SMEFT@NLO

Automated one-loop computations in the SMEFT

[G. Durieux, C. Degrande, F. Maltoni, KM, C. Zhang, E. Vryonidou; arXiv:2008.11743]

[J. Ellis, M. Madigan, KM, V. Sanz & T. You; arXiv:2012.02779]

http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO

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New Physics from Precision at High Energies, KITP

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SMEFT is…

$$\mathcal{L}_{\text{eff}} = \sum_i \frac{c_i \mathcal{O}_i^D}{\Lambda^{D-4}}$$

Model independent

- Underlying assumptions

Heavy new physics: $M > E_{exp}$

SM field content & gauge symmetries

Linear EWSB: Higgs = doublet

Systematically improvable

- Double expansion *higher dim.* $\frac{E^2}{\Lambda^2}$ & $\{g_S,\, g,\, g'\}$ *more loops*

Global

- Model independence: we don't know what operators NP will generate
- Patterns & correlations among observables are key
- Ultimate goal: complete SMEFT likelihood confronted with HEP data

EWPO, Higgs, multiboson, top, DY, flavor,…

Established part of LHC programme

SMEFT interpretation

Improving sensitivity:

$$\Delta o_n = o_n^{\mathrm{EXP}} - o_n^{\mathrm{SM}} = \sum_i \frac{a_{n,i}^{(6)}(\mu)\, c_i^{(6)}(\mu)}{\Lambda^2} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

Global nature

As many observables as possible

Identify patterns & correlations in fits

Exploit energy-growth

Sensitivity

Experiment:

Best measurements & understanding of uncertainties and correlations

Theory:

Best available predictions for observables (NLO, NNLO, N3LO,…)

Interpretation

Relies on accurate knowledge of the size & correlation among a_i

Determining $c_i^{(6)}$ requires most precise available SMEFT predictions

SMEFT@NLO

NLO computations for SMEFT: very active field

- Non-universal K-factors in EFT space ⇔ new information at NLO
- Loop-induced sensitivity
- Control theoretical uncertainties
- Experimental interest in higher precision for SMEFT analyses/interpretations

Challenge: many processes x many operators

- LO ⇒ NLO = more cross-talk/operators/complexity
- Automated tools for fixed-order/NLO+PS are essential to the LHC programme

SMEFT@NLO *[Degrande et al.; arXiv:2008.11743]*
http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO

- UFO model for `MadGraph5_aMC@NLO`
- Process-independent implementation: SMEFT in top-specific flavor limit

http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO

Standard Model Effective Theory at One-Loop in QCD

Céline Degrande, Gauthier Durieux, Fabio Maltoni, Ken Mimasu, Eleni Vryonidou & Cen Zhang, arXiv:2008.11743

The implementation is based on the Warsaw basis of dimension-six SMEFT operators, after canonical normalization. Electroweak input parameters are taken to be G_F, M_Z, M_W. The CKM matrix is approximated as a unit matrix, and a $U(2)_q \times U(2)_u \times U(3)_d \times (U(1)_l \times U(1)_e)^3$ flavor symmetry is enforced. It forbids all fermion masses and Yukawa couplings except that only of the top quark. The model therefore implements the five-flavor scheme for PDFs.

A new coupling order, `NP=2`, is assigned to SMEFT interactions. The cutoff scale `Lambda` takes a default value of 1 TeV^{-2} and can be modified along with the Wilson coefficients in the `param_card`. Operators definitions, normalisations and coefficient names in the UFO model are specified in definitions.pdf. The notations and normalizations of top-quark operator coefficients comply with the LHC TOP WG standards of 1802.07237. Note however that the flavor symmetry enforced here is slightly more restrictive than the baseline assumption there (see the dim6top page for more information). This model has been validated at tree level against the `dim6top` implementation (see 1906.12310 and the comparison details).

Current implementation

UFO model: SMEFTatNLO_v1.0.tar.gz

The current implementation imposes CP conservation. In the quark sector, it focuses primarily on top-quark interactions. The light-quark current operator, qqHDH, uuHDH, ddHDH, with coefficients `cpq3i`, `cpqMi`, `cpu`, `cpd` are however included. The triple-gluon operator, with coefficient `cG`, is currently not available (see the loop-capable GGG implementation). Vertices including more than four scalars or four leptons are not included. Scalar and tensor `QQll` operators, with coefficients `ctlS3`, `ctlT3`, and `cblS3`, break our flavor symmetry assumption and are not available for one-loop computations. Top-quark flavor-changing interactions, not compatible with the imposed flavor symmetry, are not included (see the loop-capable TopFCNC implementation).

Unlike prescribed by the LHC TOP WG, the top quark chromomagnetic-dipole operator coefficient `ctG` is normalized with a factor of the strong coupling, g_S. This normalization factor temporarily ensures compatibility with the 2.X.X series of MadGraph5_aMC@NLO but may be dropped in the future. As with every other appearance of this coupling in MadGraph5_aMC@NLO, its value is renormalisation-group evolved to the QCD renormalization scale (set in the run_card).

```
MG5_aMC>import model SMEFTatNLO
MG5_aMC>generate p p > t t~ NP=2 [QCD]
MG5_aMC>output
MG5_aMC>launch
```

'QCD' loops
coloured particles,
strong coupling or
4-fermion couplings

What's in the box?

‘Warsaw’ basis

[Grzadkowski et al.; JHEP 1010 (2010) 085]

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}	$(\bar l_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
~~$Q_{\varphi\widetilde G}$~~	~~$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$~~	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}	$(\bar q_p \sigma^{\mu\nu} T^A u_r) \widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
~~$Q_{\varphi\widetilde W}$~~	~~$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$~~	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r) \tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} T^A d_r) \varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r) \tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
~~$Q_{\varphi\widetilde WB}$~~	~~$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$~~	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r) \varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	~~Q_{duq}~~	~~$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(q^{\gamma j}_s)^T C l^k_t\right]$~~
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	~~Q_{qqu}~~	~~$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(u^\gamma_s)^T C e_t\right]$~~
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	~~$Q_{qqq}^{(1)}$~~	~~$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$~~
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	~~$Q_{qqq}^{(3)}$~~	~~$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$~~
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	~~Q_{duu}~~	~~$\varepsilon^{\alpha\beta\gamma}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(u^\gamma_s)^T C e_t\right]$~~

Some symmetries imposed to control parameter space

- CP, B and flavor conservation
- Top-specific flavour structure of 2 & 4 fermion operators

Flavor symmetry

Approximate flavor symmetry in the SM

- SM: broken by Yukawa interactions
- SMEFT: broken by $\psi^2 X\varphi, \psi^2\varphi^3, (\bar{L}R)(\bar{L}R), (\bar{L}R)(\bar{R}L)$ & $\mathcal{O}_{\varphi ud}$
- + any off-diagonal or non-universal entries of other 2F operators

SMEFTatNLO: minimal extension to single out top quark

universal	$U(3)_L \times U(3)_e \times U(3)_Q \times U(3)_u \times U(3)_d$
top	$U(3)_L \times U(3)_e \times U(2)_Q \times U(2)_u \times U(3)_d$

cf. Minimal flavor violation

[Buras et al.; PLB 500 (2001) 161]
[D'Ambrosio et al.; NPB 645 (2002) 155]

Yukawa	$\psi^2 H^3 : (\varphi^\dagger\varphi)^2(\bar{Q}\, t\, \tilde{\varphi})$
Dipoles	$\psi^2 X H : (\bar{Q}\,\sigma^{\mu\nu}\, t\, \tilde{\varphi})B_{\mu\nu}\ [W^I_{\mu\nu}, G^a_{\mu\nu}]$
3rd gen. currents	$\psi^2 H^2 D : (\varphi^\dagger \overleftrightarrow{D}_\mu\, \varphi)(\bar{Q}\,\gamma^\mu\, Q)\ [(\bar{Q}\,\gamma^\mu\tau^I\, Q), (\bar{t}\,\gamma^\mu\, t), \ldots]$
3rd gen. 4F	$\psi^4 : (\bar{Q}\,\gamma^\mu\, Q)(\bar{q}\,\gamma_\mu\, q), (\bar{Q}\,\gamma^\mu\, Q)(\bar{Q}\,\gamma_\mu\, Q), \ldots$

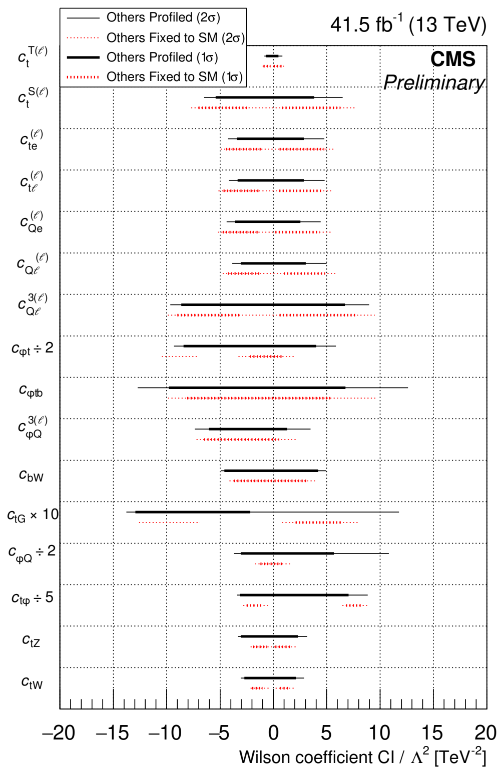
See `dim6top`

[Aguilar-Saavedra et al.; arXiv:1802.07237]

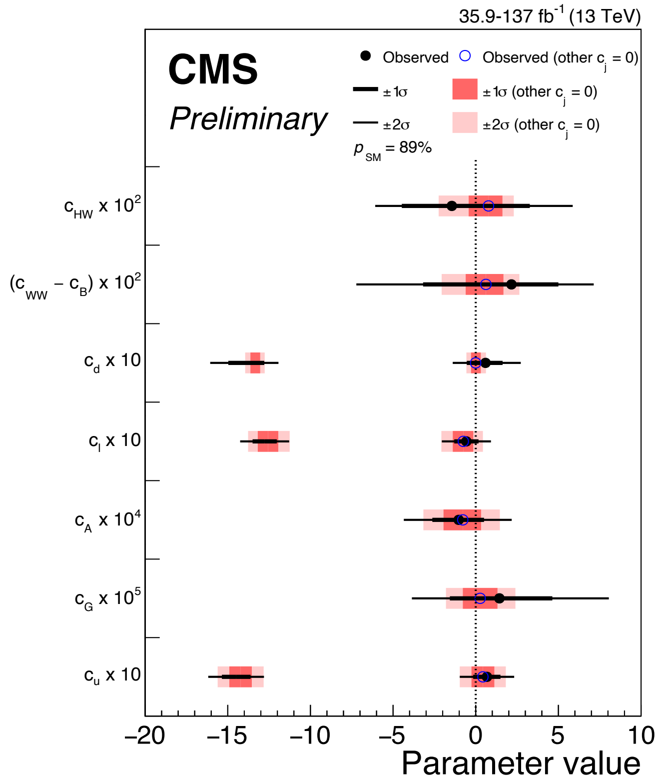
[CMS-PAS-TOP-001] [CMS-PAS-HIG-19-005] [CERN-EP-2020-034]

NLO QCD OK ✔

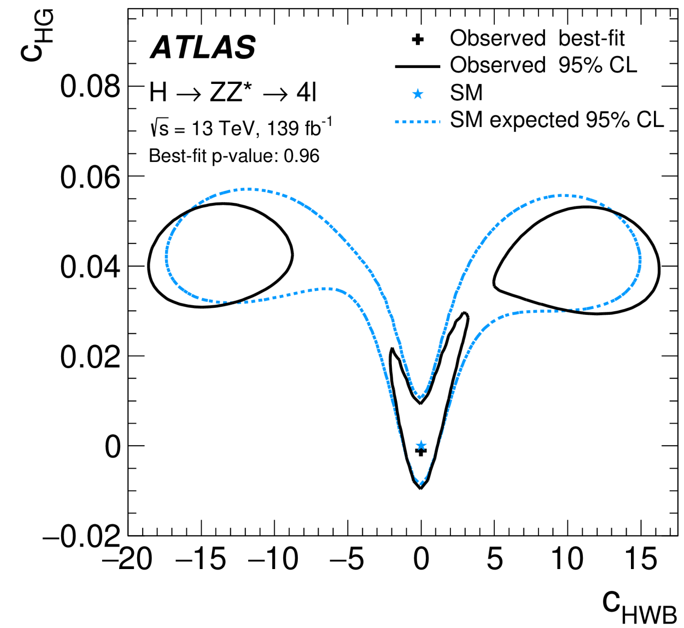
ttH, ttZ, ttW, tW, tZ, tH



Higgs combination

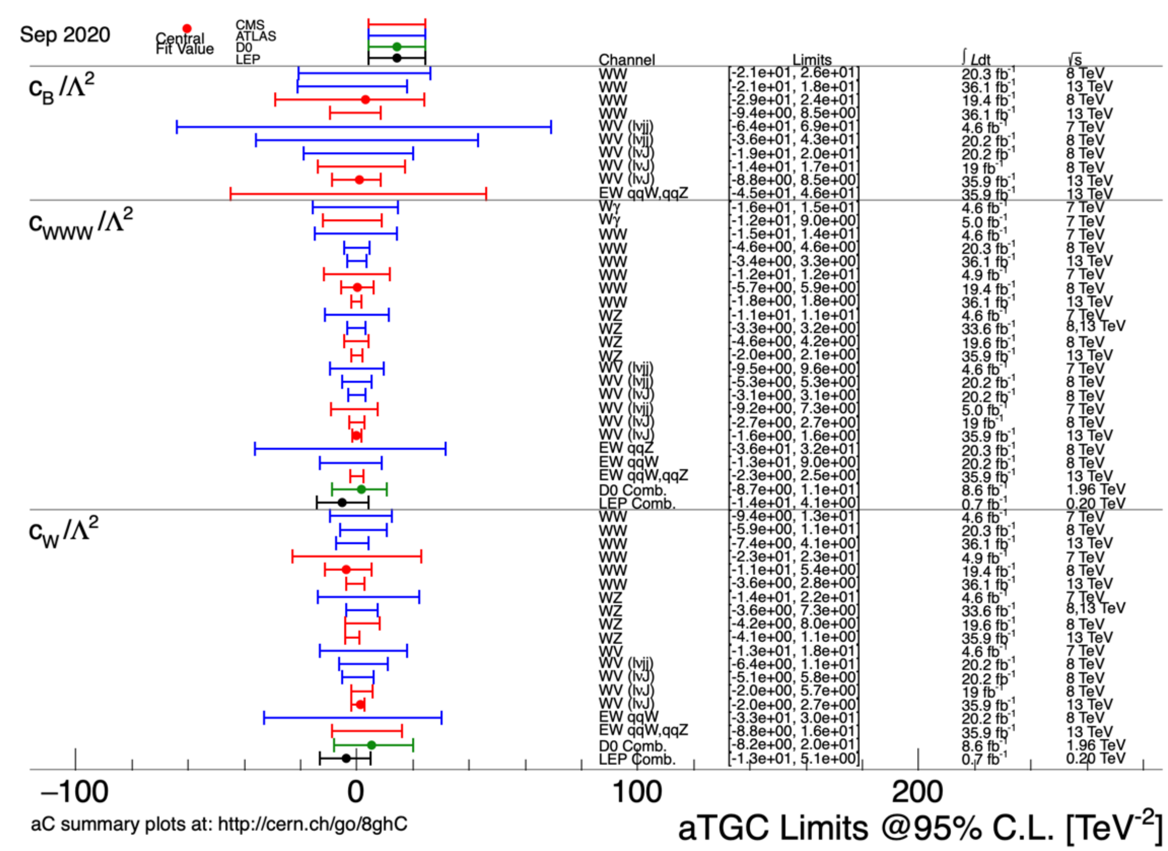


H → 4l



hh (LO),
VVV,
VBS,
tt,
4top,
…

WW & WZ



[ATLAS; PRD 99 (2017) 072009] ttV

Coefficients	$C_{\phi Q}^{(3)}/\Lambda^2$	$C_{\phi t}/\Lambda^2$	C_{tB}/Λ^2	C_{tW}/Λ^2
Previous indirect constraints at 68% CL	[−4.7, 0.7]	[−0.1, 3.7]	[−0.5, 10]	[−1.6, 0.8]
Previous direct constraints at 95% CL	[−1.3, 1.3]	[−9.7, 8.3]	[−6.9, 4.6]	[−0.2, 0.7]
Expected limit at 68% CL	[−2.1, 1.9]	[−3.8, 2.7]	[−2.9, 3.0]	[−1.8, 1.9]
Expected limit at 95% CL	[−4.5, 3.6]	[−23, 4.9]	[−4.2, 4.3]	[−2.6, 2.6]
Observed limit at 68% CL	[−1.0, 2.7]	[−2.0, 3.5]	[−3.7, 3.5]	[−2.2, 2.1]
Observed limit at 95% CL	[−3.3, 4.2]	[−25, 5.5]	[−5.0, 5.0]	[−2.9, 2.9]
Expected limit at 68% CL (linear)	[−1.9, 2.0]	[−3.0, 3.2]	–	–
Expected limit at 95% CL (linear)	[−3.7, 4.0]	[−5.8, 6.3]	–	–
Observed limit at 68% CL (linear)	[−1.0, 2.9]	[−1.8, 4.4]	–	–
Observed limit at 95% CL (linear)	[−2.9, 4.9]	[−4.8, 7.5]	–	–

Selected results

Some from previous works, superseded by SMEFT@NLO
A few, simple new results presented in 2008.11743

Predictions

Dim-6 SMEFT: $\mathscr{A} = \mathscr{A}_{SM} + \sum_i \mathscr{A}_i \frac{C_i}{\Lambda^2} + \mathcal{O}(\Lambda^{-3})$

$\{\mathscr{A}_i\} \Rightarrow \{\sigma_i, \sigma_{ij}\}$ $\quad \sigma = \sigma_{SM} + \sum_i \sigma_i \frac{C_i}{\Lambda^2} + \sum_{j\geq i} \sigma_{ij} \frac{C_i C_j}{\Lambda^4} + \mathcal{O}(\Lambda^{-4})$

Higher orders (dim > 6) unspecified

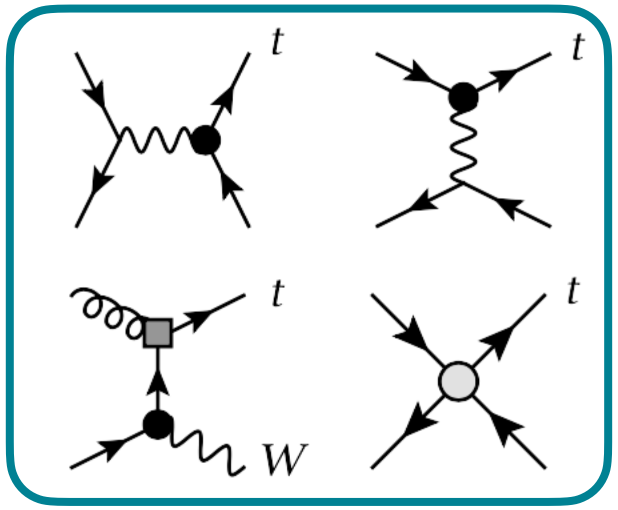
- σ_{ij} formally same order as $\sigma_i^{(8)}$
- Relative importance is model/power-counting dependent
- EFT validity assessment depends further on data sensitivity

We always report both: $\{\sigma_i, \sigma_{ij}\}$

- σ_{ij} contain valuable information
- Can be used in a variety of ways (included in prediction, error estimates,…)

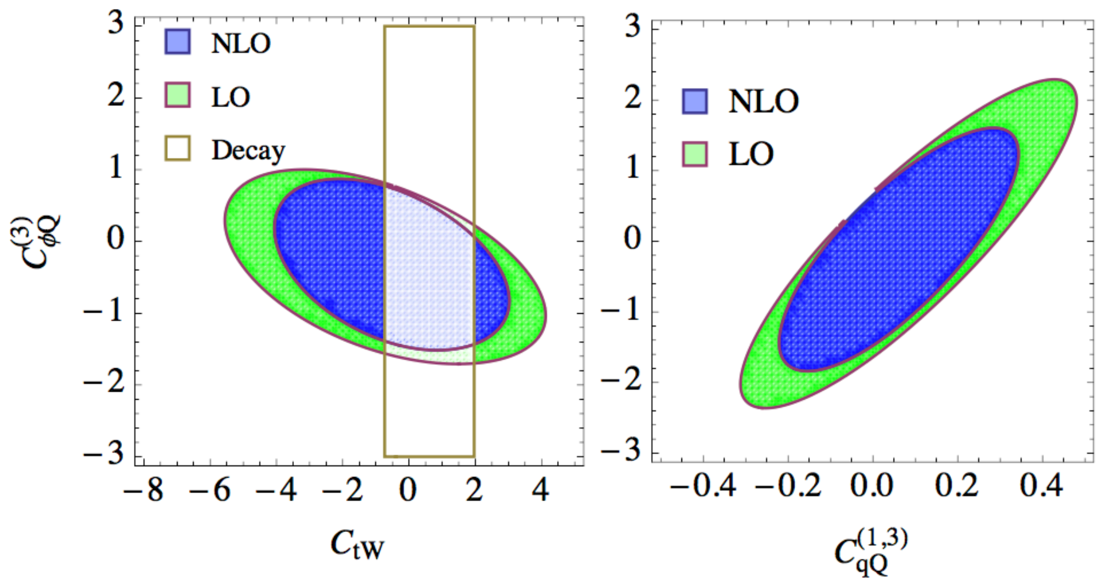
Single top

[Zhang; PRL 116 (2016) 162002]

