Summary of recent Higgs EFT results

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LHC Higgs Working Group workshop - Nov 28, 2022

Outline of the talk

- ➡ Kappa parametrisation on effective couplings and extension to Wilson coefficients
- ➡ EFT Lagrangian expansions and EFT interpretation
- ➡ Highlights on recent Higgs EFT results in ATLAS and CMS
  - interpretation of full Run 2 STXS results using EFT parametrisation [also discussed in M. Knight and A. Cueto's talks later in the session]
  - $H \to ZZ \to 4l$ in CMS and off-shell analysis
  - constraining EFT parameters in differential $H \to \gamma\gamma$ ATLAS analysis
  - $H \to \tau\tau$ EFT analysis in CMS and combination with on-shell $H \to ZZ$ and $H \to \gamma\gamma$
  - towards a global EFT fit: Higgs+EW EFT combination using Principal Component Analysis
  - a quick glimpse on double Higgs EFT results
- ➡ Wrapping-up and conclusions

Kappa parametrisation and Wilson coefficients

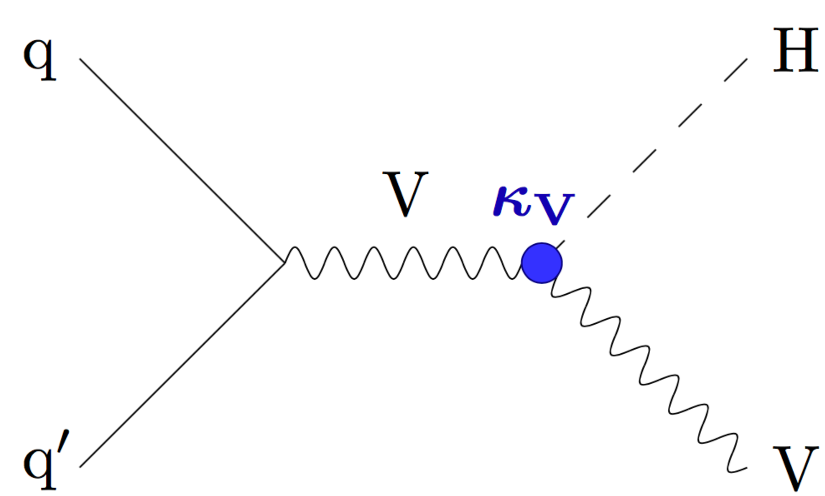
- ➡ Experimental profile of the Higgs boson with Run 1 and Run 2 data is becoming very precise
  - large set of precision measurements performed with Run 2 data
- ➡ Precision measurement is key to look for deviations of SM couplings: achieved using low-energy approximation (EFT) to UV complete theory

Wilson coefficients (if c=0 → SM)

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

Tensor structure of EFT terms

- ➡ Kappa parametrisation introduced to 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)

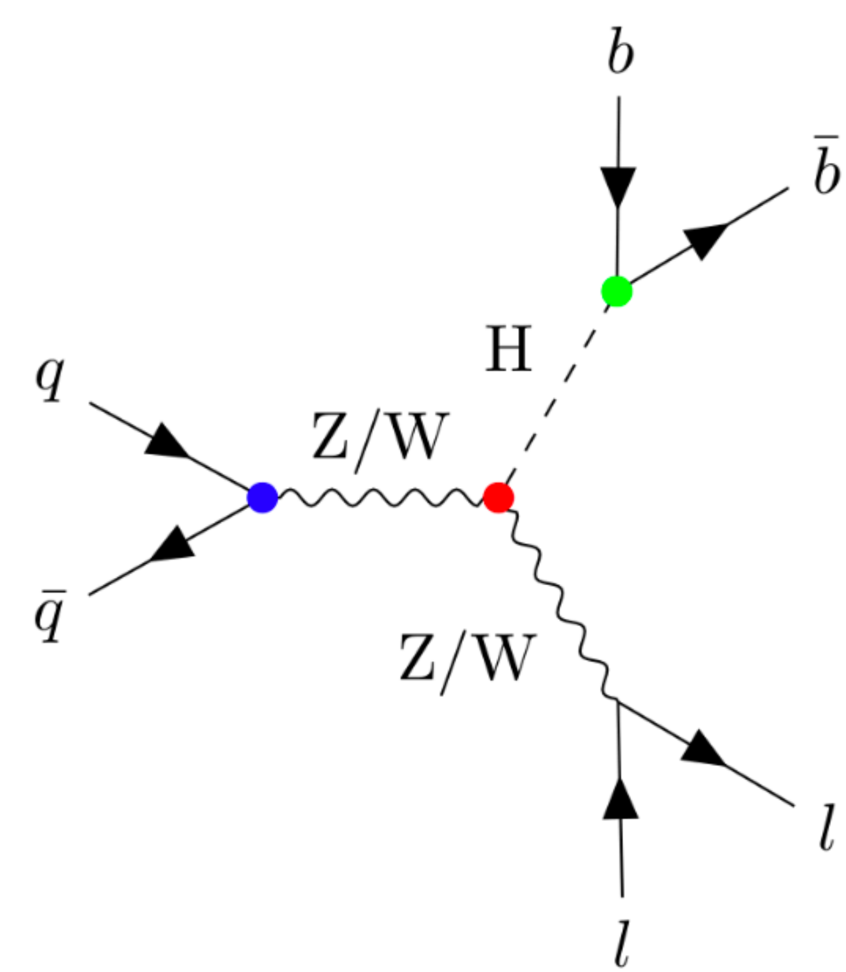


Wilson coefficients & EFT Lagrangian expansion

- Explicit expansion of SM lagrangian in $1/\Lambda$ gives rise to observables where 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 (both are dim-6 operators)
- Some EFT contributions are CP-odd operators (with tilde): access on those operators is relevant as non vanishing components indicate CP violation

Example of VH→bb channel

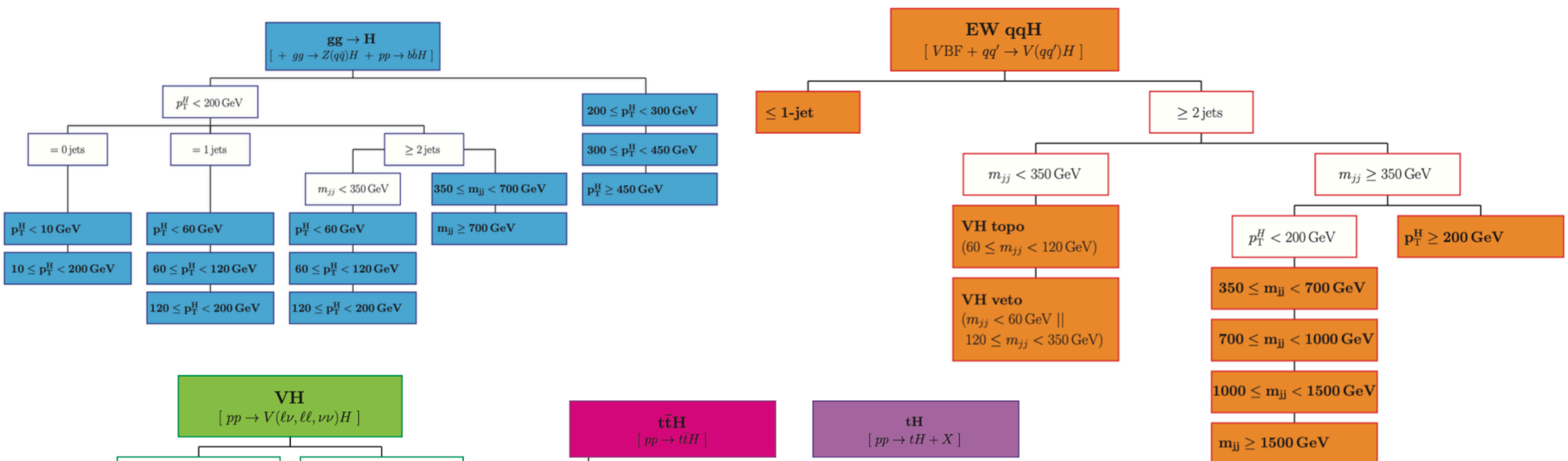
Operator	Wilson coefficient	Lagrangian modification	Channels
$\mathcal{O}_{Hq}^{(1)} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{q}\gamma^\mu q$	cHj1	qqV vertex, HVqq contact term	Zll
$\mathcal{O}_{Hq}^{(3)} = iH^\dagger \sigma^i \overleftrightarrow{D}_\mu H \bar{q}\sigma^i\gamma^\mu q$	cHj3	qqV vertex, 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
$\mathcal{O}_{bH} = (H^\dagger H)(\bar{q}bH)$	cbHRe + cbHIm	hbb coupling	Zll, Wlv

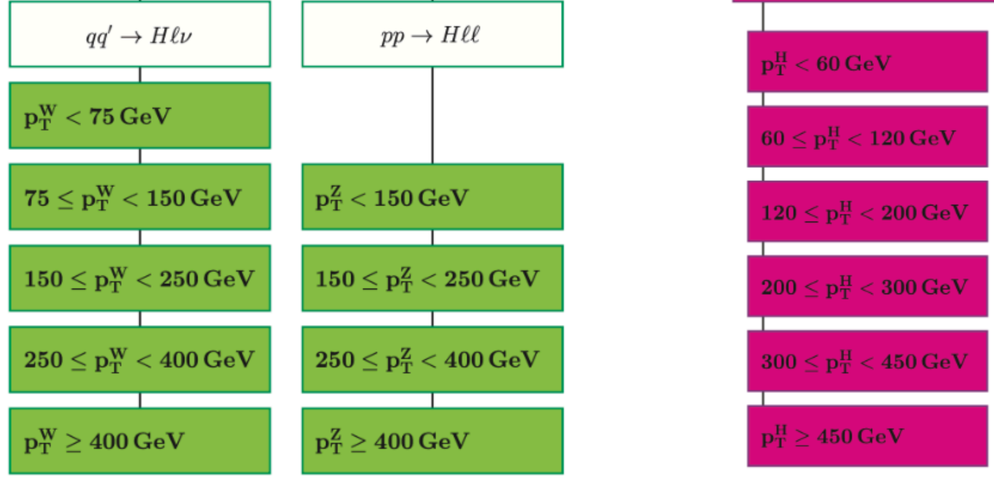


EFT interpretation using STXS

STXS Step 1.2

- Fundamental to keep all relevant operators in interpretation results due to interference effects
- No single measurement constraints all operators at the same time - 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 (H→γγ, ZZ, WW, ττ, bb) included with full Run 2 statistics
- Targeting all production modes in STXS bins

