The 10th Annual
Large Hadron Collider Physics Conference
May 16-21, 2022

2022 LHCP TAIPEI Online

Higgs Effective Field Theory Results at ATLAS & CMS

May, 19th 2022

LHCP2022

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Outline

- Introduction to **EFTs** & operators relevant to the **Higgs-boson sector**
- **Steps towards global EFT efforts**
  - ATLAS-CONF-2021-053
  - The **Higgs big picture**: ATLAS combined EFT interpretation of production & decay
  - ATL-PHYS-PUB-2021-010
  - ATLAS combination of ***H→WW**+jets** & **non-resonant *WW*** measurements
- HIGG-2019-13
- ATLAS **differential & inclusive *H→γγ***: EFT interpretation
- HIG-21-013
- CMS **off-shell Higgs production evidence**: BSM scenarios for the on/off-shell interplay
- HIG-19-009 HIG-20-007
- Higgs **anomalous couplings** by CMS in the $H\to ZZ^*\to 4\ell$ & $H\to\tau\tau$ decay channels

EFTs & Higgs Sector: the Theoretical Framework

- No New Physics (NP) beyond SM + Higgs boson at the LHC, increasing focus on indirect exploration
- **Effective Field Theories (EFTs)**: probe indirect signals of NP in an agnostic & systematic way ("model-independent"), see CAVEATs in J. Rojo's talk
  - Assumption: NP degrees of freedom can be integrated out, Higgs is SM-like & NP can manifest itself through **higher-dim effective interactions among SM fields**
- Non-redundant set of operators generally used by ATLAS & CMS to extract results: **Warsaw basis** (59+h.c. dim-6 operators)
- **Indirect sensitivity to NP effects enhanced on tails** (**~Q^2/Λ^2**) as compared to bulk (~v^2/Λ^2)

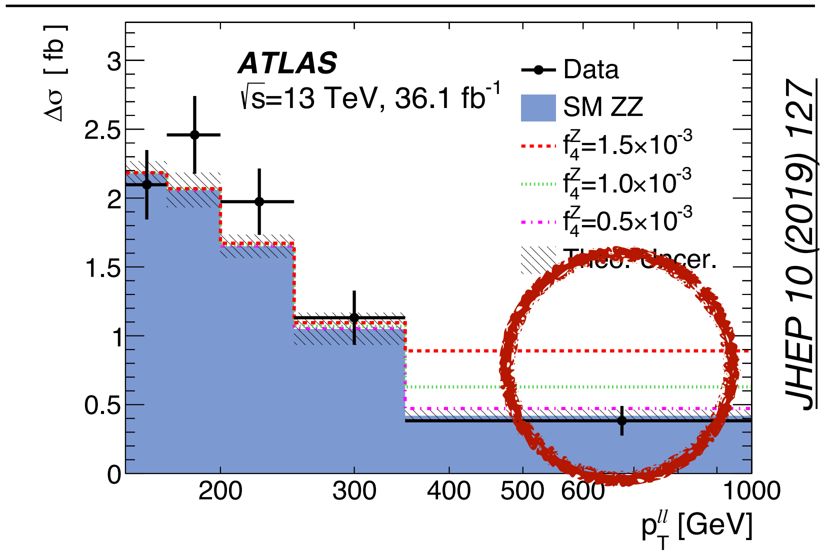
$$\mathscr{L} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i c_i^{(6)}\mathcal{O}_i^{(6)} + \frac{1}{\Lambda^4}\sum_i c_i^{(8)}\mathcal{O}_i^{(8)} + \dots$$

Scale of New Physics, typically chosen as 1 TeV

Coefficient	Operator	Example process
c_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{H}\,G^A_{\mu\nu}$	g g → t t̄ H
c_{uW} c_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{H}\,W^I_{\mu\nu}$ $(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\,B_{\mu\nu}$	q q → Z → t t̄ H
$c^{(1)}_{qq}$ $c^{(3)}_{qq}$ c_{qq} $c^{(31)}_{qq}$ c_{uu} $c^{(1)}_{uu}$ $c^{(1)}_{qu}$ $c^{(8)}_{ud}$ $c^{(8)}_{qu}$ $c^{(8)}_{qd}$	$(\bar{q}_p\gamma_\mu q_t)(\bar{q}_r\gamma^\mu q_s)$ $(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$ $(\bar{q}_p\gamma_\mu q_t)(\bar{q}_r\gamma^\mu q_s)$ $(\bar{q}_p\gamma_\mu\tau^I q_t)(\bar{q}_r\gamma^\mu\tau^I q_s)$ $(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$ $(\bar{u}_p\gamma_\mu u_t)(\bar{u}_r\gamma^\mu u_s)$ $(\bar{q}_p\gamma_\mu q_t)(\bar{u}_r\gamma^\mu u_s)$ $(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$ $(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$ $(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$	q q → t t̄ H
c_G	$f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	g g → t t̄ H

See A. Martin's talk

ATLAS-CONF-2020-053



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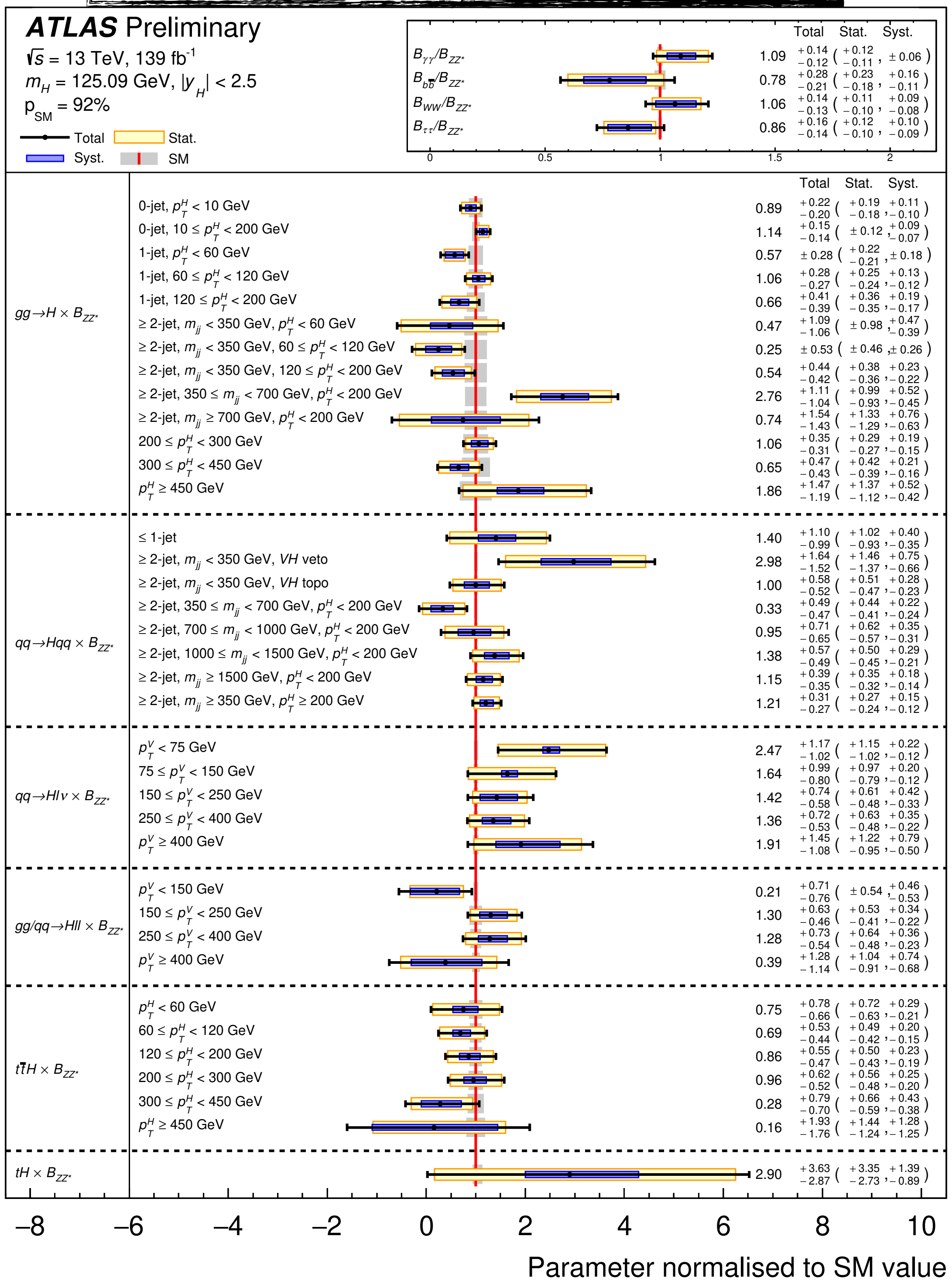
Coefficient	Operator	Example process
c_{HDD}	$\left(H^\dagger D^\mu H\right)^*\left(H^\dagger D_\mu H\right)$	q q → Z Z → q q H
c_{HG}	$H^\dagger H\,G^A_{\mu\nu}G^{A\mu\nu}$	g g → H
c_{HB}	$H^\dagger H\,B_{\mu\nu}B^{\mu\nu}$	q q → Z Z → q q H
c_{HW}	$H^\dagger H\,W^I_{\mu\nu}W^{I\mu\nu}$	q q → W W → q q H
c_{HWB}	$H^\dagger\tau^I H\,W^I_{\mu\nu}B^{\mu\nu}$	q q → γ Z → q q H
c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$	H → ℓ ℓ
$c^{(1)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$	q q → Z → ℓ ℓ H
$c^{(3)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p\tau^I\gamma^\mu l_r)$	q q → W → ν ℓ H
c_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$	q q → Z → e e H
$c^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$	q q → Z H → ℓ ℓ H
$c^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p\tau^I\gamma^\mu q_r)$	q q → W H → ℓ ν H
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$	u u → Z H → ℓ ℓ H
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$	d d → Z H → ℓ ℓ H

EFT Interpretation of ATLAS Higgs STXS Combination

ATLAS-CONF-2021-053

- **STXS framework**: fiducial bins to measure kinematic properties of the Higgs boson production across decay channels
    - Kinematic regions help **isolate NP effects,** typically **tails** of distributions with enhanced sensitivity
    - This approach does **not** require **detector-level SMEFT simulation** -> acceptance corrections
    - **37 kinematic bins** across 5 production modes, exploiting 5 major decay channels (*bb, WW*, ττ, ZZ*, γγ*)
- Measurements **statistically limited**

Cross-section results from STXS regions

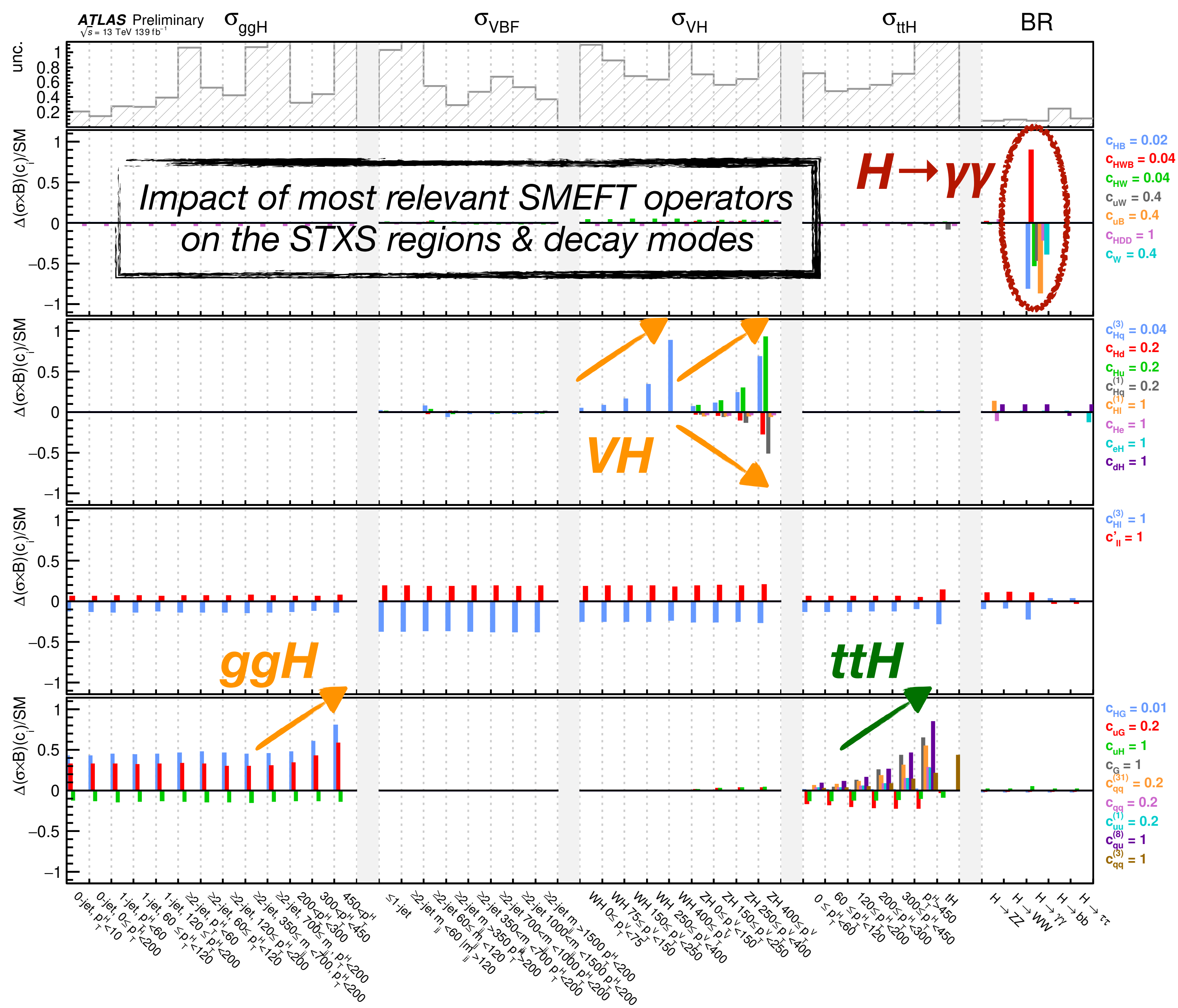


Last “preliminary” result by CMS: CMS-PAS-HIG-19-005

EFT Interpretation of ATLAS Higgs STXS Combination

ATLAS-CONF-2021-053

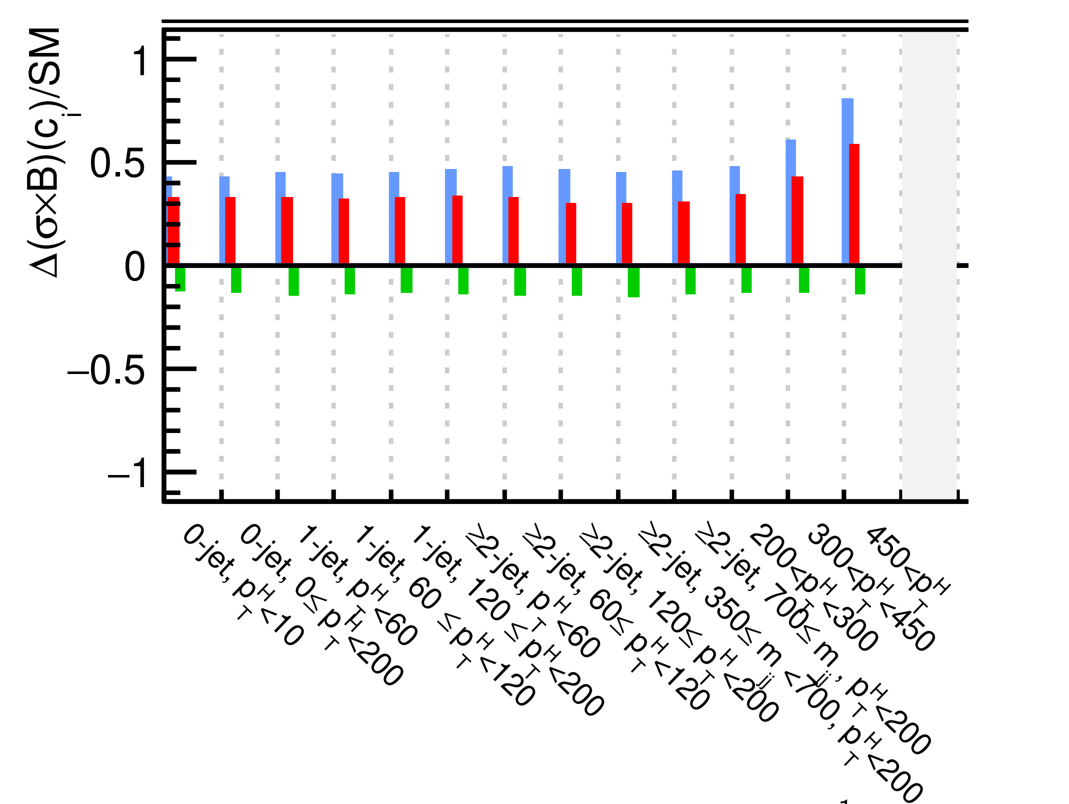
- SMEFT dependence parameterised as polynomials in Wilson coefficients
  - **Only linear dependence** considered for current result
  - SMEFTSim (SMEFTatNLO) for tree-level EFT contributions (loop-induced QCD processes)
- Relative impact of most relevant operators wrt SM
  - **Increasing impact vs. $p_T^V \sim p_T^H$**
  - **Strong effects in the $H\to\gamma\gamma$ decay BR**
- Many operators lead to similar modifications: not enough info in measurements to constrain them all
  - **-> Principal Component Analysis**

