EFT Interpretation of Top Quark Measurements at the LHC

7th Large Hadron Collider Physics 2019
May 20-25, 2019, Puebla, Mexico

PROLAY KUMAR MAL
NATIONAL INSTITUTE OF SCIENCE EDUCATION & RESEARCH
BHUBANESWAR, INDIA

Top Quark Effective Field Theory

- Expansion of the SM Lagrangian with higher-order operators to model New Physics (NP) at an energy scale, Λ
  - SM Lagrangian ($\mathcal{L}_{SM}$) consists of Dimension-4 operators
  - Dimension-5 operators typically excluded as they do not conserve lepton number
  - The Effective Lagrangian ($\mathcal{L}_{eff}$) is a series of dimension-6 operators ($\mathcal{O}_i$) with dimensionless Wilson coefficients (c_i) to parametrize the NP interaction strength
  - Theoretically consistent, Model independent approach
- LHCTop Working Group proposal for EFT interpretation:
  - In total, 59 dimension-6 operators conserving baryon number and lepton numbers
  - Several of them are relevant for Top EFT interpretation

arXiv:1802.07237 [hep-ph]

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\sum_i c_i \mathcal{O}_i + \cdots$$

LHCTopWG EFT Proposal

4-Quark Operators

$$O_{qq}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{q}_k\gamma_\mu q_l),$$
$$O_{qq}^{3(ijkl)} = (\bar{q}_i\gamma^\mu\tau^I q_j)(\bar{q}_k\gamma_\mu\tau^I q_l),$$
$$O_{qu}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{u}_k\gamma_\mu u_l),$$
$$O_{qu}^{8(ijkl)} = (\bar{q}_i\gamma^\mu T^A q_j)(\bar{u}_k\gamma_\mu T^A u_l),$$
$$O_{qd}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{d}_k\gamma_\mu d_l),$$
$$O_{qd}^{8(ijkl)} = (\bar{q}_i\gamma^\mu T^A q_j)(\bar{d}_k\gamma_\mu T^A d_l),$$
$$O_{uu}^{(ijkl)} = (\bar{u}_i\gamma^\mu u_j)(\bar{u}_k\gamma_\mu u_l),$$
$$O_{ud}^{1(ijkl)} = (\bar{u}_i\gamma^\mu u_j)(\bar{d}_k\gamma_\mu d_l),$$
$$O_{ud}^{8(ijkl)} = (\bar{u}_i\gamma^\mu T^A u_j)(\bar{d}_k\gamma_\mu T^A d_l),$$
$$^\ddagger O_{quqd}^{1(ijkl)} = (\bar{q}_i u_j)\,\varepsilon\,(\bar{q}_k d_l),$$
$$^\ddagger O_{quqd}^{8(ijkl)} = (\bar{q}_i T^A u_j)\,\varepsilon\,(\bar{q}_k T^A d_l),$$

2-Quark Operators

$$^\ddagger O_{u\varphi}^{(ij)} = \bar{q}_i u_j \tilde{\varphi}\,(\varphi^\dagger\varphi),$$
$$O_{\varphi q}^{1(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_i\gamma^\mu q_j),$$
$$O_{\varphi q}^{3(ij)} = (\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{q}_i\gamma^\mu\tau^I q_j),$$
$$O_{\varphi u}^{(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_i\gamma^\mu u_j),$$
$$^\ddagger O_{\varphi ud}^{(ij)} = (\tilde{\varphi}^\dagger iD_\mu\varphi)(\bar{u}_i\gamma^\mu d_j),$$
$$^\ddagger O_{uW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I u_j)\,\tilde{\varphi}W^I_{\mu\nu},$$
$$^\ddagger O_{dW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I d_j)\,\varphi W^I_{\mu\nu},$$
$$^\ddagger O_{uB}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}u_j)\quad\tilde{\varphi}B_{\mu\nu},$$
$$^\ddagger O_{uG}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}T^A u_j)\,\tilde{\varphi}G^A_{\mu\nu},$$

