Testing the EFT paradigm with top quark final states in pp collisions at LHC with ATLAS and CMS

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on behalf of the ALTAS and CMS Collaborations

TOP2021

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ATLAS helper: Peter Berta

Effective field theory (EFT)

- So far no evidence of BSM physics at the LHC
- Direct detection might be out of range at $\Lambda \gg E_{\mathrm{LHC}}$

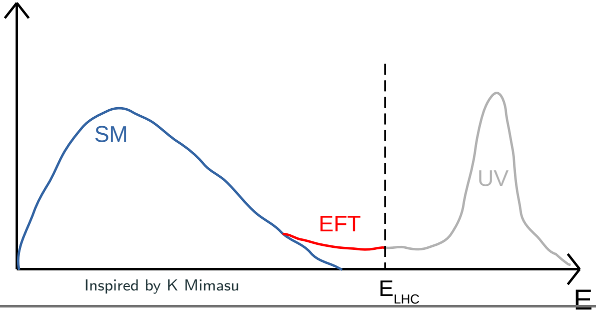
$\rightarrow$ Expand SM: $\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$

(here: dim-6 expansion, dim-5 and dim-7 would violate lepton/baryon numbers)

- Wilson coefficients c_i modify the SM vertices

$\rightarrow$ Deviations visible in SM precision measurements

- Model independent

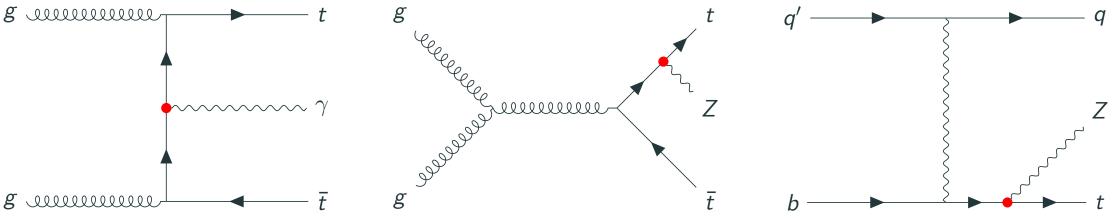


Inspired by K Mimasu

EFT interpretations

- In the top sector, EFT effects can be observed in various final states: $t\bar{t}$, $t\bar{t}Z$, $t\bar{t}\gamma$, $t\bar{t}H$, tZq, ...
- Two ways of using EFT:
  1. Re-parametrization of cross section measurements
  2. Dedicated EFT measurements

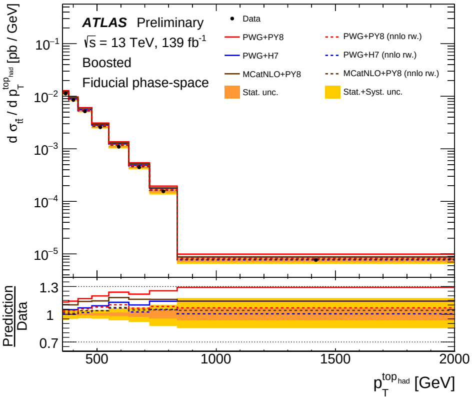
(This talk does not include spin-related observables or FCNC searches)



Boosted $t\bar{t}$ at ATLAS New at TOP2021!

[ATLAS-CONF-2021-031]

- Measurement of various $t\bar{t}$ observables in boosted regime
- Single lepton, 2 b-tagged jets, 1 top tag $\rightarrow$ $t\bar{t}$ purity $> 95\%$
- p_T of hadronically decaying top sensitive to c_{tG} and $c_{tq}^{(8)}$
- Jet energy scale calibrated using m_t
- Dominant uncertainties: $t\bar{t}$ modeling, b tagging, jet energy calibration

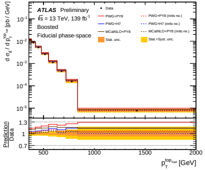


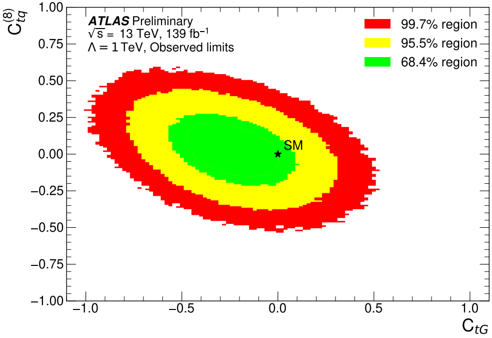
For analysis details see Johannes' talk and Luca's talk

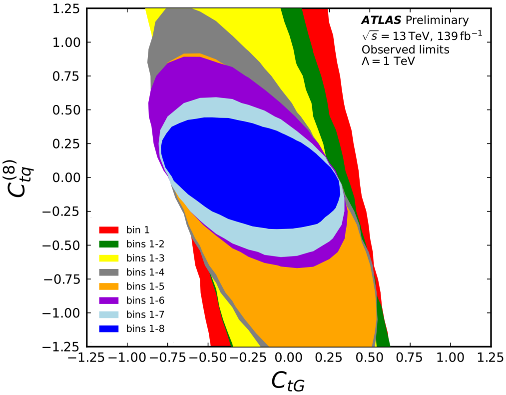
Boosted $t\bar{t}$ at ATLAS New at TOP2021!

