Top-quark EFT interpretations in CMS

Overview of the EFT interpretation strategies used in the top quark sector in CMS

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Outline

1. The Standard Model Effective Field Theory
2. EFT in top-quark physics
3. EFT approach within the top-quark group
4. Highlighted analyses
5. Organization within CMS and beyond
6. Conclusion

Outline

1. The Standard Model Effective Field Theory
2. EFT in top-quark physics

What is EFT?

3. EFT approach within the top-quark group
4. Highlighted analyses

EFT in TOP PAG

5. Organization within CMS and beyond

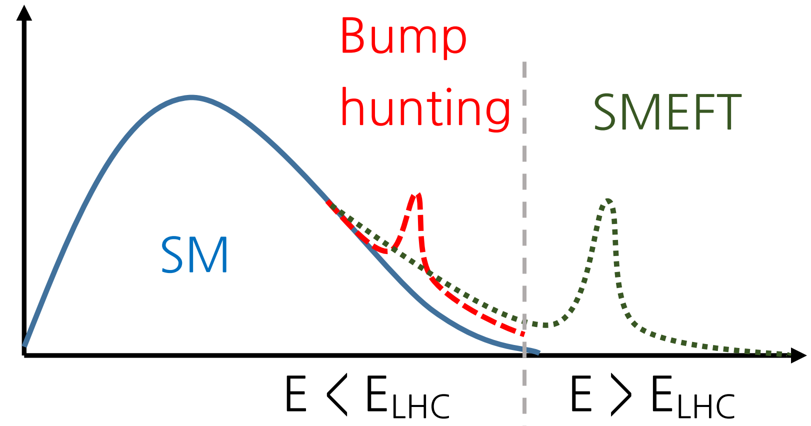
Organization in CMS

6. Conclusion

The Standard Model Effective Field Theory

Lack of direct evidence for BSM physics at the LHC
⟶ Standard Model Effective Field Theory (SMEFT):

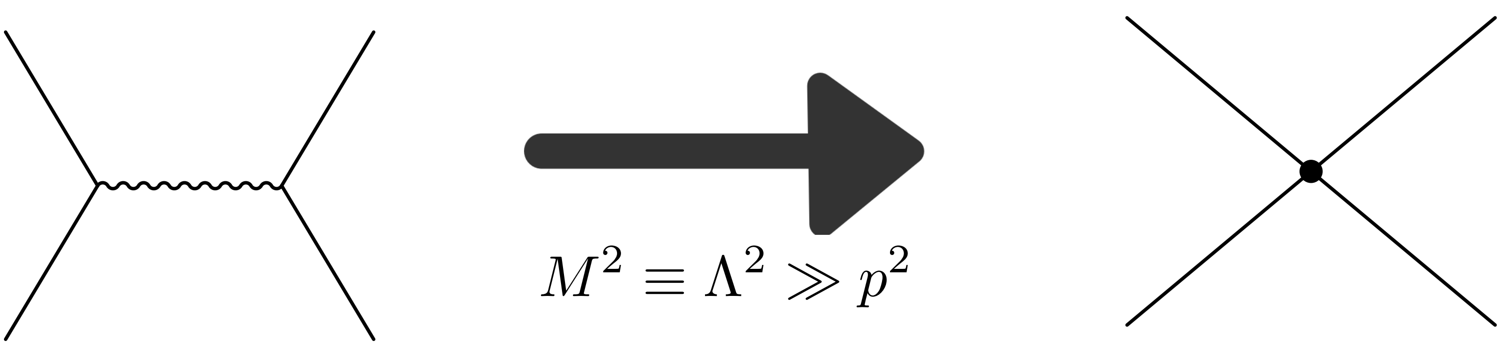
- model-independent interpretation
- New physics at high energy scales
- Heightened energy dependence and modified kinematics



Extend SM Lagrangian up to dim. 6:

(→ Leading B & L conserving contributions)

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{C_i}{\Lambda^2} O_i^{(6)}$$



$$\frac{g_*^2}{p^2 - M^2}$$

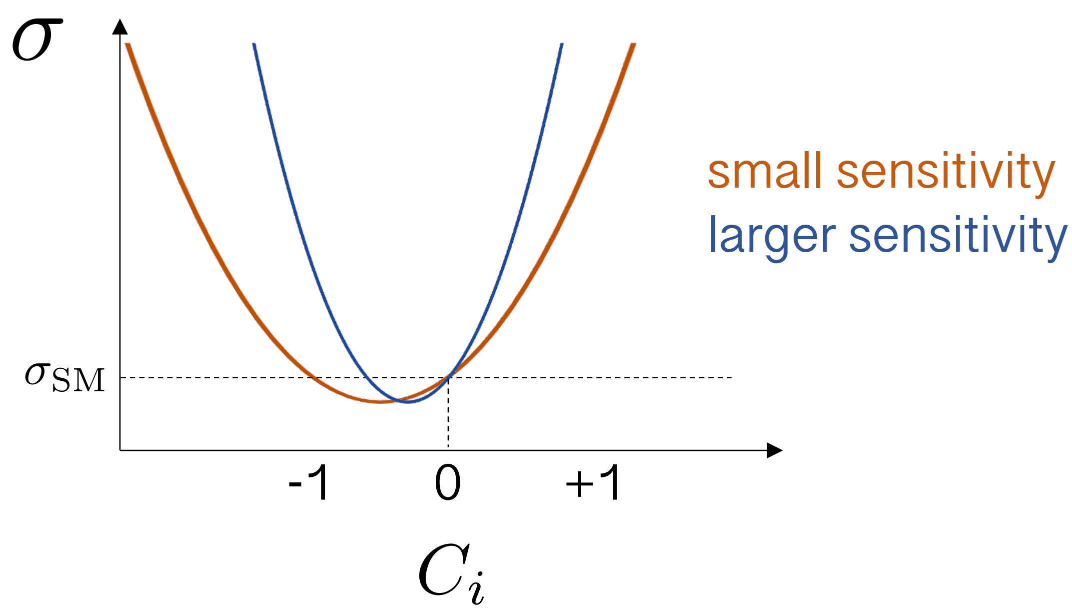
dim. 6 $\boxed{-\frac{g_*^2}{\Lambda^2}}\left[1 + \cancel{\frac{p^2}{\Lambda^2}} + \cancel{\frac{p^4}{\Lambda^4}} + \cancel{\cdots}\right]$

The name of the game:
parametrize sensitivity to SMEFT operators

interference quadratic (pure EFT)

$$\sigma = \sigma_{SM} + \sum_i \frac{C_i}{\Lambda^2}\,\tilde{\sigma}_i + \sum_{i,j} \frac{C_i\,C_j}{\Lambda^4}\,\tilde{\delta}_{i,j}$$

1 operator: $\sigma = \sigma_{\mathrm{SM}} + \mathrm{p}_1 \cdot \frac{C_i}{\Lambda^2} + \mathrm{p}_2 \cdot \frac{C_i^2}{\Lambda^4}$



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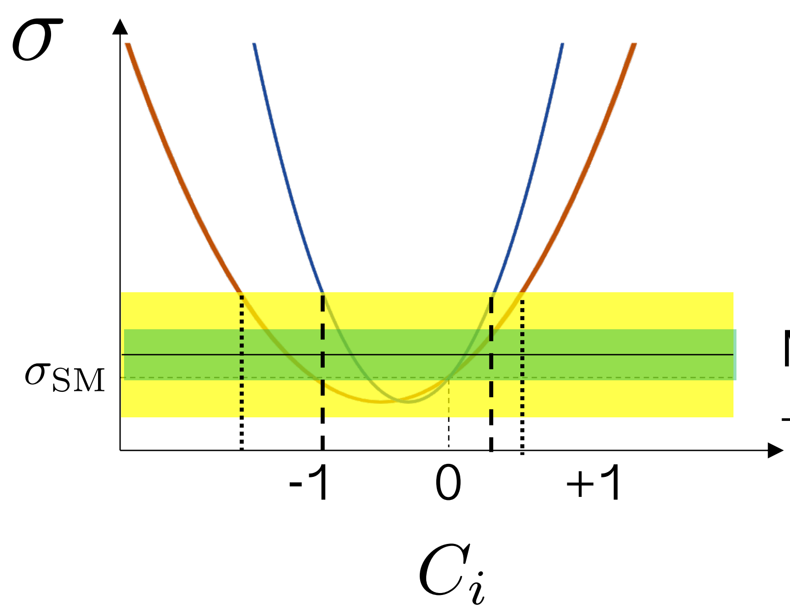


Measurement
→ limits on Wilson Coeff.

The Standard Model Effective Field Theory

Warsaw basis of dim. 6 operators (*B. Grzadkowsk, et al. [JHEP 1010 (2010) 085]*)

Depending on flavor assumptions, 59 up to 2499 independent operators

→ For a given final-state, many simultaneous contributions possible!

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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\star (\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

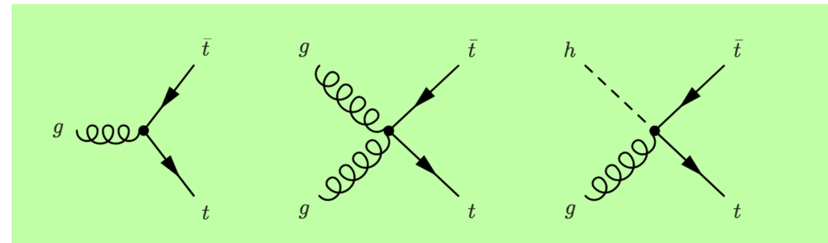
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q^{(1)}_{\varphi l}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q^{(3)}_{\varphi l}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q^{(1)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q^{(3)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde W B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	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}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q^{(1)}_{qq}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q^{(3)}_{qq}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q^{(1)}_{lq}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q^{(3)}_{lq}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q^{(1)}_{qu}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q^{(1)}_{ud}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q^{(8)}_{qu}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q^{(8)}_{ud}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q^{(1)}_{qd}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q^{(8)}_{qd}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

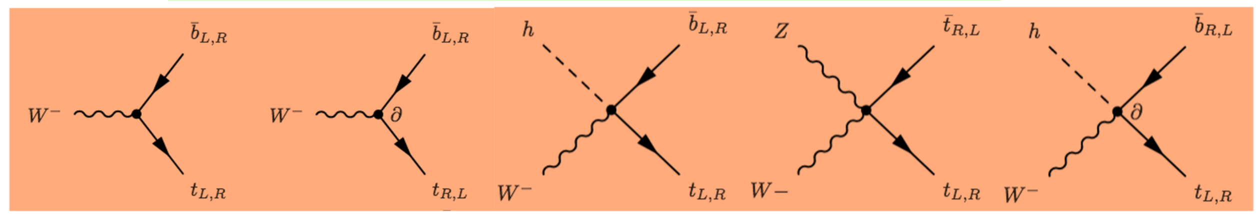
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l^j_p e_r)(\bar d_s q^j_t)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(q^{\gamma j}_s)^T C l^k_t\right]$
$Q^{(1)}_{quqd}$	$(\bar q^j_p u_r)\varepsilon_{jk}(\bar q^k_s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

EFT enters in many top quark interactions

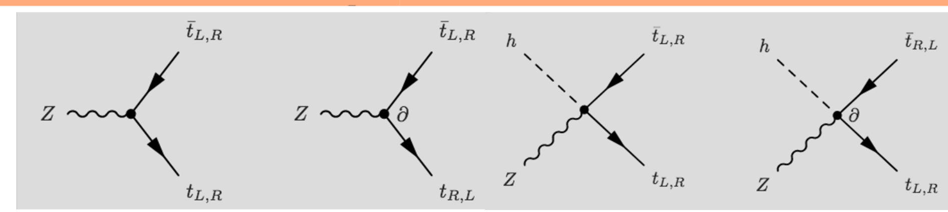
top-gluon interactions



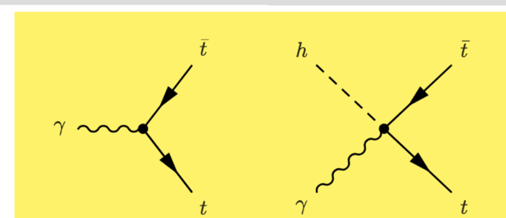
top-W interactions



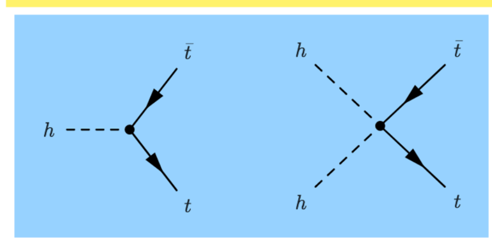
top-Z interactions



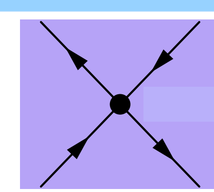
top-γ interactions



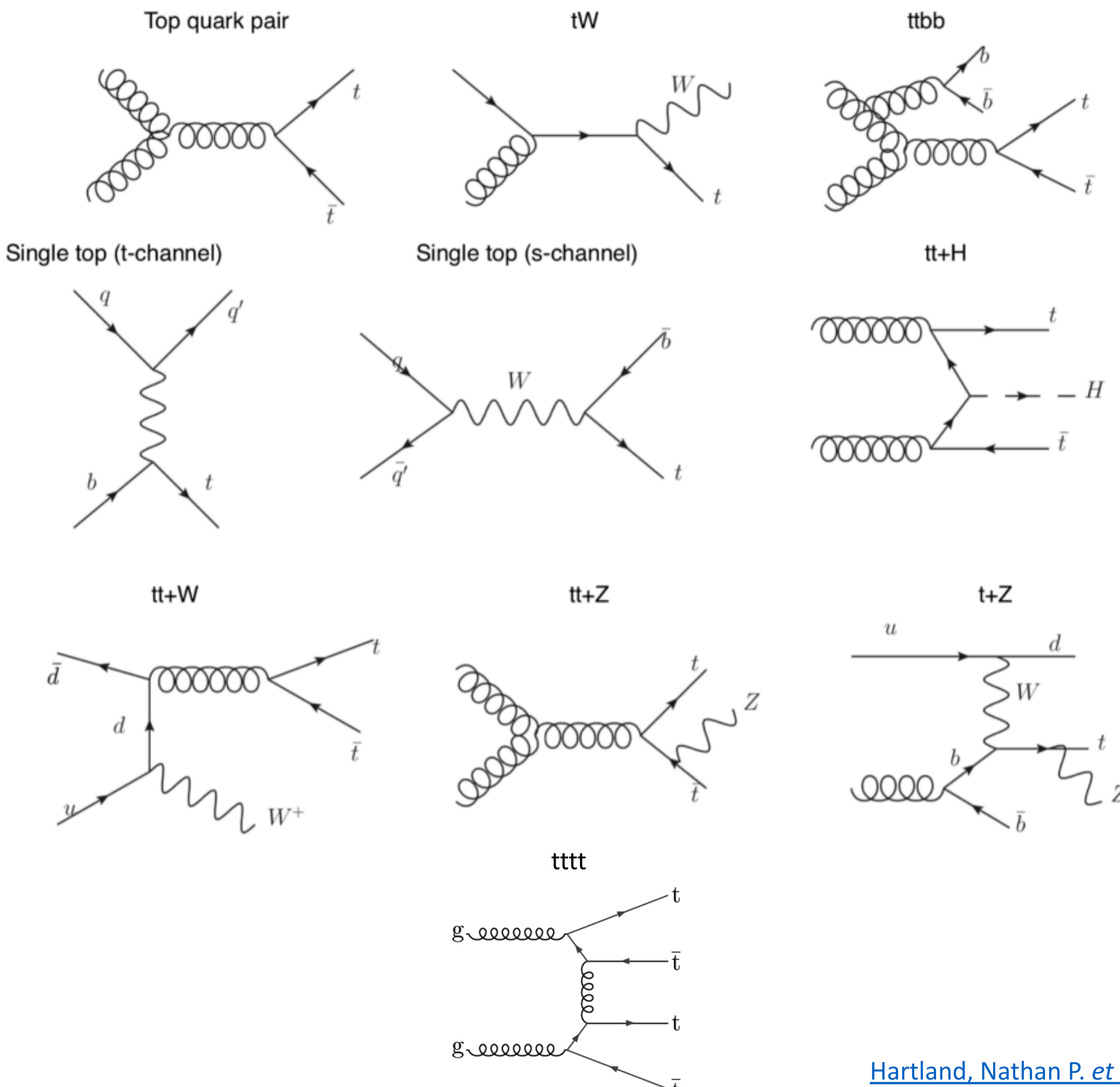
top-Higgs interactions



4-fermion interactions



… and therefore in many different final states!



Notation	Sensitivity at $\mathcal{O}(\Lambda^{-2})$ ($\mathcal{O}(\Lambda^{-4})$)								
	$t\bar{t}$	single-top	tW	tZ	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}H$	$t\bar{t}t\bar{t}$	$t\bar{t}b\bar{b}$
OQQ1								✓	✓
OQQ8								✓	✓
OQt1								✓	✓
OQt8								✓	✓
OQb1									✓
OQb8									✓
Ott1								✓	
Otb1									✓
Otb8									✓
OQtQb1									(✓)
OQtQb8									(✓)
O81qq	✓				✓	✓	✓	✓	✓
O11qq	[✓]				[✓]	[✓]	[✓]	✓	✓
O83qq	✓	[✓]		[✓]	✓	✓	✓	✓	✓
O13qq	[✓]	✓		✓	[✓]	[✓]	[✓]	✓	✓
O8qt	✓				✓	✓	✓	✓	✓
O1qt	[✓]				[✓]	[✓]	[✓]	✓	✓
O8ut	✓					✓	✓	✓	✓
O1ut	[✓]					[✓]	[✓]	✓	✓
O8qu	✓					✓	✓	✓	✓
O1qu	[✓]					[✓]	[✓]	✓	✓
O8dt	✓					✓	✓	✓	✓
O1dt	[✓]					[✓]	[✓]	✓	✓
O8qd	✓					✓	✓	✓	✓
O1qd	[✓]					[✓]	[✓]	✓	✓
OtG	✓		✓		✓	✓	✓	✓	✓
OtW		✓	✓	✓					
ObW		(✓)	(✓)	(✓)					
OtZ				✓		✓			
Off		(✓)	(✓)	(✓)					
Ofq3		✓	✓	✓					
OpQM				✓		✓			
Opt				✓		✓			
Otp							✓		

Hartland, Nathan P. *et al.* JHEP 1904 (2019) 100 arXiv:1901.05965 [hep-ph]

EFT approaches within the TOP group

Different EFT approaches so far in TOP PAG

1. Reinterpretation of an inclusive measurement

- A quantity, usually a cross section, is measured.
- Used to constrain relevant Wilson coefficients using a simple *EFT parametrization*
- Resulting limits are scalable and can be combined beyond LHC
- No EFT MC events are needed
- **Examples:** TOP-17-005 (ttZ/W), TOP-17-019 (4tops)

2. Reinterpretation of unfolded differential measurements

- A (set of) quantity(ies), preferably sensitive to EFT, are measured at *particle* or *parton* level
- Need differential information with EFT at *generator level*
- It is scalable and can be combined beyond LHC if the bin-to-bin correlations, etc. are provided
- Examples: TOP-17-017 (diff. top pair), TOP-18-006 (spin corr.),

3. Hybrid EFT measurement at the detector level

a) **Reweight** with "SMEFT/EFT" at gen-level, translate to detector level under SM assumption, and compare with the data.
Example: TOP-18-009 (ttZ)

b) **Yield parametrization** with SMEFT, estimate at generator level, and translate to detector-level via SM
Example: TOP-17-020 (tW/tt dilepton)

4. Direct (global) EFT measurement with data

- Based on simulated SMEFT samples
- No SM assumption
- Include EFT in all processes
- Example: TOP-19-001 (in preparation)
→ constrain a large list of operators affecting ttZ, ttW, ttH, tZq (properly taking into account the interference effects between different final-states)

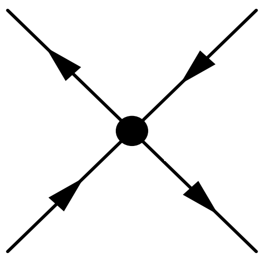
Approach 1

Highlights: 4-top EFT reinterpretation

TOP-17-019 (*JHEP 11 (2019) 082*):
4-top quark production in the single lepton and opposite sign dilepton analysis.

→ 95% CL upper limit at 48 fb (5.2 × SM)

Parametrization of 4-top cross section on a set of 4-heavy-quark (tttt) dim 6-operators is derived at gen level



$$\sigma_{t\bar{t}t\bar{t}} = \sigma^{\mathrm{SM}}_{t\bar{t}t\bar{t}} + \frac{1}{\Lambda^2}\sum_k C_k \sigma^{(1)}_k + \frac{1}{\Lambda^4}\sum_{j\le k} C_j C_k \sigma^{(2)}_{j,k}$$

Operator	$\sigma^{(1)}_k$	$\sigma^{(2)}_{j,k}$			
		$\mathcal{O}^1_{\mathrm{tt}}$	$\mathcal{O}^1_{\mathrm{QQ}}$	$\mathcal{O}^1_{\mathrm{Qt}}$	$\mathcal{O}^8_{\mathrm{Qt}}$
$\mathcal{O}^1_{\mathrm{tt}}$	0.39	5.59	0.36	−0.39	0.3
$\mathcal{O}^1_{\mathrm{QQ}}$	0.47		5.49	−0.45	0.13
$\mathcal{O}^1_{\mathrm{Qt}}$	0.03			1.9	−0.08
$\mathcal{O}^8_{\mathrm{Qt}}$	0.28				0.45

Operator	Expected C_k/Λ^2 (TeV^{-2})	Observed (TeV^{-2})
$\mathcal{O}^1_{\mathrm{tt}}$	[−2.0, 1.9]	[−2.2, 2.1]
$\mathcal{O}^1_{\mathrm{QQ}}$	[−2.0, 1.9]	[−2.2, 2.0]
$\mathcal{O}^1_{\mathrm{Qt}}$	[−3.4, 3.3]	[−3.7, 3.5]
$\mathcal{O}^8_{\mathrm{Qt}}$	[−7.4, 6.3]	[−8.0, 6.8]

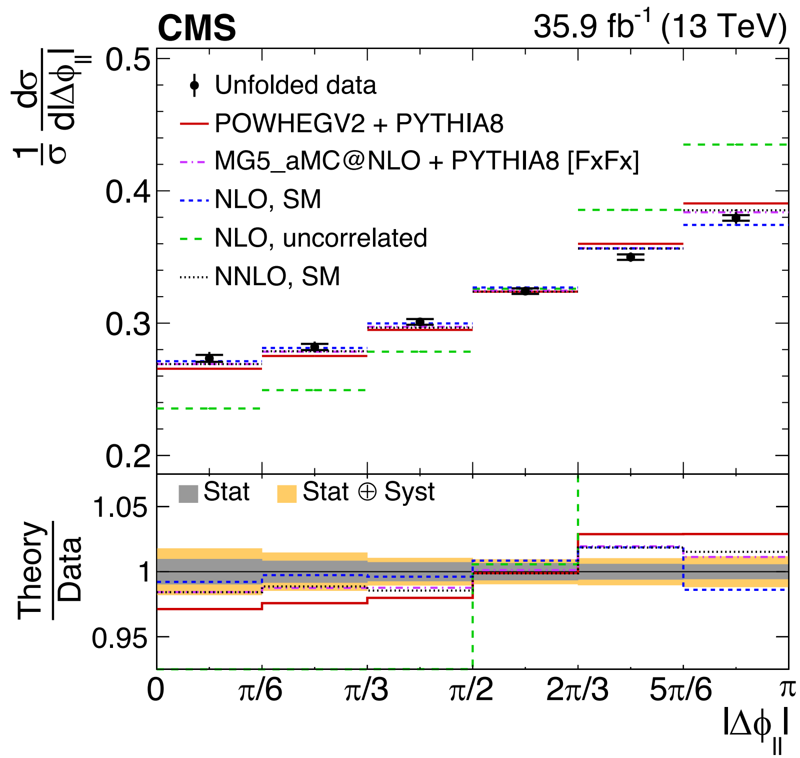
Limits are derived on individual operators **and by marginalizing other operators** (shown in table to the left).

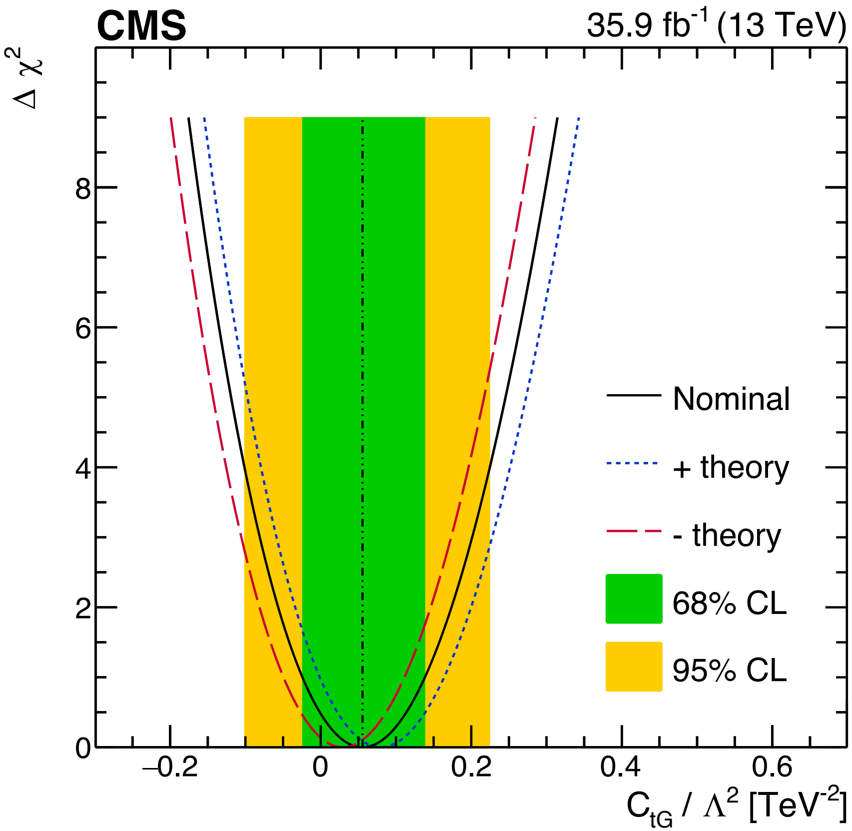
Approach 2

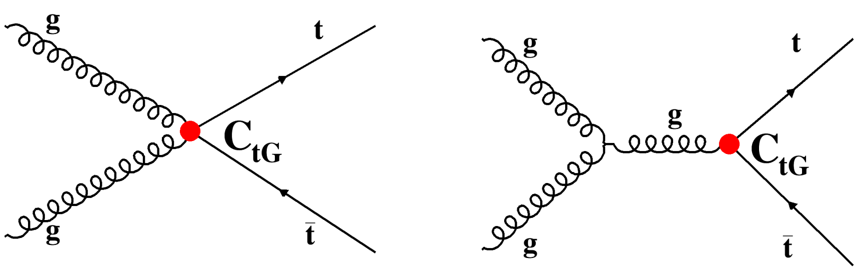
Highlights: $t\bar{t}$ polarization and spin correlation

TOP-18-006 (*Phys. Rev. D 100 (2019) 072002*):
Differential (unfolded) $t\bar{t}$ cross section measurement as a function of polarization angles.

→ limits are derived on the chromomagnetic dipole operator $C_{tG}^{(I)}$, based on gen-level EFT effects (therefore assuming SM acceptance etc.)







$$-0.24 < C_{tG}/\Lambda^2 < 0.07 \text{ and}$$
$$-0.33 < C_{tG}^{I}/\Lambda^2 < 0.20\ \text{TeV}^{-2}$$

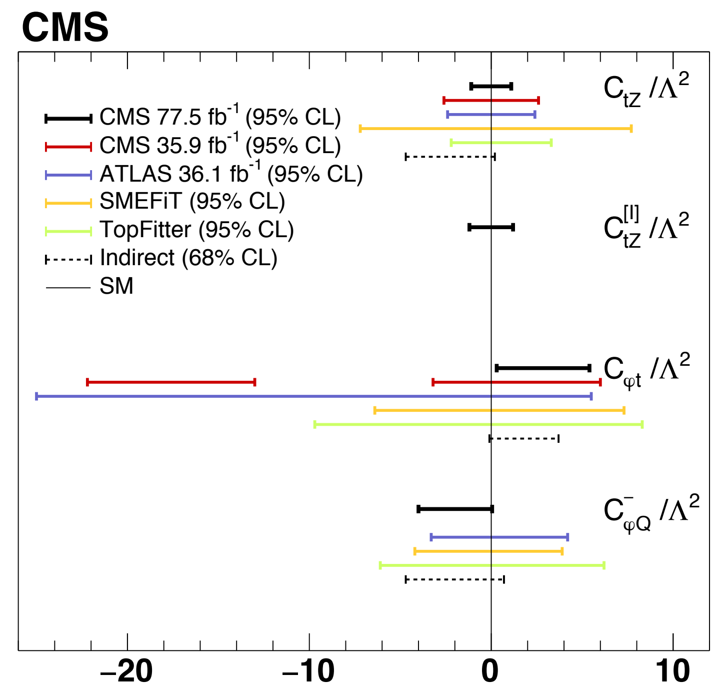
Approach 3a

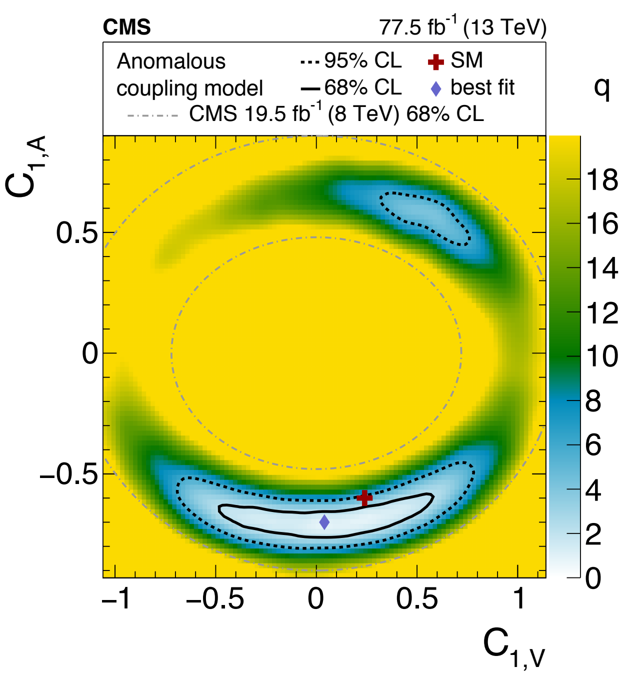
Highlights: Differential measurement of $t\bar{t}Z$

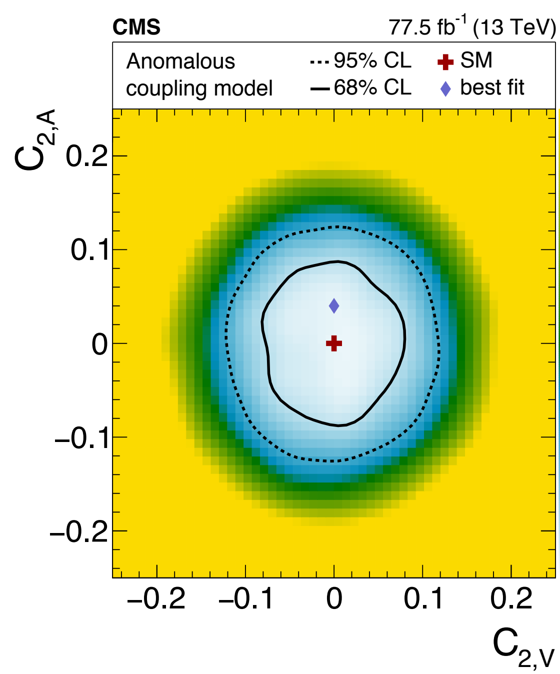
TOP-18-009: Differential measurement of $t\bar{t}Z$ production (submitted to JHEP)

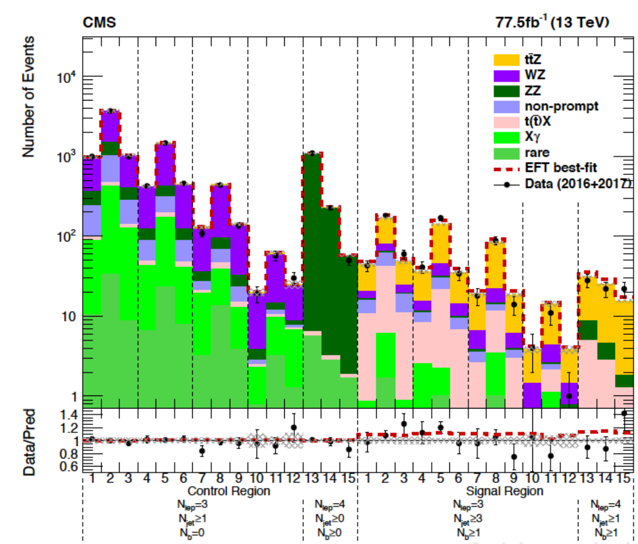
EFT (and anomalous coupling) effects are estimated at generator-level and reweighing is then applied at the detector-level

→ 1D and 2D limits are derived on 4 EFT operators and two anomalous couplings







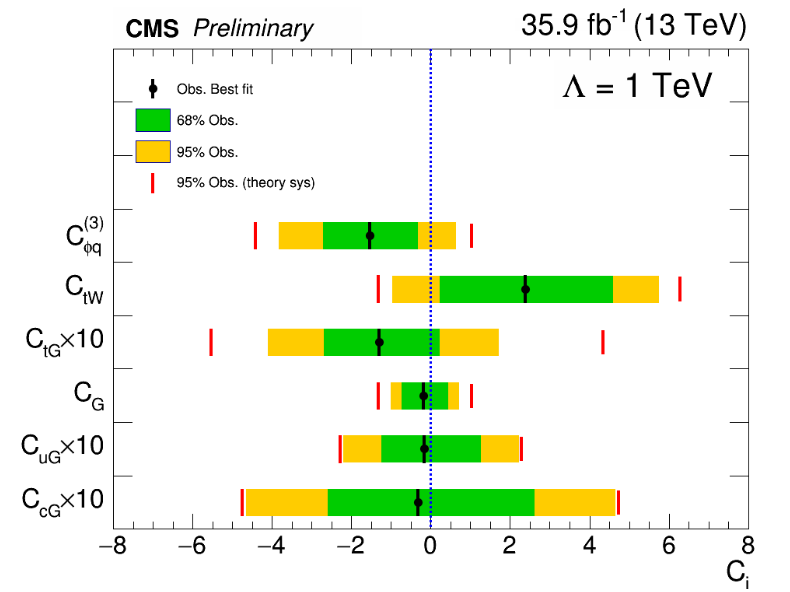


Highlights: new physics in tW and $t\bar{t}$ (dilepton)

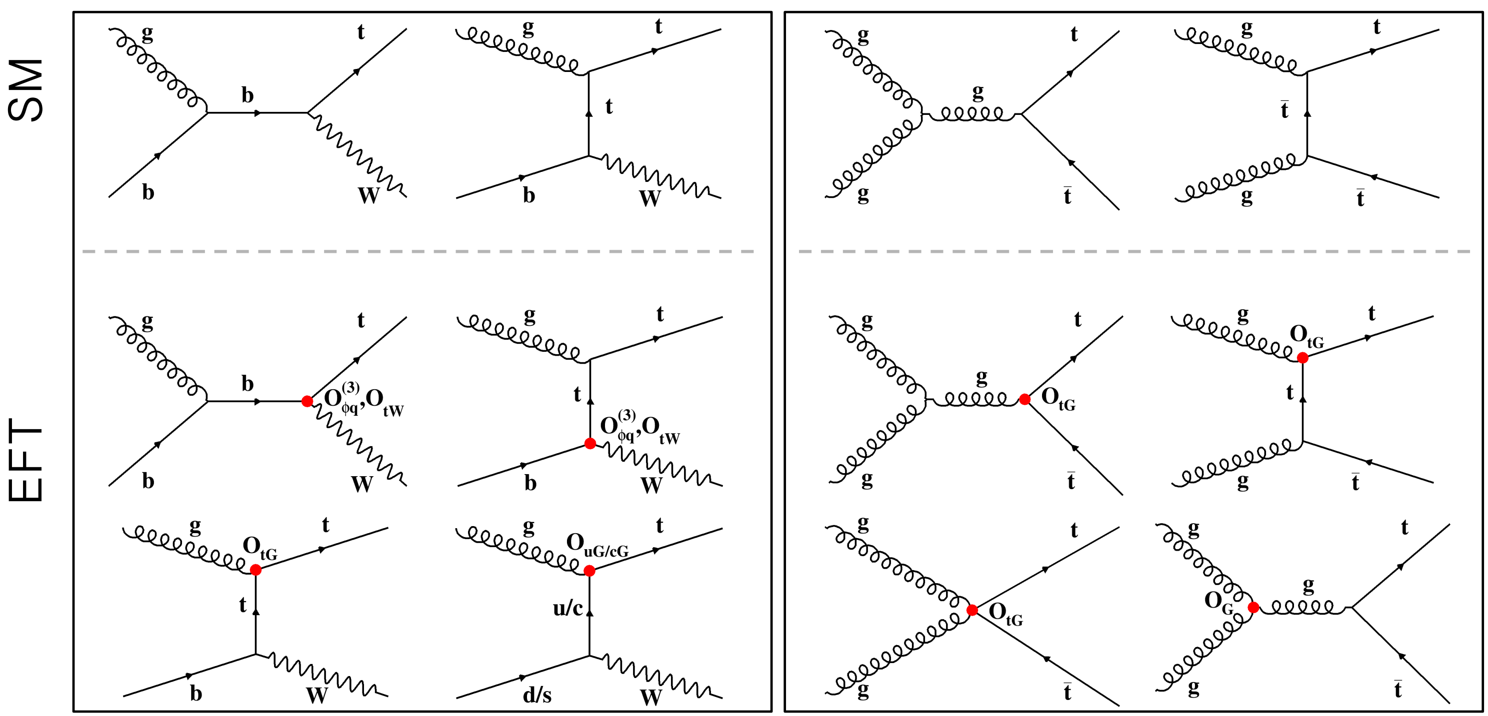
TOP-17-020 (*Eur. Phys. J. C 79 (2019) 886*):
Search for new physics in the dilepton channel (tW and $t\bar{t}$). Use of dedicated MVA methods

EFT estimated at parton level and projected with appropriate acceptance factors (and unc.)

→ limits are derived on several operators (also FCNC)



Single-top (tW) Top-quark pair ($t\bar{t}$)



$$O_{\phi q}^{(3)} = (\phi^+ \tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q),$$

$$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W_{\mu\nu}^I,$$

$$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G_{\mu\nu}^A,$$

$$O_G = f_{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu},$$

$$O_{u(c)G} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G_{\mu\nu}^A,$$

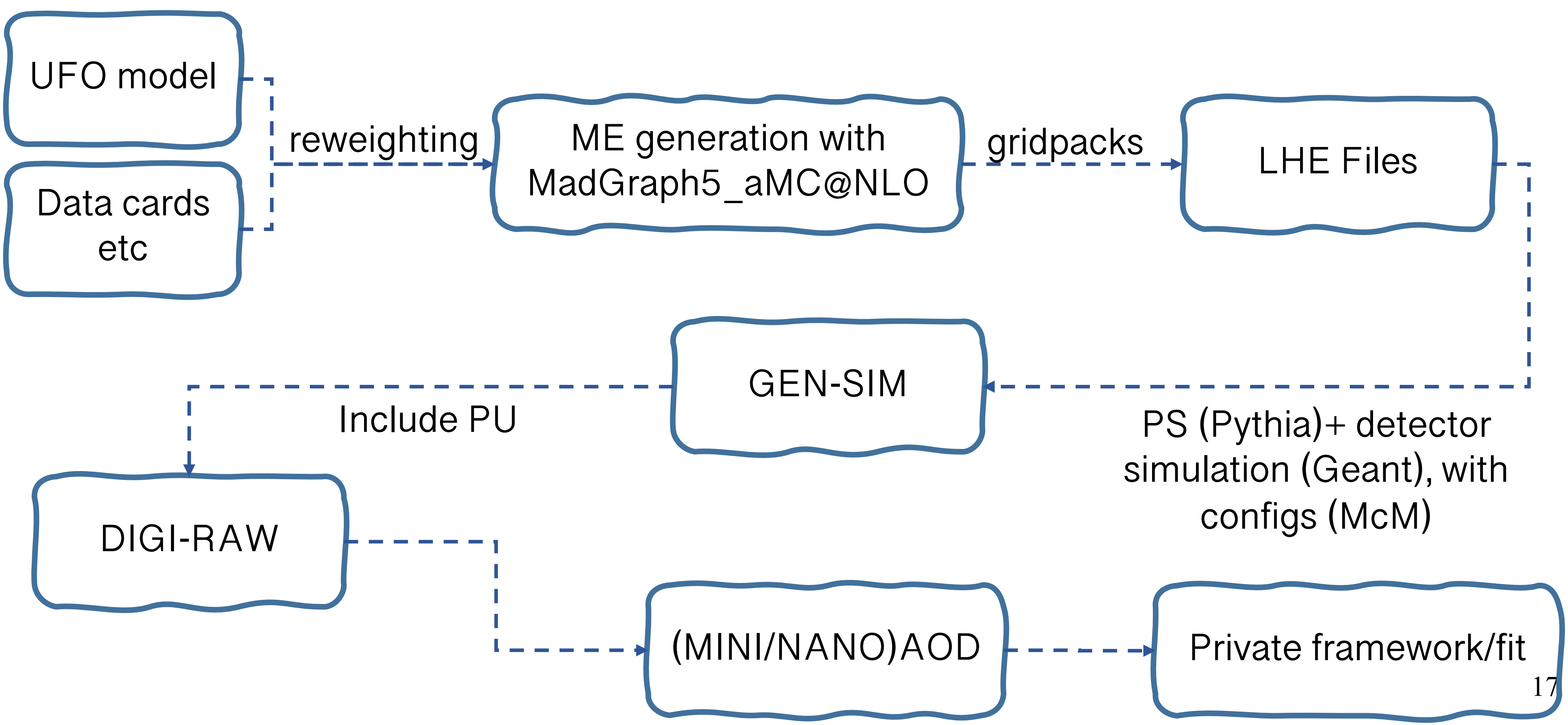
Approach 4

Highlights: generic search for EFT in tt+X

TOP-19-001 ***(Pre-approval‼ Preliminary results‼!):***

→ constrain a list of 12 operators affecting ttZ, ttW, ttH, tZq (properly taking into account the interference effects between different final-states)

→ Derive limits on the Wilson coefficients using the data at the detector level (no unfolding‼)



Organization of EFT in TOP / CMS

The TOP EFT forum

So far, the EFT activities in the TOP PAG have been coordinated within the EFT Forum

EFT Forum was created in the winter of 2017

There has been a close collaboration with theoreticians within the LHCtopWG

These results were summarized in the EFT note: http://arxiv.org/abs/1802.07237 which serves as guideline for top-quark EFT analyses at the LHC.

The forum has been heavily involved in shaping and scrutinizing the EFT analyses outlined above.

This forum has been very successful
→ now it is time to switch to a more structured approach: The TOP EFT subgroup

Interpreting top-quark LHC measurements in the standard-model effective field theory

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Abstract

This note proposes common standards and prescriptions for the effective-field-theory interpretation of top-quark measurements at the LHC.

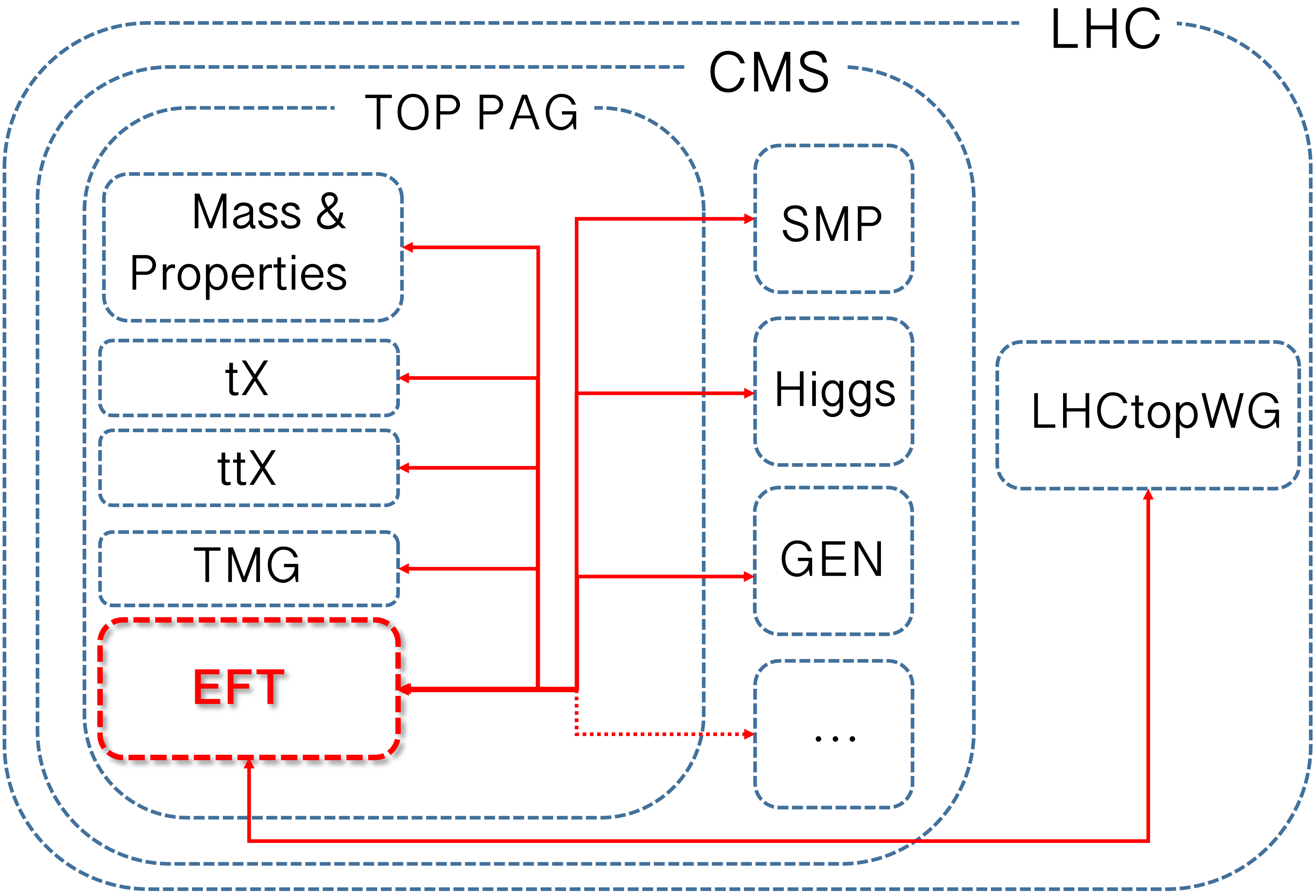
From EFT forum to an EFT subgroup

September 2019: Moved from EFT Forum towards an EFT subgroup

EFT Forum → **EFT subgroup**

- **TOP-EFT Twiki:** https://twiki.cern.ch/twiki/bin/view/CMS/TOPEFT
- **Github:** 🚧 https://github.com/cms-analysis/TopEFT 🚧
- **Hypernews:** Top Physics: EFT → hn-cms-top-eft
  EFT discussions (cross-PAG) → hn-cms-eft
- **Meetings:** bi-weekly meetings on Mon. 14:00 - 16:00

Interplay on EFT within CMS and beyond



Conclusions & outlook

EFTs provide a generic and model-independent way of searching for new (BSM) physics effects at high energy scales at the LHC

Within the Top-quark group in CMS, a clear vision concerning EFT is in place, which has already resulted in several publications with various approaches

Interplay between Physics Analysis Groups is actively ongoing in through a new CMS-wide EFT forum.

→ A bright and active future for EFTs lies ahead!