2-Quark-2-Lepton Operators

$$O_{lq}^{1(ijkl)} = (\bar{l}_i\gamma^\mu l_j)(\bar{q}_k\gamma^\mu q_l),$$
$$O_{lq}^{3(ijkl)} = (\bar{l}_i\gamma^\mu\tau^I l_j)(\bar{q}_k\gamma^\mu\tau^I q_l),$$
$$O_{lu}^{(ijkl)} = (\bar{l}_i\gamma^\mu l_j)(\bar{u}_k\gamma^\mu u_l),$$
$$O_{eq}^{(ijkl)} = (\bar{e}_i\gamma^\mu e_j)(\bar{q}_k\gamma^\mu q_l),$$
$$O_{eu}^{(ijkl)} = (\bar{e}_i\gamma^\mu e_j)(\bar{u}_k\gamma^\mu u_l),$$
$$^\ddagger O_{lequ}^{1(ijkl)} = (\bar{l}_i e_j)\,\varepsilon\,(\bar{q}_k u_l),$$
$$^\ddagger O_{lequ}^{3(ijkl)} = (\bar{l}_i\sigma^{\mu\nu}e_j)\,\varepsilon\,(\bar{q}_k\sigma_{\mu\nu}u_l),$$
$$^\ddagger O_{ledq}^{(ijkl)} = (\bar{l}_i e_j)(\bar{d}_k q_l),$$

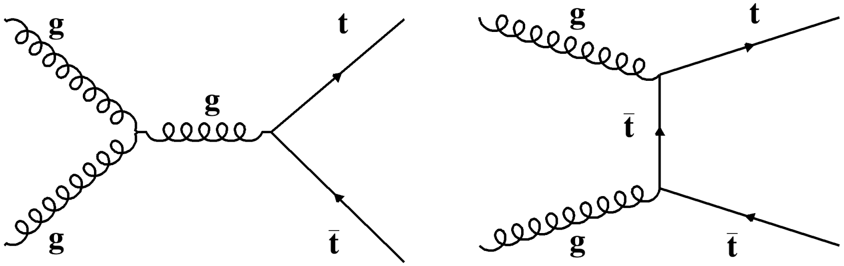
arXiv:1802.07237 [hep-ph]

- Prescriptions for EFT interpretation from LHC Top quark Measurements
- Number of degrees of freedom
  - Four heavy quarks: 11 + 2 CPV
  - Two light and two heavy quarks: 14
  - Two heavy quarks and bosons: 9 + 6 CPV
  - Two heavy quarks and two leptons: (8 + 3 CPV) x 3 lepton flavors
- Top EFT Operators implemented at tree-level in dim6top UFO model:

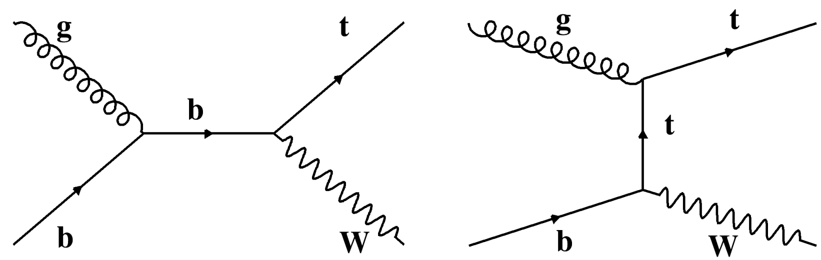
https://feynrules.irmp.ucl.ac.be/wiki/dim6top

Top Analyses for EFT Interpretation

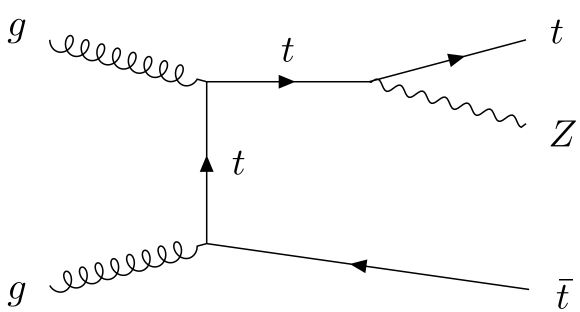
- **Various dimension-6 operators can effect the top quark production processes at the LHC in different production modes**
- **CMS/ATLAS interpretation for the following processes at √s=13 TeV so far**