[ATLAS-CONF-2021-031]

- Bin contents are parameterised as function of c_{tG} and $c_{tq}^{(8)}$
- c_{tG} sensitive to inclusive cross section
- $c_{tq}^{(8)}$ affects high-p_T region





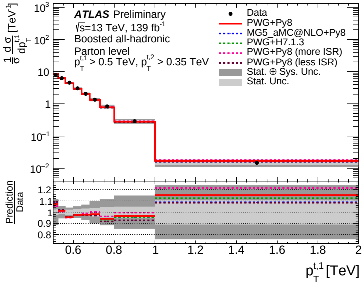


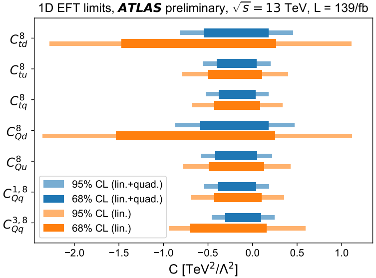
Boosted $t\bar{t}$ at ATLAS New at TOP2021!

[ATLAS-CONF-2021-66]

- Similar measurement in all-jets $t\bar{t}$
- 2 large-radius jets with $p_T > 500(350)$ GeV
- DNN top tagger
- Dominant uncertainties:
  statistics, jet-related, modeling
- EFT interpretation of unfolded p_T of had. top
- 1D and 2D limits

For analysis details see Johannes' talk

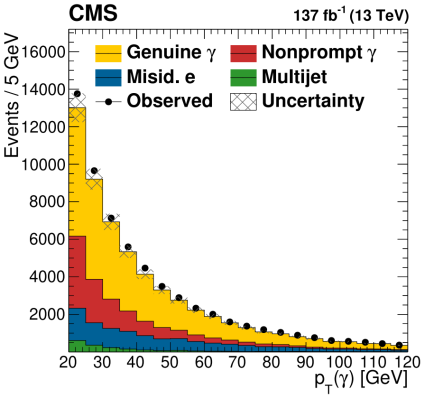




New at TOP2021!

- Single lepton channel
- Backgrounds:
  fake γ: no match to gen photon/electron
  misidentified e: match to gen electron
  QCD multijet: non-prompt lepton
- Exp. uncertainties:
  Photon identification, Jet energy scale and resolution, b tagging
- Modelling uncertainties:
  ISR/FSR modeling
- Background estimation uncertainties:
  Misidentified electrons, hadronic/fake photons, Wγ background estimation

For analysis details
see Josha's talk

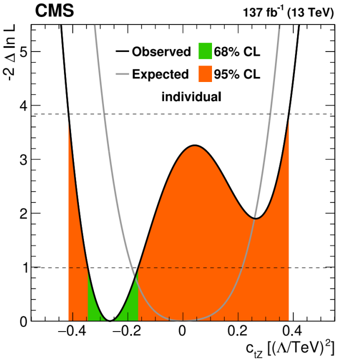


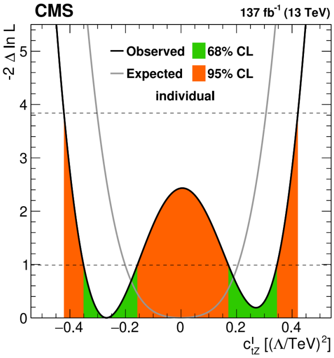
$t\bar{t}\gamma$ at CMS

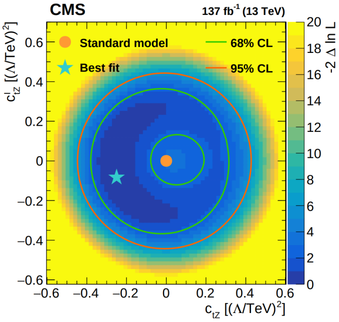
[CMS-TOP-18-010], Submitted to JHEP

New at TOP2021!

- EFT interpretation with $p_T(\gamma)$ at detector level
- Constraints on c_{tZ} and c^{I}_{tZ}
- Compatible cross section results from ATLAS but without EFT interpretation [JHEP 09 (2020) 049]







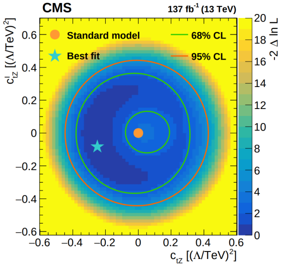
$t\bar{t}\gamma$ combination at CMS New at TOP2021!

[CMS-TOP-21-004]

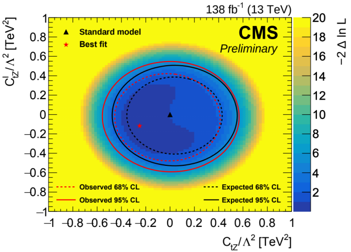
- Similar measurement in dilepton (e^+e^-, $\mu^+\mu^-$, $e^\pm\mu^\mp$)
- Dominant uncertainties: Statistical, luminosity, modeling
- Combination with single lepton tightens limits on c_{tZ} and c^I_{tZ}

→ Tightest constraints on c_{tZ} and c^I_{tZ}

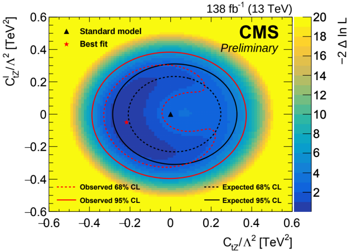
Single Lepton



Dilepton



Combination



For analysis details see Gianny's talk

Energy asymmetry in $t\bar{t}$ at ATLAS

[CERN-EP-2021-181]

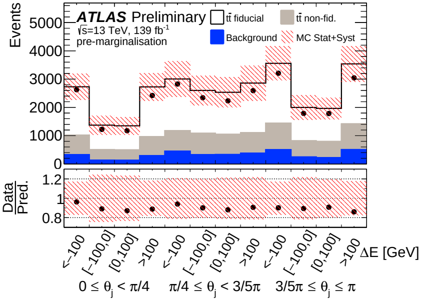
New at TOP2021!

