SMEFT(@NLO) operators in MadGraph

G. Durieux, C. Degrande, F. Maltoni, KM, C. Zhang, E. Vryonidou;
PRD 103 (2021) 9, 096024

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

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King's College London

SMEFT-Tools workshop, University of Zurich

14th of September 2022

Outline

Recent progress in SMEFT implementations for **MG5**

- "recent": since the last SMEFT-Tools workshop in 2019 ;)

MC tools for SMEFT (dim-6) are quite mature

HEL *[Alloul et al.; JHEP 1404 (2014) 110]* http://feynrules.irmp.ucl.ac.be/wiki/HEL

SMEFTfr *[Dedes et al.; JHEP 1706 (2017) 143]* *[Misiak et al.; JHEP 1902 (2019) 051]* htttps://www.few.edu.pl/smeft

SMEFTsim *[Brivio et al.; JHEP 1712 (2017) 070]* *[Brivio; JHEP 04 (2021) 073]* https://smeftsim.github.io

dim6top *[Aguilar-Saavedra et al.; arXiv:1802.07237]* *http://feynrules.irmp.ucl.ac.be/wiki/dim6top*

- Other "process-specific" implementations: **POWHEG-BOX**, **MFCM**, **HPAIR**,…

SMEFTsim is the standard for LO exp./pheno analysis

Ilaria's talk on Friday

My focus today: NLO/loops via **SMEFTatNLO**

- Motivation & selected results
- Applications (improving NP sensitivity)

[Degrande, et al.; EPJC 77 (2017) 4, 262] http://feynrules.irmp.ucl.ac.be/wiki/HELatNLO

[Durieux, et al.; PRD 103 (2021) 9, 096024] http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO

SMEFT is…

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

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

Peter's talk
Jorge's on Friday

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

$\mathscr{L}(c_i) \Rightarrow$ **indirectly constrain many UV models**

SMEFT interpretation

Improving sensitivity means improving…

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

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 ⇒ **NLO**

Why NLO/loops?

In general: improve precision/accuracy of predictions

- Correct normalisations & shapes, better scale & PDF uncertainties

Old reasons: same as for SM predictions

- QCD corrections: a minimum to control hadron collider uncertainties
- EW corrections: for extra accuracy and in specific phase space regions

New reasons: specific to (SM)EFT interpretation

- First order where non-trivial effects come in: **running & mixing** of coefficients
- Opportunities for **loop-induced** sensitivity: new contributions at loop level
- Best possible understanding of patterns & correlations among coefficients

Deviations?	✗	✓
Better:	*Reflection of new physics* ***reach***	*Pinpointing of new physics* ***origin***

Running & mixing

EFT based on existence of scale separation: $\Lambda_{BSM} \gg E_{exp.}$

- Coefficients are generated (matching) & measured at different scales
- QFT: couplings depend on the scale at which they are defined (running)
- EFT: couplings **run & mix** into one another $\Rightarrow$ anomalous dimensions γ_{ij}

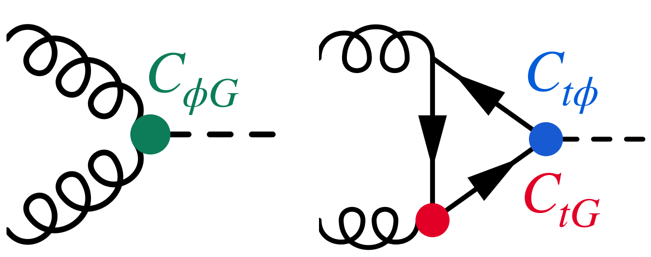
$$\frac{dc_i(\mu)}{d\log\mu} = \frac{\alpha(\mu)}{\pi}\gamma_{ij}c_j(\mu)$$

Assuming $c_i = 0$ at low scale is not valid

ex: Gluon fusion Higgs production

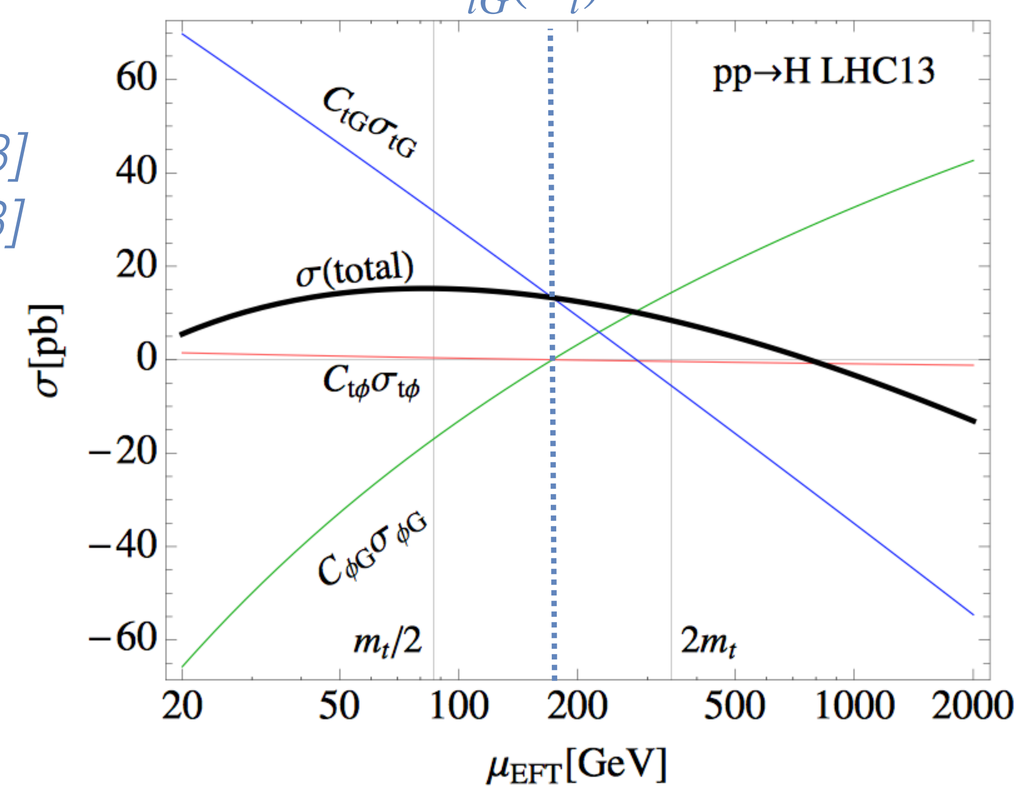
[Maltoni, Vryonidou & Zhang; JHEP 1610 (2016) 123]

[Deutschmann et al.; JHEP 1712 (2017) 063]



$C_{\phi G}$ (LO) scale dep. cancelled by running C_{tG} (NLO)

$C_{tG}(m_t) = 1$



Only **global** approach makes sense

Finite terms

RG structure is universal ⇒ process independent

- Only encodes a part of the NLO corrections
- **'LO-like'** & only relevant when a measurement probes very different scales

Counterpart: finite terms ⇒ process dependent

- **'Genuine NLO'** & must be studied process-by-process
- Often dominant over RG for LHC energy ($E_{exp.}$) & sensitivity (Λ_{BSM})

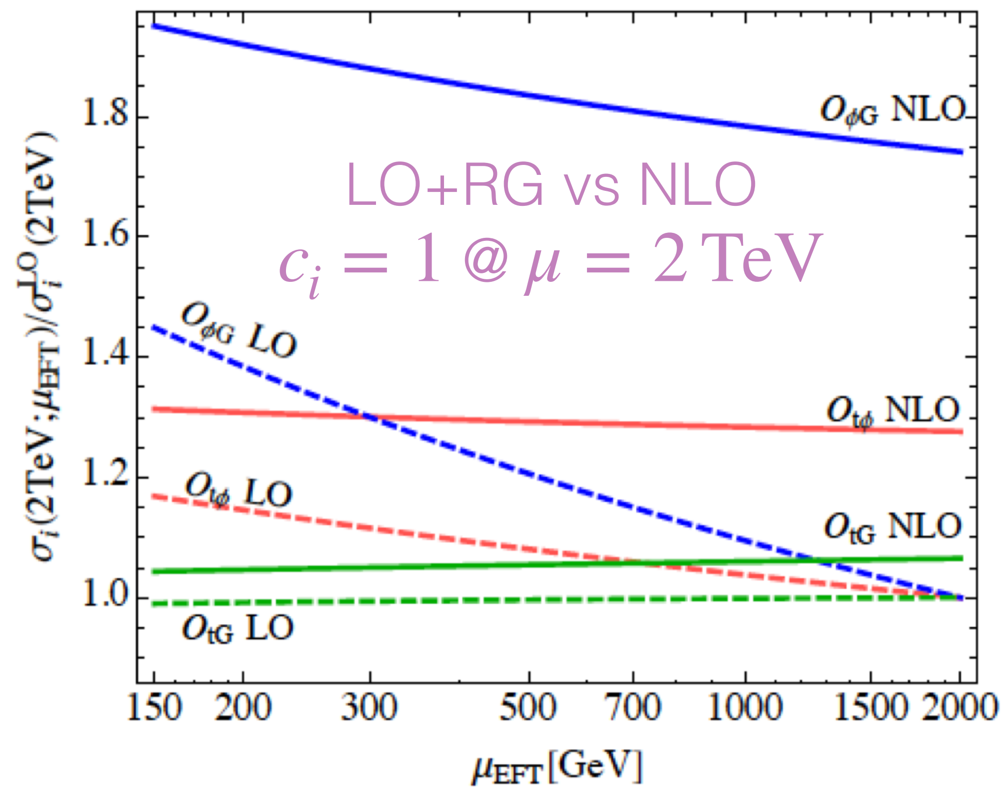
ex: $t\bar{t}H$ production

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

- RG severely underestimates NLO
- Similar observations in other calculations, *e.g.*, Higgs & Z boson decays

[Gauld, Pecjak & Scott; PRD 94 (2016) 7, 074045]

[Hartmann, Shepherd & Trott; JHEP 03 (2017) 060]

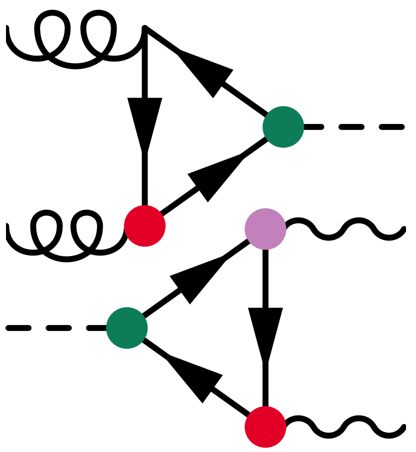


Loop sensitivity

Not just higher precision: new, loop-induced sensitivity

- Operators can appear for the first time at loop-level
- Weakly constrained directions meet precisely measured observables
- ➡ Large allowed Wilson coefficients overcome loop factors

Example: top couplings in hVV vertex

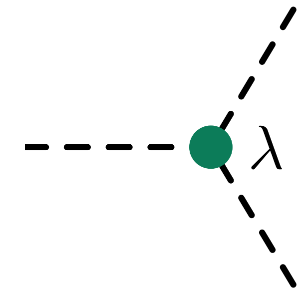


- Yukawa, current & dipole couplings in $gg \to h$ & $h \to \gamma\gamma/Z\gamma$
- (Weakly) constrained at tree-level by $t\bar{t}\gamma/Z/H$ & $t\bar{t}$

Top EW coupling bounds dominated by Higgs data!

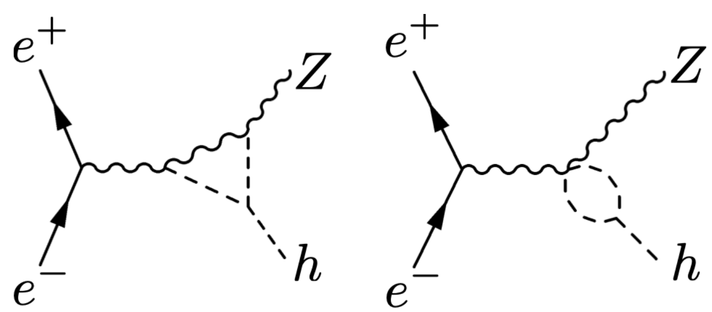
- Weak dipoles & $Z\bar{t}t$ current operators $\left(C_{tW}, C_{tZ}, C^{(-)}_{\varphi Q}, C^{3}_{\varphi Q}, C_{\varphi t}\right)$ [Ethier et al.; JHEP 11 (2021) 089]
- Also contributions to $gg \to Zh/ZZ/Z\gamma/WW$
- Complementary indirect sensitivity from non-top data

Loop sensitivity: κ_λ



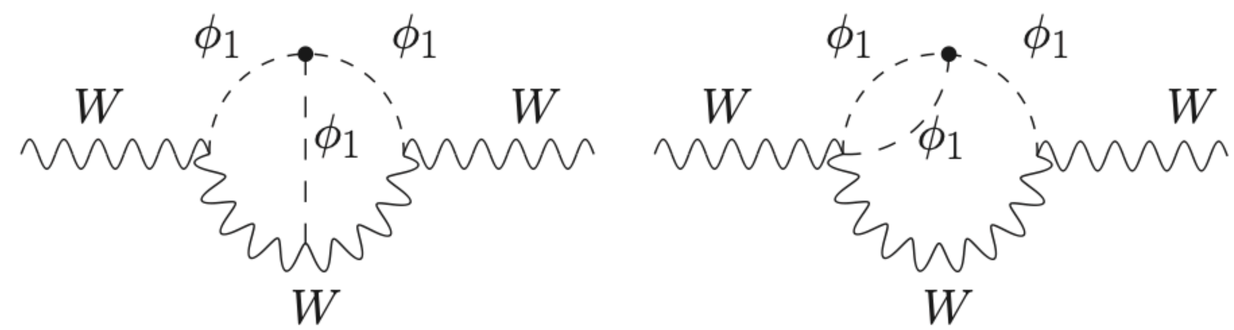
Higgs **self-coupling** sensitivity in **single-Higgs** production

e^+e^- collider



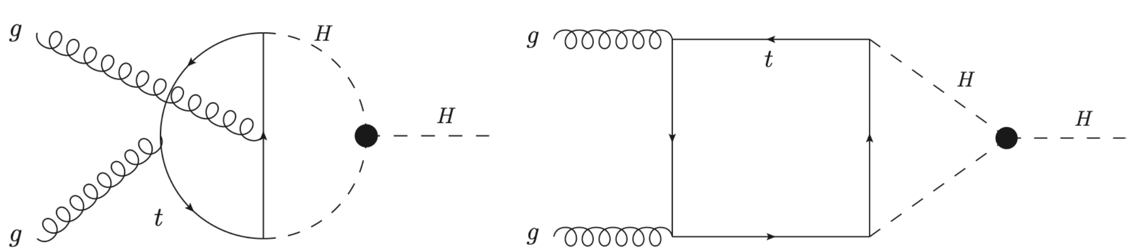
[McCullough; PRD 90 (2014) 1, 015001]

EW precision observables

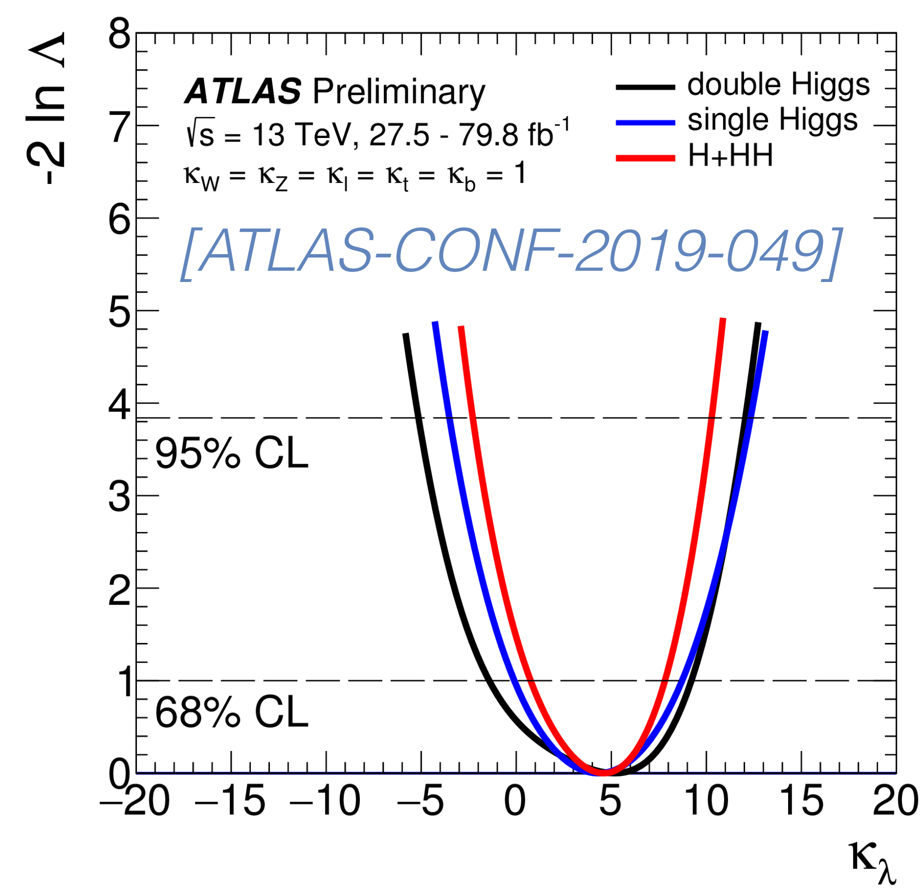


[Degrassi, Fedele & Giardino; JHEP 04 (2017) 155]

LHC



[Gorbahn & Haisch; JHEP 10 (2016) 094]
[Degrassi et al.; JHEP 12 (2016) 080]



[ATLAS-CONF-2019-049]