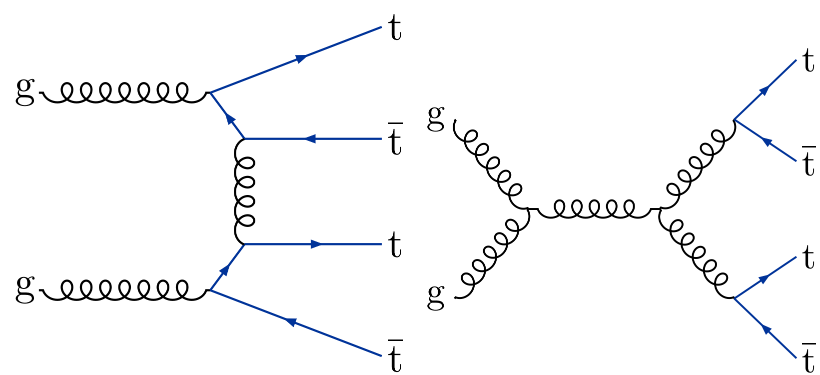
CMS: 35.9 fb^{-1}



CMS: 35.9 fb^{-1}



ATLAS: 36.1 fb^{-1}
CMS: 77.5 fb^{-1}



CMS: 35.8 fb^{-1}

Interpretation of ttZ measurements

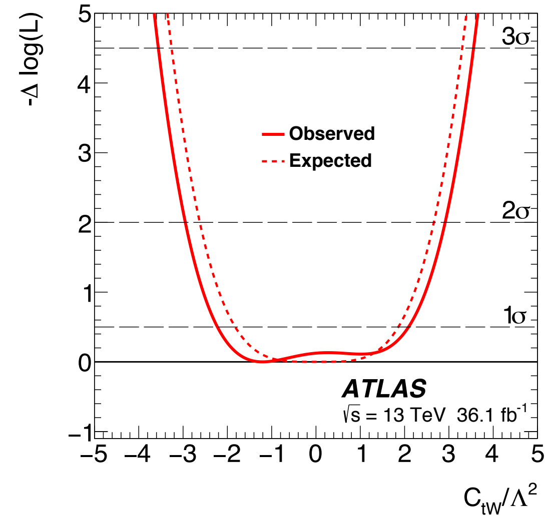
- Same-sign and Opposite sign dilepton, tri-lepton and tetra-lepton inclusive cross-section analysis
- 5 operators can modify the ttZ rates:

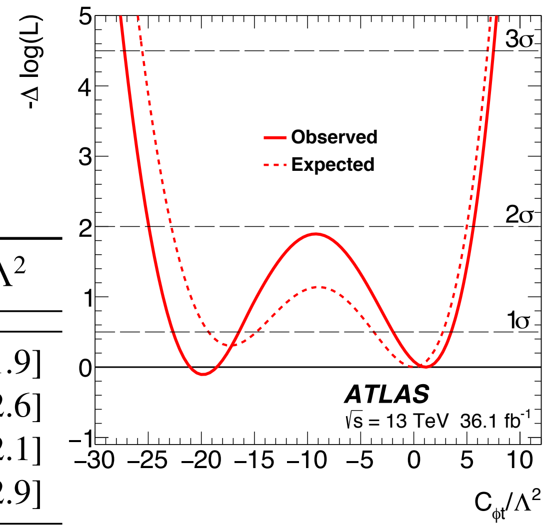
$$O_{\phi Q}^{(3)}, O_{\phi Q}^{(1)}, O_{\phi t}, O_{tW}, O_{tB}$$

- $\mathcal{O}^{(3)}_{\Phi Q}$ and $\mathcal{O}^{(1)}_{\Phi Q}$ are contribute to ttZ vertex as a linear combination
  - Measurement is sensitive to the difference: $\mathcal{O}^{(3)}_{\Phi Q}$ - $\mathcal{O}^{(1)}_{\Phi Q}$
- Only one operator is considered at a time

Phys. Rev D 99, 072009 (2019)

Coefficients	$C_{\phi Q}^{(3)}/\Lambda^2$	$C_{\phi t}/\Lambda^2$	C_{tB}/Λ^2	C_{tW}/Λ^2
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]