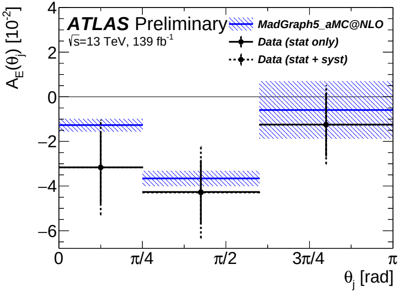
- Usually charge asymmetry measured as rapidity asymmetry
- Here: measure energy asymmetry in boosted $t\bar{t}$ +jet (single lepton)
- θ_j: angle of additional jet to z-axis
- $\Delta E = E_t - E_{\bar{t}}$: energy difference
- Top quark charge from lepton
- Define asymmetry:

$$A_E = \frac{\sigma(\theta_j|\Delta E>0) - \sigma(\theta_j|\Delta E<0)}{\sigma(\theta_j|\Delta E>0) + \sigma(\theta_j|\Delta E<0)}$$

- Statistical uncertainty dominates

For analysis details see Johannes' talk

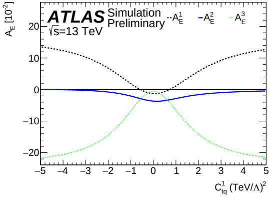


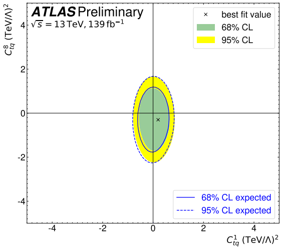


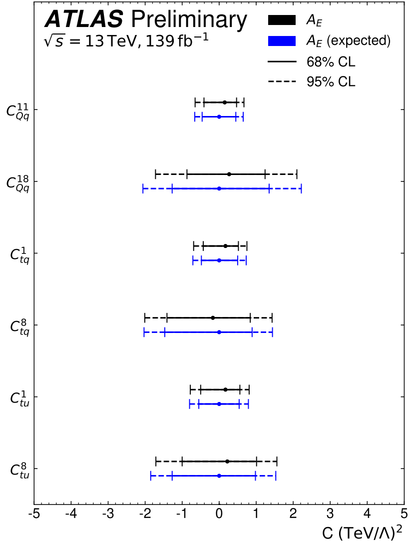
Energy asymmetry in $t\bar{t}$ at ATLAS
[CERN-EP-2021-181]

New at TOP2021!

- Paremetrize A_E as function of c_i
- 6 WCs found to be sensitive to A_E (A_E^i is A_E in bin i)
- 1D and 2D bounds



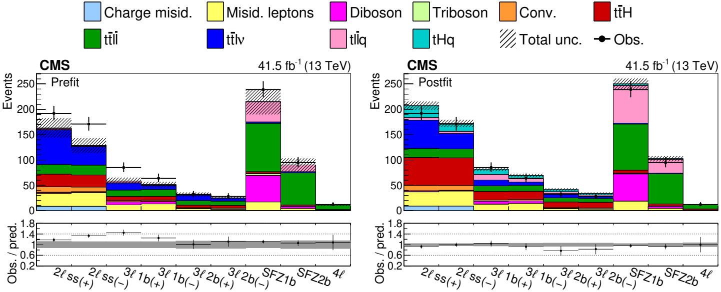




Top + additional leptons at CMS

[JHEP 03 (2021) 095]

- Signals: ttH, ttlν, ttll, tHq, tllq; multi-lepton analysis
- 35 signal regions (lepton channels + jet multiplicities)
- Testing 16 operators (split into ttV and ttll/ttlν)
- Direct extraction at detector level
- Background from non-prompt and charge mis-Id leptons estimated in data



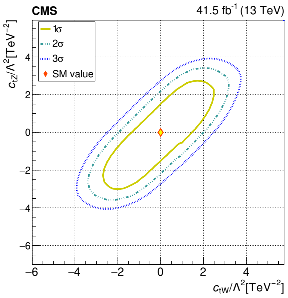
Operators involving two quarks and one or more bosons			
Operator	Definition	WC	Lead processes affected
$^{\ddagger}O_{u\varphi}^{(ij)}$	$\bar{q}_i u_j \tilde{\varphi}\,(\varphi^\dagger\varphi)$	$c_{t\varphi} + ic^I_{t\varphi}$	$t\bar{t}H$, tHq
$O_{\varphi q}^{1(ij)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_i\gamma^\mu q_j)$	$c^-_{\varphi Q} + c^3_{\varphi Q}$	$t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, tHq, $tl\bar{l}q$
$O_{\varphi q}^{3(ij)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{q}_i\gamma^\mu\tau^I q_j)$	$c^3_{\varphi Q}$	$t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, tHq, $tl\bar{l}q$
$O_{\varphi u}^{(ij)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_i\gamma^\mu u_j)$	$c_{\varphi t}$	$t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, $tl\bar{l}q$
$^{\ddagger}O_{\varphi ud}^{(ij)}$	$(\tilde{\varphi}^\dagger iD_\mu\varphi)(\bar{u}_i\gamma^\mu d_j)$	$c_{\varphi tb} + ic^I_{\varphi tb}$	$t\bar{t}H$, $tl\bar{l}q$, tHq
$^{\ddagger}O_{uW}^{(ij)}$	$(\bar{q}_i\sigma^{\mu\nu}\tau^I u_j)\,\tilde{\varphi}W^I_{\mu\nu}$	$c_{tW} + ic^I_{tW}$	$t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, tHq, $tl\bar{l}q$
$^{\ddagger}O_{dW}^{(ij)}$	$(\bar{q}_i\sigma^{\mu\nu}\tau^I d_j)\,\varphi W^I_{\mu\nu}$	$c_{bW} + ic^I_{bW}$	$t\bar{t}H$, $t\bar{t}l\bar{l}$, tHq, $tl\bar{l}q$
$^{\ddagger}O_{uB}^{(ij)}$	$(\bar{q}_i\sigma^{\mu\nu}u_j)\,\tilde{\varphi}B_{\mu\nu}$	$(c_W c_{tW} - c_{tZ})/s_W +$ $i(c_W c^I_{tW} - c^I_{tZ})/s_W$	$t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, tHq, $tl\bar{l}q$
$^{\ddagger}O_{uG}^{(ij)}$	$(\bar{q}_i\sigma^{\mu\nu}T^A u_j)\,\tilde{\varphi}G^A_{\mu\nu}$	$g_s(c_{tG} + ic^I_{tG})$	$t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, tHq, $tl\bar{l}q$