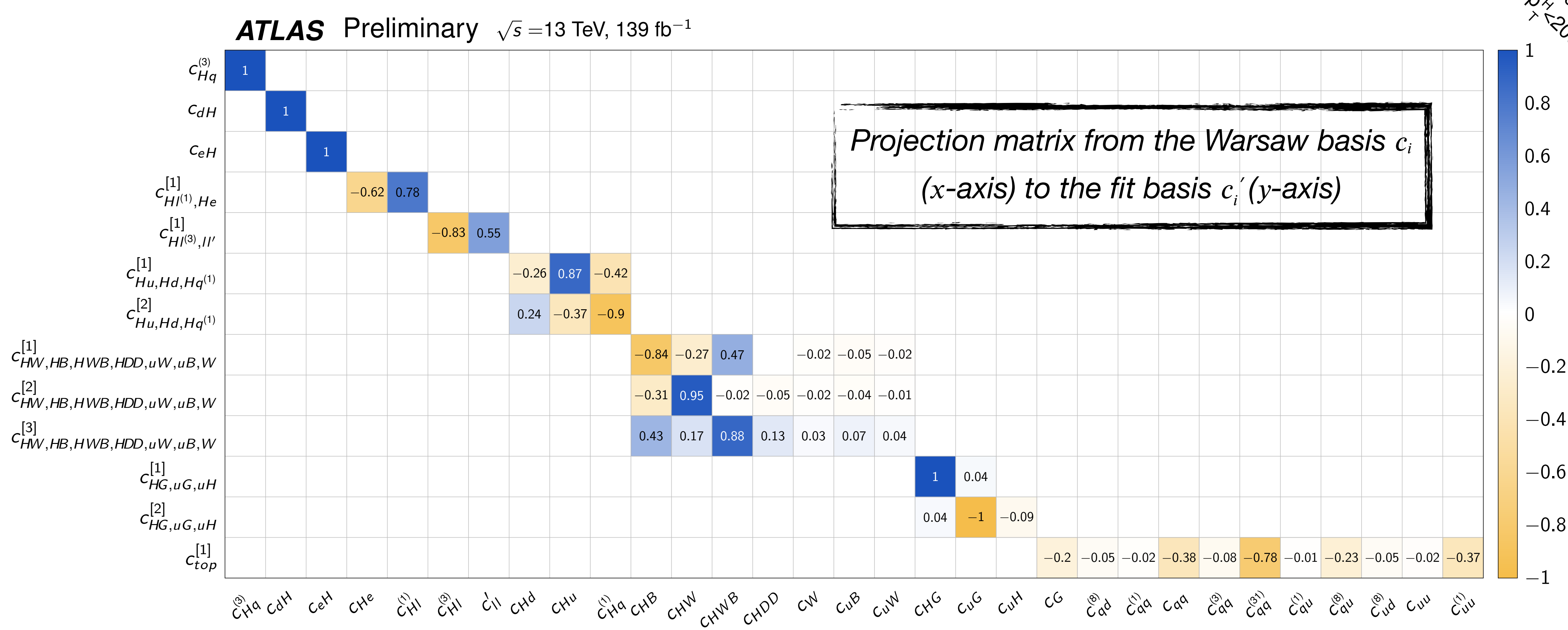


When Information is Not Enough… PCA

ATLAS-CONF-2021-053

- What if we really wanted to **constrain many operators at the same time**?
  - Many operators tend to have **similar impact**
  - **Not enough information** in measurements to constrain all EFT parameters
- **Principal Component Analysis (PCA)** of Fisher information to identify sensitive directions
- Fit **basis** defined with PCA in operator groups - fit only sensitive components, **rest fixed to SM**
- Operator grouping dictated by **experimental sensitivity**

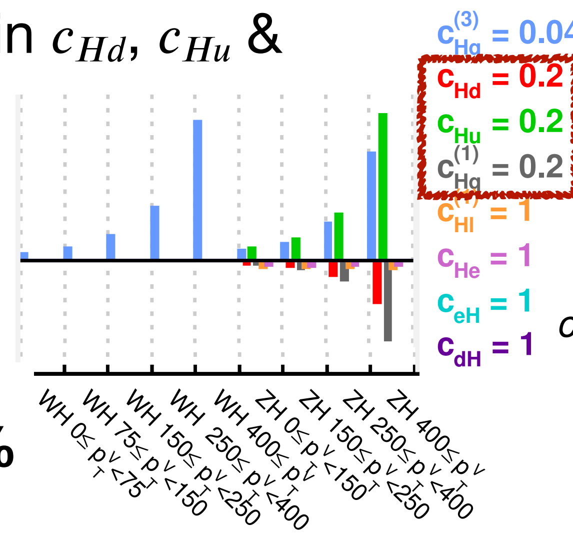


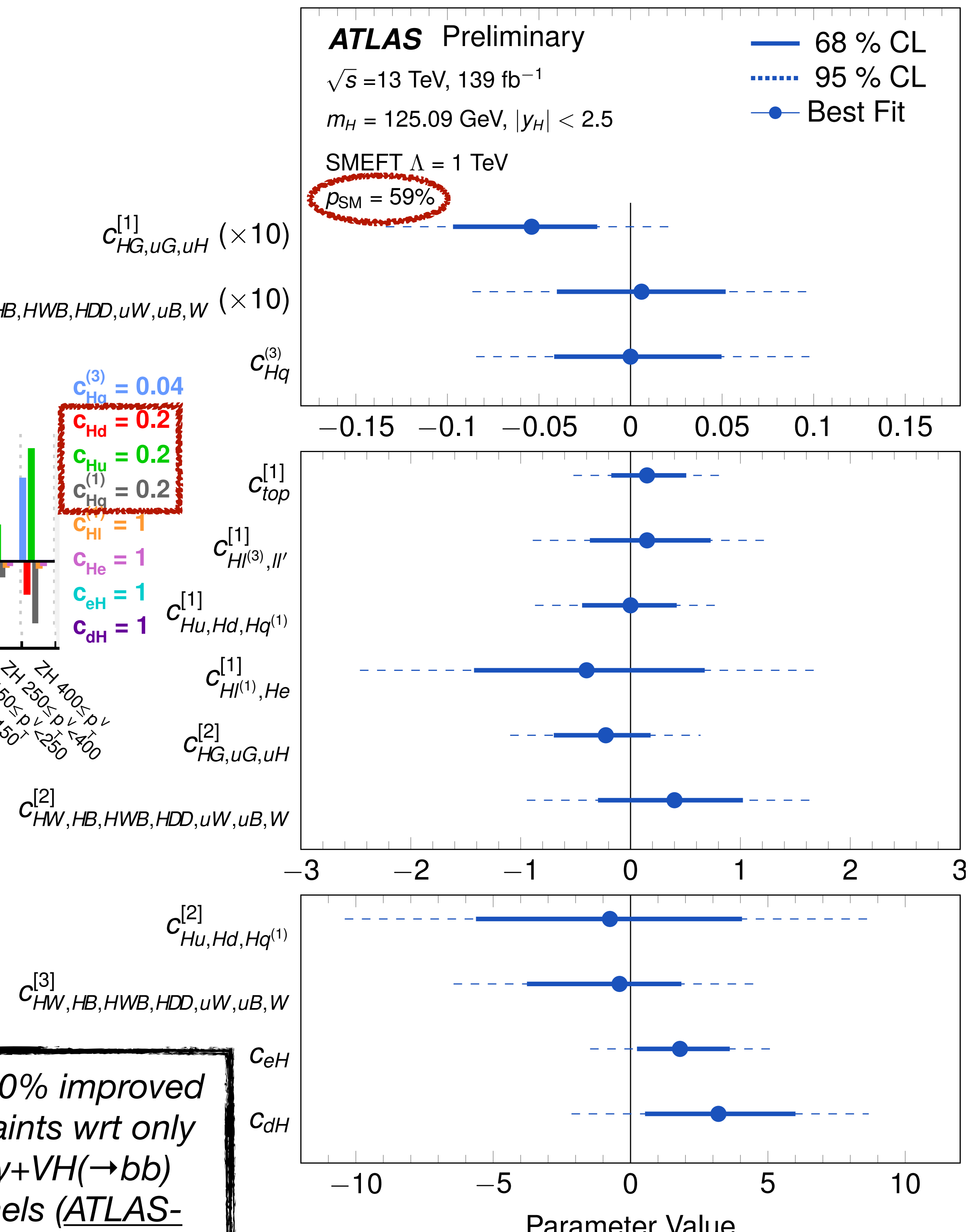


EFT Interpretation of ATLAS Higgs STXS Combination

ATLAS-CONF-2021-053

- Limits obtained from **simultaneously measuring 3(10 linear combinations of) Wilson coefficients**
- ***VH* differential** binning able to constrain **2 directions**, completely degenerate in c_{Hd}, c_{Hu} & $c^{(1)}_{Hq}$ otherwise
- Data is consistent with the SM, **59% compatibility** *p*-value
- **Limits** provide a proxy to the **allowed scale of New Physics** in the relevant processes
  - $c^{(3)}_{Hq} < 0.1 \rightarrow \frac{\Lambda}{\sqrt{c^{(3)}_{Hq}}} > 3$ TeV

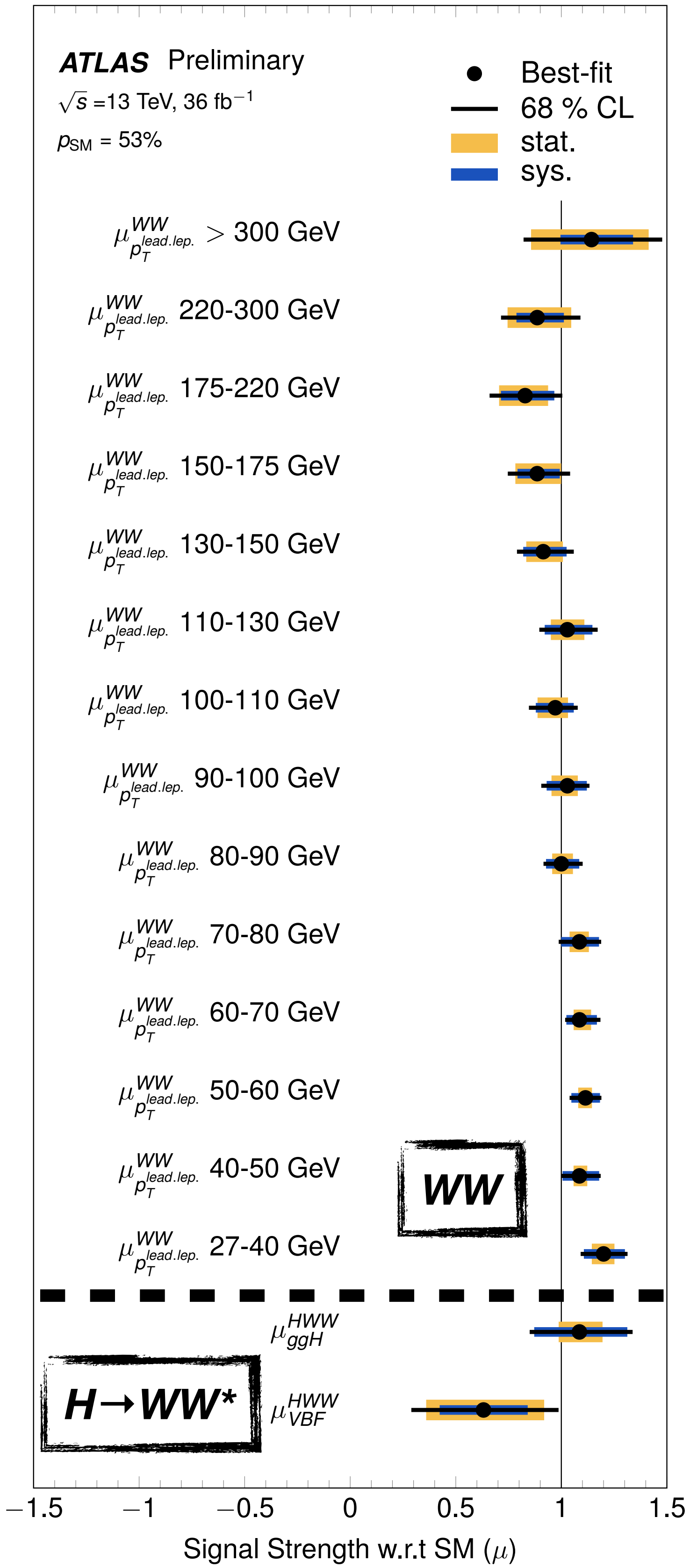




Up to 70% improved constraints wrt only 4ℓ+γγ+VH(→bb) channels (ATLAS-CONF-2020-053)

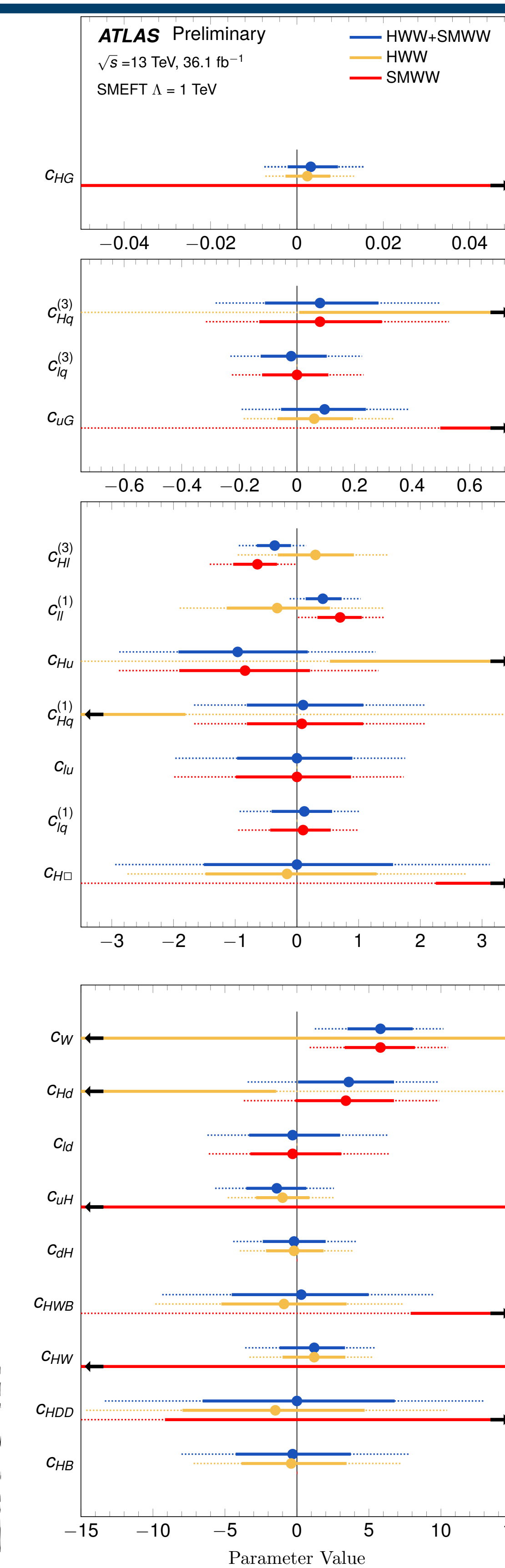
Towards a Global EFT: *H→WW** & *WW* Combination

ATL-PHYS-PUB-2021-010



- **Template analysis to overcome challenges foreseen for future (global) EFT combinations of measurements**
- Input analyses: ATLAS **resonant *H→WW**** (*ggH* & *VBF*, 1 free par/mode) & **non-resonant *WW*** (unfolded differential xsec) measurements at 36.1 fb^{-1} (2015 & 2016 datasets)
    - **Overlap** in event selections removed & **correlation of systematic** uncertainties carefully studied to build final fit model

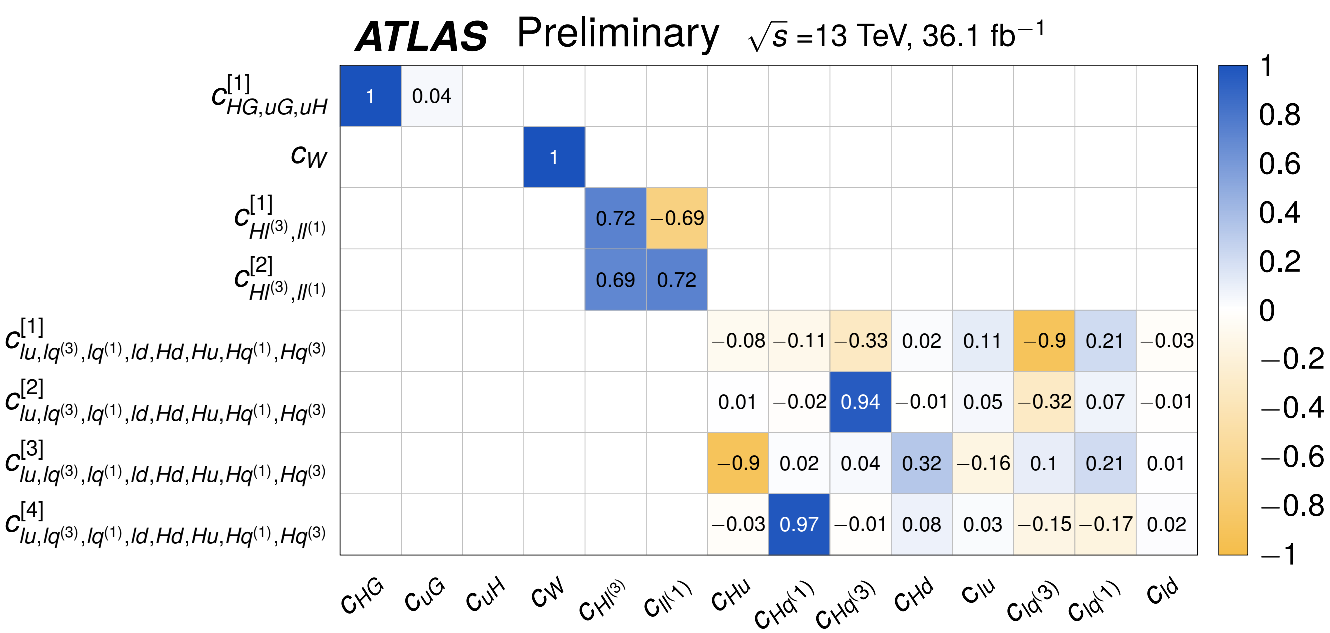
Scans of all Wilson coefficients one-at-a-time with others fixed to 0