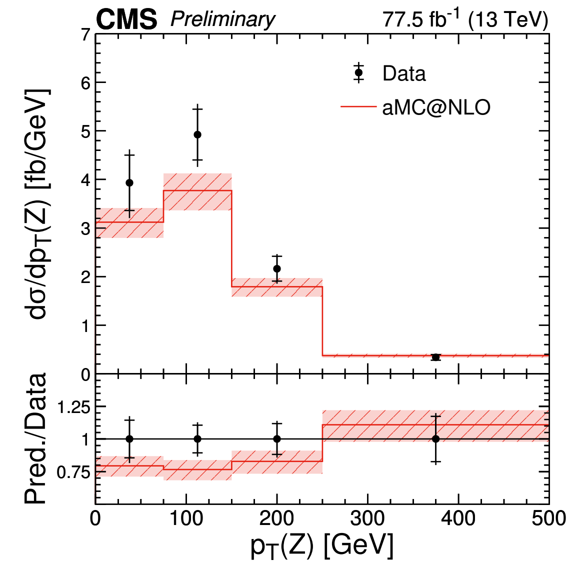
Interpretation of ttZ measurements

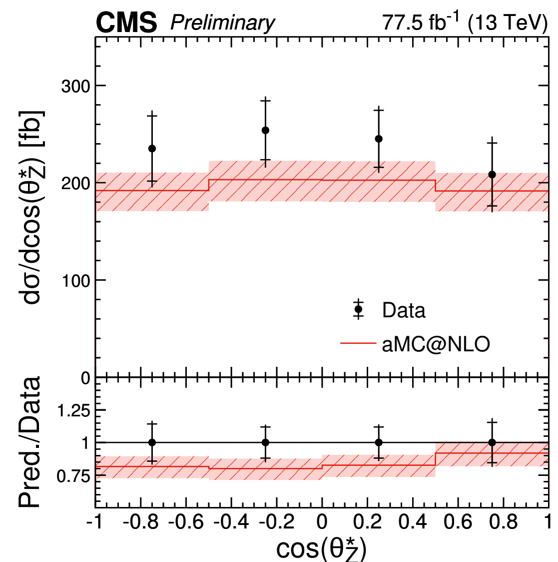
- tri-lepton and tetra-lepton cross-section analysis
- Dimension-6 operators that affect the ttZ production rate:

$$
\begin{aligned}
c_{tZ} &= \mathrm{Re}\left(-\sin\theta_W C_{uB}^{(33)} + \cos\theta_W C_{uW}^{(33)}\right) \\
c_{tZ}^{[I]} &= \mathrm{Im}\left(-\sin\theta_W C_{uB}^{(33)} + \cos\theta_W C_{uW}^{(33)}\right) \\
c_{\phi t} &= C_{\phi t} = C_{\phi u}^{(33)} \\
c_{\phi Q}^{-} &= C_{\phi Q} = C_{\phi q}^{1(33)} - C_{\phi q}^{3(33)},
\end{aligned}
$$

CMS-PAS-TOP-18-009

- EFT ttZ signal weight estimation at the generator level wrt the SM signal strength
- Reconstructed events reweighted to obtain the EFT signal shape