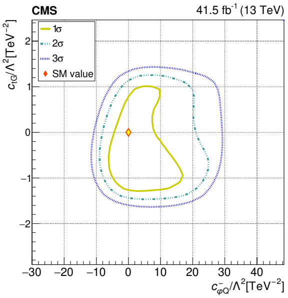
Operators involving two quarks and two leptons			
Operator	Definition	WC	Lead processes affected
$O_{\ell q}^{1(ijkl)}$	$(\bar{\ell}_i\gamma^\mu\ell_j)(\bar{q}_k\gamma^\mu q_\ell)$	$c^{-(\ell)}_{Q\ell} + c^{3(\ell)}_{Q\ell}$	$t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, $tl\bar{l}q$
$O_{\ell q}^{3(ijkl)}$	$(\bar{\ell}_i\gamma^\mu\tau^I\ell_j)(\bar{q}_k\gamma^\mu\tau^I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

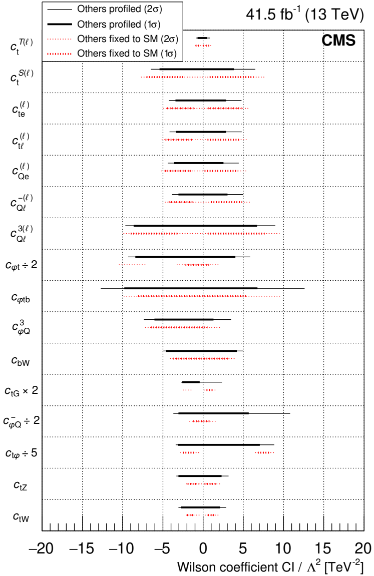
Top + additional leptons at CMS

[JHEP 03 (2021) 095]

- Obtain 1D and 2D limits
- Good agreement with SM
- Limiting uncertainties:
  - theory and modeling
  - jet energy scale, lepton identification and isolation, luminosity



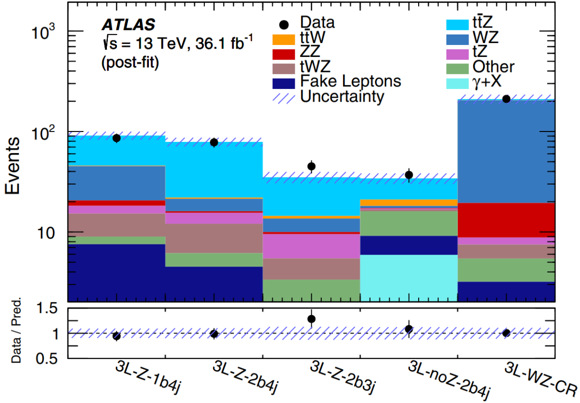


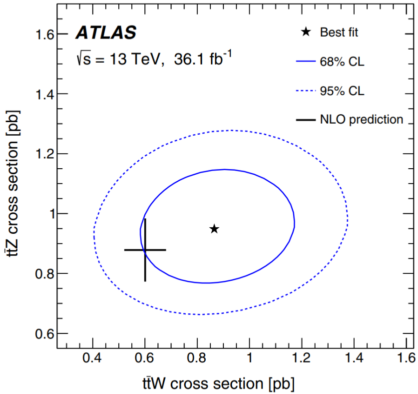


$t\bar{t}Z$ and $t\bar{t}W$ at ATLAS

[PHYS. REV. D 99, 072009 (2019)]

- Measurement of $t\bar{t}Z$ and $t\bar{t}W$ cross sections in 2ℓ, 3ℓ, 4ℓ regions
- Backgrounds: Z+jets, $t\bar{t}$ + non-prompt or misidentified leptons, WZ, ZZ
- Dominant uncertainties: Modeling of signal and backgrounds, b tagging

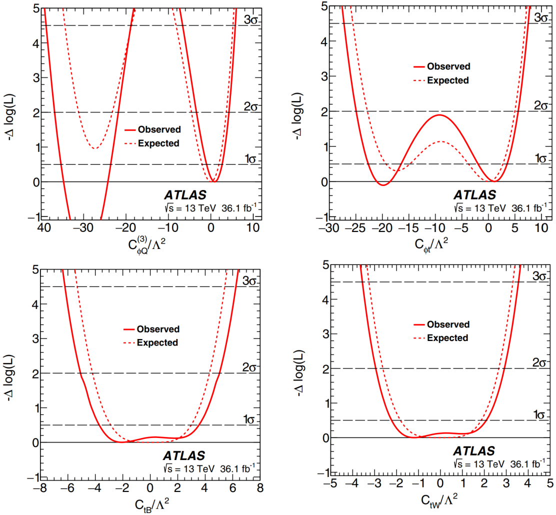




$t\bar{t}Z$ and $t\bar{t}W$ at ATLAS

[PHYS. REV. D 99, 072009 (2019)]

