Top EFT at CMS

Jon S. Wilson on behalf of the CMS Collaboration

Baylor University

Large Hadron Collider Physics Conference
17 May 2022

- Effective Field Theory (EFT) is a model-independent approach to physics beyond the standard model
- Assume that new physics exists at some scale Λ beyond the current reach of experiments
- Enumerate all renormalizable terms in the Lagrangian, ordered by their mass dimension
- Multiply terms up to some maximum mass dimension by vector of Wilson coefficients
- SM corresponds to all coefficients at zero
- Analyses measure coefficients

The EFT Langrangian

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_{d=4}^{\infty} \sum_{i} \frac{1}{\Lambda^{d-4}} c_i^{(d)} \mathcal{O}_i^{(d)}$$

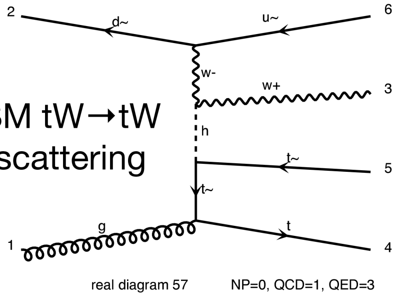
where d is the mass dimension, $c_i^{(d)}$ is a Wilson coefficient, and $\mathcal{O}_i^{(d)}$ is a renormalizable operator

Historical / other EFTs include

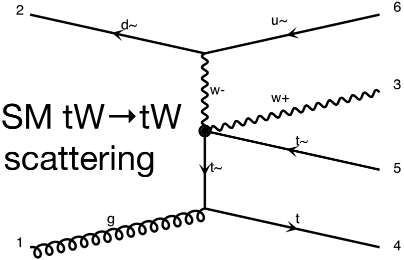
- Fermi's theory of beta decay
- BCS theory of superconductivity
- many others, especially in condensed matter physics

- The EFT most useful for top quark physics at CMS is the standard model EFT, or SMEFT
- Usually look at dimension-6 operators
  - The SM already contains dimension-2 and -4 operators
  - Only one dimension-5 operator exists, which provides neutrino mixing
  - The fun stuff starts at dimension-6
- Need a useful basis for the vector space of dim-6 Wilson coefficients
- Most commonly used is "Warsaw basis" [JHEP 10 (2010) 085]
- 63 total operators, of which 4 produce baryon-number violation
- Implemented for MC as "dim6top" [https://feynrules.irmp.ucl.ac.be/wiki/dim6top]
- Other bases sometimes used when more convenient for specific analyses

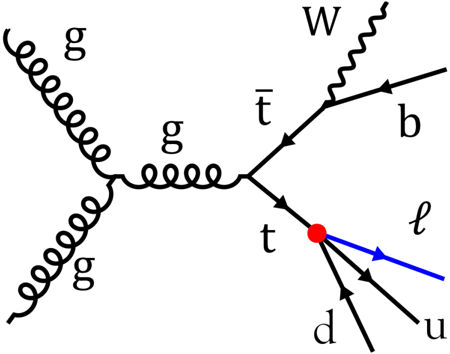
SM tW→tW scattering

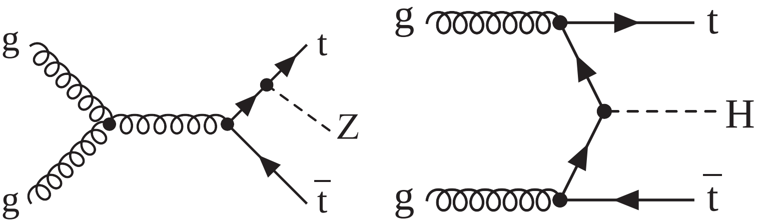


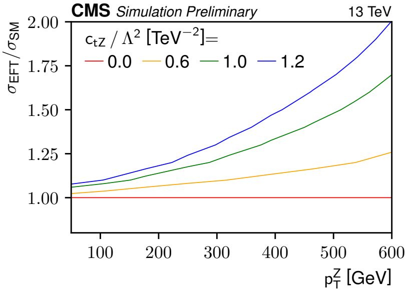
BSM tW→tW scattering

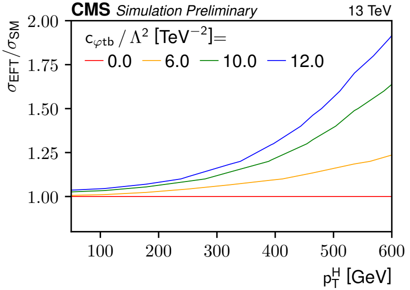


- Operators may alter rates/spectra for SM processes directly or via interference (diagrams on left)
- Or allow SM-forbidden processes (below)
- Make precision top measurements and perform searches involving top to constrain top-related Wilson coefficients



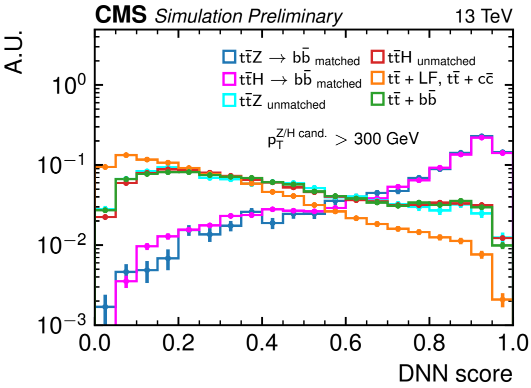




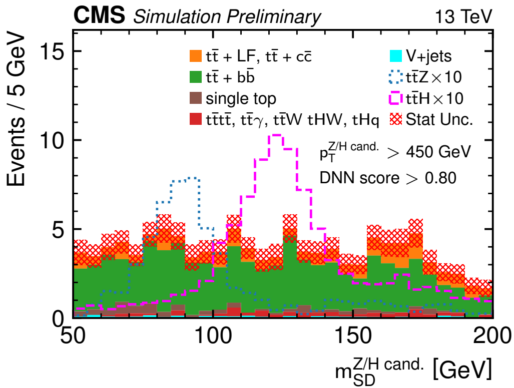


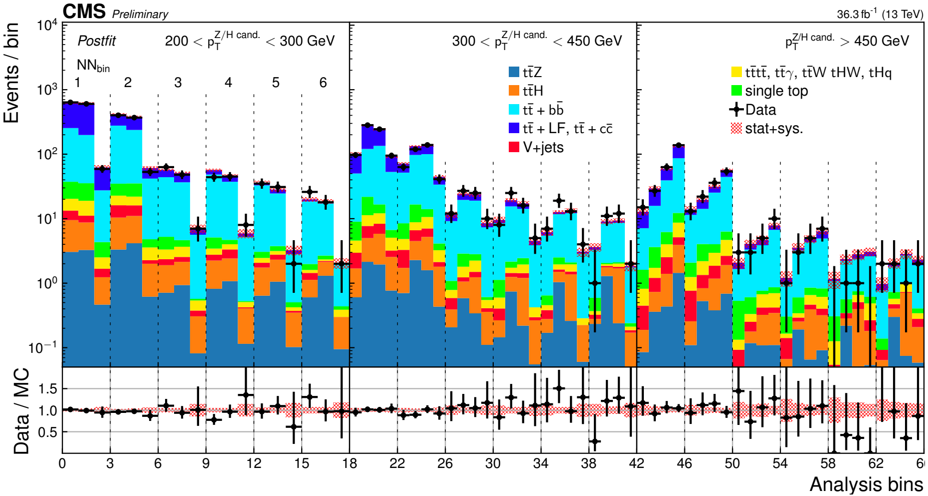
- Measure $t\bar{t}Z/t\bar{t}H$ when $p_T(Z/H)$ is large
- EFT effects more pronounced at high $p_T(Z/H)$
- Select events with one charged lepton, missing p_T, and jets
- Reconstruct Z/H as single $b\bar{b}$-tagged large-radius jet
- Most important background is $t\bar{t}+b\bar{b}$
- Measure 8 WCs: $c_{t\varphi}$, $c^{-}_{\varphi Q}$, $c^{3}_{\varphi Q}$, $c_{\varphi t}$, $c_{\varphi tb}$, c_{tW}, c_{bW}, c_{tZ}

- NN trained to distinguish $t\bar{t}Z/H$ from backgrounds



- Divide events among bins as functions of NN score, Z/H jet mass, and $p_T(Z/H)$
  - $p_T(Z/H)$ provides EFT sensitivity
  - NN score provides a high-purity region
  - Z/H jet mass provides sidebands to help control backgrounds

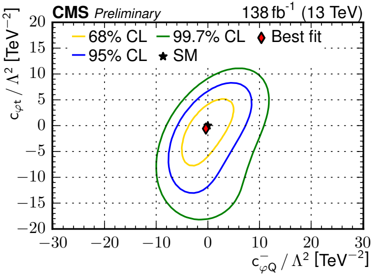


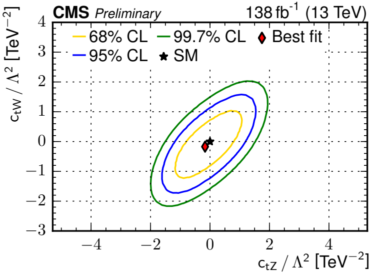


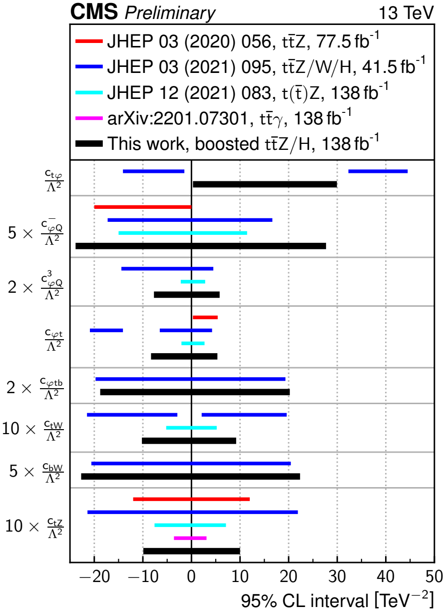
- 2016 data
- 3 large groups $p_T(Z/H)$ bins
- 6 medium subgroups are NN bins
- Individual bins are Z/H jet mass bins
- Use this, plus 2017/18, to constrain WCs

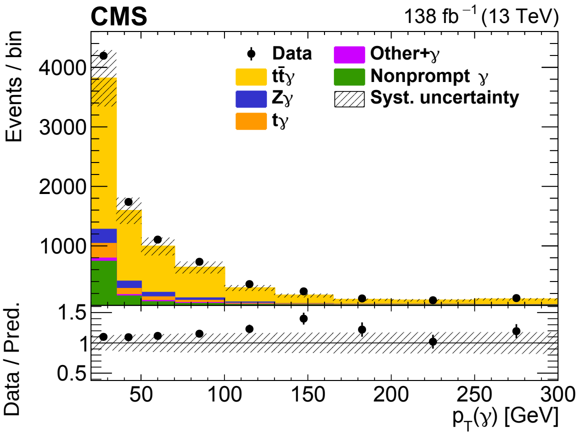
- Showing 2016 as example; fit to three years simultaneously

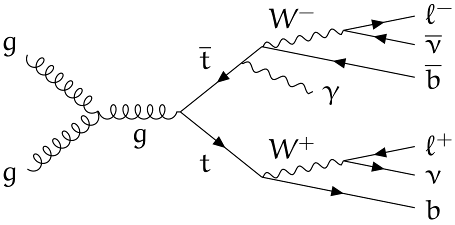
- Vary the $t\bar{t}Z/H$ signal and $t\bar{t} + b\bar{b}$ background as functions of the WCs
- Perform 1-D and 2-D likelihood scans for each WC and pair of WCs
- Consistent with SM (all WCs zero) at 95% CL
- Novel phase space with highly-boosted Z/H
- Complementary to other analyses
- Comparable sensitivity