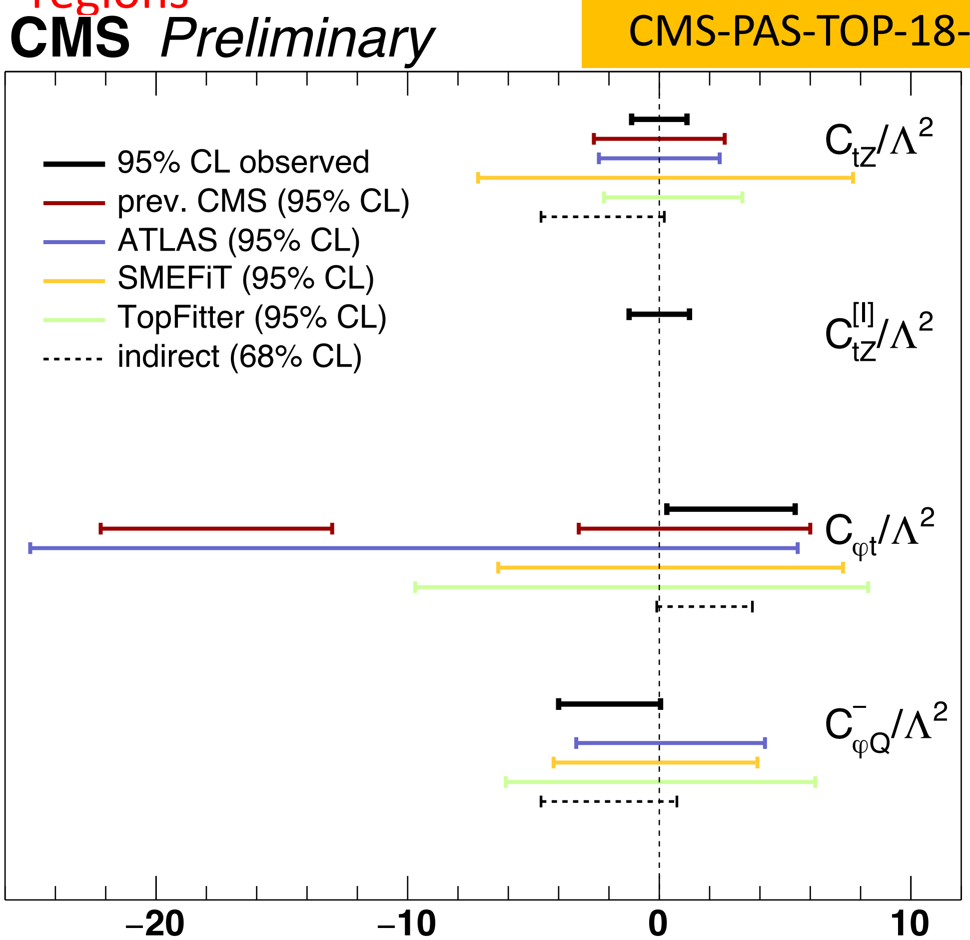


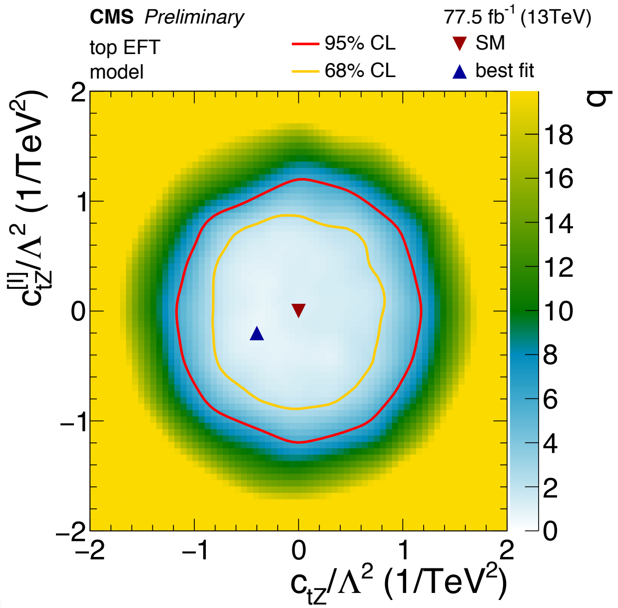


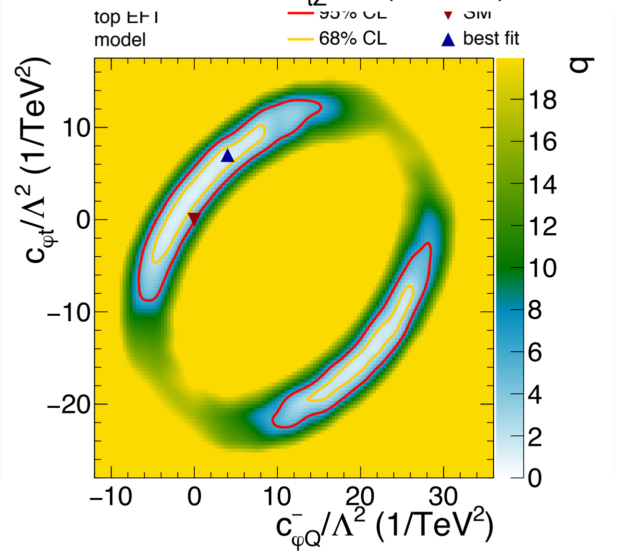
Interpretation of ttZ measurements

- ✧ Simultaneous fit to p_T^Z and $\cos\theta^*$ (the angle between the lepton and Z-candidate in rest frame of Z) distributions in different signal regions

