Joint Annual Meeting of the ÖPG and SPS 2021

Measurement of the inclusive and differential $t\bar{t}\gamma$ cross sections and EFT interpretation in the single-lepton channel at CMS

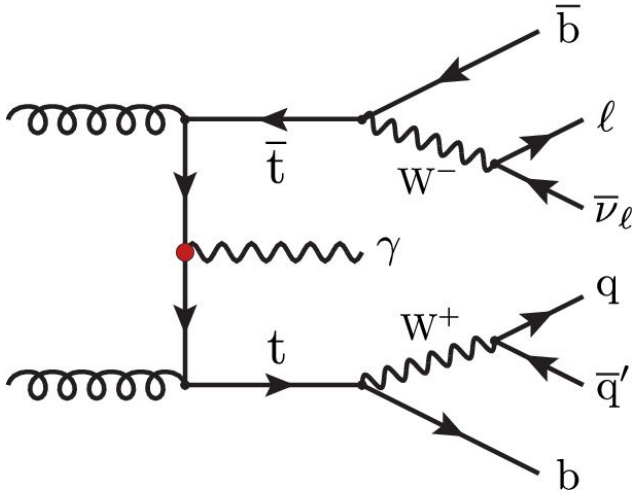
Lukas Lechner (Hephy, Vienna)

Introduction

- **Inclusive and differential cross section measurement of tt+γ in the l+jets channel**
  - First measurement of tt+γ at 13 TeV from CMS
  - Current data set allows for a detailed study of the production of tt+γ
  - Unfolding of several differential distributions to the particle level

- **SM effective field theory interpretation of the result**
  - Direct access of the EWK coupling of the top quark
  - Probes the tγ coupling, very sensitive probe of new physics

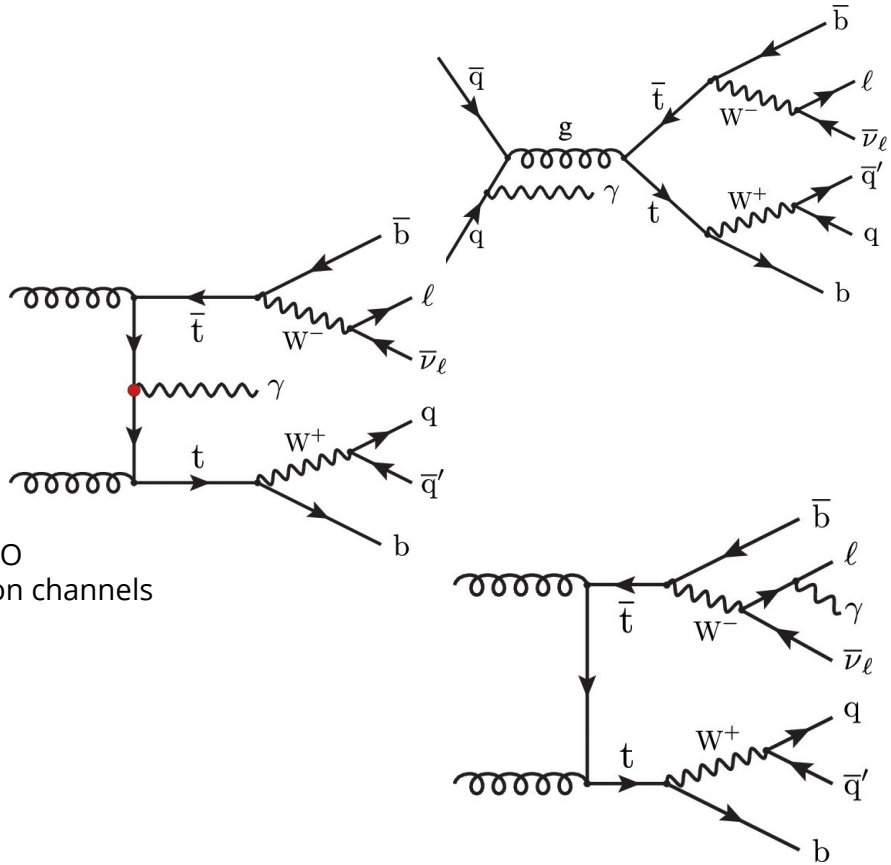
- **Results on arXiv** arXiv: 2107.01508 **and submitted to JHEP**



Signal Simulation

- **Signal Simulation using Madgraph_aMC@NLO**
  - Interfaced with Pythia8 using CP5 Tune
- **Simulated 2 → 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→ 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

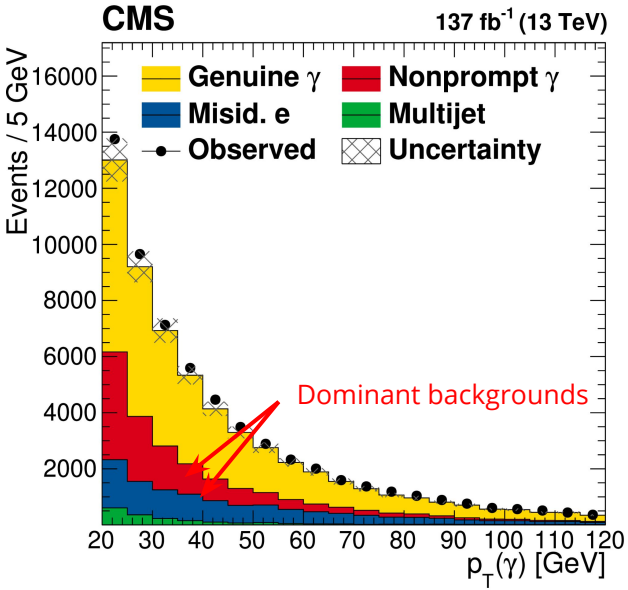
    $\sigma_{\text{pred.}}$ (ttγ) = 773 ± 135 fb

