EFT interpretations (ATLAS/CMS) of single-Higgs and Higgs boson pair production

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on behalf of ATLAS and CMS Collaborations

Standard Model at the LHC - Rome, May 7-10 2024

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**

➡ **This talk will focus on recent EFT interpretations results in ATLAS/CMS for Higgs and double Higgs analyses**

- EFT parametrisation models
- EFT interpretation using STXS scheme and full combination of Run 2 single Higgs analyses
- highlights on optimal observable analyses targeting constraints on SMEFT EFT or anomalous coupling basis ($H\rightarrow ZZ$, $H\rightarrow WW$, $H\rightarrow\tau\tau$)
- extending constraints on EFT coefficients using SMEFT or HEFT basis in double Higgs analyses
- example of global EFT fit using Higgs and EWK constraints

SM Effective field theory

- ➡ **Experimental profile of the Higgs boson with Run 1/ 2 data becoming very precise**
- ➡ **Precision measurement is key to look for deviations of SM couplings: achieved using low-energy approximation (EFT) to UV complete theory**

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

- ➡ **Under the assumption that the theory cut-off is much larger than the energy, SMEFT series can be truncated at dimension 6**
  - dimension 5 operators violates L number conservation hence not relevant for LHC studies
- ➡ **Warsaw basis often used to derive set of operators which can be accessed and constrained by analyses**
- ➡ **Dimension 8 operators often neglected and contributing as $1/\Lambda^4$**

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)

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

SM

Interference of SM and NP

Pure NP

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

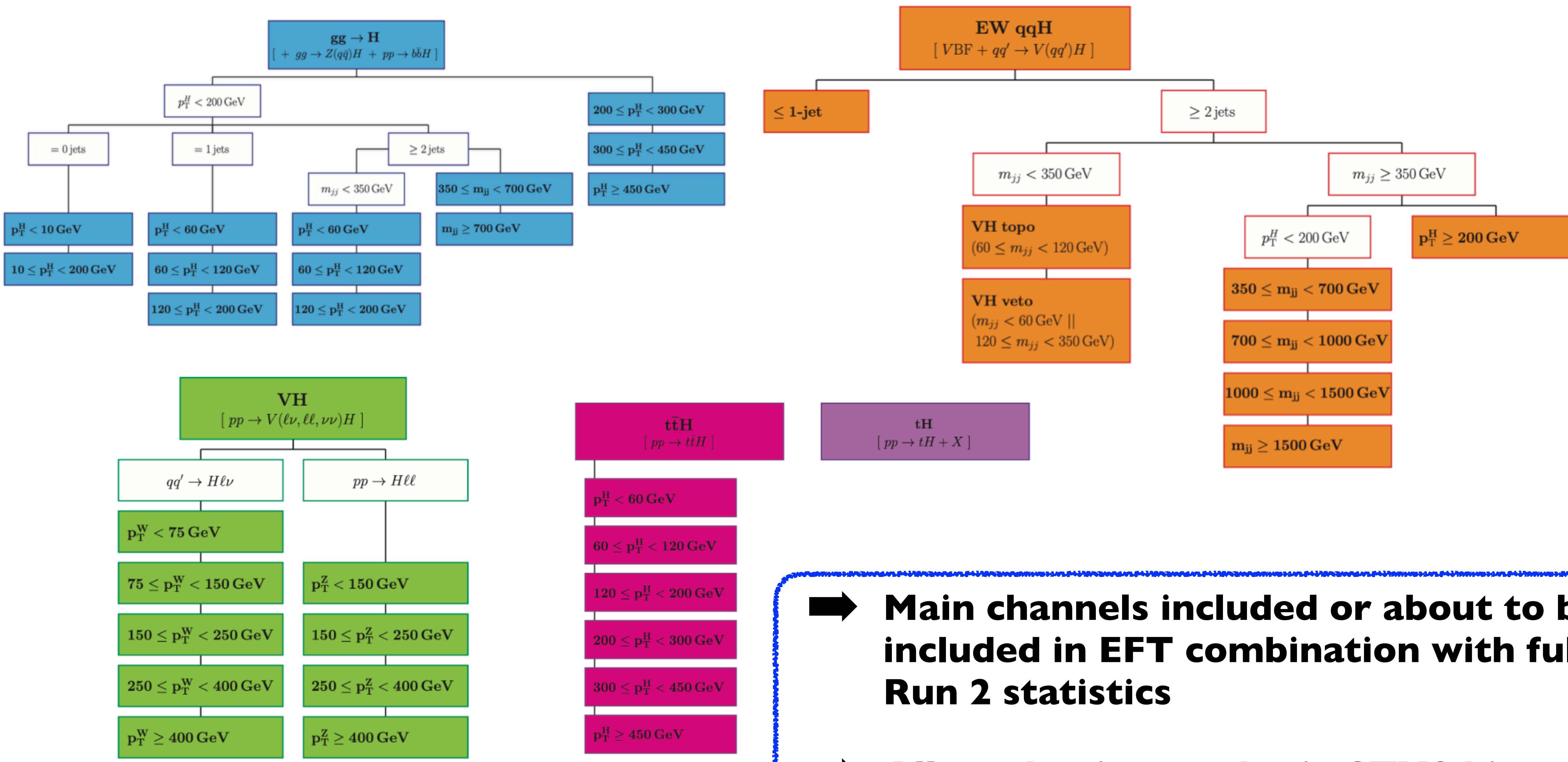
- **SMEFT [link] is a popular model for EFT interpretation using dim-6 operators**
- **Some EFT contributions are CP-odd operators: access on those operators is relevant as non vanishing components indicate CP violation**

EFT interpretation using STXS 1.2 categorisation

➡ **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



➡ **Main channels included or about to be included in EFT combination with full Run 2 statistics**

➡ **All production modes in STXS bins**

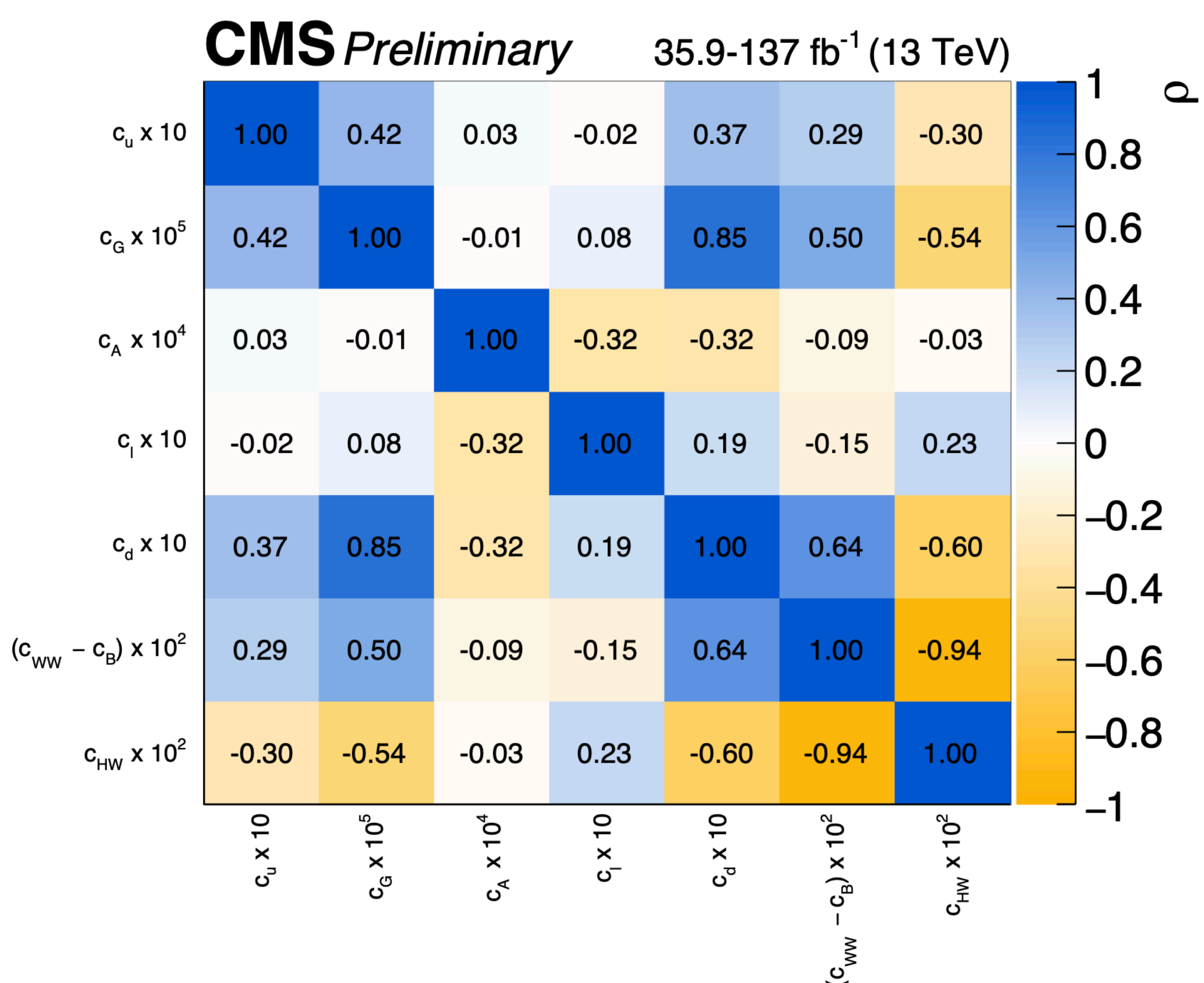
EFT interpretation using STXS

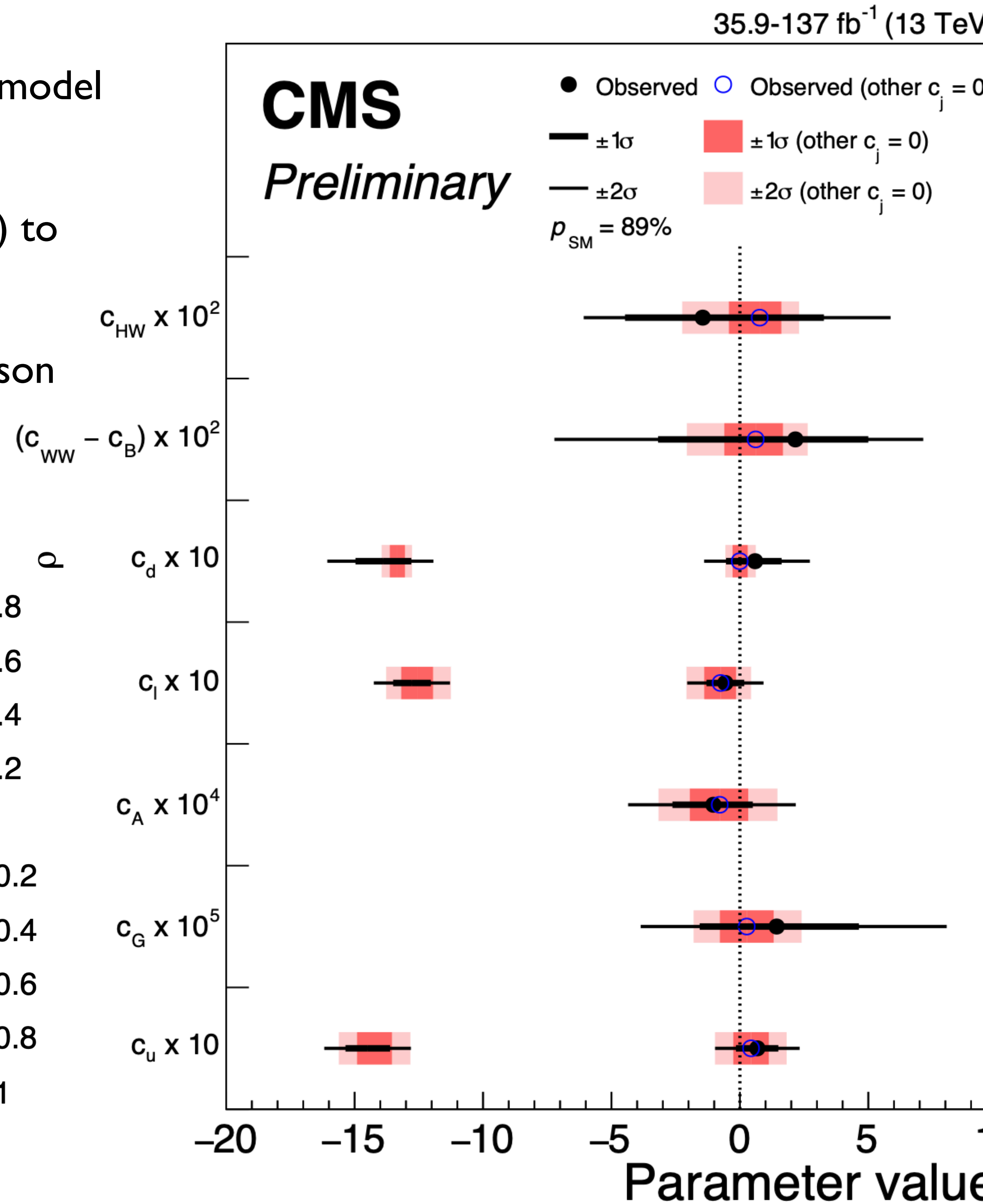
➡ **Assumption of EFT interpretation in STXS bins: 1) no EFT effects on background components, 2) acceptance corrections in STXS bins to account for EFT effects**

➡ EFT coupling constraints extracted in HEL model (definition in backup)

➡ No optimal observables (angles, kinematics) to enhance analysis sensitivity to EFT effects

➡ Results provided with all freely-floating Wilson coefficients and profiling one at a time





EFT Higgs - choice of parameters

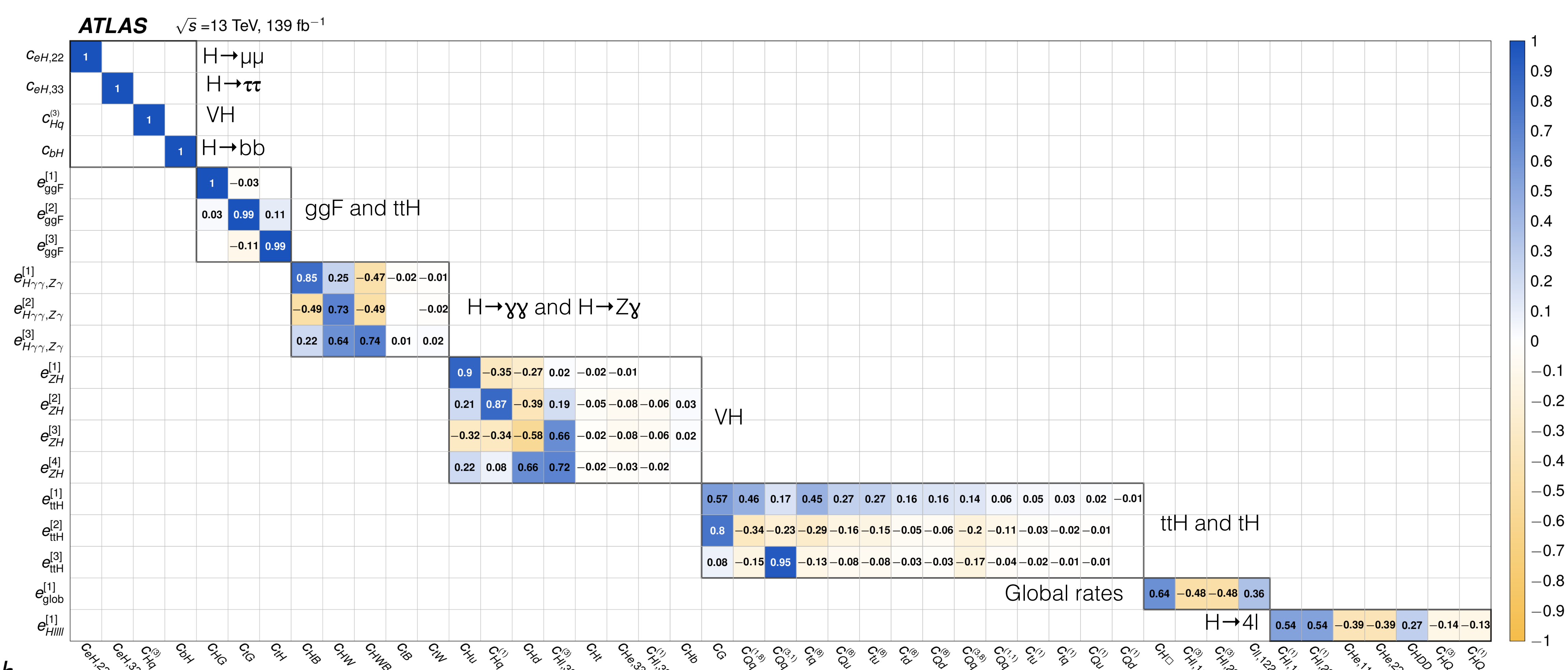
arXiv:2402.05742 (submitted to JHEP)

➡ **Combined all Higgs final states and performed principal component analysis on SMEFT Fisher information matrix in the limit of Gaussian STXS measurements**

$$V^{-1}_{\mathrm{SMEFT}} = P^{T}_{(i,k',X)\to(j)}\, V^{-1}_{\mathrm{STXS}}\, P_{(i,k',X)\to(j)}$$

➡ **Eigenvalue decomposition of SMEFT Fisher information matrix leads to eigenvectors which are constrained in the measurement**

- sensitivity criteria observations defining a new rotated basis achieving fit stability, fit-parameter interpretability and no flat directions in the likelihood scans due to poor sensitivity

