SMEFT parameterisations for STXS

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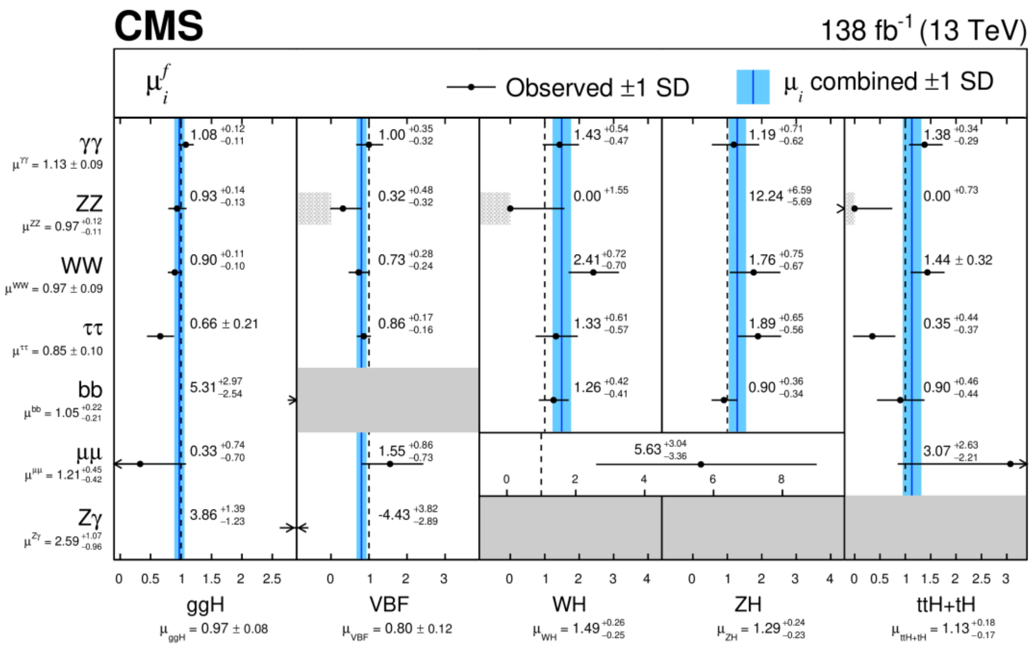
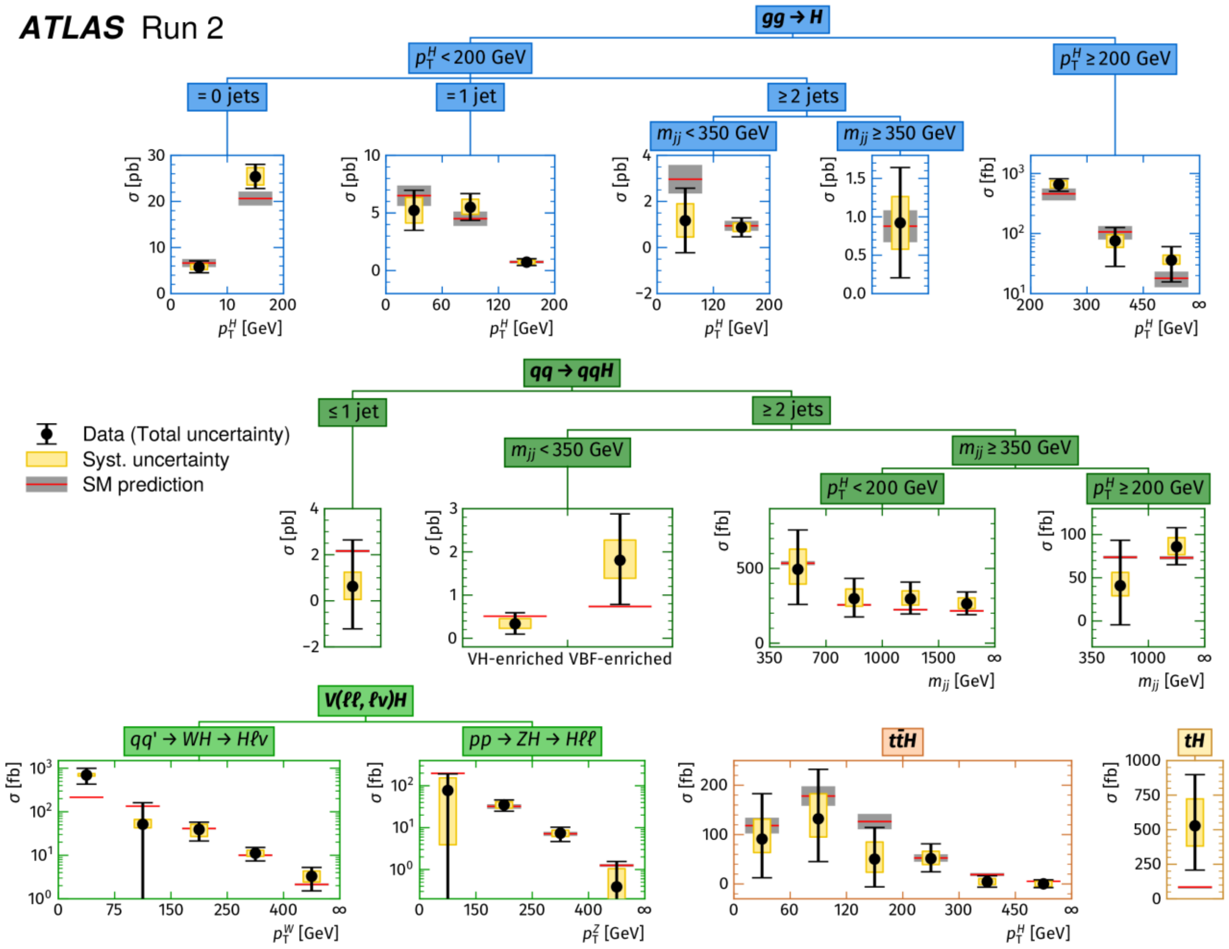
19th Workshop of the LHC Higgs Working Group

Introduction: Why SMEFT?

- General success of the SM, so far, at the LHC in the Higgs and other sectors



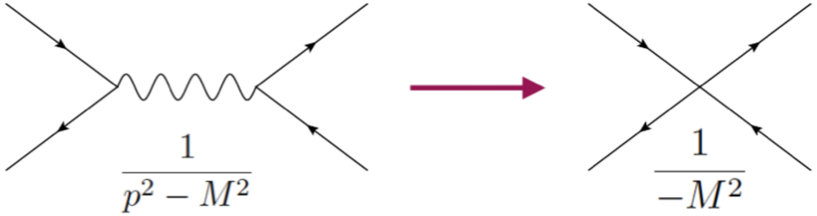


- SMEFT allows to systematically interpret large datasets assuming that new physics will only appear at higher scales

Introduction: SMEFT formalism

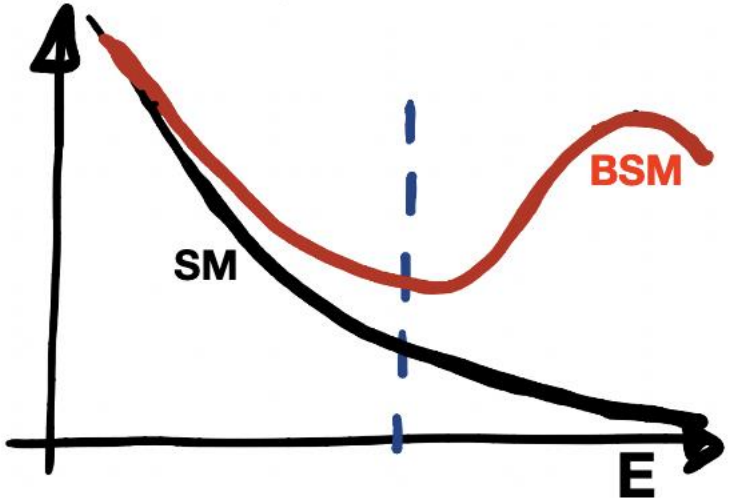
- SMEFT extends the SM Lagrangian with higher-order operators keeping the same symmetries and particle content as the SM

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



- Constraining an EFT coefficient → Constrain several UV theories

- SMEFT is a complete QFT theory allowing for NLO calculations (in contrast to κ-framework)



SMEFT choices

TRUNCATION OF THE EXPANSION
(dimension of the considered operators)

→

DIM-6, $1/\Lambda^2$ or $1/\Lambda^4$
(Analytical calculations available for $gg \rightarrow h \rightarrow \gamma\gamma$ up to dim-8)

BASIS AND INPUT SCHEME

→

WARSAW
(RGE known)
mW INPUT SCHEME
(mW, mZ and G_F fixed)

FLAVOUR SYMMETRY

→

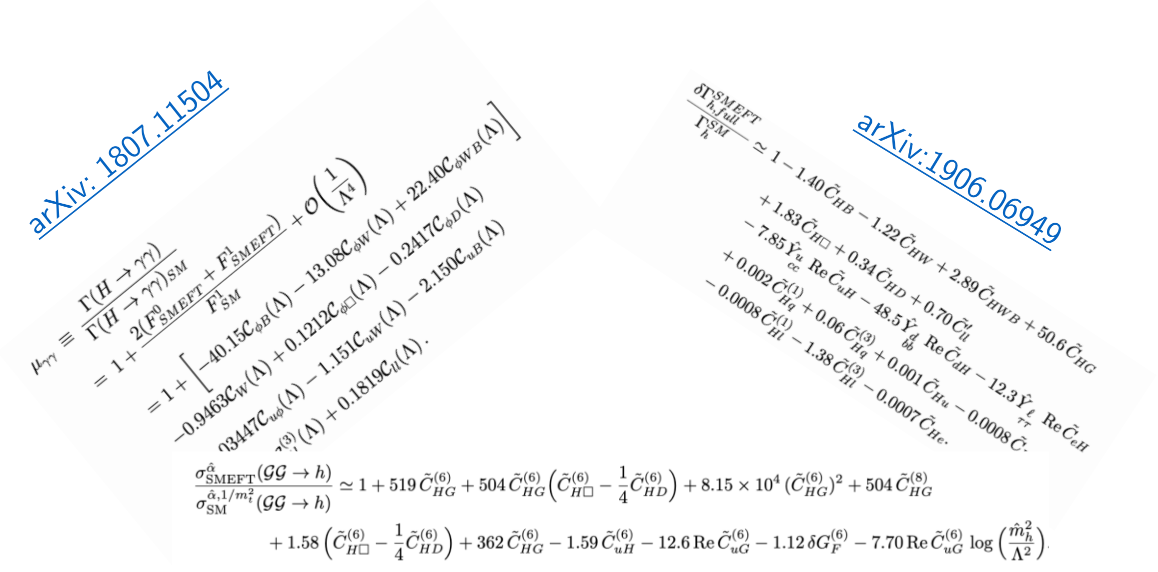
SEVERAL CHOICES

$U(3)^5 \rightarrow$
$U(3)_L x U(3)_e x U(2)_Q x(2)_u x U(2/3)_d$

SMEFT calculations

- SMEFT predictions in the Warsaw basis can be obtained through:

ANALYTICAL CALCULATIONS



arXiv: 1807.11504

$$\mu_{\gamma\gamma} \equiv \frac{\Gamma(H\to\gamma\gamma)}{\Gamma(H\to\gamma\gamma)_{SM}} = 1 + \frac{2(F^0_{SMEFT} + F^1_{SMEFT})}{F^1_{SM}} + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

$$= 1 + \Big[-40.15\mathcal{C}_{\phi B}(\Lambda) - 13.08\mathcal{C}_{\phi W}(\Lambda) + 22.40\mathcal{C}_{\phi WB}(\Lambda)\Big]$$

$$-0.9463\mathcal{C}_{W}(\Lambda) + 0.1212\mathcal{C}_{\phi\Box}(\Lambda) - 0.2417\mathcal{C}_{\phi D}(\Lambda)$$

$$03447\mathcal{C}_{u\phi}(\Lambda) - 1.151\mathcal{C}_{uW}(\Lambda) - 2.150\mathcal{C}_{uB}(\Lambda)$$

$$\mathcal{C}^{(3)}(\Lambda) + 0.1819\mathcal{C}_{ll}(\Lambda).$$

arXiv:1906.06949

$$\frac{\delta\Gamma^{SMEFT}_{h,full}}{\Gamma^{SM}_h} \simeq 1 - 1.40\,\tilde{C}_{HB} - 1.22\,\tilde{C}_{HW} + 2.89\,\tilde{C}_{HWB} + 50.6\,\tilde{C}_{HG}$$

$$+ 1.83\,\tilde{C}_{H\Box} + 0.34\,\tilde{C}_{HD} + 0.70\,\tilde{C}'_{ll}$$

$$- 7.85\,\hat{Y}^{u}_{cc}\,\mathrm{Re}\,\tilde{C}_{uH} - 48.5\,\hat{Y}^{d}_{bb}\,\mathrm{Re}\,\tilde{C}_{dH} - 12.3\,\hat{Y}^{\ell}_{\tau\tau}\,\mathrm{Re}\,\tilde{C}_{eH}$$

$$+ 0.002\,\tilde{C}^{(1)}_{Hq} + 0.06\,\tilde{C}^{(3)}_{Hq} + 0.001\,\tilde{C}_{Hu} - 0.0008\,\tilde{C}$$

$$- 0.0008\,\tilde{C}^{(1)}_{Hl} - 1.38\,\tilde{C}^{(3)}_{Hl} - 0.0007\,\tilde{C}_{He}.$$

$$\frac{\sigma^{\hat{\alpha}}_{\mathrm{SMEFT}}(\mathcal{G}\mathcal{G}\to h)}{\sigma^{\hat{\alpha},1/m_t^2}_{\mathrm{SM}}(\mathcal{G}\mathcal{G}\to h)} \simeq 1 + 519\,\tilde{C}^{(6)}_{HG} + 504\,\tilde{C}^{(6)}_{HG}\left(\tilde{C}^{(6)}_{H\Box} - \frac{1}{4}\tilde{C}^{(6)}_{HD}\right) + 8.15\times10^4\,(\tilde{C}^{(6)}_{HG})^2 + 504\,\tilde{C}^{(8)}_{HG}$$

$$+ 1.58\left(\tilde{C}^{(6)}_{H\Box} - \frac{1}{4}\tilde{C}^{(6)}_{HD}\right) + 362\,\tilde{C}^{(6)}_{HG} - 1.59\,\tilde{C}^{(6)}_{uH} - 12.6\,\mathrm{Re}\,\tilde{C}^{(6)}_{uG} - 1.12\,\delta G^{(6)}_{F} - 7.70\,\mathrm{Re}\,\tilde{C}^{(6)}_{uG}\,\log\left(\frac{\hat{m}_h^2}{\Lambda^2}\right).$$

arXiv:2109.05595

😀 Can be directly used in parametrisations

😫 No flexibility

UNIVERSAL FEYNMAN OUTPUTS TO BE INTERFACED WITH MC GENERATORS

Link

SMEFTsim

☞Dim-6 operators at LO

☞10 models with different flavour structure and input parameter scheme

☞ Effective vertices for ggh, h$\gamma\gamma$ and hZγ

☞Linearised propagator corrections

arXiv:2008.11743

SMEFT@NLO

☞Dim-6 operators compatible with NLO QCD calculations

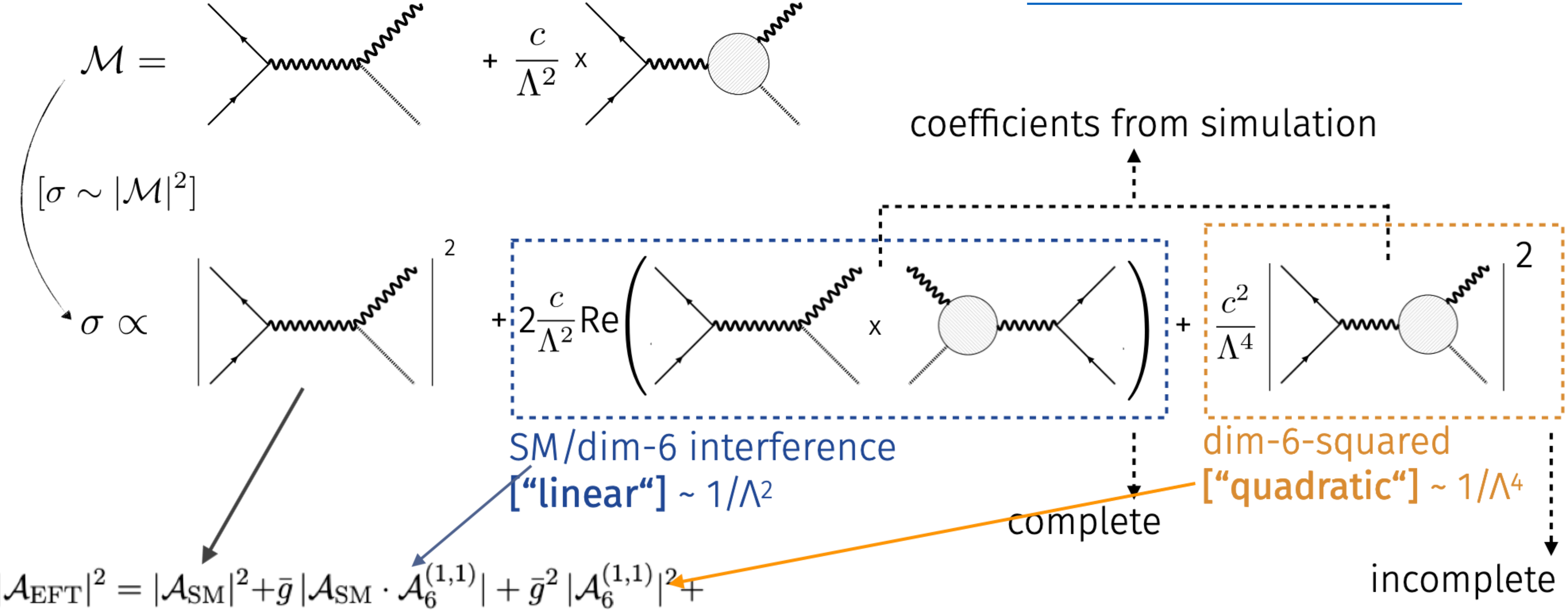
☞mW-input parameter scheme

☞$U(3)_L \times U(3)_e \times U(2)_Q \times (2)_u \times U(3)_d$ flavour symmetry

😀 Very flexible, predictions can be obtained for a large variety of processes

SMEFT calculations

Brian Moser @ HIGGS2020



coefficients from simulation

SM/dim-6 interference
["linear"] ~ 1/Λ²

dim-6-squared
["quadratic"] ~ 1/Λ⁴

complete

incomplete

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

- Linear part is fully known, while quadratic part can help to assess the convergence of the expansion

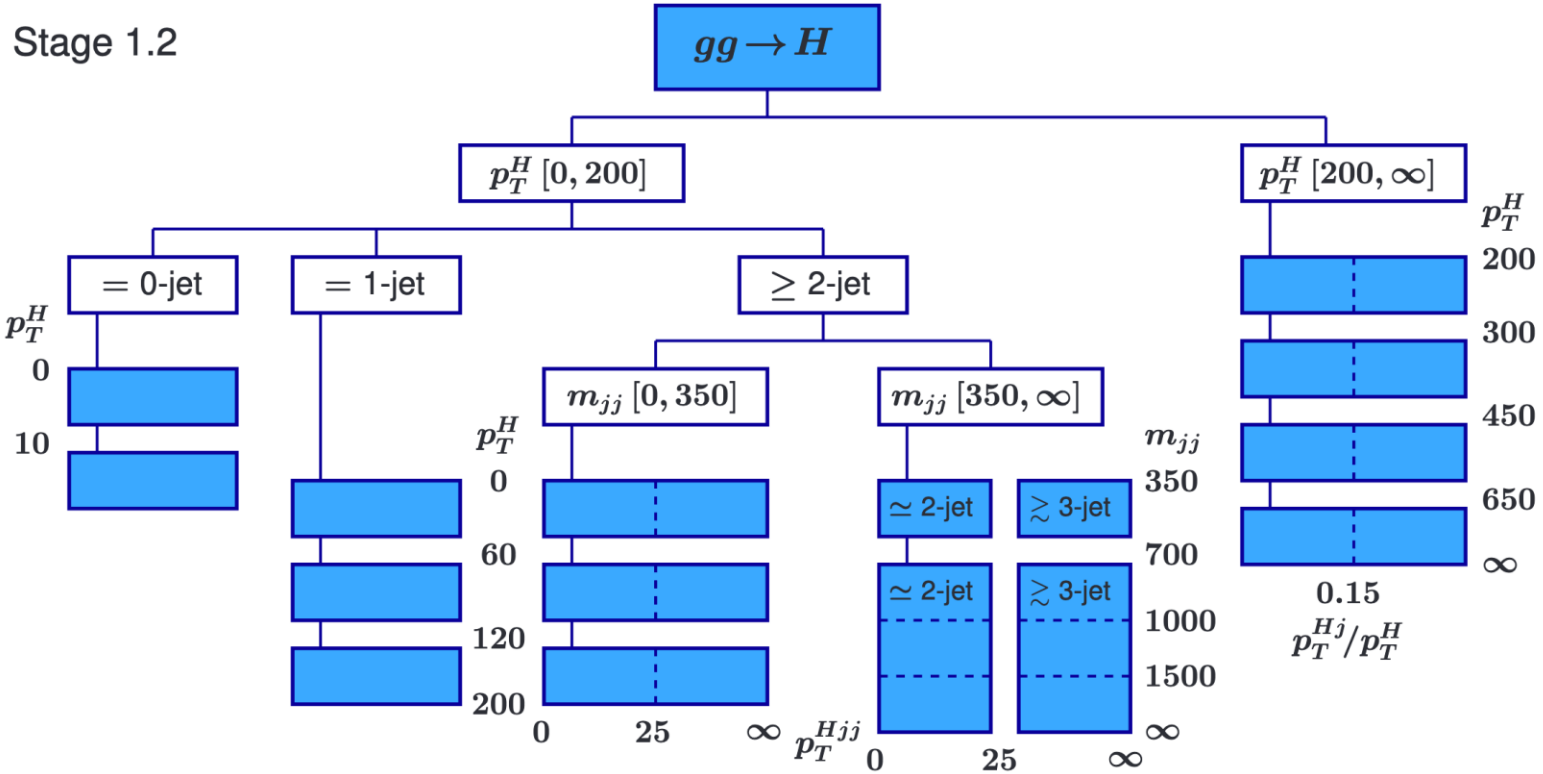
Parametrisations

- Simplified template cross sections provide a natural framework for SMEFT interpretations

✚ Maximizing experimental sensitivity
✚ Isolation of possible BSM effects
− Not fully fiducial

✚ Minimizing the theoretical uncertainties
✚ Suitable for global combinations
− No Higgs decay information

- Different productions modes are targeted separately in different bins
- Bins defined at high momentum/invariant mass with enhanced EFT effects



Parametrisations

- For STXS interpretations, the likelihoods are reparametrized in terms of the Wilson coefficients

$$(\sigma\times B)^{i,H\to X} = (\sigma\times B)^{i,H\to X}_{\mathrm{SM,(N(N))NLO}}\left(1+\frac{\sigma^i_{\mathrm{int,(N)LO}}}{\sigma^i_{\mathrm{SM,(N)LO}}}+\frac{\sigma^i_{\mathrm{BSM,(N)LO}}}{\sigma^i_{\mathrm{SM,(N)LO}}}\right)\left(\frac{1+\frac{\Gamma^{H\to X}_{\mathrm{int}}}{\Gamma^{H\to X}_{\mathrm{SM}}}+\frac{\Gamma^{H\to X}_{\mathrm{BSM}}}{\Gamma^{H\to X}_{\mathrm{SM}}}}{1+\frac{\Gamma^{H}_{\mathrm{int}}}{\Gamma^{H}_{\mathrm{SM}}}+\frac{\Gamma^{H}_{\mathrm{BSM}}}{\Gamma^{H}_{\mathrm{SM}}}}\right)$$

