First Evidence of Single Top Production in Association with a Photon

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On behalf of CMS collaboration
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Motivations for SM $t+\gamma$ measurement.

Strategy of SM $t+\gamma$ measurement.

Data and MC based background estimation.

Signal to background discrimination.

Systematic uncertainties.

Results and prospects.


Single Top Production

First observation

<table>
<thead>
<tr>
<th>Processes</th>
<th>$\sigma$ (13 TeV) pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>t-channel</td>
<td>217.0</td>
</tr>
<tr>
<td>tW-channel</td>
<td>71.2</td>
</tr>
<tr>
<td>s-channel</td>
<td>11.4</td>
</tr>
<tr>
<td>$t\gamma j$</td>
<td>2.95</td>
</tr>
<tr>
<td>$tZj$</td>
<td>0.8</td>
</tr>
</tbody>
</table>
**t+γ Motivations**

- The process can probe the couplings of top-photon and W boson-photon which are sensitive to the new physics.

- **This process is a background for several important SM processes** $ttγ$, $tH$, $ttH$,...

- Background for new physics processes such as $tγ$ and $tγ$+jet FCNC processes.
The cross section is sensitive to the top quark electric, magnetic dipole moments and top quark electric charge.

\[ \mathcal{L}_{t\bar{t}\gamma} = -eQ_t \bar{t}\gamma^\mu tA^\mu - iet \frac{\sigma_{\mu\nu} q^\nu}{2m_t} (\kappa + i\bar{\kappa}\gamma_5) tA^\mu, \]

\[ \kappa = Q_t a_t, \quad \bar{\kappa} = \frac{2m_t}{e} d_t. \]

Predicted SM values:
\[ a_t = 0.02 \Rightarrow k = 0.013 \]
\[ d_t < 10^{-30} \Rightarrow k < 5.7 \times 10^{-14} \]

The SM radiatively generates these couplings through electroweak loop corrections, which turn out to be too small to be observed at the LHC. This opens up the possibility to search for new physics in the top quark sector.

Direct probe is also possible via $t\bar{t}\gamma$ production (Tevatron and LHC).

There are indirect constraints from $b \rightarrow s\gamma$ decay as well as neutron EDM on top quark electric and magnetic dipole moments ($d_t < 3 \times 10^{-15} e.cm$).

\textbf{t+\gamma Motivations}

The cross section is also sensitive to the WW\gamma coupling.

EW theory is non-Abelian \implies gauge bosons possess weak charge \implies they interact with each other
The following triple and quartic self-interactions between EW Bosons appear:

\begin{align*}
\mathcal{L}_{WW\gamma} = -ie \left( W^\dagger_{\mu\nu} W^\mu A^\nu - W^\dagger_{\mu} A_\nu W^{\mu\nu} \right) + i\kappa_\gamma W^\dagger_{\mu} W_\nu F^\mu\nu + \frac{2\lambda}{m_W^2} W^\dagger_{\alpha\beta} W_\delta F^\delta\alpha,
\end{align*}

In the SM at tree level $k_\gamma=1$ and $\lambda=0$

\begin{itemize}
\item Directly probed via $W\gamma$ production at LHC at 7 TeV
  \begin{itemize}
  \item CMS: $-0.38 < \Delta k_\gamma < 0.29$, $-0.050 < \lambda < 0.037$
  \item ATLAS: $-0.46 < \Delta k_\gamma < 0.41$, $-0.065 < \lambda < 0.061$
  \end{itemize}
\item They are also constrained in LEP and Tevatron
\item Indirectly by $b \rightarrow s\gamma$ decay
\end{itemize}

\begin{itemize}
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\end{itemize}
The normalized cross section $\sigma(t\gamma_j)/\sigma(tj)$ as a function of anomalous couplings is investigated. The advantage is many experimental and theoretical uncertainties are canceled out. jet energy scale, lepton identification, b-jet tagging, luminosity, PDF, and variation of scales.

Direct Probe of ttγ (history)

- Coupling of top quark and photon can be directly probed by measuring the ttγ Cross section.

Measurements of the production cross section of tt+γ have been performed by:

- CDF at the Tevatron using ppbar collisions at $\sqrt{s} = 1.96$ TeV
- ATLAS at the LHC using pp collisions at $\sqrt{s} = 7, 8, 13$ TeV.
- CMS Collaboration at $\sqrt{s} = 8$ TeV.

<table>
<thead>
<tr>
<th>Category</th>
<th>$R$</th>
<th>$\sigma_{\text{fid}}^{\text{tt}+\gamma}$ (fb)</th>
<th>$\sigma_{\text{tt}+\gamma}$ (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>e+jets</td>
<td>$(5.7 \pm 1.8) \times 10^{-4}$</td>
<td>138 ± 45</td>
<td>582 ± 187</td>
</tr>
<tr>
<td>$\mu$+jets</td>
<td>$(4.7 \pm 1.3) \times 10^{-4}$</td>
<td>115 ± 32</td>
<td>453 ± 124</td>
</tr>
<tr>
<td>Combination</td>
<td>$(5.2 \pm 1.1) \times 10^{-4}$</td>
<td>127 ± 27</td>
<td>515 ± 108</td>
</tr>
<tr>
<td>Theory</td>
<td>---</td>
<td>---</td>
<td>592 ± 71 (scales) ± 30 (PDFs)</td>
</tr>
</tbody>
</table>
Distinctive signatures in addition to the single top quark are:

- A light energetic jet which tends to fly in the forward/backward region.
- A photon in the final state.

Signal is generated with Madgraph at NLO ($p_T > 10$ GeV, $|\eta| < 2.6$, $\Delta R > 0.05$)

$\sigma(pp \to t\gamma j)$ [NLO] = 2.95 pb

Sensitive to the $tt\gamma$ coupling (electric and magnetic moments of top quark) and $WW\gamma$ coupling (gauge boson couplings). *Eur.Phys.J. C76 (2016) no.10, 533*

Background for SM processes, $tt+V/H$, $tqH$. 
The analysis is performed at $\sqrt{s}= 13$ TeV using the 2016 data which corresponds to 35.9 fb$^{-1}$.

Only the muon decay channel was considered.
Object Selections

Photon Selection:
- Only one isolated tight photon with $E_T > 25$ GeV and $|\eta| < 1.4442$ is required.

Muon Selection:
- Require exactly one tight ID muon
- $p_T > 26$ GeV, $|\eta| < 2.4$
- $I_{rel} = \frac{1}{p_T} \sum E_T(\text{Track}+\text{Ecal}+\text{Hcal}+\text{Muon}) < 0.15$ within a cone of $\Delta R=0.4$

Loose Muon Veto:
- To suppress DY, dibosons and $Z+\gamma$, ...
- Events are vetoed if there is an additional loose muon
- $p_T > 15$ GeV, $|\eta| < 2.4$
- $I_{rel} < 0.25$ within a cone of $\Delta R=0.4$

Light Jet Selection:
- Require to have at least one AK4PF Jet.
- $p_T > 40$ GeV, $|\eta| < 4.7$

B-jet Selection:
- Exactly 1 b-tagged jet within $p_T > 40$ GeV, $|\eta| < 2.4$.

Electron Veto:
- To suppress backgrounds which contain electrons.
- veto events containing electron
- $p_T > 20$ GeV, $|\eta| < 2.5$

MET:
- To suppress any background with no W boson in the final state.
- Missing transverse energy, MET > 30 GeV.

Additional Requirements:
- Less effects from ISR/FSR $\Delta R(\gamma,X) > 0.5$ $X=$jets, b-jet, $\mu$
Top quark reconstruction needs the W boson reconstruction in the first step using the muon and neutrino.

**Assumptions are:**
- \( \text{MET}_x \) and \( \text{MET}_y \) equal to \( P_x \) and \( P_y \) of invisible neutrino.
- Selected muon is considered as W decay product.
- W mass used as a constraint to find the \( p_z \) of neutrino.
- **Solving the quadratic equation to find the \( p_z \) of neutrino:**

The top quark candidate is reconstructed by combining the reconstructed W boson and the b-jet candidate.
Backgrounds with prompt(Genuine) photon:

- $t\bar{t}+\gamma$: (Estimated from data)
- $Z+\gamma+\text{jet}$, $W+\gamma+\text{jet}$, $WW+\gamma$, $WZ+\gamma$,.. : (Estimated from MC simulation)

Backgrounds with (misidentified) photon:
- Jets can be mis-reconstructed as photon:
  - $Tt\bar{t}$, $W+\text{jet}$, $DY\text{Jets}$, Single top ($t$-, $s$-, $tW$-channels), $WW$, $WZ$, $ZZ$: (Estimated from data)

\[
\sigma = \text{Pb(NLO)}
\]

<table>
<thead>
<tr>
<th>Process</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W+\text{jets(lep decay)}$</td>
<td>$6\times10^4$</td>
</tr>
<tr>
<td>$DY$</td>
<td>$2\times10^4$</td>
</tr>
<tr>
<td>$tt\bar{t}$</td>
<td>831</td>
</tr>
<tr>
<td>$W\gamma\text{jets(lep decay)}$</td>
<td>489</td>
</tr>
<tr>
<td>$Z\gamma\text{jets(lep decay)}$</td>
<td>118</td>
</tr>
<tr>
<td>$\text{ST t-ch(lep decay)}$</td>
<td>71</td>
</tr>
<tr>
<td>$\text{ST tW-ch}$</td>
<td>71(LO)</td>
</tr>
<tr>
<td>$WW$</td>
<td>63</td>
</tr>
<tr>
<td>$WZ$</td>
<td>47</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>16.5</td>
</tr>
<tr>
<td>$\text{ST s-ch(lep decay)}$</td>
<td>3.3</td>
</tr>
<tr>
<td><strong>Signal</strong></td>
<td>2.95</td>
</tr>
</tbody>
</table>
Processes with Prompt Photon

- Estimation of the events with real $\gamma$ is done based on MC samples via matching with the generator parental information.
  - $Z+\gamma+\text{Jet}$
  - $W+\gamma+\text{Jet}$
  - $WW\gamma$
  - $WZ\gamma$

  **Matching Criteria:**
  - $\Delta R(\text{Rec}(\gamma), \text{Gen}(\gamma)) < 0.2$
  - $(P_T(\text{Rec}(\gamma)) - P_T(\text{Gen}(\gamma)))/P_T(\text{Gen}(\gamma)) < 0.1$
  - If Mother particle is leptons, quarks, bosons and $\gamma \rightarrow \text{Real}$

- Estimation of the main background via dedicated Control Region.
  - $t\bar{t}+\gamma$

- Additional contribution form $\text{electron} \rightarrow \text{photon}$ miss-identification.
  Photon have to be matched with an electron with the same matching criteria.
  - $t\bar{t}+\text{jets}$
  - Diboson

\[ \text{proton} \rightarrow \text{e}^+\text{MissId}\gamma \]
How Jets Fake Photons

30% of jet containment is photon originating from $\pi^0$...

$\Sigma pT(ch \text{ Hadron}) / pT_\gamma$

Data

Genuine

Fake
Estimation of Events with Fake Photon

Goal is to obtain shape and normalization of fake events in the SR:
- Method quite relies on data.
- Method does not use any information from SR.

If variables are uncorrelated (has to be verified):
→ shape of var1 distribution independent of choice of var2
→ background in signal region predicted by scaling of control sample

\[
\frac{\text{Events with fake photon in } D}{\text{Events in } C} = \frac{\text{Events in } A}{\text{Events in } B}
\]

Correlation between PFCHIso and \( \sigma_{\eta\eta} \) is few percent therefore the variables are suitable to be used as inputs of ABCD method.

EF is calculated in the 6 separate bins of photon’s \( p_T \).

Obtain the shape and normalization of fake events in SR for each distribution by weighting each event in the PLJ sample with the EF(\( P_{T\gamma} \)).
Any **correlation** between PF charge isolation and $\sigma_{i\eta i\eta}$ leads to change of Extrapolation Factor when one changes the border of side-band regions.

- Possible contaminations of prompt photons in the regions A, B, and C.

- The statistical uncertainty is also considered as another source of uncertainty in the fake background estimation.
ttbar+γ Estimation

✧ ttbar+γ is our main background and it is subjected to several source of systematic uncertainties.
✧ ttγ Control Region:

- Exactly 2 b-tagged jet
- Rest criteria are the same
- Purity of CR for ttγ events is 84%.
- Contribution of signal in the CR is negligible.

- Strategy to estimate the ttγ:
- Normalization of ttγ left float in both CR and SR.
- Fit into the SR and CR simultaneously in order to constrain the ttγ from CR and extract the ttγ normalization in the SR.

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Control Plots
- Event yields after the full event selection in data and each source of SM background contribution.

- The expected yields are presented with both statistical and systematic uncertainties.

<table>
<thead>
<tr>
<th>Process</th>
<th>Event yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{t}t + \gamma$</td>
<td>$1401 \pm 131$</td>
</tr>
<tr>
<td>$W\gamma + \text{jets}$</td>
<td>$329 \pm 78$</td>
</tr>
<tr>
<td>$Z\gamma + \text{jets}$</td>
<td>$232 \pm 55$</td>
</tr>
<tr>
<td>Misidentified photon</td>
<td>$374 \pm 74$</td>
</tr>
<tr>
<td>$t\gamma$ (s- and tW-channel)</td>
<td>$57 \pm 8$</td>
</tr>
<tr>
<td>$VV\gamma$</td>
<td>$8 \pm 3$</td>
</tr>
<tr>
<td>Total background</td>
<td>$2401 \pm 178$</td>
</tr>
<tr>
<td>Expected signal</td>
<td>$154 \pm 24$</td>
</tr>
<tr>
<td>Total SM prediction</td>
<td>$2555 \pm 180$</td>
</tr>
<tr>
<td>Data</td>
<td>$2535$</td>
</tr>
</tbody>
</table>
Signal and Background Discrimination

✧ Train signal against the ttbar+γ as this is the main background.
✧ Several variables to have maximum possible discrimination.
✧ BDT approach is used.

- Pseudorapidity of the light jet
- Cosine angle of muon and light-jet in the top rest frame
- Pseudorapidity of the Muon candidate
- Angular separation of the light-jet and photon $\Delta R(l - jet, \gamma)$
- Reconstructed top quark mass
- Jet multiplicity
- Reconstructed transverse mass of $W$ boson
- Charge of muon candidate
## Systematic Uncertainties

<table>
<thead>
<tr>
<th>Process</th>
<th>$W+\gamma+\text{jet}$</th>
<th>$Z+\gamma+\text{jet}$</th>
<th>Diboson</th>
<th>tw-ch,s-ch</th>
<th>$+\gamma+\text{jet}$</th>
<th>Misidentified</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>shape</td>
<td>norm</td>
<td>shape</td>
<td>norm</td>
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<td>X</td>
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<td>Pileup</td>
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<tr>
<td><strong>JES</strong></td>
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<tr>
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<td><strong>Signal Model</strong></td>
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<td><strong>b-tagging</strong></td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
Data is parameterized based on the BDT variable as the following:

\[ F(x_{BDT}) = C_{signal} S_{signal}(x_{BDT}) + C_{W\gamma jet} S_{W\gamma jet}(x_{BDT}) + C_{t\bar{t}\gamma jet} S_{t\bar{t}\gamma jet}(x_{BDT}) + C_{Z\gamma jet} S_{Z\gamma jet}(x_{BDT}) + C_{fake} S_{fake}(x_{BDT}) + C_B S_B(x_{BDT}). \]

Only \( C_{signal} \) and \( C_{ttb\gamma} \) left to float in the final likelihood fit and rest only let to float within their assigned errors.

Simultaneous fit into the SR and CR in order to measure the signal cross section.

- Expected significance found to be 3.0\( \sigma \).
- Observed significance found to be 4.4\( \sigma \) with corresponding p-value = 4.27x10^{-6}.
- The measured cross section in the region \( E_{T,\gamma} > 25 \text{ GeV}, |\eta| < 1.4442 \) and \( \Delta R(X, \gamma) > 0.5 \), where \( X = \mu, b \text{ jet}, \text{ light jet} \), is found to be \( \sigma(tq\gamma) \times B = 115 \pm 17 \text{ (stat.) } +/- 33/27 \text{ (syst.) fb} \).
- SM cross section is calculated with the amc@NLO and it is found to be \( \sigma(tq\gamma) \times B \times A_{c\gamma} = 81\pm4 \text{ fb} \).
- The normalization of \( tt\gamma \) found to be 1221 ± 121.
Summary

- First time measurement is performed for the SM single top+γ using 35.9 fb\(^{-1}\) of 2016 data recorded by CMS.

- Expected significance found to be 3.0\(\sigma\) including all sources of systematic uncertainties.

- Observed significance is 4.4\(\sigma\) which shows a strong evidence of this process.

- The measured cross section in the region \(E_{T,\gamma} > 25\ \text{GeV}, \ |\eta| < 1.4442\) and \(\Delta R(X, \gamma) > 0.5\), where \(X = \mu, \ b\ \text{jet}, \ \text{light jet}\), is found to be:

\[
115 \pm 17 \ (\text{stat.}) \ +/- \ 33/27 \ (\text{syst.}) \ fb
\]

which is in agreement with the SM prediction of 81 \(\pm\) 4 fb.
Backup
Defining an Asymmetry:
- To distinguish the contributions from the different Lorentz structures in the vertices of $tt\gamma$ and $WW\gamma$.
- Momentum dependence is also investigated.

$$A_{t,\gamma} = \frac{N(\cos(\bar{p}_t, \bar{p}_\gamma) > 0) - N(\cos(\bar{p}_t, \bar{p}_\gamma) < 0)}{N(\cos(\bar{p}_t, \bar{p}_\gamma) > 0) + N(\cos(\bar{p}_t, \bar{p}_\gamma) < 0)},$$
Systematic Uncertainties

- **Luminosity**: Variation of luminosity by 2.5% according to the recommendation.
- \((p_T, \eta)\) dependent uncertainties on SF are applied: Muon Id and Isolation, Photon Id, Ele Veto, and HLT.
- Photon energy scale
- Uncertainties on the b-jet tagging and miss-tagging SFs applied
- Fake events estimation: Systematical and statistical uncertainties for fake photon contribution
- JES/JER
- Pileup: Changing the total inelastic cross section by 5% up and down and count the difference as systematic uncertainty.
- Rate uncertainty:
  - Uncertainty on the cross sections of processes we estimated by MC samples separately for each process and uncorrelated between processes
- **Due to the choice of PDFs**: Variation of about 100 pdf sets of NNPDF3.0 considered as a pdf uncertainty.
- Variation of scales
- Uncertainty due to the choice of showering model: using samples showered with Pythia and Herwig
- Uncertainty due to un-clustered particles in the MET
- Uncertainty on \(tt+\gamma\) shape in the SR