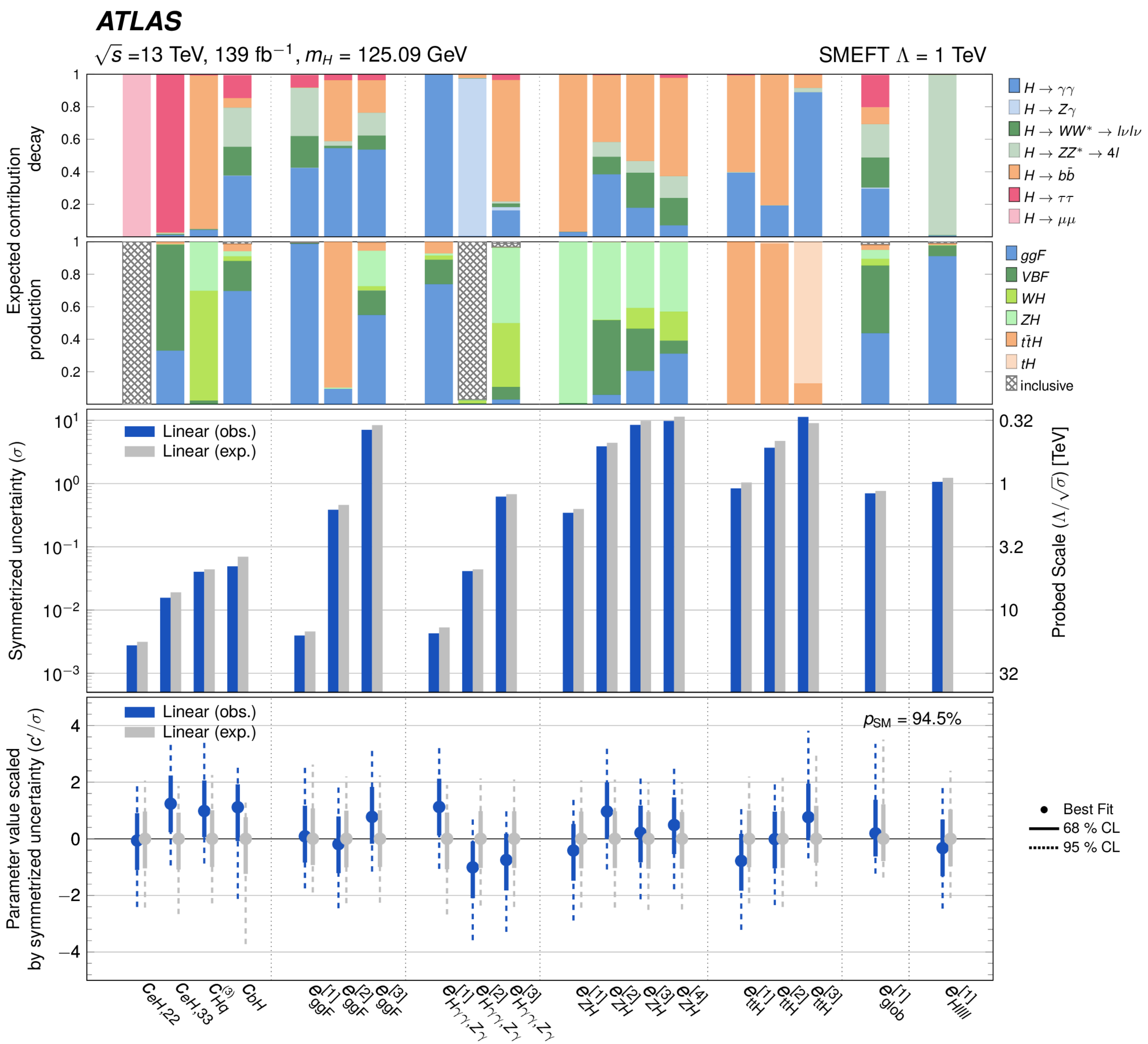


EFT Higgs fit - linear model

arXiv:2402.05742 (submitted to JHEP)

➡ **Linearised SMEFT model (SM p-value 94.5%): contribution of each measured production/decay extracted using Fisher information matrix**

➡ **Most of WC's are statistically dominated - some WC's entirely constrained by single channels**

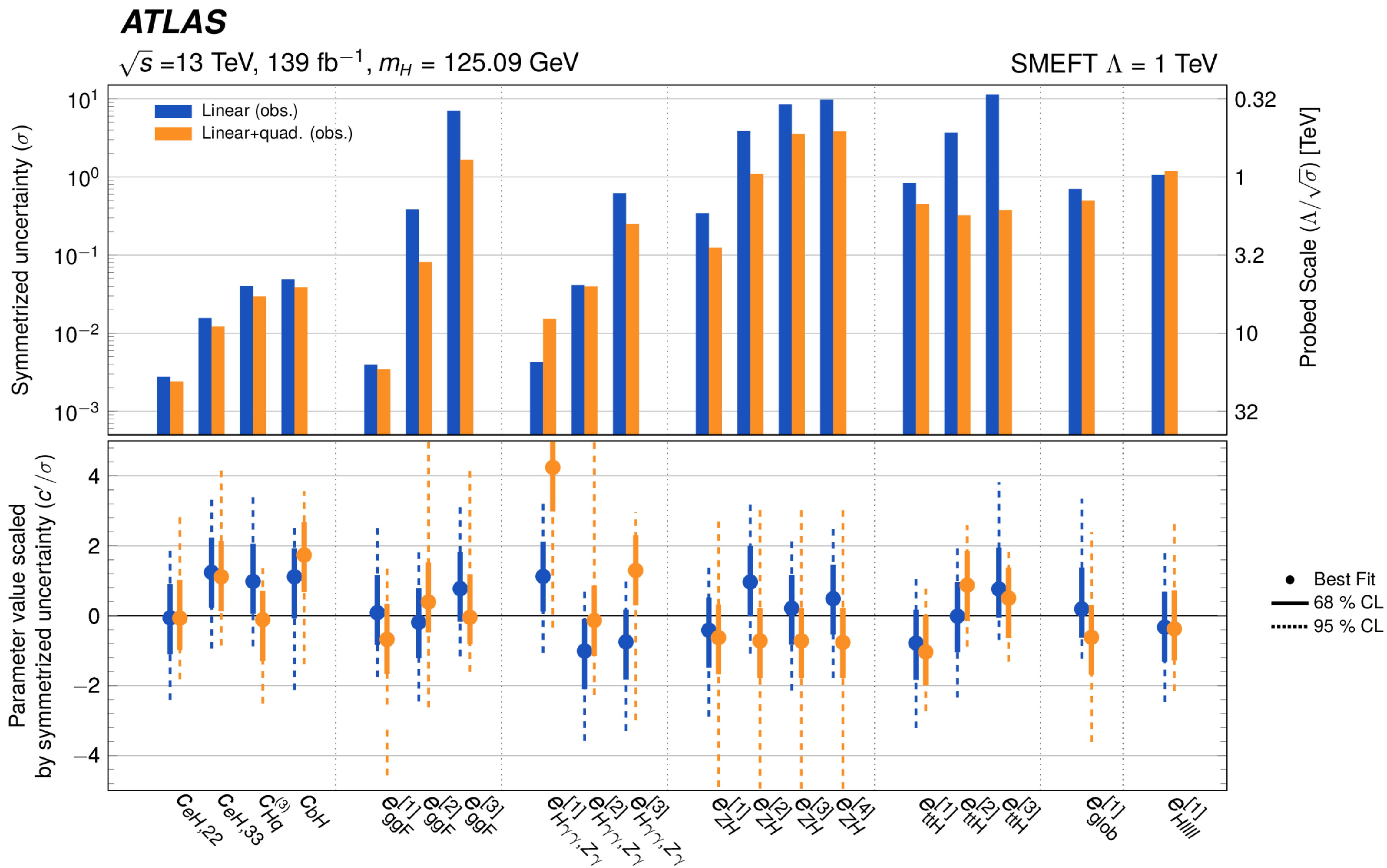


EFT Higgs fit including quadratic terms

arXiv:2402.05742 (submitted to JHEP)

➡ **Constraints on the model with quadratic terms in most cases stronger then linear-only model (mostly for weak impact of BSM/SM interference terms)**

- observed uncertainties smaller than expected for quadratic due to double minima structure
- difference between linear/quadratic magnitude as indicator of missing SM dim-8 interference term



EFT Higgs using differential measurements

arXiv:2402.05742 (submitted to JHEP)

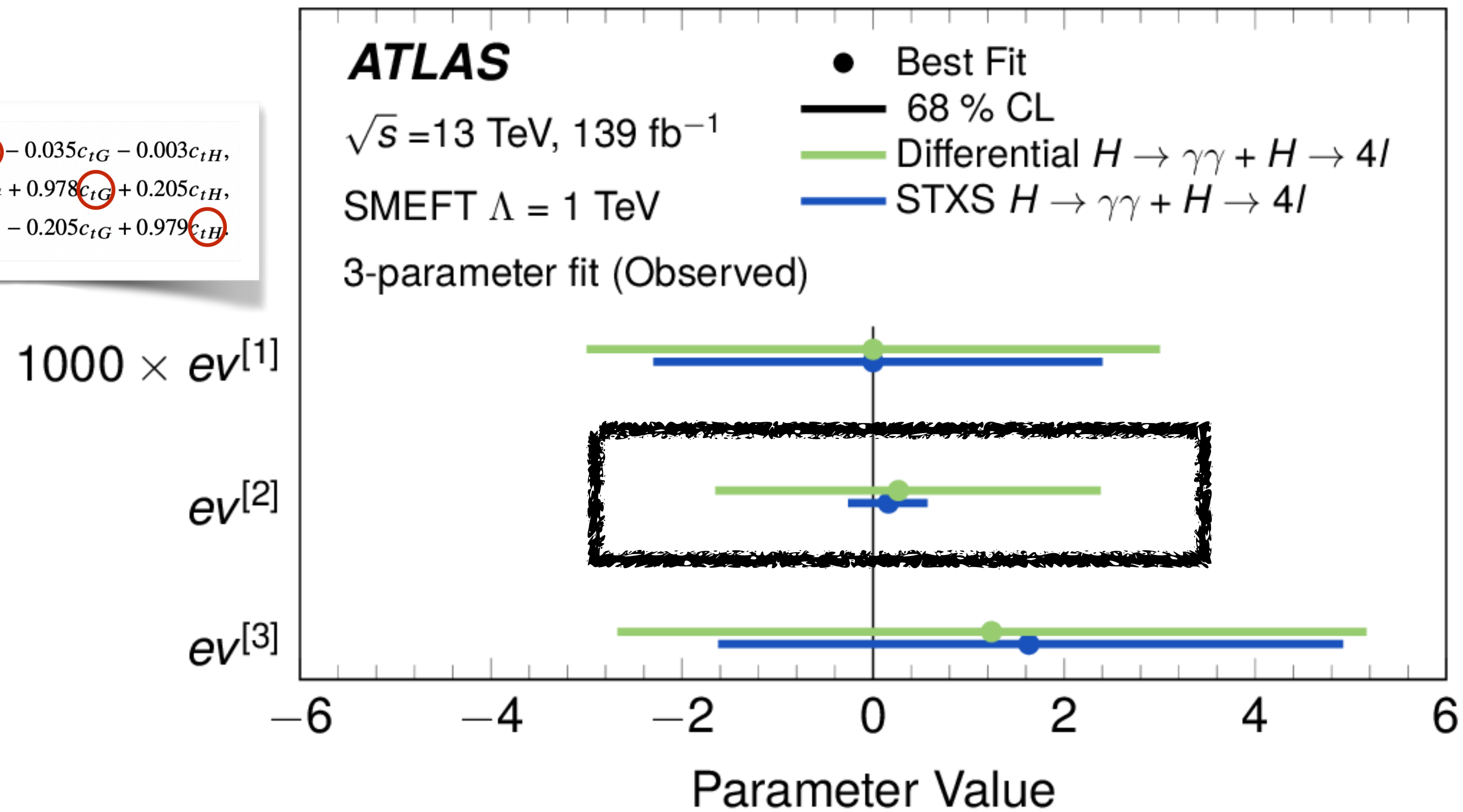
➡ **Along with STXS, SMEFT operators can also be constrained from fiducial cross-section measurements (unfolded to particle-level) using pt(H) in H→γγ/ZZ**

- fine granularity of kinematic regions in differential observables + large sensitivity to EFT in high pt(H), however inclusive treatment of Higgs production modes (unlike in STXS approach)
  - expected drop in sensitivity using differential approach compared to STXS interpretation
- probing EFT contact term in production and decay: rotation defines a new set of eigenvectors which are decorrelated and extracted simultaneously

➡ **Significantly large drop in EFT sensitivity using differential approach compared to STXS**

$$ev^{[1]} = 0.999c_{HG} - 0.035c_{tG} - 0.003c_{tH},$$
$$ev^{[2]} = 0.035c_{HG} + 0.978c_{tG} + 0.205c_{tH},$$
$$ev^{[3]} = -0.005c_{HG} - 0.205c_{tG} + 0.979c_{tH}.$$

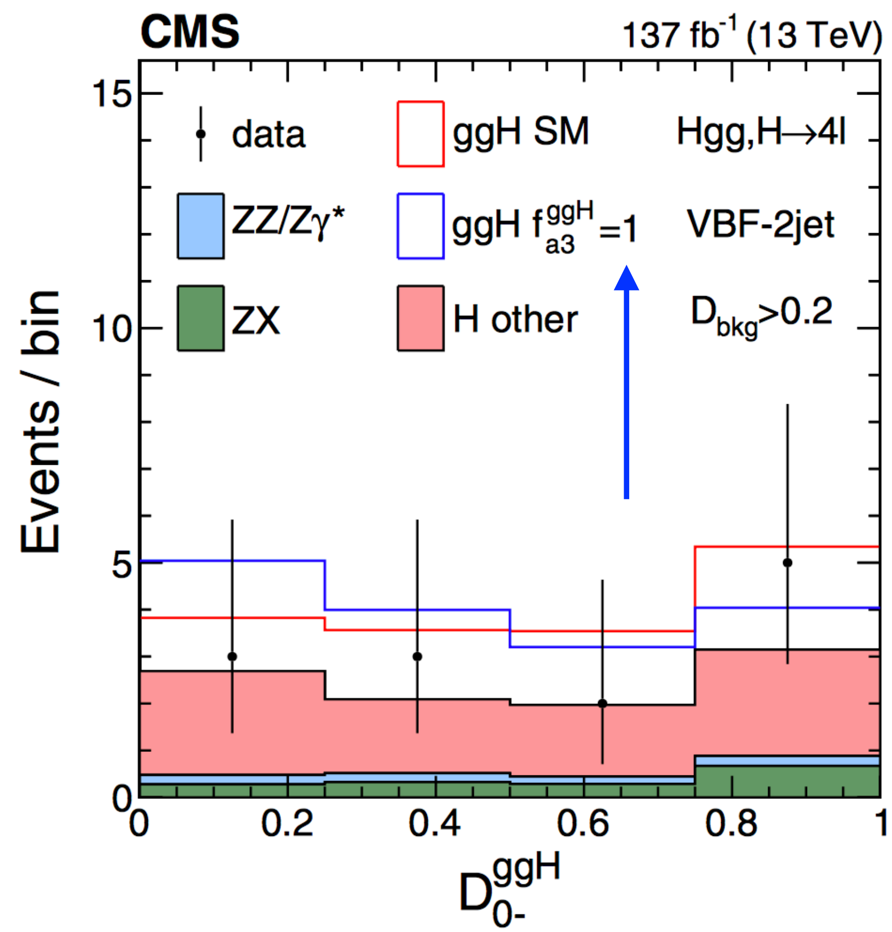
- differential measurements probe distributions of single observable inclusively in production mode
- accessing separate measurement of ggF and ttH production in STXS makes difference for ev[2]

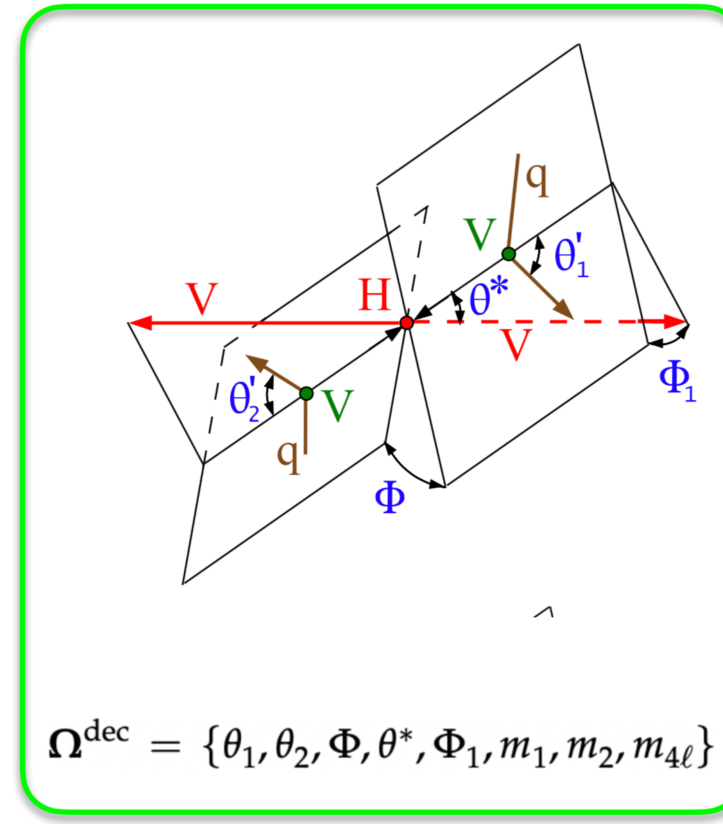


Anomalous couplings - H->ZZ->4l

➡ **Full production and decay kinematic to constrain Wilson coefficients**

- MEM (MELA) employed to separate production modes/ discriminate signal vs backgrounds
- MELA to tackle EFT tensor structure



