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Search for new physics via top quark production in dilepton final states at $\sqrt{s}$ = 13 TeV

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Outline

- Introduction
- Dataset & samples
- Triggers & event selection
- Background study
- Signal extraction
- Systematic uncertainties
- Exclusion limits
- Summary

Introduction

- Top quark is the heaviest Standard Model (SM) particle, close to the electroweak symmetry breaking scale, the top quark is expected to play an important role in several new physics scenarios.

- If new physics is too heavy to appear directly in the available energy, it could affect SM interactions indirectly, through modifications of SM couplings or enhancements of rare SM processes.

- In this way, the effective Lagrangian is

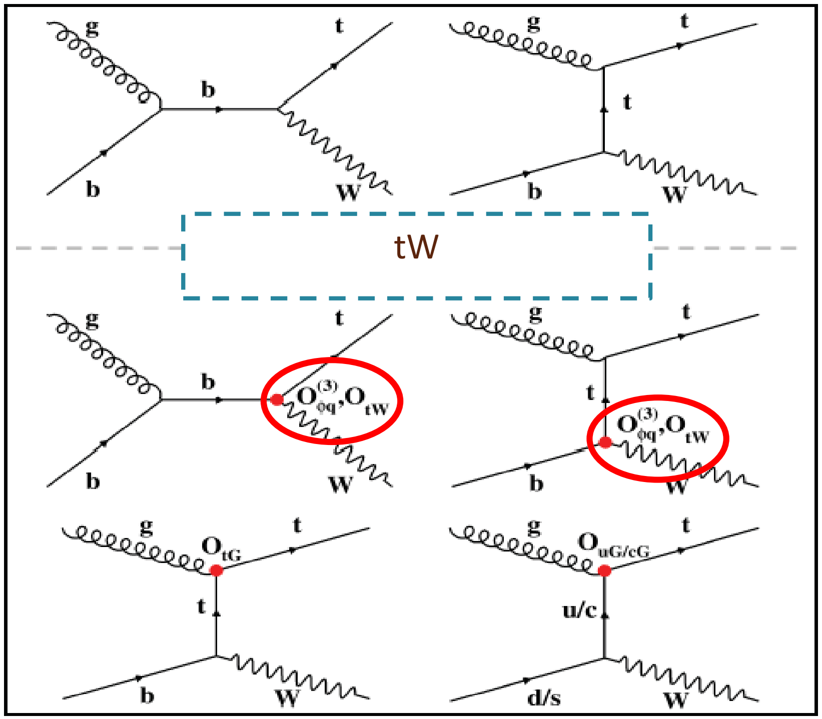
  (Λ represents the energy scale beyond which new physics becomes relevant):

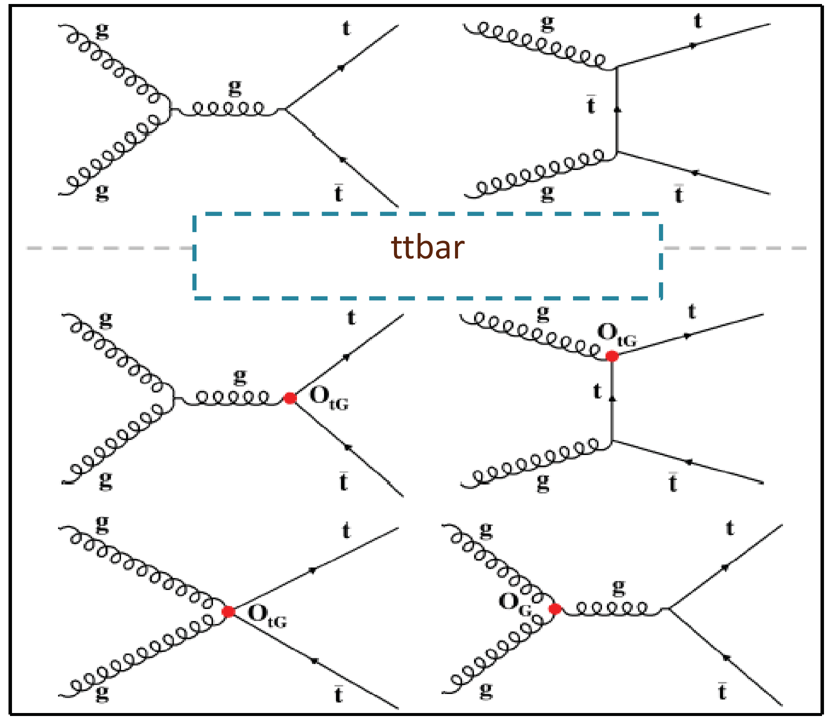
$$L_{eff} = L_0 + \frac{1}{\Lambda} L_1 + \frac{1}{\Lambda^2} L_2 + \cdots$$

- It is useful to introduce a model independent approach to parametrize and to constrain possible deviations from SM predictions, independently of the fundamental theory of new physics.

Introduction

- An effective field theory (EFT) approach is followed to **search for new physics in the top quark sector in the dilepton final states**.





The operators $O^{(3)}_{\phi q}$ and O_{tW} modify the SM interaction between W boson, top and b quark (Wtb), its effect can be probed in both top quark decays and single top quark production.

Phys. Rev. D 83 (2011) 034006

Phys. Rev. D 91 (2015) 074017

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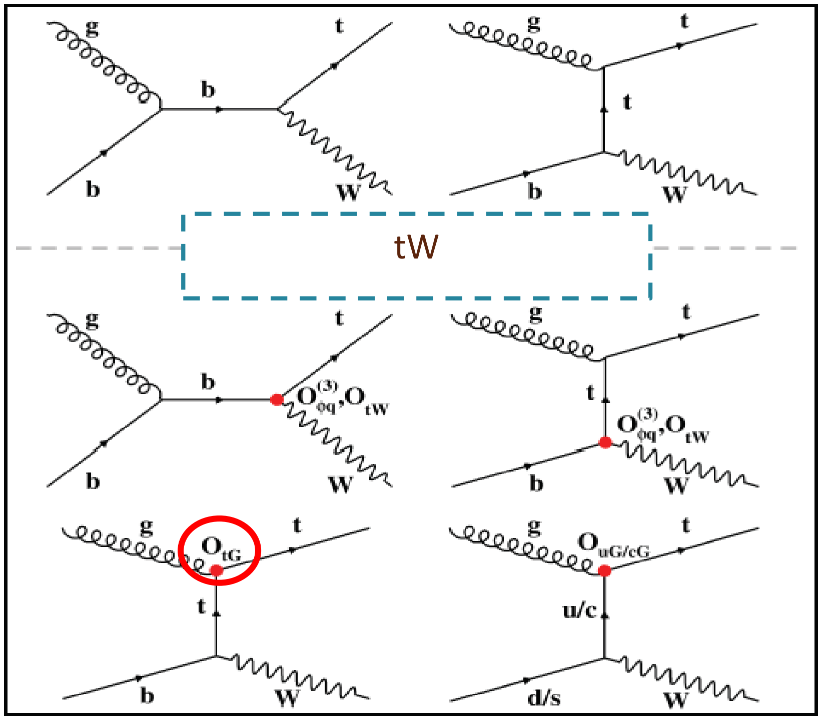

