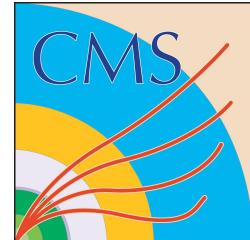


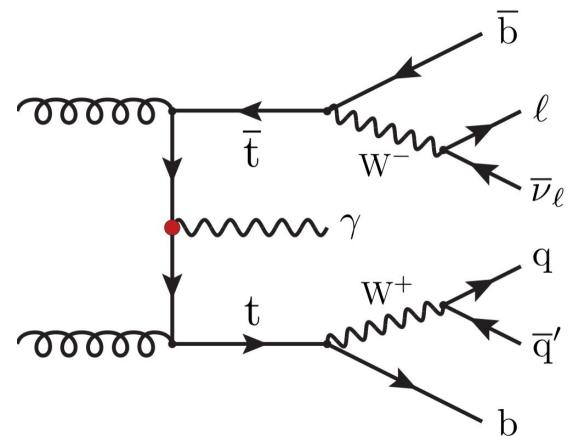
Latest $t\bar{t}+\gamma$ results from CMS and comparison with ATLAS

Lukas Lechner* (HephY, Vienna), Carmen Diez Pardos (U. Siegen)
on behalf of the CMS and ATLAS Collaborations



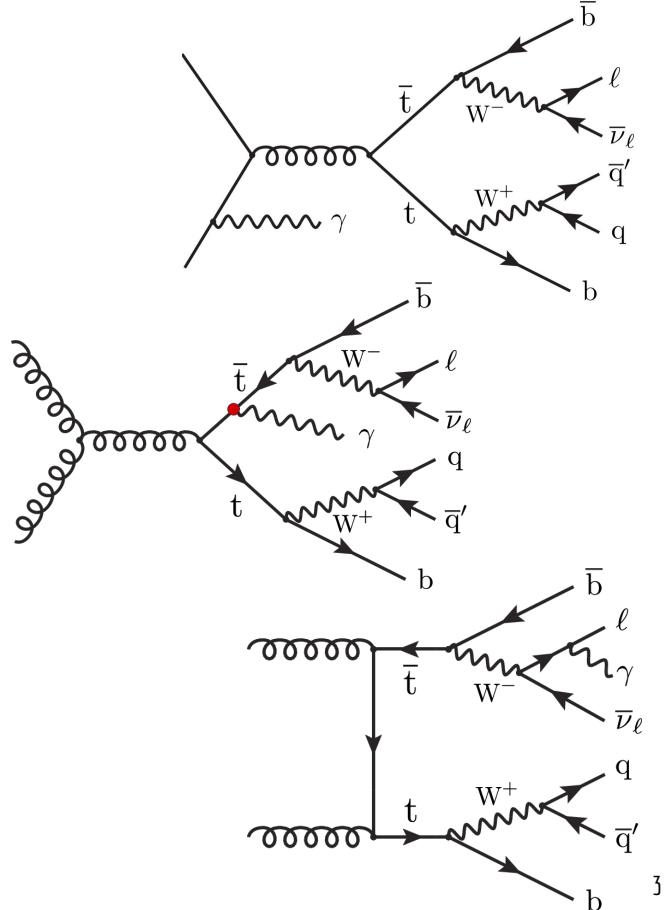
Introduction

- Inclusive and differential cross section measurement of $t\bar{t}+\gamma$ in the l+jets channel
 - First measurement of $t\bar{t}+\gamma$ at 13 TeV from CMS
 - Current data set allows for a detailed study of the production of $t\bar{t}+\gamma$
 - Unfolding of several differential distributions to particle level
- SM effective field theory interpretation of the result
 - Direct access of the EWK coupling of the top quark
 - Probes the $t\gamma$ coupling, very sensitive probe of new physics
- Comparison to $t\bar{t}+\gamma$ ATLAS results at 13 TeV
 - l+jets, dilepton channel using a data set of 36.1 fb^{-1} (2016)
[\(Eur. Phys. J. C 79 \(2019\) 5, 382\)](#)
 - ee channel using a data set of 139 fb^{-1} (Run 2)
[\(JHEP 09 \(2020\) 049\)](#)



Signal Simulation

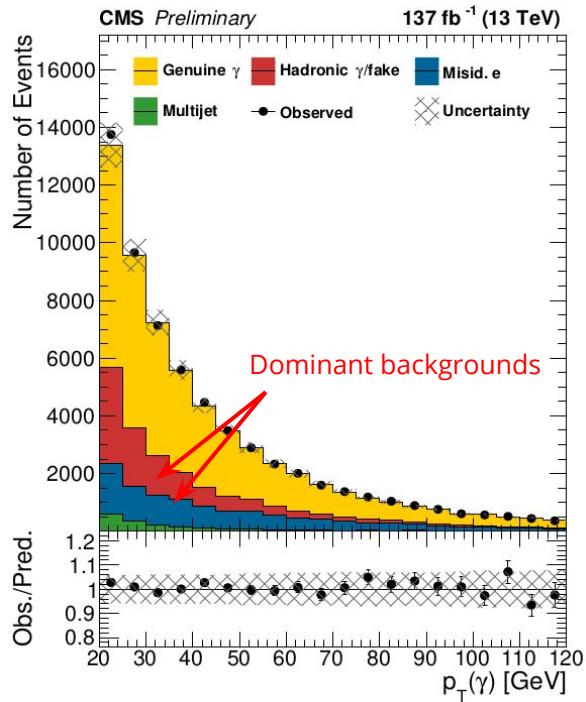
- **Signal Simulation using Madgraph_aMC@NLO**
 - Interfaced with Pythia8 using CP5 Tune
- **Simulated $2 \rightarrow 7$ process w/ photon originating from**
 - Initial state quark, top quark or any top decay product
 - Overlapping phase space in ttbar due to photons from showering removed
- **Simulated at LO, cross section normalized to NLO (QCD)**
 - NLO/LO k-factor calculation using Madgraph_aMC@NLO in a $2 \rightarrow 3$ process, k-factor of 1.49 inclusive in the lepton channels
 - Cross section prediction from simulation
 - 17.5% theory uncertainty from scale/PDF/ α_s variations
 - $\sigma_{\text{pred.}} (\text{tt}\gamma) = 773 \pm 135 \text{ fb}$