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
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	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	$f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$

EFT interpretation using STXS (3)

ATLAS-CONF-2021-053

- Main assumption of EFT interpretation in STXS bins - no EFT effects on background components, not fully justified for MC-driven background predictions
- Results on constraints derived on 10 linear and linear+quadratic combinations of EFT Wilson coefficients

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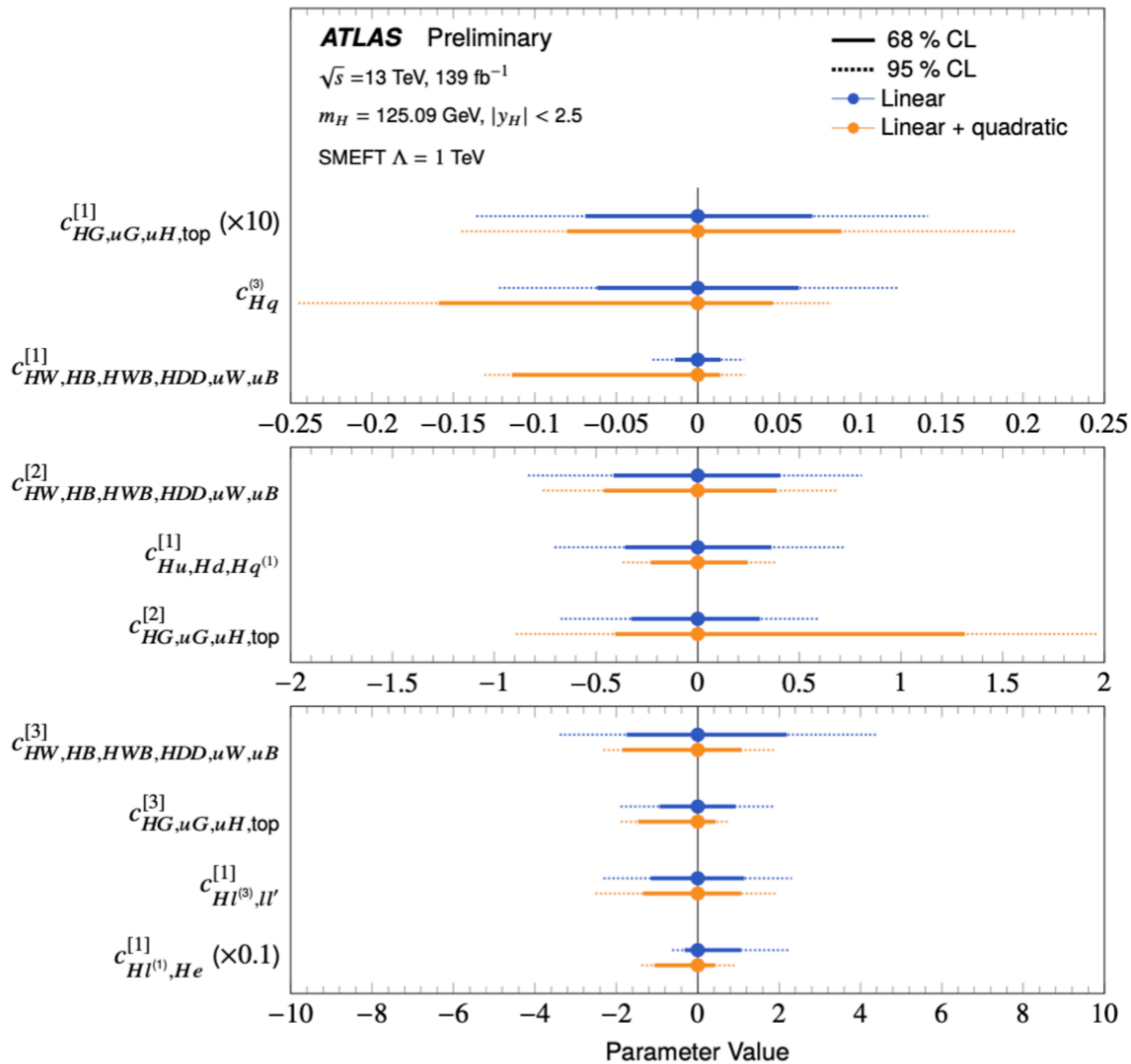
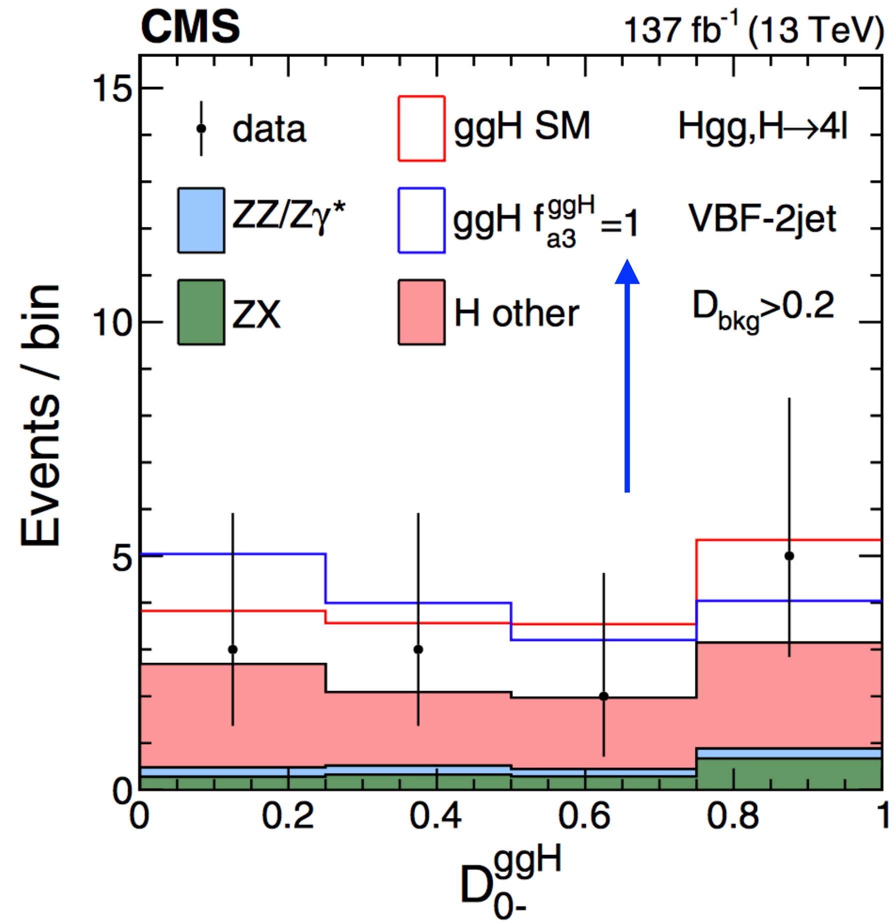
- No optimal observables (angles, kinematics) to enhance analysis sensitivity to EFT effects
    - interpretation of EFT effects in STXS categorisations
- Dependency of acceptance on EFT coefficients studied and explicitly accounted for H→ZZ and H→WW channels
    - very small dependency for other decay modes due to more inclusive selections

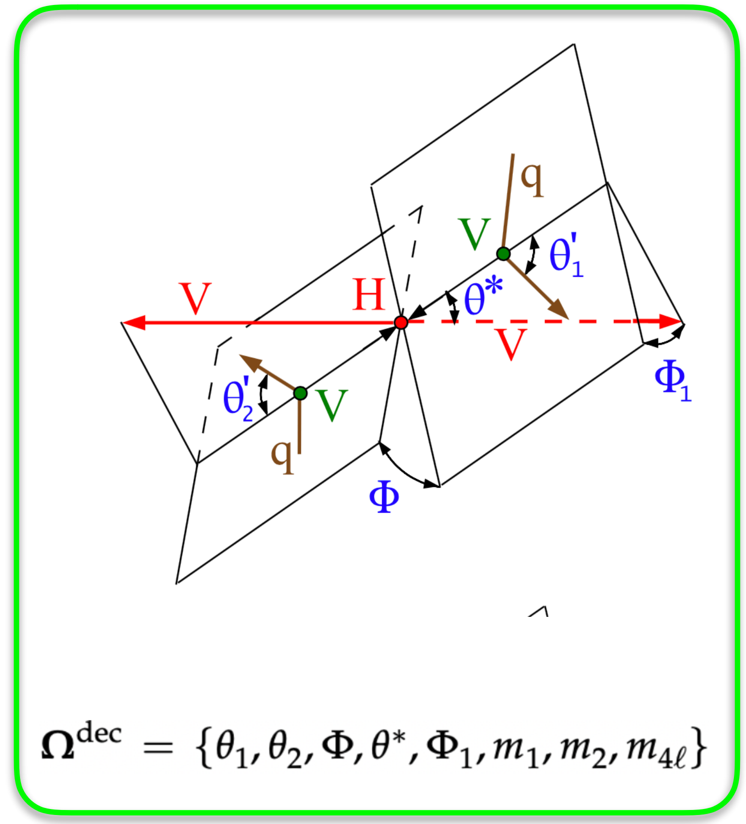


On-shell H->ZZ->4l

Phys. Rev. D 104 (2021) 052004

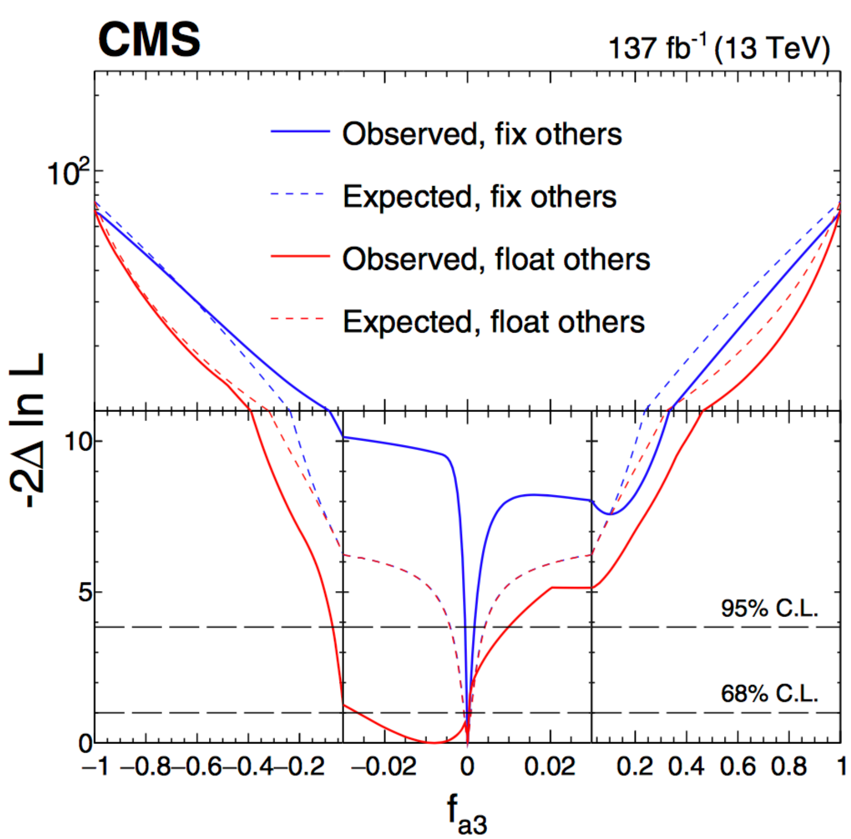
- Using full production and decay kinematic information to constrain Wilson coefficients
  - MEM (MELA) employed to separate production modes/ discriminate signal vs backgrounds
  - using optimal observables included in MELA to tackle EFT tensor structure