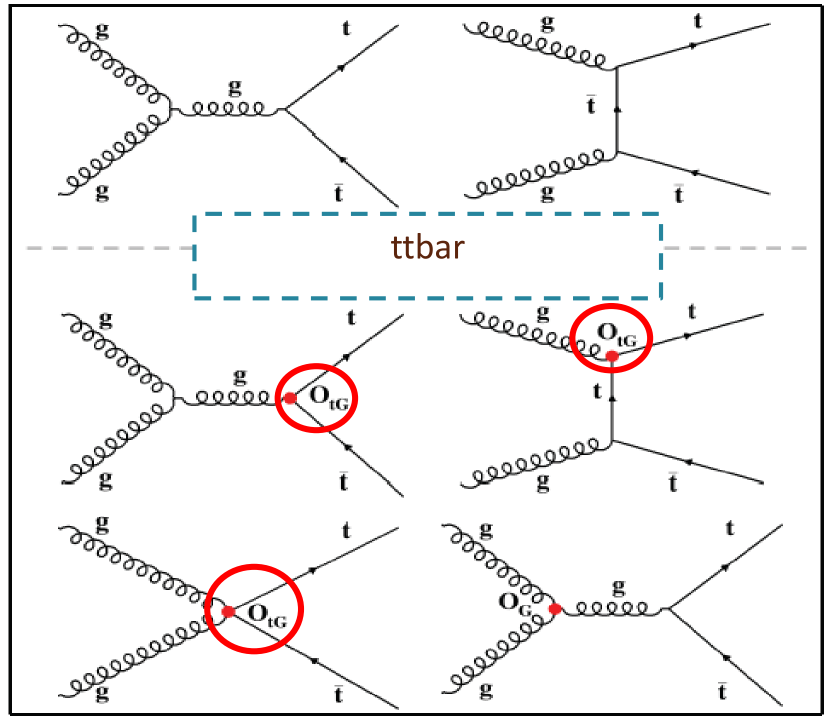

The operator O_{tG}, called as the chromomagnetic dipole moment operator of the top quark, can be investigated in both tW and top quark pair production.

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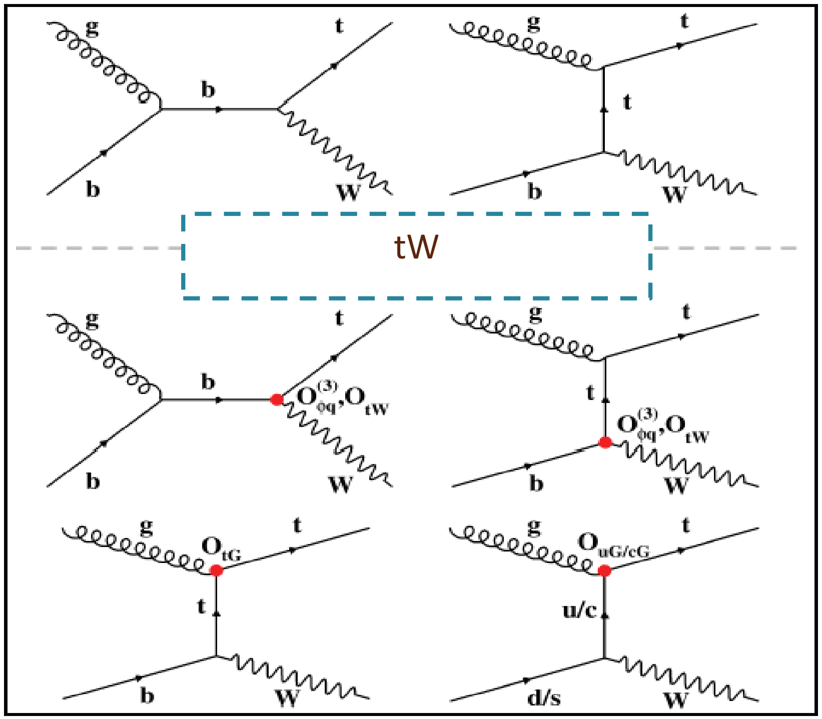

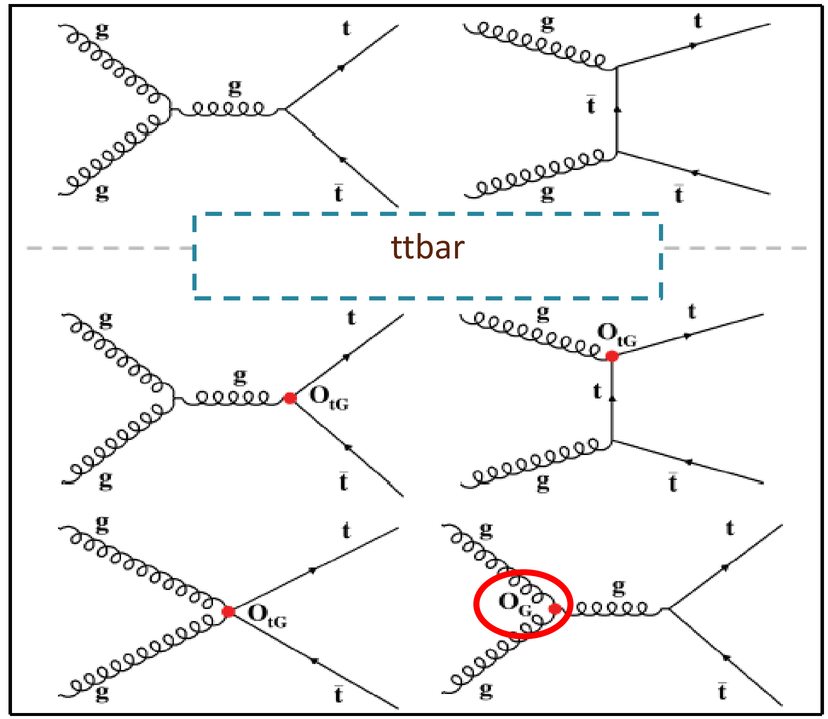

The triple gluon field strength operator O_G represents the only genuinely gluonic CP conserving term which can appear at dimension 6 within an effective strong interaction Lagrangian