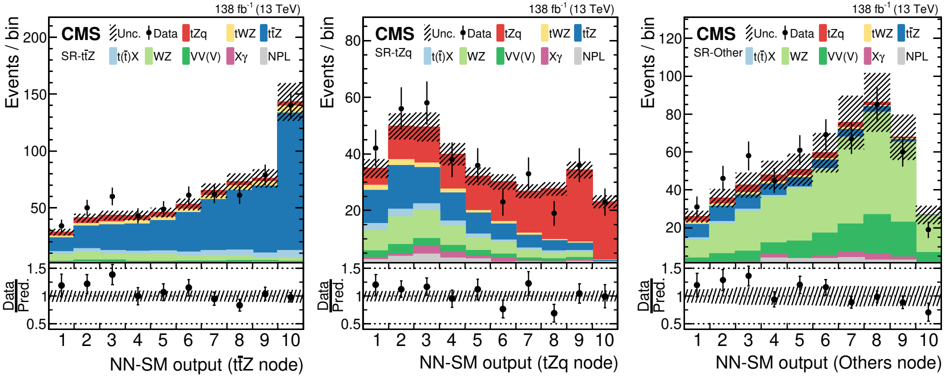
- Interpretation with re-parameterization of $\sigma_{t\bar{t}Z}$
- Operators: $\mathcal{O}_{\phi Q}^{(3)}, \mathcal{O}_{\phi Q}^{(1)}, \mathcal{O}_{\phi t}, \mathcal{O}_{tW}, \mathcal{O}_{tB}$ $(c_{\phi Q}^{(3)} - c_{\phi Q}^{(1)}$ evaluated with $c_{\phi Q}^{(1)} = 0)$
- Simultaneous fit of all $t\bar{t}Z$ regions
- One WC varied at a time



$t/t\bar{t}+Z$ at CMS   New at TOP2021!

[CMS-TOP-21-001]

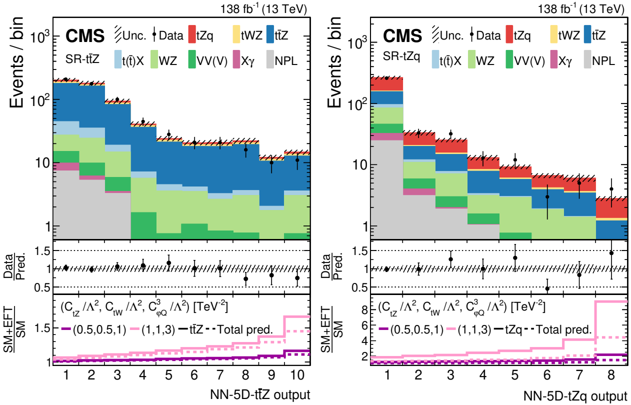
- Targeted signals: $t\bar{t}Z$, tZq, tWZ
- MVA distinguishes $t\bar{t}Z$ (+tWZ)/tZq/background processes
- 33 inputs: lepton/jet properties, b tagging, event observables
- Categorize by maximum value in output nodes



$t/t\bar{t}$ +Z at CMS New at TOP2021!

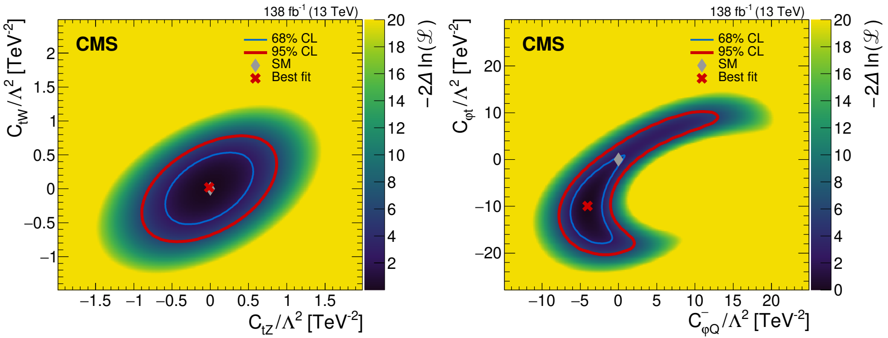
[CMS-TOP-21-001]

- A second MVA separates SM vs EFT scenarios (separately for $t\bar{t}$Z and tZq categories)
- 5 operators considered: $\mathcal{O}_{tZ}$, $\mathcal{O}_{tW}$, $\mathcal{O}^{3}_{\varphi Q}$, $\mathcal{O}^{-}_{\varphi Q}$, $\mathcal{O}_{\varphi t}$
- Training for single operators and simultaneously (5D)



$t/t\bar{t}$ +Z at CMS   New at TOP2021!