- Several choices in the parametrisations:
    - pQCD order of the calculations
    - Merging of bins/partial widths according to best known cross-sections or SM results of the EFT calculations
    - Inclusion of linear propagator corrections
    - How to treat ratios: Taylor expansions vs full ratios in the likelihood
    - Inclusion of acceptance effects due to requirements in the reconstructed objects in different analyses

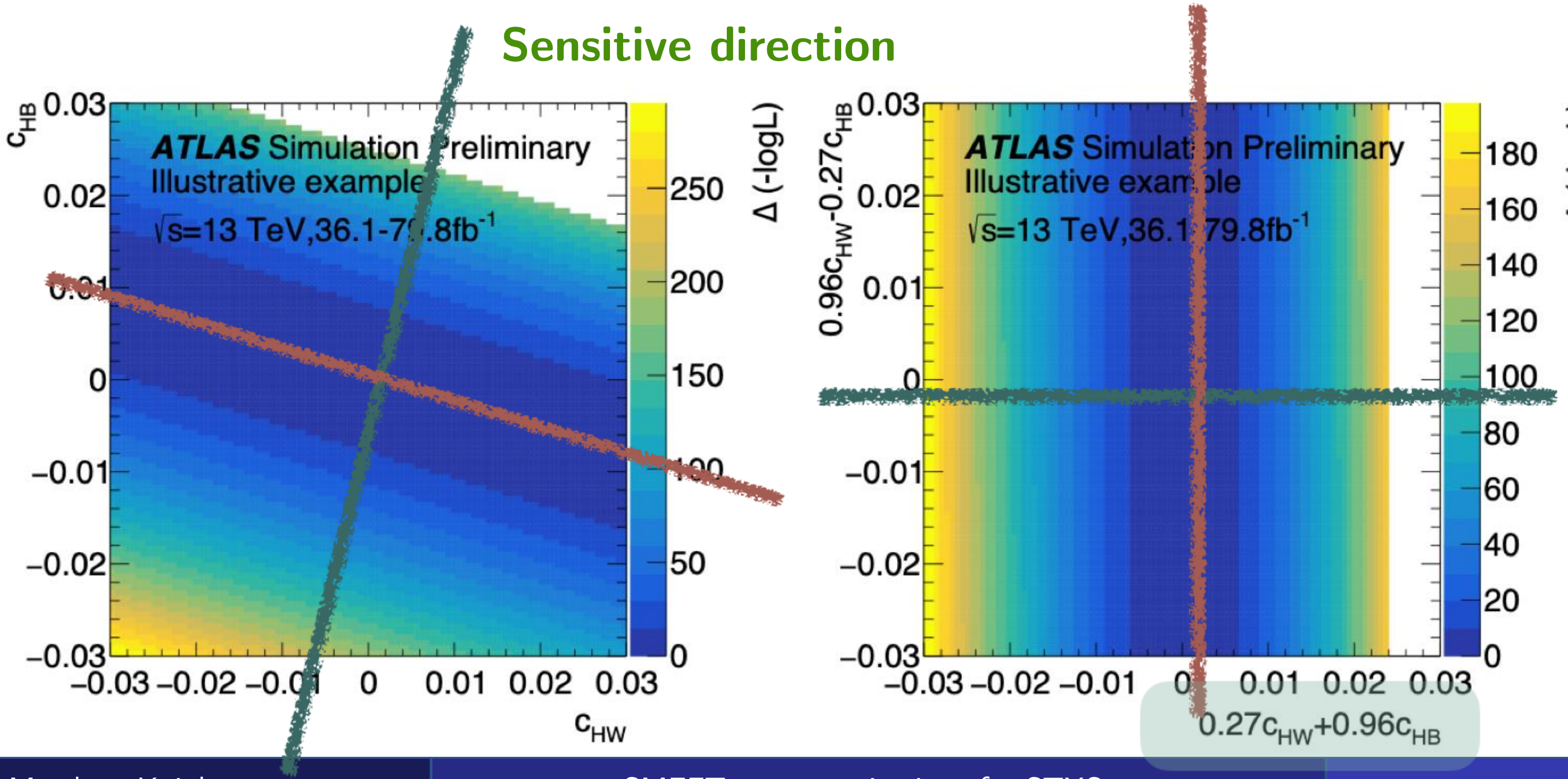
$$\frac{\sigma^i_{\mathrm{int}}}{\sigma^i_{\mathrm{SM}}} = \sum_j A^{\sigma_i}_j c_j \qquad \frac{\sigma^i_{\mathrm{BSM}}}{\sigma^i_{\mathrm{SM}}} = \sum_{jk} B^{\sigma_i}_{jk} c_j c_k$$

$$\frac{\Gamma^{H\to X}_{\mathrm{int}}}{\Gamma^{H\to X}_{\mathrm{SM}}} = \sum_j A^{\Gamma^{H\to X}}_j c_j \qquad \frac{\Gamma^{H\to X}_{\mathrm{BSM}}}{\Gamma^{H\to X}_{\mathrm{SM}}} = \sum_{jk} B^{\Gamma^{H\to X}}_{jk} c_j c_k$$

$$\frac{\Gamma^{H}_{\mathrm{int}}}{\Gamma^{H}_{\mathrm{SM}}} = \sum_j A^{\Gamma^{H}}_j c_j \qquad \frac{\Gamma^{H}_{\mathrm{BSM}}}{\Gamma^{H}_{\mathrm{SM}}} = \sum_{jk} B^{\Gamma^{H}}_{jk} c_j c_k,$$

Constrained parameters

- Higgs STXS measurements are sensitive to a large number of operators
  - Not enough constraining power even in combined measurements
- The goal is to not set to the SM value a priory to any parameter and instead make a simultaneous fit to take into account correlations among parameters
  - Perform a PCA starting from the inverse of the covariance matrix of the measurement and propagating the linear-only parametrisation
  - Keep all operators but remove flat directions



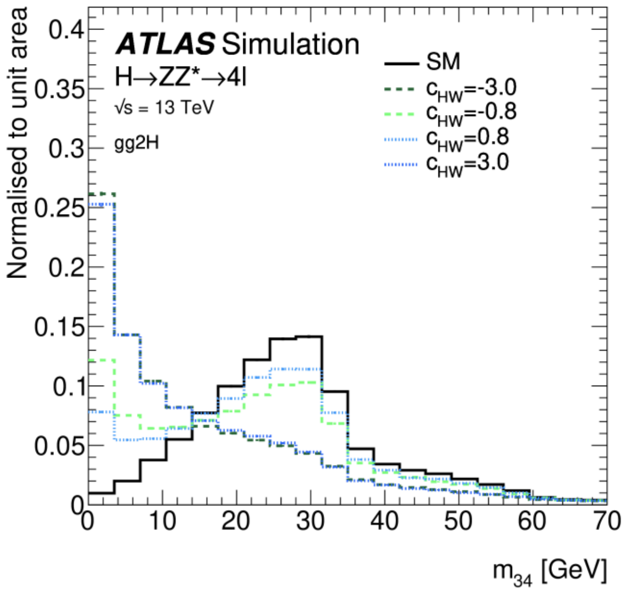
Sensitive direction

Illustrative example from [ATL-PUB-2019-042]

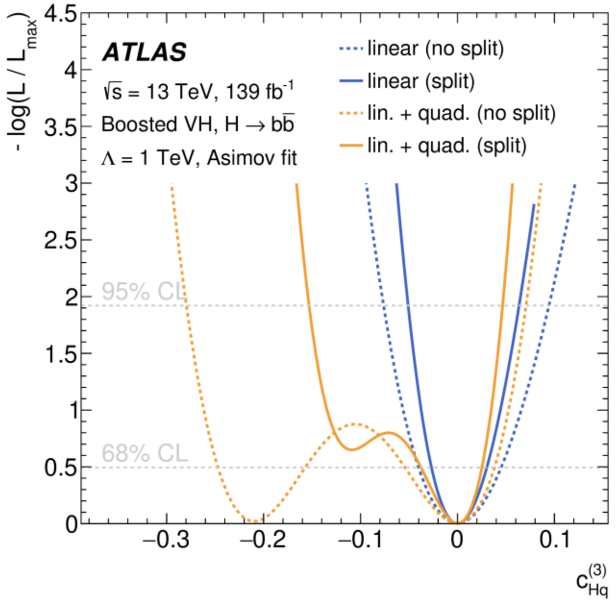
Experimental interpretations

SMEFT STXS interpretations in ATLAS

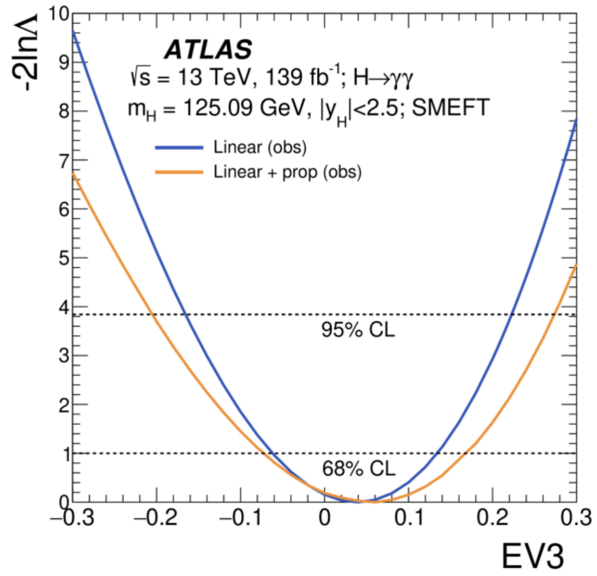
- Common trend to include SMEFT interpretations in single channel analysis
  - Less constraining power than STXS combinations
  - But useful when additional studies or other ways of presenting the results are checked



Acceptance effects in H->4l



Impact of splitting high pTV bins in H->bb



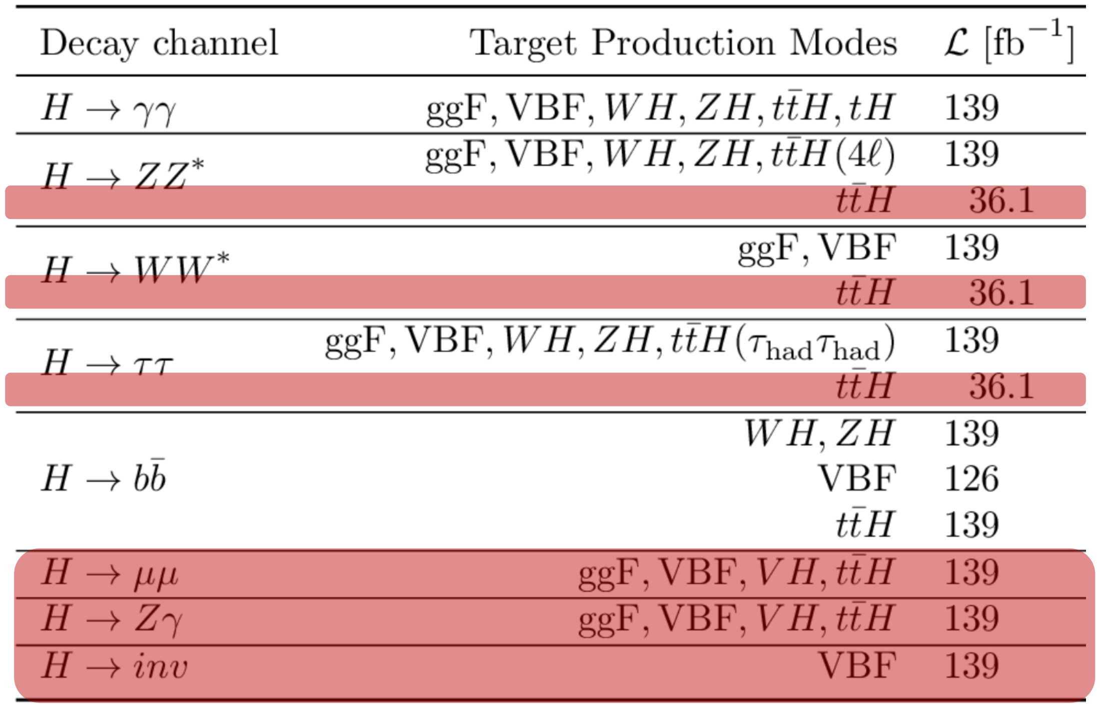
Effects of linear propagator corrections in $H\rightarrow\gamma\gamma$

- In the following, we will focus on **interpretations of combined measurements**

SMEFT STXS interpretations in ATLAS

ATLAS-CONF-2021-053

- Combined Higgs results based on likelihood level combination
  - Product of individual analyses likelihood
  - Negligible overlap between them
  - Coherent treatment of signal modelling uncertainties across analyses

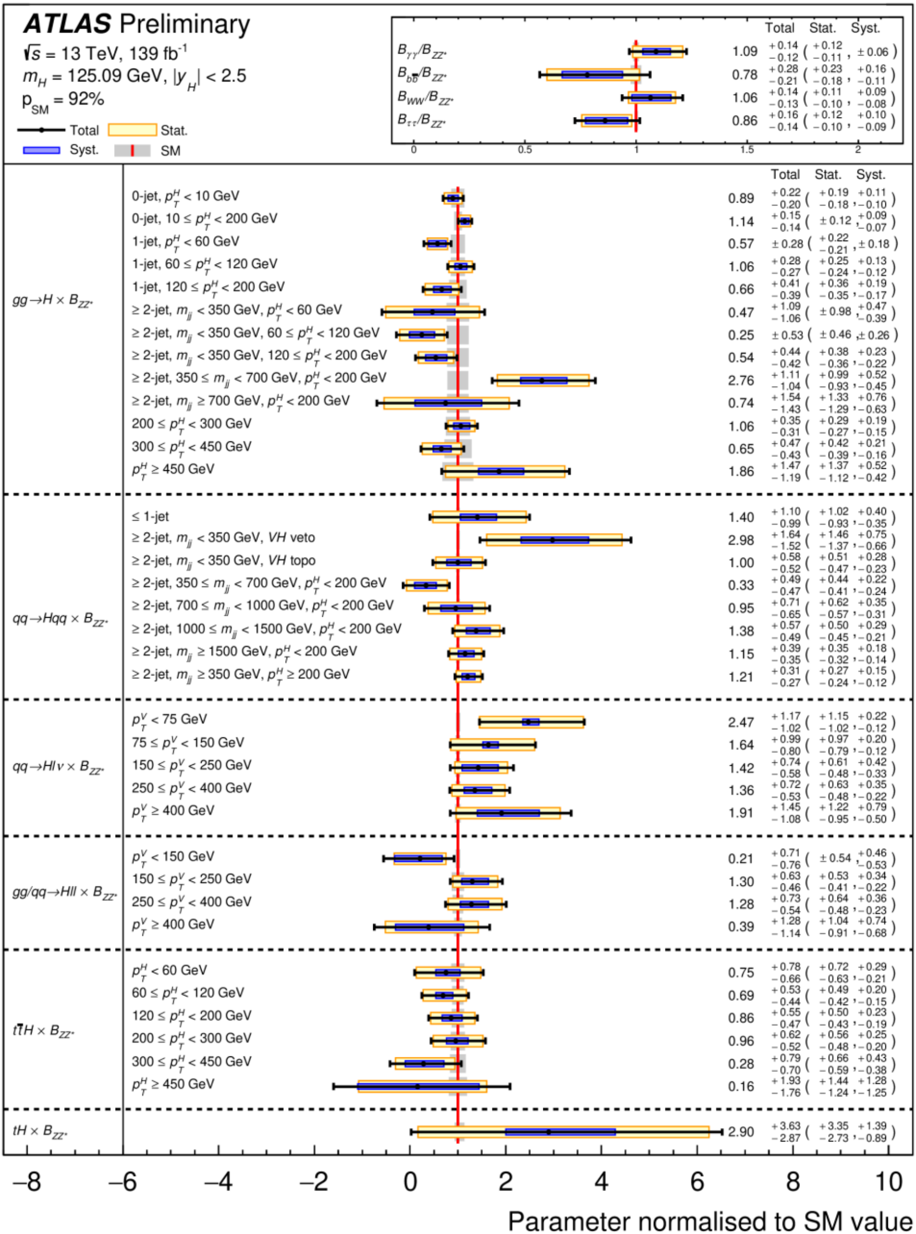


Decay channel	Target Production Modes	$\mathcal{L}$ [fb^{-1}]
$H \rightarrow \gamma\gamma$	$\mathrm{ggF}, \mathrm{VBF}, WH, ZH, t\bar{t}H, tH$	139
$H \rightarrow ZZ^*$	$\mathrm{ggF}, \mathrm{VBF}, WH, ZH, t\bar{t}H(4\ell)$	139
	$t\bar{t}H$	36.1
$H \rightarrow WW^*$	$\mathrm{ggF}, \mathrm{VBF}$	139
	$t\bar{t}H$	36.1
$H \rightarrow \tau\tau$	$\mathrm{ggF}, \mathrm{VBF}, WH, ZH, t\bar{t}H(\tau_{\mathrm{had}}\tau_{\mathrm{had}})$	139
	$t\bar{t}H$	36.1
$H \rightarrow b\bar{b}$	WH, ZH	139
	VBF	126
	$t\bar{t}H$	139
$H \rightarrow \mu\mu$	$\mathrm{ggF}, \mathrm{VBF}, VH, t\bar{t}H$	139
$H \rightarrow Z\gamma$	$\mathrm{ggF}, \mathrm{VBF}, VH, t\bar{t}H$	139
$H \rightarrow inv$	VBF	139

🟥 = Not included in STXS measurements

- Not all input analyses used for STXS measurements (and thus SMEFT interpretation)
  - SMEFTsim3.0 with U(3)^5 symmetry and mW-input scheme for tree level processes
  - SMEFT@NLO for loop-induced processes
  - Analytical calculations for H→$\gamma\gamma$ at NLO EW
  - Detector acceptance corrections for H→4l and H→lνlν
  - Only CP-even coefficients

SMEFT STXS interpretations in ATLAS

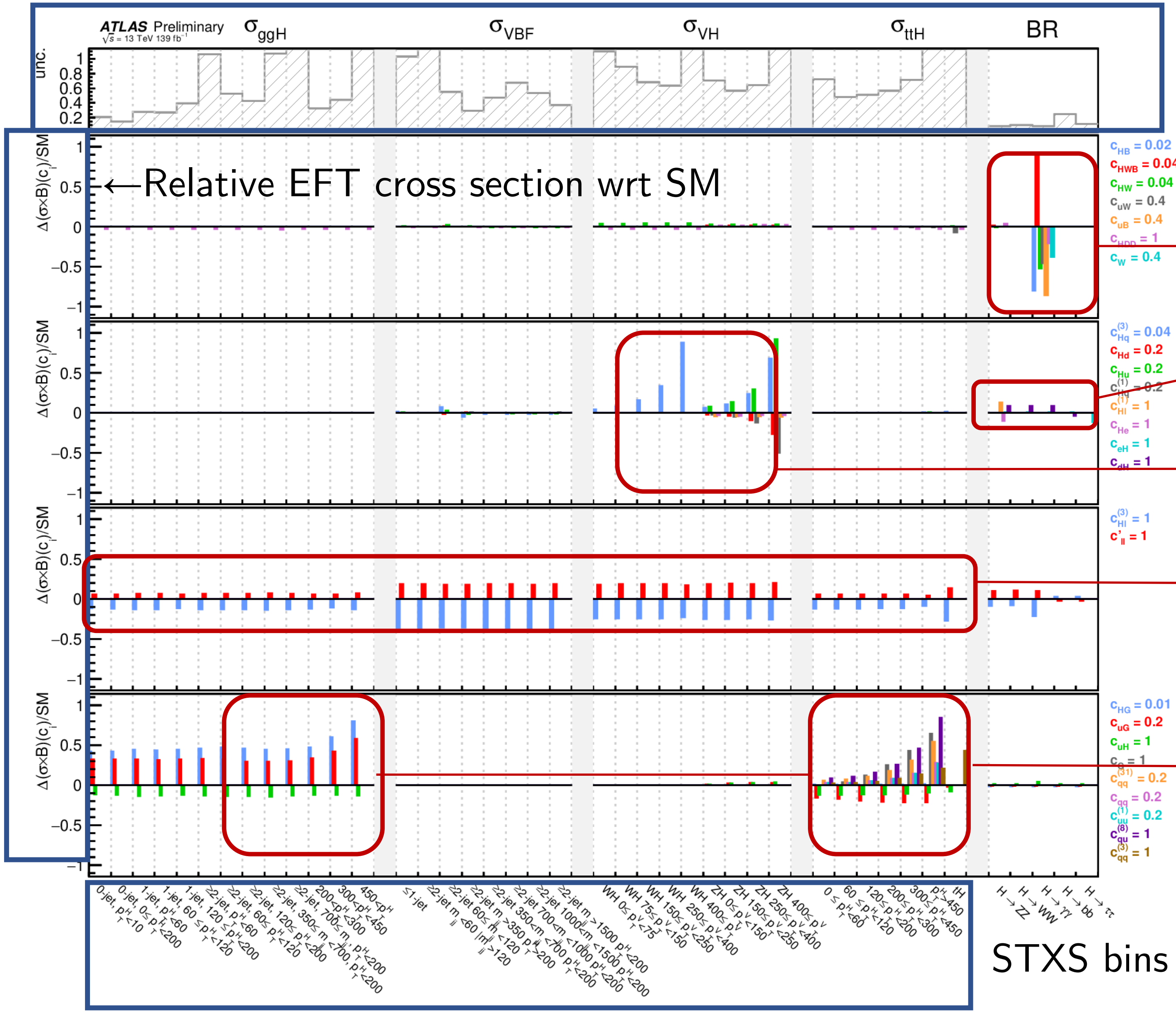


ATLAS-CONF-2021-053

- 37 kinematic bins measured across 5 production modes
    - Cross-sections of the bin span over 4 orders of magnitude
- Larger reach in transverse momentum or invariant mass thanks to the combination of analyses
    - qq→Hqq access to higher mjj values thanks to HWW
    - Boosted VHbb has an increased reach in pTV wrt. Resolved analysis
    - ttHbb gives access to high pTH tail in ttH

SMEFT STXS interpretations in ATLAS

ATLAS-CONF-2021-053



Relative uncertainty

←Relative EFT cross section wrt SM

STXS bins

H→$\gamma\gamma$ (Large effects from cHW, cHB and cHWB)

Different decays have unique sensitivities to some operators (e.g cdH in H→bb)

Operators with enhanced effects in pTV tails: cHq3, cHq1, cHu, cHd

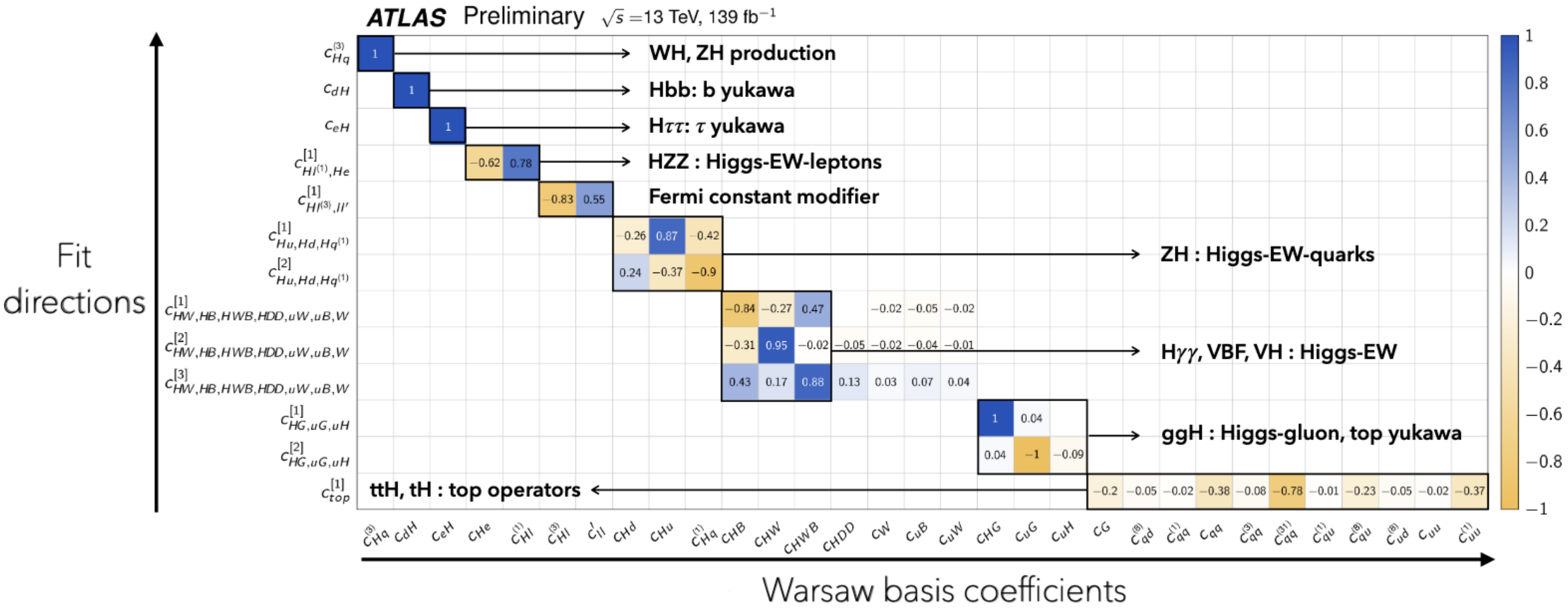
Modifications of Fermi constant in SMEFT (cHl3, cll1)

Increased effects of cHG in tails of pTH for ggH.

