ICPPA-2020

Experimental results on EFT interpretations of SM and Higgs boson measurements

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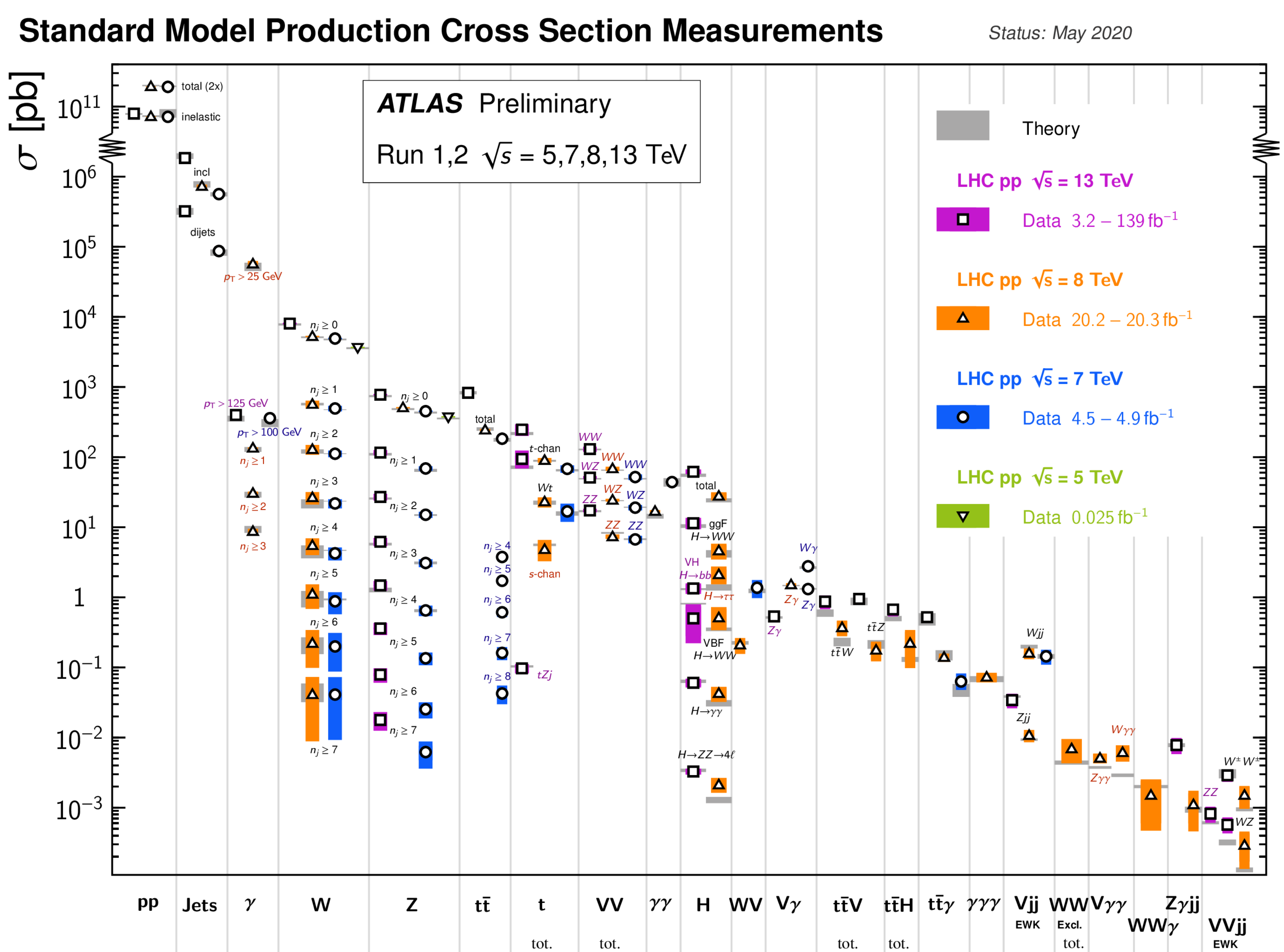
SM measurements

So far, no hints of BSM physics from direct searches at the LHC …



… but a wide plethora of SM precision measurements available

The Standard Model Effective Field Theory

- SMEFT allows a systematic interpretation of large data sets in terms of new physics (NP)
  - It does not assume that the theory is valid at arbitrarily high energies.

- Extends the SM Lagrangian by adding new operators of d>4 suppressed by the NP energy scale, $1/\Lambda^{d-4}$
  - Valid for Λ>> vev. Keeps same fields and symmetries as the SM

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i \frac{c_i^{d=6}}{\Lambda^2}\mathcal{O}^{d=6} + \sum_i \frac{c_i^{d=8}}{\Lambda^4}\mathcal{O}^{d=8}$$

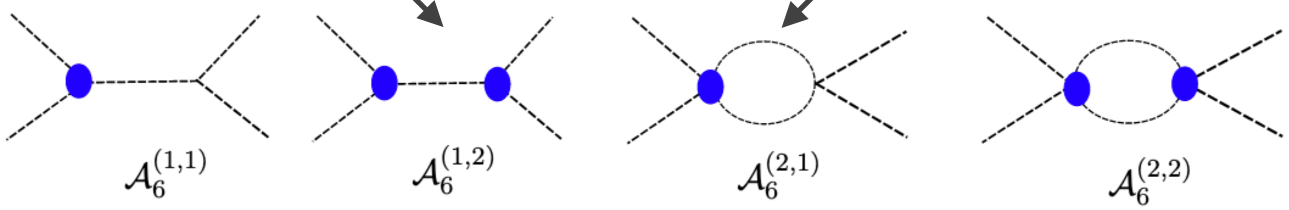
  - Only c_i/Λ^{d-4} is measurable
  - Several operator bases can be worked out, different conventions in use

- Constrain EFT coefficients ➞ constrain large classes of UV theories

Higher orders in SMEFT and other concepts

More insertions

More loops



And higher dimensional operators

Interference

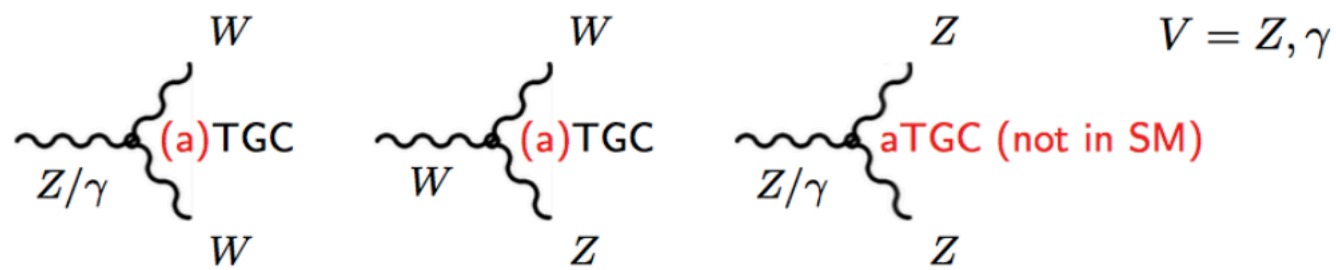
Quadratic

$$|\mathcal{A}_{\mathrm{EFT}}|^2 = |\mathcal{A}_{\mathrm{SM}}|^2 + \bar{g}\,|\mathcal{A}_{\mathrm{SM}} \cdot \mathcal{A}_6^{(1,1)}| + \bar{g}^2\,|\mathcal{A}_6^{(1,1)}|^2 + \bar{g}^2\,|\mathcal{A}_{\mathrm{SM}} \cdot \mathcal{A}_6^{(1,2)}| + \frac{\bar{g}}{\Lambda^2}\,|\mathcal{A}_{\mathrm{SM}} \cdot \mathcal{A}_8^{(1,1)}| + \dots$$

From 1809.04189

- Naive expectation: dim-6-interf > dim-6 quadratic ~ dim-8 interference
  - Not always true (e.g. if interference is suppressed)
  - Studies of quadratic terms can be a test of the EFT convergence
- Typically, a LO SMEFT is used
  - But SMEFT compatible with NLO corrections, unlike kappa-framework or anomalous couplings.
- No clear recommendations on uncertainties for EFT predictions.
- In differential measurements, effect of operators usually growing with $(E/\Lambda)^{d-4}$
  - Measure in tails of distributions
- Growth of amplitude with energy can violate unitarity ➞EFT no longer valid

From aTGCs to EFTs



- aTGCs controlled by 3 CP-conserving parameters $\{\delta_1{}^V, \kappa_V, \lambda_V\}$. Additional terms needed for neutral gauge couplings and aQGCs. Lagrangian approach

$$-ig_{WWV}[g_1^V(W^+_{\mu\nu}W^{-\mu}V^\nu - W^-_{\mu\nu}W^{+\mu}V^\nu) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu}] - i\frac{\lambda_V}{m_W^2}V^{\mu\nu}W^{+\rho}_\nu W^-_{\rho\mu}$$

- Can add more terms adding derivatives (with additional 1/Mw scaling).
- Not necessarily gauge invariant
- Leads to unitarity violation ➞ Use e.g. form factors
- EFT operators in dimension-6 for TGCs

$$g_1^Z = 1 + c_W\frac{m_Z^2}{\Lambda^2}$$

$$\kappa_\gamma = 1 + (c_w + c_B)\frac{m_W^2}{2\Lambda^2}$$

$$\mathcal{O}_B = (D_\mu H^\dagger)B^{\mu\nu}D_\nu H$$

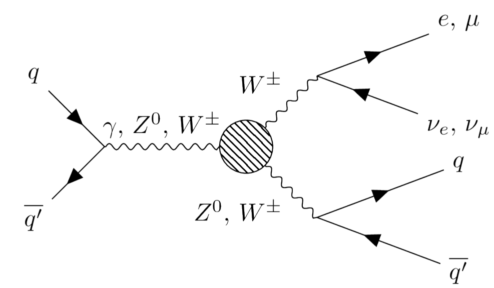
$$\mathcal{O}_W = (D_\mu H)^\dagger W^{\mu\nu}D_\nu H \qquad \mathcal{O}_{\tilde{W}} = (D_\mu H)^\dagger \tilde{W}^{\mu\nu}D_\nu H$$

$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu}W^\nu_\rho W^{\rho\nu}] \qquad \mathcal{O}_{W\tilde{W}W} = \mathrm{Tr}[W_{\mu\nu}W^\nu_\rho \tilde{W}^{\rho\nu}]$$

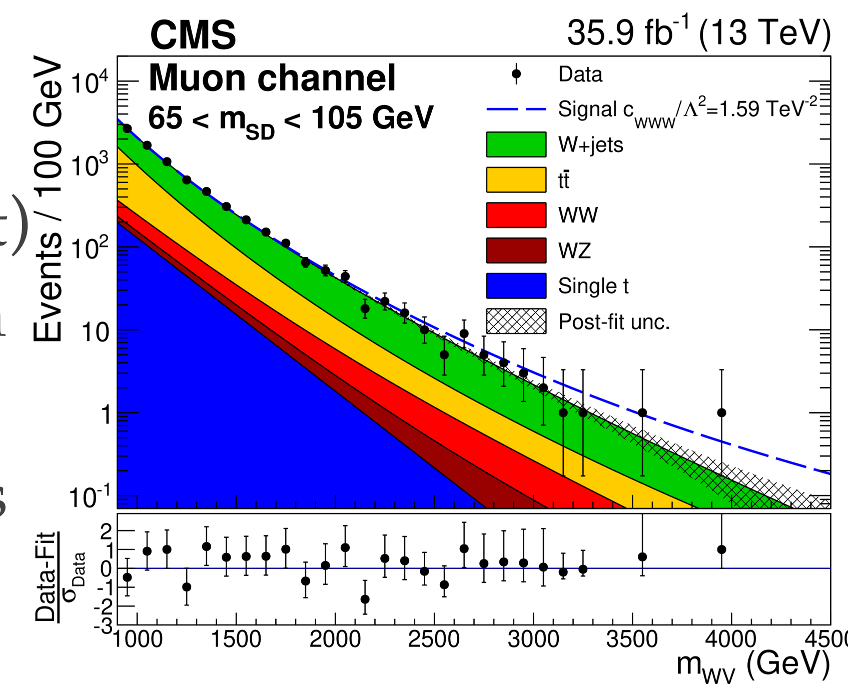
Others in Backup

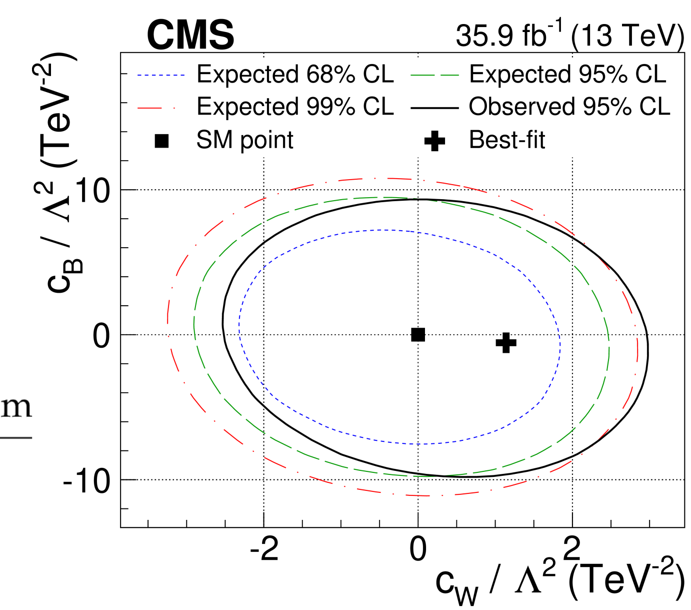
- In EFT many other operators affect vector-boson measurements, usually not considered since they were well constrained at LEP (this is basis dependent)

CMS: WW and WZ



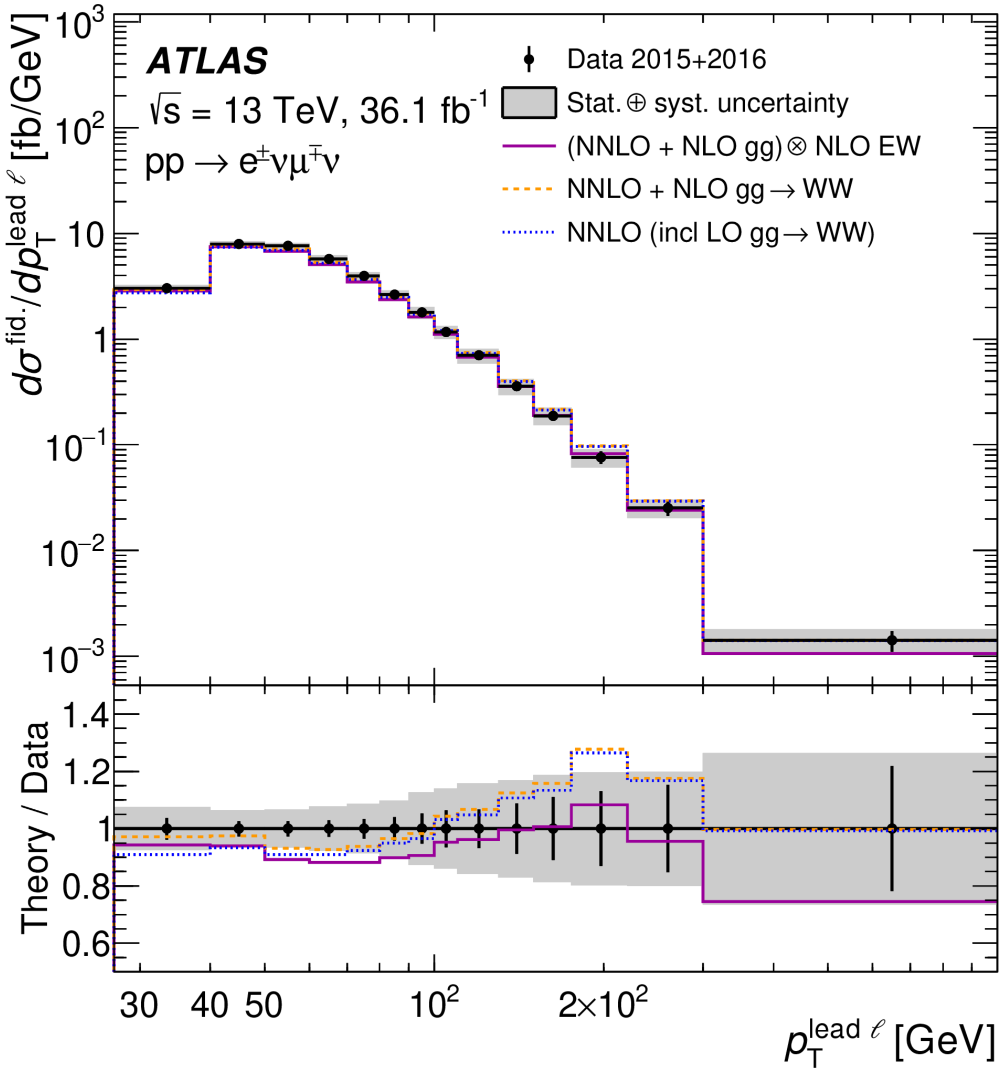
- Dedicated measurement for constraining anomalous $WW\gamma$ and WWZ couplings
- W decaying leptonically and Z or W hadronically (fat jet)
  - Semi-leptonic channels offer a good balance between purity and efficiency
  - Reduction of W+jets with jet substructure techniques
- Limits from 2D unbinned LH fits to (m_{SD},m_{WV})
- c_{WWW} and c_W similar impact in WW and WZ, c_B much greater in WW region.
  - Little separation power between c_{WWW} and c_W
- Improvement wrt. 8 TeV results