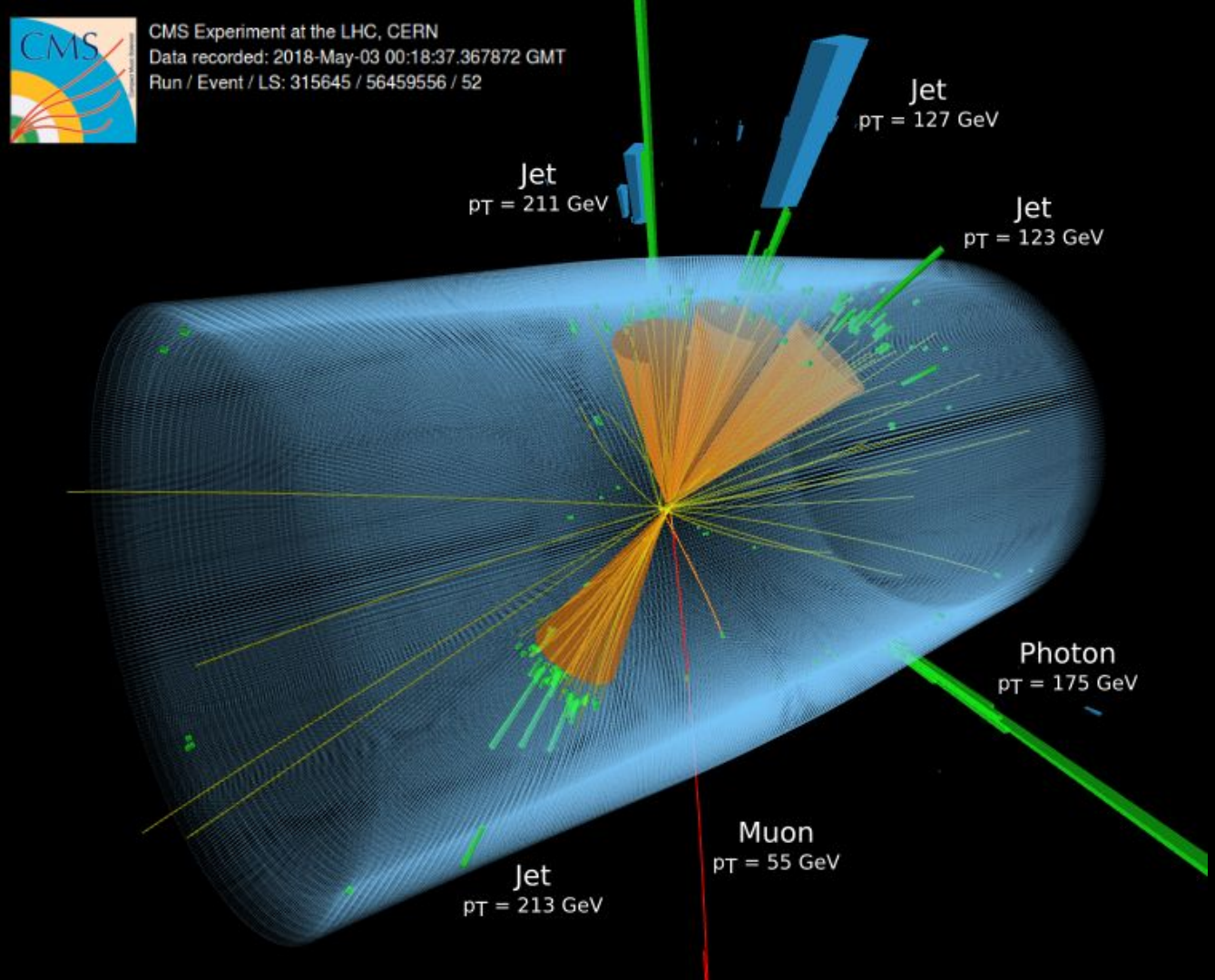


Event Selection

- **tt+γ 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
  - ΔR(γ, l) > 0.4, ΔR(γ, jets) > 0.1, ΔR(l, 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




CMS Experiment at the LHC, CERN
Data recorded: 2018-May-03 00:18:37.367872 GMT
Run / Event / LS: 315645 / 56459556 / 52
Jet
pT = 127 GeV
Jet
pT = 211 GeV
Jet
pT = 123 GeV
Photon
pT = 175 GeV
Muon
pT = 55 GeV
Jet
pT = 213 GeV

