PROCEEDINGS OF SCIENCE

Top cross-section measurements and rare $t\bar{t}X$ processes

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Recent cross-section measurements of top pair production, single-top production, and rare top associated production by the CMS and ATLAS collaborations are presented. These results include the very first Run III results at $\sqrt{s}$=13.6 TeV as well as most precise inclusive and differential top-quark cross sectional measurements and observations to date in Run II and $\sqrt{s}$=13 TeV. This includes the first observation of four-top production in both ATLAS[9] and CMS [11] and the first evidence of tWZ production [10]. This diverse set of measurements showcase very sensitive results beyond historical expectations that are driven by improved analysis strategies and techniques on the parts of both experiments. Results are generally in good agreement with Standard Model expectations with some excesses, motivating continued exploration in Run III and the HL-LHC as well as improved theoretical calculations and modeling strategies.

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1. Introduction

The top quark is the heaviest known fundamental particle with a mass of about 173 GeV. Its large mass is very close to the scale of electroweak symmetry breaking (EWSB) and leads to a large coupling to the Higgs boson. The top quark is only the only quark that has a such a short enough lifetime that it decays before hadronizing. Whats more, it is produced in very large quantities at the Large Hadron Collider (LHC) mainly through top pair-production as a result of gluon fusion For example 120 million $t\bar{t}$ events are produced at 10 Hz at a center-of-mass energy of 13 TeV. These unique properties make the top quark an ideal probe of the standard model (SM) as well as a potential window to revealing new physics beyond the standard model.

The presented ATLAS and CMS analyses showcase inclusive and differential cross section measurements related to top pair production, single top production, and top associated production.

2. Top pair production

Top pair production, where gluon fusion or quark-antiquark annihilation leads to the production of a top-antitop pair, is the dominant top production mode at the LHC. The very first top pair production inclusive cross section measurements in Run III at $\sqrt{s}$=13.6 TeV are presented by ATLAS [8] and CMS [14]. The Summer 2022 Run III CMS analysis in the single electron/muon + jets channel measured an inclusive cross section of $\sigma(pp \to t\bar{t})$ = 882 ± 23(stat+syst) ±20 (lumi) pb [14]. The first ATLAS Run III results were measured in the opposite-sign di-lepton (electron+muon) channel with additional b-tagged jets and included a 2022 inclusive cross-section measurement ($\sigma(pp \to t\bar{t})$ = 859 ± 4(stat) ±22 (syst)±19 (lumi) pb) and a fiducial Z-boson cross-section measurement ($\sigma(pp \to Z_{ll}^{fid.})$ = 751 ± 0.3(stat)±15 (syst) ±17 (lumi) pb), as well as a ratio measurement of $R_{t\bar{t}/Z} = 1.144 \pm 0.006$(stat)±0.022 (syst) ±0.003 (lumi) [8]. These results are consistent with SM expectations, as shown in the LHCTOPWG summary plot shown in Figure 1.

Relevant Run II top pair-production results are also presented. An ATLAS measurement at 13 TeV represents the most precise inclusive $\sigma_{t\bar{t}}$ measurement to date in the $e\mu$ final state ($\sigma(pp \to t\bar{t})$ = 829 ± 1(stat) ±13 (syst)±8 (lumi) ±2 (beam) pb), due to an impressive reduction of systematic uncertainties [5]. They also present a differential cross section measurement as a function of 8 kinematic variables, which shows good agreement with SM predictions except in the tails, motivating improved simulation and theoretical NNLO (next-to-next-to leading order) and EW (electroweak) corrections. Example single and double differential distributions can be found in Figure 2. ATLAS also presented a boosted $t\bar{t}$ differential jet substructure measurement in the lepton+jets and all-hadronic final states, including single and double differential $\sigma_{t\bar{t}}$s for 8 variables related to charged jet components [6]. Meanwhile, CMS presented a search for Lorentz invariance violation in $t\bar{t}$ in the $e\mu$ dilepton final state in 2016+2017, using the differential $\sigma_{t\bar{t}}$ as a function of sidereal time in an EFT framework [4]. These results were consistent with SM expectations.