Parametrization	aTGC	Expected limit	Observed limit	Observed best-fit	8 TeV observed lim
EFT	c_{WWW}/Λ^2 (TeV^{-2})	[-1.44, 1.47]	[-1.58, 1.59]	-0.26	[-2.7, 2.7]
	c_W/Λ^2 (TeV^{-2})	[-2.45, 2.08]	[-2.00, 2.65]	1.21	[-2.0, 5.7]
	c_B/Λ^2 (TeV^{-2})	[-8.38, 8.06]	[-8.78, 8.54]	1.07	[-14, 17]
LEP	λ_Z	[-0.0060, 0.0061]	[-0.0065, 0.0066]	-0.0010	[-0.011, 0.011]
	Δg_1^Z	[-0.0070, 0.0061]	[-0.0061, 0.0074]	0.0027	[-0.009, 0.024]
	$\Delta\kappa_Z$	[-0.0074, 0.0078]	[-0.0079, 0.0082]	-0.0010	[-0.018, 0.013]

ATLAS: WW

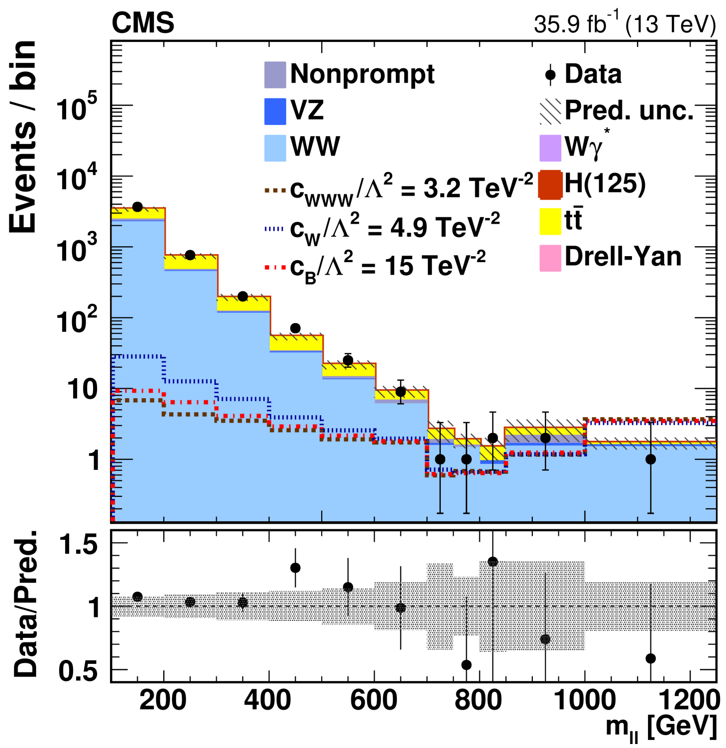


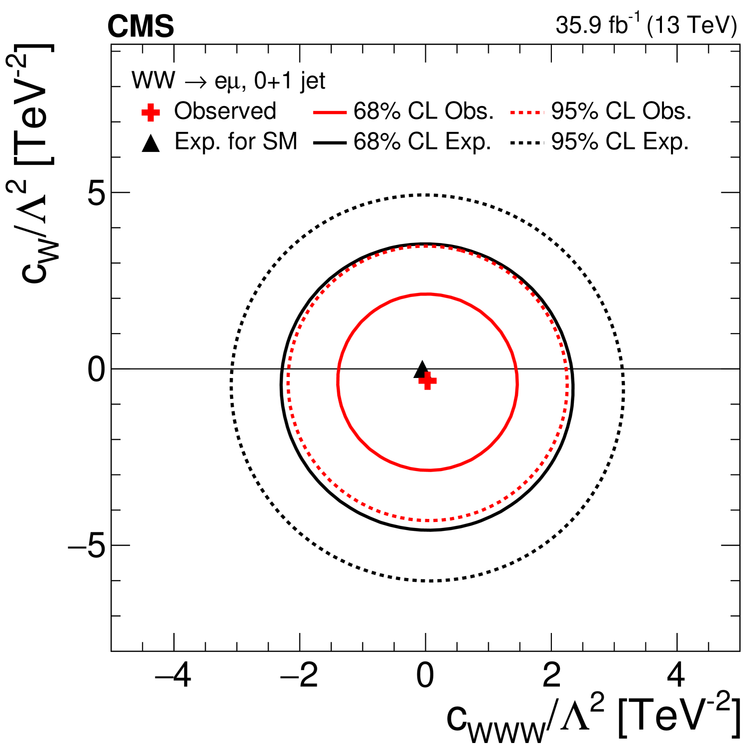
- WW→eνμν. More background than WZ, need to suppress ttbar with jet veto
- Limits from unfolded leading p_T^l differential cross section
  - BSM terms behave as SM in the unfolding
- Large EW corrections in the p_T^l tail
- Less sensitive to O_W, O_{WWW} than WZ
- Studied relevance of quadratic terms
  - Relevant especially for O_{WWW}

Operator	95% CL (linear and quadratic terms)	95% CL (linear terms only)
c_{WWW}/Λ^2	[-3.4 TeV^{-2} , 3.3 TeV^{-2}]	[-179 TeV^{-2} , -17 TeV^{-2}]
c_W/Λ^2	[-7.4 TeV^{-2} , 4.1 TeV^{-2}]	[-13.1 TeV^{-2} , 7.1 TeV^{-2}]
c_B/Λ^2	[-21 TeV^{-2} , 18 TeV^{-2}]	[-104 TeV^{-2} , 101 TeV^{-2}]

Parameter	Observed 95% CL [TeV^{-2}]	Expected 95% CL [TeV^{-2}]
c_{WWW}/Λ^2	[-3.4 , 3.3]	[-3.0 , 3.0]
c_W/Λ^2	[-7.4 , 4.1]	[-6.4 , 5.1]
c_B/Λ^2	[-21 , 18]	[-18 , 17]
$c_{\tilde{W}WW}/\Lambda^2$	[-1.6 , 1.6]	[-1.5 , 1.5]
$c_{\tilde{W}}/\Lambda^2$	[-76 , 76]	[-91 , 91]

CMS: WW

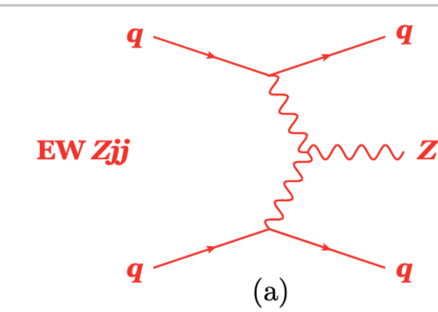




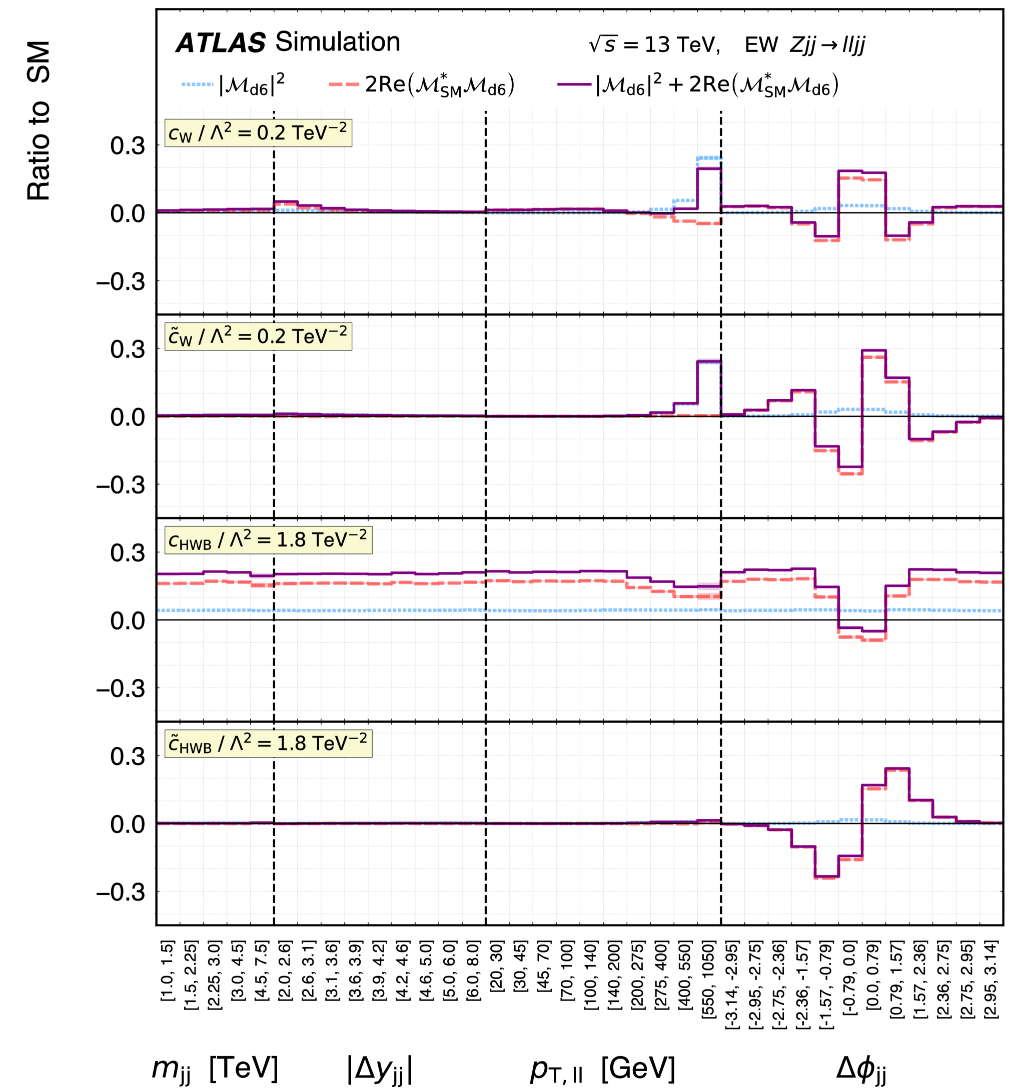
- Two methodologies (sequential cuts and random forests) studied for background estimation.
- $WW \rightarrow l^+\nu l^-\nu$ with 0 or 1-jet
- Limits from $m_{e\mu}$ templates (not sensitive to higher-order QCD effects or jet energy scale). BSM terms behave as SM in the unfolding
- Only different flavour event sample
  - Same flavour has larger contamination from DY
  - $m_{e\mu}$>100 GeV to reduce Higgs contribution
- Almost a factor 2 better more stringent than ATLAS
  - Due to the usage of 1-jet measurement

Coefficients	68% confidence interval		95% confidence interval	
(TeV^{-2})	expected	observed	expected	observed
c_{WWW}/Λ^2	$[-1.8, 1.8]$	$[-0.93, 0.99]$	$[-2.7, 2.7]$	$[-1.8, 1.8]$
c_W/Λ^2	$[-3.7, 2.7]$	$[-2.0, 1.3]$	$[-5.3, 4.2]$	$[-3.6, 2.8]$
c_B/Λ^2	$[-9.4, 8.4]$	$[-5.1, 4.3]$	$[-14, 13]$	$[-9.4, 8.5]$

ATLAS: EW Zjj



- Differential cross sections for EW Zjj production (Z to ee or μμ) for the first time. Full Run 2 analysis
- Shape and normalisation of strong Zjj from data-driven method (significant modelling unc. in the predictions)
- Using Warsaw basis as implemented in SMEFTsim package
- Also exploits parity odd observables, $\Delta\phi_{jj}$, for the constraint of CP-even and CP-odd operators
- Checked importance of quadratic terms
  - Constraints mainly from interference (test of EFT convergence), no unitarity violation issues.



Wilson coefficient	Includes $\lvert\mathcal{M}_{d6}\rvert^2$	95% confidence interval [TeV^{-2}] Expected	Observed	p-value (SM)
c_W/Λ^2	no	[−0.30, 0.30]	[−0.19, 0.41]	45.9%
	yes	[−0.31, 0.29]	[−0.19, 0.41]	43.2%
$\tilde{c}_W/\Lambda^2$	no	[−0.12, 0.12]	[−0.11, 0.14]	82.0%
	yes	[−0.12, 0.12]	[−0.11, 0.14]	81.8%
c_{HWB}/Λ^2	no	[−2.45, 2.45]	[−3.78, 1.13]	29.0%
	yes	[−3.11, 2.10]	[−6.31, 1.01]	25.0%
$\tilde{c}_{HWB}/\Lambda^2$	no	[−1.06, 1.06]	[0.23, 2.34]	1.7%
	yes	[−1.06, 1.06]	[0.23, 2.35]	1.6%

$\Delta\phi_{jj}=y_f-y_b$ with $y_f>y_b$

Beyond dim-6: nTGC and aQGC

- No neutral gauge couplings in SM or from dimension-6 operators at tree-level
- They first appear at dimension 8

$$\mathcal{O}_{B\tilde{W}} = iH^\dagger \tilde{B}_{\mu\nu} W^{\mu\rho}\{D_\rho, D^\nu\}H \qquad \mathcal{O}_{WW} = iH^\dagger W_{\mu\nu} W^{\mu\rho}\{D_\rho, D^\nu\}H$$

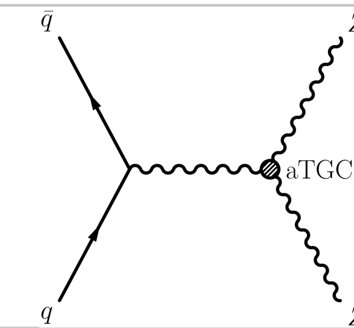
$$\mathcal{O}_{BW} = iH^\dagger B_{\mu\nu} W^{\mu\rho}\{D_\rho, D^\nu\}H \qquad \mathcal{O}_{BB} = iH^\dagger B_{\mu\nu} B^{\mu\rho}\{D_\rho, D^\nu\}H$$

- Operators with quartic vertices appear at dimension 8
- Assume processes probing aQGC have negligible contribution from dimension-6 operators (constrained by other measurements)
- Lagrangian terms:

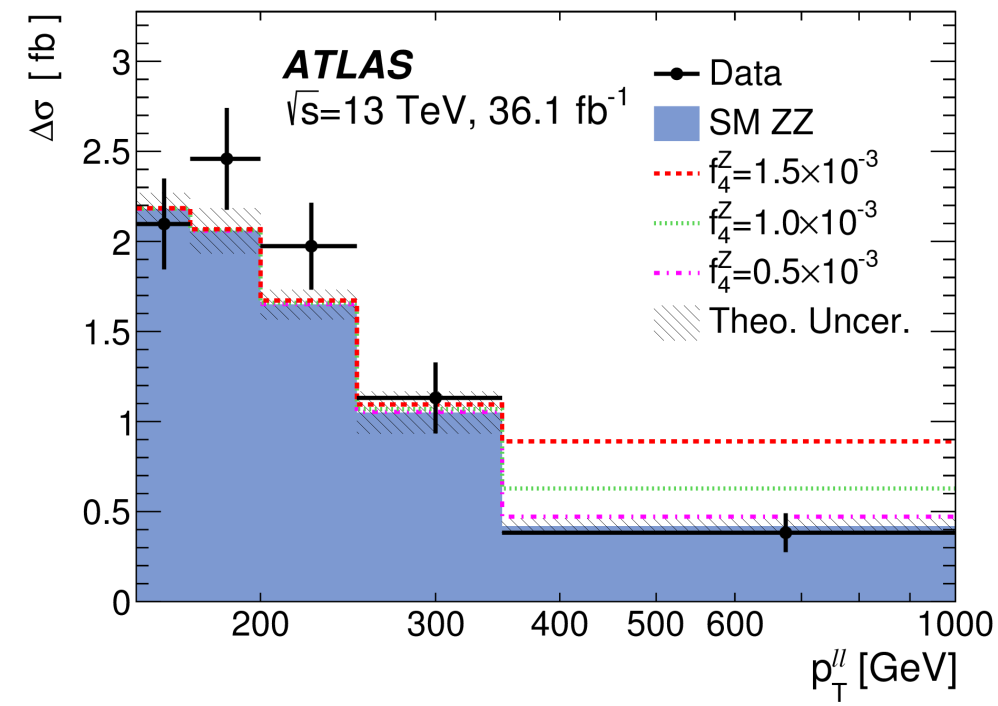
$$\mathcal{L}_{S,0-1} \propto (D_\mu \Phi)^4, \quad \mathcal{L}_{M,0-7} \propto (F^{\mu\nu})^2 (D_\mu \Phi)^2, \quad \mathcal{L}_{T,0-9} \propto (F^{\mu\nu})^4$$

