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# Top quark production in association with a vector boson at the LHC

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## Abstract

Cross section measurements of top quark production in association with a vector boson in proton-proton collisions at  $\sqrt{s} = 13$  TeV at the CERN LHC provide an important probe of the electroweak top quark couplings. In this contribution, recent results of the ATLAS and CMS Collaborations for the measurement of top quark pair and single top quark production in association with a photon or a Z boson are presented. Both inclusive and differential cross section measurements are performed, and the results are compared to state-of-the-art predictions in the standard model of particle physics.

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# Top quark production in association with a vector boson at the LHC

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ON BEHALF OF THE ATLAS & CMS COLLABORATIONS

Cross section measurements of top quark production in association with a vector boson in proton-proton collisions at  $\sqrt{s} = 13$  TeV at the CERN LHC provide an important probe of the electroweak top quark couplings. In this contribution, recent results of the ATLAS and CMS Collaborations for the measurement of top quark pair and single top quark production in association with a photon or a Z boson are presented. Both inclusive and differential cross section measurements are performed, and the results are compared to state-of-the-art predictions in the standard model of particle physics.

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# 1 Introduction

Top quark production in association with a vector boson provides an important probe of the electroweak couplings of the top quark. As precise predictions within the standard model (SM) of particle physics become available, inclusive and differential cross section measurements can be used to test our theoretical understanding of the production mechanisms. The experimental results are also used to constrain models of physics beyond the SM, e.g. through interpretations in the framework of the SM effective field theory.

Results of the ATLAS [1] and CMS [2] experiments for inclusive cross section measurements of top quark pair ( $t\bar{t}$ ) and single top quark ( $t$ ) production in association with a photon ( $\gamma$ ), a Z boson, or a W boson are summarized in Table 1. For the results, the experiments used proton-proton (pp) collision data recorded at  $\sqrt{s} = 13$  TeV between 2015 and 2018 at the CERN LHC. In this contribution, the most recent results for  $t\bar{t}\gamma$ ,  $t\bar{t}Z$ , and  $tZq$  production are presented.

process	measurement			prediction	
fiducial $t\bar{t}\gamma + tW\gamma$ ( $e\mu$ )	ATLAS	$39.6 \pm 2.5$ fb	[3]	$38.5 \pm 1.9$ fb [4, 5]	
fiducial $t\bar{t}\gamma$ ( $\ell$ +jets)	CMS	$798 \pm 49$ fb	[6]	$773 \pm 135$ fb	
fiducial $t\bar{t}\gamma$ ( $2\ell$ )	CMS	$174.4 \pm 6.6$ fb	[7]	$153 \pm 25$ fb	
fiducial $t\gamma q$ ( $\mu$ +jets)	CMS	$115 \pm 30$ fb	[8]	$81 \pm 4$ fb	
$t\bar{t}Z$	CMS	$950 \pm 80$ fb	[9]	$859 \pm 78$ fb [11]	
	ATLAS	$990 \pm 90$ fb	[10]		
$tZq, Z \rightarrow \ell\ell$	ATLAS	$97 \pm 15$ fb	[12]	$94 \pm 3$ fb [14]	
	CMS	$87.9 \pm 10.0$ fb	[13]		
$t\bar{t}W$	CMS	$770 \pm 170$ fb	[15]	$722 \pm 74$ fb [17]	
	ATLAS	$870 \pm 190$ fb	[16]		

Table 1: Summary of inclusive cross section measurements and SM predictions for associated top quark production processes. Dedicated SM calculations are referenced. Otherwise, the SM expectation has been evaluated by the experimental collaboration with an MC event generator.

## 2 Measurements of $t\bar{t}\gamma$ production

The ATLAS Collaboration measured  $\gamma$ -associated top quark production in  $e\mu$  events, using  $139 \text{ fb}^{-1}$  of data [3]. A fiducial phase space is defined at parton-level for the combined  $t\bar{t}\gamma$  and  $tW\gamma$  production as signal process. A template fit is performed to

the scalar  $p_T$  sum of the reconstructed objects (photon, leptons, jets). The inclusive cross section is measured with a precision of 6.3%, and found in agreement with the dedicated SM prediction from Ref. [4, 5].

The CMS Collaboration measured  $t\bar{t}\gamma$  production in  $\ell$ +jets ( $2\ell$ ) events, using  $137\text{ fb}^{-1}$  ( $138\text{ fb}^{-1}$ ) of data [6, 7]. A fiducial phase space for both measurements is defined at particle-level. For the  $\ell$ +jets analysis [6], a template fit is performed to the invariant mass distribution of the three selected jets, split by lepton flavour and jet multiplicity, and background contributions are constrained from control regions. The inclusive cross section is measured with a precision of 6.1%. For the  $2\ell$  analysis [7], a template fit is performed to the photon  $p_T$  distribution, split by lepton flavour. The inclusive cross section is measured with a precision of 3.8%. Both results are found in agreement with the SM expectation as evaluated with an MC event generator.

All three results also present differential cross section measurements, and apply unfolding procedures to correct for detector resolution effects and to extrapolate the distributions to the fiducial phase space at parton- (ATLAS) or particle-level (CMS). Two examples are shown in Figure 1, and are compared to different SM predictions.

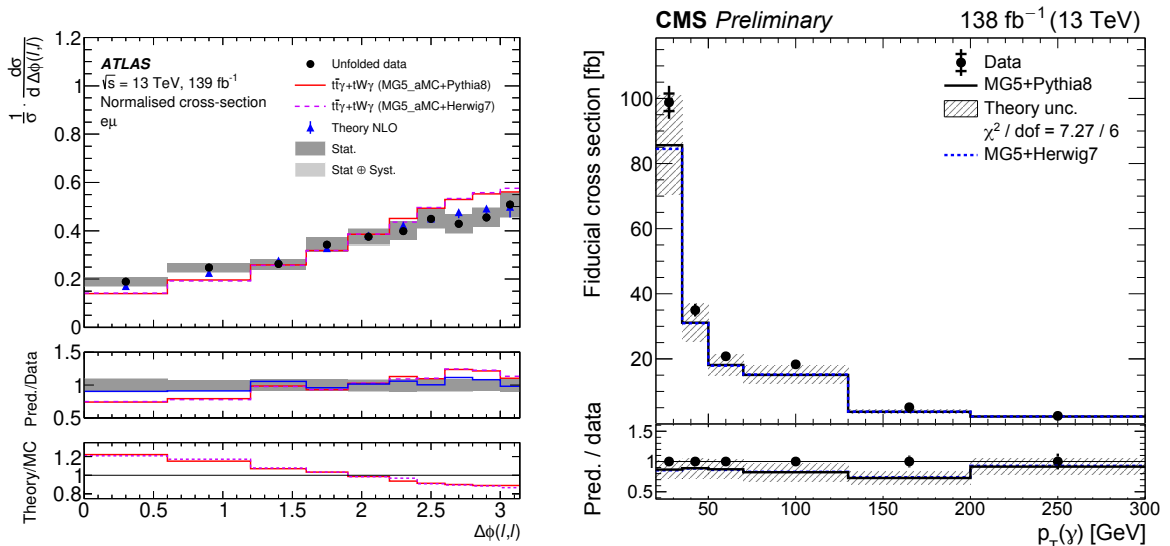


Figure 1: (Left) Normalized differential  $t\bar{t}\gamma+tW\gamma$  production cross section as a function of the azimuthal angle between the two leptons [3]. (Right) Absolute differential  $t\bar{t}\gamma$  production cross section as a function of the photon  $p_T$  [7].

### 3 Measurements of $t\bar{t}Z$ production

The  $t\bar{t}Z$  production process was measured in  $3\ell$  and  $4\ell$  events by the CMS Collaboration using  $77.5\text{ fb}^{-1}$  of data [9], and by the ATLAS Collaboration using  $139\text{ fb}^{-1}$  of data [10]. In both measurements, a template fit is performed to the distributions of

lepton, jet, and b-jet multiplicity. The inclusive cross section is measured by the CMS Collaboration with a precision of 8.2%, and by the ATLAS Collaboration with a precision of 9.5%. Both results are in agreement with each other, and also in agreement with the dedicated SM prediction from Ref. [11].

In both results, differential cross section measurements are presented as well. For the CMS result, two distributions are measured in  $3\ell$  events, and an unfolding procedure is applied to correct for detector resolution effects and to extrapolate to parton-level. For the ATLAS result, several distributions are measured for different channels, and are extrapolated to parton- or particle-level. Two examples are shown in Figure 2, and are compared to different SM predictions.

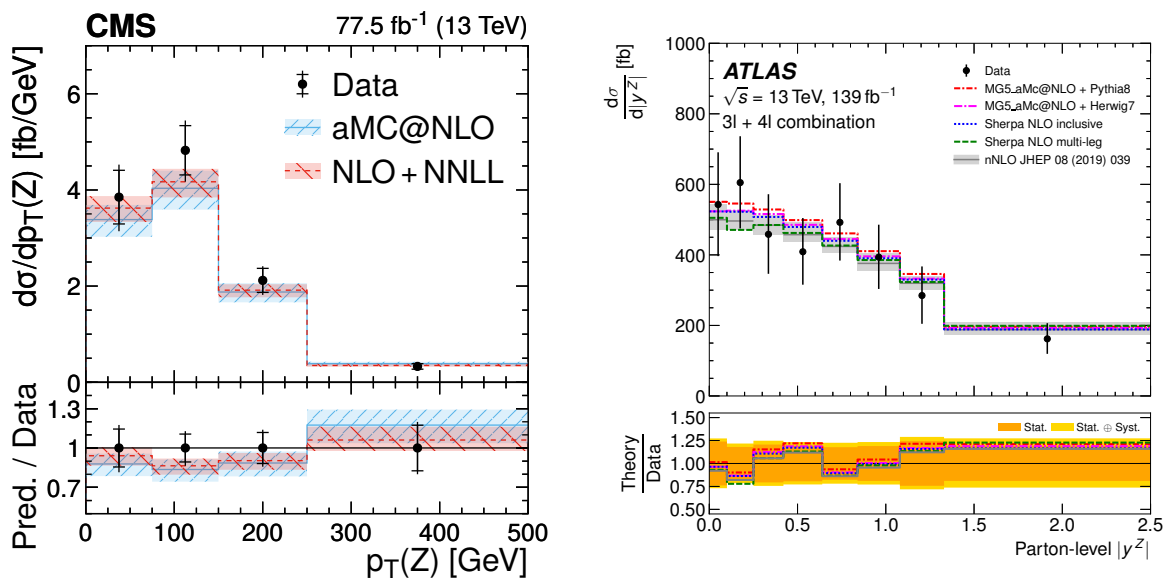


Figure 2: (Left) Absolute differential  $t\bar{t}Z$  production cross section as a function of the  $Z$  boson  $p_T$  [9]. (Right) Absolute differential  $t\bar{t}Z$  production cross section as a function of the  $Z$  boson rapidity [10].

## 4 Measurements of $tZq$ production

The  $tZq$  production in the  $3\ell$  channel was measured by the ATLAS Collaboration in events with 2–3 jets using  $139\text{ fb}^{-1}$  of data [12], and by the CMS Collaboration in events with at least two jets using  $138\text{ fb}^{-1}$  of data [13]. In both measurements, a machine-learning discriminant is trained to distinguish between the  $tZq$  signal and background processes (especially  $t\bar{t}Z$  and diboson production). Template fits are performed to the discriminant distributions, split by jet and b-jet multiplicities, and background contributions are constrained from control regions. The inclusive cross section is measured by the ATLAS Collaboration with a precision of 14%, and by the

CMS Collaboration with a precision of 11%. Both results are in agreement with each other, and are also in agreement with the SM expectation evaluated in Ref. [14].

The CMS Collaboration also performed a differential cross section measurement, using a multiclass machine-learning discriminant to distinguish simultaneously between the  $tZq$  signal and the different classes of background processes. A likelihood-based unfolding procedure is applied to correct for detector resolution effects, to extrapolate to parton- or particle-level, and to also constrain background contributions from control regions. Two examples are shown in Figure 3, and are compared to different SM predictions.

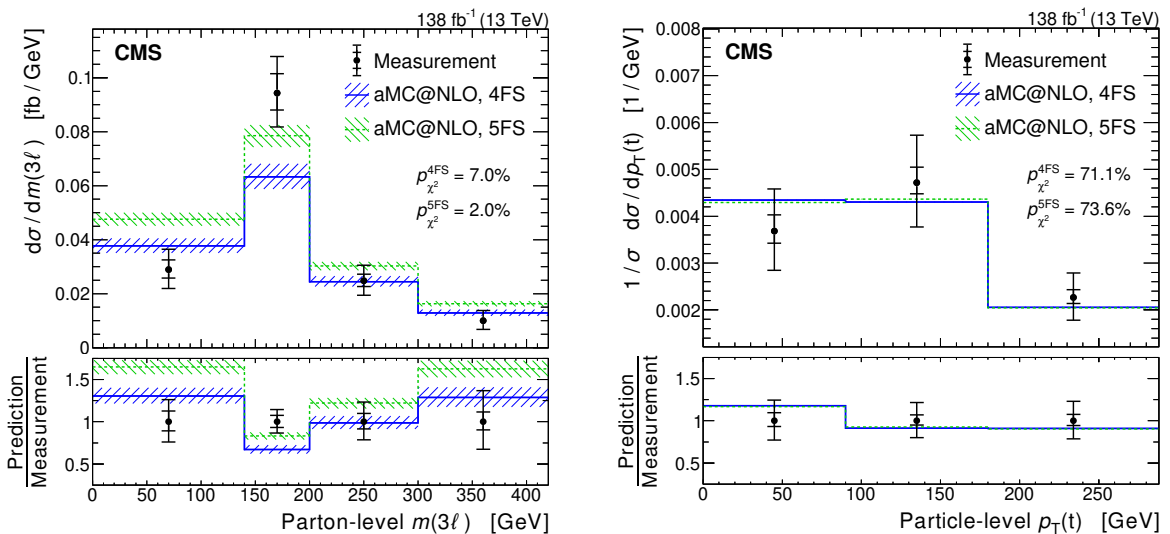


Figure 3: (Left) Absolute differential  $tZq$  production cross section as a function of the invariant mass of the three leptons [13]. (Right) Normalized differential  $tZq$  production cross section as a function of the top quark  $p_T$  [13].

## 5 Summary

Cross section measurements of top quark production in association with a photon or a  $Z$  boson, performed on proton-proton collision data recorded at  $\sqrt{s} = 13$  TeV with the ATLAS and CMS experiments at the CERN LHC, are presented. Very precise results are obtained for the inclusive production cross sections, and found in agreement with the expectation from the standard model of particle physics. Various differential distributions are measured as well, and unfolding procedures are applied to present differential cross sections at parton- and particle-level.

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