3. Single-top production

Single top production is a good probe of electroweak physics, with the most commonly occurring (73%) t-channel as the "golden channel" most sensitive to FCNC (flavor changing neutral

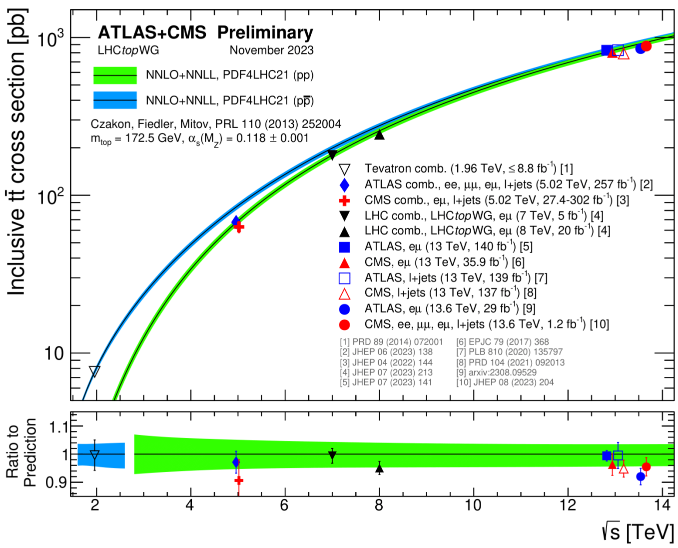
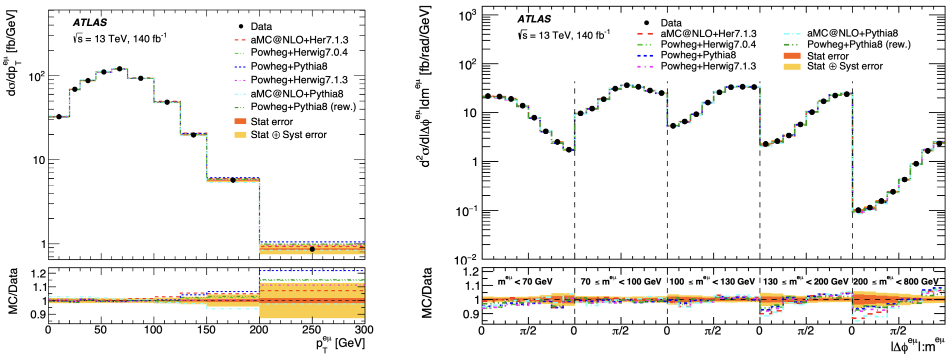


Figure 1: Summary of LHC and Tevatron measurements of the top-pair production cross-section as a function of the centre-of-mass energy compared to the NNLO QCD calculation complemented with NNLL resummation (top++2.0), including the most recent 13.6 TeV Run III results. The theory band represents uncertainties due to renormalisation and factorisation scale, parton density functions and the strong coupling. The measurements and the theory calculation are quoted at a top mass of 172.5 GeV. Measurements made at the same centre-of-mass energy are slightly offset for clarity. Figure provided by the LHC Top Working Group.

currents). The less common (24%) tW channel has been observed at the LHC and is a good probe of BSM couplings, but the s-channel (3%) has not yet been observed.

ATLAS presents the first evidence of s-channel production at 13 TeV with an observed (expected) significance of 3.3 (3.9) standard deviations in the single-lepton final state. This analysis used a data-driven QCD background estimation and the matrix-element method to derive the signal probability per event $P(S|X)$ to achieve this result, which measured a cross section of $\sigma_{s-channel}$ = 8.2 ± 0.6 (stat)$^{3.5}_{-2.9}$ (syst) pb [7]. ATLAS also presented the production of single tops/anti-tops in the t-channel with the exchange of a virtual W in the single-lepton channel at 13 TeV [2], using a neural-network (NN) based signal vs. background discrimination strategy and including EFT interpretations and a CKM result. These results show good agreement with the SM, and example SR postfit distributions for tops and anti-tops as well as a summary of top/antitop cross section ratio measurements can be found in Figure 3.

tWZ production, which is good potential probe of new physics and EFT interactions, was also measured for the first time by CMS [10]. This analysis, in the multi-lepton final state, used binary and multiclass NNs to identify signal and backgrounds (tWZ, $t\bar{t}Z$, other). Evidence of tWZ production was found for the first time with a measured σ_{WZ} of 0.37 ± 0.5 (stat) ±0.10 (syst) pb and an observed (expected) significance of 3.5 (1.4) standard deviations. Example postfit distributions of the binary and multiclass classifiers are shown in Figure 4.