Also from ctG in both ggH and ttH and cqq31, cuu1,cqu8, cqq3 in ttH

SMEFT STXS interpretations in ATLAS

[R. Balasubramanian](#) [ATLAS-CONF-2021-053](#)

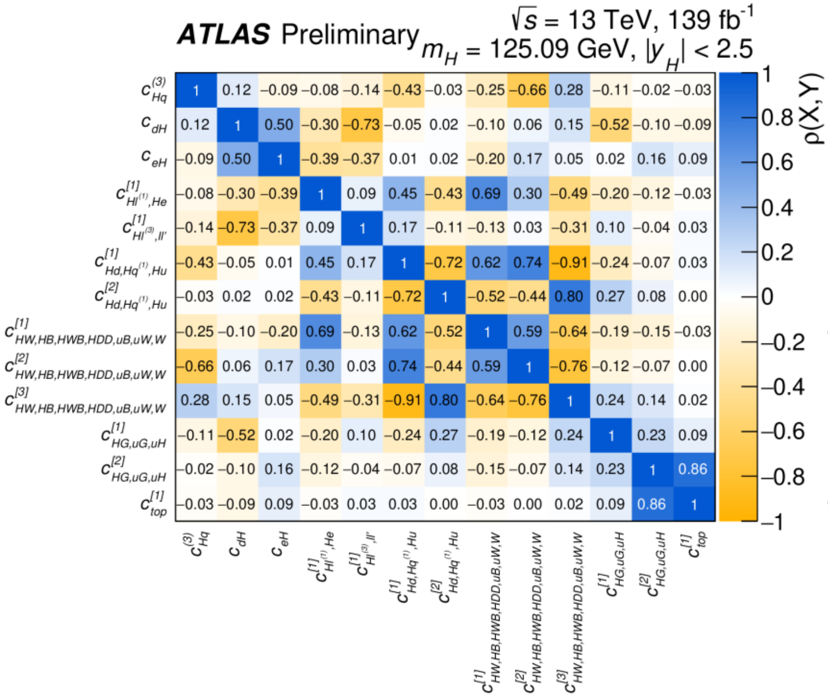


- PCA analysis after grouping operators according to their impacts in physics processes
    - 13 parameters can be proven with uncertainties $\lesssim 2$ and manageable correlations

SMEFT STXS interpretations in ATLAS

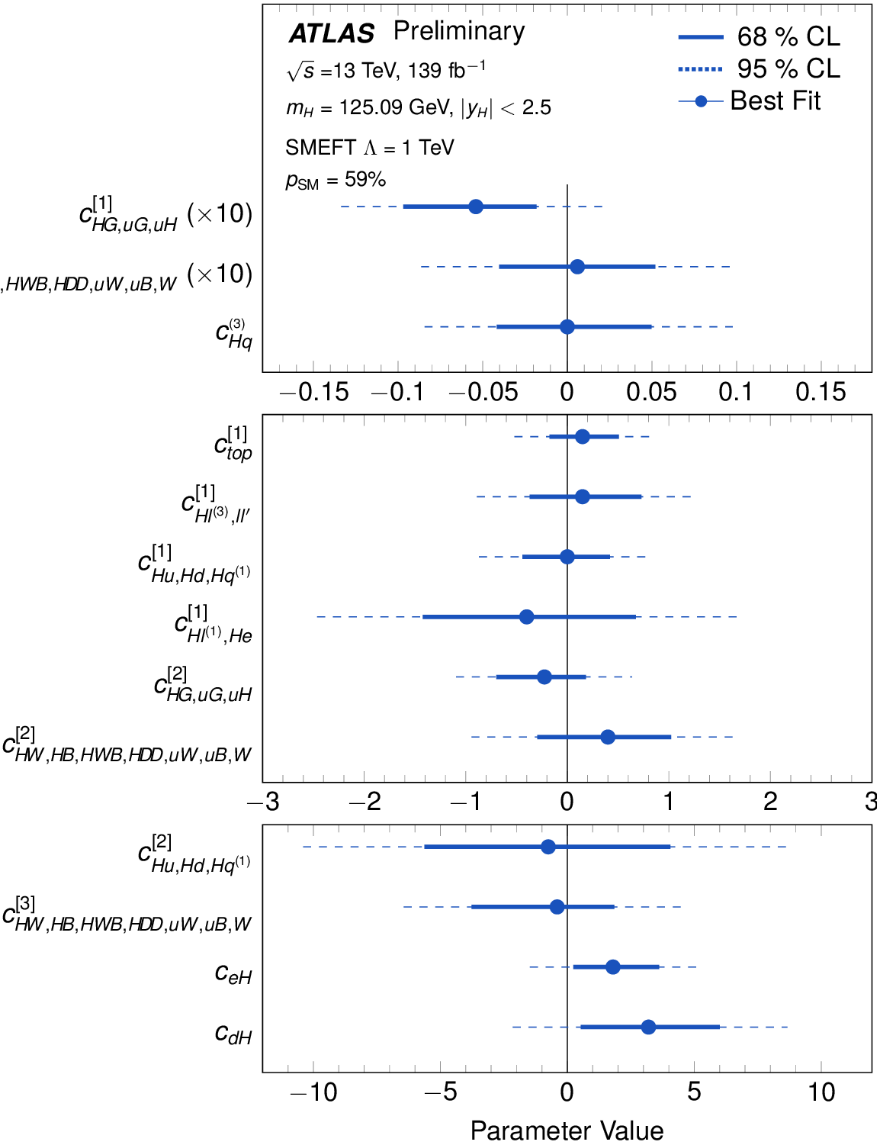
ATLAS-CONF-2021-053

- Results provided considering only the linear dependence on Wilson coefficients
- In agreement with SM ($c_i = 0$)
- Sensitivity improvement from previous rounds of these interpretations
- Correlations in the results from different groups can be understood from the effects of the parametrisations in the different STXS bins
  - Correlations between the same grouping come mostly from induced correlations through other POIs



ATLAS Preliminary $\sqrt{s}$ = 13 TeV, 139 fb^{-1} m_H = 125.09 GeV, $|y_H| < 2.5$

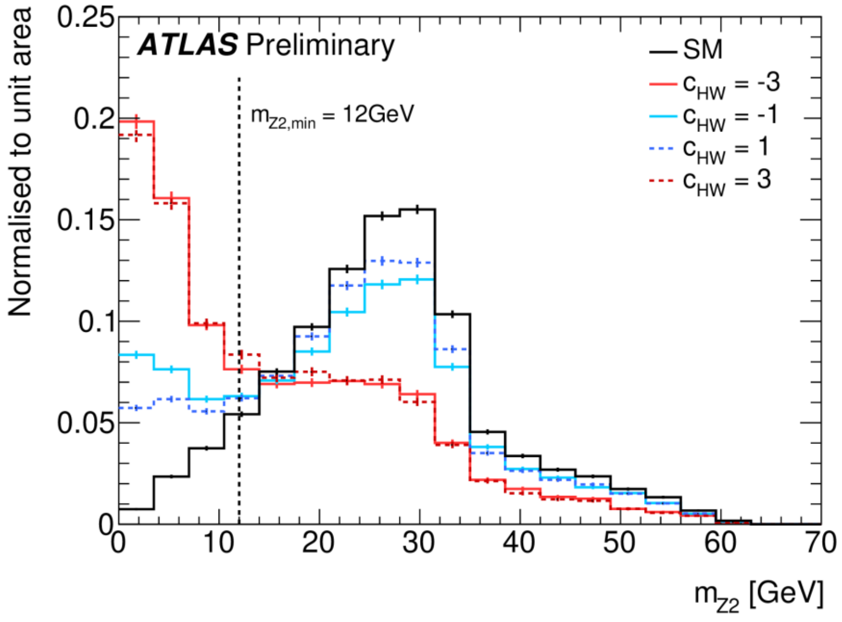
	$c_{Hq}^{(3)}$	c_{dH}	c_{eH}	$c^{[1]}_{Hl^{(1)},He}$	$c^{[1]}_{Hl^{(3)},ll'}$	$c^{[1]}_{Hd,Hq^{(1)},Hu}$	$c^{[2]}_{Hd,Hq^{(1)},Hu}$	$c^{[1]}_{HW,HB,HWB,HDD,uB,uW,W}$	$c^{[2]}_{HW,HB,HWB,HDD,uB,uW,W}$	$c^{[3]}_{HW,HB,HWB,HDD,uB,uW,W}$	$c^{[1]}_{HG,uG,uH}$	$c^{[2]}_{HG,uG,uH}$	$c^{[1]}_{top}$
$c_{Hq}^{(3)}$	1	0.12	−0.09	−0.08	−0.14	−0.43	−0.03	−0.25	−0.66	0.28	−0.11	−0.02	−0.03
c_{dH}	0.12	1	0.50	−0.30	−0.73	−0.05	0.02	−0.10	0.06	0.15	−0.52	−0.10	−0.09
c_{eH}	−0.09	0.50	1	−0.39	−0.37	0.01	0.02	−0.20	0.17	0.05	0.02	0.16	0.09
$c^{[1]}_{Hl^{(1)},He}$	−0.08	−0.30	−0.39	1	0.09	0.45	−0.43	0.69	0.30	−0.49	−0.20	−0.12	−0.03
$c^{[1]}_{Hl^{(3)},ll'}$	−0.14	−0.73	−0.37	0.09	1	0.17	−0.11	−0.13	0.03	−0.31	0.10	−0.04	0.03
$c^{[1]}_{Hd,Hq^{(1)},Hu}$	−0.43	−0.05	0.01	0.45	0.17	1	−0.72	0.62	0.74	−0.91	−0.24	−0.07	0.03
$c^{[2]}_{Hd,Hq^{(1)},Hu}$	−0.03	0.02	0.02	−0.43	−0.11	−0.72	1	−0.52	−0.44	0.80	0.27	0.08	0.00
$c^{[1]}_{HW,HB,HWB,HDD,uB,uW,W}$	−0.25	−0.10	−0.20	0.69	−0.13	0.62	−0.52	1	0.59	−0.64	−0.19	−0.15	−0.03
$c^{[2]}_{HW,HB,HWB,HDD,uB,uW,W}$	−0.66	0.06	0.17	0.30	0.03	0.74	−0.44	0.59	1	−0.76	−0.12	−0.07	0.00
$c^{[3]}_{HW,HB,HWB,HDD,uB,uW,W}$	0.28	0.15	0.05	−0.49	−0.31	−0.91	0.80	−0.64	−0.76	1	0.24	0.14	0.02
$c^{[1]}_{HG,uG,uH}$	−0.11	−0.52	0.02	−0.20	0.10	−0.24	0.27	−0.19	−0.12	0.24	1	0.23	0.09
$c^{[2]}_{HG,uG,uH}$	−0.02	−0.10	0.16	−0.12	−0.04	−0.07	0.08	−0.15	−0.07	0.14	0.23	1	0.86
$c^{[1]}_{top}$	−0.03	−0.09	0.09	−0.03	0.03	0.03	0.00	−0.03	0.00	0.02	0.09	0.86	1



SMEFT STXS interpretations in ATLAS

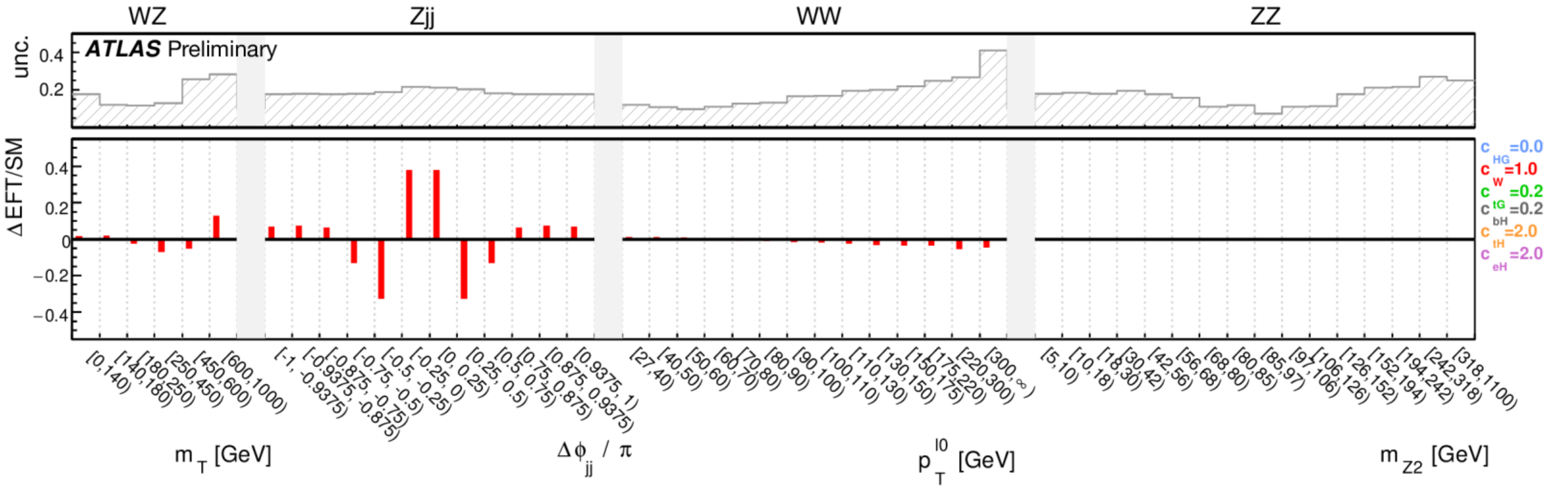
ATL-PHYS-PUB-2022-037

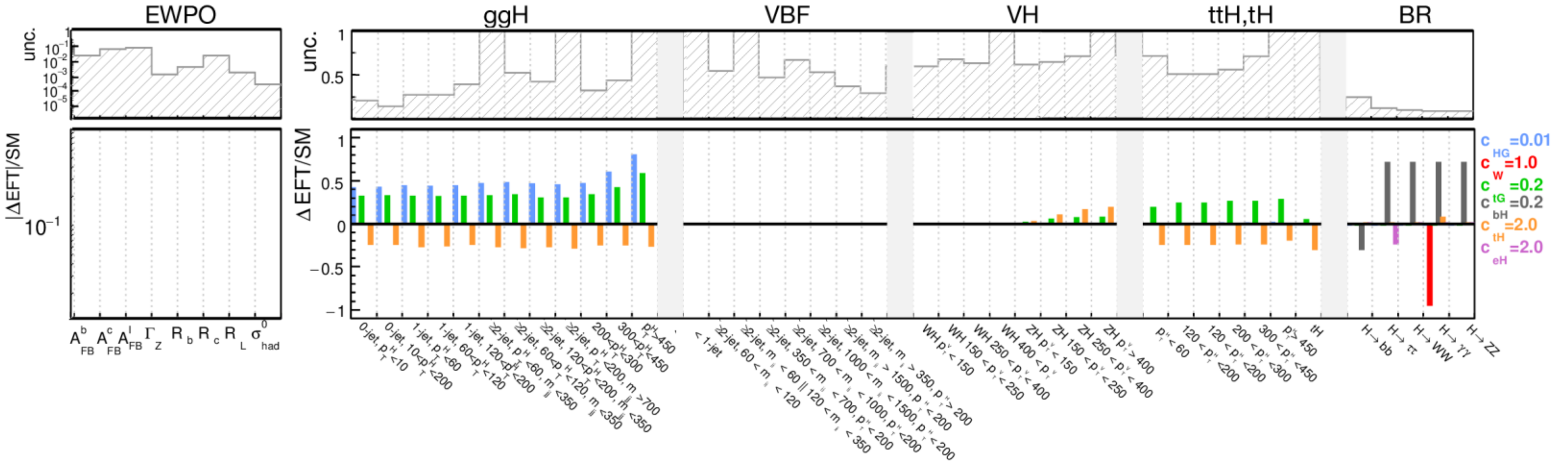
- Interpretations of combined measurements from Higgs (same dataset as in the previous analysis), diboson and EWPO from LEP
  - Focus on the impact of Higgs measurements
- Main changes in the parametrisation:
  - Move from $U(3)^5$ to $U(3)_L \times U(3)_e \times U(2)_Q \times (2)_u \times U(2)_d$ (in light of more global combinations including top data)
  - Inclusion of linear propagator corrections in the parametrisation
  - Acceptance corrections re-evaluated for the analysis including linear propagator corrections.
    - The Lorentzian functions are Taylor-expanded to keep only terms up to $1/\Lambda^2$ or up to $1/\Lambda^4$ once they are added to the production and decay side parametrisation
- Parametrisation of EW pole observables only in the linear approximations
  - Two different fit setups: Higgs+diboson and Higgs+diboson+EWPO



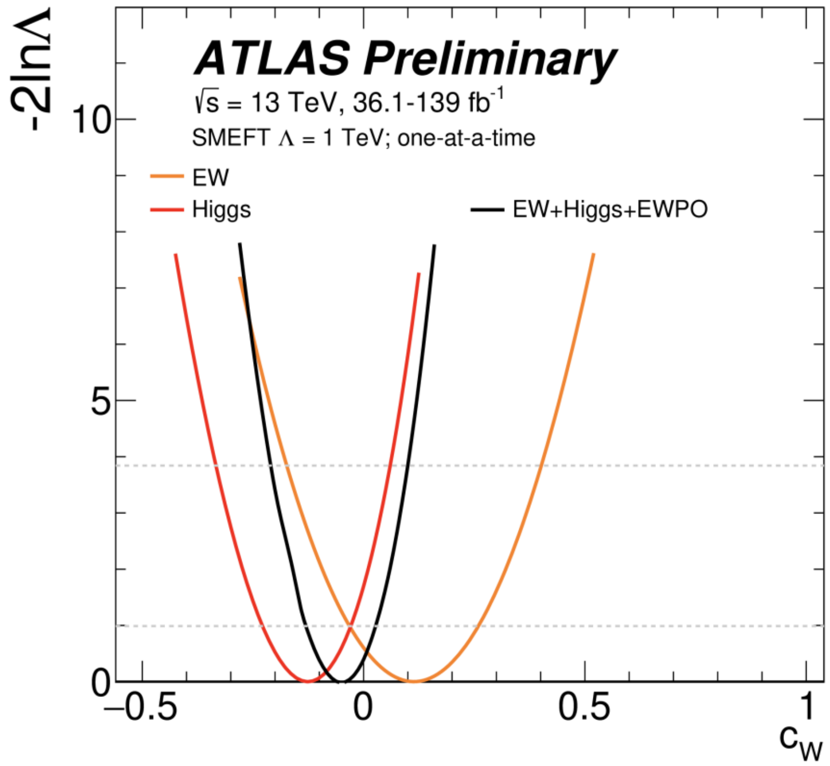
SMEFT STXS interpretations in ATLAS

ATL-PHYS-PUB-2022-037

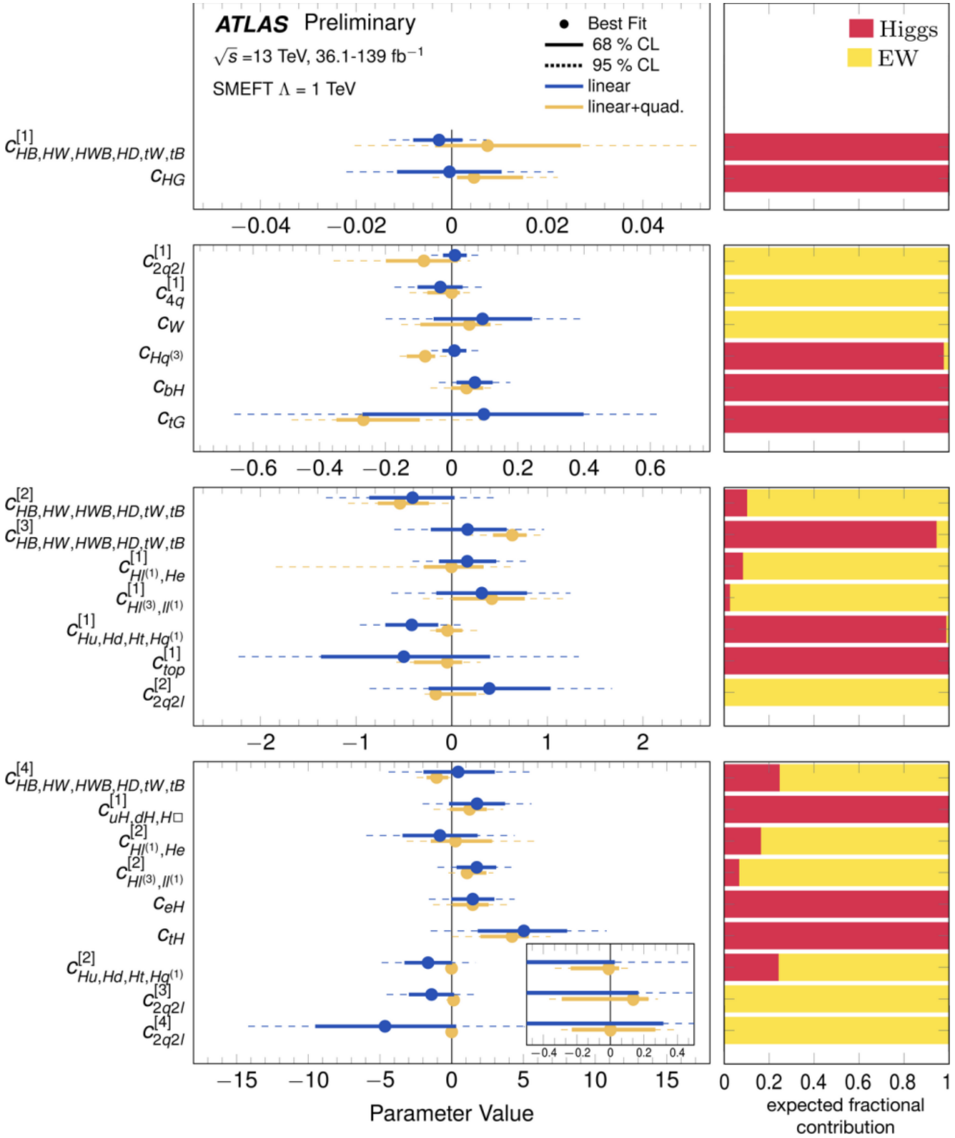




- Parametrisation in terms of few Wilson coefficients
  - cW has an impact in diboson and $H\rightarrow\gamma\gamma$ measurement
  - Gain from combination