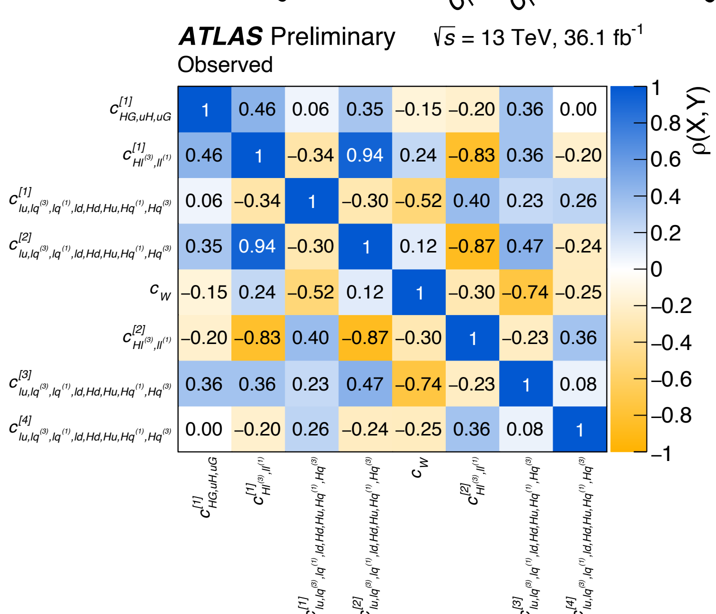


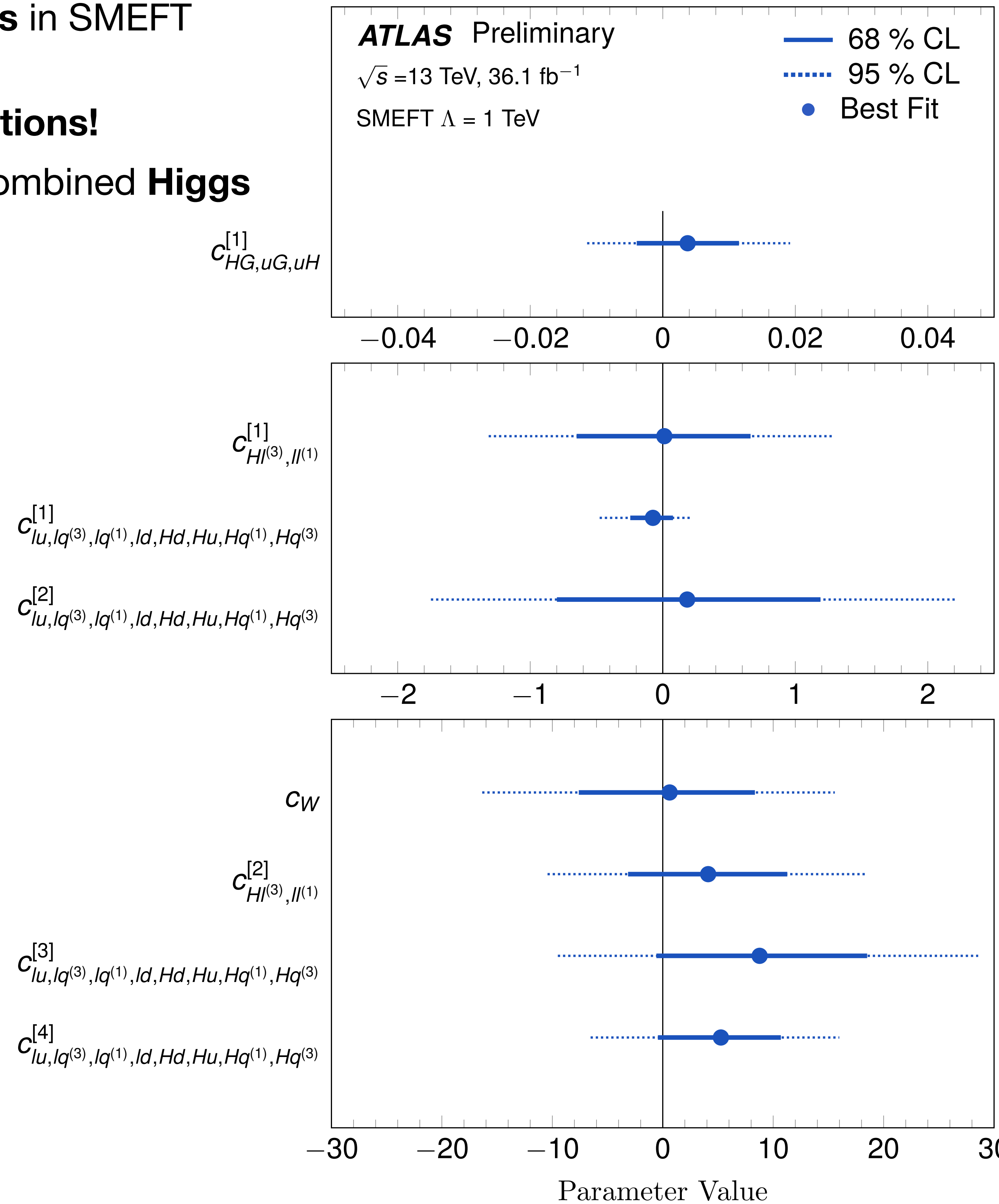
Towards a Global EFT: $H \to WW^*$ & WW Combination

ATL-PHYS-PUB-2021-010

- **PCA** exploited
- Simultaneously probe **8 mutually orthogonal directions** in SMEFT parameter space using the $H \to WW^*$ + WW inputs
- **Proof-of-concept towards more global EFT combinations!**
  - Next step: perform EFT fit **simultaneously** on all combined **Higgs STXS** & **all combined EW data** (work in progress)



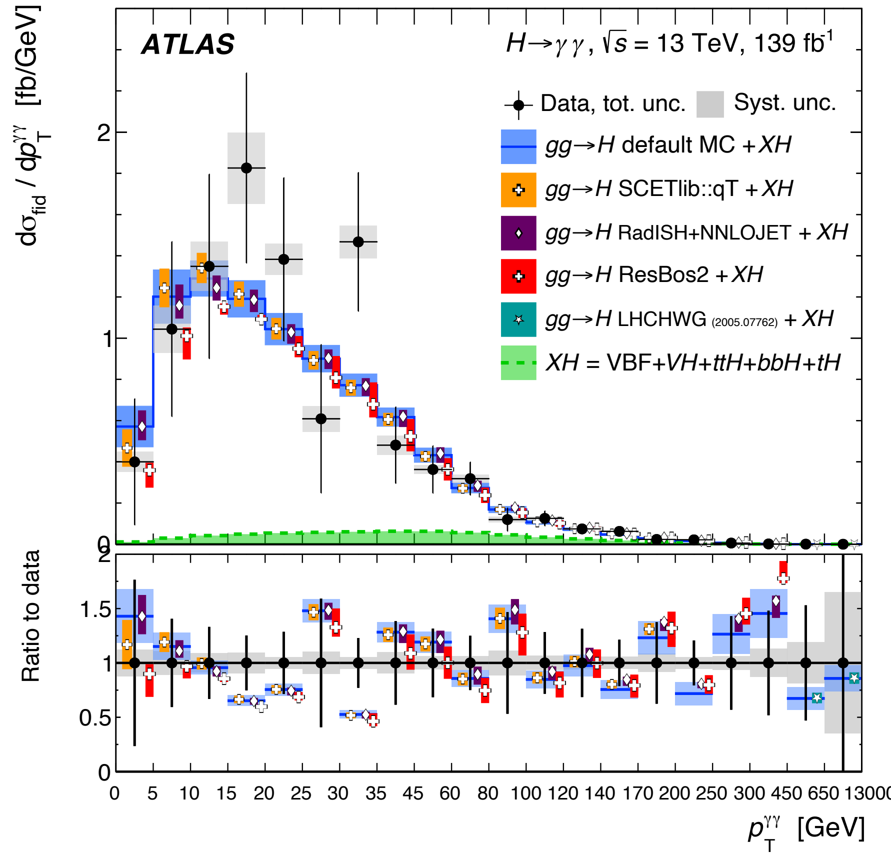


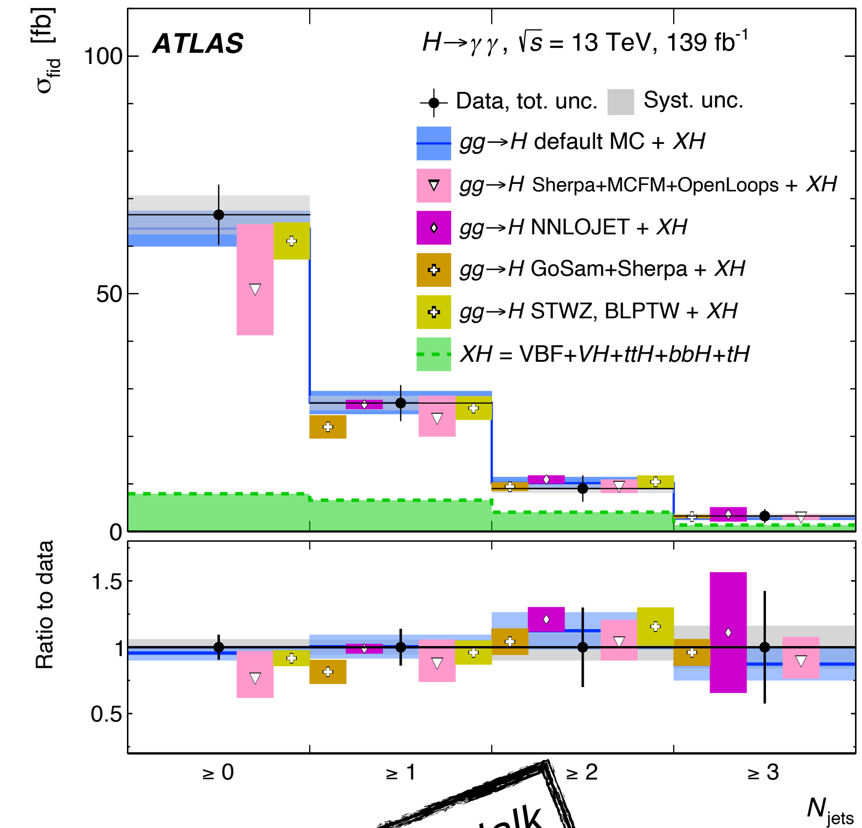


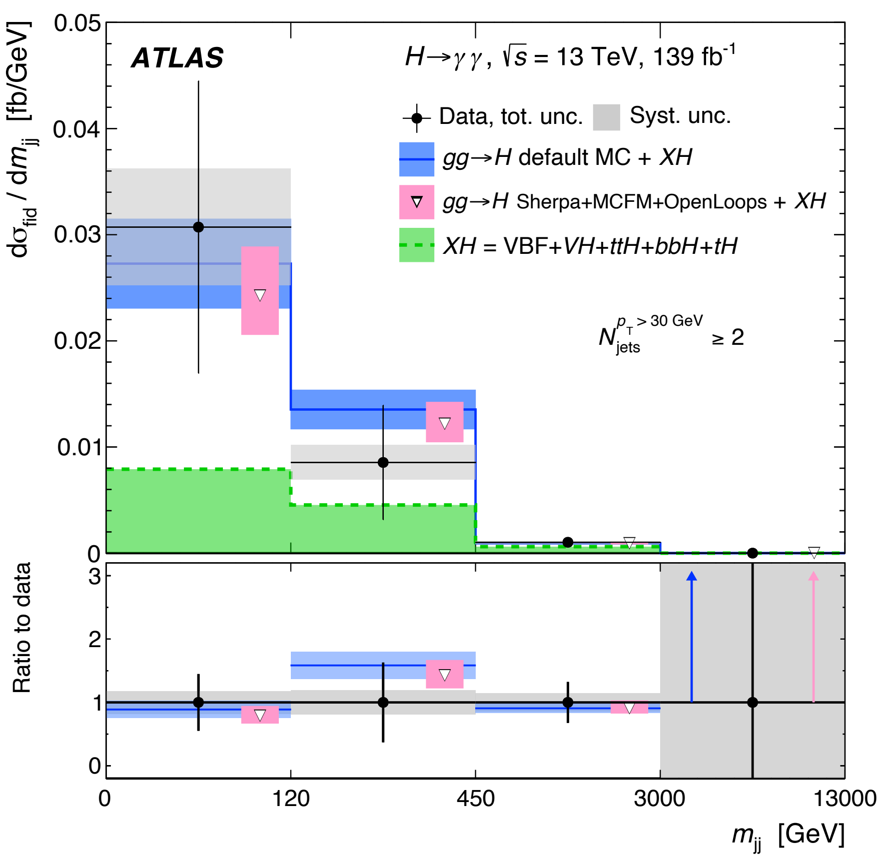
Inclusive & Diff Fiducial Cross-Sections in $H\rightarrow\gamma\gamma$

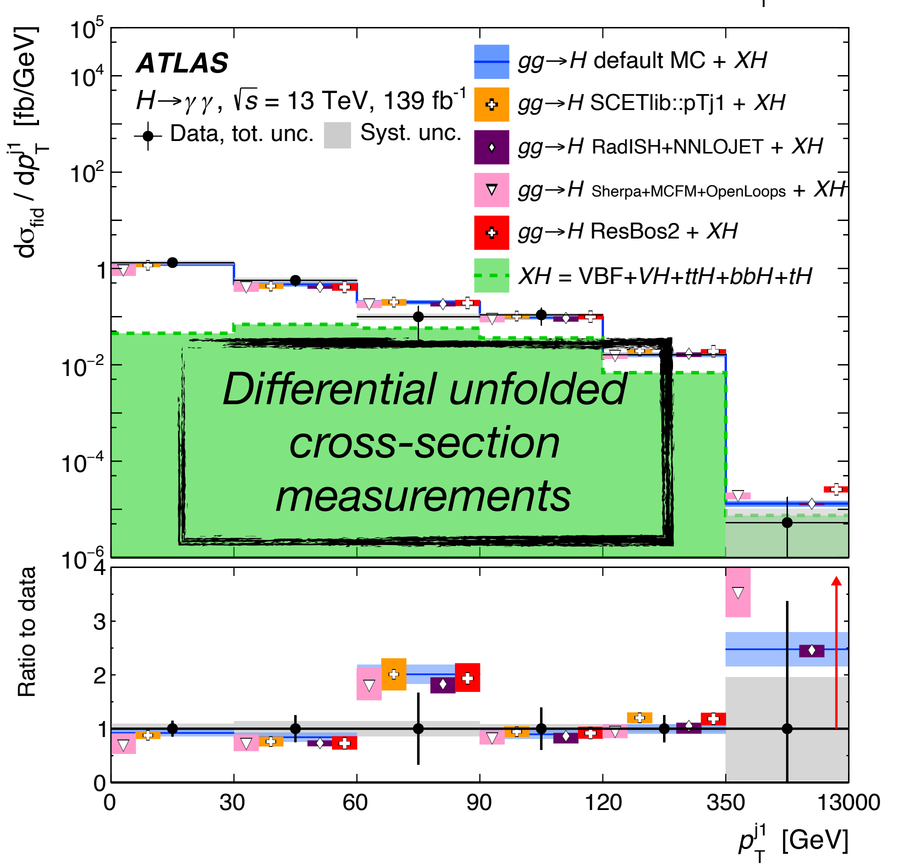
HIGG-2019-13

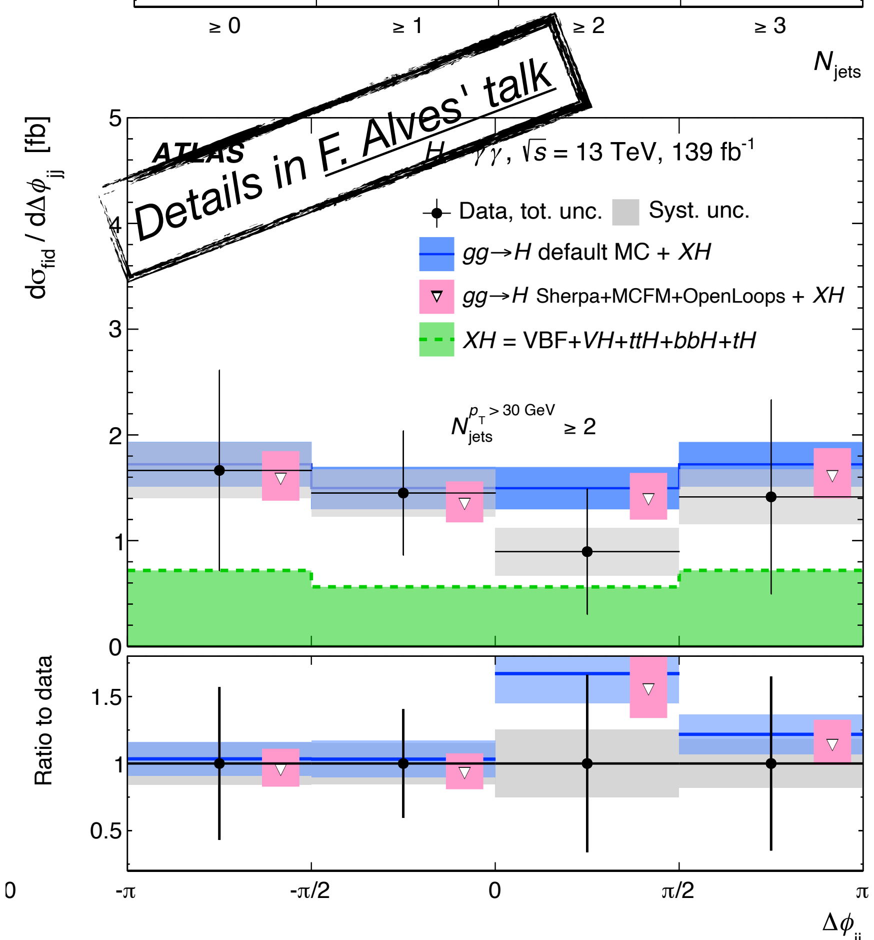
- **Twenty differential unfolded cross-sections**
    - As functions of $p_T^{\gamma\gamma}$, N_{jets} , m_{jj}, p_T^{j1} & $\Delta\Phi_{jj}$
- **Statistical uncertainty dominates**
- Results in **agreement with SM** predictions







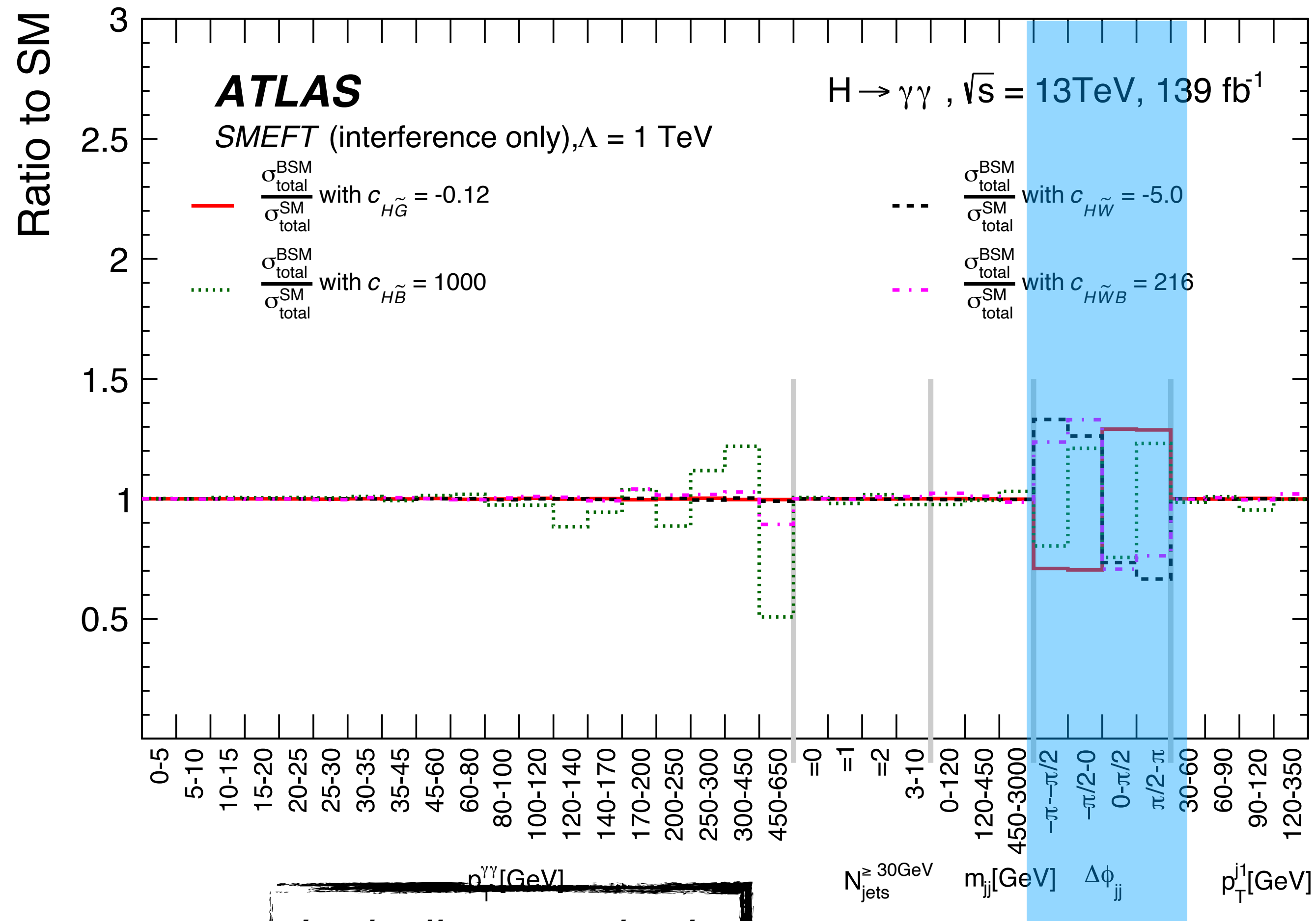




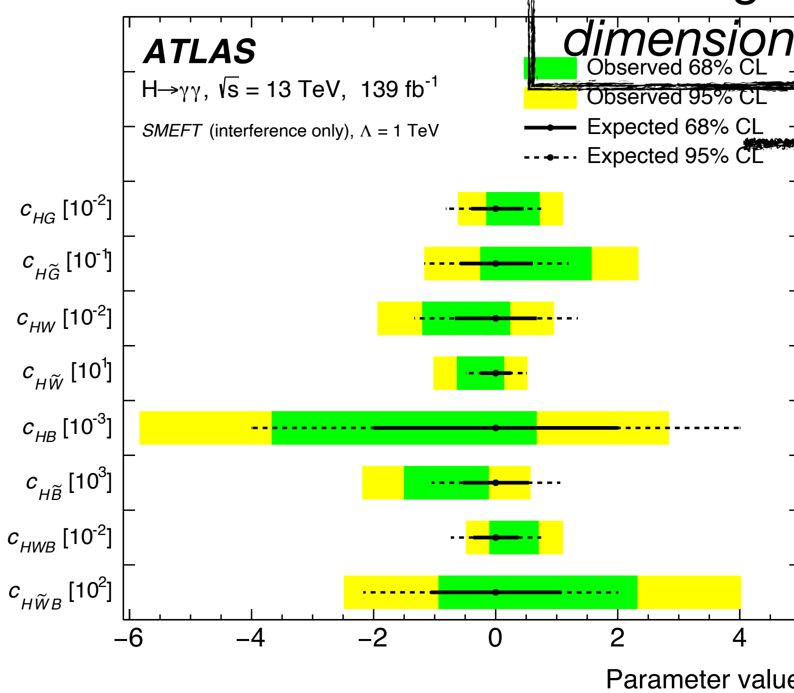
Inclusive & Diff Fiducial Cross-Sections in $H\to\gamma\gamma$: EFT