CMS-PAS-TOP-18-009

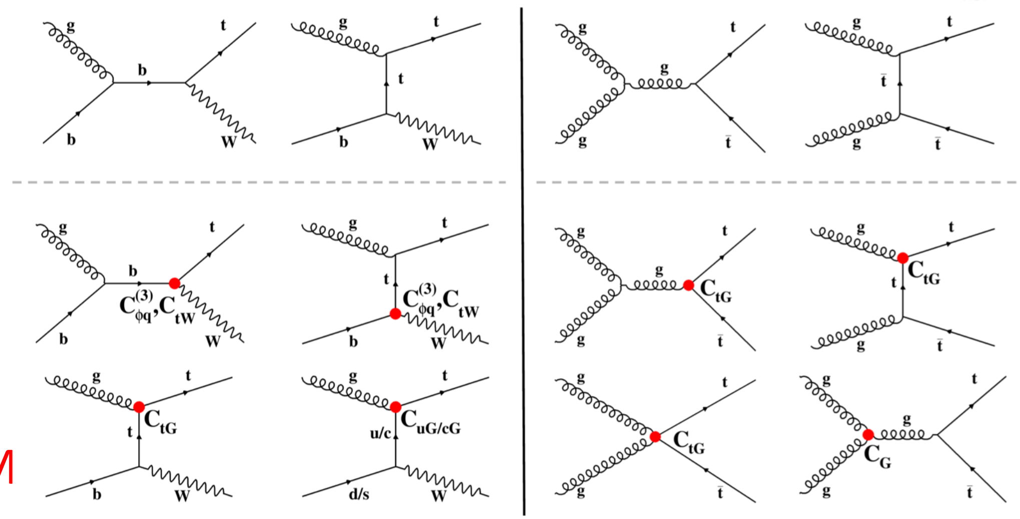




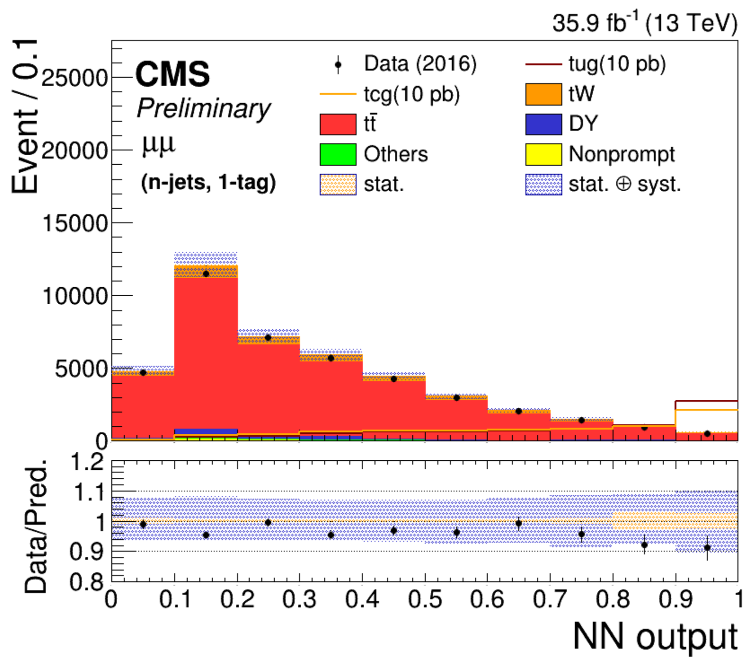


New Physics limits with tW/tt→ dilepton

arXiv:1903.11144 [hep-ex]
submitted to EPJC



- Final state signature with two isolated leptons and b-jets
- Signal categorization:
  - tt: 2 leptons + >=2 bjets
  - tW: 2 leptons + 0-1 bjet
- Wilson coefficients sensitive to BSM contributions to the tt and tW production: C_G, $C^{(3)}_{\Phi q}$, C_{tW}, C_{tG}, C_{uG}, and C_{cG}; C_{tG} can be probed with both tW and tt
- Simultaneous fits in different dilepton & b-tagged regions: C_G
- Neural Network based separation between tt , tW and FCNC signal
  - tt vs tW: $C^{(3)}_{\Phi q}$, C_{tW}, C_{tG}
  - SM (tt+tW) vs FCNC tW: C_{uG}, and C_{cG}



New Physics limits with tW/tt→ dilepton

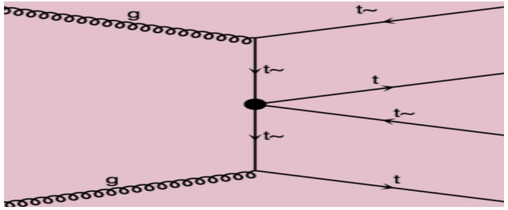
arXiv:1903.11144 [hep-ex]
submitted to EPJC