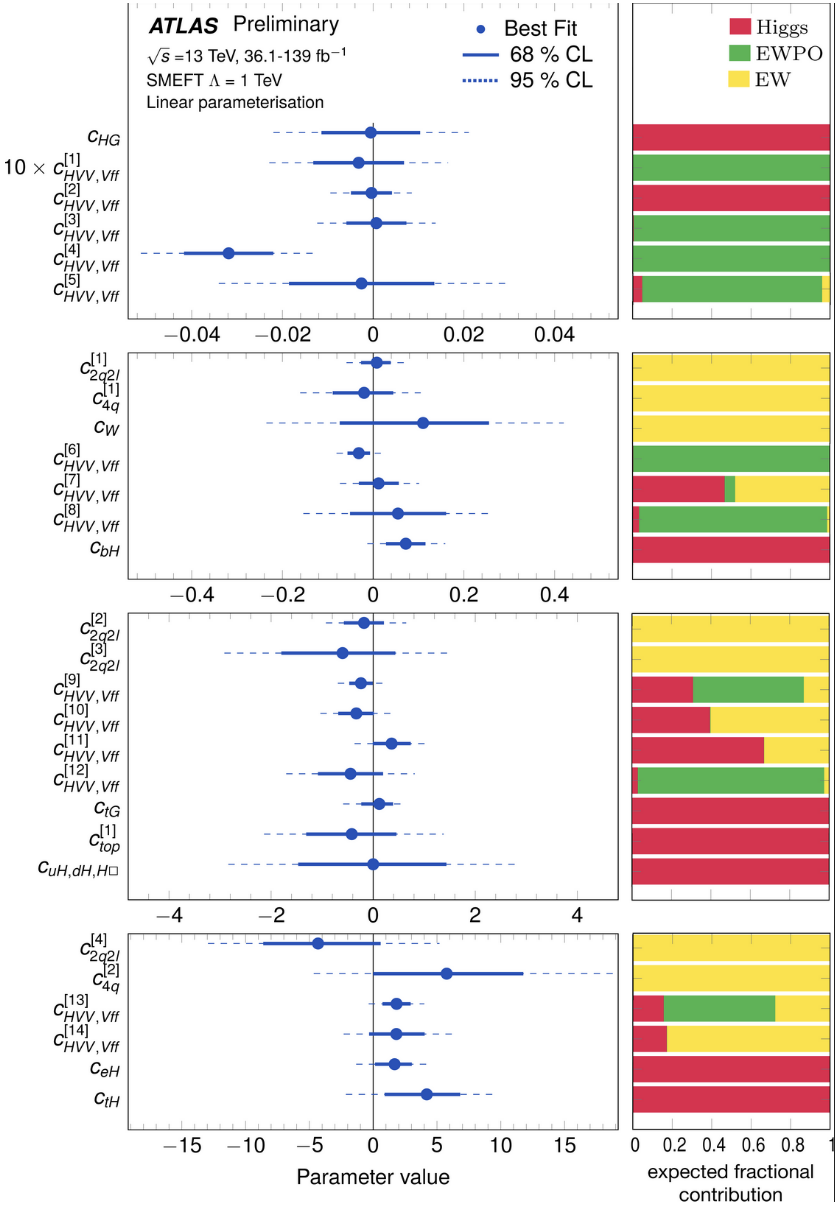
SMEFT STXS interpretations in ATLAS



ATL-PHYS-PUB-2022-037

- Trying to use as many single operators as possible in the fit basis
- Separate cHG, ctG and cuH group (less correlations than in single Higgs analyses)
- Several POIs constrained solely by Higgs results but also nice interplay with diboson data in some others

SMEFT STXS interpretations in ATLAS



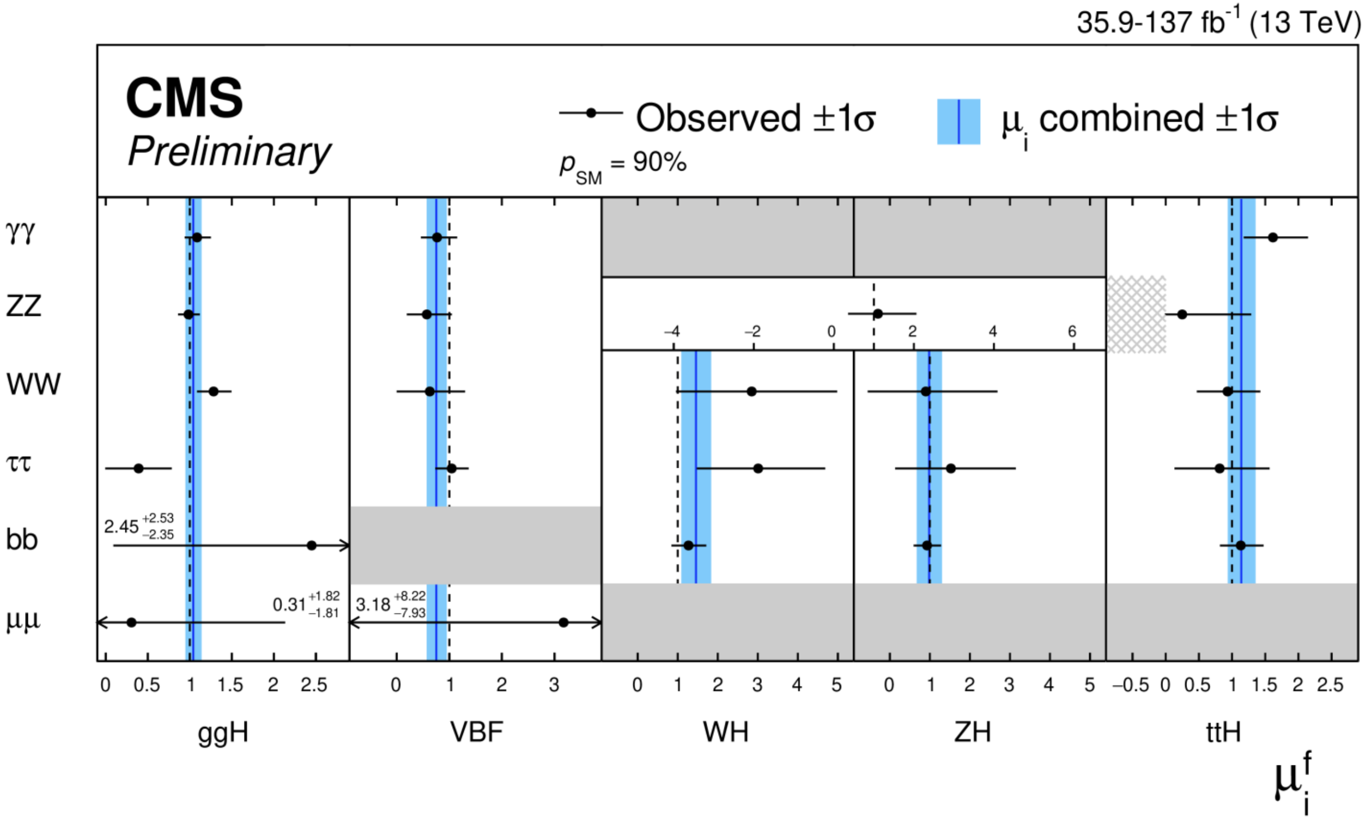
ATL-PHYS-PUB-2022-037

- The inclusion of EWPO LEP observables induces large correlations favoring the grouping of large number of parameters
    - 6 Wilson coefficients measured alone
- Measurements are in agreement with SM expectations
    - Except for cHVV,Vff[4] whose excess comes from the tension in the A_{FB} measurements from LEP
- Results from the full likelihood fit compared to those using a simplified NLL following a multi-variate Gaussian approach
    - Minimal differences between both methods

SMEFT STXS interpretations in CMS

HIG-19-005

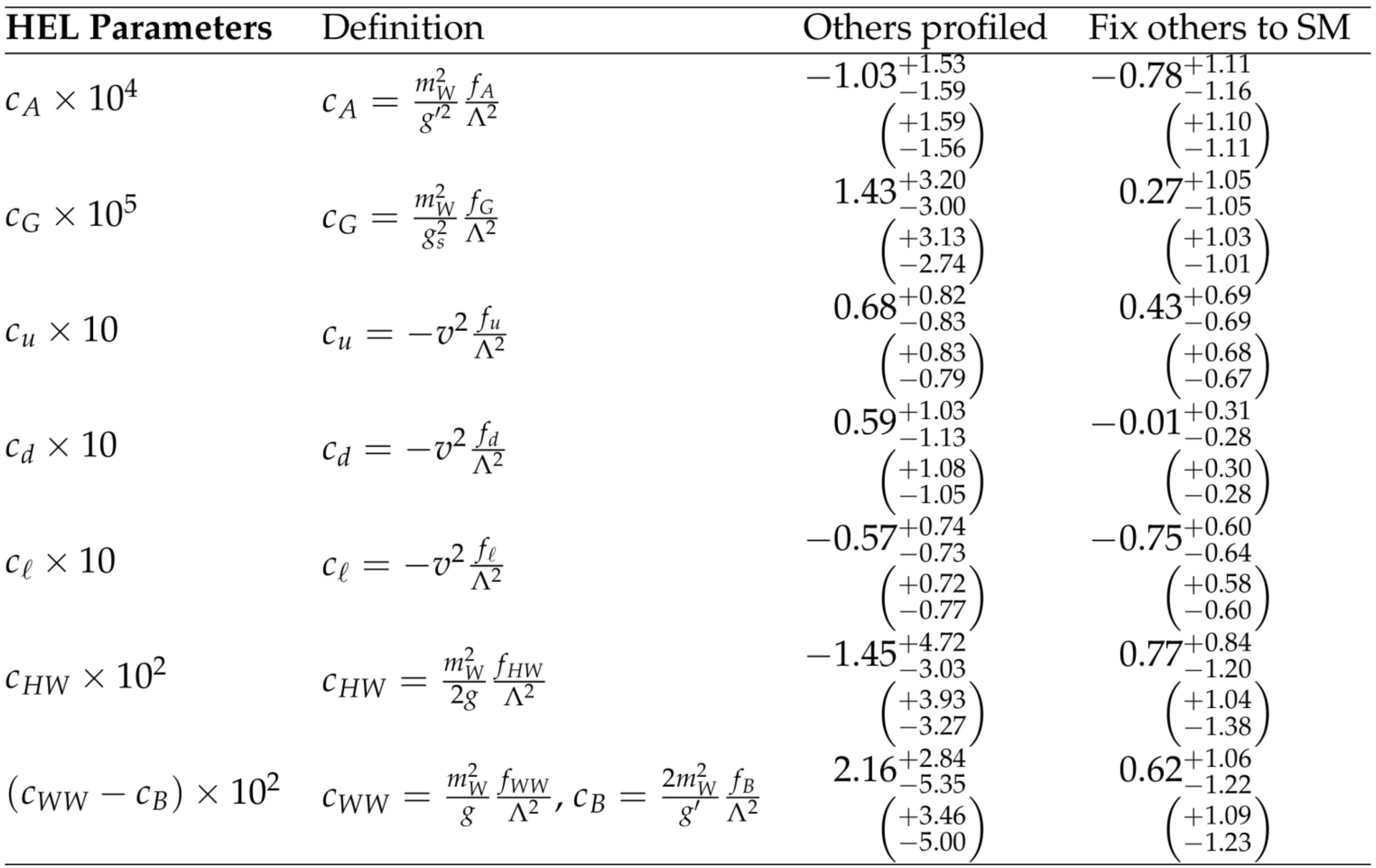
- Combination of production modes and decay rates of the Higgs couplings
- Interpretation done using the HEL Lagrangian
- Interference and quadratic terms considered
- Considering coefficients not tightly constrained by other measurements
- No acceptance corrections for detector effects applied



SMEFT STXS interpretations in CMS

HIG-19-005

- Results provided in two different scenarios:
  - Profiling other parameters
  - Fixing other parameters to the SM value
- The first one provides looser constraints, but takes into account correlations
- Results consistent with the SM expectation



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

Future CMS STXS interpretation

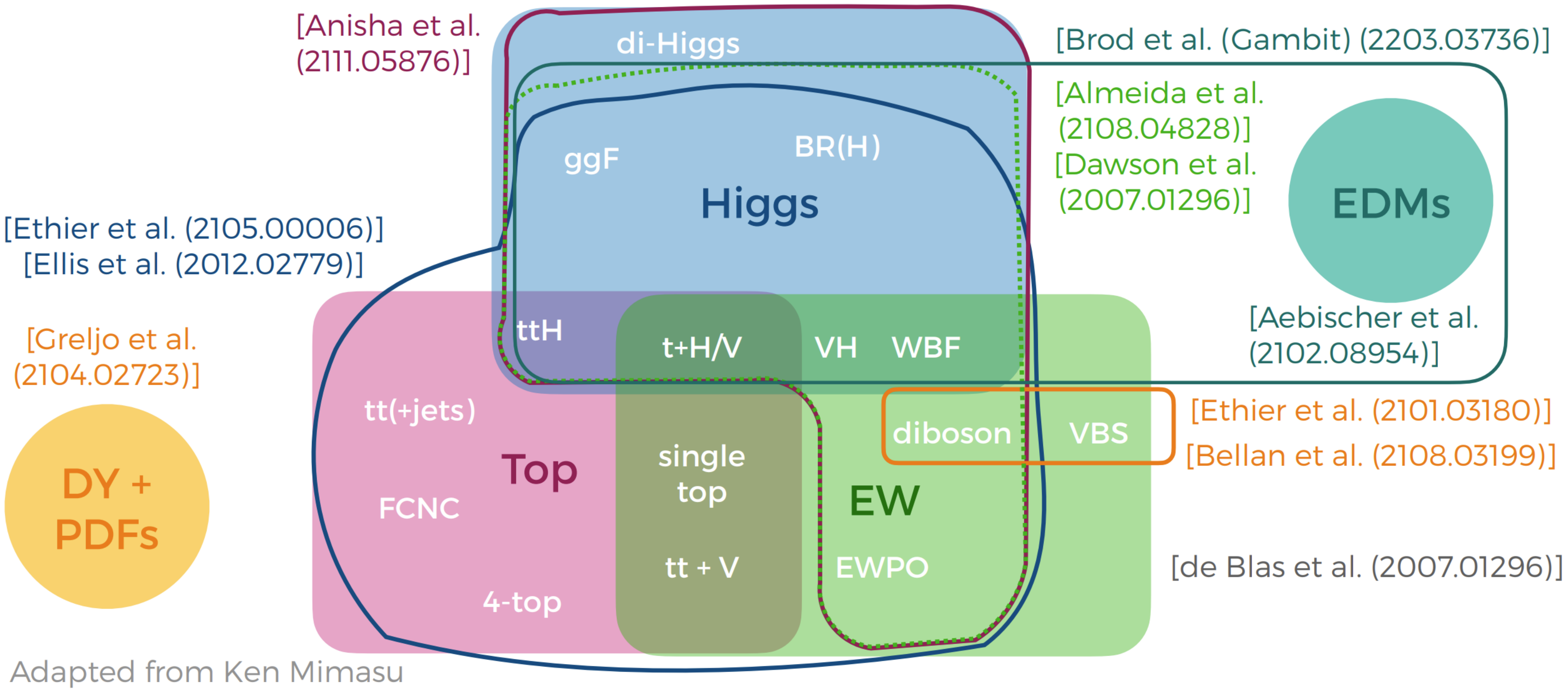
- Combination of full Run2 STXS measurements is ongoing
  - Better statistics will lead to tighter and more directions of constraint

- Major changes and improvements to parameterisation
  - Moving to Warsaw basis
  - Aligning with LHC EFT WG conventions for EFT combination between experiments
    - Input parameter scheme: $\{G_F, m_Z, m_W\}$
    - Flavour scheme: $U(2)^3_{q,u,d}U(3)^2_{l,e}$ (`topU3l` in SMEFTsim)
  - Quadratic parameterization considering all CP-even and CP-odd operators*
  - Using mainly `SMEFTsim` with `SMEFT@NLO` for loop-induced processes (ggH and $ggZH$)
  - Analytical derivations for $H \to \gamma\gamma$ and $H \to Z\gamma$ including one-loop electroweak SMEFT corrections
  - Acceptance corrections for $H \to 4l$ and $H \to l\nu l\nu$
  - Taking inspiration from dedicated EFT analyses where necessary
- PCA and rotation of Wilson Coefficients

*except where SMEFT@NLO is used

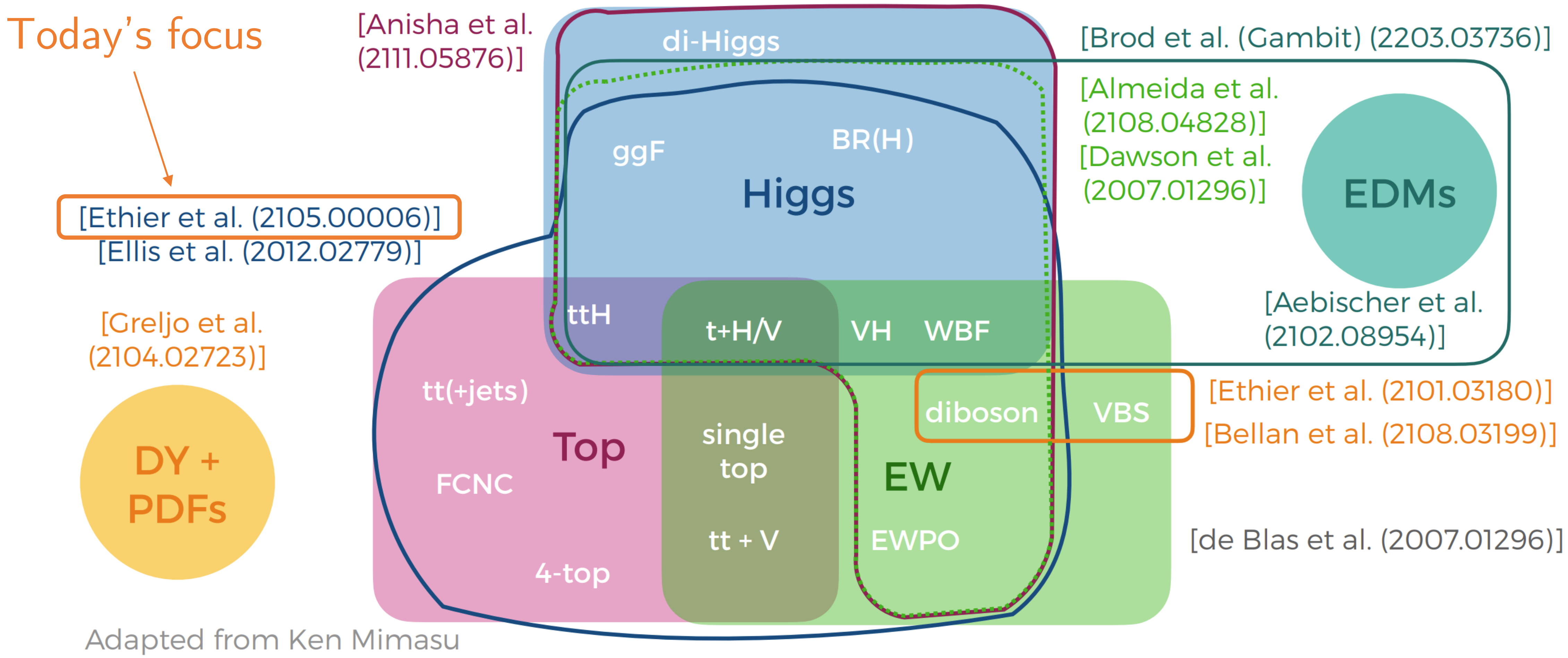
Theoretical interpretations

Global fits from theory community



Slide taken from Anke Biekoetter's talk at LHC EFT WG 4th General Meeting (May 2022)

Global fits from theory community



Adapted from Ken Mimasu

Slide taken from Anke Biekoetter's talk at LHC EFT WG 4th General Meeting (May)

SMEFiT Global Fit

Combined SMEFT interpretation of Higgs, diboson, and top quark data from the LHC [2105.00006]

- Datasets:
    - LHC: Higgs, top, and diboson (VV) production
    - LEP: Electroweak precision observables (EWPO) + VV production
- Constrains 36 independent directions in EFT space
    - Marginalised constraints without PCA
- Extensive `SMEFT@NLO` usage in Higgs
    - All but VBF and $H \to X$ ($X \neq b\bar{b}$) have NLO corrections
- No acceptance corrections in STXS parameterisation

Framework designed to search indirectly for new physics using broadest possible dataset

Top and EW inputs

Category	Process	n_{dat}
Top quark production	$t\bar{t}$ (inclusive)	94
	$t\bar{t}Z, t\bar{t}W$	14
	Single top (inclusive)	27
	tZ, tW	9
	$t\bar{t}t\bar{t}, t\bar{t}b\bar{b}$	6
	Total	**150**
Diboson production	LEP-2	40
	LHC	30
	Total	**70**

Mixture of Run1 and (mostly) partial Run2 results from CMS and ATLAS (see backup)

→ WW production differential in $\cos(\theta_W)$

→ WZ and WW from Run2 2016 (~36 fb^{-1}) (backup)

EWPO from LEP not included as a dataset
Instead introduced by setting certain linear combinations of C_i to zero (see later)

→ Unlike ATLAS interpretation and, for example, 2012.02779 (global fit by J. Ellis et al.)

