EFT with top quarks in CMS

LHCP2021, 7-12 June 2021

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Introduction

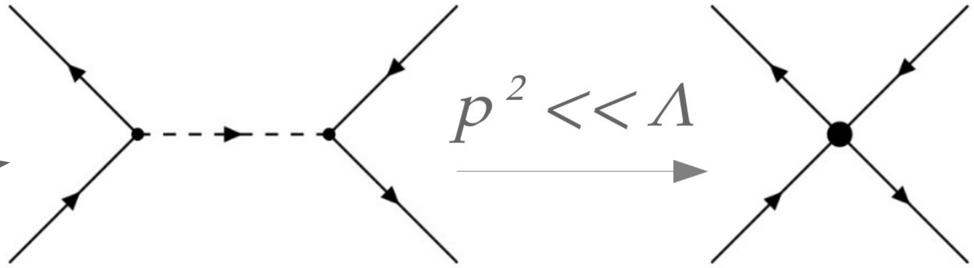
- Several motivations for physics beyond the standard model: hierarchy problem, dark matter astrophysical evidences, matter-antimatter asymmetry…

- However, no evidences observed at the LHC.
  - New particles have not been observed at the energy scales of the LHC.

- What if new physics at an energy scale Λ above Λ_{LHC}?

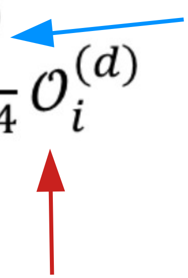
→ EFT approach

as in Fermi theory of beta decays



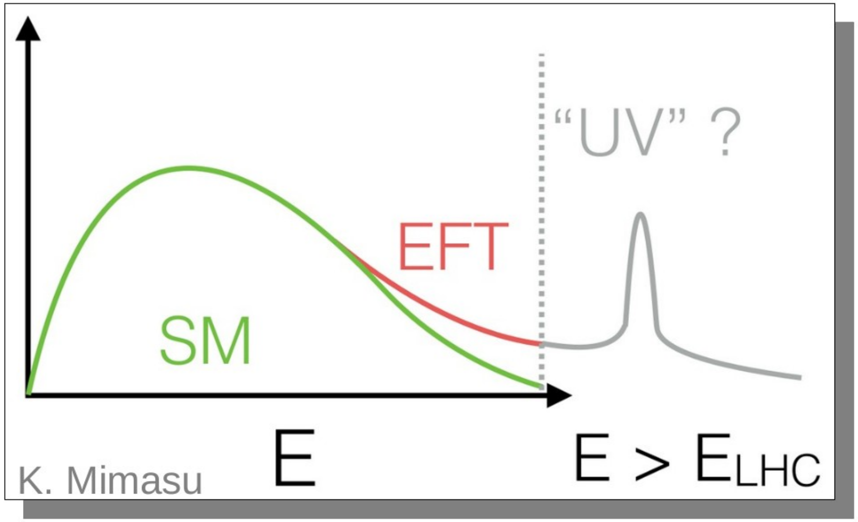
Effective field theories

- EFT approach used for looking for physics if $\Lambda >> \Lambda_{LHC}$.
- Lagrangian expansion:



$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d,i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

Wilson coefficients (WC)



- New higher-order operators.
- Model-independent.
- General predictions, correlated in different observables and processes.

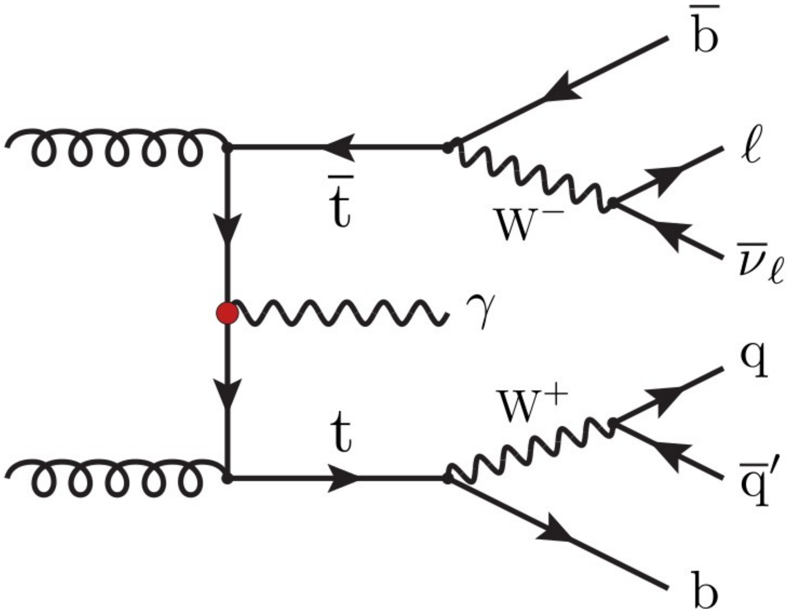
- EFT with top physics: precision measurements at the LHC – sensitivity to several top quark-related WCs.

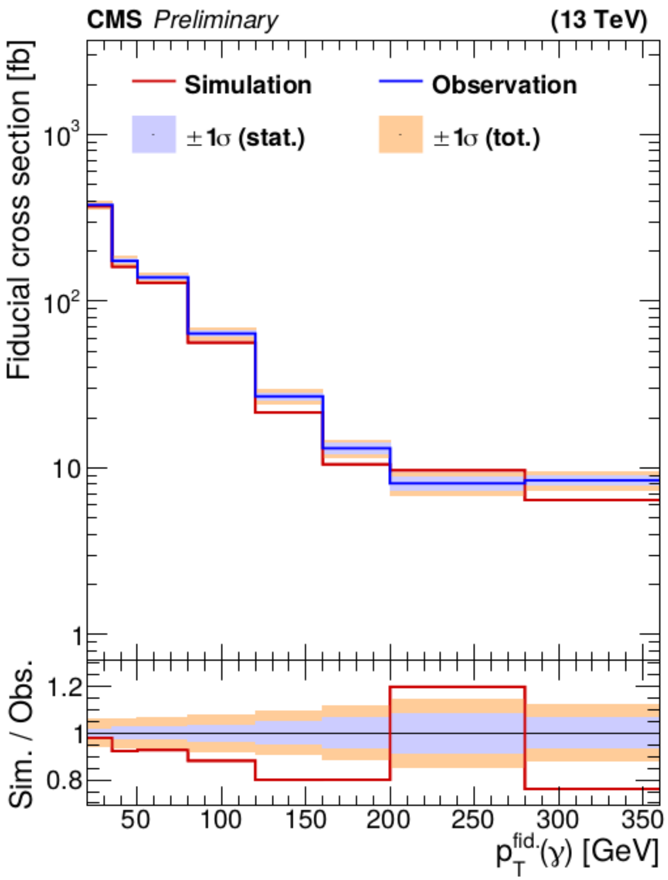
EFT with $t\bar{t}+\gamma$ events

CMS-PAS-TOP-18-010

NEW

- Inclusive and differential cross section measurement of $t\bar{t}+\gamma$ in single-lepton events.
- Selected events contain a e/μ and at least 3 jets, one of which is b-tagged.
- Backgrounds: hadronic γ/fake, misidentified e, QCD multijet.