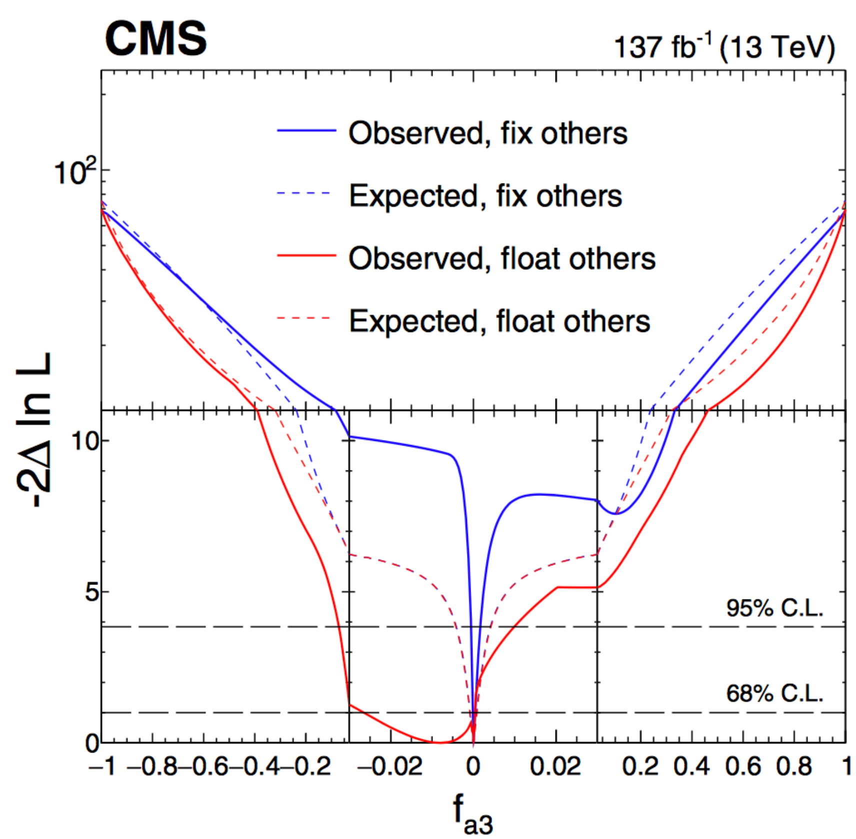


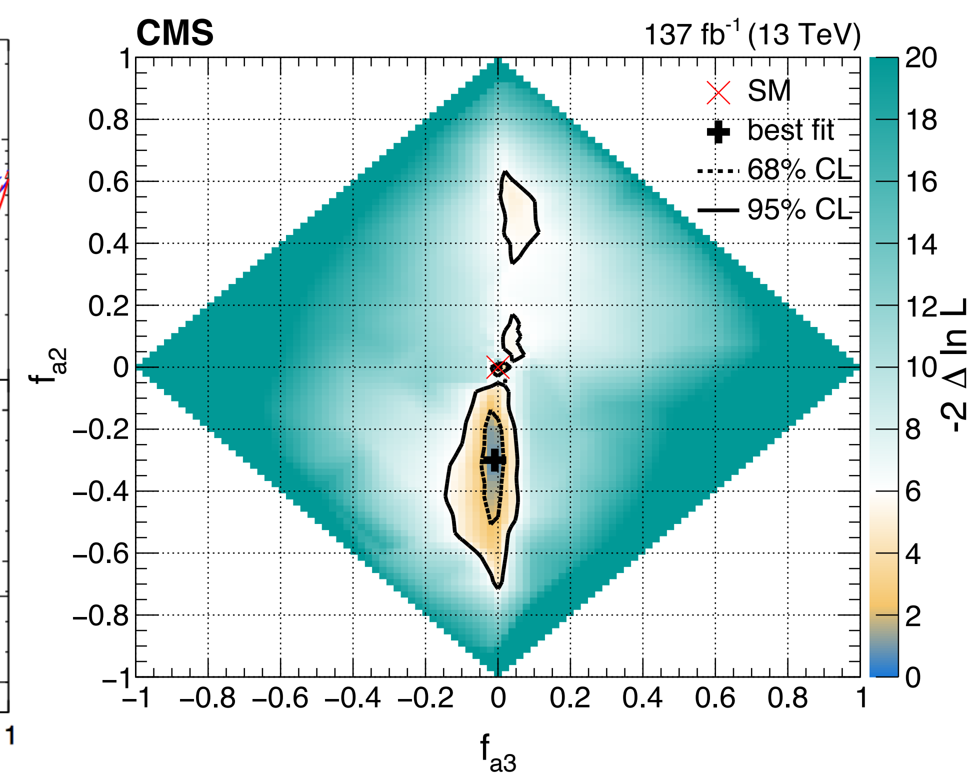
Phys. Rev. D 104 (2021) 052004

➡ **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





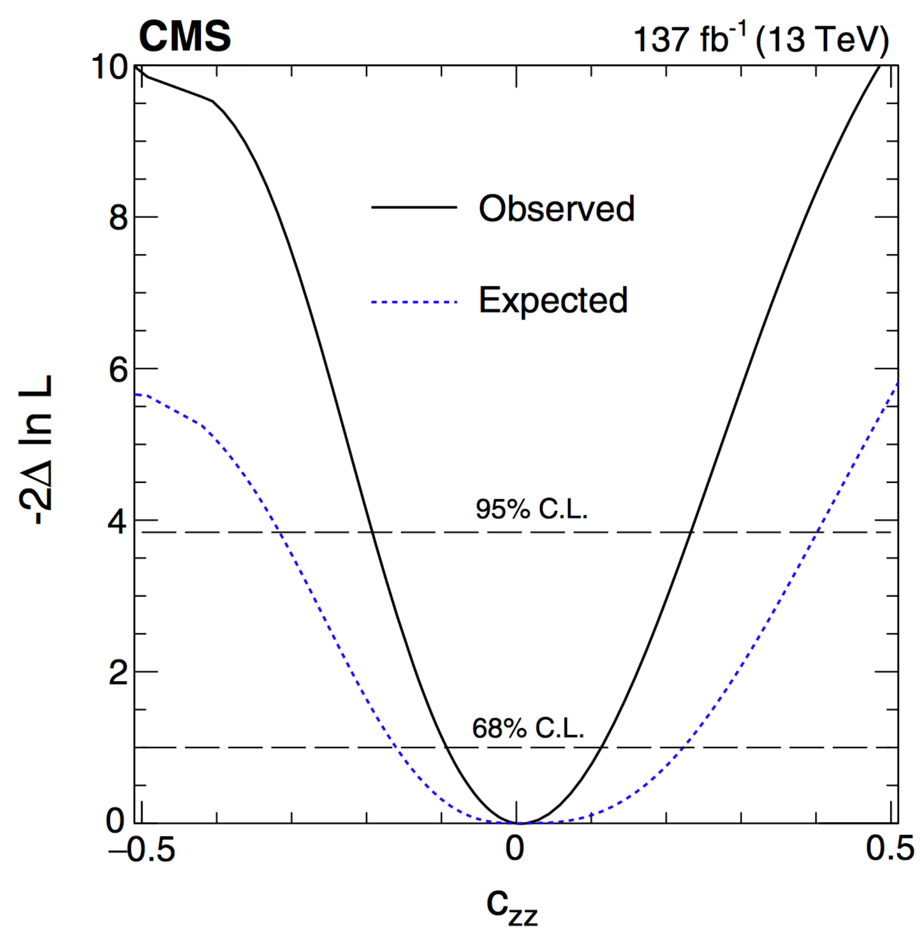
Anomalous couplings - H->ZZ->4L (2)

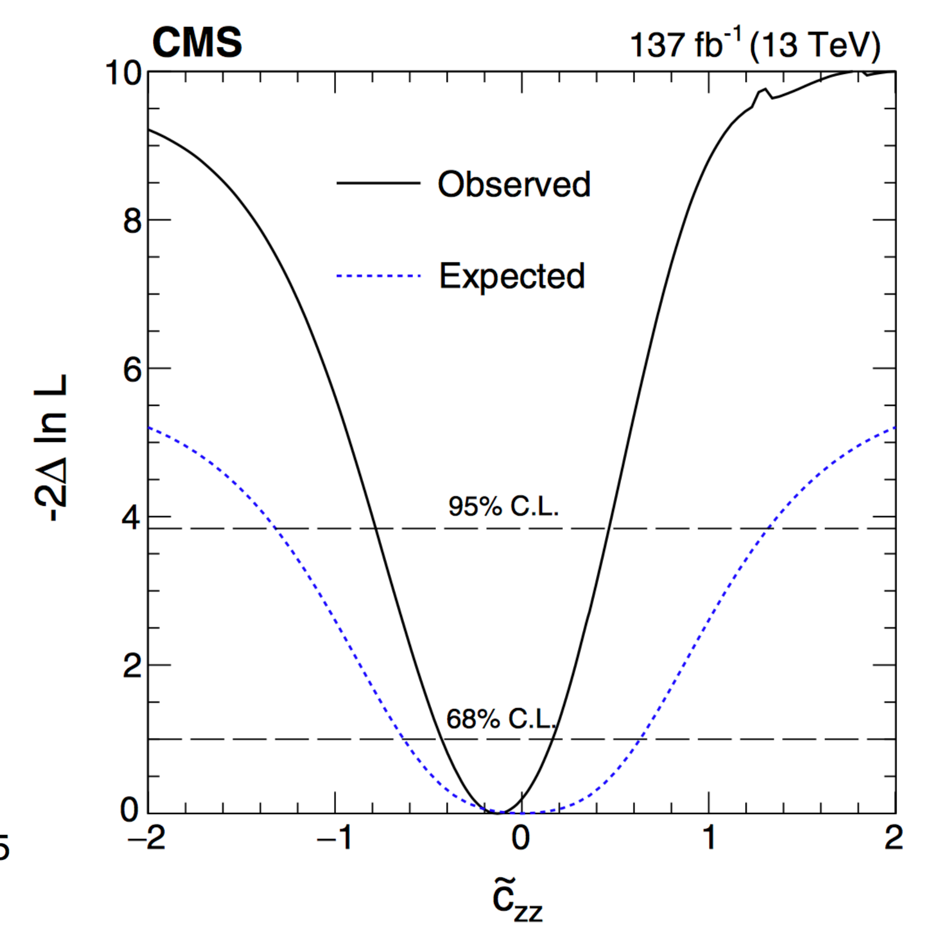
Phys. Rev. D 104 (2021) 052004

- **Performing 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}	$0.00^{+0.05}_{-0.05}$	$0.00^{+0.03}_{-0.08}$
CP-odd → $c_{H\tilde{W}}$	$-0.23^{+0.51}_{-0.52}$	$0.00^{+1.11}_{-1.11}$
$c_{H\tilde{W}B}$	$-0.25^{+0.56}_{-0.57}$	$0.00^{+1.21}_{-1.21}$
$c_{H\tilde{B}}$	$-0.06^{+0.15}_{-0.16}$	$0.00^{+0.33}_{-0.33}$

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



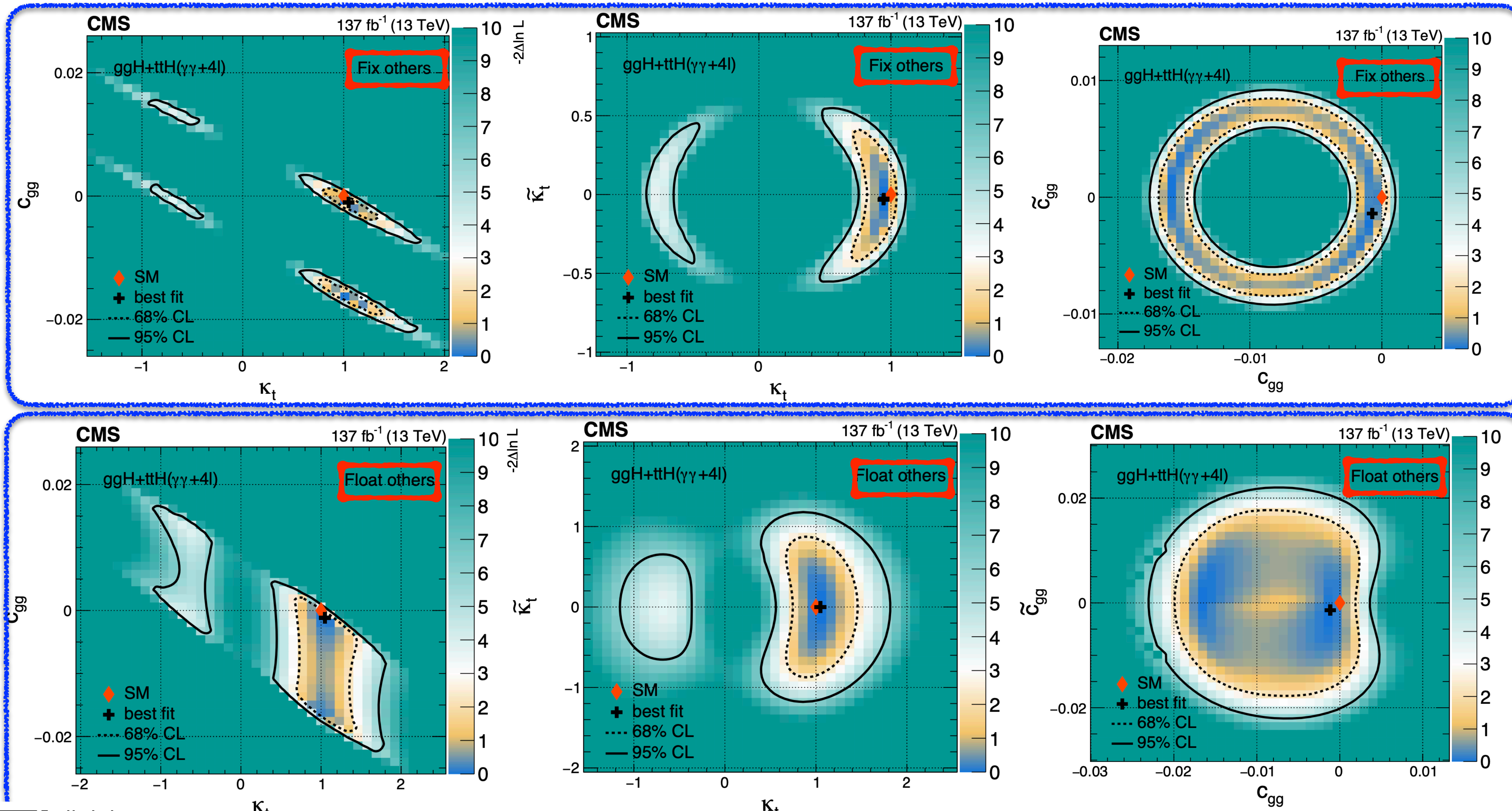


EFT combination across channels & operators

Phys. Rev. D 104 (2021) 052004

➡ **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



EFT H->ZZ using off-shell

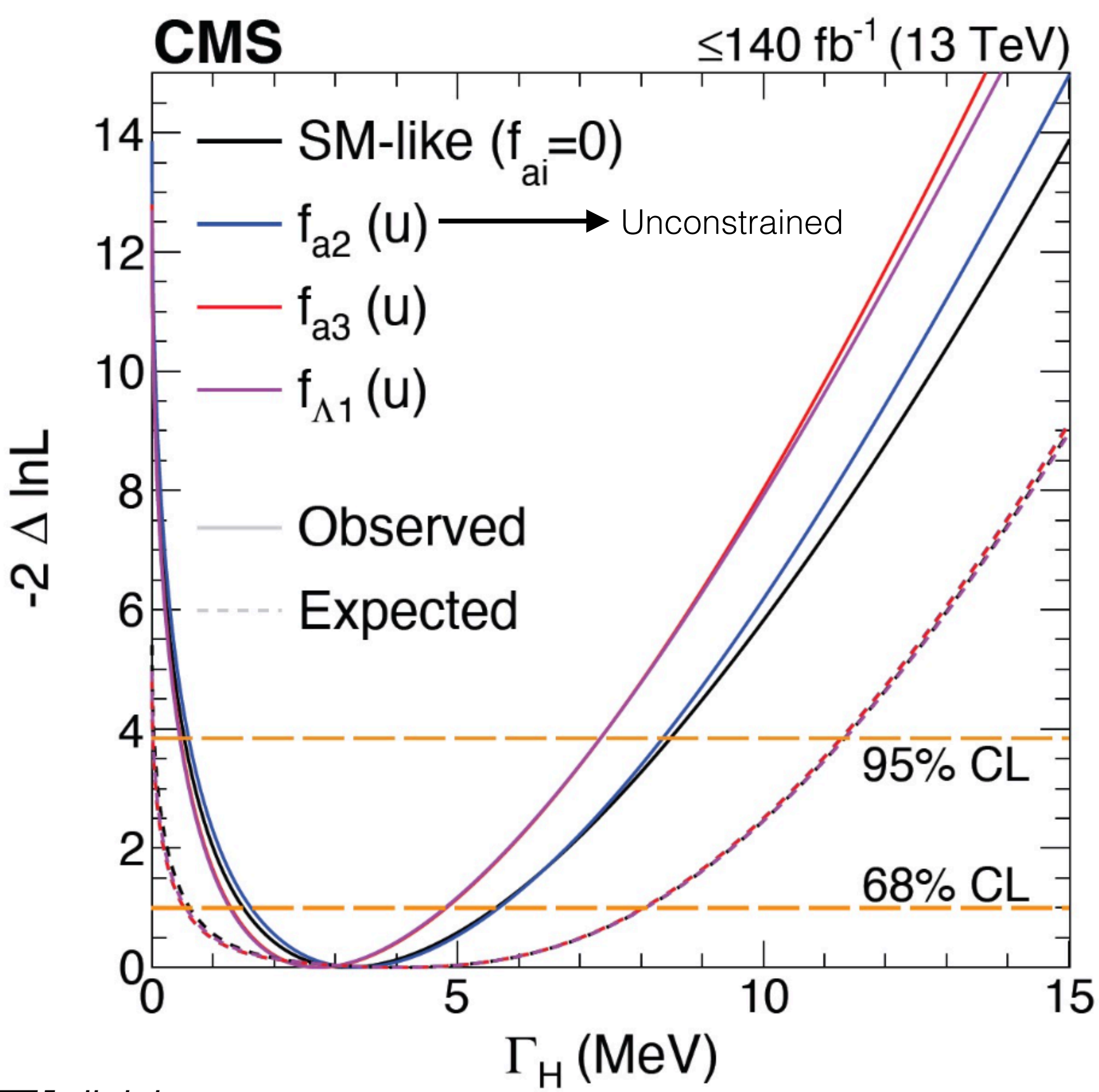
Nat. Phys. 18 (2022) 1329

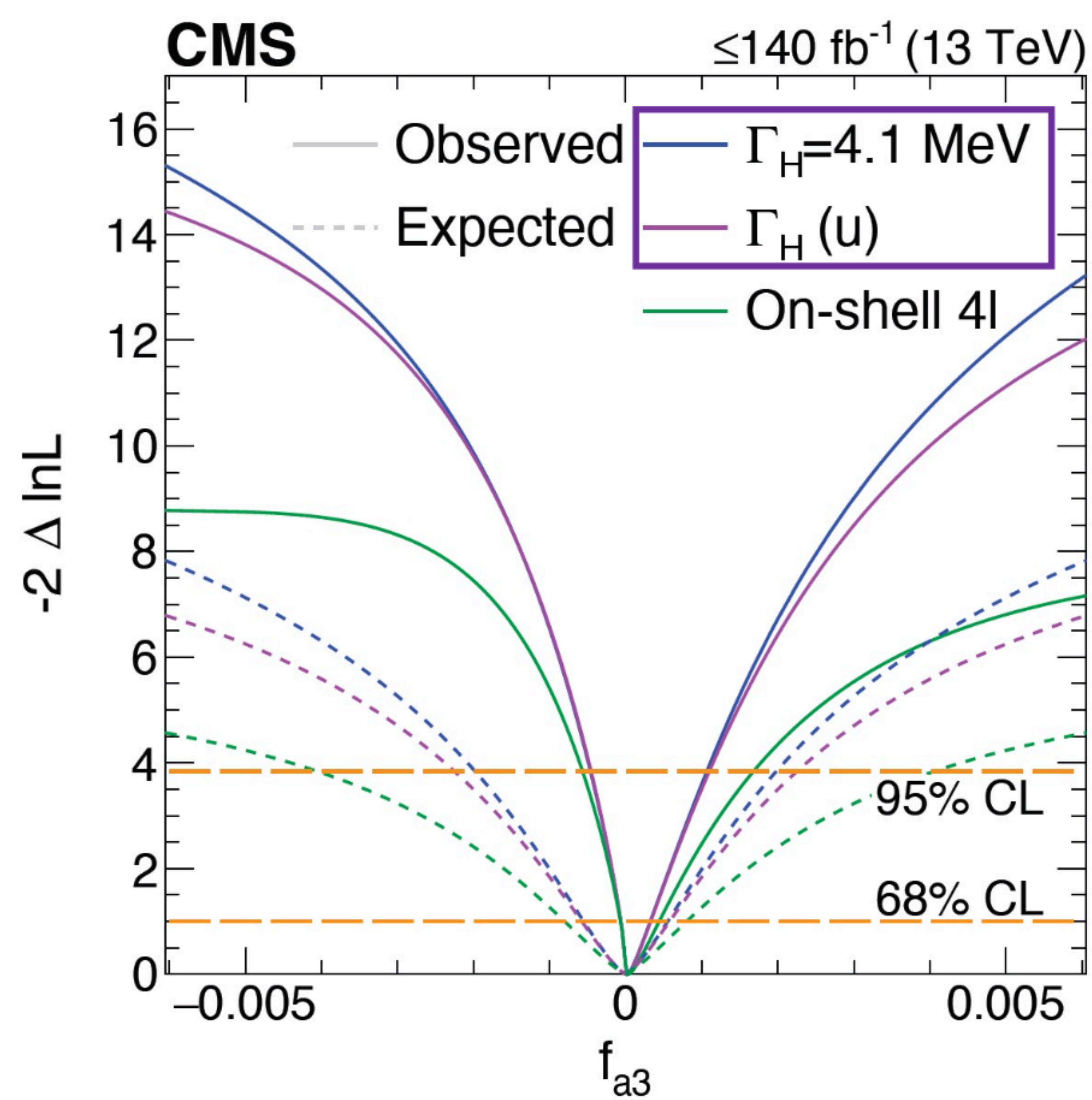
➡ **Working assumption in off-shell coupling no BSM modifying running coupling in combination of on- and off-shell production → interpretation for Higgs width**

