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Measurement of the Inclusive Top-Quark Pair + Photon Production Cross Section

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Abstract

The production cross section of top-quark pairs associated with a photon $t\bar{t}+\gamma$ is determined in the muon+jets decay channel using 19.7 fb-1 of data taken at $\sqrt{s} = 8\,\text{TeV}$ with the CMS detector. The relative fraction of $t\bar{t}+\gamma$ events normalized to inclusive $t\bar{t}$ production is measured. Using an inclusive CMS cross section measurement, the $t\bar{t}+\gamma$ cross section is determined and found to agree with the standard model expectation.

Keywords: top quark, photon, cross section, muon channel, template fit

1. Introduction

A measurement of the $t\bar{t}+\gamma$ production cross section is presented [1], making a step towards a direct quantification of the electromagnetic interaction of the standard model top quark. Modifications in the top quark couplings might be important indications of physics beyond the standard model (BSM) [2]. We use a dataset of $\mathcal{L}_{\text{int}} = 19.7\,\text{fb}^{-1}$ of integrated luminosity, recorded in pp collisions at $\sqrt{s} = 8$ with the CMS detector in 2012.

The measurement is performed in the *muon + jets* channel, requiring one isolated muon, at least four jets and the presence of an isolated hard photon. Our measured observable, $R = \sigma_{t\bar{t}+\gamma}/\sigma_{t\bar{t}}$, allows for the the cancellation of factors and their associated systematic uncertainties, such as luminosity and trigger efficiency. The $\sigma_{t\bar{t}+\gamma}$ cross section is obtained by multiplication of the measured value of R with a recent $t\bar{t}$ cross section measurement performed by CMS [3].

2. Signal and background modeling

The fiducial signal region is defined to be the final state of the process $\text{pp} \to \text{W}^{+}\text{W}^{-}\text{b}\bar{\text{b}}\gamma$, with the phase space requirements $E_{\text{T}}(\gamma) > 20\,\text{GeV}$and $\Delta R(\gamma, \text{b}/\bar{\text{b}}) > 0.1$ for the photon [1]. Simulated events are generated in the $t\bar{t}+\gamma$ signal region with the WHIZARD event generator (v. 2.0.7) [4]. The cross section of the signal sample is obtained as the LO generator cross section times a NLO k-factor [5], which amounts to $\sigma^{\text{sig}}_{t\bar{t}+\gamma} = 1.8\pm0.5\,\text{pb}$.

The $t\bar{t}$ background sample is simulated with the MADGRAPH (v. 5.1.1.0) event generator [6]. In order to avoid double counting, events are removed if they contain a showered photon that satisfies the phase space requirements of our signal region. The $t\bar{t}$ sample cross section is taken from next-to-next-to-leading-order (NNLO) calculation [7] and amounts to $\sigma_{t\bar{t}} = 245.8^{+8.8}_{-10.5}$ pb. Further background processes are W and Z/γ boson production with additional jets and single top-quark production (t- and tW-channels).

3. Object reconstruction and event selection

Top-quark pair events in the muon + jets channel provide a clear signal signature. This channel is generally characterized by the presence of an isolated high-p_{T} muon, missing transverse momentum, and at least four high-transverse-momentum jets, including two jets originating from b quarks [8].

For every event, single particle candidates are reconstructed using the particle flow algorithm [9]. The resulting list of particles are classified into separate cate-

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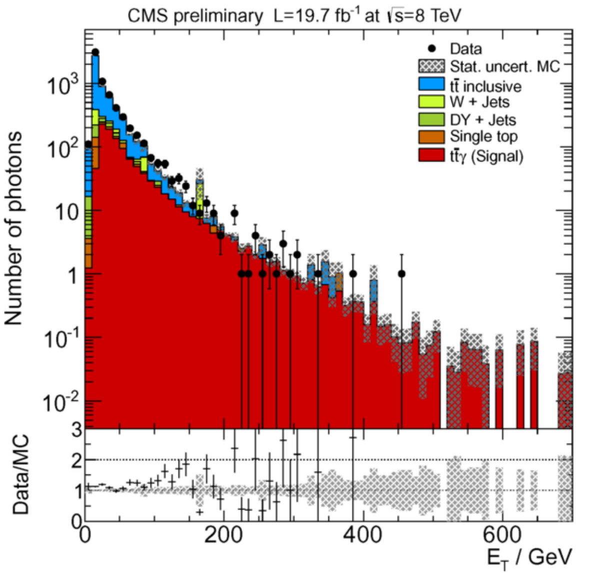

Figure 1: Distribution of the transverse photon energy spectrum after application of selection requirements.

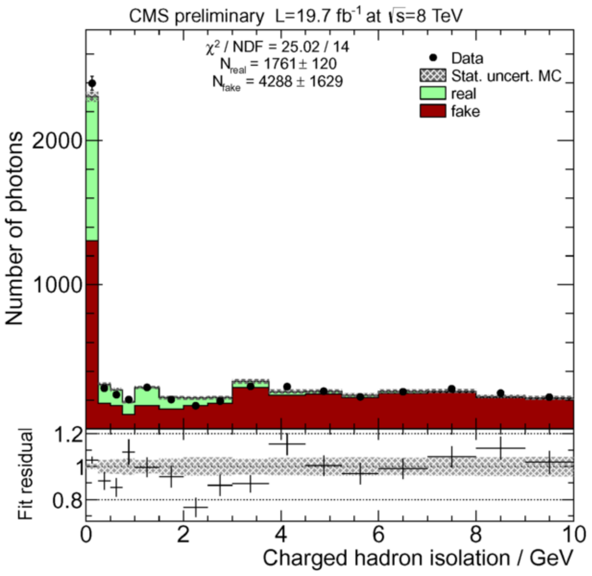

Figure 2: Template fit result. The signal and background templates are scaled to the fit parameters, N_{real} and N_{fake}, respectively.

gories (charged tracks, photons, neutral hadrons, electrons, muons). Isolated muons and electrons are identified, and remaining particles are clustered into jets using the anti-k_t algorithm with a distance parameter of 0.5 [10]. Jets originating from b quarks are identified by a "combined secondary vertex" (CSV) algorithm [11]. Photons are identified with discriminants using shower-shapes in the calorimeters as well as isolations variables.

Events, selected by the CMS trigger system requiring the presence of a single isolated muon with a transverse energy larger than 24 GeV, are **preselected** for this analysis if they contain exactly one isolated muon fulfilling $p_{\mathrm{T}} > 26$ GeV and $|\eta| < 2.1$ and contain at least four jets with $|\eta| < 2.5$ and $p_{\mathrm{T}} > 55,\ 45,\ 35,\ 20$ GeV, respectively. At least one b-tagged jet is required. Events are rejected if there is one or more electrons or additional muon candidates. After preselection, $N^{presel} = 256665$ events are found in the data. The purity of $t\bar{t}$ events, including the $t\bar{t}+\gamma$ signal fraction, is estimated from simulated events to be $\pi_{t\bar{t}} = 84.3\,\%$. The remaining fraction contains 9 % W+jets events, 5 % single top-quark events and a negligible fraction of DY+jets events.

Events are **selected** if they contain at least one photon fulfilling the requirements $E_{\mathrm{T}}(\gamma) > 25$ GeV and $|\eta(\gamma)| < 1.444$, where the latter requirement constrains photons to the CMS ECAL barrel region. The transverse energy distribution of photon candidates in selected events is shown in Fig. 1.

The quantity of correctly identified prompt photons is estimated with a binned maximum likelihood template fit. Since the main source of misidentified photons is of hadronic nature, the 'charged hadron isolation' is well-discriminating and thus used for the fit. It is defined as the scalar sum of energy of all charged hadronic particle flow candidates reconstructed inside a cone of $\Delta R < 0.4$ around the photon candidate. The fit template for signal photons is obtained from simulation. The background shape is obtained from a combined sideband of photon identification criteria. Fig. 2. shows the fit result. Applying the purity of $t\bar{t}+\gamma$ events in the simulated signal template, $\pi^{\mathrm{real}}_{t\bar{t}+\gamma} = 66.7\,\%$, the background-subtracted number of signal events, $N^{\mathrm{sig}}_{t\bar{t}+\gamma} = 1175 \pm 80\,(\mathrm{stat.})$, is observed.

4. Systematic uncertainties

Systematic uncertainties arise from detector effects as well as from theoretical uncertainties and mis-modeling in the simulation. Correction factors are applied where necessary to improve the description of the data by the simulation. Each systematic uncertainty is investigated separately, and determined individually by variation of the corresponding efficiency, resolution, or scale within its uncertainty. The overall uncertainty is derived by adding the individual contributions in quadrature.

The largest uncertainty arises from the modeling of the background in the template fit. It is evaluated using comparisons of MC generators, hadronization/showering models, and additional out-of-time pileup simulation. Real and fake templates are derived from each sample and pseudo-data distributions are generated according to the real and fake yields fitted in the data. The pseudo-data are then re-fitted and relative deviations are taken as systematic uncertainty. The estimated systematic uncertainty from background modeling is 23 % on the final results.

Further systematic uncertainties are related to the normalization of signal and background samples, PDF uncertainty, pileup, top quark p_{T} modeling, b-tagging, and jet energy correction and resolution estimates.

5. Cross section

The main measured observables in this analysis is the normalized cross section $R = \sigma_{t\bar{t}+\gamma}/\sigma_{t\bar{t}}$. It is calculated using parameters from both selection stages and the number of signal events $N^{\mathrm{sig}}_{t\bar{t}+\gamma}$ estimated in the data,

$$R \equiv \frac{\sigma_{t\bar{t}+\gamma}}{1} \cdot \frac{1}{\sigma_{t\bar{t}}} = \frac{N^{\mathrm{sig}}_{t\bar{t}+\gamma}}{\epsilon_\gamma} \cdot \frac{1}{N^{\mathrm{presel}}\,\pi_{t\bar{t}}},$$

where N^{presel} is the number of preselected $t\bar{t}$ events in the data, and the following quantities are determined from simulation: the purity of preselected $t\bar{t}$ events $\pi_{t\bar{t}} = 84.3\,\%$, the efficiency of photon identification and cleaning $\epsilon_\gamma = 50.7\,\%$.

The $t\bar{t}+\gamma$ cross section is calculated using a measurement of the $t\bar{t}$ cross section by CMS at $\sqrt{s} = 8$, $\sigma^{CMS}_{t\bar{t}} = 227 \pm 15\,\mathrm{pb}$ [12], taking the total uncertainty on the $t\bar{t}$ cross section measurement into account as a systematic uncertainty. The normalized cross section R and the cross section $\sigma_{t\bar{t}+\gamma}$ are observed to be:

$$\begin{aligned} R &= (1.07\ \pm 0.07\,(stat.)\ \pm 0.27\,(syst.))\,\% \\ \sigma_{t\bar{t}+\gamma} &= 2.4\ \pm 0.2\,(stat.)\ \pm 0.6\,(syst.)\,\mathrm{pb} \end{aligned}$$

Our measurement is in agreement with the standard model cross section of $\sigma^{SM}_{t\bar{t}+\gamma} = 1.8 \pm 0.5\,\mathrm{pb}$, for the $t\bar{t}+\gamma$ process as defined in Section 2.

6. Summary

The top-quark pair + photon production cross section is investigated with the full $19.7\,\mathrm{fb}^{-1}$ of pp collision data collected by CMS in 2012 at $\sqrt{s} = 8\,\mathrm{TeV}$. For this measurement, the signal region is defined by the final state of the process $\mathrm{pp} \to \mathrm{W}^+\mathrm{W}^-\mathrm{b}\bar{\mathrm{b}}\gamma$, with a transverse energy of the photon of $E_{\mathrm{T}}(\gamma) > 20\,\mathrm{GeV}$ and a distance between the photon and the b quark in $\eta - \phi$ space, $\Delta R(\gamma, \mathrm{b}/\bar{\mathrm{b}}) > 0.1$. Top-quark pair events in the muon + jets channel, with an additional hard photon candidate, are selected. Using an isolation discriminant, a maximum likelihood template fit is performed to estimate the true photon yield from prompt emission. The largest contribution to the systematic uncertainty of 23 % arises from the modeling of the background in the template fit. We measure the normalized and inclusive top-quark pair + photon production cross section to be $\sigma_{t\bar{t}\gamma} = 2.4\ \pm 0.2\,(stat.)\ \pm 0.6\,(syst.)\,\mathrm{pb}$ and $R = \sigma_{t\bar{t}\gamma}/\sigma_{t\bar{t}} = (1.07\ \pm 0.07\,(stat.)\ \pm 0.27\,(syst.))\,\%$, respectively. This result is in agreement with the standard model expectation, the most accurate measurement of the $t\bar{t}+\gamma$ process to date, and the first at a center-of-mass energy of 8 TeV.

References

[1] CMS Collaboration, Measurement of the top-quark pair + photon production cross section in the muon + jets channel in pp collisions at 8 TeV, CMS Physics Analysis Summary TOP-13-011.

[2] J. Aguilar-Saavedra, A minimal set of top anomalous couplings, Nucl.Phys. B812 (2009) 181. arXiv:0811.3842, doi:10.1016/j.nuclphysb.2008.12.012.

[3] S. Chatrchyan, et al., The CMS experiment at the CERN LHC, JINST 3 (2008) S08004. doi:10.1088/1748-0221/3/08/S08004.

[4] W. Kilian, T. Ohl, J. Reuter, WHIZARD: Simulating multi-particle processes at LHC and ILC, Eur.Phys.J. C71 (2011) 1742. arXiv:0708.4233, doi:10.1140/epjc/s10052-011-1742-y.

[5] K. Melnikov, M. Schulze, A. Scharf, QCD corrections to top quark pair production in association with a photon at hadron colliders, Phys.Rev. D83 (2011) 074013. arXiv:1102.1967, doi:10.1103/PhysRevD.83.074013.

[6] J. Alwall, P. Demin, S. de Visscher, R. Frederix, M. Herquet, et al., MadGraph/MadEvent v4: The new web generation, JHEP 0709 (2007) 028. arXiv:0706.2334, doi:10.1088/1126-6708/2007/09/028.

[7] M. Czakon, P. Fiedler, A. Mitov, The total top quark pair production cross-section at hadron colliders through $O(\alpha_S^4)$, Phys.Rev.Lett. 110 (2013) 252004. arXiv:1303.6254, doi:10.1103/PhysRevLett.110.252004.

[8] S. Chatrchyan, et al., Measurement of the $t\bar{t}$ production cross section in pp collisions at 7 tev in lepton + jets events using b-quark jet identification, Phys.Rev. D84 (2011) 092004. arXiv:1108.3773, doi:10.1103/PhysRevD.84.092004.

[9] CMS Collaboration, Particle-flow event reconstruction in CMS and performance for jets, taus, and MET, CMS Physics Analysis Summary PFT-09-001.

[10] M. Cacciari, G. P. Salam, G. Soyez, The anti-k(t) jet clustering algorithm, JHEP 0804 (2008) 063. arXiv:0802.1189, doi:10.1088/1126-6708/2008/04/063.

[11] CMS Collaboration, b-jet identification in the CMS experiment, CMS Physics Analysis Summary BTV-11-004.

[12] CMS Collaboration, Top pair cross section in dileptons, CMS Physics Analysis Summary TOP-12-007.

[13] S. Chatrchyan, et al., Determination of jet energy calibration and transverse momentum resolution in CMS, JINST 6 (2011) P11002. arXiv:1107.4277, doi:10.1088/1748-0221/6/11/P11002.