Rare and new top quark interactions in CMS

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Clara Ramón Álvarez

On behalf of the CMS Collaboration

clara.ramon.alvarez@cern.ch

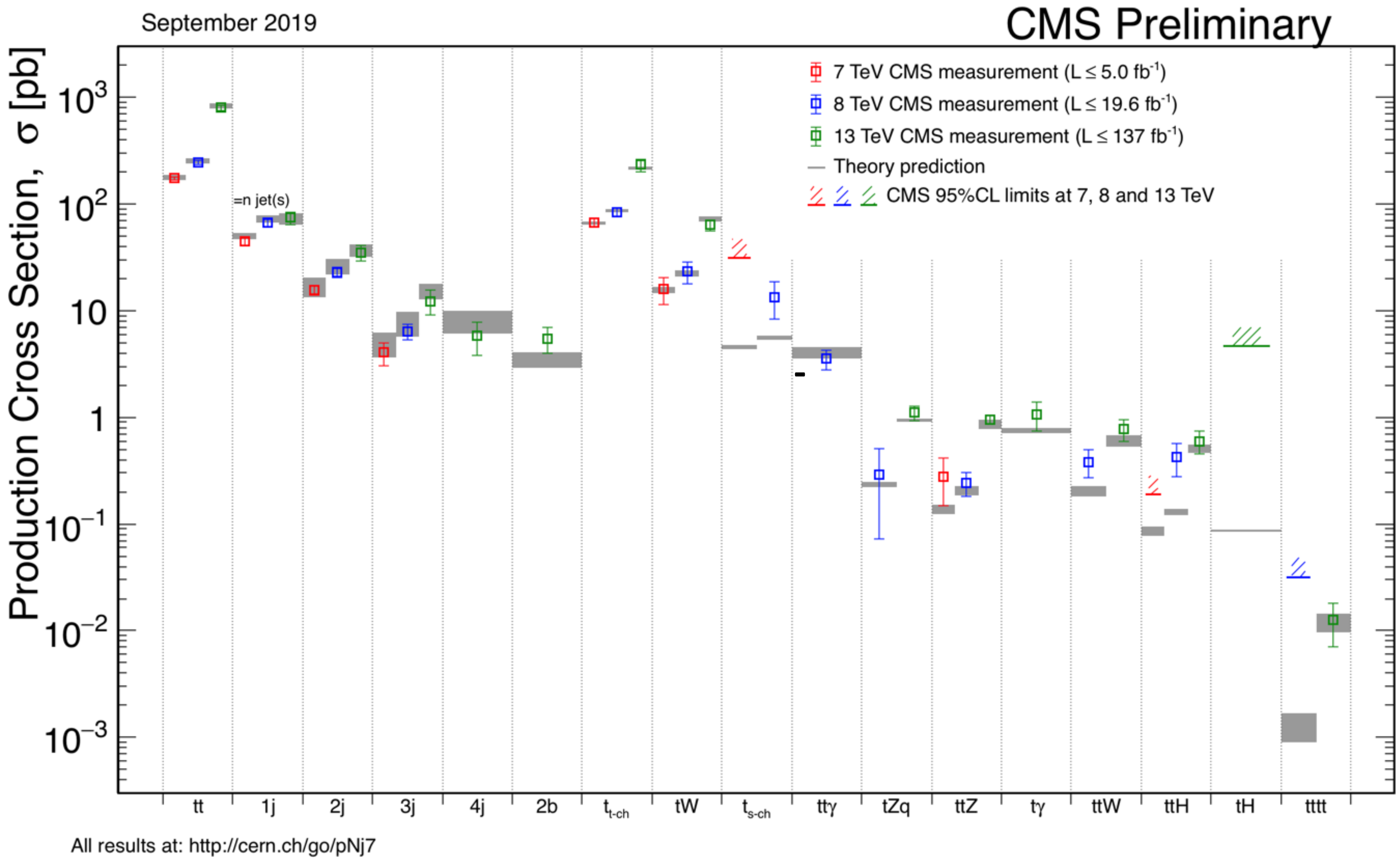
Universidad de Oviedo

ICTEA
Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias

Introduction

Top-quark production can be used to look for **New Physics**:

- Effective Field Theory frameworks (EFT)
- Searches for Flavour Changing Neutral currents
- CP-violation
- …



Introduction: EFT

- No clear sign of New Physics @LHC from direct searches

- Allows to search for BSM effects in a model independent way, using precision measurements

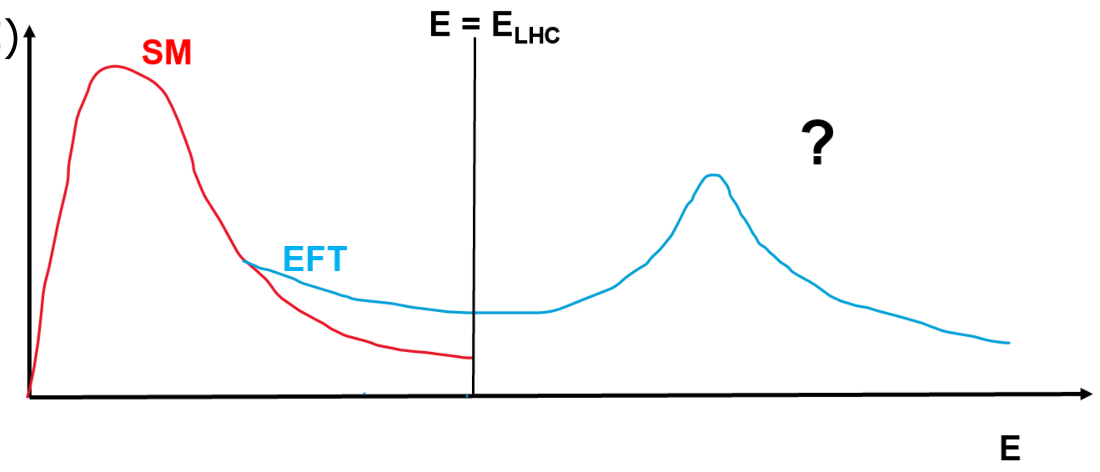
- SM Effective Field Theory (SMEFT) parametrize the effect of physics up to an energy scale (Λ).

- The Lagrangian can be expressed as an expansion in higher dimensional (d) operators ($\mathcal{O}$) consisting on SM fields

Wilson coeficients (WC)

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

Suppresed by $1/\Lambda$, computation up to dim 6



Introduction: EFT

Wilson coeficients

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

Suppresed by $1/\Lambda$, computation up to dim 6

- 59 non-redundant dim-6 operators
- Depending on CP/flavour assumptions

CERN-LPCC-2018-01

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		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}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

Table 3: Four-fermion operators.

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}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

Table 2: Dimension-six operators other than the four-fermion ones.

$t\bar{t}Z$

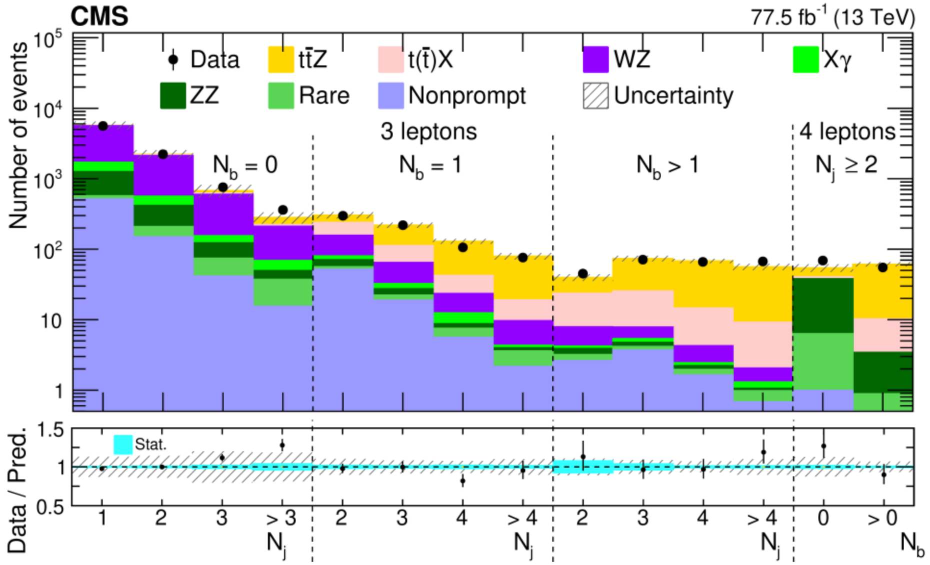
2016 and 2017 data

Baseline Selection (Inclusive Measurement):

- 3 or 4 leptons
- $N_{Jet} > 0$

N_{Jet} and $N_{B\text{-}tag}$ Classification

JHEP 03 (2020) 056



EFT interpretation:

- SMEFT in the Warsaw basis is used
- 4 relevant coefficients used for the parametrization: $c_{tZ},\ c_{tZ}^{[I]}, c_{\phi t}, \overline{c}_{\phi Q}$
- Expressed using Warsaw basis:

EW dipole momentum

$$c_{tZ} = \mathrm{Re}\left(-\sin\theta_W C_{uB}^{(33)} + \cos\theta_W C_{uW}^{(33)}\right)$$

$$c_{tZ}^{[I]} = \mathrm{Im}\left(-\sin\theta_W C_{uB}^{(33)} + \cos\theta_W C_{uW}^{(33)}\right)$$

Anomalous neutral current interactions

$$c_{\phi t} = C_{\phi t} = C_{\phi u}^{(33)}$$

$$c_{\phi Q}^{-} = C_{\phi Q} = C_{\phi q}^{1(33)} - C_{\phi q}^{3(33)},$$

θ_W : weak mixing angle

To assume Wtb vertex to be the SM one → $\square$ = 0

$$O_{uB}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} u_j) \quad \tilde{\varphi} B_{\mu\nu}$$

$$O_{uW}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} \tau^I u_j)\ \tilde{\varphi} W_{\mu\nu}^I$$

$$O_{\varphi u}^{(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{u}_i \gamma^\mu u_j)$$

$$O_{\varphi q}^{1(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}_i \gamma^\mu q_j)$$

$$O_{\varphi q}^{3(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_i \gamma^\mu \tau^I q_j)$$