Phys. Rev. D 51 (1995) 2360

Introduction

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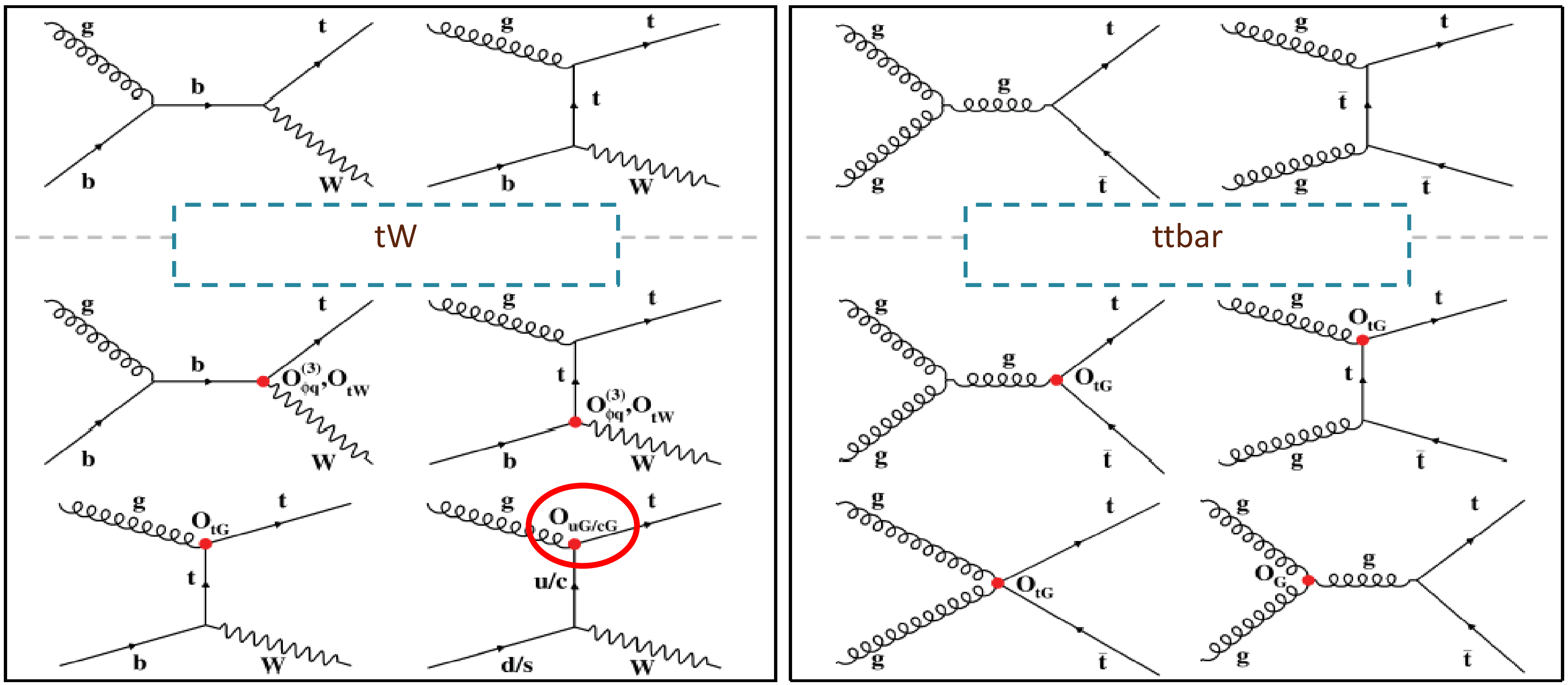

The operators O_{cG} and O_{uG} lead to flavor changing neutral current (FCNC) interactions of top quark and contribute to the tW production.

Introduction

- The dimension-six operators and the related effective Lagrangians relevant for dilepton final states, can be written as:

  (where $C_{\phi q}^{(3)}$, C_{tW}, C_{tG} , C_G and $C_{c(u)G}$ stand for the dimensionless Wilson coefficients, also called effective couplings.)

$$
\begin{aligned}
O_{\phi q}^{(3)} &= (\phi^+ \tau^I D_\mu \phi)(\bar{q}\gamma^\mu \tau^I q), & L_{eff} &= \frac{C_{\phi q}^{(3)}}{\sqrt{2}\Lambda^2} g v^2 \bar{b}\gamma^\mu P_L t W_\mu^- + h.c.,\\
O_{tW} &= (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\phi} W_{\mu\nu}^I, & L_{eff} &= -2\frac{C_{tW}}{\Lambda^2} v \bar{b}\sigma^{\mu\nu} P_R t \partial_\nu W_\mu^- + h.c.,\\
O_{tG} &= (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G_{\mu\nu}^A, & L_{eff} &= \frac{C_{tG}}{\sqrt{2}\Lambda^2} v \left(\bar{t}\sigma^{\mu\nu}\lambda^A t\right) G_{\mu\nu}^A + h.c.,\\
O_G &= f_{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}, & L_{eff} &= \frac{C_G}{\Lambda^2} f_{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu} + h.c.,\\
O_{u(c)G} &= (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi} G_{\mu\nu}^A, & L_{eff} &= \frac{C_{u(c)G}}{\sqrt{2}\Lambda^2} v \left(\bar{u}\,(\bar{c})\,\sigma^{\mu\nu}\lambda^A t\right) G_{\mu\nu}^A + h.c.,
\end{aligned}
$$

Phys. Rev. D 83 (2011) 034006

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- When EFT couplings are non-zero, $t\bar{t}$ or tW cross section contains

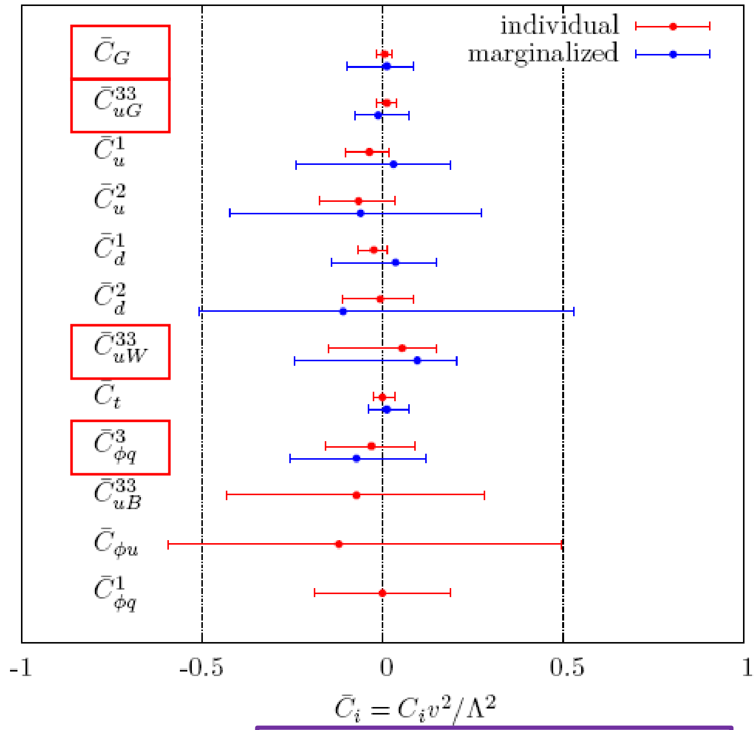
$$\sigma = \sigma_{SM} + C_i \sigma_i^{(1)} + C_i^2 \sigma_i^{(2)}$$

SM term | Interference term | Pure new physics term

- The search is sensitive to new physics contributions to the $t\bar{t}$ and tW production, and the six effective couplings, $C_{\phi q}^{(3)}$, C_{tW}, C_{tG} , C_G and $C_{c(u)G}$ are constrained independently.