- 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**

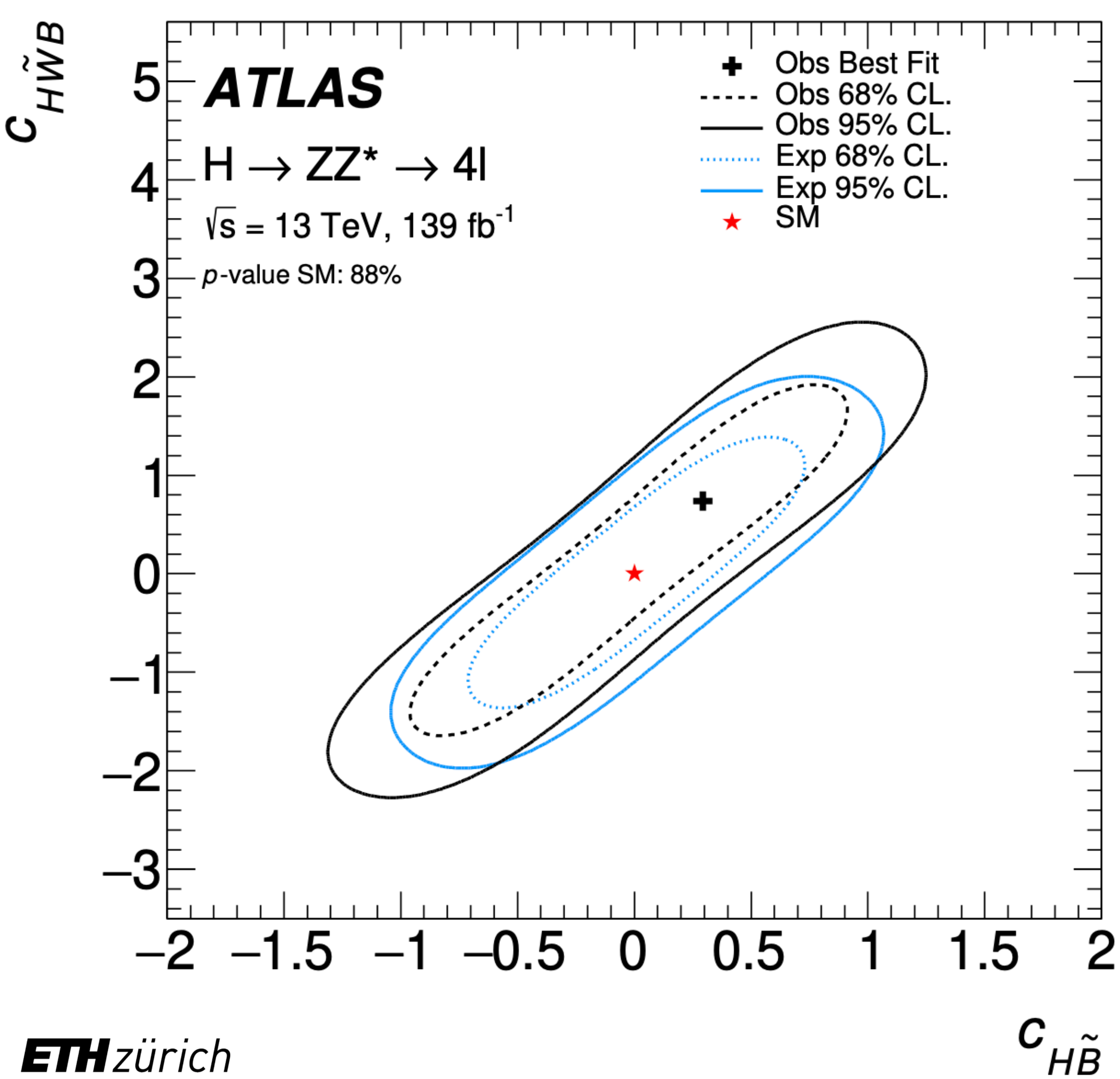


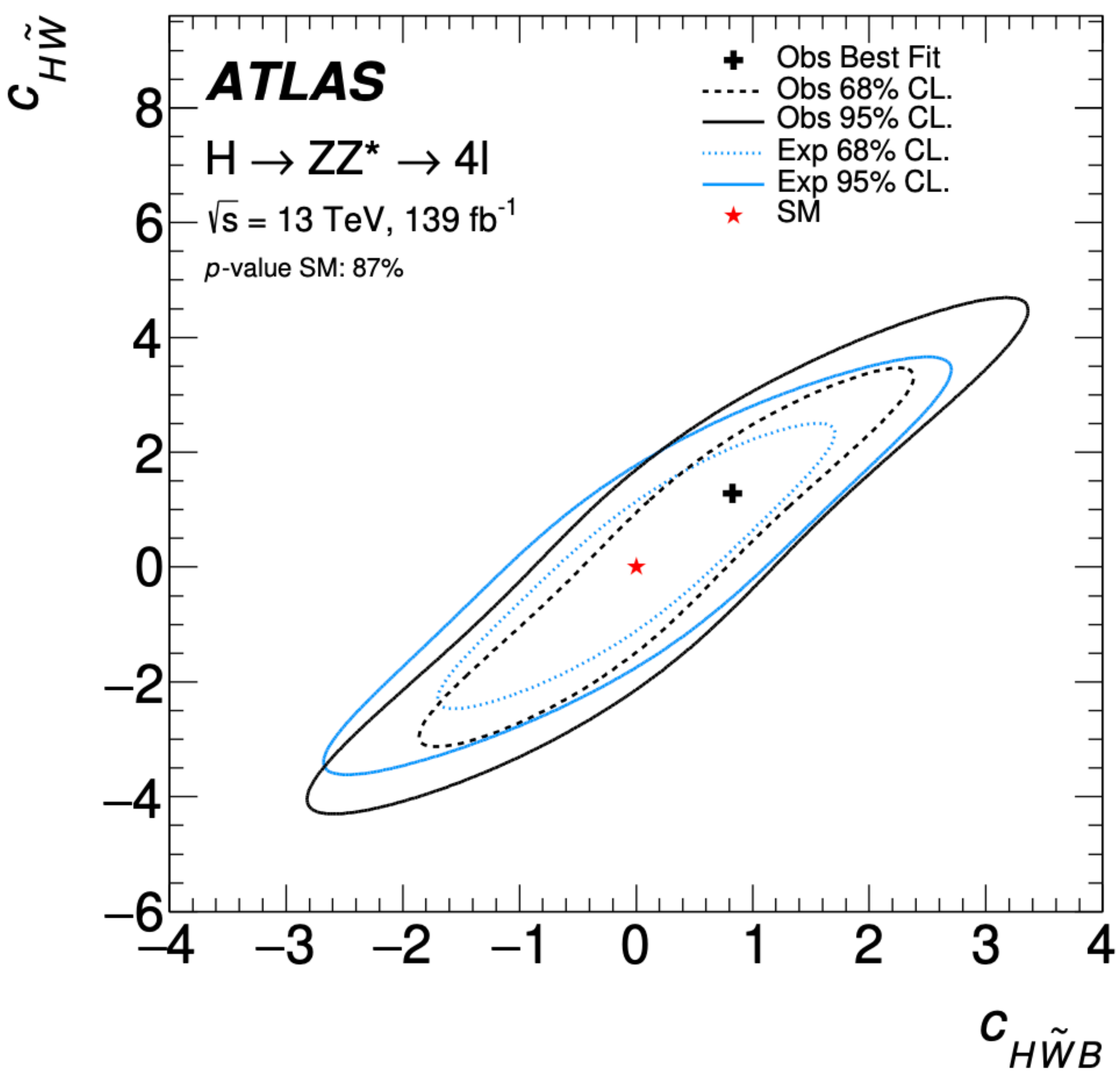


EFT constraints and CP tests in H->ZZ

- **Search for CP violation using SMEFT framework in HZZ(4l) final state**
  - BSM CP-odd dim-6 couplings constrained using matrix element-based optimal observables
  - VBF production mode sensitive to CP structure
- **Results provided with freely-floating parameters to account for correlations**
  - measurements in agreement with SM CP-even prediction

arXiv:2304.0961 (submitted to JHEP)

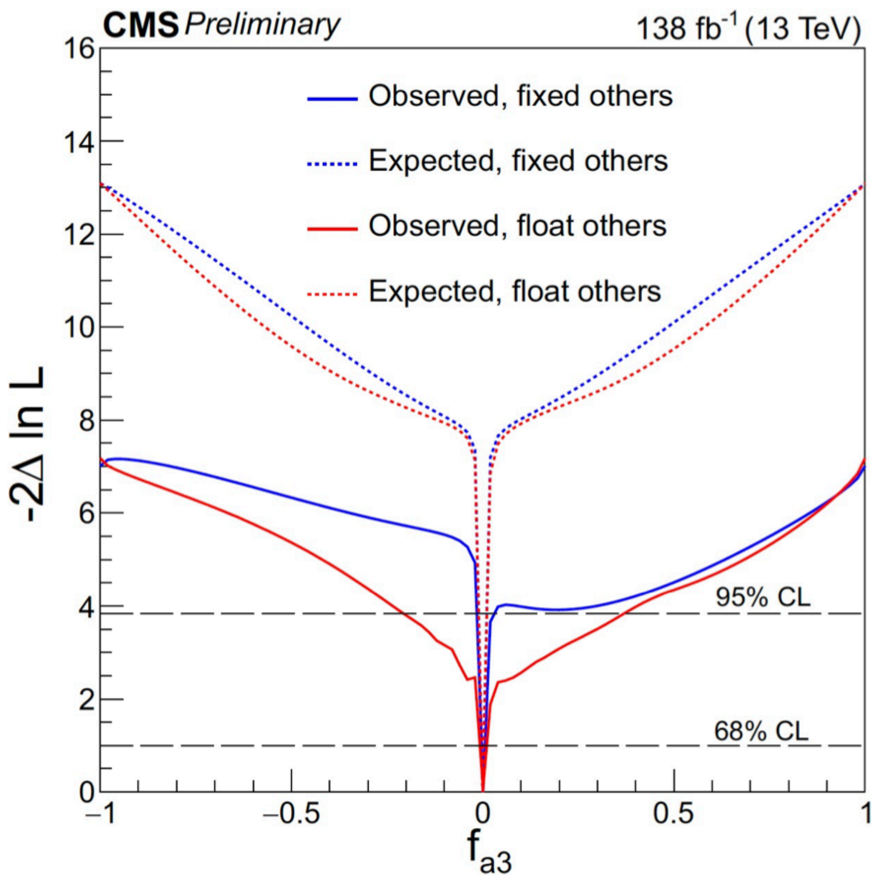




Extending anomalous HVV constraints to H->WW

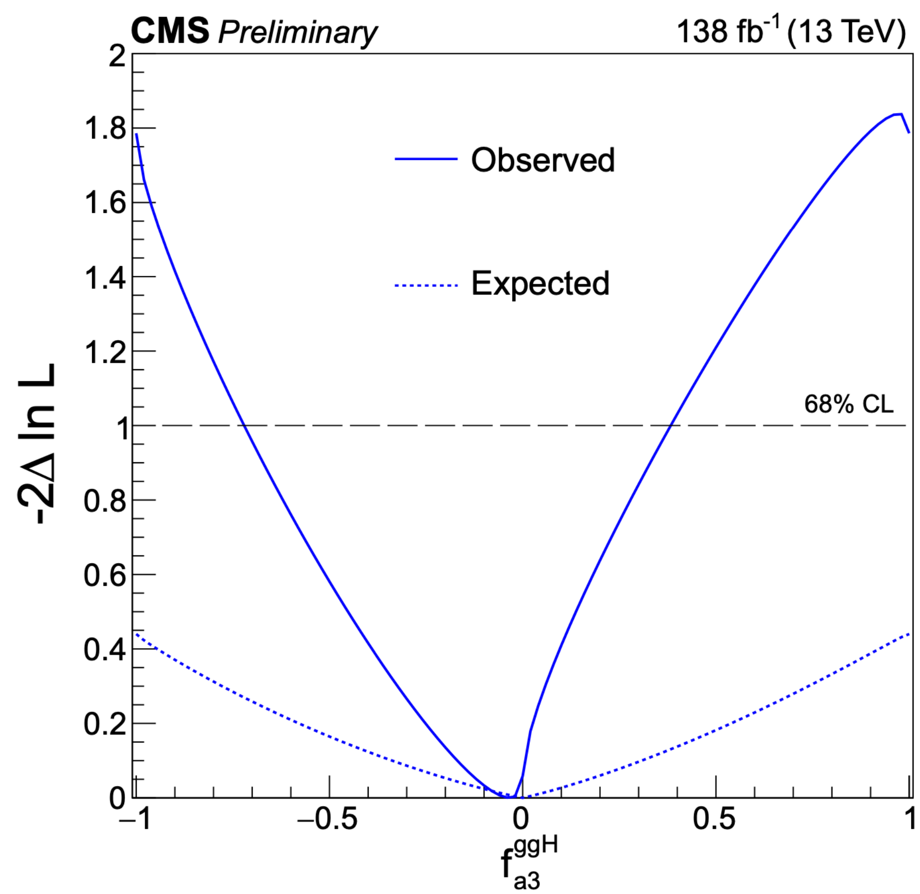
CMS PAS HIG-22-008 (submitted to EPJC)

- **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: 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}	$0.03^{+0.13}_{-0.26}$	$0.0^{+0.11}_{-0.14}$
$c_{H\tilde{W}}$	$-0.26^{+0.67}_{-0.50}$	$0.0^{+0.48}_{-0.52}$
$c_{H\tilde{W}B}$	$-0.54^{+1.37}_{-1.03}$	$0.0^{+0.99}_{-1.07}$
$c_{H\tilde{B}}$	$-0.08^{+0.20}_{-0.15}$	$0.0^{+0.15}_{-0.16}$

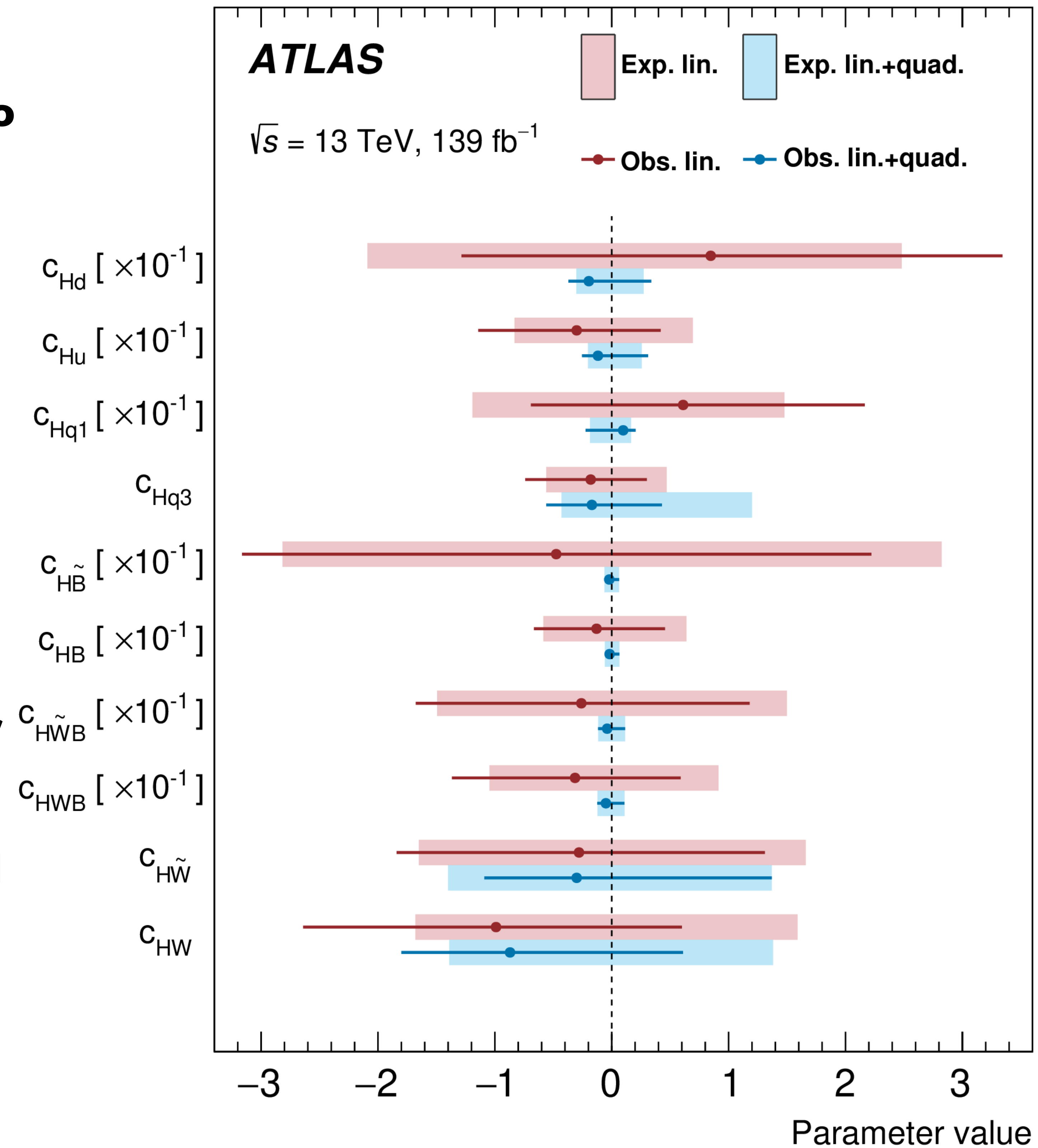


SMEFT EFT in H->WW channel

Phys. Rev. D 108, 072003 (2023)

➡ Interpretation of differential fiducial cross-sections in terms of SMEFT constraints

- ➡ **Analysis does not have sensitivity to all Wilson coefficients in HWW phase-space (VBF production)**
- ➡ **EFT coefficients constrained one at a time using most discriminating differential distributions**
  - results provided for CP-even and CP-odd Wilson coefficients (using CP-sensitive $\Delta\phi_{jj}$ observable)
- ➡ **Considered EFT expansion in linear and linear+quadratic**
- ➡ **Results in good agreement with SM prediction**