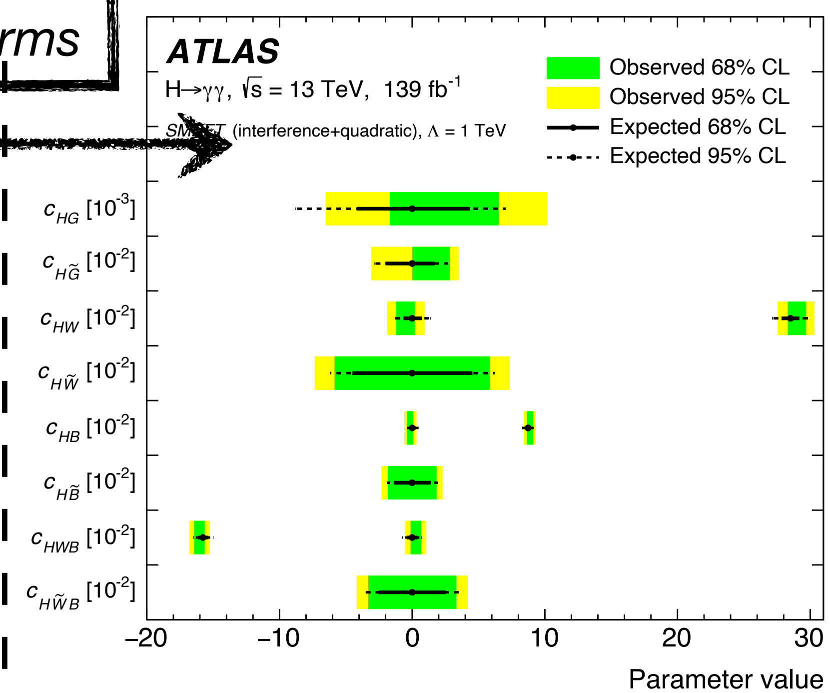
HIGG-2019-13

- $\Delta\Phi_{jj}$ observable only is sensitive to CP-odd coefficients, with interference only
- Sizable **effect of quadratic terms** from dim-6 operators
    - **Same order as neglected interference terms from dim-8 operators**
- SMEFT constraints extracted on **8 Wilson coefficients** (one at a time, others fixed to 0)



Including quadratic dimension-6 terms

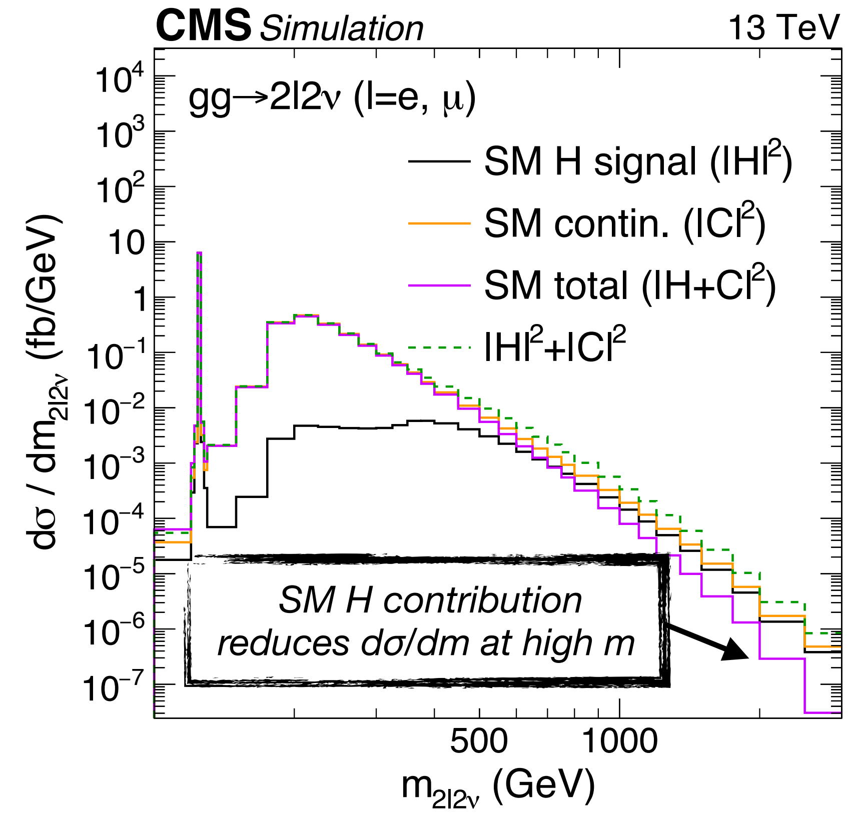


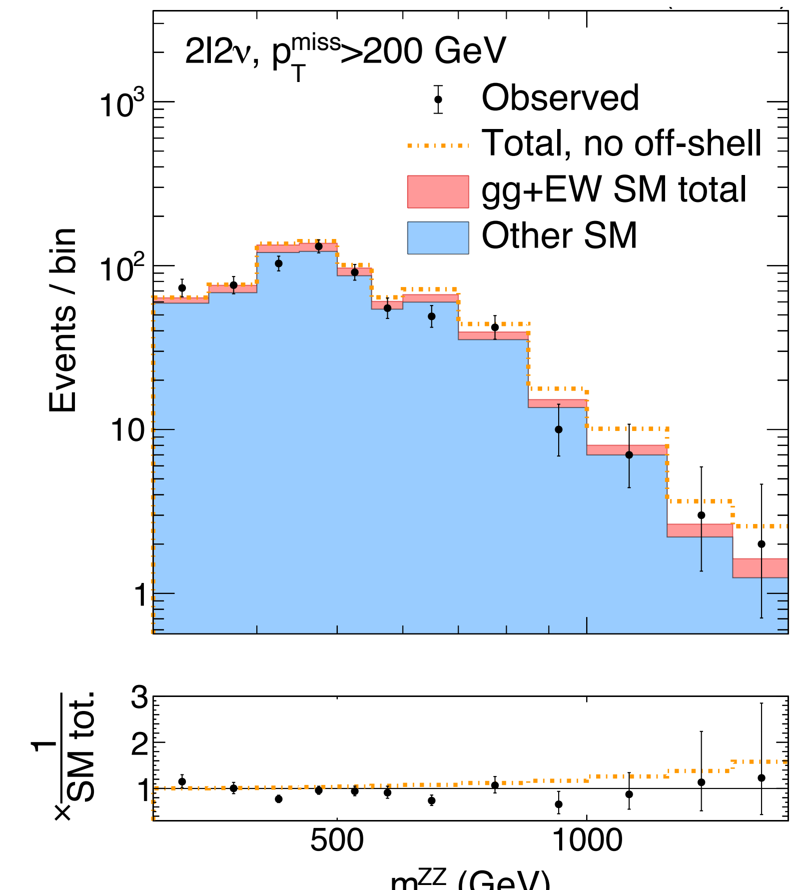


Off-Shell Evidence & BSM Scenarios

HIG-21-013

- Measurement of **Higgs width**
  - Null width ↔ no SM H contribution , large width ↔ increased $d\sigma / dm_{2\ell 2\nu}$
- Off-shell Higgs production in $H \rightarrow ZZ^* \rightarrow 2\ell 2\nu$ is very sensitive to **CP-violating couplings**
- **3.6σ** exclusion of no off-shell (no-width) scenario, **first evidence for off-shell production of the Higgs boson** !
- The **combination** of $2\ell 2\nu$ off-shell analysis **with 4ℓ** analyses has significant sensitivity to ***HVV*** **CP** contributions





Off-Shell Evidence & BSM Scenarios

HIG-21-013

- Effect of *HVV* couplings on the Higgs width tested
  - Parameterisation of **anomalous *HVV*** contributions: ***a₂*** CP-conserving, ***a₃*** CP-violating & ***Λ₁*** first-order term in the expansion of SM-like tensor structure with dipole form factor in invariant masses of the 2 *Z* bosons

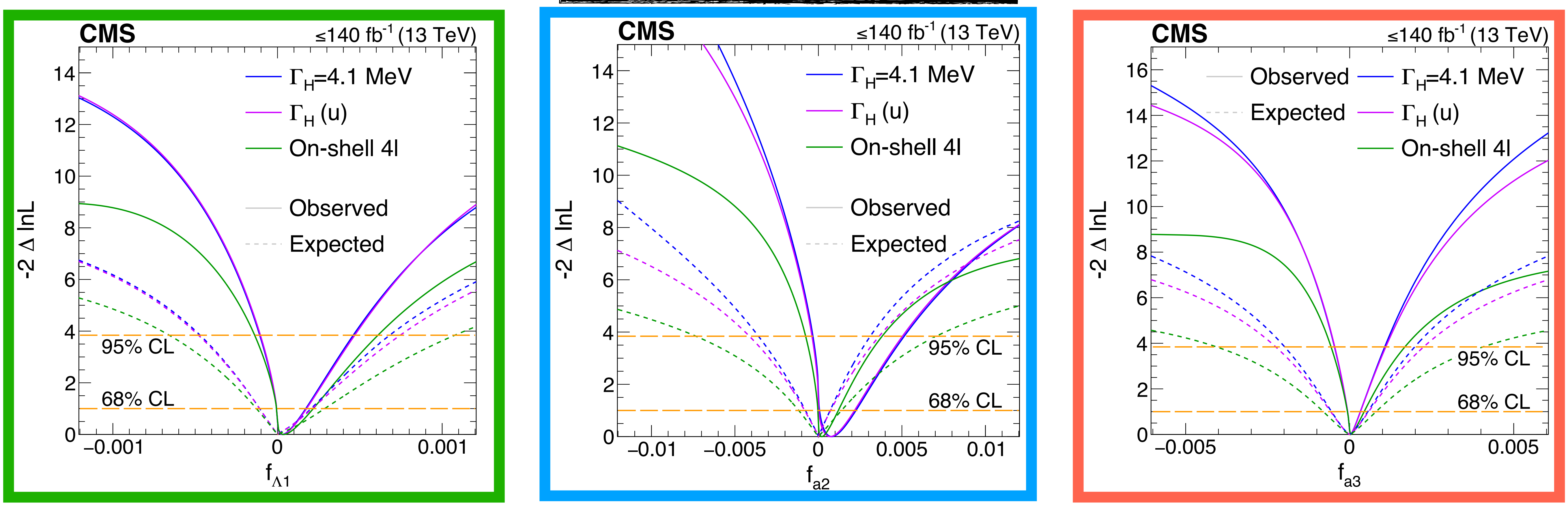
$$\mathcal{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

$$\sigma(j \to H \to f) \propto \frac{\left(\sum_{il} \alpha_{il}^{(j)} a_i a_l\right)\left(\sum_{mn} \alpha_{mn}^{(f)} a_m a_n\right)}{\Gamma_H}$$

Narrow-width approximation

- Ratios of couplings can be expressed through **fractional contributions f_{ai} of the couplings a_i to xsec of a given decay**

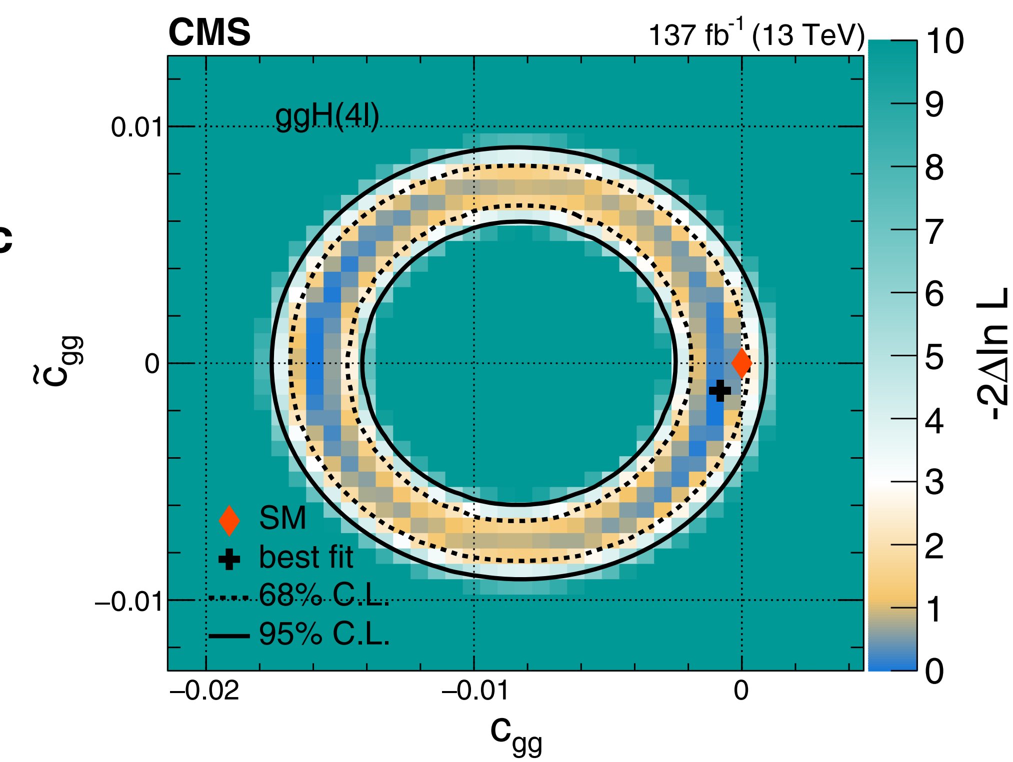
Assumption: ggH loop amplitudes do not receive BSM contributions

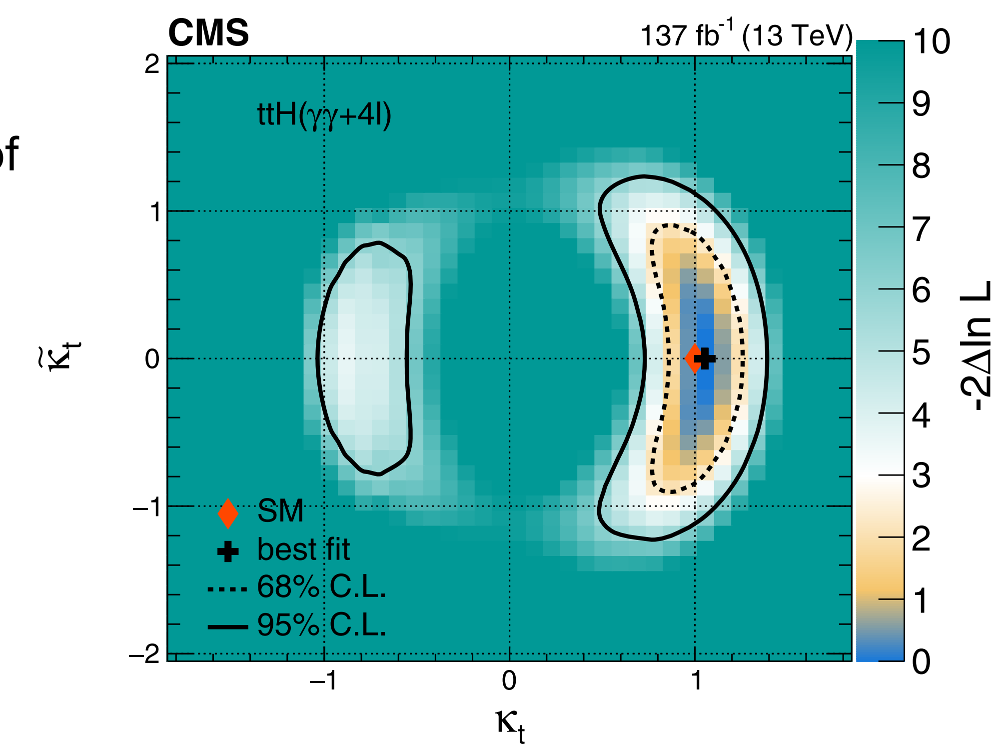


Constraints on Anomalous Higgs Couplings using $H\to4\ell$

HIG-19-009

- Comprehensive study: **CP-violation, anomalous couplings & tensor structure of Higgs interactions** in ***$H\to ZZ^*\to4\ell$* decay**
- Detector-level matrix-element based observables defined using **kinematic properties** of particles in production & decay
- **Parameterisation** of **production & decay** based on scattering amplitude then connected to **SMEFT formulation**
  - CP-even/odd **Higgs-gluon effective** & **top-quark Yukawa couplings constrained** by *ggH* & *ttH*
  - Impose SU(2)×U(1) symmetry to **relate parameters to SMEFT**
  - Operator basis chosen as couplings of mass eigenstates: translation of SMEFT results to bosonic **dim-6 operators in Warsaw basis**