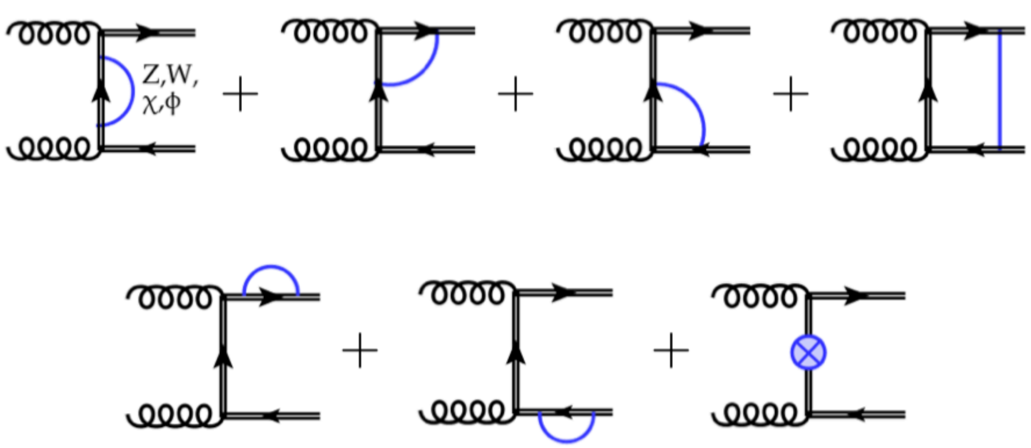
Loop sensitivity in top data

Precision measurements $\Rightarrow$ $t\bar{t}$ production

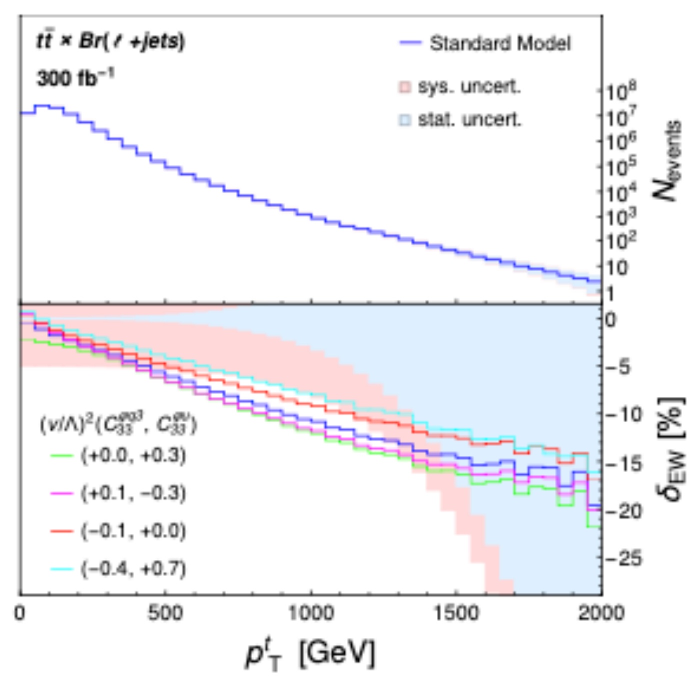
- Few-percent-level precision at LHC

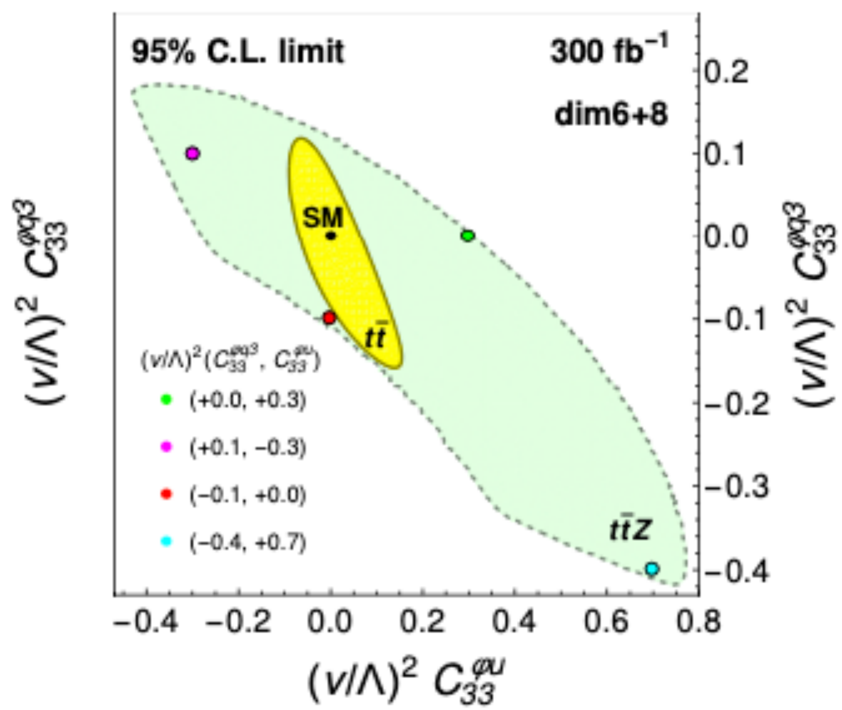
EW top couplings: loops of tops & EW gauge bosons

- Enhanced at high energy by logarithms of $\hat{s}/m_V^2$



[Martini & Schulze; JHEP 04 (2020) 017]

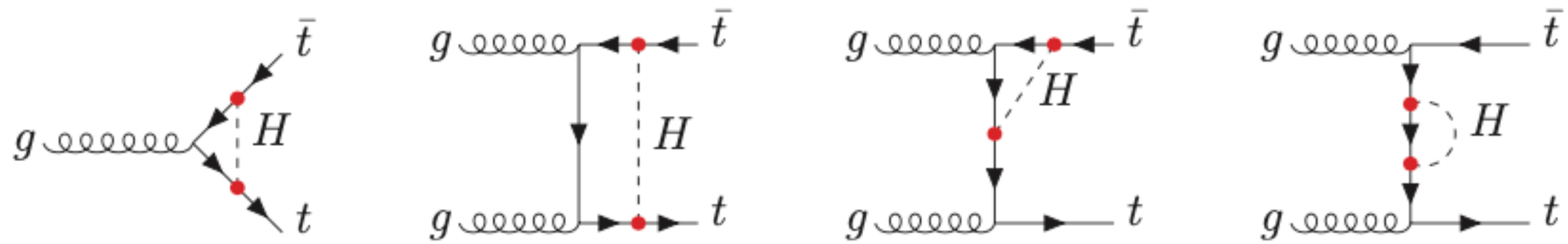




Promising sensitivity to current operators

- Better than $t\bar{t}Z$ prospects using $\Delta\phi_{\ell\ell}$ distribution with 300 fb^{-1}

y_t in $t\bar{t}$



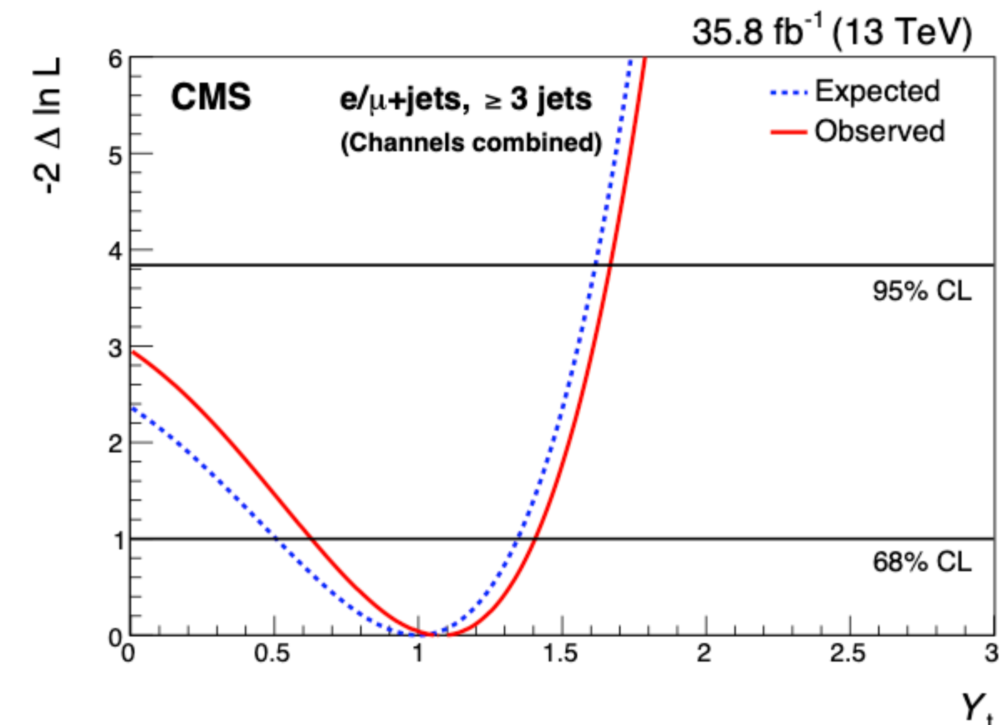
Top Yukawa coupling

- Electroweak corrections to $t\bar{t}$ known for ~ 15 years
- Proposal to constrain y_t recently carried out by CMS
- Double differential $(m_{t\bar{t}}, |\Delta y_{t\bar{t}}|)$ measurement

[Kühn, Scharf & Uwer; PRD 91 (2015) 1, 014020]

[CMS; PRD 100, 072007 (2019)]

Channel	Best fit Y_t		95% CL upper limit	
	Expected	Observed	Expected	Observed
3 jets	$1.00^{+0.66}_{-0.90}$	$1.62^{+0.53}_{-0.78}$	<2.17	<2.59
4 jets	$1.00^{+0.50}_{-0.72}$	$0.87^{+0.51}_{-0.77}$	<1.88	<1.77
≥5 jets	$1.00^{+0.59}_{-0.83}$	$1.27^{+0.55}_{-0.74}$	<2.03	<2.23
Combined	$1.00^{+0.35}_{-0.48}$	$1.07^{+0.34}_{-0.43}$	<1.62	<1.67



CPV extension: *[Martini et al.; PRD 104 (2021) 5, 055045]*

$$-\frac{m_t}{v}\bar{\psi}_t\left(\kappa + \mathrm{i}\,\tilde{\kappa}\gamma_5\right)\psi_t\, H \Leftrightarrow \kappa = 1 - \frac{v}{\sqrt{2}m_t}\frac{v^2}{\Lambda^2}\mathrm{Re}\left[C_{tt}^{u\varphi}\right], \quad \tilde{\kappa} = -\frac{v}{\sqrt{2}m_t}\frac{v^2}{\Lambda^2}\mathrm{Im}\left[C_{tt}^{u\varphi}\right]$$

Automation

Loop computations in 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.; PRD 103 (2021) 9, 096024]
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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	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}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

Some symmetries imposed to control parameter space

- CP, B and flavor conservation, CKM = **1**
- Top-specific flavour structure of 2 & 4 fermion operators 2499 ⇒ ~80

see `dim6top` [Aguilar-Saavedra et al.; arXiv:1802.07237]

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

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	$\psi^4 : (\bar{Q}\, \gamma^\mu\, Q)(\bar{q}\, \gamma_\mu\, q), (\bar{Q}\, \gamma^\mu\, Q)(\bar{Q}\, \gamma_\mu\, Q), \ldots$

cf. Minimal flavor violation

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

See `dim6top`

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

Implementation

FeynRules $\Rightarrow$ $\mathscr{L}_{\text{renorm.}}$ $\Rightarrow$ FeynArts $\Rightarrow$ $\mathscr{A}_{\text{loop}}$ $\Rightarrow$ CTs $\Rightarrow$ UFO

[Degrande; Comput.Phys.Commun. 197 (2015) 239-262]

Counterterms: **FeynRules** module **NLOCT**

- Renormalisation: UV - MSbar for couplings, on-shell for mass & WF
- Finite: R2 - rational terms from the numerator of d-dim. loop integrals *[Ossola, Papadopoulos & Pittau; JHEP 05 (2008) 004]*

* Dev. version needed for higher rank integrals in SMEFT/new color algebra

- Evanescent operators: follow *[Buras & Weisz; Nucl. Phys. B 333 (1990) 66]*
- γ^5: anti-commuting, no cyclic trace property, 'reading points' for Dirac trace *[Kreimer; arXiv:hep-ph/9401354]*
- Anomalies: 'covariant scheme' to preserve QCD Ward identity

[Bardeen & Zumino; Nucl. Phys. B 244 (1984) 421]
[Fox, Low & Zhang; JHEP 03 (2018) 074]
See also: [Ferruglio; JHEP 03 (2021) 128]
[Bonnefoy et al.; JHEP 05 (2021) 153]
Talk by L. Vecchi tomorrow

Currently:
Up to 5 pt amplitudes
Loops involving the strong coupling OR 4F operators

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

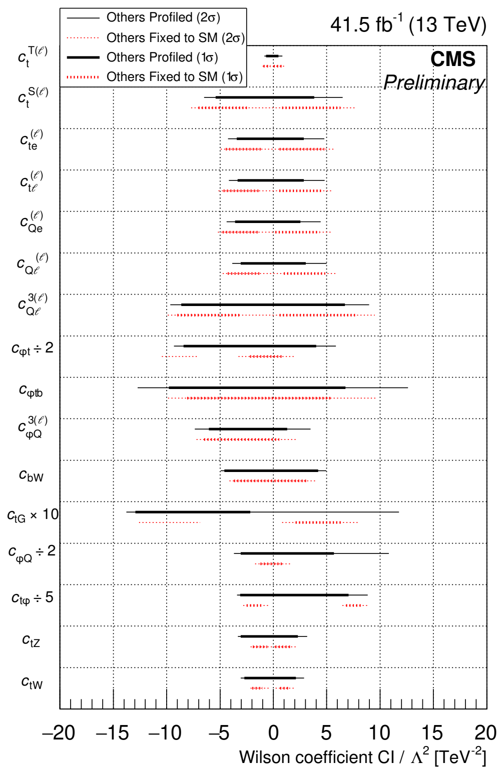
Validated at LO against existing implementations

- `dim6top` & `SMEFTsim`

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

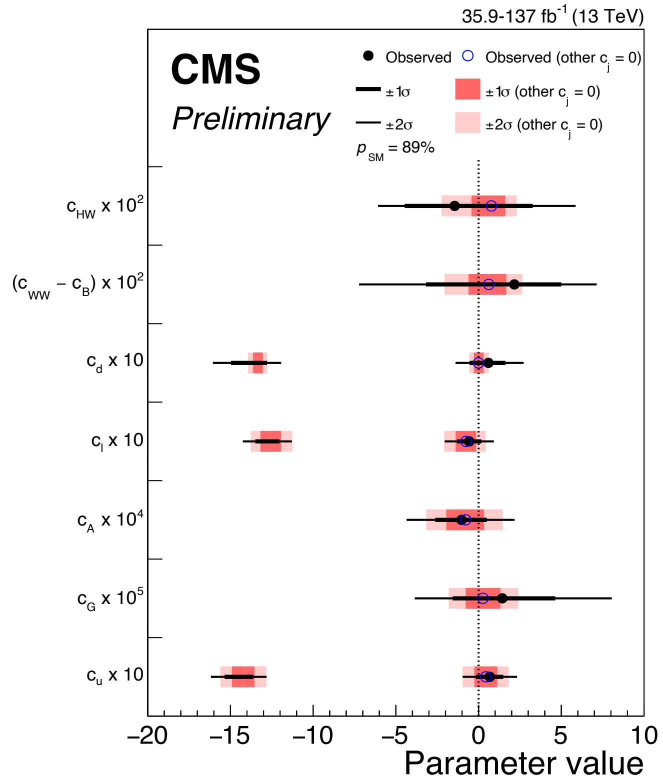
[CMS-PAS-TOP-001]

ttH, ttZ, ttW, tW, tZ, tH



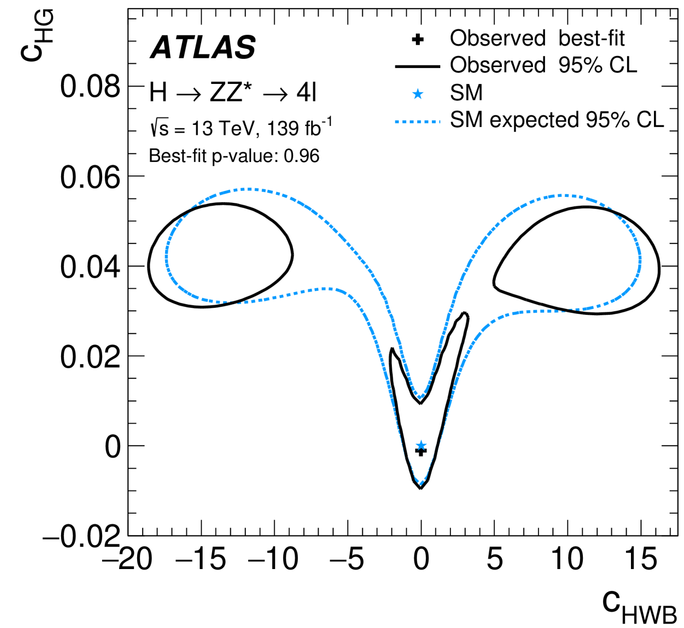
[CMS-PAS-HIG-19-005]

Higgs combination



[CERN-EP-2020-034]

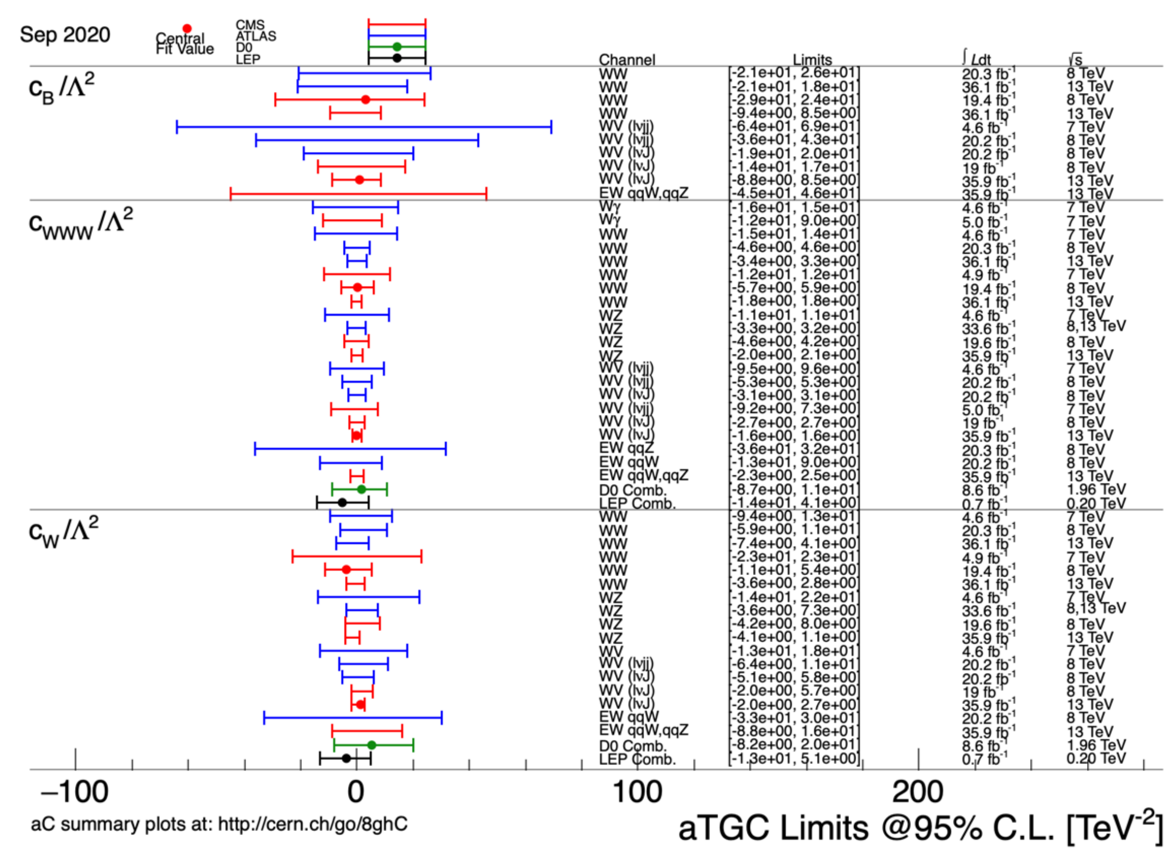
H → 4l



NLO QCD OK ✔

hh (LO), VVV, VBS, tt, 4top, …

WW & WZ



[ATLAS; PRD 99 (2017) 072009]

ttV

Coefficients	$\mathcal{C}^{(3)}_{\phi Q}/\Lambda^2$	$\mathcal{C}_{\phi t}/\Lambda^2$	$\mathcal{C}_{tB}/\Lambda^2$	$\mathcal{C}_{tW}/\Lambda^2$
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]	–	–

