PROCEEDINGS OF SCIENCE

Measurements of $t\bar{t} + X$ in ATLAS and CMS

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We summarize the recent results from the ATLAS and CMS collaborations on the measurements of the cross sections of $t\bar{t}$+W , $t\bar{t}$+Z , $t\bar{t}+\gamma$, and $t\bar{t}b\bar{b}$ processes using data collected in proton-proton collisions at the LHC at $\sqrt{s}$ = 8 and 13 TeV.

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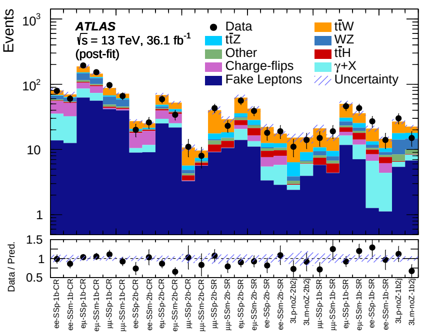
1. $t\bar{t}$ + W Production

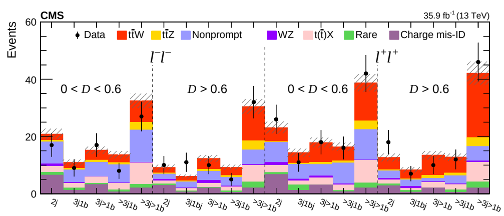
The current published results on the measurement of the $t\bar{t}$ + W cross section use a data sample with a total luminosity of 36 fb^{-1} collected by each experiment. The analyses apply a single lepton triggers and separate the data and simulated samples into several signal regions depending on the lepton electric charge and flavor, number of jets and b tagged jets, see Table 1. In the ATLAS analysis [1], the analysis applies a MVA to distinguish the prompt lepton from the nonprompt ℓ originating from hadron decays, γ conversions or misidentified jets. A second MVA is used to suppress the misidentified electron charge in the SS channel. Control regions (CR) are constructed to estimate the following largest backgrounds. The charge-flip CR has the charge requirement removed. The fake leptons CR uses the matrix method or tight-to-loose likelihood technique to estimate this background contribution. Several orthogonal samples are produced by inverting the lepton charge or flavor, and the number of jets. In the CMS analysis [2], a BDT is constructed using the variables N_j, N_b, H_T, p_T^{miss}, p_T^{ℓ}, M_T, and $\Delta R(\ell, j$. The contribution from fake leptons is estimated using the tight-to-loose method with a corrected lepton p_T as a function of lepton p_T and η. The charge misidentification and WZ diboson contributions are also extracted with data driven methods. Additional backgrounds are taken from the simulation predictions, $t(t)X = ttH$, tqZ, rare=multibosons. The largest systematic uncertainties are from the data-driven background statistics and the modeling of the $t\bar{t}$ + W in the case of the ATLAS analysis while the nonprompt and ttX background estimations and the statistical uncertainty in the nonprompt background method are the largest in the CMS result. ATLAS measures a cross section of $\sigma_{ttW} = 0.87 \pm 0.13(\text{stat}) \pm 0.14(\text{syst})$ pb and CMS measures $\sigma_{ttW} = 0.77^{+0.12}_{-0.11}(\text{stat})^{+0.13}_{-0.12}(\text{syst})$ pb, and separated by W charge $\sigma_{ttW^+} = 0.58 \pm 0.09(\text{stat})^{+0.09}_{-0.08}(\text{syst})$ pb and $\sigma_{ttW^-} = 0.19 \pm 0.07(\text{stat}) \pm 0.06(\text{syst})$ pb

Processes (ℓ = e, μ)		Channel	Signal Region
$t\bar{t}$ + W	$t\bar{t} \to 1\ell$	SS2ℓ	12 (sign, flavor, N_b)
	$t\bar{t} \to 2\ell$	3ℓ	8 (sign, N_j, N_b)

Table 1: Number of signal regions per $t\bar{t}$ + W processes and lepton flavor (ℓ) as a function of charge sign, flavor, number of jets N_j, and b tagged jets N_b.