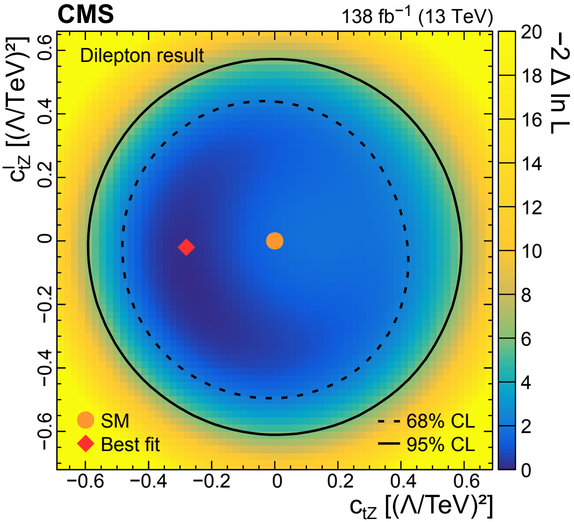




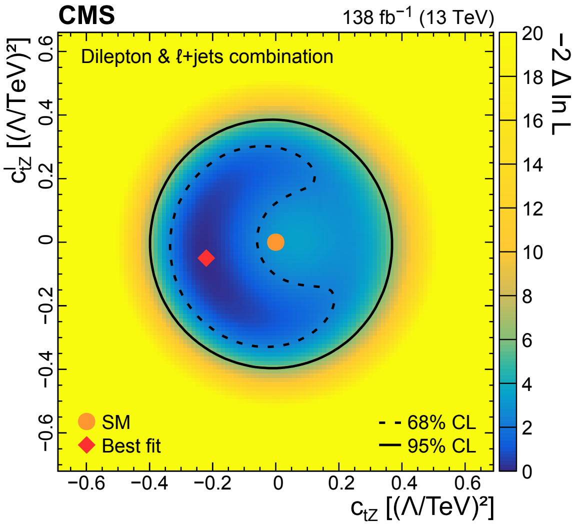


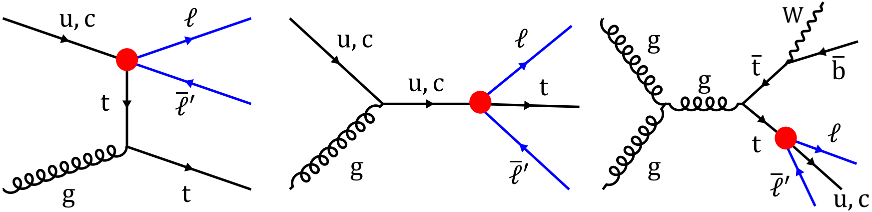
- $t\bar{t}\gamma$ production in dilepton final state
- Measure differential cross section as function of $p_T(\gamma)$
- Non-prompt photon background estimated from data in a sideband region
- Other backgrounds estimated from MC and validated in a separate control region
- See CMS $t\bar{t}X/tX$ talk Wednesday by Carlos Vico Villalba in Top Physics 3

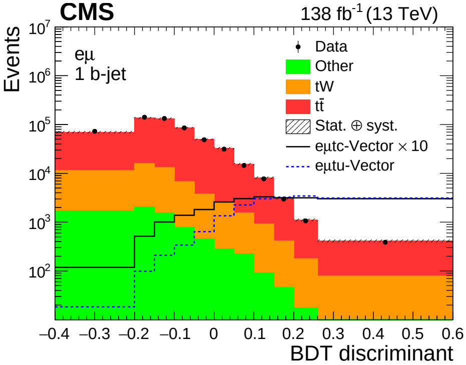
- Differential cross section used to constrain Wilson coefficients c_{tZ} and c^{I}_{tZ}
- WCs $c_{t\gamma}$ and $c^{I}_{t\gamma}$ also explored, but are degenerate with c_{tZ}/c^{I}_{tZ} in this analysis
- 1-D and 2-D likelihood scans; showing 2-D scan here
- Combine result with JHEP 12 (2021) 180: $t\bar{t}\gamma$ in lepton+jets final state
- Results consistent with the SM



- Differential cross section used to constrain Wilson coefficients c_{tZ} and c^{I}_{tZ}
- WCs $c_{t\gamma}$ and $c^{I}_{t\gamma}$ also explored, but are degenerate with c_{tZ}/c^{I}_{tZ} in this analysis
- 1-D and 2-D likelihood scans; showing 2-D scan here
- Combine result with JHEP 12 (2021) 180: $t\bar{t}\gamma$ in lepton+jets final state
- Results consistent with the SM



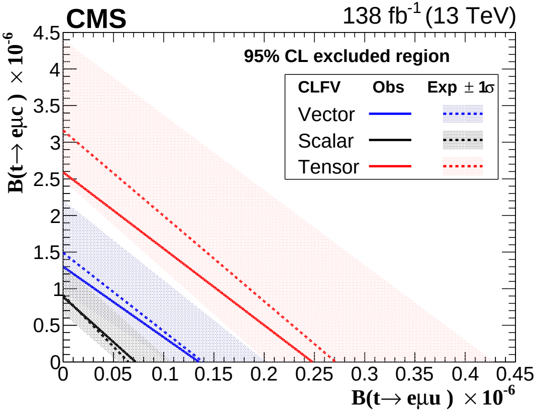




- Search for charged lepton flavor violation with top
- Forbidden in SM, so no EFT–SM interference
- $e\mu tq$ vertex in production or decay
- Sensitive to WCs $c_{e\mu tc}$ and $c_{e\mu tu}$, in scalar, vector, and tensor variants
- Select events with opposite-charge $e\mu$ and jets
- Use a BDT to separate signal from BG
- $e\mu tc$ and $e\mu tu$ very similar

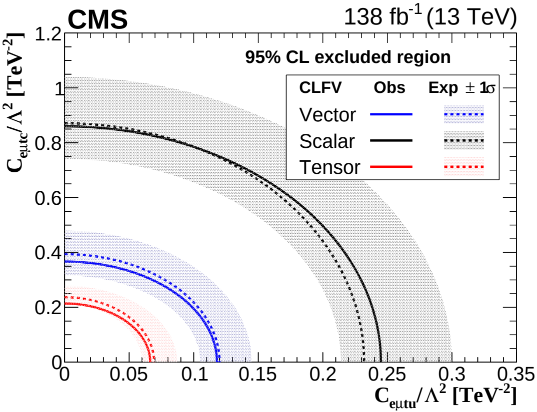
Vertex	Int. type	Cross section [fb] Exp	Obs	$C_{e\mu tq}/\Lambda^2$ [TeV $^{-2}$] Exp	Obs	$\mathcal{B}(10^{-6})$ Exp	Obs
	Vector	7.02	6.78	0.12	0.12	0.14	0.13
$e\mu tu$	Scalar	5.63	6.25	0.23	0.24	0.06	0.07
	Tensor	10.01	9.18	0.07	0.06	0.27	0.25
	Vector	11.21	9.73	0.39	0.37	1.49	1.31
$e\mu tc$	Scalar	9.11	8.88	0.87	0.86	0.91	0.89
	Tensor	21.02	17.22	0.24	0.21	3.16	2.59

- No sign of charged lepton flavor violation
- Set limits on cross sections
- Scalar, vector, tensor contribute differently to production vs. decay
- Scalar cross section limits strongest, tensor weakest
- Translate into branching ratio exclusions
- Excluded region above and right of curves



- Near-degeneracy of BDT shapes makes exclusion curves nearly straight lines

- EFT interpretation
- Exclusion in $c_{e\mu tc}$-$c_{e\mu tu}$ plane above, right of curves
- Hierarchy among scalar, vector, tensor scenarios reversed
- Near-degeneracy, plus zero interference between $e\mu tc$ and $e\mu tu$, makes exclusion curves nearly ellipses
  - Sensitive to roughly $c_{e\mu tc}^2 + c_{e\mu tu}^2$
- World's strongest limits on charged lepton flavor violation in top sector

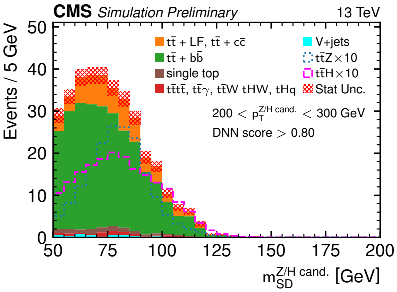


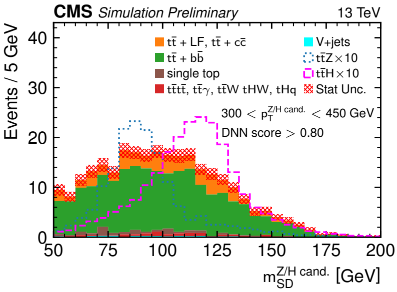
- EFT is a powerful tool for studying the dynamics of the top sector
- And for searching for signs of new physics
- Model independent and amenable to combinations and global fits
- CMS has produced total of 13 top EFT publications in Runs 1 and 2, and many more are on the way
- Including three presented today
  - $t\bar{t}Z$ and $t\bar{t}H$ with highly-boosted Z or H
  - $t\bar{t}\gamma$ in the dilepton final state
  - Charged lepton flavor violation in opposite-charge $e\mu$ final state

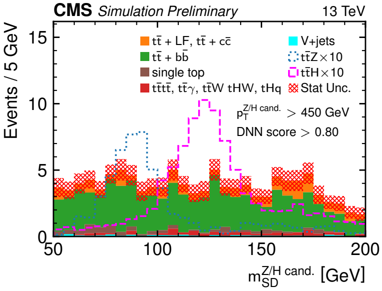
Backup: Boosted $t\bar{t}Z/H$

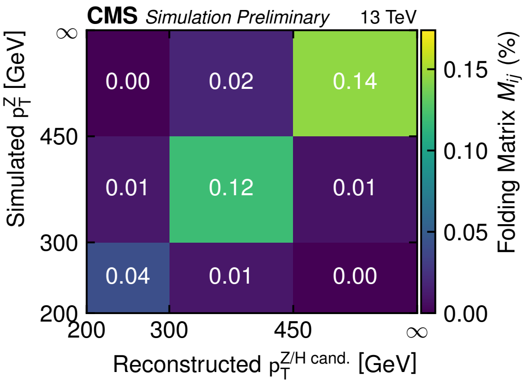
Operator	Definition	WC
$^{\ddagger}O_{u\varphi}^{(ij)}$	$\bar{q}_i u_j \tilde{\varphi}\,(\varphi^\dagger \varphi)$	$c_{t\varphi} + i c_{t\varphi}^I$
$O_{\varphi q}^{1(ij)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}_i \gamma^\mu q_j)$	$c_{\varphi Q}^{-} + c_{\varphi Q}^{3}$
$O_{\varphi q}^{3(ij)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_i \gamma^\mu \tau^I q_j)$	$c_{\varphi Q}^{3}$
$O_{\varphi u}^{(ij)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{u}_i \gamma^\mu u_j)$	$c_{\varphi t}$
$^{\ddagger}O_{\varphi ud}^{(ij)}$	$(\tilde{\varphi}^\dagger i D_\mu \varphi)(\bar{u}_i \gamma^\mu d_j)$	$c_{\varphi tb} + i c_{\varphi tb}^I$
$^{\ddagger}O_{uW}^{(ij)}$	$(\bar{q}_i \sigma^{\mu\nu} \tau^I u_j)\,\tilde{\varphi} W_{\mu\nu}^I$	$c_{tW} + i c_{tW}^I$
$^{\ddagger}O_{dW}^{(ij)}$	$(\bar{q}_i \sigma^{\mu\nu} \tau^I d_j)\,\varphi W_{\mu\nu}^I$	$c_{bW} + i c_{bW}^I$
$^{\ddagger}O_{uB}^{(ij)}$	$(\bar{q}_i \sigma^{\mu\nu} u_j)\,\tilde{\varphi} B_{\mu\nu}$	$(\mathcal{C}_W c_{tW} - c_{tZ})/\mathcal{S}_W + i(\mathcal{C}_W c_{tW}^I - c_{tZ}^I)/\mathcal{S}_W$