Introduction

- Several searches for new physics in the top quark sector including new non-SM couplings have been performed at the Tevatron and LHC colliders.
- A variety of limits have been set on the Wtb anomalous coupling, the top chromomagnetic dipole moment, and top quark FCNC by the D0, ATLAS and CMS Collaborations.
- A global fit [JHEP 04 (2016) 015] of top quark effective field theory is performed to experimental data and constrains are set.



	CMS	ATLAS	Phenomenological
$C_{\phi q}^{(3)}$	-	-	[-2.512, 1.456]
C_{tW}	-	-	[-2.416, 2.416]
C_{tG}	-	-	[-0.288, 0.624]
C_G	-	-	[-0.288, 0.432]
$B(t \to cg)$	$< 2.0 * 10^{-5}$	$< 4.0 * 10^{-5}$	-
$B(t \to ug)$	$< 4.1 * 10^{-4}$	$< 2.0 * 10^{-4}$	-

Phys. Lett. B 713 (2012) 165
JHEP 04 (2017) 124
Eur. Phys. J. C 77 (2017) 264
JHEP 02 (2017) 028
JHEP 01 (2015) 053
Phys. Rev. D 93 (2016) 052007
Phys. Lett. B 693 (2010) 81
Phys. Rev. Lett 102 (2009) 151801
Eur. Phys. J. C 76 (2016) 55

Dataset & samples

Data

- 35.9 fb^{-1} integrated luminosity data collected at 2016 by CMS.

Simulated signal events (MC)

- Signal events are simulated using MADGRAPH5@NLO event generator at the leading order (LO).
- Cross sections for $t\bar{t}$ and tW production [in pb] for the various effective couplings for $\Lambda = 1$ TeV are shown:

$$\sigma = \sigma_{SM} + C_i \sigma_i^{(1)} + C_i^2 \sigma_i^{(2)}$$

Channel	Variable	C_G	$C_{\phi q}^{(3)}$	C_{tW}	C_{tG}	C_{uG}	C_{cG}
$t\bar{t}$	$\sigma_i^{(1)-LO}$	31.9	-	-	137	-	-
	$\sigma_i^{(1)-NLO}/\sigma_i^{(1)-LO}$	-	-	-	1.48 [19]	-	-
	$\sigma_i^{(2)-LO}$	102.3	-	-	16.4	-	-
	$\sigma_i^{(2)-NLO}/\sigma_i^{(2)-LO}$	-	-	-	1.44 [19]	-	-
tW	$\sigma_i^{(1)-LO}$	-	6.7	-4.5	3.3	0	0
	$\sigma_i^{(1)-NLO}/\sigma_i^{(1)-LO}$	-	1.32 [20]	1.27 [20]	1.27 [20]	0	0
	$\sigma_i^{(2)-LO}$	-	0.2	1	1.2	16.2	4.6
	$\sigma_i^{(2)-NLO}/\sigma_i^{(2)-LO}$	-	1.31	1.18	1.06	1.27	1.27

Triggers & event selection

- The triggers:

Use a combination of dilepton and single lepton triggers.

The dilepton triggers select events with at least two leptons with loose isolation requirements and pT threshold are shown:

Channel	pT threshold Electron (GeV)	pT threshold Muon (GeV)
ee	23 (12)	-
$\mu\mu$	-	17 (8)
$e\mu$	23 (13)	8 (22)

Single lepton triggers require at least one isolated muon (electron) with pT > 24 (27) GeV.

Electron
- pT > 20 GeV
- $|\eta| < 2.4$

Muon
- pT > 20 GeV
- $|\eta| < 2.4$

Jet/bjets
- pT > 30 GeV
- $|\eta| < 2.4$
- $\triangle R(\text{jet, lepton}) > 0.4$

Analysis cut
- At least 1 pair of leptons
- pT of leading lepton > 25 GeV
- Opposite sign charge
- MET > 60 GeV
- Out of Z mass windows [76, 106] GeV.

- All official correction are applied on MC to match data.
- Events are categorized to ee, $\mu\mu$ and $e\mu$ channels.
- Events are further categorized to [n-jet, m-btag-jet] regions.

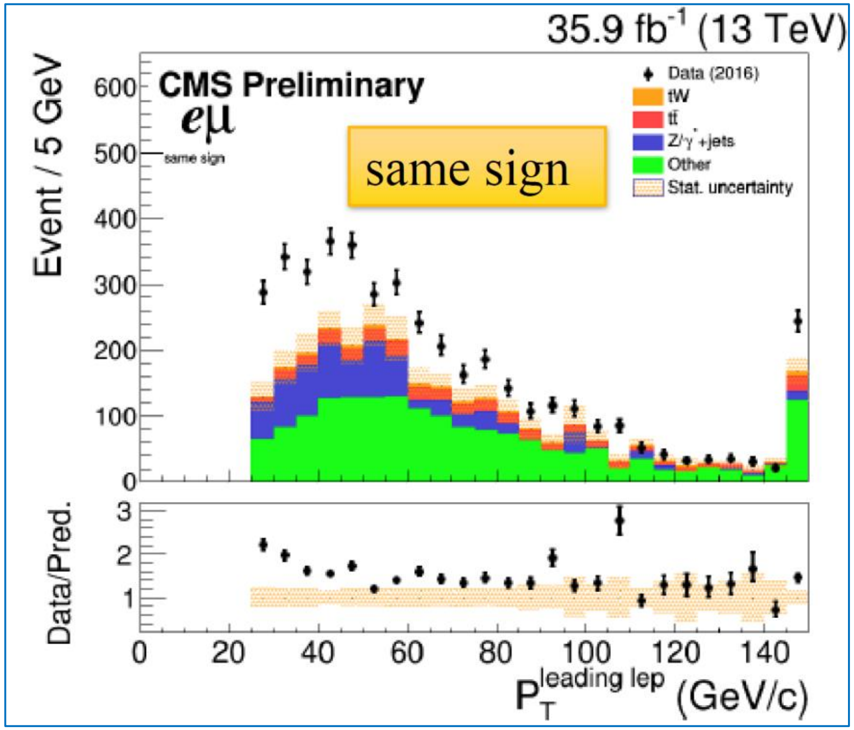
Background study

■ The contributions of SM processes leading to two prompt leptons in the final state are estimated from simulated samples and are normalized to the data luminosity.

■ These contributions originate mainly from $t\bar{t}$, tW and DY production. Other SM processes, such as diboson, $t\bar{t}$+V and $t\bar{t}$+g have significantly smaller contributions.

For the jet fake lepton backgrounds which include W+jet and QCD process are estimated by data-driven technique called **same sign** method

- ☐ We use the fact that the probability of assigning positive or negative charge to the misidentified jet should be equal.
- ☐ The contributions of all other backgrounds are subtracted from data in same sign region using MC samples to find jet contribution.