Eff. coupling	Channel	Observed	Expected
C_G	ee	$-0.14^{+0.51}_{-0.82}$ [−1.14 , 0.83]	$0.00^{+0.59}_{-0.90}$ [−1.20 , 0.88]
	eμ	$-0.18^{+0.42}_{-0.73}$ [−1.01 , 0.70]	$0.00^{+0.51}_{-0.82}$ [−1.08 , 0.77]
	μμ	$-0.14^{+0.44}_{-0.75}$ [−1.06 , 0.75]	$0.00^{+0.57}_{-0.88}$ [−1.16 , 0.85]
	Combined	$-0.18^{+0.42}_{-0.73}$ [−1.01 , 0.70]	$0.00^{+0.51}_{-0.82}$ [−1.07 , 0.76]
$C^{(3)}_{\phi q}$	ee	$1.12^{+2.89}_{-1.18}$ [−4.03 , 4.37]	$0.00^{+1.74}_{-2.53}$ [−6.40 , 3.27]
	eμ	$-0.70^{+0.59}_{-2.16}$ [−3.74 , 1.61]	$0.00^{+1.12}_{-1.34}$ [−2.57 , 2.15]
	μμ	$1.13^{+2.86}_{-0.87}$ [−3.58 , 4.46]	$0.00^{+1.92}_{-2.20}$ [−4.68 , 3.66]
	Combined	$-1.52^{-0.33}_{-2.71}$ [−3.82 , 0.63]	$0.00^{+0.88}_{-1.05}$ [−2.04 , 1.63]
C_{tW}	ee	$6.18^{+7.81}_{-3.02}$ [−4.16 , 8.95]	$0.00^{+6.81}_{-2.02}$ [−3.33 , 8.12]
	eμ	$1.64^{+5.59}_{-0.80}$ [−1.89 , 6.68]	$0.00^{+6.19}_{-1.40}$ [−2.39 , 7.18]
	μμ	$-1.40^{+7.79}_{-3.00}$ [−4.23 , 9.01]	$0.00^{+6.97}_{-2.18}$ [−3.63 , 8.42]
	Combined	$2.38^{+4.57}_{+0.22}$ [−0.96 , 5.74]	$0.00^{+5.93}_{-1.14}$ [−1.91 , 6.70]
C_{tG}	ee	$-0.19^{+0.02}_{-0.40}$ [−0.65 , 0.22]	$0.00^{+0.21}_{-0.22}$ [−0.44 , 0.41]
	eμ	$-0.03^{+0.11}_{-0.19}$ [−0.34 , 0.27]	$0.00^{+0.15}_{-0.17}$ [−0.34 , 0.29]
	μμ	$-0.15^{+0.02}_{-0.34}$ [−0.53 , 0.19]	$0.00^{+0.18}_{-0.19}$ [−0.40 , 0.35]
	Combined	$-0.13^{+0.02}_{-0.27}$ [−0.41 , 0.17]	$0.00^{+0.14}_{-0.15}$ [−0.30 , 0.28]
C_{uG}	ee	$-0.017^{+0.22}_{-0.22}$ [−0.37 ,0.37]	$0.00^{+0.29}_{-0.29}$ [−0.42 , 0.42]
	eμ	$-0.017^{+0.17}_{-0.17}$ [−0.29 ,0.29]	$0.00^{+0.26}_{-0.26}$ [−0.38 , 0.38]
	μμ	$-0.017^{+0.17}_{-0.17}$ [−0.29 ,0.29]	$0.00^{+0.27}_{-0.27}$ [−0.38 , 0.38]
	Combined	$-0.017^{+0.13}_{-0.13}$ [−0.22 ,0.22]	$0.00^{+0.21}_{-0.21}$ [−0.30 , 0.30]
C_{cG}	ee	$-0.032^{+0.47}_{-0.47}$ [−0.78 ,0.78]	$0.00^{+0.63}_{-0.63}$ [−0.92 , 0.92]
	eμ	$-0.032^{+0.34}_{-0.34}$ [−0.60 ,0.60]	$0.00^{+0.56}_{-0.56}$ [−0.81 , 0.81]
	μμ	$-0.032^{+0.36}_{-0.36}$ [−0.63 ,0.63]	$0.00^{+0.58}_{-0.58}$ [−0.84 , 0.84]
	Combined	$-0.032^{+0.26}_{-0.26}$ [−0.46 ,0.46]	$0.00^{+0.46}_{-0.46}$ [−0.65 , 0.65]

- ✧ No excess in data have been observed and limits on the 6 coupling constants are set
- ✧ First experimental bound on C_G from top quark results
- ✧ The limits on C_{uG} and C_{cG} are translated into the FCNC branching ratios at 95% CL:
  - ✧ BR(t→cg)<0.53%
  - ✧ BR(t→ug)<0.12%

Search for 4 top quarks

CMS-PAS-TOP-17-019



- Inclusive cross-section in single lepton and opposite sign dilepton signatures
- In SM, NLO predicted

  $\sigma_{pp \rightarrow tttt} \approx 9$ fb at $\sqrt{s}$=13 TeV
- Event categorization based on number jets and tagged jets
- Only relevant EFT dimension-6 operators: $\mathcal{O}^1_{tt}$, $\mathcal{O}^1_{QQ}$, $\mathcal{O}^1_{Qt}$ and $\mathcal{O}^8_{Qt}$
- Probe for 4 heavy quark interactions including tttt operator
- Observed cross-section is consistent with the SM and is used to constrain the EFT coupling parameters