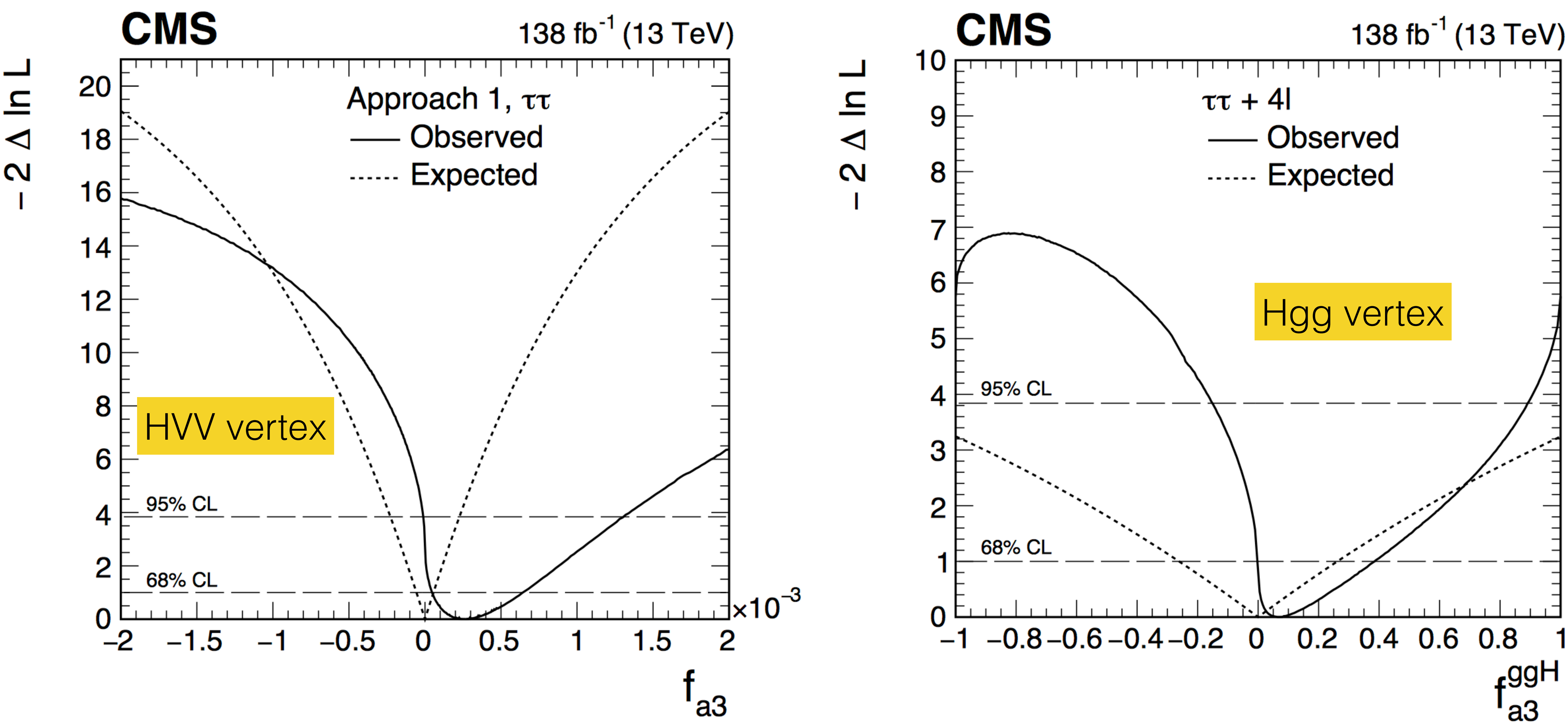


EFT extraction in H->ττ

➡ **Targeting measurement of EFT vertices using SMEFT and anomalous couplings**

- VBF production: HVV EFT vertex, ggH production: Hgg EFT vertex
- HVV vertex constrained using $H\to\tau\tau$ decay in VBF production while Hgg vertex uses combination of $H\to\tau\tau$ and $H\to ZZ\to 4l$

➡ **Pure CP-odd hypothesis for Higgs couplings to gluons excluded at 2.4σ**



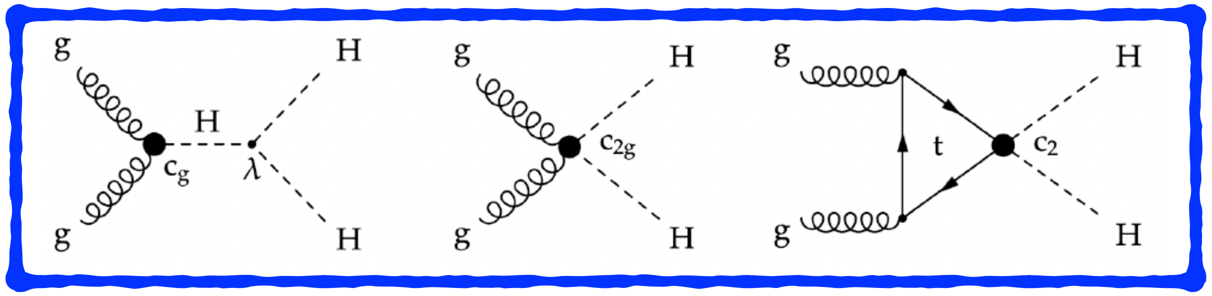
EFT in double Higgs analyses

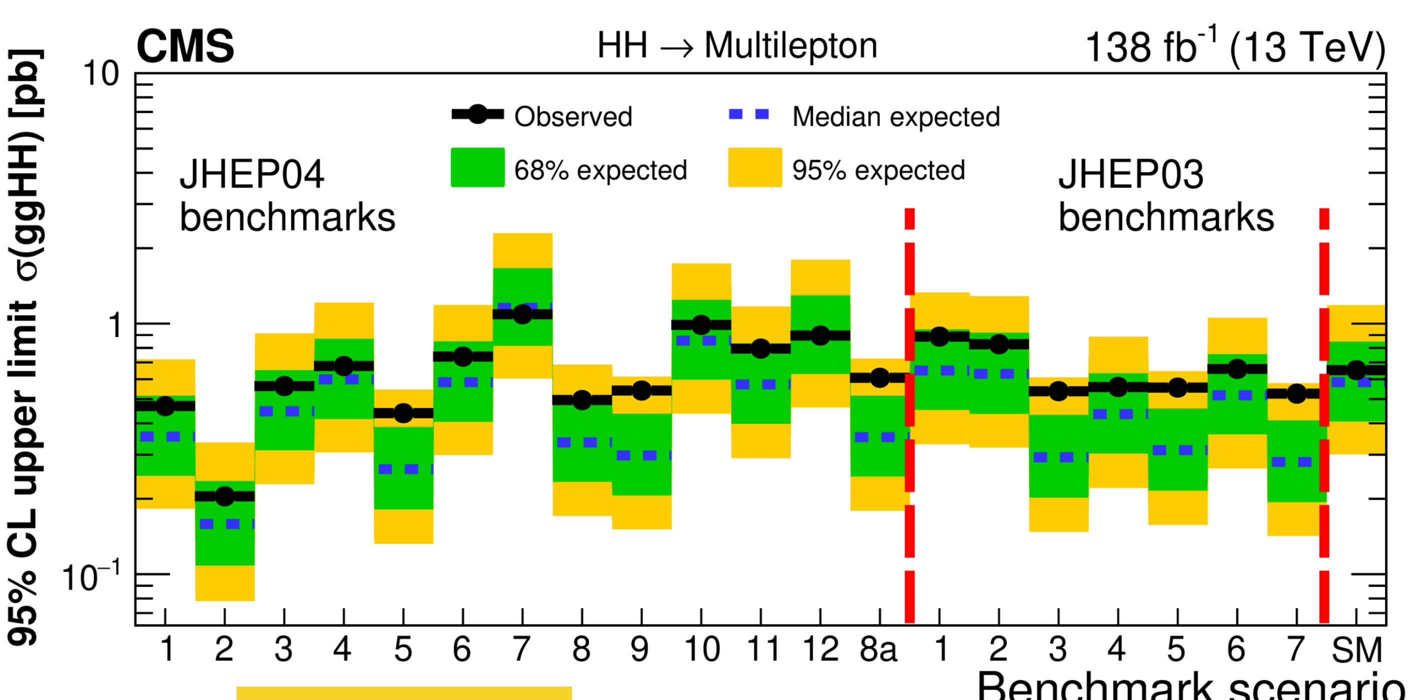
➡ **Benchmark models varying coupling strengths and parameter values spanning dim-6 EFT (HEFT model)**

- 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)

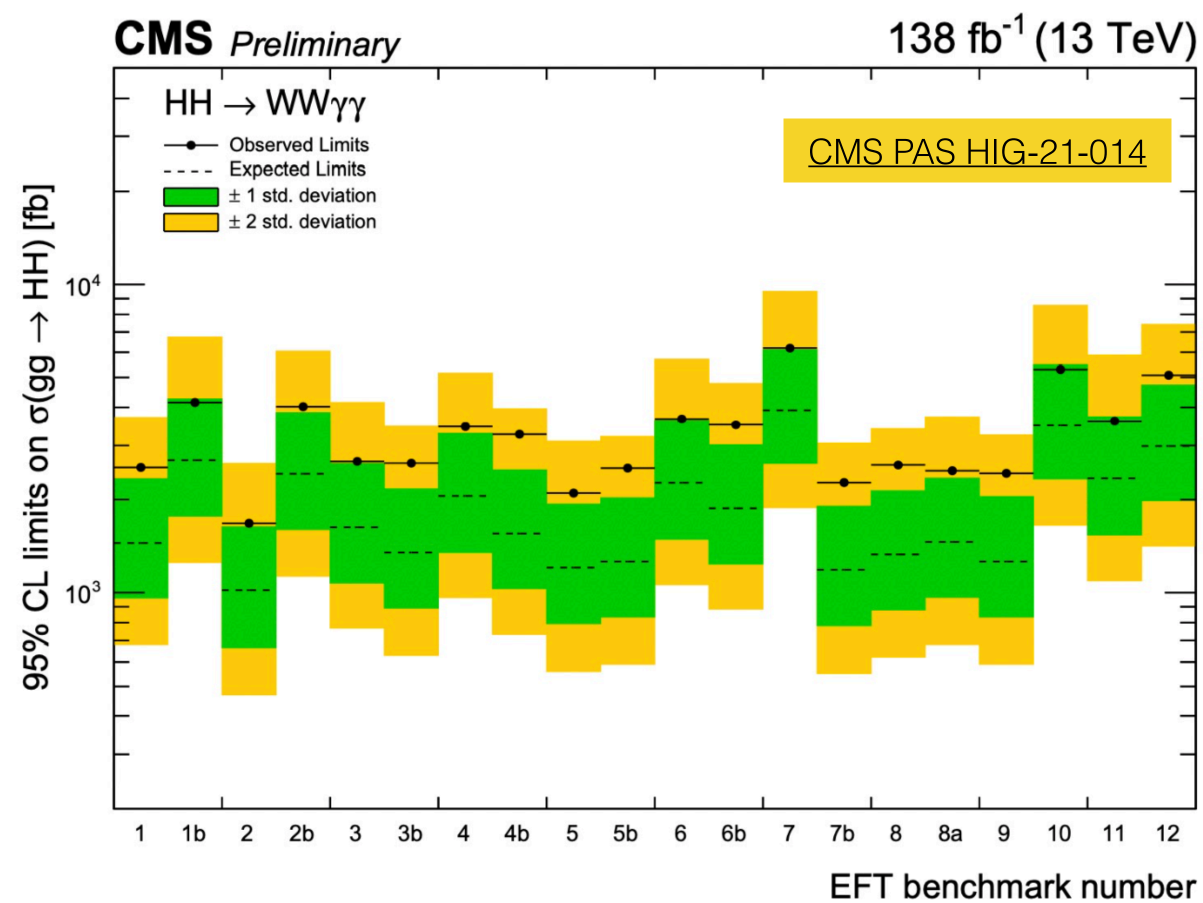
Benchmark	κ_λ	κ_t	c_2	c_g	c_{2g}
SM	1.0	1.0	0.0	0.0	0.0
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	-0.8	0.6
3	1.0	1.0	-1.5	0.0	-0.8
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	-1
6	2.4	1.0	0.0	0.2	-0.2
7	5.0	1.0	0.0	0.2	-0.2
8	15.0	1.0	0.0	-1	1
9	1.0	1.0	1.0	-0.6	0.6
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	1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