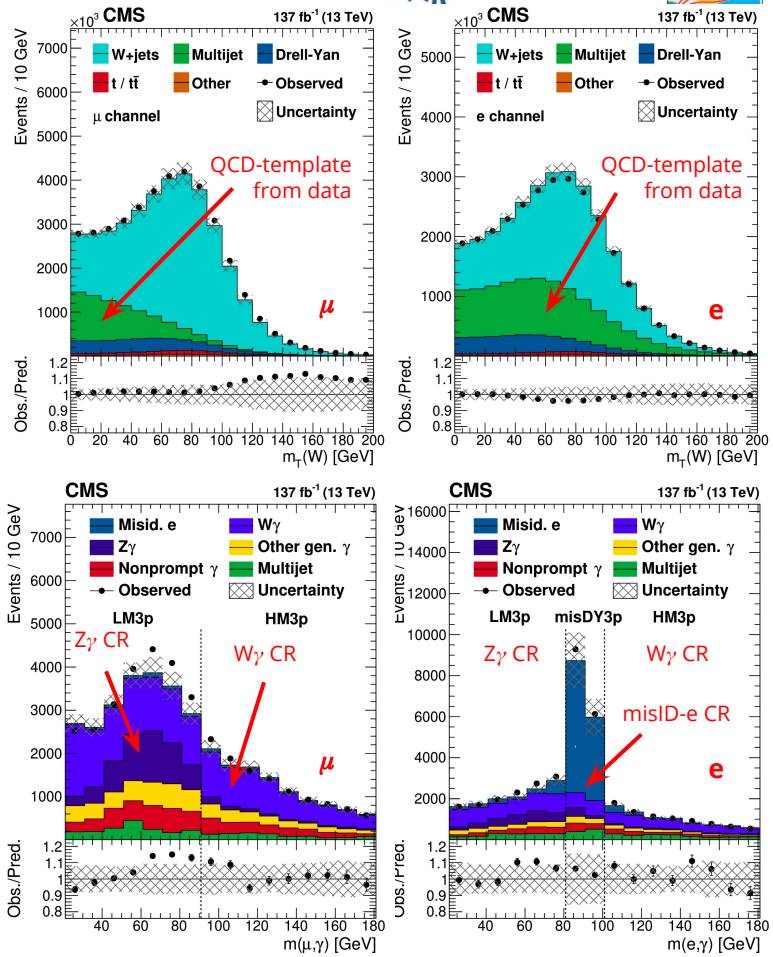
arXiv: 2107.01508

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 $m_T(W)$

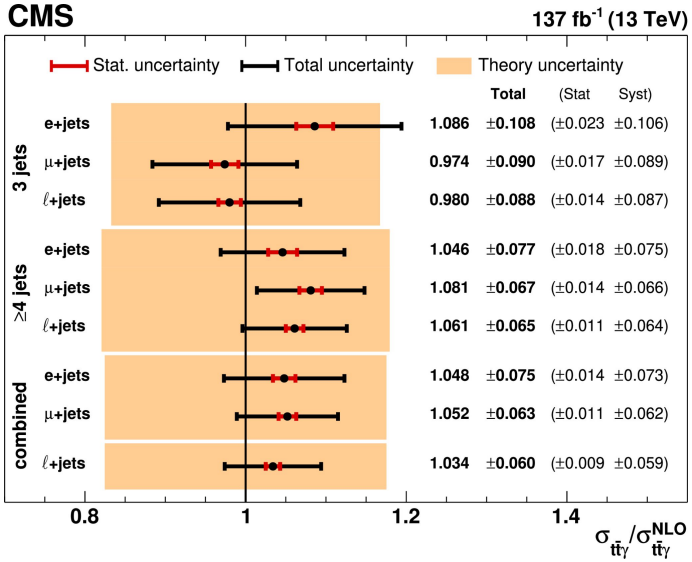
- **Hadronic γ/fake background**
  - ABCD method using sidebands with loosened criteria on the ECAL shower shape observable $\sigma_{\eta\eta}$ and the photon charged-hadron isolation

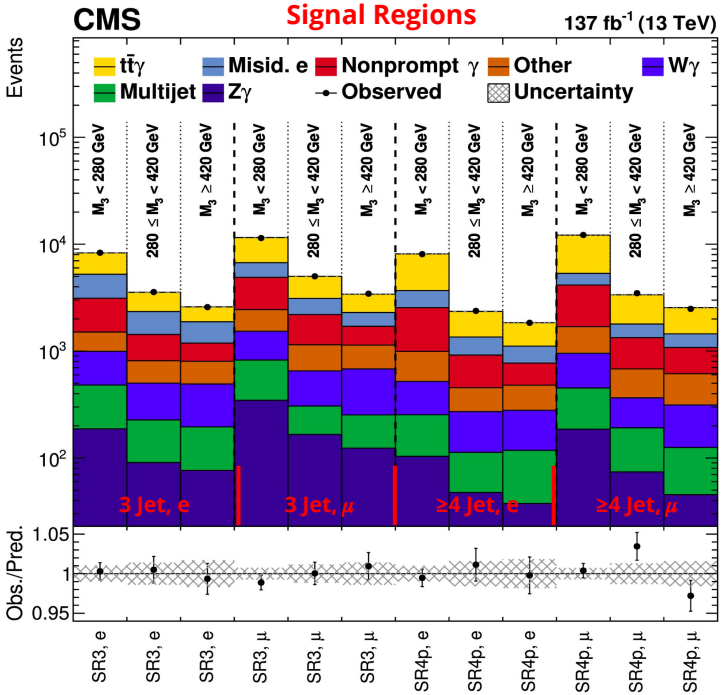
- **Misidentified electron and $W\gamma$/$Z\gamma$ background**
  - $N_{b\text{-jet}} = 0$ selection dominated by $W\gamma$/$Z\gamma$/misID-e events
  - Invariant mass of the lepton and the photon $m(l,\gamma)$ used to separate processes



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**





σ_{fid} ($t\bar{t}\gamma$) = 800 ± 46 (syst) ± 7 (stat) fb

Systematic Uncertainties

- **Dominant experimental uncertainty sources:**
  - Photon identification
  - Jet energy scale and resolution
  - B-tagging

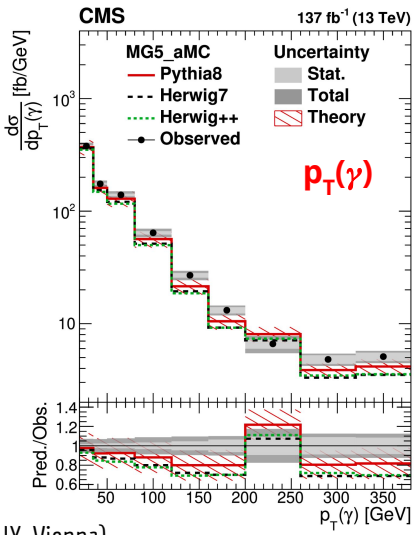
- **Dominant modelling uncertainty sources:**
  - ISR/FSR modelling