arXiv:1905.07163

ATLAS: ZZ→2l2ν



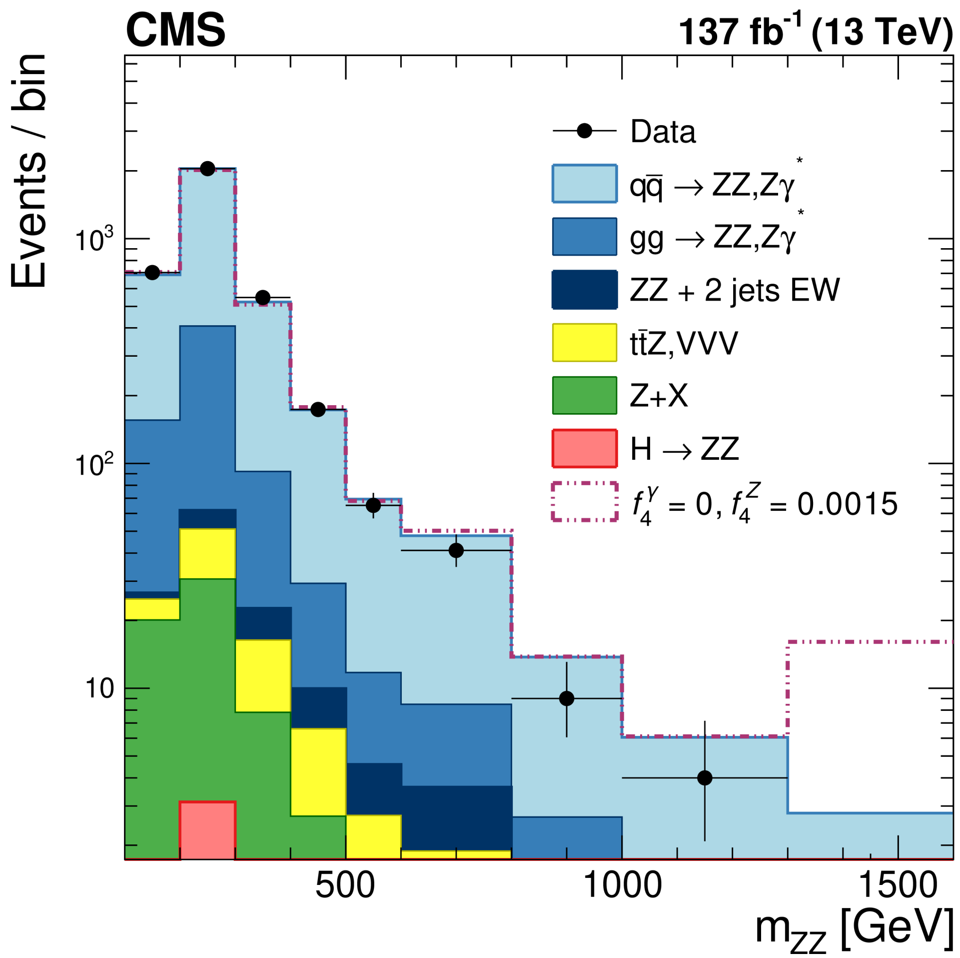
- ZZ→2l2ν. Larger branching fraction than 4l
  - Also larger backgrounds
  - One Z boson boosted recoiling against the other
- nTGC limits from unfolded p_T^{ll} (>150 GeV) distribution
- Sensitivity range found to be within unitarity bounds, no form factors applied.
- Sensitivity limited by statistical uncertainty in data (40%)
- Log-Likelihood ratio relying on Gaussian approximation (at least 10 events in the higher p_T^{ll} bins)



	f_4^γ	f_4^Z	f_5^γ	f_5^Z
Expected [$\times 10^{-3}$]	[−1.3, 1.3]	[−1.1, 1.1]	[−1.3, 1.3]	[−1.1, 1.1]
Observed [$\times 10^{-3}$]	[−1.2, 1.2]	[−1.0, 1.0]	[−1.2, 1.2]	[−1.0, 1.0]

1-dimensional 95% CL

CMS: ZZ→4l



	Expected 95% CL	Observed 95% CL
aTGC parameter	$\times 10^{-4}$	$\times 10^{-4}$
f_4^Z	-8.8 ; 8.3	-6.6 ; 6.0
f_5^Z	-8.0 ; 9.9	-5.5 ; 7.5
f_4^γ	-9.9 ; 9.5	-7.8 ; 7.1
f_5^γ	-9.2 ; 9.8	-6.8 ; 7.5
EFT parameter	TeV^{-4}	TeV^{-4}
$C_{\tilde{B}W}/\Lambda^4$	-3.1 ; 3.3	-2.3 ; 2.5
C_{WW}/Λ^4	-1.7 ; 1.6	-1.4 ; 1.2
C_{BW}/Λ^4	-1.8 ; 1.9	-1.4 ; 1.3
C_{BB}/Λ^4	-1.6 ; 1.6	-1.2 ; 1.2

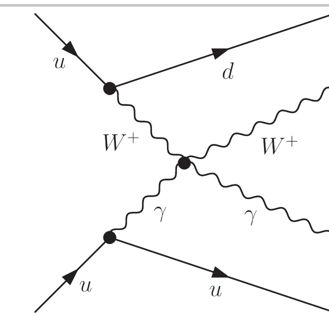
- Three different channels 4e, 2e2μ, 4μ. Both Z bosons on-shell, mass range 60-120 GeV
  - Interpretation from the combination of 3 channels in the four-lepton mass
- One-loop EW corrections applied as a cross check
  - Improve in the limits by 4-6%

$Z\gamma\gamma$ constrained by ATLAS Z(νν)γ analysis

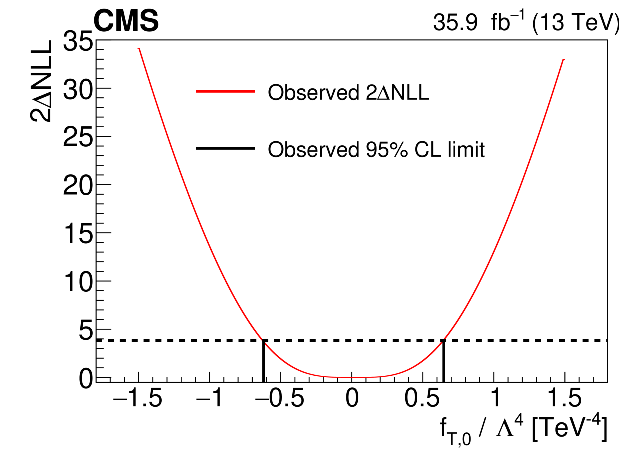
- Most stringent limits on ZZZ and ZZγ anomalous couplings

Similar strategy but looser constraints (36/fb) in ATLAS ZZ->4l analysis

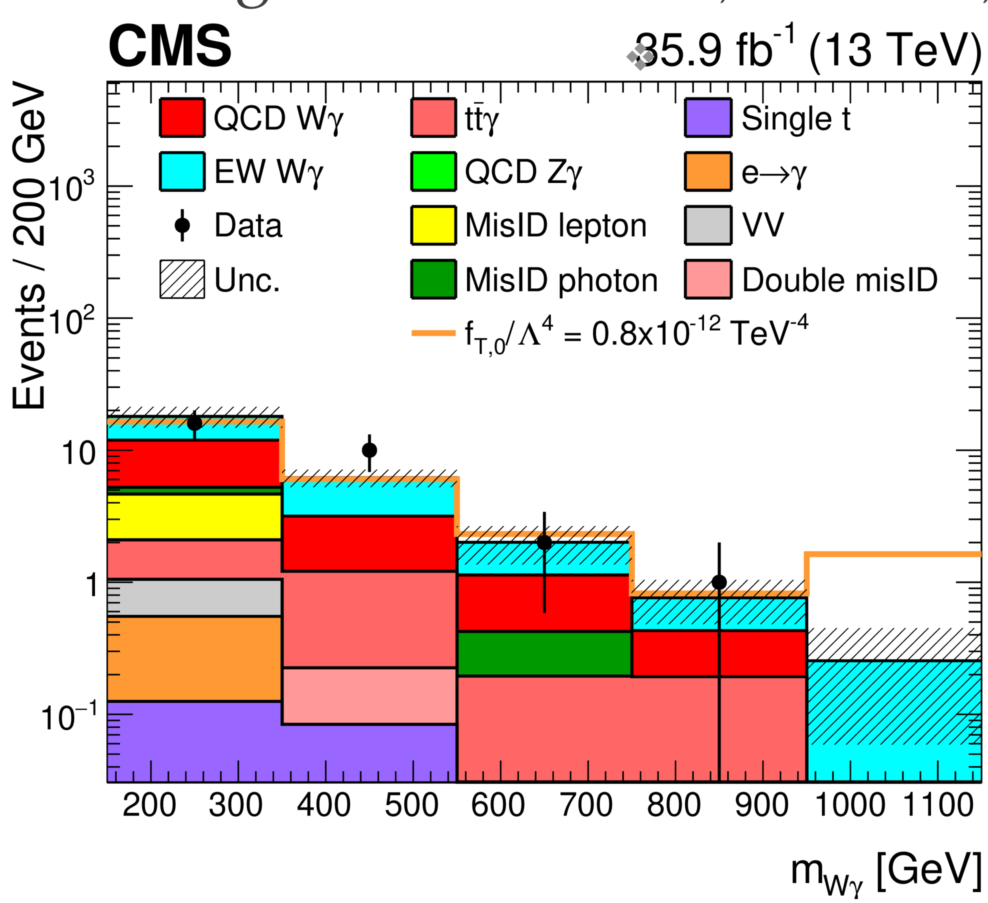
CMS: Wγ VBS



- W decaying in the leptonic (e or μ) channel
- $p_T^{\gamma} > 25$ GeV, $m_{jj} > 500$ GeV, $|\Delta\eta_{jj}| > 2.5$
  - EW extraction from 2-D template fits to (m_{jj}, $m_{l\gamma}$)
- aQGC limits from fits to $m_{\gamma W}$ distribution
  - Using Eboli basis
- Limits set from profile likelihood test statistic
- Most stringent limits on $f_{M,2\text{-}5}$ and $f_{T,6\text{-}7}$

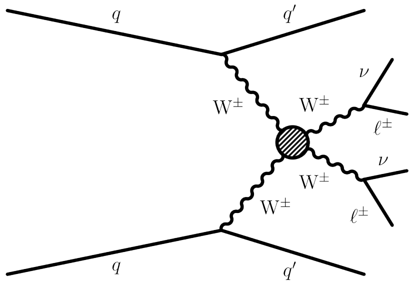


Parameters	Exp. limit	Obs. limit	$\mathcal{U}_{\text{bound}}$
$f_{M,0}/\Lambda^4$	$[-8.1, 8.0]$	$[-7.7, 7.6]$	1.0
$f_{M,1}/\Lambda^4$	$[-12, 12]$	$[-11, 11]$	1.2
$f_{M,2}/\Lambda^4$	$[-2.8, 2.8]$	$[-2.7, 2.7]$	1.3
$f_{M,3}/\Lambda^4$	$[-4.4, 4.4]$	$[-4.0, 4.1]$	1.5
$f_{M,4}/\Lambda^4$	$[-5.0, 5.0]$	$[-4.7, 4.7]$	1.5
$f_{M,5}/\Lambda^4$	$[-8.3, 8.3]$	$[-7.9, 7.7]$	1.8
$f_{M,6}/\Lambda^4$	$[-16, 16]$	$[-15, 15]$	1.0
$f_{M,7}/\Lambda^4$	$[-21, 20]$	$[-19, 19]$	1.3
$f_{M,0}/\Lambda^4$	$[-0.6, 0.6]$	$[-0.6, 0.6]$	1.4
$f_{M,1}/\Lambda^4$	$[-0.4, 0.4]$	$[-0.3, 0.4]$	1.5
$f_{M,2}/\Lambda^4$	$[-1.0, 1.2]$	$[-1.0, 1.2]$	1.5
$f_{M,5}/\Lambda^4$	$[-0.5, 0.5]$	$[-0.4, 0.4]$	1.8
$f_{M,6}/\Lambda^4$	$[-0.4, 0.4]$	$[-0.3, 0.4]$	1.7
$f_{M,7}/\Lambda^4$	$[-0.9, 0.9]$	$[-0.8, 0.9]$	1.8

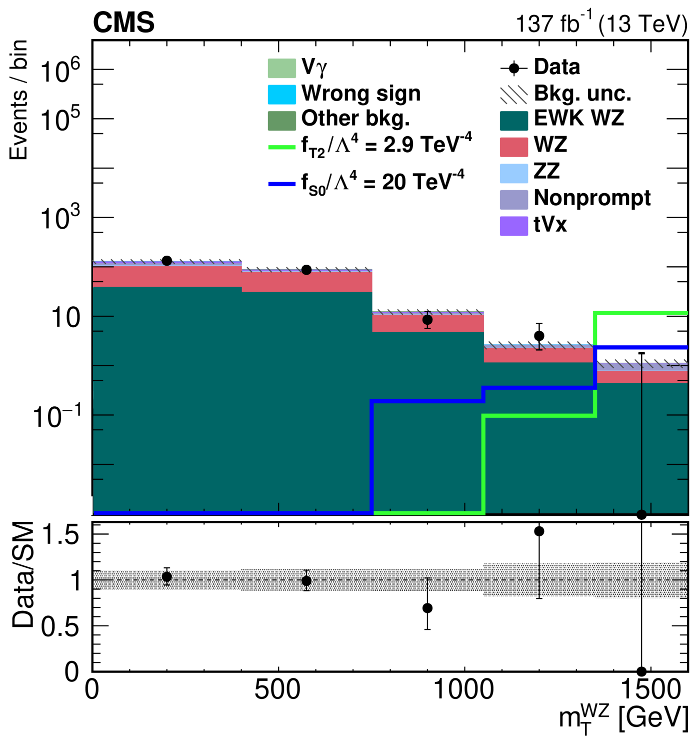


Similar strategy followed in Zγ SMP-18-007 arXiv:2005.01173

CMS:WZ and ssWW



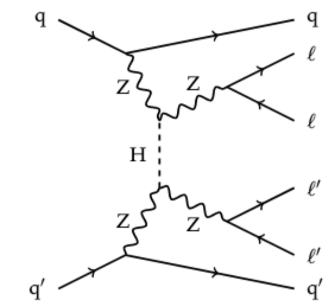
- $W^{\pm}Z \rightarrow l^{\pm}\nu l'^{\pm}l'^{\mp}$and $WW \rightarrow l^{\pm}\nu l'^{\pm}\nu$
  - ssWW cleanest channel in terms of EW signal to QCD bkg. ratio
- EW WZ signal separated from WZ QCD process using a BDT approach
- aQGC limits from fits to the transverse mass of the diboson system distribution
  - Eboli basis. Cutting the EFT integration at the unitarity limit
- Improvement over other leptonic measurements of WZ and WW
  - But less restrictive than semileptonic final states

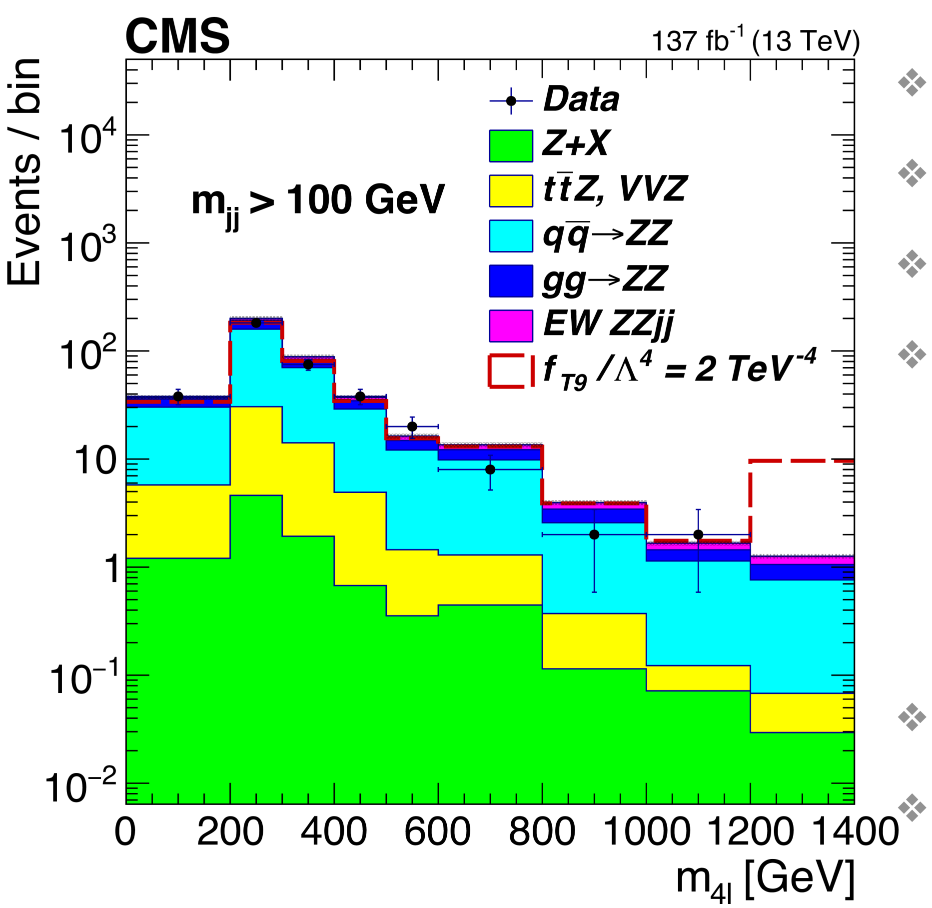


Including unitarization

	Observed ($W^{\pm}W^{\pm}$) (TeV^{-4})	Expected ($W^{\pm}W^{\pm}$) (TeV^{-4})	Observed (WZ) (TeV^{-4})	Expected (WZ) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{T0}/Λ^4	[-1.5, 2.3]	[-2.1, 2.7]	[-1.6, 1.9]	[-2.0, 2.2]	[-1.1, 1.6]	[-1.6, 2.0]
f_{T1}/Λ^4	[-0.81, 1.2]	[-0.98, 1.4]	[-1.3, 1.5]	[-1.6, 1.8]	[-0.69, 0.97]	[-0.94, 1.3]
f_{T2}/Λ^4	[-2.1, 4.4]	[-2.7, 5.3]	[-2.7, 3.4]	[-4.4, 5.5]	[-1.6, 3.1]	[-2.3, 3.8]
f_{M0}/Λ^4	[-13, 16]	[-19, 18]	[-16, 16]	[-19, 19]	[-11, 12]	[-15, 15]
f_{M1}/Λ^4	[-20, 19]	[-22, 25]	[-19, 20]	[-23, 24]	[-15, 14]	[-18, 20]
f_{M6}/Λ^4	[-27, 32]	[-37, 37]	[-34, 33]	[-39, 39]	[-22, 25]	[-31, 30]
f_{M7}/Λ^4	[-22, 24]	[-27, 25]	[-22, 22]	[-28, 28]	[-16, 18]	[-22, 21]
f_{S0}/Λ^4	[-35, 36]	[-31, 31]	[-83, 85]	[-88, 91]	[-34, 35]	[-31, 31]
f_{S1}/Λ^4	[-100, 120]	[-100, 110]	[-110, 110]	[-120, 130]	[-86, 99]	[-91, 97]

CMS: ZZ VBS





- Four lepton final state with two high m_{jj} jets
- EW signal separated using a matrix element discriminant
- Evidence of the process achieved
- Sensitivity to charged- (T0-T2) and neutral-current operators.
  - Limits from the invariant mass of the four leptons
  - Measurement statistically limited
- Most stringent tests of neutral-current op. (T8, T9)
- Unitarity upper bounds from this paper

Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
f_{T0}/Λ^4	-0.37	0.35	-0.24	0.22	2.4
f_{T1}/Λ^4	-0.49	0.49	-0.31	0.31	2.6
f_{T2}/Λ^4	-0.98	0.95	-0.63	0.59	2.5
f_{T8}/Λ^4	-0.68	0.68	-0.43	0.43	1.8
f_{T9}/Λ^4	-1.5	1.5	-0.92	0.92	1.8

EFT in the Higgs sector

- Anomalous HVV couplings strategy also followed in the Higgs sector

$$A(X_{J=0} \to VV) = \frac{1}{v}\left(g_1 m_V^2 \epsilon_1^* \epsilon_2^* + g_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_4 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

- Moving to EFT several bases are or have been used for the interpretation of the results -> Mapping from one complete basis to another can be done

- Warsaw basis: First non-redundant set of operators proposed.