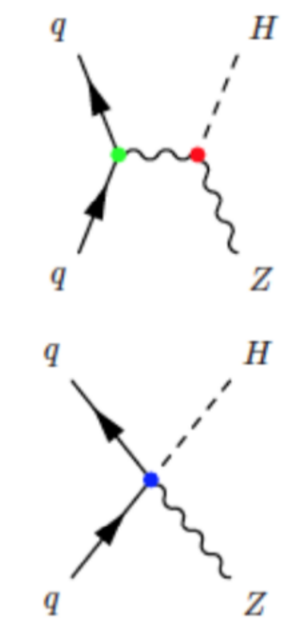
Selected results

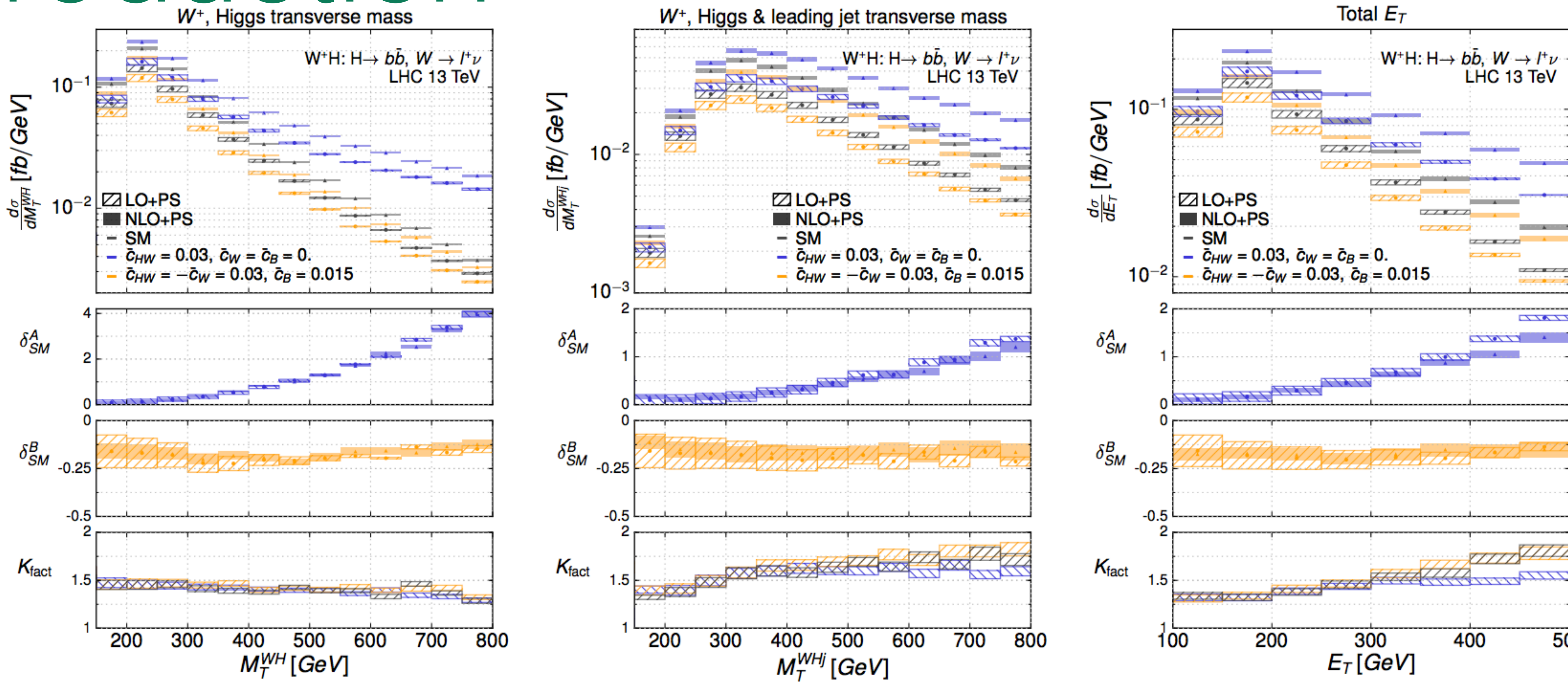
Some from previous works, superseded by SMEFT@NLO
A few, simple new results presented in *[PRD 103 (2021) 9, 096024]*

Higgs production

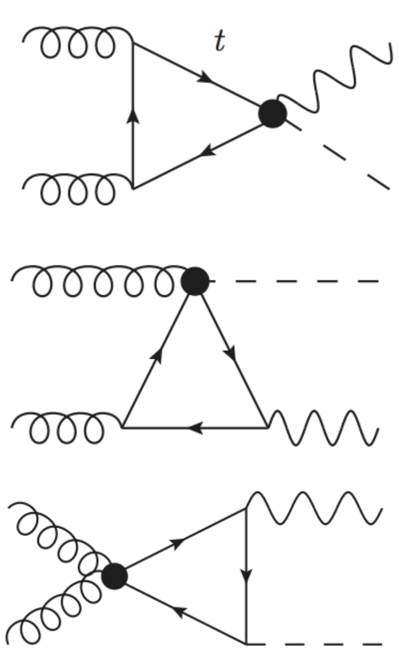
[Degrande, et al.; EPJC 77 (2017) 4, 262]

Quark-initiated



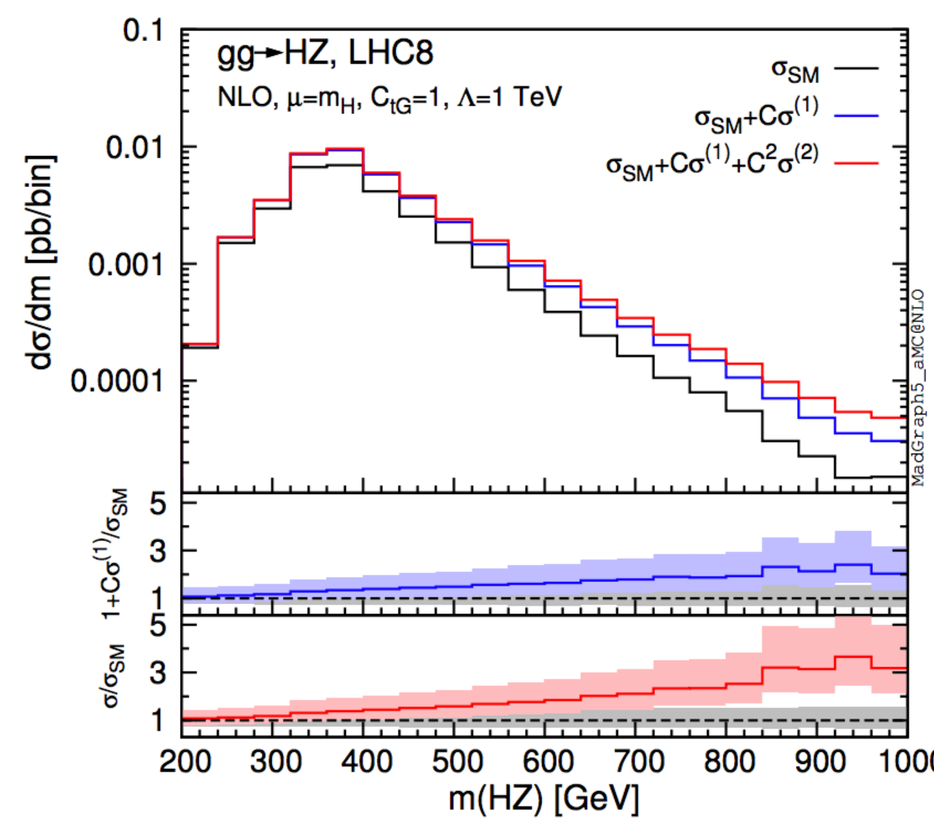


gg, loop-induced

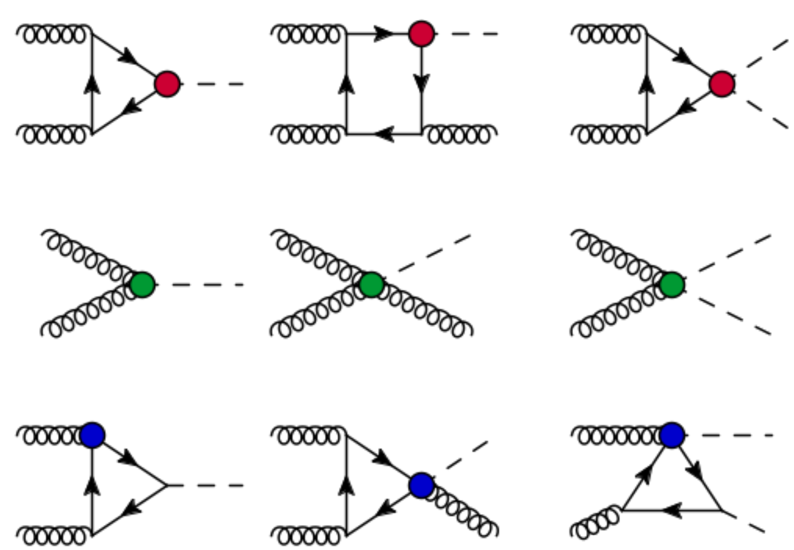


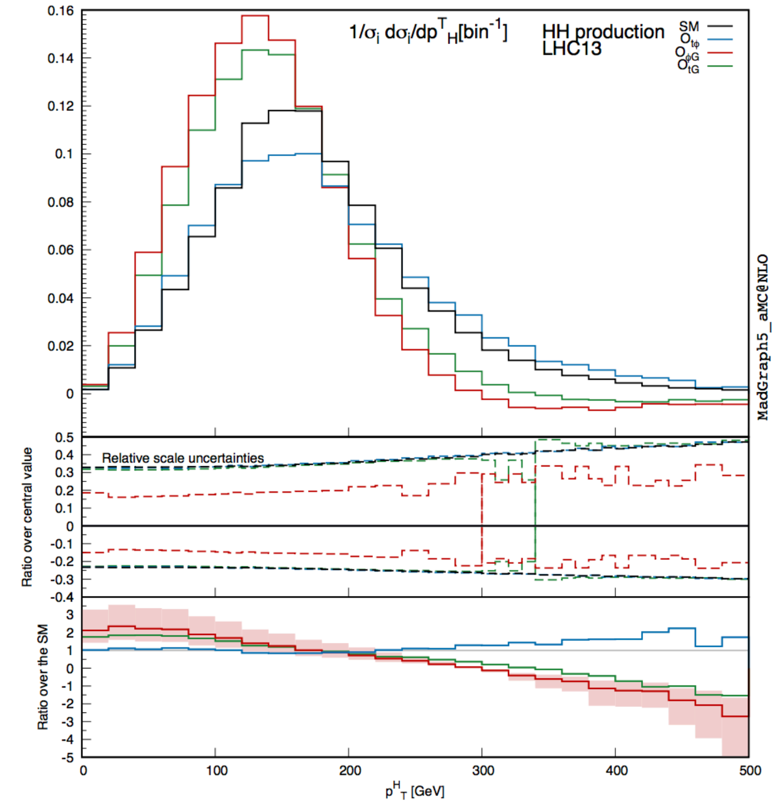
[Bylund et al.; JHEP 1605 (2016) 052]

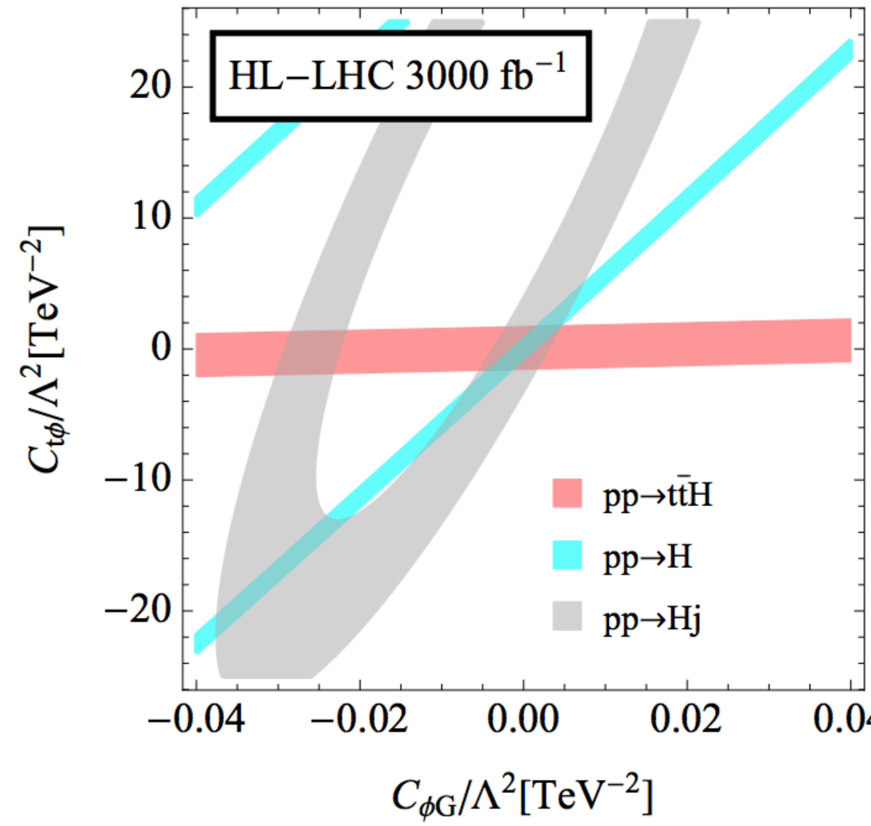
[fb]	SM		$\mathcal{O}_{tG}$	$\mathcal{O}_{\phi Q}^{(1)}$
8TeV	$29.15^{+40.0\%}_{-26.6\%}$	$\sigma_i^{(1)}$	$10.37^{+41.3\%}_{-27.2\%}$	$1.719^{+42.5\%}_{-27.6\%}$
		$\sigma_i^{(2)}$	$1.621^{+45.1\%}_{-28.7\%}$	$0.0469^{+46.5\%}_{-29.2\%}$
		$\sigma_i^{(1)}/\sigma_{SM}$	$0.356^{+0.9\%}_{-0.8\%}$	$0.0590^{+1.8\%}_{-1.4\%}$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



loop-sensitivity, gg -> H/Hj/HH

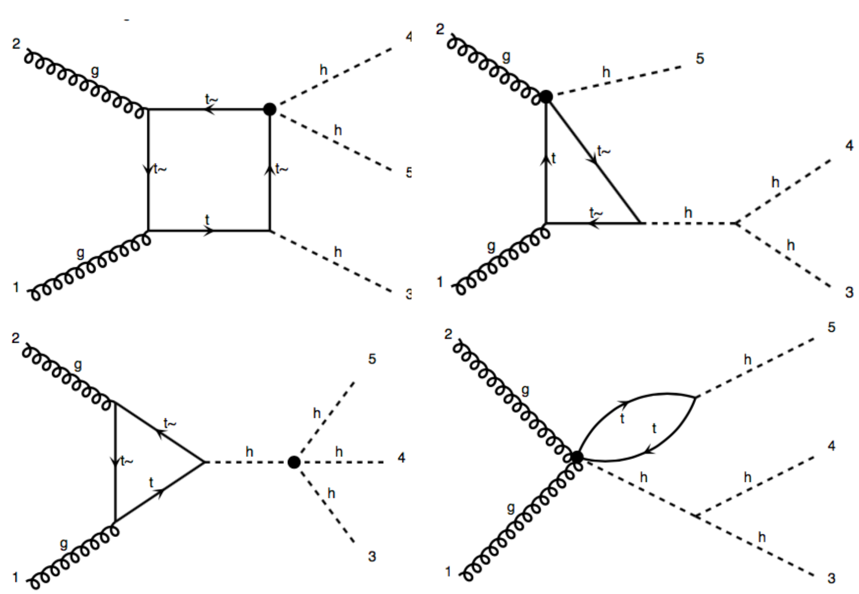




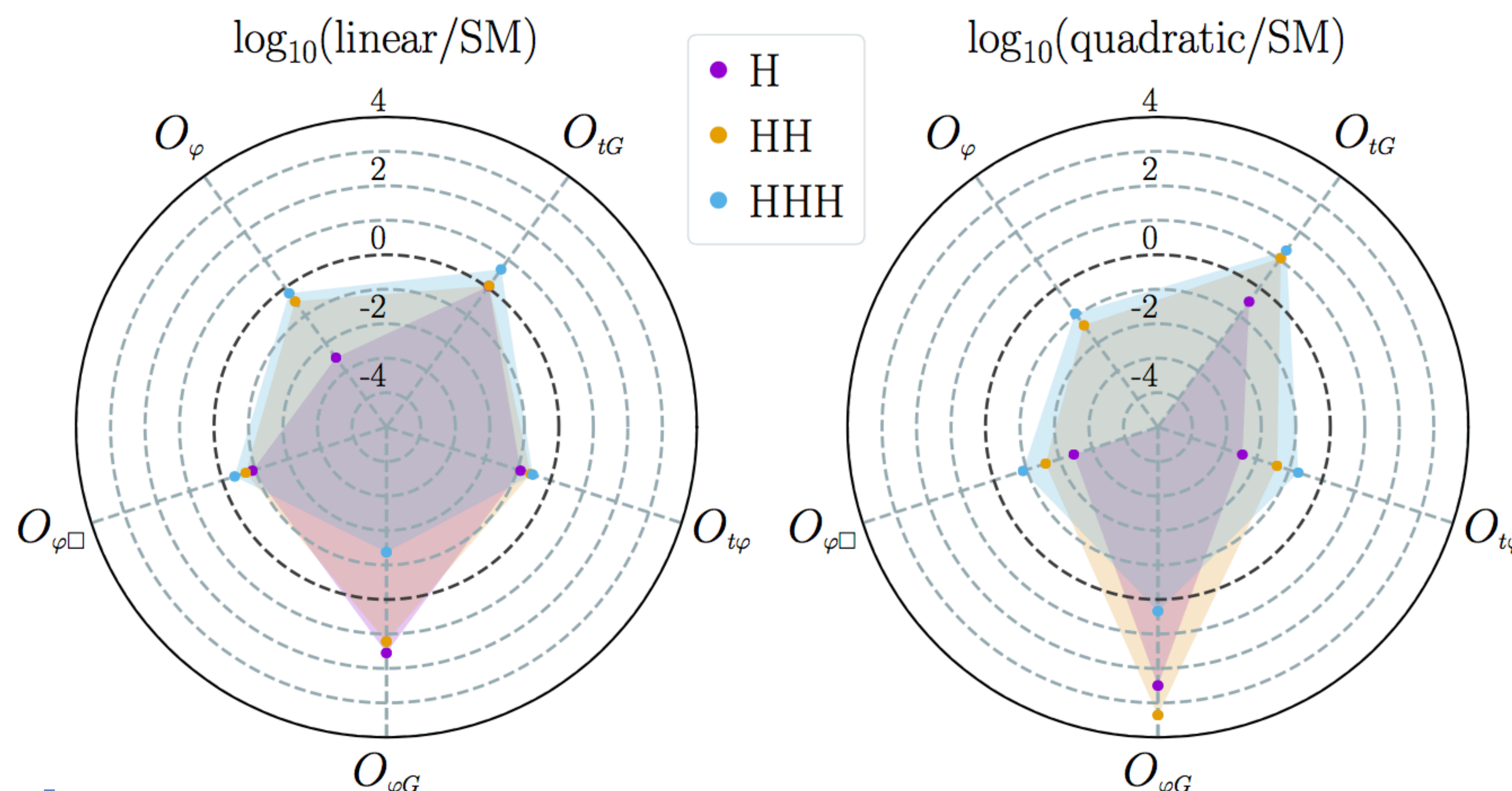


[Maltoni, Vryonidou & Zhang; JHEP 1610 (2016) 123]

gg -> H/HH/HHH (100 TeV)