$t\bar{t}Z$

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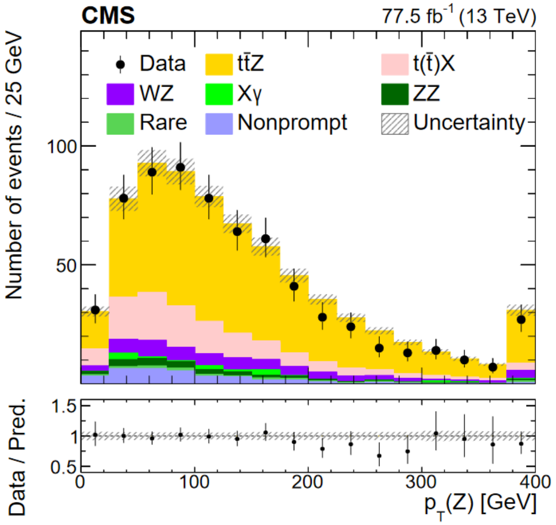
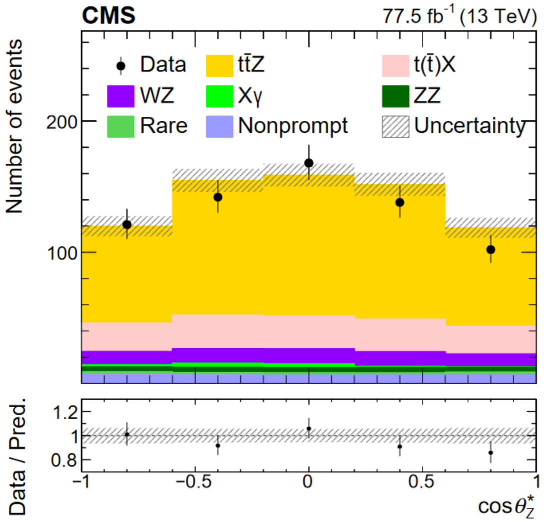
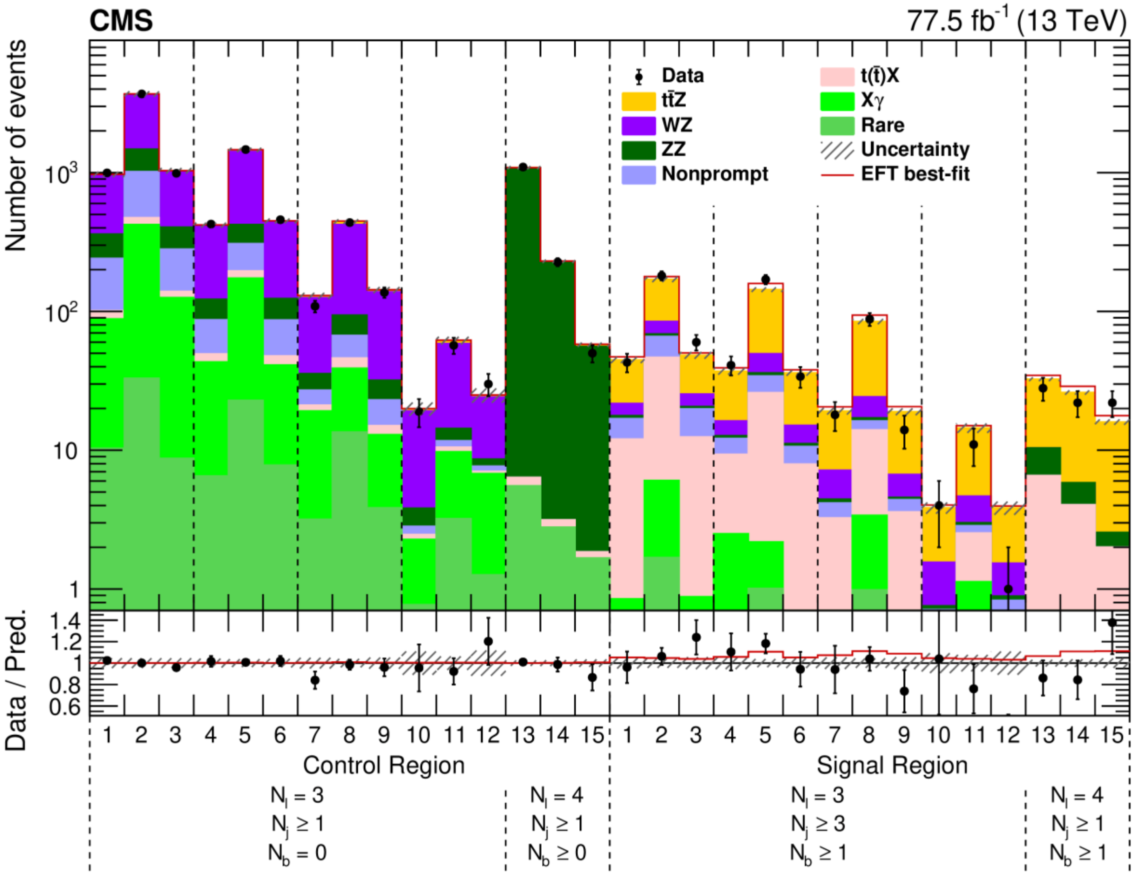
Classification to enhance sensitivity:

Events are further classified in bins of $p_T(Z)$ and bins of $cos(\theta^*_Z)$ (cosine of the angle between the negative charged lepton and the Z candidate in the Z rest frame.)







Procedure:

- gen-level samples for SM and SMEFT (LO) produced with grid in the parameter space
- Weight SMEFT/SM applied to detector-level SM sample
- Simultaneous fit using all N_{Lep} categories split in N_{Jet}, $N_{B\text{-}tag}$, $p_T(Z), cos(\theta^*_Z)$

$t\bar{t}Z$

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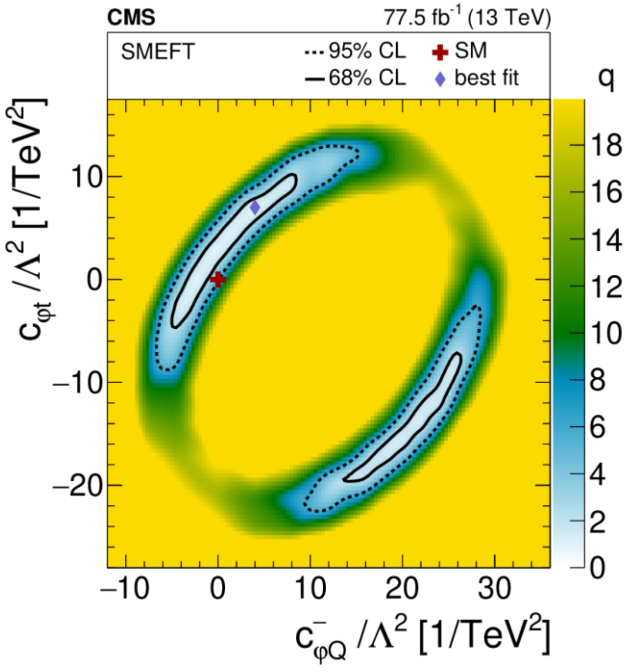
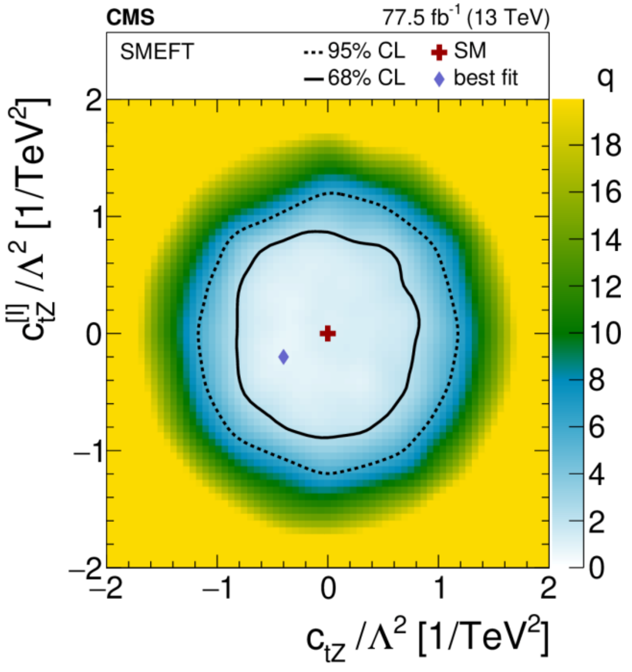
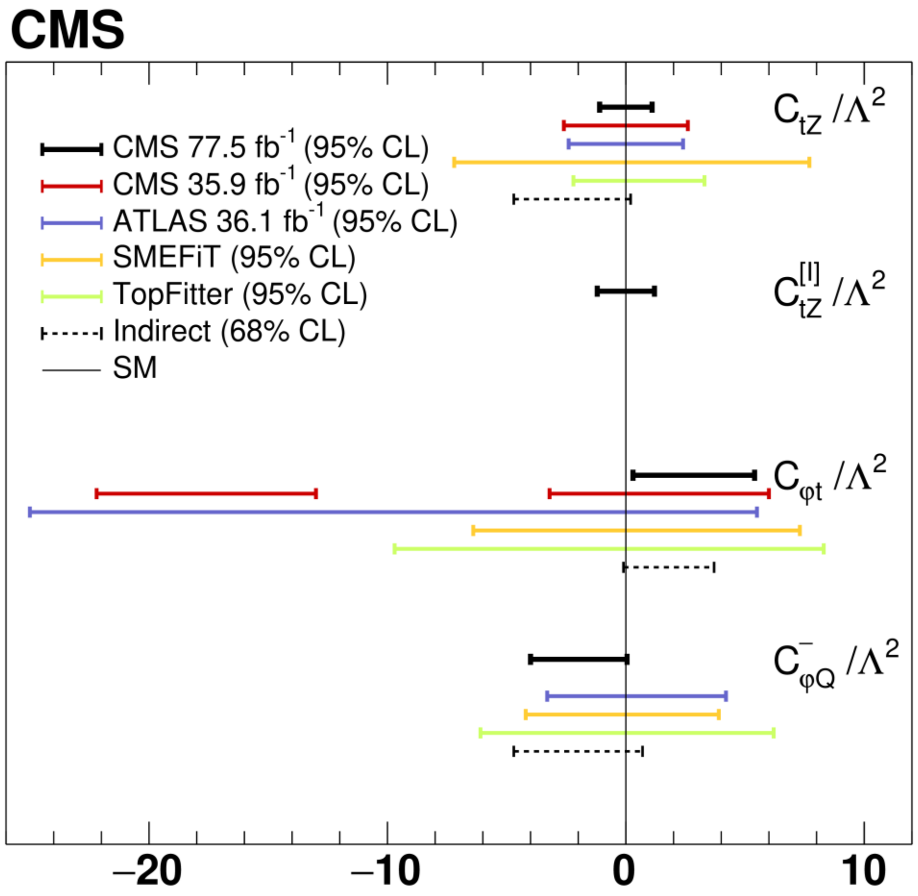
Results:

- Most stringent direct constrains on top quark EW dipole moments and top-Z vector couplings
- Good agreement with SM







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

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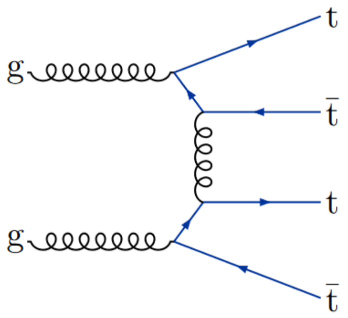
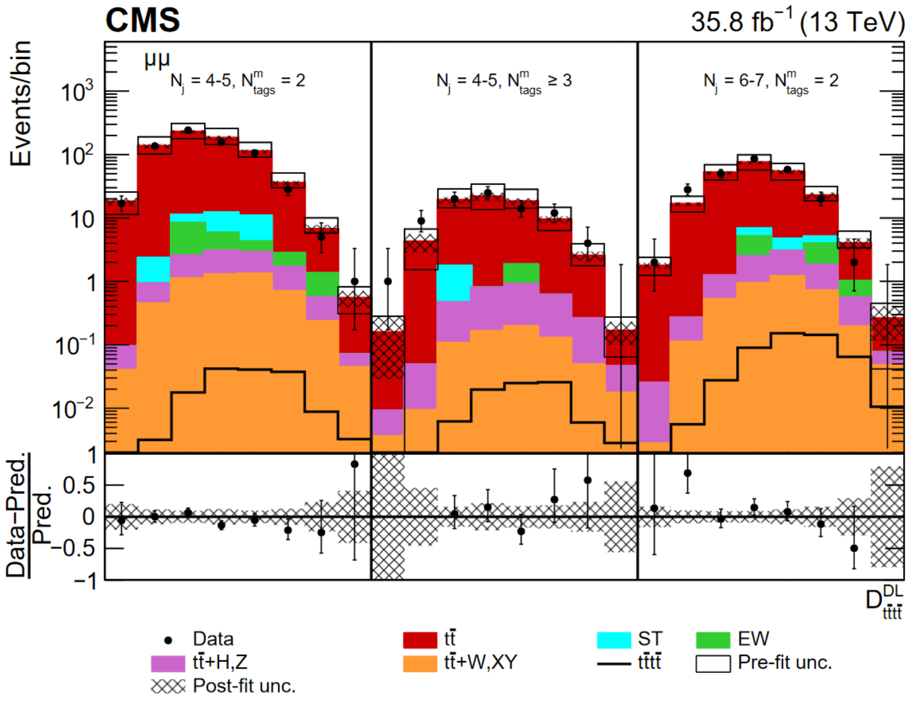
Very low cross section process $\sigma(\mathrm{NLO}) \sim 9$ fb (not yet observed)



2016 data

Baseline Selection: 2ℓOS and single lepton final states

Strategy:
BDT used to identify hadronic top decays. A second **BDT** is used to discriminate $t\bar{t}t\bar{t}$ from $t\bar{t}$. This takes as input the first BDT, event topology, event activity, $N_{B\text{-tag}}$



EFT Interpretation:
- Sensitive to 4-fermion interactions
- SMEFT in the Warsaw basis is used
- Four operators relevant at LO production

$$\mathcal{O}^1_{\mathrm{tt}} = \left(\bar{\mathrm{t}}_{\mathrm{R}}\gamma^\mu \mathrm{t}_{\mathrm{R}}\right)\left(\bar{\mathrm{t}}_{\mathrm{R}}\gamma_\mu \mathrm{t}_{\mathrm{R}}\right),$$
$$\mathcal{O}^1_{\mathrm{QQ}} = \left(\bar{\mathrm{Q}}_{\mathrm{L}}\gamma^\mu \mathrm{Q}_{\mathrm{L}}\right)\left(\bar{\mathrm{Q}}_{\mathrm{L}}\gamma_\mu \mathrm{Q}_{\mathrm{L}}\right),$$
$$\mathcal{O}^1_{\mathrm{Qt}} = \left(\bar{\mathrm{Q}}_{\mathrm{L}}\gamma^\mu \mathrm{Q}_{\mathrm{L}}\right)\left(\bar{\mathrm{t}}_{\mathrm{R}}\gamma_\mu \mathrm{t}_{\mathrm{R}}\right),$$
$$\mathcal{O}^8_{\mathrm{Qt}} = \left(\bar{\mathrm{Q}}_{\mathrm{L}}\gamma^\mu T^A \mathrm{Q}_{\mathrm{L}}\right)\left(\bar{\mathrm{t}}_{\mathrm{R}}\gamma_\mu T^A \mathrm{t}_{\mathrm{R}}\right),$$

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

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Procedure:

- Cross section is parametrized at LO in terms of WC

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

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

- Simulation of EFT effects implemented using FeynRules and MadGraph_aMC@NLO

- In the limit setting kinematics of $t\bar{t}t\bar{t}$ assumed to be the SM one.