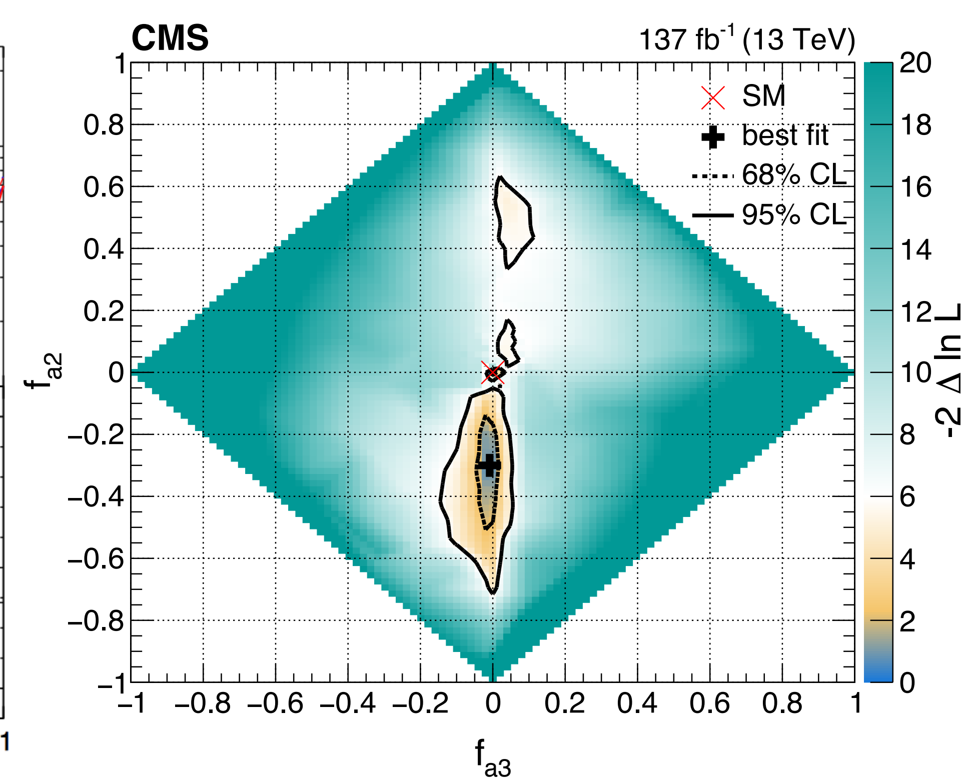




- Constraints HVV using Anomalous Coupling approach - extended to WC constraints using SMEFT

- Using various hypotheses on combined AC fit
  - fixing all couplings but one to SM expectations or all couplings profiled in the fit model
  - sensitivity to CP structure in HZZ decay



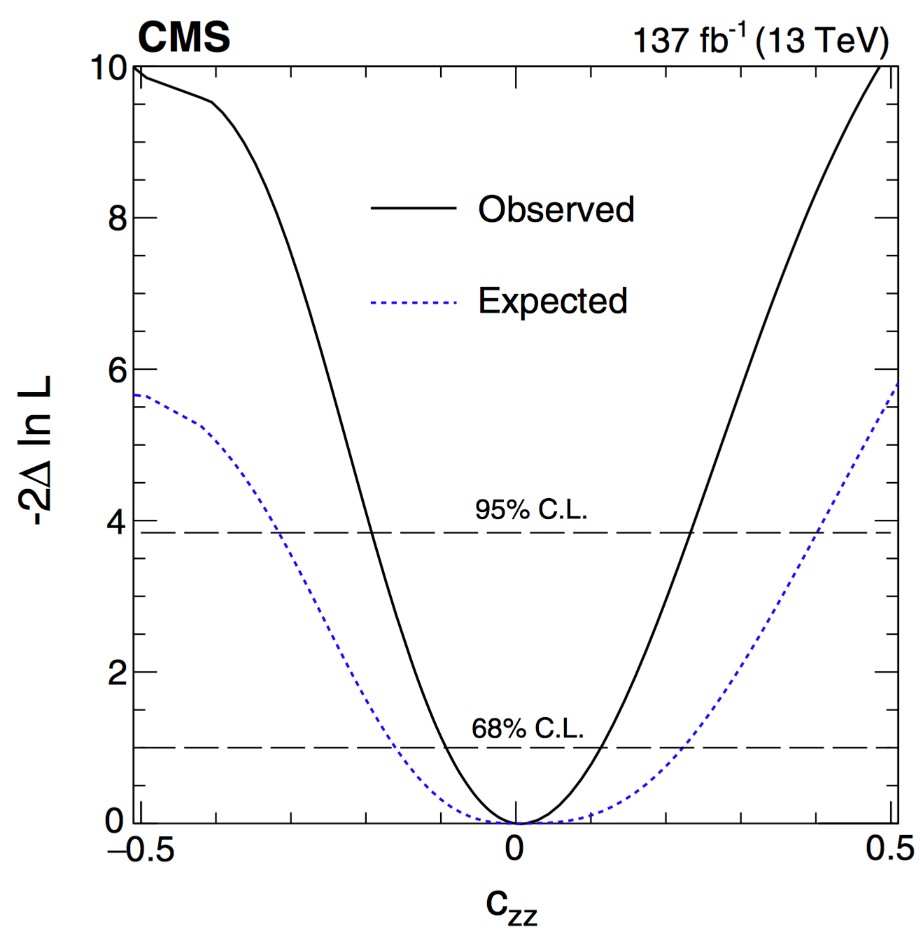


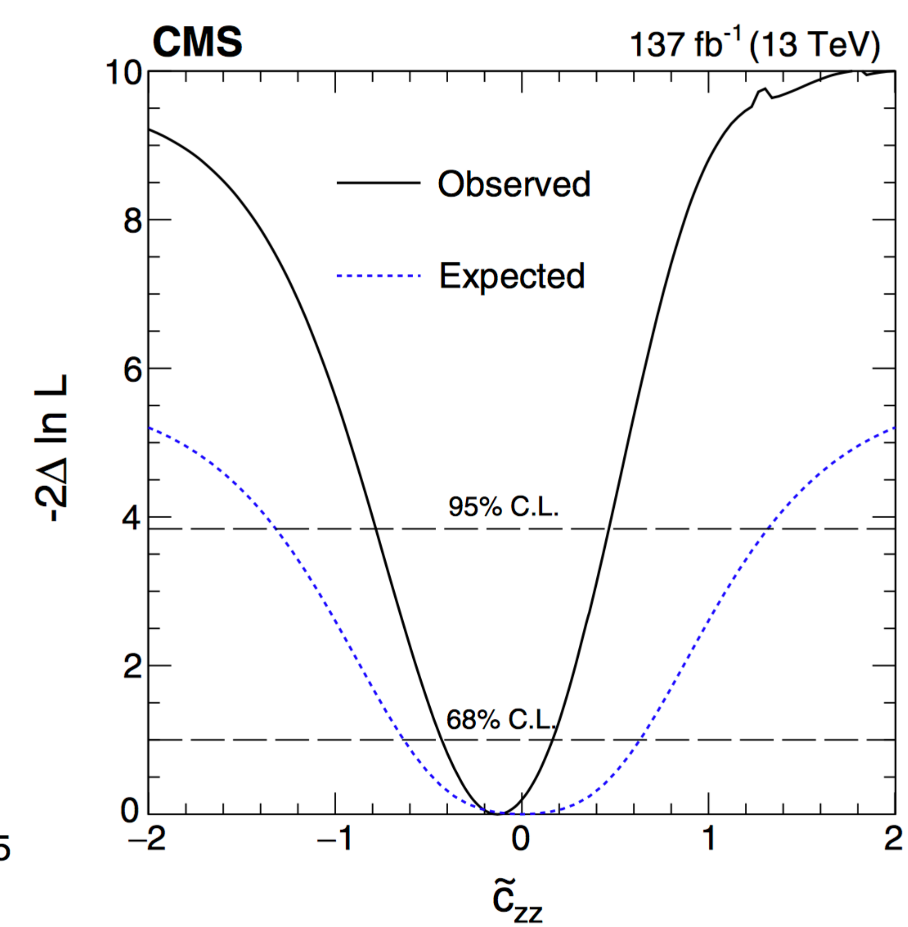
On-shell H->ZZ->4l (2)

- Performing simultaneous fit to all Wilson coefficients: targeting HZZ couplings using VBF and VH production 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