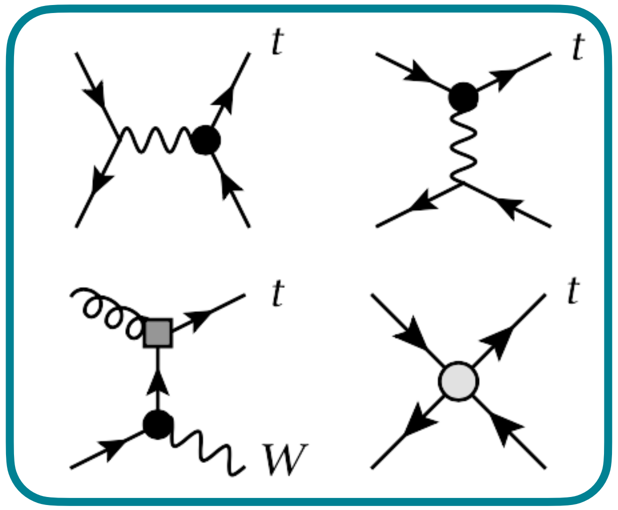
[Degrande et al.; PRD 103 (2021) 9, 096024]



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

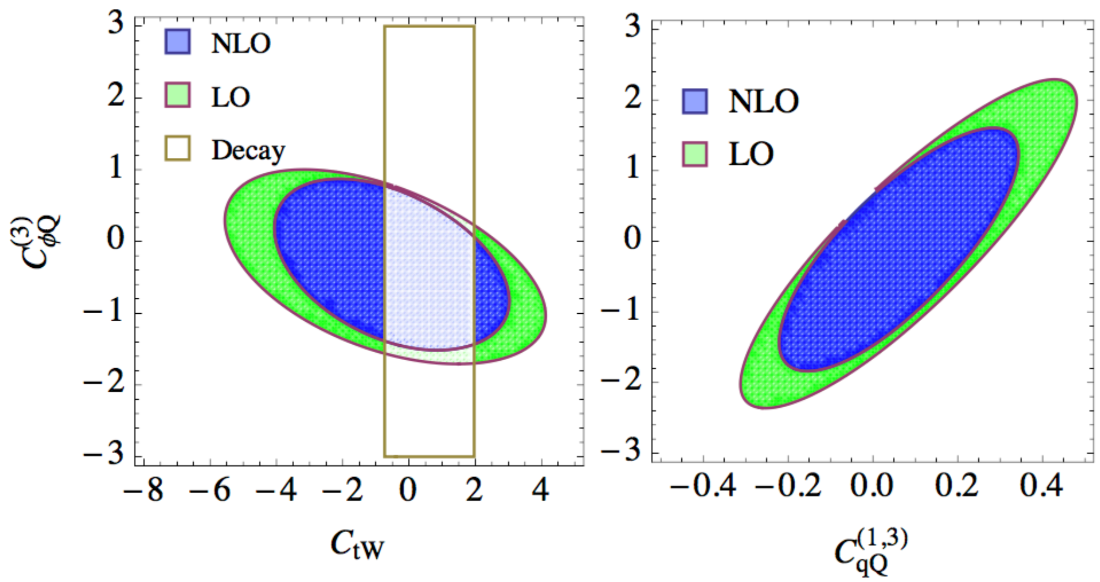
Top/Higgs

[Zhang; PRL 116 (2016) 162002]

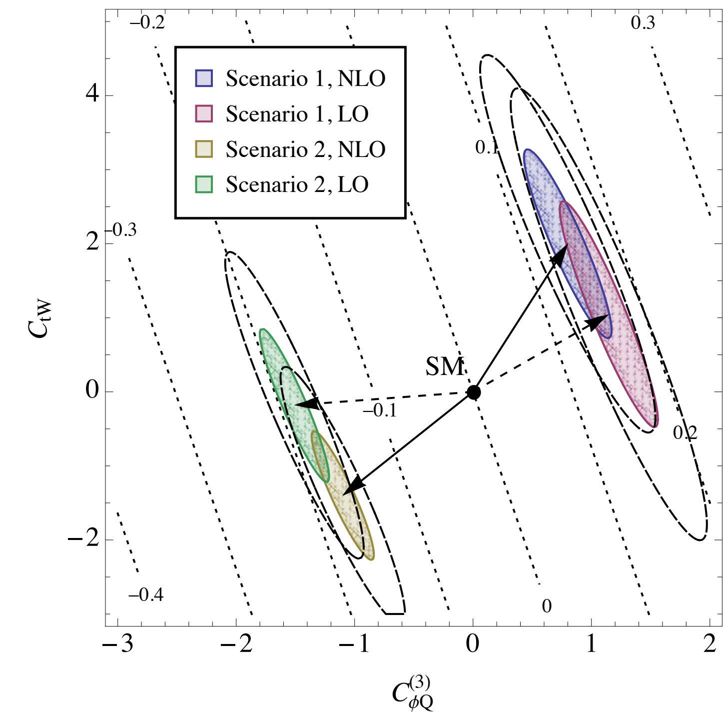


tj, tb, tW

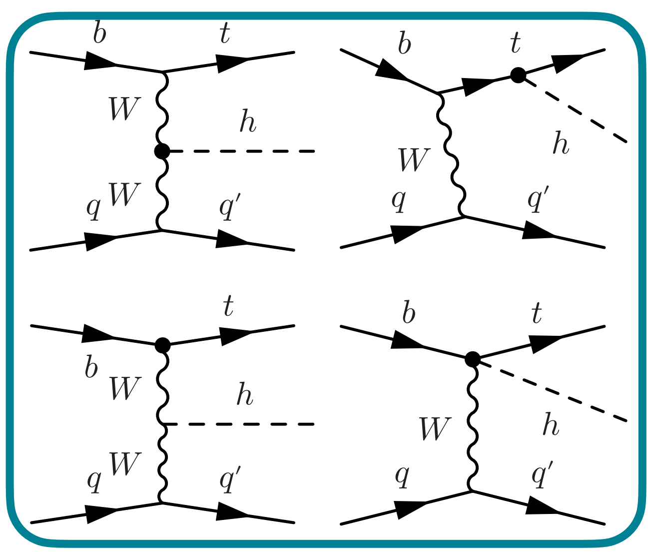
Fit without deviation



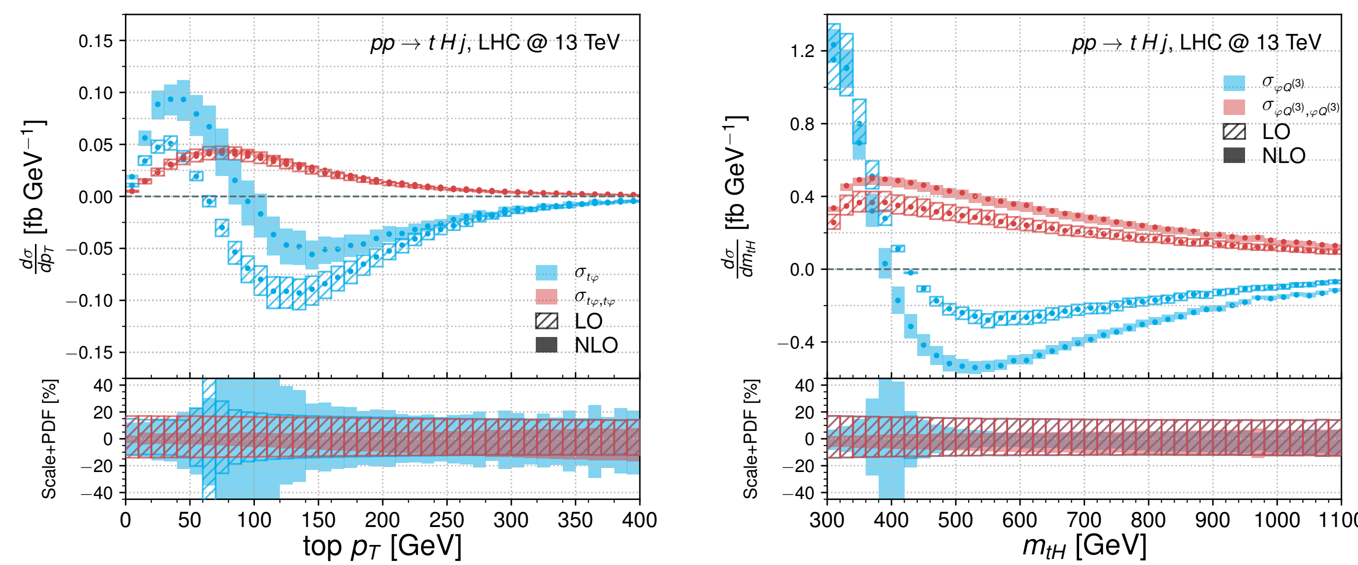
Fit with a (hypothetical) deviation



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



t Z j & t H j

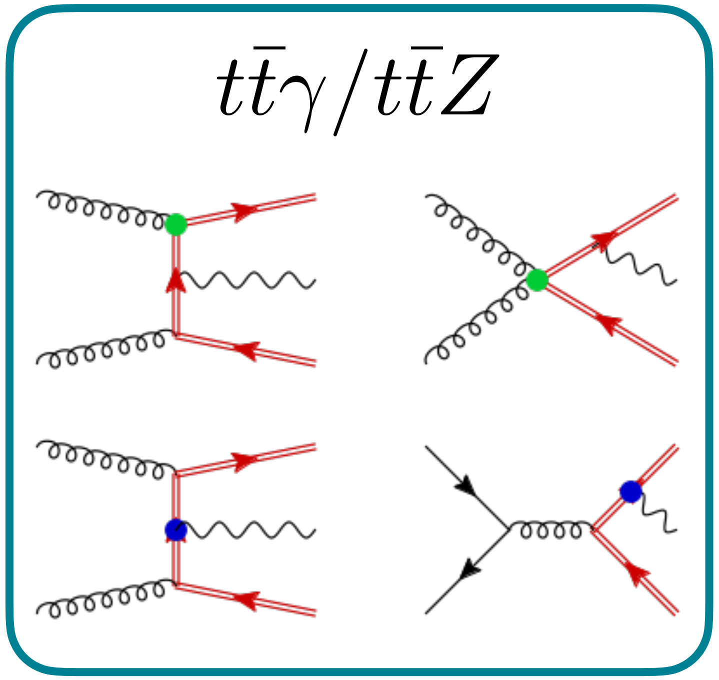


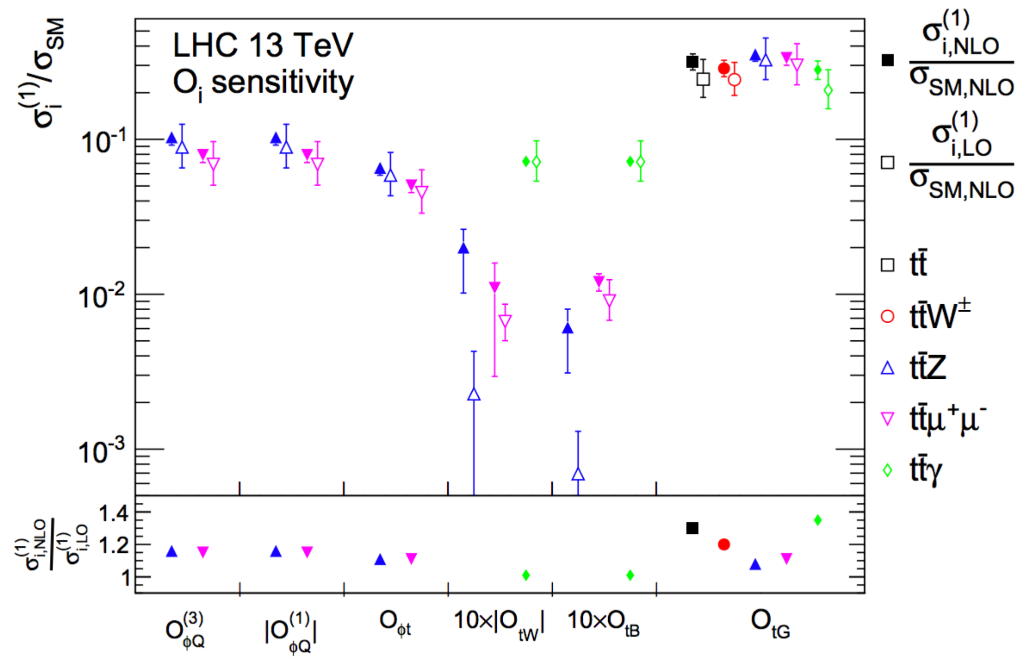
σ [fb]	K-factor
σ_{SM}	1.32
$\sigma_{\varphi W}$	0.96
$\sigma_{\varphi W,\varphi W}$	1.20
$\sigma_{t\varphi}$	0.20
$\sigma_{t\varphi,t\varphi}$	1.09
σ_{tW}	1.14
$\sigma_{tW,tW}$	1.54
$\sigma_{\varphi Q^{(3)}}$	3.31
$\sigma_{\varphi Q^{(3)},\varphi Q^{(3)}}$	1.36

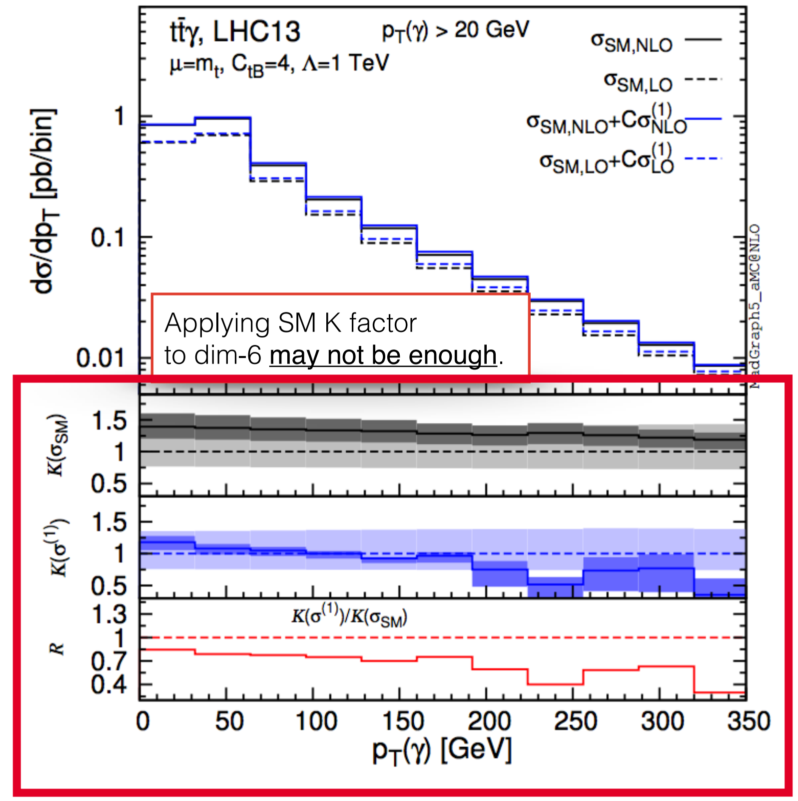
Different patterns of phase-space cancellations at LO/NLO lead to non-trivial & "strange" K factors

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

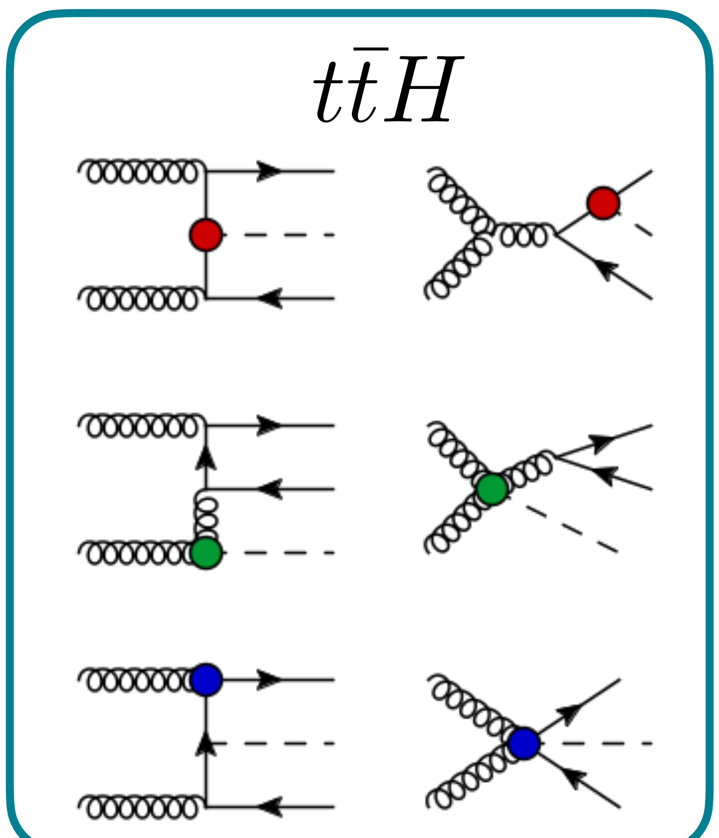
NLO > LO: more sensitive!

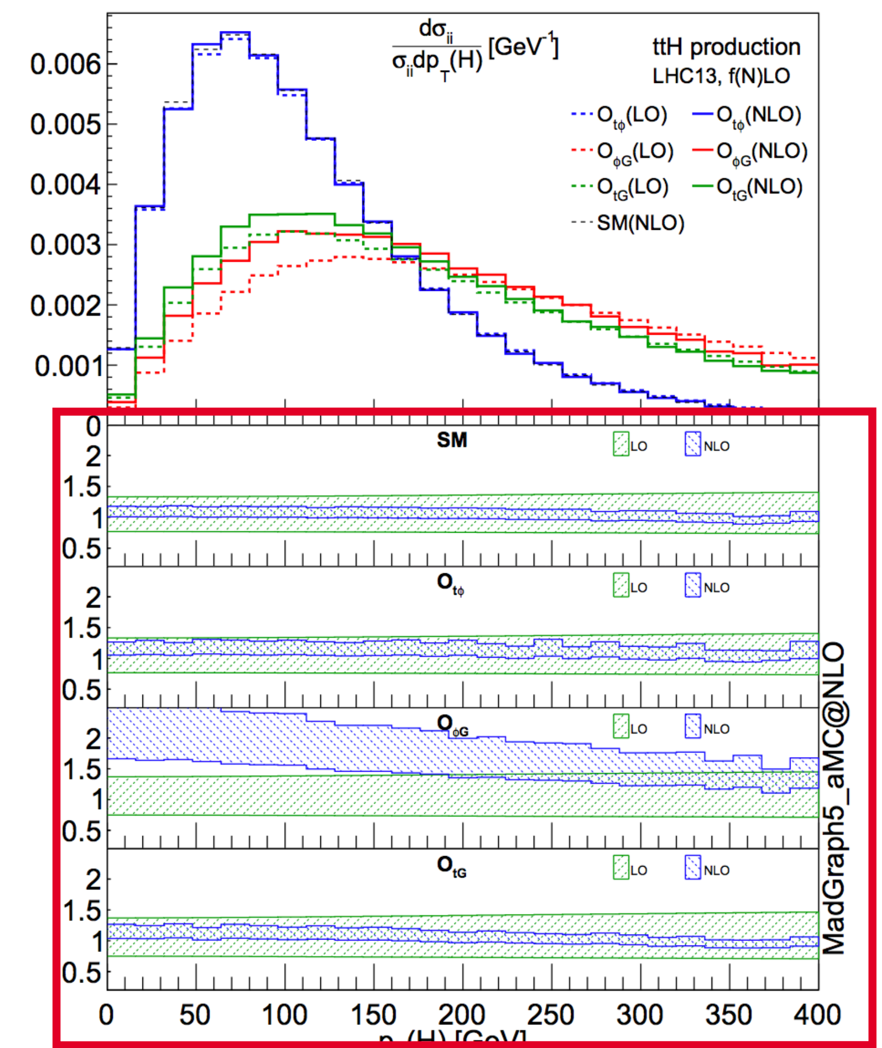






[Maltoni, Vryonidou & Zhang; JHEP 1610 (2016) 123]





13 TeV	σ LO	σ NLO	K
σ_{SM}	$0.464^{+0.161}_{-0.11}$	$0.507^{+0.0}_{-0.0}$	1.09
$\sigma_{t\phi}$	$-0.055^{+0.0}_{-0.0}$	-0.062^{+0}_{-0}	1.13
$\sigma_{\phi G}$	$0.627^{+0.225}_{-0.15}$	$0.872^{+0.1}_{-0.1}$	1.39
σ_{tG}	$0.470^{+0.167}_{-0.11}$	$0.503^{+0.0}_{-0.0}$	1.07
$\sigma_{t\phi,t\phi}$	$0.0016^{+0.0}_{-0.0}$	$0.0019^{+0.}_{-0.}$	1.17
$\sigma_{\phi G,\phi G}$	$0.646^{+0.27}_{-0.17}$	$1.021^{+0.2}_{-0.1}$	1.58
$\sigma_{tG,tG}$	$0.645^{+0.27}_{-0.17}$	$0.674^{+0.0}_{-0.0}$	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
$\sigma_{\phi G,tG}$	$0.627^{+0.25}_{-0.16}$	$0.859^{+0.1}_{-0.1}$	1.37

Non-universal K-factors in rates & distributions

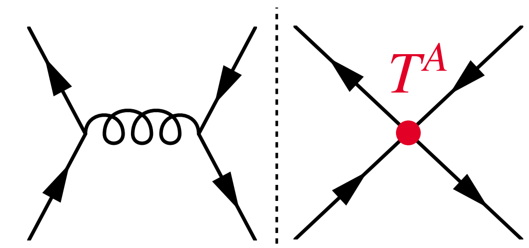
[Degrande, Durieux, Maltoni, KM, Vryonidou & Zhang; PRD 103 (2021) 9, 096024]

4F in top pair

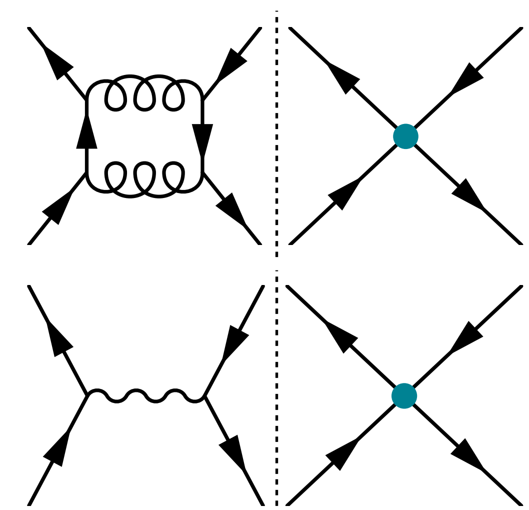
LHC 13 TeV, SM = 744 pb, K-factor = 1.46, central scale choice = m_t

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

color-octet qqtt:
- *dominant operators in ttbar*
- *Non SM-like corrections*



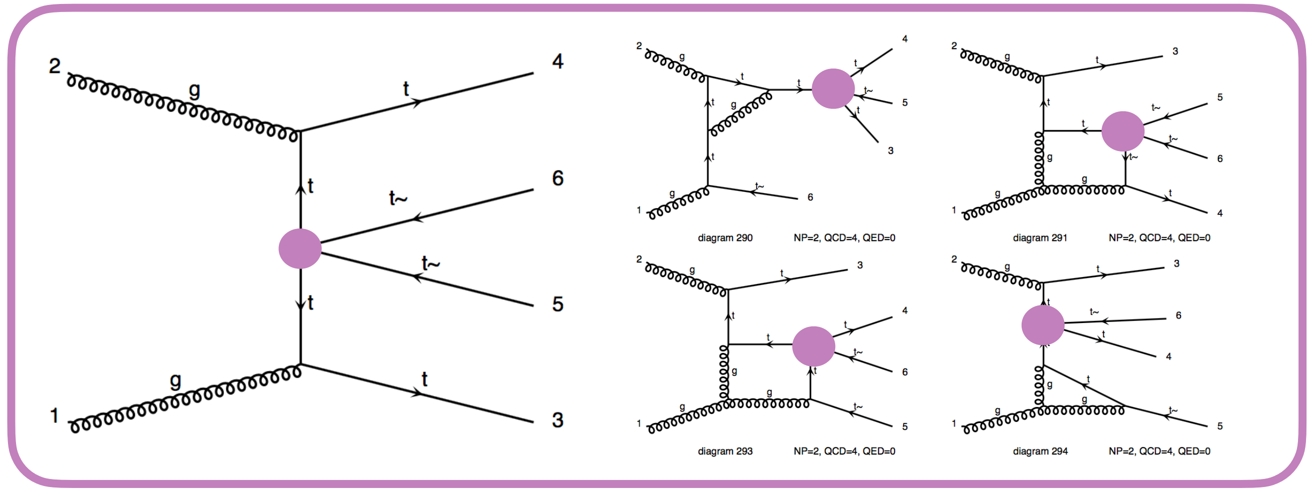
color-singlet qqtt:
- *int. with QCD ttbar at NLO*
- *[x] int. with EW ttbar*
- *No error control at LO*



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], $c_i/\Lambda^2 = 1\,\text{TeV}^{-2}$

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

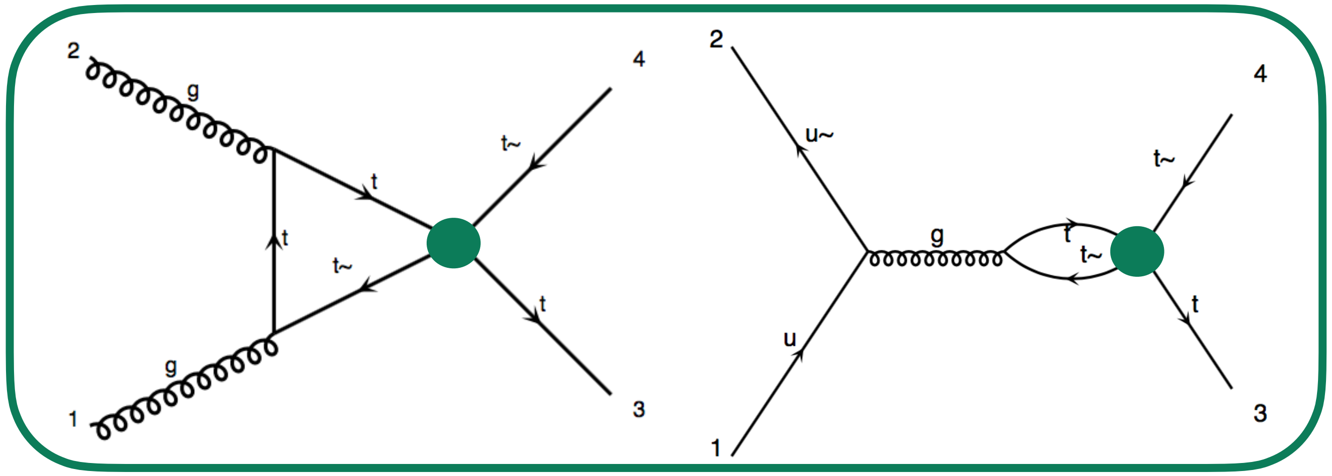
- Relative impact slightly decreases from LO to NLO
- Square typically receives larger corrections

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

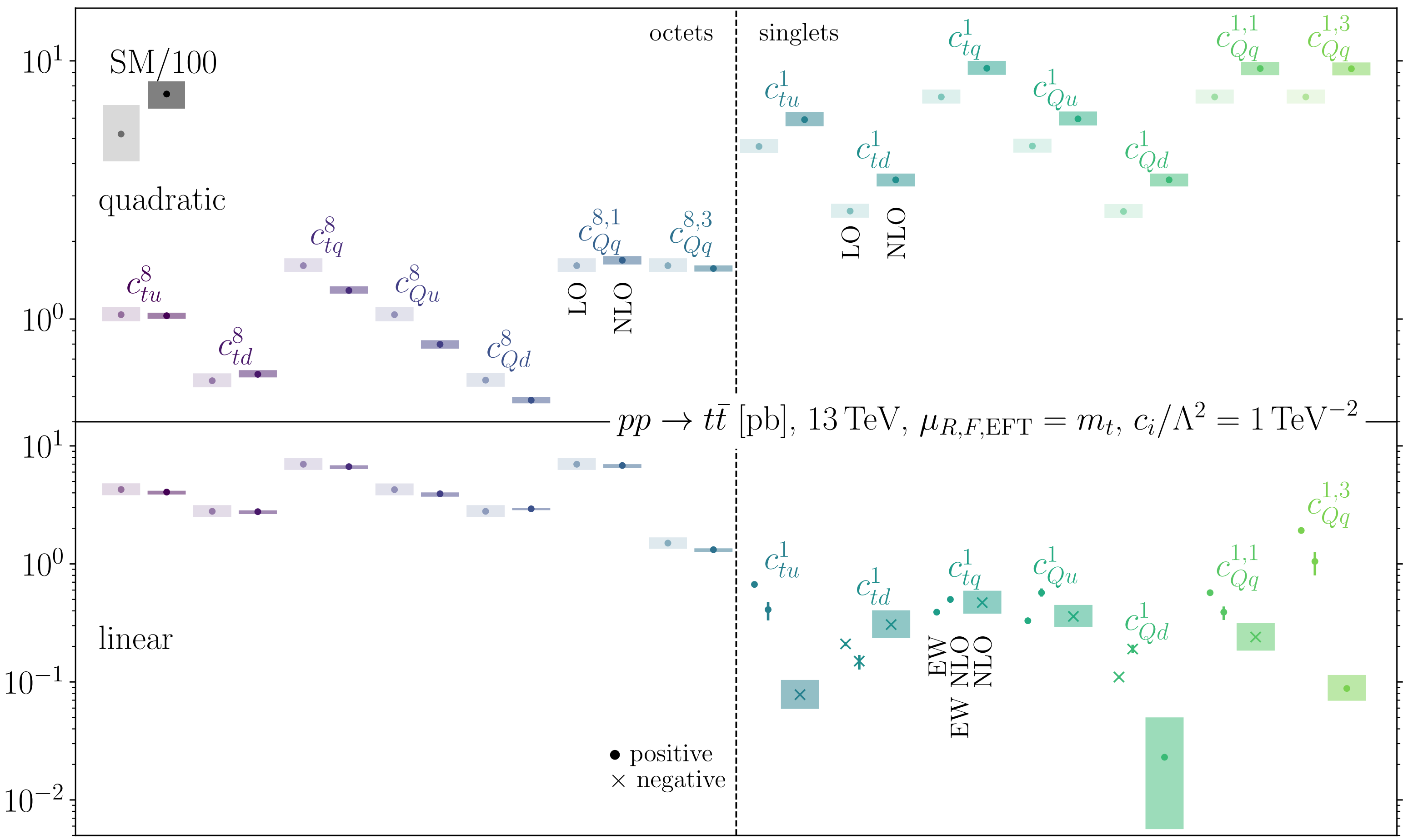
$\sigma(pp \to t\bar{t})$ [pb], $c_i/\Lambda^2 = 1$ TeV^{-2}

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

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

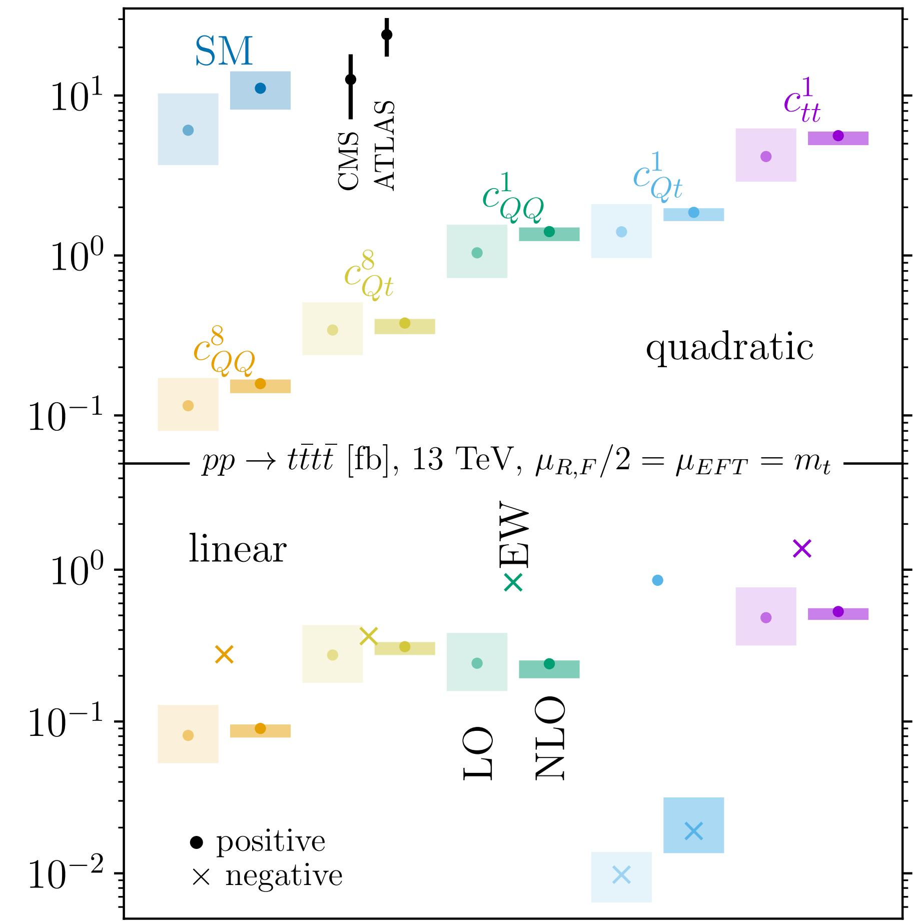
4F in 2/4 top

$t\bar{t}$

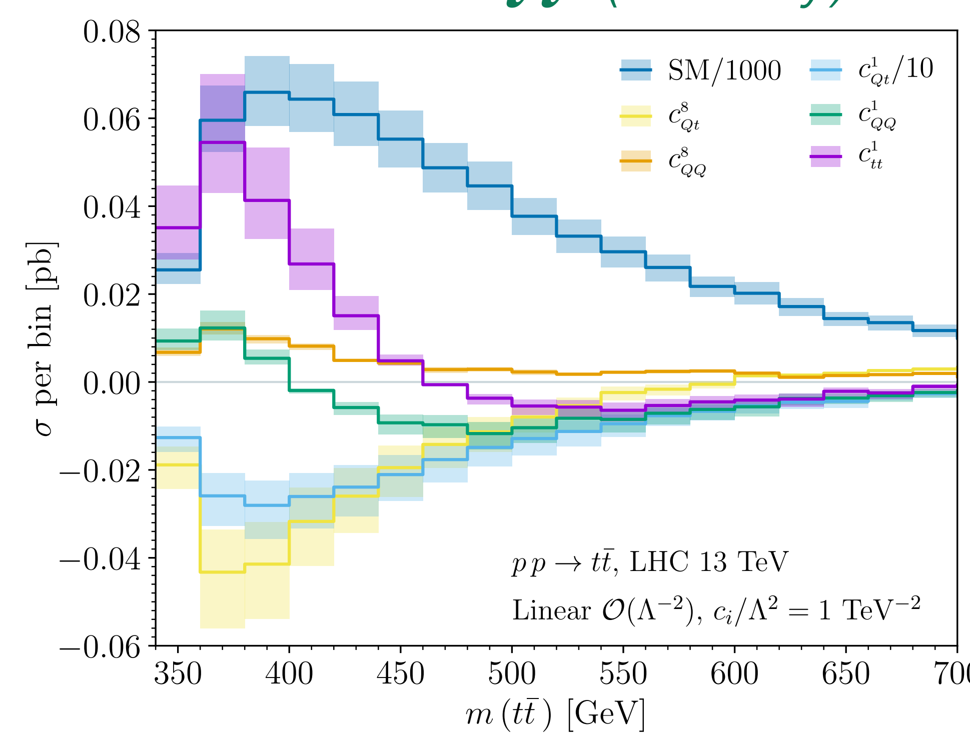


thanks to Gauthier for summary plots!