Higgs Inputs

- Consider inclusive and differential (incl. STXS) signal strengths
  - Choose differential where there is an overlap of events

$\sqrt{s}$ [TeV]	$\mathcal{L}$ [fb^{-1}]	Modes	Observables	N_{dat}	Exp.	Ref.
7+8	20	$ggH, VBF, Vh, t\bar{t}h$ $h \to \gamma\gamma, VV, \tau\tau, b\bar{b}, Z\gamma, \mu\mu$	Incl. μ_i^f	20	ATLAS+CMS	1606.02266
8	20		Incl. μ_i^f	2	ATLAS	1507.04548
13	80	$ggH, VBF, Vh, t\bar{t}h$ $h \to \gamma\gamma, WW, ZZ, \tau\tau, b\bar{b}$	Incl. μ_i^f	16	ATLAS	1909.02845
13	36.9		Incl. μ_i^f	24	CMS	1809.10733
13	35.9	$ggH, VBF, Vh, t\bar{t}h$ $h \to ZZ, \gamma\gamma, b\bar{b}$	$d\sigma/dp_T^h$	9	CMS	1812.06504
13	39.1	$ggH, VBF, Vh, t\bar{t}h$ $h \to ZZ \to 4l$	$d\sigma/dp_T^h$	9	ATLAS	1805.10197
13	79.8	$Wh, Zh, h \to b\bar{b}$	$d\sigma/dp_T^V$	5	ATLAS	1903.04618
13	79.8	$ggF, h \to ZZ$	$\sigma_{ggF}(p_T^h, N_{jets})$	6	ATLAS	1909.02845
13	77.4	$ggF, h \to \gamma\gamma$	$\sigma_{ggF}(p_T^h, N_{jets})$	6	CMS	2103.06956

→ Split Vh into Wh and Zh

STXS

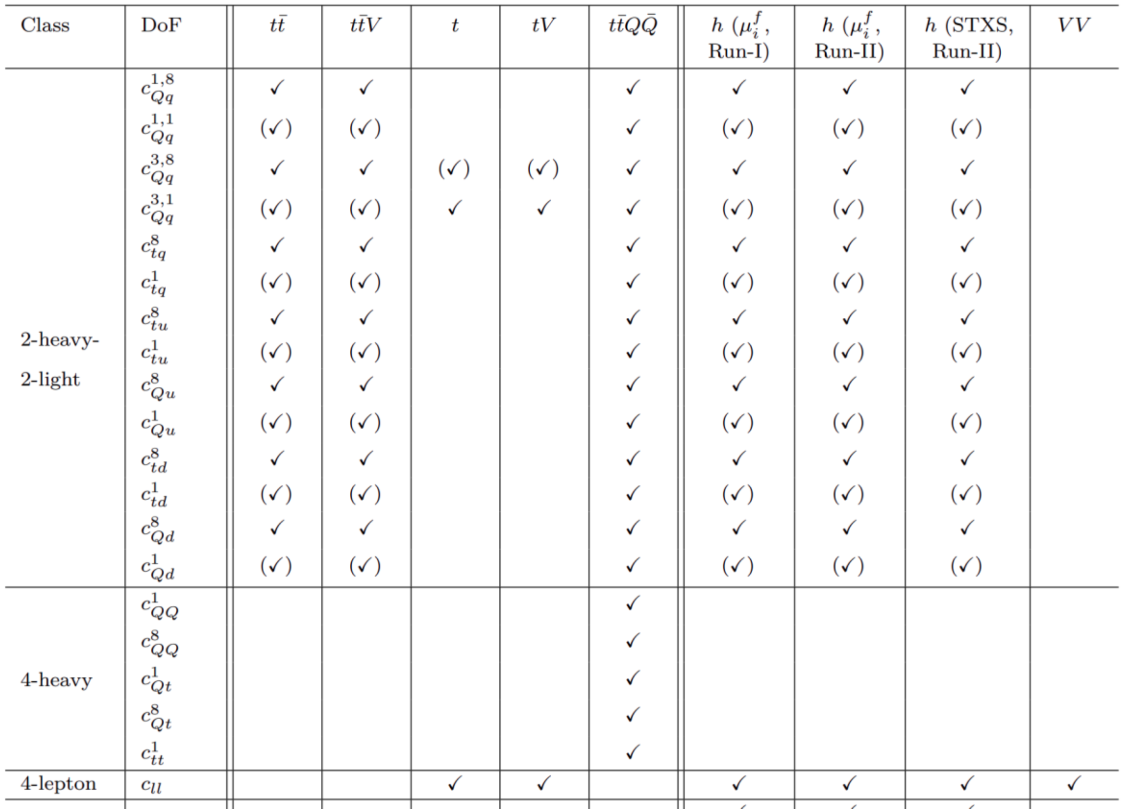
- Better constraints possible in future by including full Run2 results now published by CMS and ATLAS

Operator basis

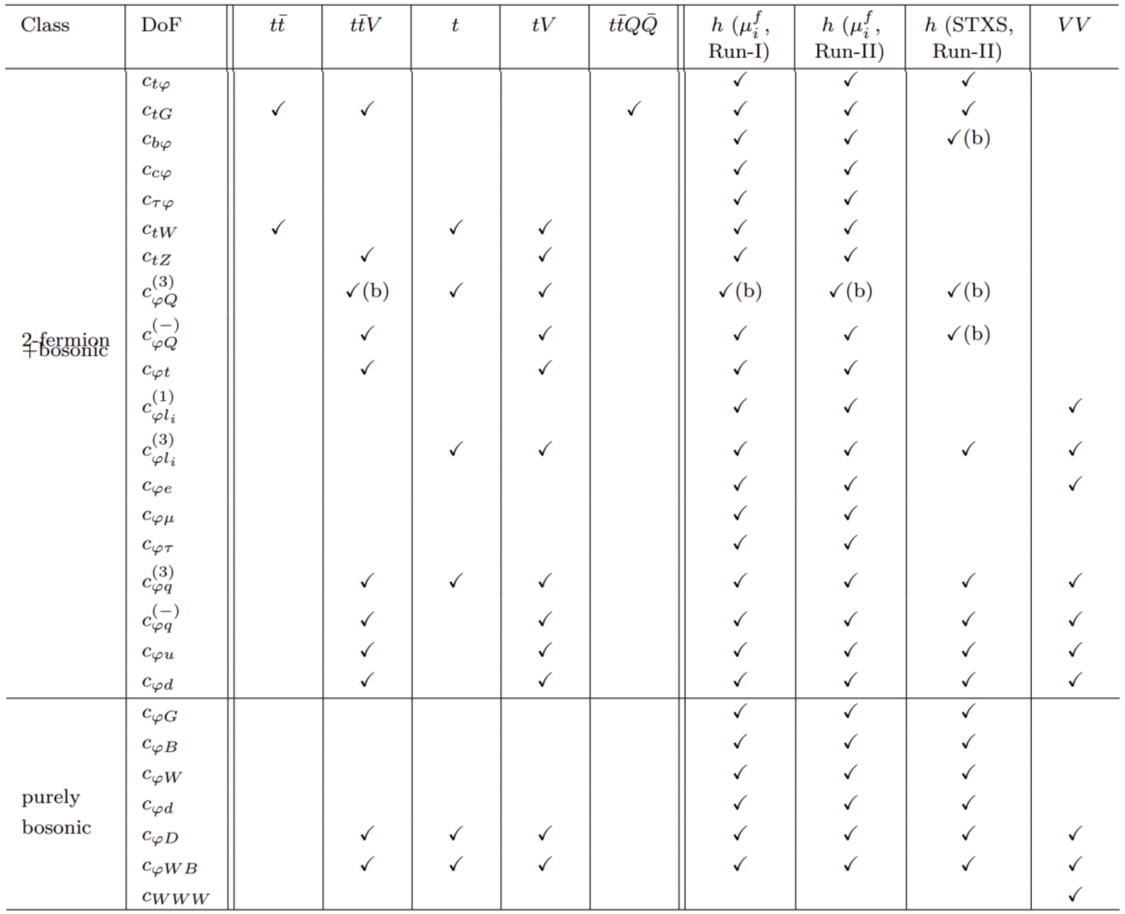
- Warsaw basis and $\{m_W, m_Z, G_F\}$ input parameter scheme
- Flavour scheme: $U(2)_q \times U(2)_u \times U(3)_d$ (aligned with `SMEFT@NLO`)
    - Slightly different to `SMEFTsim topU3l`: $U(2)_q \times U(2)_u \times U(2)_d$ where third generation is treated completely independently
    - Universal symmetry in the lepton sector: $(U(1)_l \times U(1)_e)^3$
- Initially consider 50 DoF
- After applying EWPO constraints 36 independent DoFs remain

Class	N_{dof}	Independent DOFs	DoF in EWPOs
four-quark (two-light-two-heavy)	14	$c_{Qq}^{1,8}$, $c_{Qq}^{1,1}$, $c_{Qq}^{3,8}$, $c_{Qq}^{3,1}$, c_{tq}^{8}, c_{tq}^{1}, c_{tu}^{8}, c_{tu}^{1}, c_{Qu}^{8}, c_{Qu}^{1}, c_{td}^{8}, c_{td}^{1}, c_{Qd}^{8}, c_{Qd}^{1}	
four-quark (four-heavy)	5	c_{QQ}^{1}, c_{QQ}^{8}, c_{Qt}^{1}, c_{Qt}^{8}, c_{tt}^{1}	
four-lepton	1		$c_{\ell\ell}$
two-fermion (+ bosonic fields)	23	$c_{t\varphi}$, c_{tG}, $c_{b\varphi}$, $c_{c\varphi}$, $c_{\tau\varphi}$, c_{tW}, c_{tZ}, $c_{\varphi Q}^{(3)}$, $c_{\varphi Q}^{(-)}$, $c_{\varphi t}$	$c_{\varphi\ell_1}^{(1)}$, $c_{\varphi\ell_1}^{(3)}$, $c_{\varphi\ell_2}^{(1)}$, $c_{\varphi\ell_2}^{(3)}$, $c_{\varphi\ell_3}^{(1)}$, $c_{\varphi\ell_3}^{(3)}$, $c_{\varphi e}$, $c_{\varphi\mu}$, $c_{\varphi\tau}$, $c_{\varphi q}^{(3)}$, $c_{\varphi q}^{(-)}$, $c_{\varphi ui}$, $c_{\varphi di}$
Purely bosonic	7	$c_{\varphi G}$, $c_{\varphi B}$, $c_{\varphi W}$, $c_{\varphi d}$, c_{WWW}	$c_{\varphi WB}$, $c_{\varphi D}$
Total	50 (36 independent)	34	16 (2 independent)

Operator dependence



Class	DoF	$t\bar{t}$	$t\bar{t}V$	t	tV	$t\bar{t}Q\bar{Q}$	h (μ_i^f, Run-I)	h (μ_i^f, Run-II)	h (STXS, Run-II)	VV
2-heavy-2-light	$c_{Qq}^{1,8}$	✓	✓			✓	✓	✓	✓	
	$c_{Qq}^{1,1}$	(✓)	(✓)			✓	(✓)	(✓)	(✓)	
	$c_{Qq}^{3,8}$	✓	✓	(✓)	(✓)	✓	✓	✓	✓	
	$c_{Qq}^{3,1}$	(✓)	(✓)	✓	✓	✓	(✓)	(✓)	(✓)	
	c_{tq}^{8}	✓	✓			✓	✓	✓	✓	
	c_{tq}^{1}	(✓)	(✓)			✓	(✓)	(✓)	(✓)	
	c_{tu}^{8}	✓	✓			✓	✓	✓	✓	
	c_{tu}^{1}	(✓)	(✓)			✓	(✓)	(✓)	(✓)	
	c_{Qu}^{8}	✓	✓			✓	✓	✓	✓	
	c_{Qu}^{1}	(✓)	(✓)			✓	(✓)	(✓)	(✓)	
	c_{td}^{8}	✓	✓			✓	✓	✓	✓	
	c_{td}^{1}	(✓)	(✓)			✓	(✓)	(✓)	(✓)	
	c_{Qd}^{8}	✓	✓			✓	✓	✓	✓	
	c_{Qd}^{1}	(✓)	(✓)			✓	(✓)	(✓)	(✓)	
4-heavy	c_{QQ}^{1}					✓				
	c_{QQ}^{8}					✓				
	c_{Qt}^{1}					✓				
	c_{Qt}^{8}					✓				
	c_{tt}^{1}					✓				
4-lepton	c_{ll}			✓	✓		✓	✓	✓	✓



Class	DoF	$t\bar{t}$	$t\bar{t}V$	t	tV	$t\bar{t}Q\bar{Q}$	h (μ_i^f, Run-I)	h (μ_i^f, Run-II)	h (STXS, Run-II)	VV
2-fermion +bosonic	$c_{t\varphi}$						✓	✓	✓	
	c_{tG}	✓	✓			✓	✓	✓	✓	
	$c_{b\varphi}$						✓	✓	✓(b)	
	$c_{c\varphi}$						✓	✓		
	$c_{\tau\varphi}$						✓	✓		
	c_{tW}	✓		✓	✓		✓	✓		
	c_{tZ}		✓		✓		✓	✓		
	$c_{\varphi Q}^{(3)}$		✓(b)	✓	✓		✓(b)	✓(b)	✓(b)	
	$c_{\varphi Q}^{(-)}$		✓		✓		✓	✓	✓(b)	
	$c_{\varphi t}$		✓		✓		✓	✓		
	$c_{\varphi l_i}^{(1)}$						✓	✓		✓
	$c_{\varphi l_i}^{(3)}$			✓	✓		✓	✓	✓	✓
	$c_{\varphi e}$						✓	✓		✓
	$c_{\varphi \mu}$						✓	✓		
	$c_{\varphi \tau}$						✓	✓		
	$c_{\varphi q}^{(3)}$		✓	✓	✓		✓	✓	✓	✓
	$c_{\varphi q}^{(-)}$		✓		✓		✓	✓	✓	✓
	$c_{\varphi u}$		✓		✓		✓	✓	✓	✓
	$c_{\varphi d}$		✓		✓		✓	✓	✓	✓
purely bosonic	$c_{\varphi G}$						✓	✓	✓	
	$c_{\varphi B}$						✓	✓	✓	
	$c_{\varphi W}$						✓	✓	✓	
	$c_{\varphi d}$						✓	✓	✓	
	$c_{\varphi D}$		✓	✓	✓		✓	✓	✓	✓
	$c_{\varphi WB}$		✓	✓	✓		✓	✓	✓	✓
	c_{WWW}									✓

- Many operators depend on multiple sectors
  - Helps to break degeneracies and constrain more directions simultaneously

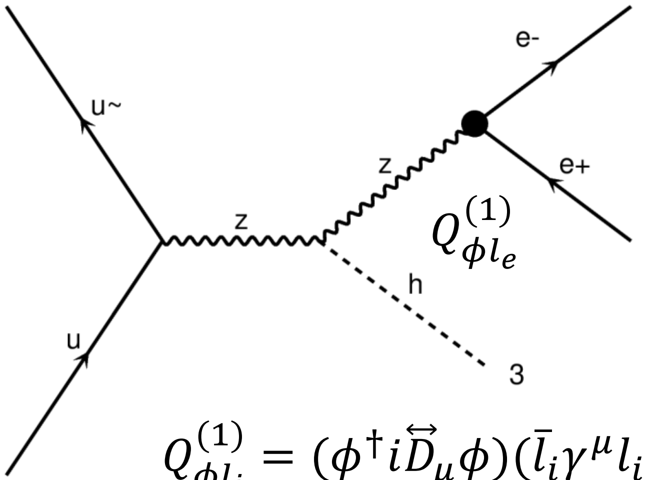
Treatment of EWPO

- Electroweak precision variables place constraints on:

  $Q_{\phi WB}, Q_{\phi D}, Q^1_{\phi q}, Q^3_{\phi q}, Q_{\phi u_i}, Q_{\phi d_i}, Q^3_{\phi l_i}, Q^1_{\phi l_i}, Q_{\phi e/\mu/\tau}, Q_{ll}$

- For example, Γ_Z is dependent on $Q^1_{\phi q}$
  - LEP measurements of Z BRs will well constrain this
  - No need to constrain with Higgs physics and 'waste' a constraining direction
- Two approaches:
  1. Include EWPO as an additional dataset and parameterise the observables (as in ATLAS combination)
  2. Set directions in SMEFT space to zero (approach used here)
     - Set 14 directions to zero and parameterise two remaining directions with $c_{\phi WB}$ and $c_{\phi D}$
- In principle, LHC can compete with LEP EWPO diboson channels

  → approach 1 is optimal… but approach 2 is an easier first step
- Approach 2 to be included in updated version of SMEFiT



$$Q^{(1)}_{\phi l_i} = (\phi^\dagger i\overleftrightarrow{D}_\mu \phi)(\bar{l}_i \gamma^\mu l_i)$$

$$\begin{pmatrix} c^{(3)}_{\varphi\ell_i} \\ c^{(1)}_{\varphi\ell_i} \\ c_{\varphi e/\mu/\tau} \\ c^{(-)}_{\varphi q} \\ c^{(3)}_{\varphi q} \\ c_{\varphi u} \\ c_{\varphi d} \\ c_{\ell\ell} \end{pmatrix} = \begin{pmatrix} -\frac{1}{t_W} & -\frac{1}{4t_W^2} \\ 0 & -\frac{1}{4} \\ 0 & -\frac{1}{2} \\ \frac{1}{t_W} & \frac{1}{4s_W^2} - \frac{1}{6} \\ -\frac{1}{t_W} & -\frac{1}{4t_W^2} \\ 0 & \frac{1}{3} \\ 0 & -\frac{1}{6} \\ 0 & 0 \end{pmatrix} \begin{pmatrix} c_{\varphi WB} \\ c_{\varphi D} \end{pmatrix}$$

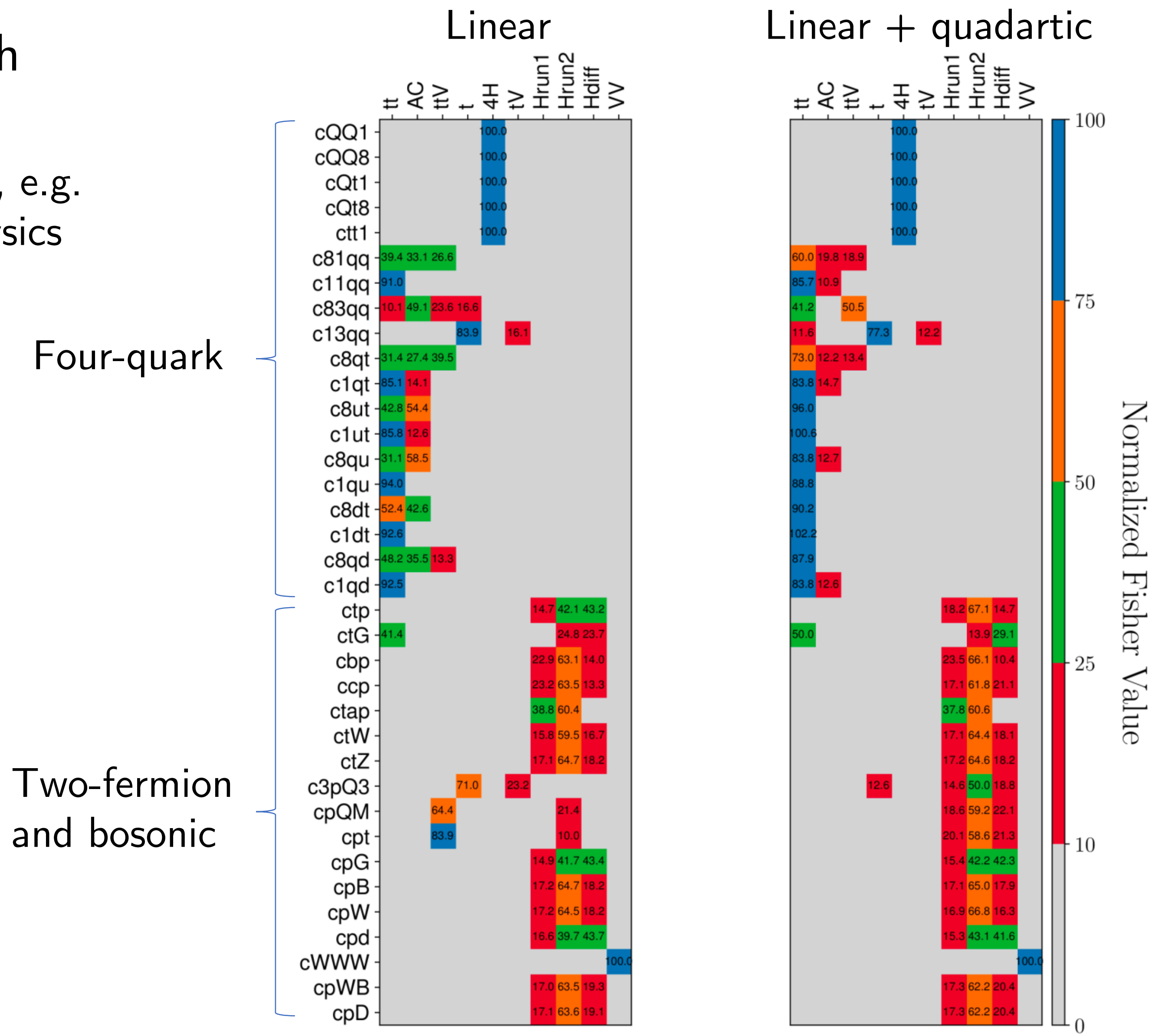
Parameterisation

- Linear and linear + quadratic parameterisations derived with `SMEFT@NLO`
- Higgs scaling equations re-expanded to appropriate order
    - $\mu_j^i(c_k) = \sigma_i(c_k) \times \Gamma_j(c_k)/\Gamma_T(c_k) \longrightarrow$ 1st or 2nd order
- Extensive use of NLO SMEFT predictions
- Comparing to ATLAS Higgs parameterisation, NLO is now also included for:
    - $pp \rightarrow Vh$ (only $gg \rightarrow Zh$ in ATLAS)
    - $t\bar{t}h$
    - $H \rightarrow b\bar{b}$
- No acceptance corrections applied in STXS
- Parton-level calculations only
    - Interpretations from ATLAS and CMS tend to use Pythia for parton shower and hadronisation

Category	Process	SM	Code/Ref	SMEFT
Top quark production	$t\bar{t}$ (incl)	NNLO QCD	`MG5_aMC` NLO + NNLO K-fact	NLO QCD
	$t\bar{t}+V$	NLO QCD	`MG5_aMC` NLO	LO QCD + NLO SM K-fact
	single-t (incl)	NNLO QCD	`MG5_aMC` NLO + NNLO K-fact	NLO QCD
	$t+V$	NLO QCD	`MG5_aMC` NLO	LO QCD + NLO SM K-fact
	$t\bar{t}t\bar{t},\ t\bar{b}t\bar{b}$	NLO QCD	`MG5_aMC` NLO	LO QCD + NLO SM K-fact
Higgs production and decay	$gg \rightarrow h$	NNLO QCD + NLO EW	HXSWG	NLO QCD
	VBF	NNLO QCD + NLO EW	HXSWG	LO QCD
	$h+V$	NNLO QCD + NLO EW	HXSWG	NLO QCD
	$ht\bar{t}$	NNLO QCD + NLO EW	HXSWG	NLO QCD
	$h \rightarrow X$	NNLO QCD + NLO EW	HXSWG	NLO QCD ($X = b\bar{b}$) LO QCD ($X \neq b\bar{b}$)
Diboson production	$e^+e^- \rightarrow W^+W^-$	NNLO QCD + NLO EW	LEP EWWG	LO QCD
	$pp \rightarrow VV'$	NNLO QCD	`MATRIX`	NLO QCD

Principle component analysis (PCA)

- Use PCA to illustrate c_i dependency on each dataset
    - Constraining power tends to stay within a sector, e.g. four-quark operators best constrained by top physics


Four-quark

Two-fermion and bosonic

Linear

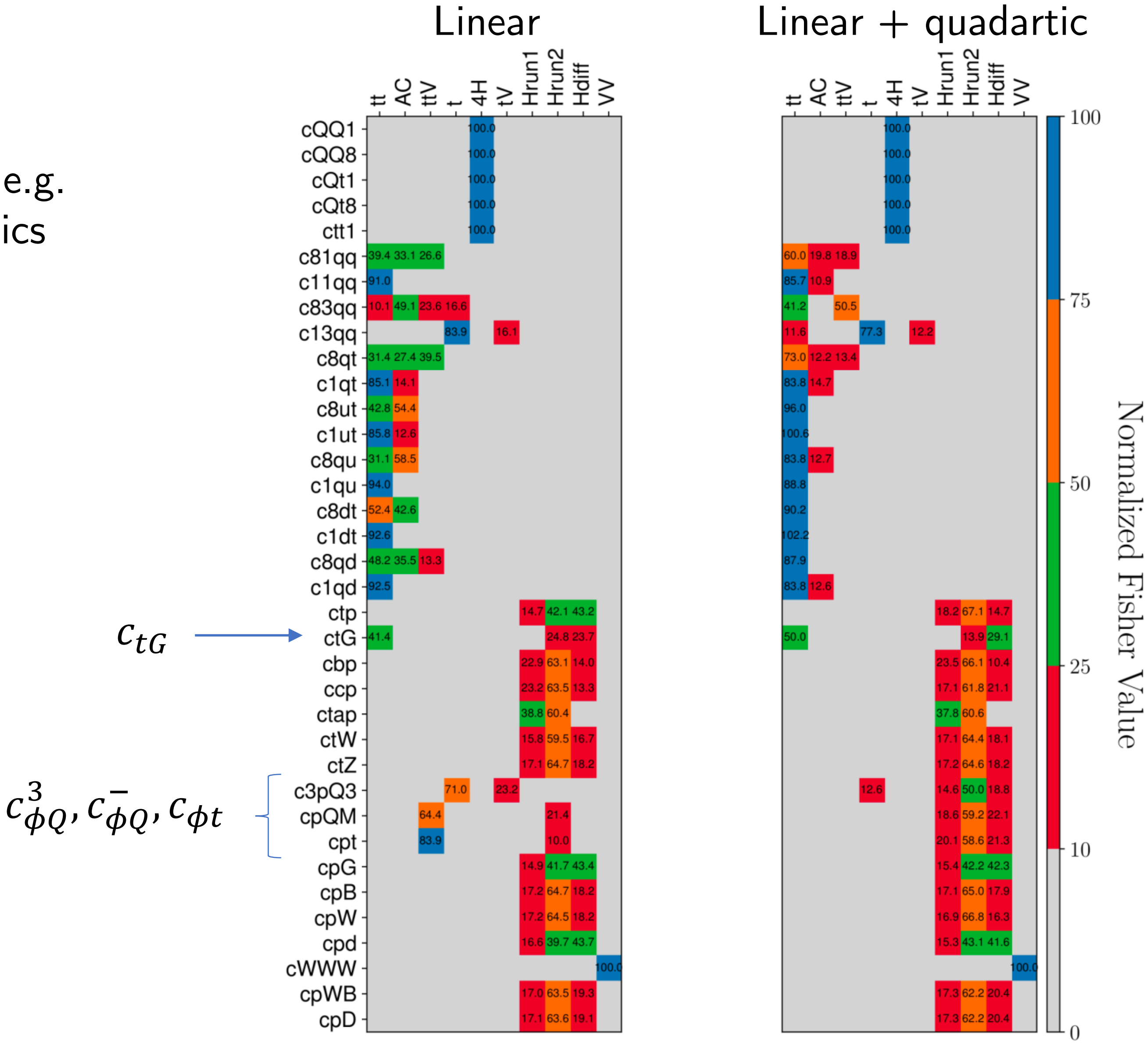
	tt	AC	ttV	t	4H	tV	Hrun1	Hrun2	Hdiff	VV
cQQ1					100.0					
cQQ8					100.0					
cQt1					100.0					
cQt8					100.0					
ctt1					100.0					
c81qq	39.4	33.1	26.6							
c11qq	91.0									
c83qq	10.1	49.1	23.6	16.6						
c13qq				83.9		16.1				
c8qt	31.4	27.4	39.5							
c1qt	85.1	14.1								
c8ut	42.8	54.4								
c1ut	85.8	12.6								
c8qu	31.1	58.5								
c1qu	94.0									
c8dt	52.4	42.6								
c1dt	92.6									
c8qd	48.2	35.5	13.3							
c1qd	92.5									
ctp							14.7	42.1	43.2	
ctG	41.4							24.8	23.7	
cbp							22.9	63.1	14.0	
ccp							23.2	63.5	13.3	
ctap							38.8	60.4		
ctW							15.8	59.5	16.7	
ctZ							17.1	64.7	18.2	
c3pQ3				71.0		23.2				
cpQM			64.4					21.4		
cpt			83.9					10.0		
cpG							14.9	41.7	43.4	
cpB							17.2	64.7	18.2	
cpW							17.2	64.5	18.2	
cpd							16.6	39.7	43.7	
cWWW										100.0
cpWB							17.0	63.5	19.3	
cpD							17.1	63.6	19.1	