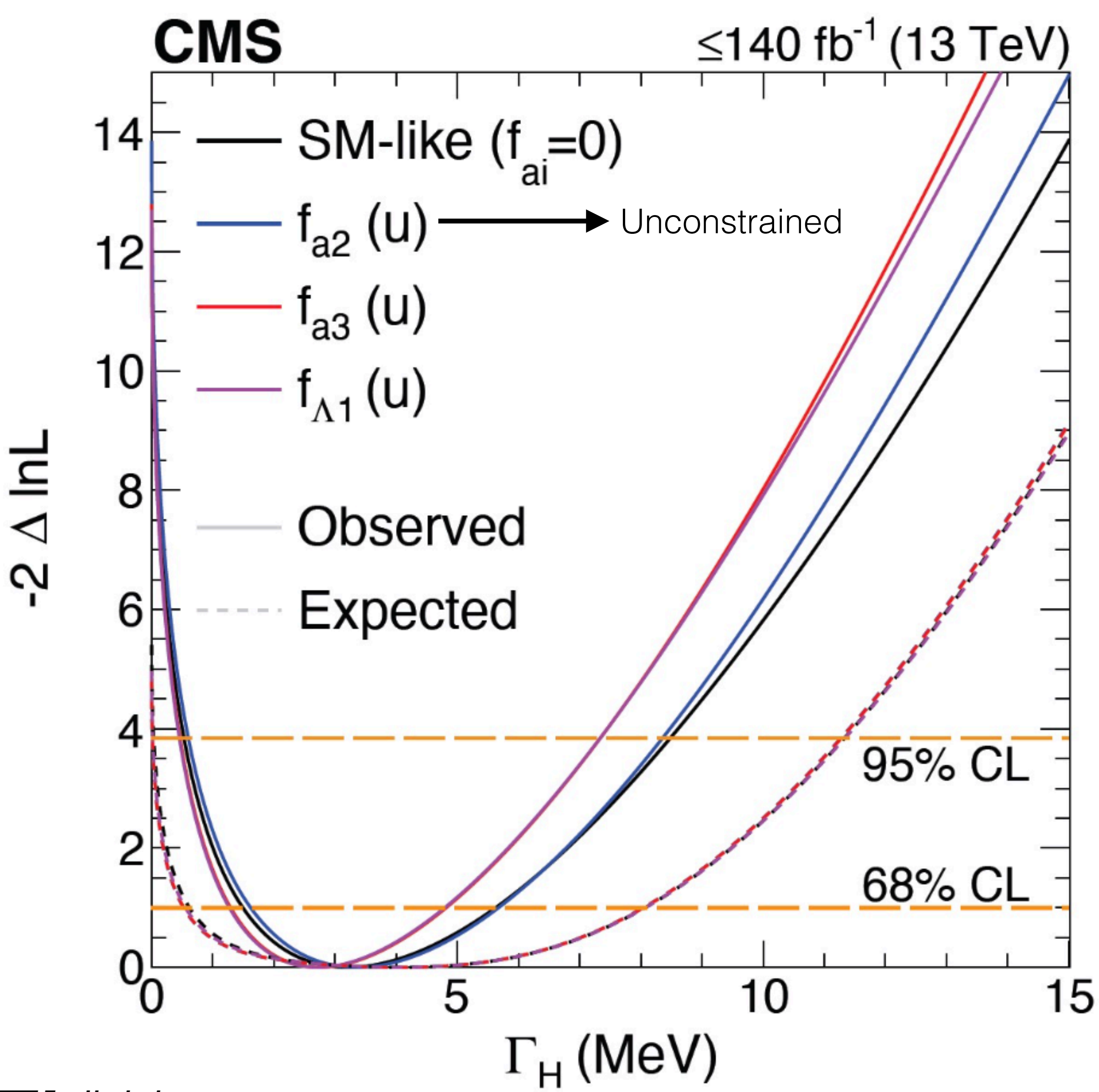


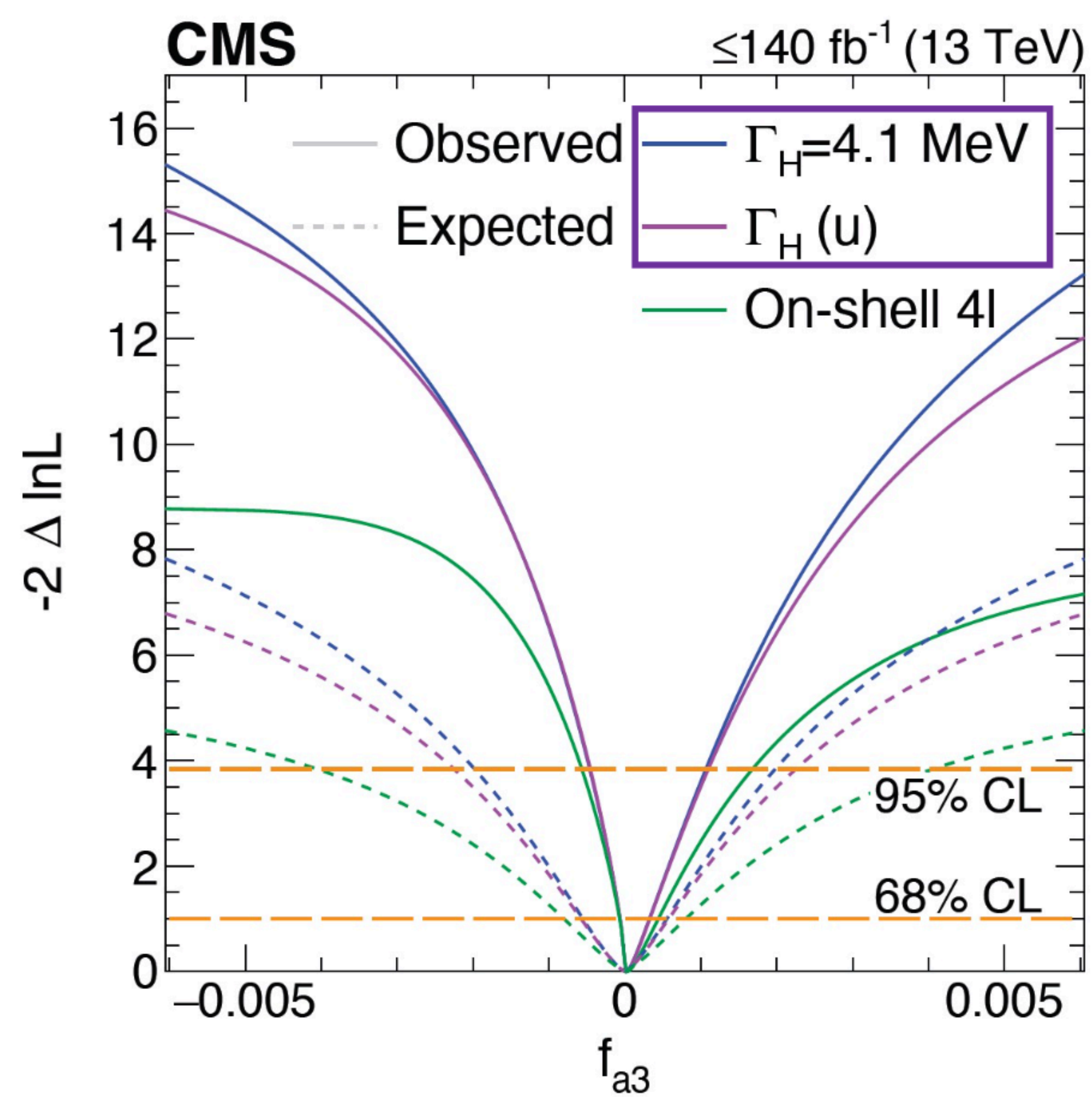


H->ZZ->4l using off-shell

Nat. Phys. 18 (2022) 1329

- ➡ Working assumption in off-shell coupling extraction technique: no BSM modifying running coupling in combination between on- and off-shell production → interpretation in terms of 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) observed when AC included on HVV vertex