(a) Event yields from control regions, SS and 3ℓ results from the ATLAS collaboration for the $t\bar{t}$ + W analysis.



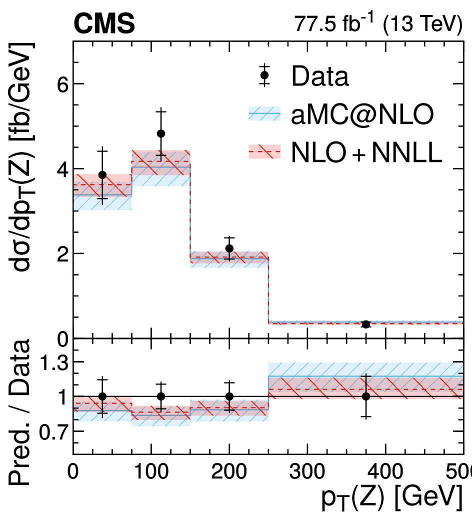
(b) Predicted and observed yields from the CMS $t\bar{t}$ + W results.

2. $t\bar{t}$ + Z Production

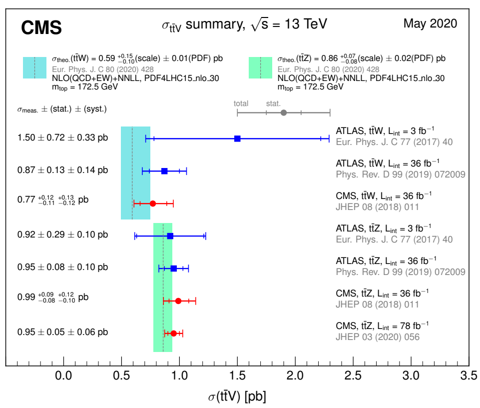
The ATLAS $t\bar{t}$ + Z analysis uses a very similar approach as the $t\bar{t}$ + W analysis using a sample of 36.1 fb^{-1} while CMS has a dedicated analysis with a sample of 77.5 fb^{-1} [3]. The $t\bar{t}$ + Z decays are classified according to the number of leptons in the final state. Table 2 lists the processes, channels, and signal regions used in the $t\bar{t}$ + Z analyses. The current analyses concentrate on the trilepton and tetralepton final states. Small background contributions from $t(t)X$ where X =H, W, WZ, Zq, Hq, HW, VV(V=W,Z), $t\bar{t}$, and rare = VVV, Xγ are taken from simulation. The yield of WZ(3ℓ) is estimated using a CR with N_b = 0 events. The yield of ZZ(4ℓ) is estimated using a CR with reconstructed ZZ events. The fake leptons are controlled with a CR that vetoes Z(3ℓ) events. CMS has recently made some improvements to its analysis using more inclusive lepton triggers that combine the single, dilepton, and trilepton triggers. A dedicated MVA is used for the lepton selection which has a 15% increase in the prompt lepton efficiency and the fake rate is reduced by 2-to-4 times with respect to the previous CMS selection. ATLAS reports a result of σ_{ttZ} = 0.95 ± 0.08(stat) ± 0.10(syst) pb

Processes (ℓ = e, μ)		Channel	Signal Region
$t\bar{t}$ + Z	$t\bar{t} \to 0\ell$	OS2ℓ	4 (N_j, N_b)
	$t\bar{t} \to 1\ell$	3ℓ	8 (sign, N_j, N_b)
	$t\bar{t} \to 2\ell$	4ℓ	4 (flavor, N_j, N_b)

Table 2: Number of signal regions per $t\bar{t}$ + Z processes and lepton flavor (ℓ) as a function of charge sign, flavor, number of jets N_j, and b tagged jets N_b.



(a) Measured absolute differential $t\bar{t}$ + Z production cross sections in the full phase space as a function of p_T of the Z boson. The inner (outer) vertical lines indicate the statistical (total) uncertainties. The solid histogram shows the predictions from the MadGraph5 aMC@NLO, and NLO+NNLL accuracy.