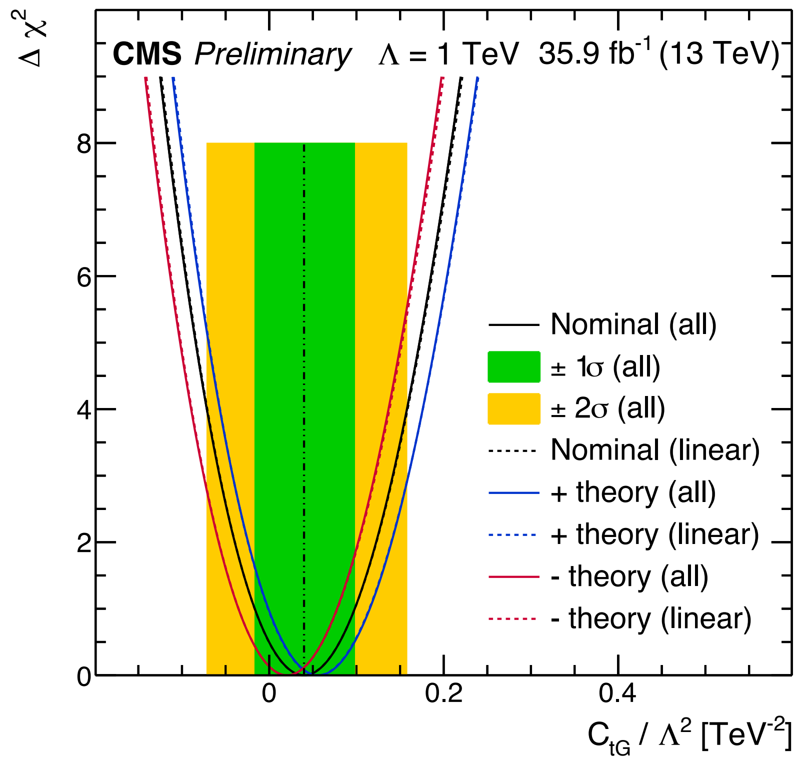
$$\mathcal{O}^1_{tt} = (\bar{t}_R \gamma^\mu t_R)(\bar{t}_R \gamma_\mu t_R)\,,$$
$$\mathcal{O}^1_{QQ} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{Q}_L \gamma_\mu Q_L)\,,$$
$$\mathcal{O}^1_{Qt} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{t}_R \gamma_\mu t_R)\,,$$
$$\mathcal{O}^8_{Qt} = \left(\bar{Q}_L \gamma^\mu T^A Q_L\right)\left(\bar{t}_R \gamma_\mu T^A t_R\right),$$

Operator	Expected C_k/Λ^2 (TeV $^{-2}$)	Observed (TeV $^{-2}$)
$\mathcal{O}^1_{tt}$	[−1.5, 1.4]	[−2.2, 2.1]
$\mathcal{O}^1_{QQ}$	[−1.5, 1.4]	[−2.2, 2.0]
$\mathcal{O}^1_{Qt}$	[−2.5, 2.4]	[−3.7, 3.5]
$\mathcal{O}^8_{Qt}$	[−5.7, 4.5]	[−8.0, 6.8]

Top Chromo-magnetic Dipole Moment

- Anomalous Chromo-Magnetic Dipole Moment (CMDM) of the top quark corresponds to the $\mathcal{O}_{tG}$ operator in EFT
- Top pair Spin Density matrix measurement using the dilepton events
- Simultaneous fit using 20 parton-level differential distributions sensitive to tt spin correlation and top polarization:
  - $-0.07 < C_{tG}/\Lambda^2 < 0.16$ at 95% CL
- Previous constraints on C_{tG}/Λ^2 using the $d\sigma/d\Delta\phi(l,l)$ JHEP 02, 149 (2019)
  - $-0.06 < C_{tG}/\Lambda^2 < 0.41$ at 95% CL

CMS-PAS-TOP-18-006



Summary & Conclusions

- ✧ With the 2016 and 2017 datasets both ATLAS and CMS have completed some of the key analyses related to Top quarks
- ✧ No clear evidence for the New Physics contribution into the Top physics is observed yet
- ✧ Many top quark results (FCNC, differential cross-section, 4 top) have been interpreted using Effective Field Theory approach using relevant dimension-6 operators (recommended by the LHCTopWG)
  - ✧ For quite a few sensitive channels, Top quark related Wilson Coefficients are best constrained
- ✧ Many more Top EFT interpretation to follow using Run 2 measurements
  - ✧ Further exploration of different approaches considering consistent treatment of different top production processes

References

- ✧ LHCTopWG: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWG
- ✧ ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
- ✧ CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP