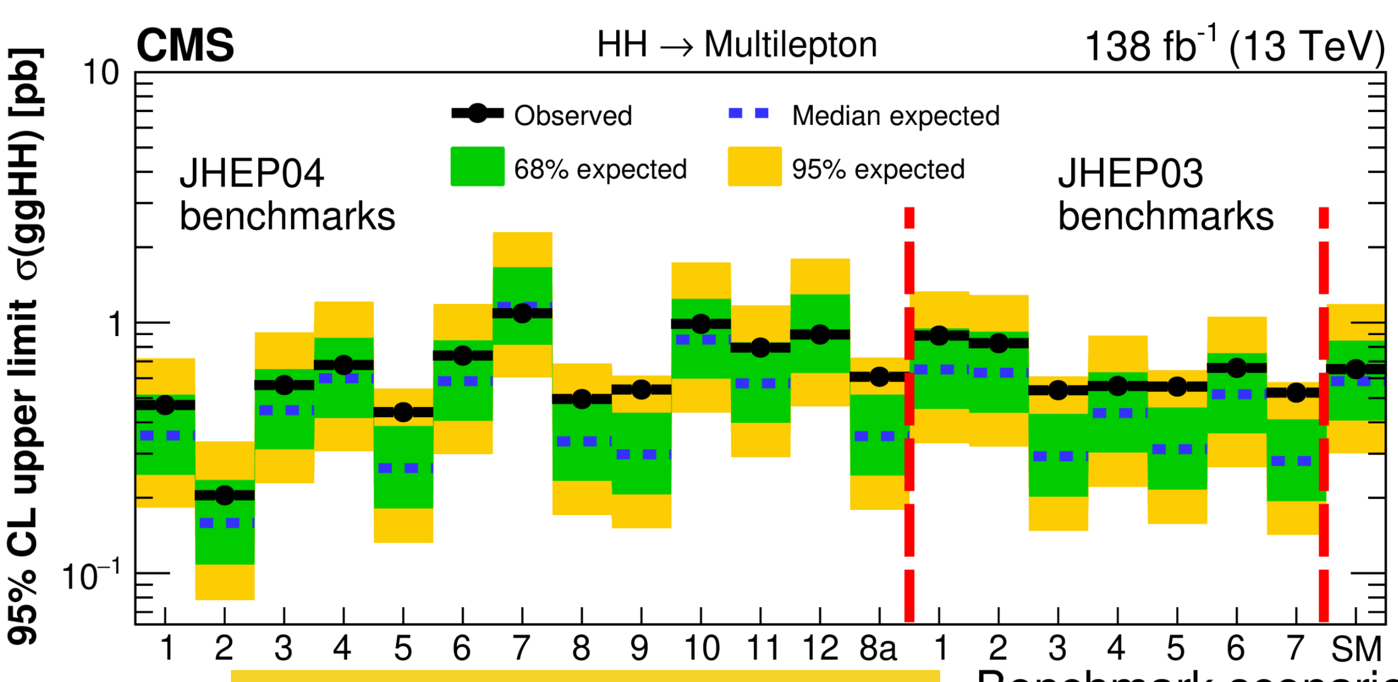
EFT interpretations in double Higgs analyses