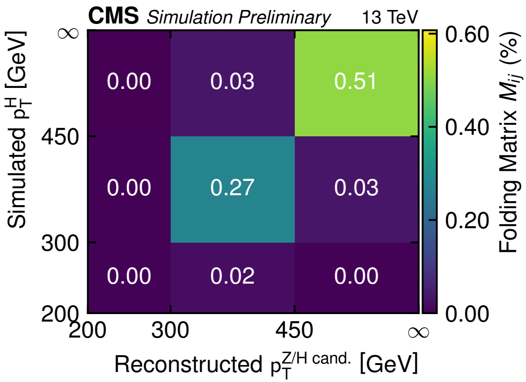
Missing transverse momentum	$p_T^{miss} > 20$ GeV
=1 electron or muon	$p_T(e) > 30$ (35 GeV) in 2016 (2017 and 2018) $p_T(\mu) > 30$ GeV $\lvert\eta(e)\rvert < 2.5$, $\lvert\eta(\mu)\rvert < 2.4$
≥1 AK8 jet	$p_T > 200$ GeV, $\lvert\eta\rvert < 2.4$ $50 < m_{SD} < 200$ GeV
=1 Z or Higgs boson candidate AK8 jet	Highest $b\bar{b}$ tagger score (>0.8)
≥5 AK4 jets (may overlap AK8 jet)	$p_T > 30$ GeV, $\lvert\eta\rvert < 2.4$
≥2 b-tagged AK4 jets	Satisfy medium DeepCSV b-tag requirements ΔR(Z or Higgs boson candidate AK8 jet) > 0.8

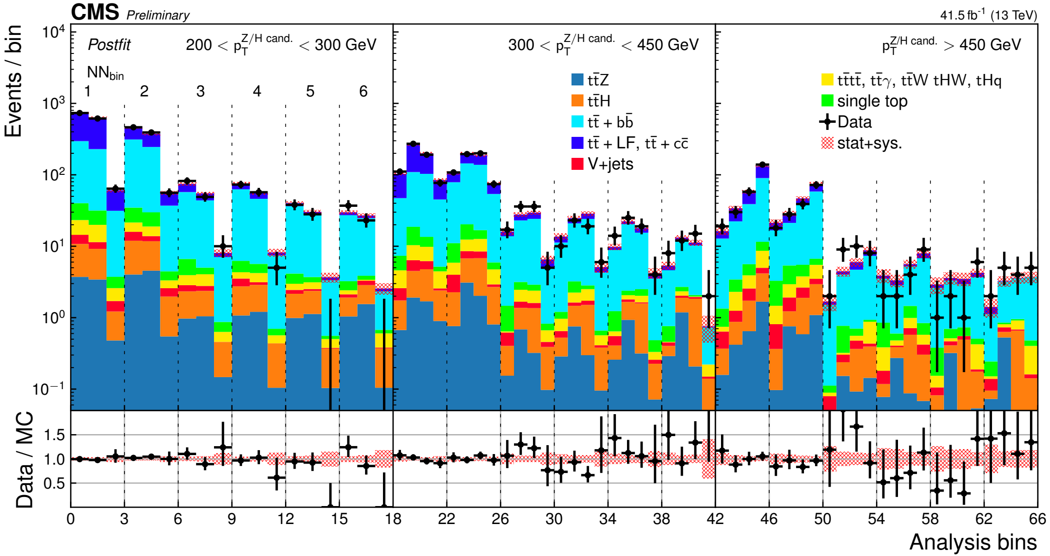

CMS Simulation Preliminary
13 TeV
Events / 5 GeV
tt̄ + LF, tt̄ + cc̄
tt̄ + bb̄
single top
tt̄tt̄, tt̄γ, tt̄W tHW, tHq
V+jets
tt̄Z×10
tt̄H×10
Stat Unc.
200 < p_T^{Z/H cand.} < 300 GeV
DNN score > 0.80
m_SD^{Z/H cand.} [GeV]

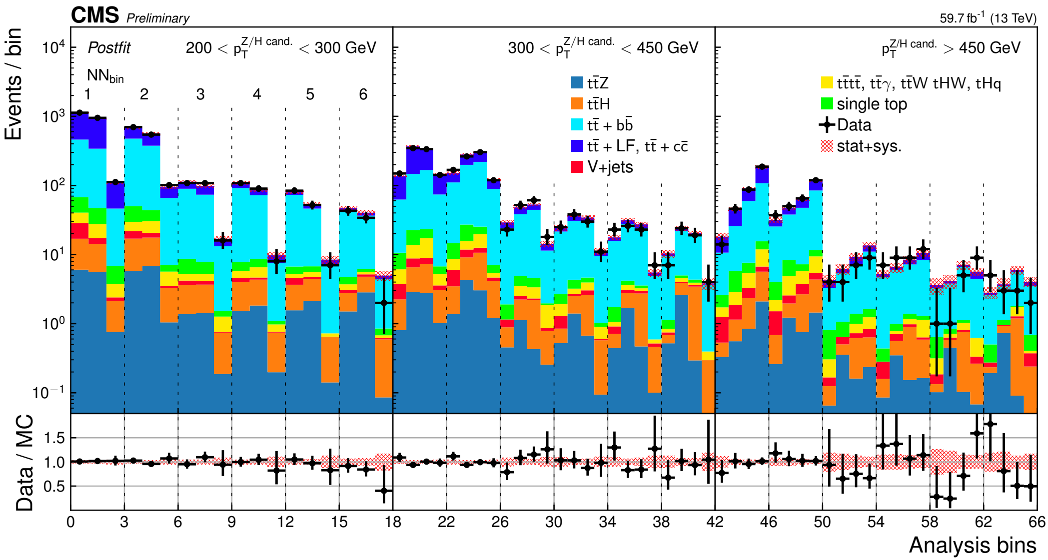

CMS Simulation Preliminary
13 TeV
Events / 5 GeV
tt̄ + LF, tt̄ + cc̄
tt̄ + bb̄
single top
tt̄tt̄, tt̄γ, tt̄W tHW, tHq
V+jets
tt̄Z×10
tt̄H×10
Stat Unc.
300 < p_T^{Z/H cand.} < 450 GeV
DNN score > 0.80
m_SD^{Z/H cand.} [GeV]

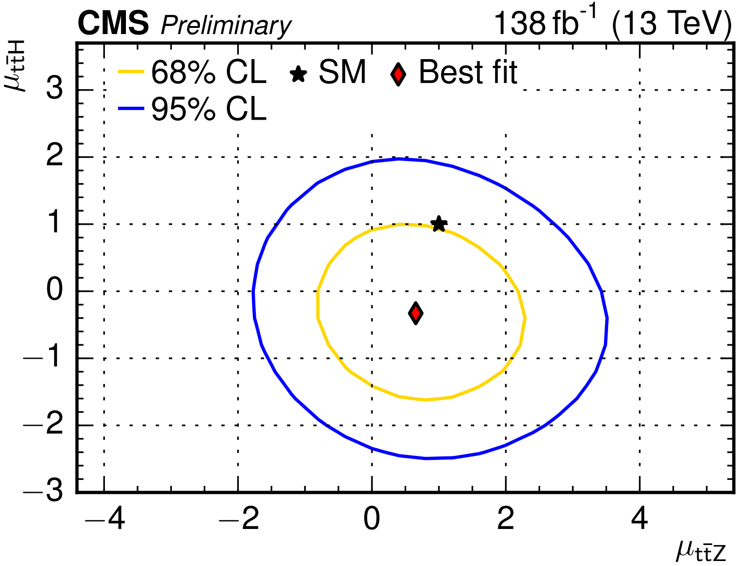

CMS Simulation Preliminary
13 TeV
Events / 5 GeV
tt̄ + LF, tt̄ + cc̄
tt̄ + bb̄
single top
tt̄tt̄, tt̄γ, tt̄W tHW, tHq
V+jets
tt̄Z×10
tt̄H×10
Stat Unc.
p_T^{Z/H cand.} > 450 GeV
DNN score > 0.80
m_SD^{Z/H cand.} [GeV]


CMS Simulation Preliminary 13 TeV
Simulated p_T^Z [GeV]
Reconstructed $p_T^{Z/H\ cand.}$ [GeV]
Folding Matrix M_{ij} (%)
200
300
450
∞
0.00 0.02 0.14
0.01 0.12 0.01
0.04 0.01 0.00
0.00 0.05 0.10 0.15


CMS Simulation Preliminary 13 TeV
Simulated p_T^H [GeV]
Reconstructed $p_T^{Z/H\ cand.}$ [GeV]
Folding Matrix M_{ij} (%)
200
300
450
∞
0.00 0.03 0.51
0.00 0.27 0.03
0.00 0.02 0.00
0.00 0.20 0.40 0.60

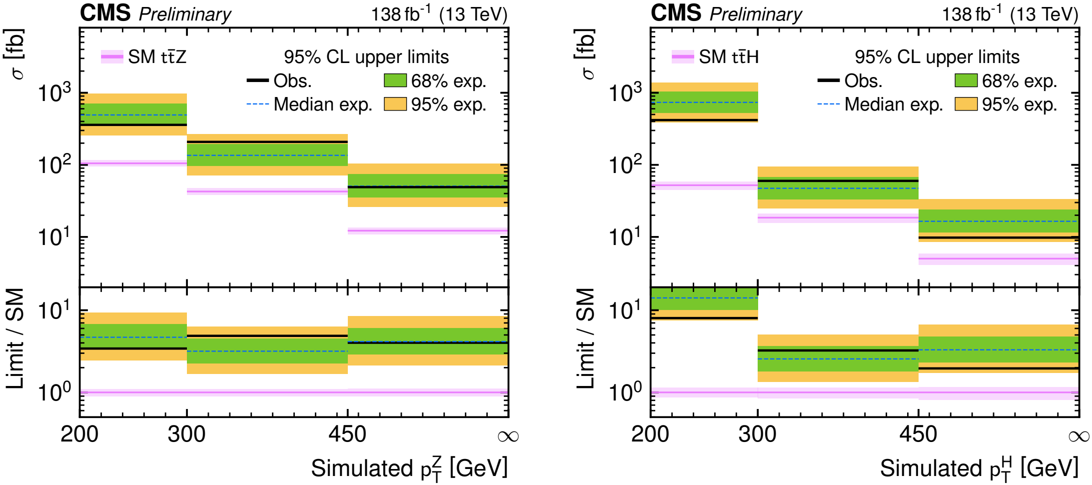

CMS Preliminary
41.5 fb-1 (13 TeV)
Postfit
200 < pT Z/H cand. < 300 GeV
300 < pT Z/H cand. < 450 GeV
pT Z/H cand. > 450 GeV
NNbin
1
2
3
4
5
6
tt̄Z
tt̄H
tt̄ + bb̄
tt̄ + LF, tt̄ + cc̄
V+jets
tt̄tt̄, tt̄γ, tt̄W tHW, tHq
single top
Data
stat+sys.
Events / bin
Data / MC
Analysis bins