HH→WWγγ →





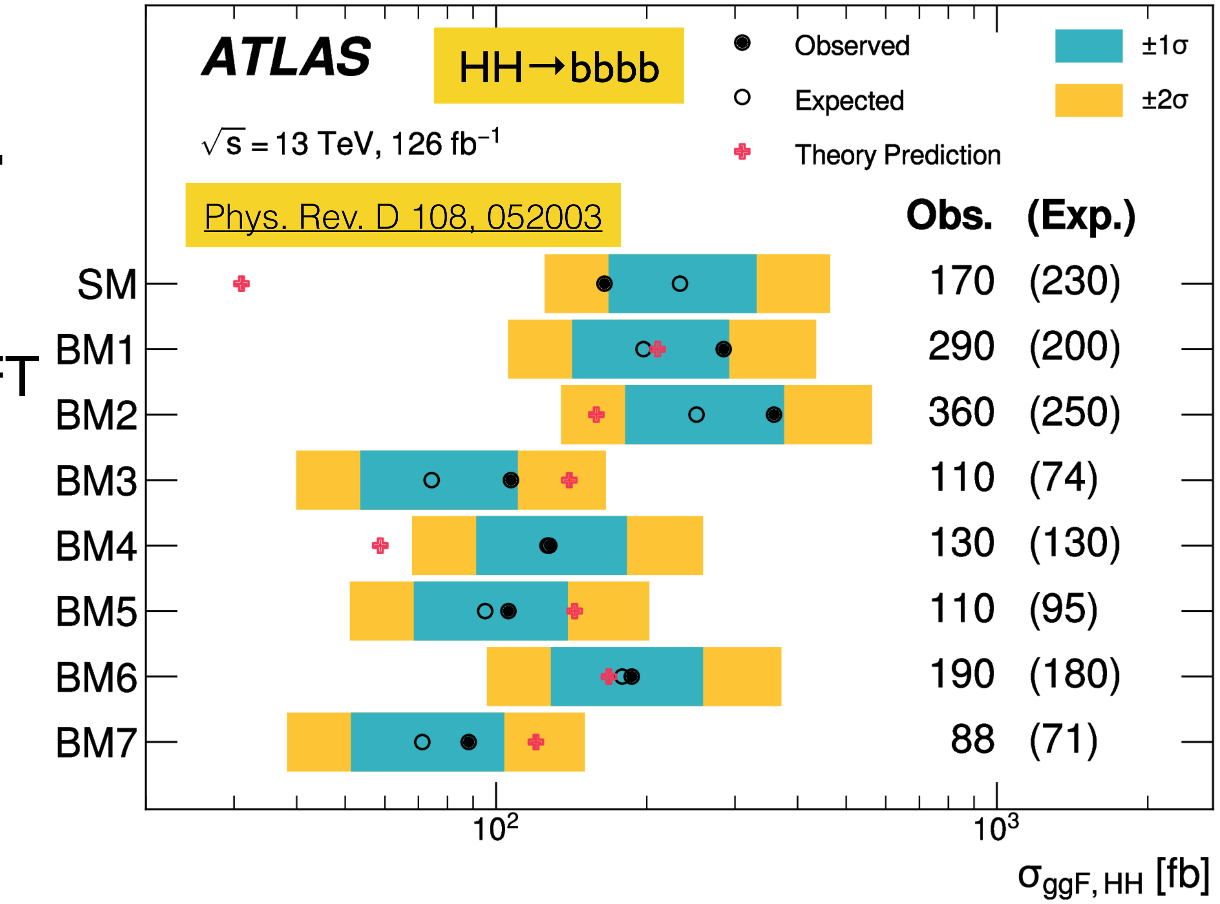
JHEP 07 (2023) 095

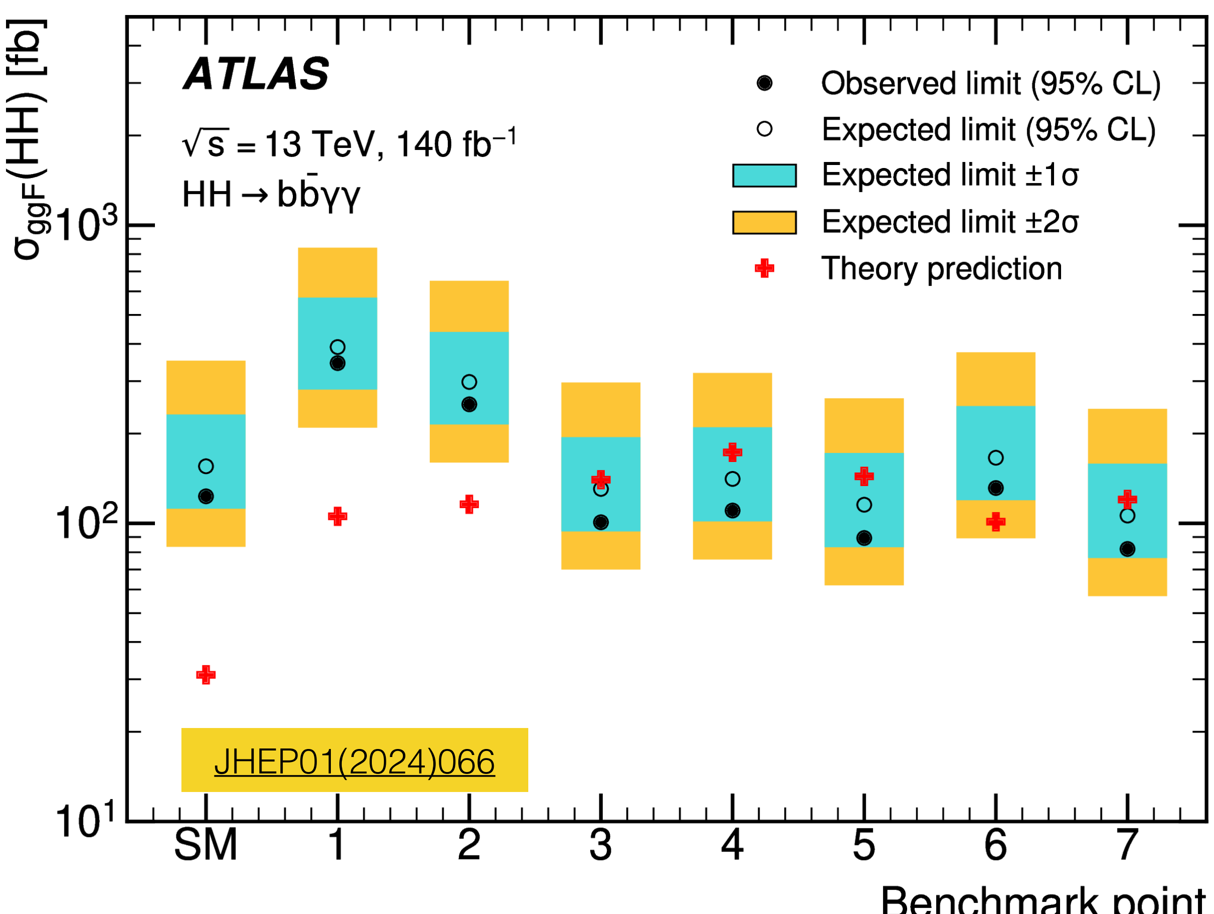


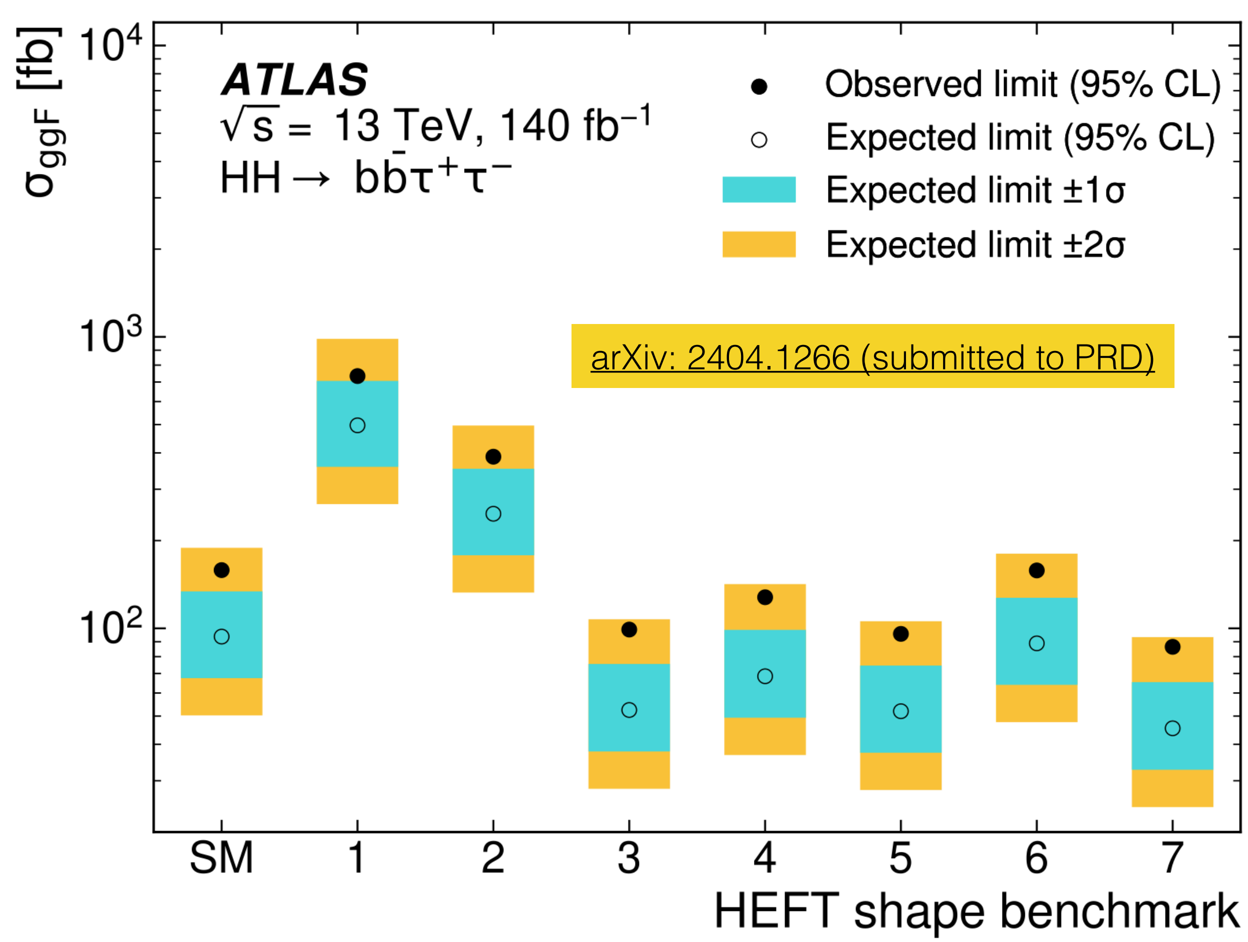
EFT in double Higgs analyses (2)

➡ **HH analyses interpreted in HEFT/SMEFT basis**

- HH→bbγγ: excluded 4 of the considered 7 HEFT benchmark points
- HH→bbττ: one dimensional constraints on SMEFT/HEFT coefficients
- similar approach for HH→bbbb analysis







ATLAS EXPERIMENT

LHC EFT constraints towards global EFT fit

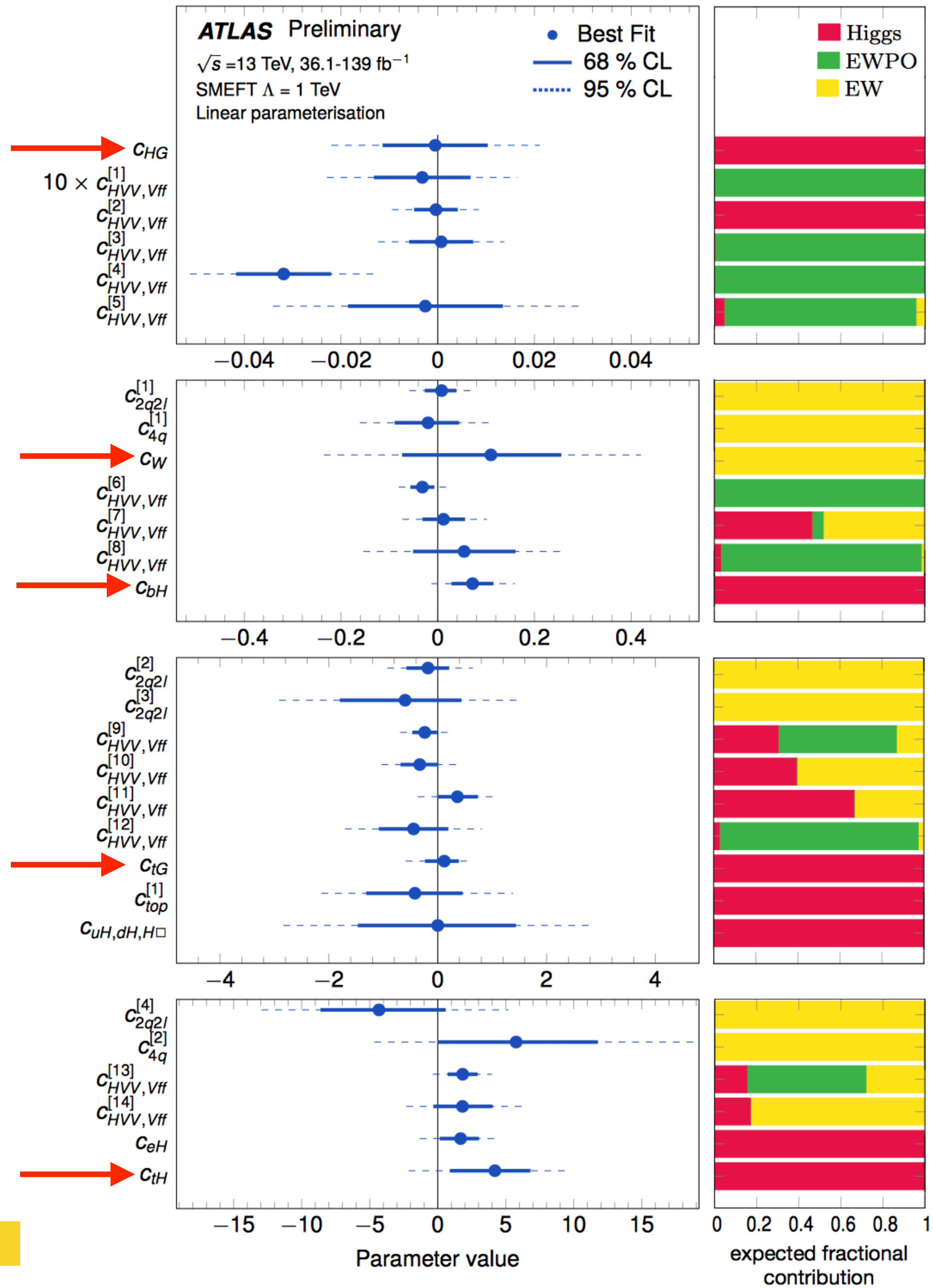
➡ **Aim for global fits of many operators using several input physics measurements**

➡ **Constraining 22 linear combination and 6 WC's associated to:**

- Higgs STXS measurements, EW differential distributions (WW,WZ, 4l, VBF momenta) and LEP/SLD information
- EFT extraction using linear component
- data overlap across datasets carefully considered and removed from the combination whenever relevant

➡ **Principal Component Analysis (PCA) to extract relevant WC's**

➡ **Tensions with SM: known discrepancies in EW precision measurements observables**



ATLAS-PHYS-PUB-2022-037

Wrapping-up & conclusions

➡ **Precision measurements is key to look for deviations on SM couplings: several Effective Field Theory interpretations of Higgs measurements in CMS and ATLAS**

➡ **EFT interpretation of STXS/differential 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

➡ **Several dedicated measurements of EFT effects in ATLAS/CMS single and double Higgs analyses using optimal observables to enhance EFT effects**

➡ **Developing Principal Component 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
- Important to assess interpretability and compatibility of EFT results using PCA analyses

➡ **Ongoing effort in CMS+ATLAS to provide common STXS+SMEFT parameterisation in the context of the LHC EFT WG [LHC EFT WG prediction note]**

➡ **Several more EFT interpretation using Run 2 results will be released soon - stay tuned!**

Additional slides

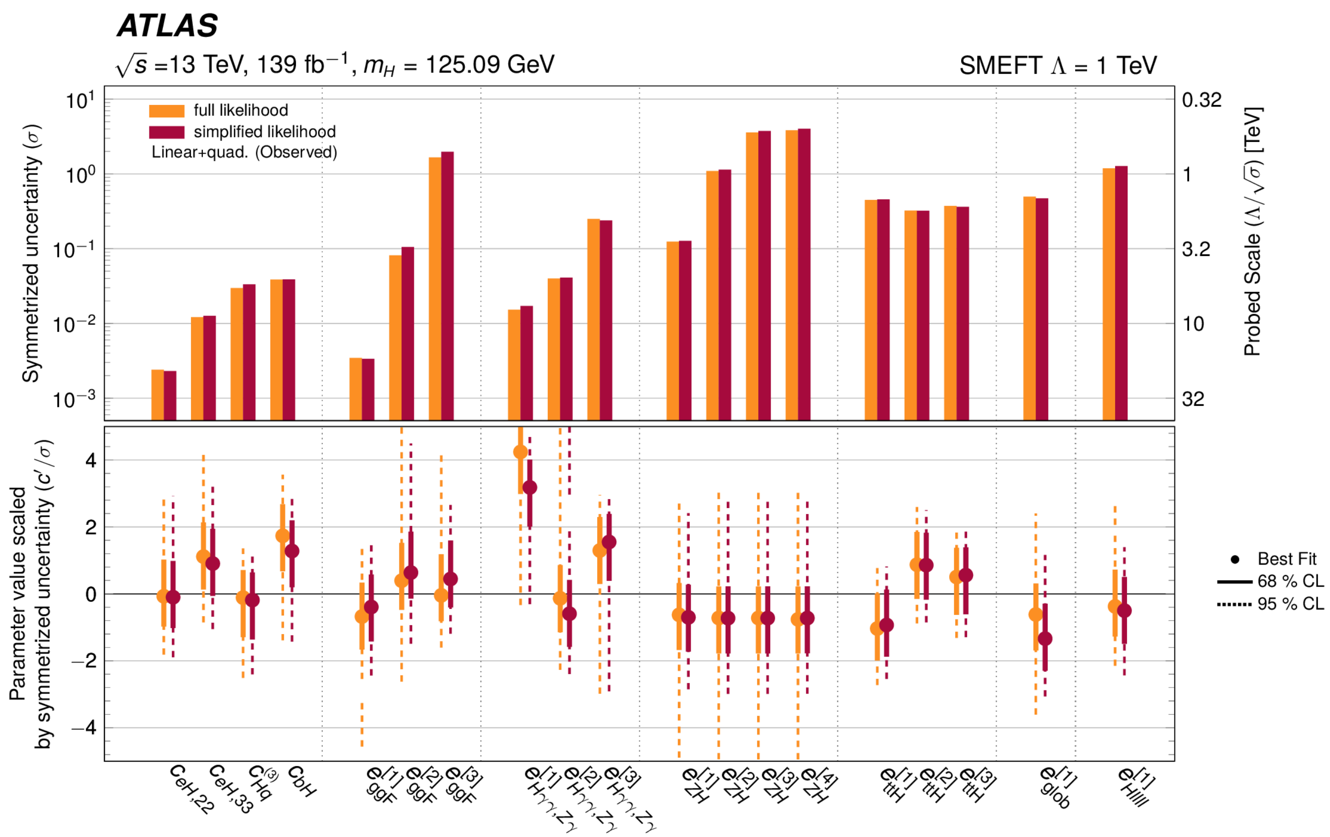
Check on validity of Gaussian approximation

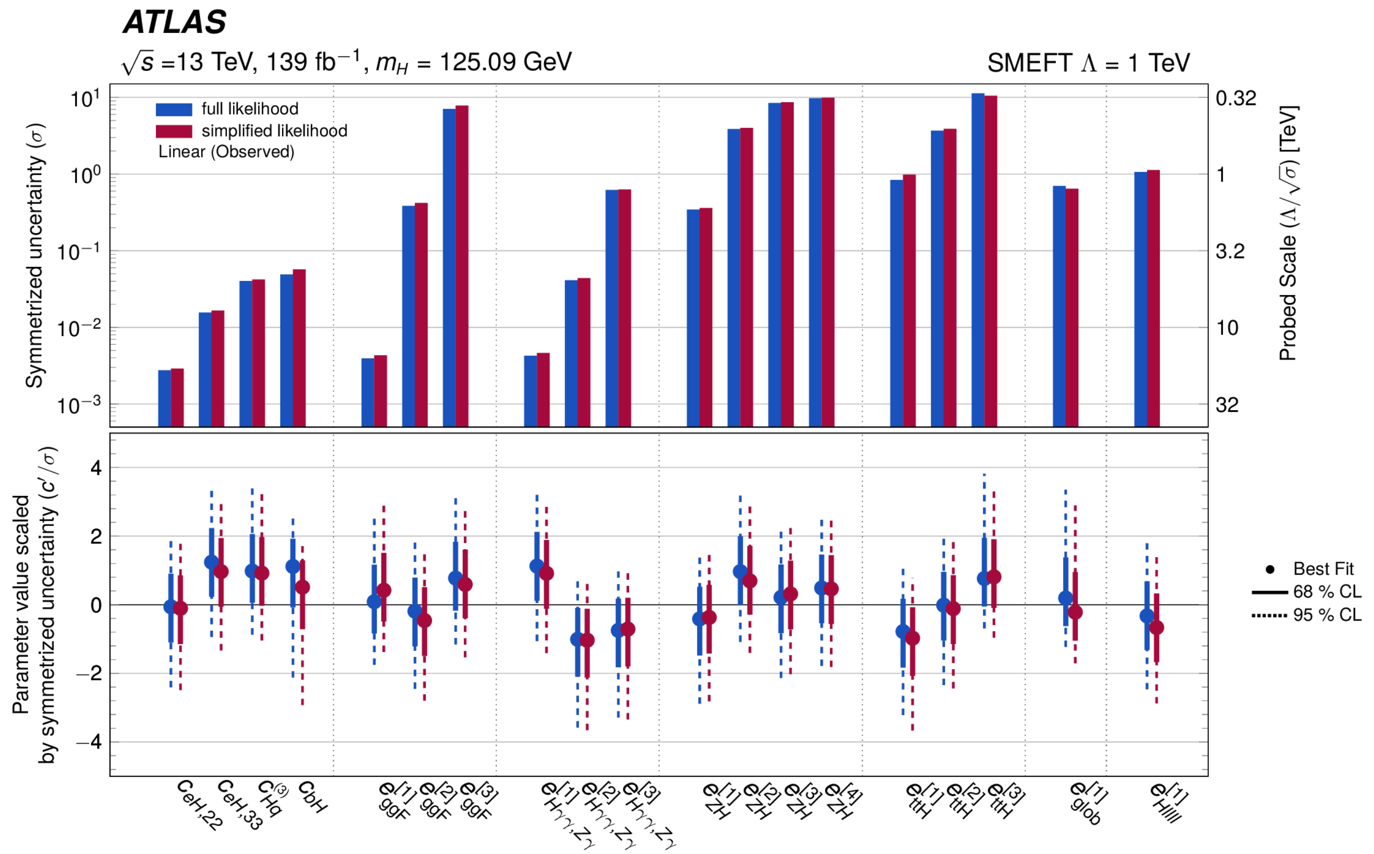
arXiv:2402.05742 (submitted to JHEP)

➡ **Tested difference in central values and uncertainty employing full likelihoods and multivariate Gaussian approximations for EFT combinations**

- STXS interpretation model - combined likelihood functions based on the STXS results
  - all non-Gaussian effects accounted for (experimental/theory uncertainty models)
  - complexity of the full likelihood combination
- combined likelihoods based on simplified approach straightforward to implement

➡ **Generally good agreement in expected/observed parameter estimation for linear-only and linear+quadratic EFT extraction**

