Measurement of the inclusive and differential ttγ 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+\(\gamma\) in the l+jets channel
  - First measurement of tt+\(\gamma\) at 13 TeV from CMS
  - Current data set allows for a detailed study of the production of tt+\(\gamma\)
  - 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 t\(\gamma\) 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 $2 \rightarrow 7$ 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/$\alpha_s$ variations

\[ \sigma_{\text{pred.}}(t\bar{t}\gamma) = 773 \pm 135 \text{ fb} \]
Event Selection

- **tt+γ signal region selection**
  - Exactly one isolated e (μ) \((p_T > 35 \text{ (30)} \text{ GeV}, |\eta| < 2.4)\)
  - Exactly one isolated photon \((p_T > 20 \text{ GeV}, |\eta| < 1.4442)\)
  - At least three jets \((p_T > 30 \text{ GeV}, |\eta| < 2.4)\)
  - 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

Dominant backgrounds

\[ \text{Events / 5 GeV} \]

\[ \text{p}_T(\gamma) \text{ [GeV]} \]

Lukas Lechner (HEPHY, Vienna)

ÖPG & SPS 2021
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 $\gamma$/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**
  - $N_{b,jet} = 0$ 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

![CMS signal regions graph](image)

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

---

<table>
<thead>
<tr>
<th>Source</th>
<th>Correlation</th>
<th>Uncertainty [%] yield $\sigma_{(H_T)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated luminosity</td>
<td>partial</td>
<td>2.3–2.5</td>
</tr>
<tr>
<td>Pileup</td>
<td>100%</td>
<td>0.5–2.0</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>—</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Electron reconstruction and identification</td>
<td>100%</td>
<td>0.2–1.7</td>
</tr>
<tr>
<td>Muon reconstruction and identification</td>
<td>partial</td>
<td>0.5–0.7</td>
</tr>
<tr>
<td>Photon reconstruction and identification</td>
<td>100%</td>
<td>0.4–1.4</td>
</tr>
<tr>
<td>$p_T(e)$ and $p_T(\gamma)$ reconstruction</td>
<td>100%</td>
<td>0.1–1.2</td>
</tr>
<tr>
<td>JES</td>
<td>partial</td>
<td>1.0–4.1</td>
</tr>
<tr>
<td>JER</td>
<td>—</td>
<td>0.4–1.6</td>
</tr>
<tr>
<td>$b$ tagging</td>
<td>100% (2017/2018)</td>
<td>0.8–1.6</td>
</tr>
<tr>
<td>L1 prefiring</td>
<td>100% (2016/2017)</td>
<td>0.3–0.9</td>
</tr>
<tr>
<td>Tune</td>
<td>100%</td>
<td>0.1–1.9</td>
</tr>
<tr>
<td>Color reconnection</td>
<td>100%</td>
<td>0.4–3.6</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>100%</td>
<td>1.0–5.6</td>
</tr>
<tr>
<td>PDF</td>
<td>100%</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>ME scales $\mu_\alpha$, $\mu_\beta$</td>
<td>100%</td>
<td>0.4–4.7</td>
</tr>
<tr>
<td>Multijet normalization</td>
<td>100%</td>
<td>1.3–6.5</td>
</tr>
<tr>
<td>Nonprompt photon background</td>
<td>100%</td>
<td>1.2–2.7</td>
</tr>
<tr>
<td>Misidentified $e$</td>
<td>—</td>
<td>2.5–8.0</td>
</tr>
<tr>
<td>$Z\gamma$ normalization</td>
<td>100%</td>
<td>0.6–2.5</td>
</tr>
<tr>
<td>$W\gamma$ normalization</td>
<td>100%</td>
<td>1.0–3.5</td>
</tr>
<tr>
<td>$DY$ normalization</td>
<td>100%</td>
<td>0.1–1.1</td>
</tr>
<tr>
<td>$t\bar{t}$ normalization</td>
<td>100%</td>
<td>1.0–1.9</td>
</tr>
<tr>
<td>&quot;Other&quot; bkg. normalization</td>
<td>100%</td>
<td>0.3–1.0</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td></td>
<td>5.7</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td></td>
<td>0.9</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>5.8</td>
</tr>
</tbody>
</table>
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

![Graphs showing comparisons between theoretical predictions and observed data for $p_T(\gamma)$, $|\eta(\gamma)|$, and $\Delta R(\gamma, l)$](image-url)
**SMEFT Interpretation**

- **SMEFT interpretation** of dim-6 operators
- Constraining 2 Wilson coefficients \( c_{tZ} \) and \( c_{t'\gamma} \) 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

[Graphs and diagrams showing profiles of Wilson coefficients and energy scale]
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, Herwig++, Herwig7
- Tight constraints on 2 Wilson coefficients ($c_{tZ}$, $c_{tZ}^I$) using the dim6top SMEFT model

- CMS results
  added to the new
  ttV summary plot:

- Results on arXiv
  arXiv: 2107.01508
  and submitted to JHEP

$L_{\text{av}} = 36.1\text{ fb}^{-1}$

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

Lukas Lechner (HEPHY, Vienna)  
ÖPG & SPS 2021
Backup: Control Regions

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

Lukas Lechner (HEPHY, Vienna)
Backup: Fiducial Phase Space Definition

- **Fiducial phase space definition in CMS**

<table>
<thead>
<tr>
<th></th>
<th>Photon</th>
<th>e (µ)</th>
<th>Jet</th>
<th>b jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T &gt; 20\text{ GeV}$</td>
<td>$p_T &gt; 35$ (30) GeV</td>
<td>$p_T &gt; 30\text{ GeV}$</td>
<td>$p_T &gt; 30\text{ GeV}$</td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt; 1.4442$</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>no hadronic origin</td>
<td>no hadronic origin</td>
<td>$\Delta R(\text{jet, } \ell) &gt; 0.4$</td>
<td>$\Delta R(\text{b jet, } \ell) &gt; 0.4$</td>
<td></td>
</tr>
<tr>
<td>$\Delta R(\ell, \gamma) &gt; 0.4$</td>
<td>$\Delta R(\text{jet, } \gamma) &gt; 0.1$</td>
<td>$\Delta R(\text{b jet, } \gamma) &gt; 0.1$</td>
<td>matched to b hadrons</td>
<td></td>
</tr>
</tbody>
</table>

- = 1 lepton (e/µ)
- = 1 photon
- $\geq 3$ jets, $\geq 1$ b-tagged
Backup: Correlation Matrices

- Correlation matrices of the unfolded results at the particle level
Backup: SMEFT Operators

- Relevant Wilson coefficients in $t\bar{t}+\gamma$:
  - $c_{tZ}$, $c_{tW}^I$
  - $(c_{tW}, c_{tW}^I)$

- Modified coupling of the top to the $Z$ and $\gamma$ are linked via $\theta_w$

\[
\begin{pmatrix}
O_{uB}^{(33)} \\ O_{uW}^{(33)}
\end{pmatrix}
= 
\begin{pmatrix}
c_W & s_W \\ -s_W & c_W
\end{pmatrix}
\begin{pmatrix}
(t\sigma^{\mu\nu}P^R t) A_{\mu\nu} (v+h) \\ (t\sigma^{\mu\nu}P^R t) Z_{\mu\nu} (v+h) \\ (b\sigma^{\mu\nu}P^R t) W^{-}_{\mu\nu} (v+h)
\end{pmatrix}
\]

- 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 $c_{tW}$

\[
c_{t\gamma} = \text{Re} \left( \cos \theta_W C_{uB}^{(33)} + \sin \theta_W C_{uW}^{(33)} \right)
\]

\[\dagger O_{uB}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} u_j) \tilde{\varphi} B_{\mu\nu}\]

\[\dagger O_{uW}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} \tau^I u_j) \tilde{\varphi} W^{I\mu\nu}\]
Backup: SMEFT Interpretation

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

- SMEFT interpretation of dim-6 operators
- Constraining 2 Wilson coefficients ($c_{tZ}$, $c_{tZ}$) 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
Backup: SMEFT Interpretation

- **SMEFT interpretation** of dim-6 operators
- Constraining 2 Wilson coefficients \((c_{\text{tZ}}, c_{\text{tZ}}')\) 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

<table>
<thead>
<tr>
<th>Wilson coefficient</th>
<th>68% CL interval ((\Lambda/\text{TeV})^2)</th>
<th>95% CL interval ((\Lambda/\text{TeV})^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(c_{\text{tZ}})</td>
<td>(c_{\text{tZ}}' = 0) prof.</td>
<td>([-0.19, 0.21])</td>
</tr>
<tr>
<td></td>
<td></td>
<td>([-0.29, 0.32])</td>
</tr>
<tr>
<td></td>
<td>(c_{\text{tZ}}) prof.</td>
<td>([-0.19, 0.21])</td>
</tr>
<tr>
<td></td>
<td>(c_{\text{tZ}}' = 0) prof.</td>
<td>([-0.29, 0.32])</td>
</tr>
<tr>
<td></td>
<td>(c_{\text{tZ}'}) prof.</td>
<td>([-0.20, 0.20])</td>
</tr>
<tr>
<td></td>
<td>(c_{\text{tZ}}) prof.</td>
<td>([-0.20, 0.20])</td>
</tr>
</tbody>
</table>

**CMS**

- CMS 137 fb\(^{-1}\) \(t\bar{t}\)
  - CMS 77.5 fb\(^{-1}\) \(t\bar{t}\)Z
    - JHEP 03 (2020) 056
- CMS 36 fb\(^{-1}\) \(t\bar{t}\)Z
  - JHEP 09 (2016) 011
- CMS 41.5 fb\(^{-1}\) \(t\bar{t}\)+leptons
  - JHEP 03 (2021) 095
- ATLAS 36 fb\(^{-1}\) \(t\bar{t}\)Z
  - Phys. Rev. D 99, 072009
- Global fit
  - JHEP 04 (2021) 279

- CMS 137 fb\(^{-1}\) \(t\bar{t}\)
  - (this result)
- CMS 77.5 fb\(^{-1}\) \(t\bar{t}\)Z
  - JHEP 03 (2020) 056

---

Lukas Lechner (HEPHY, Vienna)