CMS Preliminary
59.7 fb^{-1} (13 TeV)
Postfit
$200 < p_T^{Z/H\ cand.} < 300$ GeV
$300 < p_T^{Z/H\ cand.} < 450$ GeV
$p_T^{Z/H\ cand.} > 450$ GeV
NN$_{bin}$
1 2 3 4 5 6
$t\bar{t}Z$
$t\bar{t}H$
$t\bar{t} + b\bar{b}$
$t\bar{t}$ + LF, $t\bar{t} + c\bar{c}$
V+jets
$t\bar{t}t\bar{t}$, $t\bar{t}\gamma$, $t\bar{t}W$ tHW, tHq
single top
Data
stat+sys.
Events / bin
Data / MC
Analysis bins

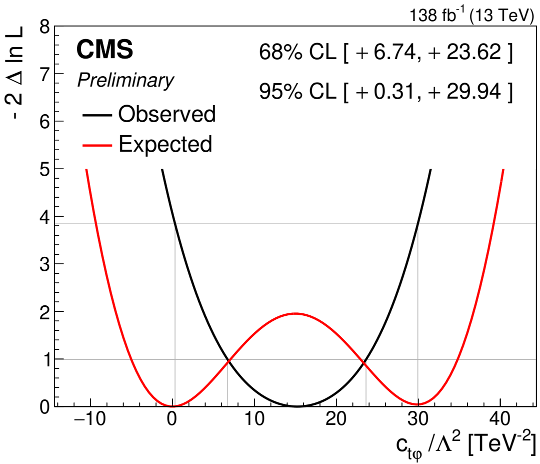

CMS Preliminary
138 fb-1 (13 TeV)
68% CL
SM
Best fit
95% CL
μttH
μttZ
3
2
1
0
−1
−2
−3
−4
−2
0
2
4

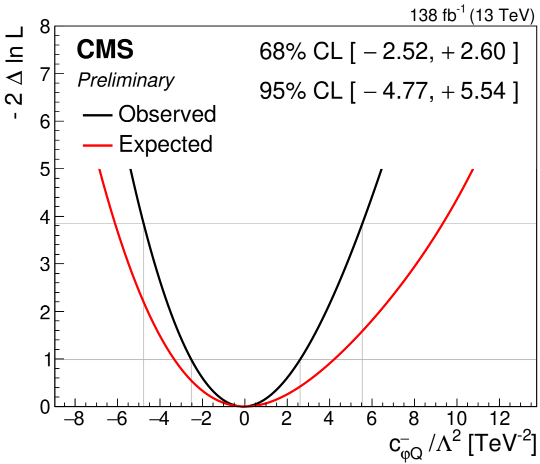
Signal strength	Observed $\pm 1\sigma$	Stat.	MC Stat.	Experiment	Theory	Expected $\pm 1\sigma$
$\mu_{t\bar{t}Z}$	$0.65^{+1.05}_{-0.98}$	$^{+0.80}_{-0.76}$	$^{+0.37}_{-0.38}$	$^{+0.38}_{-0.31}$	$^{+0.42}_{-0.38}$	$1.00^{+0.92}_{-0.84}$
$\mu_{t\bar{t}H}$	$-0.33^{+0.87}_{-0.85}$	$^{+0.72}_{-0.65}$	$^{+0.32}_{-0.34}$	$^{+0.19}_{-0.17}$	$^{+0.30}_{-0.38}$	$1.00^{+0.79}_{-0.73}$

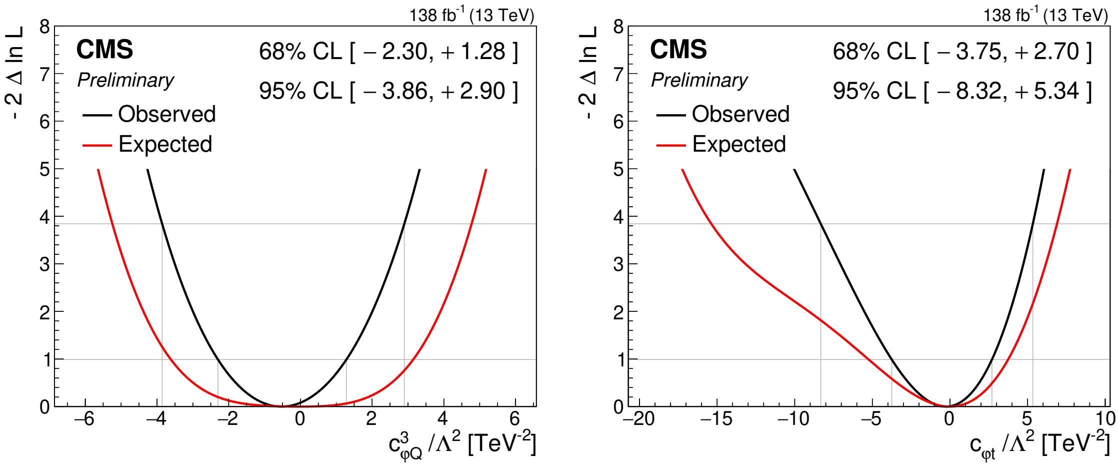
Source of uncertainty	$\Delta\mu_{t\bar{t}Z}$	$\Delta\mu_{t\bar{t}H}$
$t\bar{t} + c\bar{c}$ cross section	$^{+0.24}_{-0.22}$	$^{+0.17}_{-0.16}$
$t\bar{t} + b\bar{b}$ cross section	$^{+0.17}_{-0.23}$	$^{+0.15}_{-0.22}$
$t\bar{t} + 2b$ cross section	$^{+0.03}_{-0.03}$	$^{+0.10}_{-0.10}$
μ_R and μ_F scales	$^{+0.19}_{-0.14}$	$^{+0.10}_{-0.16}$
Parton shower	$^{+0.15}_{-0.16}$	$^{+0.06}_{-0.05}$
Top quark p_T modeling in $t\bar{t}$	$^{+0.01}_{-0.01}$	$^{+0.11}_{-0.13}$
b-tag efficiency	$^{+0.25}_{-0.13}$	$^{+0.10}_{-0.11}$
$b\bar{b}$-tag efficiency	$^{+0.17}_{-0.12}$	$^{+0.04}_{-0.03}$
Jet energy scale and resolution	$^{+0.11}_{-0.10}$	$^{+0.11}_{-0.12}$
Jet mass scale and resolution	$^{+0.10}_{-0.11}$	$^{+0.08}_{-0.08}$

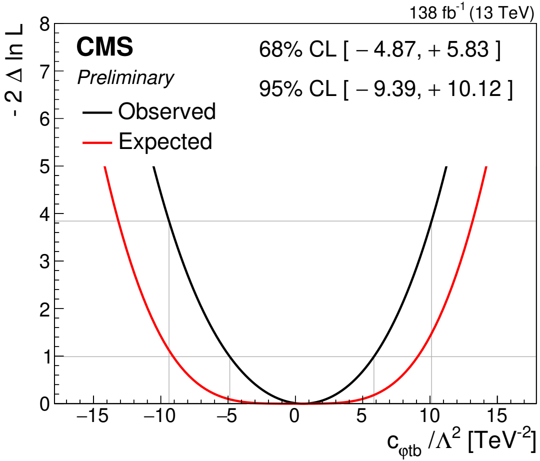

CMS Preliminary
138 fb-1 (13 TeV)
σ [fb]
SM tt̄Z
95% CL upper limits
Obs.
68% exp.
Median exp.
95% exp.
Limit / SM
200
300
450
∞
Simulated p_T^Z [GeV]
CMS Preliminary
138 fb-1 (13 TeV)
SM tt̄H
Simulated p_T^H [GeV]

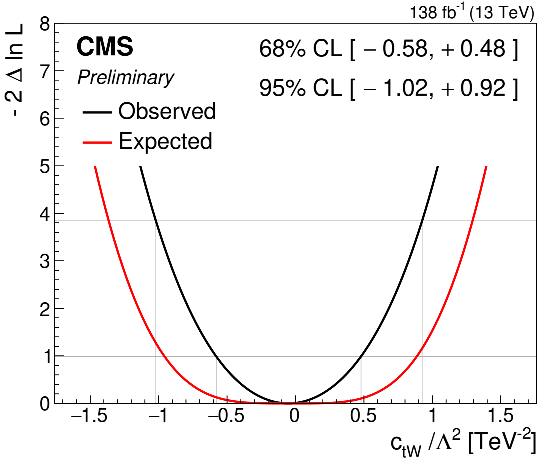
Signal	$p_T^{Z/H}$ (GeV) interval	95% CL upper limit (fb)	95% CL upper limit / SM
$t\bar{t}Z$	(200, 300]	$359\ (492^{+216}_{-143})$	$3.42\ (4.69^{+2.06}_{-1.36})$
	(300, 450]	$208\ (135^{+58}_{-39})$	$4.88\ (3.17^{+1.37}_{-0.91})$
	$(450, \infty)$	$49.1\ (50.7^{+23.0}_{-15.4})$	$4.02\ (4.16^{+1.89}_{-1.26})$
$t\bar{t}H$	(200, 300]	$418\ (736^{+296}_{-210})$	$8.02\ (14.1^{+5.7}_{-4.0})$
	(300, 450]	$59.9\ (47.3^{+20.5}_{-13.9})$	$3.24\ (2.55^{+1.11}_{-0.75})$
	$(450, \infty)$	$9.78\ (16.5^{+7.4}_{-4.9})$	$1.96\ (3.30^{+1.49}_{-0.98})$

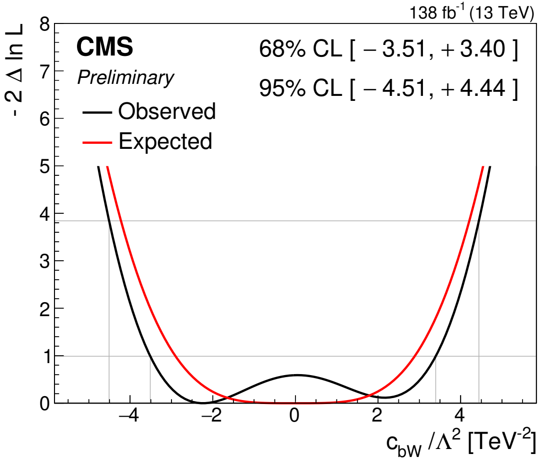

138 fb-1 (13 TeV)
CMS
Preliminary
68% CL [+ 6.74, + 23.62]
95% CL [+ 0.31, + 29.94]
Observed
Expected
- 2 Δ ln L
$c_{t\varphi}/\Lambda^2$ [TeV-2]

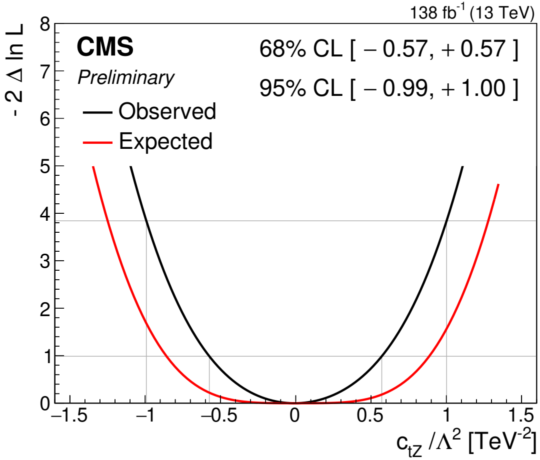

138 fb-1 (13 TeV)
CMS
Preliminary
68% CL [− 2.52, + 2.60]
95% CL [− 4.77, + 5.54]
Observed
Expected
- 2 Δ ln L
$c^{-}_{\varphi Q}/\Lambda^2$ [TeV-2]