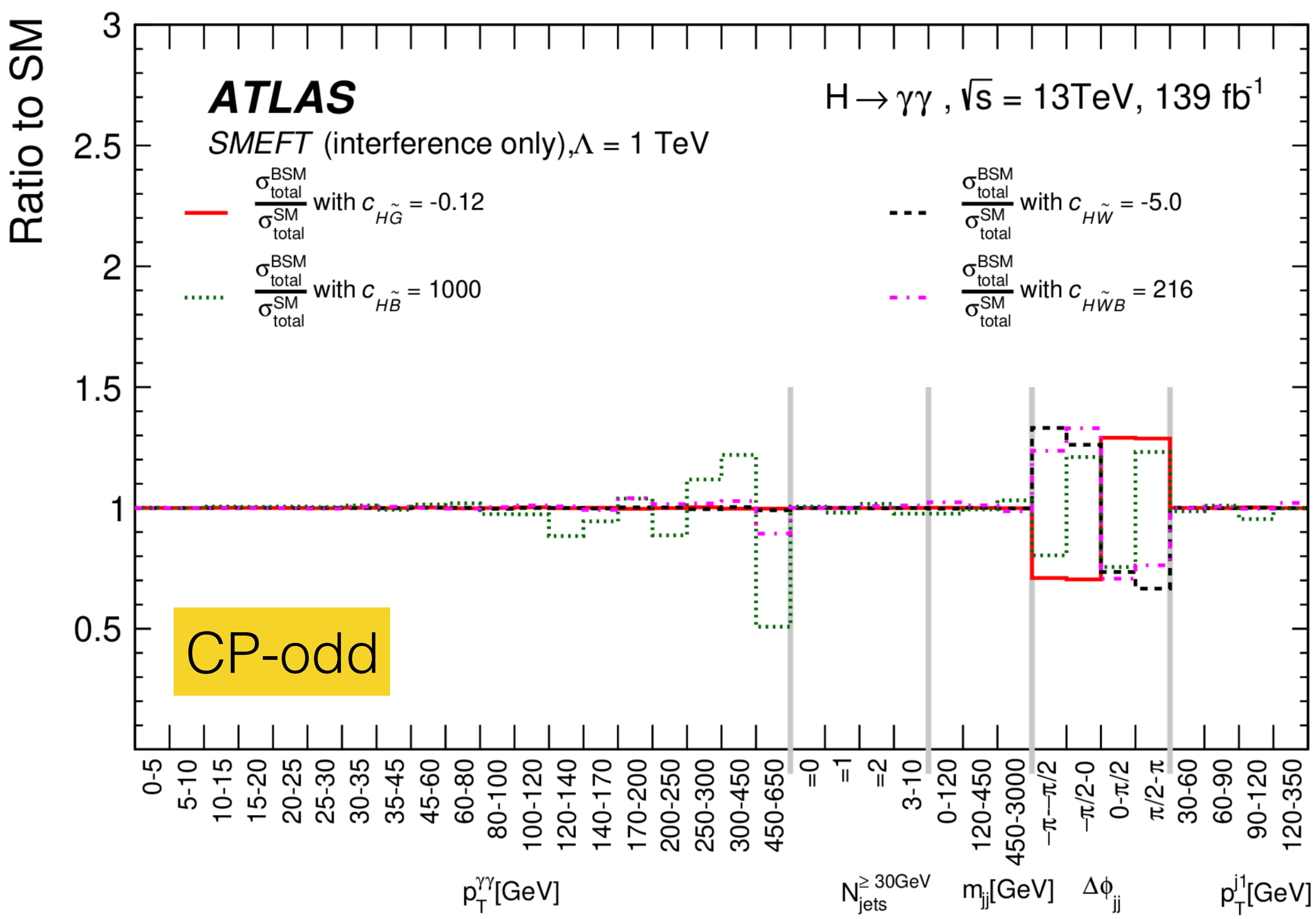


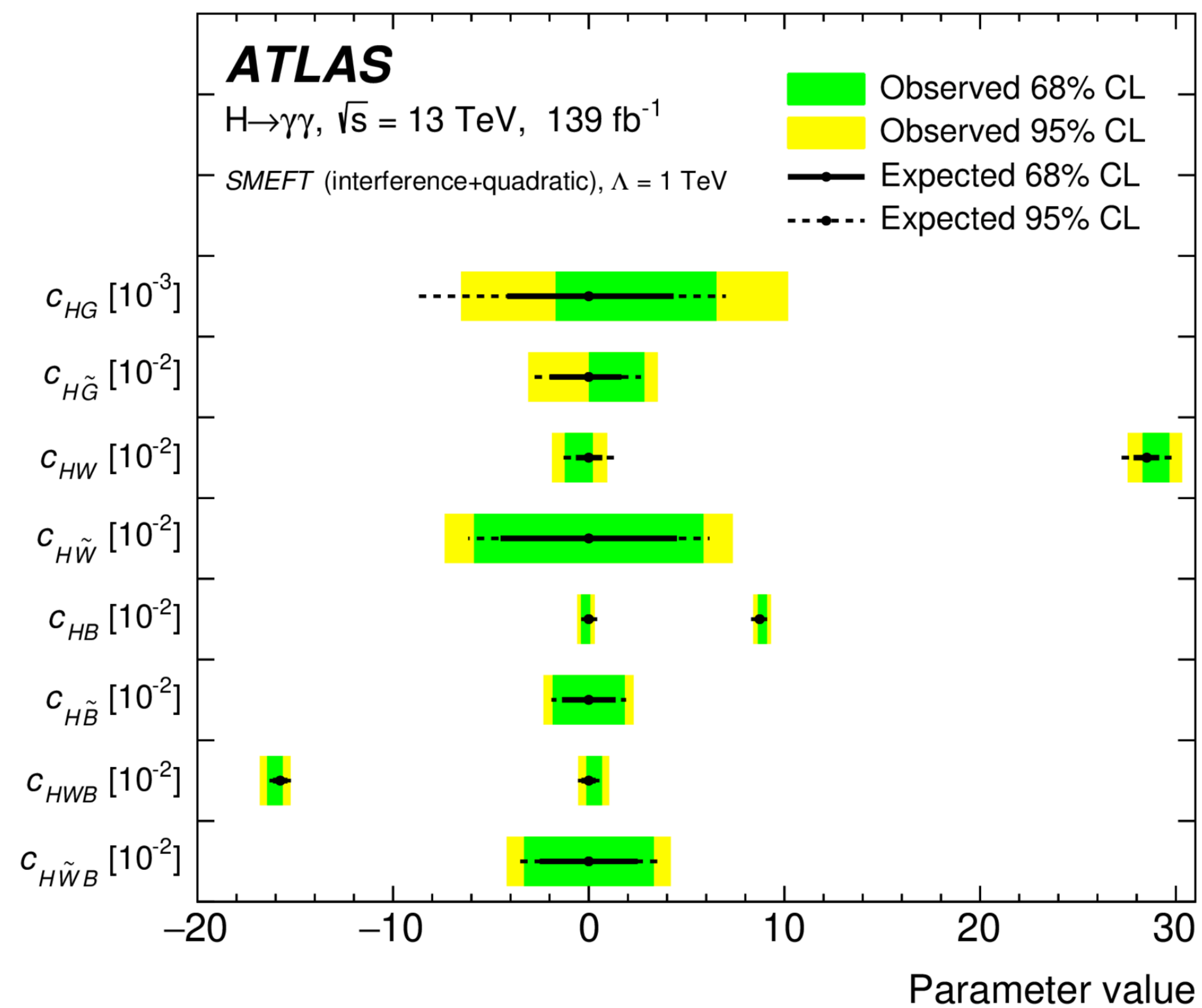


H->γγ differential

JHEP 08 (2022) 027

- Test of CP-even and CP-odd EFT WC's using differential distributions in bins of pt(γγ), NJet, ΔΦ(jj)
- Extracted constraints on EFT parameters by freely-floating one parameter at a time and fixing the other WC's to zero
  - achieved good constraints on CP-even operators, still weak constraints on CP-odd operators despite presence of dedicated categories in ΔΦ(jj)