- SILH basis: Designed to capture effects in which BSM couples to SM bosons

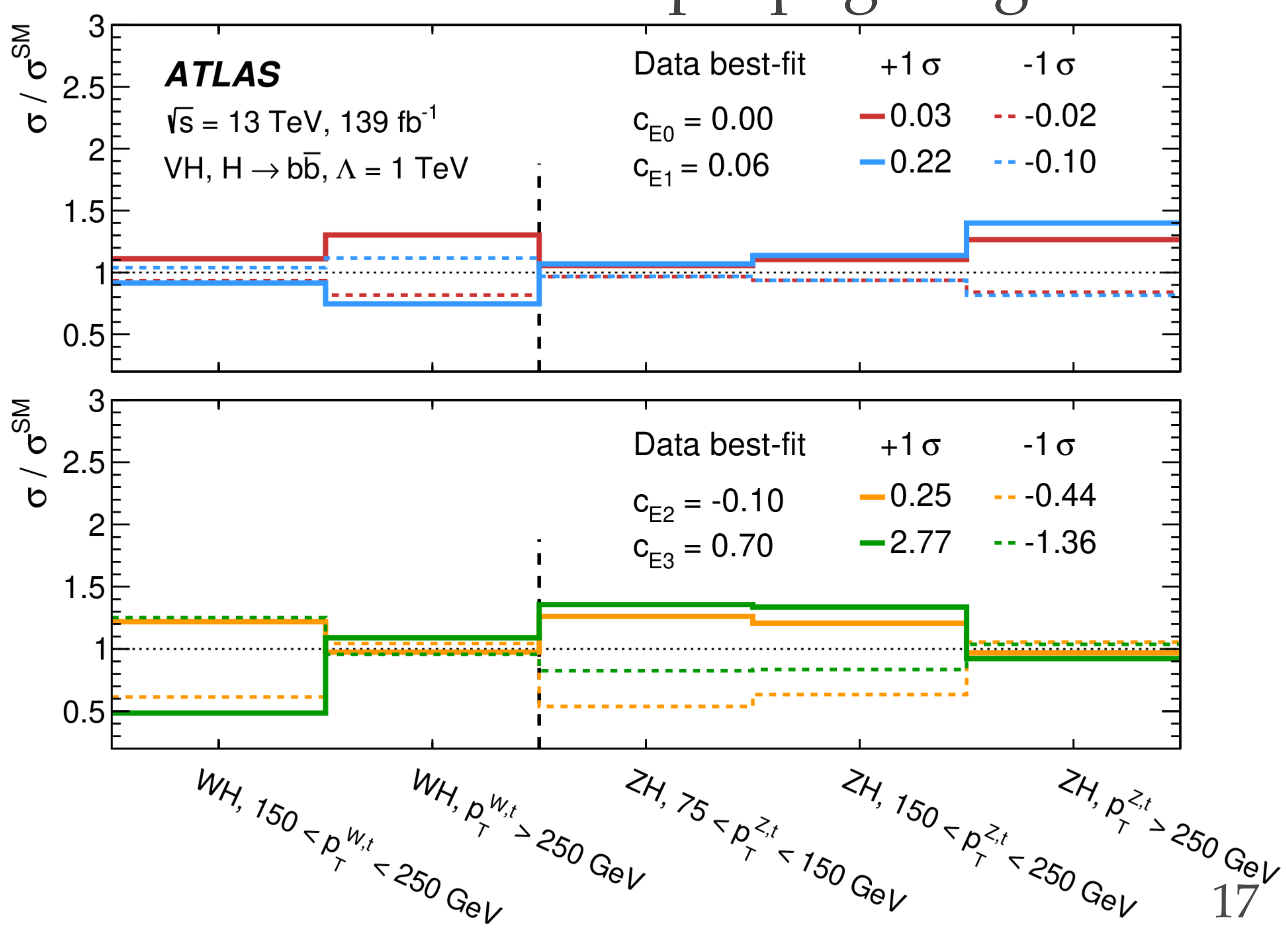
- Higgs basis: From BSM primaries.

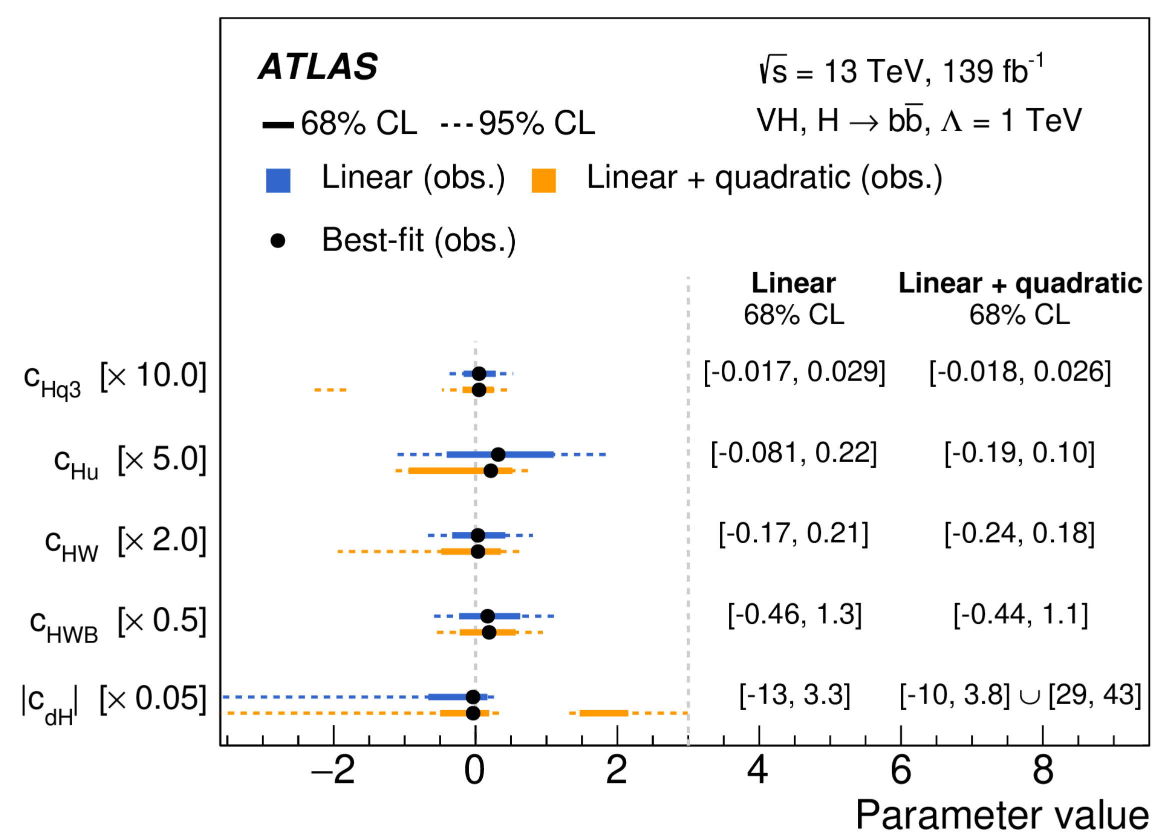
Basis	Underlying gauge symmetry	Fields used in the Lagrangian
Warsaw, SILH	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Gauge-eigenstates
BSM primaries, Higgs	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Mass-eigenstates
Higgs/BSM characterisation	$SU(3)_C \times U(1)_{EM}$	Mass-eigenstates

From Eur. Phys. J. C (205) 75:583

ATLAS: H→bb (resolved)

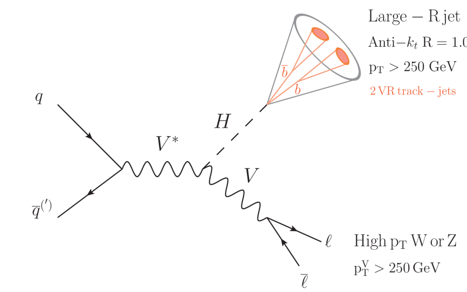
- Measurement of STXS using full run 2 dataset and the Warsaw basis as implemented in SMEFTsim (flavour universality)
- No a-priori assumption on the set of parameters to use in the fit, retain those with more sensitivity in the measurement for 1-D fits (neglects correlations).
- 5-D fits using most sensitive directions of the measurement
  - Diagonalising EFT matrix starting from the Fisher information matrix of the measurement and propagating the EFT parametrisation ATL-PHYS-PUB-2019-042

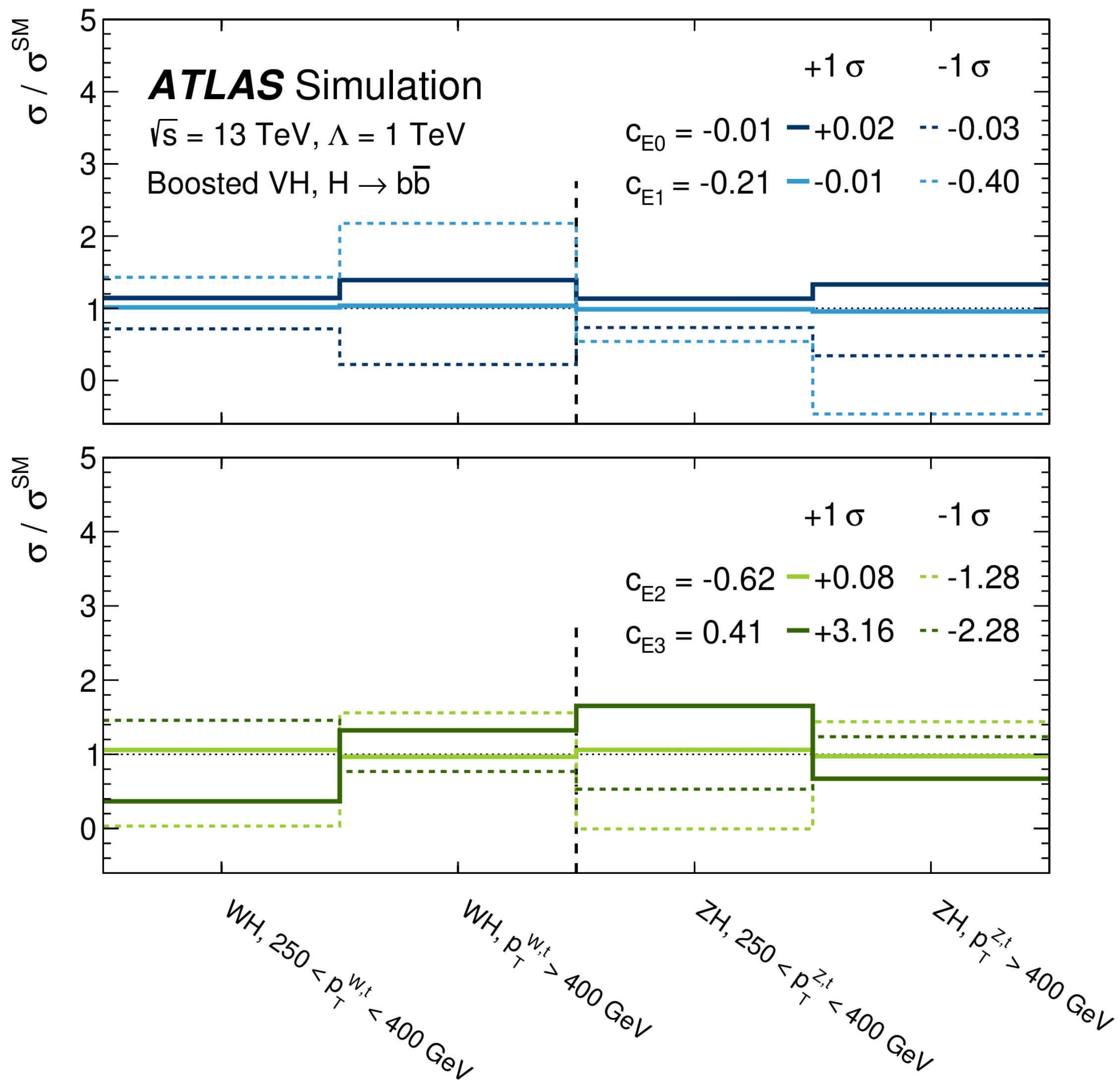


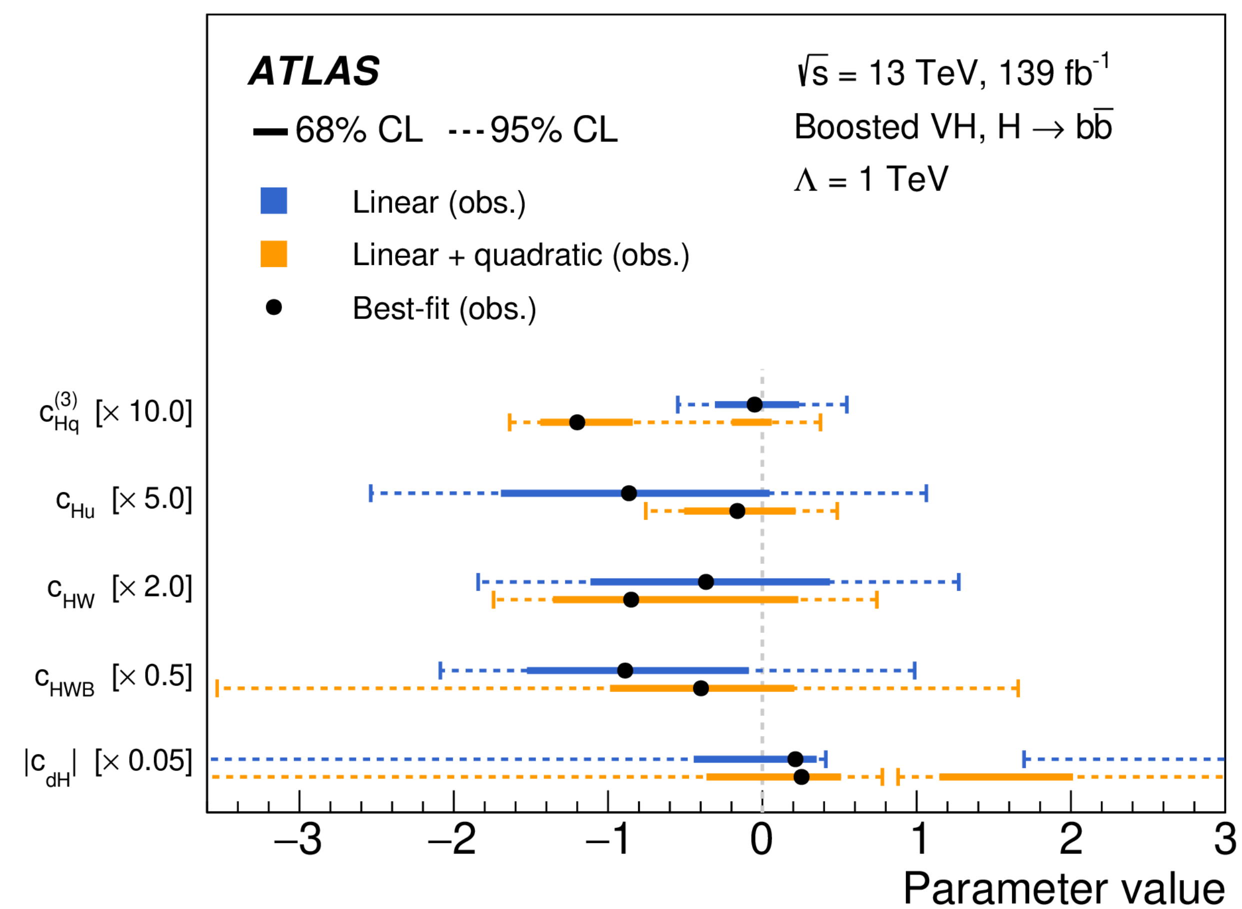


arXiv:2008.02508

ATLAS: H→bb (boosted)