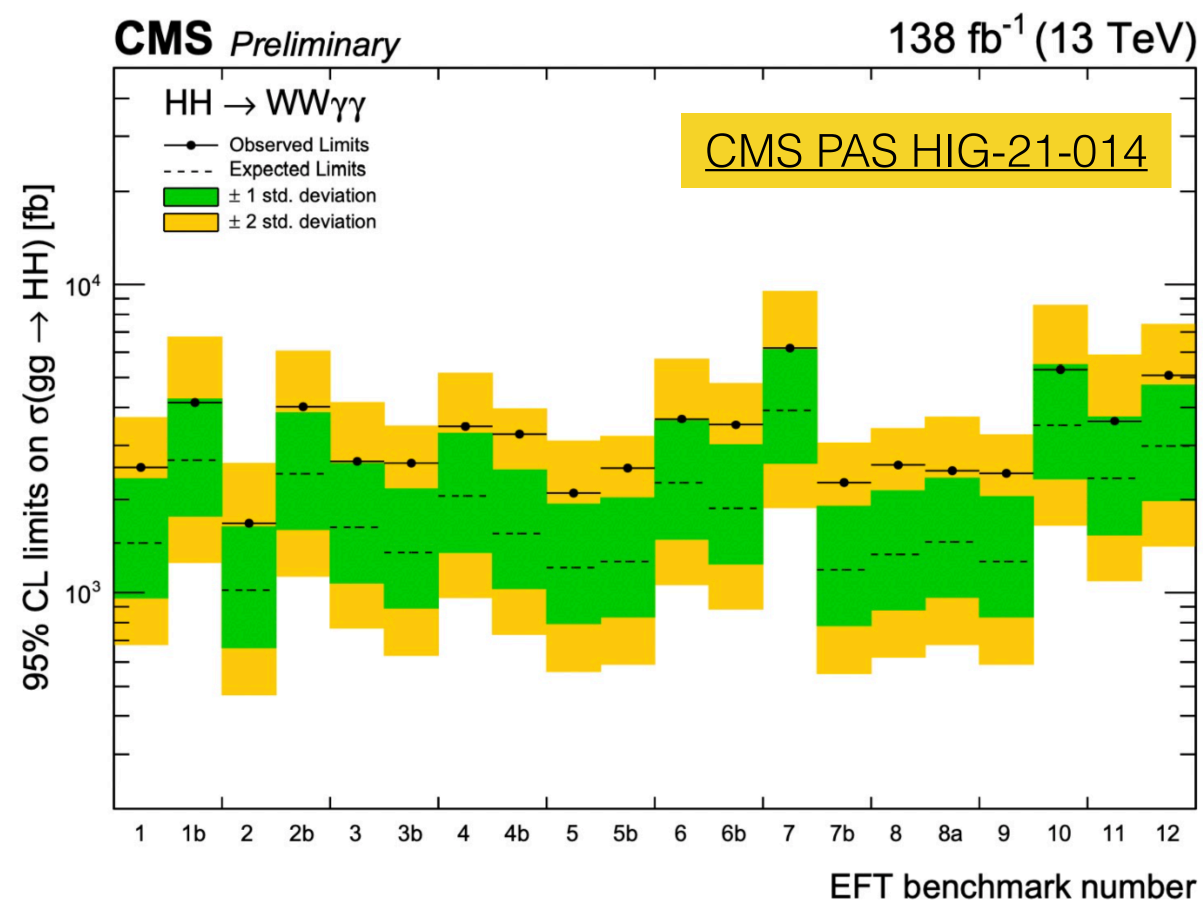
- Several benchmark models defined by varying coupling strengths and parameter values spanning dim-6 EFT phase spaces
  - performed analysis by reweighting signal samples to each EFT benchmark model
  - extract limit for each benchmark: HH→WWγγ, HH→bbbb, HH→ Multilepton (WWWW, WWττ, ττττ)

Benchmark	κ_λ	κ_t	c_2	c_g	c_{2g}
SM	1.0	1.0	0.0	0.0	0.0
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	-0.8	0.6
3	1.0	1.0	-1.5	0.0	-0.8
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	-1
6	2.4	1.0	0.0	0.2	-0.2
7	5.0	1.0	0.0	0.2	-0.2
8	15.0	1.0	0.0	-1	1
9	1.0	1.0	1.0	-0.6	0.6
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	1	-1
12	15.0	1.0	1.0	0.0	0.0

HH→WWγγ







arXiv: 2206.10268 (sub to JHEP)