Event Selection

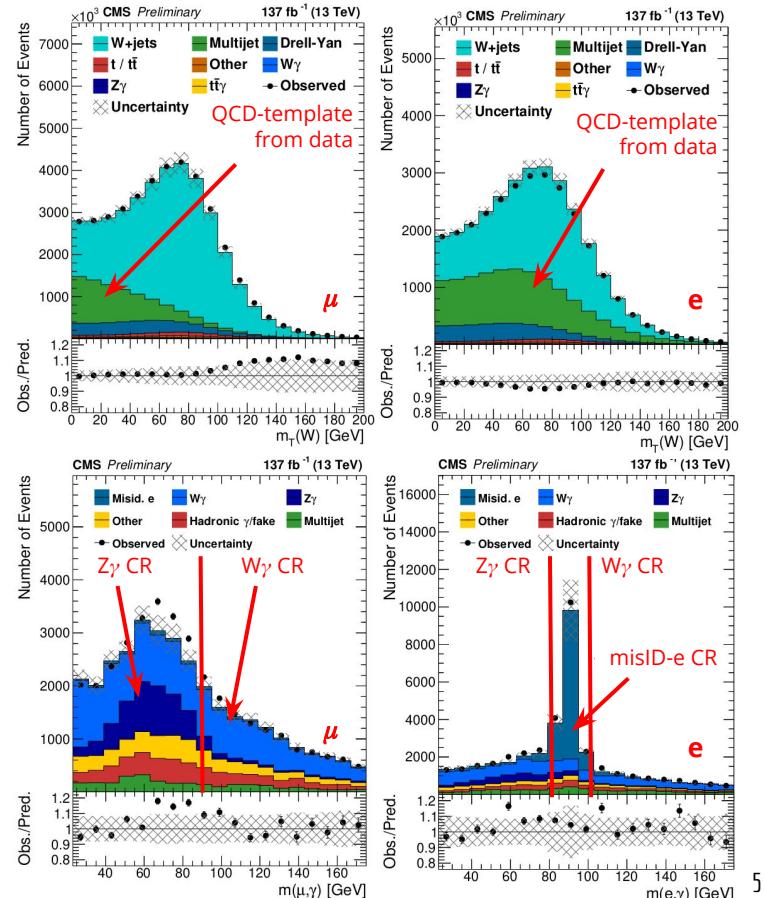
- **$t\bar{t}+\gamma$ signal region selection**
 - Exactly one isolated e (μ) ($p_T > 35$ (30) GeV, $|\eta| < 2.4$)
 - Exactly one isolated photon ($p_T > 20$ GeV, $|\eta| < 1.4442$)
 - At least three jets ($p_T > 30$ GeV, $|\eta| < 2.4$)
 - At least one of the jets originates from a b-quark
 - $\Delta R(\gamma, l) > 0.4$, $\Delta R(\gamma, \text{jets}) > 0.1$, $\Delta R(l, \text{jets}) > 0.4$

- **Event categorization**
 - **Genuine γ :** photon from ISR, top or top decay products
 - **Misidentified e:** photon with electron gen-match
 - **Hadronic γ / fake:** nonprompt γ or no γ/e gen-match
 - **QCD multijet:** nonprompt lepton



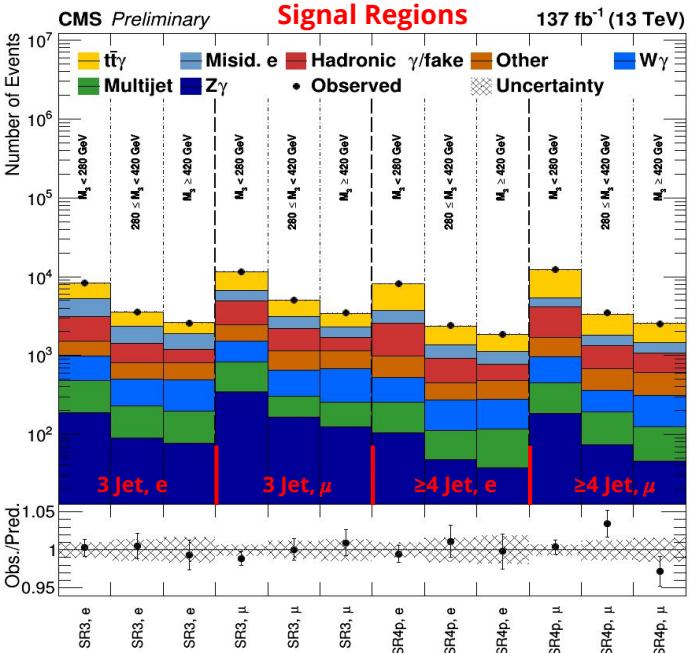
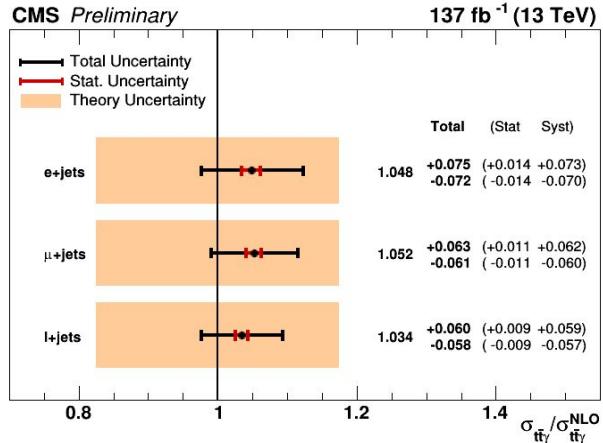
Background Estimation