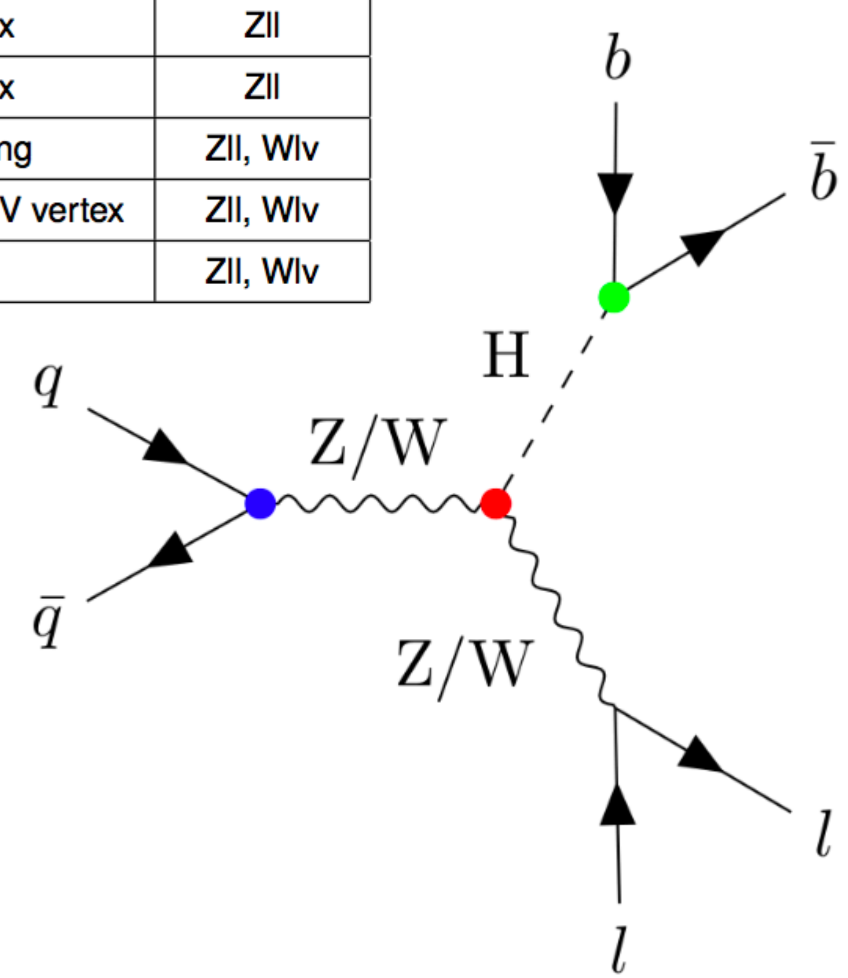




Wilson coefficients & EFT Lagrangian expansion

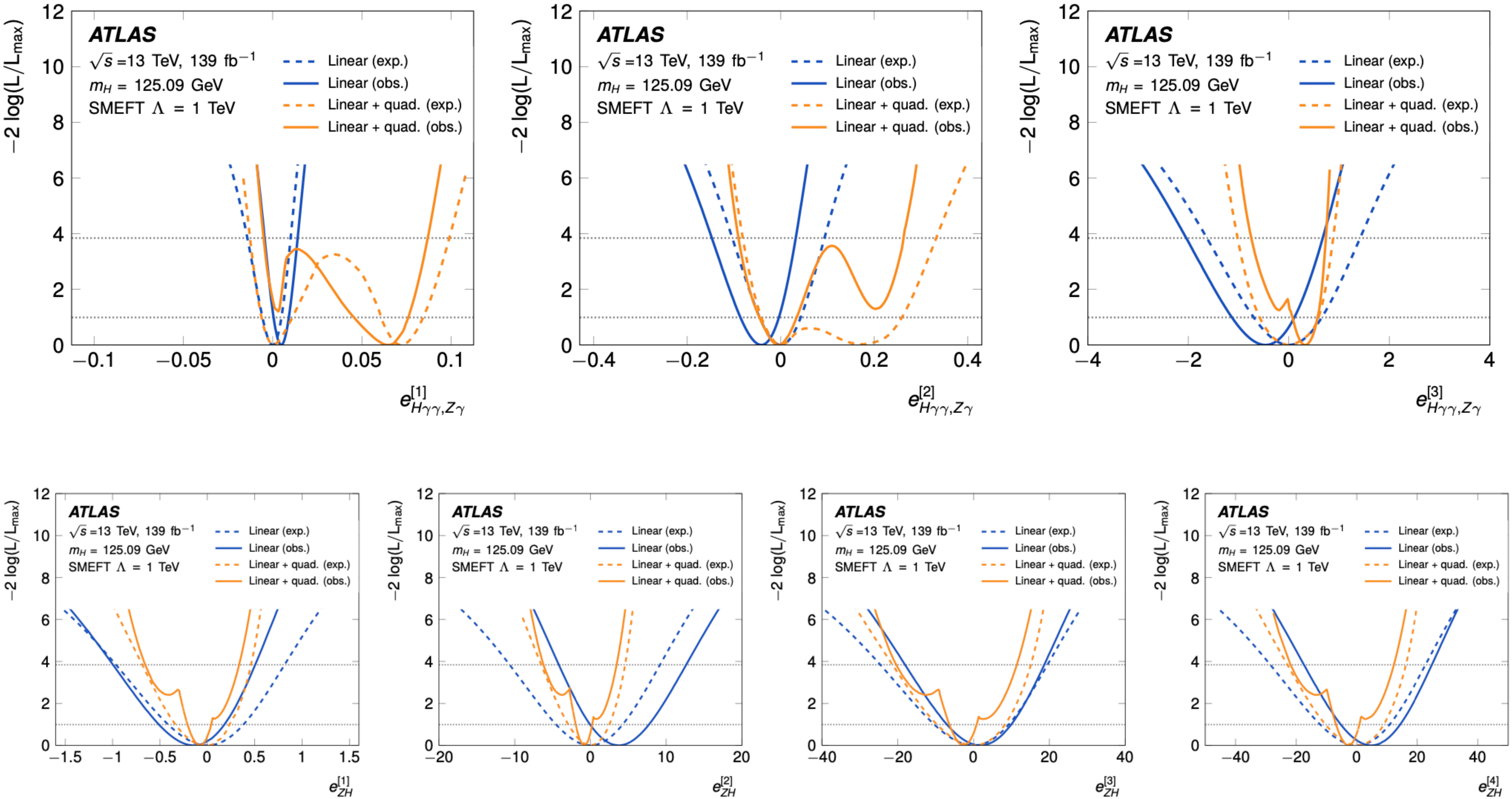
Example of VH→bb channel

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
$\mathcal{O}_{bH} = (H^\dagger H)(\bar{q}bH)$	cbHRe + cbHIm	hbb coupling	Zll, Wlv



EFT Higgs fit including quadratic terms

[arXiv:2402.05742 (submitted to JHEP)](arXiv:2402.05742)



EFT interpretation using STXS

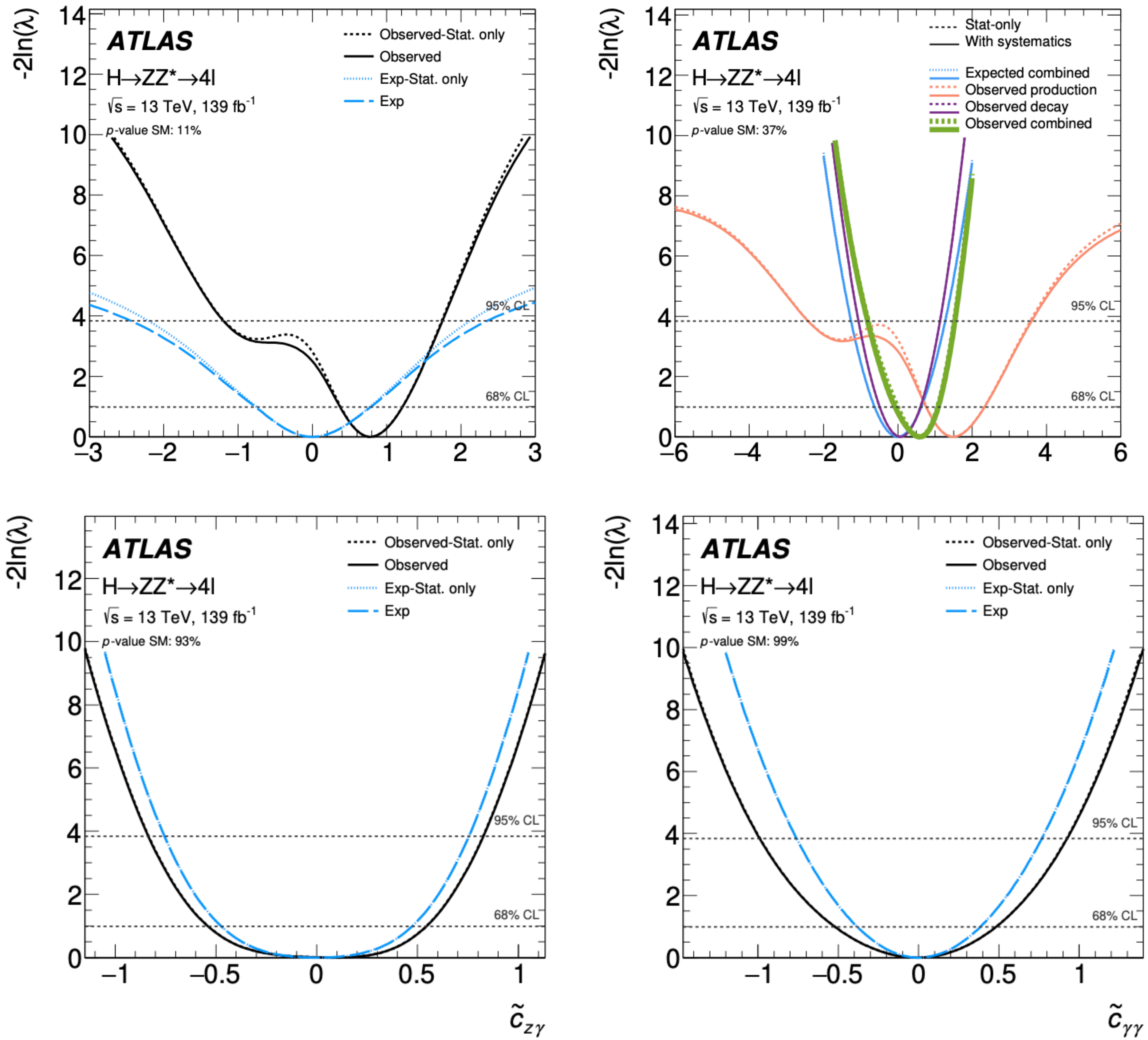
➡ Constraints on main WC's in STXS bins affecting following vertices

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

EW+Higgs interactions | Boson couplings to fermions | 4-fermion interactions

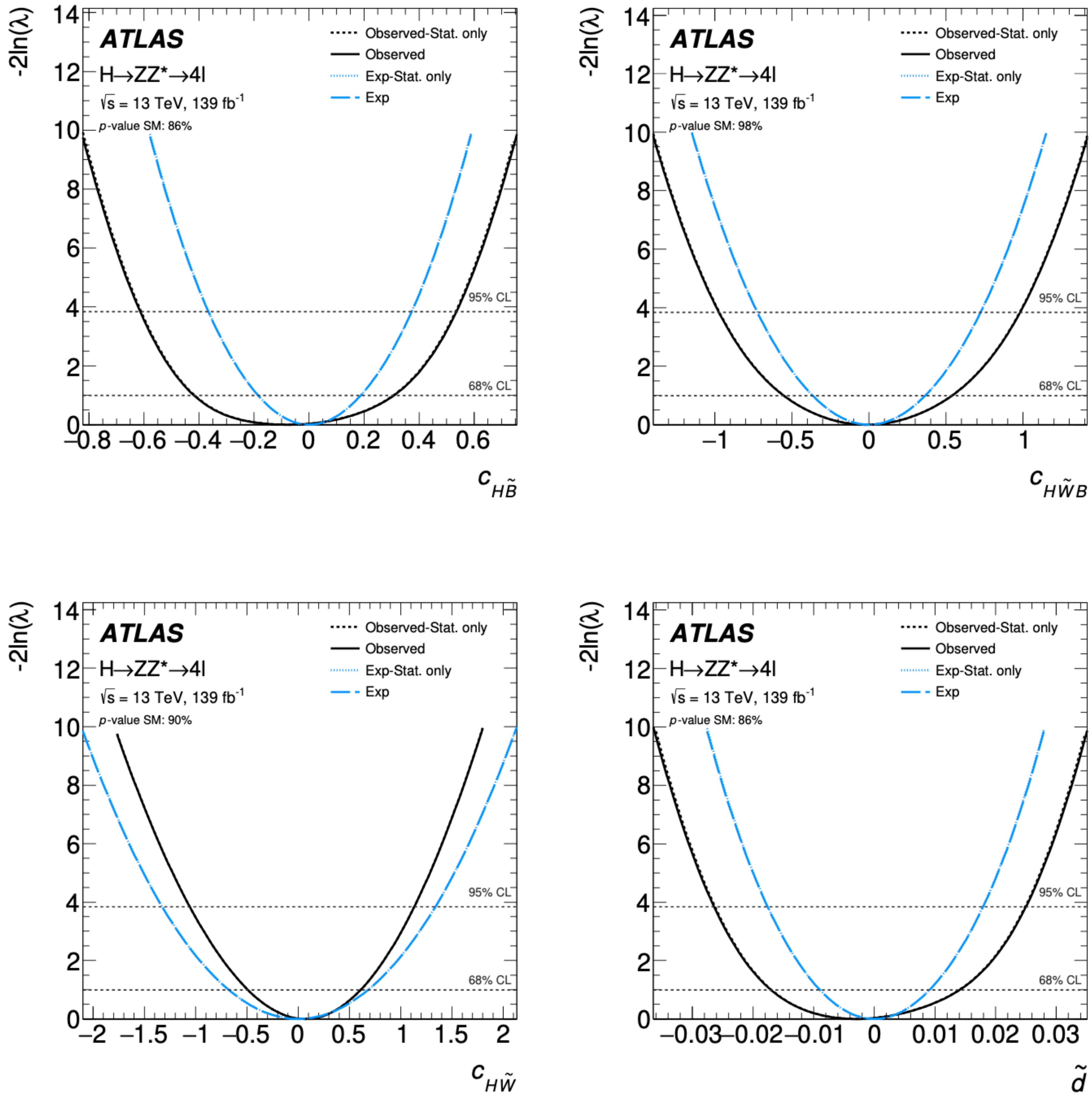
Wilson coefficient	Operator	Wilson coefficient	Operator
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	c_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{H}\,G^A_{\mu\nu}$
c_{HDD}	$(H^\dagger D^\mu H)^*\,(H^\dagger D_\mu H)$	c_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\,\widetilde{H}\,W^I_{\mu\nu}$
c_{HG}	$H^\dagger H\,G^A_{\mu\nu}G^{A\mu\nu}$	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	$f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$

H->ZZ ATLAS


ATLAS
H→ZZ*→4l
√s = 13 TeV, 139 fb-1
p-value SM: 11%
Observed-Stat. only
Observed
Exp-Stat. only
Exp
95% CL
68% CL
-2ln(λ)
ATLAS
H→ZZ*→4l
√s = 13 TeV, 139 fb-1
p-value SM: 37%
Stat-only
With systematics
Expected combined
Observed production
Observed decay
Observed combined
95% CL
68% CL
-2ln(λ)
ATLAS
H→ZZ*→4l
√s = 13 TeV, 139 fb-1
p-value SM: 93%
Observed-Stat. only
Observed
Exp-Stat. only
Exp
95% CL
68% CL
-2ln(λ)
c̃zγ
ATLAS
H→ZZ*→4l
√s = 13 TeV, 139 fb-1
p-value SM: 99%
Observed-Stat. only
Observed
Exp-Stat. only
Exp
95% CL
68% CL
-2ln(λ)
c̃γγ