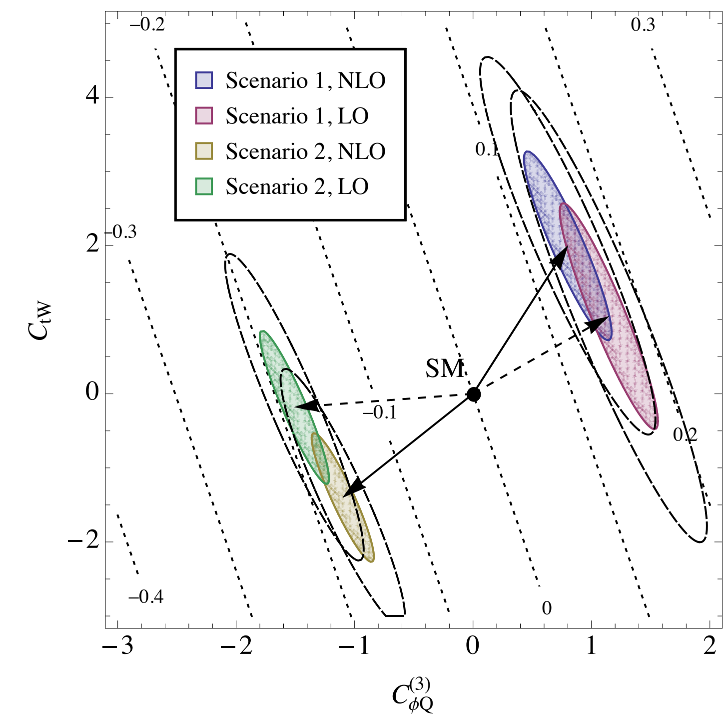


tj, tb, tW

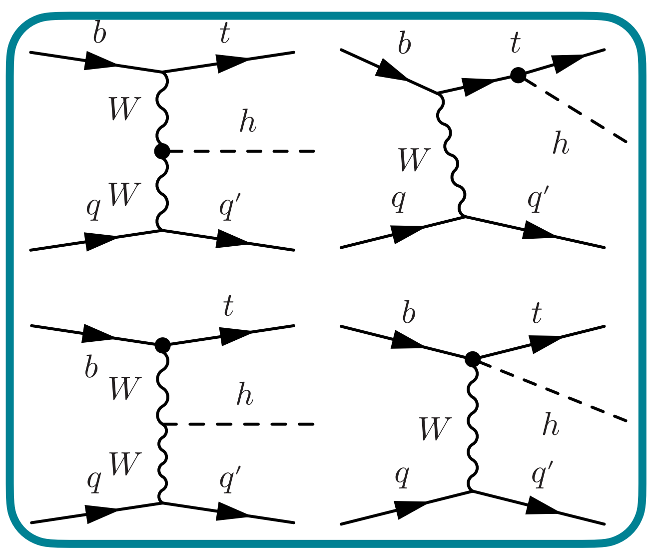
Fit without deviation



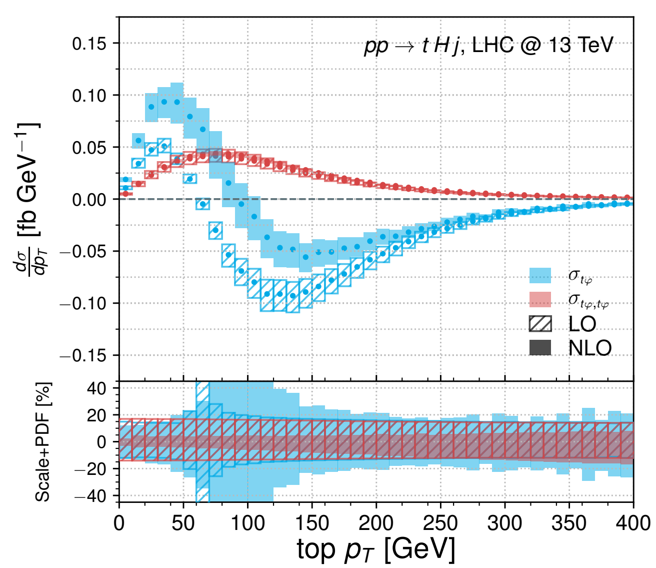
Fit with a (hypothetical) deviation

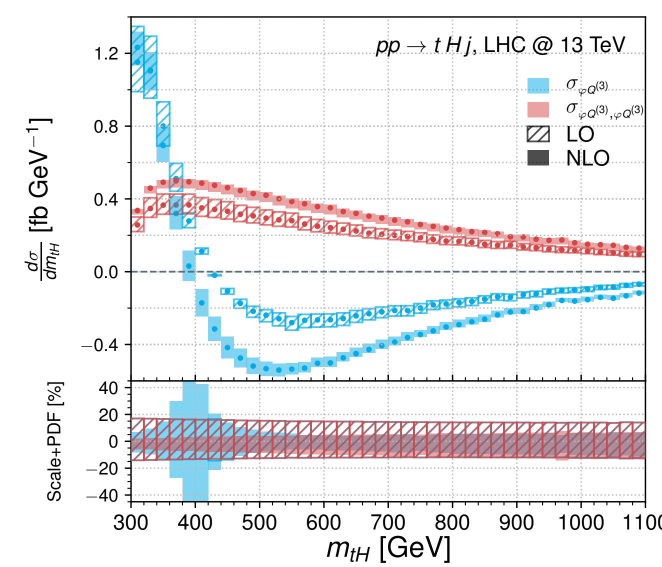


[Degrande et al.; JHEP 10 (2018) 005]



t Z j & t H j





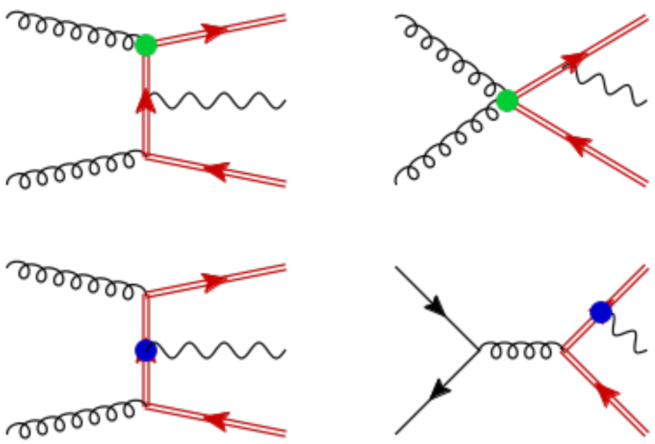
σ [fb]	K-factor
σ_{SM}	1.32
$\sigma_{\varphi W}$	0.96
$\sigma_{\varphi W,\varphi W}$	1.20
$\sigma_{t\varphi}$	0.20
$\sigma_{t\varphi,t\varphi}$	1.09
σ_{tW}	1.14
$\sigma_{tW,tW}$	1.54
$\sigma_{\varphi Q^{(3)}}$	3.31
$\sigma_{\varphi Q^{(3)},\varphi Q^{(3)}}$	1.36

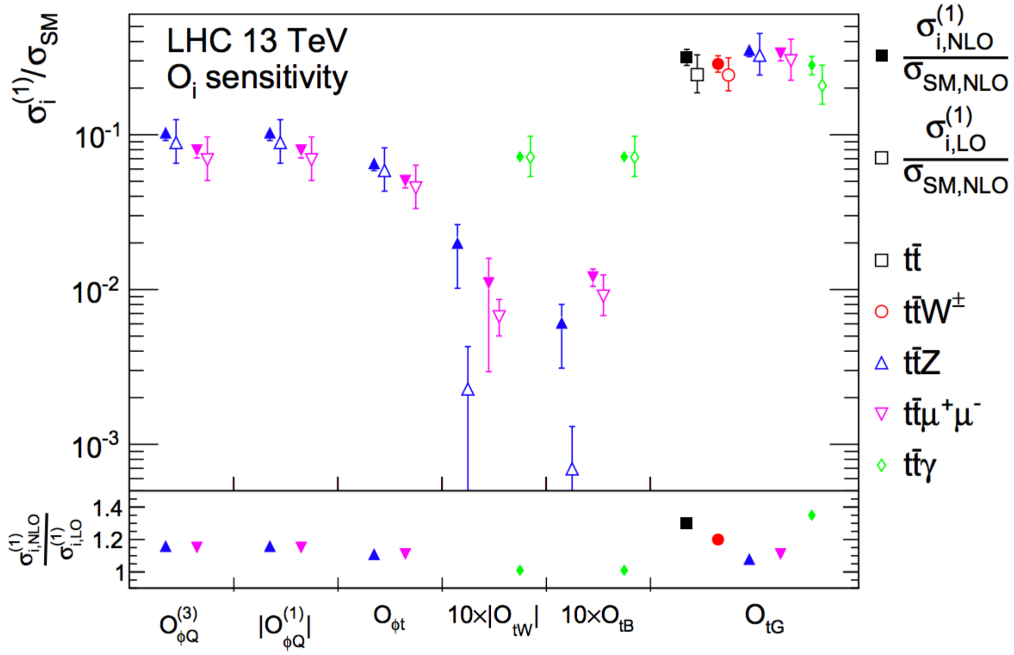
Different patterns of phase-space cancellations at LO/NLO lead to non-trivial & “strange” K factors

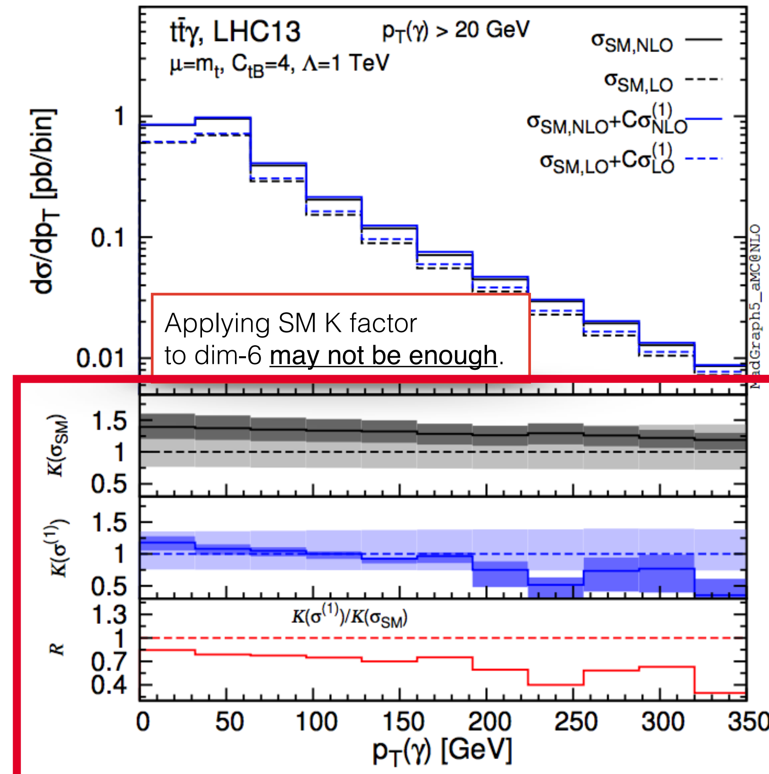
[Bylund et al.; JHEP 1605 (2016) 052]

NLO > LO

$t\bar{t}\gamma/t\bar{t}Z$

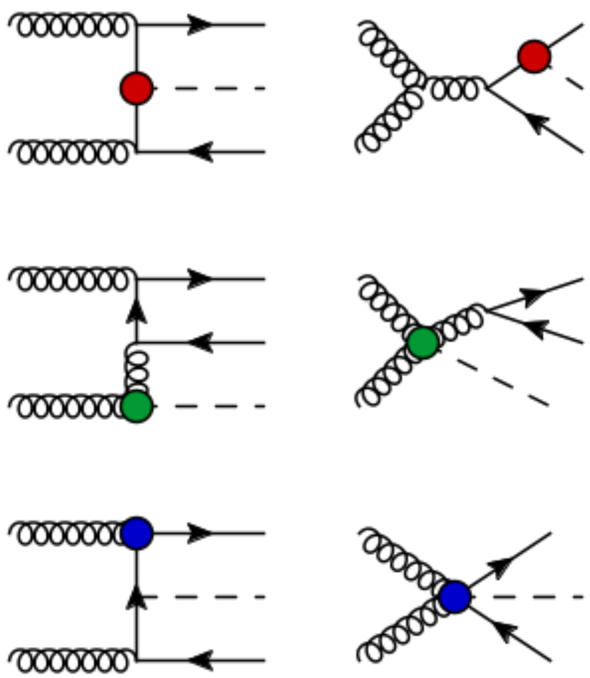


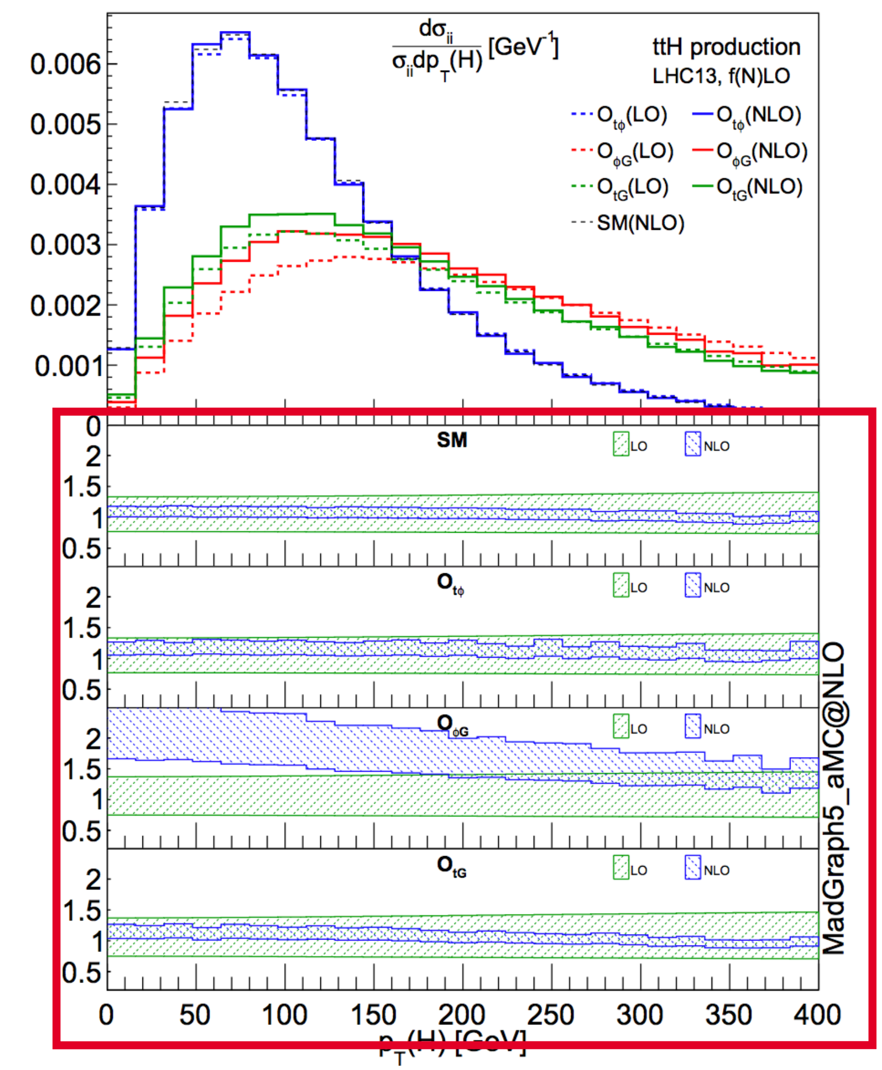




[Maltoni, Vryonidou & Zhang; JHEP 1610 (2016) 123]

$t\bar{t}H$



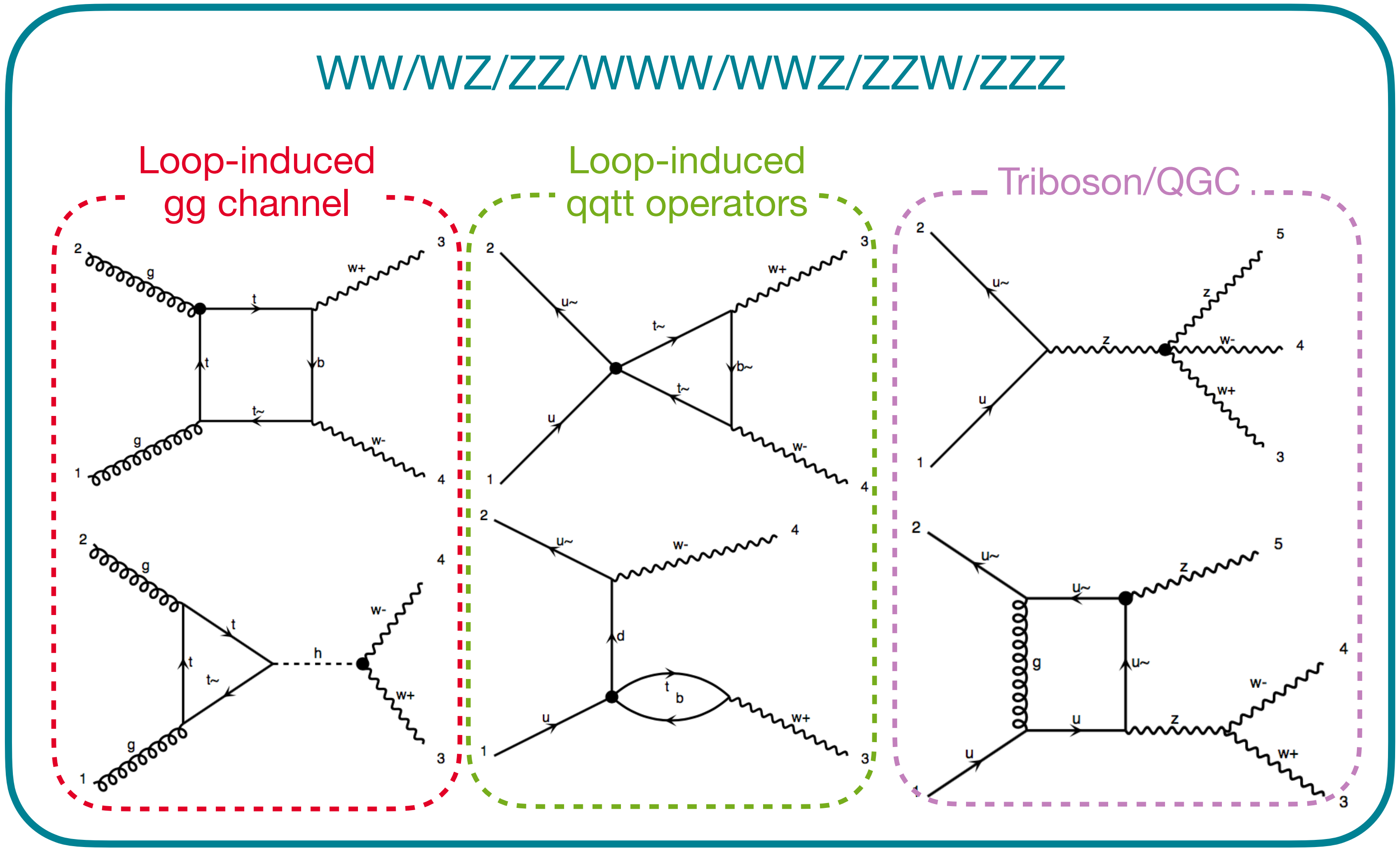


13 TeV	σ LO	σ NLO	K
σ_{SM}	$0.464^{+0.161}_{-0.111}$	$0.507^{+0.03}_{-0.0}$	1.09
$\sigma_{t\phi}$	$-0.055^{+0.0}_{-0.0}$	-0.062^{+0}_{-0}	1.13
$\sigma_{\phi G}$	$0.627^{+0.225}_{-0.153}$	$0.872^{+0.1}_{-0.1}$	1.39
σ_{tG}	$0.470^{+0.167}_{-0.114}$	$0.503^{+0.03}_{-0.0}$	1.07
$\sigma_{t\phi,t\phi}$	$0.0016^{+0.00}_{-0.00}$	$0.0019^{+0.}_{-0.}$	1.17
$\sigma_{\phi G,\phi G}$	$0.646^{+0.274}_{-0.178}$	$1.021^{+0.2}_{-0.1}$	1.58
$\sigma_{tG,tG}$	$0.645^{+0.276}_{-0.178}$	$0.674^{+0.03}_{-0.0}$	1.04
$\sigma_{t\phi,\phi G}$	$-0.037^{+0.0}_{-0.0}$	-0.053^{+0}_{-0}	1.42
$\sigma_{t\phi,tG}$	$-0.028^{+0.0}_{-0.0}$	-0.031^{+0}_{-0}	1.10
$\sigma_{\phi G,tG}$	$0.627^{+0.252}_{-0.166}$	$0.859^{+0.1}_{-0.1}$	1.37