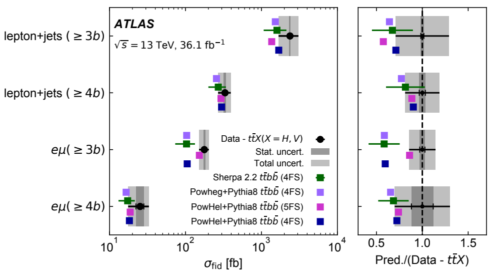
(b) Summary of the $t\bar{t}$ + W and $t\bar{t}$ + Z results from the ATLAS and CMS collaborations compared with the theoretical predictions.

3. $t\bar{t} + \gamma$ Production

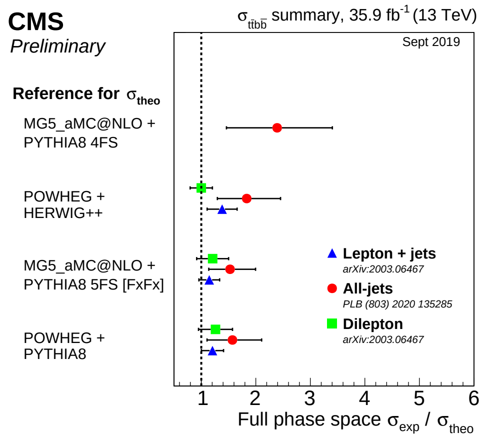
The basis of this analysis is the standard $t\bar{t}$ selection criteria with a procedure to separate the prompt from non-prompt photons. The prompt photon comes directly from the matrix elements. Fake photons or non-prompt photons originate from jet misidentification (a photon from a jet fragmentation or hadron decay) and electron misidentification (an electron missing a track, failed tracking or calorimeter matching, fake photon-conversion vertex, or a photon from a hard electron bremsstrahlung. The cross section is measured in a fiducial phase space defined by a photon with loose kinematic constraints. The largest systematic uncertainties are from the fit procedure to extract the cross section, JES, and MC modeling scales. CMS reports a measurement of $\sigma^{\rm fid}_{tt\gamma} = 127 \pm 27$ fb using 19.7 fb^{-1} at $\sqrt{s} = 8$ TeV [4], while ATLAS measures $\sigma^{2\ell}_{tt\gamma} = 44.2 \pm 0.9(\text{stat})^{+2.6}_{-2.4}(\text{syst})$ fb using 139 fb^{-1} at $\sqrt{s} = 13$ TeV using a sample of dilepton e-μ events [5, 6].

4. $t\bar{t} + b\bar{b}$ Production

The single lepton analysis uses events with at least 6 jets while the dilepton analysis at least 4 jets. A discriminator is constructed with b tagging jet information. In the case of ATLAS [9], all jets in the event are considered for the training while CMS [8] uses additional jets not associated to the $t\bar{t}$ system. ATLAS single lepton uses a 2D fit over the 3rd and 4th b tagged jet discriminator and the dilepton uses a 1D fit over the 3rd b tagged jet discriminator. CMS uses a 2D template fit with additional b tagged jets and extracts the $t\bar{t}jj$ and ratio of $\sigma_{t\bar{t}bb}/\sigma_{t\bar{t}jj}$. The leading systematic uncertainties are from b tagging, JES, ISR, $t\bar{t}c$ background, and the parton shower. CMS also has a dedicated analysis in the all hadronic channel [7]. It requires at least 8 jets. The QCD is rejected with a MVA built from a quark/gluon likelihood and jet combination matching. A BDT with inputs from a χ^2-mass variables and b tagging discriminators from additional jets. Control regions from the MVA side bands are chosen to control the background. The dominant systematic uncertainties are from b tagging, quark/gluon likelihood, renormalization and factorization scales, and MC statistics. Figures 3a and 3b summarize the results from ATLAS and CMS experiments.



(a) Summary of the $t\bar{t}b\bar{b}$ results from ATLAS.



(b) Summary of the CMS measurements of the $t\bar{t}b\bar{b}$ processes.

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