ATLAS EXPERIMENT

H->ZZ ATLAS

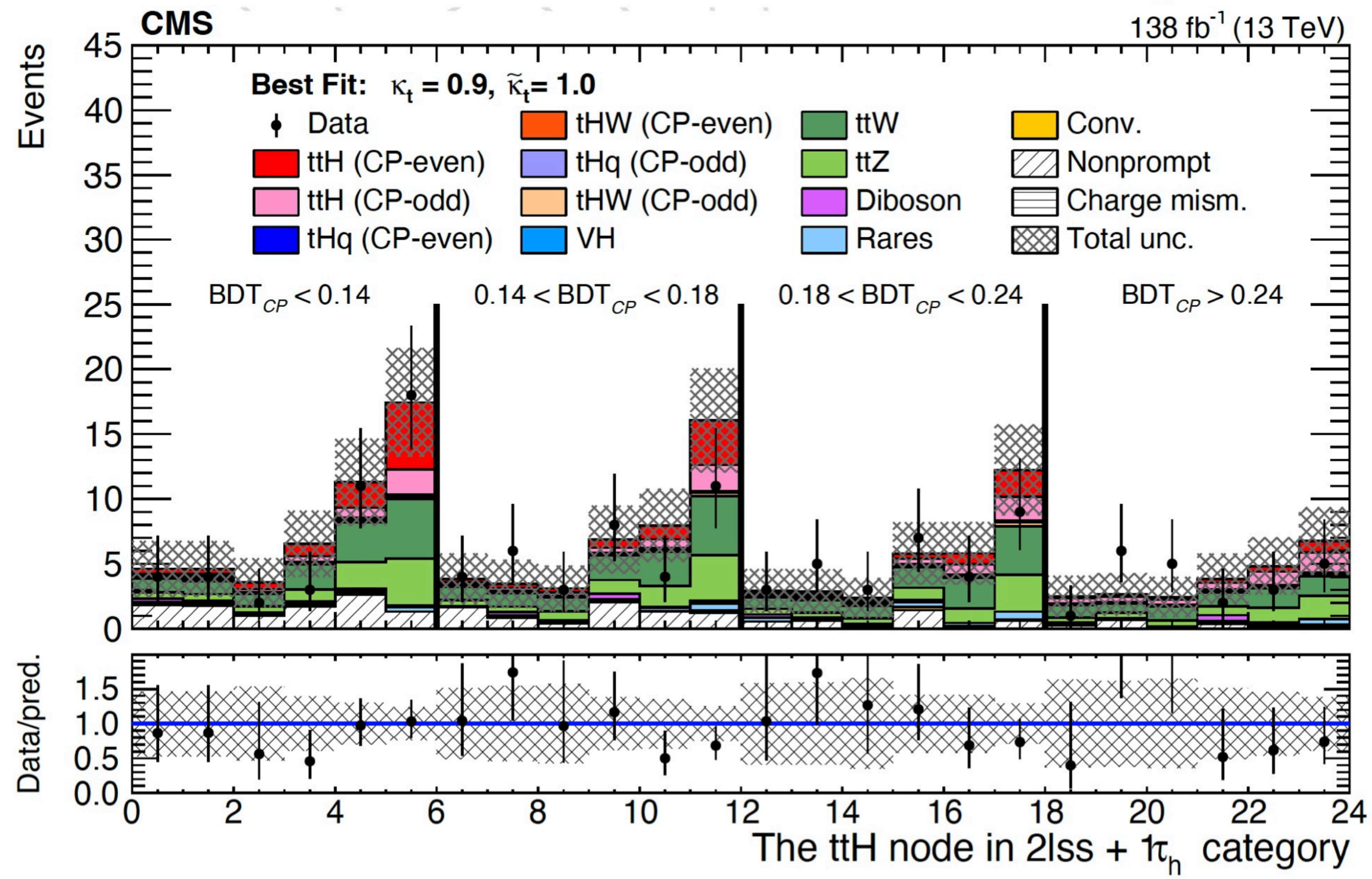


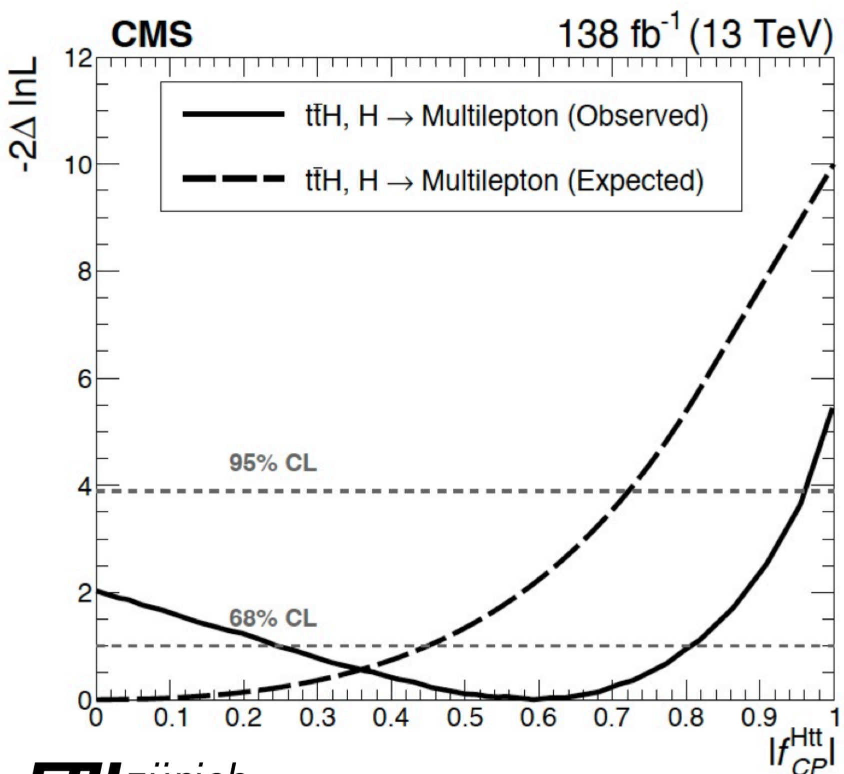
ETH zürich

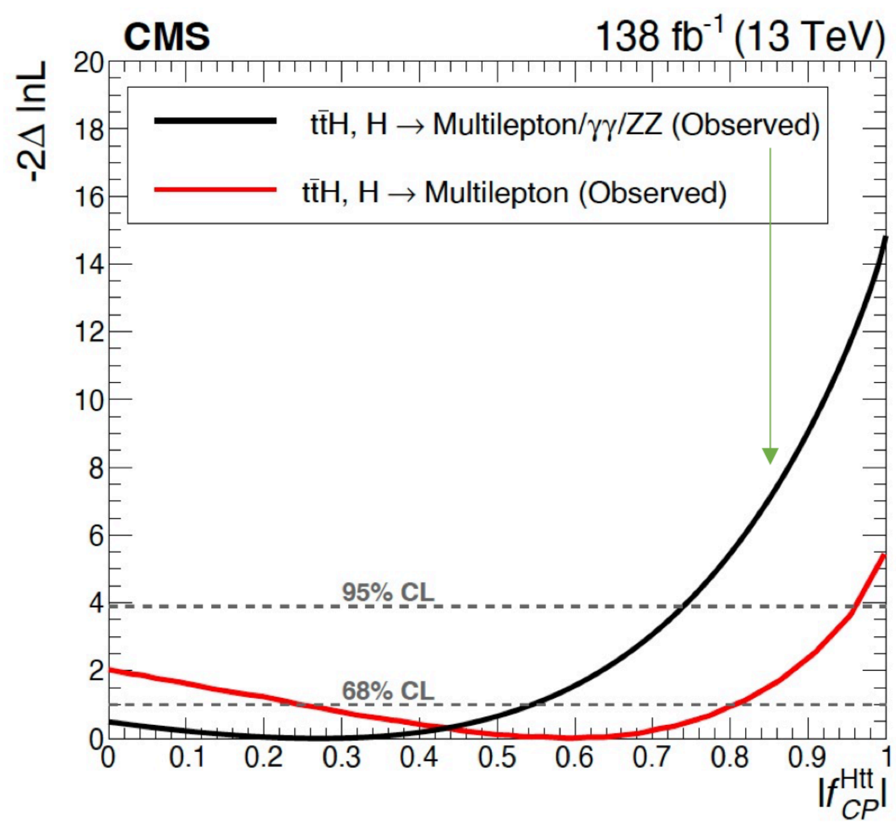
CP violation in ttH/tH

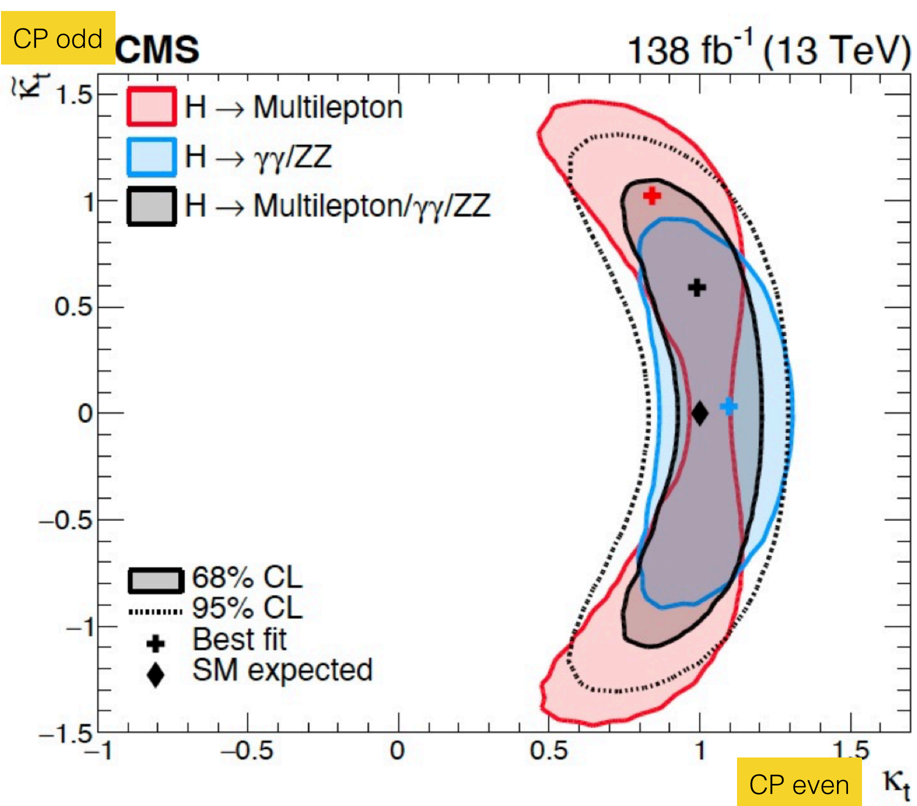
JHEP 07 (2023) 092

- **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









EFT basis definition

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

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

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

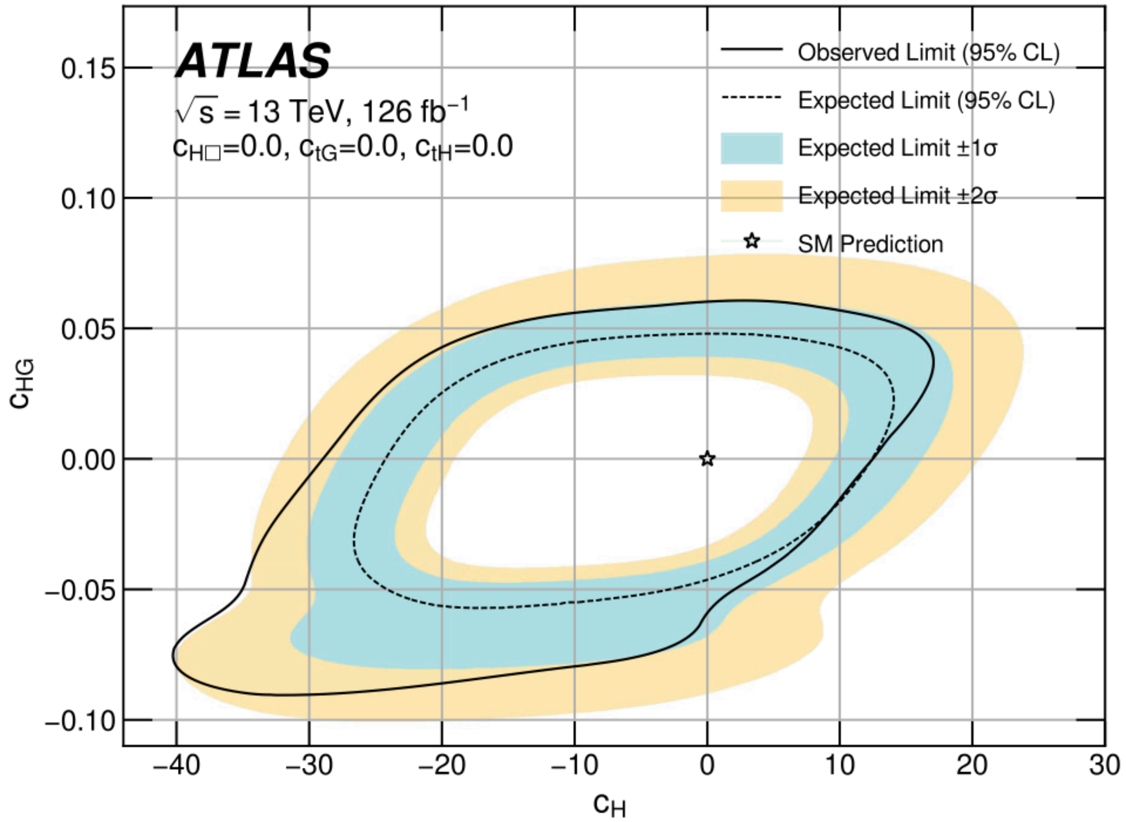
HVV couplings - gg couplings (only non zero contributions are a2 and a3)

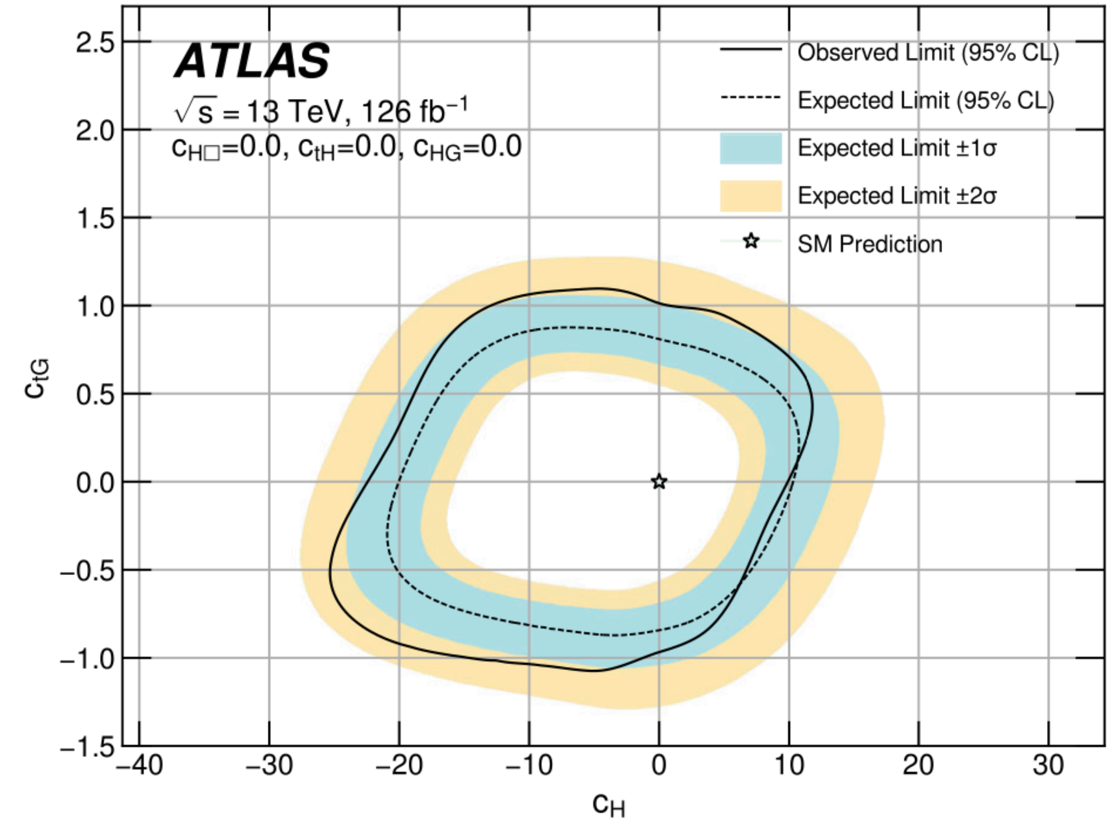
$$c_{zz} = -\frac{s_w^2 c_w^2}{2\pi\alpha} a_2,$$
$$\tilde{c}_{zz} = -\frac{s_w^2 c_w^2}{2\pi\alpha} a_3.$$

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

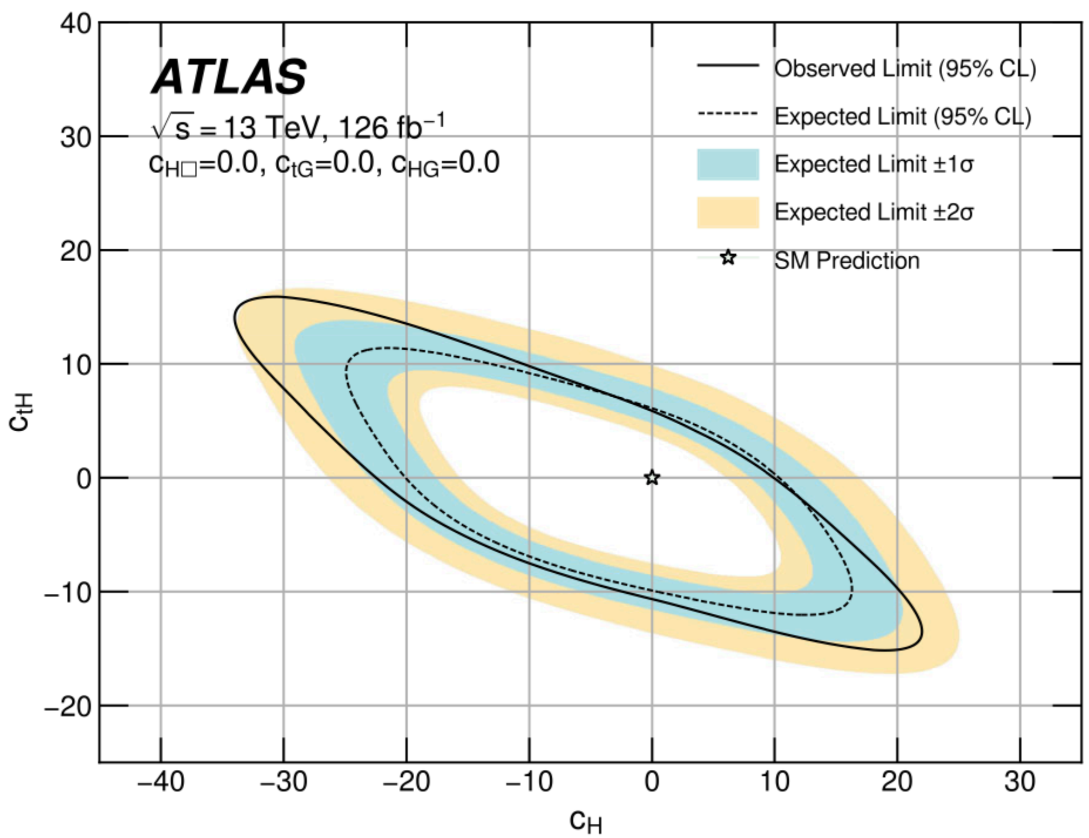
EFT interpretation

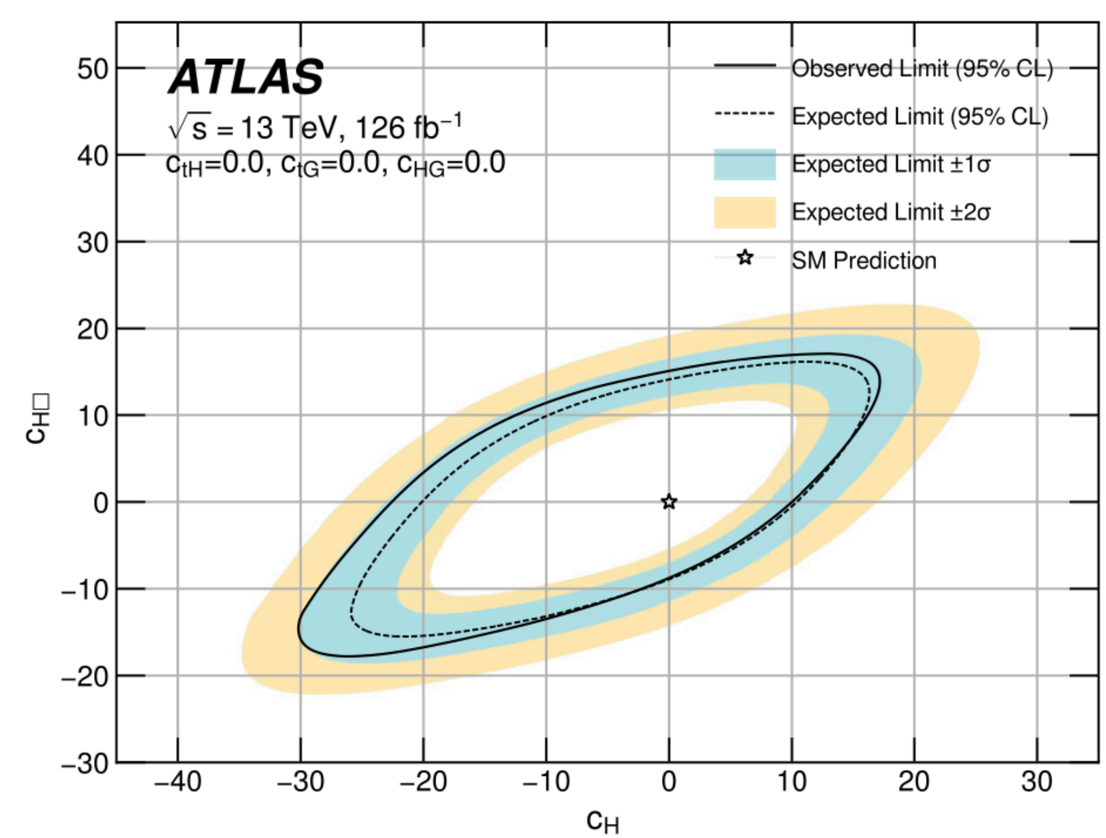
ATLAS HH4b EFT interpretation





Phys. Rev. D 108, 052003





HEL parameters

HEL Parameters	Definition	Others profiled	Fix others to SM
$c_A \times 10^4$	$c_A = \frac{m_W^2}{g'^2} \frac{f_A}{\Lambda^2}$	$-1.03^{+1.53}_{-1.59}$ $\left(^{+1.59}_{-1.56}\right)$	$-0.78^{+1.11}_{-1.16}$ $\left(^{+1.10}_{-1.11}\right)$
$c_G \times 10^5$	$c_G = \frac{m_W^2}{g_s^2} \frac{f_G}{\Lambda^2}$	$1.43^{+3.20}_{-3.00}$ $\left(^{+3.13}_{-2.74}\right)$	$0.27^{+1.05}_{-1.05}$ $\left(^{+1.03}_{-1.01}\right)$
$c_u \times 10$	$c_u = -v^2 \frac{f_u}{\Lambda^2}$	$0.68^{+0.82}_{-0.83}$ $\left(^{+0.83}_{-0.79}\right)$	$0.43^{+0.69}_{-0.69}$ $\left(^{+0.68}_{-0.67}\right)$
$c_d \times 10$	$c_d = -v^2 \frac{f_d}{\Lambda^2}$	$0.59^{+1.03}_{-1.13}$ $\left(^{+1.08}_{-1.05}\right)$	$-0.01^{+0.31}_{-0.28}$ $\left(^{+0.30}_{-0.28}\right)$
$c_\ell \times 10$	$c_\ell = -v^2 \frac{f_\ell}{\Lambda^2}$	$-0.57^{+0.74}_{-0.73}$ $\left(^{+0.72}_{-0.77}\right)$	$-0.75^{+0.60}_{-0.64}$ $\left(^{+0.58}_{-0.60}\right)$
$c_{HW} \times 10^2$	$c_{HW} = \frac{m_W^2}{2g} \frac{f_{HW}}{\Lambda^2}$	$-1.45^{+4.72}_{-3.03}$ $\left(^{+3.93}_{-3.27}\right)$	$0.77^{+0.84}_{-1.20}$ $\left(^{+1.04}_{-1.38}\right)$
$(c_{WW} - c_B) \times 10^2$	$c_{WW} = \frac{m_W^2}{g} \frac{f_{WW}}{\Lambda^2}, c_B = \frac{2m_W^2}{g'} \frac{f_B}{\Lambda^2}$	$2.16^{+2.84}_{-5.35}$ $\left(^{+3.46}_{-5.00}\right)$	$0.62^{+1.06}_{-1.22}$ $\left(^{+1.09}_{-1.23}\right)$

HH->WWγγ SM 95% CL exclusion limits