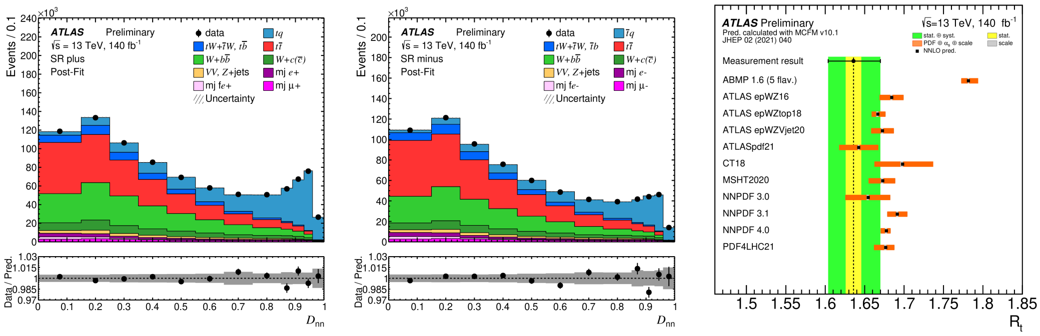
(a) **(b)**

Figure 2: (a) Absolute differential cross-sections as a function of $p_T^{e\mu}$, and absolute double-differential cross-sections as a function of $|\Delta\phi^{e\mu}|$ in bins of $m^{e\mu}$ with statistical (orange) and statistical plus systematic uncertainties (yellow)[5]. The data points are placed at the centre of each bin. The results are compared with the predictions from different Monte Carlo generators normalised to the Top++ prediction: the baseline Powheg+Pythia8.230 $t\bar{t}$ sample (blue), aMC@NLO+Herwig 7.1.3 (red), Powheg+Herwig 7.0.4 (green), Powheg+Herwig 7.1.3 (purple), aMC@NLO+Pythia 8.230 (cyan) and Powheg+Pythia8.230 rew. (dark green), which refers to Powheg+Pythia8.230 reweighted according to the top-quark pT. The lower panel shows the ratios of the predictions to data, with the bands indicating the statistical and systematic uncertainties.

4. Top associated production

Top associated production, or top pair production in association with other particles, represent rare and often unexplored processes that provide opportunities to search for hints of new BSM physics. Four-top production in particular was the subject of many presented analyses, including a CMS four-top combined result that included the all-hadronic channel for the very first time by employing data-driven and NN-based background estimation techniques [13] as well as the observation of four-top production in the same-sign dilepton and multilepton channels in both CMS [11] and ATLAS [9]. Both observations involved legacy reprocessing and improvements on Run II data, with the CMS result taking advantage of a looser event selection and seperate multi-class BDTs for the $t\bar{t}t\bar{t}$ signal and $t\bar{t}V$ and $t\bar{t}$ backgrounds and the ATLAS result taking advantage of a looser event selection, improved $t\bar{t}t$ and $t\bar{t}W$ background estimation, and GNN based signal vs. background discrimination. The CMS and ATLAS results observed (expected) a significance of 5.5(4.9)σ and 6.1(4.3)σ respectively, representing small excesses beyond SM expectations. Representative postfit distributions for these results are shown in Figure 5.

An inclusive measurement and the first differential measurement of $t\bar{t}W$ was also presented by ATLAS in the same-sign dilepton and multi-lepton final states [3]. including robust MC modeling and systematic uncertainties. The measured inclusive cross section was $\sigma(pp \to t\bar{t}W) = 890 \pm 50$ (stat) ± 70 (syst) fb, which while higher than theoretical predictions is consistent with previous measurements. This analysis also presented normalized differential measurements for 7 observables, which were generally consistent with the SM. ATLAS also presented the first observation of $t\gamma$ production in the single-lepton, single-gamma +jets final state using NNs to seperate signal from background. The observed (expected) significance was 9.3 (6.8) σ.