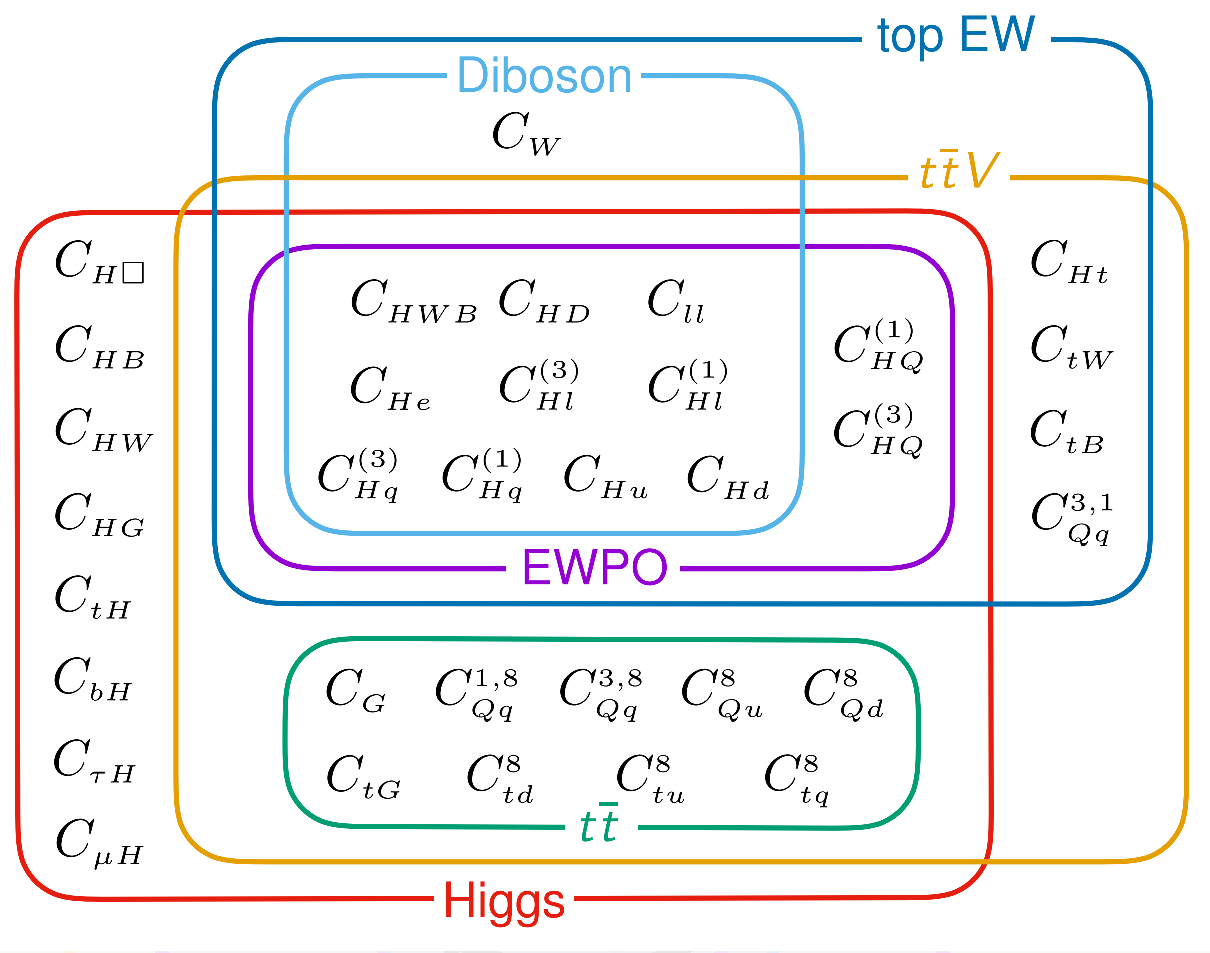
$t\bar{t}t\bar{t}$



$t\bar{t}$ *(4 heavy)*



Impact on new physics reach



(AKA improving fits)

Status: fits

Global new physics searches via high precision/energy

- Z & W-pole data: handle on the EW gauge sector

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

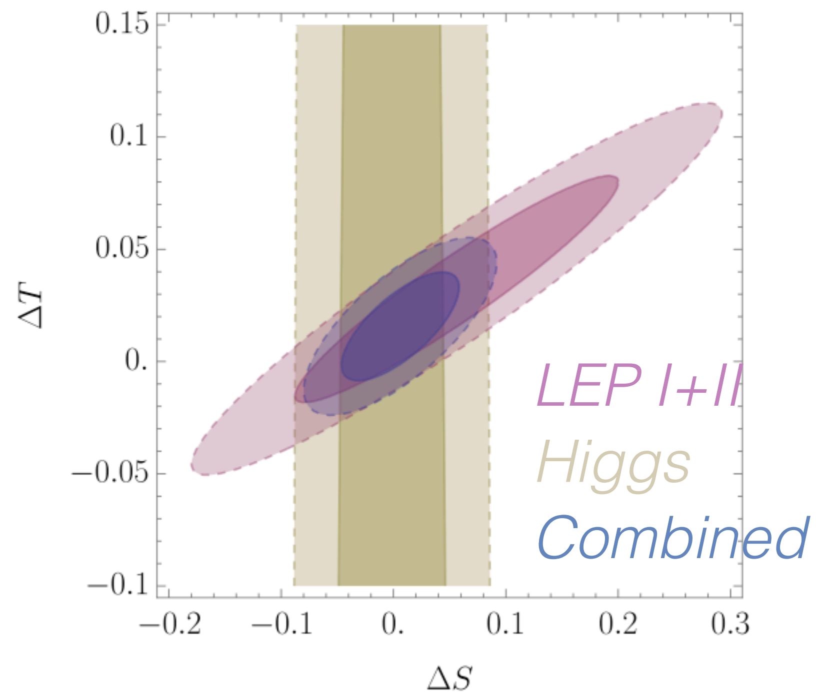
- LHC: thriving Higgs & top programmes
- Probing gauge interactions at high energy (VV, VBS, VVV, …)

We know that Higgs data greatly complements LEP

- Access unconstrained directions in parameter space
- 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]
[Berthier, Bjorn & Trott; JHEP 09 (2016) 157]
[Biekötter Corbett & Plehn; SciPost Phys 6 (2019) 6, 064]
[Anisha et al; arXiv:2111.05876]……

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



Next step: combine Higgs & top data

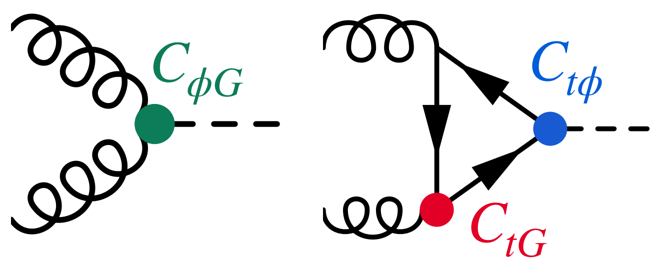
[Maltoni, Vryonidou & Zhang; JHEP 1610 (2016) 123]

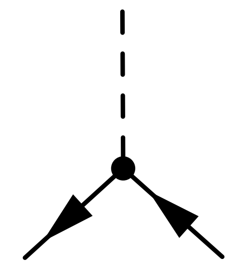
Top/Higgs interplay

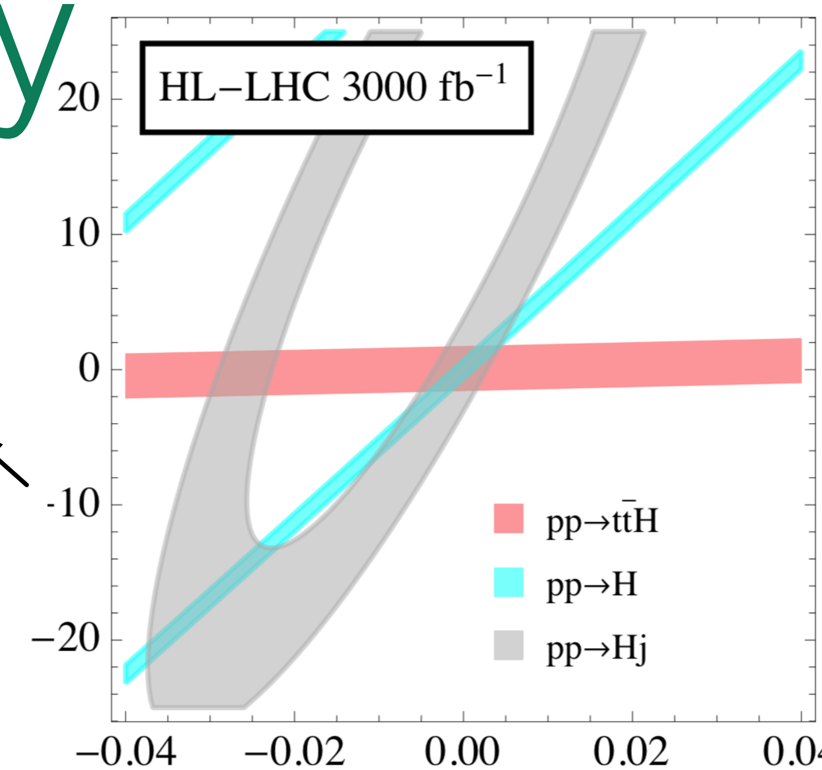
$C_{\phi G}$ *Point-like*

$C_{t\phi}$ *Yukawa*

C_{tG} *Dipole*

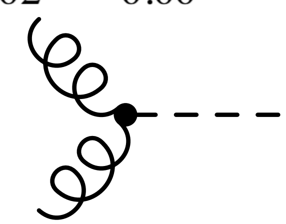






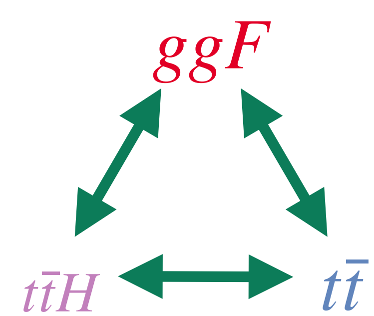
$gg \to h$ is well measured now…

- X Can't exclude top partners/anomalous Yukawa
- Degeneracy in coefficient/model space



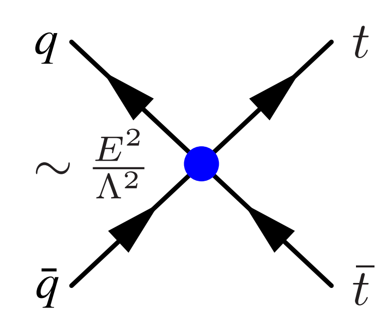
Need more data to break degeneracy

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



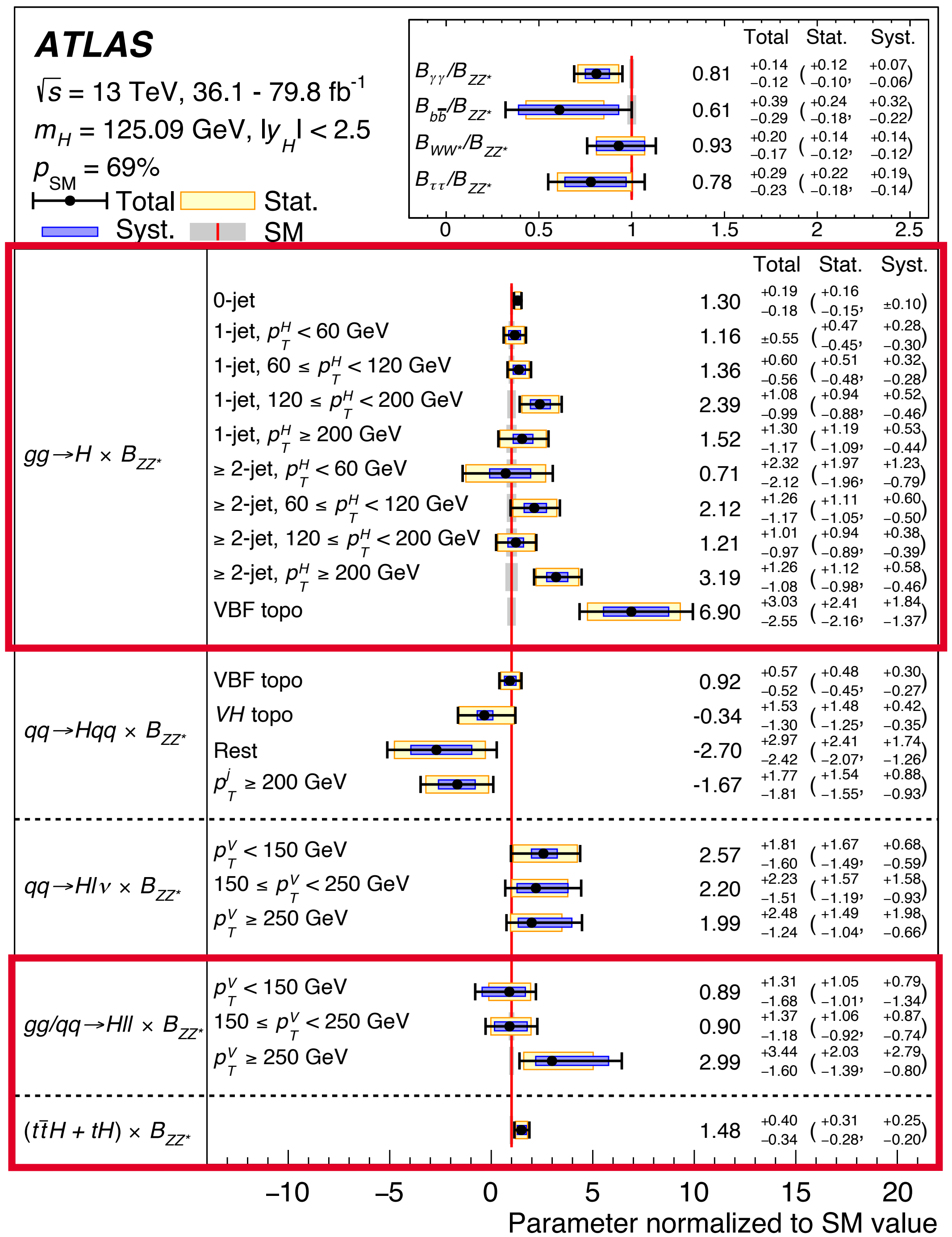
Several other new interactions can affect $t\bar{t}$

- 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?

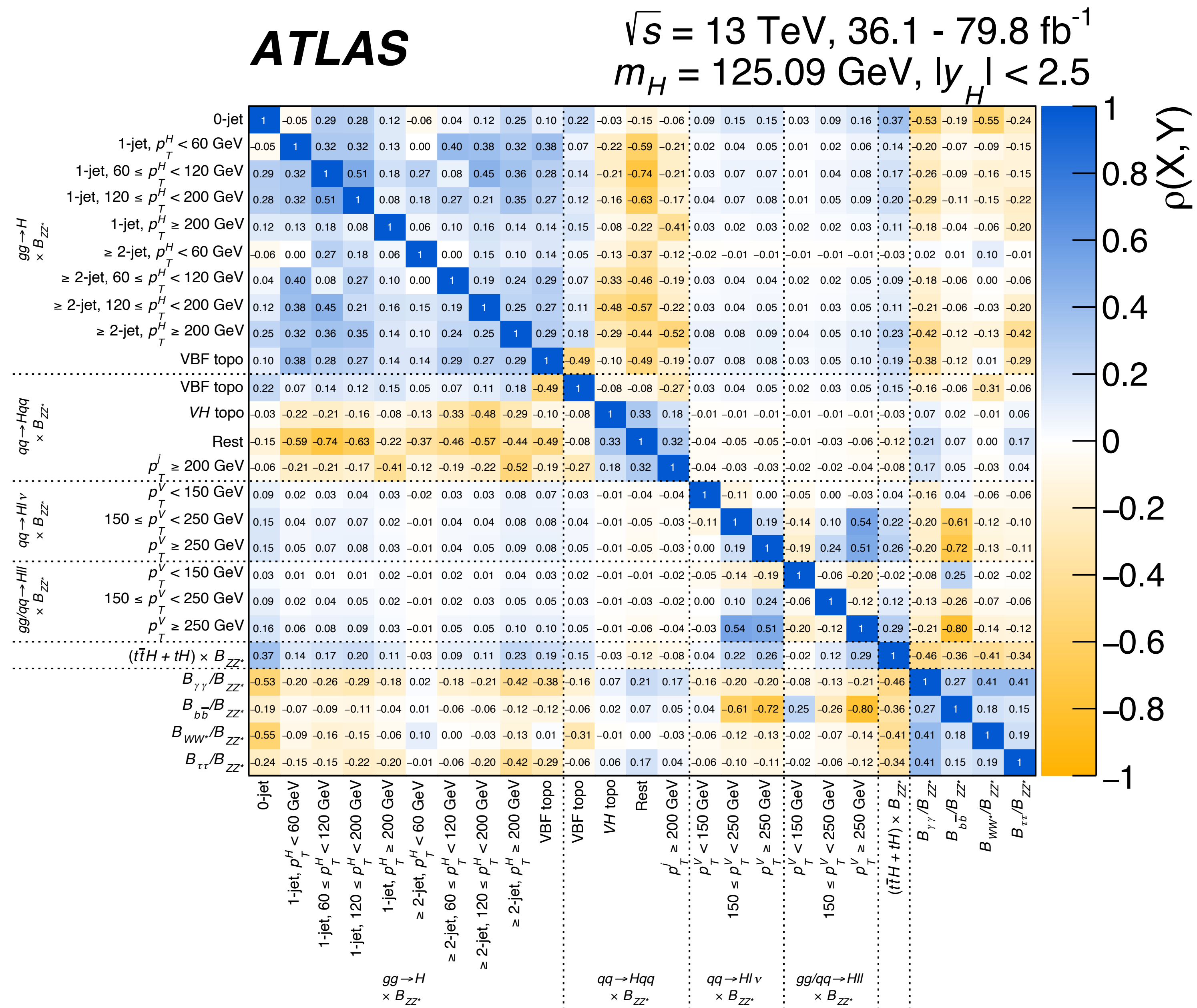


STXS

(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]

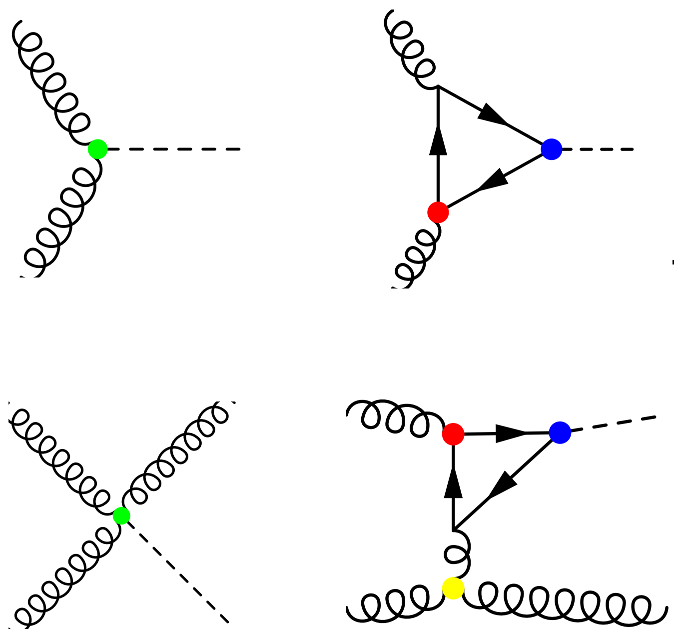
[ATLAS-CONF-2020-026]