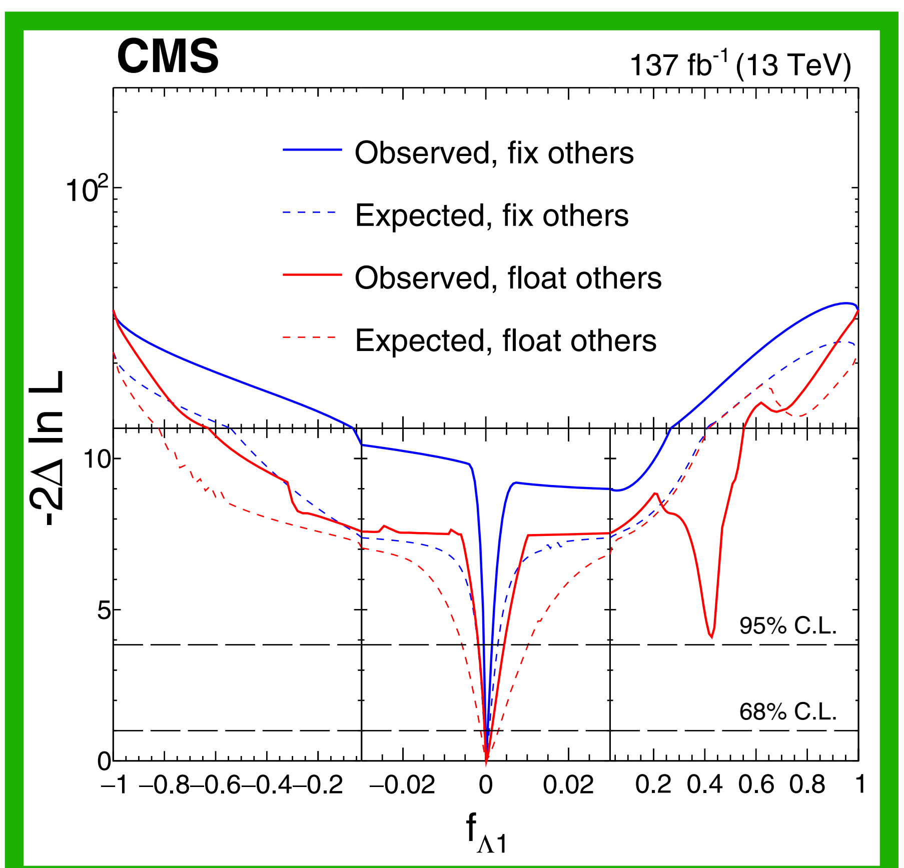
Channels	Coupling	Observed	Expected
Assumption: only 1/3 parameters in (c_{HW}, c_{HWB}, c_{HB}) is independent	$c_{H\Box}$	$0.04^{+0.43}_{-0.45}$	$0.00^{+0.75}_{-0.93}$
VBF & VH & $H\to4\ell$	c_{HD}	$-0.73^{+0.97}_{-4.21}$	$0.00^{+1.06}_{-4.60}$
	c_{HW}	$0.01^{+0.18}_{-0.17}$	$0.00^{+0.39}_{-0.28}$
	c_{HWB}	$0.01^{+0.20}_{-0.18}$	$0.00^{+0.42}_{-0.31}$
	c_{HB}	$0.00^{+0.05}_{-0.05}$	$0.00^{+0.03}_{-0.08}$
	$c_{H\tilde{W}}$	$-0.23^{+0.51}_{-0.52}$	$0.00^{+1.11}_{-1.11}$
	$c_{H\tilde{W}B}$	$-0.25^{+0.56}_{-0.57}$	$0.00^{+1.21}_{-1.21}$
	$c_{H\tilde{B}}$	$-0.06^{+0.15}_{-0.16}$	$0.00^{+0.33}_{-0.33}$

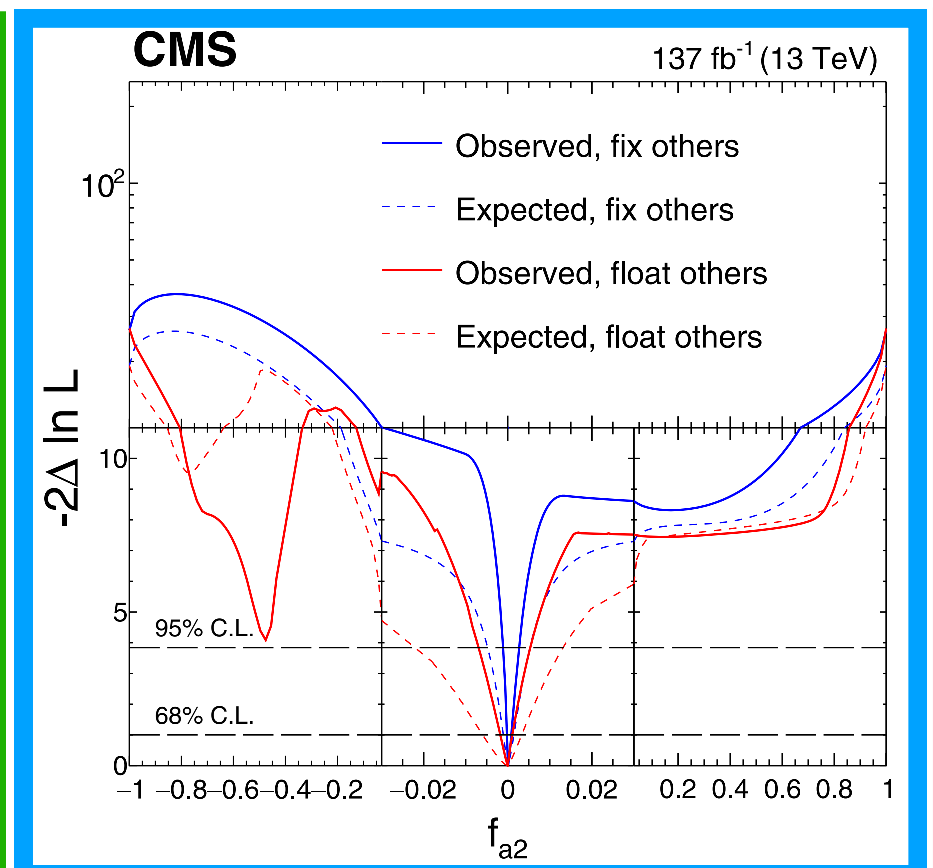
Similar CP-odd/even k_t results in ATLAS-CONF-2022-016

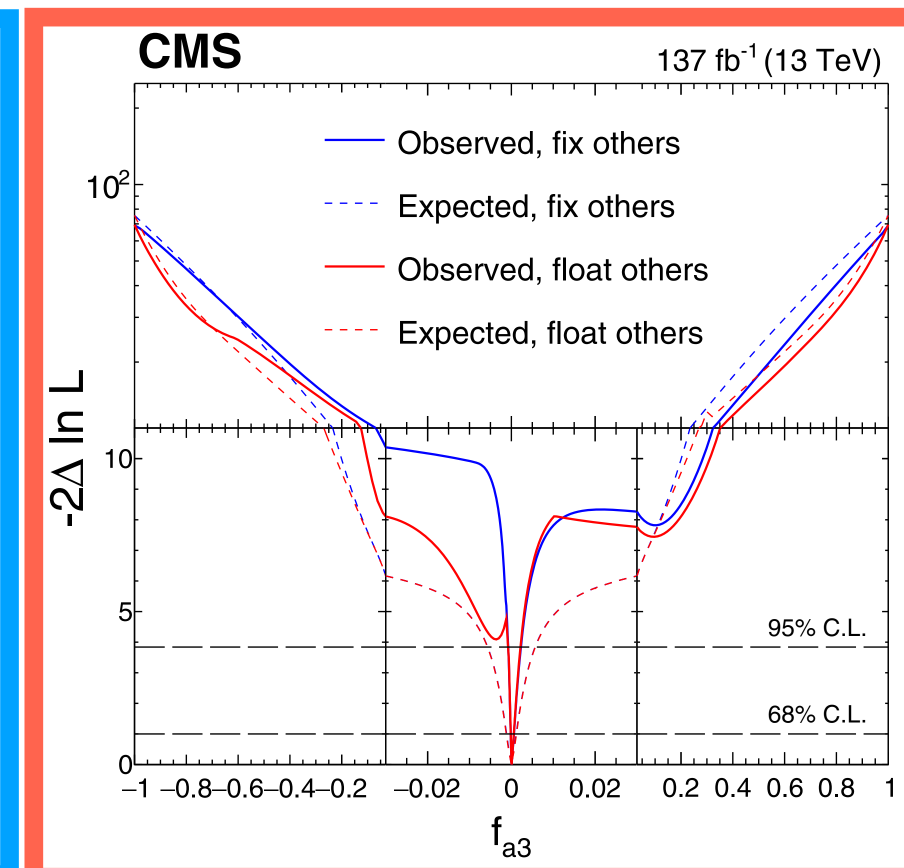
Constraints on Anomalous Higgs Couplings using $H\to4\ell$

HIG-19-009

- **Diff cross-sections parameterised**
  - a_i=real couplings describing *HVV*, *Hff* or *Hgg* vertex
- **Signal strength** parameters **unconstrained** in all cases
  - Measured signal strengths: $\mu_{ggH}=0.86^{+0.13}_{-0.11}$, $\mu_{VH+VBF}=1.10^{+0.50}_{-0.42}$, $\mu_{ttH}=0.17^{+0.70}_{-0.17}$







Constraints on Anomalous Higgs Couplings using $H \to \tau\tau$

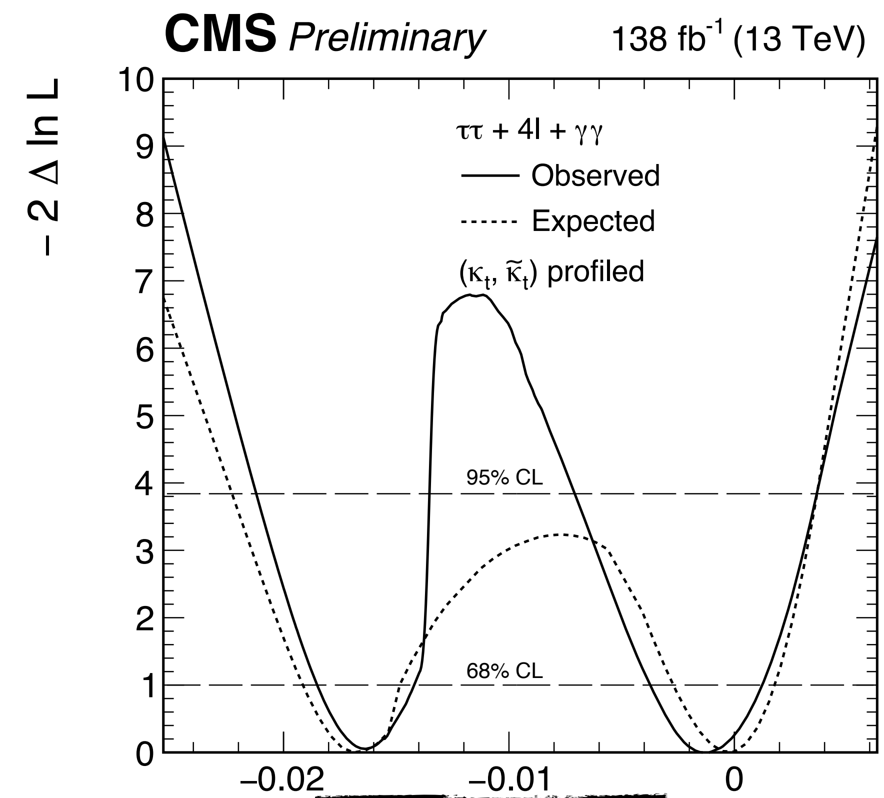
HIG-20-007

- Study of **anomalous interactions** of the *H* boson with vector bosons, including CP violation in the ***H→ττ* decay channel produced through *ggH* & *VBF+VH***
    - Use 4 most sensitive channels: $\tau_{had}\tau_{had}$, $\mu\tau_{had}$, $e\tau_{had}$, $e\mu$
- **Matrix-element variables** used to separate anomalous couplings from SM
- **Combination with *4ℓ* & *γγ*** to constrain anomalous couplings
- **Anomalous CP-even/odd couplings translated into EFT parameters** in addition to κ_f & $\tilde{\kappa}_f$:

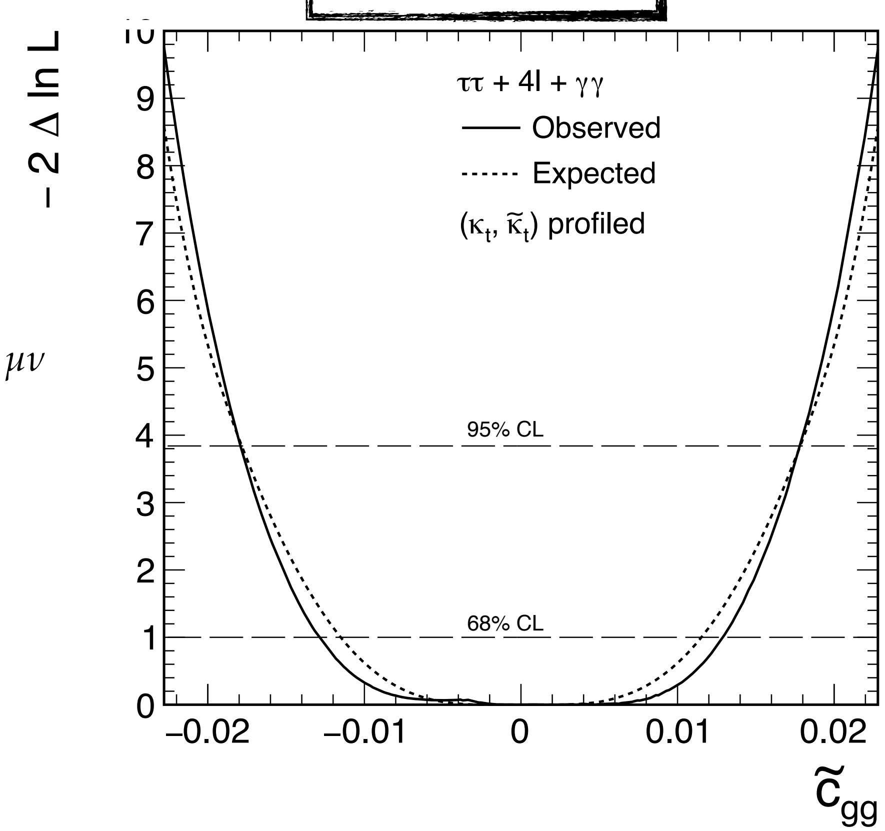
$$\mathcal{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V}1}^2 \epsilon_{\mathrm{V}1}^* \epsilon_{\mathrm{V}2}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

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

- ***c_{gg}* & *$\tilde{c}_{gg}$* constraints profiling κ_t & $\tilde{\kappa}_t$** (constrained by *ttH/tH(4ℓ/γγ)*)



κt & κ̃t profiled



Conclusion

- Several Higgs EFT studies produced by the ATLAS & CMS Collaborations
- **No significant deviations from the Standard Model observed** (so far!)
- Innovative techniques & growing pool of EFT combinations to overcome limited info/sensitivity from "single" inputs
    - Use of **basis rotation** to extract maximum information
    - **Tests of combinations of measurements** from Higgs & other sectors
- Clear roadmap ahead: **combine Higgs with EW & top measurements**
    - Combined EW interpretation available already, see talk by E. Soldatov
- Stay tuned for more & more stringent EFT results to come!

ADDITIONAL MATERIAL

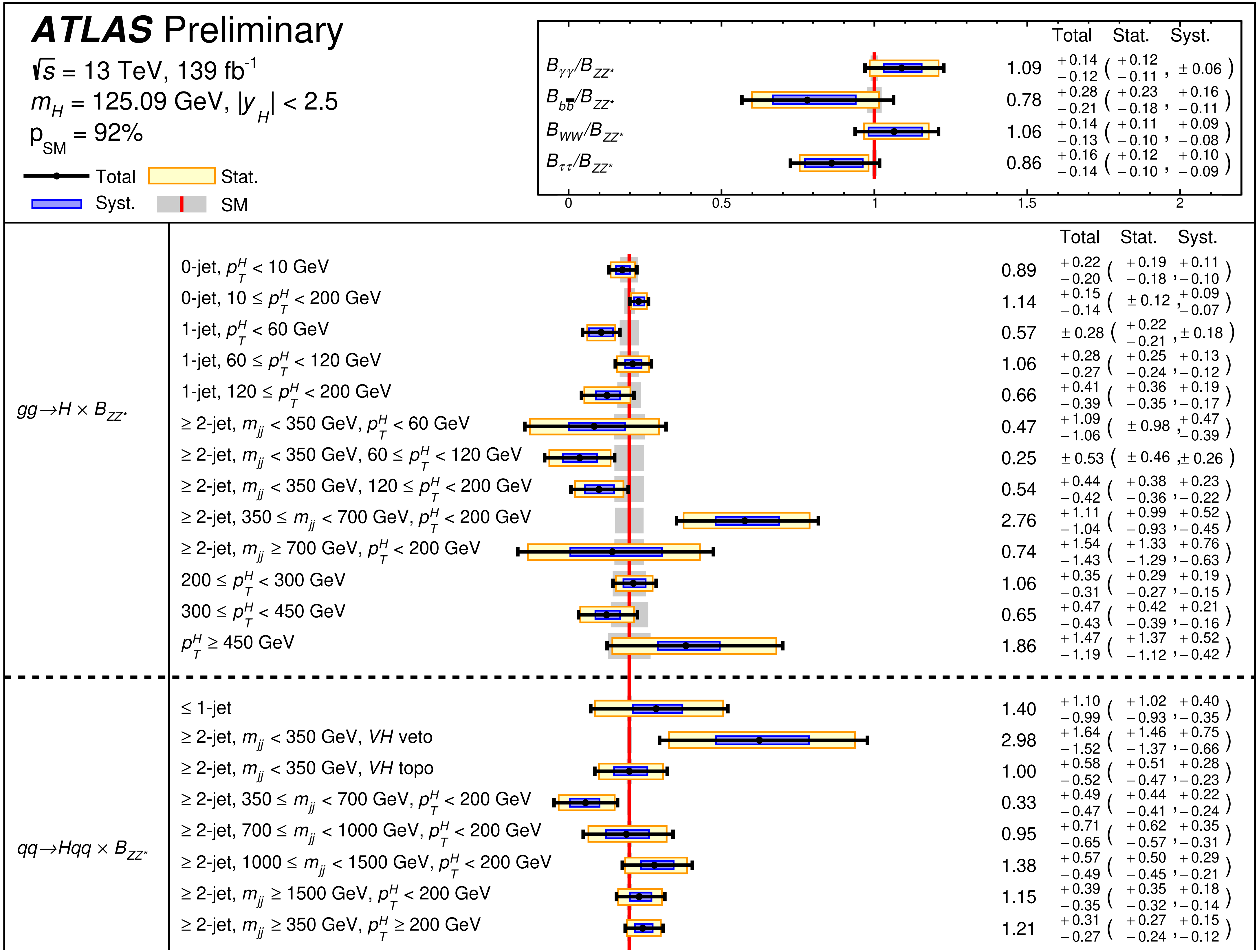
EFTs & Higgs Sector: List of dim-6 Operators

Wilson coefficients c_i & corresponding dimension-6 SMEFT operators $O_i^{(6)}$ used in ATLAS-CONF-2021-053

