Measurement of the semileptonic $tt+\gamma$ production cross section at 8 TeV

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submitted to JHEP
Overview

- Associated production of top quarks provides an interesting check of the standard model and window where new physics could show up
  - Provides measurements which are directly sensitive to the couplings of the top quark

- Measuring the $t\bar{t}+\gamma$ production cross section
  - Allows for probing the electroweak coupling of the top quark
  - Directly sensitive to the top quark charge
  - Any deviations from the SM prediction could be hints at new physics
tt+γ Cross Section Measurement

• Measuring the production cross section of tt+γ production using 19.7 fb\(^{-1}\) of data collected by the CMS experiment at a center of mass energy of 8 TeV

• Performed in the lepton+jets final state (e or μ)

• Fiducial cross section is measured relative to inclusive tt production

• arXiv:1706.08128 submitted to JHEP
Selection

• Selection is split into two levels:
  • **Top quark selection**: events with a top quark pair signature
  • **Photon selection**: passing the top quark selection and have at least one photon present

• **Top quark selection:**
  • Require exactly 1 lepton (e or mu)
    • Veto events with additional leptons passing loose requirements
  • At least 3 jets, one of which is b-tagged
  • $p_T^{\text{miss}} > 20 \text{ GeV}$

• **Photon Selection:**
  • At least one photon, $p_T > 25 \text{ GeV}$, $|\eta| < 1.44$, isolated from other activity in event
Top quark pair production

- Measurement is performed as a ratio of $t\bar{t}+\gamma$ to $t\bar{t}$ production cross sections:

$$R = \frac{\sigma_{t\bar{t}+\gamma}^{\text{fid}}}{\sigma_{t\bar{t}}} = \frac{N_{t\bar{t}+\gamma}}{N_{t\bar{t}}} \cdot \frac{\epsilon_{t\bar{t}}^\text{fit} A_{t\bar{t}}^\text{fit}}{N_{t\bar{t}}}$$

- Need to measure both the number of $t\bar{t}+\gamma$ events (after photon selection) and number of top quark pair events at top quark selection level.

- Fit to $M_3$ variable (mass of 3-jet combination with highest summed $p_T$) used to extract $N_{t\bar{t}}$

$e+\text{jets}$: $N_{t\bar{t}} = 162200 \pm 1600$ (stat)

$\mu+\text{jets}$: $N_{t\bar{t}} = 219100 \pm 1900$ (stat)

Distribution of $M_3$ after top quark selection fit

- 19.7 fb$^{-1}$ (8 TeV)

- Data points and histograms for different processes.
After photon selection, backgrounds can be split into two categories:

- Top pair events with fake photons
- Non-top processes with real photons ($W+\gamma$, $Z+\gamma$)

Each of these backgrounds is estimated using fits to different variables:

- $M3$ is used to distinguish top from non-top processes
- Photon charged hadron isolation can be used to separate prompt from nonprompt photons
Top quark purity

- Top quark purity ($\pi_{tt}$), defined as fraction of events coming from top pair events, measured with fit to $M_3$ distribution
  - Measured after the photon selection is applied
  - Templates for top events (tt or tt+$\gamma$), $W+\gamma$, and other backgrounds taken from simulation

<table>
<thead>
<tr>
<th>Event Type</th>
<th>$\pi_{tt}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e+\text{jets}$</td>
<td>0.70 ± 0.08 (stat)</td>
</tr>
<tr>
<td>$\mu+\text{jets}$</td>
<td>0.68 ± 0.06 (stat)</td>
</tr>
</tbody>
</table>
Photon purity

- Photon purity ($\pi_{\gamma}$), fraction of events coming from prompt photons, measured through a fit to the photon isolation
  - Prompt photons (or also misidentified electrons) will be isolated
  - Hadronic/nonprompt photons will be less isolated
- Templates for both derived from data
  - Isolated photons template taken from measuring isolation in random cone
  - Nonprompt template taken from inverting selection requirements on photon shower shape ($\sigma_{\eta\eta}$)

Results of fit to photon isolation

**e+jets:**
$\pi_{\gamma} = 0.57 \pm 0.06 \text{ (stat)}$

**$\mu$+jets:**
$\pi_{\gamma} = 0.53 \pm 0.06 \text{ (stat)}$
**N_{tt+\gamma} Measurement**

- Combine the information from the top quark purity, photon purity, and number of events observed in data into a $\chi^2$ function
  - Fit to rates of signal and primary background contributions ($V+\gamma$ and nonprompt photons)
  - Maximizing Likelihood function $L = e^{-\chi^2/2}$

$$
\chi^2 = \frac{(\pi_\gamma^{\text{data}} - \pi_\gamma^{\text{MC}})^2}{\sigma^2_{\pi_\gamma}} + \frac{(\pi_{tt}^{\text{data}} - \pi_{tt}^{\text{MC}})^2}{\sigma^2_{\pi_{tt}}} + \frac{(N_{\text{data}} - N_{\text{MC}})^2}{\sigma^2_N}
$$