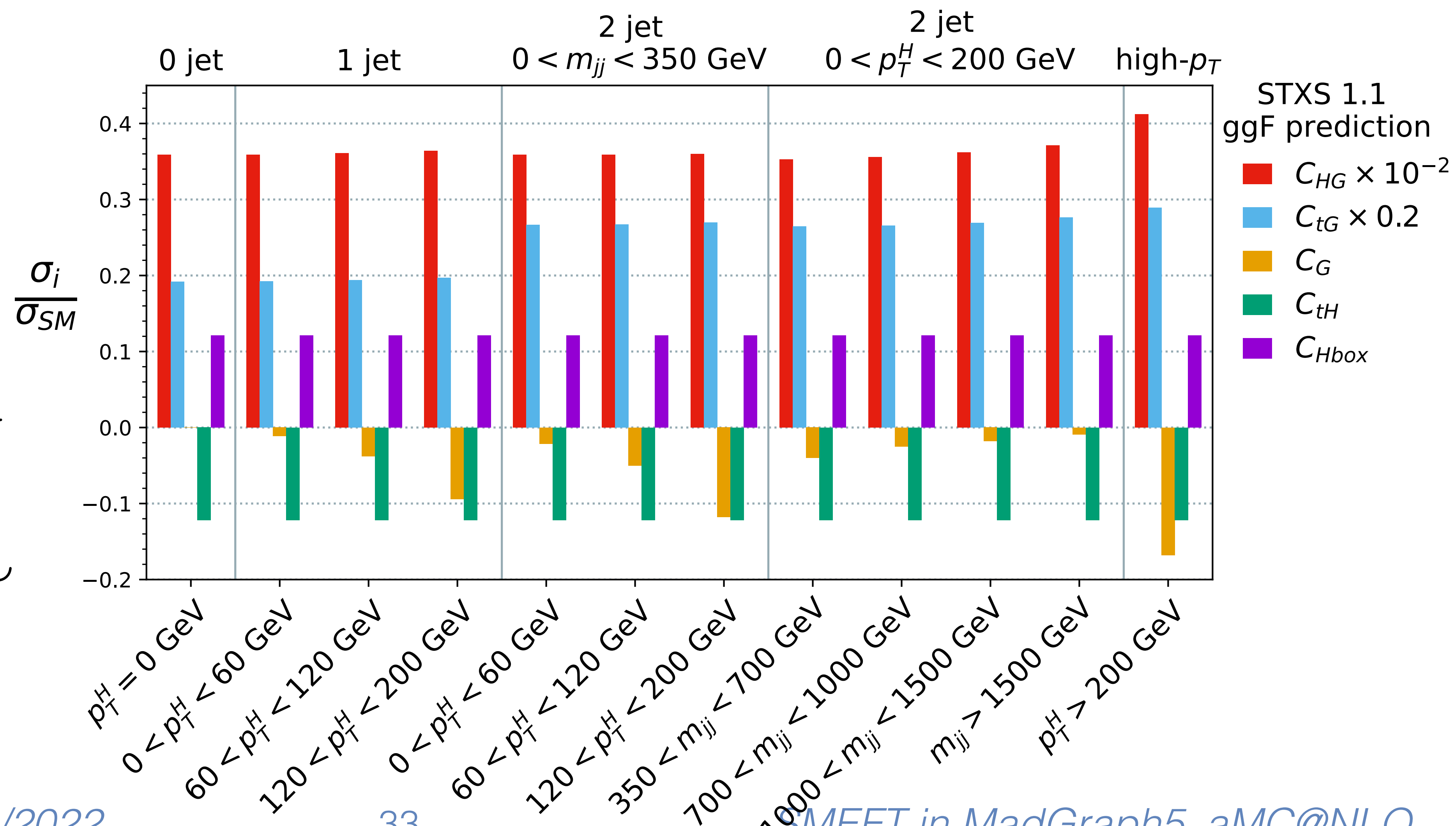
[ATLAS; EPJC 81 (2021) 178]

SMEFT ggF in fits

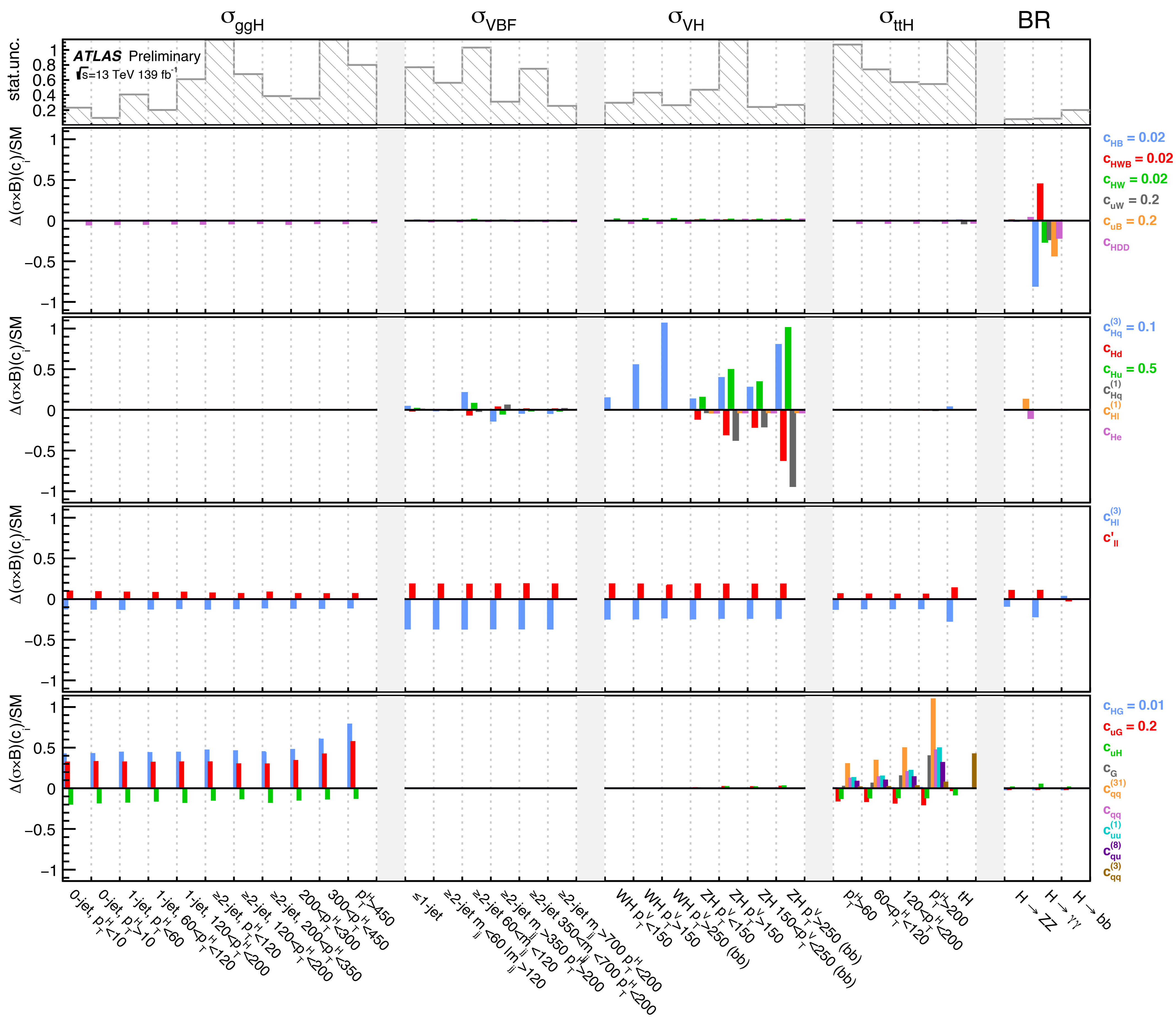
STXS ⇔ gluon fusion in the SMEFT

- 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



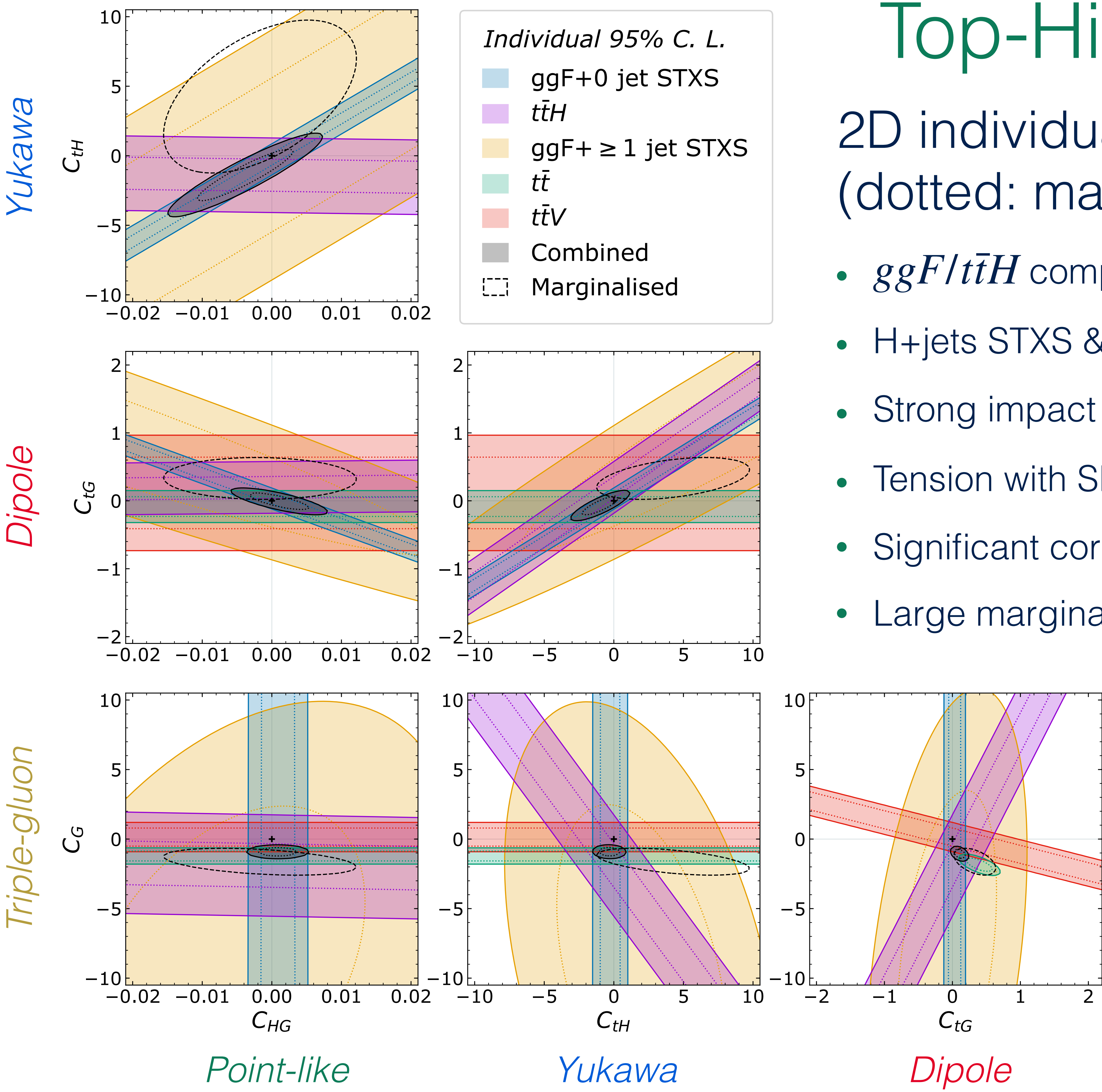


See also: [ATLAS-CONF-2021-053],[ATL-PHYS-PUB-2021-010]



[Ellis, Madigan, KM, Sanz, You; JHEP 04 (2021) 279]

Top-Higgs interplay



2D individual constraints (dotted: marginalised)

- $ggF/t\bar{t}H$ 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)