Signal extraction

■ In order to investigate the effect of the introduction of the new effective couplings, it is important to find suitable variables with high discrimination power between the signal and the background.

■ Depending on the couplings, the total rate (yield) or the distribution of the output of a neural network algorithm (NN) is employed. The NN algorithm used in this analysis is a multilayer perceptron.

$O_{\phi q}^{(3)}, O_{tW}, O_{tG}$	Using Multi Layer Perceptron (MLP) to split SM tW(as signal) and SM $t\bar{t}$ (as background)
O_{cG}, O_{uG}	Using MLP to split FCNC tW (signal) and SM tW+ $t\bar{t}$ (background)
O_G	No shape analysis →no MVA

Signal extraction

The introduction of the O_G operator affects only the $t\bar{t}$ production, we use the total number of events (yield) in various (n-jets, m-tags) categories to constrain the C_G effective coupling.

In order to observe deviations from SM tW production in the presence of the where $O_{\phi q}^{(3)}$, O_{tW}, and O_{tG} effective operators, we need to separate tW events from the large number of tt events.

For these FCNC operators, new physics effects on final-state particle distributions are expected to be distinguishable from SM processes. NN (NN_{FCNC}) is used to separate the SM backgrounds ($t\bar{t}$ and tW events together) and the new physics signals for events with exactly one b-tag jet with no requirement on the number of light jets (n-jets,1-tag).

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

Systematic uncertainties

The normalization and shape of the signal and the backgrounds are both affected by different sources of systematic uncertainty. For each source, an induced variation can be parametrized, and treated as a nuisance parameter in the fit.

Experimental uncertainties

- Luminosity: 2.5%
- Pile-up reweighting: minimum bias xsis varied by 4.6%
- Lepton reconstruction, identification and isolation and Trigger scale factors
- Jet energy scale and resolution
- Un-clustered energy
- b-tagging/mis-tagging

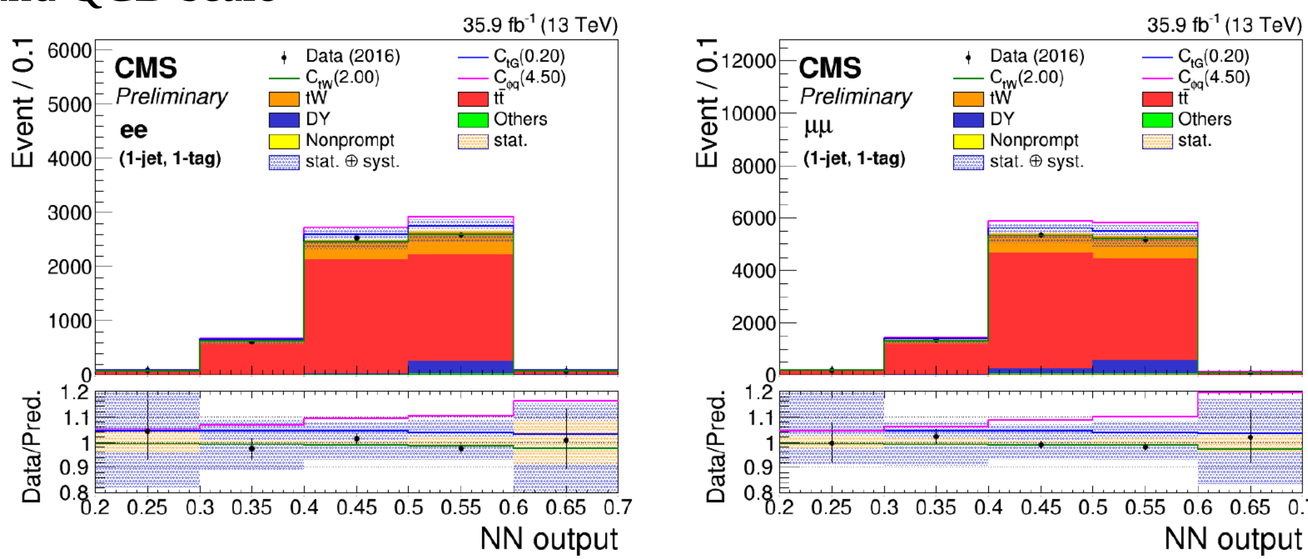
$t\bar{t}$ and tW modeling uncertainty

- Renormalization/factorization scale (QCD scale)
- Parton Distribution Functions (PDF) (only $t\bar{t}$)
- Top mass
- tW/$t\bar{t}$ interference (DS/DR)
- ME/PS matching (hdamp variation-only $t\bar{t}$)
- Scale variations of initial state radiation and final state radiation (ISR/FSR)
- Color reconnection (only $t\bar{t}$)
- Underlying event (only $t\bar{t}$)

Systematic uncertainties

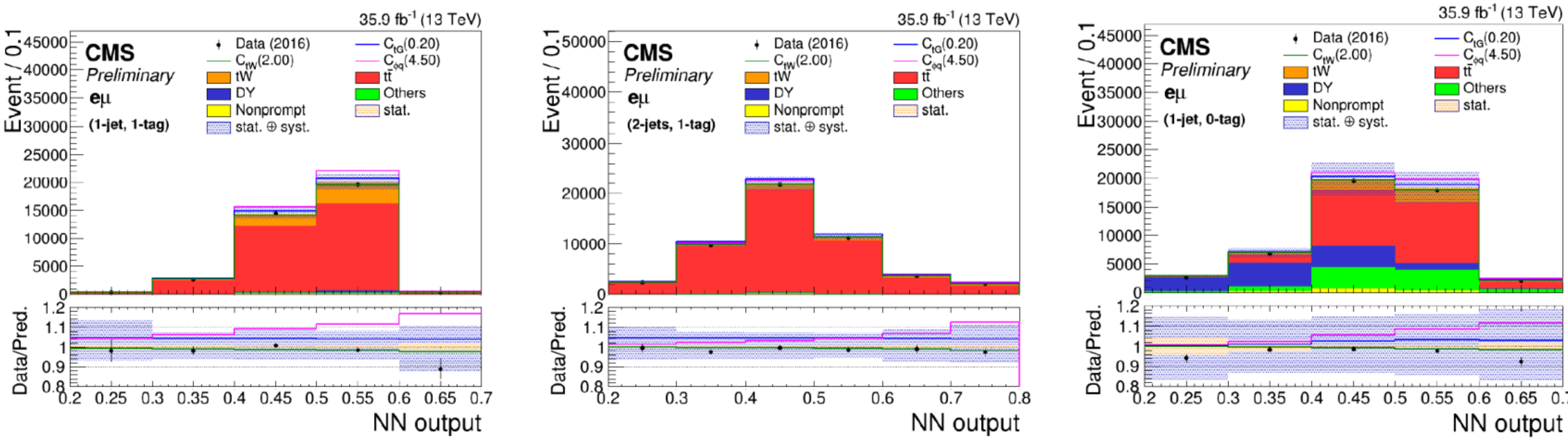
- $t\bar{t}$ normalization: 5% for $O_{\phi q}^{(3)}$, O_{tW}, O_{tG} and FCNC ($O_{c(u)G}$)
- tW normalization: 10% for O_G, and FCNC ($O_{c(u)G}$)
- DY modeling uncertainty: PDF and QCD scale (only consider for eμ channel in 1jet-0tag region)
- DY normalization error:
  - ee and μμ channels: 30%
  - eμ channel: 1jet, 0tag region is 15%, for other regions is 50%
- Prompt background (except $t\bar{t}$, tW, DY) normalization: 50%
- Non-prompt background (from same sign) normalization: 50%
- tW FCNC: PDF and QCD scale

$O_{\phi q}^{(3)}$, O_{tW}, and O_{tG}



The NN output distributions for data and MC in different categories used in the limit setting.

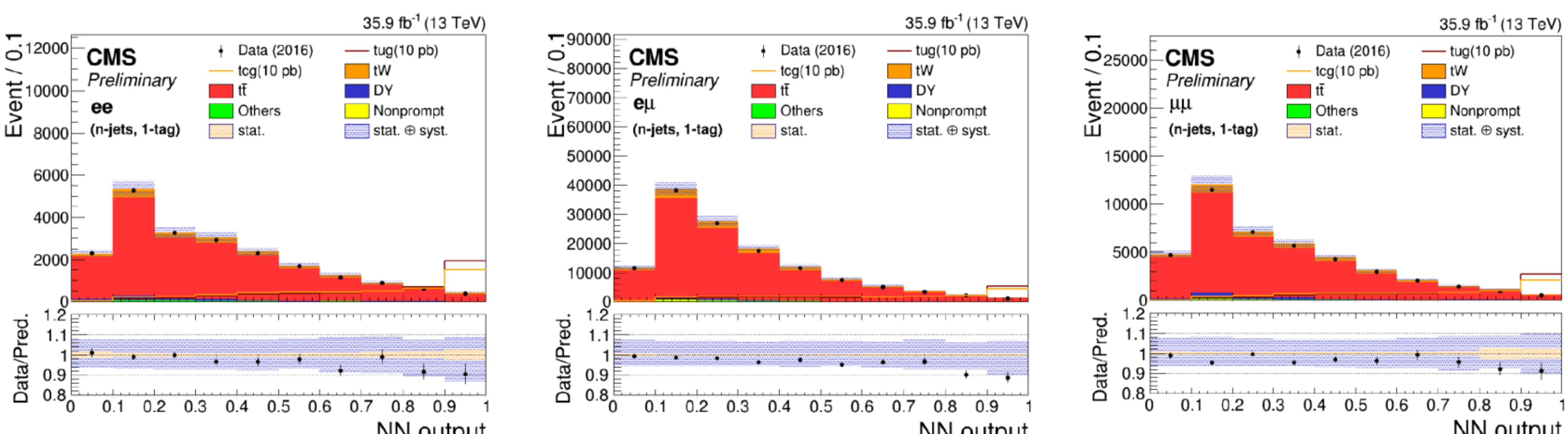
Systematic uncertainties



$C_{\phi q}^{(3)}$, C_{tW}, and C_{tG}

The NN output distributions for data and MC in different categories used in the limit setting.

C_{cg} and C_{uG}

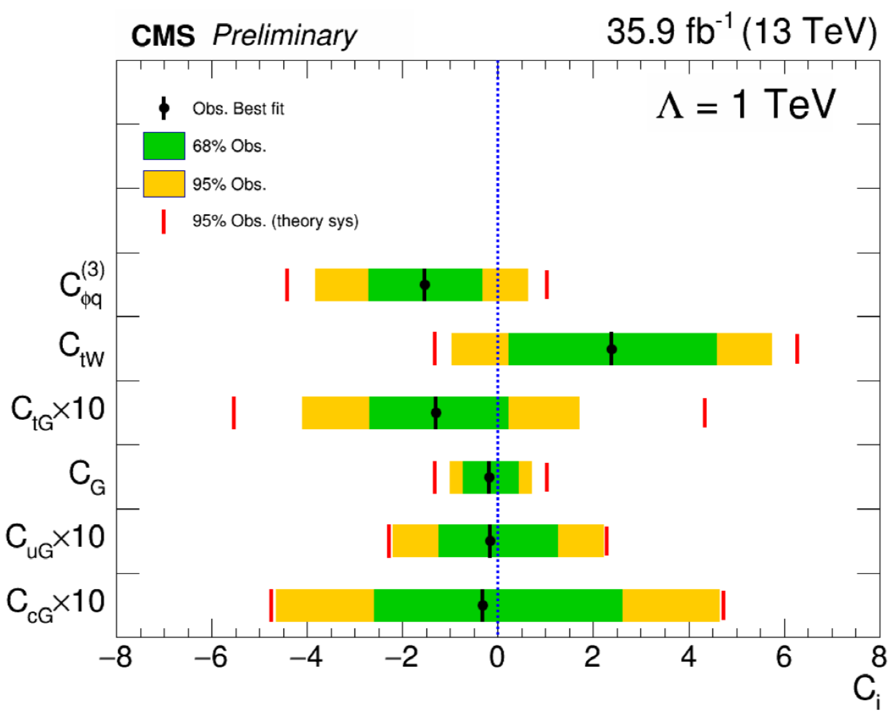


Limit

	Our results	CMS	ATLAS	Phenomenological
$C_{\phi q}^{(3)}$	[-3.97, 0.55]	-	-	[-2.512, 1.456]
C_{tW}	[-0.92, 5.71]	-	-	[-2.416, 2.416]
C_{tG}	[-0.30, 0.26]	-	-	[-0.288, 0.624]
C_{G}	[-0.96, 0.65]	-	-	[-0.288, 0.432]
$B(t \to cg)$	$< 5.7 * 10^{-4}$	$< 2.0 * 10^{-5}$	$< 4.0 * 10^{-5}$	-
$B(t \to ug)$	$< 2.4 * 10^{-3}$	$< 4.1 * 10^{-4}$	$< 2.0 * 10^{-4}$	-