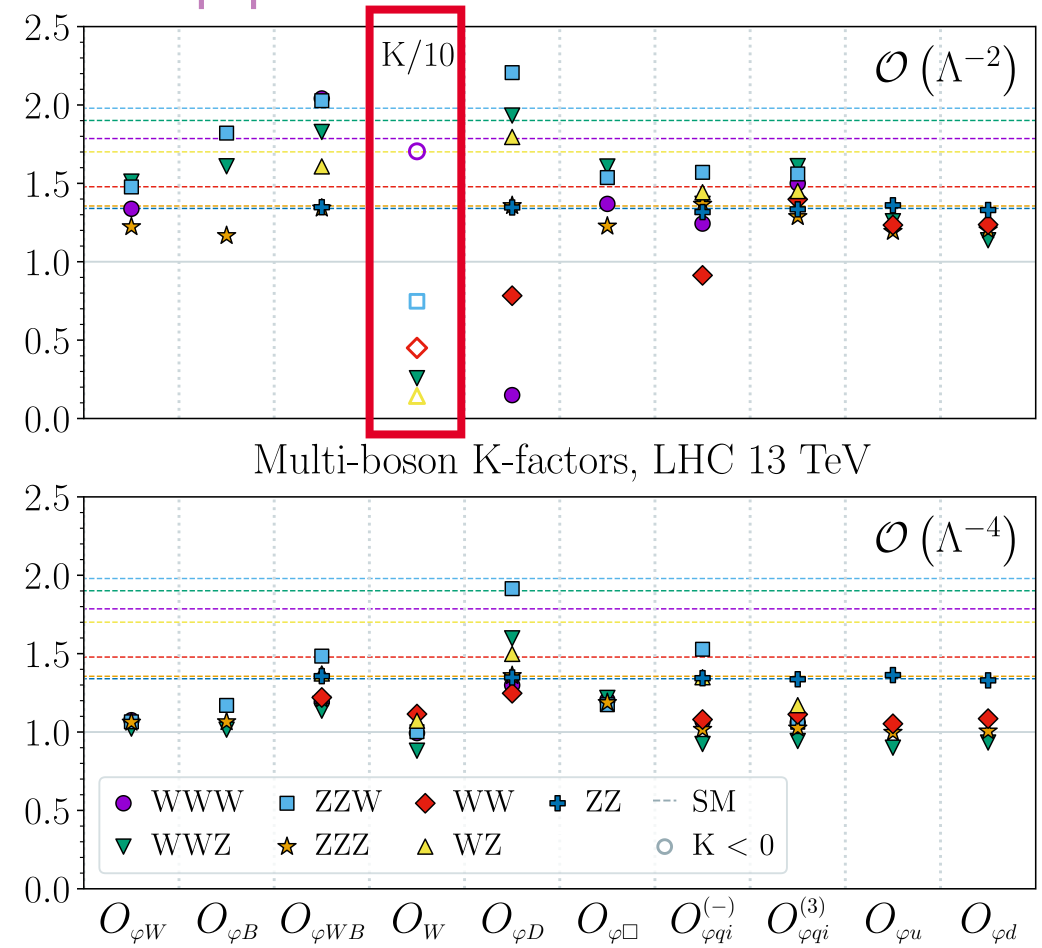
Non-universal K-factors in rates & distributions

[Degrande, Durieux, Maltoni, KM, Vryonidou & Zhang; arXiv:2008.11743]

Multiboson



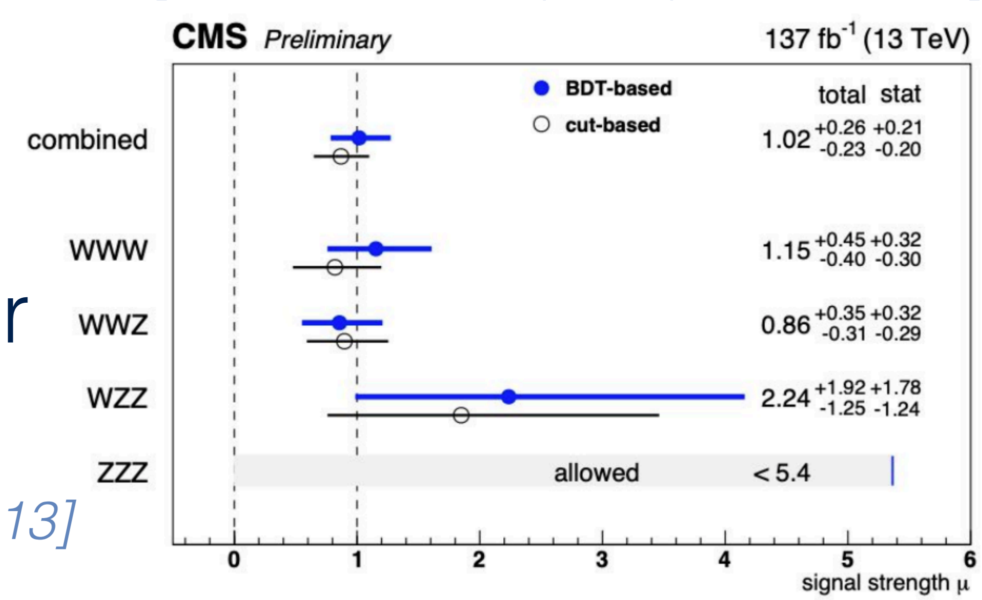
qq-initiated K-factors



Non-universal NLO corrections, different from SM

Large, negative K-factors for triple gauge operator, c_W
Non-interference/cancellation at LO broken at NLO

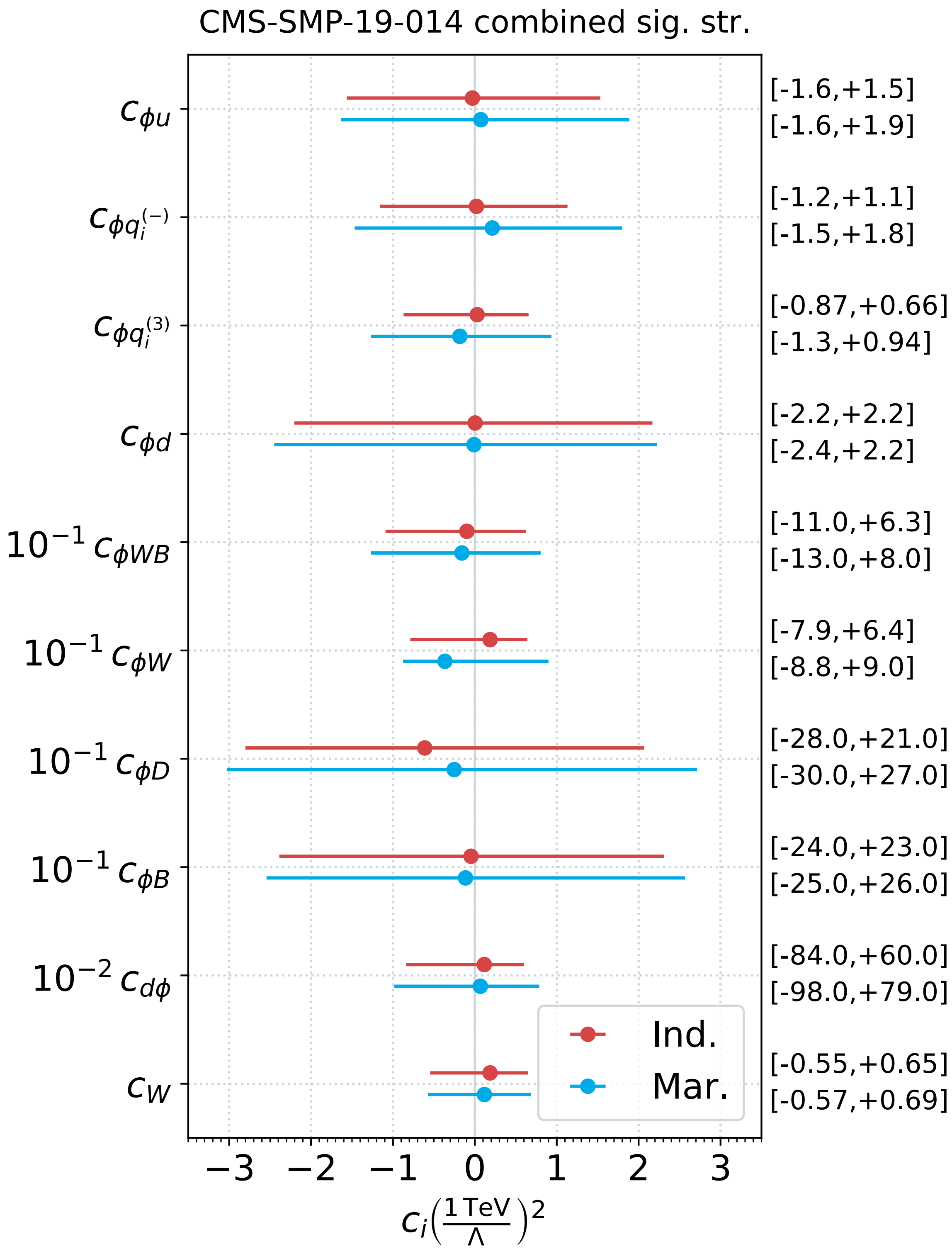
[CMS; PRL 125 (2020) 15, 151802]

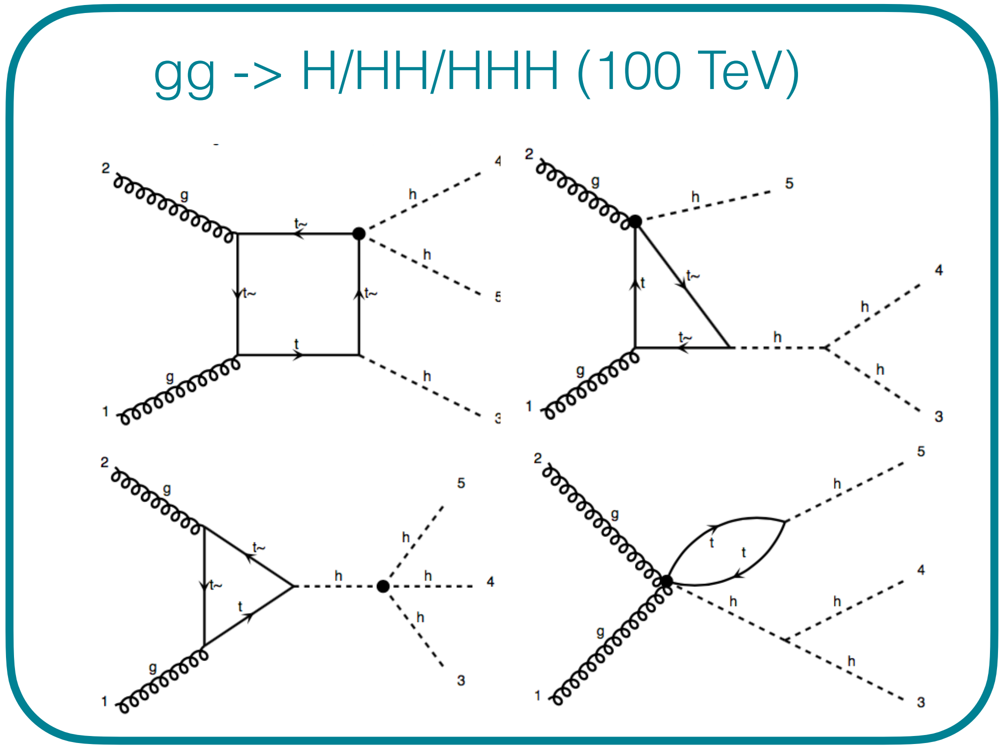


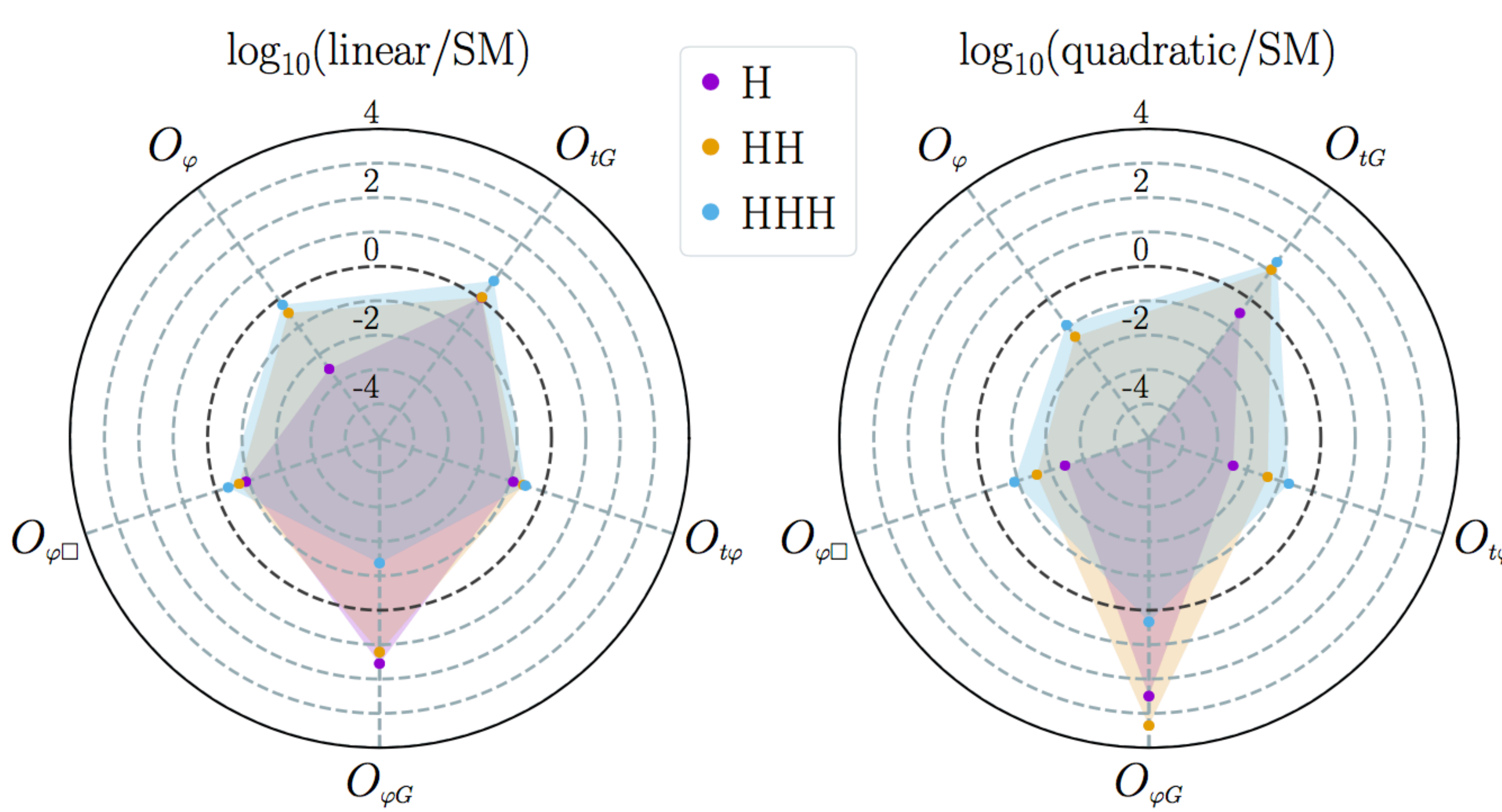
First triboson observation by CMS last year

- Also strong evidence from ATLAS
- New window into SMEFT? [ATLAS; PLB 798 (2019) 134913]

Triboson sensitivity







- Next: combine with diboson/EWPO

Projected FCC-hh reach: 1%, 5% and 50% on H, HH and HHH

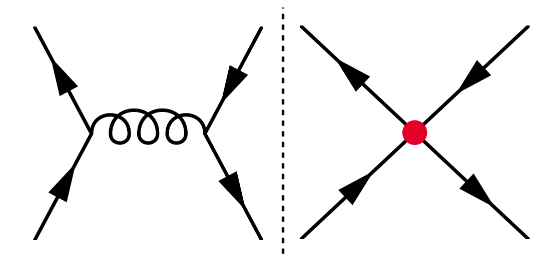
4F in top pair

LHC 13 TeV, SM = 744 pb, K-factor = 1.46, central scale choice = m_t

	Interference			Square		
c_i	$\mathcal{O}(\Lambda^{-2})$ LO	$\mathcal{O}(\Lambda^{-2})$ NLO	K	$\mathcal{O}(\Lambda^{-4})$ LO	$\mathcal{O}(\Lambda^{-4})$ NLO	K
c_{tu}^{8}	$4.27^{+11\%}_{-9\%}$	$4.06^{+1\%}_{-3\%}$	0.95	$1.04^{+6\%}_{-5\%}$	$1.03^{+2\%}_{-2\%}$	0.99
c_{td}^{8}	$2.79^{+11\%}_{-9\%}$	$2.77^{+1\%}_{-3\%}$	0.99	$0.577^{+6\%}_{-5\%}$	$0.611^{+3\%}_{-2\%}$	1.06
c_{tq}^{8}	$6.99^{+11\%}_{-9\%}$	$6.67^{+1\%}_{-3\%}$	0.95	$1.61^{+6\%}_{-5\%}$	$1.29^{+3\%}_{-2\%}$	0.80
c_{Qu}^{8}	$4.26^{+11\%}_{-9\%}$	$3.93^{+1\%}_{-4\%}$	0.92	$1.04^{+6\%}_{-5\%}$	$0.798^{+3\%}_{-3\%}$	0.77
c_{Qd}^{8}	$2.79^{+11\%}_{-9\%}$	$2.93^{+0\%}_{-1\%}$	1.05	$0.58^{+6\%}_{-5\%}$	$0.485^{+2\%}_{-2\%}$	0.84
$c_{Qq}^{8,1}$	$6.99^{+11\%}_{-9\%}$	$6.82^{+1\%}_{-3\%}$	0.98	$1.61^{+6\%}_{-5\%}$	$1.69^{+3\%}_{-3\%}$	1.05
$c_{Qq}^{8,3}$	$1.50^{+10\%}_{-9\%}$	$1.32^{+1\%}_{-3\%}$	0.88	$1.61^{+6\%}_{-5\%}$	$1.57^{+2\%}_{-2\%}$	0.98
c_{tu}^{1}	$[0.67^{+1\%}_{-1\%}]$	$-0.078(7)^{+31\%}_{-23\%}$ $[0.41^{+13\%}_{-17\%}]$	0.61	$4.66^{+6\%}_{-5\%}$	$5.92^{+6\%}_{-5\%}$	1.27
c_{td}^{1}	$[-0.21^{+1\%}_{-2\%}]$	$-0.306^{+30\%}_{-22\%}$ $[-0.15^{+10\%}_{-13\%}]$	0.71	$2.62^{+6\%}_{-5\%}$	$3.46^{+5\%}_{-5\%}$	1.32
c_{tq}^{1}	$[0.39^{+0\%}_{-1\%}]$	$-0.47^{+24\%}_{-18\%}$ $[0.50^{+3\%}_{-2\%}]$	1.28	$7.25^{+6\%}_{-5\%}$	$9.36^{+6\%}_{-5\%}$	1.29
c_{Qu}^{1}	$[0.33^{+0\%}_{-0\%}]$	$-0.359^{+23\%}_{-17\%}$ $[0.57^{+6\%}_{-5\%}]$	1.72	$4.68^{+6\%}_{-5\%}$	$5.96^{+6\%}_{-5\%}$	1.27
c_{Qd}^{1}	$[-0.11^{+0\%}_{-1\%}]$	$0.023(6)^{+114\%}_{-75\%}$ $[-0.19^{+6\%}_{-5\%}]$	1.72	$2.61^{+6\%}_{-5\%}$	$3.46^{+5\%}_{-5\%}$	1.31
$c_{Qq}^{1,1}$	$[0.57^{+0\%}_{-1\%}]$	$-0.24^{+30\%}_{-22\%}$ $[0.39^{+9\%}_{-12\%}]$	0.68	$7.25^{+6\%}_{-5\%}$	$9.34^{+5\%}_{-5\%}$	1.29
$c_{Qq}^{1,3}$	$[1.92^{+1\%}_{-1\%}]$	$0.088(7)^{+28\%}_{-20\%}$ $[1.05^{+17\%}_{-22\%}]$	0.55	$7.25^{+6\%}_{-5\%}$	$9.32^{+5\%}_{-5\%}$	1.29

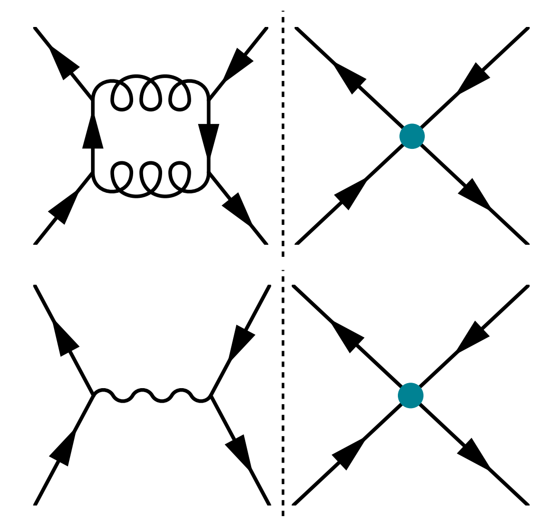
color-octet qqtt:

- *dominant operators in ttbar*
- *Non SM-like corrections*



color-singlet qqtt:

- *int. with QCD ttbar at NLO*
- *[x] int. with EW ttbar*
- *No error control at LO*

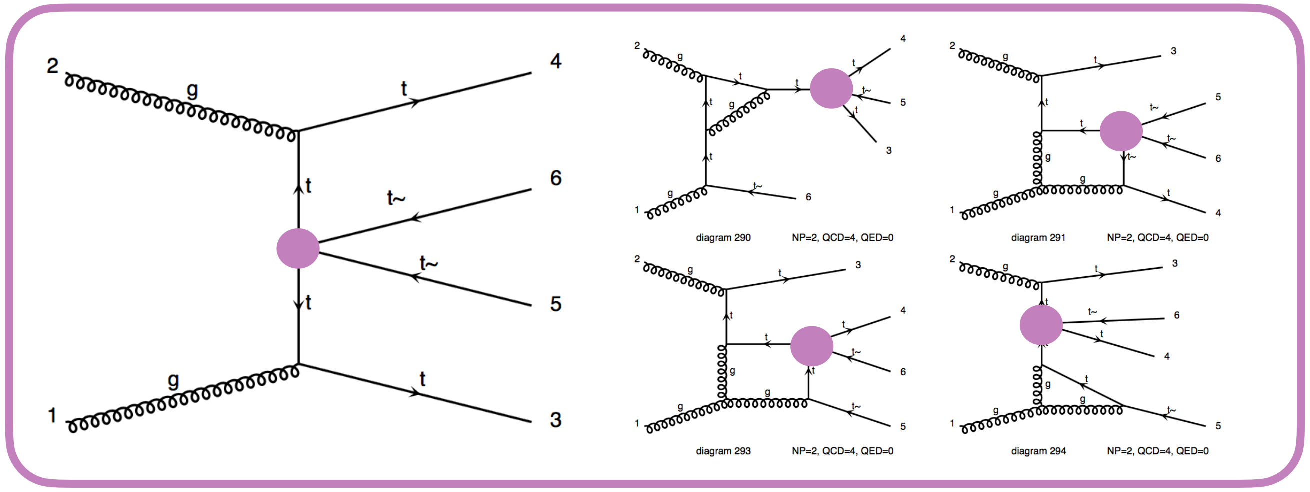


NLO can break degeneracies in fits

- C's enter e.g., $m_{t\bar{t}}$, in fixed combinations at LO

4F in 4 top

$\sigma(pp \to t\bar{t}t\bar{t})$ [fb], $c_i/\Lambda^2 = 1\,\text{TeV}^{-2}$



! different from arXiv version !

c_i	*Interference* $\mathcal{O}(\Lambda^{-2})$ LO		NLO	K	*Square* $\mathcal{O}(\Lambda^{-4})$ LO	NLO	K
c^8_{QQ}	$0.081^{+55\%}_{-33\%}$	[−0.277]	$0.090^{+4\%}_{-11\%}$	1.1	$0.115^{+46\%}_{-29\%}$	$0.158^{+4\%}_{-11\%}$	1.37
c^8_{Qt}	$0.274^{+54\%}_{-33\%}$	[−0.365]	$0.311^{+5\%}_{-10\%}$	1.14	$0.342^{+46\%}_{-29\%}$	$0.378^{+4\%}_{-13\%}$	1.10
c^1_{QQ}	$0.242^{+55\%}_{-33\%}$	[−0.826]	$0.24(3)^{+3\%}_{-18\%}$	0.99	$1.039^{+47\%}_{-29\%}$	$1.41^{+4\%}_{-11\%}$	1.36
c^1_{Qt}	$-0.0098(10)^{+38\%}_{-33\%}$	[0.852]	$-0.019(9)^{+63\%}_{-27\%}$	1.9	$1.406^{+46\%}_{-30\%}$	$1.86^{+4\%}_{-10\%}$	1.32
c^1_{tt}	$0.483^{+55\%}_{-33\%}$	[−1.38]	$0.53(8)^{+3\%}_{-10\%}$	1.10	$4.154^{+47\%}_{-29\%}$	$5.61^{+4\%}_{-11\%}$	1.35

QCD corrections to inclusive 4 top production in SMEFT

- Central scale choice: $\mu = 2m_t$

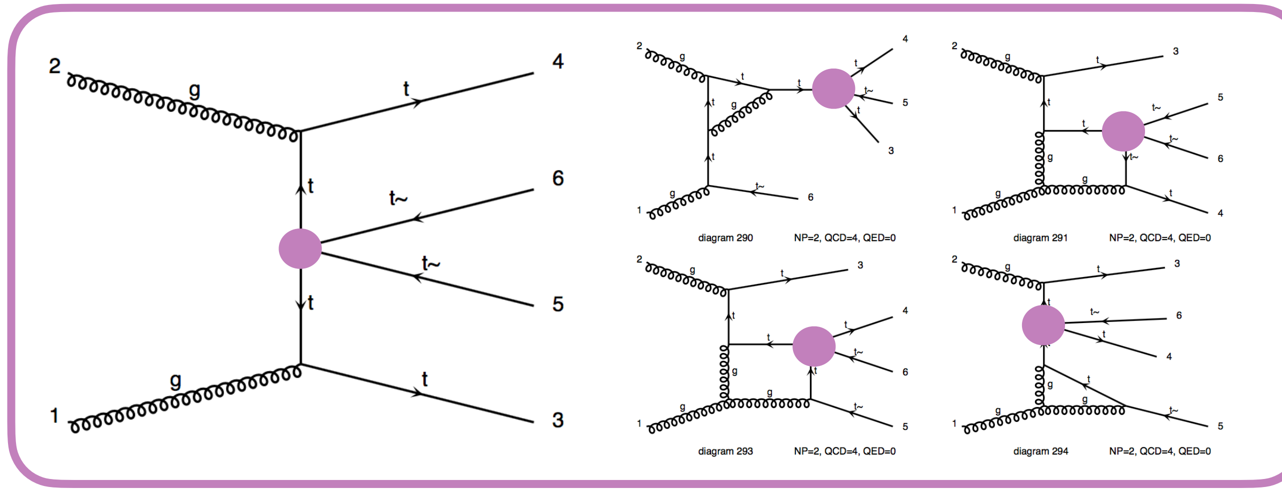
$$\text{SM} = 11.1^{+25\%}_{-25\%}\,\text{fb}\ \ (K = 1.83)$$

Computationally challenging

- ~1 week per operator run on CP3 computing cluster

4F in 4 top

[Degrande, Durieux, Maltoni, KM, Vryonidou & Zhang; arXiv:2008.11743]



$\sigma(pp \to t\bar{t}t\bar{t})$ [fb], $c_i/\Lambda^2 = 1\,\mathrm{TeV}^{-2}$

! different from arXiv version !

c_i	*Interference* $\mathcal{O}(\Lambda^{-2})$ LO		NLO	K	*Square* $\mathcal{O}(\Lambda^{-4})$ LO	NLO	K
c^8_{QQ}	$0.081^{+55\%}_{-33\%}$	$[-0.277]$	$0.090^{+4\%}_{-11\%}$	1.1	$0.115^{+46\%}_{-29\%}$	$0.158^{+4\%}_{-11\%}$	1.37
c^8_{Qt}	$0.274^{+54\%}_{-33\%}$	$[-0.365]$	$0.311^{+5\%}_{-10\%}$	1.14	$0.342^{+46\%}_{-29\%}$	$0.378^{+4\%}_{-13\%}$	1.10
c^1_{QQ}	$0.242^{+55\%}_{-33\%}$	$[-0.826]$	$0.24(3)^{+3\%}_{-18\%}$	0.99	$1.039^{+47\%}_{-29\%}$	$1.41^{+4\%}_{-11\%}$	1.36
c^1_{Qt}	$-0.0098(10)^{+38\%}_{-33\%}$	$[0.852]$	$-0.019(9)^{+63\%}_{-27\%}$	1.9	$1.406^{+46\%}_{-30\%}$	$1.86^{+4\%}_{-10\%}$	1.32
c^1_{tt}	$0.483^{+55\%}_{-33\%}$	$[-1.38]$	$0.53(8)^{+3\%}_{-10\%}$	1.10	$4.154^{+47\%}_{-29\%}$	$5.61^{+4\%}_{-11\%}$	1.35

Reduction of scale uncertainty, relatively lower than SM

K-factors lower than SM $\quad \mathrm{SM} = 11.1^{+25\%}_{-25\%}\,\mathrm{fb}\;\;(K = 1.83)$

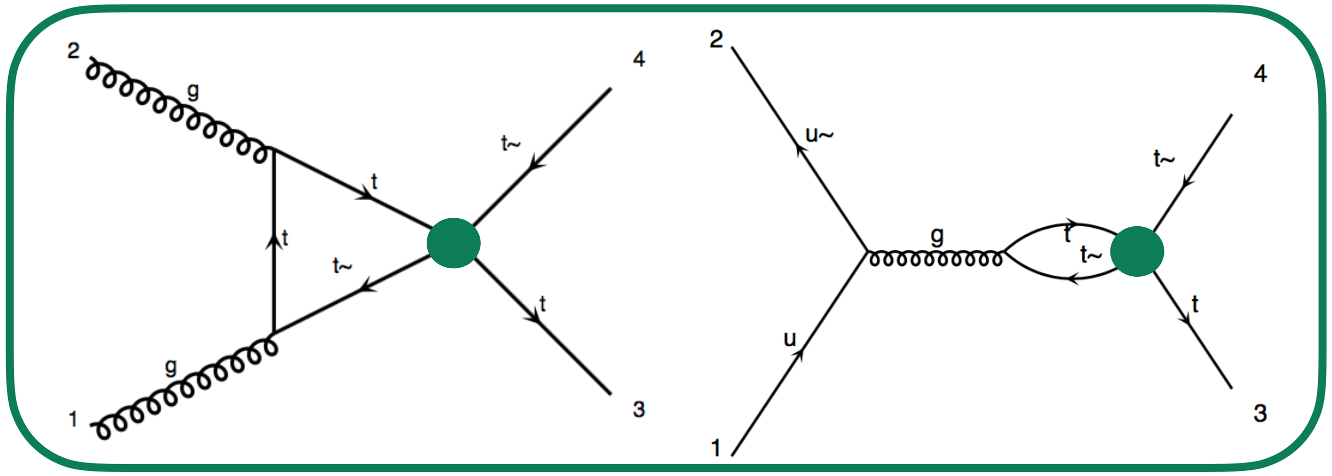
- Relative impact slightly decreases from LO to NLO
- Square typically receives larger corrections

$K^1_{QQ} \neq K^8_{QQ}$

Indirect sensitivity from $t\bar{t}$

Loop-induced effects from 4 top operators in $t\bar{t}$

- $q\bar{q} \to t\bar{t}$: mixing with $q\bar{q}t\bar{t}$ ops.
  $(\bar{t}\gamma^{\mu}t)(\bar{t}\gamma_{\mu}t) \to (\bar{t}\,\gamma^{\mu}\,T_A D^{\nu}\,t)\,G^A_{\mu\nu}$
- $gg \to t\bar{t}$: finite contribution
- $b\bar{b} \to t\bar{t}$: small piece from Q



$gg \to t\bar{t}$ amplitude: Helicity structure doesn't match SM

- No interference in the massless limit [Craig et al.; JHEP 08 (2020) 086]
- Form-factor doesn't grow with energy like $q\bar{q}t\bar{t}$ contact interactions
- Main effects near $t\bar{t}$ threshold

Indirect sensitivity from $t\bar{t}$

Results

- Octet $q\bar{q}t\bar{t}$ for reference
- [EW interference]
- 1-2 orders of magnitude smaller
- Competition/cancellation between gg and qq channels
- Λ^{-4} automatically (loop) suppressed

$\sigma(pp \to t\bar{t})$ [pb], $c_i/\Lambda^2 = 1\,\mathrm{TeV}^{-2}$

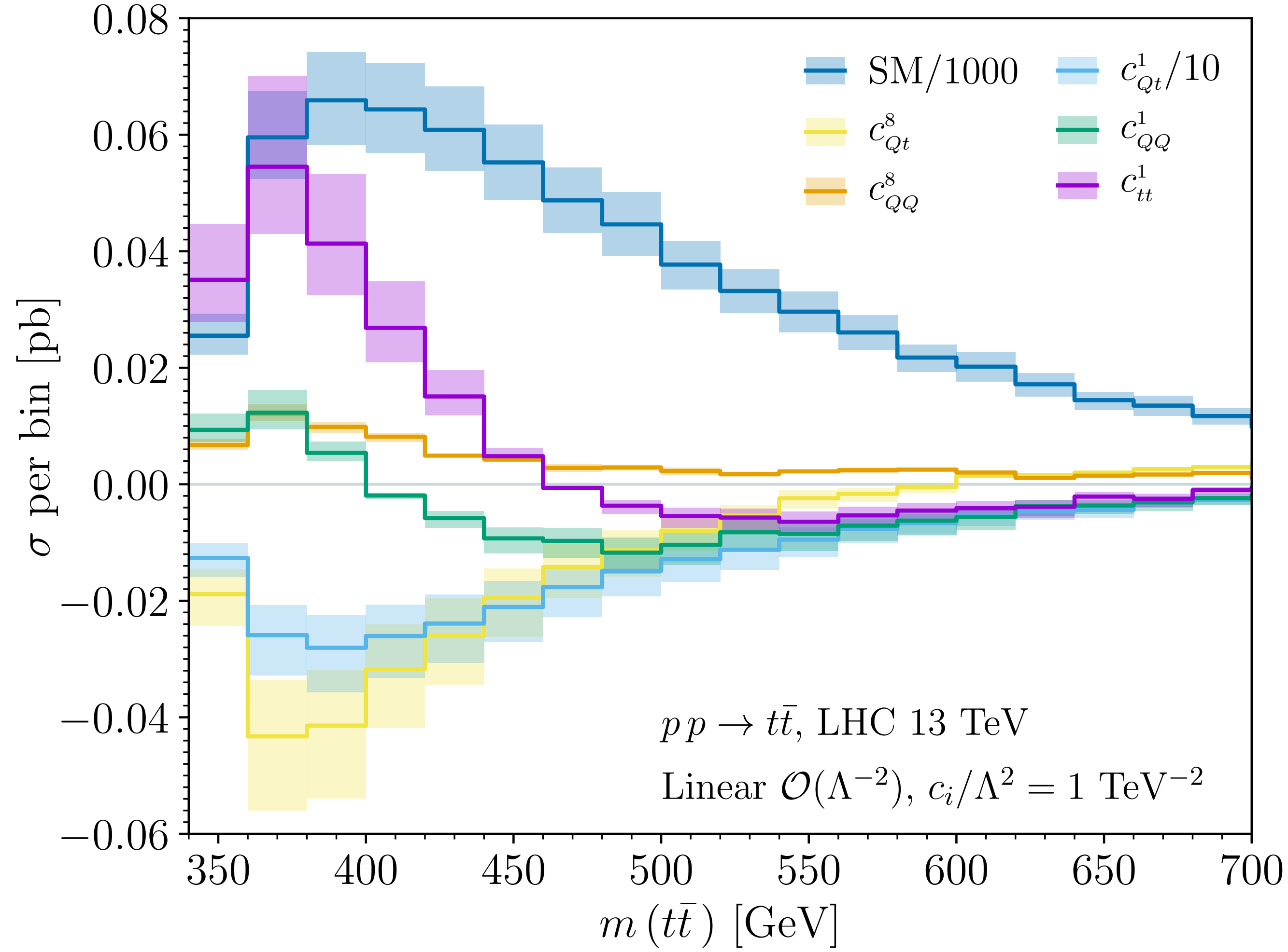
c_i	$\mathcal{O}(\Lambda^{-2})$ LO	$\mathcal{O}(\Lambda^{-2})$ NLO		$\mathcal{O}(\Lambda^{-4})$ LO	$\mathcal{O}(\Lambda^{-4})$ NLO
c_{tu}^{8}	$4.27^{+11\%}_{-9\%}$	$4.06^{+1\%}_{-3\%}$		$1.04^{+6\%}_{-5\%}$	$1.03^{+2\%}_{-2\%}$
c_{td}^{8}	$2.79^{+11\%}_{-9\%}$	$2.77^{+1\%}_{-3\%}$		$0.577^{+6\%}_{-5\%}$	$0.611^{+3\%}_{-2\%}$
c_{tq}^{8}	$6.99^{+11\%}_{-9\%}$	$6.67^{+1\%}_{-3\%}$		$1.61^{+6\%}_{-5\%}$	$1.29^{+3\%}_{-2\%}$
c_{Qu}^{8}	$4.26^{+11\%}_{-9\%}$	$3.93^{+1\%}_{-4\%}$		$1.04^{+6\%}_{-5\%}$	$0.798^{+3\%}_{-3\%}$
c_{Qd}^{8}	$2.79^{+11\%}_{-9\%}$	$2.93^{+0\%}_{-1\%}$		$0.58^{+6\%}_{-5\%}$	$0.485^{+2\%}_{-2\%}$
$c_{Qq}^{8,1}$	$6.99^{+11\%}_{-9\%}$	$6.82^{+1\%}_{-3\%}$		$1.61^{+6\%}_{-5\%}$	$1.69^{+3\%}_{-3\%}$
$c_{Qq}^{8,3}$	$1.50^{+10\%}_{-9\%}$	$1.32^{+1\%}_{-3\%}$		$1.61^{+6\%}_{-5\%}$	$1.57^{+2\%}_{-2\%}$
c_{QQ}^{8}	$0.0586^{+27\%}_{-25\%}$	$0.125^{+10\%}_{-11\%}$		$0.00628^{+13\%}_{-16\%}$	$0.0133^{+7\%}_{-5\%}$
c_{Qt}^{8}	$0.0583^{+27\%}_{-25\%}$	$-0.107(6)^{+40\%}_{-33\%}$		$0.00619^{+13\%}_{-16\%}$	$0.0118^{+8\%}_{-5\%}$
c_{QQ}^{1}	$[-0.11^{+15\%}_{-18\%}]$	$-0.039(4)^{+51\%}_{-33\%}$	$[-0.12^{+7\%}_{-5\%}]$	$0.0282^{+13\%}_{-16\%}$	$0.0651^{+5\%}_{-6\%}$
c_{Qt}^{1}	$[-0.068^{+16\%}_{-18\%}]$	$-2.51^{+29\%}_{-21\%}$	$[-0.12^{+3\%}_{-6\%}]$	$0.0283^{+13\%}_{-16\%}$	$0.066^{+5\%}_{-6\%}$
c_{tt}^{1}	×	$0.215^{+23\%}_{-18\%}$		×	×

- One intriguing number from c^{1}_{Qt}, similar in size to $q\bar{q}t\bar{t}$ octets! *$\sigma_{\rm int}$ suppressed in 4t*
- ~ Few percent effect near $t\bar{t}$ threshold assuming current bound ~ 3.5

q^2 dependence

Lack of energy growth

- Sign changes over phase space lead to suppressions
- Quark and gluon channels often have opposite sign
- Optimistic: need few percent precision near threshold

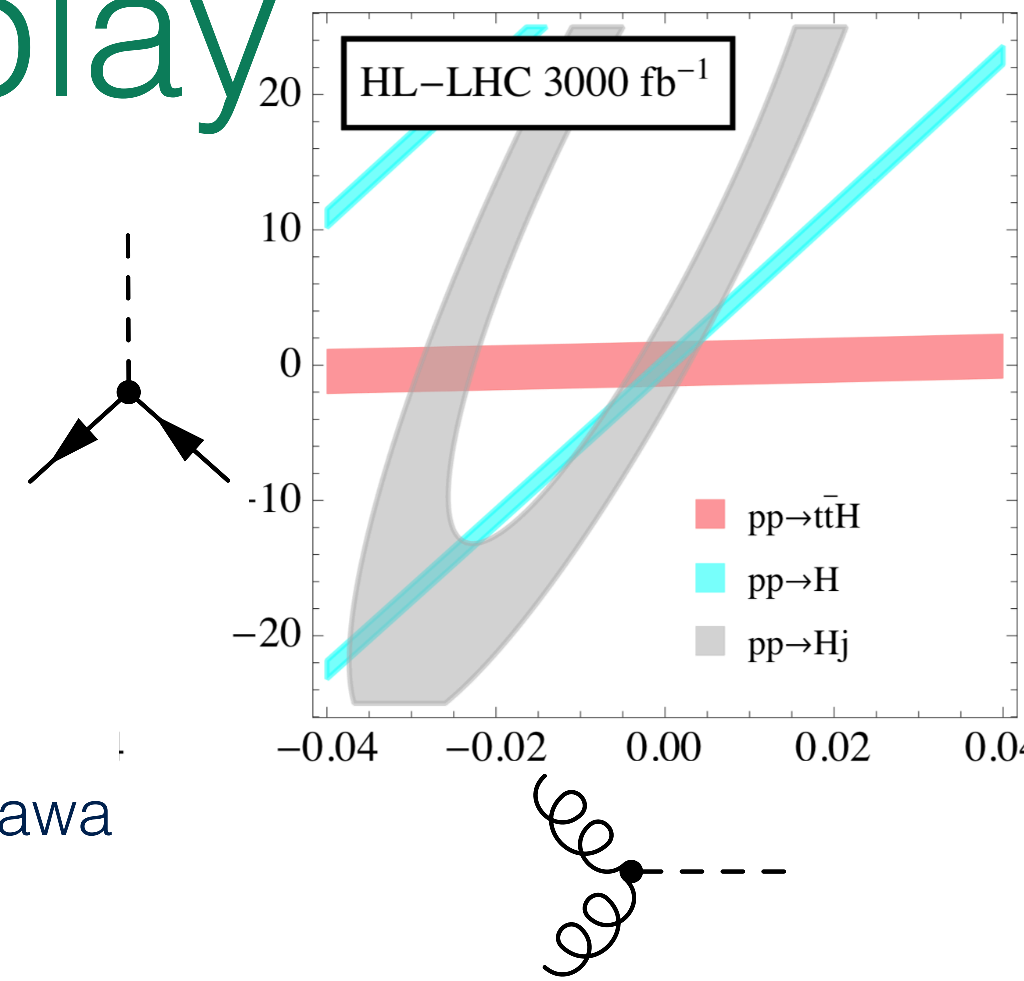


Completely different dependence to $t\bar{t}t\bar{t}$

- Limited prospects but may be at least useful for breaking $t\bar{t}t\bar{t}$ degeneracies
- Further study required

Top/Higgs interplay

[Maltoni, Vryonidou & Zhang; JHEP 1610 (2016) 123]



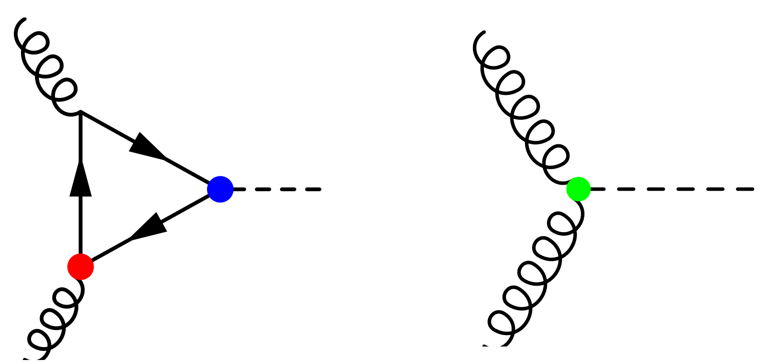
Inextricably linked in the SM

- Yukawa interaction controls ggF
- Strong BSM motivation to study tops

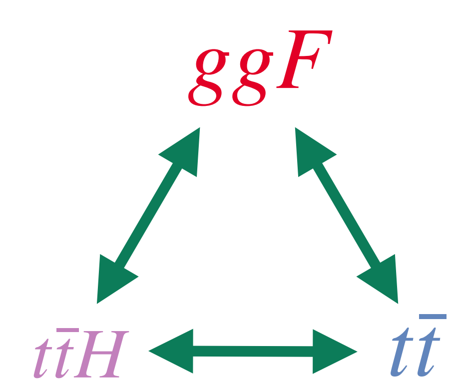
ggF is well measured now

- Cannot exclude top partners/anomalous Yukawa

C_{HG} Point-like
C_{tH} Yukawa
C_{tG} Dipole



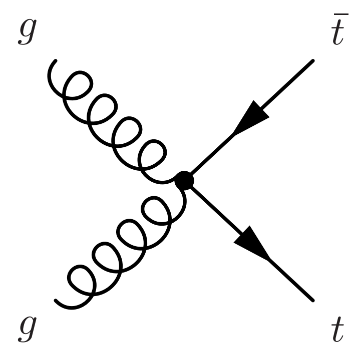
Blind direction in BSM scenarios
=
Effective coupling degeneracy



Need more data to break degeneracy

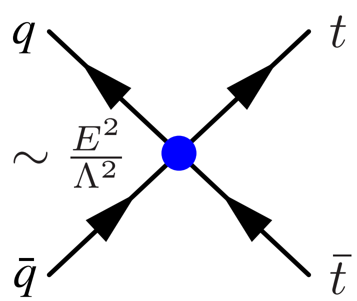
- $t\bar{t}H$ production for direct Yukawa measurement
- $t\bar{t}$ data to constrain dipole

The role of top data



$t\bar{t}$ cross section measurements constrain C_{tG}

- Indirectly improve bounds on C_{HG} and C_{tH}

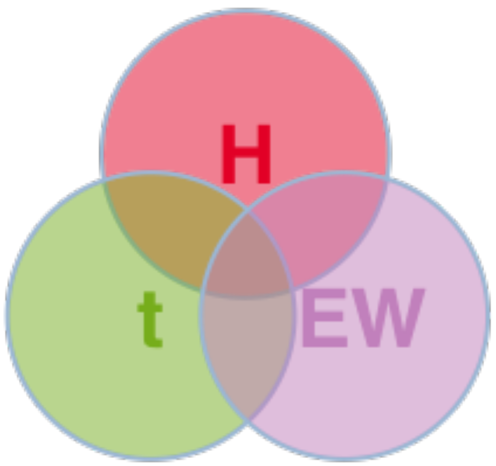


Several other new interactions can affect $t\bar{t}$

- Notably $q\bar{q}t\bar{t}$ operators, of which there are many (14)
- To what extent do these limit ultimate NP sensitivity in top/Higgs sector?

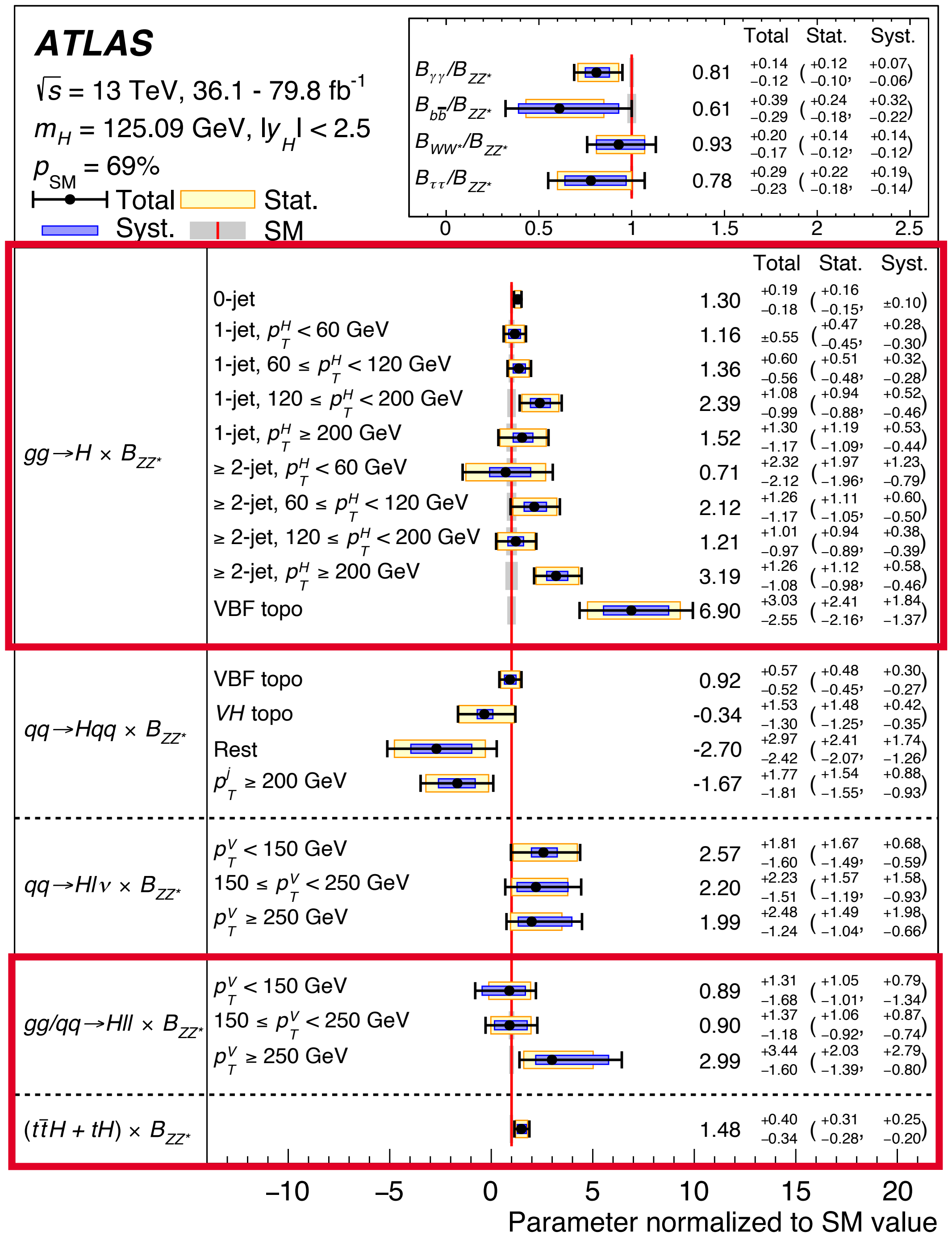
Can only be addressed in combined fit

- Beyond tree-level (at least for ggF)
- Identify other cross-talk (non-trivial correlations)
- Broaden range of applicability to UV models

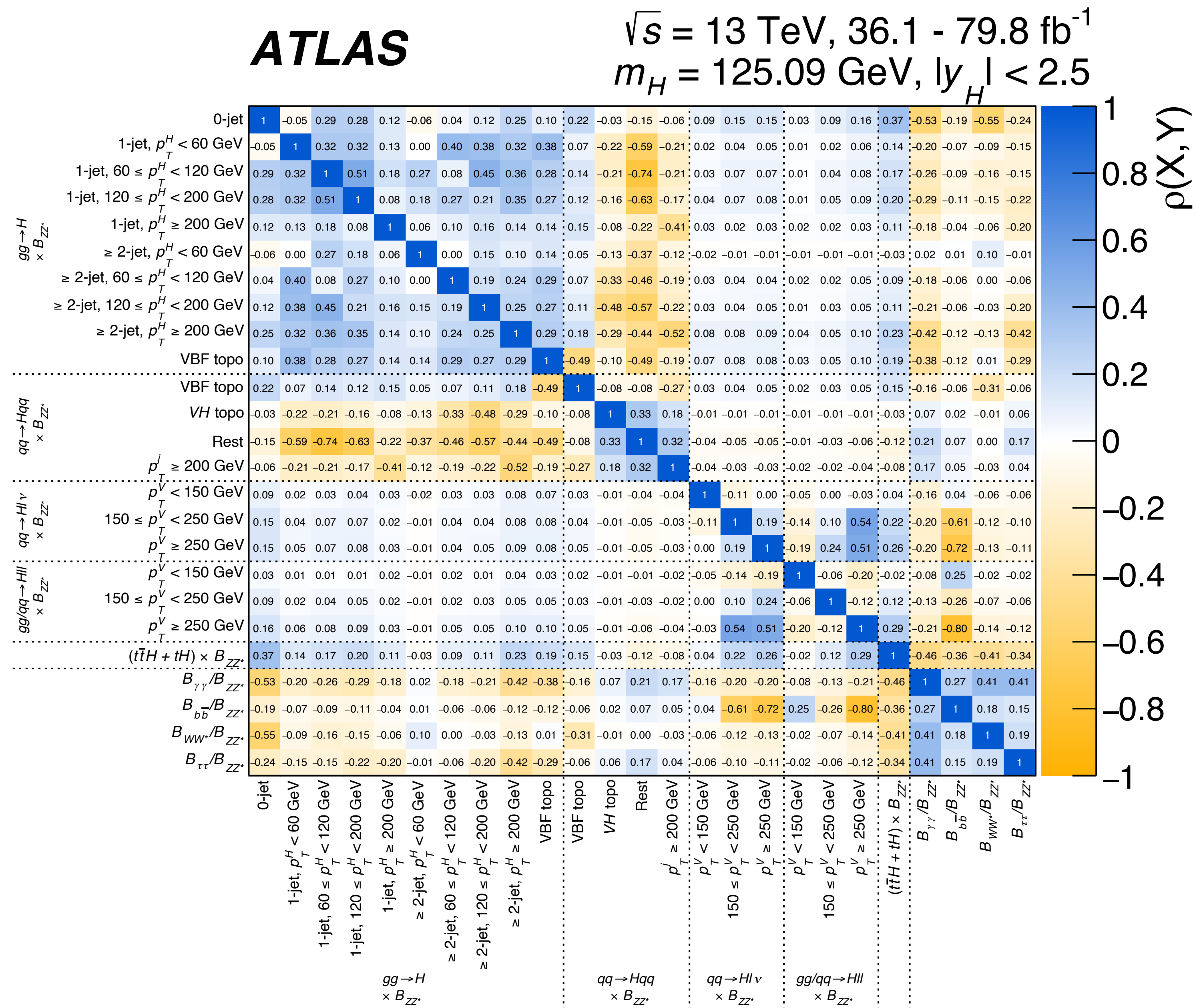


STXS

(Simplified Template Cross Sections)



[ATLAS; PRD 101 (2020) 012002]



See also:

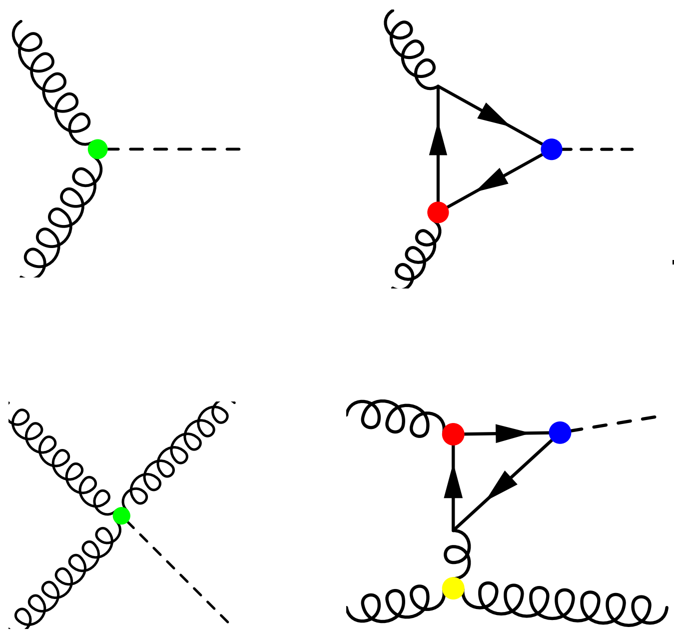
[CMS-HIG-19-015]
[CMS-PAS-HIG-19-010]
[CMS-HIG-19-001]
[ATLAS-CONF-2020-053]
[ATLAS; EPJC 80 (2020) 10]
[ATLAS-CONF-2020-026]
[ATLAS; EPJC 81 (2021) 178]

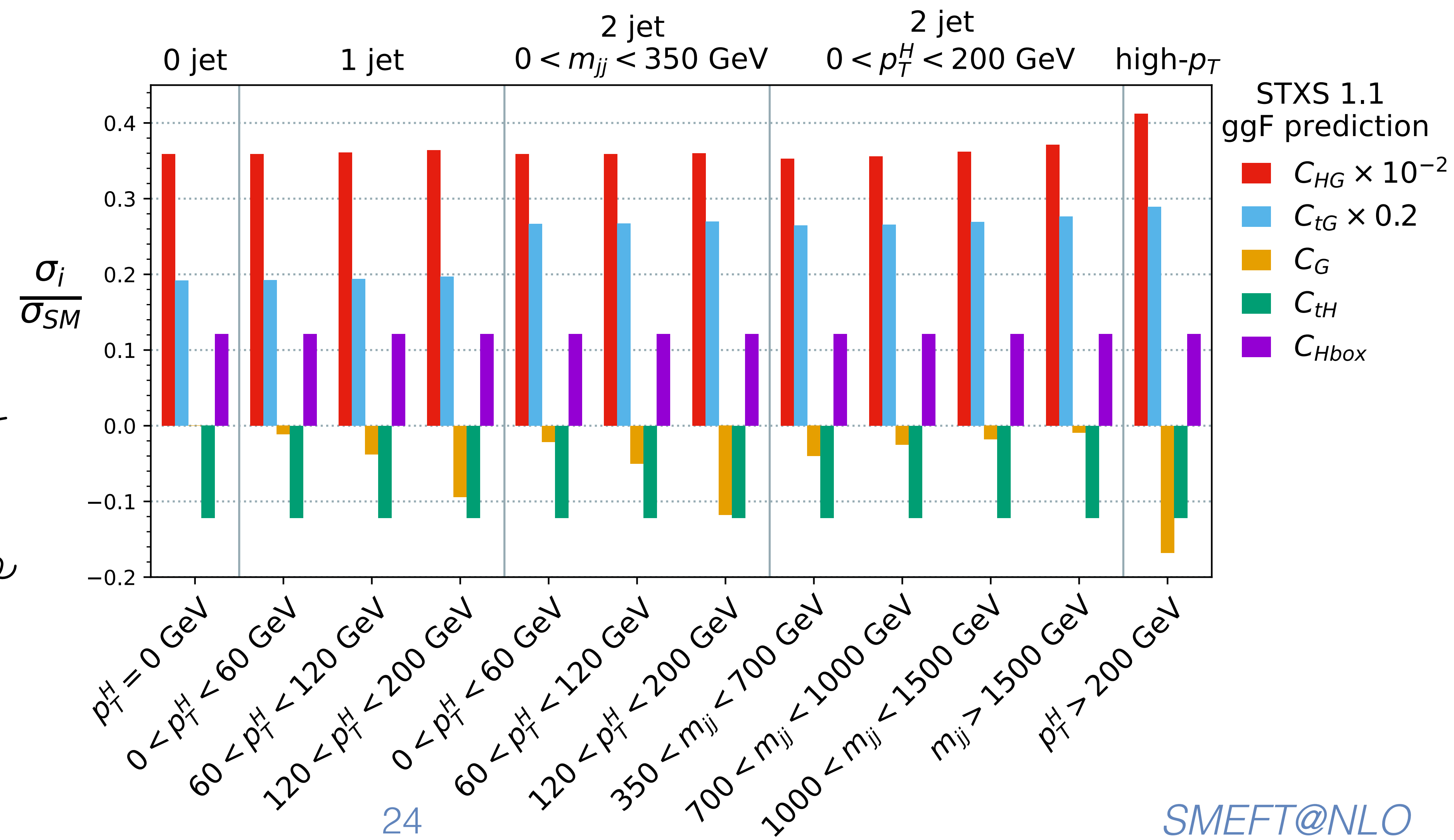
[Ellis, Madigan, KM, Sanz, You; arXiv:2012.02779]
See also: [ATLAS-CONF-2020-053]

Improving fits

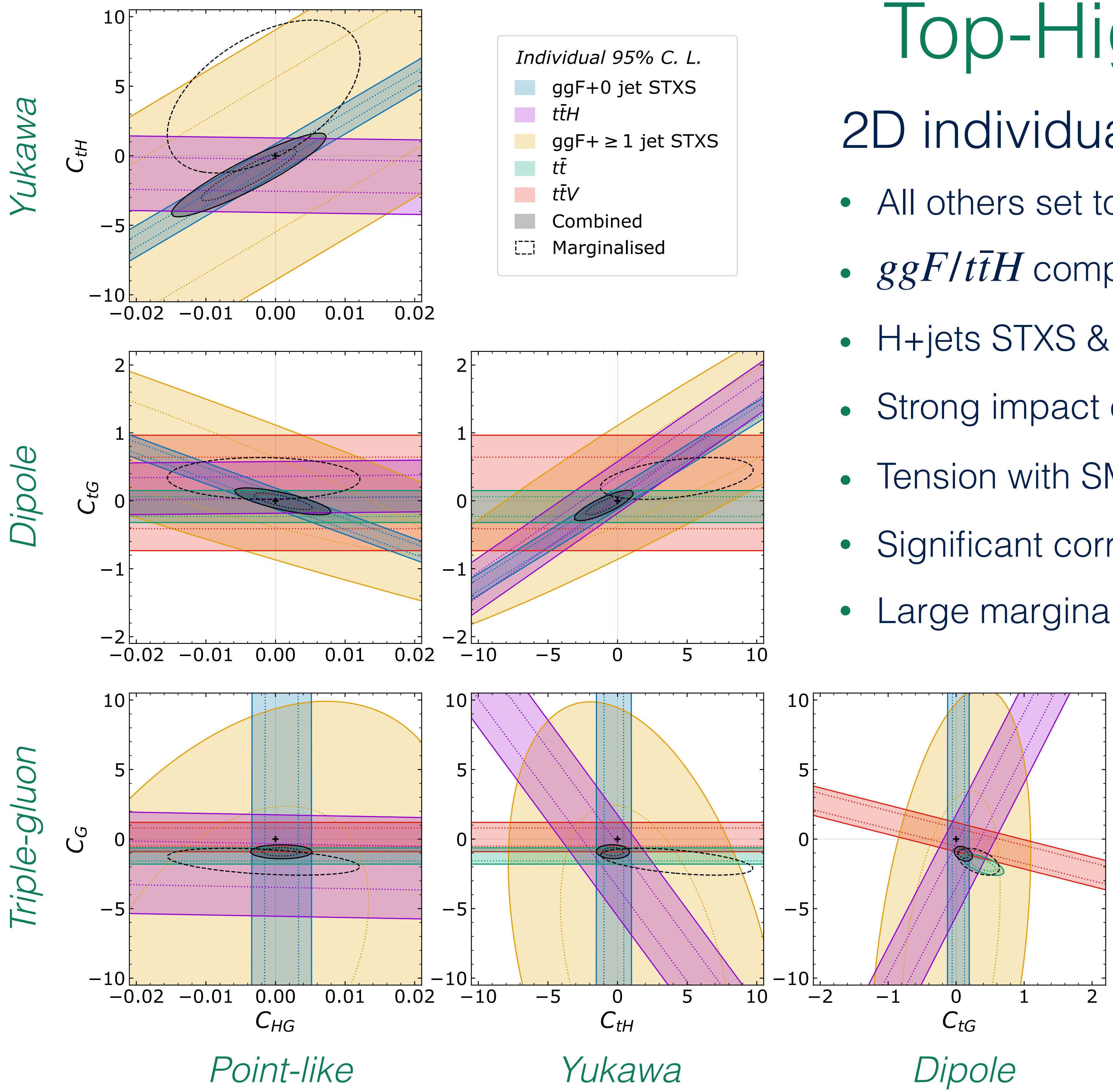
STXS ⇔ gluon fusion in the SMEFT

- LO in the SM is one-loop
- Tree-EFT x loop-SM + loop-EFT x loop-SM interference terms
- Heavy top limit is OK for 0-jet, breaks down at high-p_T





Top-Higgs interplay

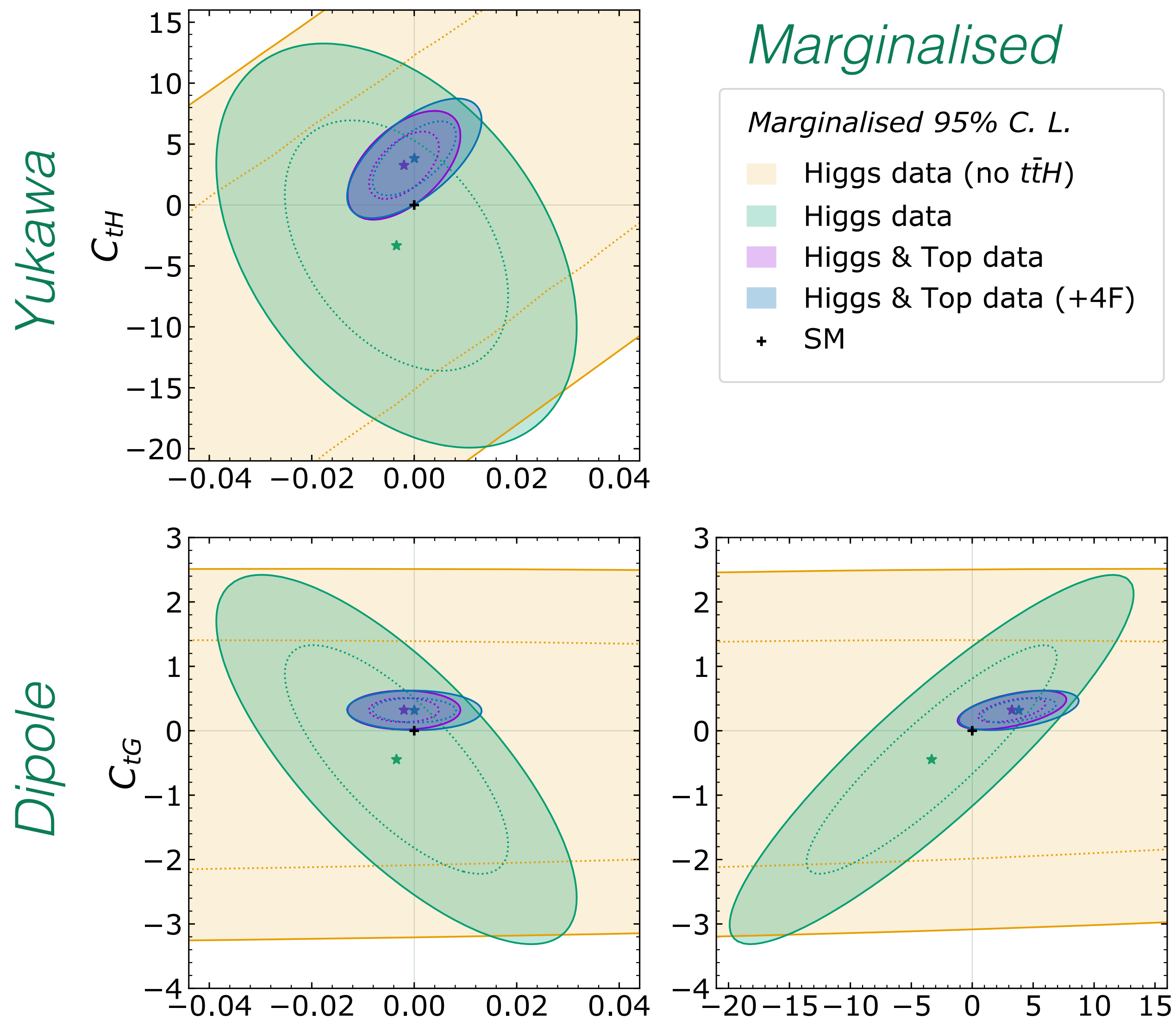


2D individual constraints

- All others set to 0
- $ggF/t\bar{t}H$ complementarity for (C_{HG}, C_{tH})
- H+jets STXS & $t\bar{t}V$ not yet competitive
- Strong impact of $t\bar{t}$ evident for (C_{tG}, C_G)
- Tension with SM $> 2\sigma$
- Significant correlations remain
- Large marginalisation effects (including 4F)

What is the concrete impact of 4F?

4F impact



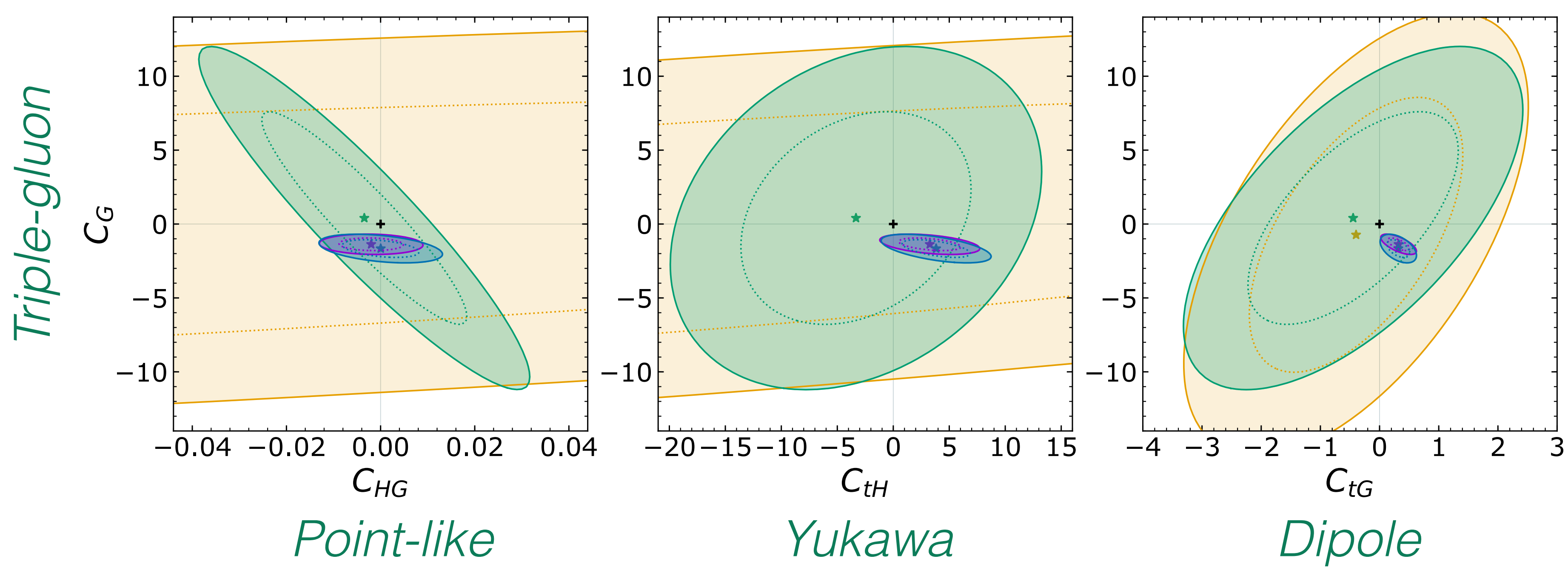
Fit to 'Higgs-only' subspace

$C_{H\Box}, C_{HG}, C_{HW}, C_{HB}, C_{tH}, C_{bH}, C_{\tau H}, C_{\mu H}$
$+\ C_{tG}\ \&\ C_G$

- Allow a closed fit to Higgs data only
- Emphasises impact of $t\bar{t}H\ \&\ t\bar{t}$

Now add in $t\bar{t}$ 4F operators

$+\ C^{3,8}_{Qq}, C^{1,8}_{Qq}, C^{8}_{Qu}, C^{8}_{Qd}, C^{8}_{tq}, C^{8}_{tu}, C^{8}_{td}$



- Relatively mild impact
- Preferred $t\bar{t}$ phase space is different

  C_{tG} : low $m_{t\bar{t}}$

  $4F$: high $m_{t\bar{t}}$

- Able to constrain them independently

Conclusions & future plans

SMEFT@NLO is a milestone in tools for SMEFT predictions

- Automated, fully-differential computations up to one-loop
- NLO+PS, loop-induced, tree-loop interference
- Crucial for inputs to global SMEFT likelihood for LHC & beyond

Planned extensions

- Generalise flavor structure: $U(2)^5$ (b chirality flipping operators)
- 4 light fermion operators (qqqq & qqll)
- CP violation
- Open to suggestions/requests!

Work in progress for running of Wilson coefficients in MG5

Long term: EW loops, already possible for the SM in MG5

Next week: HEFT 2021
USTC Hefei, China

https://indico.ihep.ac.cn/event/13632/

Backup

Technical details

Lepton sector: $[U(1)_L \times U(1)_e]^3$, flavor diagonal (e,μ,τ)

5-flavor scheme (massless b) & CKM=$\mathbb{1}$

EW input scheme: $\{G_F, m_W, m_Z\}$

- Relevant field redefinitions & EW parameter shifts performed

EFT ($\overline{MS}$) renormalisation scale: `mueft`

- Separate, fixed renormalisation scale for Wilson coefficients
- MG5 does not run the Wilson coefficients (yet)
- Usual `muR` & `muF` are kept for α_S & PDFs

Validated at LO against existing implementations

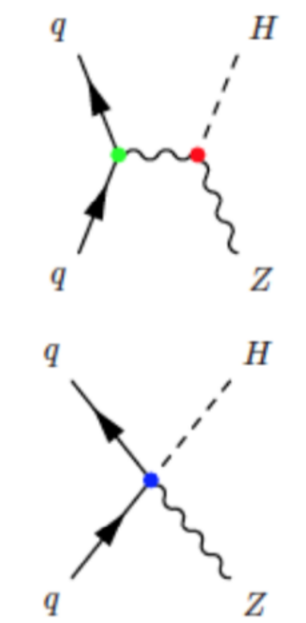
- `dim6top` & `SMEFTsim`

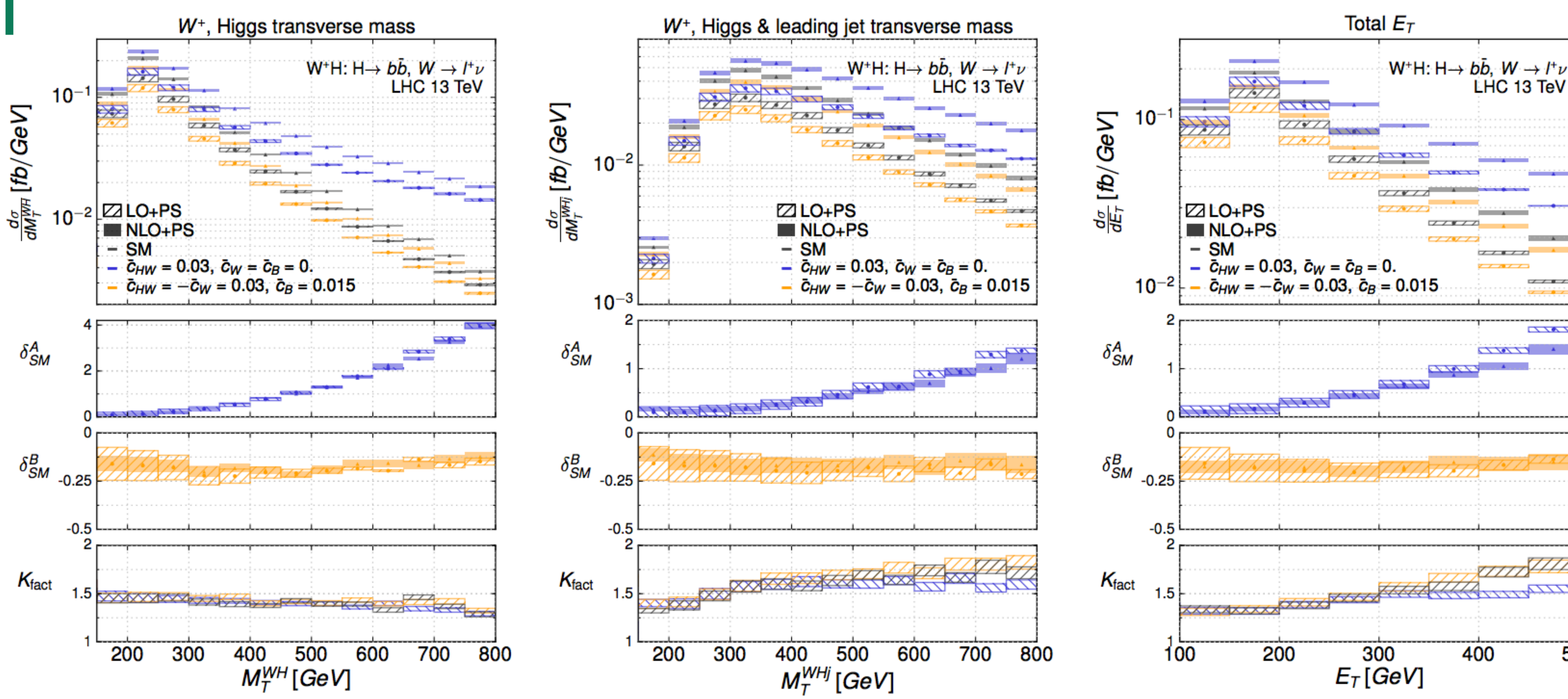
[Aguilar-Saavedra et al.; arXiv:1802.07237]
[Brivio Jiang & Trott; JHEP 12 (2017) 070]
[Brivio; arXiv:2012.11343]

pp →ZH

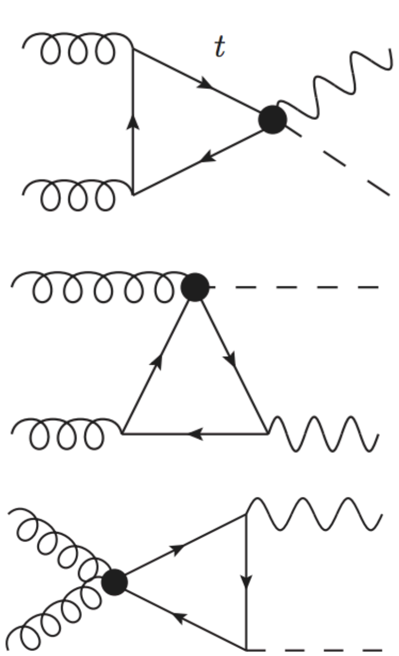
[Degrande, et al.; EPJC 77 (2017) 4, 262]

Quark-initiated



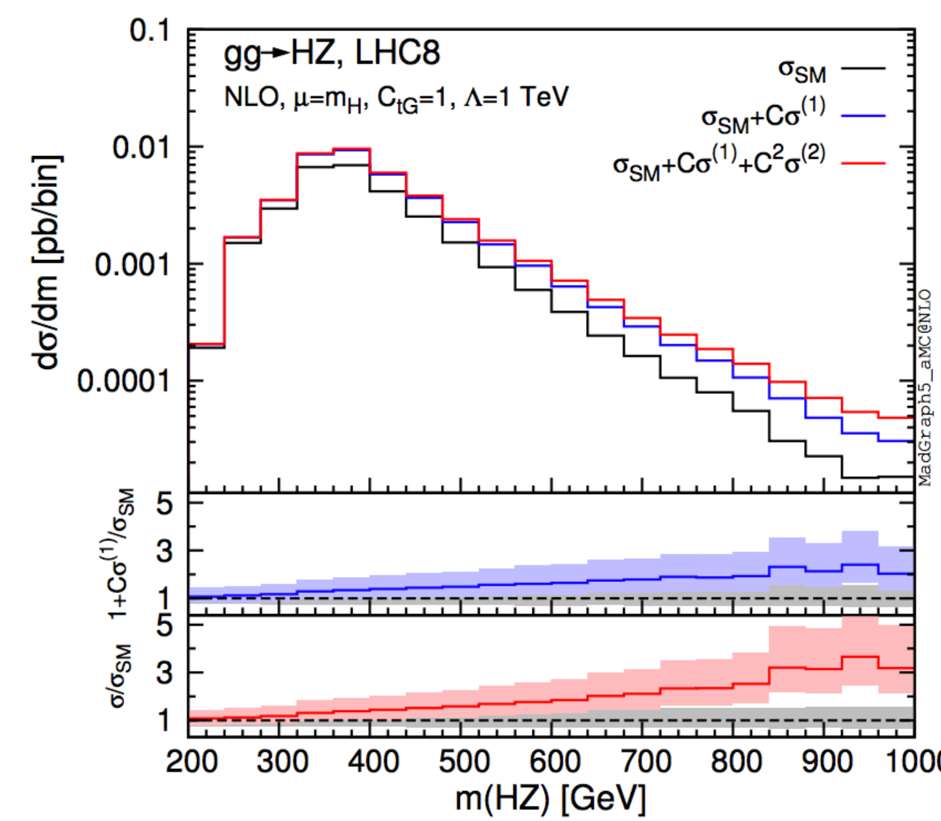


gg, loop-induced



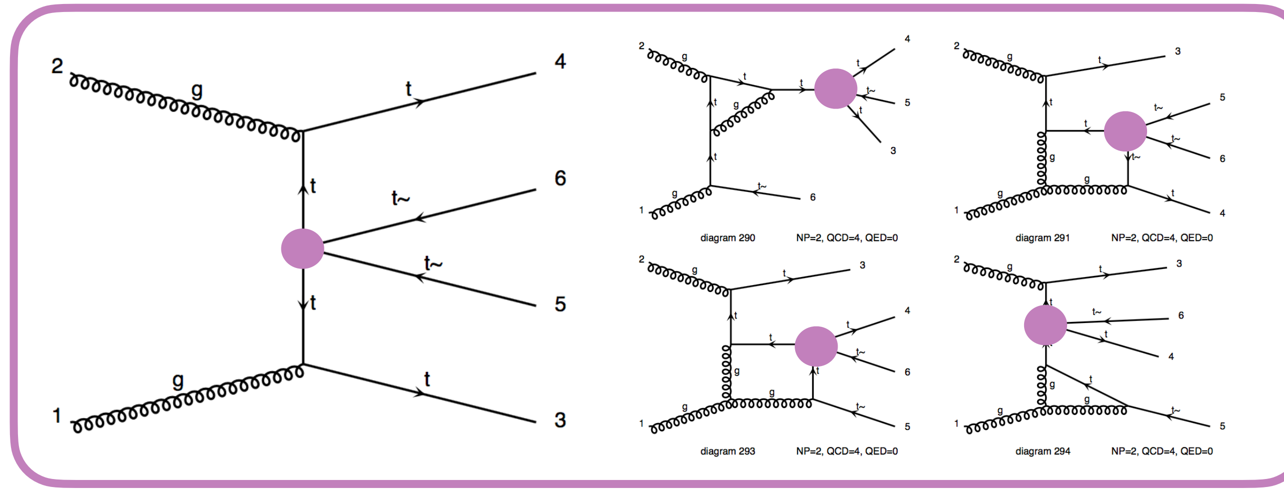
[Bylund et al.; JHEP 1605 (2016) 052]