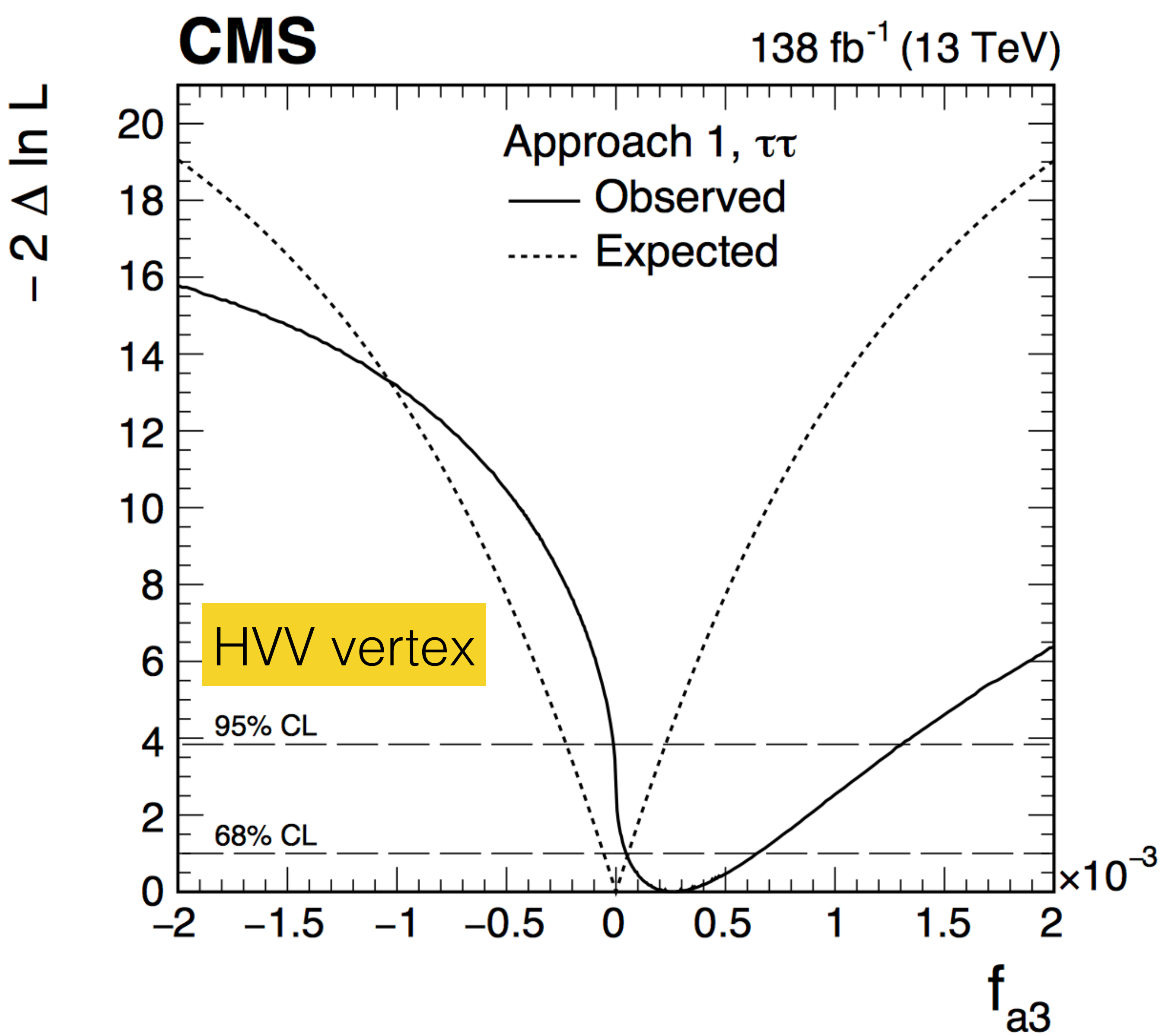


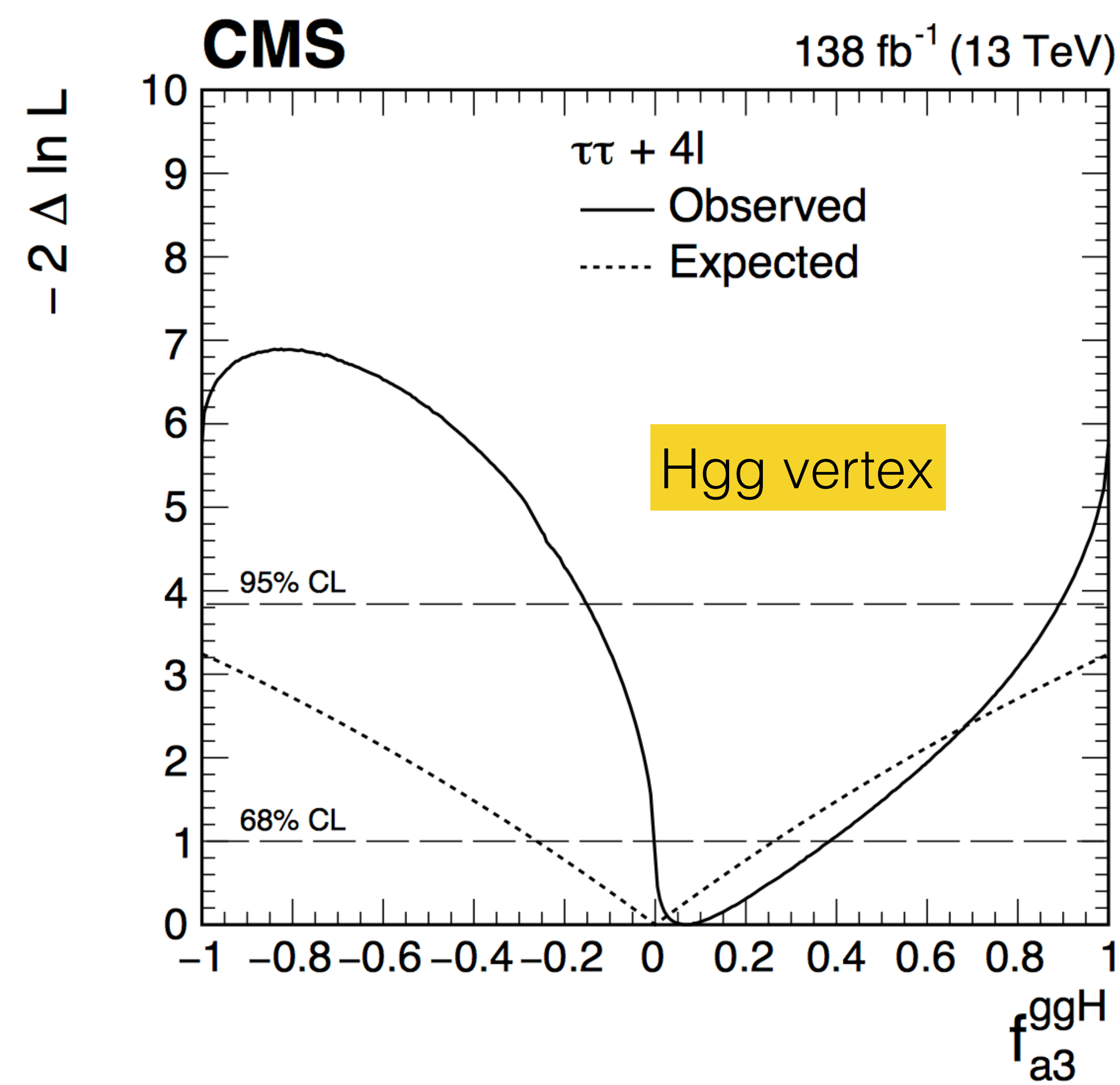
H->ττ analysis

arXiv: 2205.05120 (sub to PRD)

- 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)

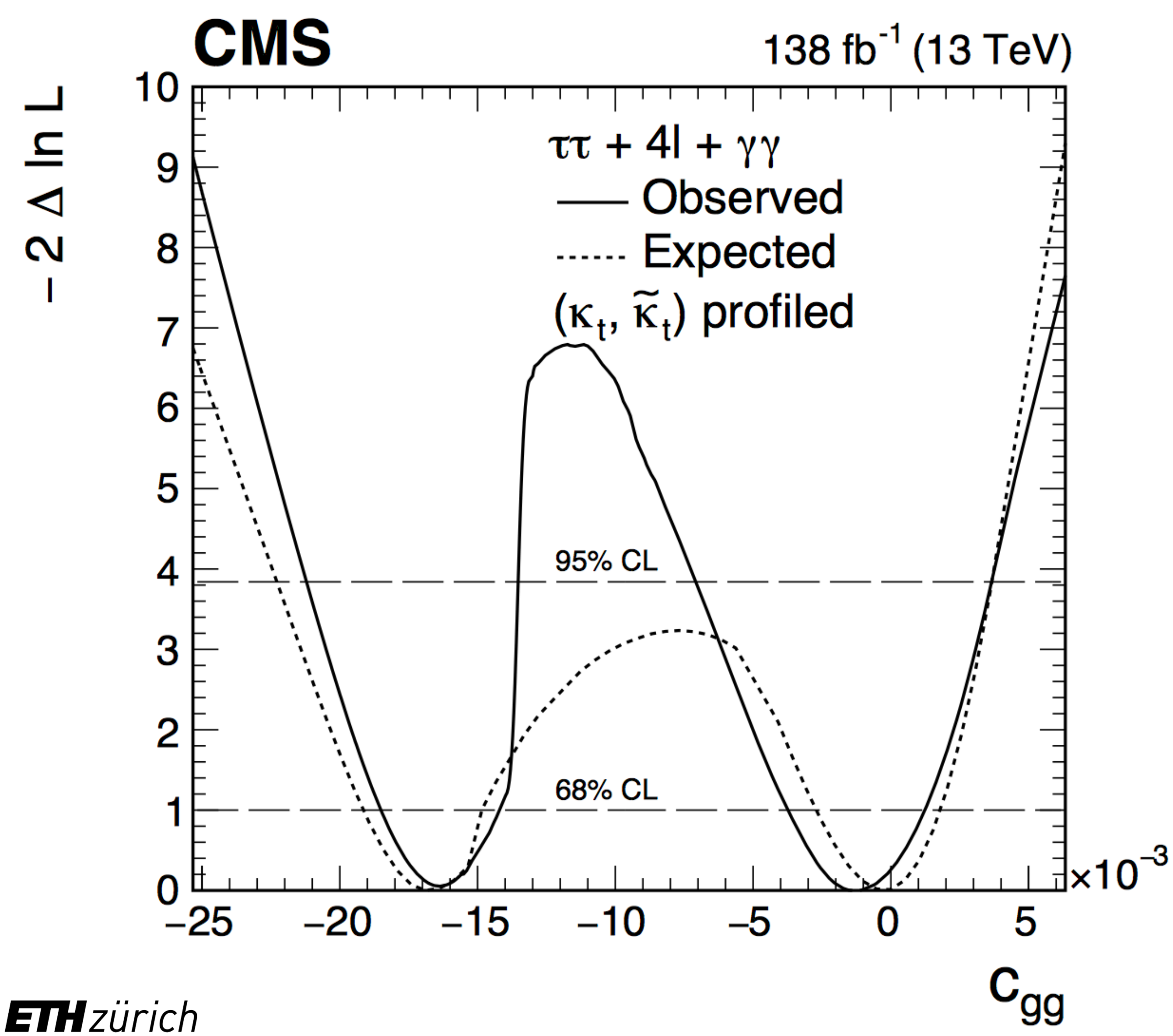
✓ pure CP-odd hypothesis for Higgs couplings to gluons excluded at 2.4σ

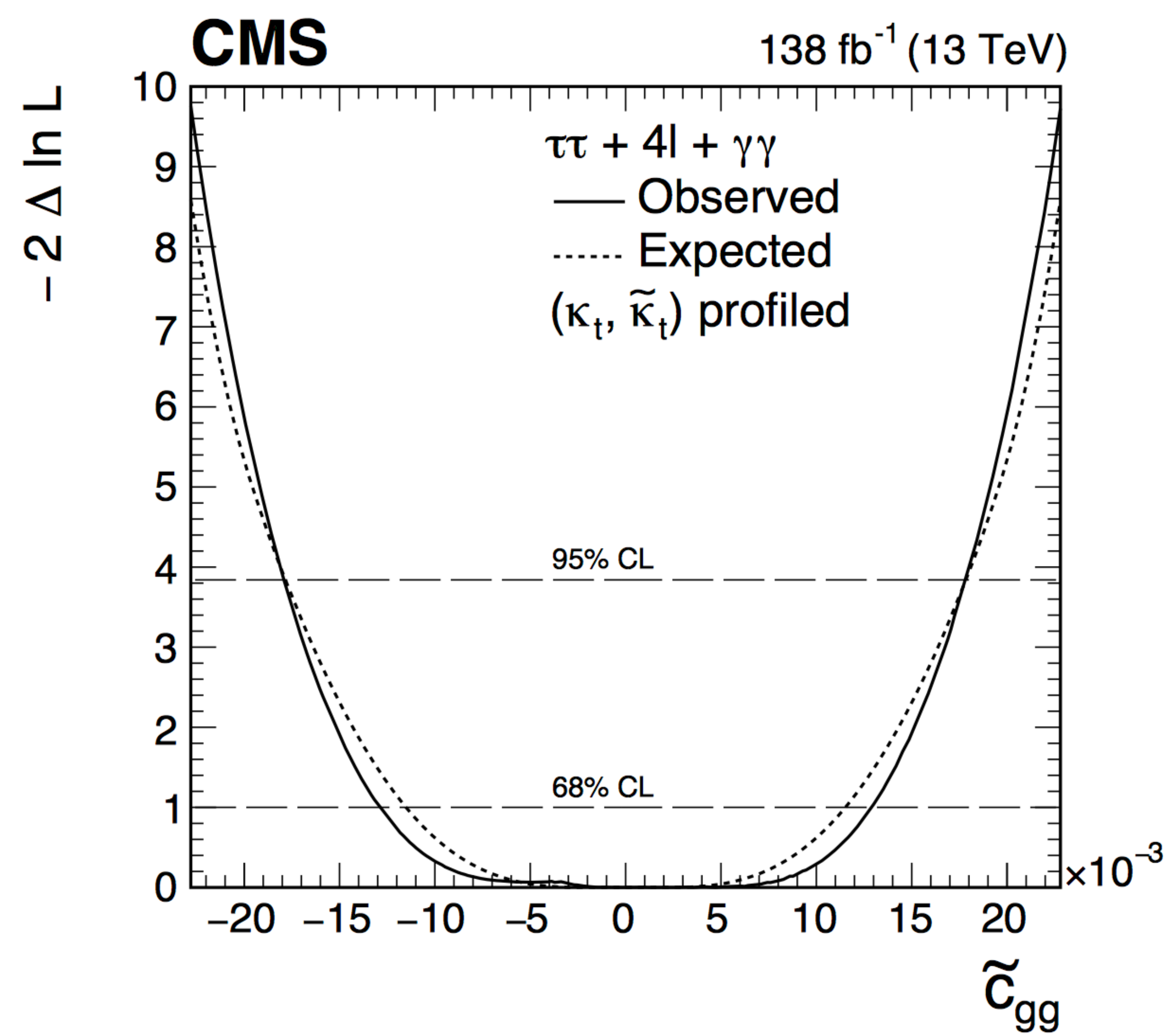




H->ττ analysis (2)

- Further studies performed to access Hff couplings combining H→ZZ, ttH→γγ and H→ττ in the gluon-fusion production mode - combination improves limits on anomalous couplings by around 25%
    - achieved constraints on c(gg) and CP-odd c(gg) operators