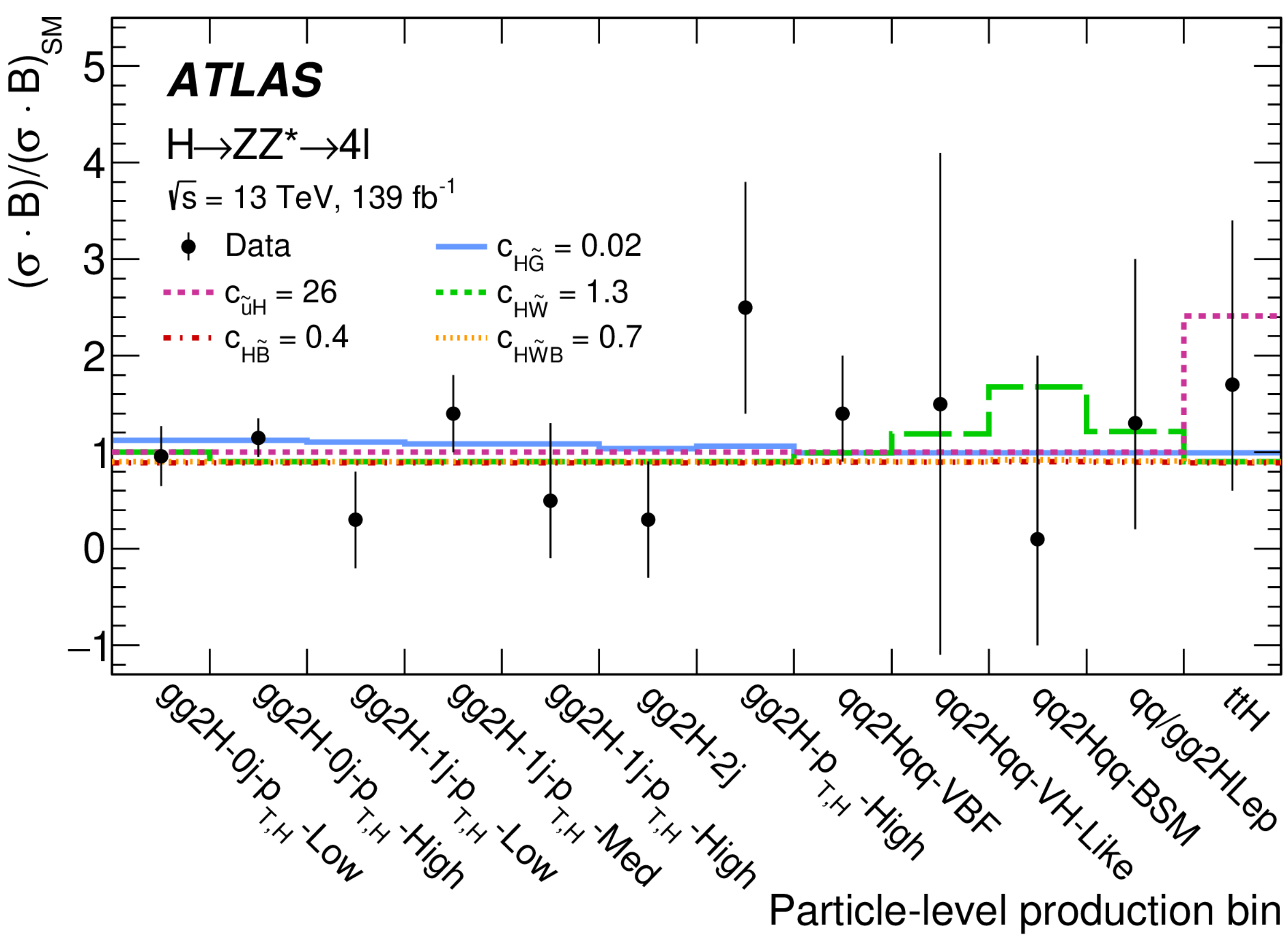




Coefficient	Eigenvalue	Eigenvector combination
c_{EA}	1500.0	$0.99 \cdot c_{Hq}^{(3)} + 0.11 \cdot c_{Hu}$
c_{EB}	26.9	$0.82 \cdot c_{Hu} - 0.49 \cdot c_{Hq}^{(1)} - 0.24 \cdot c_{Hd} - 0.13 \cdot c_{Hq}^{(3)}$
c_{EC}	2.2	$0.67 \cdot \mathcal{I}_{BR} + 0.66 \cdot c_{HW} + 0.18 \cdot c_{Hq}^{(1)} - 0.16 \cdot c_{Hl}^{(3)} + 0.14 \cdot c_{HWB} + 0.12 \cdot c_{ll}^{(1)}$
c_{ED}	0.1	$0.70 \cdot c_{Hq}^{(1)} + 0.52 \cdot c_{HWB} + 0.27 \cdot c_{Hu} - 0.27 \cdot c_{HW} - 0.24 \cdot c_{Hd} + 0.13 \cdot c_{HB}$

- Similar strategy as in the resolved analysis
- Expected more sensitivity to EFT at higher transverse momentum
- Constraints not improved wrt. resolved analysis

ATLAS: H→4l

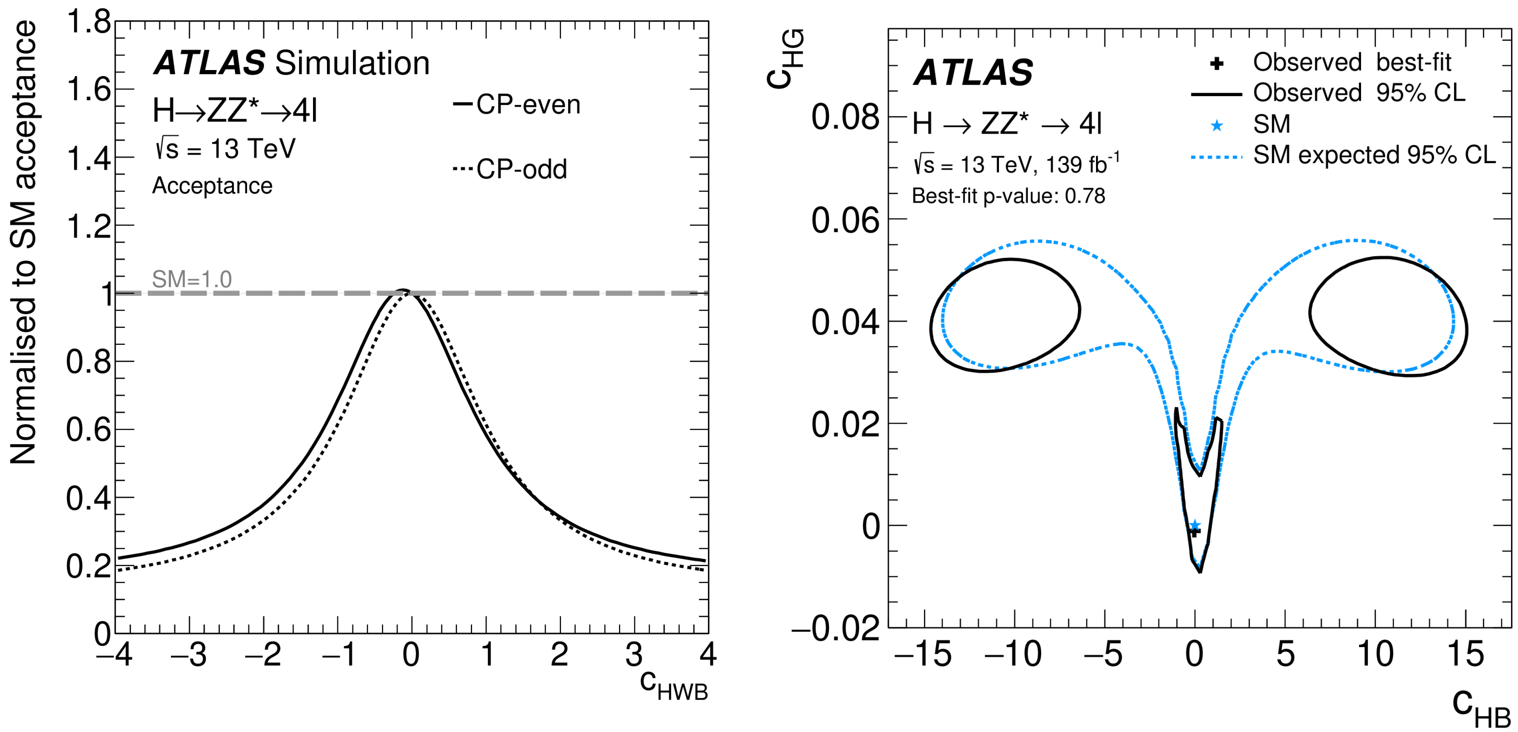


- Interpretation of STXS measurements in the Warsaw basis
- Main operators affecting the measurement are selected
- Studies of the linear and quadratic terms as well as CP-even and CP-odd operators

- CP-odd operators only appear in the quadratic terms
- For several operators, quadratic terms are relevant

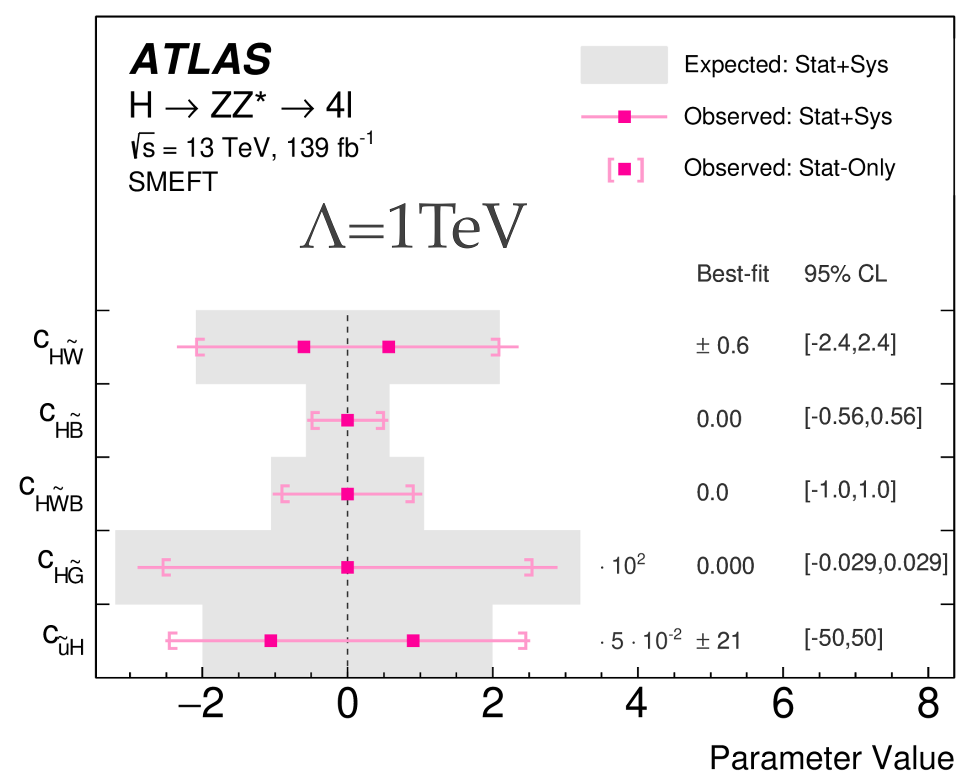
CP-even Operator	CP-even Structure	CP-even Coeff.	CP-odd Operator	CP-odd Structure	CP-odd Coeff.	Impact on production	Impact on decay
O_{uH}	$HH^\dagger \bar{q}_p u_r \tilde{H}$	c_{uH}	O_{uH}	$HH^\dagger \bar{q}_p u_r \tilde{H}$	$c_{\tilde{u}H}$	ttH	-
O_{HG}	$HH^\dagger G^A_{\mu\nu} G^{\mu\nu A}$	c_{HG}	$O_{H\tilde{G}}$	$HH^\dagger \tilde{G}^A_{\mu\nu} G^{\mu\nu A}$	$c_{H\tilde{G}}$	ggF	Yes
O_{HW}	$HH^\dagger W^l_{\mu\nu} W^{\mu\nu l}$	c_{HW}	$O_{H\widetilde{W}}$	$HH^\dagger \widetilde{W}^l_{\mu\nu} W^{\mu\nu l}$	$c_{H\widetilde{W}}$	VBF, VH	Yes
O_{HB}	$HH^\dagger B_{\mu\nu} B^{\mu\nu}$	c_{HB}	$O_{H\tilde{B}}$	$HH^\dagger \tilde{B}_{\mu\nu} B^{\mu\nu}$	$c_{H\tilde{B}}$	VBF, VH	Yes
O_{HWB}	$HH^\dagger \tau^l W^l_{\mu\nu} B^{\mu\nu}$	c_{HWB}	$O_{H\widetilde{W}B}$	$HH^\dagger \tau^l \widetilde{W}^l_{\mu\nu} B^{\mu\nu}$	$c_{H\widetilde{W}B}$	VBF, VH	Yes

ATLAS: H→4l



- Parametrisation of STXS production cross sections. But 4l selection can be affected by EFT operators.
  - Acceptance effects taken into account
  - Shown to be relevant.

- Limits from 1-D fits, correlations studied through 2D fits.
  - Not trivial correlations between most of the parameter pairs

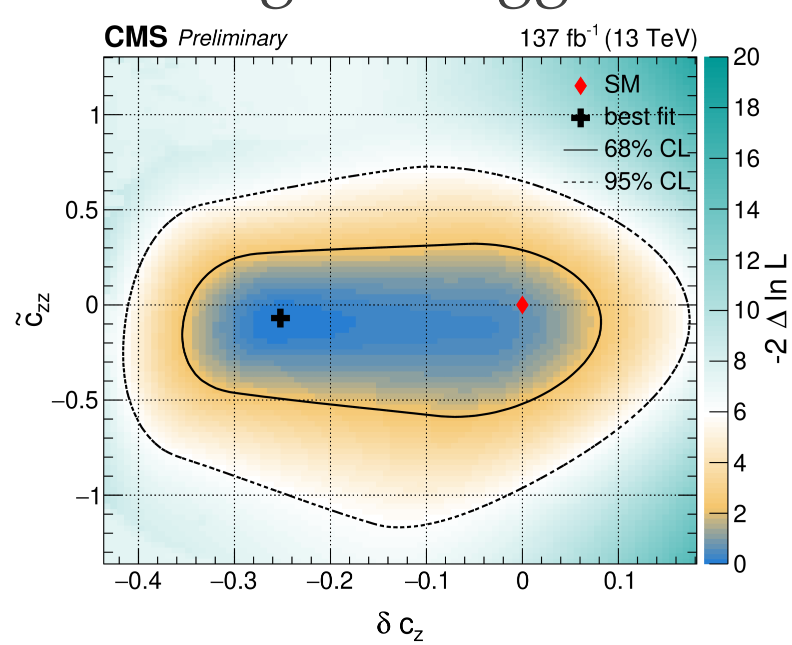


CMS:H→4l

- Dedicated search for Higgs anomalous coupling
  - 2 in Htt couplings (magnitude and the phase, ttH and ggH combined)
  - 2 in ggH couplings: c_{gg} and its CP-odd counterpart
  - 5 anomalous couplings for HVV, simplifications to conserve custodial sym.