- **QCD multijet background**
 - Estimated in sidebands with loosened lepton isolation criteria, validated in $N_\gamma = 0$ selections
 - Transfer factor measured in a template fit in the transverse W boson candidate mass $m_T(W)$
- **Hadronic γ /fake background**
 - ABCD method using sidebands with loosened criteria on the ECAL shower shape observable $\sigma_{\eta\eta}$ and the photon charged-hadron isolation
- **Misidentified electron and $W\gamma/Z\gamma$ background**
 - $N_{b\text{-jet}} = 0$ selection dominated by $W\gamma/Z\gamma/\text{misID-e}$ events
 - Invariant mass of the lepton and the photon $m(l,\gamma)$ used to separate processes



Results - Inclusive Cross Section Measurement

- Inclusive cross section extracted fitting control and signal regions** in bins of 3 jet and ≥ 4 jet selections in e/μ channel
- Signal regions binned in 3 bins of the 3-jet invariant mass M_{3j}
- 5.8% total uncertainty**
- Dominant uncertainties** from signal modelling, background estimation, photon identification and jet energy scale



$$\sigma_{\text{fid}}(\text{tt}\gamma) = 800 \pm 46 \text{ (syst)} \pm 7 \text{ (stat)} \text{ fb}$$

Systematic Uncertainties

- **Dominant experimental uncertainty sources:**

- Photon identification
- Jet energy scale and resolution
- B-tagging

- **Dominant modelling uncertainty sources:**

- ISR/FSR modelling

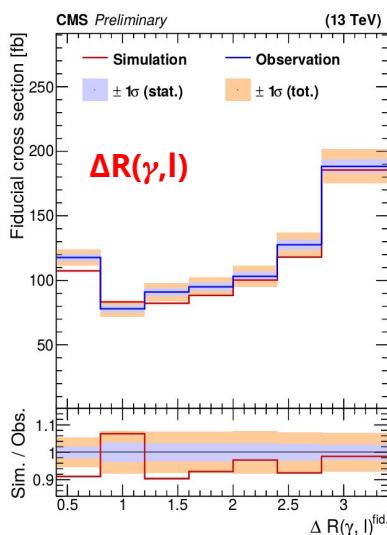
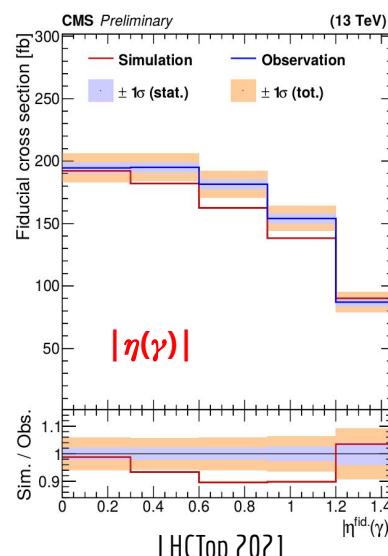
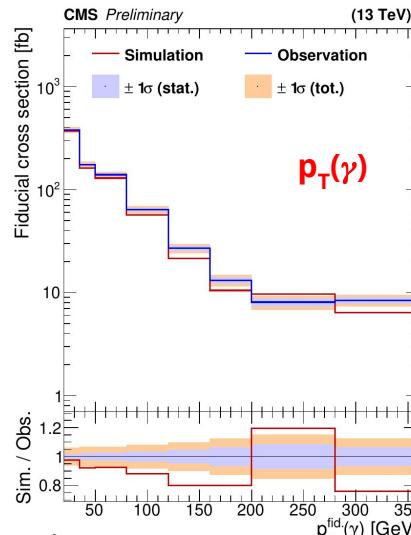
- **Dominant background estimation uncertainty sources:**

- Misidentified electron estimation
- Hadronic/fake photon estimation
- $W\gamma$ background estimation

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

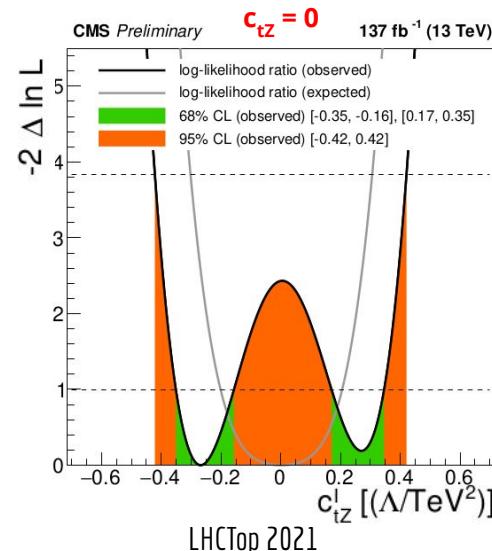
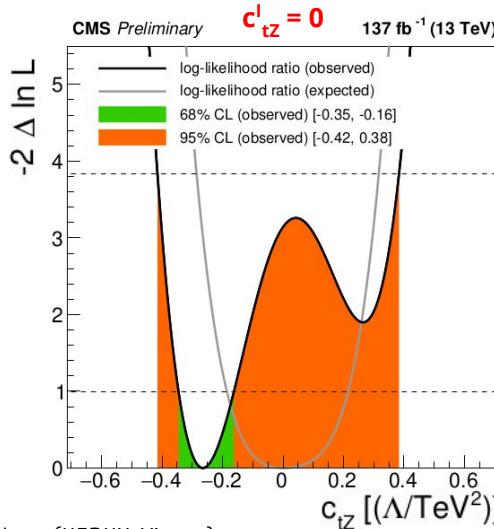
Results - Differential Cross Section Measurement

- **Unfolded postfit differential distributions in $p_T(\gamma)$, $|\eta(\gamma)|$ and $\Delta R(\gamma, l)$ to particle level**
 - Unfolding of single postfit uncertainty sources, summed taking correlations into account
- The detector response matrix is almost diagonal → **unregularized unfolding**
- Measured differential cross sections are **compared to NLO in QCD calculations**
 - Good agreement with simulations using MadGraph5MC@NLO + Pythia8



SMEFT Interpretation

- SMEFT interpretation** of dim-6 operators
- Constraining **2 Wilson coefficients** (c_{tz} , c_{tz}^I) using the dim6top SMEFT model
- $p_T(\gamma)$ distribution is found to be most sensitive to modified $t\gamma$ couplings
- Standard Model within the 95% CL interval** of the best fit value

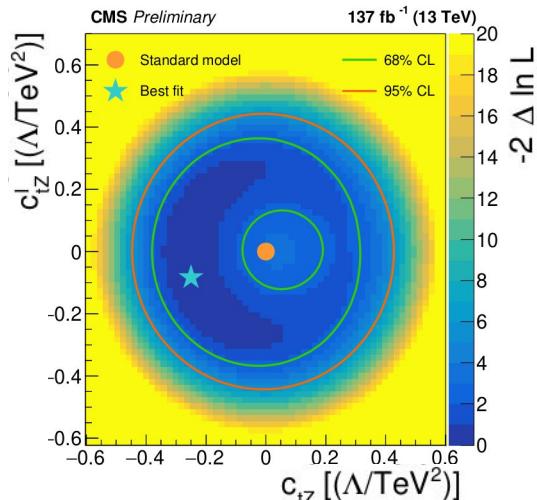
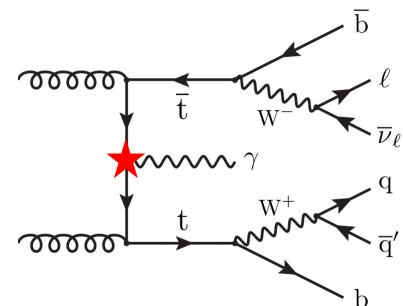


$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda} \sum_i c_i \mathcal{O}_i + \frac{1}{\Lambda^2} \sum_j c_j \mathcal{O}_j$$

Wilson coefficient

dim-6 operator

energy scale



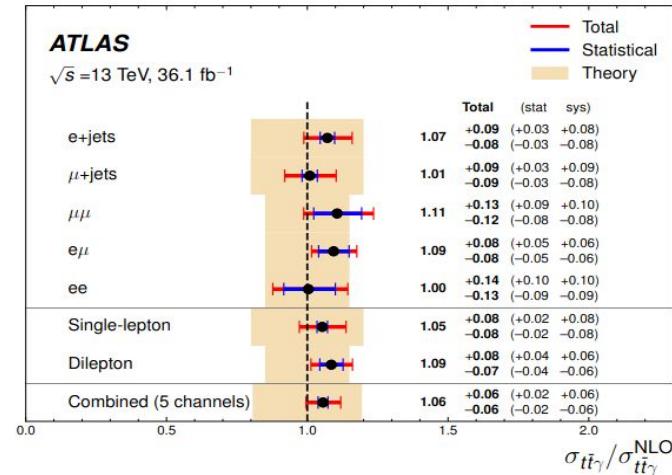
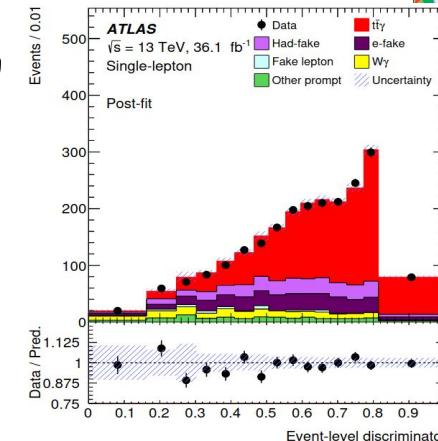
Comparison to ATLAS 2016 Results

- Comparison to l+jets ATLAS 2016 results**
 - Similar signal simulation using $2 \rightarrow 7$ process
 - ATLAS: NLO/LO k-factor from theory calculations (M.Schulze)
 - ATLAS k-factors: 1.30 (l+jets) and 1.44 (dilepton)
 - CMS k-factor: 1.49 (combined)
 - Differences in the object/event selection (next slides)
 - Differences in the background estimation methods (next slides)
- Fiducial cross-section extraction by fitting event level discriminator (ELD) output**
 - NN trained with N_{jet} , $p_T(\text{jet})$, b-tag scores, MET, $m(l,\gamma)$, PPT
 - Dom. systematics: JES, signal modelling, PU, PPT
 - 8.1% (7.0%) total uncertainty in l+jets (dilepton)

- Similar good agreement with NLO (QCD) predictions**

$$\sigma_{\text{fid}}^{\text{SL}}(t\bar{t}\gamma) = 521 \pm 41 \text{ (syst)} \pm 9 \text{ (stat)} \text{ fb}$$

$$\sigma_{\text{fid}}^{\text{DL}}(t\bar{t}\gamma) = 69 \pm 4 \text{ (syst)} \pm 3 \text{ (stat)} \text{ fb}$$



Comparison to ATLAS 2016 Results

ATLAS background estimation methods

- ABCD method for **fake photon background** normalization
 - Prompt photon tagger (PPT) for fake photon background separation
- Tag and probe method for **misidentified electrons** in two control regions using the $Z \rightarrow ee$ process
- Validation regions for **$V\gamma$ background**
 - Free parameter for $W\gamma$ normalization in the fit: good separation from signal by ELD
 - $W\gamma$ validation region: $N_{\text{jet}} = 2$ (3), $N_{\text{b-jet}} = 1$, $E_T^{\text{miss}} > 40 \text{ GeV}$, $\text{ELD} < 0.04$, $m(l,\gamma) < 80 \text{ GeV}$
- **Fake lepton background:** loose to tight lepton fit
 - Fake lepton and real lepton efficiency factors

CMS background estimation methods

- ABCD method for **fake photon background** normalization
- In situ measurement of **misidentified electrons** processes in control regions using the $Z \rightarrow ee$ process
- In situ measurement of **$V\gamma$ processes** in control regions
 - Free parameter for $W\gamma$ normalization in the fit: good separation in control regions
 - $W\gamma$ control region: $N_{\text{jet}} = 3$ (≥ 4), $N_{\text{b-jet}} = 0$, $m(\mu,\gamma) > m_Z$ or $m(e,\gamma) > m_Z + 10 \text{ GeV}$
- **Fake lepton background** from loose lepton Isolation sidebands, TF from $m_T(W)$ fit to data

Comparison to ATLAS 2016 Results

- **Comparison of the object selections between ATLAS and CMS**
 - Reflects the fiducial phase space definition

	CMS 13 TeV	ATLAS 13 TeV
Photon	$p_T(\gamma) > 20 \text{ GeV}$ $ \eta(\gamma) < 1.4442$	$ \eta(\gamma) < 2.37$
e	$p_T(e) > 35 \text{ GeV}$ $ \eta(e) \in [0, 1.44], [1.57, 2.4]$	$p_T(e) > 25 \text{ GeV}$ $ \eta(e) \in [0, 1.37], [1.52, 2.47]$
μ	$p_T(\mu) > 30 \text{ GeV}$ $ \eta(\mu) < 2.4$	$p_T(\mu) > 25 \text{ GeV}$ $ \eta(\mu) < 2.5$
Jets	$p_T(j) > 30 \text{ GeV}$ $ \eta(j) < 2.4$	$p_T(j) > 25 \text{ GeV}$ $ \eta(j) < 2.5$
Photon/Lepton	$\Delta R(\ell, \gamma) > 0.4$	$\Delta R(\ell, \gamma) > 1.0$
Photon/Jets	$\Delta R(j, \gamma) > 0.1$	$\Delta R(j, \gamma) > 0.4$
Lepton/Jets	$\Delta R(\ell, j) > 0.4$	

- **Comparison of the event selections between ATLAS and CMS**
 - CMS: $3 + \geq 4$ jet selections
 - ATLAS: ≥ 4 jet selection, $|m(e, \gamma) - m_z| > 5 \text{ GeV}$

Comparison to ATLAS 2016

ATLAS 36.1 fb⁻¹

Source	Single lepton (%)	Dilepton (%)
Signal modelling	± 1.6	± 2.9
Background modelling	± 4.8	± 2.9
Photon	± 1.1	± 1.1
Prompt-photon tagger	± 4.0	-
Leptons	± 0.3	± 1.3
Jets	± 5.4	± 2.0
b-tagging	± 0.9	± 0.4
Pile-up	± 2.0	± 2.3
Luminosity	± 2.3	± 2.3
MC sample size	± 1.9	± 1.7
Total systematic uncertainty	± 7.9	± 5.8
Data sample size	± 1.5	± 3.8
Total uncertainty	± 8.1	± 7.0

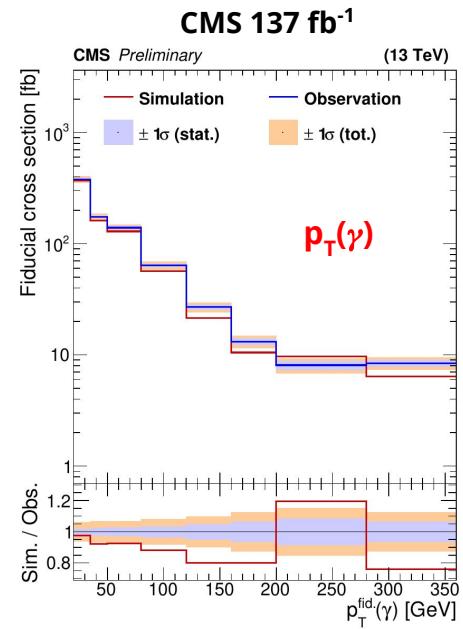
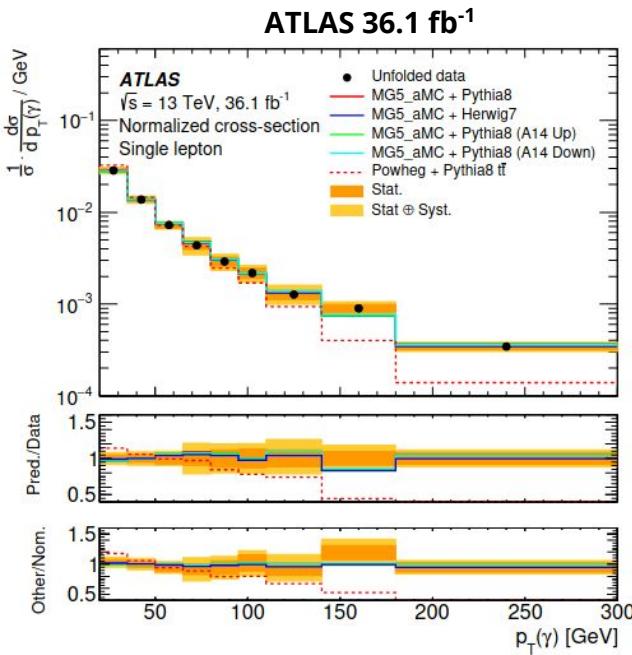
Signal modelling in ATLAS:

- μ_R / μ_F variations
- ISR / FSR variations from Pythia Tune
- PDF (100 eigenvector set of NNPDF set)
- Parton shower (MG5aMC + Pythia/Herwig)

	CMS 137 fb⁻¹	Correlation	Uncertainty (%)
		yield	$\sigma(t\bar{t}\gamma)$
Experimental	Integrated luminosity	partial	2.3–2.5 1.8
	Pileup	✓	<2.0 <0.5
	Trigger efficiency	–	0.1–0.5 <0.5
	Electron reconstruction and identification	✓	0.2–1.7 <0.5
	Muon reconstruction and identification	partial	0.5–0.7 0.7
	Photon reconstruction and identification	✓	0.4–1.4 1.0
	$p_T(e)$ and $p_T(\gamma)$ reconstruction	✓	<1.2 <0.5
	JES	partial	1.0–4.1 1.9
	JER	–	0.4–1.6 0.6
	b tagging	2017/2018	0.8–1.6 1.1
Theoretical	L1 prefireing	2016/2017	0.3–0.9 <0.5
	Tune	✓	0.1–1.9 <0.5
	Color reconnection	✓	0.4–3.6 0.6
	ISR/FSR	✓	1.0–5.6 1.9
	PDF	✓	<0.5 <0.5
Background	ME scales μ_R, μ_F	✓	0.4–4.7 <0.5
	Multijet normalization	✓	1.3–6.5 0.9
	hadronic photon estimation	✓	1.2–2.7 2.0
	Misidentified e	–	2.5–8.0 1.8
	Z γ normalization	✓	0.6–2.5 0.5
	W γ normalization	✓	1.0–3.5 2.4
	DY normalization	✓	0.1–1.1 1.0
	t \bar{t} normalization	✓	1.0–1.9 1.0
	“Other” bkg. normalization	✓	0.3–1.0 <0.5
	Total systematic uncertainty		5.7
Statistical	Statistical uncertainty		0.9
	Total		5.8

Comparison to ATLAS 2016 Results

- **Comparison of unfolded distributions between ATLAS and CMS**
 - Same observables unfolded in l+jets: $p_T(\gamma)$, $|\eta(\gamma)|$, $\Delta R(\gamma,l)$
- **ATLAS: Unfolding of prefit observables**
 - Iterative Bayesian unfolding (RooUnfold)
 - Comparison of various showering algorithms and tunes
 - Normalized cross section comparison
 - Softer $p_T(\gamma)$ for ttbar + parton shower
- **CMS: Unfolding of postfit observables**
 - Unfolding using χ^2 minimization (TUnfold)
 - Unfolding of postfit uncertainty sources, summed taking correlations into account
- **Good agreement observed**
 - Small deviations in CMS covered by theory uncertainties



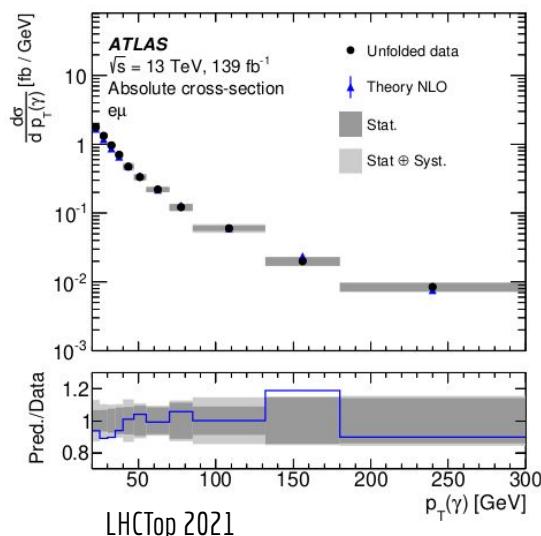
Comparison to ATLAS Run 2 Results

- ATLAS RunII result with 139 fb^{-1} in the $e\mu$ -channel
- Measurement of $t\bar{t}\gamma + tW\gamma$ production**
 - Signal simulation including resonant and non-resonant diagrams, interferences, off-shell effects of the top quarks and W bosons
 - Cross section at parton level

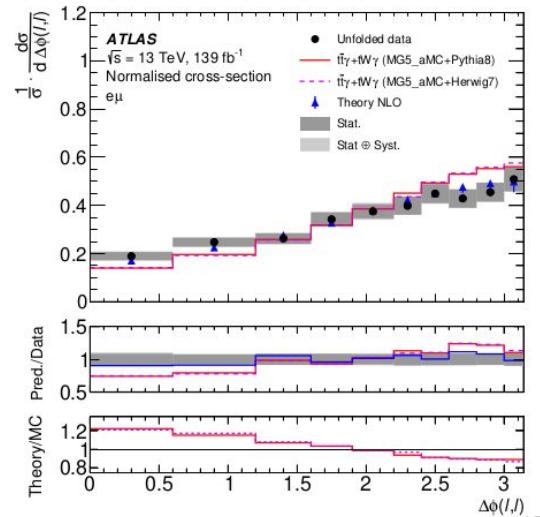
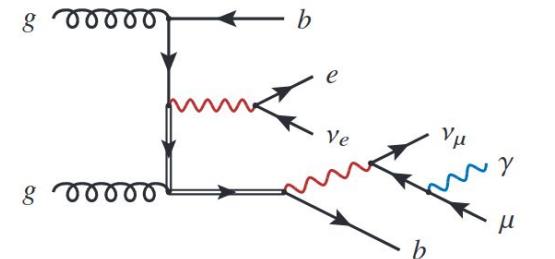
$$\sigma_{\text{fid}} = 39.6^{+2.5}_{-2.1} \text{ (syst)} \pm 0.8 \text{ (stat)} \text{ fb}$$

- Comparison to full NLO theory calculations for $\text{pp} \rightarrow e\mu\nu\bar{v}bb\gamma$**
[\(JHEP 1810 \(2018\) 158\)](#)

$$\sigma_{\text{NLO}} = 38.50^{+0.56}_{-2.18} \text{ (scale)}^{+1.04}_{-1.18} \text{ (PDF)} \text{ fb}$$



Interference with $tW\gamma$:

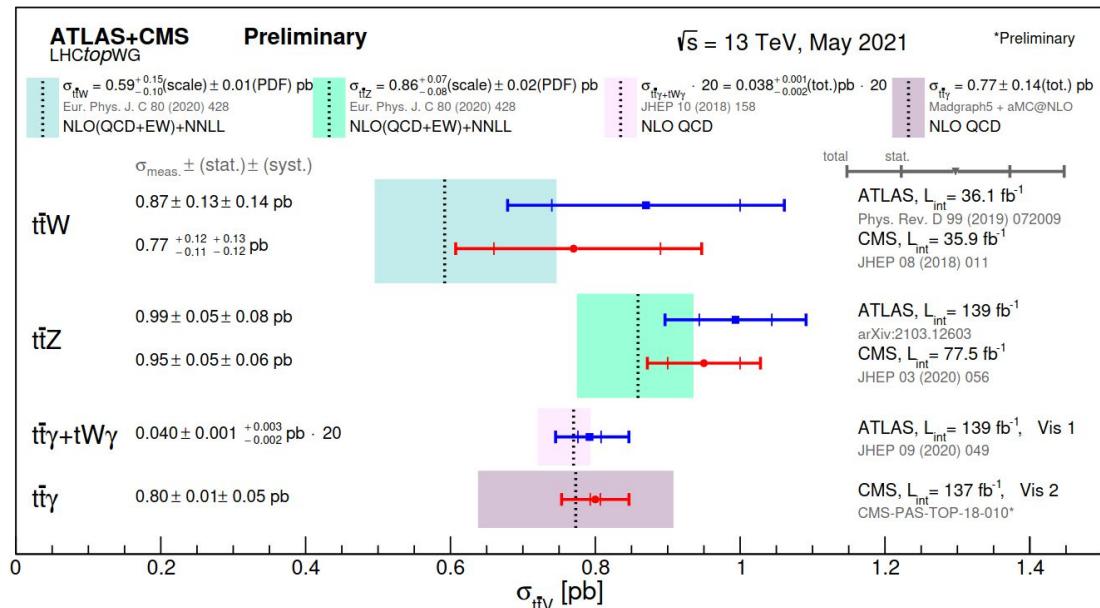


Summary

- First inclusive and differential measurement of $t\bar{t}+\gamma$ at 13 TeV from CMS
- 5.8% total uncertainty in the inclusive measurement
- Particle-level distributions in $p_T(\gamma)$, $|\eta(\gamma)|$ and $\Delta R(\gamma, l)$ compared to MadGraph5MC@NLO + Pythia8
- Tight constraints on 2 Wilson coefficients (c_{tz} , c^l_{tz}) using the dim6top SMEFT model

$$\sigma_{\text{fid}}(t\bar{t}\gamma) = 800 \pm 46 \text{ (syst)} \pm 7 \text{ (stat)} \text{ fb}$$

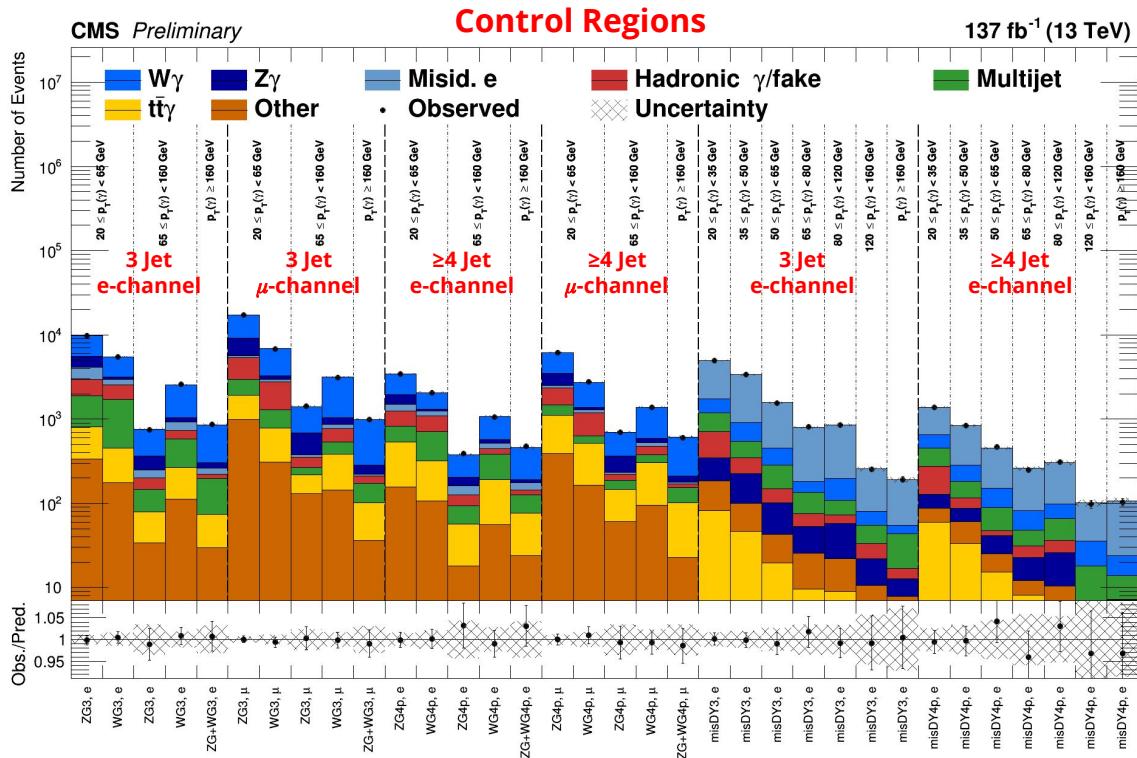
- Comparison to ATLAS 2016 and RunII results
[\(Eur. Phys. J. C 79 \(2019\) 5, 382\)](#)
[\(JHEP 09 \(2020\) 049\)](#)
- ATLAS and CMS results added to the new $t\bar{t}V$ summary plot:



Backup

Backup: Control Regions

- **$N_{b\text{-jet}} = 0$ control regions**
 - $W\gamma / Z\gamma / \text{misID-e}$ normalization measured in situ
- **Control regions binned in**
 - $m(l, \gamma)$
 - 3 jet and ≥ 4 jet selections
 - e/μ channel
 - $p_T(\gamma)$
- **QCD multijet background estimated from data**
- **Control regions used in the inclusive and differential fit setups**



Backup: Fiducial Phase Space Definition

- **Fiducial phase space definition in CMS**

Photon	e (μ)	Jet	b jet
$p_T > 20 \text{ GeV}$	$p_T > 35 \text{ (30) GeV}$	$p_T > 30 \text{ GeV}$	$p_T > 30 \text{ GeV}$
$ \eta < 1.4442$	$ \eta < 2.4$	$ \eta < 2.4$	$ \eta < 2.4$
no hadronic origin	no hadronic origin	$\Delta R(\text{jet}, \ell) > 0.4$	$\Delta R(\text{b jet}, \ell) > 0.4$
$\Delta R(\ell, \gamma) > 0.4$		$\Delta R(\text{jet}, \gamma) > 0.1$	$\Delta R(\text{b jet}, \gamma) > 0.1$
isolated			matched to b hadrons