[fb]	SM		$\mathcal{O}_{tG}$	$\mathcal{O}_{\phi Q}^{(1)}$
8TeV	$29.15^{+40.0\%}_{-26.6\%}$	$\sigma_i^{(1)}$	$10.37^{+41.3\%}_{-27.2\%}$	$1.719^{+42.5\%}_{-27.6\%}$
		$\sigma_i^{(2)}$	$1.621^{+45.1\%}_{-28.7\%}$	$0.0469^{+46.5\%}_{-29.2\%}$
		$\sigma_i^{(1)}/\sigma_{SM}$	$0.356^{+0.9\%}_{-0.8\%}$	$0.0590^{+1.8\%}_{-1.4\%}$
		$\sigma_i^{(2)}/\sigma_i^{(1)}$	$0.156^{+2.6\%}_{-2.0\%}$	$0.0273^{+2.8\%}_{-2.3\%}$
13TeV	$93.6^{+34.3\%}_{-23.8\%}$	$\sigma_i^{(1)}$	$34.6^{+35.2\%}_{-24.5\%}$	$5.91^{+36.4\%}_{-24.9\%}$
		$\sigma_i^{(2)}$	$6.09^{+39.2\%}_{-26.1\%}$	$0.182^{+40.2\%}_{-26.6\%}$
		$\sigma_i^{(1)}/\sigma_{SM}$	$0.370^{+0.7\%}_{-0.9\%}$	$0.0631^{+1.6\%}_{-1.5\%}$
		$\sigma_i^{(2)}/\sigma_i^{(1)}$	$0.176^{+2.9\%}_{-2.1\%}$	$0.0309^{+2.8\%}_{-2.2\%}$



4F in 4 top

[Degrande, Durieux, Maltoni, KM, Vryonidou & Zhang; arXiv:2008.11743]



$\sigma(pp \to t\bar{t}t\bar{t})$ [fb], $c_i/\Lambda^2 = 1\,\mathrm{TeV}^{-2}$

! different from arXiv version !

c_i	*Interference* $\mathcal{O}(\Lambda^{-2})$ LO		NLO	K	*Square* $\mathcal{O}(\Lambda^{-4})$ LO	NLO	K
c^8_{QQ}	$0.081^{+55\%}_{-33\%}$	$[-0.277]$	$0.090^{+4\%}_{-11\%}$	1.1	$0.115^{+46\%}_{-29\%}$	$0.158^{+4\%}_{-11\%}$	1.37
c^8_{Qt}	$0.274^{+54\%}_{-33\%}$	$[-0.365]$	$0.311^{+5\%}_{-10\%}$	1.14	$0.342^{+46\%}_{-29\%}$	$0.378^{+4\%}_{-13\%}$	1.10
c^1_{QQ}	$0.242^{+55\%}_{-33\%}$	$[-0.826]$	$0.24(3)^{+3\%}_{-18\%}$	0.99	$1.039^{+47\%}_{-29\%}$	$1.41^{+4\%}_{-11\%}$	1.36
c^1_{Qt}	$-0.0098(10)^{+38\%}_{-33\%}$	$[0.852]$	$-0.019(9)^{+63\%}_{-27\%}$	1.9	$1.406^{+46\%}_{-30\%}$	$1.86^{+4\%}_{-10\%}$	1.32
c^1_{tt}	$0.483^{+55\%}_{-33\%}$	$[-1.38]$	$0.53(8)^{+3\%}_{-10\%}$	1.10	$4.154^{+47\%}_{-29\%}$	$5.61^{+4\%}_{-11\%}$	1.35

Current limits ~ O(few) TeV^{-2}: square > interference

c_i & normalisation independent measure: $\xi_i \equiv \frac{1}{2}\,|\sigma^i_{\mathrm{int.}}|/(\sigma_{\mathrm{SM}}\sigma^i_{\mathrm{sq.}})^{\frac{1}{2}}$

ξ_{4t}

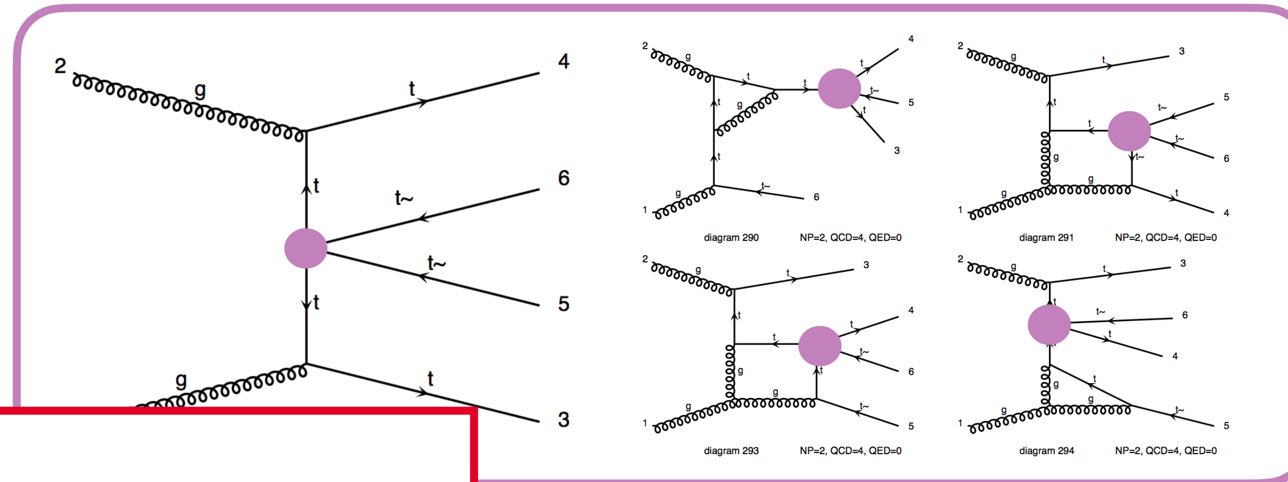
c_{4t}	QQ^8	Qt^8	QQ^1	Qt^1	tt
LO	0.048	0.095	0.048	0.002	0.048
NLO	0.034	0.075	0.03	-	0.034

$\xi_{t\bar{t}}$

c_{2t}	Qq^{8,1}	tq^8	tu^8
LO	0.12	0.12	0.092
NLO	0.096	0.11	0.073

4 top

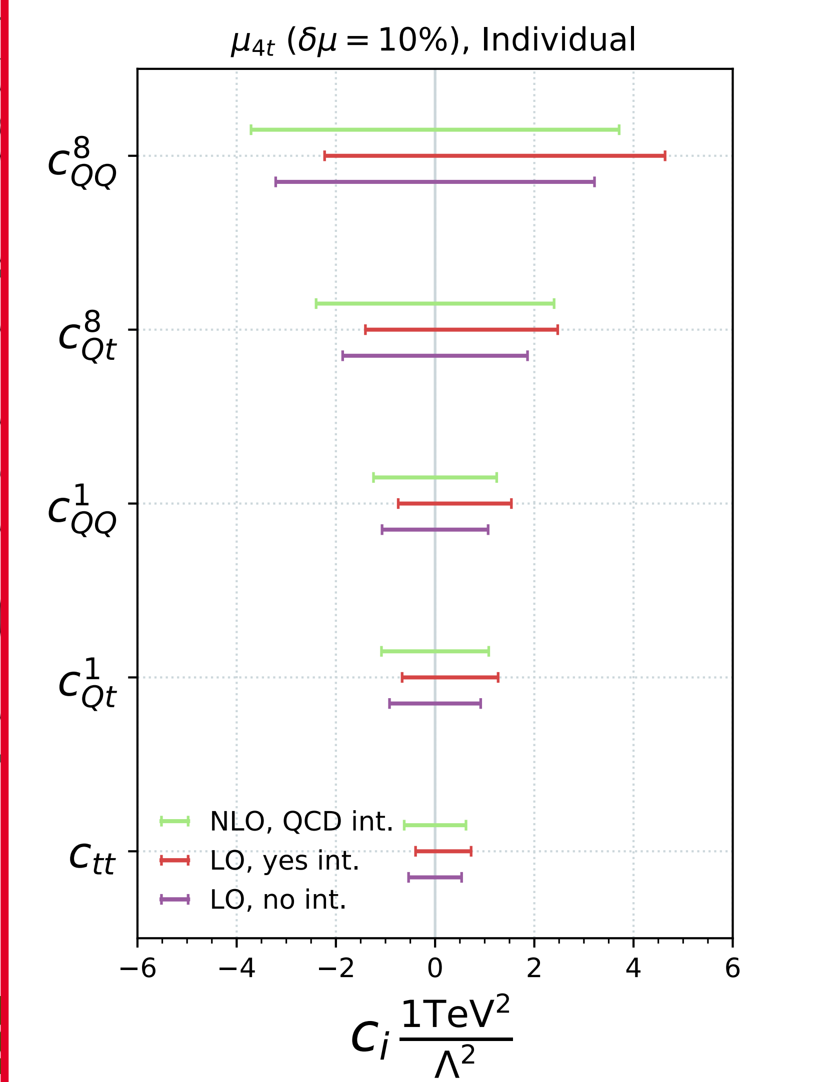
[Degrande, Durieux, Maltoni, KM, Vryonidou & Zhang; arXiv:20



$\sigma(pp \to t\bar{t}t\bar{t})$ [fb], $c_i/\Lambda^2 = 1$ T

...fferent from arXiv version !

c_i	Interference LO		Square LO	$\mathcal{O}(\Lambda^{-4})$ NLO	K
c^8_{QQ}	$0.081^{+55\%}_{-33\%}$	[–	...$5^{+46\%}_{-29\%}$	$0.158^{+4\%}_{-11\%}$	1.37
c^8_{Qt}	$0.274^{+54\%}_{-33\%}$	[–	...$2^{+46\%}_{-29\%}$	$0.378^{+4\%}_{-13\%}$	1.10
c^1_{QQ}	$0.242^{+55\%}_{-33\%}$	[–	...$9^{+47\%}_{-29\%}$	$1.41^{+4\%}_{-11\%}$	0.93
c^1_{Qt}	$-0.0098(10)^{+38\%}_{-33\%}$	[(	...$6^{+46\%}_{-30\%}$	$1.86^{+4\%}_{-10\%}$	1.32
c^1_{tt}	$0.483^{+55\%}_{-33\%}$	[-	...$4^{+47\%}_{-29\%}$	$5.61^{+4\%}_{-11\%}$	1.35



Interference booste... $t\bar{t}t\bar{t}$ amplitude

ξ_{4t}

C_{4t}	QQ^8	Qt^8	QQ^1		
LO	0.048	0.095	0.048	[illegible]	[illegible]
NLO	0.034	0.075	0.03	-	0.034
+EW	0.33	0.25	0.33	0.29	0.27

$\sigma_{\text{sq.}}$

	QQ^8	Qt^8	QQ^1	Qt^1	tt
LO	2.4	1.1	0.8	0.6	0.33
NLO	1.8	1.0	0.6	0.5	0.25
Limit	5.4	6.8	2.0	3.5	1.9

Status in a nutshell

Global new physics searches via high precision/energy

[Han & Skiba; PRD 71 (2005) 075009]
[Falkowski & Riva; JHEP 02 (2015) 039]

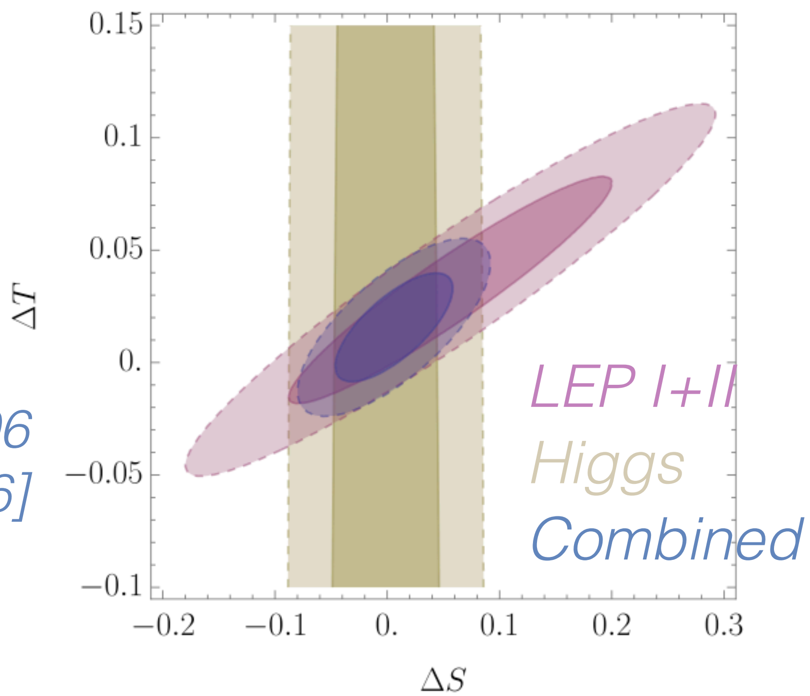
- Z & W-pole data: handle on the EW gauge sector
- LHC: thriving Higgs & top programmes
- Probing gauge interactions at high energy (VV, VBS, VVV, …)

How much cross-talk? Where does being global matter?

We know that Higgs physics greatly complements LEP data

- Access to parameter directions not probed at LEP
- Allows for a closed fit to flavor-universal SMEFT
- Crucial to combine EWPO, Diboson & Higgs data

[Corbett et al.; PRD 87 (2013) 015022]
[Pomarol & Riva; JHEP 01 (2014) 151]
[Ellis, Sanz & You; JHEP 03 (2015) 157]
[Biekötter Corbett & Plehn; SciPost Phys 6 (2019) 6, 064]…
[Ellis et al.; JHEP 06 (2018) 146]



The fit

arXiv:2012.02779 **Top, Higgs, Diboson and Electroweak Fit to the Standard Model Effective Field Theory**

John Ellis,[a,b,c] Maeve Madigan,[d] Ken Mimasu,[a] Veronica Sanz[e,f] and Tevong You[b,d,g]

Global SMEFT interpretation of 4 categories of data

14 • Electroweak Precision Observables (EWPO): Z-pole & W-mass

118 • LEP2 & LHC diboson production: differential WW, WZ, Zjj

72 • Higgs measurements: signal strengths & STXS

124 • Top data: single-top, ttbar & asymmetries, ttV, tZ, tW

Based on [Ellis et al.; JHEP 06 (2018) 146]

Big thanks to authors of SMEFiT analysis [JHEP 04 (2019) 100] for sharing some of their top predictions

328 measurements across categories

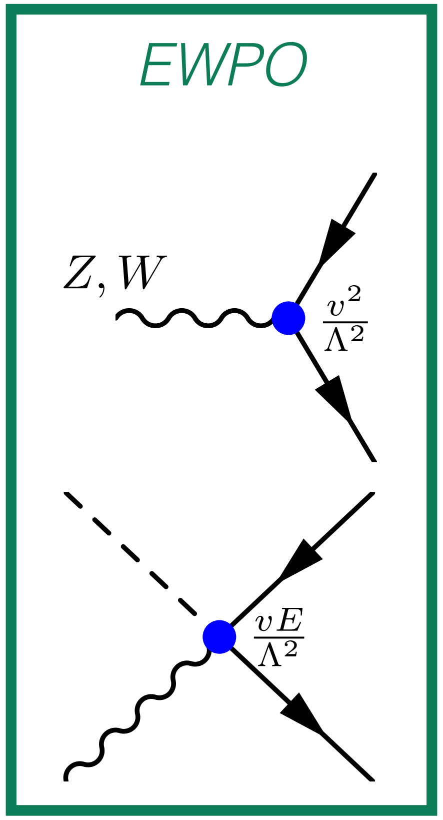
- Chosen to be statistically independent & maximise reach
- Correlations included when publicly available (mostly are)

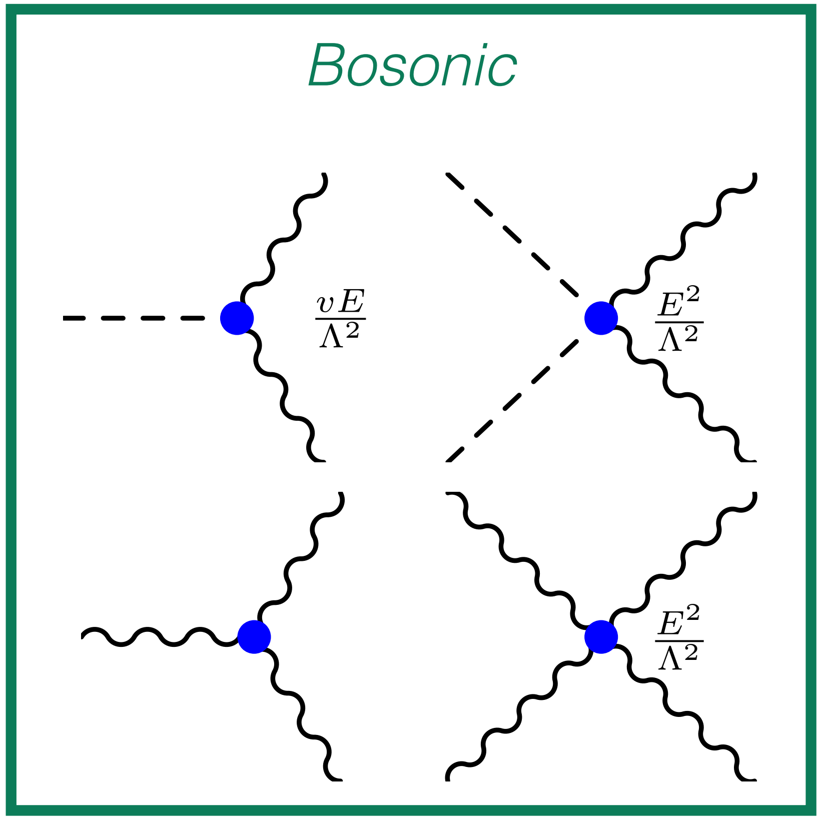
Linear EFT approximation: $$\mu_X \equiv \frac{X}{X_{SM}} = 1 + \sum_i a_i^X \frac{C_i}{\Lambda^2} + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