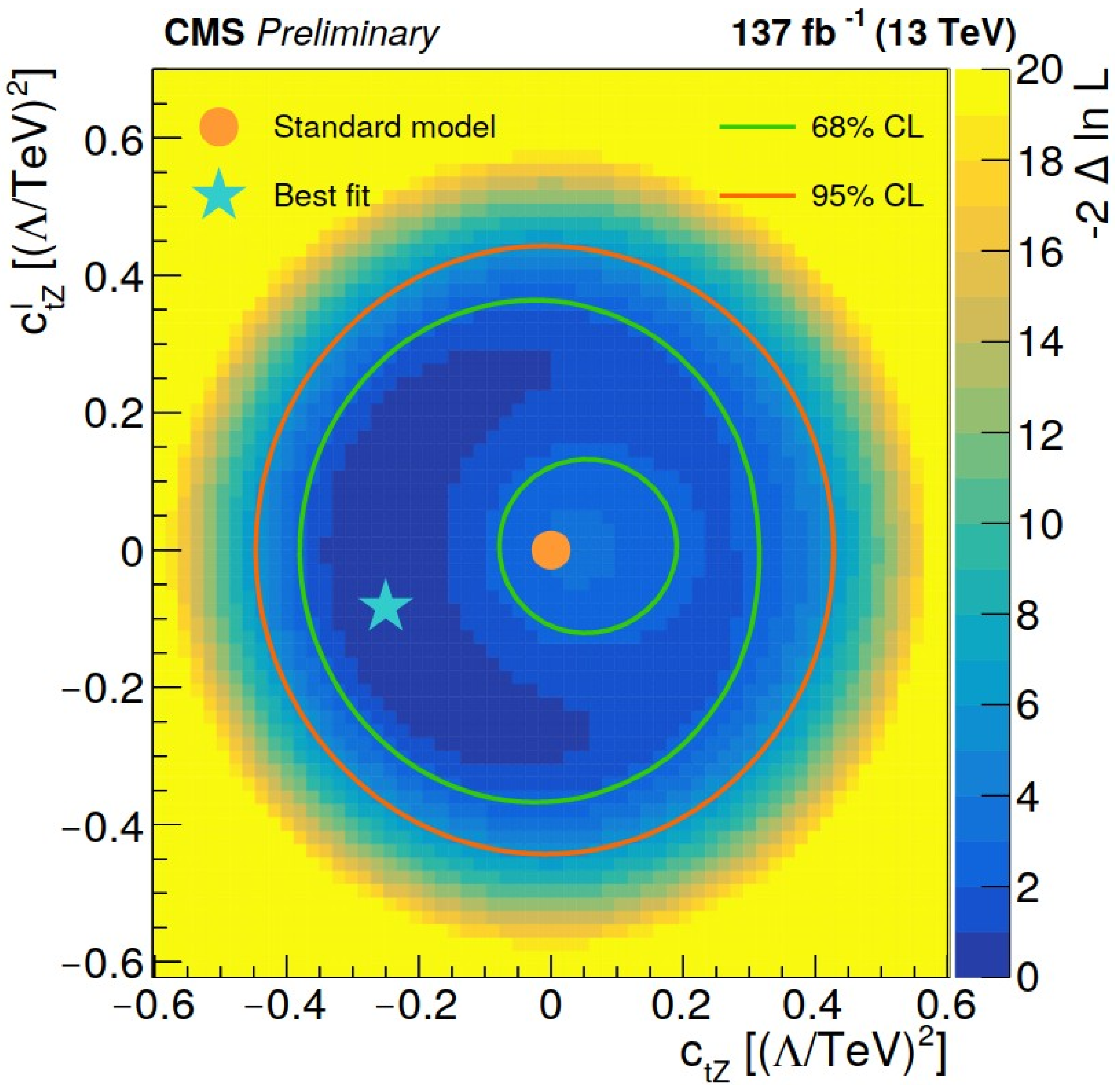


- Event categories in bins of jet multiplicities and M_{3j}.
- Inclusive measurement with a total uncertainty of 5.8%.
- Unfolded distributions and differential cross sections.

EFT with tt+γ events

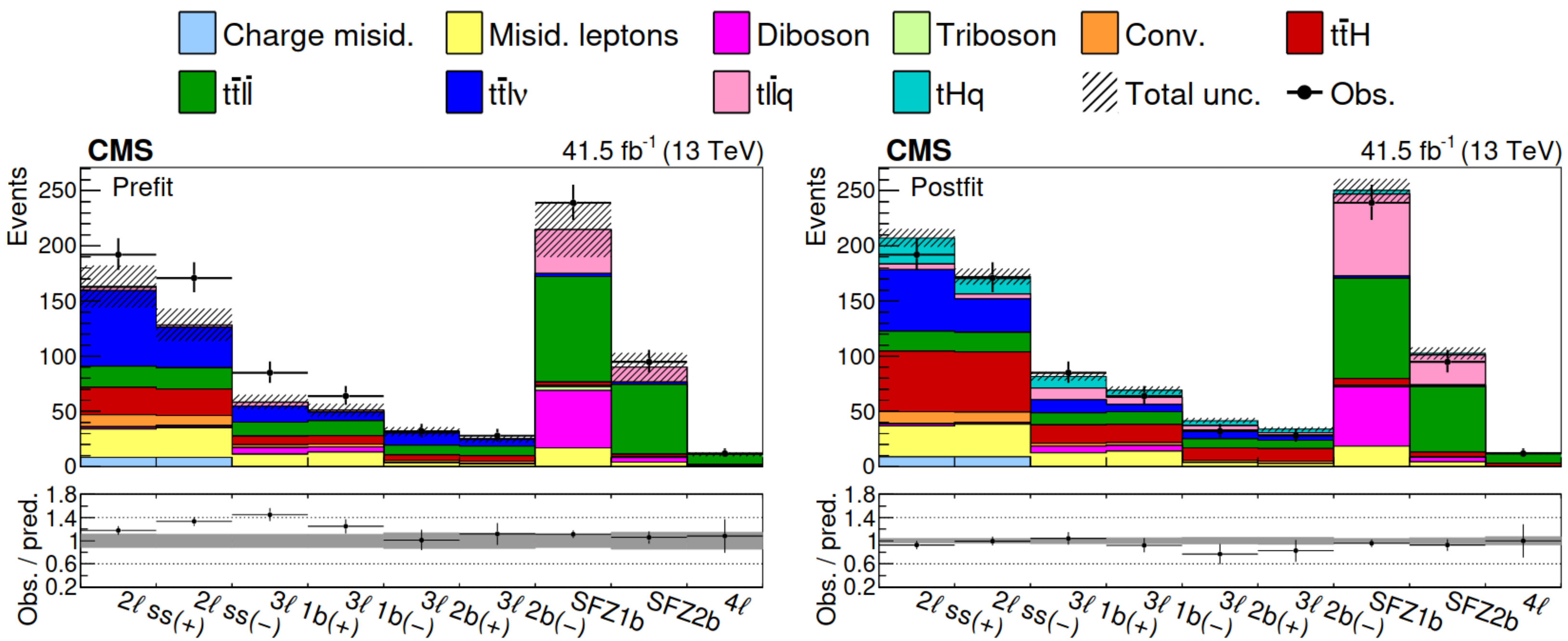
CMS-PAS-TOP-18-010

- EFT interpretation – two WCs are tested using $p_T(\gamma)$ distribution.
- EFT probed at gen level. Samples generated for some values for the two WC. A reweighting is derived and applied to the signal.
- Strongest limits on c_{tZ}, c^{l}_{tZ} to date.



EFT with top quarks in multilepton final states

- Target: ttll, ttlv, ttlq, ttH, tHq in final states with 2lSS, 3l, 4l and multiple jets, b-tagged jets (41.5fb^{-1}). JHEP 03 (2021) 095
- EFTs propagated to all relevant process. 16 WC are considered.
- EFTs tested at reco level using global fits.
- Categories to optimize the sensitivity to the different WC and processes.



EFT parameterization

- EFT effects included using a reweighing method – using madgraph to generate events with different weights for different values of the WCs.

- Weight function obtained through a quadratic fit for each event.

$$w\left(\frac{\vec{c}}{\Lambda^2}\right) = s_0 + \sum_j s_{1,j}\frac{c_j}{\Lambda^2} + \sum_j s_{2,j}\frac{c_j^2}{\Lambda^4} + \sum_j \sum_k s_{3,jk}\frac{c_j}{\Lambda^2}\frac{c_k}{\Lambda^2}$$