[CMS-TOP-21-001]

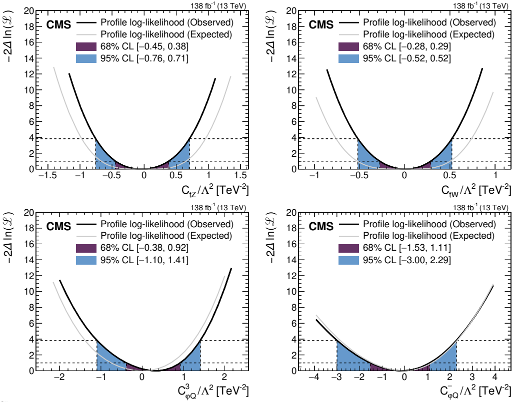


- 2D scans of log-likelihood (all other coefficients set to 0)
- No deviation from SM observed
- Improved limits of previous $t\bar{t}Z$ measurement [JHEP 03 (2020) 056]

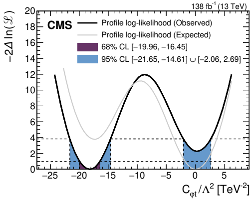
$t/t\bar{t}$ +Z at CMS   New at TOP2021!

[CMS-TOP-21-001]

- Extraction of WC limits in 1D and 5D
- Limiting uncertainties:
  - theory
  - non-prompt lepton systematics



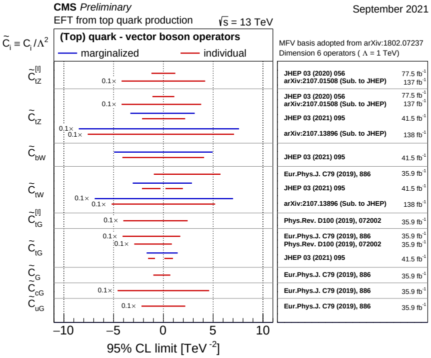
WC/Λ^2 [TeV^{-2}]	95% CL confidence intervals			
	Other WCs fixed to SM		5D fit	
	Expected	Observed	Expected	Observe
c_{tZ}	$[-0.97, 0.96]$	$[-0.76, 0.71]$	$[-1.24, 1.17]$	$[-0.85, 0.76]$
c_{tW}	$[-0.76, 0.74]$	$[-0.52, 0.52]$	$[-0.96, 0.93]$	$[-0.69, 0.70]$
$c^3_{\varphi Q}$	$[-1.39, 1.25]$	$[-1.10,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

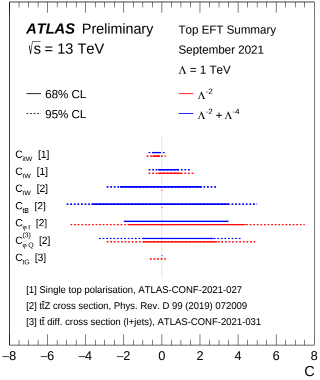


Summary

[ATLAS Summary Figures], [CMS Summary Figures]

- LHC has entered precision era and we can use EFT as a tool to interpret SM measurements
- Already dedicated EFT analyses in place
- ATLAS and CMS have provided excellent measurements in the top sector
- Many more analyses to come!





More summary plots: [CMS], [ATLAS]

additional material

$t\bar{t}\gamma$ at CMS

[CMS-TOP-18-010]

	Source	Correlation	Uncertainty [%] yield	Uncertainty [%] $\sigma(t\bar{t}\gamma)$
Experimental	Integrated luminosity	partial	2.3–2.5	1.8
	Pileup	100%	0.5–2.0	<0.5
	Trigger efficiency	—	<0.5	<0.5
	Electron reconstruction and identification	100%	0.2–1.7	<0.5
	Muon reconstruction and identification	partial	0.5–0.7	0.7
	Photon reconstruction and identification	100%	0.4–1.4	1.0
	$p_T(e)$ and $p_T(\gamma)$ reconstruction	100%	0.1–1.2	<0.5
	JES	partial	1.0–4.1	1.9
	JER	—	0.4–1.6	0.6
	b tagging	100% (2017/2018)	0.8–1.6	1.1
	L1 prefiring	100% (2016/2017)	0.3–0.9	<0.5
Theoretical	Tune	100%	0.1–1.9	<0.5
	Color reconnection	100%	0.4–3.6	0.6
	ISR/FSR	100%	1.0–5.6	1.9
	PDF	100%	<0.5	<0.5
	ME scales μ_R, μ_F	100%	0.4–4.7	<0.5
Background	Multijet normalization	100%	1.3–6.5	0.9
	Nonprompt photon background	100%	1.2–2.7	2.0
	Misidentified e	—	2.5–8.0	1.8
	$Z\gamma$ normalization	100%	0.6–2.5	0.5
	$W\gamma$ normalization	100%	1.0–3.5	2.4
	DY normalization	100%	0.1–1.1	1.0
	$t\bar{t}$ normalization	100%	1.0–1.9	1.0
	"Other" bkg. normalization	100%	0.3–1.0	<0.5
	Total systematic uncertainty			5.7
	Statistical uncertainty			0.9
	Total			5.8

	Wilson coefficient		68% CL interval $(\Lambda/\text{TeV})^2$	95% CL interval $(\Lambda/\text{TeV})^2$
Expected	c_{tZ}	$c^I_{tZ} = 0$	[−0.19, 0.21]	[−0.29, 0.32]
		profiled	[−0.19, 0.21]	[−0.29, 0.32]
	c^I_{tZ}	$c_{tZ} = 0$	[−0.20, 0.20]	[−0.30, 0.31]
		profiled	[−0.20, 0.20]	[−0.30, 0.31]
Observed	c_{tZ}	$c^I_{tZ} = 0$	[−0.35, −0.16]	[−0.42, 0.38]
		profiled	[−0.35, 0.07]	[−0.42, 0.39]
	c^I_{tZ}	$c_{tZ} = 0$	[−0.35, −0.16], [0.17, 0.35]	[−0.42, 0.42]
		profiled	[−0.32, 0.31]	[−0.41, 0.41]