- $\pi_\gamma^{\text{data(MC)}}$: photon purity in data (MC), with uncertainty $\sigma_{\pi_\gamma}$
- $\pi_{tt}^{\text{data(MC)}}$: top purity in data (MC), with uncertainty $\sigma_{\pi_{tt}}$
- $N_{\text{data(MC)}}$: number of events in data (MC), with uncertainty $\sigma_N$

**e+jets:**
\[N_{tt+\gamma} = 338 \pm 53 \text{ (stat)}\]

**\(\mu\)+jets:**
\[N_{tt+\gamma} = 442 \pm 69 \text{ (stat)}\]
Uncertainties

• For each systematic, measurement is repeated with each parameter varied within uncertainties

• Largest uncertainty from:
  • Statistical uncertainty in fit
  • Top quark mass: ±1 GeV change in mass used in simulation ($m_t=172.5$ GeV)
  • Jet energy scale uncertainties
  • Scale uncertainties, doubling and halving scale used in simulation ($\mu_R=\mu_F=Q=\sqrt{m_t^2+\sum p_T^2}$)

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical likelihood fit</td>
<td>15.5</td>
</tr>
<tr>
<td>Top quark mass</td>
<td>7.9</td>
</tr>
<tr>
<td>JES</td>
<td>6.9</td>
</tr>
<tr>
<td>Fact. and renorm. scale</td>
<td>6.7</td>
</tr>
<tr>
<td>ME/PS matching threshold</td>
<td>3.9</td>
</tr>
<tr>
<td>Photon energy scale</td>
<td>2.4</td>
</tr>
<tr>
<td>JER</td>
<td>2.3</td>
</tr>
<tr>
<td>Multijet estimate</td>
<td>2.0</td>
</tr>
<tr>
<td>Electron misid. rate</td>
<td>1.3</td>
</tr>
<tr>
<td>Z+jets scale factor</td>
<td>0.8</td>
</tr>
<tr>
<td>Pileup</td>
<td>0.6</td>
</tr>
<tr>
<td>Background normalization</td>
<td>0.6</td>
</tr>
<tr>
<td>Top quark $p_T$ reweighting</td>
<td>0.4</td>
</tr>
<tr>
<td>b tagging scale factor</td>
<td>0.3</td>
</tr>
<tr>
<td>Muon efficiency</td>
<td>0.3</td>
</tr>
<tr>
<td>Electron efficiency</td>
<td>0.1</td>
</tr>
<tr>
<td>PDFs</td>
<td>0.1</td>
</tr>
<tr>
<td>Muon energy scale</td>
<td>0.1</td>
</tr>
<tr>
<td>Electron energy scale</td>
<td>0.1</td>
</tr>
<tr>
<td>Total</td>
<td>20.7</td>
</tr>
</tbody>
</table>
Results

\[ R = \frac{\sigma_{tt+\gamma}^{\text{fid}}}{\sigma_{tt}} = \frac{N_{tt+\gamma}}{\epsilon_{tt+\gamma}} \cdot \frac{\epsilon_{\text{top}} A_{\text{top}}^{tt}}{N_{tt}} \]

- Cross section measured in fiducial region of $\ell$+jets final state of the top decay with photon having $p_T > 25$ GeV & $|\eta| < 1.44$
- Efficiencies and acceptances are taken from simulation
- Cross section can be extracted by multiplying $R$ by measured value of tt cross section

\[ \sigma_{tt} = 244.9 \pm 1.4 \text{ (stat)}^{+6.3}_{-5.5} \text{ (syst)} \pm 6.4 \text{ (lumi)} \]

<table>
<thead>
<tr>
<th>Category</th>
<th>$R$</th>
<th>$\sigma_{tt+\gamma}^{\text{fid}}$ (fb)</th>
<th>$\sigma_{tt+\gamma} \times B$ (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>e+jets</td>
<td>$(5.7 \pm 1.8) \times 10^{-4}$</td>
<td>$138 \pm 45$</td>
<td>$582 \pm 187$</td>
</tr>
<tr>
<td>$\mu$+jets</td>
<td>$(4.7 \pm 1.3) \times 10^{-4}$</td>
<td>$115 \pm 32$</td>
<td>$453 \pm 124$</td>
</tr>
<tr>
<td>Combination</td>
<td>$(5.2 \pm 1.1) \times 10^{-4}$</td>
<td>$127 \pm 27$</td>
<td>$515 \pm 108$</td>
</tr>
<tr>
<td>Theory</td>
<td>–</td>
<td>–</td>
<td>$592 \pm 71 \text{ (scales)} \pm 30 \text{ (PDFs)}$</td>
</tr>
</tbody>
</table>
Summary

- Measurement of the associated production of top quark-antiquark pair with a photon in the semileptonic final state presented
- Using 19.7 fb$^{-1}$ of data collected at center-of-mass energy of 8 TeV
- Ratio of the $t\bar{t}+\gamma$ to $t\bar{t}$ production cross sections measured to be
  \[
  R = \frac{\sigma_{t\bar{t}+\gamma}^{\text{fid.}}}{\sigma_{t\bar{t}}} = \left(5.2 \pm 1.1\right) \times 10^{-4}
  \]
- Cross section for $t\bar{t}+\gamma$ measured to be in agreement with SM prediction:
  \[
  \sigma_{t\bar{t}+\gamma}^{\text{fid.}} = 127 \pm 27 \text{ fb}
  \]
  \[
  \sigma_{t\bar{t}+\gamma} \times B = 515 \pm 108 \text{ fb}
  \]
Backup Slide
Signal Simulation

• $tt+\gamma$ MC is simulated in Madgraph v5.1.3.30

• 2-$\rightarrow$7 production
  • Photon can come be radiated from top quark, decay products of top quark, or ISR

• Generator level photon cuts:
  • $p_T > 13$ GeV
  • $|\eta| < 3.0$
  • $\Delta R = \sqrt{(\Delta \phi^2 + \Delta \eta^2)} > 0.3$, between generated photon and other generated particles

• Overlap removal:
  • Events are removed from $tt$ MC which fall within the $tt+\gamma$ signal definition to avoid double counting
Reconstructed Object Selection

**Trigger:**
- **e+jets:** $p_T > 27$ GeV, $|\eta| < 2.5$
- **$\mu$+jets:** $p_T > 24$ GeV, $|\eta| < 2.1$

**Electrons:**
- $p_T > 35$ GeV
- $|\eta| < 2.5$
- $I_{rel} < 0.1$
- Tight ID
- Loose: $p_T > 20$, $|\eta| < 2.5$

**Muons:**
- $p_T > 26$ GeV
- $|\eta| < 2.1$
- $I_{rel} < 0.2$
- Tight ID
- Loose: $p_T > 10$, $|\eta| < 2.5$

**Jets:**
- anti-$k_T$, R=0.5 jets
- $p_T > 30$ GeV
- $|\eta| < 2.4$
- Energy corrected for pileup

**Photons:**
- $p_T > 25$ GeV
- $|\eta| < 1.44$ (ECAL barrel)
- Conversion rejection and identification requirements applied

**B-tagging:**
- Combined Secondary Vertex tagger
- “Medium” working point
- ~70% efficiency, 1-2% mistag rate
Fiducial Region Cuts

Cuts applied at generator level in MC

Electrons
- $p_T > 35$ GeV
- $|\eta| < 2.5$

Muons:
- $p_T > 26$ GeV
- $|\eta| < 2.1$

Jets:
- $p_T > 30$ GeV
- $|\eta| < 2.4$

Photons:
- $p_T > 25$ GeV
- $|\eta| < 1.44$ (ECAL barrel)

MET:
- $\sum p_T(\nu) > 20$ GeV

Require exactly one lepton, at least 3 jets (one coming from b), MET, and at least one photon
MC Event Categories

• Splitting MC events into 3 categories, based on where photon comes from
  • Genuine photons: events with a real, prompt photon
  • Misidentified electrons: reconstruction misidentifies a generated photon as an electron
  • Nonprompt/fake photons: reconstructed photon not matched to prompt photon or misidentified electron, or matched to generated non-prompt photon
## Event Yields in the e+jets final state

<table>
<thead>
<tr>
<th>Sample</th>
<th>Genuine photon</th>
<th>Misid. electron</th>
<th>Nonprompt photon</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}+\gamma$</td>
<td>$312 \pm 17$</td>
<td>$0.2 \pm 0.1$</td>
<td>$8.5 \pm 0.9$</td>
<td>$321 \pm 17$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$-$</td>
<td>$22 \pm 3$</td>
<td>$215 \pm 13$</td>
<td>$237 \pm 14$</td>
</tr>
<tr>
<td>W+\gamma</td>
<td>$75 \pm 25$</td>
<td>$-$</td>
<td>$-$</td>
<td>$75 \pm 25$</td>
</tr>
<tr>
<td>W+jets</td>
<td>$-$</td>
<td>$-$</td>
<td>$60 \pm 15$</td>
<td>$60 \pm 15$</td>
</tr>
<tr>
<td>Z+\gamma</td>
<td>$14 \pm 5$</td>
<td>$1.3 \pm 1.1$</td>
<td>$0.5^{+0.7}_{-0.5}$</td>
<td>$16 \pm 5$</td>
</tr>
<tr>
<td>Z+jets</td>
<td>$-$</td>
<td>$43 \pm 28$</td>
<td>$11 \pm 6$</td>
<td>$54 \pm 30$</td>
</tr>
<tr>
<td>Single t</td>
<td>$11 \pm 3$</td>
<td>$2.0 \pm 1.3$</td>
<td>$16 \pm 4$</td>
<td>$29 \pm 7$</td>
</tr>
<tr>
<td>QCD multijet</td>
<td>$-$</td>
<td>$-$</td>
<td>$31 \pm 18$</td>
<td>$31 \pm 18$</td>
</tr>
<tr>
<td>Total</td>
<td>$412 \pm 31$</td>
<td>$69 \pm 29$</td>
<td>$342 \pm 28$</td>
<td>$823 \pm 52$</td>
</tr>
<tr>
<td>Data</td>
<td>$-$</td>
<td>$-$</td>
<td>$-$</td>
<td>$935$</td>
</tr>
</tbody>
</table>

## Event Yields in the µ+jets final state

<table>
<thead>
<tr>
<th>Sample</th>
<th>Genuine photon</th>
<th>Misid. electron</th>
<th>Nonprompt photon</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}+\gamma$</td>
<td>$407 \pm 23$</td>
<td>$0.4 \pm 0.3$</td>
<td>$11 \pm 1$</td>
<td>$418 \pm 24$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$-$</td>
<td>$31 \pm 5$</td>
<td>$291 \pm 16$</td>
<td>$322 \pm 17$</td>
</tr>
<tr>
<td>W+\gamma</td>
<td>$140 \pm 41$</td>
<td>$-$</td>
<td>$9.0 \pm 6.7$</td>
<td>$149 \pm 45$</td>
</tr>
<tr>
<td>W+jets</td>
<td>$-$</td>
<td>$-$</td>
<td>$57 \pm 14$</td>
<td>$57 \pm 14$</td>
</tr>
<tr>
<td>Z+\gamma</td>
<td>$21 \pm 7$</td>
<td>$-$</td>
<td>$1.4 \pm 0.9$</td>
<td>$23 \pm 7$</td>
</tr>
<tr>
<td>Z+jets</td>
<td>$-$</td>
<td>$-$</td>
<td>$9.6 \pm 5.8$</td>
<td>$10 \pm 6$</td>
</tr>
<tr>
<td>Single t</td>
<td>$12 \pm 3$</td>
<td>$1.5 \pm 1.3$</td>
<td>$25 \pm 13$</td>
<td>$38 \pm 14$</td>
</tr>
<tr>
<td>QCD multijet</td>
<td>$-$</td>
<td>$-$</td>
<td>$36 \pm 20$</td>
<td>$36 \pm 20$</td>
</tr>
<tr>
<td>Total</td>
<td>$580 \pm 48$</td>
<td>$33 \pm 5$</td>
<td>$440 \pm 33$</td>
<td>$1053 \pm 61$</td>
</tr>
<tr>
<td>Data</td>
<td>$-$</td>
<td>$-$</td>
<td>$-$</td>
<td>$1136$</td>
</tr>
</tbody>
</table>
Likelihood Fit

\[ \chi^2(SF_{tt+\gamma}, SF_{V+\gamma}, SF_{jet\rightarrow\gamma}) = \left( \frac{\pi_{\gamma}^{\text{data}} - \pi_{\gamma}^{\text{MC}}}{\sigma_{\gamma}^2} \right)^2 + \left( \frac{\pi_{tt}^{\text{data}} - \pi_{tt}^{\text{MC}}}{\sigma_{tt}^2} \right)^2 + \left( \frac{N_{\text{data}} - N_{\text{MC}}}{\sigma_N^2} \right)^2 \]

- Scale factors for \(tt+\gamma\), \(V+\gamma\), and nonprompt fake rates come into play in the MC predictions of the photon purity (\(\pi_\gamma^{\text{MC}}\)), top quark purity(\(\pi_{tt}^{\text{MC}}\)), and total number of events (\(N_{\text{MC}}\))
  - \(\pi_\gamma^{\text{MC}}\) = fraction of events in genuine photon or misid. electron categories
  - \(\pi_{tt}^{\text{MC}}\) = fraction of events coming from \(tt+\gamma\) or \(tt\)
  - \(N_{\text{MC}}\) = total number of MC events (effected by all three rates)

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<td>–</td>
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</tr>
<tr>
<td>(W+\text{jets})</td>
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<td>–</td>
<td>60 ± 15</td>
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<td>823 ± 52</td>
</tr>
<tr>
<td>Data</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>935</td>
</tr>
</tbody>
</table>