SM

SM-EFT interference

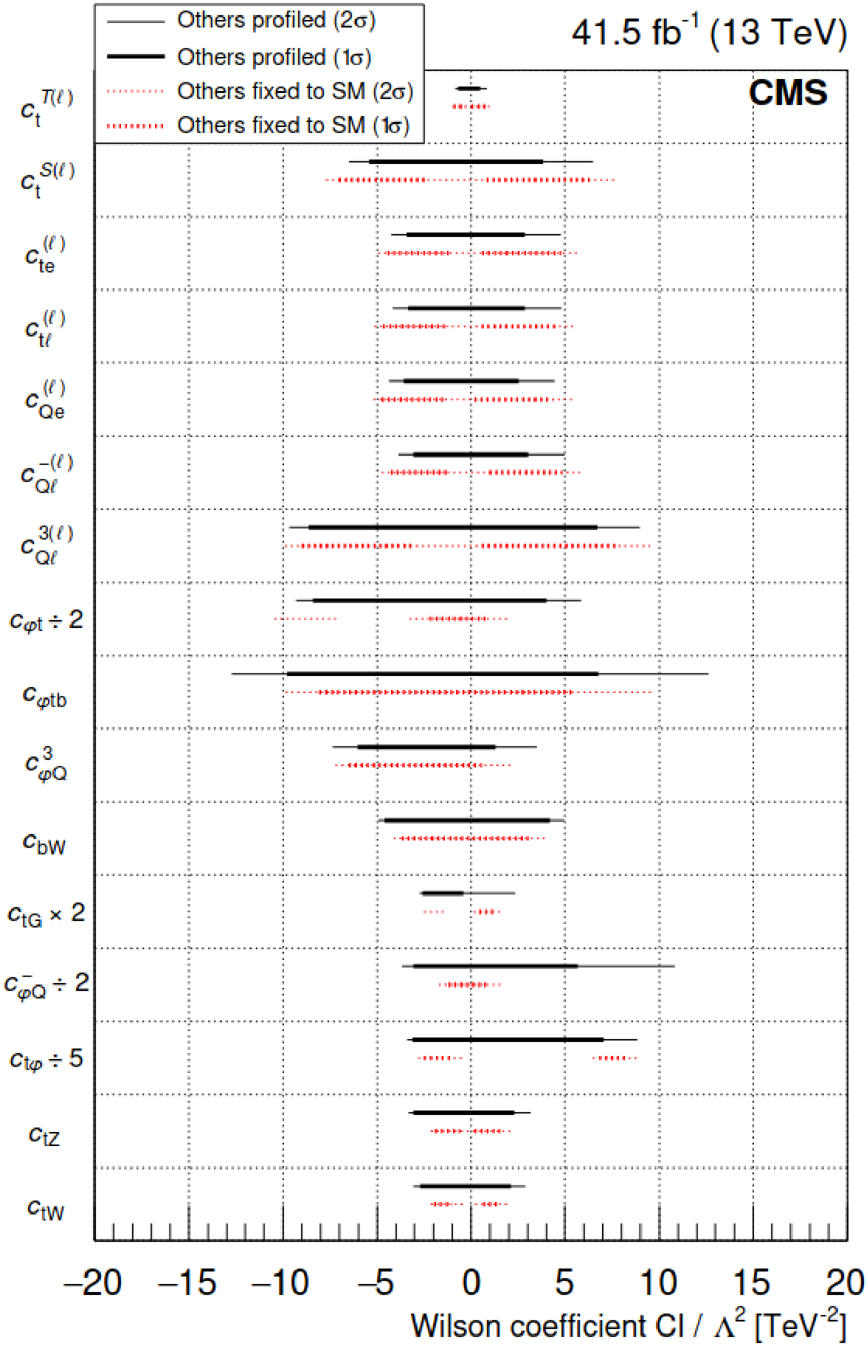
Pure EFT

EFT-EFT interference

- Coefficients for different events are summed to obtain weight functions for yields or different distributions.

- Expected yields at any point of the EFT parameter space obtained by evaluation the weight function at any WC point.

EFT with tops in multilepton final states



JHEP 03 (2021) 095

- A profiled likelihood fit is performed simultaneously in all categories and extract confidence intervals for all the WC.

- Two different procedures:
  - WC is scanned and the rest are nuisance parameters.
  - WC is scanned and the rest are set to zero (SM).

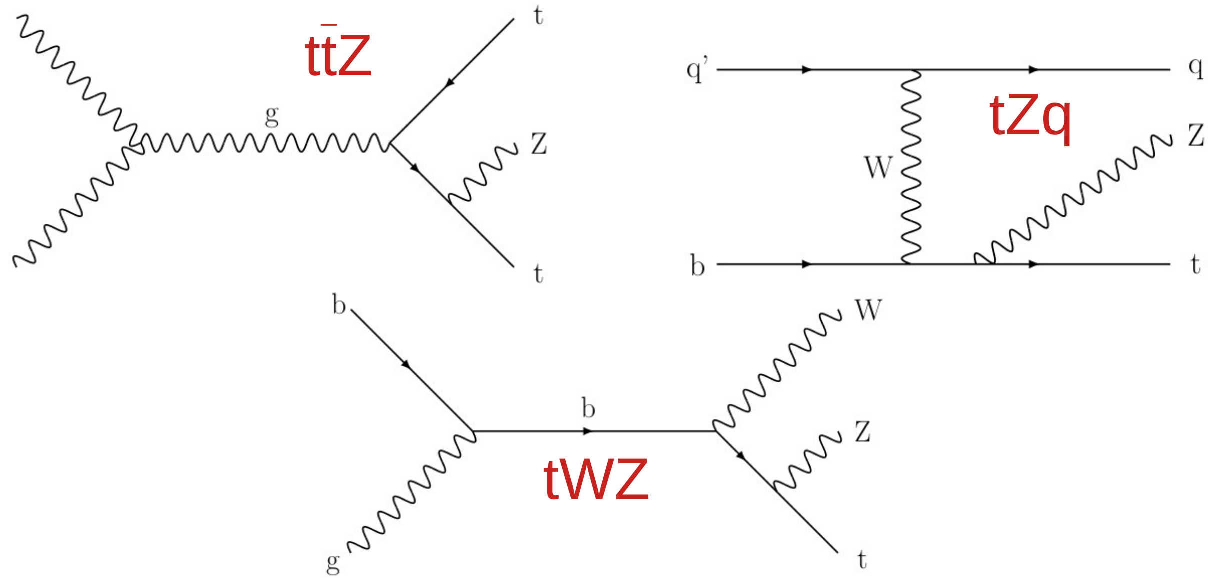
- Results show that the extracted 2σ CL for the 16 WC are compatible with SM.

EFT in t(t)Z events

CMS-PAS-TOP-21-001

NEW

- Probing EFT with tZ/ttZ events in multilepton final states.
- Full Run2 dataset, 138 fb^{-1}.



- Focus on 5 dim-6 operators:

Operator	WC
$\mathcal{O}_{tZ}$	c_{tZ}
$\mathcal{O}_{tW}$	c_{tW}
$\mathcal{O}^{3}_{\varphi Q}$	$c^{3}_{\varphi Q}$
$\mathcal{O}^{-}_{\varphi Q}$	$c^{-}_{\varphi Q}$
$\mathcal{O}_{\varphi t}$	$c_{\varphi t}$

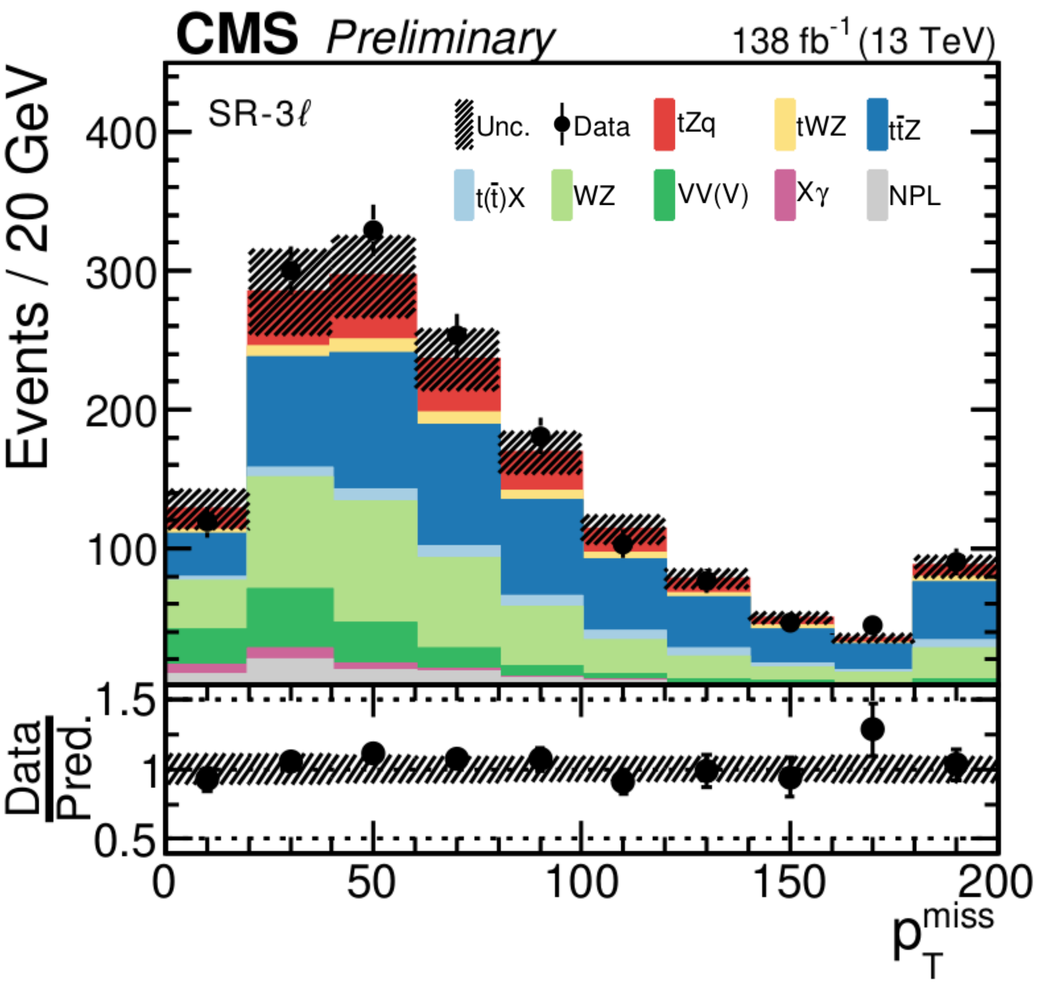
- Same method as in the previous analysis: a per-yield weight function is obtained – can be evaluated at any point of the WC parameter space.
- Global fit at reco level.
- Multivariate techniques used to enhance the sensitivity to new physics arising from EFT operators.