Boosted $t\bar{t}$ at ATLAS

[ATLAS-CONF-2021-031]

Source	Uncertainty [%]	Uncertainty [%] (no JSF)
Statistical (data)	±0.4	±0.4
JSF statistical (data)	±0.4	—
Statistical (MC)	±0.2	±0.1
Hard scatter	±0.5	±0.8
Hadronisation	±2.0	±1.8
Radiation (IFSR + h_{damp})	$^{+1.0}_{-1.6}$	$^{+1.4}_{-2.3}$
PDF	±0.1	±0.1
Top-quark mass	$^{+0.8}_{-1.1}$	±0.1
Jets	±0.7	±4.2
b-tagging	±2.4	±2.4
Leptons	±0.8	±0.8
$E_{\mathrm{T}}^{\mathrm{miss}}$	±0.1	±0.1
Pileup	±0.4	±0.0
Luminosity	±1.8	±1.8
Backgrounds	±0.7	±0.6
Total systematics	$^{+4.1}_{-4.3}$	$^{+5.8}_{-6.0}$
Total	$^{+4.1}_{-4.3}$	$^{+5.8}_{-6.0}$

Wilson coefficient	Marginalised 95% intervals		Individual 95% intervals		
	Expected	Observed	Expected	Observed	Global fit [99]
C_{tG}	[-0.44, 0.44]	[-0.68, 0.21]	[-0.41, 0.42]	[-0.63, 0.20]	[0.007, 0.111]
$C_{tq}^{(8)}$	[-0.35, 0.35]	[-0.30, 0.36]	[-0.35, 0.36]	[-0.34, 0.27]	[-0.40, 0.61]

Energy asymmetry in $t\bar{t}$ at ATLAS

[CERN-EP-2021-181]

Scenario	$\Delta A_E\,[10^{-2}]$ $0 \leq \theta_j < \frac{\pi}{4}$	$\Delta A_E\,[10^{-2}]$ $\frac{\pi}{4} < \theta_j \leq \frac{3\pi}{5}$	$\Delta A_E\,[10^{-2}]$ $\frac{3\pi}{5} \leq \theta_j \leq \pi$
Data stat.	1.60	1.40	1.40
$t\bar{t}$ modeling	0.08	0.87	0.34
$t\bar{t}$ response MC stat	0.51	0.42	0.42
W+jets modeling and PDF	0.29	0.49	0.42
Single top modeling	0.28	0.60	0.29
$t\bar{t}$ and single top PDF	0.08	0.10	0.07
Multijet	0.53	0.54	0.51
Jet energy resolution	0.98	0.40	0.36
Other detector uncertainties	0.42	0.43	0.30
Total	2.10	2.00	1.80

$C\,(\text{TeV}/\Lambda)^2$	$A_E\ (\Lambda^{-4})$ 68% CL	$A_E\ (\Lambda^{-4})$ 95% CL	$A_E\ (\Lambda^{-2})$ 68% CL	$A_E\ (\Lambda^{-2})$ 95% CL
C^{11}_{Qq}	$[-0.41, 0.47]$	$[-0.65, 0.67]$	$[-0.68, 4.06]$	$[-3.36, 6.16]$
C^{18}_{Qq}	$[-0.87, 1.24]$	$[-1.72, 2.10]$	$[-1.26, 4.76]$	$[-3.24, 9.64]$
C^{1}_{tq}	$[-0.43, 0.52]$	$[-0.69, 0.75]$	$[-0.60, 5.76]$	$[-3.42, 9.36]$
C^{8}_{tq}	$[-1.41, 0.84]$	$[-2.01, 1.43]$	$[-1.86, 1.70]$	$[-3.30, 3.98]$
C^{1}_{tu}	$[-0.50, 0.56]$	$[-0.78, 0.81]$	$[-0.96, 5.82]$	$[-4.72, 8.88]$
C^{8}_{tu}	$[-1.00, 1.01]$	$[-1.71, 1.56]$	$[-1.30, 2.52]$	$[-3.02, 4.66]$

Top + additional leptons at CMS

[JHEP 03 (2021) 095]

Source	Type	c_{tW}	$c_{t\varphi}$	$c_{Q\ell}^{-(\ell)}$	$c_{t\ell}^{(\ell)}$
Integrated luminosity	rate	6%	2%	1%	<1%
JES	rate+shape	6%	2%	1%	<1%
b jet tag		1%	5%	8%	<1%
b jet tag HF fraction	rate+shape				
b jet tag HF stats (linear)	rate+shape				
b jet tag HF stats (quadratic)	rate+shape				
b jet tag LF fraction	rate+shape				
b jet tag LF stats (linear)	rate+shape				
b jet tag LF stats (quadratic)	rate+shape				
c jet mistag		<1%	12%	8%	2%
b jet tag charm (linear)	rate+shape				
b jet tag charm (quadratic)	rate+shape				
PDF (gg)	rate	1%	<1%	<1%	<1%
PDF ($gg_{t\bar{t}H}$)	rate	<1%	1%	<1%	<1%
PDF ($q\bar{q}$)	rate	1%	<1%	<1%	<1%
PDF (qg_{tHq})	rate	<1%	<1%	<1%	<1%
$\mu_{R,F}$ scale ($t\bar{t}H$)	rate	2%	5%	<1%	<1%
$\mu_{R,F}$ scale ($t\bar{t}\gamma$)	rate	1%	1%	<1%	<1%
$\mu_{R,F}$ scale ($t\bar{t}V$)	rate	15%	4%	1%	<1%
$\mu_{R,F}$ scale (tHq)	rate	1%	1%	<1%	<1%
$\mu_{R,F}$ scale (V)	rate	<1%	<1%	<1%	<1%
$\mu_{R,F}$ scale (VV)	rate	<1%	<1%	<1%	<1%
$\mu_{R,F}$ scale (VVV)	rate	<1%	<1%	<1%	<1%
PDF	shape	2%	1%	<1%	<1%
$\mu_{R,F}$ scales	shape	<1%	6%	1%	<1%
FSR	rate+shape	1%	11%	7%	2%
ISR	rate+shape	<1%	8%	3%	<1%
Parton matching	rate+shape	1%	10%	5%	1%
Additional radiation	rate+shape	11%	3%	1%	<1%
Lepton ident./isol.	rate+shape	4%	2%	<1%	<1%
Trigger efficiency	rate+shape	2%	1%	<1%	1%
Pileup	rate+shape	1%	1%	<1%	<1%
Lepton misident.	rate+shape	2%	70%	29%	<1%
Lepton misident. (stat)	rate+shape				
Charge misident.	rate	3%	2%	<1%	<1%