Results:

- Limits are set on C_k/Λ using the rate from the combination with **EPJC 78 (2018) 140**
- Marginalized constraints are set at 95% CL

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

- Improved constraints with respect to previous measurement **Chin. Phys. C42 (2018) 023104**

Operator	Chin. Phys. C42 (2018) 023104
$\mathcal{O}^1_{tt}$	[-2.92,2.80]
$\mathcal{O}^1_{QQ}$	
$\mathcal{O}^1_{Qt}$	[-4.97,4.90]
$\mathcal{O}^8_{Qt}$	[-10.3,9.33]

$t(\bar{t})$ + leptons

2017 data

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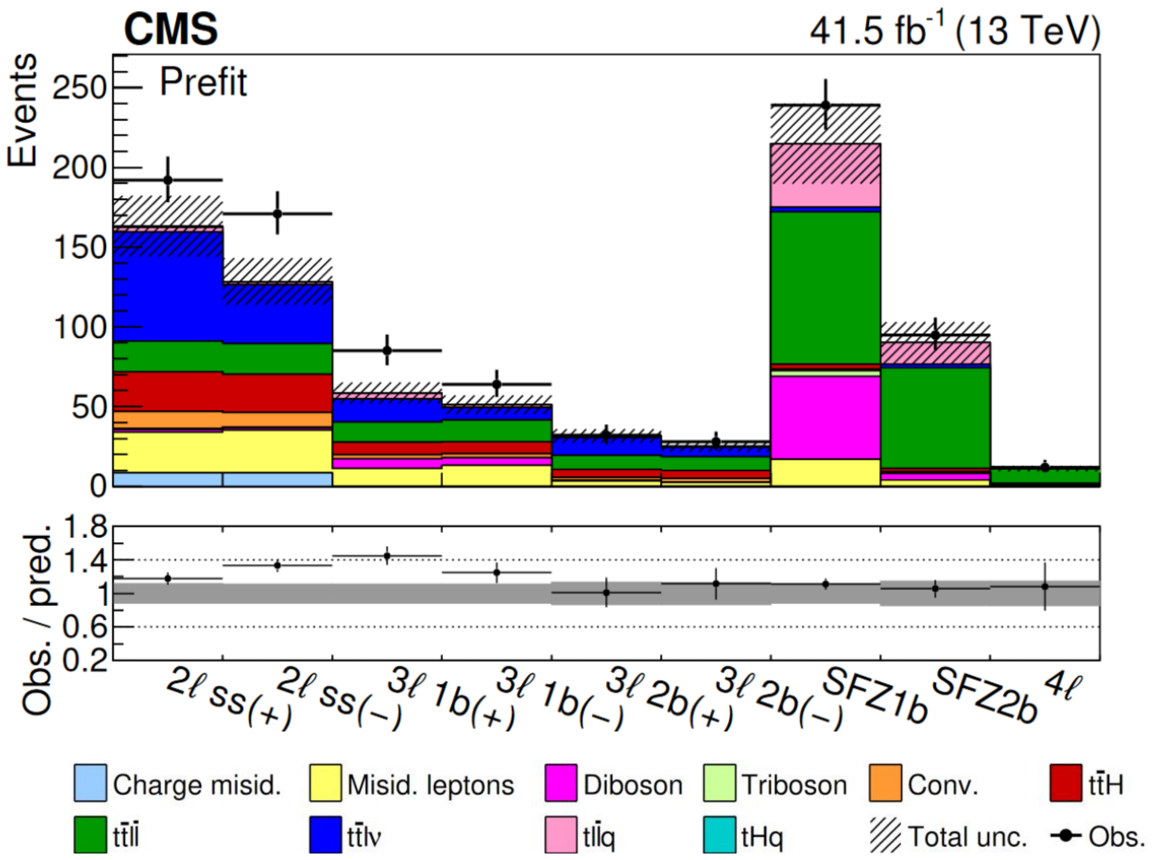
Targeting **$t\bar{t}H$, tH, $t\bar{t}ll$, $t\bar{t}l\nu$, $t\bar{t}lq$**

Baseline Selection:

- MVA to select prompt leptons
- 2 same sign, 3 and 4 leptons categories
- Jet and b-tag multiplicity, charge OSSF mass used to categorize
- **35 signal regions**



Strategy:

Signal samples modelled at LO including EFT

Using detector-level observables

Yields are parametrized as function of WC → event weights parametrized as function of WC

$\mathrm{t(\bar{t})}$ + leptons

Operators:

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- Dim-6 in the Warsaw basis
- Operators involved in interaction with at least one top
- 16 Operators used:

Operators involving two quarks and one or more bosons			
Operator	Definition	WC	Lead processes affected
$^{\ddagger}O_{\mathrm{u}\varphi}^{(ij)}$	$\bar{\mathrm{q}}_i \mathrm{u}_j \tilde{\varphi}\,(\varphi^{\dagger}\varphi)$	$c_{\mathrm{t}\varphi} + i c_{\mathrm{t}\varphi}^{I}$	$\mathrm{t\bar{t}H}$, tHq
$O_{\varphi\mathrm{q}}^{1(ij)}$	$(\varphi^{\dagger} i\overleftrightarrow{D}_{\mu}\varphi)(\bar{\mathrm{q}}_i\gamma^{\mu}\mathrm{q}_j)$	$c_{\varphi Q}^{-} + c_{\varphi Q}^{3}$	$\mathrm{t\bar{t}H}$, $\mathrm{t\bar{t}l\nu}$, $\mathrm{t\bar{t}l\bar{l}}$, tHq, $\mathrm{tl\bar{l}q}$
$O_{\varphi\mathrm{q}}^{3(ij)}$	$(\varphi^{\dagger} i\overleftrightarrow{D}_{\mu}^{I}\varphi)(\bar{\mathrm{q}}_i\gamma^{\mu}\tau^{I}\mathrm{q}_j)$	$c_{\varphi Q}^{3}$	$\mathrm{t\bar{t}H}$, $\mathrm{t\bar{t}l\nu}$, $\mathrm{t\bar{t}l\bar{l}}$, tHq, $\mathrm{tl\bar{l}q}$
$O_{\varphi\mathrm{u}}^{(ij)}$	$(\varphi^{\dagger} i\overleftrightarrow{D}_{\mu}\varphi)(\bar{\mathrm{u}}_i\gamma^{\mu}\mathrm{u}_j)$	$c_{\varphi\mathrm{t}}$	$\mathrm{t\bar{t}H}$, $\mathrm{t\bar{t}l\nu}$, $\mathrm{t\bar{t}l\bar{l}}$, $\mathrm{tl\bar{l}q}$
$^{\ddagger}O_{\varphi\mathrm{ud}}^{(ij)}$	$(\tilde{\varphi}^{\dagger} iD_{\mu}\varphi)(\bar{\mathrm{u}}_i\gamma^{\mu}\mathrm{d}_j)$	$c_{\varphi\mathrm{tb}} + i c_{\varphi\mathrm{tb}}^{I}$	$\mathrm{t\bar{t}H}$, $\mathrm{tl\bar{l}q}$, tHq
$^{\ddagger}O_{\mathrm{uW}}^{(ij)}$	$(\bar{\mathrm{q}}_i\sigma^{\mu\nu}\tau^{I}\mathrm{u}_j)\,\tilde{\varphi}\mathrm{W}_{\mu\nu}^{I}$	$c_{\mathrm{tW}} + i c_{\mathrm{tW}}^{I}$	$\mathrm{t\bar{t}H}$, $\mathrm{t\bar{t}l\nu}$, $\mathrm{t\bar{t}l\bar{l}}$, tHq, $\mathrm{tl\bar{l}q}$
$^{\ddagger}O_{\mathrm{dW}}^{(ij)}$	$(\bar{\mathrm{q}}_i\sigma^{\mu\nu}\tau^{I}\mathrm{d}_j)\,\varphi\mathrm{W}_{\mu\nu}^{I}$	$c_{\mathrm{bW}} + i c_{\mathrm{bW}}^{I}$	$\mathrm{t\bar{t}H}$, $\mathrm{t\bar{t}l\bar{l}}$, tHq, $\mathrm{tl\bar{l}q}$
$^{\ddagger}O_{\mathrm{uB}}^{(ij)}$	$(\bar{\mathrm{q}}_i\sigma^{\mu\nu}\mathrm{u}_j)\,\tilde{\varphi}\mathrm{B}_{\mu\nu}$	$(c_{\mathrm{W}}c_{\mathrm{tW}} - c_{\mathrm{tZ}})/s_{\mathrm{W}} + i(c_{\mathrm{W}}c_{\mathrm{tW}}^{I} - c_{\mathrm{tZ}}^{I})/s_{\mathrm{W}}$	$\mathrm{t\bar{t}H}$, $\mathrm{t\bar{t}l\nu}$, $\mathrm{t\bar{t}l\bar{l}}$, tHq, $\mathrm{tl\bar{l}q}$
$^{\ddagger}O_{\mathrm{u}G}^{(ij)}$	$(\bar{\mathrm{q}}_i\sigma^{\mu\nu}T^{A}\mathrm{u}_j)\,\tilde{\varphi}G_{\mu\nu}^{A}$	$\mathrm{g_s}(c_{\mathrm{t}G} + i c_{\mathrm{t}G}^{I})$	$\mathrm{t\bar{t}H}$, $\mathrm{t\bar{t}l\nu}$, $\mathrm{t\bar{t}l\bar{l}}$, tHq, $\mathrm{tl\bar{l}q}$

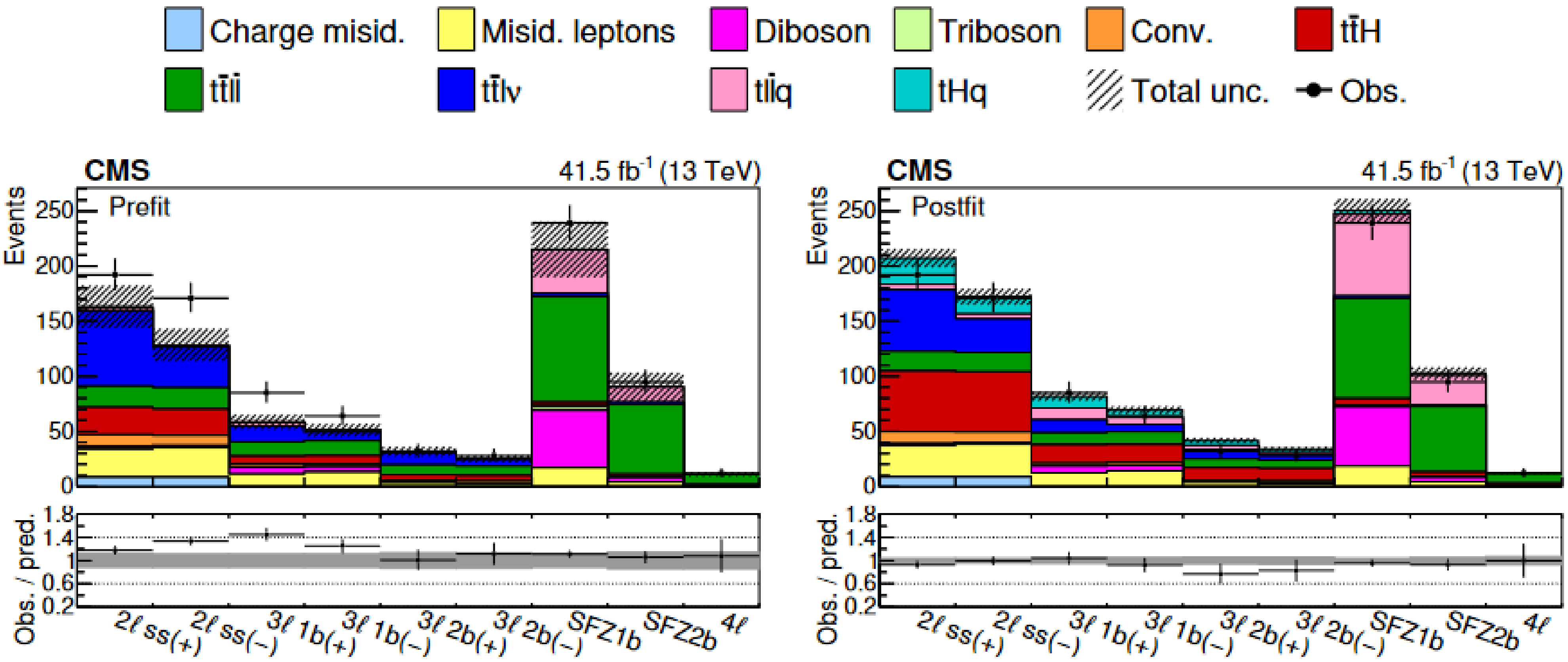
Operators involving two quarks and two leptons			
Operator	Definition	WC	Lead processes affected
$O_{\ell\mathrm{q}}^{1(ijkl)}$	$(\bar{\ell}_i\gamma^{\mu}\ell_j)(\bar{\mathrm{q}}_k\gamma^{\mu}\mathrm{q}_{\ell})$	$c_{Q\ell}^{-(\ell)} + c_{Q\ell}^{3(\ell)}$	$\mathrm{t\bar{t}l\nu}$, $\mathrm{t\bar{t}l\bar{l}}$, $\mathrm{tl\bar{l}q}$
$O_{\ell\mathrm{q}}^{3(ijkl)}$	$(\bar{\ell}_i\gamma^{\mu}\tau^{I}\ell_j)(\bar{\mathrm{q}}_k\gamma^{\mu}\tau^{I}\mathrm{q}_{\ell})$	$c_{Q\ell}^{3(\ell)}$	$\mathrm{t\bar{t}l\nu}$, $\mathrm{t\bar{t}l\bar{l}}$, $\mathrm{tl\bar{l}q}$
$O_{\ell\mathrm{u}}^{(ijkl)}$	$(\bar{\ell}_i\gamma^{\mu}\ell_j)(\bar{\mathrm{u}}_k\gamma^{\mu}\mathrm{u}_{\ell})$	$c_{\mathrm{t}\ell}^{(\ell)}$	$\mathrm{t\bar{t}l\bar{l}}$
$O_{\mathrm{eq}}^{(ijkl)}$	$(\bar{\mathrm{e}}_i\gamma^{\mu}\mathrm{e}_j)(\bar{\mathrm{q}}_k\gamma^{\mu}\mathrm{q}_{\ell})$	$c_{Q\mathrm{e}}^{(\ell)}$	$\mathrm{t\bar{t}l\bar{l}}$, $\mathrm{tl\bar{l}q}$
$O_{\mathrm{eu}}^{(ijkl)}$	$(\bar{\mathrm{e}}_i\gamma^{\mu}\mathrm{e}_j)(\bar{\mathrm{u}}_k\gamma^{\mu}\mathrm{u}_{\ell})$	$c_{\mathrm{te}}^{(\ell)}$	$\mathrm{t\bar{t}l\bar{l}}$
$^{\ddagger}O_{\ell\mathrm{equ}}^{1(ijkl)}$	$(\bar{\ell}_i\mathrm{e}_j)\,\varepsilon\,(\bar{\mathrm{q}}_k\mathrm{u}_{\ell})$	$c_{\mathrm{t}}^{S(\ell)} + i c_{\mathrm{t}}^{SI(\ell)}$	$\mathrm{t\bar{t}l\bar{l}}$, $\mathrm{tl\bar{l}q}$
$^{\ddagger}O_{\ell\mathrm{equ}}^{3(ijkl)}$	$(\bar{\ell}_i\sigma^{\mu\nu}\mathrm{e}_j)\,\varepsilon\,(\bar{\mathrm{q}}_k\sigma_{\mu\nu}\mathrm{u}_{\ell})$	$c_{\mathrm{t}}^{T(\ell)} + i c_{\mathrm{t}}^{TI(\ell)}$	$\mathrm{t\bar{t}l\nu}$, $\mathrm{t\bar{t}l\bar{l}}$, $\mathrm{tl\bar{l}q}$

$t(\bar{t})$ + leptons

[JHEP 03 (2021) 095]

Results:

- Simultaneous fit to the 16 WC and nuisance parameters using all 35 SR
- Post fit plot: increase in tHq is due to the low sensitivity to this process added to the fact that it receives large enhancements from the EFT operators considered

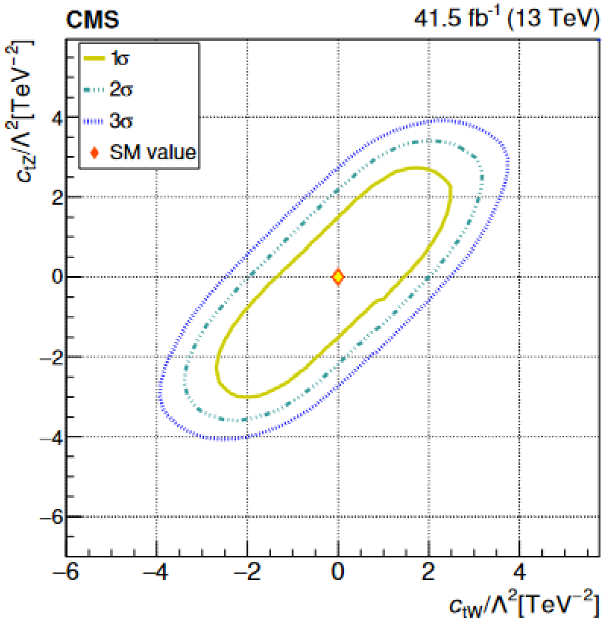


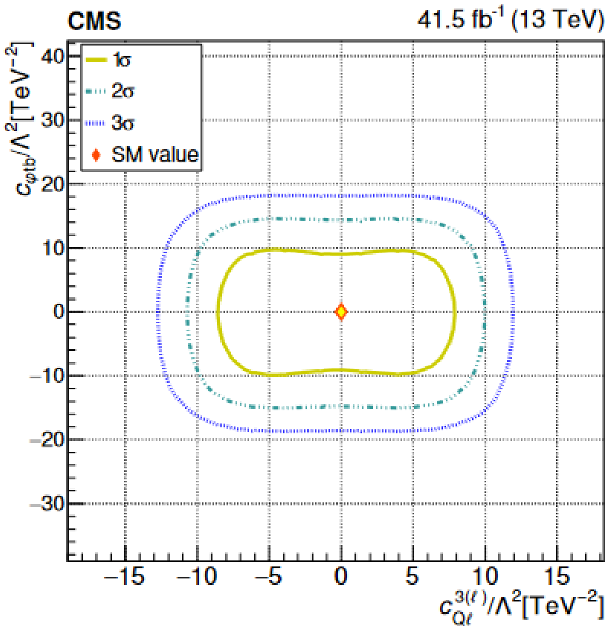
$t(\bar{t})$ + leptons

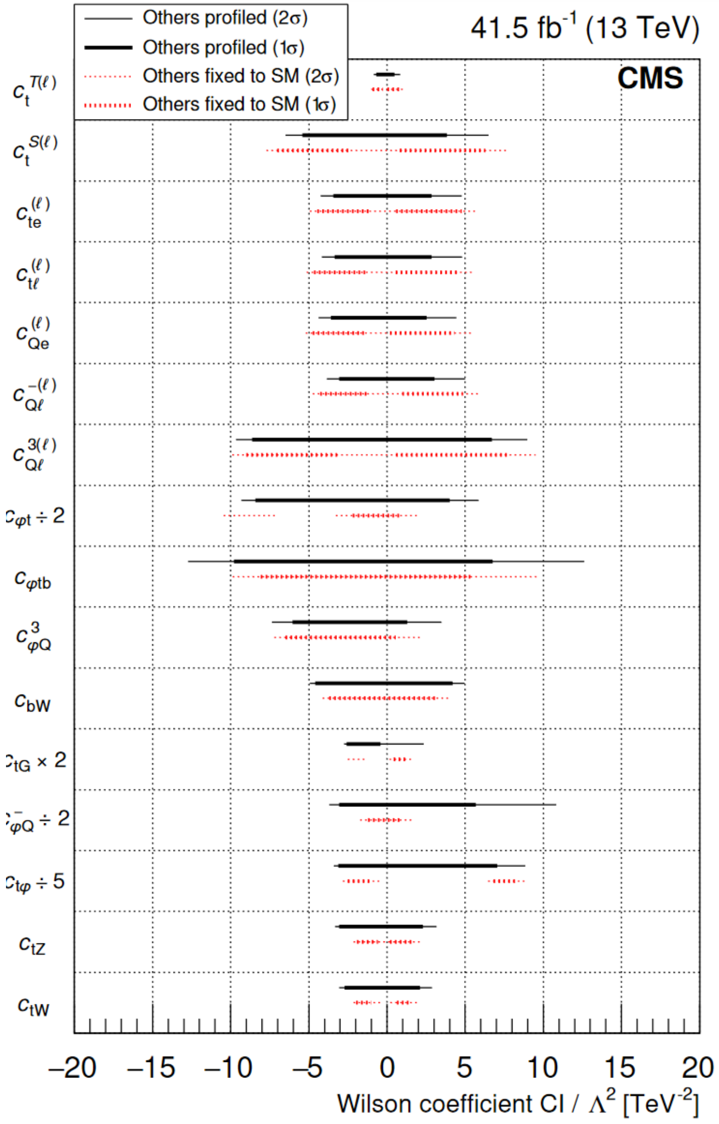
JHEP 03 (2021) 095

Results:

- Simultaneous fit to the 16 WC and nuisance parameters using all 35 SR
- One dim CL for all considered WC
- 2-d CL with other WC treated as unconstrained
- Results in agreement with SM







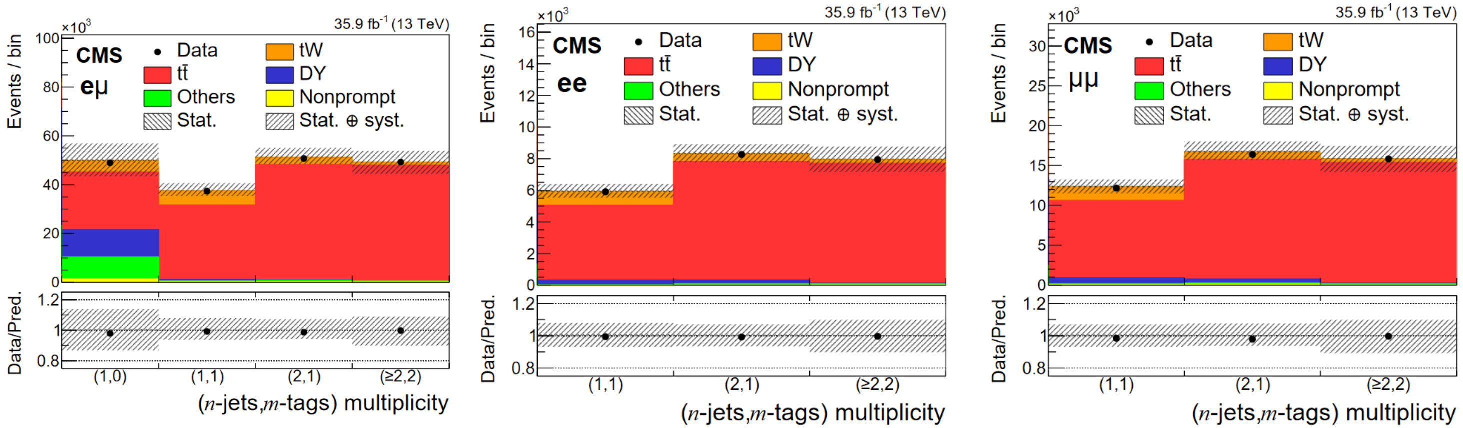
$t\bar{t}$ + tW to dilepton

2016 data

Eur Phy J. C. 2019 886

Baseline Selection:

- Two leptons OS
- At least 1 jet
- Categorization in flavour, jet and b-tag multiplicity



Operators Involved:

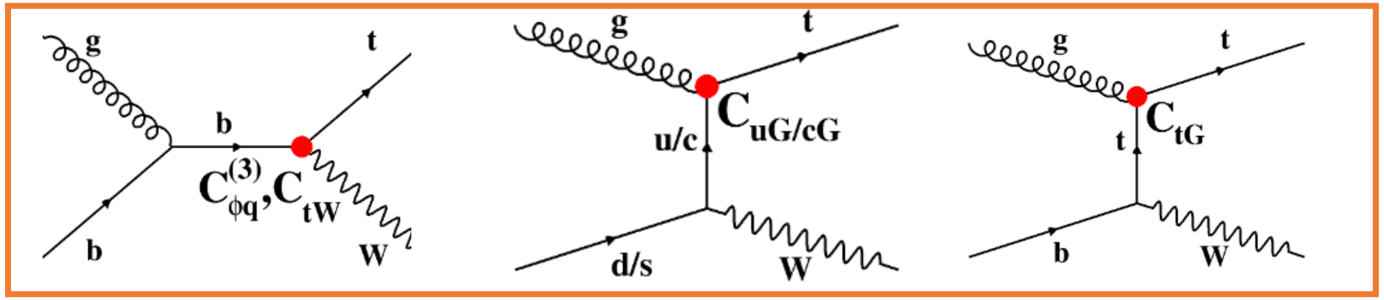
$$O_{\phi q}^{(3)} = (\phi^{+}\tau^{i}D_{\mu}\phi)(\bar{q}\gamma^{\mu}\tau^{i}q)$$

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

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

$$O_{G} = f_{abc}G^{a\nu}_{\mu}G^{b\rho}_{\nu}G^{c\mu}_{\rho},$$

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



$t\bar{t}$ + tW to dilepton

[Eur Phy J. C. 2019 886]

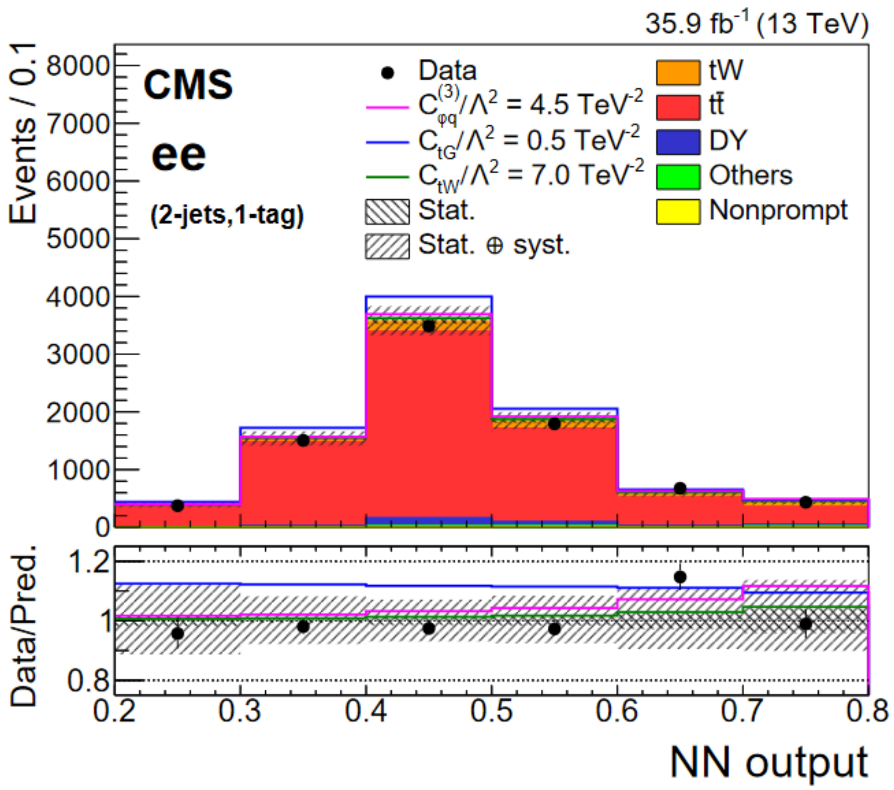
Discriminant variable

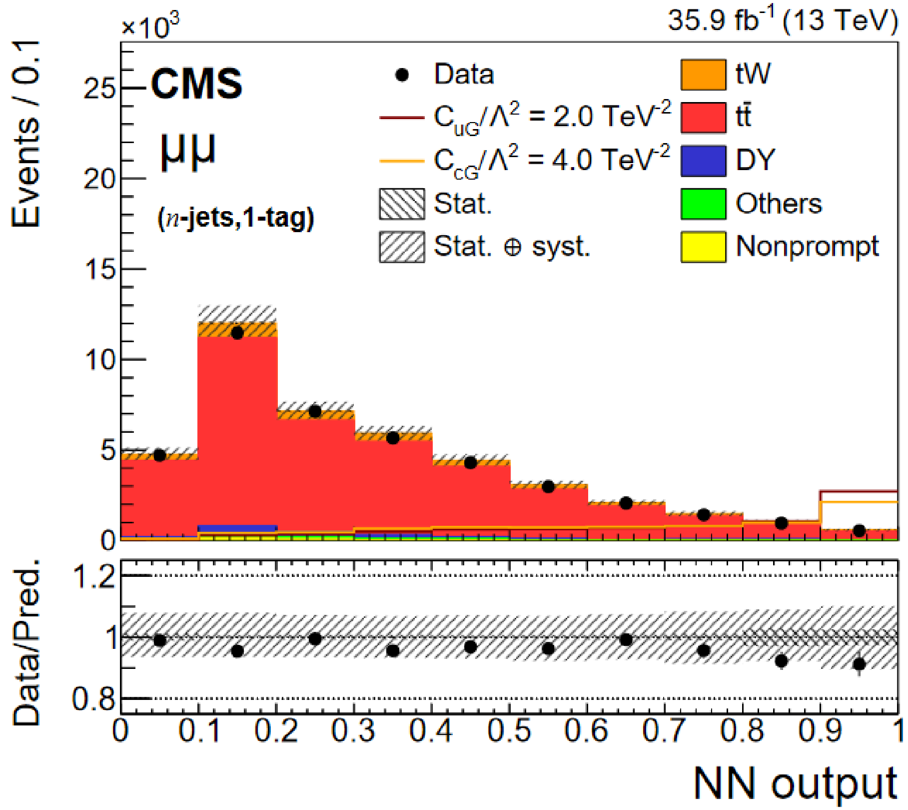
Total Yield to constrain C_G

Dedicated Neural Networks to

a) Separate tW vs. $t\bar{t}$ → used in tW sensitive categories

b) Spilt FCNC from SM bkg → used to constrain C_{uG}, C_{cG} in 2 jets,1 tag categories



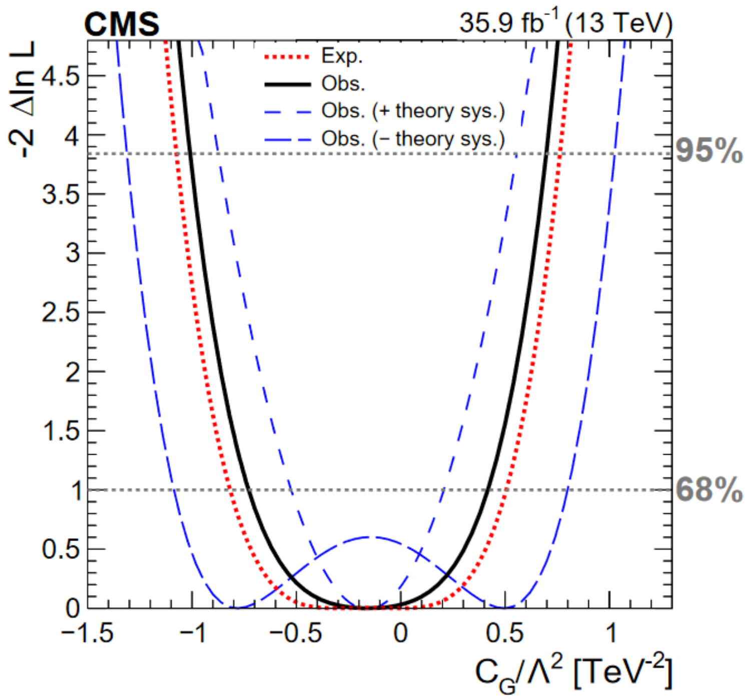


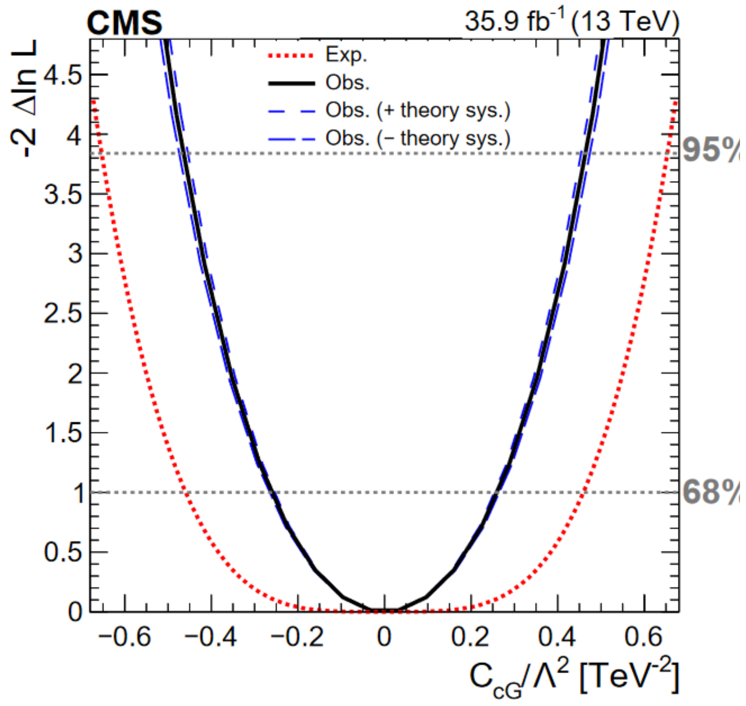
$t\bar{t}$ + tW to dilepton

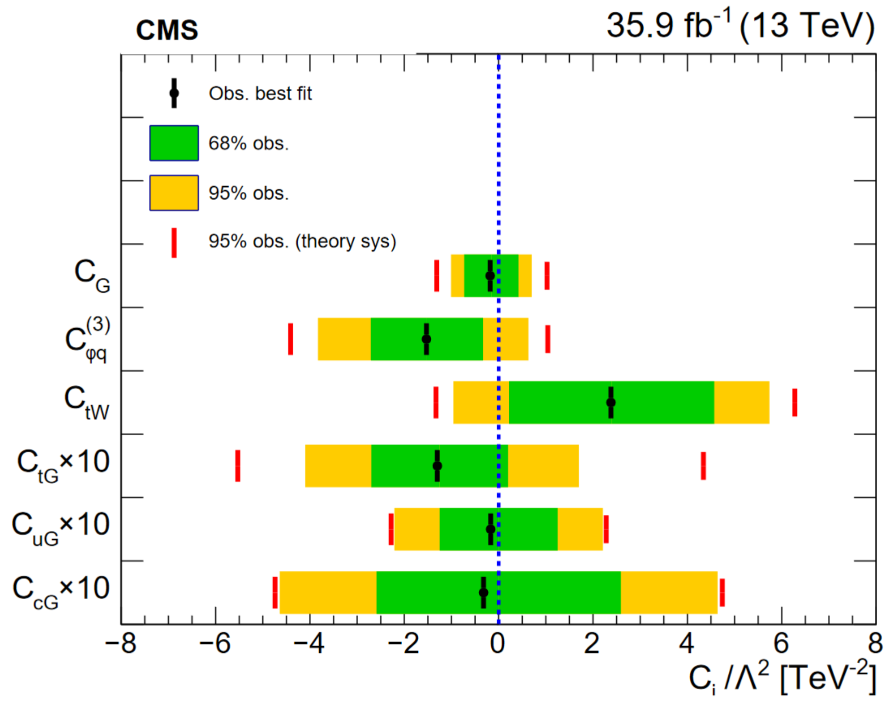
Results

Eur Phy J. C. 2019 886

NN outputs in each category or Yields (if no NN needed) used to perform a Likelihood fit
Each parameter is fit at a time







First time $t\bar{t}$ and tW used in this kind of search

Top polarization and $t\bar{t}$ spin correlations

BSM predictions modify top chromomagnetic and chromoelectric dipole moment (CEDM and CMDM)

Phys. Rev. D 100, 072002

2016 data

Baseline Selection:

- Two leptons OS
- At least 2 jets (at least 1 b-tag)

Strategy:

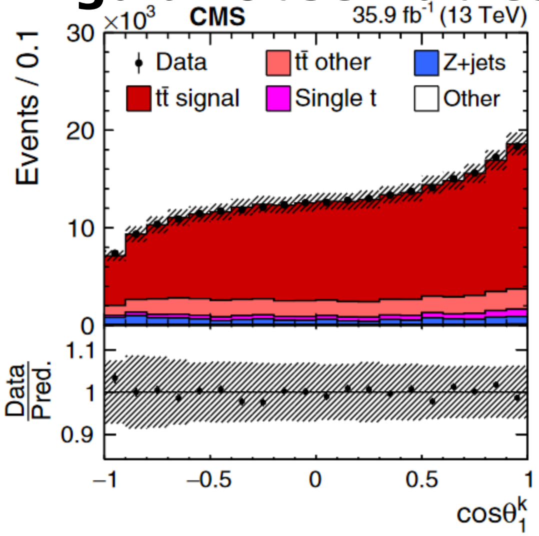
Kinematic reconstruction of $t\bar{t}$ system

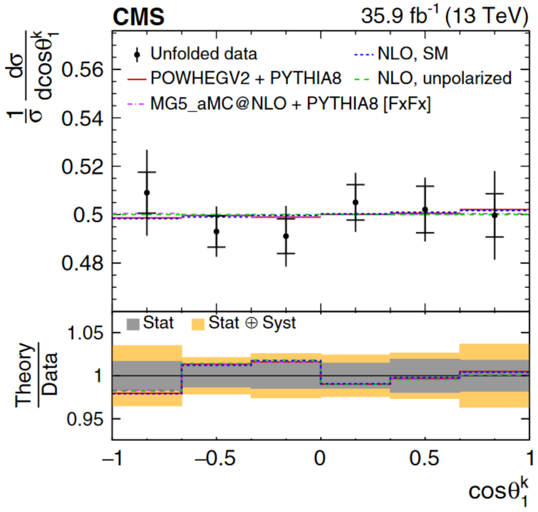
- All combinations of lep. and jets
- Constrains: m_W, MET from neutrinos, m_{top}
- Four momentum reconstructed

Allows to use reconstruct angular observables

Unfolding to parton level to measure diff. cross-section using 22 observables

Angular observables:





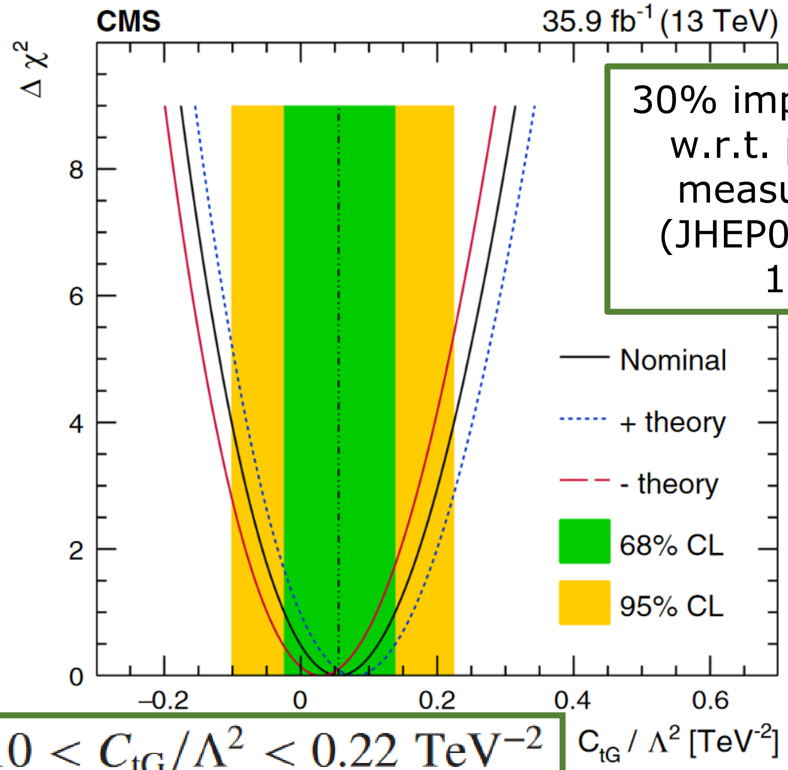
Top polarization and $t\bar{t}$ spin correlations

This measurement of the spin correlations is sensitive to 11 dim-6 operators.
Limits are set on this operators by using simultaneous fits to measured norm. diff. x-sections.

Phys. Rev. D 100, 072002

Constrain CMDM

The operator responsible for anomalous CMDM is: $O_{tG} = y_t g_S (\bar{Q}\sigma^{\mu\nu}T^a t)\tilde{\phi}G^a_{\mu\nu},$



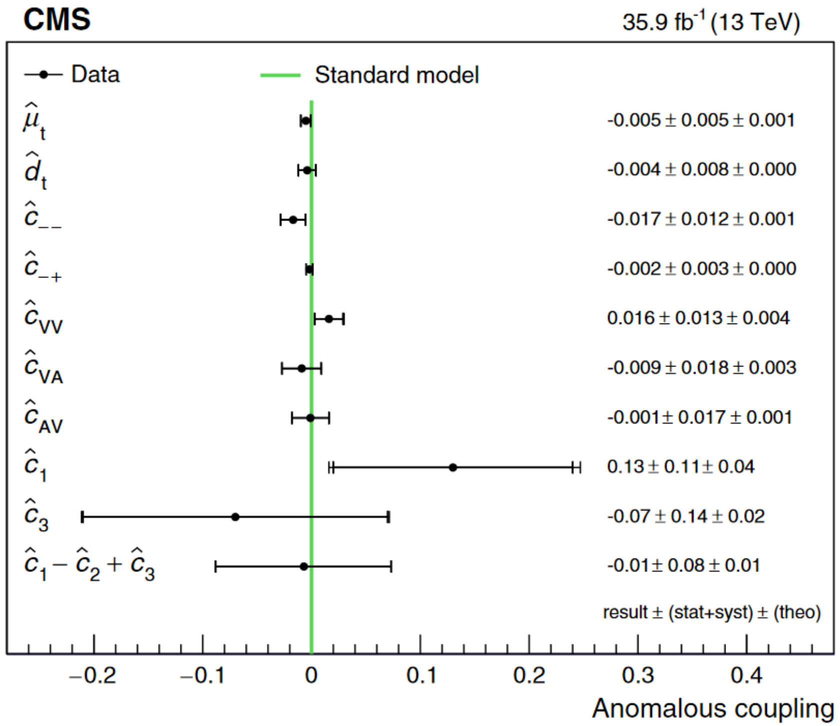
30% improvement w.r.t. previous measurement (JHEP02 (2019) 149)

$-0.10 < C_{tG}/\Lambda^2 < 0.22\ \text{TeV}^{-2}$

Constraints on Anomalous couplings

Limits on each coupling setting the others to 0:

CEDM: $-0.33 < C^I_{tG}/\Lambda^2 < 0.20\ \text{TeV}^{-2}$



CP violating top coupling

Top interaction with chromo electric dipole moment (CEDM) is a potential source of CP violation

CMS-PAS-TOP-18-007

$$\mathcal{L} = \frac{g_S}{2}\bar{t}T^a\sigma^{\mu\nu}(a_t^g + i\gamma_5 d_t^g)tG^{\mu\nu}$$

CP-odd CEDM

Cromo magnetic dipole momentum

2016 data

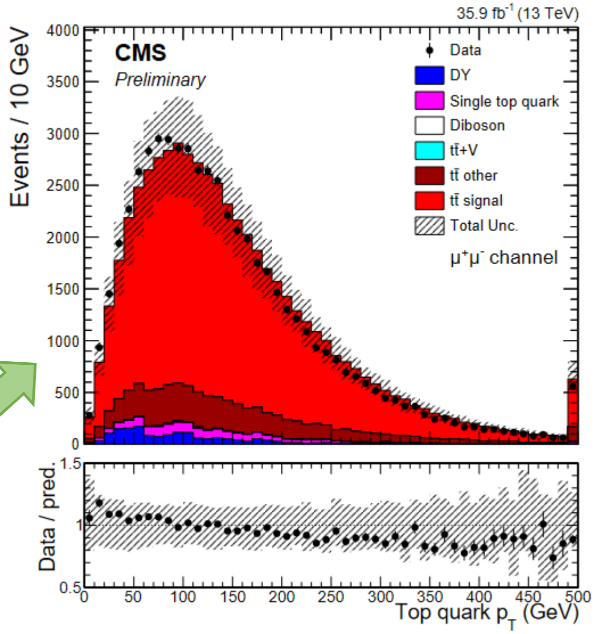
Baseline Selection:

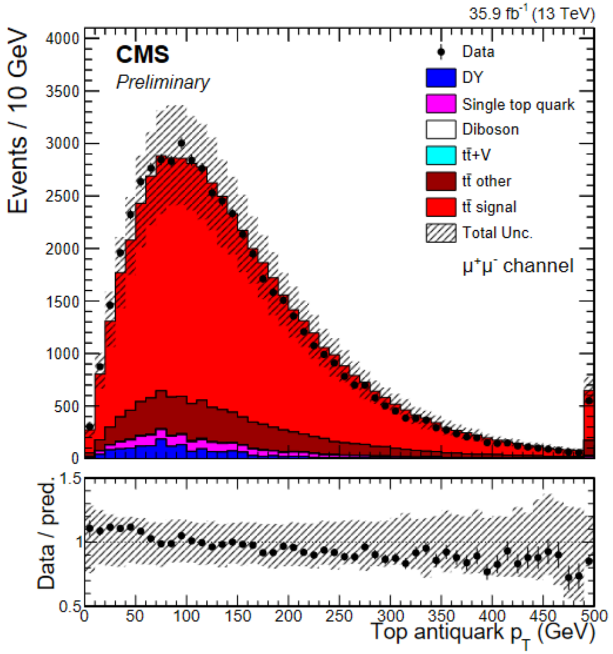
- Two leptons OS
- At least 2 Jets
- At least 1 b-tag

Strategy:

Kinematic reconstruction of $t\bar{t}$ system

- All combinations of lep. and Jets
- Constrains: m_W, MET from neutrions, m_{top}
- Four momentum reconstructed





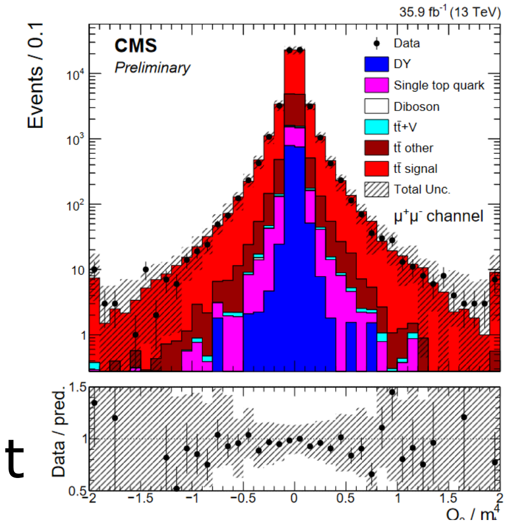
Observables: Levi-civita of leptons, reconstructed (anti-)top ($\mathcal{O}_1$) and (anti-)b jets ($\mathcal{O}_3$)

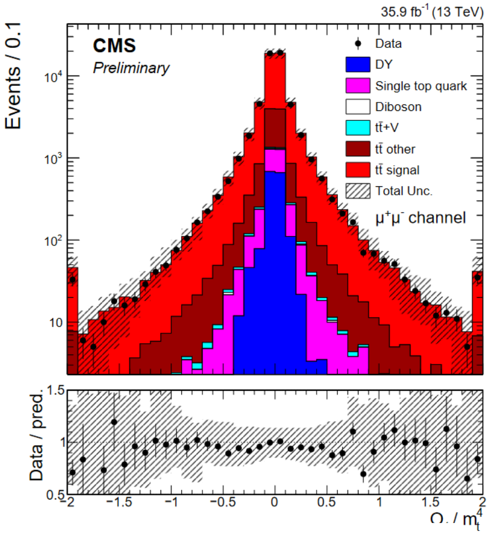
CP violating top coupling

CMS-PAS-TOP-18-007

$\mathcal{O}_i$ are odd under CP transformations:

$$A_i = \frac{N(\mathcal{O}_i > 0) - N(\mathcal{O}_i < 0)}{N(\mathcal{O}_i > 0) + N(\mathcal{O}_i < 0)}.$$

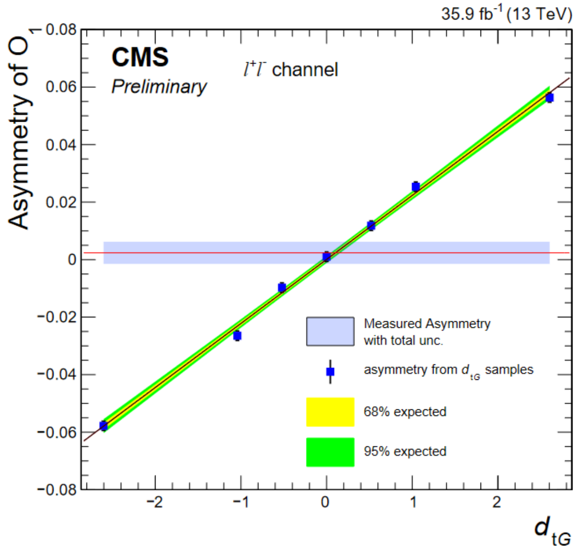


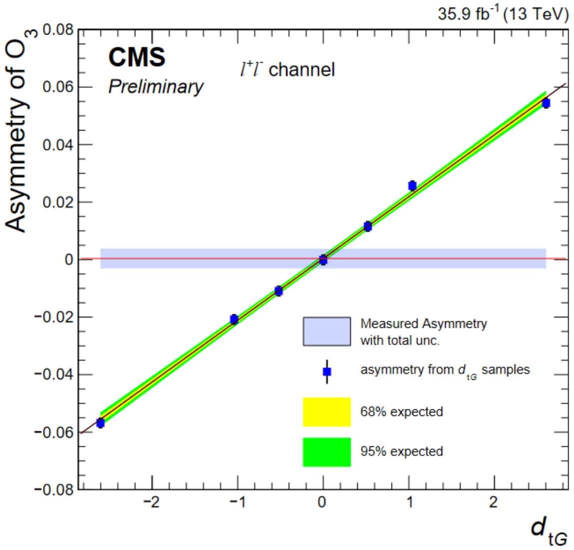


The asymmetry (A) and the cross-section are simultaneously extracted from the fit

This allows to measure the CEDM, in agreement with SM

Physics observable	d_{tG}	CEDM (10^{-18} $g_s \cdot$ cm)
$\mathcal{O}_1$	$0.10 \pm 0.12(\text{stat}) \pm 0.12(\text{syst})$	$0.58 \pm 0.69(\text{stat}) \pm 0.70(\text{syst})$
$\mathcal{O}_3$	$0.00 \pm 0.13(\text{stat}) \pm 0.10(\text{syst})$	$-0.01 \pm 0.72(\text{stat}) \pm 0.58(\text{syst})$

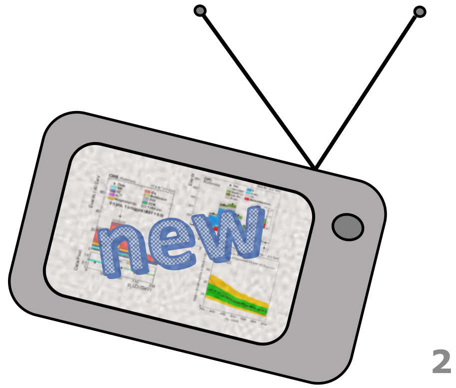




Summary

- LHC is now capable of measuring **rare SM** processes **with top quarks**.
- EFT measurements are key in the search for new physics @LHC.
- Precision measurements are needed for these BSM searches.
- Most of the analyses are not using the full Run 2 data yet.
- **Many new analysis coming, so stay tuned!**

http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/TOP/index.html



Thank You!

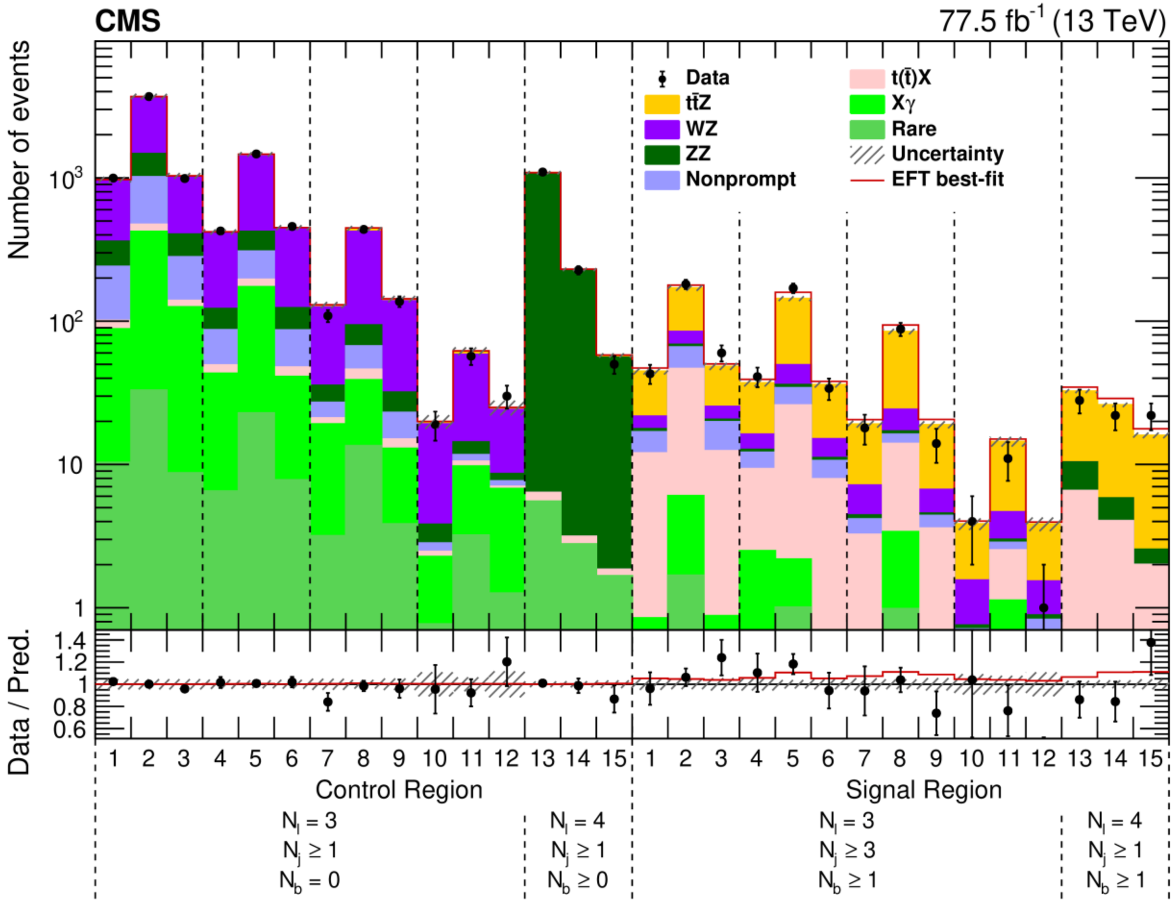
Back up

-

$t\bar{t}Z$ - EFT Interpretation

JHEP 03 (2020) 056

- Regions defined using $p_T(Z)$ and $cos(\theta_Z^*)$



N_ℓ	N_b	N_j	N_Z	$p_T(Z)$ (GeV)	$-1 \leq \cos\theta_Z^* < -0.6$	$-0.6 \leq \cos\theta_Z^* < 0.6$	$0.6 \leq \cos\theta_Z^*$
3	≥ 1	≥ 3	1	0–100	SR1	SR2	SR3
				100–200	SR4	SR5	SR6
				200–400	SR7	SR8	SR9
				≥ 400	SR10	SR11	SR12
4	≥ 1	≥ 1	1	0–100		SR13	
				100–200		SR14	
				≥ 200		SR15	
3	0	≥ 1	1	0–100	CR1	CR2	CR3
				100–200	CR4	CR5	CR6
				200–400	CR7	CR8	CR9
				≥ 400	CR10	CR11	CR12
4	≥ 0	≥ 1	2	0–100		CR13	
				100–200		CR14	
				≥ 200		CR15	

Coefficient	Expected 68% CL	Expected 95% CL	Observed 68% CL	Observed 95% CL	Previous CMS constraints Exp. 95% CL	Previous CMS constraints Obs. 95% CL	Indirect constraints 68% CL
c_{tZ}/Λ^2	$[-0.7, 0.7]$	$[-1.1, 1.1]$	$[-0.8, 0.5]$	$[-1.1, 1.1]$	$[-2.0, 2.0]$	$[-2.6, 2.6]$	$[-4.7, 0.2]$
$c_{tZ}^{[I]}/\Lambda^2$	$[-0.7, 0.7]$	$[-1.1, 1.1]$	$[-0.8, 1.0]$	$[-1.2, 1.2]$	—	—	—
$c_{\phi t}/\Lambda^2$	$[-1.6, 1.4]$	$[-3.4, 2.8]$	$[1.7, 4.2]$	$[0.3, 5.4]$	$[-20.2, 4.0]$	$[-22.2, -13.0]$ $[-3.2, 6.0]$	$[-0.1, 3.7]$
$c_{\phi Q}^{-}/\Lambda^2$	$[-1.1, 1.1]$	$[-2.1, 2.2]$	$[-3.0, -1.0]$	$[-4.0, 0.0]$	—	—	$[-4.7, 0.7]$

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

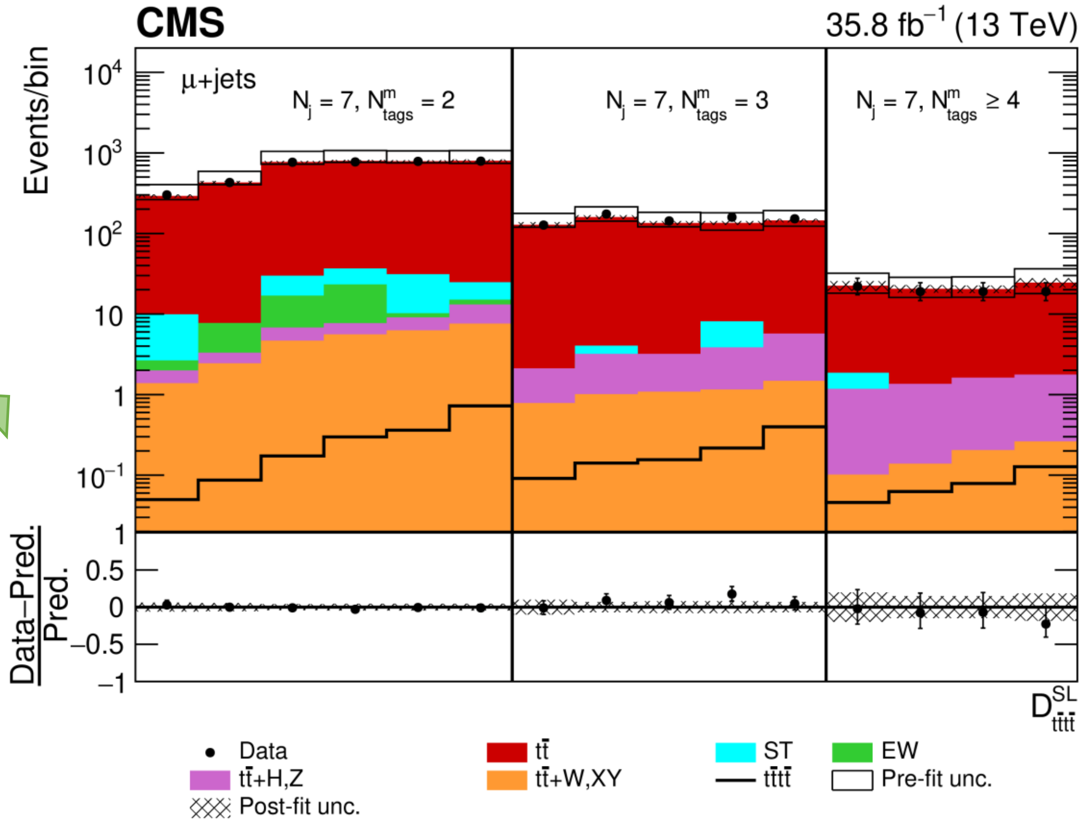
2016 data

Baseline Selection:

2ℓOS and single lepton final states

	ee	$\mu\mu$	$e\mu$	e	μ
$m_{\ell\ell}$	>20 GeV + Z veto		> 20 GeV	-	
N_{jet}	≥4			≥8	≥7
$N_{B\text{-}tag}$	≥2			≥ 2	

JHEP 11 (2019) 082



Strategy:

BDT used to identify hadronic top decays.
A second **BDT** is used to discriminate $t\bar{t}t\bar{t}$ from $t\bar{t}$. This takes as input the first BDT, event topology, event activity, $N_{B\text{-}tag}$

Combination with EPJC 78 (2018) 140 (2016 multilepton):

$$\sigma = 13^{+11}_{-9}\ \text{fb}$$

Observed (expected) significance = 1.4 (1.1)

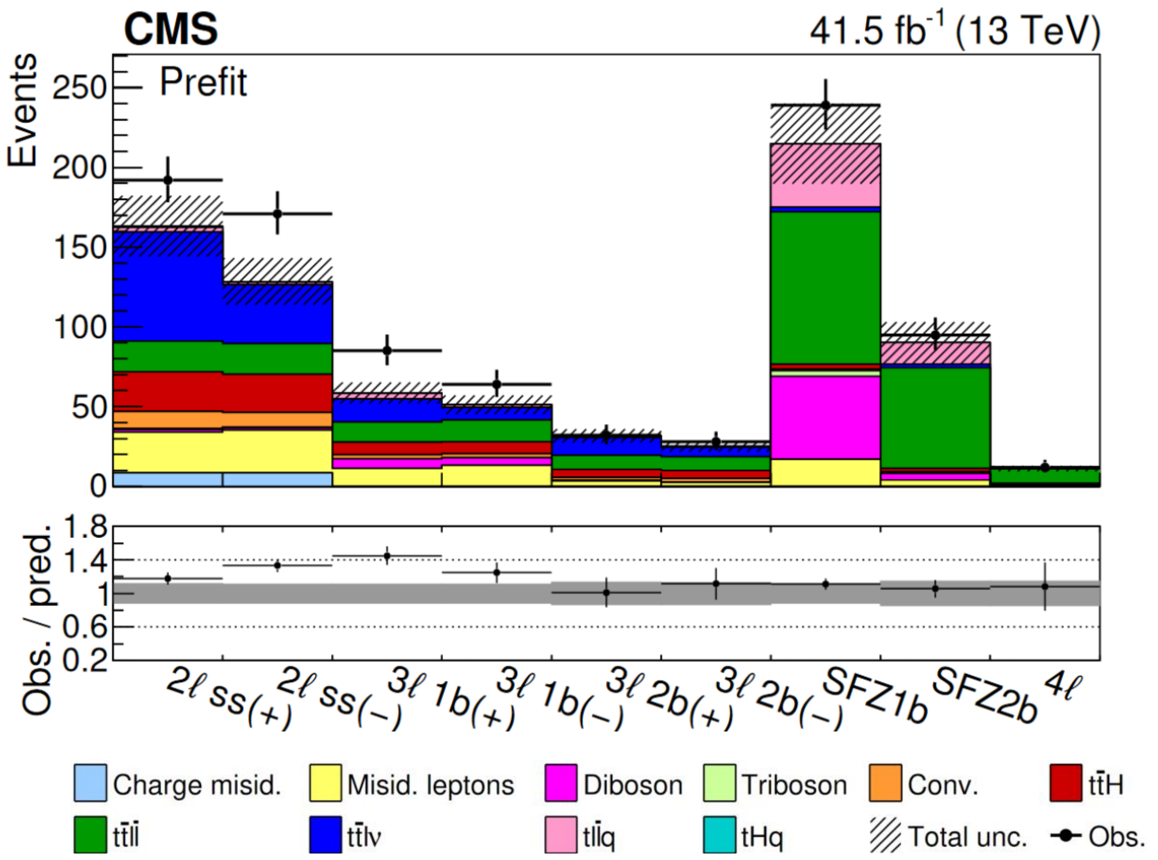
$t(\bar{t})$ + leptons

2017 data
Baseline Selection:

- 2 same sign, 3 and 4 leptons categories
- Jet and b-tag multiplicity used to categorize
- 35 signal regions

JHEP 03 (2021) 095

Selection	$2\ell ss$	3ℓ		$\geq 4\ell$
Leptons	Exactly 2 leptons	Exactly 3 leptons		$\geq$4 leptons
Charge requirements	$\sum_\ell q < 0, \sum_\ell q > 0$	$\sum_\ell q < 0, \sum_\ell q > 0$	—	—
Jet multiplicity	4, 5, 6, $\geq$7 jets	2, 3, 4, $\geq$5 jets	2, 3, 4, $\geq$5 jets	2, 3, $\geq$4 jets
Number of b jets	$\geq$2 b jets	1, $\geq$2 b jets	1, $\geq$2 b jets	$\geq$2 b jets
Dilepton mass	—	$\lvert m_{\ell\ell} - m_Z \rvert > 10\,\text{GeV}$	$\lvert m_{\ell\ell} - m_Z \rvert \leq 10\,\text{GeV}$	—



$t\bar{t}$ + tW to dilepton

Eur Phy J. C. 2019 886

Discriminant variable

Total Yield to constrain C_G

Dedicated Neural Networks to

a) Separate tW vs. $t\bar{t}$ → used in tW sensitive categories
b) Spilt FCNC from SM bkg → used to constrain C_{uG}, C_{cG} in 2 jets,1 tag categories

Table 3 Summary of the observables used to probe the effective couplings in various (n-jets,m-tags) categories in the ee, eμ, and μμ channels

Eff. coupling	Channel	Categories				
		1-jet, 0-tag	1-jet, 1-tag	2-jets, 1-tag	>2-jets, 1-tag	≥2-jets, 2-tags
C_G	ee	–	Yield	Yield	–	Yield
	eμ	Yield	Yield	Yield	–	Yield
	μμ	–	Yield	Yield	–	Yield
$C_{\phi q}^{(3)}, C_{tW}, C_{tG}$	ee	–	NN_{11}	NN_{21}	–	Yield
	eμ	NN_{10}	NN_{11}	NN_{21}	–	Yield
	μμ	–	NN_{11}	NN_{21}	–	Yield
C_{uG}, C_{cG}	ee	–	NN_{FCNC}			–
	eμ	–	NN_{FCNC}			–
	μμ	–	NN_{FCNC}			–

$t\bar{t}$ + tW to dilepton

Discriminant variable

Total Yield to constrain C_G

Dedicated Neural Networks to

a) Separate tW vs. $t\bar{t}$ → used in tW sensitive categories
b) Spilt FCNC from SM bkg → used to constrain C_{uG}, C_{cG} in 2 jets,1 tag categories

Eur Phy J. C. 2019 886

Uncertainty	C_G (%)	$C^{(3)}_{\phi q}$ (%)	C_{tW} (%)	C_{tG} (%)	C_{uG} (%)	C_{cG} (%)
Trigger	10.2	2.3	7.0	2.9	1.7	2.5
Lepton ident./isolation	7.4	1.1	1.2	23.0	<1	<1
Jet energy scale	<1	25.0	17.8	4.9	<1	<1
tW DS/DR	<1	24.2	4.4	3.0	7.6	7.8
ME/PS matching	<1	4.9	9.9	1.2	<1	<1
ISR scale	<1	5.0	5.6	<1	<1	<1
FSR scale	5.8	4.4	4.0	10.2	<1	<1
DY background	<1	7.5	5.5	21.5	<1	<1
Nonprompt background	<1	1.4	5.8	<1	<1	<1
Integrated luminosity	13.1	<1	1.1	18.8	<1	<1
Statistical	5.8	2.3	23.7	<1	72.6	73.6
MC statistical	<1	12.1	3.7	5.2	2.9	2.5

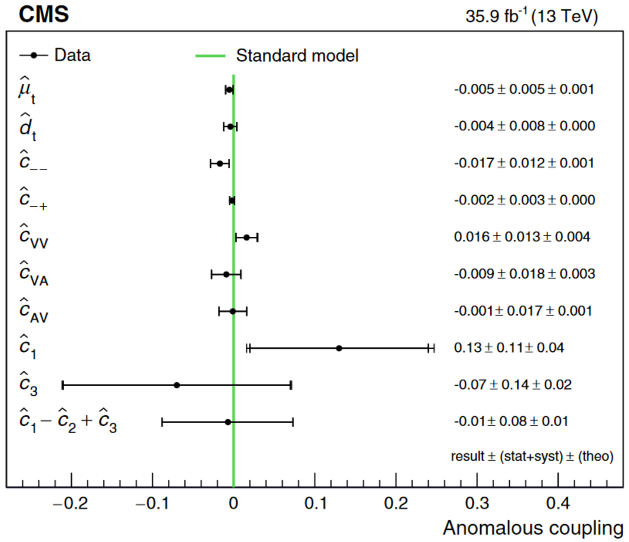
Top polarization and tt spin correlations

Constrain on Anomalous couplings

Phys. Rev. D 100, 072002

Limits on each coupling setting the others to 0:

Coupling	Operator type	Symmetry properties
$\hat{\mu}_t$	2 quarks plus gluon(s)	P-even, CP-even
$\hat{d}_t$	2 quarks plus gluon(s)	P-odd, CP-odd
$\hat{c}_{--}$	2 quarks plus gluon(s)	P-odd, CP-odd
$\hat{c}_{-+}$	2 quarks plus gluon(s)	P-even, CP-odd
$\hat{c}_{VV}$	4 quarks (weak isospin 0)	P-even, CP-even
$\hat{c}_{VA}$	4 quarks (weak isospin 0)	P-odd, CP-even
$\hat{c}_{AV}$	4 quarks (weak isospin 0)	P-odd, CP-even
$\hat{c}_{AA}$	4 quarks (weak isospin 0)	P-even, CP-even
$\hat{c}_1$	4 quarks (weak isospin 1)	CP-even
$\hat{c}_2$	4 quarks (weak isospin 1)	CP-even
$\hat{c}_3$	4 quarks (weak isospin 1)	CP-even



	95% C.L.	Theoretical unc.	χ^2	Coefficients
$\hat{\mu}_t$	$-0.014 < \hat{\mu}_t < 0.004$	± 0.001	7	$C_{kk}, C_{nn}, C_{rk}+C_{kr}, D$
$\hat{d}_t$	$-0.020 < \hat{d}_t < 0.012$	...	9	$B_2^r, B_1^n, C_{nr}-C_{rn}, C_{nk}-C_{kn}$
$\hat{c}_{--}$	$-0.040 < \hat{c}_{--} < 0.006$	± 0.001	7	$B_2^r, B_1^n, C_{nr}-C_{rn}, C_{nk}-C_{kn}$
$\hat{c}_{-+}$	$-0.009 < \hat{c}_{-+} < 0.005$	...	11	$B_1^n, B_2^n, B_1^{r*}, C_{nk}+C_{kn}$
$\hat{c}_{VV}$	$-0.011 < \hat{c}_{VV} < 0.042$	± 0.004	7	$C_{kk}, C_{nn}, C_{rk}+C_{kr}, D$
$\hat{c}_{VA}$	$-0.044 < \hat{c}_{VA} < 0.027$	± 0.003	9	$B_2^k, B_2^r, C_{kk}, C_{nr}+C_{rn}$
$\hat{c}_{AV}$	$-0.035 < \hat{c}_{AV} < 0.032$	± 0.001	6	$B_1^{k*}, B_2^{k*}, B_1^{r*}, B_2^{r*}$
$\hat{c}_1$	$-0.09 < \hat{c}_1 < 0.34$	± 0.04	7	$C_{kk}, C_{nn}, C_{rk}+C_{kr}, D$
$\hat{c}_3$	$-0.35 < \hat{c}_3 < 0.21$	± 0.02	9	$B_2^k, B_2^r, C_{kk}, C_{nr}+C_{rn}$
$\hat{c}_1-\hat{c}_2+\hat{c}_3$	$-0.17 < \hat{c}_1-\hat{c}_2+\hat{c}_3 < 0.15$	± 0.01	6	$B_1^{k*}, B_2^{k*}, B_1^{r*}, B_2^{r*}$