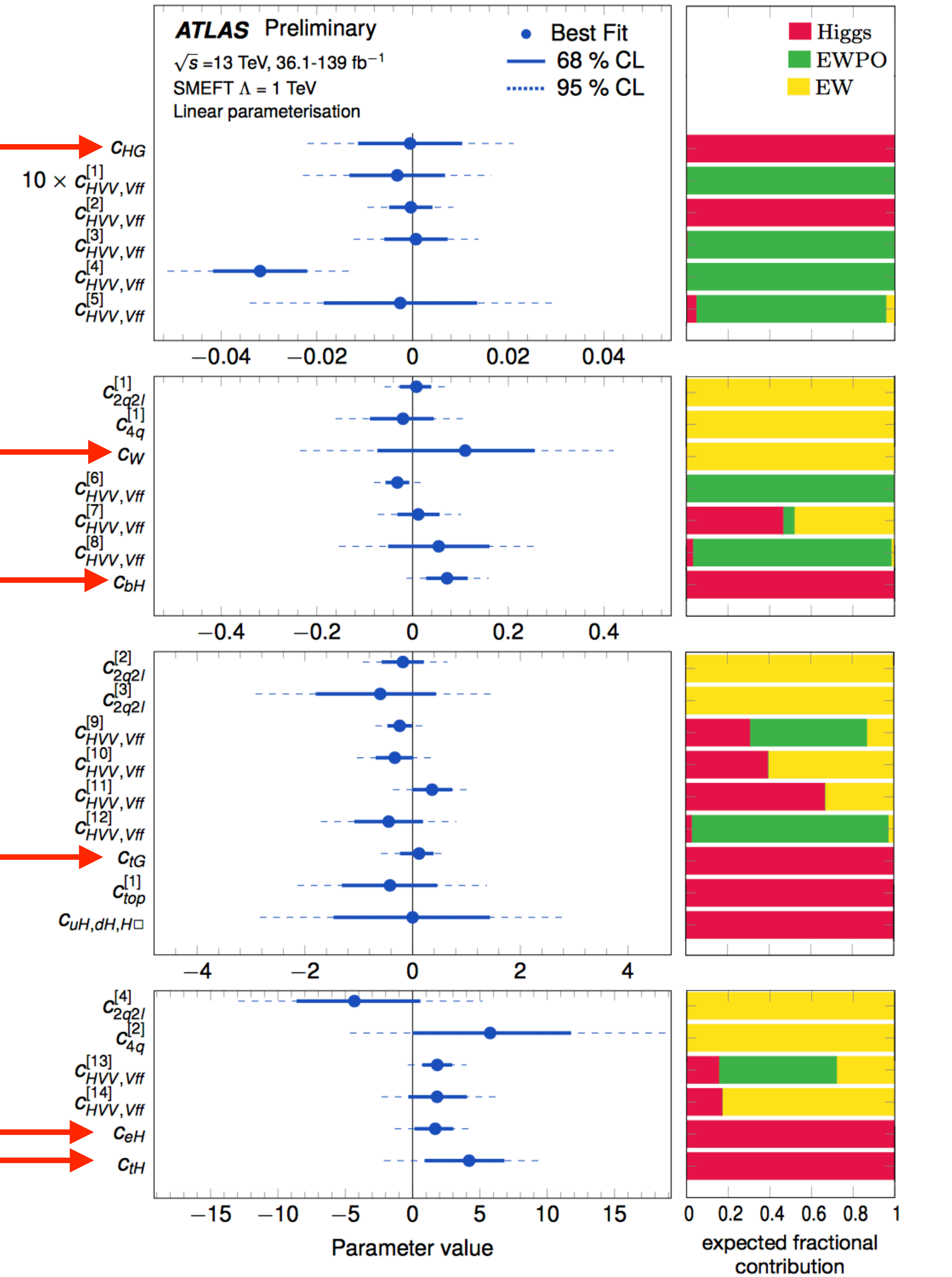




LHC EFT constraints towards global EFT fit

ATLAS-PHYS-PUB-2022-037

- 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) employed to extract relevant WC's
  - complementary of several measurement (expected non negligible fractional contributions)
- Tensions with SM dominated by known discrepancies in backward/forward asymmetry observables in EW precision measurements

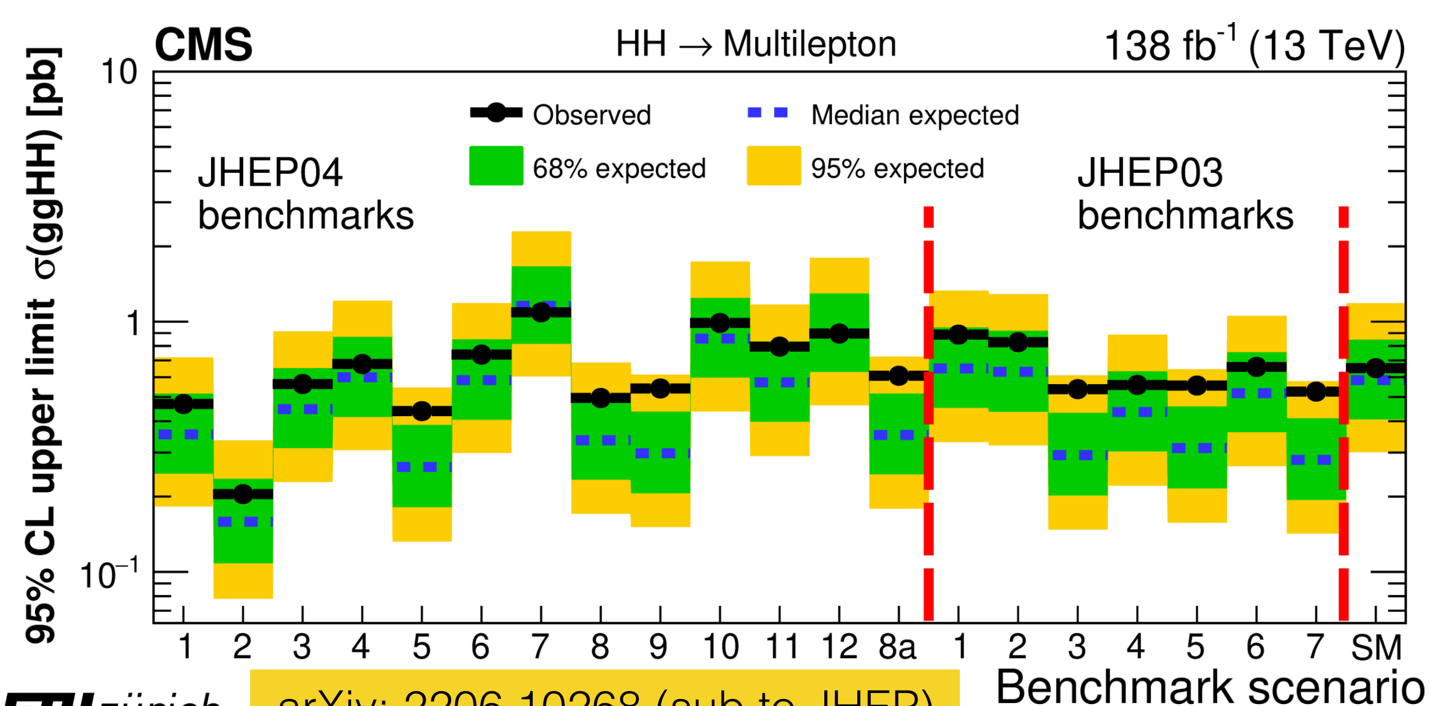


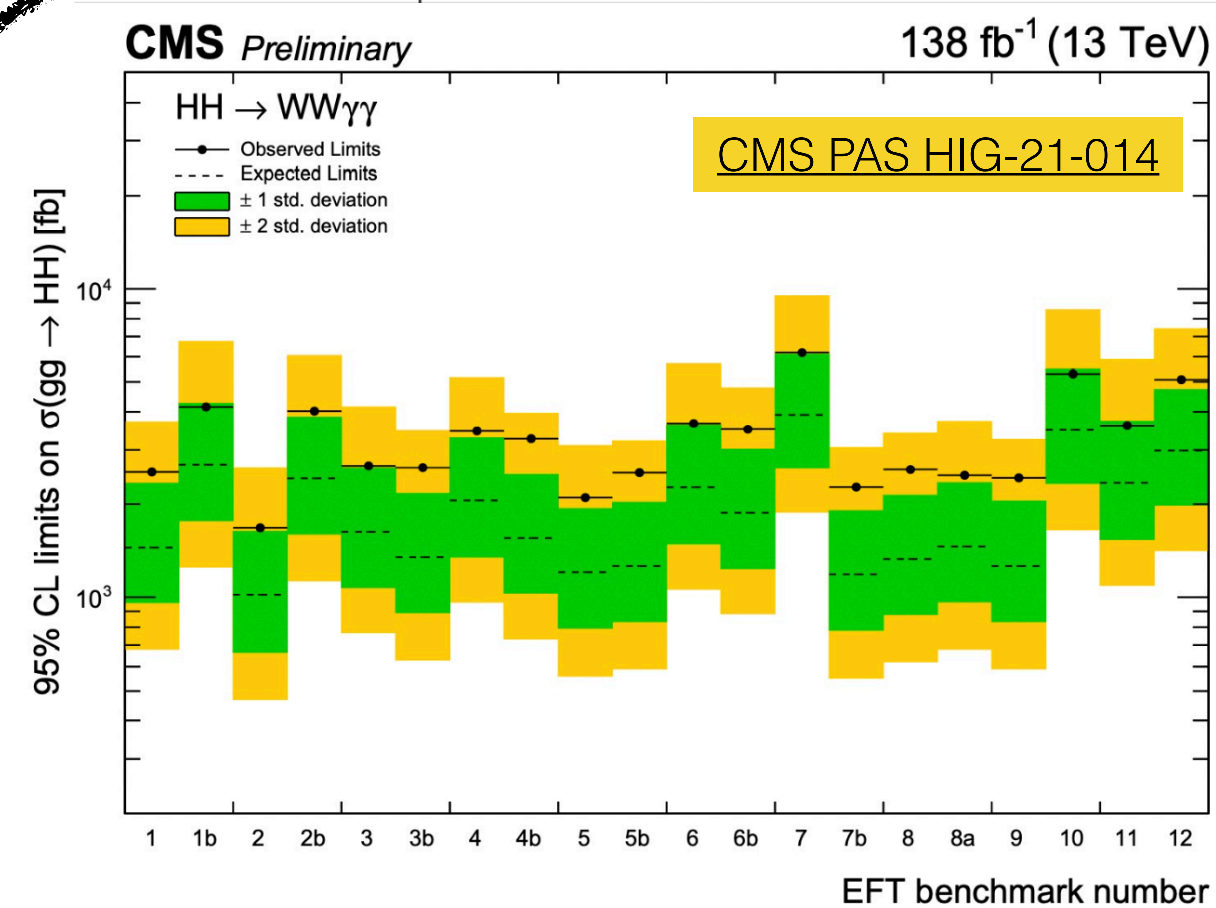
EFT interpretations in double Higgs analyses