Concrete impact of 4F operators found to be small

Affect different part of $t\bar{t}$ phase space

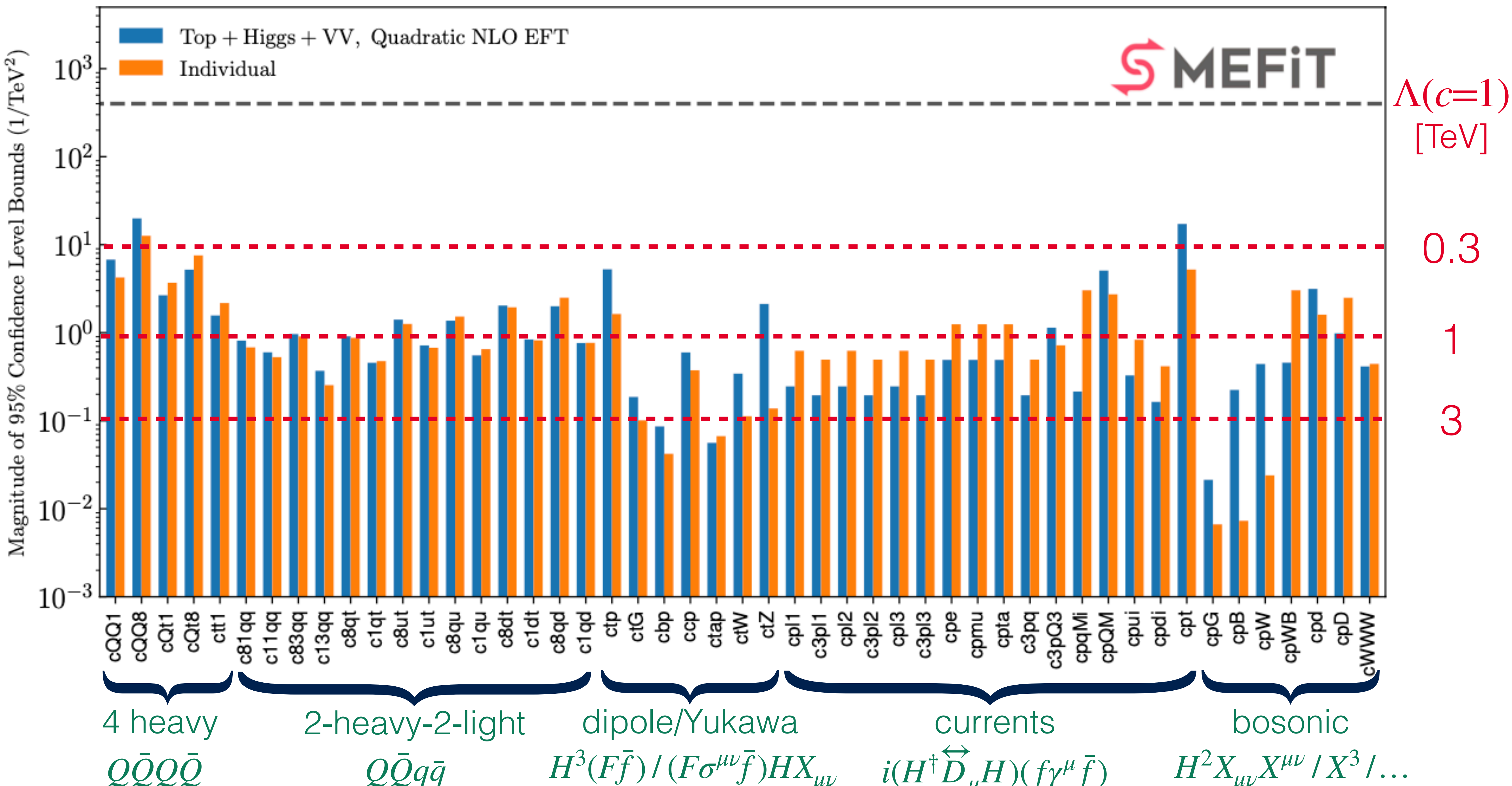
C_{tG} : low $m_{t\bar{t}}$

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

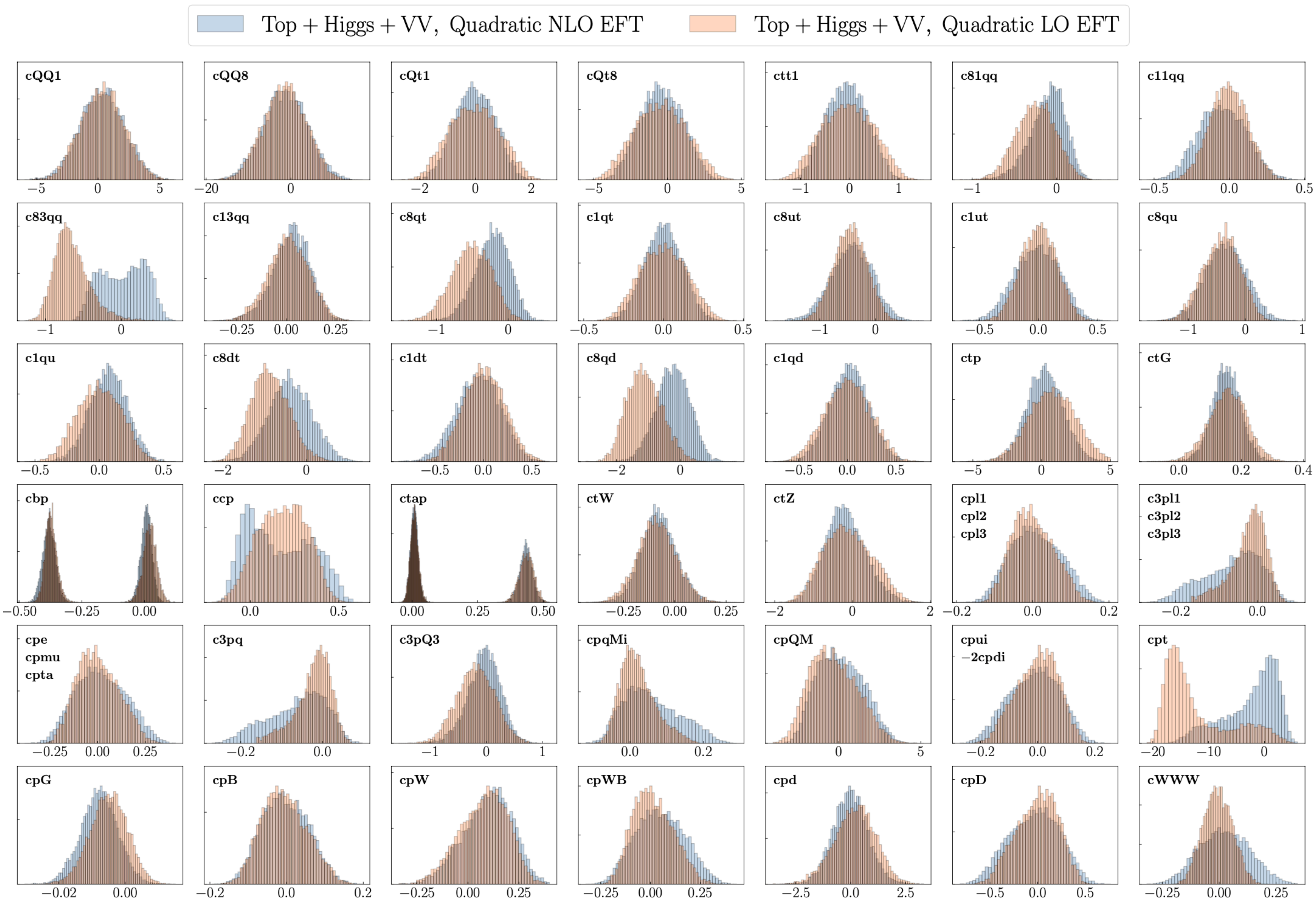
SMEFT fit @ NLO

Top, Higgs & Diboson w/ 'perfect' EWPO

- NLO QCD
- top loop sensitivity
- Quadratic terms

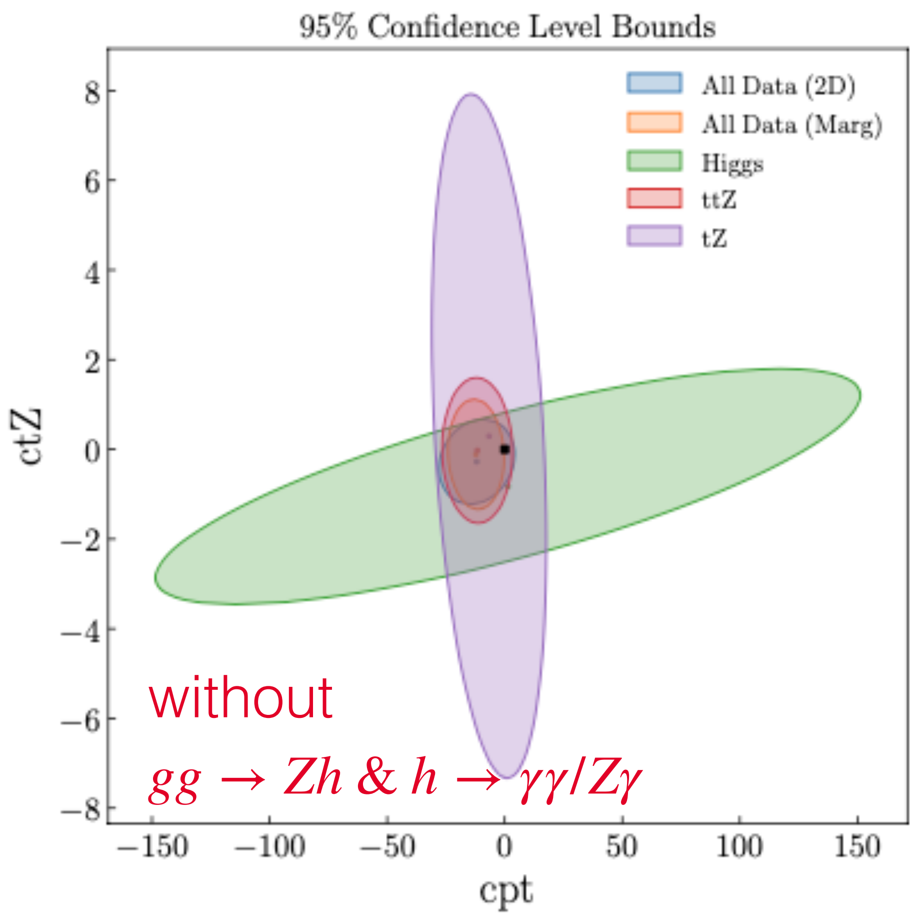


NLO vs LO

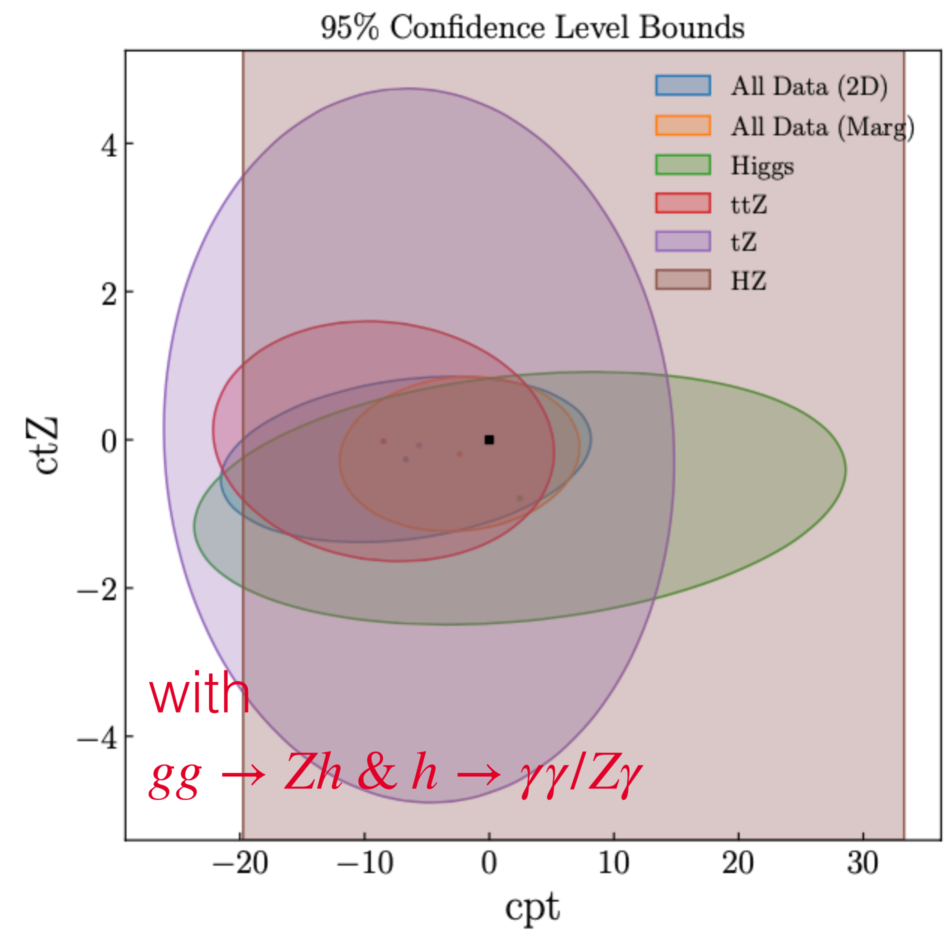

Top + Higgs + VV, Quadratic NLO EFT
Top + Higgs + VV, Quadratic LO EFT
cQQ1
cQQ8
cQt1
cQt8
ctt1
c81qq
c11qq
c83qq
c13qq
c8qt
c1qt
c8ut
c1ut
c8qu
c1qu
c8dt
c1dt
c8qd
c1qd
ctp
ctG
cbp
ccp
ctap
ctW
ctZ
cpl1
cpl2
cpl3
c3pl1
c3pl2
c3pl3
cpe
cpmu
cpta
c3pq
c3pQ3
cpqMi
cpQM
cpui
−2cpdi
cpt
cpG
cpB
cpW
cpWB
cpd
cpD
cWWW

Top couplings via Higgs

Tree

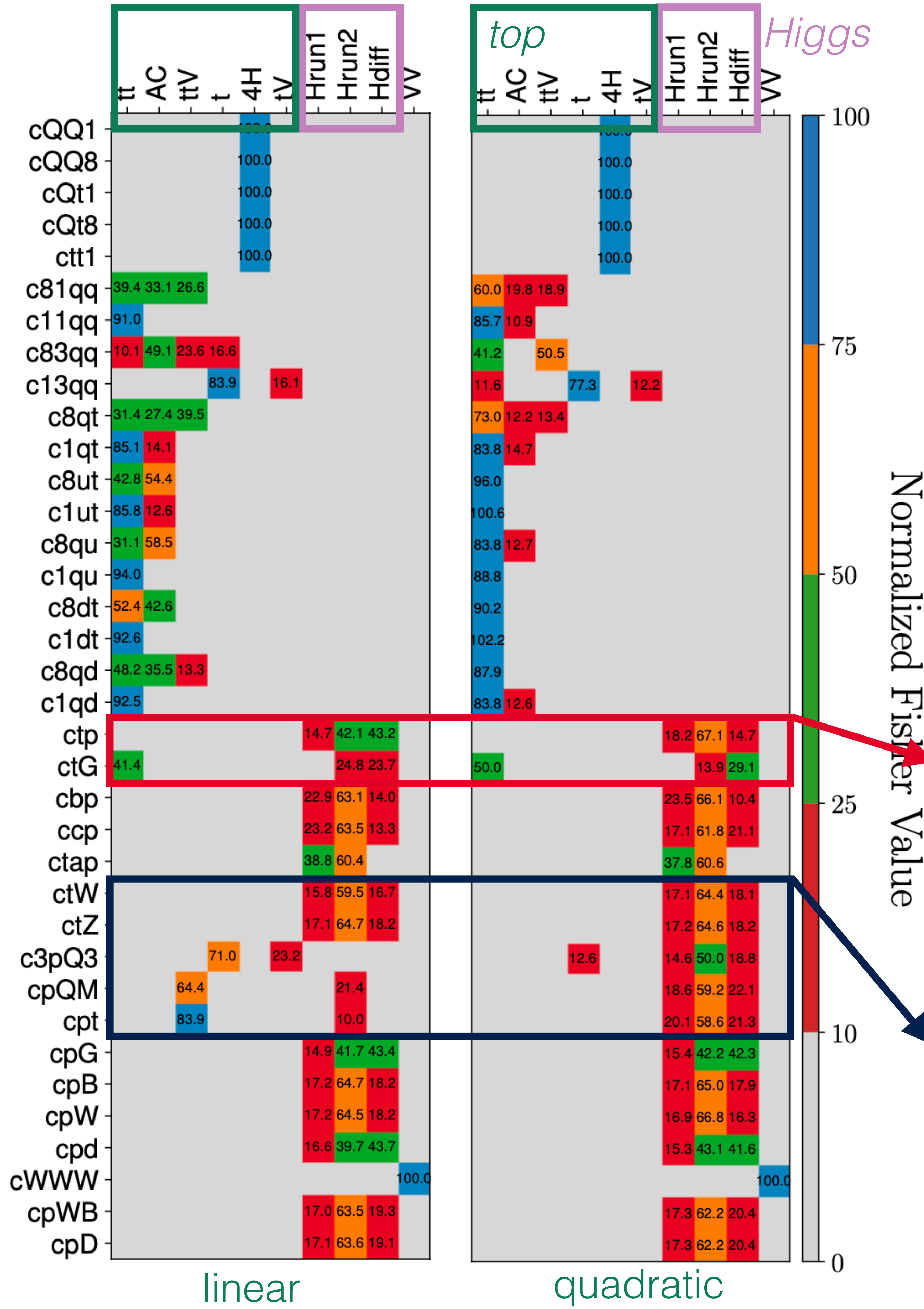


Loop



- Significant effects on individual observable sensitivities, e.g., tZ
- Loop-induced processes bring new constraints ($h \to \gamma\gamma/\gamma Z$)

'EW' loops, not in SMEFTatNLO [Vryonidou & Zhang; JHEP 08 (2018) 036]



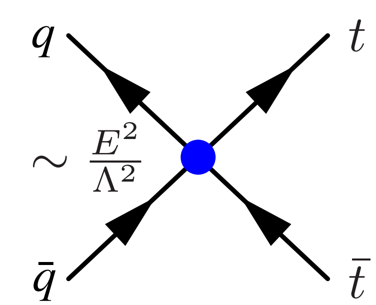
Constraining power

[Ethier et al.; JHEP 11 (2021) 089]

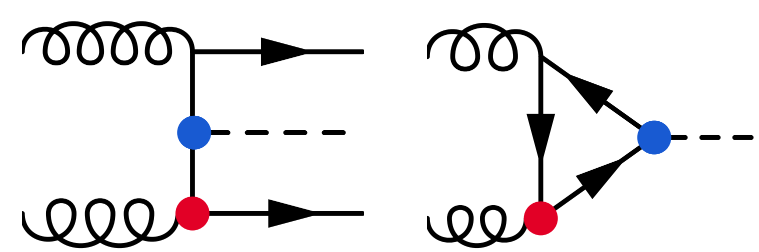
Fisher Information:

Hessian of Log-likelihood at the best-fit point

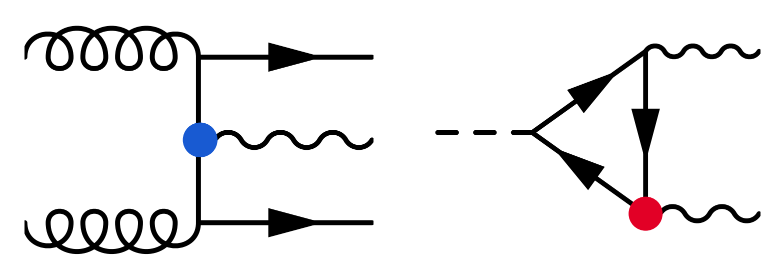
4F operators: mostly top data



Yukawa & Chromo-dipole

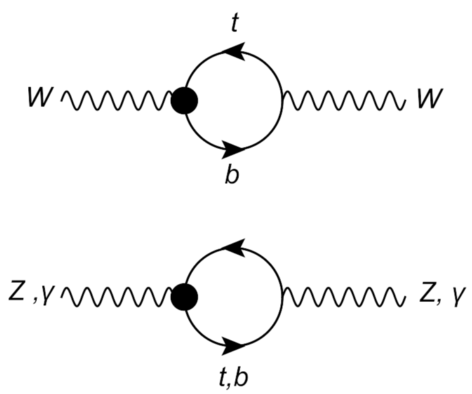


$t\bar{t}V$ couplings



NLO EW for SMEFT

Z-pole observables



[Zhang, Greiner & Willenbrock; PRD 86 (2012) 014024]

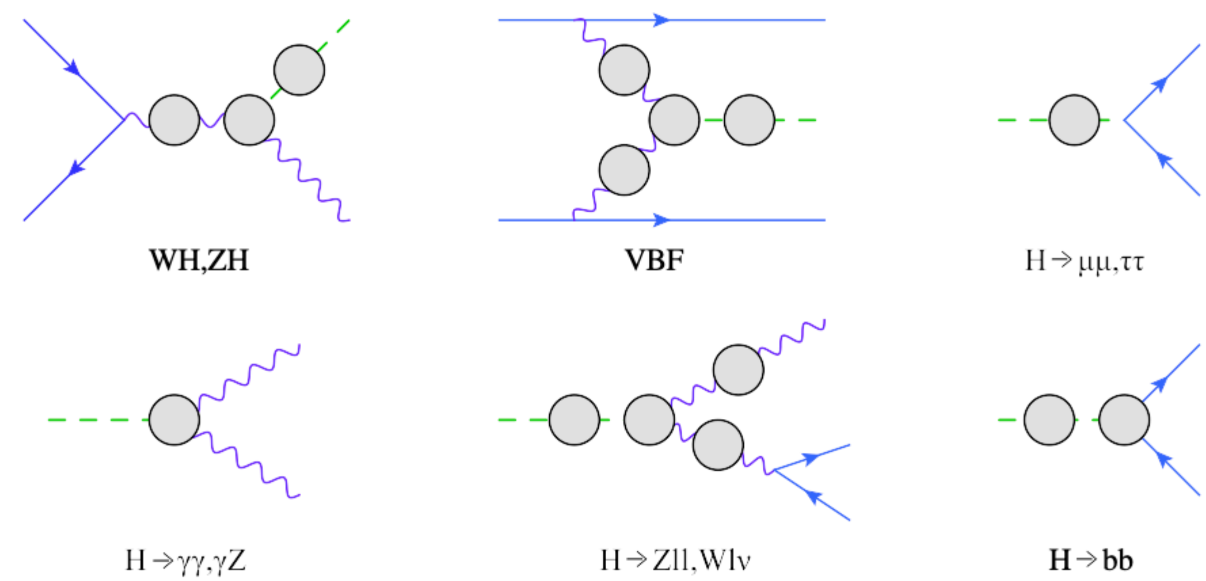
Next frontier for `SMEFTatNLO`

- SM already implemented in MG5
- NLOCT has the capacity
- First step: Sudakov approximation
- Dominant effects $-\alpha^k \log^n(s/m_w^2)$
  $s \gg m_w^2$

[Denner & Pozzorini; EPJC 18 (2001) 461-4801 & EPJC 21 (2001) 63-79]
[Pagani & Zaro; JHEP 02 (2022) 161]

EW Higgs production & decay

[Zhang & Vryonidou; JHEP 08 (2018) 036]



Reweighting-based methods

	$\gamma\gamma$	γZ	bb	WW*	ZZ*
gg	(-100%,1980%)	(-88%,200%)	(-40%,48%)	(-40%,47%)	(-40%,46%)
VBF	(-100%,1880%)	(-88%,170%)	(-6.1%,5.3%)	(-6.8%,6.7%)	(-8.8%,9.2%)
WH	(-100%,1880%)	(-88%,170%)	(-5.5%,4.2%)	(-6.1%,5.6%)	(-7.8%,7.9%)
ZH	(-100%,1880%)	(-87%,170%)	(-6.5%,5.9%)	(-7.1%,7.1%)	(-9.4%,9.9%)

EWPO @ NLO in SMEFT

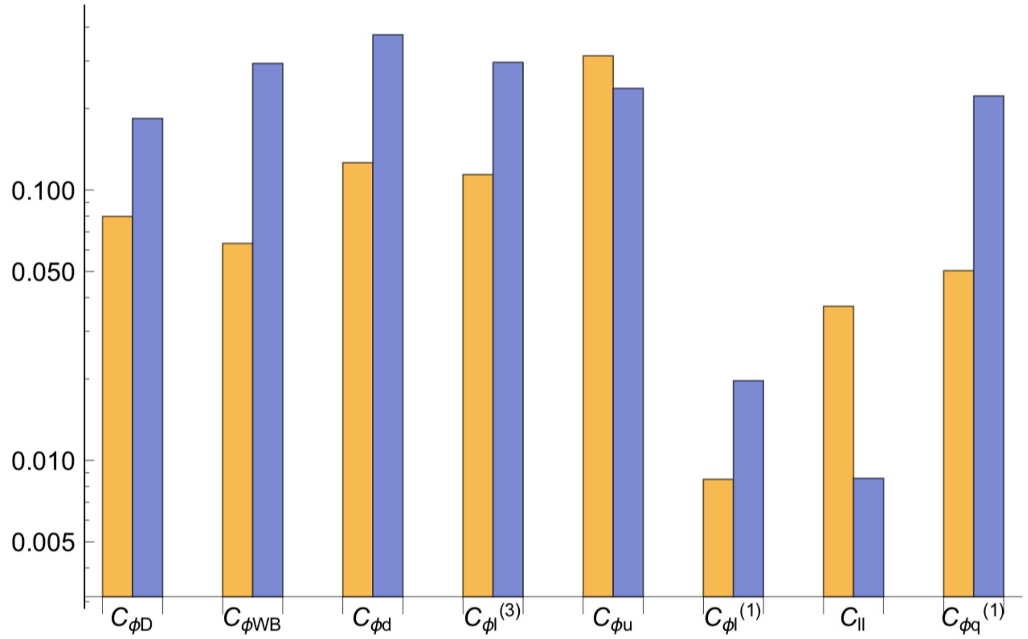
[Dawson & Giardino; PRD 101 (2020) 1, 013001]

QCD & EW corrections to Z & W pole observables

- First **'complete NLO'** SMEFT fit result

LO	10 operators 8 constraints	**NLO**	32 operators 10 constraints

- **LO:** blind direction closed by adding, *e.g.*, Higgs/Diboson data
- **NLO:** fit is no longer closed, need more data (calculations)



O(20-30%) corrections in marginalised fit

Coefficient	LO	NLO
$\mathcal{C}_{\phi D}$	$[-0.034, 0.041]$	[-0.039,0.051]
$\mathcal{C}_{\phi WB}$	$[-0.080, 0.0021]$	$[-0.098, 0.012]$
$\mathcal{C}_{\phi d}$	$[-0.81, -0.093]$	$[-1.07, -0.03]$
$\mathcal{C}_{\phi l}^{(3)}$	$[-0.025, 0.12]$	$[-0.039, 0.16]$
$\mathcal{C}_{\phi u}$	$[-0.12, 0.37]$	$[-0.21, 0.41]$
$\mathcal{C}_{\phi l}^{(1)}$	$[-0.0086, 0.036]$	$[-0.0072, 0.037]$
$\mathcal{C}_{ll}$	$[-0.085, 0.035]$	$[-0.087, 0.033]$
$\mathcal{C}_{\phi q}^{(1)}$	$[-0.060, 0.076]$	$[-0.095, 0.075]$

Conclusions & future plans

HL-LHC: precision SMEFT era

SMEFT@NLO is a milestone in tools for SMEFT predictions

- Crucial for inputs to global SMEFT likelihood for LHC & beyond
- Now: exploitation phase, many calculations yet to be done!

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

Thanks!