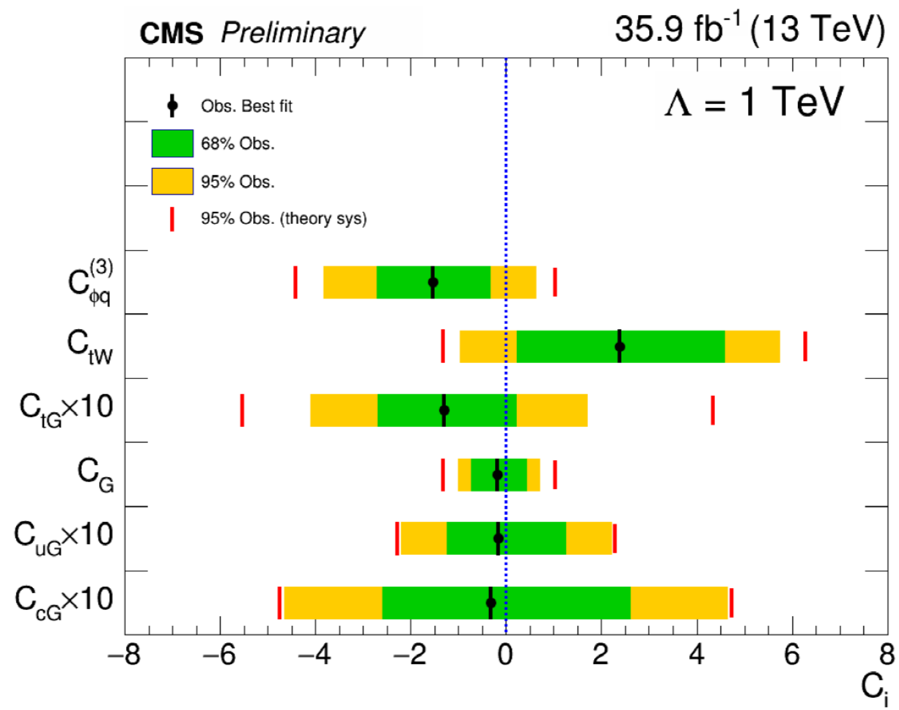
Observed best fit together with one and two standard deviation bounds on the top quark effective couplings.

The blue dashed line shows the SM expectation and the red vertical lines indicate the 95% CL bounds including the theoretical uncertainties.



Summary

- A search for new physics in top quark interactions in dilepton final states has been performed.
- The first search for new physics that uses the tW process.
- EFT is used for new physics parameterization.
- All 2016 data is analyzed (35.9 fb^{-1}).



- The results are interpreted to constrain the relevant effective couplings using a dedicated multivariate analysis.

Thank you !

Back up

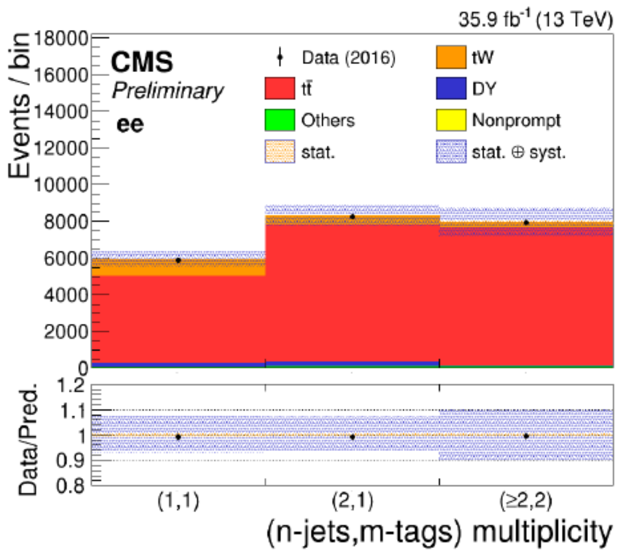
Analysis Note : AN-20-006

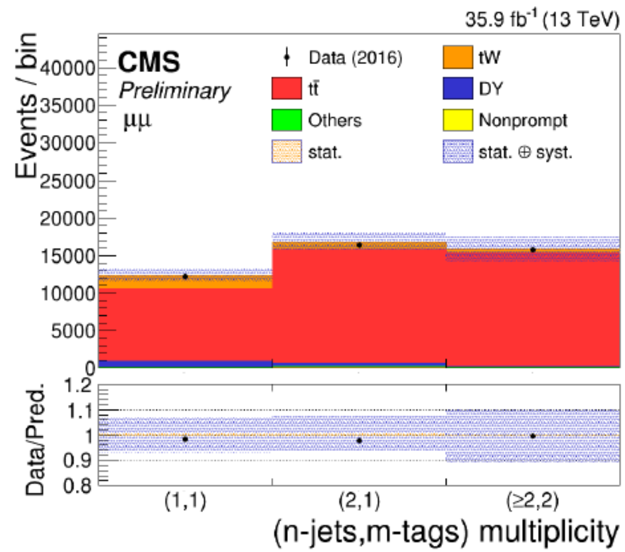
Number of events Data/prediction

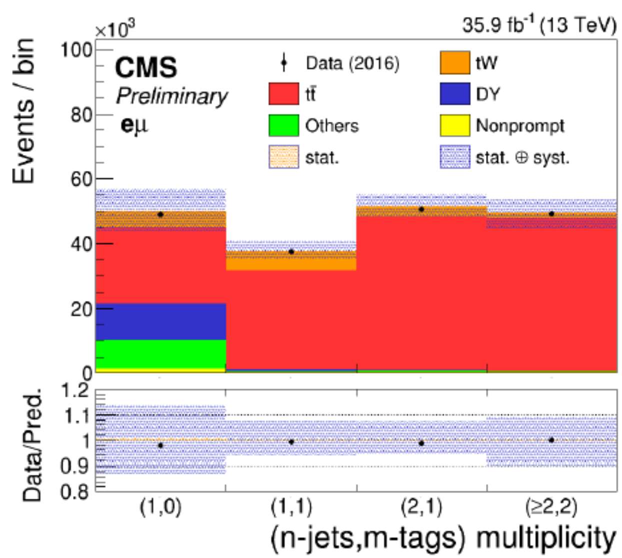
Table 2: Numbers of expected events from tW, $t\bar{t}$ and DY production, from the remaining backgrounds (other and nonprompt backgrounds), total background contribution and observed events in data after all selections for the ee, eμ and $\mu\mu$ channels and for various (n-jets,m-tags) categories. The uncertainties correspond to the statistical contribution only for the individual background predictions and to the quadratic sum of the statistical and systematic contributions for the total background predictions.

Channel	(n-jets,m-tags)	Prediction					Data
		tW	$t\bar{t}$	DY	Other + nonprompt	Total predicted yield	
ee	(1,1)	884±8	4741±15	258±50	53±5	5936±470	5902±76
	(2,1)	518±6	7479±19	241±53	94±5	8331±597	8266±90
	(≥2,2)	267±4	7561±18	46±24	99±4	7973±819	7945±89
eμ	(1,0)	4835±20	23557±35	11352±277	10294±72	50038±6931	48973±221
	(1,1)	6048±22	30436±38	561±66	629±13	37673±2984	37370±193
	(2,1)	3117±16	47206±48	278±48	781±9	51382±3714	50725±225
	(≥2,2)	1450±10	47310±46	32±22	598±9	49391±5010	49262±221
$\mu\mu$	(1,1)	1738±12	9700±21	744±90	183±5	12366±879	12178±110
	(2,1)	989±9	14987±27	501±75	275±5	16751±1276	16395±128
	(≥2,2)	508±6	15136±26	82±24	163±5	15889±1714	15838±125