- = 1 lepton (e/ μ)
- = 1 photon
- ≥ 3 jets, ≥ 1 b-tagged

Backup: SMEFT Operators

- **Relevant Wilson coefficients in $t\bar{t}+\gamma$:**
 - c_{tZ}, c_{tZ}^\dagger
 - (c_{tW}, c_{tW}^\dagger)
- **Modified coupling of the top to the Z and γ are linked via θ_W**

$$\begin{pmatrix} \mathcal{O}_{uB}^{(33)} \\ \mathcal{O}_{uW}^{(33)} \end{pmatrix} = \begin{pmatrix} c_W & s_W \\ -s_W & c_W \\ 0 & 2 \end{pmatrix}^T \begin{pmatrix} (\bar{t}\sigma^{\mu\nu}P_R t) A_{\mu\nu} (v+h) \\ (\bar{t}\sigma^{\mu\nu}P_R t) Z_{\mu\nu} (v+h) \\ (\bar{b}\sigma^{\mu\nu}P_R t) W_{\mu\nu}^- (v+h) \end{pmatrix}.$$

$$\begin{aligned} {}^\ddagger \mathcal{O}_{uB}^{(ij)} &= (\bar{q}_i \sigma^{\mu\nu} u_j) \tilde{\varphi} B_{\mu\nu} \\ {}^\ddagger \mathcal{O}_{uW}^{(ij)} &= (\bar{q}_i \sigma^{\mu\nu} \tau^I u_j) \tilde{\varphi} W_{\mu\nu}^I \end{aligned}$$

- **dim6top model describes the $t\bar{t}Z$ coupling in one parameter (c_{tZ})**
 $c_{tZ} = \text{Re} \left(-\sin \theta_W C_{uB}^{(33)} + \cos \theta_W C_{uW}^{(33)} \right) \quad c_{tW} = \text{Re} \left(C_{uW}^{(33)} \right)$
- **$t\bar{t}\gamma$ vertex modification is described using c_{tZ} and c_{tW}**
 $c_{t\gamma} = \text{Re} \left(\cos \theta_W C_{uB}^{(33)} + \sin \theta_W C_{uW}^{(33)} \right)$

Backup: ATLAS ELD Input Variables

- Input variables of the event level discriminator

Variable	Description	Single lepton	Dilepton
PPT	Prompt-photon tagger output	✓	
H_T	Scalar sum of the p_T of the leptons and jets	✓	
$m(\gamma, \ell)$	Invariant mass of the system of the photon and the lepton	✓	
E_T^{miss}	Missing transverse energy	✓	✓
m_W^T	Reconstructed transverse mass of the leptonically decaying W -boson $= \sqrt{2 \times p_T(\ell) \times E_T^{\text{miss}} \times (1 - \cos(\Delta\phi(\ell, E_T^{\text{miss}})))}$	✓	
N_{jets}	Jet multiplicity	✓	
$p_T(j_1)$	p_T of the leading jet (ordered in p_T)	✓	✓
$p_T(j_2)$	p_T of the sub-leading jet	✓	✓
$p_T(j_3)$	p_T of the third jet	✓	
$p_T(j_4)$	p_T of the fourth jet	✓	
$p_T(j_5)$	p_T of the fifth jet	✓	
$N_{b\text{-jets}}$	b -jet multiplicity	✓	✓
$b_1(j)$	highest b -tagging score of all jets	✓	✓
$b_2(j)$	second highest b -tagging score of all jets	✓	✓
$b_3(j)$	third highest b -tagging score of all jets	✓	
$m(\ell, \ell)$	Invariant mass of the system of the two leptons		✓

Backup: ATLAS 2016 χ^2 Test of Unfolded Results

Predictions	$p_T(\gamma)$		$ \eta(\gamma) $		$\Delta R(\gamma, \ell)$	
	χ^2/ndf	$p\text{-value}$	χ^2/ndf	$p\text{-value}$	χ^2/ndf	$p\text{-value}$
MG5_AMC + PYTHIA8	3.2/8	0.92	0.7/7	1.0	5.0/8	0.76
MG5_AMC + HERWIG7	2.3/8	0.97	0.9/7	1.0	4.8/8	0.78
MG5_AMC + PYTHIA8 (A14 Up)	3.3/8	0.91	0.8/7	1.0	4.9/8	0.77
MG5_AMC + PYTHIA8 (A14 Down)	2.6/8	0.96	0.9/7	1.0	4.6/8	0.80
POWHEG + PYTHIA8 $t\bar{t}$	25.4/8	<0.01	2.8/7	0.9	8.7/8	0.37

Predictions	$p_T(\gamma)$		$\eta(\gamma)$		$\Delta R(\gamma, \ell)$		$ \Delta\eta(\ell, \ell) $		$\Delta\phi(\ell, \ell)$	
	χ^2/ndf	$p\text{-value}$	χ^2/ndf	$p\text{-value}$	χ^2/ndf	$p\text{-value}$	χ^2/ndf	$p\text{-value}$	χ^2/ndf	$p\text{-value}$
MG5_AMC + PYTHIA8	1.7/8	0.99	7.4/7	0.39	6.9/8	0.55	3.0/7	0.89	14.4/8	0.07
MG5_AMC + HERWIG7	2.0/8	0.98	7.4/7	0.39	6.6/8	0.58	3.1/7	0.88	14.4/8	0.07
MG5_AMC + PYTHIA8 (A14 Up)	1.6/8	0.99	8.4/7	0.30	7.4/8	0.49	3.4/7	0.85	14.0/8	0.08
MG5_AMC + PYTHIA8 (A14 Down)	1.6/8	0.99	7.9/7	0.34	7.5/8	0.48	3.2/7	0.87	14.4/8	0.07
POWHEG + PYTHIA8 $t\bar{t}$	20.1/8	0.01	10.8/7	0.15	8.6/8	0.38	4.5/7	0.72	9.8/8	0.28



CMS Experiment at the LHC, CERN
Data recorded: 2018-May-03 00:18:37.367872 GMT
Run / Event / LS: 315645 / 56459556 / 52