WC/Λ^2[TeV^{-2}]	2σ interval (others profiled)	2σ interval (others fixed to SM)
c_{tW}	[−3.08, 2.87]	[−2.15, −0.29]∪[0.21, 1.96]
c_{tZ}	[−3.32, 3.15]	[−2.14, 2.19]
$c_{t\varphi}$	[−16.98, 44.26]	[−14.12, −1.46]∪[32.30, 44.48]
$c_{\varphi Q}^{-}$	[−7.59, 21.65]	[−3.45, 3.33]
c_{tG}	[−1.38, 1.18]	[−1.26, −0.69]∪[0.08, 0.79]
c_{bW}	[−4.95, 4.95]	[−4.12, 4.09]
$c_{\varphi Q}^{3}$	[−7.37, 3.48]	[−7.21, 2.25]
$c_{\varphi tb}$	[−12.72, 12.63]	[−9.87, 9.67]
$c_{\varphi t}$	[−18.62, 12.31]	[−20.91, −14.10]∪[−6.52, 4.24]
$c_{Q\ell}^{3(\ell)}$	[−9.67, 8.97]	[−9.91, 9.50]
$c_{Q\ell}^{-(\ell)}$	[−4.02, 4.99]	[−4.76, 5.83]
$c_{Qe}^{(\ell)}$	[−4.38, 4.59]	[−5.20, 5.36]
$c_{t\ell}^{(\ell)}$	[−4.29, 4.82]	[−5.15, 5.51]
$c_{te}^{(\ell)}$	[−4.24, 4.86]	[−4.97, 5.80]
$c_{t}^{S(\ell)}$	[−6.52, 6.52]	[−7.70, 7.70]
$c_{t}^{T(\ell)}$	[−0.84, 0.84]	[−1.01, 1.01]

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

$t\bar{t}Z$ and $t\bar{t}W$ at ATLAS

[PHYS. REV. D 99, 072009 (2019)]

Uncertainty	$\sigma_{t\bar{t}Z}$	$\sigma_{t\bar{t}W}$
Luminosity	2.9%	4.5%
Simulated sample statistics	2.0%	5.3%
Data-driven background statistics	2.5%	6.3%
JES/JER	1.9%	4.1%
Flavor tagging	4.2%	3.7%
Other object-related	3.7%	2.5%
Data-driven background normalization	3.2%	3.9%
Modeling of backgrounds from simulation	5.3%	2.6%
Background cross sections	2.3%	4.9%
Fake leptons and charge misID	1.8%	5.7%
$t\bar{t}Z$ modeling	4.9%	0.7%
$t\bar{t}W$ modeling	0.3%	8.5%
Total systematic	10%	16%
Statistical	8.4%	15%
Total	13%	22%

Coefficients	$C^{(3)}_{\phi Q}/\Lambda^2$	$C_{\phi t}/\Lambda^2$	C_{tB}/Λ^2	C_{tW}/Λ^2
Previous indirect constraints at 68% C.L.	$[-4.7, 0.7]$	$[-0.1, 3.7]$	$[-0.5, 10]$	$[-1.6, 0.8]$
Previous direct constraints at 95% C.L.	$[-1.3, 1.3]$	$[-9.7, 8.3]$	$[-6.9, 4.6]$	$[-0.2, 0.7]$
Expected limit at 68% C.L.	$[-2.1, 1.9]$	$[-3.8, 2.7]$	$[-2.9, 3.0]$	$[-1.8, 1.9]$
Expected limit at 95% C.L.	$[-4.5, 3.6]$	$[-23, 4.9]$	$[-4.2, 4.3]$	$[-2.6, 2.6]$
Observed limit at 68% C.L.	$[-1.0, 2.7]$	$[-2.0, 3.5]$	$[-3.7, 3.5]$	$[-2.2, 2.1]$
Observed limit at 95% C.L.	$[-3.3, 4.2]$	$[-25, 5.5]$	$[-5.0, 5.0]$	$[-2.9, 2.9]$
Expected limit at 68% C.L. (linear)	$[-1.9, 2.0]$	$[-3.0, 3.2]$	...	...
Expected limit at 95% C.L. (linear)	$[-3.7, 4.0]$	$[-5.8, 6.3]$	...	...
Observed limit at 68% C.L. (linear)	$[-1.0, 2.9]$	$[-1.8, 4.4]$	...	...
Observed limit at 95% C.L. (linear)	$[-2.9, 4.9]$	$[-4.8, 7.5]$	...	...

(Quadratic term dominant for c_{tW} and c_{tB})