Wrapping-up & conclusions

- **Precision measurements is key to look for deviations on SM couplings: several Effective Field Theory interpretations of Higgs measurements in CMS**
  - beyond kappa framework and complementary to direct searches for New Physics
- **EFT interpretation of STXS results allows to probe EFT parameters using various Higgs production modes**
  - EFT effects parametrised in STXS bins and dedicated acceptance corrections in analysis phase-space
  - main drawback(s)/assumptions:
    - no dedicated sensitivity to CP and no optimal observables to improve EFT effect sensitivity
    - assuming no modifications of background shapes/normalisation due to EFT effects
- **Dedicated measurements of EFT effects in CMS analyses: $H\to ZZ/WW$, $H\to\tau\tau$, started exploring double Higgs analyses**
- **Developing PCA analyses to tackle large combinations and simultaneous constraints on Wilson coefficients**
  - very relevant for global EW+Higgs EFT combination and to select non flat directions in EFT space
- **Ongoing effort in CMS+ATLAS to provide common STXS+SMEFT parameterisation in the context of the LHC EFT WG [LHC EFT workshop, Dec 2022]**
- **Several more EFT interpretation Run 2 results will be released soon - stay tuned!**

Additional slides

EFT interpretation using STXS (2)

➡ **Constraints on main WC's in STXS bins affecting following vertices**

- EW+Higgs boson interactions, boson couplings to fermions and 4-fermion interactions