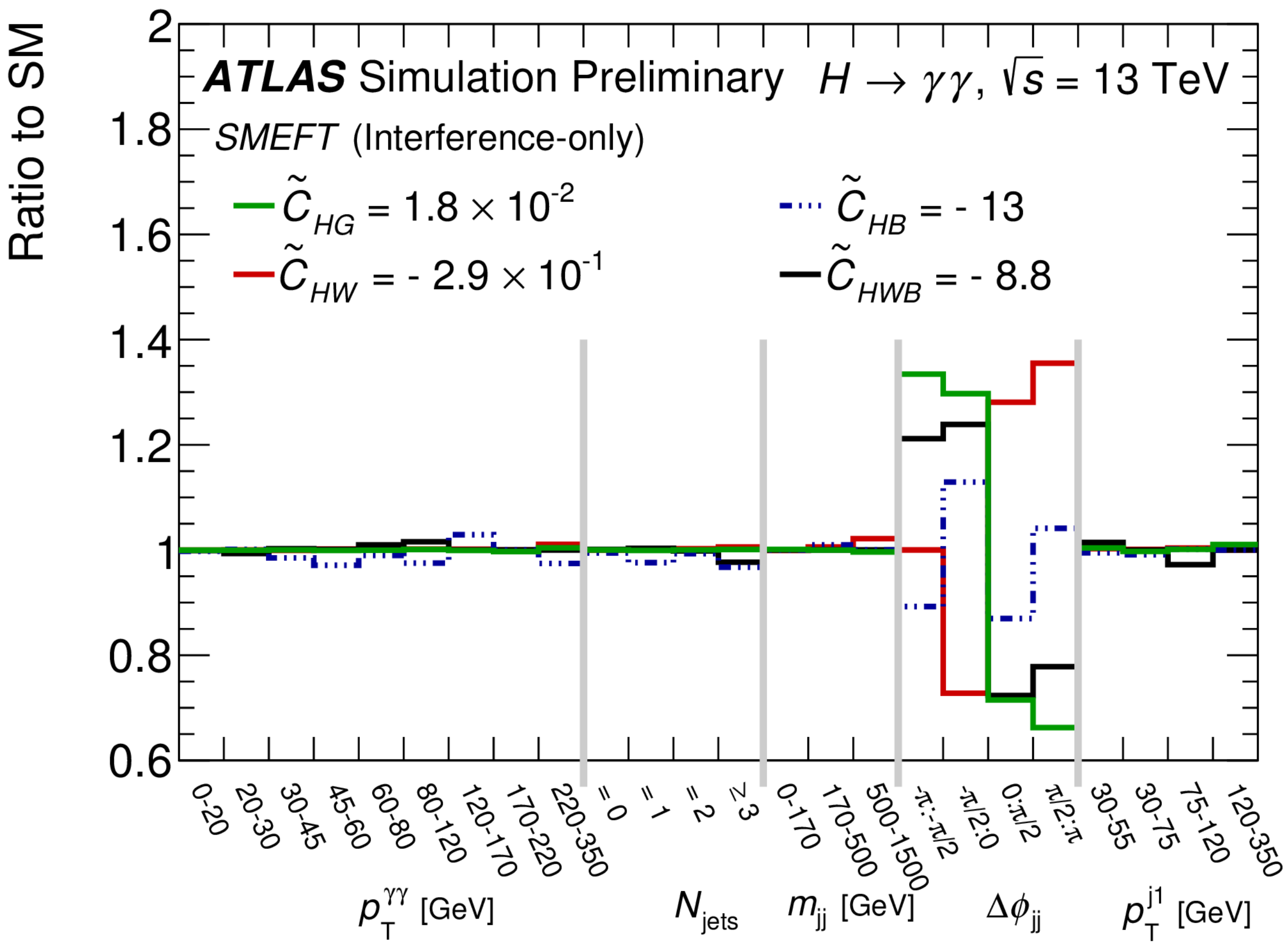
$$A(\mathrm{HVV}) = \frac{1}{v}\left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} + \frac{\kappa_3^{\mathrm{VV}} (q_{\mathrm{V1}} + q_{\mathrm{V2}})^2}{\left(\Lambda_Q^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^*$$
$$+ \frac{1}{v} a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$

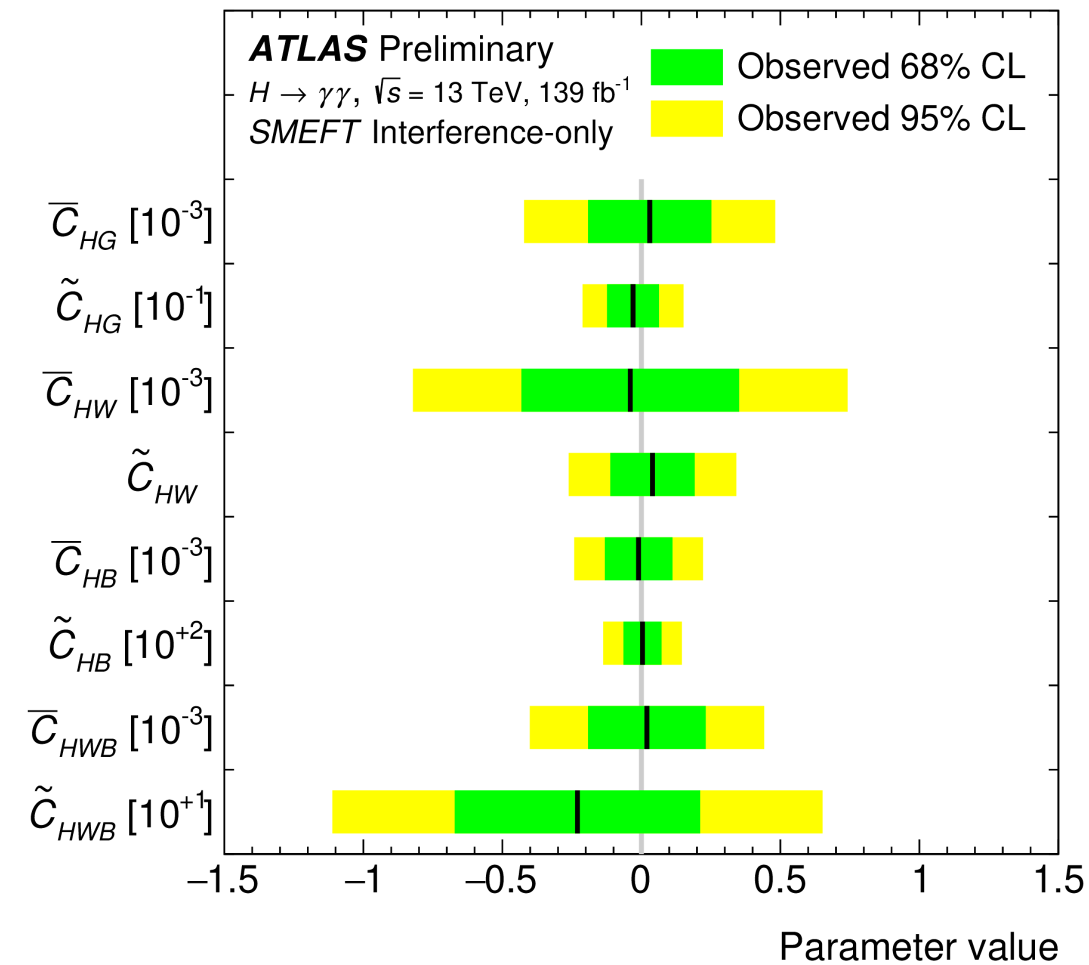
  - EFT interpretation using the Higgs basis
- Matrix element techniques to identify the production mechanism



Channels	Coupling	Observed	Expected	Observed correlation			
ggH	c_{gg}	$0.0056^{+0.0025}_{-0.0039}$	$0.0084^{+0.0007}_{-0.0084}$		1		
	$\tilde{c}_{gg}$	$-0.0058^{+0.0037}_{-0.0024}$	$0.0000^{+0.0085}_{-0.0085}$		+0.980	1	
$\mathrm{t\bar{t}H}$	κ_{t}	$1.06^{+0.14}_{-0.18}$	$1.00^{+0.15}_{-0.23}$		1		
	$\tilde{\kappa}_{\mathrm{t}}$	$0.00^{+0.76}_{-0.72}$	$0.00^{+0.80}_{-0.80}$		0.000	1	
$\mathrm{t\bar{t}H + ggH}$	κ_{f}	$0.76^{+0.23}_{-0.21}$	$1.00^{+0.26}_{-0.39}$		1		
	$\tilde{\kappa}_{\mathrm{f}}$	$-0.21^{+0.28}_{-0.12}$	0.00 ± 0.37		+0.745	1	
$\mathrm{VBF + VH + H \to 4\ell}$	δc_z	$-0.25^{+0.27}_{-0.07}$	$0.00^{+0.10}_{-0.28}$	1			
	c_{zz}	$0.03^{+0.10}_{-0.10}$	$0.00^{+0.22}_{-0.16}$	+0.144	1		
	$c_{z\Box}$	$-0.03^{+0.04}_{-0.04}$	$0.00^{+0.06}_{-0.09}$	−0.186	−0.847	1	
	$\tilde{c}_{zz}$	$-0.11^{+0.30}_{-0.31}$	$0.00^{+0.63}_{-0.63}$	+0.077	−0.016	+0.009	1

ATLAS: H→$\gamma\gamma$

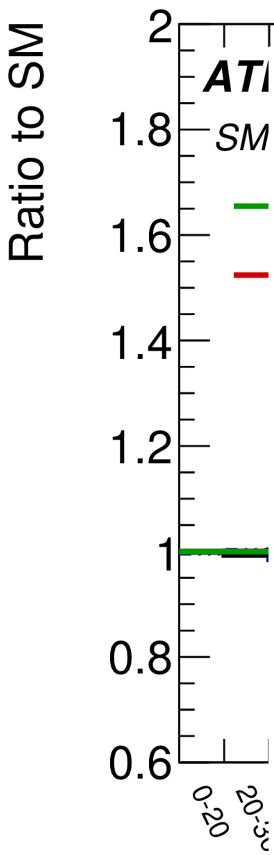


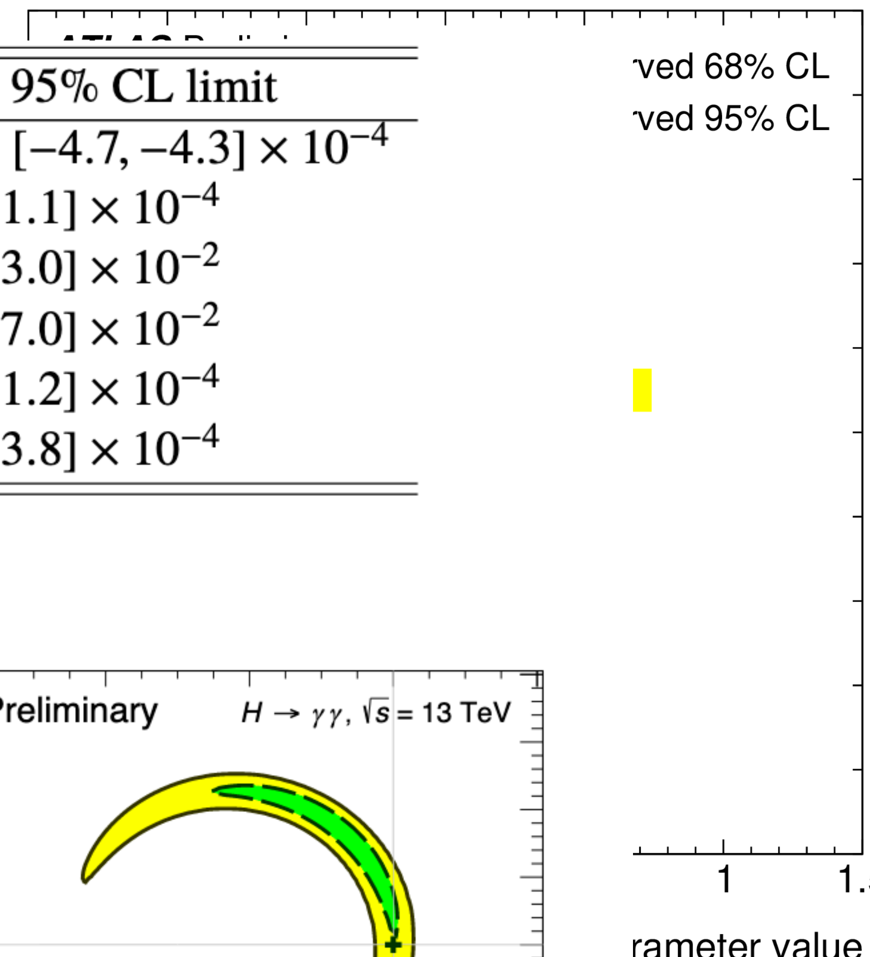


- EFT interpretation from differential cross sections using Warsaw and SILH bases
- Introduced CP-odd observables to constrain CP-odd operators at interference level
- Operators studied are the ones modifying mainly ggH and the H-> $\gamma\gamma$ decay.
- Limits from 1-D fits

$$\mathcal{L} = \frac{1}{\sqrt{(2\pi)^k |C|}} \exp\left(-\frac{1}{2}\left(\vec{\sigma}_{\text{data}} - \vec{\sigma}_{\text{pred}}\right)^T C^{-1}\left(\vec{\sigma}_{\text{data}} - \vec{\sigma}_{\text{pred}}\right)\right),$$

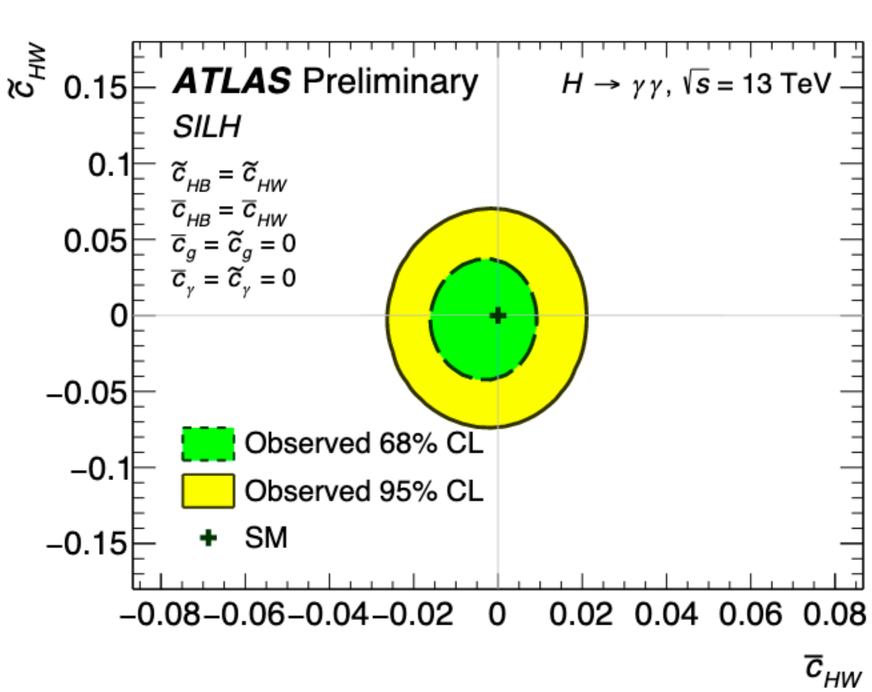
ATLAS: H→$\gamma\gamma$

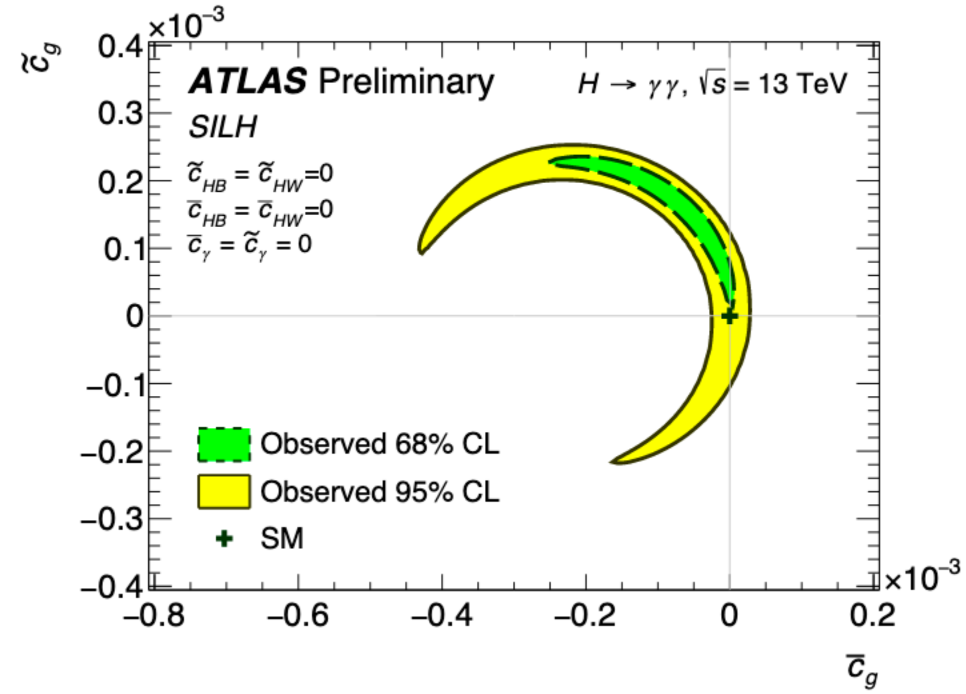




Coefficient	Observed 95% CL limit	Expected 95% CL limit
$\bar{c}_g$	$[-0.26, 0.26] \times 10^{-4}$	$[-0.25, 0.25] \cup [-4.7, -4.3] \times 10^{-4}$
$\tilde{c}_g$	$[-1.3, 1.1] \times 10^{-4}$	$[-1.1, 1.1] \times 10^{-4}$
$\bar{c}_{HW}$	$[-2.5, 2.2] \times 10^{-2}$	$[-3.0, 3.0] \times 10^{-2}$
$\tilde{c}_{HW}$	$[-6.5, 6.3] \times 10^{-2}$	$[-7.0, 7.0] \times 10^{-2}$
$\bar{c}_\gamma$	$[-1.1, 1.1] \times 10^{-4}$	$[-1.0, 1.2] \times 10^{-4}$
$\tilde{c}_\gamma$	$[-2.8, 4.3] \times 10^{-4}$	$[-2.9, 3.8] \times 10^{-4}$