Linear + quadartic

	tt	AC	ttV	t	4H	tV	Hrun1	Hrun2	Hdiff	VV
cQQ1					100.0					
cQQ8					100.0					
cQt1					100.0					
cQt8					100.0					
ctt1					100.0					
c81qq	60.0	19.8	18.9							
c11qq	85.7	10.9								
c83qq	41.2		50.5							
c13qq	11.6			77.3		12.2				
c8qt	73.0	12.2	13.4							
c1qt	83.8	14.7								
c8ut	96.0									
c1ut	100.6									
c8qu	83.8	12.7								
c1qu	88.8									
c8dt	90.2									
c1dt	102.2									
c8qd	87.9									
c1qd	83.8	12.6								
ctp							18.2	67.1	14.7	
ctG	50.0							13.9	29.1	
cbp							23.5	66.1	10.4	
ccp							17.1	61.8	21.1	
ctap							37.8	60.6		
ctW							17.1	64.4	18.1	
ctZ							17.2	64.6	18.2	
c3pQ3				12.6			14.6	50.0	18.8	
cpQM							18.6	59.2	22.1	
cpt							20.1	58.6	21.3	
cpG							15.4	42.2	42.3	
cpB							17.1	65.0	17.9	
cpW							16.9	66.8	16.3	
cpd							15.3	43.1	41.6	
cWWW										100.0
cpWB							17.3	62.2	20.4	
cpD							17.3	62.2	20.4	

Principle component analysis (PCA)

- Use PCA to illustrate c_i dependency on each dataset
  - Constraining power tends to stay within a sector, e.g. four-quark operators best constrained by top physics
  - Some cross-over between Higgs and top:
    - c_{tG} affects ggF and $t\bar{t}, t\bar{t}V, t\bar{t}Q\bar{Q}$
    - $c_{\phi t}$ affects $t\bar{t}h, th$ and $t\bar{t}, tV$
    - $c^3_{\phi Q}, c^-_{\phi Q}$ affect Vh and $t\bar{t}V, t, tV$


c_{tG}

$c^3_{\phi Q}, c^-_{\phi Q}, c_{\phi t}$

Linear

	tt	AC	ttV	t	4H	tV	Hrun1	Hrun2	Hdiff	VV
cQQ1					100.0					
cQQ8					100.0					
cQt1					100.0					
cQt8					100.0					
ctt1					100.0					
c81qq	39.4	33.1	26.6							
c11qq	91.0									
c83qq	10.1	49.1	23.6	16.6						
c13qq				83.9		16.1				
c8qt	31.4	27.4	39.5							
c1qt	85.1	14.1								
c8ut	42.8	54.4								
c1ut	85.8	12.6								
c8qu	31.1	58.5								
c1qu	94.0									
c8dt	52.4	42.6								
c1dt	92.6									
c8qd	48.2	35.5	13.3							
c1qd	92.5									
ctp							14.7	42.1	43.2	
ctG	41.4							24.8	23.7	
cbp							22.9	63.1	14.0	
ccp							23.2	63.5	13.3	
ctap							38.8	60.4		
ctW							15.8	59.5	16.7	
ctZ							17.1	64.7	18.2	
c3pQ3				71.0		23.2				
cpQM			64.4					21.4		
cpt			83.9					10.0		
cpG							14.9	41.7	43.4	
cpB							17.2	64.7	18.2	
cpW							17.2	64.5	18.2	
cpd							16.6	39.7	43.7	
cWWW										100.0
cpWB							17.0	63.5	19.3	
cpD							17.1	63.6	19.1	

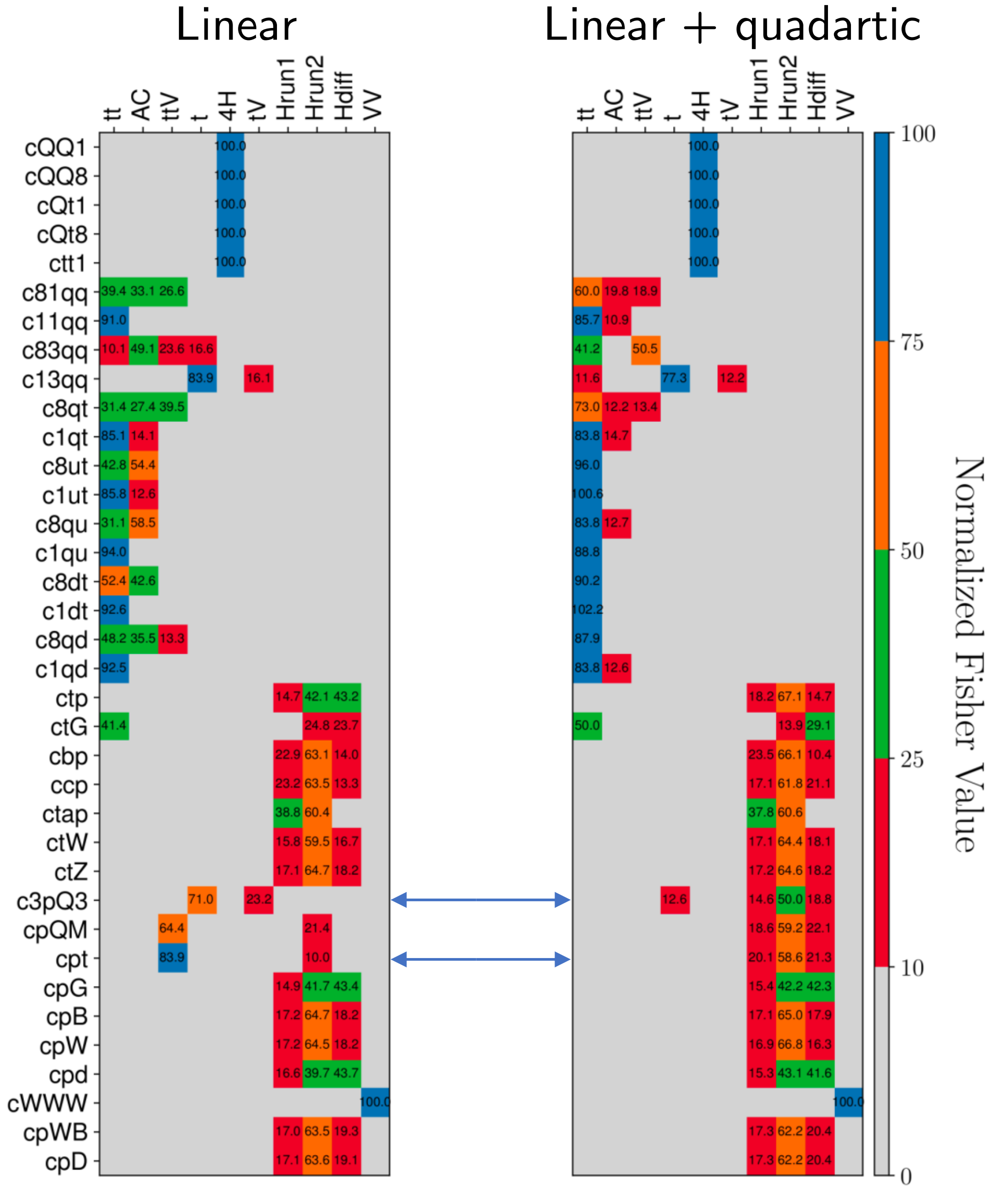
Linear + quadartic

	tt	AC	ttV	t	4H	tV	Hrun1	Hrun2	Hdiff	VV
cQQ1					100.0					
cQQ8					100.0					
cQt1					100.0					
cQt8					100.0					
ctt1					100.0					
c81qq	60.0	19.8	18.9							
c11qq	85.7	10.9								
c83qq	41.2		50.5							
c13qq	11.6			77.3		12.2				
c8qt	73.0	12.2	13.4							
c1qt	83.8	14.7								
c8ut	96.0									
c1ut	100.6									
c8qu	83.8	12.7								
c1qu	88.8									
c8dt	90.2									
c1dt	102.2									
c8qd	87.9									
c1qd	83.8	12.6								
ctp							18.2	67.1	14.7	
ctG	50.0							13.9	29.1	
cbp							23.5	66.1	10.4	
ccp							17.1	61.8	21.1	
ctap							37.8	60.6		
ctW							17.1	64.4	18.1	
ctZ							17.2	64.6	18.2	
c3pQ3				12.6			14.6	50.0	18.8	
cpQM							18.6	59.2	22.1	
cpt							20.1	58.6	21.3	
cpG							15.4	42.2	42.3	
cpB							17.1	65.0	17.9	
cpW							16.9	66.8	16.3	
cpd							15.3	43.1	41.6	
cWWW										100.0
cpWB							17.3	62.2	20.4	
cpD							17.3	62.2	20.4	

Principle component analysis (PCA)

- Use PCA to illustrate c_i dependency on each dataset
  - Constraining power tends to stay within a sector, e.g. four-quark operators best constrained by top physics
  - Some cross-over between Higgs and top:
    - c_{tG} affects ggF and $t\bar{t}, t\bar{t}V, t\bar{t}Q\bar{Q}$
    - $c_{\phi t}$ affects $t\bar{t}h, th$ and $t\bar{t}, tV$
    - $c^3_{\phi Q}, c^-_{\phi Q}$ affect Vh and $t\bar{t}V, t, tV$
- Quadratic PCA evaluated at best-fit values from global fit
  - $c^3_{\phi Q}$ and $c_{\phi t}$ become dominated by Higgs measurements
- After eigenvector decomposition:
  - 3 flat directions found in linear parameterisation
  - no flat directions found in quadratic parameterisation

  → choose not to perform a rotation



Linear

	tt	AC	ttV	t	4H	tV	Hrun1	Hrun2	Hdiff	VV
cQQ1					100.0					
cQQ8					100.0					
cQt1					100.0					
cQt8					100.0					
ctt1					100.0					
c81qq	39.4	33.1	26.6							
c11qq	91.0									
c83qq	10.1	49.1	23.6	16.6						
c13qq				83.9		16.1				
c8qt	31.4	27.4	39.5							
c1qt	85.1	14.1								
c8ut	42.8	54.4								
c1ut	85.8	12.6								
c8qu	31.1	58.5								
c1qu	94.0									
c8dt	52.4	42.6								
c1dt	92.6									
c8qd	48.2	35.5	13.3							
c1qd	92.5									
ctp							14.7	42.1	43.2	
ctG	41.4							24.8	23.7	
cbp							22.9	63.1	14.0	
ccp							23.2	63.5	13.3	
ctap							38.8	60.4		
ctW							15.8	59.5	16.7	
ctZ							17.1	64.7	18.2	
c3pQ3				71.0		23.2				
cpQM			64.4					21.4		
cpt			83.9					10.0		
cpG							14.9	41.7	43.4	
cpB							17.2	64.7	18.2	
cpW							17.2	64.5	18.2	
cpd							16.6	39.7	43.7	
cWWW										100.0
cpWB							17.0	63.5	19.3	
cpD							17.1	63.6	19.1	

Linear + quadartic

	tt	AC	ttV	t	4H	tV	Hrun1	Hrun2	Hdiff	VV
cQQ1					100.0					
cQQ8					100.0					
cQt1					100.0					
cQt8					100.0					
ctt1					100.0					
c81qq	60.0	19.8	18.9							
c11qq	85.7	10.9								
c83qq	41.2		50.5							
c13qq	11.6			77.3		12.2				
c8qt	73.0	12.2	13.4							
c1qt	83.8	14.7								
c8ut	96.0									
c1ut	100.6									
c8qu	83.8	12.7								
c1qu	88.8									
c8dt	90.2									
c1dt	102.2									
c8qd	87.9									
c1qd	83.8	12.6								
ctp							18.2	67.1	14.7	
ctG	50.0							13.9	29.1	
cbp							23.5	66.1	10.4	
ccp							17.1	61.8	21.1	
ctap							37.8	60.6		
ctW							17.1	64.4	18.1	
ctZ							17.2	64.6	18.2	
c3pQ3				12.6			14.6	50.0	18.8	
cpQM							18.6	59.2	22.1	
cpt							20.1	58.6	21.3	
cpG							15.4	42.2	42.3	
cpB							17.1	65.0	17.9	
cpW							16.9	66.8	16.3	
cpd							15.3	43.1	41.6	
cWWW										100.0
cpWB							17.3	62.2	20.4	
cpD							17.3	62.2	20.4	

Results – linear vs quadratic parametrisation

Constrain 36 (independent) + 14 (from EWPO) operators

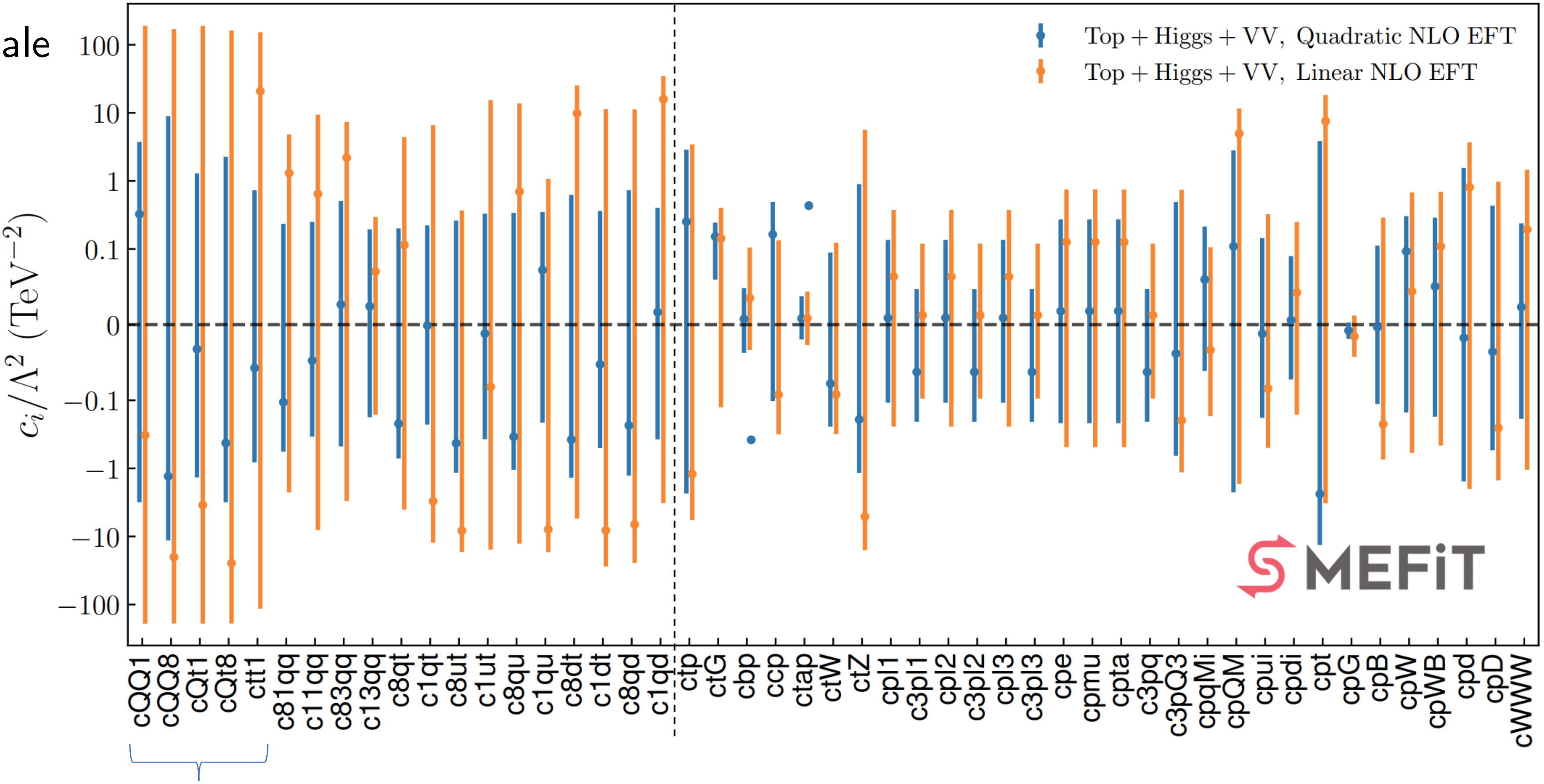
Marginalised bounds

All consistent with the SM at 95% CL for linear parameterisation

For the quadratic, all except c_{tG} are consistent

Traced back to CMS $(m_{t\bar{t}}, y_{\tau\tau})$ distributions

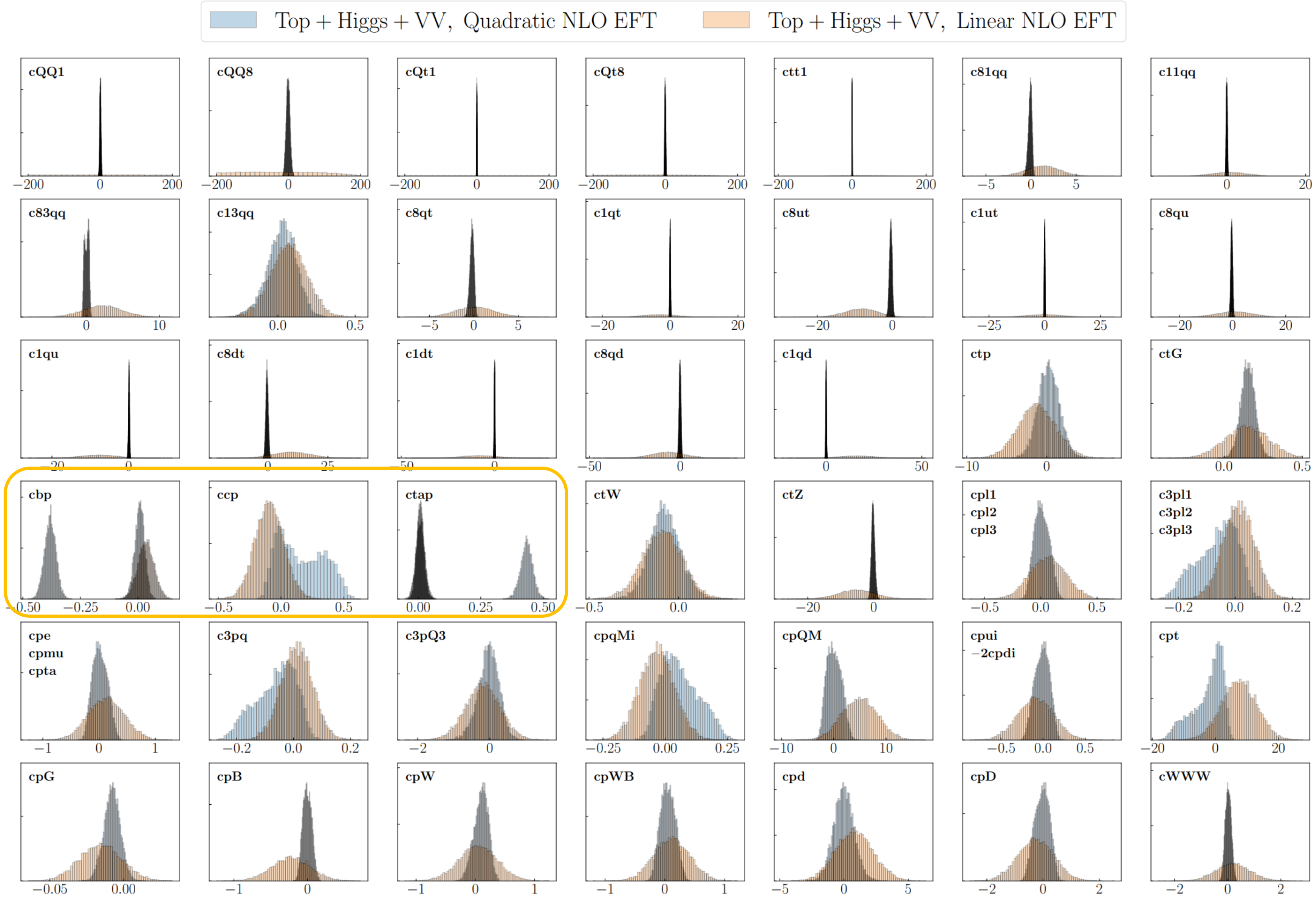
Log-scale



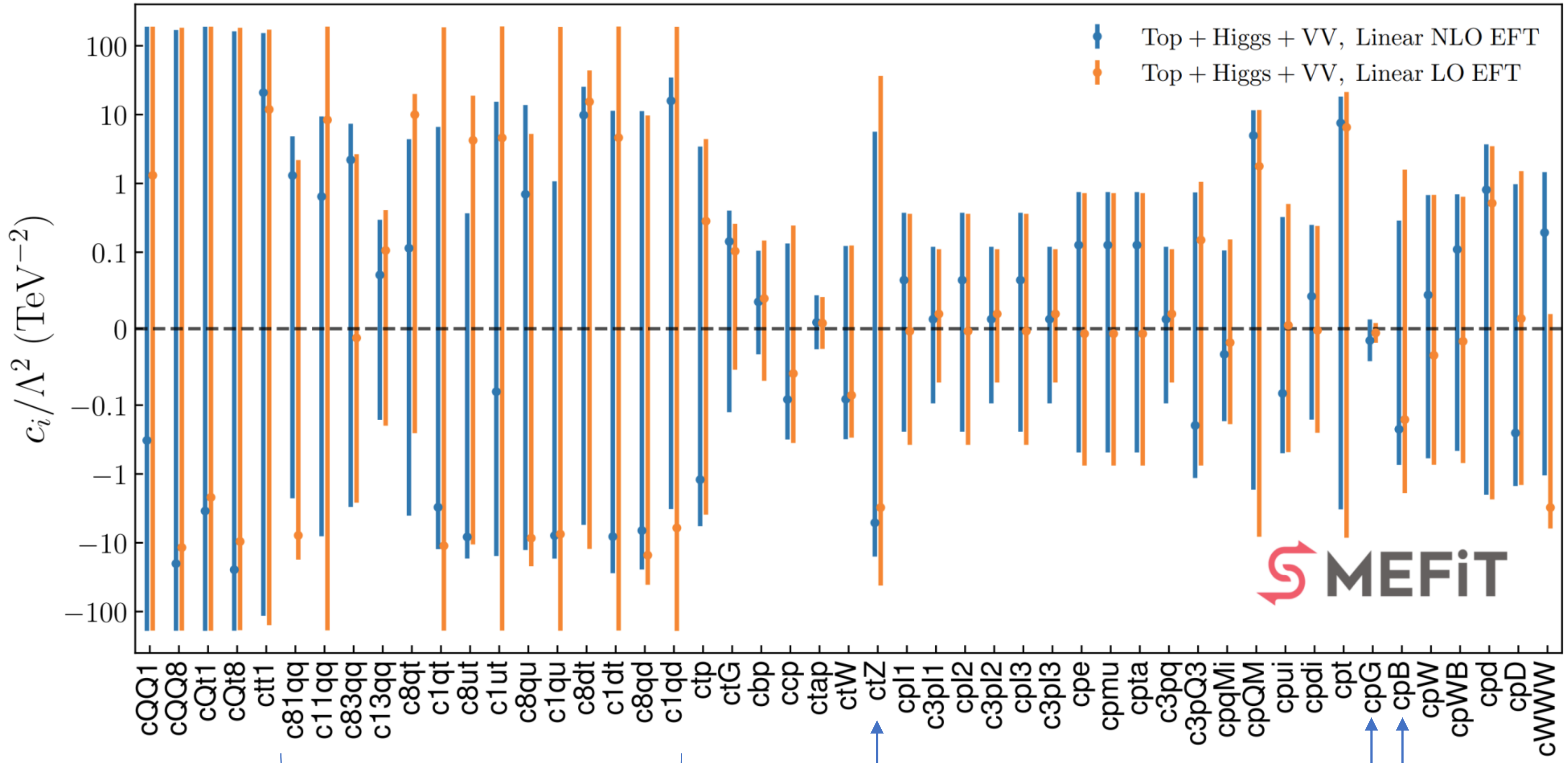
Three flat directions → degeneracy in $c^1_{QQ}, c^1_{tt}, C^1_{Qt}, C^8_{Qt}, c^8_{QQ}$ which is resolved in quadratic fit → far tighter constraints

Still order of magnitude differences, mainly in four-fermion (top dominated) c_i

Linear vs quadratic posterior probability distributions



NLO effects – linear fit



Two-light-two-heavy singlet operators no linear terms at LO → lose constraint

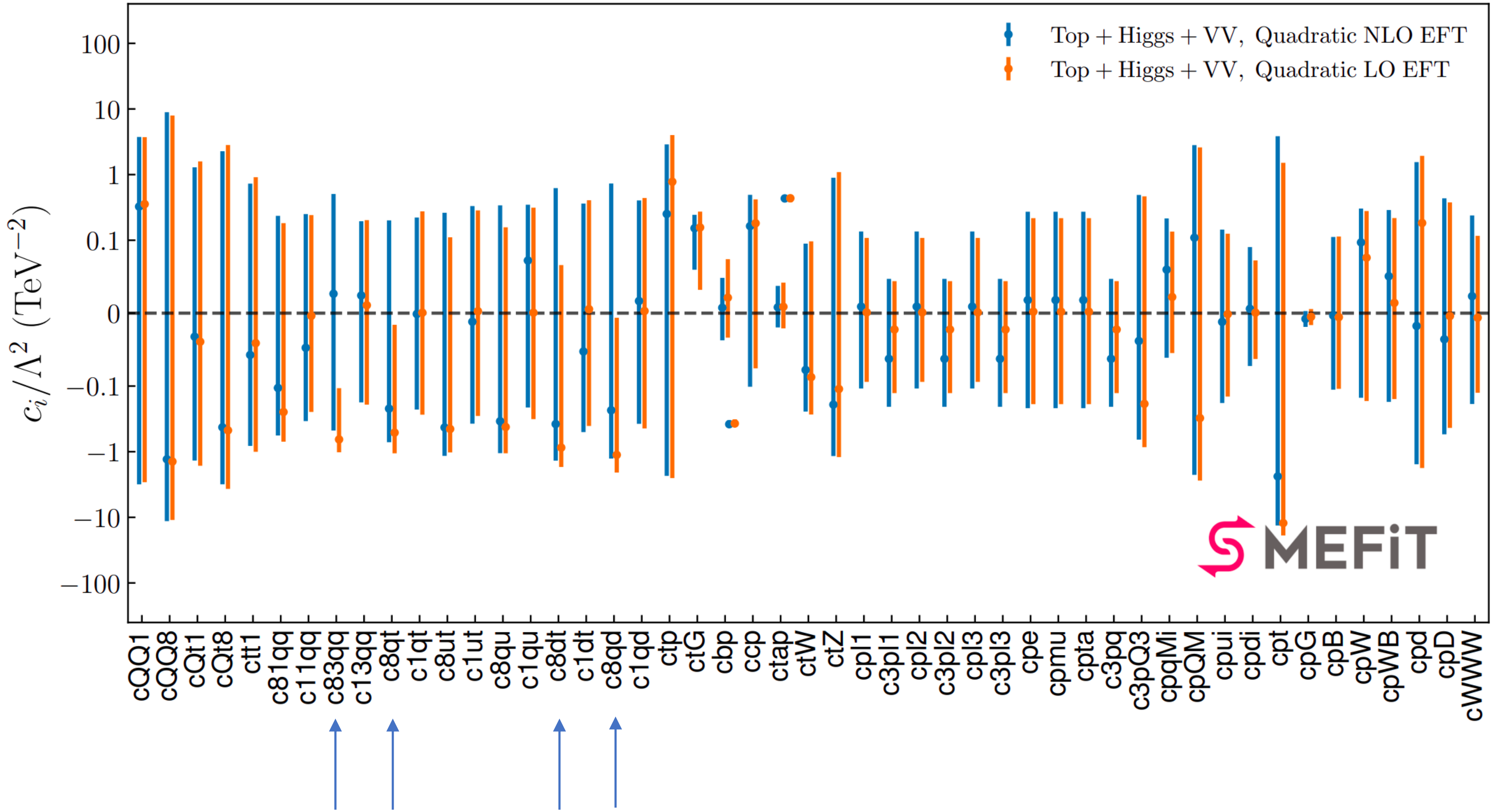
Improved constraints to $c_{tZ}, c_{\phi G}, c_{\phi B}, c_W$

NLO effects – quadratic fit

Although not as stark as for linear, there are still changes to the uncertainties and central values.

→ NLO corrections certainly needed in linear fit

→ still significant effects in quadratic fit



Common SMEFT parameterisation for STXS

Introduction

Idea: create a SMEFT parameterization of the STXS which is public and free to use by CMS, ATLAS and theorists

Motivation: efficiency and accuracy/validity

- CMS, ATLAS and theorists (>1 group) derive their own SMEFT parameterisations
  - We are wasting time developing and using our separate tools which lead to the same results*
- Quite a bit of crosstalk between experiment and theory already, e.g. support for `SMEFT@NLO` and `SMEFTsim`
  - Theorists spend time telling both experiments how to do the same thing
- Encourages collaboration between experiment and theory → more accurate interpretations
  - From theory: newest models, analytical equations, checking input parameters, theoretical discussions such as linear vs quadratic order
  - From experiment: acceptance corrections, frameworks such as EFT2Obs (incl. matching & merging)

*repetition for validation's sake is not wasted time... we'll come back to this

How would this work?

- Will use EFT2Obs to produce parameterization
  - Best established tool available to us (please let us know if you know of another!)
  - Create a separate branch for every parameterisation we want to make
    - There will inevitably be new iterations for better models, new flavour schemes, new STXS binning etc.
  - Store the parameterisation in this branch
    - Exact format is still pending, e.g. json
  - In each branch have the cards, scripts, and instructions to reproduce the parameterisation
    - Easier for anyone to bring updates and create the latest iteration
    - Transparency should also make it easier for mistakes to get noticed

- Probably will be a join effort between LHC Higgs WG2 and LHC EFT WG
- Ultimately, parameterisation and tools will be published in some note
  - Include proposal for format of parameterisations moving forward
  - Details of publication plan have not been settled

Plan moving forward

- Present the idea at the LHC EFT WG meeting on Friday
    - Are we all in agreement about the idea?
    - Gather interest in terms of person power

The following are not settled on, but I could see it playing it out like this:

- Given CMS's EFT2Obs expertise, they starts with EFT2Obs development:
    - Update to MG5 v2.9.9 (latest version validated within CMS)
    - Better handling of cases with big mismatches between EFT and SM phase space, e.g. $H \rightarrow 4f$ decay (backup)
    - Other nice-to-haves such as easy conversion between `SMEFT@NLO` and `SMEFTsim` notation
- Theorists prepare cards and other advice, e.g. what order(s) in the expansion are worth publishing
- Anyone should be able to run EFT2Obs at this point, but it'll probably be easier if it is CMS
- ATLAS use their own tools to validate the parameterisation from EFT2Obs

Discussion points

- Advantage of independent parameterisations is validation
  - I have noticed discrepancies between CMS, ATLAS and theory parameterisations

    → Mistakes are common and easy to make
  - A common parameterisation will no longer have constant validation/comparisons
  - But true 1-to-1 comparisons don't happen often anyway (different approaches and cards etc.)
  - Here, there will be a 1-to-1 comparison with ATLAS, at least initially
  - With the common parameterisation: many more eyes → greater scrutiny → less mistakes

- Handling acceptance corrections
  - Selection criteria differs between experiments → parameterisation will have to diverge at one point
  - We could have an approximate approach with Rivet routines
    - Anyone can reproduce but is simple
  - Also have more advanced approaches within experiments
    - Iteration is slower but is accurate
  - Still to be figured out, but should only affect a few equations → not a showstopper

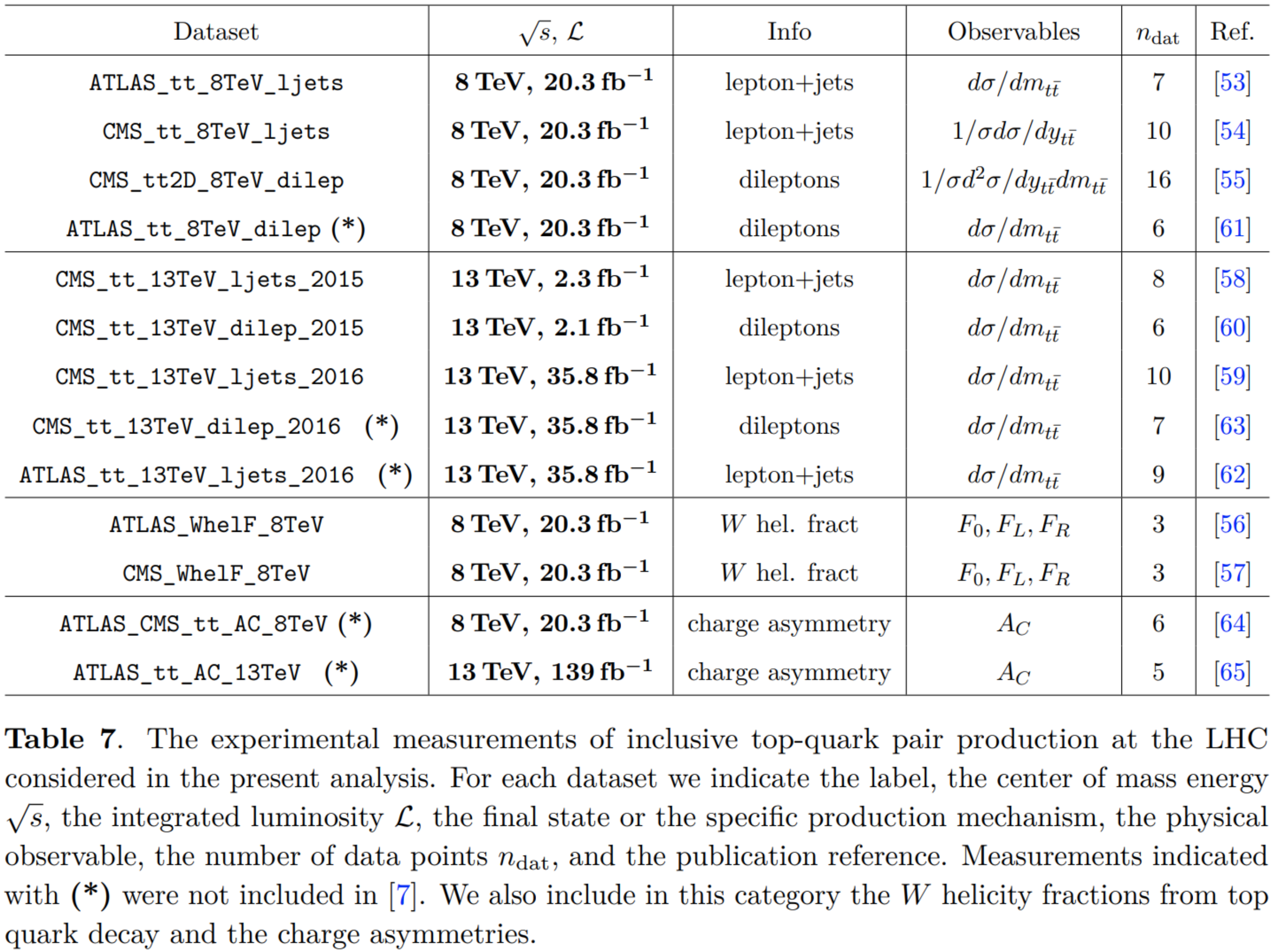
Summary

- Use SMEFT to search for indirect effects of new physics
- The STXS provides a natural framework for interpretations
  - Differential in production mode, decay mode, and p_T^H, p_T^V etc. → constrain multiple directions in SMEFT space
  - The field is increasingly moving towards global fits to also constrain as many directions as possible
- Advancements in parameterisations include:
  - PCA to find constrainable directions in the likelihood
  - NLO EFT predictions (especially in the SMEFiT interpretation)
    - Shown to be significant in SMEFTiT interpretation
  - Acceptance corrections for $H \rightarrow 4l$ (although only from ATLAS)
  - Inclusion of EWPO

- Common SMEFT STXS parameterisation is proposed
  - Should save all involved time and hopefully lead to more accurate parameterisation

Back-up Slides

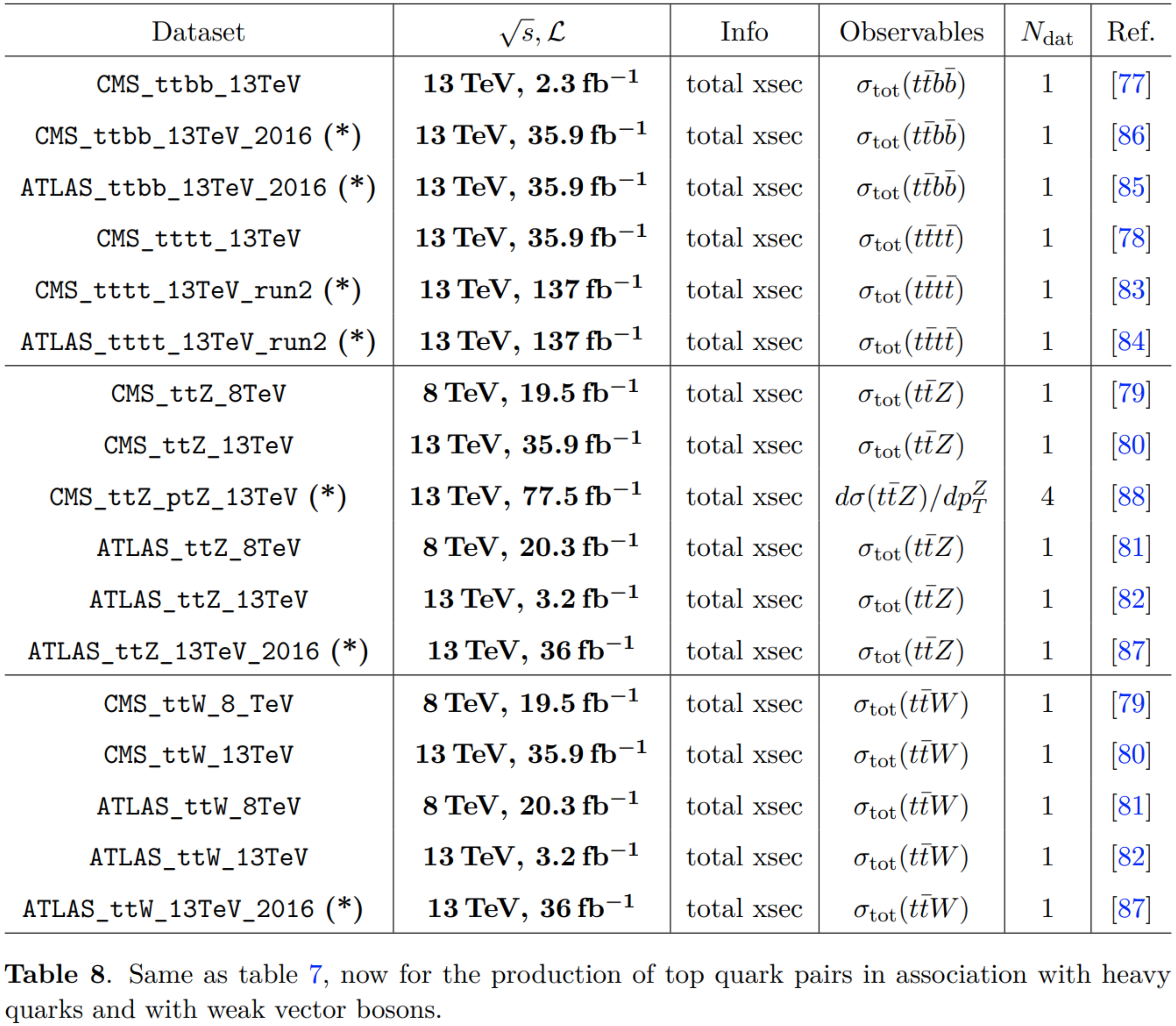
SMEFiT: $t\bar{t}$



Dataset	$\sqrt{s}$, $\mathcal{L}$	Info	Observables	$n_{\rm dat}$	Ref.
`ATLAS_tt_8TeV_ljets`	**8 TeV, 20.3 fb^{-1}**	lepton+jets	$d\sigma/dm_{t\bar{t}}$	7	[53]
`CMS_tt_8TeV_ljets`	**8 TeV, 20.3 fb^{-1}**	lepton+jets	$1/\sigma d\sigma/dy_{t\bar{t}}$	10	[54]
`CMS_tt2D_8TeV_dilep`	**8 TeV, 20.3 fb^{-1}**	dileptons	$1/\sigma d^2\sigma/dy_{t\bar{t}}dm_{t\bar{t}}$	16	[55]
`ATLAS_tt_8TeV_dilep` (*)	**8 TeV, 20.3 fb^{-1}**	dileptons	$d\sigma/dm_{t\bar{t}}$	6	[61]
`CMS_tt_13TeV_ljets_2015`	**13 TeV, 2.3 fb^{-1}**	lepton+jets	$d\sigma/dm_{t\bar{t}}$	8	[58]
`CMS_tt_13TeV_dilep_2015`	**13 TeV, 2.1 fb^{-1}**	dileptons	$d\sigma/dm_{t\bar{t}}$	6	[60]
`CMS_tt_13TeV_ljets_2016`	**13 TeV, 35.8 fb^{-1}**	lepton+jets	$d\sigma/dm_{t\bar{t}}$	10	[59]
`CMS_tt_13TeV_dilep_2016` (*)	**13 TeV, 35.8 fb^{-1}**	dileptons	$d\sigma/dm_{t\bar{t}}$	7	[63]
`ATLAS_tt_13TeV_ljets_2016` (*)	**13 TeV, 35.8 fb^{-1}**	lepton+jets	$d\sigma/dm_{t\bar{t}}$	9	[62]
`ATLAS_WhelF_8TeV`	**8 TeV, 20.3 fb^{-1}**	W hel. fract	F_0, F_L, F_R	3	[56]
`CMS_WhelF_8TeV`	**8 TeV, 20.3 fb^{-1}**	W hel. fract	F_0, F_L, F_R	3	[57]
`ATLAS_CMS_tt_AC_8TeV` (*)	**8 TeV, 20.3 fb^{-1}**	charge asymmetry	A_C	6	[64]
`ATLAS_tt_AC_13TeV` (*)	**13 TeV, 139 fb^{-1}**	charge asymmetry	A_C	5	[65]

Table 7. The experimental measurements of inclusive top-quark pair production at the LHC considered in the present analysis. For each dataset we indicate the label, the center of mass energy $\sqrt{s}$, the integrated luminosity $\mathcal{L}$, the final state or the specific production mechanism, the physical observable, the number of data points $n_{\rm dat}$, and the publication reference. Measurements indicated with (*) were not included in [7]. We also include in this category the W helicity fractions from top quark decay and the charge asymmetries.

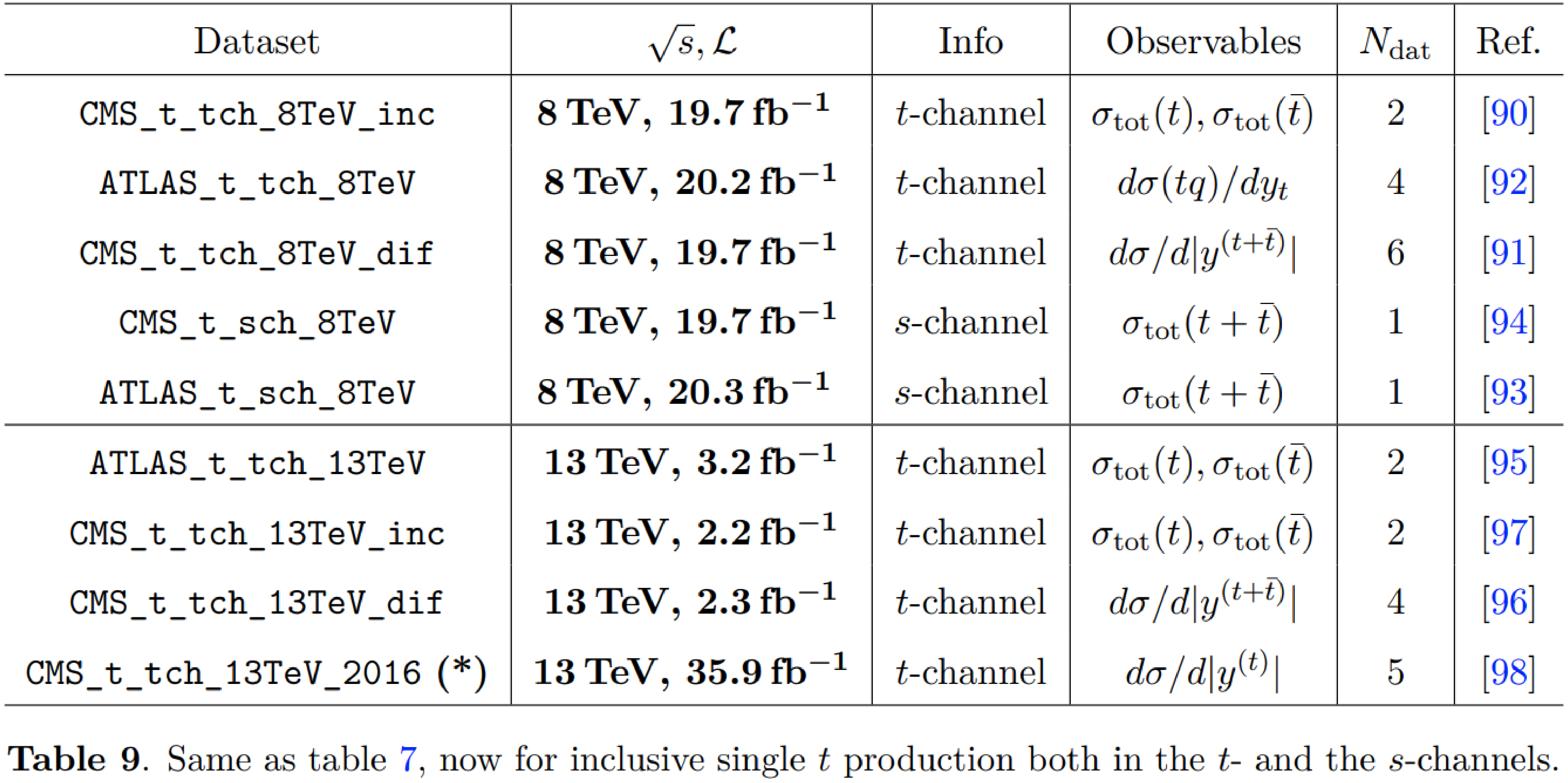
SMEFiT: $t\bar{t}W, t\bar{t}Z, t\bar{t}t\bar{t}, t\bar{t}b\bar{b}$



Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref.
`CMS_ttbb_13TeV`	**13 TeV, 2.3 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[77]
`CMS_ttbb_13TeV_2016` (*)	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[86]
`ATLAS_ttbb_13TeV_2016` (*)	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[85]
`CMS_tttt_13TeV`	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[78]
`CMS_tttt_13TeV_run2` (*)	**13 TeV, 137 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[83]
`ATLAS_tttt_13TeV_run2` (*)	**13 TeV, 137 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[84]
`CMS_ttZ_8TeV`	**8 TeV, 19.5 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[79]
`CMS_ttZ_13TeV`	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[80]
`CMS_ttZ_ptZ_13TeV` (*)	**13 TeV, 77.5 fb^{-1}**	total xsec	$d\sigma(t\bar{t}Z)/dp_T^Z$	4	[88]
`ATLAS_ttZ_8TeV`	**8 TeV, 20.3 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[81]
`ATLAS_ttZ_13TeV`	**13 TeV, 3.2 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[82]
`ATLAS_ttZ_13TeV_2016` (*)	**13 TeV, 36 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	1	[87]
`CMS_ttW_8_TeV`	**8 TeV, 19.5 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[79]
`CMS_ttW_13TeV`	**13 TeV, 35.9 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[80]
`ATLAS_ttW_8TeV`	**8 TeV, 20.3 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[81]
`ATLAS_ttW_13TeV`	**13 TeV, 3.2 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[82]
`ATLAS_ttW_13TeV_2016` (*)	**13 TeV, 36 fb^{-1}**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	1	[87]

Table 8. Same as table 7, now for the production of top quark pairs in association with heavy quarks and with weak vector bosons.

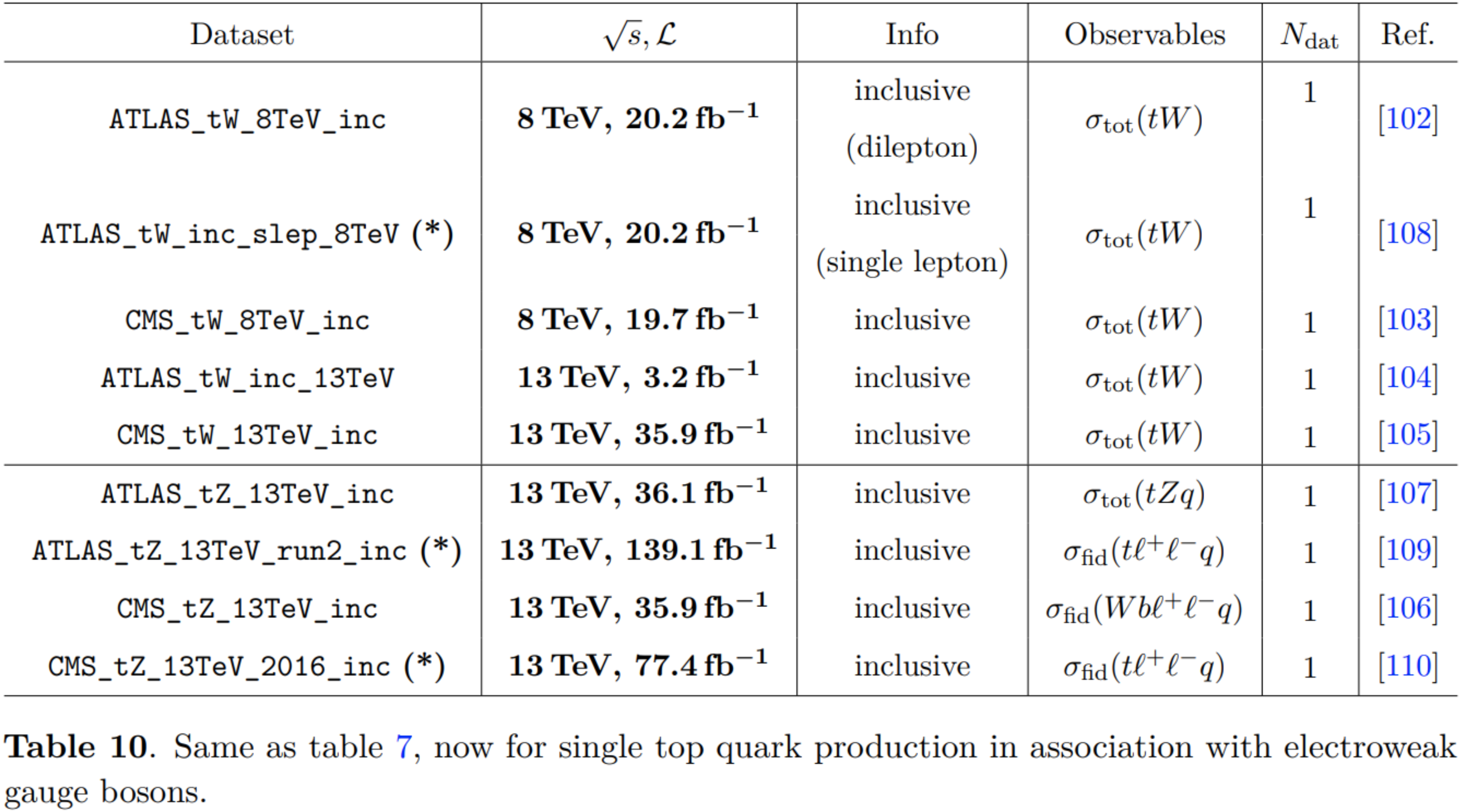
SMEFiT: single top production



Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref.
`CMS_t_tch_8TeV_inc`	**8 TeV, 19.7 fb^{-1}**	t-channel	$\sigma_{\rm tot}(t), \sigma_{\rm tot}(\bar{t})$	2	[90]
`ATLAS_t_tch_8TeV`	**8 TeV, 20.2 fb^{-1}**	t-channel	$d\sigma(tq)/dy_t$	4	[92]
`CMS_t_tch_8TeV_dif`	**8 TeV, 19.7 fb^{-1}**	t-channel	$d\sigma/d\lvert y^{(t+\bar{t})}\rvert$	6	[91]
`CMS_t_sch_8TeV`	**8 TeV, 19.7 fb^{-1}**	s-channel	$\sigma_{\rm tot}(t+\bar{t})$	1	[94]
`ATLAS_t_sch_8TeV`	**8 TeV, 20.3 fb^{-1}**	s-channel	$\sigma_{\rm tot}(t+\bar{t})$	1	[93]
`ATLAS_t_tch_13TeV`	**13 TeV, 3.2 fb^{-1}**	t-channel	$\sigma_{\rm tot}(t), \sigma_{\rm tot}(\bar{t})$	2	[95]
`CMS_t_tch_13TeV_inc`	**13 TeV, 2.2 fb^{-1}**	t-channel	$\sigma_{\rm tot}(t), \sigma_{\rm tot}(\bar{t})$	2	[97]
`CMS_t_tch_13TeV_dif`	**13 TeV, 2.3 fb^{-1}**	t-channel	$d\sigma/d\lvert y^{(t+\bar{t})}\rvert$	4	[96]
`CMS_t_tch_13TeV_2016` **(*)**	**13 TeV, 35.9 fb^{-1}**	t-channel	$d\sigma/d\lvert y^{(t)}\rvert$	5	[98]

Table 9. Same as table 7, now for inclusive single t production both in the t- and the s-channels.

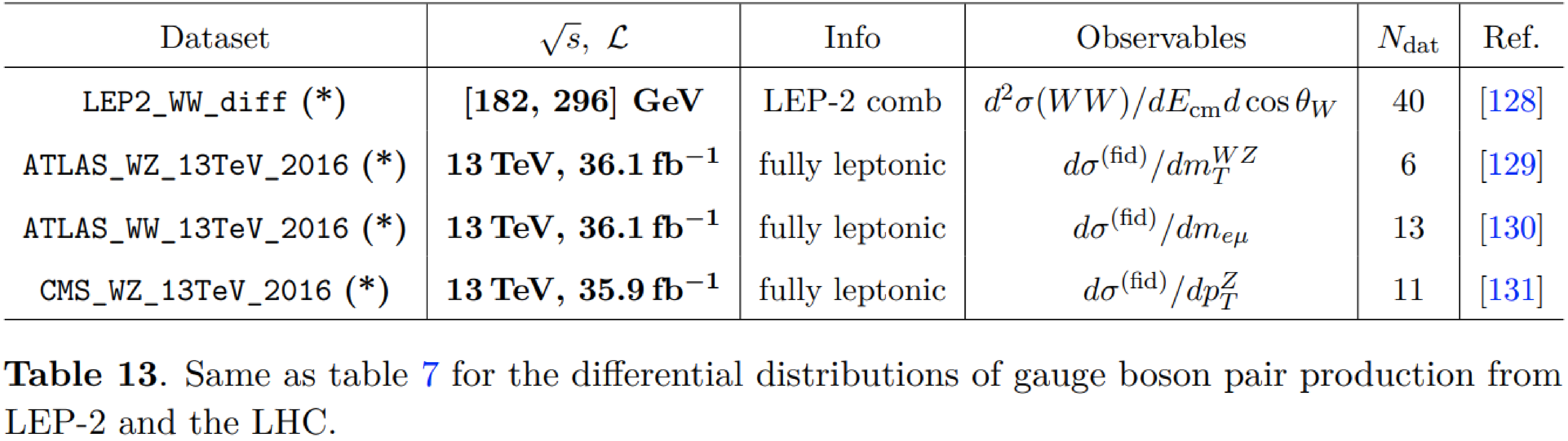
SMEFiT: single top production + W/Z



Dataset	$\sqrt{s}, \mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref.
`ATLAS_tW_8TeV_inc`	**8 TeV, 20.2 fb^{-1}**	inclusive (dilepton)	$\sigma_{\rm tot}(tW)$	1	[102]
`ATLAS_tW_inc_slep_8TeV` (*)	**8 TeV, 20.2 fb^{-1}**	inclusive (single lepton)	$\sigma_{\rm tot}(tW)$	1	[108]
`CMS_tW_8TeV_inc`	**8 TeV, 19.7 fb^{-1}**	inclusive	$\sigma_{\rm tot}(tW)$	1	[103]
`ATLAS_tW_inc_13TeV`	**13 TeV, 3.2 fb^{-1}**	inclusive	$\sigma_{\rm tot}(tW)$	1	[104]
`CMS_tW_13TeV_inc`	**13 TeV, 35.9 fb^{-1}**	inclusive	$\sigma_{\rm tot}(tW)$	1	[105]
`ATLAS_tZ_13TeV_inc`	**13 TeV, 36.1 fb^{-1}**	inclusive	$\sigma_{\rm tot}(tZq)$	1	[107]
`ATLAS_tZ_13TeV_run2_inc` (*)	**13 TeV, 139.1 fb^{-1}**	inclusive	$\sigma_{\rm fid}(t\ell^+\ell^-q)$	1	[109]
`CMS_tZ_13TeV_inc`	**13 TeV, 35.9 fb^{-1}**	inclusive	$\sigma_{\rm fid}(Wb\ell^+\ell^-q)$	1	[106]
`CMS_tZ_13TeV_2016_inc` (*)	**13 TeV, 77.4 fb^{-1}**	inclusive	$\sigma_{\rm fid}(t\ell^+\ell^-q)$	1	[110]

Table 10. Same as table 7, now for single top quark production in association with electroweak gauge bosons.

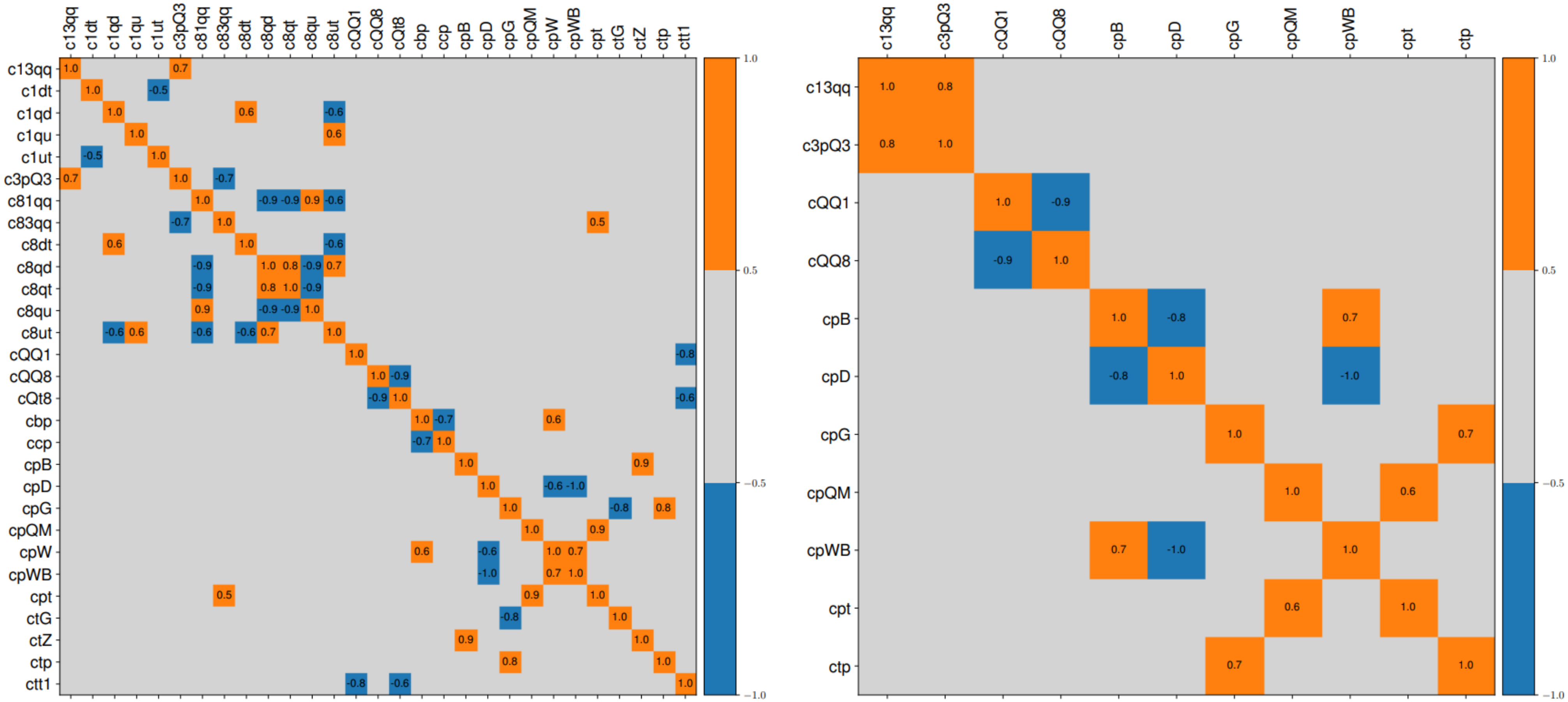
SMEFiT: diboson production



Dataset	$\sqrt{s},\ \mathcal{L}$	Info	Observables	$N_{\rm dat}$	Ref.
LEP2_WW_diff (*)	**[182, 296] GeV**	LEP-2 comb	$d^2\sigma(WW)/dE_{\rm cm}d\cos\theta_W$	40	[128]
ATLAS_WZ_13TeV_2016 (*)	**13 TeV, 36.1 fb^{-1}**	fully leptonic	$d\sigma^{(\rm fid)}/dm_T^{WZ}$	6	[129]
ATLAS_WW_13TeV_2016 (*)	**13 TeV, 36.1 fb^{-1}**	fully leptonic	$d\sigma^{(\rm fid)}/dm_{e\mu}$	13	[130]
CMS_WZ_13TeV_2016 (*)	**13 TeV, 35.9 fb^{-1}**	fully leptonic	$d\sigma^{(\rm fid)}/dp_T^Z$	11	[131]

Table 13. Same as table 7 for the differential distributions of gauge boson pair production from LEP-2 and the LHC.

SMEFiT: correlation matrices



	c13qq	c1dt	c1qd	c1qu	c1ut	c3pQ3	c81qq	c83qq	c8dt	c8qd	c8qt	c8qu	c8ut	cQQ1	cQQ8	cQt8	cbp	ccp	cpB	cpD	cpG	cpQM	cpW	cpWB	cpt	ctG	ctZ	ctp	ctt1
c13qq	1.0					0.7																							
c1dt		1.0			-0.5																								
c1qd			1.0						0.6				-0.6																
c1qu				1.0									0.6																
c1ut		-0.5			1.0																								
c3pQ3	0.7					1.0		-0.7																					
c81qq							1.0			-0.9	-0.9	0.9	-0.6																
c83qq						-0.7		1.0																	0.5				
c8dt			0.6						1.0				-0.6																
c8qd							-0.9			1.0	0.8	-0.9	0.7																
c8qt							-0.9			0.8	1.0	-0.9																	
c8qu							0.9			-0.9	-0.9	1.0																	
c8ut			-0.6	0.6			-0.6		-0.6	0.7			1.0																
cQQ1														1.0															-0.8
cQQ8															1.0	-0.9													
cQt8															-0.9	1.0													-0.6
cbp																	1.0	-0.7					0.6						
ccp																	-0.7	1.0											
cpB																			1.0								0.9		
cpD																				1.0			-0.6	-1.0					
cpG																					1.0					-0.8		0.8	
cpQM																						1.0			0.9				
cpW																	0.6			-0.6			1.0	0.7					
cpWB																				-1.0			0.7	1.0					
cpt								0.5														0.9			1.0				
ctG																					-0.8					1.0			
ctZ																			0.9								1.0		
ctp																					0.8							1.0	
ctt1														-0.8		-0.6													1.0

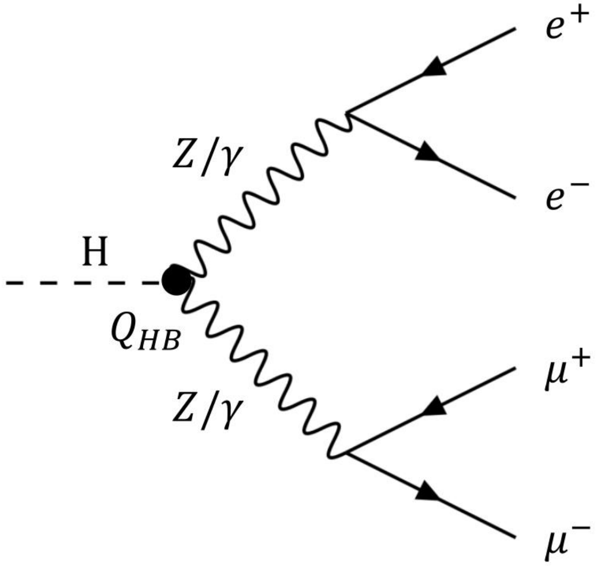
	c13qq	c3pQ3	cQQ1	cQQ8	cpB	cpD	cpG	cpQM	cpWB	cpt	ctp
c13qq	1.0	0.8									
c3pQ3	0.8	1.0									
cQQ1			1.0	-0.9							
cQQ8			-0.9	1.0							
cpB					1.0	-0.8			0.7		
cpD					-0.8	1.0			-1.0		
cpG							1.0				0.7
cpQM								1.0		0.6	
cpWB					0.7	-1.0			1.0		
cpt								0.6		1.0	
ctp							0.7				1.0

Figure 5.6. The correlation coefficients $\rho(c_i, c_j)$ between the EFT coefficients in the linear (left) and quadratic (right panel) fits. We only display the entries with significant (anti)-correlation, $|\rho| \geq 0.5$. Pairs of coefficients (c_i, c_j) that do not displayed here have a correlation coefficient below this threshold.

Handling phase space mismatches

- Reweighting as a technique is ineffective if the EFT phase space is significantly different to the SM phase space
  - If generate at SM event, there are not enough statistics in EFT phase space to get EFT prediction with low uncertainty
- Example: $H \to 4f$ decay
  - Operators such as Q_{HB} introduce photon-mediated diagrams

  → large enhancement at low m_{ll} due to $\sim \frac{1}{m_{ll}}$ term in proagator

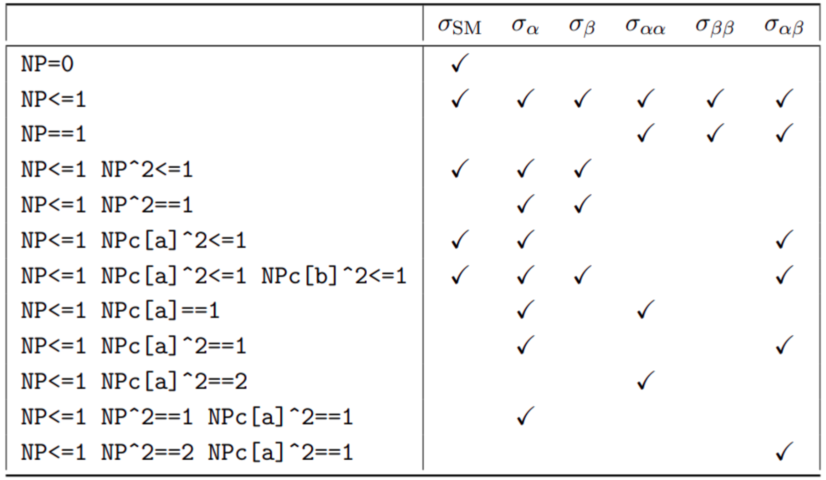


Solutions:

1. Dedicated generations (no reweighting involved)

   Can use MG5 syntax to isolate different EFT contributions →

2. Create multiple gridpacks at different c_i and reweight from there
3. Gridpacks for different phase space, e.g. one for $m_{ll} < 5$ and one for $m_{ll} > 5$ GeV



	σ_{SM}	σ_α	σ_β	$\sigma_{\alpha\alpha}$	$\sigma_{\beta\beta}$	$\sigma_{\alpha\beta}$
`NP=0`	✓					
`NP<=1`	✓	✓	✓	✓	✓	✓
`NP==1`				✓	✓	✓
`NP<=1 NP^2<=1`	✓	✓	✓			
`NP<=1 NP^2==1`		✓	✓			
`NP<=1 NPc[a]^2<=1`	✓	✓				✓
`NP<=1 NPc[a]^2<=1 NPc[b]^2<=1`	✓	✓	✓			✓
`NP<=1 NPc[a]==1`		✓		✓		
`NP<=1 NPc[a]^2==1`		✓				✓
`NP<=1 NPc[a]^2==2`				✓		
`NP<=1 NP^2==1 NPc[a]^2==1`		✓				
`NP<=1 NP^2==2 NPc[a]^2==1`						✓