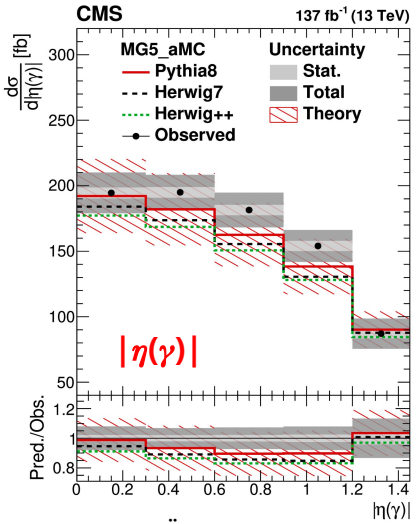
- **Dominant background estimation uncertainty sources:**
  - Misidentified electron estimation
  - Hadronic/fake photon estimation
  - $W\gamma$ background estimation

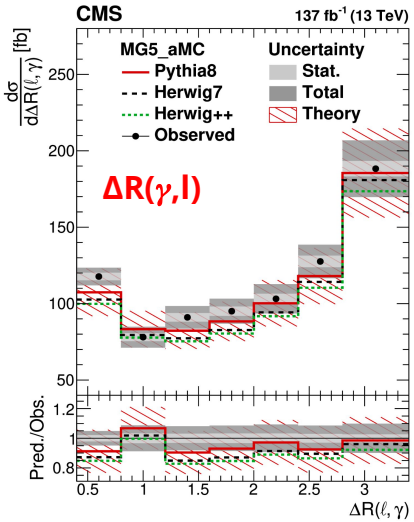
	Source	Correlation	Uncertainty [%] yield	$\sigma(t\bar{t}\gamma)$
Experimental	Integrated luminosity	partial	2.3–2.5	1.8
	Pileup	100%	0.5–2.0	<0.5
	Trigger efficiency	—	<0.5	<0.5
	Electron reconstruction and identification	100%	0.2–1.7	<0.5
	Muon reconstruction and identification	partial	0.5–0.7	0.7
	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

Results - Differential Cross Section Measurement

- **Unfolded postfit differential distributions in $p_T(\gamma)$, $|\eta(\gamma)|$ and $\Delta R(\gamma,l)$** to the 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, Herwig++, or Herwig7







arXiv: 2107.01508

SMEFT Interpretation

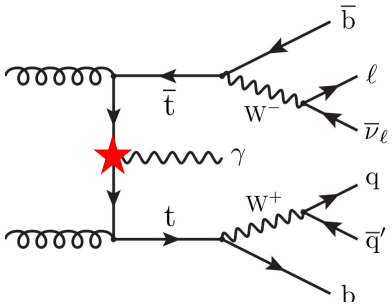
$$\mathscr{L}_{EFT} = \mathscr{L}_{SM} + \cancel{\frac{1}{\Lambda}\sum_i c_i \mathcal{O}_i} + \frac{1}{\Lambda^2}\sum_j c_j \mathcal{O}_j$$

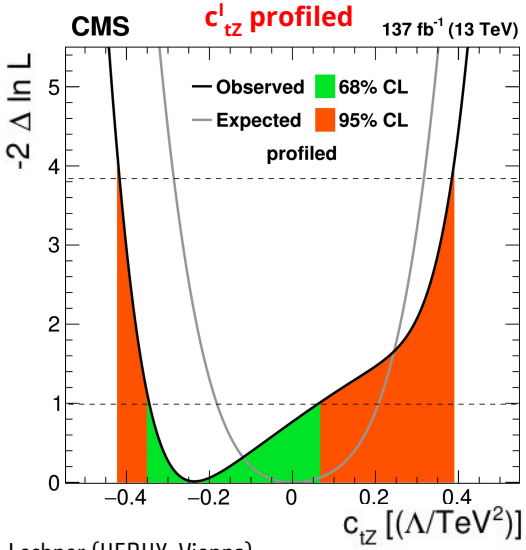
Wilson coefficient

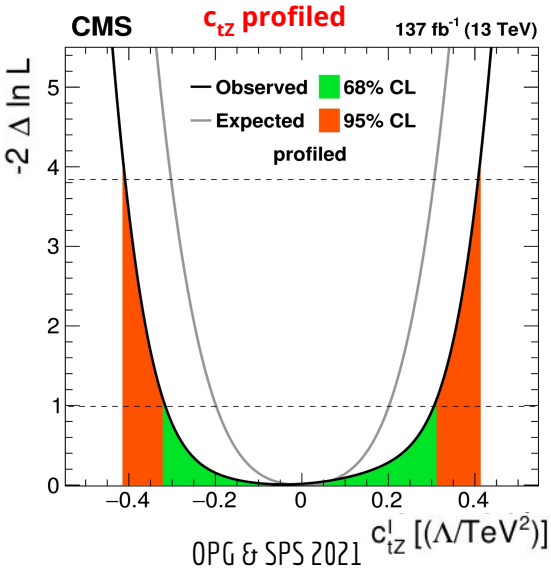
dim-6 operator

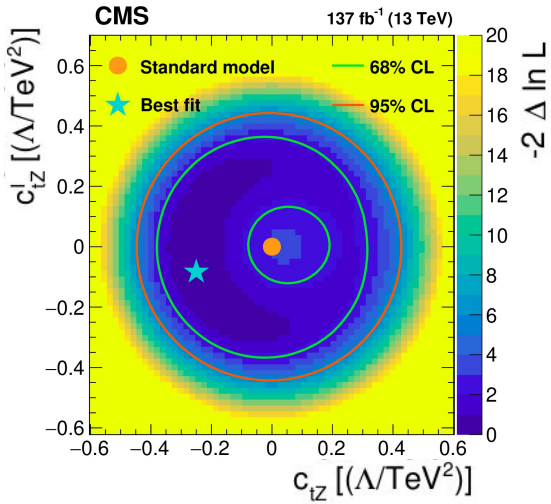
energy scale

- **SMEFT interpretation** of dim-6 operators
- Constraining **2 Wilson coefficients (c_{tZ}, c^{I}_{tZ})** 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