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}	$\left(H^\dagger D^\mu H\right)^*\left(H^\dagger D_\mu H\right)$	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	$f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$

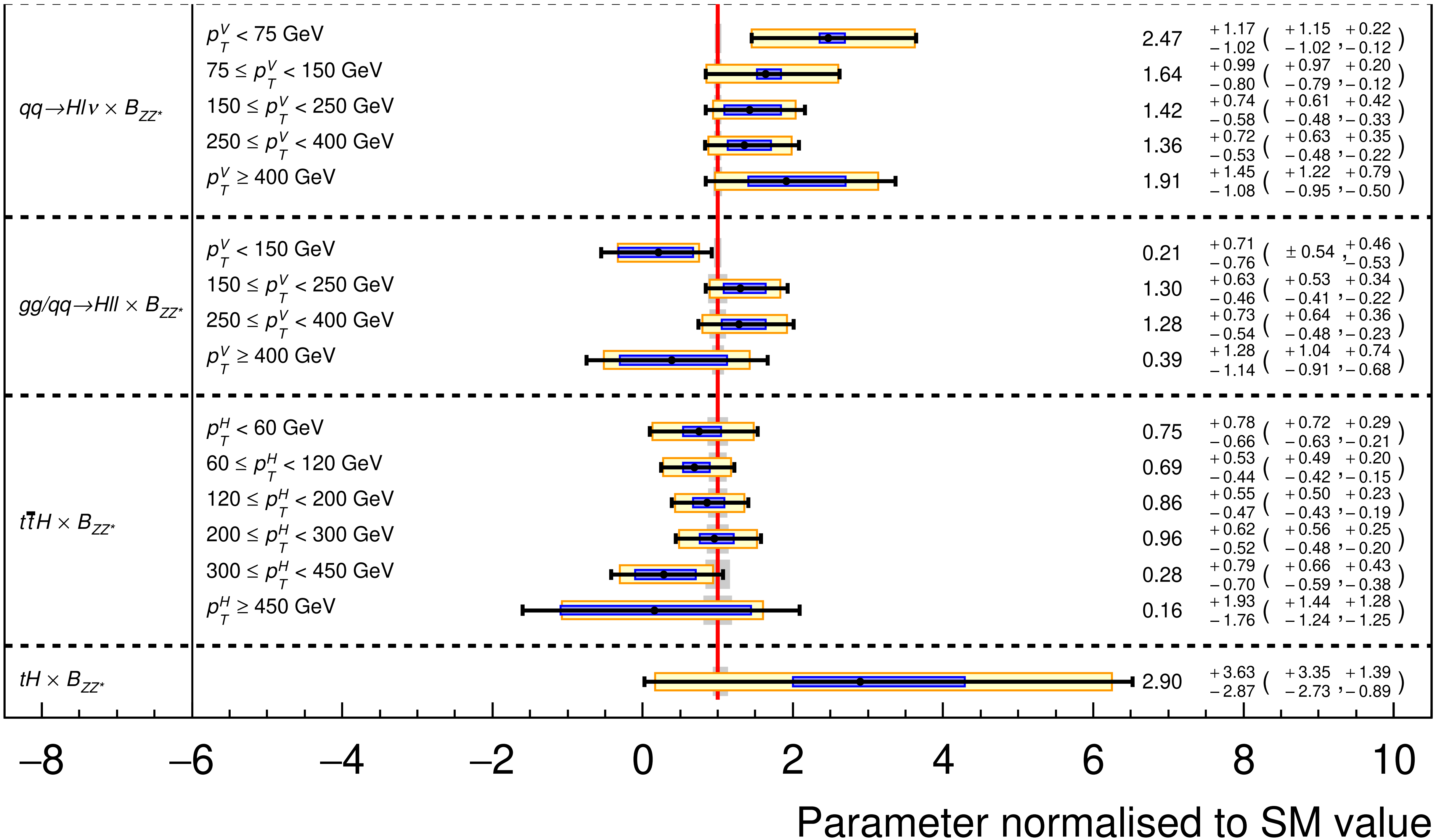
EFT Interpretation of ATLAS Higgs STXS Combination

ATLAS-CONF-2021-053



EFT Interpretation of ATLAS Higgs STXS Combination

ATLAS-CONF-2021-053



EFT Interpretation of ATLAS Higgs STXS Combination

SMEFT calculations

- Calculations for **most Higgs production and decay** modes have been performed at **LO accuracy in QCD** with SMEFTSim
- Assumption of a $U(3)5$ flavour symmetry, providing the Fermi constant, and the Z and W boson masses as inputs
- Exceptions are:
  - ***ggH, gg->ZH and H->gg*** calculations, performed at **NLO** accuracy **in QCD with** SMEFTatNLO
  - Calculations for SMEFT-SM interference terms in **H->γγ**, performed at **NLO accuracy in QED** (Phys. Rev. D 98, 095005)
  - **SMEFT modifications to background processes neglected**

EFT Interpretation of ATLAS Higgs STXS Combination

SM expected covariance matrix ~ Fisher info matrix

$$V_{\mathrm{SMEFT}}^{-1} = P_{(i,X)\to(j)}^{T}\, V_{\mathrm{STXS}}^{-1}\, P_{(i,X)\to(j)}$$

$$P_{(i,X)\to(j)} = A_j^{\sigma_i} + A_j^{\Gamma^{H\to X}} - A_j^{\Gamma^{H}}$$

Rotation matrix

ATLAS-CONF-2020-053

$$\frac{\sigma_{\mathrm{int}}^{i}}{\sigma_{\mathrm{SM}}^{i}} = \sum_j A_j^{\sigma_i} c_j$$

$$\frac{\Gamma_{\mathrm{int}}^{H\to X}}{\Gamma_{\mathrm{SM}}^{H\to X}} = \sum_j A_j^{\Gamma^{H\to X}} c_j$$

$$\frac{\Gamma_{\mathrm{int}}^{H}}{\Gamma_{\mathrm{SM}}^{H}} = \sum_j A_j^{\Gamma^{H}} c_j$$

Linear model

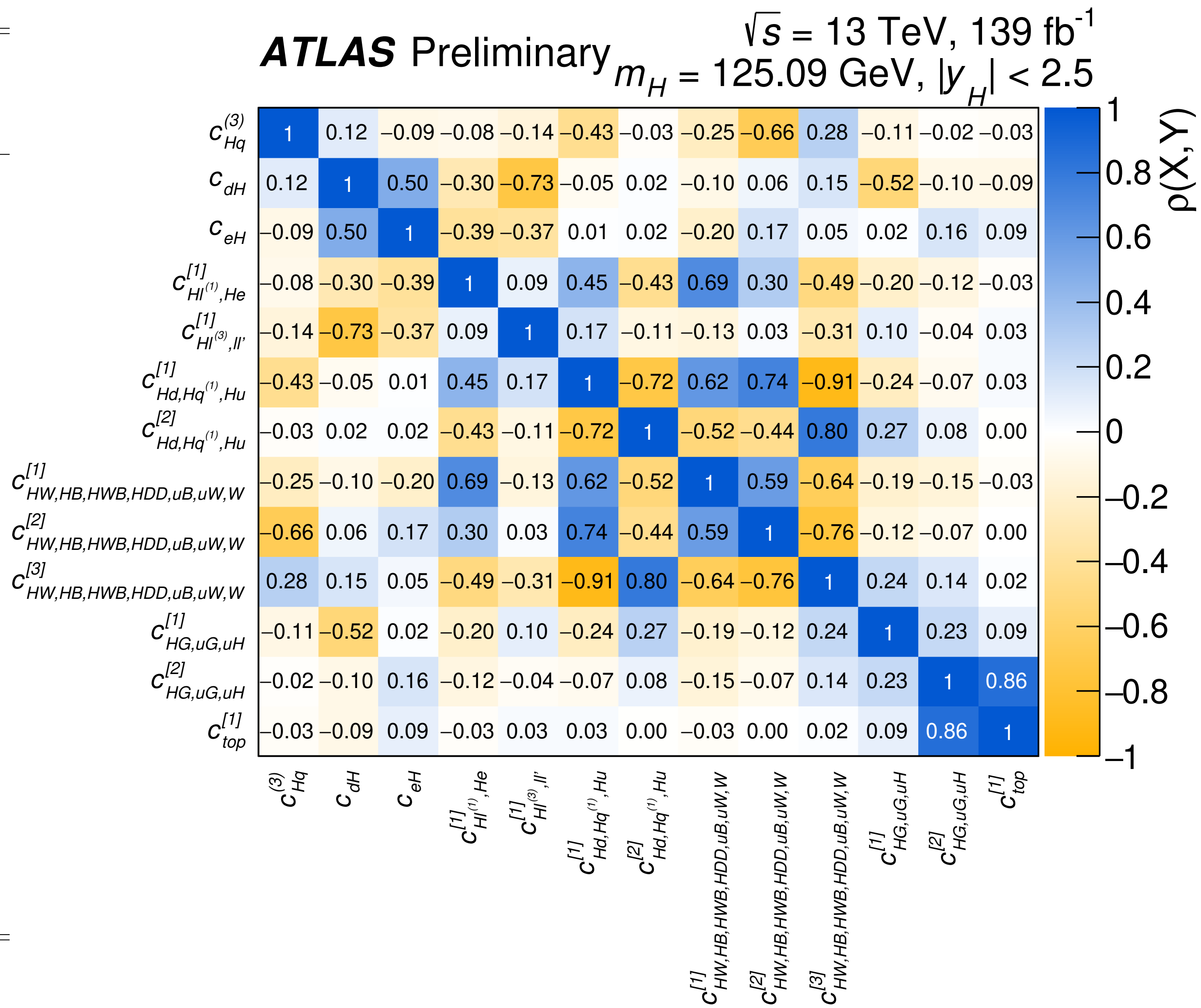
EFT Interpretation of ATLAS Higgs STXS Combination

ATLAS-CONF-2021-053

Observed & Expected measurement of c'$_i$ parameters with the SMEFT linearized models

Model Parameter (Λ = 1 TeV)	Observed Best-fit	Observed 68% CI	Observed 95% CI	Expected 68% CI	Expected 95% CI
$c^{(3)}_{Hq}$	0.0	[−0.04, 0.05]	[−0.08, 0.1]	[−0.04, 0.05]	[−0.08, 0.09]
c_{dH}	3.2	[0.5, 6]	[−2.1, 9]	[−2.7, 2.7]	[−5, 5]
c_{eH}	1.8	[0.23, 4]	[−1.5, 5]	[−1.7, 1.7]	[−3.5, 3.2]
$c^{[1]}_{HW,HB,HWB,HDD,uW,uB,W}$	0.001	[−0.004, 0.005]	[−0.009, 0.01]	[−0.005, 0.004]	[−0.009, 0.009]
$c^{[2]}_{HW,HB,HWB,HDD,uW,uB,W}$	0.4	[−0.30, 1.0]	[−0.9, 1.7]	[−0.6, 0.6]	[−1.3, 1.3]
$c^{[3]}_{HW,HB,HWB,HDD,uW,uB,W}$	−0.4	[−4, 1.9]	[−6, 5]	[−2.7, 2.8]	[−5, 6]
$c^{[1]}_{Hl^{(1)},He}$	−0.4	[−1.4, 0.7]	[−2.5, 1.7]	[−1.0, 1.0]	[−2.0, 2.0]
$c^{[1]}_{Hu,Hd,Hq^{(1)}}$	0.0	[−0.4, 0.4]	[−0.9, 0.8]	[−0.4, 0.4]	[−0.9, 0.8]
$c^{[2]}_{Hu,Hd,Hq^{(1)}}$	−0.8	[−6, 4]	[−10, 9]	[−5, 5]	[−10, 10]
$c^{[1]}_{Hl^{(3)},ll'}$	0.15	[−0.4, 0.7]	[−0.9, 1.3]	[−0.5, 0.5]	[−1.0, 1.0]
$c^{[1]}_{HG,uG,uH}$	−0.005	[−0.01, −0.0018]	[−0.013, 0.0021]	[−0.004, 0.004]	[−0.008, 0.008]
$c^{[2]}_{HG,uG,uH}$	−0.23	[−0.7, 0.18]	[−1.1, 0.6]	[−0.4, 0.5]	[−0.9, 0.9]
$c^{[1]}_{top}$	0.15	[−0.18, 0.5]	[−0.5, 0.8]	[−0.4, 0.4]	[−0.7, 0.7]

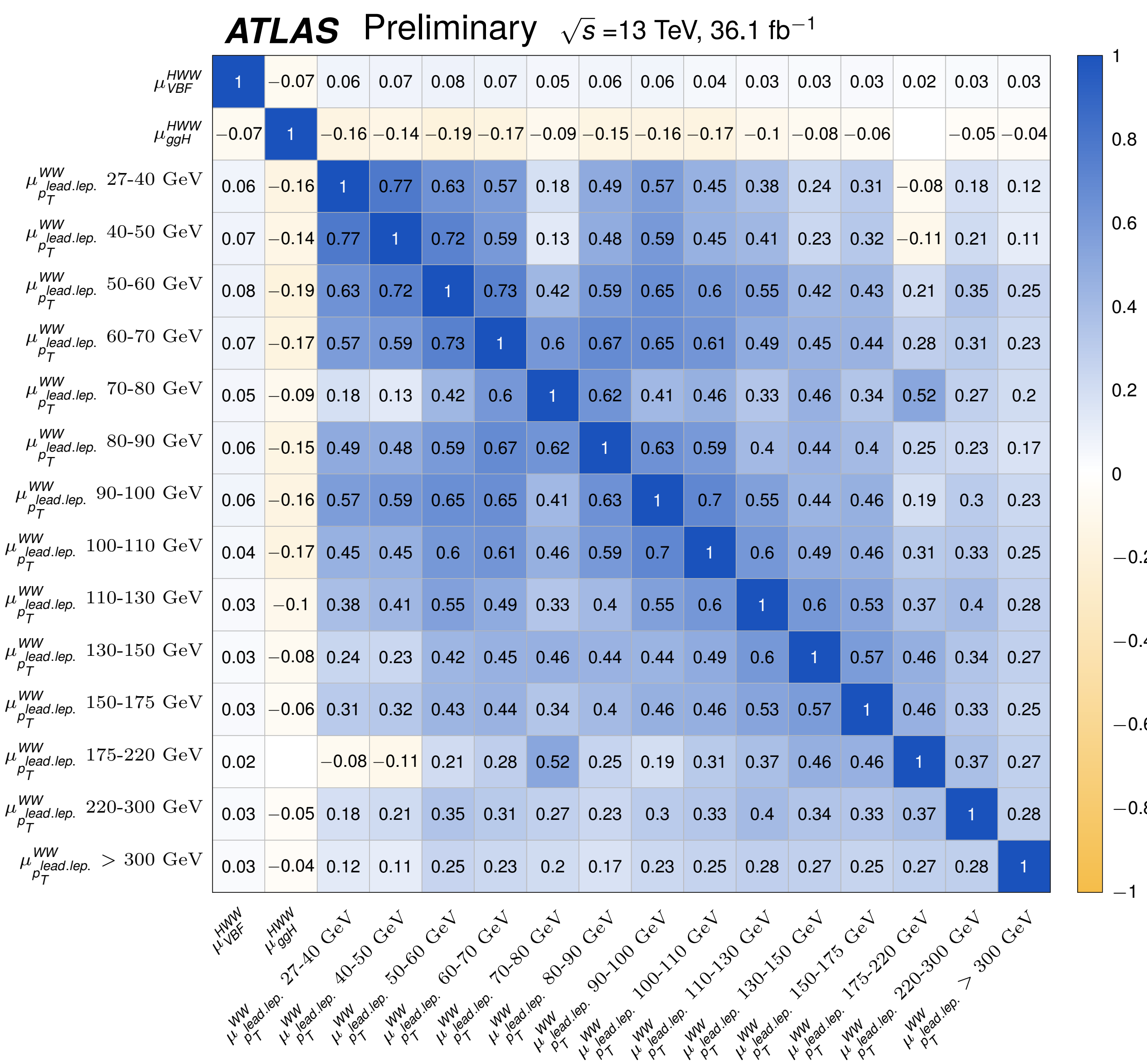
Correlation from the linearised SMEFT model for the observed data

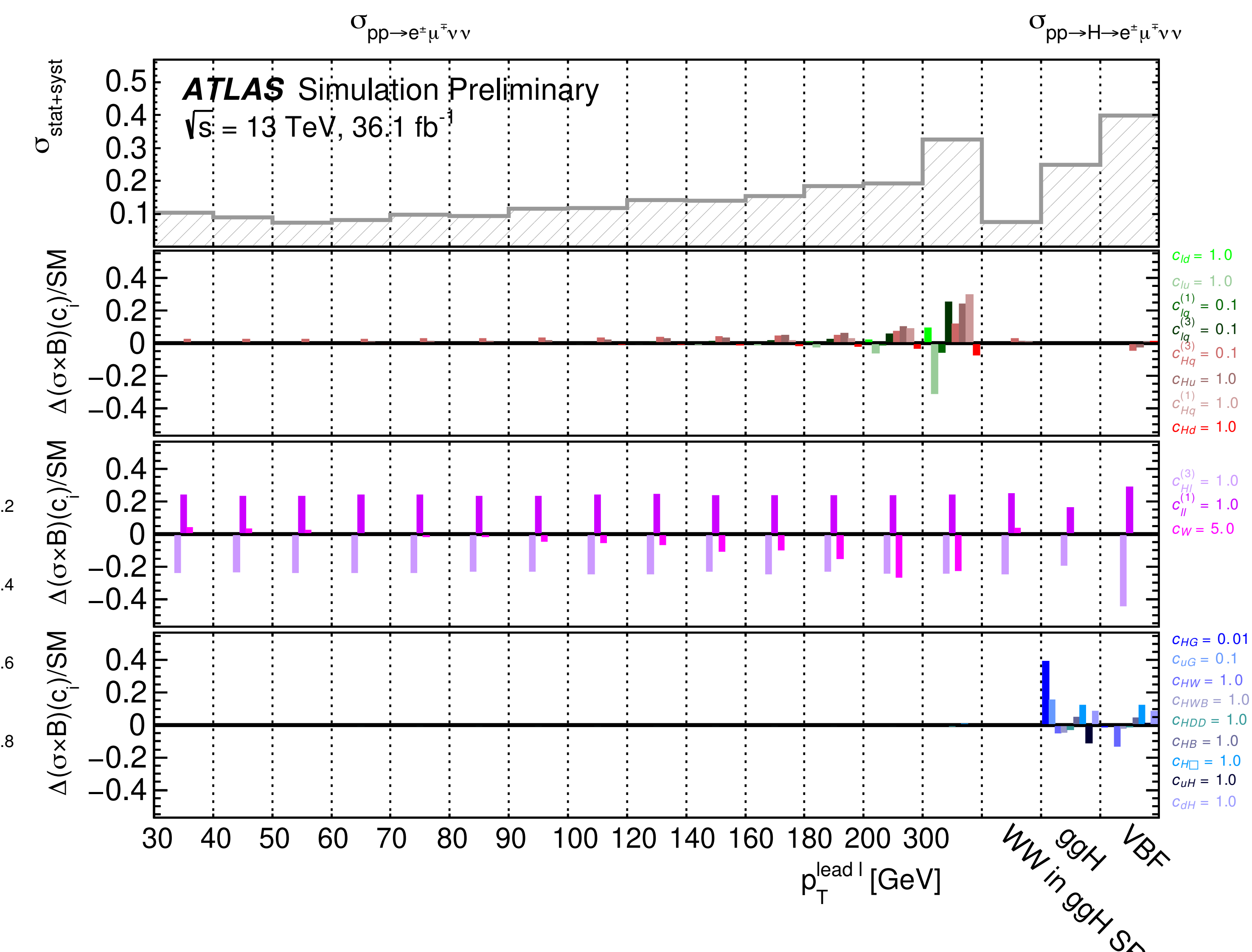


Towards a Global EFT: $H \to WW^*$ & WW Combination

ATL-PHYS-PUB-2021-010

Correlation matrix of the signal strength modifiers of the $H \to WW*$ analysis & the WW measurement