138 fb-1 (13 TeV)
CMS
Preliminary
Observed
Expected
68% CL [– 2.30, + 1.28]
95% CL [– 3.86, + 2.90]
- 2 Δ ln L
$c^3_{\varphi Q}/\Lambda^2$ [TeV-2]
138 fb-1 (13 TeV)
CMS
Preliminary
Observed
Expected
68% CL [– 3.75, + 2.70]
95% CL [– 8.32, + 5.34]
- 2 Δ ln L
$c_{\varphi t}/\Lambda^2$ [TeV-2]

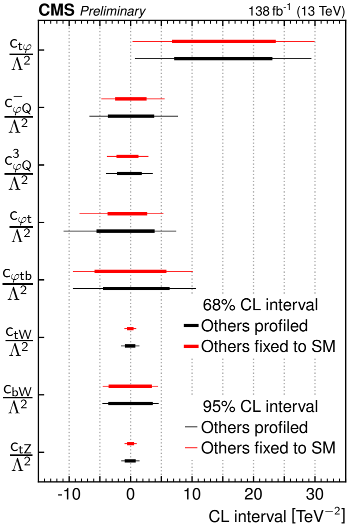

CMS
Preliminary
138 fb^{-1} (13 TeV)
68% CL [– 4.87, + 5.83]
95% CL [– 9.39, + 10.12]
Observed
Expected
- 2 Δ ln L
$c_{\varphi tb}/\Lambda^2$ [TeV^{-2}]


CMS
Preliminary
138 fb^{-1} (13 TeV)
68% CL [– 0.58, + 0.48]
95% CL [– 1.02, + 0.92]
Observed
Expected
- 2 Δ ln L
c_{tW}/Λ^2 [TeV^{-2}]

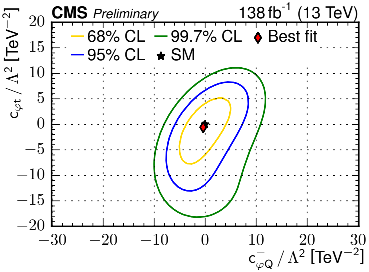

138 fb-1 (13 TeV)
CMS
Preliminary
68% CL [– 3.51, + 3.40]
95% CL [– 4.51, + 4.44]
Observed
Expected
- 2 Δ ln L
cbW /Λ2 [TeV-2]

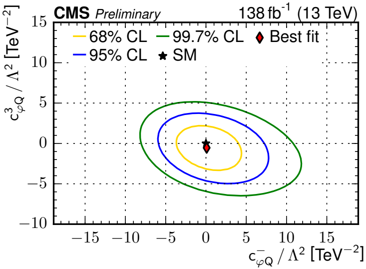

138 fb-1 (13 TeV)
CMS
Preliminary
68% CL [– 0.57, + 0.57]
95% CL [– 0.99, + 1.00]
Observed
Expected
- 2 Δ ln L
ctZ /Λ2 [TeV-2]

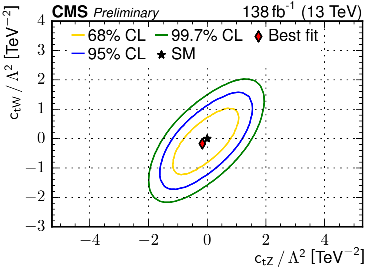
WC summary


CMS Preliminary
138 fb^{-1} (13 TeV)
$\frac{c_{t\varphi}}{\Lambda^2}$
$\frac{c^{-}_{\varphi Q}}{\Lambda^2}$
$\frac{c^{3}_{\varphi Q}}{\Lambda^2}$
$\frac{c_{\varphi t}}{\Lambda^2}$
$\frac{c_{\varphi tb}}{\Lambda^2}$
$\frac{c_{tW}}{\Lambda^2}$
$\frac{c_{bW}}{\Lambda^2}$
$\frac{c_{tZ}}{\Lambda^2}$
68% CL interval
Others profiled
Others fixed to SM
95% CL interval
Others profiled
Others fixed to SM
-10
0
10
20
30
CL interval [TeV^{-2}]

WC/Λ^2 [TeV^{-2}]	95% CL interval (others profiled)	95% CL interval (others fixed to SM)
$c_{t\varphi}$	[0.70, 29.42]	[0.31, 29.94]
$c^{-}_{\varphi Q}$	[−6.71, 7.72]	[−4.77, 5.54]
$c^{3}_{\varphi Q}$	[−4.01, 3.61]	[−3.86, 2.90]
$c_{\varphi t}$	[−10.91, 7.42]	[−8.32, 5.34]
$c_{\varphi tb}$	[−9.39, 10.65]	[−9.39, 10.12]
c_{tW}	[−1.56, 1.44]	[−1.02, 0.92]
c_{bW}	[−4.60, 4.57]	[−4.54, 4.47]
c_{tZ}	[−1.53, 1.46]	[−0.99, 1.00]

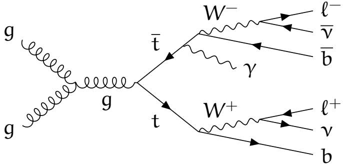

CMS Preliminary
138 fb-1 (13 TeV)
68% CL
99.7% CL
Best fit
95% CL
SM
$c_{\varphi t} / \Lambda^2$ [TeV^{-2}]
$c^{-}_{\varphi Q} / \Lambda^2$ [TeV^{-2}]

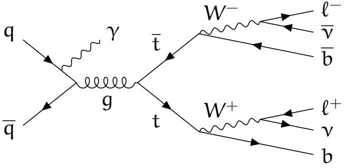

CMS Preliminary
138 fb-1 (13 TeV)
68% CL
99.7% CL
Best fit
95% CL
SM
$c^{3}_{\varphi Q} / \Lambda^2$ [TeV^{-2}]
$c^{-}_{\varphi Q} / \Lambda^2$ [TeV^{-2}]

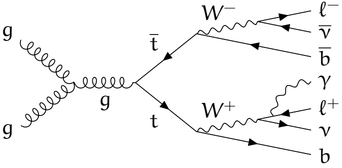

CMS Preliminary
138 fb-1 (13 TeV)
68% CL
99.7% CL
Best fit
95% CL
SM
c_{tW} / Λ^2 [TeV^{-2}]
c_{tZ} / Λ^2 [TeV^{-2}]

Name	Description
$t\bar{t}$ system	
b p_T	p_T of the leading (subleading) b jet
b score	DeepCSV score of the leading (subleading) b jet
q p_T	p_T of the leading (subleading) non-b jet
q score	DeepCSV score of the leading (subleading) non-b jet
$\Delta R(\mathrm{b},\mathrm{q})$	minimum ΔR between the leading (subleading) b jet and any non-b jet
$\Delta R(\mathrm{q},\mathrm{q})$	ΔR between the non-b jets closest and next-to-closest to the leading (subleading) b jet
$m(\mathrm{q}+\mathrm{q})$	invariant mass of the non-b jets closest and next-to-closest to the leading (subleading) b jet
$\Delta R(\mathrm{b},\mathrm{q}+\mathrm{q})$	ΔR between the leading (subleading) b jet and the sum of the nearest and next-to-nearest non-b jets
$m(\mathrm{b}+\mathrm{q}+\mathrm{q})$	invariant mass of the leading (subleading) b jet and the nearest and next-to-nearest non-b jets
$\Delta R(\mathrm{Z/H},\mathrm{b}+\mathrm{q}+\mathrm{q})$	ΔR between the Z/H boson candidate and the sum of the leading (subleading) b jet and the non-b jets nearest and next-to-nearest to the leading (subleading) b jet
$\Delta R(\mathrm{Z/H},\mathrm{b}+\mathrm{b}+\mathrm{q}+\mathrm{q}+\ell)$	ΔR between the Z/H boson candidate and the sum of the leading and subleading b jets, the non-b jets nearest and next-to-nearest to the leading (subleading) b jet, and the lepton
$m_T(\mathrm{b}+\ell+\vec{p}_T^{\,\mathrm{miss}})$	transverse mass of the subleading b jet, the lepton, and $\vec{p}_T^{\,\mathrm{miss}}$
$m(\mathrm{Z/H}+\mathrm{b})$	invariant mass of the Z/H boson candidate and the nearest b jet
$m(\mathrm{b}+\mathrm{b})$	invariant mass of the leading and subleading b jets
$\Delta R(\mathrm{b},\mathrm{b})$	ΔR between the leading and subleading b jets
$\Delta R(\mathrm{Z/H},\mathrm{q})$	ΔR between the Z/H boson candidate and the leading non-b jet
$\Delta R(\mathrm{Z/H},\mathrm{b})$	ΔR between the Z/H boson candidate and the leading b jet
$\Delta R(\mathrm{Z/H},\ell)$	ΔR between Z/H boson candidate and the lepton
$m(\mathrm{Z/H}+\ell)$	invariant mass of the Z/H boson candidate and the lepton
$\Delta R(\mathrm{b},\ell)$	ΔR between the leading (subleading) b jet and the lepton
$m(\mathrm{b}+\ell)$	invariant mass of the leading (subleading) b jet and the lepton
$N(\mathrm{b_{out}})$	number of b jets outside the Z/H boson candidate cone ($\Delta R > 0.8$)
$N(\mathrm{q_{out}})$	number of non-b jets outside the Z/H boson candiate cone ($\Delta R > 0.8$)
Event topology	
N(AK8 jets)	number of AK8 jets including the Z/H boson candidate
N(AK4 jets)	number of AK4 jets
N(Z/H)	number of AK8 jets with a minimum AK8 $\mathrm{b\bar{b}}$ tagger score of 0.8
AK8 m_{SD}	maximum m_{SD} of AK8 jets excluding the Z/H boson candidate
$H_T(\mathrm{b_{out}})$	H_T of the b jets outside the Z/H boson candidate cone ($\Delta R > 0.8$)
$H_T(\mathrm{b_{out}},\mathrm{q_{out}},\ell)$	H_T of all AK4 jets outside the Z/H boson candidate cone ($\Delta R > 0.8$) and the lepton
sphericity	sphericity calculated from the AK4 jets and the lepton **[?]**
aplanarity	aplanarity calculated from the AK4 jets and the lepton **[?]**
Z/H boson candidate substructure	
$\mathrm{b_{in}}$ score	maximum (minimum) DeepCSV score of AK4 jets within the Z/H boson candidate cone ($\Delta R \leq 0.8$)
$\Delta R(\mathrm{b_{in}},\mathrm{b_{out}})$	ΔR between a b jet within the Z/H boson candidate cone ($\Delta R \leq 0.8$) and the leading b jet outside of the Z/H boson candidate cone ($\Delta R > 0.8$)
$N(\mathrm{b_{in}})$	number of b jets within the Z/H boson candidate cone ($\Delta R \leq 0.8$)
$N(\mathrm{q_{in}})$	number of non-b jets within the Z/H boson candidate cone ($\Delta R \leq 0.8$)
Z/H $\mathrm{b\bar{b}}$ score	AK8 $\mathrm{b\bar{b}}$ tagger score of the Z/H boson candidate