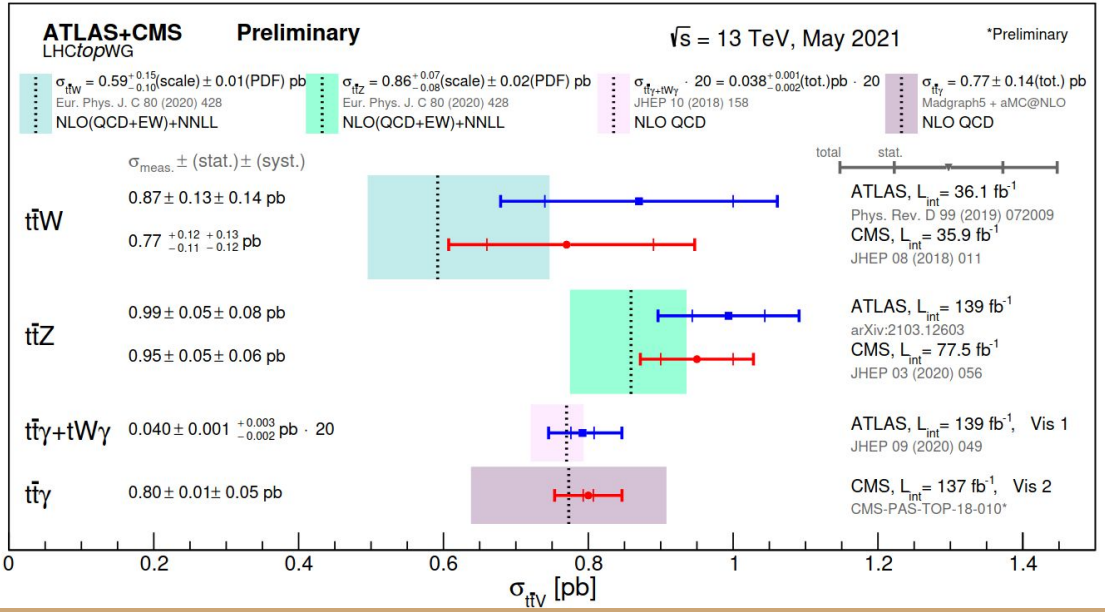


Summary

- **First inclusive and differential measurement of tt+γ 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, Herwig++, Herwig7
- **Tight constraints on 2 Wilson coefficients (c_{tZ}, c^{l}_{tZ})** using the dim6top SMEFT model