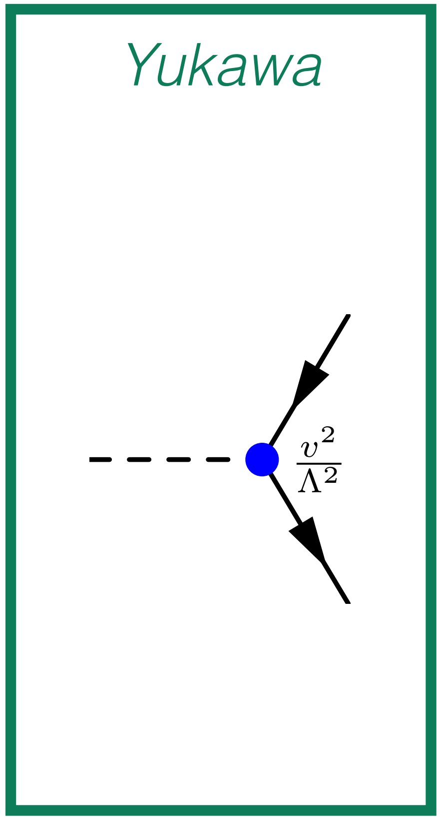
Degrees of freedom

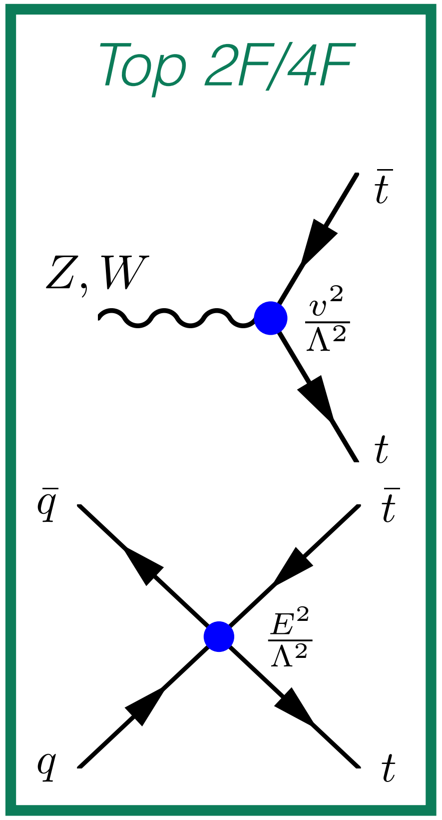
EWPO:	$\mathcal{O}_{HWB}\,,\ \mathcal{O}_{HD}\,,\ \mathcal{O}_{ll}\,,\ \mathcal{O}_{Hl}^{(3)}\,,\ \mathcal{O}_{Hl}^{(1)}\,,\ \mathcal{O}_{He}\,,\ \mathcal{O}_{Hq}^{(3)}\,,\ \mathcal{O}_{Hq}^{(1)}\,,\ \mathcal{O}_{Hd}\,,\ \mathcal{O}_{Hu}\,,$	
Bosonic:	$\mathcal{O}_{H\Box}\,,\ \mathcal{O}_{HG}\,,\ \mathcal{O}_{HW}\,,\ \mathcal{O}_{HB}\,,\ \mathcal{O}_{W}\,,\ \mathcal{O}_{G}\,,$	
Yukawa:	$\mathcal{O}_{\tau H}\,,\ \mathcal{O}_{\mu H}\,,\ \mathcal{O}_{bH}\,,\ \mathcal{O}_{tH}\,,$	20
Top 2F:	$\mathcal{O}_{HQ}^{(3)}\,,\ \mathcal{O}_{HQ}^{(1)}\,,\ \mathcal{O}_{Ht}\,,\ \mathcal{O}_{tG}\,,\ \mathcal{O}_{tW}\,,\ \mathcal{O}_{tB}\,,$	
Top 4F:	$\mathcal{O}_{Qq}^{3,1}\,,\ \mathcal{O}_{Qq}^{3,8}\,,\ \mathcal{O}_{Qq}^{1,8}\,,\ \mathcal{O}_{Qu}^{8}\,,\ \mathcal{O}_{Qd}^{8}\,,\ \mathcal{O}_{tQ}^{8}\,,\ \mathcal{O}_{tu}^{8}\,,\ \mathcal{O}_{td}^{8}\,.$	+14

In total: 20(34) d.o.f. for the two flavor scenarios

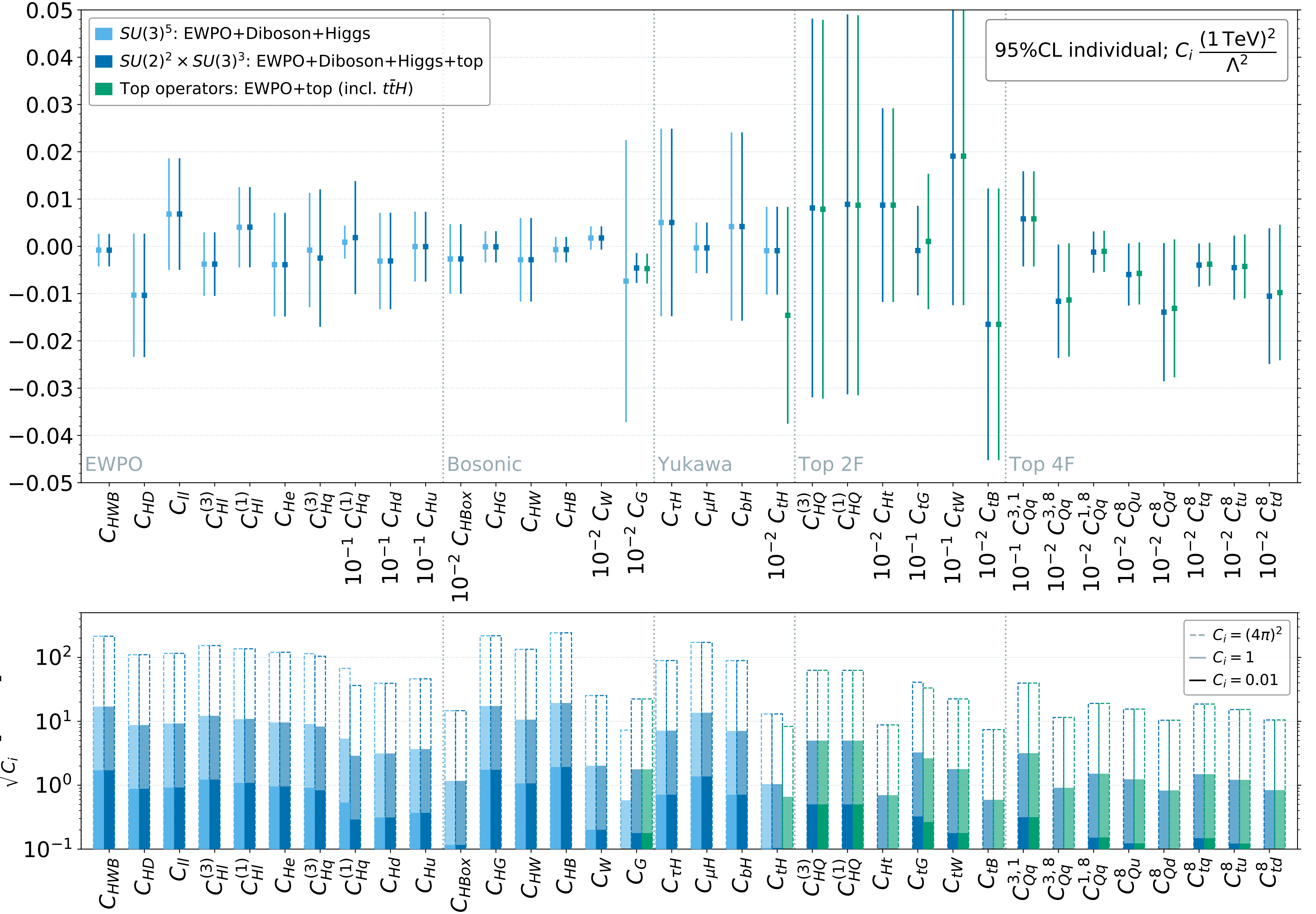




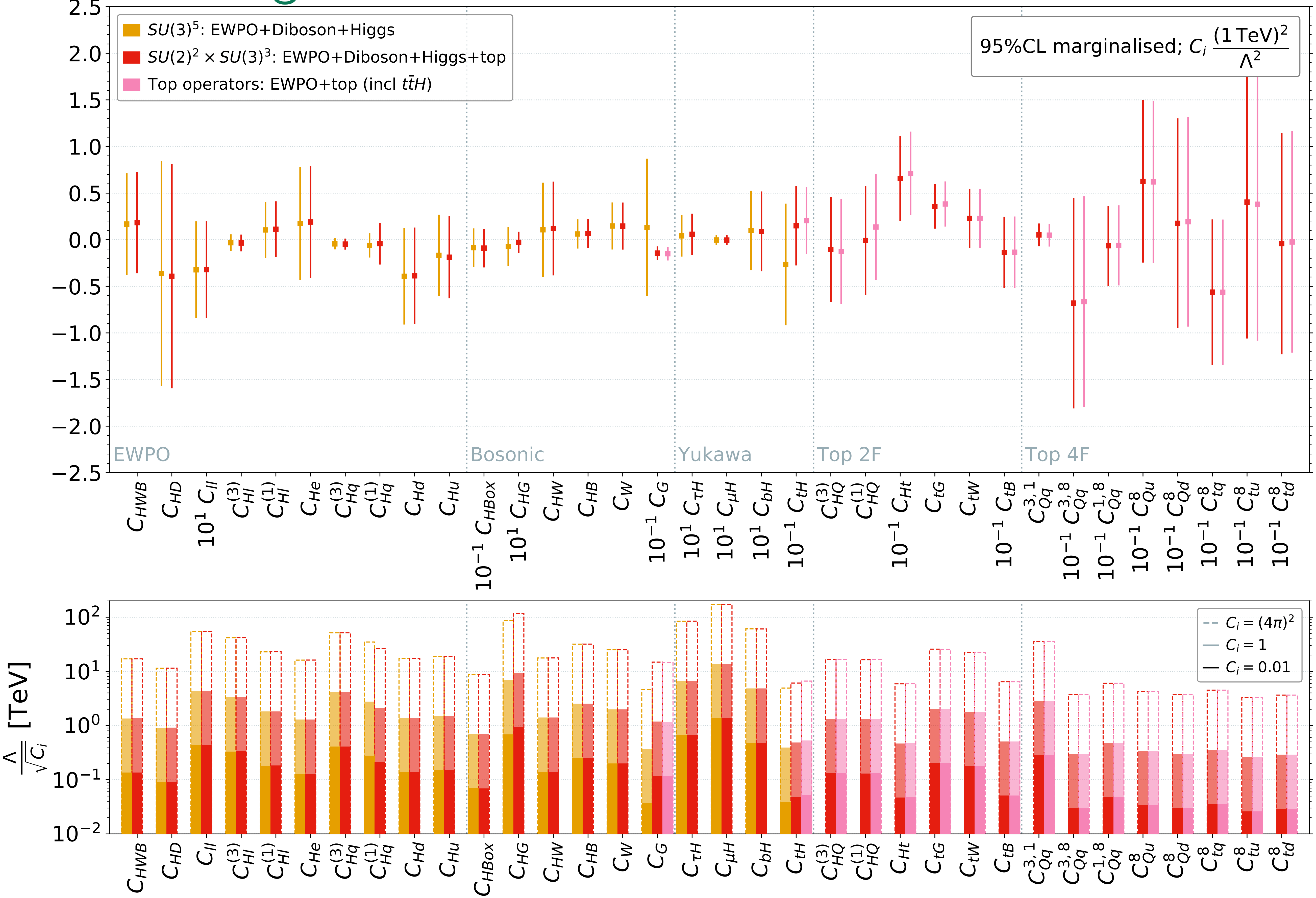




Full fit: individual



Full fit: marginalised



Correlations

Block diagonal: correlations *within* 'sector'

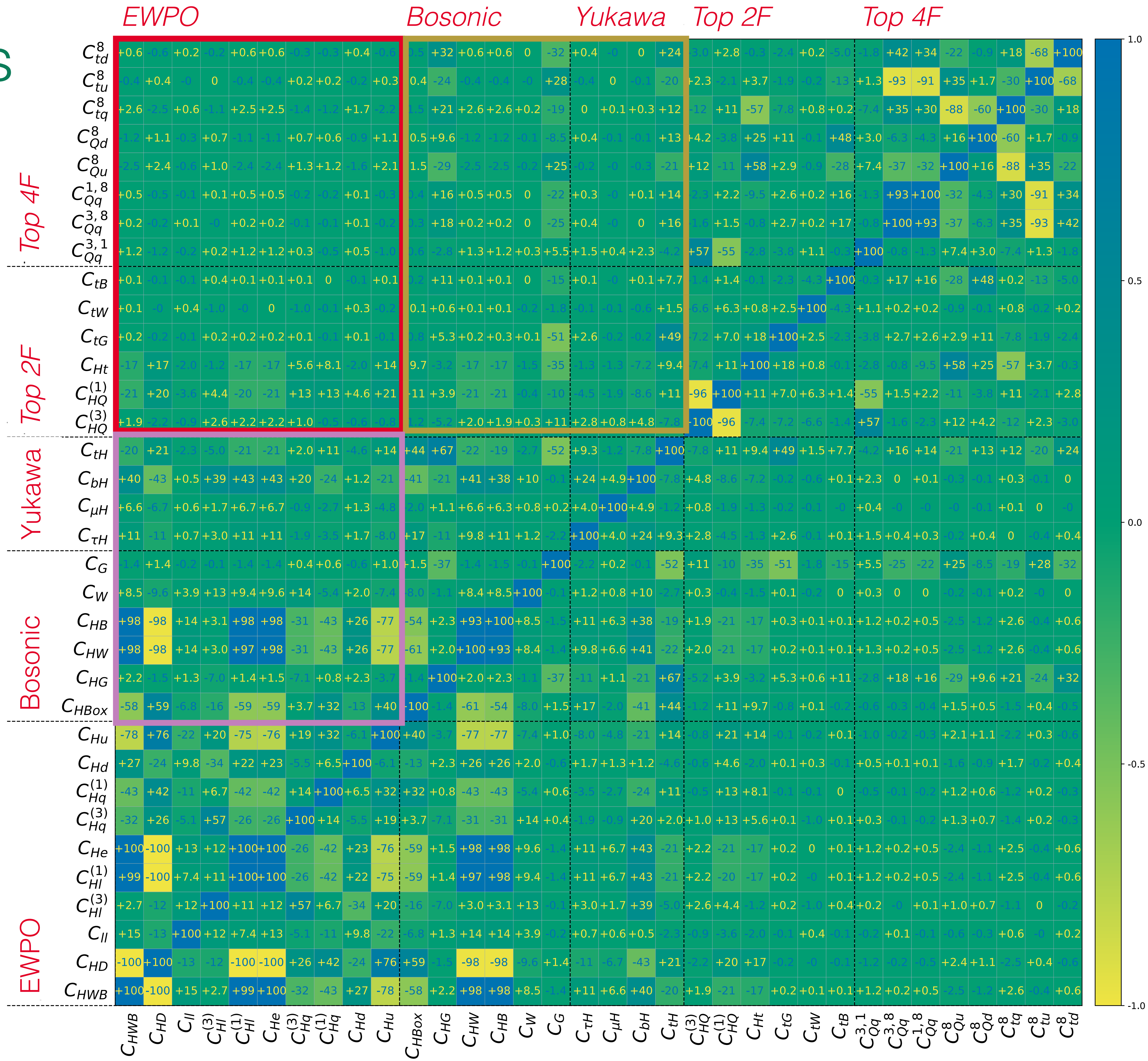
Block off-diagonal: correlations *among* 'sectors'

EWPO & top ~uncorrelated

EWPO-Higgs $C_{HB}, C_{HW}, C_{H\Box}$ & Yukawa with EWPO

Higgs precision rivalling LEP

Top-Higgs C_{HG}, C_G, C_{tH} with 4F



PCA

Relative constraining power (%)

EWPO	LEP WW	Run 1, μ	Run 2, μ	STXS	LHC WW	LHC Zjj	$t\bar{t}$	single top	$t\bar{t}V$
6	–	15	29	50	–	–	–	–	–
35	–	13	28	23	–	–	–	–	–
59	–	7	16	18	–	–	–	–	–
–	–	5	94	1	–	–	–	–	–
99	–	–	–	–	–	–	–	–	–
95	–	–	–	–	3	–	–	–	–
99	–	–	–	–	–	–	–	–	–
–	–	21	45	33	–	–	–	–	–
74	–	2	4	14	6	–	–	–	–
18	–	8	19	55	–	–	–	–	–
73	22	–	–	–	3	–	–	–	–
7	2	5	53	4	29	–	–	–	–
–	–	–	3	–	–	–	–	96	–
7	–	2	39	2	46	–	–	3	–
–	–	–	10	4	–	–	57	–	28
94	2	–	–	–	2	–	–	–	–
–	2	–	–	–	11	86	–	–	–
65	14	2	4	10	4	1	–	–	–
–	–	–	–	–	–	–	99	–	–
–	–	–	–	–	–	–	84	15	–
–	–	–	13	6	–	–	48	–	32
90	5	–	–	1	2	–	–	–	–
–	–	–	5	2	–	–	79	–	13
–	–	–	–	–	–	–	3	78	18
2	3	27	40	12	6	–	4	–	4
–	–	1	2	–	–	–	15	4	77
4	4	14	33	23	7	1	12	–	2
–	–	1	3	1	–	–	4	–	89
–	–	3	10	4	–	–	28	2	53
1	–	8	27	16	2	–	32	–	12
–	–	–	–	–	–	–	58	–	41
–	–	–	–	–	–	–	90	–	10
–	–	–	–	–	–	–	61	–	38
–	–	–	–	–	–	–	95	–	5

Single field extensions

Name	Spin	SU(3)	SU(2)	U(1)	Name	Spin	SU(3)	SU(2)	U(1)
S	0	1	1	0	Δ_1	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
S_1	0	1	1	1	Δ_3	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
φ	0	1	2	$\frac{1}{2}$	Σ	$\frac{1}{2}$	1	3	0
Ξ	0	1	3	0	Σ_1	$\frac{1}{2}$	1	3	-1
Ξ_1	0	1	3	1	U	$\frac{1}{2}$	3	1	$\frac{2}{3}$
B	1	1	1	0	D	$\frac{1}{2}$	3	1	$-\frac{1}{3}$
B_1	1	1	1	1	Q_1	$\frac{1}{2}$	3	2	$\frac{1}{6}$
W	1	1	3	0	Q_5	$\frac{1}{2}$	3	2	$-\frac{5}{6}$
W_1	1	1	3	1	Q_7	$\frac{1}{2}$	3	2	$\frac{7}{6}$
N	$\frac{1}{2}$	1	1	0	T_1	$\frac{1}{2}$	3	3	$-\frac{1}{3}$
E	$\frac{1}{2}$	1	1	-1	T_2	$\frac{1}{2}$	3	3	$\frac{2}{3}$
T	$\frac{1}{2}$	3	1	$\frac{2}{3}$	TB	$\frac{1}{2}$	3	2	$\frac{1}{6}$

Considered single field extensions of the SM

- Complete tree-level matching dictionary is known *[de Blas et al.; JHEP 03 (2018) 109]*
- Interpret in terms of simplified 1 & 2 parameter versions of the models

One parameter models

Model	C_{HD}	C_{ll}	C^3_{Hl}	C^1_{Hl}	C_{He}	$C_{H\Box}$	$C_{\tau H}$	C_{tH}	C_{bH}
S						-1			
S_1		1							
Σ			$\frac{5}{8}$	$\frac{3}{16}$			$\frac{y_\tau}{4}$		
Σ_1			$-\frac{5}{8}$	$-\frac{3}{16}$			$\frac{y_\tau}{8}$		
N			$-\frac{1}{4}$	$\frac{1}{4}$					
E			$-\frac{1}{4}$	$-\frac{1}{4}$			$\frac{y_\tau}{2}$		
Δ_1					$\frac{1}{2}$		$\frac{y_\tau}{2}$		
Δ_3					$-\frac{1}{2}$		$\frac{y_\tau}{2}$		
B_1	1					$-\frac{1}{2}$	$-\frac{y_\tau}{2}$	$-\frac{y_t}{2}$	$-\frac{y_b}{2}$
Ξ	-2					$\frac{1}{2}$	y_τ	y_t	y_b
W_1	$-\frac{1}{4}$					$-\frac{1}{8}$	$-\frac{y_\tau}{8}$	$-\frac{y_t}{8}$	$-\frac{y_b}{8}$
φ							$-y_\tau$	$-y_t$	$-y_b$
$\{B, B_1\}$						1	y_τ	y_t	y_b
$\{Q_1, Q_7\}$								y_t	

Model	C_{HG}	C^3_{Hq}	C^1_{Hq}	$(C^3_{Hq})_{33}$	$(C^1_{Hq})_{33}$	C_{Hu}	C_{Hd}	C_{tH}	C_{bH}
U		$-\frac{1}{4}$	$\frac{1}{4}$	$-\frac{1}{4}$	$\frac{1}{4}$			$\frac{y_t}{2}$	
D		$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{4}$				$\frac{y_b}{2}$
Q_5							$-\frac{1}{2}$		$\frac{y_b}{2}$
Q_7						$\frac{1}{2}$		$\frac{y_t}{2}$	
T_1		$-\frac{5}{8}$	$-\frac{3}{16}$	$-\frac{5}{8}$	$-\frac{3}{16}$			$\frac{y_t}{4}$	$\frac{y_b}{8}$
T_2		$-\frac{5}{8}$	$\frac{3}{16}$	$-\frac{5}{8}$	$\frac{3}{16}$			$\frac{y_t}{8}$	$\frac{y_b}{4}$
T	$-\frac{M_T^2}{v^2}\frac{\alpha_s(0.02)}{8\pi}$			$-\frac{1}{2}\frac{M_T^2}{v^2}$	$\frac{1}{2}\frac{M_T^2}{v^2}$			$y_t\frac{M_T^2}{v^2}$	

$$\times \frac{\lambda^2}{M^2}$$

One parameter models