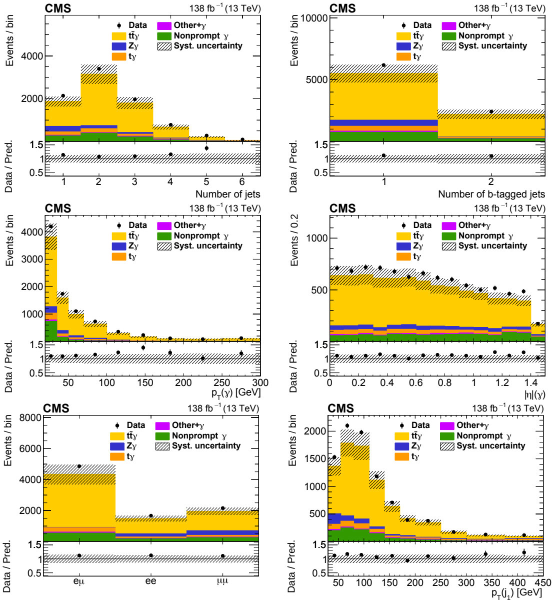
Backup: $t\bar{t}\gamma$


g
g
g
$\bar{t}$
t
γ
W^-
W^+
ℓ^-
$\bar{\nu}$
$\bar{b}$
ℓ^+
ν
b

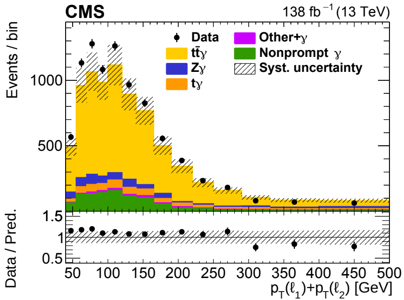

q
$\bar{q}$
γ
g
$\bar{t}$
t
W^-
W^+
ℓ^-
$\bar{\nu}$
$\bar{b}$
ℓ^+
ν
b

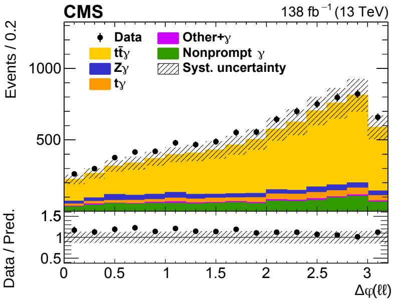

g
g
g
$\bar{t}$
t
W^-
W^+
ℓ^-
$\bar{\nu}$
$\bar{b}$
γ
ℓ^+
ν
b

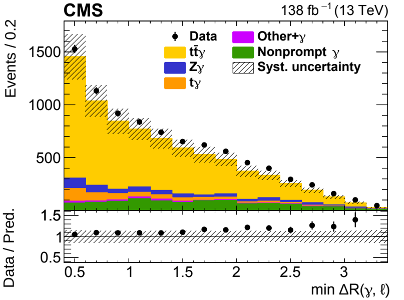
Kinematic plots signal region

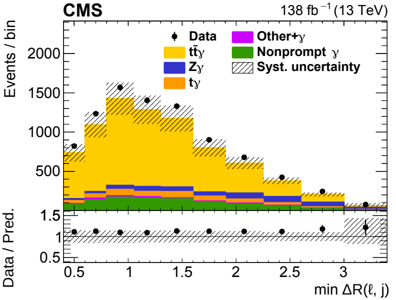


Kinematic plots signal region

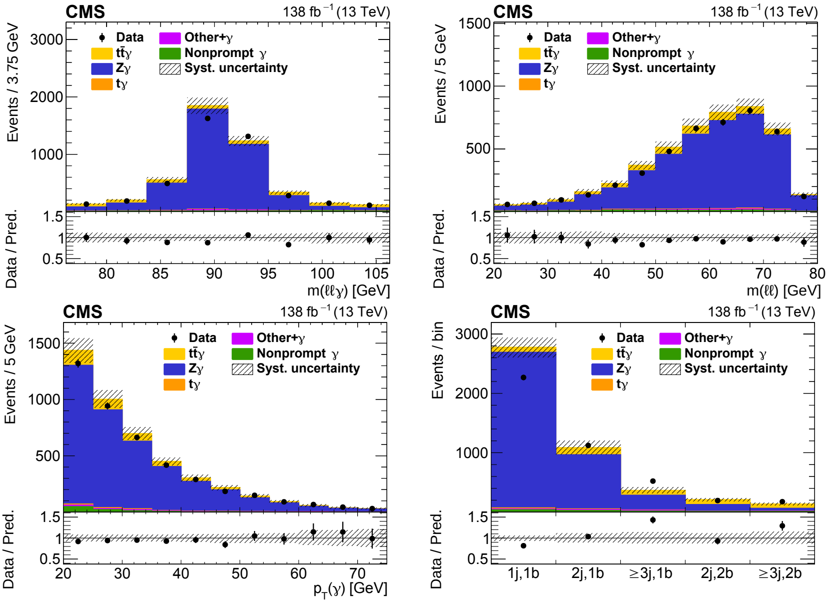


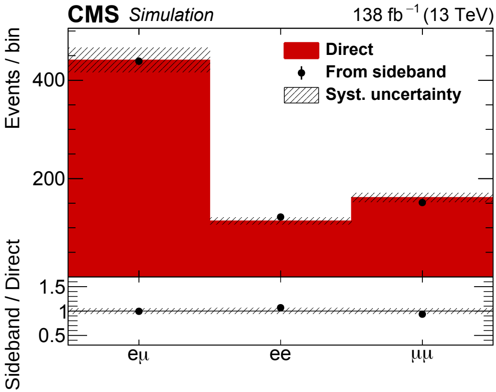


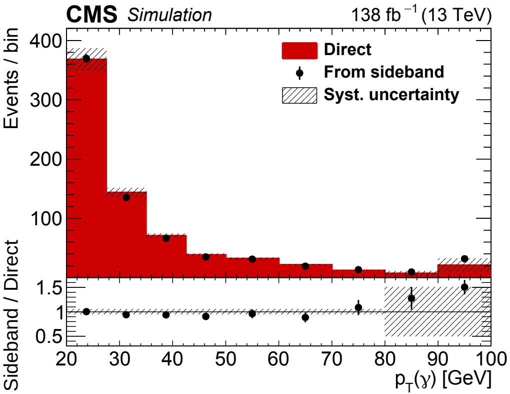




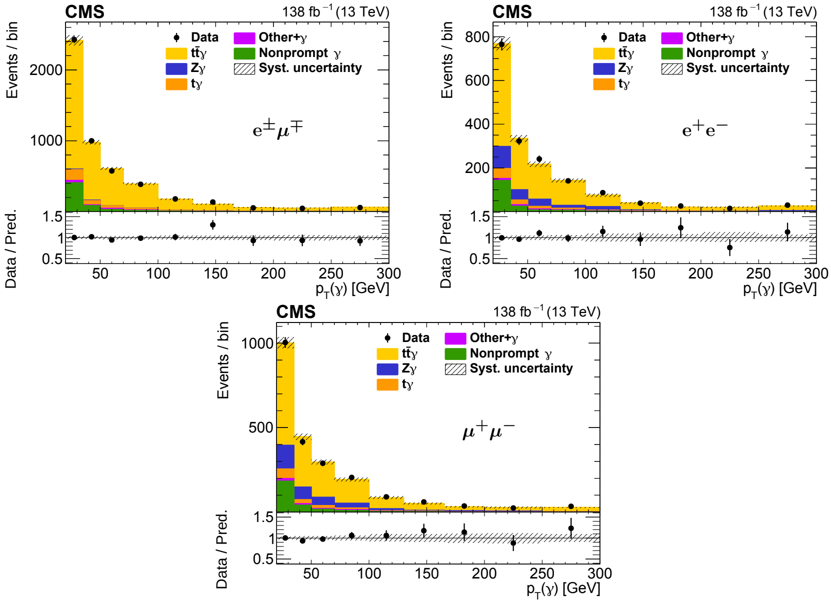
Kinematic plots: Z gamma region

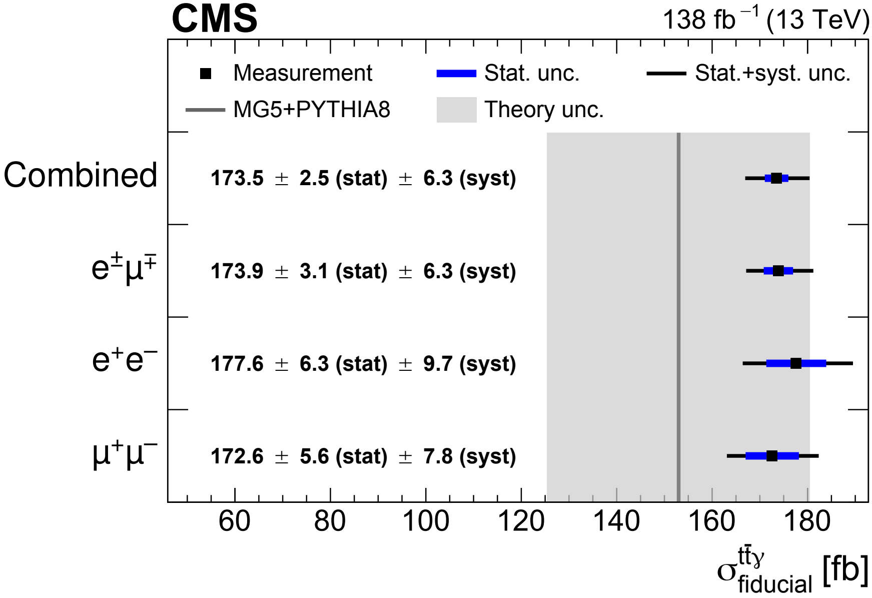


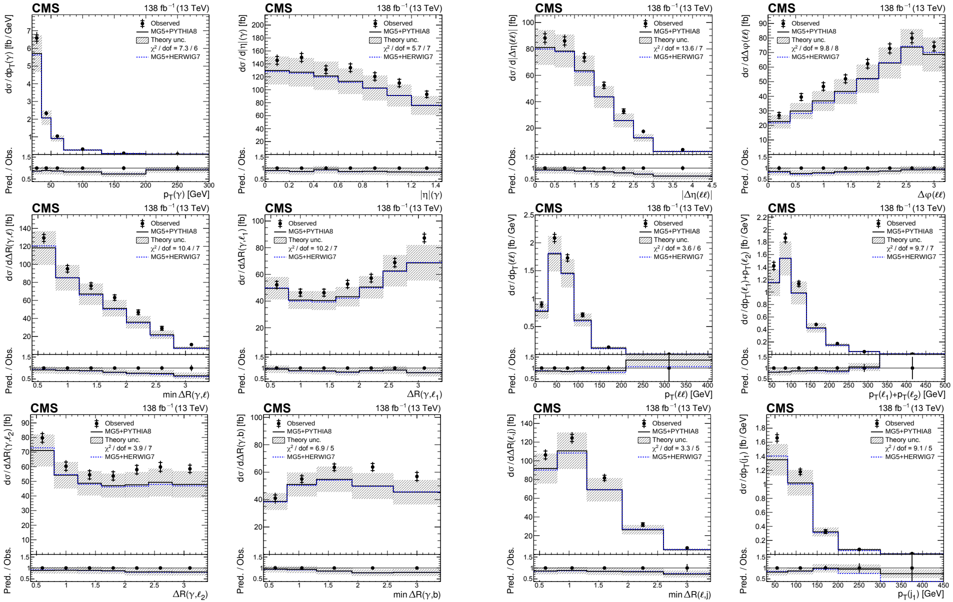

CMS Simulation
138 fb^{-1} (13 TeV)
Direct
From sideband
Syst. uncertainty
Events / bin
Sideband / Direct
400
200
1.5
1
0.5
eμ
ee
μμ