Impact of most relevant SMEFT operators on the analyses regions

Inclusive & Diff Fiducial Cross-Sections in $H\rightarrow\gamma\gamma$: EFT

HIGG-2019-13

Coefficient	95% CL, interference-only terms	95% CL, interference and quadratic terms
c_{HG}	$[-6.1, 11.0] \times 10^{-3}$	$[-6.5, 10.2] \times 10^{-3}$
$c_{H\widetilde{G}}$	$[-0.12, 0.23]$	$[-3.1, 3.5] \times 10^{-2}$
c_{HW}	$[-1.9, 0.9] \times 10^{-2}$	$[-1.8, 1.0] \times 10^{-2} \cup [0.28, 0.30]$
$c_{H\widetilde{W}}$	$[-10.2, 5.2]$	$[-7.3, 7.3] \times 10^{-2}$
c_{HB}	$[-5.8, 2.8] \times 10^{-3}$	$[-5.5, 3.0] \times 10^{-3} \cup [8.4, 9.3] \times 10^{-2}$
$c_{H\widetilde{B}}$	$[-21.8, 5.7] \times 10^{2}$	$[-2.3, 2.3] \times 10^{-2}$
c_{HWB}	$[-5.2, 10.7] \times 10^{-3}$	$[-0.17, -0.15] \cup [-5.5, 9.8] \times 10^{-3}$
$c_{H\widetilde{W}B}$	$[-2.5, 4.0] \times 10^{2}$	$[-4.0, 4.0] \times 10^{-2}$

Including quadratic dimension-6 terms

Inclusive & Diff Fiducial Cross-Sections in $H\rightarrow\gamma\gamma$: EFT

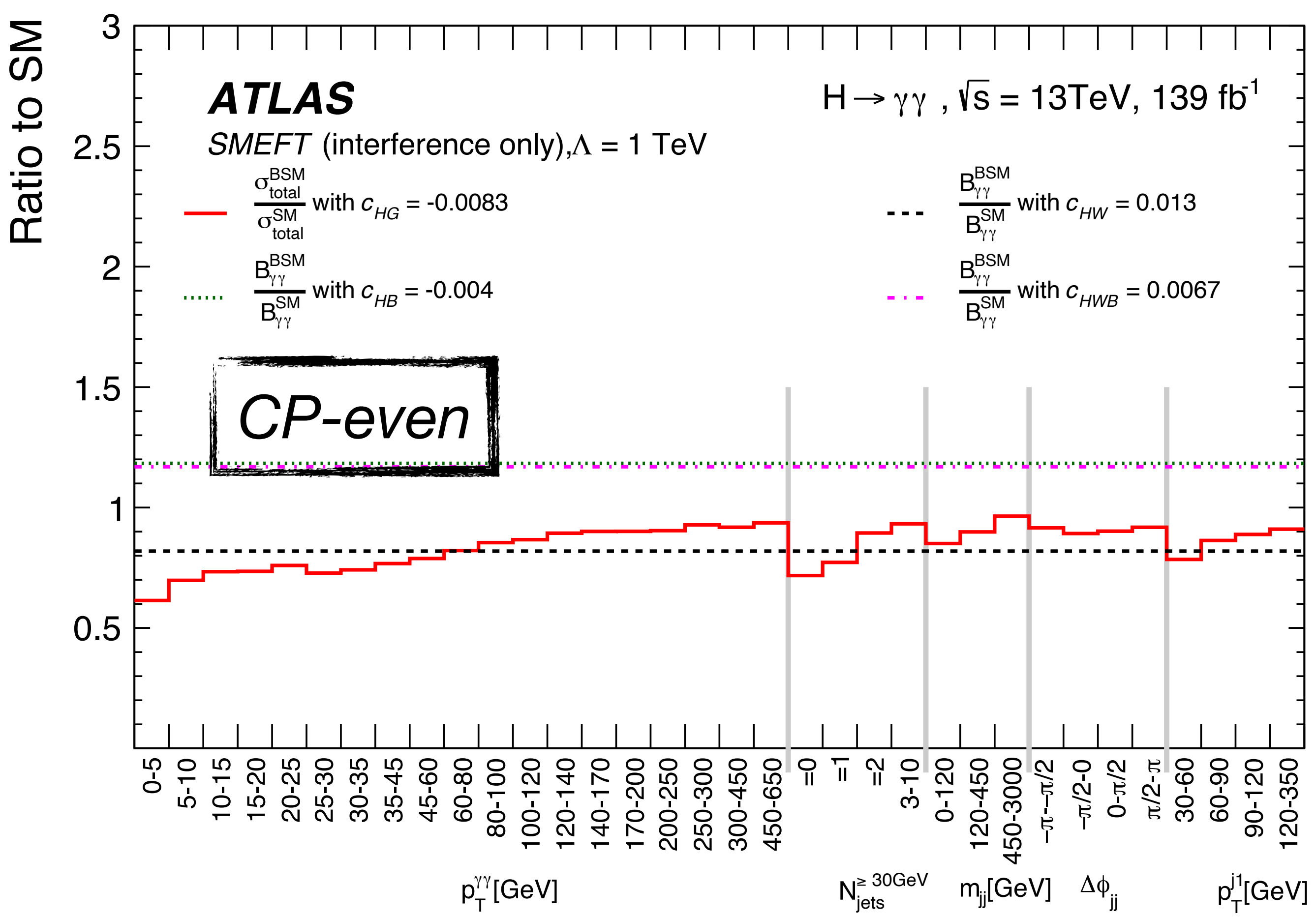
HIGG-2019-13

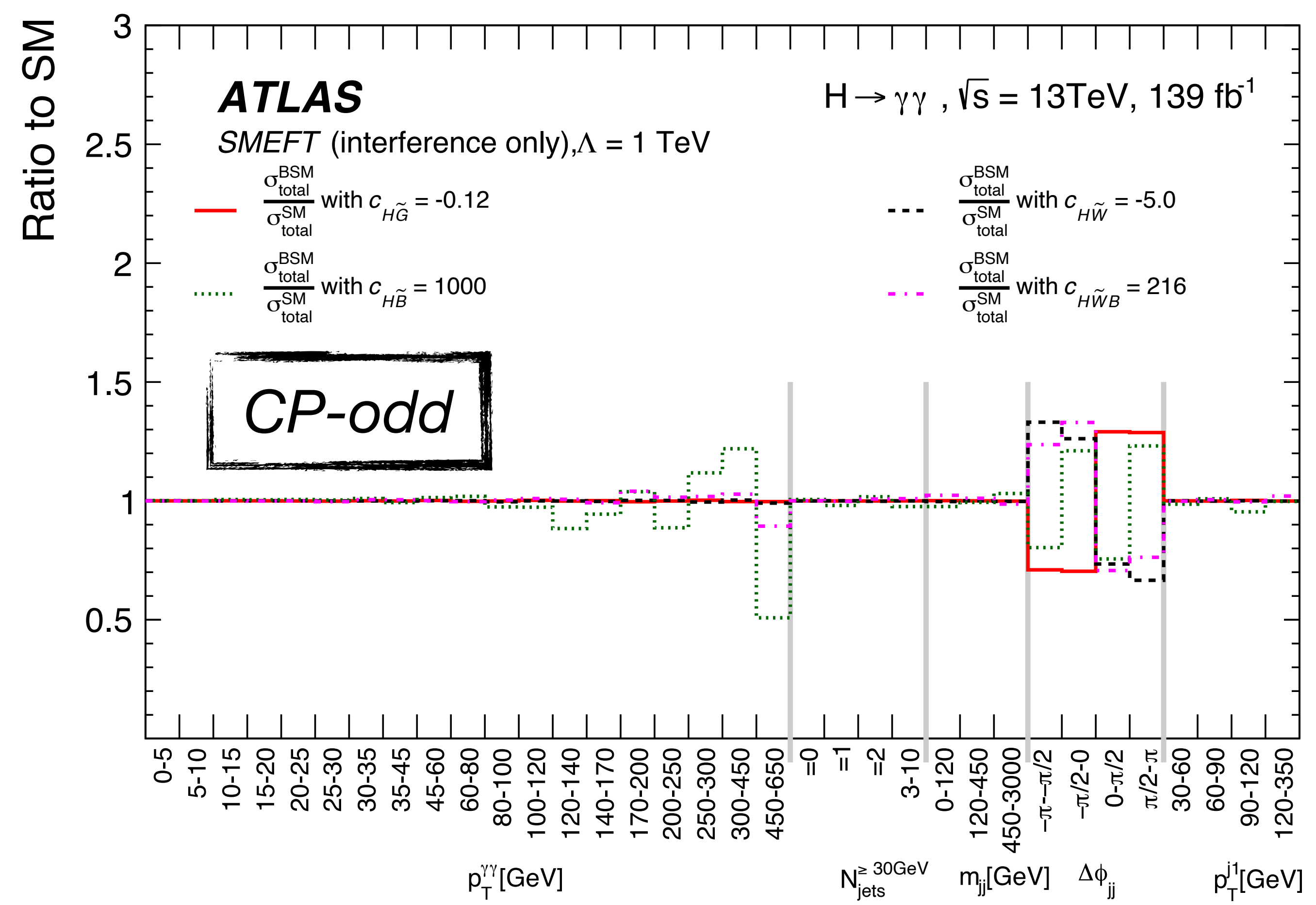
Considered operators

$$\mathcal{L}_{\text{eff}}^{\text{SMEFT}} \supset \quad c_{HG}O'_g + c_{HW}O'_{HW} + c_{HB}O'_{HB} + c_{HWB}O'_{HWB}$$
$$+ c_{H\tilde{G}}\tilde{O}'_g + c_{H\tilde{W}}\tilde{O}'_{HW} + c_{H\tilde{B}}\tilde{O}'_{HB} + c_{H\tilde{W}B}\tilde{O}'_{HWB}$$

$$\longrightarrow \sigma \propto |\mathcal{M}_{\text{EFT}}|^2 = |\mathcal{M}_{\text{SM}}|^2 + 2Re(\mathcal{M}^*_{\text{SM}}\mathcal{M}_{\text{d6}}) + |\mathcal{M}_{\text{d6}}|^2$$

SMEFTSim package exploited

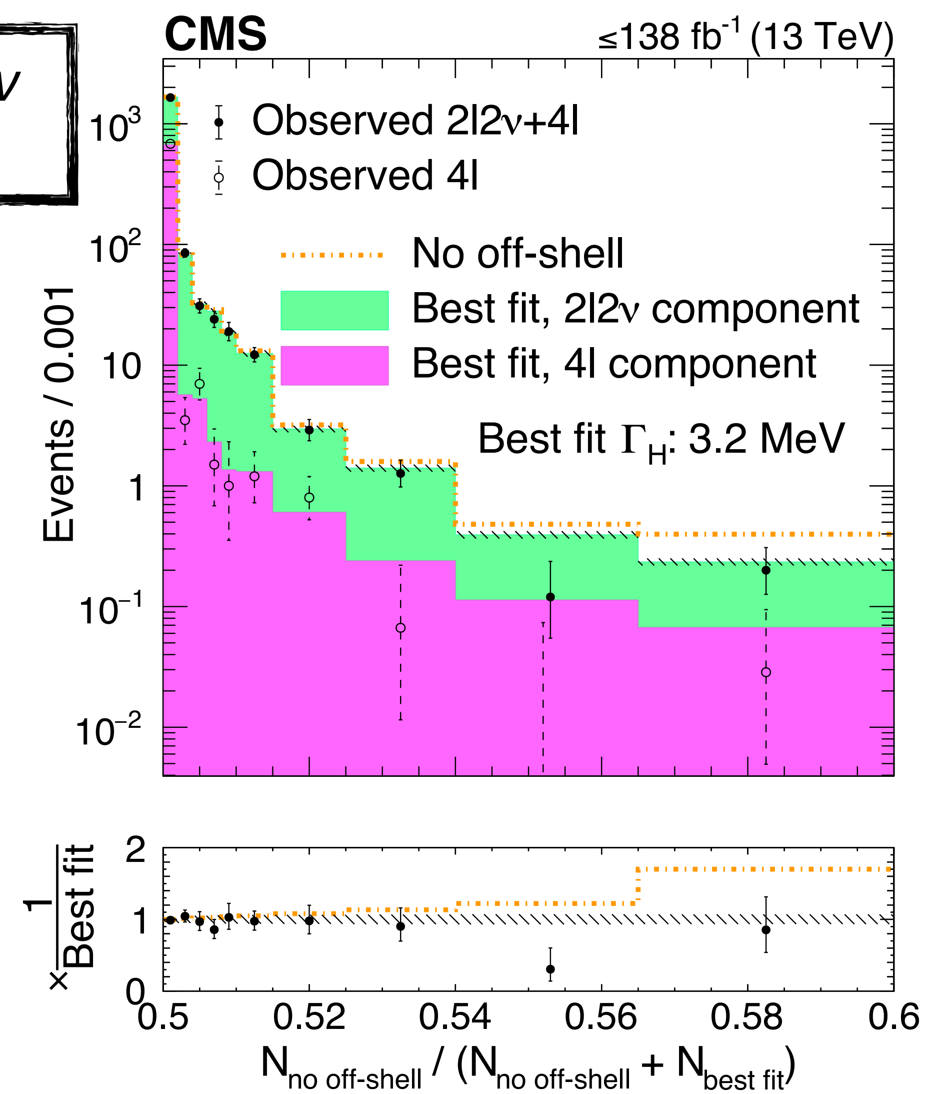




Off-Shell Evidence & BSM Scenarios

HIG-21-013

Ratios of the post-fit number of events in each 2ℓ2ν and 4ℓ off-shell signal region bin



Summary of results on Γ_H

Param.	Cond.	Observed 68%	Observed 95% CL	Expected 68%	Expected 95% CL
Γ_H	SM-like	$3.2^{+2.4}_{-1.7}$	$^{+5.3}_{-2.7}$	$^{+4.0}_{-3.48}$	$^{+7.2}_{-4.065}$
Γ_H	f_{a2} (u)	$3.4^{+2.3}_{-1.8}$	$^{+5.0}_{-2.8}$	$^{+3.9}_{-3.6}$	$^{+7.2}_{-4.085}$
Γ_H	f_{a3} (u)	$2.7^{+2.1}_{-1.4}$	$^{+4.6}_{-2.2}$	$^{+3.9}_{-3.6}$	$^{+7.2}_{-4.085}$
Γ_H	$f_{\Lambda1}$ (u)	$2.7^{+2.1}_{-1.4}$	$^{+4.5}_{-2.2}$	$^{+4.0}_{-3.6}$	$^{+7.2}_{-4.081}$

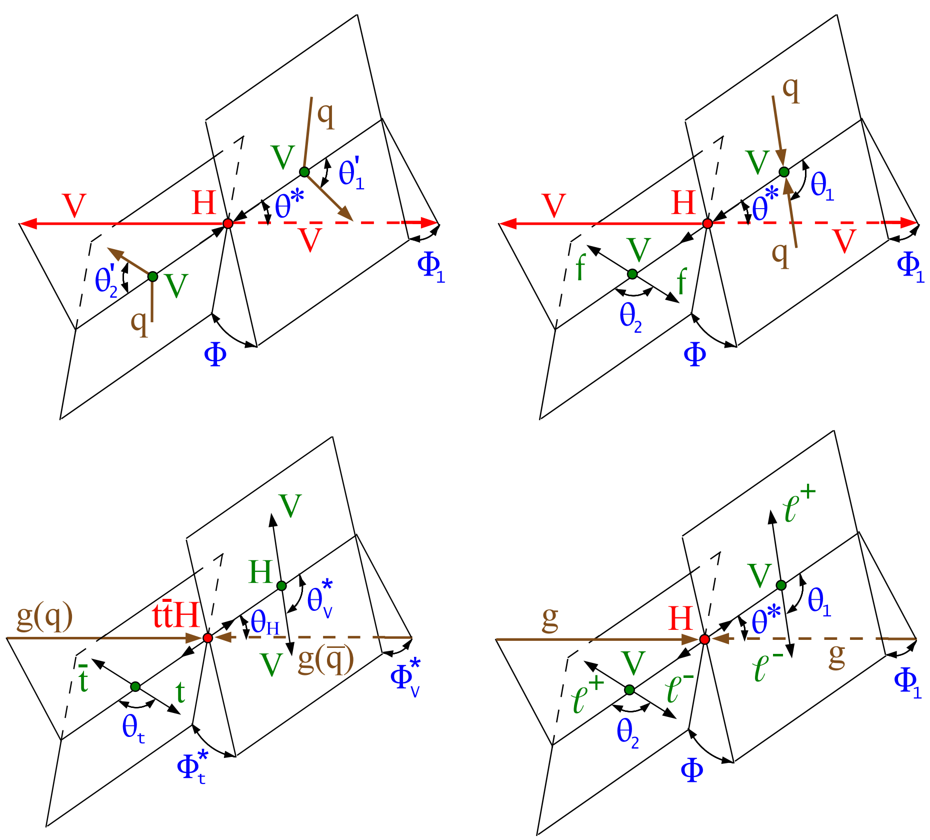
Summary of anomalous HVV coupling parameters