In SILH basis

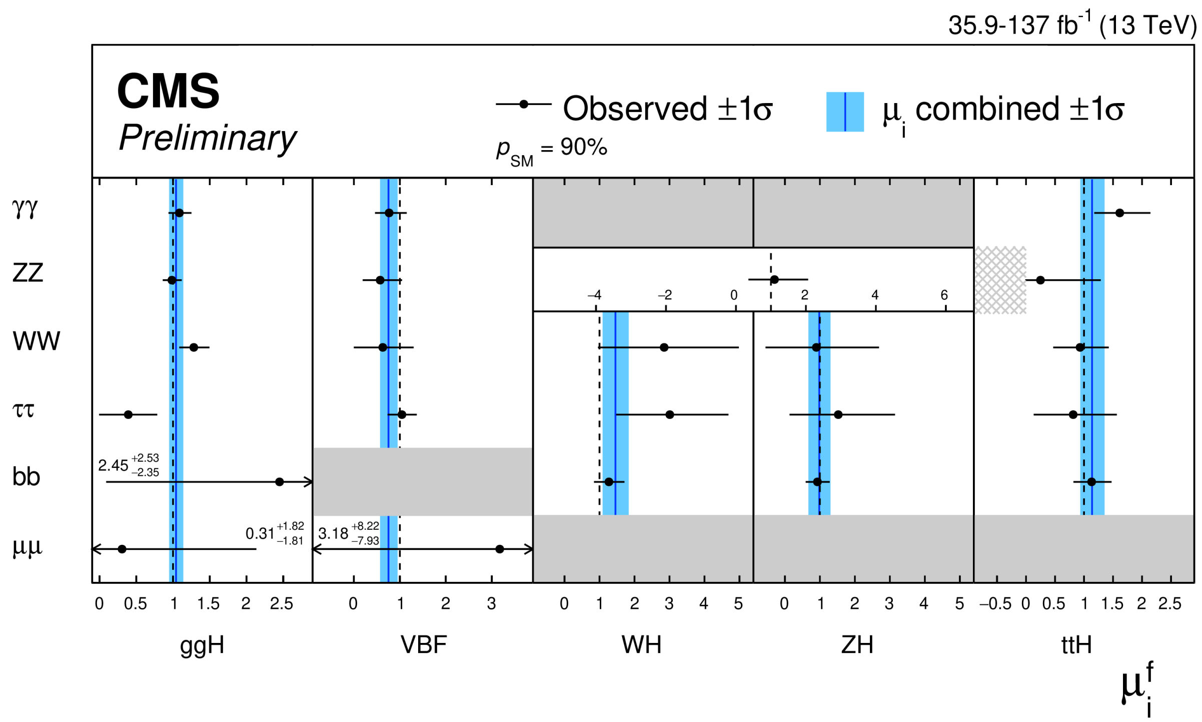




- EFT ir … H basis
- Introd … ence level
- Opera … ay.
- Limits

$$\mathcal{L} = \frac{1}{\sqrt{(2\pi)^k |C|}} \exp\left(-\frac{1}{2}(\vec{\sigma}_{\text{data}} - \vec{\sigma}_{\text{pred}})^T C^{-1} (\vec{\sigma}_{\text{data}} - \vec{\sigma}_{\text{pred}})\right),$$

CMS: Higgs Combination



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

- Combined measurements of the production and decay rates of the Higgs boson and its couplings to vector bosons and fermions
- Interpretation in the HEL Lagrangian
  - SILH basis with flavour universality
- Signal strength values reparametrized in terms of EFT coefficients.
- Only interference term considered
  - CP-even terms not tightly constrained by other data
- Acceptance effects not taken into account
- Limits from simultaneous likelihood fits in the chosen parameters.
  - Significant differences in the constraints compared to 1-D fits

Summary

- Many different precision measurements used to constrain BSM effects in terms of EFT or anomalous couplings presented.
  - Several differences in the methodology but all of them tending to include an EFT interpretation taking into account dim-6 operators (not for aQGCs)

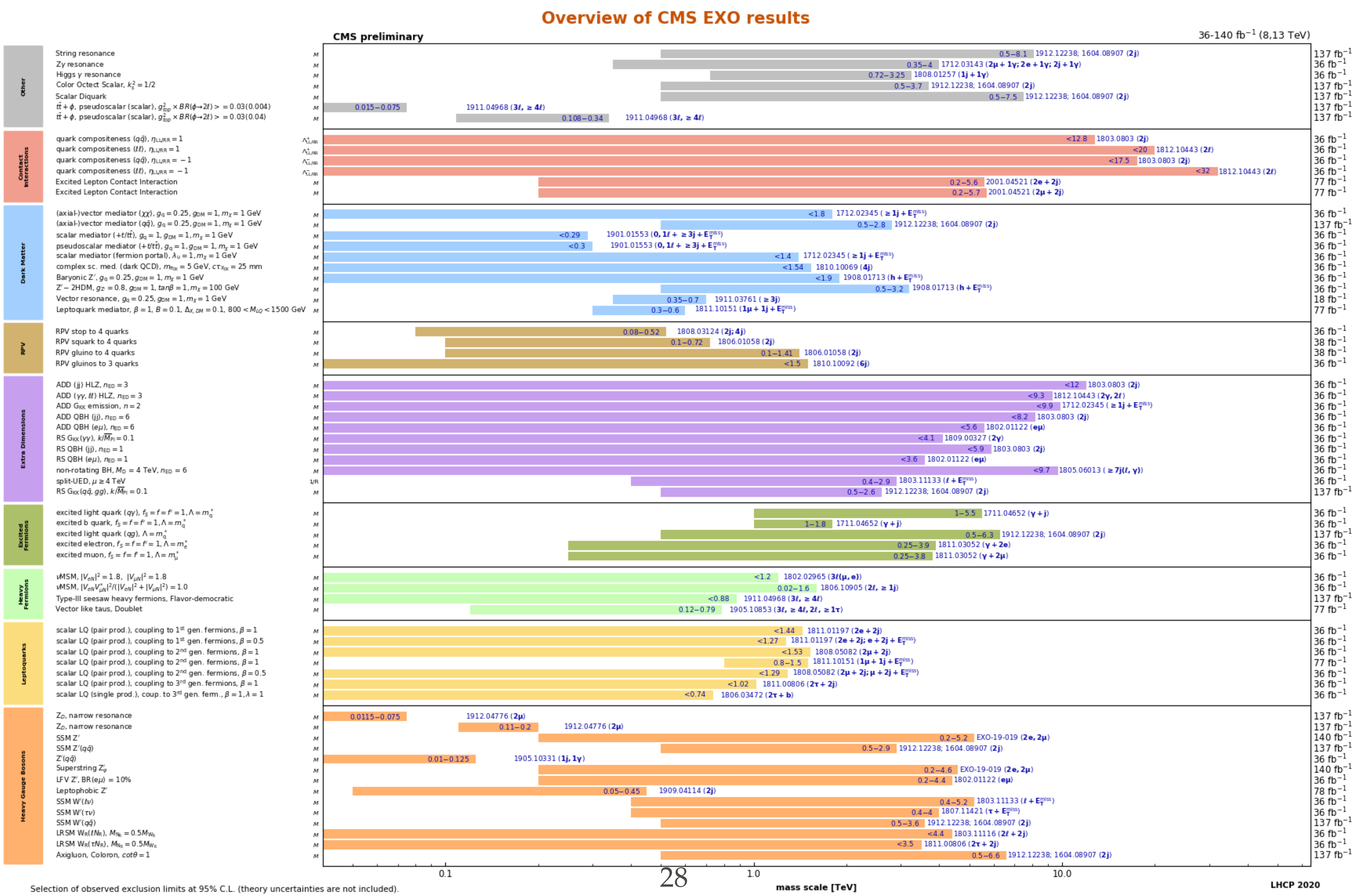
- No deviations from the SM found in the analyses
  - Constraints of parameters improved significantly wrt. previous measurements in the EW measurements
  - More difficult to compare in the Higgs case

- Operators or effects to constrain typically chosen a priori based on symmetries, previous constraints etc…
  - But EFT parameter space shows large correlations in general and different assumptions considered between different analyses/experiments

THANKS!

BACK UP

BSM searches



Relations between aTGCs and EFT

$$
\begin{aligned}
g_1^Z &= 1 + c_W \frac{m_Z^2}{2\Lambda^2} \\
\kappa_\gamma &= 1 + (c_W + c_B)\frac{m_W^2}{2\Lambda^2} \\
\kappa_Z &= 1 + (c_W - c_B \tan^2\theta_W)\frac{m_W^2}{2\Lambda^2} \\
\lambda_\gamma &= \lambda_Z = c_{WWW}\frac{3g^2 m_W^2}{2\Lambda^2} \\
g_4^V &= g_5^V = 0 \\
\tilde{\kappa}_\gamma &= c_{\tilde{W}}\frac{m_W^2}{2\Lambda^2} \\
\tilde{\kappa}_Z &= -c_{\tilde{W}} \tan^2\theta_W \frac{m_W^2}{2\Lambda^2} \\
\tilde{\lambda}_\gamma &= \tilde{\lambda}_Z = c_{\tilde{W}WW}\frac{3g^2 m_W^2}{2\Lambda^2}
\end{aligned}
$$

$$
\begin{aligned}
f_1^\gamma &= 1 + c_{WWW}\frac{3g^2 P^2}{4\Lambda^2} \\
f_1^Z &= 1 + c_W \frac{m_Z^2}{\Lambda^2} - c_{WWW}\frac{3g^2 P^2}{4\Lambda^2} \\
f_2^\gamma &= f_2^Z = c_{WWW}\frac{3g^2 m_W^2}{2\Lambda^2} \\
f_3^\gamma &= 2 + (c_B + c_W)\frac{m_W^2}{2\Lambda^2} + c_{WWW}\frac{3g^2 m_W^2}{2\Lambda^2} \\
f_3^Z &= 2 + \left(c_W(1+\cos^2\theta_W) - c_B \sin^2\theta_W\right)\frac{m_Z^2}{2\Lambda^2} + c_{WWW}\frac{3g^2 m_W^2}{2\Lambda^2} \\
f_4^V &= f_5^V = 0 \\
f_6^\gamma &= +c_{\tilde{W}}\frac{m_W^2}{2\Lambda^2} - c_{\tilde{W}WW}\frac{3g^2 m_W^2}{2\Lambda^2} \\
f_6^Z &= -c_{\tilde{W}} \tan^2\theta_W \frac{m_W^2}{2\Lambda^2} - c_{\tilde{W}WW}\frac{3g^2 m_W^2}{2\Lambda^2} \\
f_7^\gamma &= f_7^Z = -c_{\tilde{W}WW}\frac{3g^2 m_W^2}{4\Lambda^2}
\end{aligned}
$$

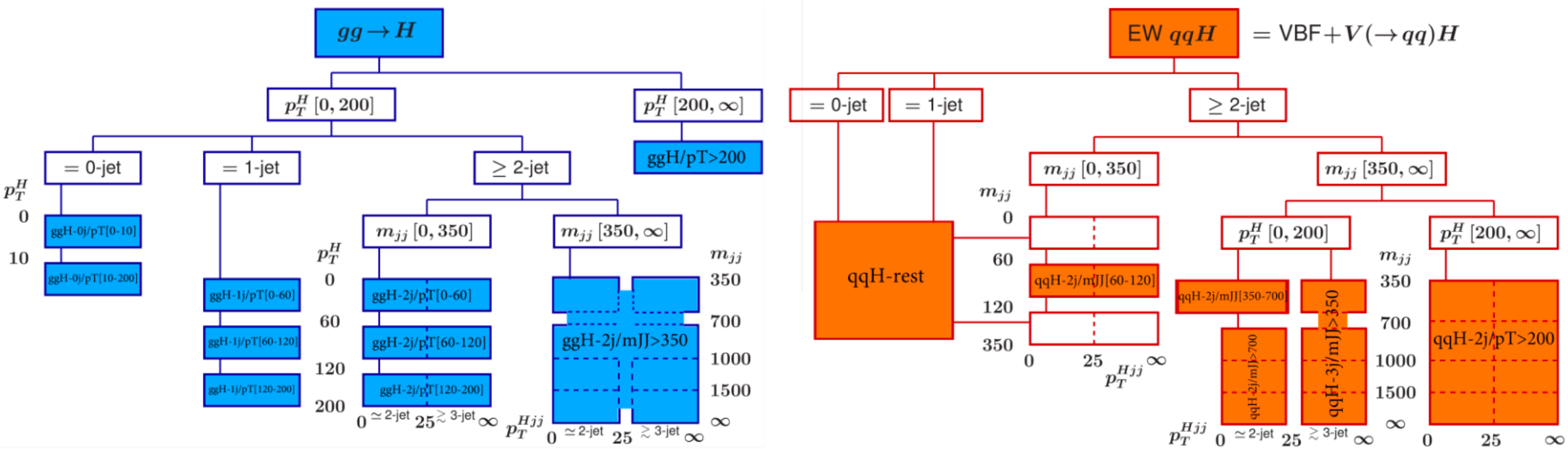
Vertex function approach

$$\begin{aligned}\Gamma_V^{\alpha\beta\mu} &= f_1^V(q-\bar{q})^\mu g^{\alpha\beta} - \frac{f_2^V}{M_W^2}(q-\bar{q})^\mu P^\alpha P^\beta + f_3^V(P^\alpha g^{\mu\beta} - P^\beta g^{\mu\alpha}) \\ &\quad + i f_4^V (P^\alpha g^{\mu\beta} + P^\beta g^{\mu\alpha}) + i f_5^V \epsilon^{\mu\alpha\beta\rho}(q-\bar{q})_\rho \\ &\quad - f_6^V \epsilon^{\mu\alpha\beta\rho} P_\rho - \frac{f_7^V}{m_W^2}(q-\bar{q})^\mu \epsilon^{\alpha\beta\rho\sigma} P_\rho (q-\bar{q})_\sigma\end{aligned}$$

- Momentum-space analogue of the Lagrangian approach
- P, q, $\bar{q}$ are the four-momenta of V, W_-, W_+, respectively.

Simplified template cross sections

- The Simplified Template Cross-Section (STXS) measurements, which are the most common type of the results in ATLAS and CMS, are often used to probe the Higgs boson couplings.
- The advantage of STXS measurements are the following:
  - ✚ Maximizing experimental sensitivity
  - ✚ Minimizing the theoretical uncertainties
  - ✚ Isolation of possible BSM effects
  - ✚ Suitable for global combinations
  - ▬ Not fully fiducial
  - ▬ No Higgs decay information
- The STXS measurements are performed in two steps:
  - The Stage 0 bin definitions essentially correspond to the production mode measurements.
  - The Stage 1 brings additional bins based on kinematics.



- The goal is that the full granularity should become accessible in the combination of all decay channels.

Warsaw basis

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\,\varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\,\varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

Table 2: Dimension-six operators other than the four-fermion ones.

SILH basis

$$\Delta\mathcal{L}^{(6)} = \boxed{\Delta\mathcal{L}_{SILH}} + \Delta\mathcal{L}_{cc} + \Delta\mathcal{L}_{dipole} + \Delta\mathcal{L}_{V} + +\Delta\mathcal{L}_{4\psi}$$

16 operators

(12 CP even, 4 CP odd)

SILH operators

Giudice, Grojean, Pomarol, Rattazzi JHEP 0706 (2007) 045

$$\begin{aligned}
\Delta\mathcal{L}_{SILH} = &\frac{\bar{c}_H}{2v^2}\,\partial^\mu(H^\dagger H)\,\partial_\mu(H^\dagger H) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\,\lambda}{v^2}\,(H^\dagger H)^3 \\
&+ \left(\frac{\bar{c}_u}{v^2}\,y_u\,H^\dagger H\,\bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}\,y_d\,H^\dagger H\,\bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}\,y_l\,H^\dagger H\,\bar{L}_L H l_R + h.c.\right) \\
&+ \frac{i\bar{c}_W\,g}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i + \frac{i\bar{c}_B\,g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu}) \\
&+ \frac{i\bar{c}_{HW}\,g}{m_W^2}\,(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{i\bar{c}_{HB}\,g'}{m_W^2}\,(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
&+ \frac{\bar{c}_\gamma\,g'^2}{m_W^2}\,H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{\bar{c}_g\,g_S^2}{m_W^2}\,H^\dagger H G^a_{\mu\nu} G^{a\mu\nu} \\
&+ \frac{i\tilde{c}_{HW}\,g}{m_W^2}\,(D^\mu H)^\dagger \sigma^i (D^\nu H) \tilde{W}^i_{\mu\nu} + \frac{i\tilde{c}_{HB}\,g'}{m_W^2}\,(D^\mu H)^\dagger (D^\nu H) \tilde{B}_{\mu\nu} \\
&+ \frac{\tilde{c}_\gamma\,g'^2}{m_W^2}\,H^\dagger H B_{\mu\nu} \tilde{B}^{\mu\nu} + \frac{\tilde{c}_g\,g_S^2}{m_W^2}\,H^\dagger H G^a_{\mu\nu} \tilde{G}^{a\mu\nu}
\end{aligned}$$

6

	Bosonic CP-even		Bosonic CP-odd
O_H	$\frac{1}{2v^2}\left[\partial_\mu(H^\dagger H)\right]^2$		
O_T	$\frac{1}{2v^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$		
O_6	$-\frac{\lambda}{v^2}(H^\dagger H)^3$		
O_g	$\frac{g_s^2}{m_W^2}H^\dagger H\, G^a_{\mu\nu}G^a_{\mu\nu}$	$\tilde{O}_g$	$\frac{g_s^2}{m_W^2}H^\dagger H\,\tilde{G}^a_{\mu\nu}G^a_{\mu\nu}$
O_γ	$\frac{g'^2}{m_W^2}H^\dagger H\, B_{\mu\nu}B_{\mu\nu}$	$\tilde{O}_\gamma$	$\frac{g'^2}{m_W^2}H^\dagger H\,\tilde{B}_{\mu\nu}B_{\mu\nu}$
O_W	$\frac{ig}{2m_W^2}\left(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H\right)D_\nu W^i_{\mu\nu}$		
O_B	$\frac{ig'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)\partial_\nu B_{\mu\nu}$		
O_{HW}	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger\sigma^i D_\nu H\right)W^i_{\mu\nu}$	$\tilde{O}_{HW}$	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger\sigma^i D_\nu H\right)\widetilde{W}^i_{\mu\nu}$
O_{HB}	$\frac{ig'}{m_W^2}\left(D_\mu H^\dagger D_\nu H\right)B_{\mu\nu}$	$\tilde{O}_{HB}$	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger D_\nu H\right)\widetilde{B}_{\mu\nu}$
O_{2W}	$\frac{1}{m_W^2}D_\mu W^i_{\mu\nu}D_\rho W^i_{\rho\nu}$		
O_{2B}	$\frac{1}{m_W^2}\partial_\mu B_{\mu\nu}\partial_\rho B_{\rho\nu}$		
O_{2G}	$\frac{1}{m_W^2}D_\mu G^a_{\mu\nu}D_\rho G^a_{\rho\nu}$		
O_{3W}	$\frac{g^3}{m_W^2}\epsilon^{ijk}W^i_{\mu\nu}W^j_{\nu\rho}W^k_{\rho\mu}$	$\tilde{O}_{3W}$	$\frac{g^3}{m_W^2}\epsilon^{ijk}\widetilde{W}^i_{\mu\nu}W^j_{\nu\rho}W^k_{\rho\mu}$
O_{3G}	$\frac{g_s^3}{m_W^2}f^{abc}G^a_{\mu\nu}G^b_{\nu\rho}G^c_{\rho\mu}$	$\tilde{O}_{3G}$	$\frac{g_s^3}{m_W^2}f^{abc}\widetilde{G}^a_{\mu\nu}G^b_{\nu\rho}G^c_{\rho\mu}$