CMS Simulation
138 fb^{-1} (13 TeV)
Direct
From sideband
Syst. uncertainty
Events / bin
Sideband / Direct
400
300
200
100
1.5
1
0.5
20
30
40
50
60
70
80
90
100
$p_T(\gamma)$ [GeV]

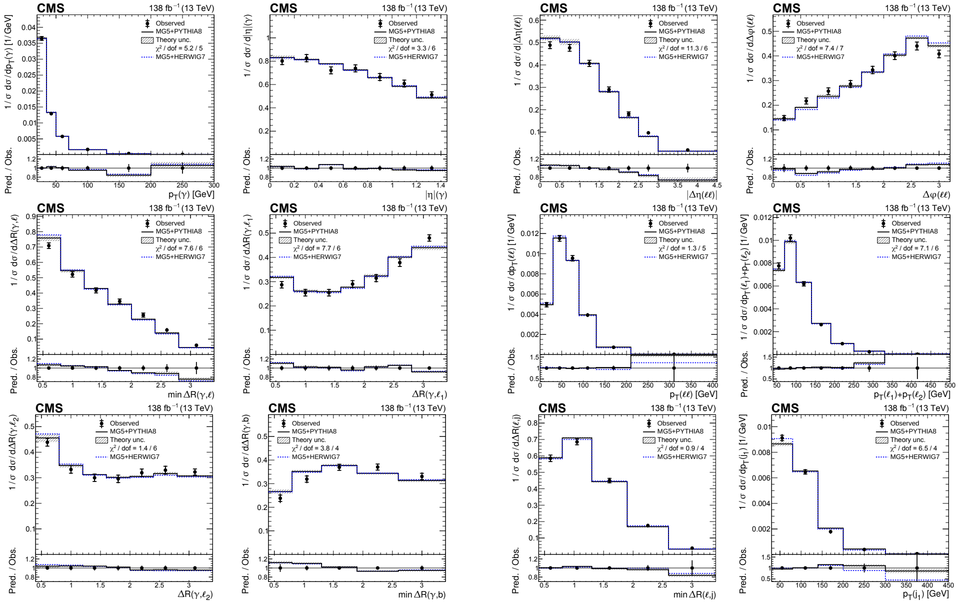
photon pT in signal region

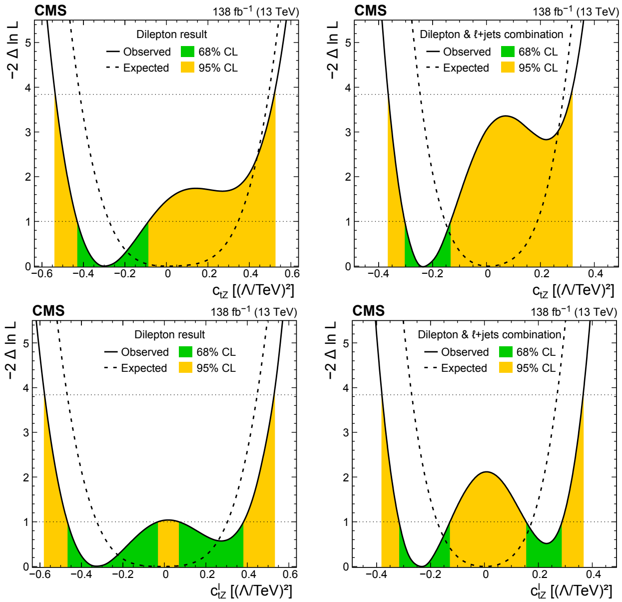


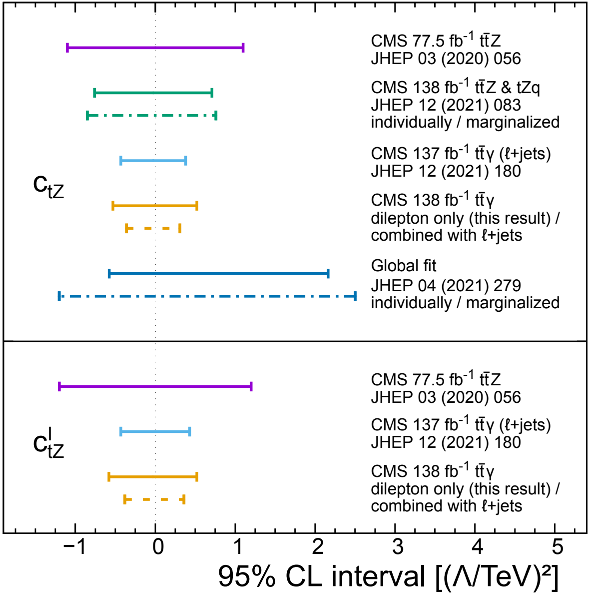

CMS
138 fb^{-1} (13 TeV)
Measurement
Stat. unc.
Stat.+syst. unc.
MG5+PYTHIA8
Theory unc.
Combined
173.5 ± 2.5 (stat) ± 6.3 (syst)
$e^{\pm}\mu^{\mp}$
173.9 ± 3.1 (stat) ± 6.3 (syst)
$e^{+}e^{-}$
177.6 ± 6.3 (stat) ± 9.7 (syst)
$\mu^{+}\mu^{-}$
172.6 ± 5.6 (stat) ± 7.8 (syst)
60
80
100
120
140
160
180
$\sigma^{t\bar{t}\gamma}_{\text{fiducial}}$ [fb]


CMS
138 fb^{-1} (13 TeV)
Observed
MG5+PYTHIA8
Theory unc.
MG5+HERWIG7
χ^2 / dof = 7.3 / 6
χ^2 / dof = 5.7 / 7
χ^2 / dof = 13.6 / 7
χ^2 / dof = 9.8 / 8
χ^2 / dof = 10.4 / 7
χ^2 / dof = 10.2 / 7
χ^2 / dof = 3.6 / 6
χ^2 / dof = 9.7 / 7
χ^2 / dof = 3.9 / 7
χ^2 / dof = 6.9 / 5
χ^2 / dof = 3.3 / 5
χ^2 / dof = 9.1 / 5
Pred. / Obs.
$d\sigma / dp_T(\gamma)$ [fb / GeV]
$p_T(\gamma)$ [GeV]
$d\sigma / d|\eta|(\gamma)$ [fb]
$|\eta|(\gamma)$
$d\sigma / d|\Delta\eta(\ell\ell)|$ [fb]
$|\Delta\eta(\ell\ell)|$
$d\sigma / d\Delta\varphi(\ell\ell)$ [fb]
$\Delta\varphi(\ell\ell)$
$d\sigma / d\Delta R(\gamma,\ell)$ [fb]
min $\Delta R(\gamma,\ell)$
$d\sigma / d\Delta R(\gamma,\ell_1)$ [fb]
$\Delta R(\gamma,\ell_1)$
$d\sigma / dp_T(\ell\ell)$ [fb / GeV]
$p_T(\ell\ell)$ [GeV]
$d\sigma / dp_T(\ell_1)+p_T(\ell_2)$ [fb / GeV]
$p_T(\ell_1)+p_T(\ell_2)$ [GeV]
$d\sigma / d\Delta R(\gamma,\ell_2)$ [fb]
$\Delta R(\gamma,\ell_2)$
$d\sigma / d\Delta R(\gamma,b)$ [fb]
min $\Delta R(\gamma,b)$
$d\sigma / d\Delta R(\ell,j)$ [fb]
min $\Delta R(\ell,j)$
$d\sigma / dp_T(j_1)$ [fb / GeV]
$p_T(j_1)$ [GeV]

Diff. cross sections




CMS
138 fb^{-1} (13 TeV)
Dilepton result
Observed
Expected
68% CL
95% CL
−2 Δ ln L
c_{tZ} [(Λ/TeV)²]
CMS
138 fb^{-1} (13 TeV)
Dilepton & ℓ+jets combination
Observed
Expected
68% CL
95% CL
−2 Δ ln L
c_{tZ} [(Λ/TeV)²]
CMS
138 fb^{-1} (13 TeV)
Dilepton result
Observed
Expected
68% CL
95% CL
−2 Δ ln L
c^{I}_{tZ} [(Λ/TeV)²]
CMS
138 fb^{-1} (13 TeV)
Dilepton & ℓ+jets combination
Observed
Expected
68% CL
95% CL
−2 Δ ln L
c^{I}_{tZ} [(Λ/TeV)²]


CMS 77.5 fb-1 tt̄Z
JHEP 03 (2020) 056
CMS 138 fb-1 tt̄Z & tZq
JHEP 12 (2021) 083
individually / marginalized
CMS 137 fb-1 tt̄γ (ℓ+jets)
JHEP 12 (2021) 180
CMS 138 fb-1 tt̄γ
dilepton only (this result) /
combined with ℓ+jets
Global fit
JHEP 04 (2021) 279
individually / marginalized
ctZ
CMS 77.5 fb-1 tt̄Z
JHEP 03 (2020) 056
CMS 137 fb-1 tt̄γ (ℓ+jets)
JHEP 12 (2021) 180
CMS 138 fb-1 tt̄γ
dilepton only (this result) /
combined with ℓ+jets
cltZ
−1
0
1
2
3
4
5
95% CL interval [(Λ/TeV)²]

Process	Cross section normalization	Event generator	Perturbative order in QCD
$t\bar{t}\gamma$	NLO	MADGRAPH5_aMC@NLO	LO
Z+jets	NNLO [49]	MADGRAPH5_aMC@NLO	LO
$Z\gamma$, $W\gamma$, VV, VVV, $t\bar{t}V$, tZq, tWZ, tHq, tHW, $t\bar{t}VV$, $t\bar{t}t\bar{t}$	NLO	MADGRAPH5_aMC@NLO	NLO
$t\bar{t}$	NNLO+NNLL [50]	POWHEG	NLO
single t (t channel)	NLO [51, 52]	POWHEG	NLO
single t (s channel)	NLO [51, 52]	MADGRAPH5_aMC@NLO	NLO
tW	NNLO [53]	POWHEG	NLO
$t\bar{t}H$	NLO	POWHEG	NLO
$gg \rightarrow ZZ$	LO	MCFM	LO

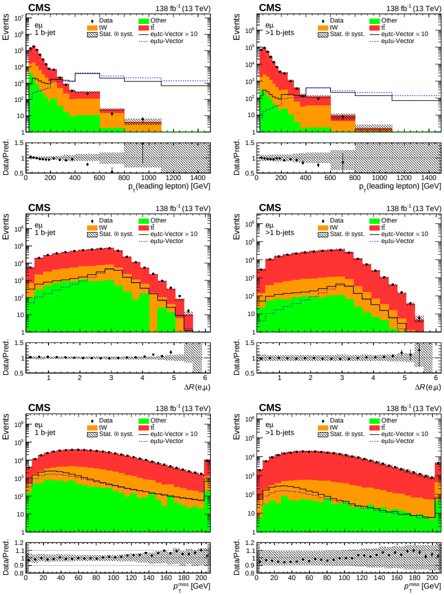
Leptons	Photons	Jets	b jets	Events
$p_T > 25\,(15)\,\text{GeV}$	$p_T > 20\,\text{GeV}$	$p_T > 30\,\text{GeV}$	$p_T > 30\,\text{GeV}$	$N_\ell = 2$ (OC)
$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 1.44$	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.4$	$N_\gamma = 1$
	$\Delta R(\gamma, \ell) > 0.4$	$\Delta R(\text{jet}, \ell) > 0.4$	$\Delta R(\text{jet}, \ell) > 0.4$	$N_\text{b} \geq 1$
	isolated	$\Delta R(\text{jet}, \gamma) > 0.1$	$\Delta R(\text{jet}, \gamma) > 0.1$	$m(\ell\ell) > 20\,\text{GeV}$
			matched to b hadron	