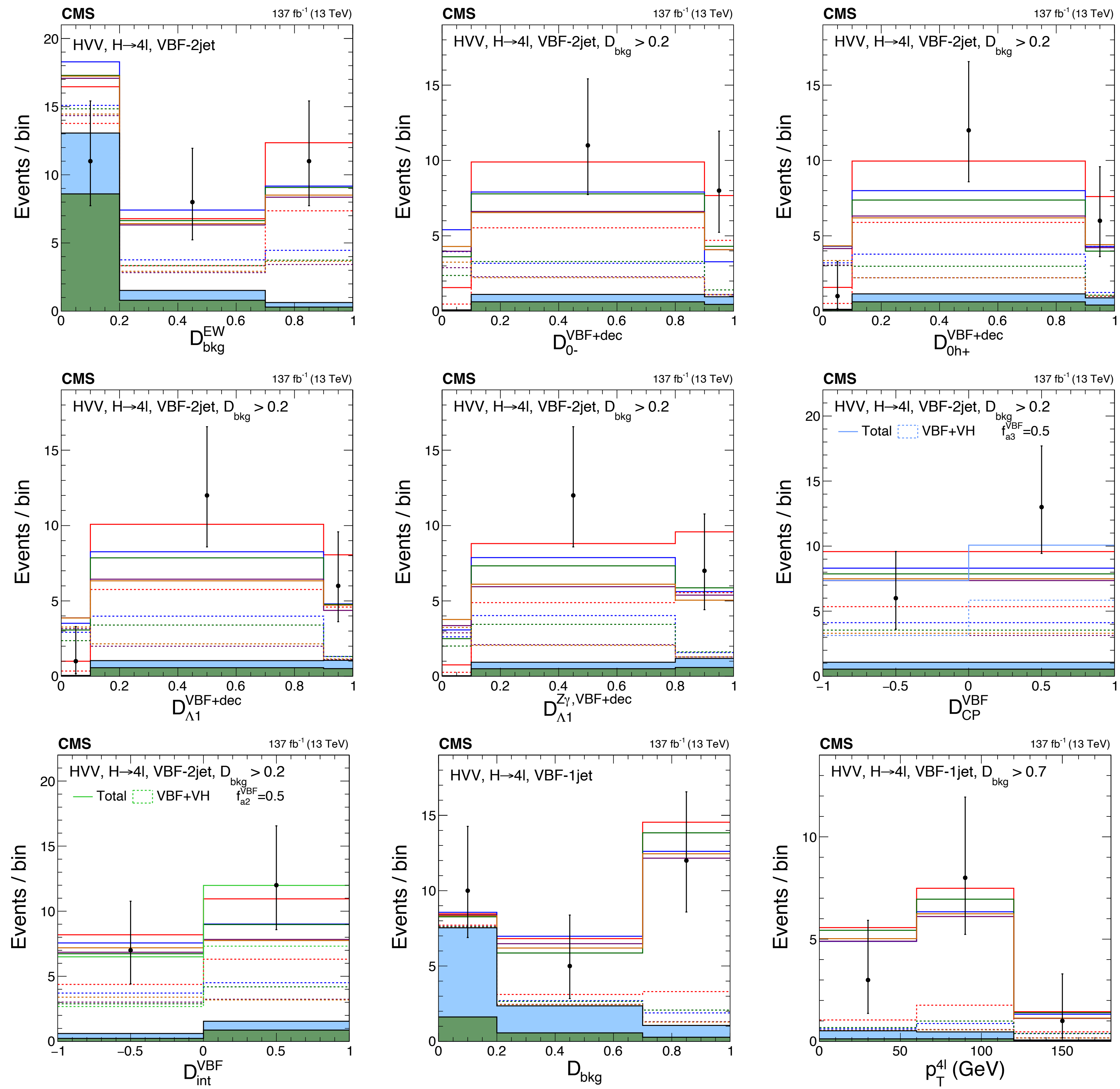
Parameter ($\times 10^5$)	Scenario	b.f.	Observed 68%	Observed 95% CL	Expected 68%	Expected 95% CL
f_{a2}	$\Gamma_H = \Gamma_H^{SM}$	79	$[6.6, 225]$	$[-32, 514]$	$[-78, 70]$	$[-359, 311]$
	Γ_H unconst.	72	$[2.7, 216]$	$[-38, 503]$	$[-82, 73]$	$[-413, 364]$
f_{a3}	$\Gamma_H = \Gamma_H^{SM}$	2.2	$[-6.4, 32]$	$[-46, 107]$	$[-55, 55]$	$[-198, 198]$
	Γ_H unconst.	2.4	$[-6.2, 33]$	$[-46, 110]$	$[-58, 58]$	$[-225, 225]$
$f_{\Lambda1}$	$\Gamma_H = \Gamma_H^{SM}$	2.9	$[-0.62, 17]$	$[-11, 46]$	$[-11, 20]$	$[-47, 68]$
	Γ_H unconst.	3.1	$[-0.56, 18]$	$[-10, 47]$	$[-11, 21]$	$[-48, 75]$

Constraints on Anomalous Higgs Couplings using *H→4ℓ*

HIG-19-009

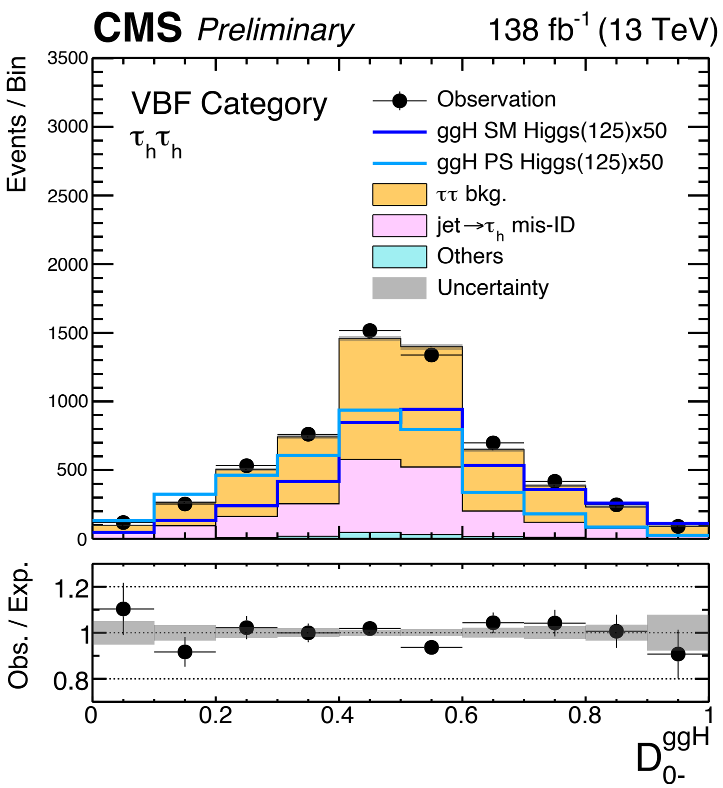
Discriminants from Matrix-Element calculations

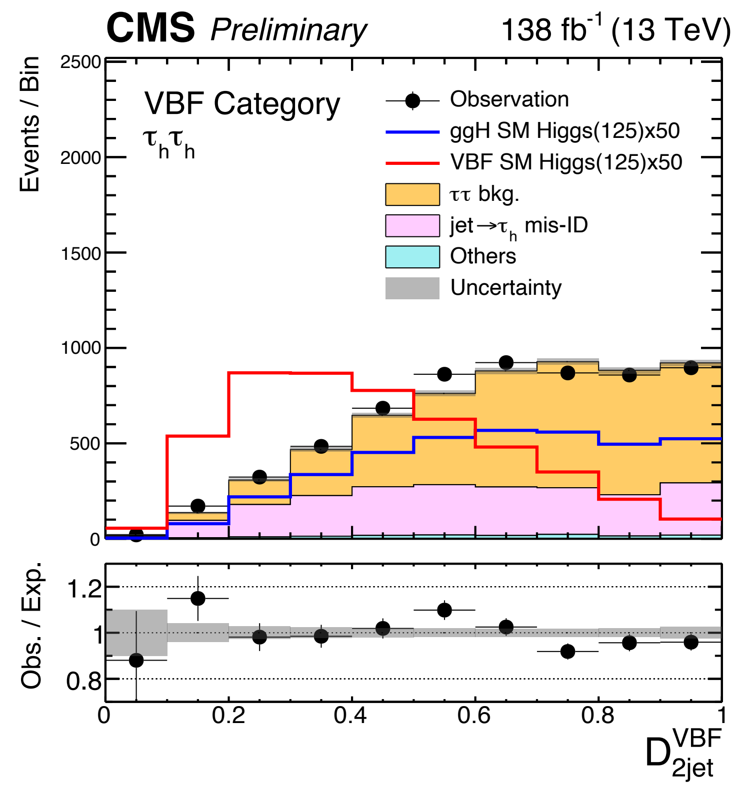


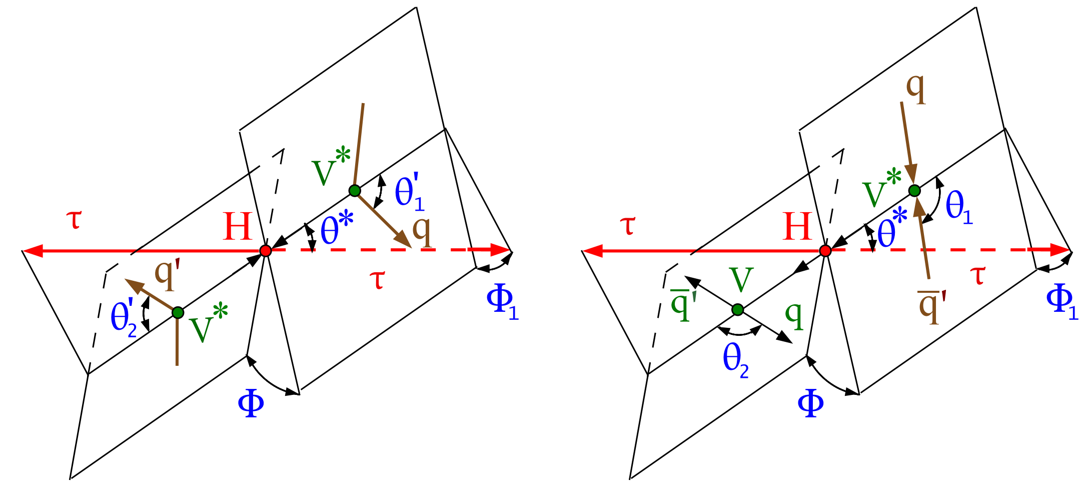


Constraints on Anomalous Higgs Couplings using $H \to \tau\tau$

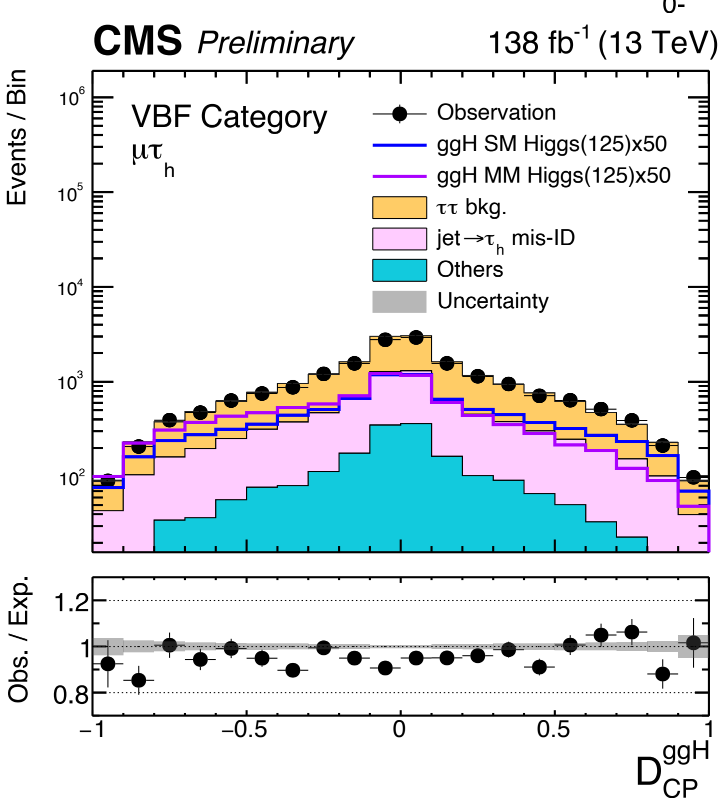
HIG-20-007

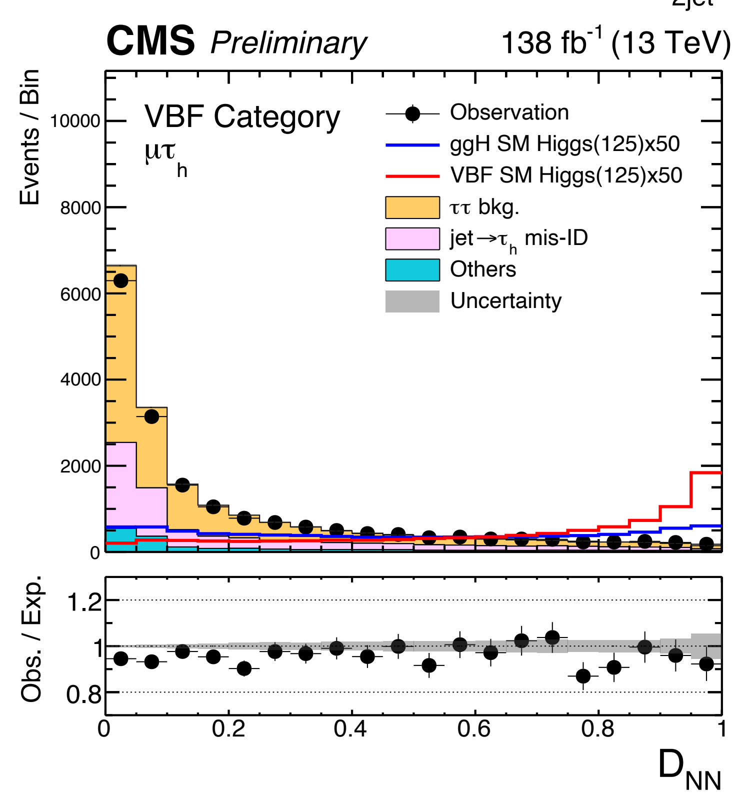






Matrix Element Likelihood Approach (MELA) combined with simple NNs





Examples of data and predictions for MELA and NN discriminants in the $\tau_h\tau_h$ and $\mu\tau_h$ channels

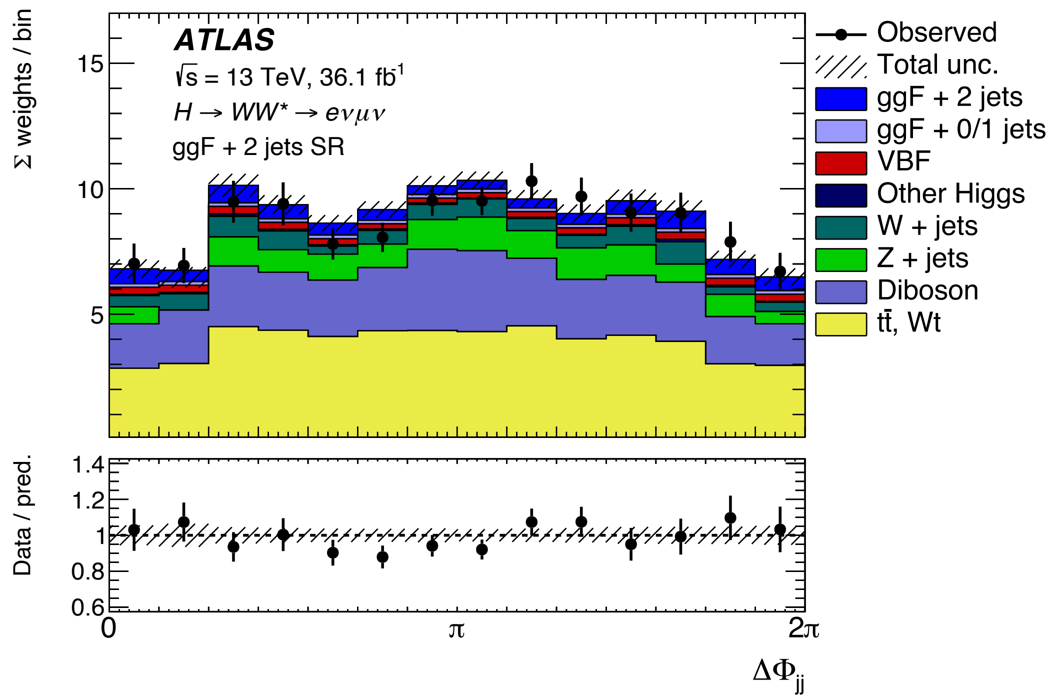
ATLAS $H \to WW^*$ + 2j CP Properties

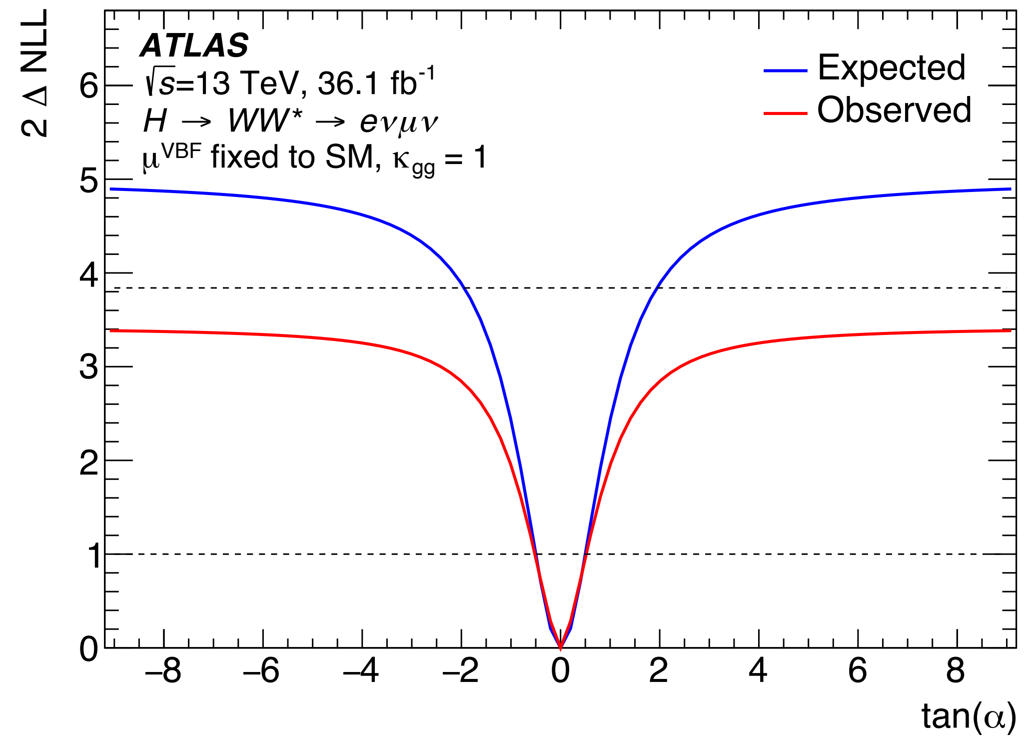
HIGG-2017-13

- *H→WW*(eν μν)* + 2j signature
- Determine constraints on CP-even & CP-odd mixing contributions to **Higgs-gluon effective interaction**
    - *ggH* dedicated category & **Higgs Characterisation model**
- **Signed** angular distance between jets as discriminant in 12 categories (BDT discriminant x $|\Delta\eta_{jj}|$)
- **-> Stringent constraints on CP-even/odd mixing contributions to Higgs-gluon eff. coupling !**

$$\mathcal{L}_0^{\text{loop}} = -\frac{g_{Hgg}}{4}\left(\kappa_{gg}\cos(\alpha)G^a_{\mu\nu}G^{a,\mu\nu} + \kappa_{gg}\sin(\alpha)G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\right)H$$

Higgs-gluon interaction effective Lagrangian





$$\tan(\alpha) = 0.0 \pm 0.4(\text{stat.}) \pm 0.3(\text{syst.})$$

ATLAS $H \to WW^*$ + 2j CP Properties

HIGG-2017-13

- Likelihood scan where **only the shape of the $\Delta\Phi_{jj}$ distribution is fitted**
- **Weaker constraints** on tan(α), but smaller sensitivity to CP-even components - thus, **more model-independent probe of CP violation**