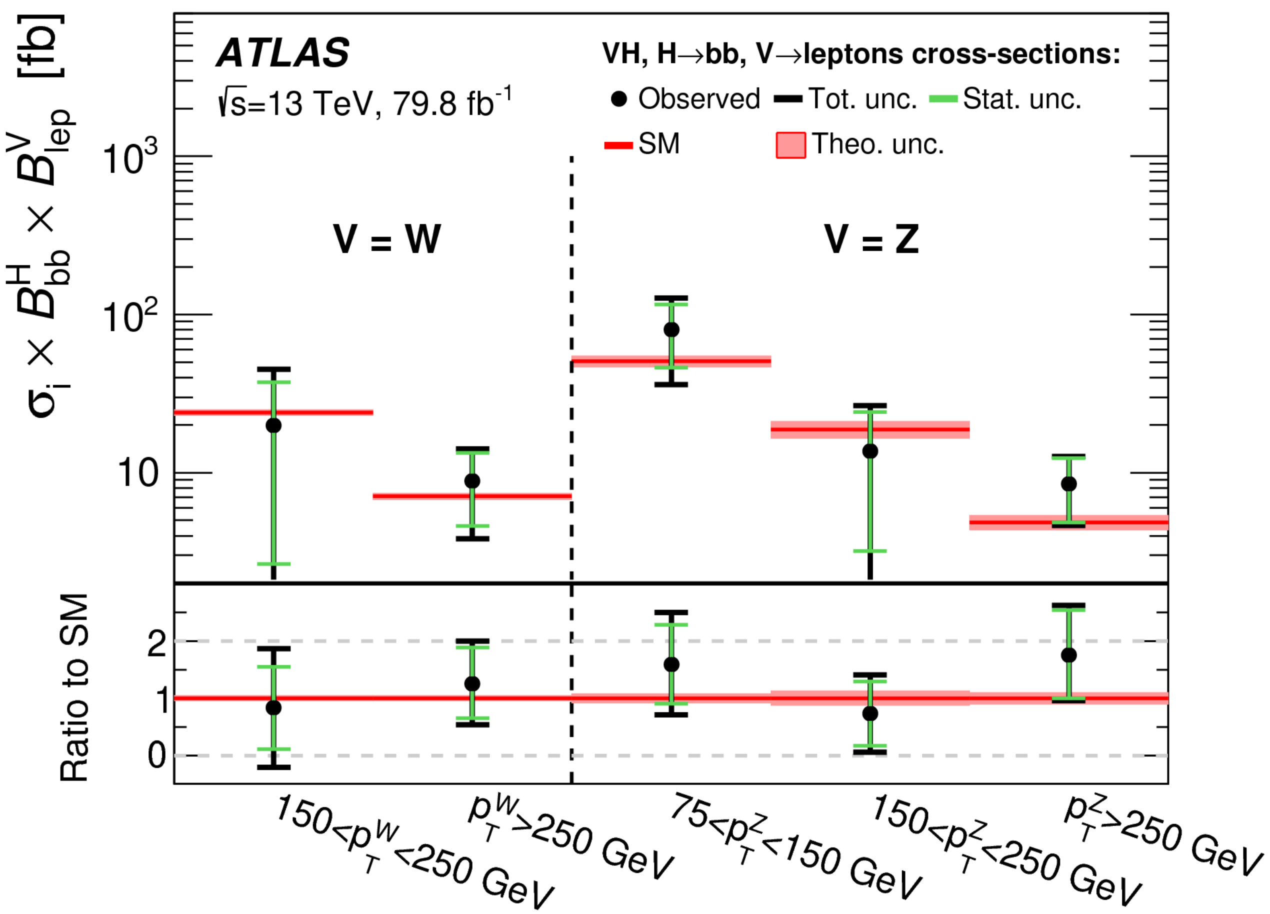
Table 1: Bosonic D=6 operators in the SILH basis.

Higgs basis

- In its gauge invariant definition

$$
\begin{aligned}
O_{\delta\lambda_3} &= -\frac{1}{v^2}(H^\dagger H)^3, \\
O_{c_{gg}} &= \frac{g_s^2}{4v^2} H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu} \\
O_{\delta c_z} &= -\frac{1}{v^2}\left[\partial_\mu (H^\dagger H)\right]^2 + \frac{3\lambda}{v^2}(H^\dagger H)^3 + \left(\sum_f \frac{\sqrt{2} m_{f_i}}{v^3} H^\dagger H \bar{f}_{L,i} H f_{R,i} + \text{h.c.}\right), \\
O_{c_{z\Box}} &= \frac{i g^3}{v^2(g^2 - g'^2)} \left(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H\right) D_\nu W^i_{\mu\nu} - \frac{i g^2 g'}{v^2(g^2 - g'^2)} \left(H^\dagger \overleftrightarrow{D}_\mu H\right) \partial_\nu B_{\mu\nu}, \\
O_{c_{zz}} &= \frac{i g (g^2 + g'^2)}{2v^2(g^2 - g'^2)} \left(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H\right) D_\nu W^i_{\mu\nu} - \frac{i g' (g^2 + g'^2)}{2v^2(g^2 - g'^2)} \left(H^\dagger \overleftrightarrow{D}_\mu H\right) \partial_\nu B_{\mu\nu} \\
&- \frac{i g}{v^2} \left(D_\mu H^\dagger \sigma^i D_\nu H\right) W^i_{\mu\nu} - \frac{i g'}{v^2} \left(D_\mu H^\dagger D_\nu H\right) B_{\mu\nu}, \\
O_{c_{z\gamma}} &= -\frac{2 i g g'^2}{v^2(g^2 + g'^2)} \left(D_\mu H^\dagger \sigma^i D_\nu H\right) W^i_{\mu\nu} + \frac{2 i g' g^2}{v^2(g^2 + g'^2)} \left(D_\mu H^\dagger D_\nu H\right) B_{\mu\nu}, \\
O_{c_{\gamma\gamma}} &= -\frac{i g g'^4}{2v^2(g^4 - g'^4)} \left(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H\right) D_\nu W^i_{\mu\nu} + \frac{i g'^5}{2v^2(g^4 - g'^4)} \left(H^\dagger \overleftrightarrow{D}_\mu H\right) \partial_\nu B_{\mu\nu} \\
&- \frac{i g g'^4}{v^2(g^2 + g'^2)^2} \left(D_\mu H^\dagger \sigma^i D_\nu H\right) W^i_{\mu\nu} + \frac{i g'^3 (2g^2 + g'^2)}{(g^2 + g'^2)^2 v^2} \left(D_\mu H^\dagger D_\nu H\right) B_{\mu\nu} + \frac{g'^2}{4v^2} H^\dagger H\, B_{\mu\nu} B_{\mu\nu}, \\
[O_{\delta y_f}]_{ij} &= -\frac{\sqrt{2 m_{f_i} m_{f_j}}}{v^3} H^\dagger H \bar{f}_{L,i} H f_{R,j} + \text{h.c.},
\end{aligned}
$$

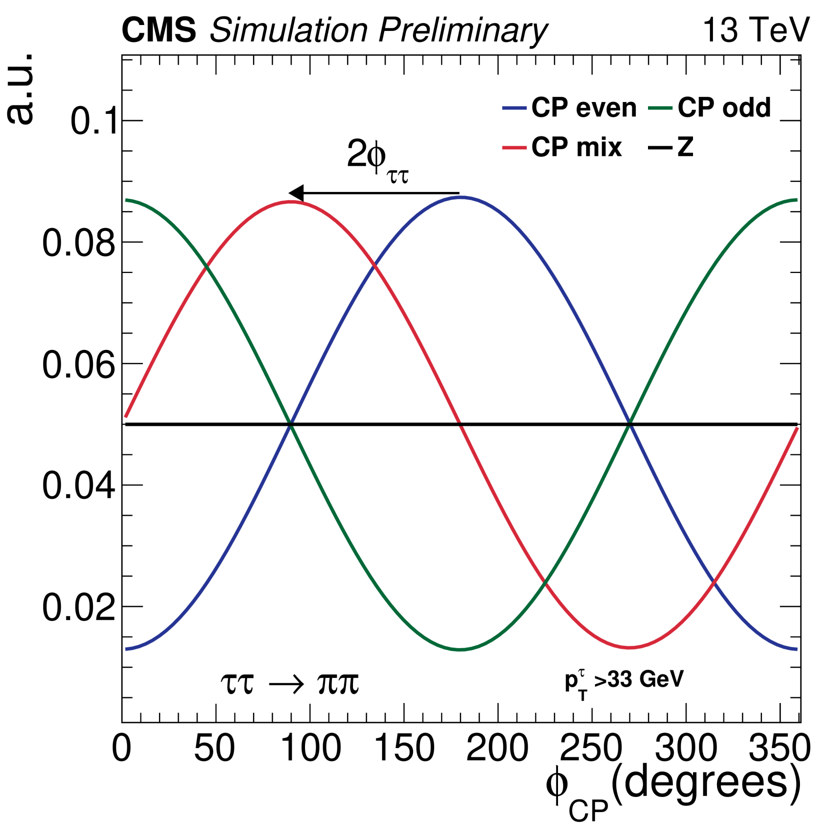
ATLAS: H→bb (resolved)

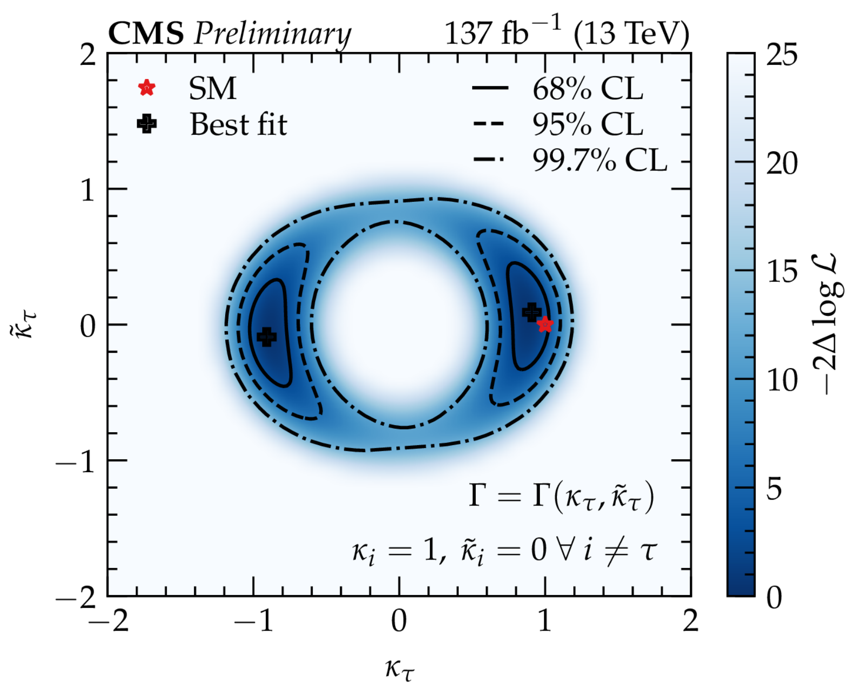


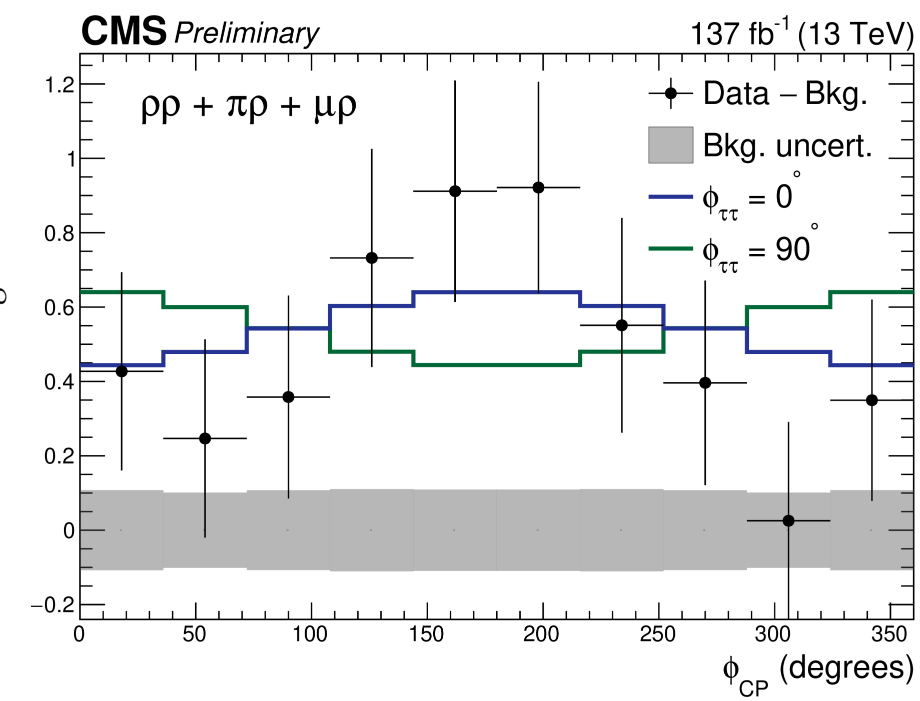
Coefficient	Expected interval	Observed interval
Results at 68% confidence level		
$\bar{c}_{HW}$	[−0.003, 0.002]	[−0.001, 0.004]
(interference only	[−0.002, 0.003]	[−0.001, 0.005])
$\bar{c}_{HB}$	[−0.066, 0.013]	[−0.078, −0.055] ⋃ [0.005, 0.019]
(interference only	[−0.016, 0.016]	[−0.005, 0.030])
$\bar{c}_W - \bar{c}_B$	[−0.006, 0.005]	[−0.002, 0.007]
(interference only	[−0.005, 0.005]	[−0.002, 0.008])
$\bar{c}_d$	[−1.5, 0.3]	[−1.6, −0.9] ⋃ [−0.3, 0.4]
(interference only	[−0.4, 0.4]	[−0.2, 0.7])
Results at 95% confidence level		
$\bar{c}_{HW}$	[−0.018, 0.004]	[−0.019,−0.010] ⋃ [−0.005, 0.006]
(interference only	[−0.005, 0.005]	[−0.003, 0.008])
$\bar{c}_{HB}$	[−0.078, 0.024]	[−0.090, 0.032]
(interference only	[−0.033, 0.033]	[−0.022, 0.049])
$\bar{c}_W - \bar{c}_B$	[−0.034, 0.008]	[−0.036,−0.024] ⋃ [−0.009, 0.010]
(interference only	[−0.009, 0.010]	[−0.006, 0.014])
$\bar{c}_d$	[−1.7, 0.5]	[−1.9, 0.7]
(interference only	[−0.8, 0.8]	[−0.6, 1.1])

- EFT interpretation of simplified template cross sections measurements (80 / fb)
- Results obtained using the SILH basis
- 1-dimensional fit to each of the operators assuming that the others vanish
  - Effect of the inclusion of quadratic terms are shown to be relevant for most of the operators

CMS: H→ττ







$$\mathcal{L}_Y = -\frac{m_\tau \mathrm{H}}{\mathrm{v}}(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i \gamma_5 \tau).$$

$$\tan(\phi_{\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}.$$

- Analysis of the CP-structure of the Yukawa H→ττ couplings
  - Both τ hadronically decaying or one leptonic and one hadronic decay
- No EFT formalism but extend the τ Yukawa sector with a CP-odd coupling
- Using ggH and VBF production modes and extracting the CP-mixing angle from a simultaneous fit to data
- Statistically limited. Observed value of $\Phi_{CP} = 0 \pm 23$ degrees at 68% C.L.

Eboli basis

a. Operators containing just $D_\mu\Phi$

The two independent operators in this class are

$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right] \tag{A5}$$

$$\mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right] \tag{A6}$$

b. Operators containing $D_\mu\Phi$ and field strength

The operators in this class are:

$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \tag{A7}$$

$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \tag{A8}$$

$$\mathcal{L}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \tag{A9}$$

$$\mathcal{L}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \tag{A10}$$

$$\mathcal{L}_{M,4} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu} \tag{A11}$$

$$\mathcal{L}_{M,5} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu} \tag{A12}$$

$$\mathcal{L}_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right] \tag{A13}$$

$$\mathcal{L}_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right] \tag{A14}$$

Eboli basis

$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right] \quad \text{(A15)}$$

$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right] \quad \text{(A16)}$$

$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right] \quad \text{(A17)}$$

$$\mathcal{L}_{T,3} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\hat{W}^{\nu\alpha}\right] \times B_{\beta\nu} \quad \text{(A18)}$$

$$\mathcal{L}_{T,4} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\alpha\mu}\hat{W}^{\beta\nu}\right] \times B_{\beta\nu} \quad \text{(A19)}$$

$$\mathcal{L}_{T,5} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta} \quad \text{(A20)}$$

$$\mathcal{L}_{T,6} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu} \quad \text{(A21)}$$

$$\mathcal{L}_{T,7} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha} \quad \text{(A22)}$$

$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta} \quad \text{(A23)}$$

$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha} \quad \text{(A24)}$$