EFT in t(t)Z events – strategy (1)

CMS-PAS-TOP-21-001

- Signal processes: tZq, ttZ, tWZ. Two search regions (SR-3l, SR-4l).
  - Selection: Events containing at least 3 leptons, at least 2 jets, at least 1 b-tagged jet and a Z boson candidate.

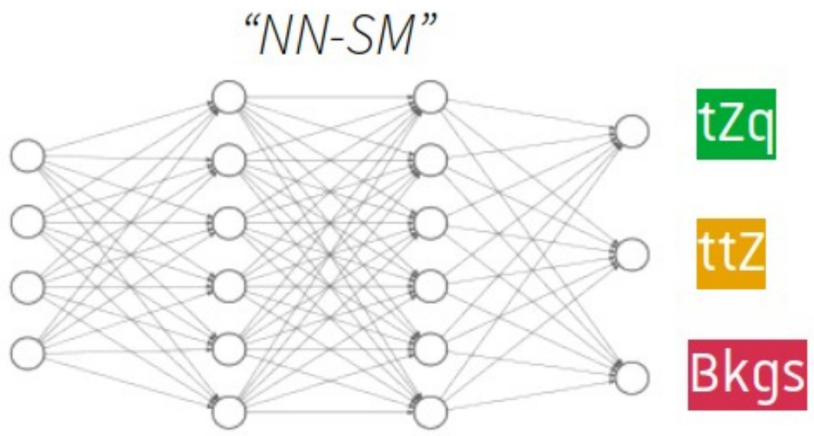
- Background processes:
  - WZ – estimated in control region (WZ CR).
  - ZZ – estimated in control region (ZZ CR).
  - Nonprompt leptons (NPL) – estimated from data.
  - Other backgrounds: t(t)X, X γ – estimated from MC simulation.

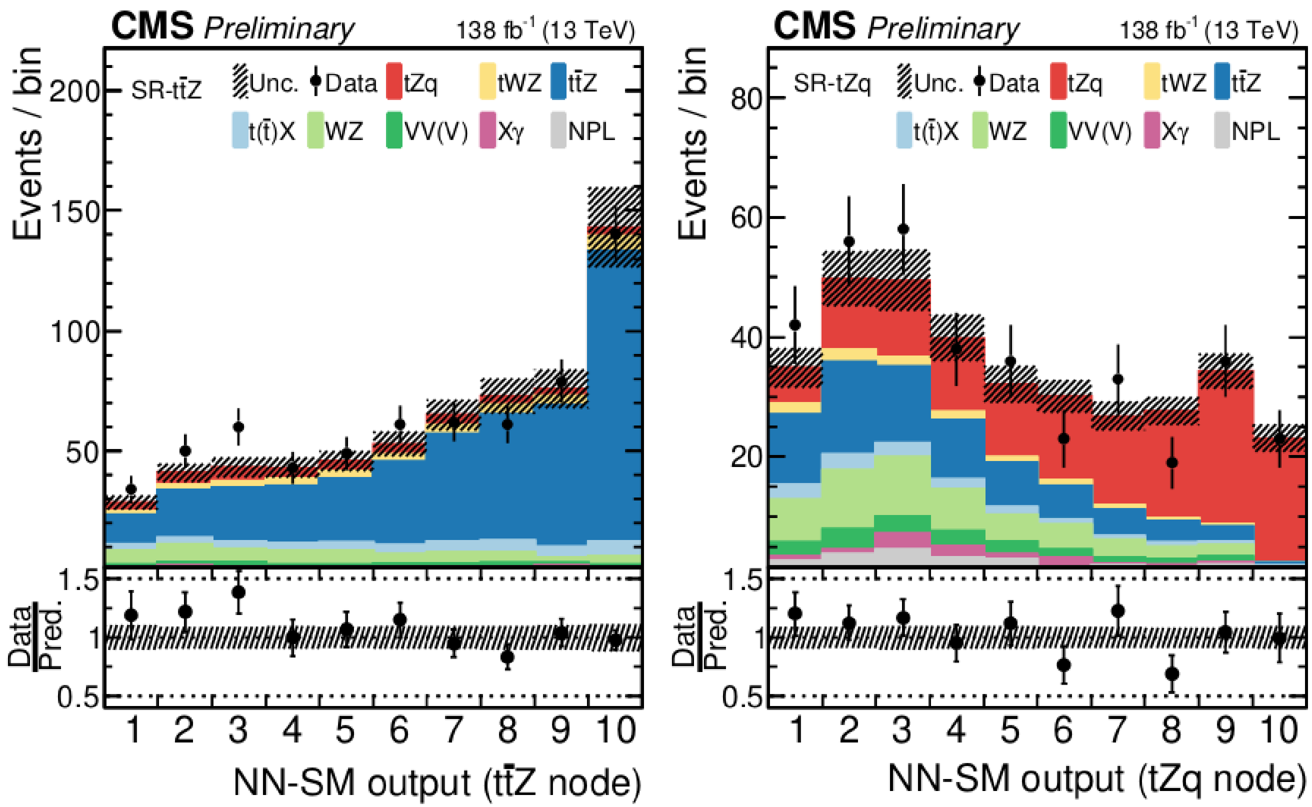


EFT in t(t)Z events – strategy (2)

CMS-PAS-TOP-21-001

- A multiclass neural network classifier is trained to optimize the selection of ttZ and tZq events in the signal regions (NN-SM).
- Three output nodes: "ttZ", "tZq" and "Bkgs".
- Training observables: kinematics of leptons and jets and the b-tagging discriminant of the jets.