σ_{fid} (ttγ) = 800 ± 46 (syst) ± 7 (stat) fb

- **CMS results added to the new ttV summary plot:**



- **Results on arXiv**

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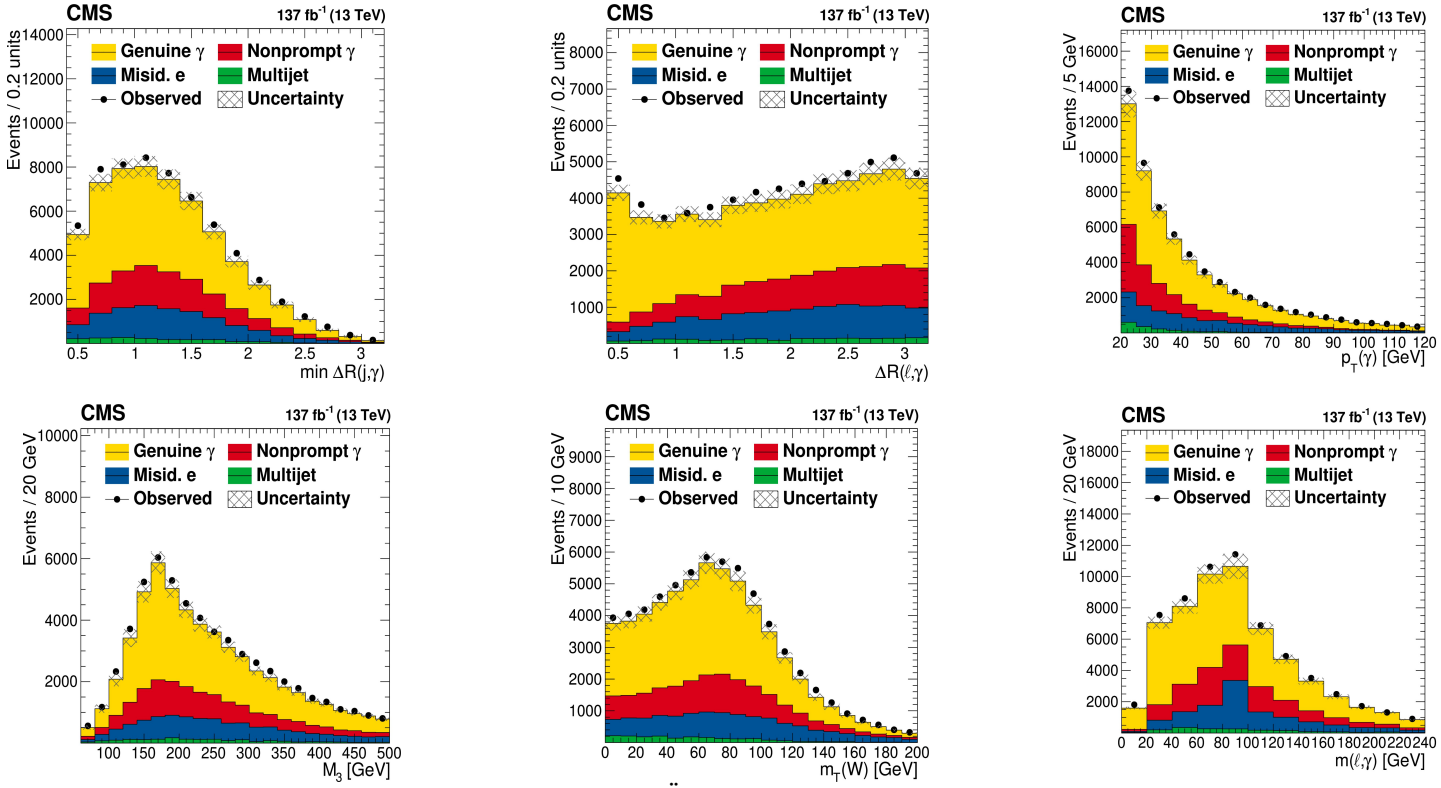
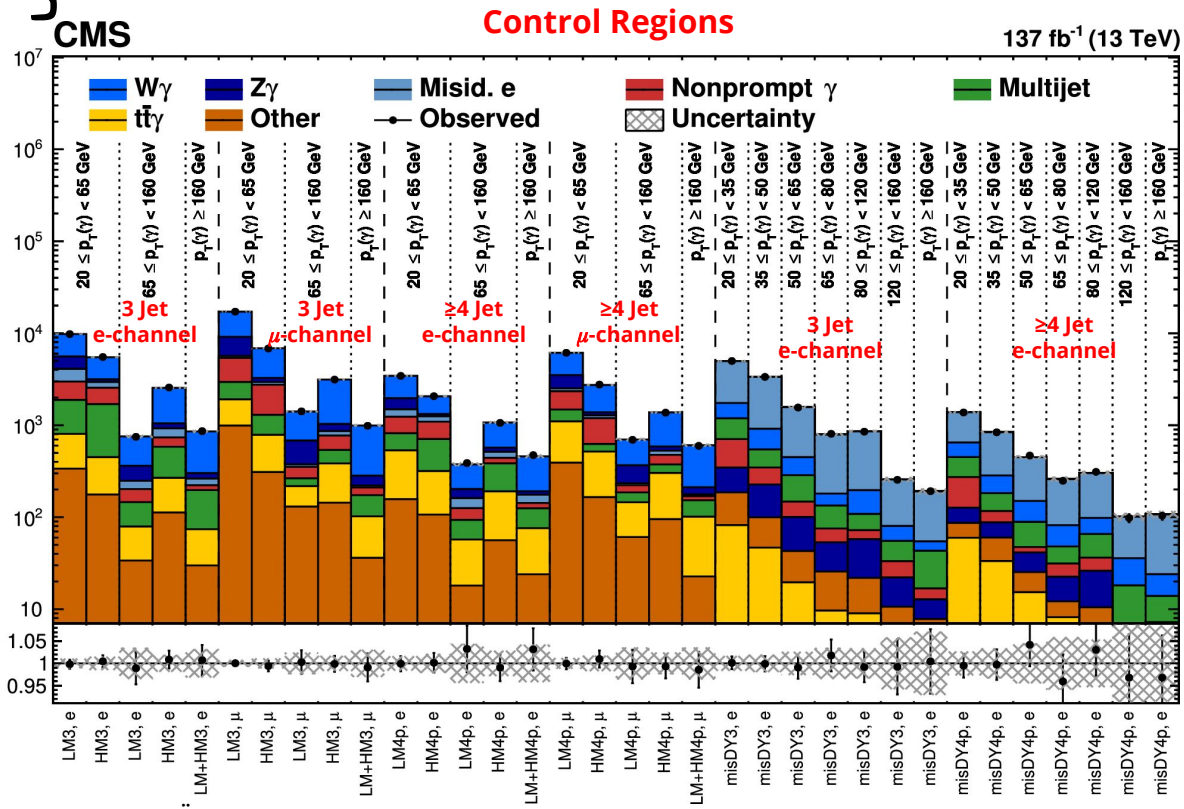
Backup

Backup: Signal Region Distributions



Backup: Control Regions

- **$N_{b\text{-jet}}$ = 0 control regions**
  - $W\gamma$ / $Z\gamma$ / misID-e normalization measured in situ
- **Control regions binned in**
  - m(l,γ)
  - 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

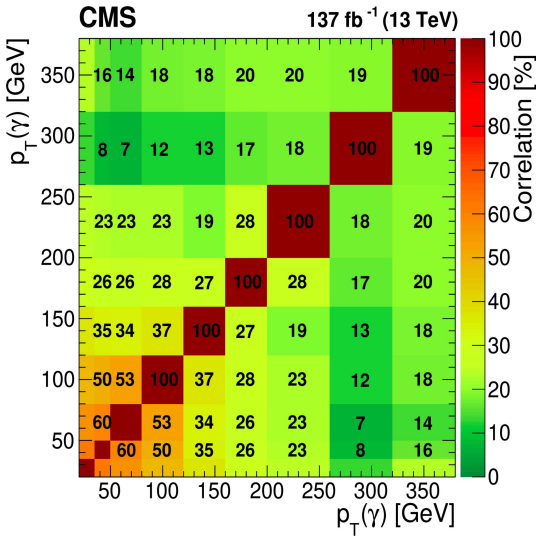
- **Fiducial phase space definition in CMS**