- 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
    - maximises differences across scenarios
    - extract limit for each benchmark - CMS results available for 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

Example of benchmarks for HH→WWγγ





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arXiv: 2206.10268 (sub to JHEP)

EFT interpretations in double Higgs analyses (2)

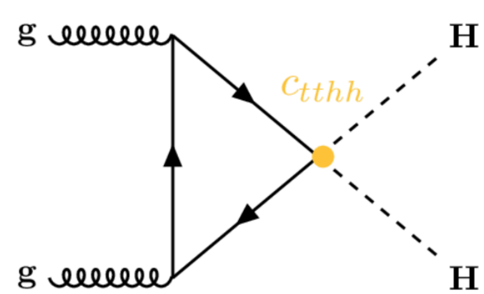
ATLAS EXPERIMENT

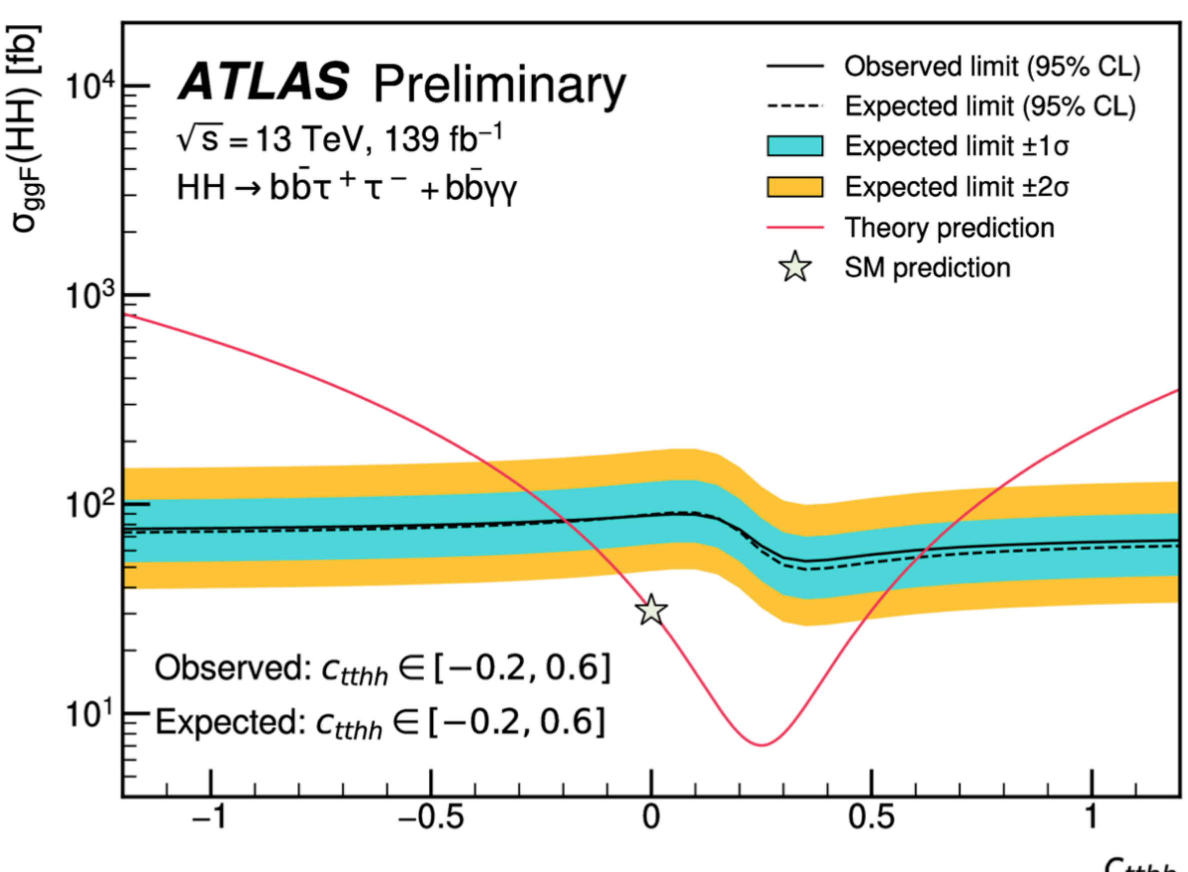
ATL-PHYS-PUB-2022-019

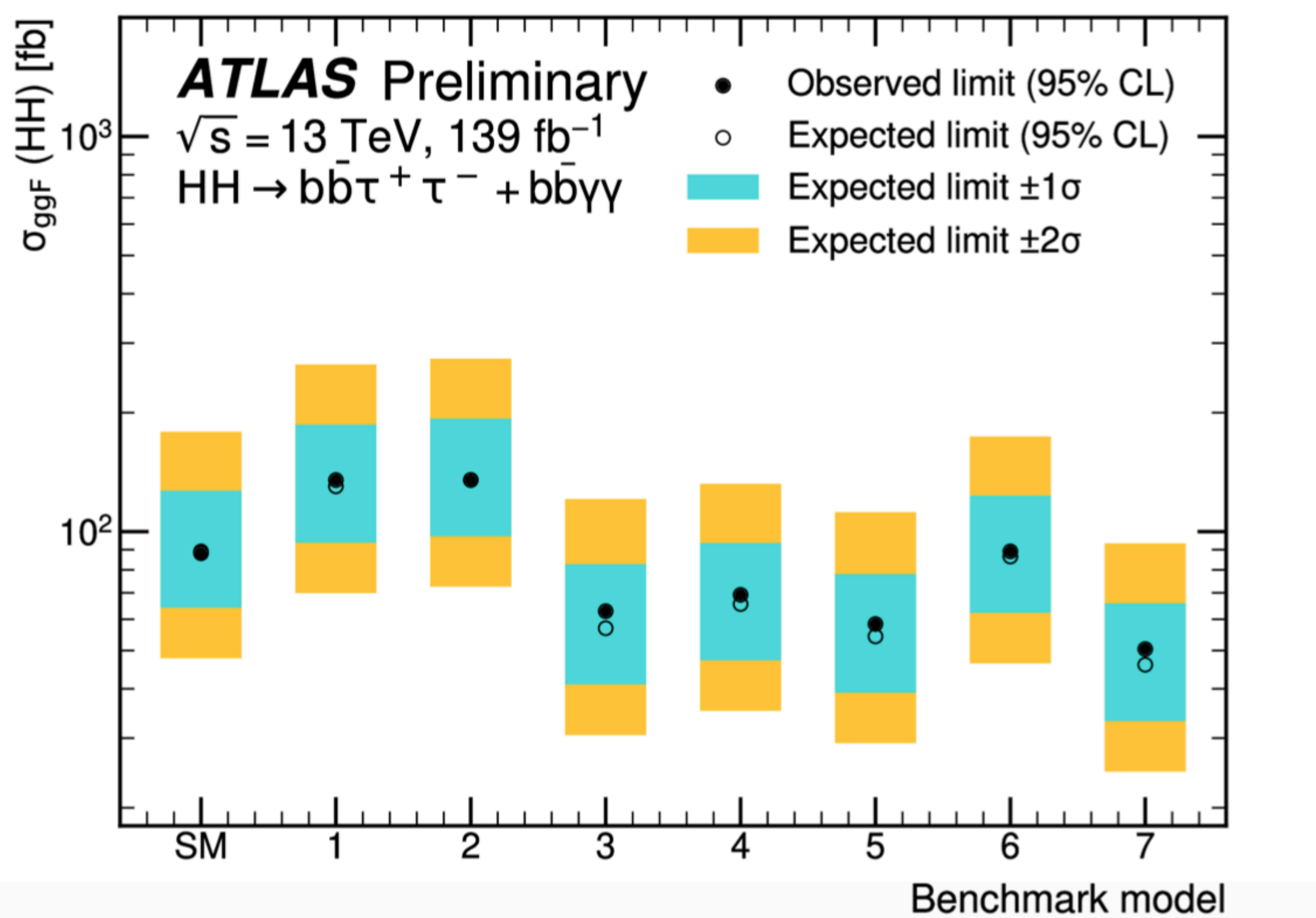
- Constraining EFT effects using benchmark scenarios w/ signal coupling modifiers: HH→bbγγ and HH→bbττ

Benchmark model	c_{hhh}	c_{tth}	c_{ggh}	c_{gghh}	c_{tthh}
SM	1	1	0	0	0
BM 1	3.94	0.94	1/2	1/3	−1/3
BM 2	6.84	0.61	0.0	−1/3	1/3
BM 3	2.21	1.05	1/2	1/2	−1/3
BM 4	2.79	0.61	−1/2	1/6	1/3
BM 5	3.95	1.17	1/6	−1/2	−1/3
BM 6	5.68	0.83	−1/2	1/3	1/3
BM 7	−0.10	0.94	1/6	−1/6	1

- Constraints also calculated for specific EFT components, i.e. BSM coupling between Higgs bosons and top quarks, c(tthh)







Wrapping-up & conclusions

➡ Precision measurements is key to look for deviations on SM couplings - several Effective Field Theory interpretations of Higgs and EW measurements by ATLAS and CMS available

- beyond kappa framework and complementary to direct searches for New Physics

➡ EFT interpretation of STXS results allow 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 ATLAS/CMS analyses: $H\to ZZ$, $H\to\gamma\gamma$, $H\to\tau\tau$, started exploring double Higgs analyses

➡ Developing PCA analyses to tackle large combinations/simultaneous constraints on Wilson coefficients

- very interesting step towards global EW+Higgs EFT combination, next step: including Top analyses in global fit

➡ Exciting ongoing activities on treatment of higher-order uncertainties, EFT effects in backgrounds, ….

Additional slides

ATLAS EXPERIMENT

EFT interpretation using STXS (2)

ATLAS-CONF-2021-053

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

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