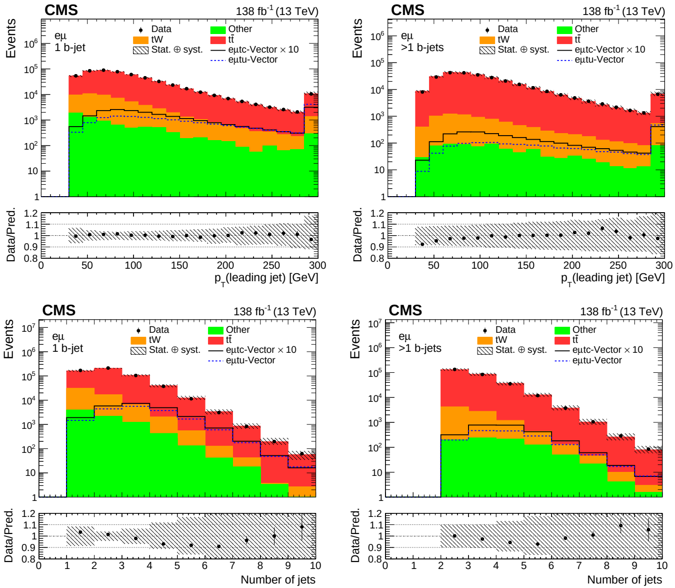
	Source	Correlation	Uncertainty [%] Prefit range	Postfit
Experimental	Integrated luminosity	∼	1.3–3.2	1.7
	Pileup	✓	0.1–1.4	0.7
	Trigger efficiency	×	0.6–1.7	0.6
	Electron selection efficiency	∼	1.0–1.3	1.0
	Muon selection efficiency	∼	0.3–0.5	0.5
	Photon selection efficiency	∼	0.4–3.6	1.1
	Electron & photon energy	✓	0.0–1.1	0.1
	Jet energy scale	∼	0.1–1.3	0.5
	Jet energy resolution	✓	0.0–0.6	<0.1
	b tagging efficiency	∼	0.9–1.4	1.1
	L1 prefiring	✓	0.0–0.8	0.3
Theoretical	Values of μ_F and μ_R	✓	0.3–3.5	1.3
	PDF choice	✓	0.3–4.5	0.3
	PS modelling: ISR & FSR scale	✓	0.3–3.5	1.3
	PS modelling: colour reconnection	✓	0.0–8.4	0.2
	PS modelling: b fragmentation	✓	0.0–2.2	0.7
	Underlying-event tune	✓	0.5	0.5
Background	$Z\gamma$ correction & normalization	✓	0.0–0.2	0.1
	$t\gamma$ normalization	✓	0.0–0.9	0.8
	Other+γ normalization	✓	0.3–1.0	0.8
	Nonprompt γ normalization	✓	0.0–1.8	0.7
	Size of simulated samples	×	1.5–7.6	0.9
	Total systematic uncertainty			3.6
	Statistical uncertainty			1.4
	Total uncertainty			3.9

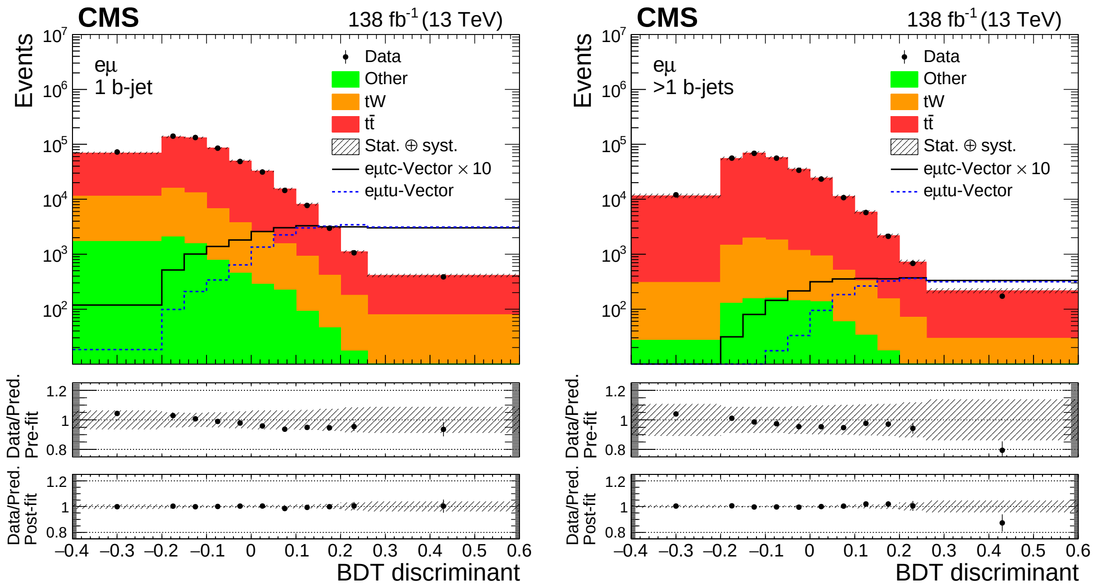
Symbol	Definition
$p_{\mathrm{T}}(\gamma)$	Transverse momentum of the photon
$\|\eta\|(\gamma)$	Absolute value of the pseudorapidity of the photon
$\min \Delta R(\gamma, \ell)$	Angular separation between the photon and the closest lepton
$\Delta R(\gamma, \ell_1)$	Angular separation between the photon and the leading lepton
$\Delta R(\gamma, \ell_2)$	Angular separation between the photon and the subleading lepton
$\min \Delta R(\gamma, \mathrm{b})$	Angular separation between the photon and the closest b jet
$\|\Delta\eta(\ell\ell)\|$	Pseudorapidity difference between the two leptons
$\Delta\varphi(\ell\ell)$	Azimuthal angle difference between the two leptons
$p_{\mathrm{T}}(\ell\ell)$	Transverse momentum of the dilepton system
$p_{\mathrm{T}}(\ell_1) + p_{\mathrm{T}}(\ell_2)$	Scalar sum of the transverse momenta of the two leptons
$\min \Delta R(\ell, \mathrm{j})$	Smallest angular separation between any of the selected leptons and jets
$p_{\mathrm{T}}(\mathrm{j}_1)$	Transverse momentum of the leading jet

	Wilson coefficient		Dilepton result 68% CL interval $[(\Lambda/\mathrm{TeV})^2]$	Dilepton result 95% CL interval $[(\Lambda/\mathrm{TeV})^2]$	Dilepton & ℓ+jets combination 68% CL interval $[(\Lambda/\mathrm{TeV})^2]$	Dilepton & ℓ+jets combination 95% CL interval $[(\Lambda/\mathrm{TeV})^2]$
Expected	c_{tZ}	$c^I_{tZ} = 0$	$[-0.28, 0.35]$	$[-0.42, 0.49]$	$[-0.15, 0.19]$	$[-0.25, 0.29]$
		profiled	$[-0.28, 0.35]$	$[-0.42, 0.49]$	$[-0.15, 0.19]$	$[-0.25, 0.29]$
	c^I_{tZ}	$c_{tZ} = 0$	$[-0.33, 0.30]$	$[-0.47, 0.45]$	$[-0.17, 0.18]$	$[-0.27, 0.27]$
		profiled	$[-0.33, 0.30]$	$[-0.47, 0.45]$	$[-0.18, 0.18]$	$[-0.27, 0.27]$
Observed	c_{tZ}	$c^I_{tZ} = 0$	$[-0.43, -0.09]$	$[-0.53, 0.52]$	$[-0.30, -0.13]$	$[-0.36, 0.31]$
		profiled	$[-0.43, 0.17]$	$[-0.53, 0.51]$	$[-0.30, 0.00]$	$[-0.36, 0.31]$
	c^I_{tZ}	$c_{tZ} = 0$	$[-0.47, -0.03] \cup [0.07, 0.38]$	$[-0.58, 0.52]$	$[-0.32, -0.13] \cup [0.16, 0.29]$	$[-0.38, 0.36]$
		profiled	$[-0.43, 0.33]$	$[-0.56, 0.51]$	$[-0.28, 0.23]$	$[-0.36, 0.35]$

Backup: Charged lepton flavor violation


CMS
138 fb-1 (13 TeV)
eμ
1 b-jet
>1 b-jets
Data
Other
tW
tt̄
Stat. ⊕ syst.
eμtc-Vector × 10
eμtu-Vector
Events
Data/Pred.
p_T(leading lepton) [GeV]
ΔR(e,μ)
p_T^miss [GeV]


CMS
138 fb^{-1} (13 TeV)
eμ
1 b-jet
Data
Other
tW
tt̄
Stat. ⊕ syst.
eμtc-Vector × 10
eμtu-Vector
Events
Data/Pred.
p$_T$(leading jet) [GeV]
CMS
138 fb^{-1} (13 TeV)
eμ
>1 b-jets
p$_T$(leading jet) [GeV]
CMS
138 fb^{-1} (13 TeV)
eμ
1 b-jet
Number of jets
CMS
138 fb^{-1} (13 TeV)
eμ
>1 b-jets
Number of jets


CMS
138 fb^{-1} (13 TeV)
eμ
1 b-jet
Data
Other
tW
$t\bar{t}$
Stat. ⊕ syst.
eμtc-Vector × 10
eμtu-Vector
Events
Data/Pred. Pre-fit
Data/Pred. Post-fit
BDT discriminant
CMS
138 fb^{-1} (13 TeV)
eμ
>1 b-jets
Data
Other
tW
$t\bar{t}$
Stat. ⊕ syst.
eμtc-Vector × 10
eμtu-Vector
Events
Data/Pred. Pre-fit
Data/Pred. Post-fit
BDT discriminant

Channel			1 b tagged	> 1 b tagged
$t\bar{t}$			477800 ± 7900	265000 ± 7100
tW			49100 ± 1300	7710 ± 250
Other			7950 ± 670	850 ± 70
Total background prediction			534900 ± 8000	273600 ± 7100
Data			537236	268781
$e\mu tu$	Vector	t decay	604 ± 2	45.2 ± 0.4
		t production	17103 ± 29	1557 ± 9
	Scalar	t decay	78.2 ± 0.2	6.1 ± 0.1
		t production	3670 ± 6	336 ± 2
	Tensor	t decay	3499 ± 9	266 ± 2
		t production	61011 ± 107	5567 ± 33
$e\mu tc$	Vector	t decay	596 ± 2	90.4 ± 0.5
		t production	1711 ± 3	166 ± 1
	Scalar	t decay	77.7 ± 0.2	11.4 ± 0.1
		t production	294 ± 1	28.5 ± 0.2
	Tensor	t decay	3467 ± 8	534 ± 3
		t production	6329 ± 13	621 ± 4

Source	$t\bar{t}$ (%)	CLFV signal	
		decay (%)	production (%)
Trigger	1.2	1.2	2.9
Electron identification and isolation	1.6	1.6	3.9
Muon identification and isolation	0.6	0.6	0.7
Electron energy scale and resolution	<0.1	<0.1	<0.1
Muon momentum scale and resolution	<0.1	<0.1	<0.1
Jet energy scale and resolution	2.5	2.1	1.2
b tagging	3.1	3.9	4.5
Pileup	0.3	0.3	0.2
ME scale	0.9	0.8	0.7
ISR/FSR scale	1.5	2.9	1.9
PDF	0.8	0.8	0.9
UE tune	0.4	—	—
ME/PS matching	<0.1	—	—
Color reconnection	1.0	—	—
MC statistical	<0.1	<0.1	<0.1