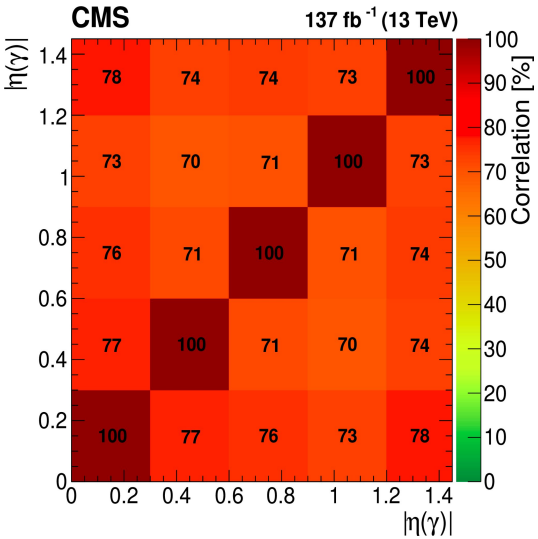
Photon	e (μ)	Jet	b jet
$p_T > 20\,\text{GeV}$	$p_T > 35\ (30)\,\text{GeV}$	$p_T > 30\,\text{GeV}$	$p_T > 30\,\text{GeV}$
$\lvert\eta\rvert < 1.4442$	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.4$
no hadronic origin	no hadronic origin	$\Delta R(\text{jet}, \ell) > 0.4$	$\Delta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

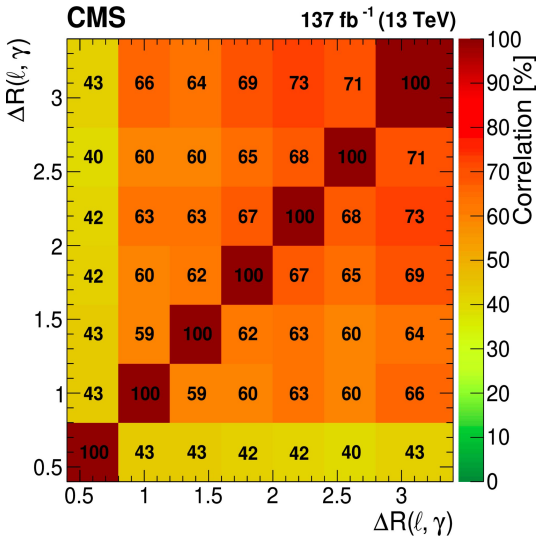
- = 1 lepton (e/μ)
- = 1 photon
- ≥ 3 jets, ≥ 1 b-tagged

Backup: Correlation Matrices

- **Correlation matrices of the unfolded results at the particle level**







Backup: SMEFT Operators

- **Relevant Wilson coefficients in tt+γ:**
  - c_{tZ}, c^{I}_{tZ}
  - (c_{tW}, c^{I}_{tW})
- **Modified coupling of the top to the Z and γ are linked via θ_W**

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

$$^{\ddagger}\mathcal{O}_{uB}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}u_j)\tilde{\varphi}B_{\mu\nu}$$
$$^{\ddagger}\mathcal{O}_{uW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I u_j)\tilde{\varphi}W^I_{\mu\nu}$$

- **dim6top model describes the ttZ coupling in one parameter (c_{tZ})**

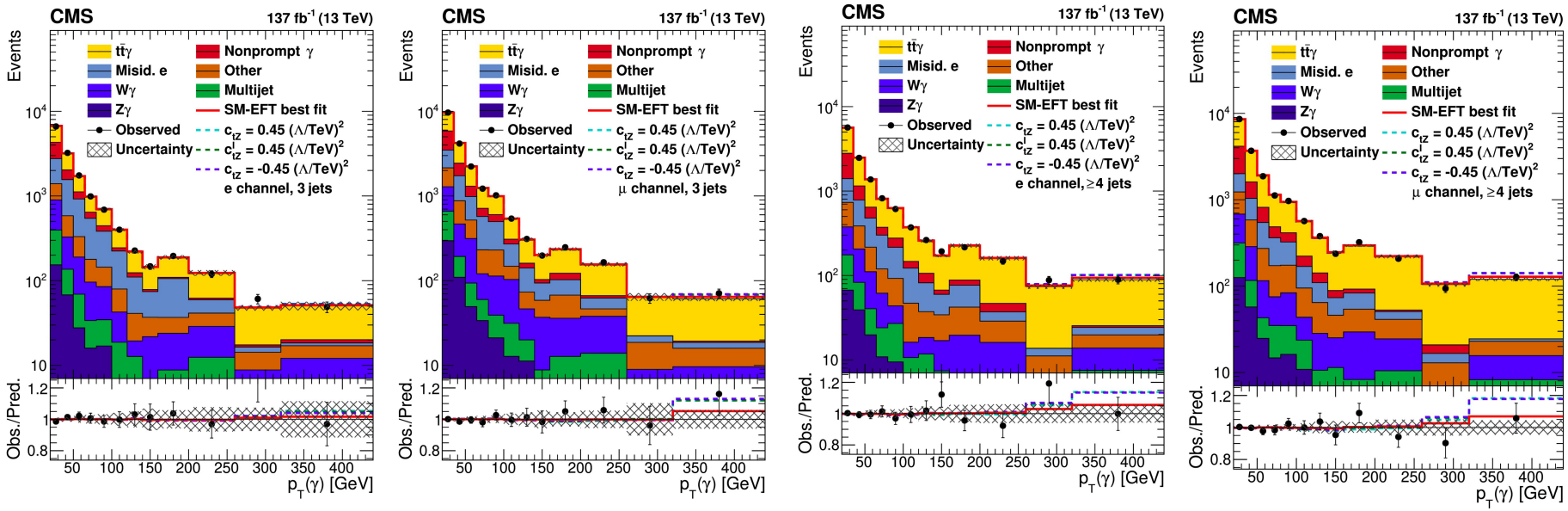
$$\mathrm{c_{tZ}} = \mathrm{Re}\left(-\sin\theta_W \mathrm{C}_{uB}^{(33)} + \cos\theta_W \mathrm{C}_{uW}^{(33)}\right) \qquad \mathrm{c_{tW}} = \mathrm{Re}\left(\mathrm{C}_{uW}^{(33)}\right)$$

- **ttγ vertex modification is described using c_{tZ} and c_{tW}**

$$\mathrm{c_{t\gamma}} = \mathrm{Re}\left(\cos\theta_W \mathrm{C}_{uB}^{(33)} + \sin\theta_W \mathrm{C}_{uW}^{(33)}\right)$$

Backup: SMEFT Interpretation

- **SMEFT interpretation** of dim-6 operators
- $p_T(\gamma)$ distribution is found to be most sensitive to modified $t\gamma$ couplings



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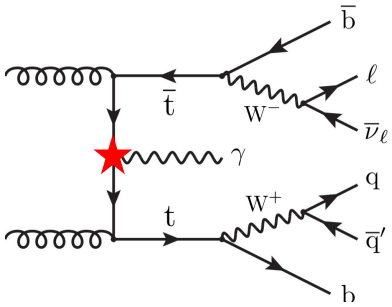
Wilson coefficient

dim-6 operator

energy scale



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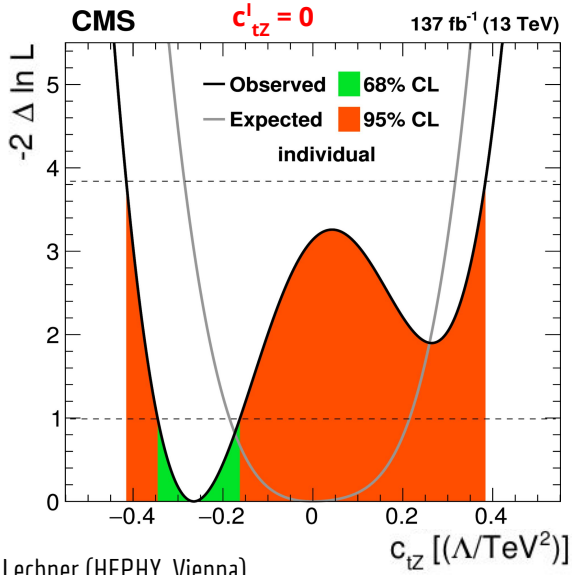

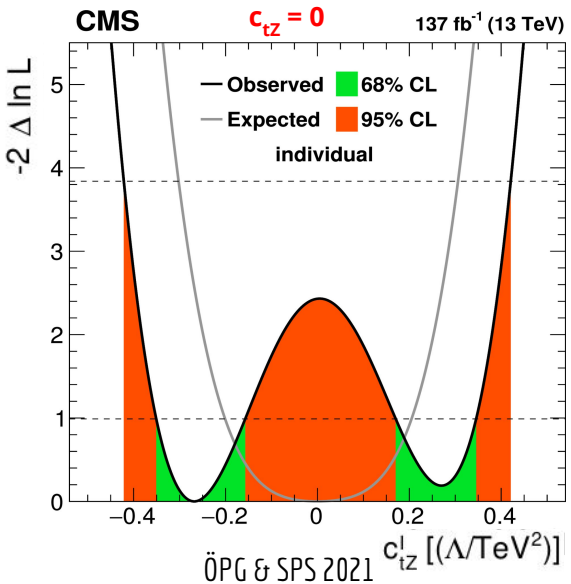

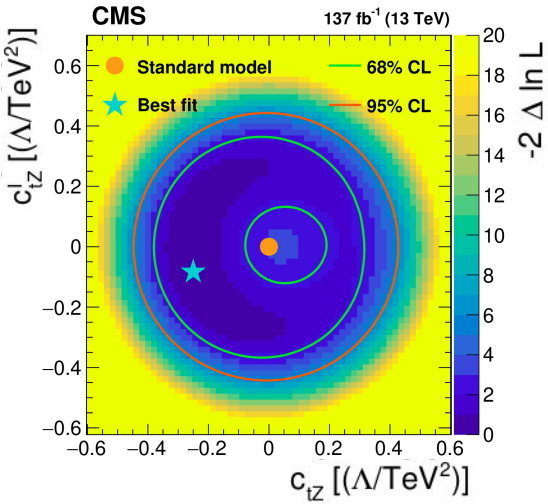

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	Wilson coefficient		68% CL interval $(\Lambda/\text{TeV})^2$	95% CL interval $(\Lambda/\text{TeV})^2$
Expected	c_{tZ}	$c^{I}_{tZ} = 0$	$[-0.19, 0.21]$	$[-0.29, 0.32]$
		profiled	$[-0.19, 0.21]$	$[-0.29, 0.32]$
	c^{I}_{tZ}	$c_{tZ} = 0$	$[-0.20, 0.20]$	$[-0.30, 0.31]$
		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	$[-0.32, 0.31]$	$[-0.41, 0.41]$