N-jets, m-btag-jets







Input of TMVA (MLP method)

Variable	Description	NN_{10}	NN_{11}	NN_{21}	NN_{FCNC}
M_{ll}	Invariant mass of dilepton system	√			√
$p_T^{\ell\ell}$	p_T of dilepton system	√		√	√
$\Delta p_T(\ell,\ell)$	$p_T^{\text{leading lepton}}$ - $p_T^{\text{sub-leading lepton}}$	√			√
$p_T^{\text{leading lepton}}$	p_T of leading lepton	√		√	√
Centrality(ℓ^{leading},jet$^{\text{leading}}$)	Scalar sum of p_T of the leading lepton and leading jet, over total energy of selected objects	√			√
Centrality(ℓ, ℓ)	Scalar sum of p_T of the leading and sub-leading leptons, over total energy of selected objects	√			√
$\Delta\phi(\ell\ell$,jet$^{\text{leading}})$	$\Delta\phi$ between dilepton system and leading jet	√	√	√	
$p_T(\ell\ell$,jet$^{\text{leading}})$	p_T of dilepton and leading jet system		√		√
$p_T(\ell^{\text{leading}}$,jet$^{\text{leading}})$	p_T of leading lepton and leading jet system		√		
Centrality($\ell\ell$,jet$^{\text{leading}}$)	Scalar sum of p_T of the dilepton system and leading jet, over total energy of selected objects		√		
$\Delta R(\ell,\ell)$	ΔR between leading and sub-leading leptons		√		
$\Delta R(\ell^{\text{leading}}$,jet$^{\text{leading}})$	ΔR between leading lepton and leading jet		√		
$M(\ell^{\text{leading}}$,jet$^{\text{leading}})$	Invariant mass of leading lepton and leading jet			√	
M(jet$^{\text{leading}}$,jet$^{\text{sub-leading}}$)	Invariant mass of leading jet and sub-leading jet			√	
$\Delta R(\ell^{\text{leading}}$,jet$^{\text{sub-leading}})$	ΔR between leading lepton and sub-leading jet			√	
$\Delta R(\ell\ell$,jet$^{\text{leading}})$	ΔR between dilepton system and leading jet			√	√
$\Delta p_T(\ell^{\text{sub-leading}}$, jet$^{\text{sub-leading}})$	$p_T^{\text{sub-leading lepton}}$ - $p_T^{\text{sub-leading jet}}$			√	
$M(\ell^{\text{sub-leading}}$, jet$^{\text{leading}})$	Invariant mass of sub-leading lepton and leading jet				√

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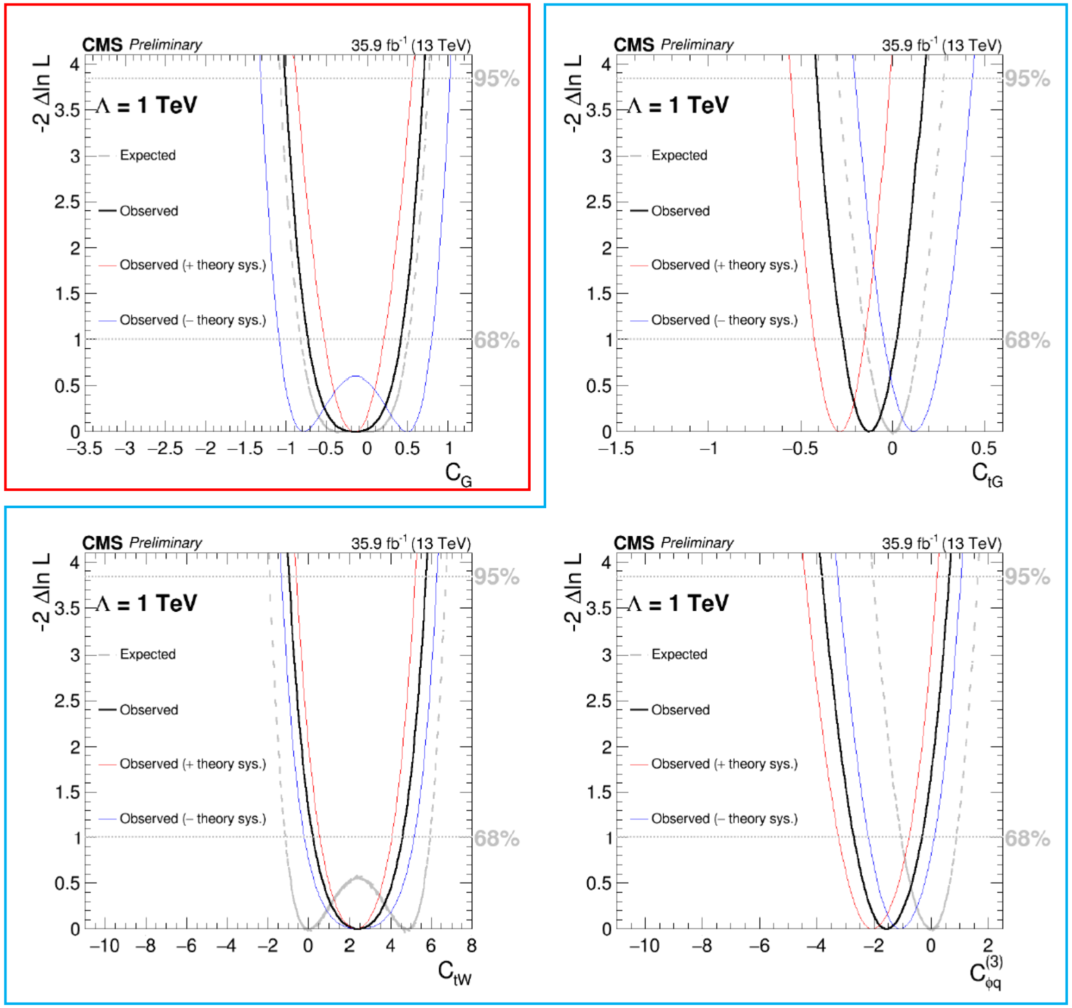
Limit (C_G, $C_{\phi q}^{(3)}$, C_{tW} and C_{tG})

For $\mathbf{C_G}$, the fit is performed simultaneously on the observed event yield in (1-jet,1-tag), (2-jets,1-tag) and (≥2-jets,2-tags) categories for ee, eμ and μμ channels. In addition, the (1-jet,0-tag) category is included only for the eμ channel.

In order to set limits on the effective couplings $\mathbf{C_{\phi q}^{(3)}}$, $\mathbf{C_{tW}}$ **and** $\mathbf{C_{tG}}$, we utilize the NN output distributions for both data and MC expectation in the (1-jet,1-tag) and (2-jets,1-tag) regions and event yields in the (2-jets,2-tags) region for the three dilepton channels.



Limit

Since the tW production via **FCNC** interactions does not interfere with the SM tW process (with the assumption of |Vtd| = |Vts| = 0), FCNC signal template is considered to set upper bound on the related Wilson coefficients.