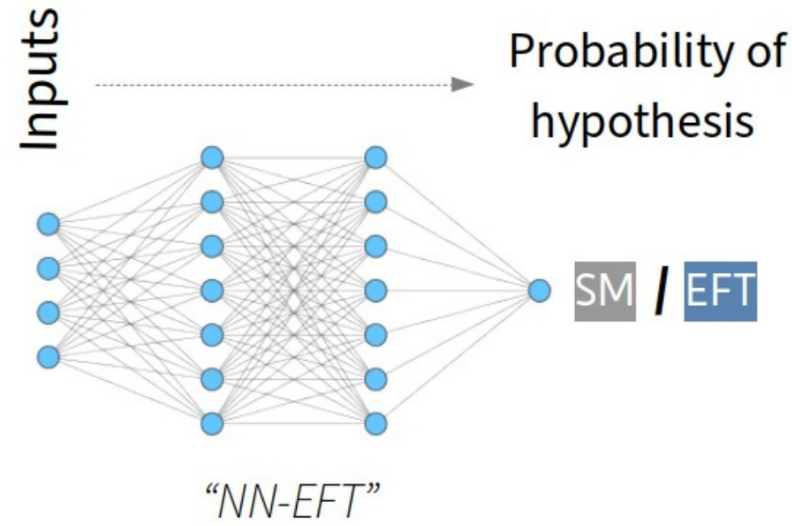


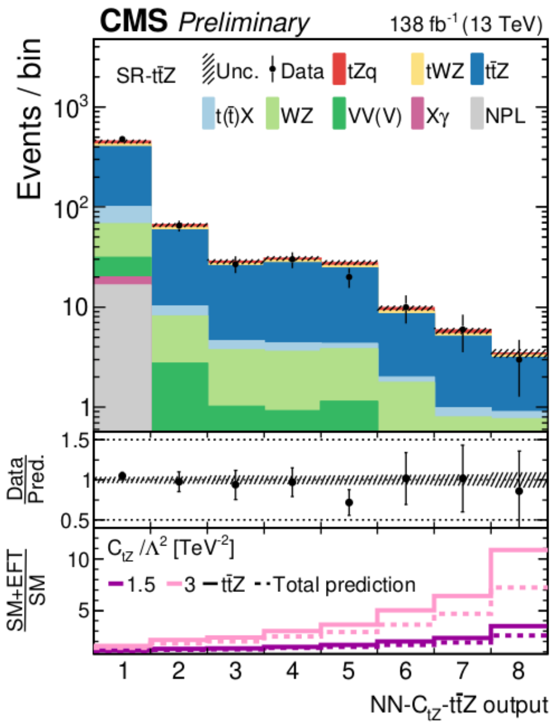


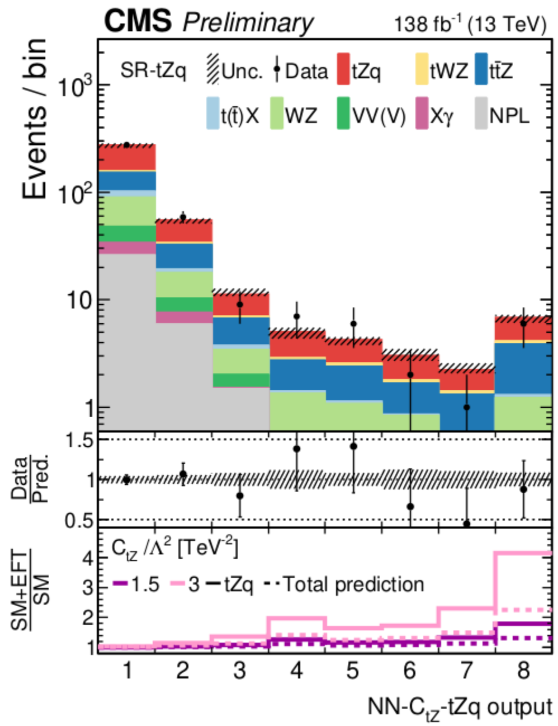
EFT in t(t)Z events – Signal extraction CMS-PAS-TOP-21-001

- Neural-network classifiers are trained to design observables with optimal sensitivity to effects arising from the target EFT operators (NN-EFTs).

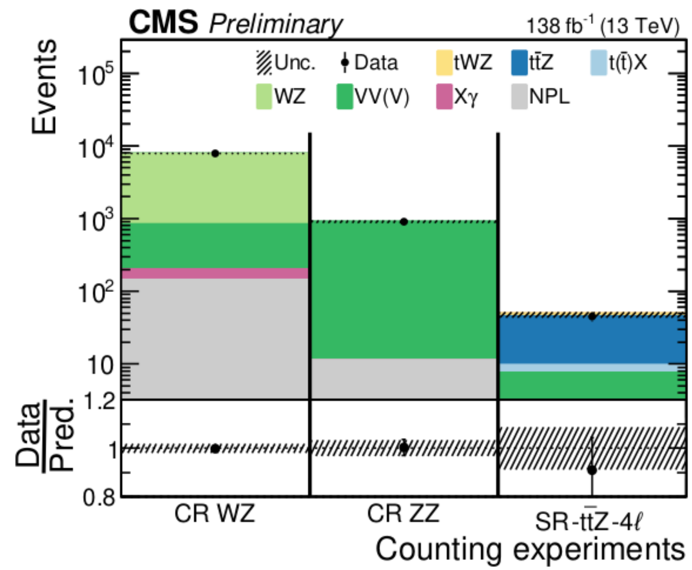
- Binary classifiers trained to discriminate SM vs EFT. The training targets individual WCs for individual processes (tZq, ttZ).
- Total of 8 NN-EFT classifiers







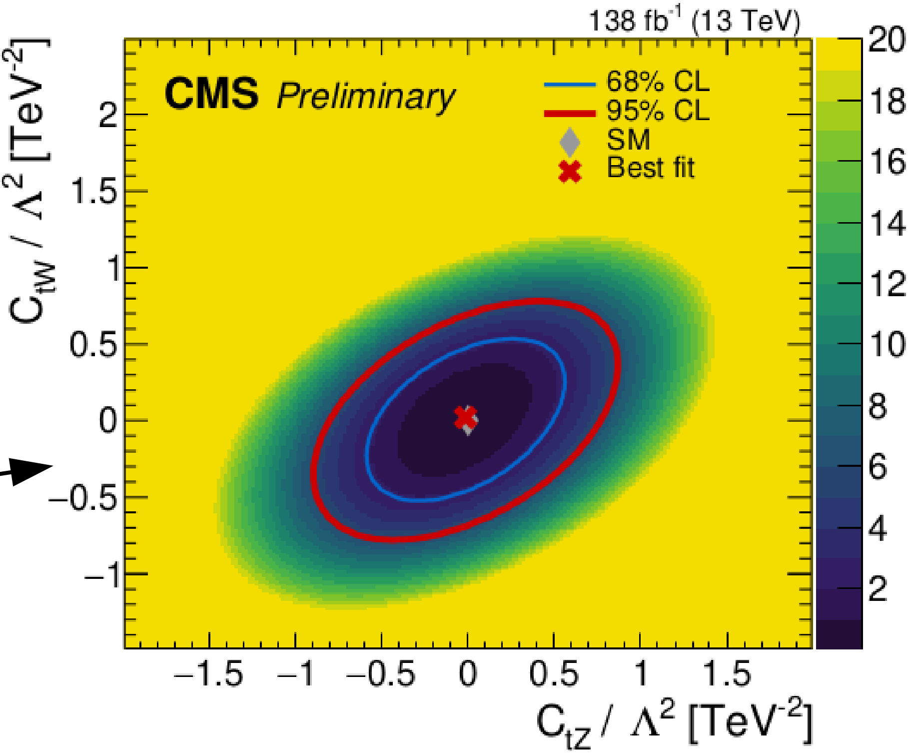
- Counting experiment for the 4l SR and the WZ, ZZ CRs.



Several fits are performed – confidence intervals for the different WCs are extracted.

EFT in t(t)Z events - Results

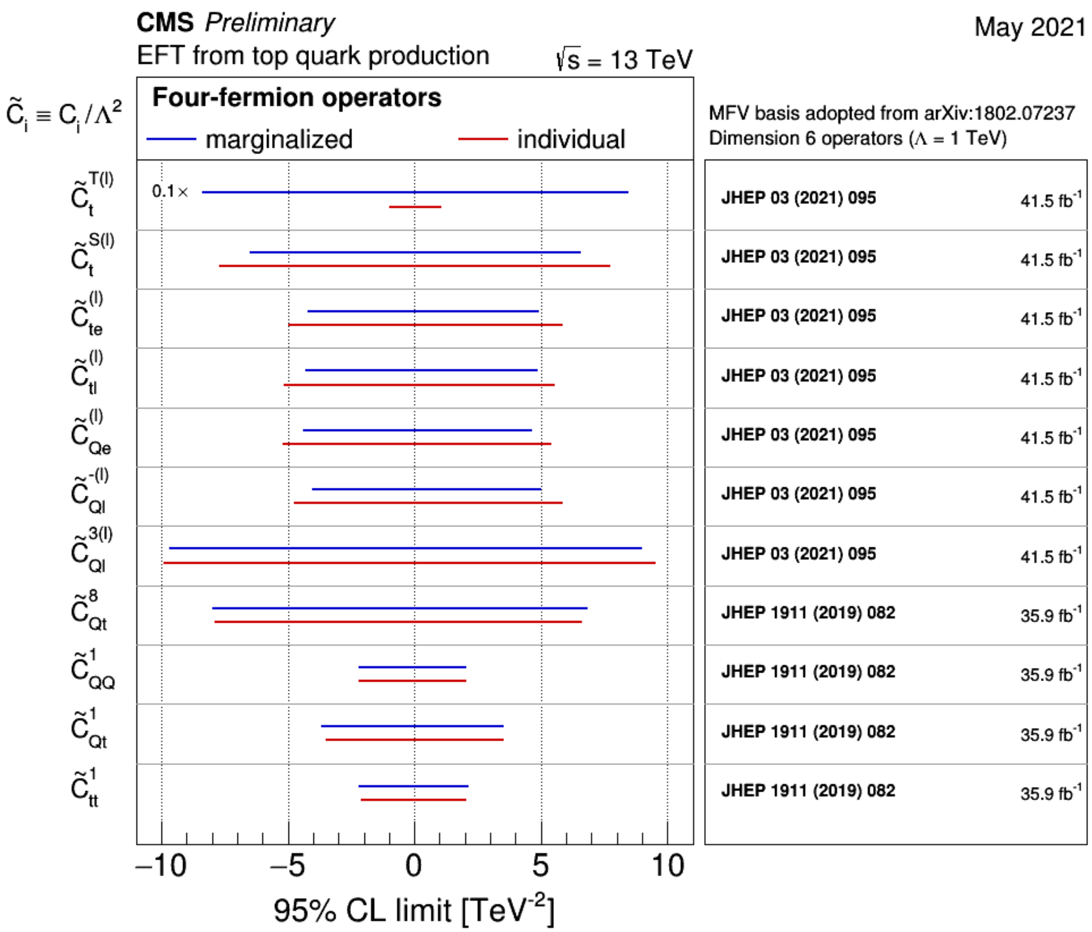
- Several fits are performed – confidence levels for the different WCs are extracted.
- Scans in WCs with 1) other WCs as nuisances and 2) other WCs set to 0.
- 95% CL intervals are set for the explored WCs with the two fitting methods.
- 2D scans are also provided.
- All the results are compatible with the SM expectations.



	Other WCs fixed to SM		5D fit	
	Expected	Observed	Expected	Observed
WC / Λ^2 [TeV^{-2}]	95% CL confidence intervals			
c_{tZ}	$[-0.97, 0.96]$	$[-0.76, 0.71]$	$[-1.24, 1.17]$	$[-0.85, 0.76]$
c_{tW}	$[-0.76, 0.74]$	$[-0.52, 0.52]$	$[-0.96, 0.93]$	$[-0.69, 0.70]$
$c^3_{\varphi Q}$	$[-1.39, 1.25]$	$[-1.10, 1.41]$	$[-1.91, 1.36]$	$[-1.26, 1.43]$
$c^-_{\varphi Q}$	$[-2.86, 2.33]$	$[-3.00, 2.29]$	$[-6.06, 14.09]$	$[-7.09, 14.76]$
$c_{\varphi t}$	$[-3.70, 3.71]$	$[-21.65, -14.61] \cup [-2.06, 2.69]$	$[-16.18, 10.46]$	$[-19.15, 10.34]$

Summary

- Effective field theories are a great tool to explore new physics at the LHC.
- Several top quark physics measurements are reaching great precision and can be used to test EFTs and constrain theory parameters.
- Both analysis tools and theory are constantly evolving. Different experimental approaches have been presented, including a new search using a MVA algorithm to improve sensitivity to EFT effects.



- New results on EFT effects in ttZ/tZq events by CMS presented for the first time. No signs of new physics so far.
- Top-EFT physics is very active – new results coming soon.

Backup slides

EFT in t(t)Z events – strategy (1)

CMS-PAS-TOP-21-001

Event selection and regions

Selection requirement	SR-3ℓ	SR-t$\bar{t}$Z-4ℓ	WZ CR	ZZ CR
Lepton multiplicity	=3	=4	=3	=4
$m_{3\ell} - m_{Z}$	—	—	>15 GeV	—
Z boson candidates multiplicity	=1	=1	=1	=2
Jet multiplicity	≥2	≥2	—	—
b jet multiplicity	≥1	≥1	=0	—
p_{T}^{miss}	—	—	>50 GeV	—

Fit configuration

Fit configuration	Region					
	SR-tZq	SR-t$\bar{t}$Z	SR-Others	SR-t$\bar{t}$Z-4ℓ	CR WZ	CR ZZ
1D c_{tZ}	NN-c_{tZ}-tZq	NN-c_{tZ}-t$\bar{t}$Z	m_{T}^{W}	Counting experiments		
1D c_{tW}	NN-c_{tW}-tZq	NN-c_{tW}-t$\bar{t}$Z				
1D $c_{\varphi Q}^{3}$	NN-$c_{\varphi Q}^{3}$-tZq	NN-$c_{\varphi Q}^{3}$-t$\bar{t}$Z				
1D $c_{\varphi Q}^{-}$	NN-SM (tZq node)	NN-SM (t$\bar{t}$Z node)				
1D $c_{\varphi t}$	NN-SM (tZq node)	NN-SM (t$\bar{t}$Z node)				
2D and 5D	NN-5D-tZq	NN-5D-t$\bar{t}$Z				

EFT in t(t)Z events – Signal extraction

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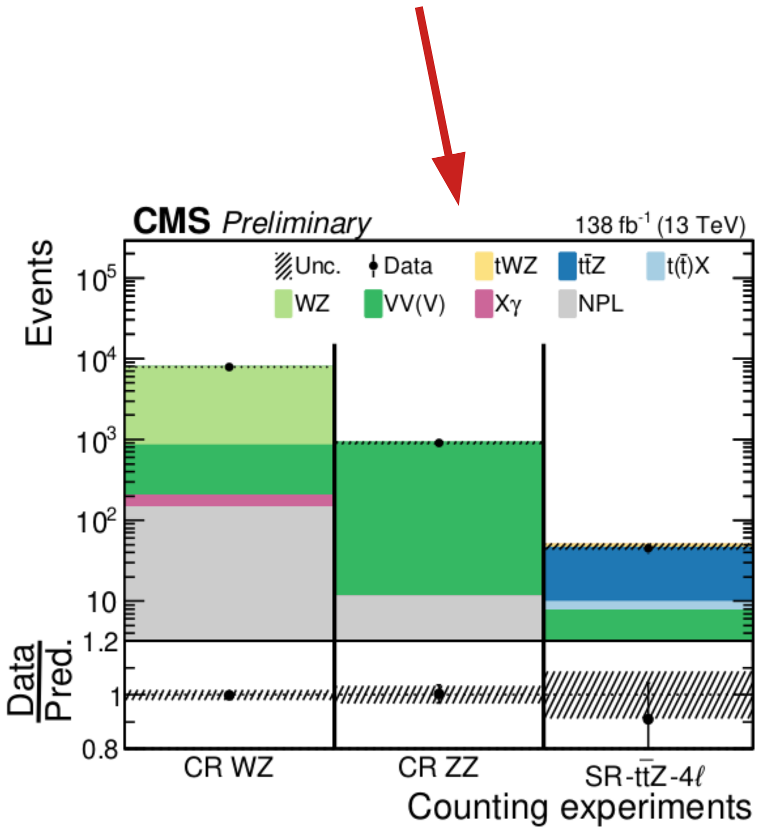
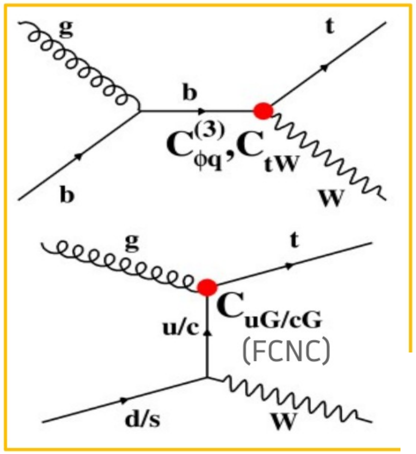
- Several fits are performed – confidence levels for the different WCs are extracted.
- Scans in WCs with 1) other WCs as nuisances and 2) other WCs set to 0.

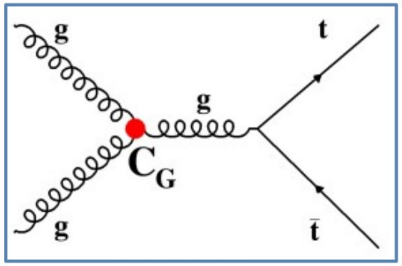


EFT search in tt/tW

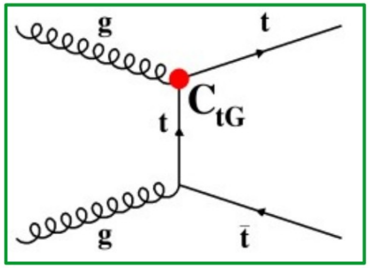
Eur. Phys. J. C 79 (2019) 886

- 2 leptons, 35.9 fb-1. Flavour and jet/btag categories.
- NN to separate tW from background and EFT effects.

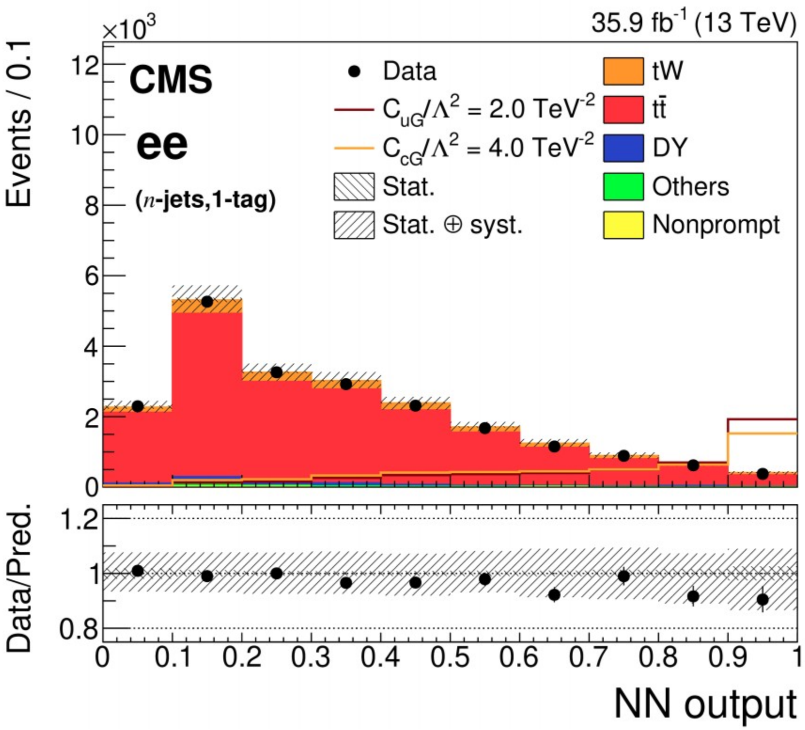




tt



tW + tt



Effective coupling	Observed [TeV^{-2}] Best fit	[68% CI]	[95% CI]	Expected [TeV^{-2}] Best fit	[68% CI]	[95% CI]
tW C_G/Λ^2	−0.18	[−0.73, 0.42]	[−1.01, 0.70]	0.00	[−0.82, 0.51]	[−1.07, 0.76]
tt $C_{\phi q}^{(3)}/\Lambda^2$	−1.52	[−2.71, −0.33]	[−3.82, 0.63]	0.00	[−1.05, 0.88]	[−2.04, 1.63]
tt+tW C_{tW}/Λ^2	2.38	[0.22, 4.57]	[−0.96, 5.74]	0.00	[−1.14, 5.93]	[−1.91, 6.70]
C_{tG}/Λ^2	−0.13	[−0.27, 0.02]	[−0.41, 0.17]	0.00	[−0.15, 0.14]	[−0.30, 0.28]
C_{uG}/Λ^2	−0.017	[−0.13, 0.13]	[−0.22, 0.22]	0.00	[−0.21, 0.21]	[−0.30, 0.30]
tW C_{cG}/Λ^2	−0.032	[−0.26, 0.26]	[−0.46, 0.46]	0.00	[−0.46, 0.46]	[−0.65, 0.65]

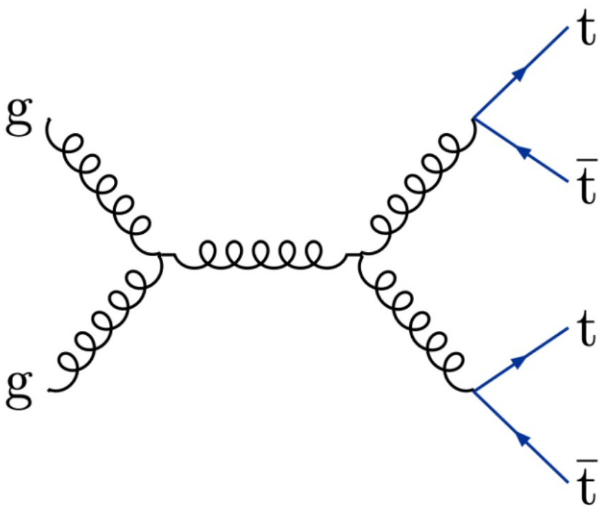
From FCNC results, limits on BR obtained at 95% CL:

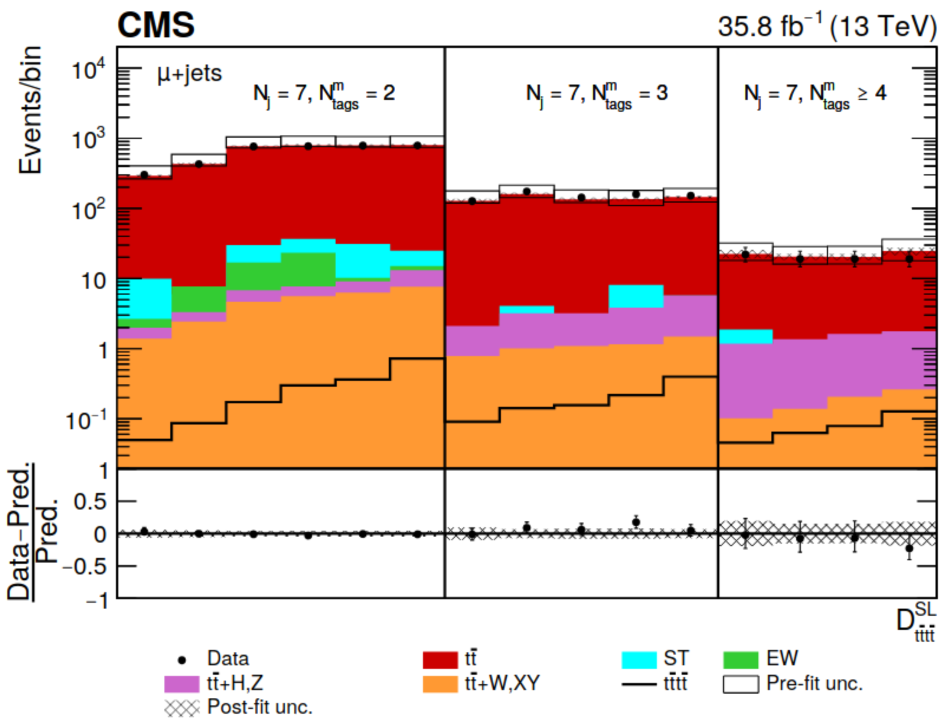
BR(t → cg) < 0.53%; BR(t → ug) < 0.12%

EFT in 4 top quarks production

JHEP 1911 (2019) 082

- Single lepton and OS dilepton production (35.8 fb^{-1}).
- A BDT classifier is used to separate signal and background.





The results are combined with the measurements in 2l SS and 3l channels.

EFT interpretation of the results using parameterization at gen level.

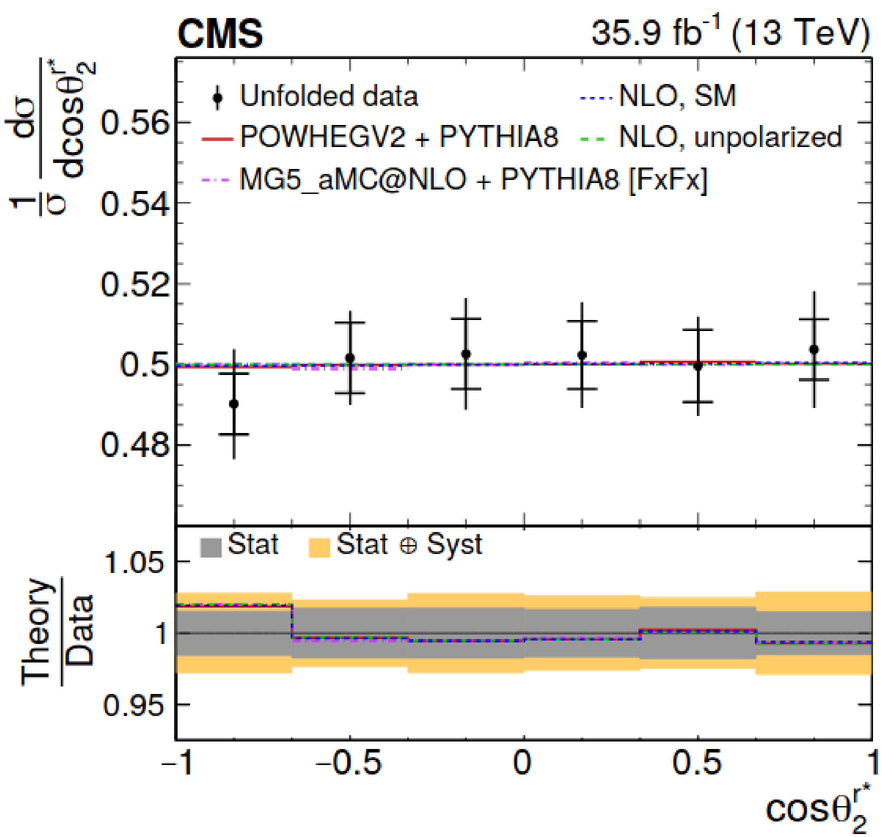
$$\sigma_{t\bar{t}t\bar{t}} = \sigma^{SM}_{t\bar{t}t\bar{t}} + \frac{1}{\Lambda^2}\sum_k C_k \sigma^{(1)}_k + \frac{1}{\Lambda^4}\sum_{j\leq k} C_j C_k \sigma^{(2)}_{j,k}$$

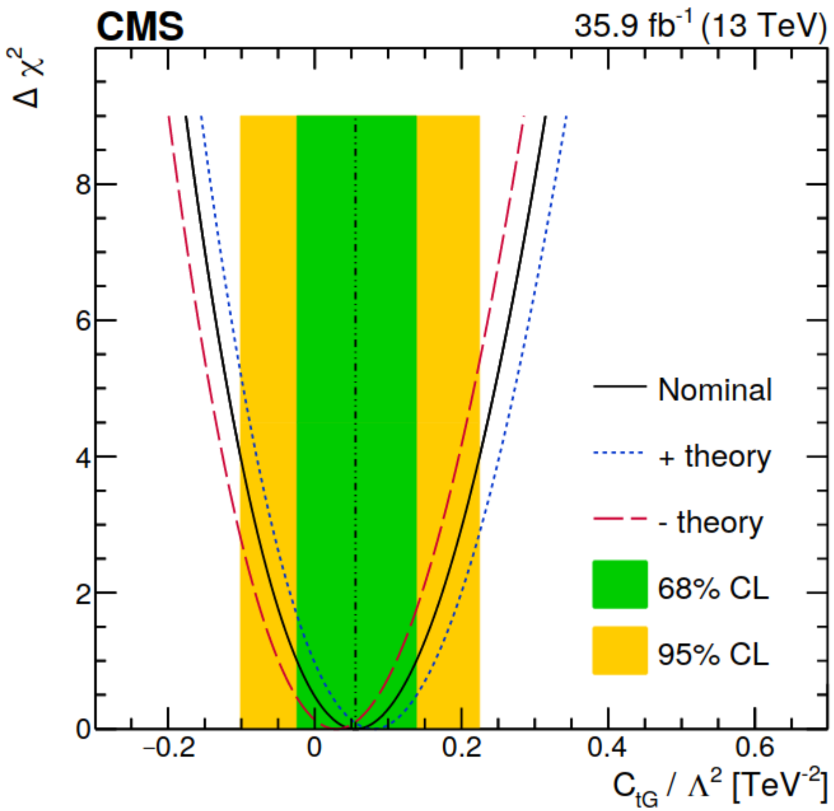
Operator	Expected C_k/Λ^2 (TeV^{-2})	Observed (TeV^{-2})
$\mathcal{O}^1_{tt}$	$[-2.0, 1.8]$	$[-2.1, 2.0]$
$\mathcal{O}^1_{QQ}$	$[-2.0, 1.8]$	$[-2.2, 2.0]$
$\mathcal{O}^1_{Qt}$	$[-3.3, 3.2]$	$[-3.5, 3.5]$
$\mathcal{O}^8_{Qt}$	$[-7.3, 6.1]$	$[-7.9, 6.6]$

Spin correlations in $t\bar{t}$ events

Phys. Rev. D 100, 072002 (2019)

- Differential cross sections are measured using 2l OS events (35.9 fb^{-1}).
- Spin correlations and top quark polarization are probed using angular distributions of reconstructed top quarks.
- Limits to the top quark chromomagnetic dipole moment are obtained from a simultaneous fit to several angular distributions.





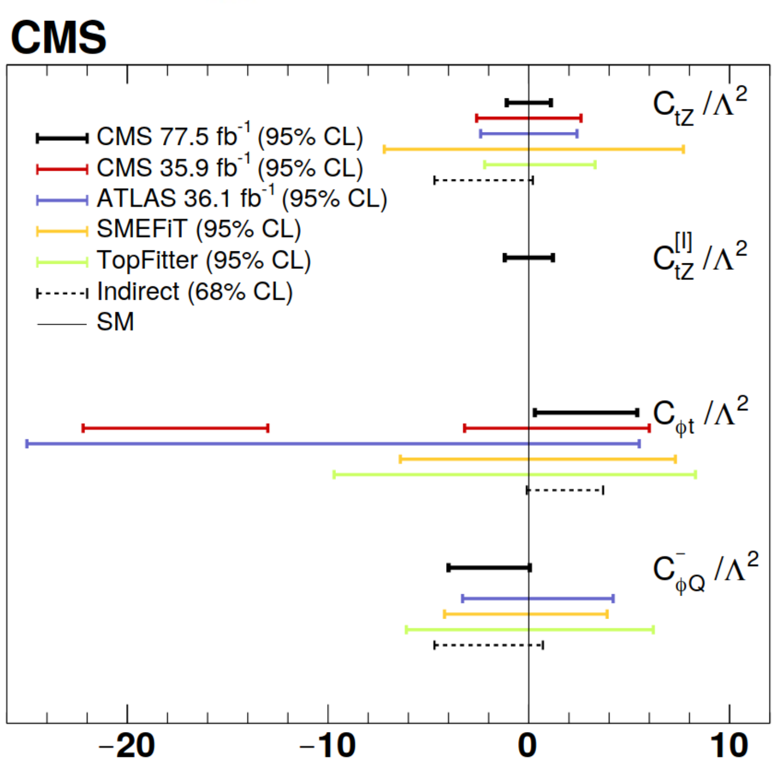
Sensitivity improves 30% w.r.t. previous results.

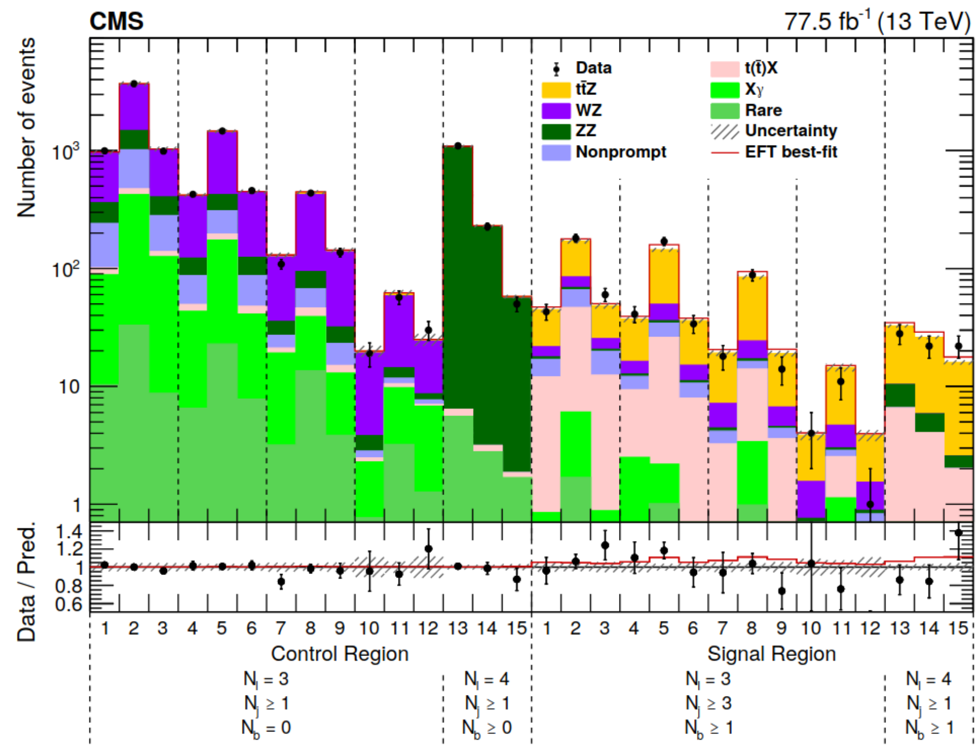
EFT interpreation with ttZ events

JHEP 03 (2020) 056

- Events with 3 and 4 leptons (77.5 fb^{-1}). Inclusive and differential ttZ cross sections are measured.

- LO gen-level events produced in fine grid of EFT parameter space.
- Weights are calculated to propagate the effect of the EFT to NLO distributions, based on $p_{\mathrm{T}}(\mathrm{Z})$ and $\cos\theta^*_{\mathrm{Z}}$ distributions.





- Weights are applied at detector level to probe the EFT contribution.

- 4 WC are constrained by fitting distributions to data.