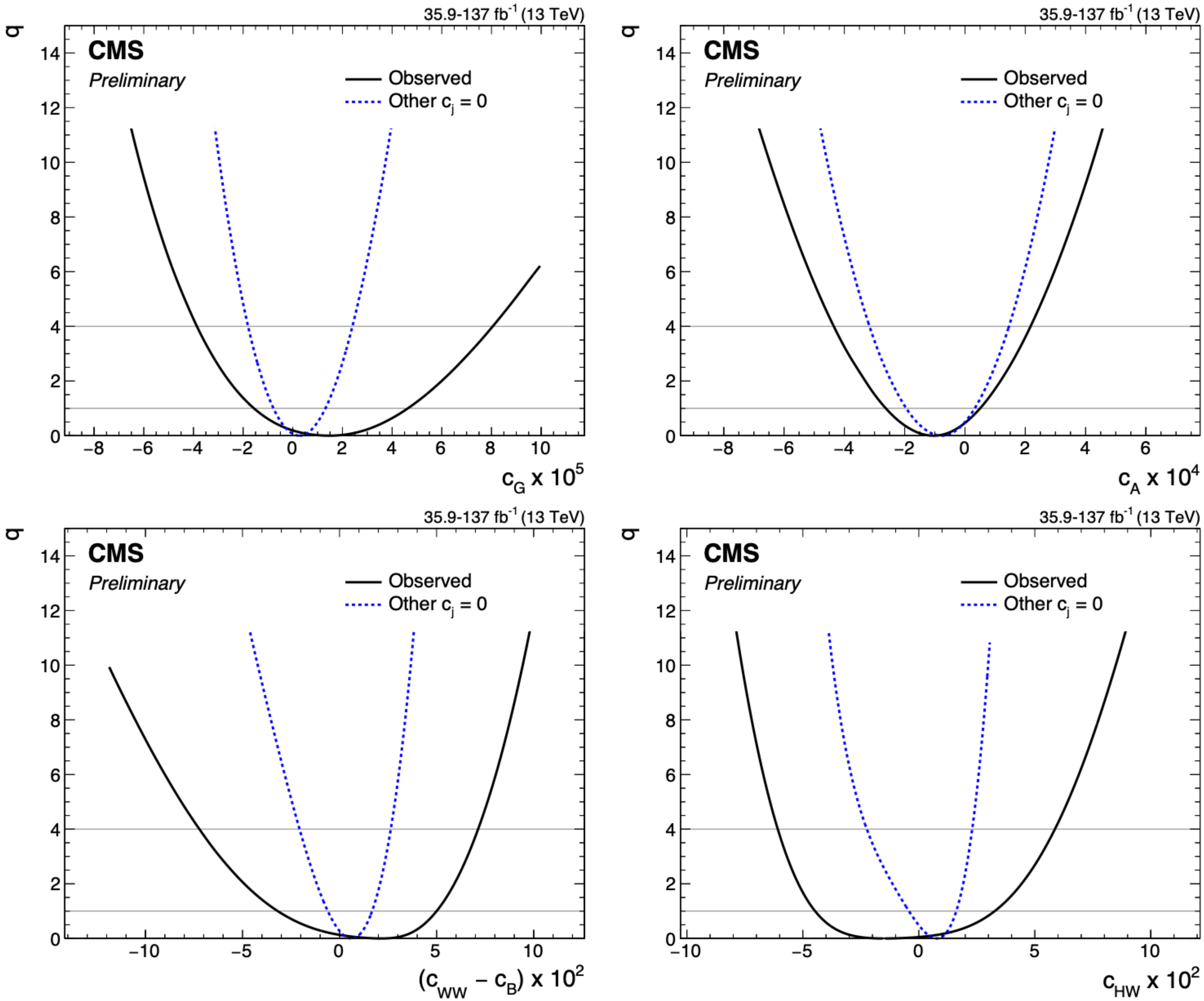
EW+Higgs interactions

Boson couplings to fermions

4-fermion interactions

Wilson coefficient	Operator	Wilson coefficient	Operator
$c_{H\square}$	$(H^\dagger H)\square(H^\dagger H)$	c_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G^A_{\mu\nu}$
c_{HDD}	$(H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$	c_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W^I_{\mu\nu}$
c_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$	c_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$
c_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$	c'_{ll}	$(\bar{l}_p \gamma_\mu l_t)(\bar{l}_r \gamma^\mu l_s)$
c_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$	$c^{(1)}_{qq}$	$(\bar{q}_p \gamma_\mu q_t)(\bar{q}_r \gamma^\mu q_s)$
c_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$	$c^{(3)}_{qq}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$	c_{qq}	$(\bar{q}_p \gamma_\mu q_t)(\bar{q}_r \gamma^\mu q_s)$
c_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$	$c^{(31)}_{qq}$	$(\bar{q}_p \gamma_\mu \tau^I q_t)(\bar{q}_r \gamma^\mu \tau^I q_s)$
c_{dH}	$(H^\dagger H)(\bar{q}_p d_r \widetilde{H})$	c_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
$c^{(1)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$	$c^{(1)}_{uu}$	$(\bar{u}_p \gamma_\mu u_t)(\bar{u}_r \gamma^\mu u_s)$
$c^{(3)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	$c^{(1)}_{qu}$	$(\bar{q}_p \gamma_\mu q_t)(\bar{u}_r \gamma^\mu u_s)$
c_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$	$c^{(8)}_{ud}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$
$c^{(1)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	$c^{(8)}_{qu}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$c^{(3)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$	$c^{(8)}_{qd}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$
c_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$	c_W	$\epsilon^{IJK} W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$
c_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$	c_G	$f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$

EFT interpretation using Higgs STXS framework



EFT basis

$$f_{a3}^{ggH} = \frac{|a_3^{gg}|^2}{|a_2^{gg}|^2 + |a_3^{gg}|^2} \, \mathrm{sign}\left(\frac{a_3^{gg}}{a_2^{gg}}\right)$$

Hff couplings - CP-even

$$|f_{CP}^{Hff}| = \left(1 + 2.38\left[\frac{1}{|f_{a_3}^{ggH}|}\right]\right)^{-1} = \sin^2\alpha^{Hff}$$

Hff couplings - CP-odd

$$f_{a_3} = \frac{|a_3^{gg}|^2}{|a_2^{gg}|^2 + |a_3^{gg}|^2} \mathrm{sign}\left(\frac{a_3^{gg}}{a_2^{gg}}\right)$$

HVV couplings - gg couplings (only non zero contributions are a2 and a3)

$$c_{zz} = -\frac{s_w^2 c_w^2}{2\pi\alpha} a_2,$$
$$\tilde{c}_{zz} = -\frac{s_w^2 c_w^2}{2\pi\alpha} a_3.$$

$$c_{gg} = -\frac{1}{2\pi\alpha_S} a_2^{gg},$$
$$\tilde{c}_{gg} = -\frac{1}{2\pi\alpha_S} a_3^{gg},$$

EFT interpretation