(a) **(b)** **(c)**

Figure 3: The observed Dnn distributions for (a) SR plus and (b) SR minus are compared with the expected distributions (histograms) from simulated events after the fit as described in the ATLAS t-channel production analysis [2]. In these distributions the signal contribution is shown stacked on top of contributions from all contributing background processes. All uncertainties considered in the analysis are included in the hatched (grey) uncertainty band. The correlations induced by the fit are taken into account. The lower panel shows the ratio of data to the prediction in each bin. (c) The measured value of R_t. The yellow band represents the statistical uncertainty and the green band the total uncertainty of the measurement. The uncertainties in the theoretical predictions include PDF, scale and α_S uncertainties. For comparison the NNLO prediction of MCFM based on different PDF sets are also included.

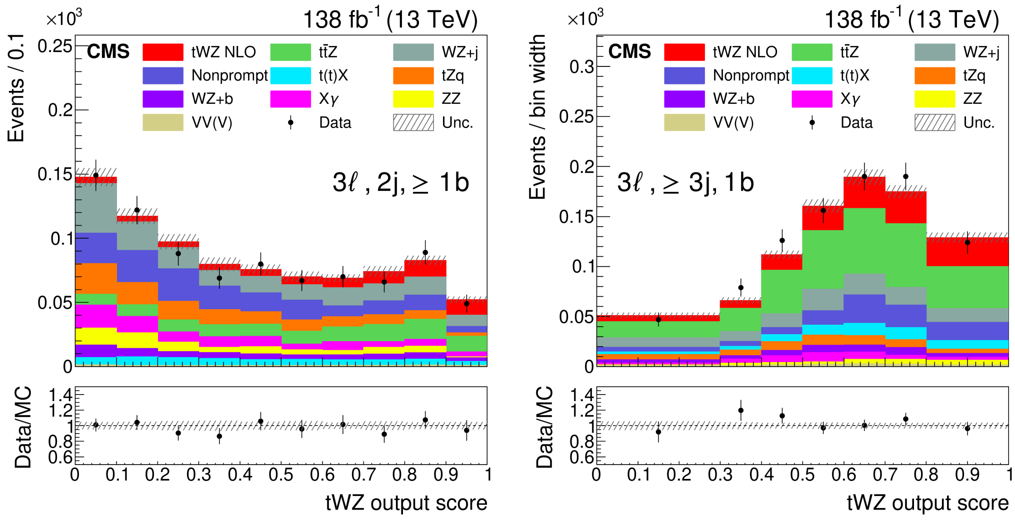
The most precise inclusive measurement to date as well as a differential measurement was shown by CMS for $t\bar{t}b\bar{b}$ in the lepton+jets final state [1] The inclusive cross-section, which was measured in 4 fiducial phase spaces of varying jet, b-tagged jet, and light-jet multiplicity and compared to various MC generators, was found to be higher than theoretical predictions but consistent with previous measurements (as with the $t\bar{t}W$ and $t\bar{t}t\bar{t}$ inclusive results). The differential measurement was done in the same fiducial regions as a function of 37 different observables and had varying compatibility with theoretical predictions.

Another relevant result was a CMS top+leptons EFT (Effective Field Theory) search using Run II data characterized by lepton, jet, and b-tagged jet multiplicities and total lepton charge [12]. This analysis searched for potential new physics parameterized vs. 26 6-dimensional EFT operators using a fit to kinematic variables including leading lepton and jet transverse momentum, and on-shell Z-boson momentum. A combined postfit distributions for all signal regions in this analysis can be found in Figure 6. No significant deviation from SM predictions was found.

These analyses showcase the challenge of top-association production measurements as well as the effectiveness of sophisticated analysis techniques. Some excesses beyond SM expectations are observed, but measurements are generally consistent with other results across experiments.

5. Conclusion

These diverse CMS and ATLAS top pair production, single-top production, and top-associated production measurements showcase the most precise inclusive and differential measurements in the top sector to date. This includes the first Run III top pair production measurement, and new evidence and observations of rare top-associated processes. Many of these measurements were



(a) **(b)**

Figure 4: Example postfit classifier distributions from CMS tWZ measurement [10].(a) Score of the tWZ output node of the binary classifier in $SR_{3l,2j}$ for events with one or more b jets and (b) score of the tWZ output node from the multiclass classifier in $SR_{3l,3j}$ for events with exactly one b jet. The VV(V) group in the legend denotes the VVV, WW, and W in association with jets backgrounds. The dashed band shows the total uncertainty (statistical and systematic) after the fit.

driven by improved analysis strategies and techniques that facilitated more-sensitive-than expected results. Generally good agreement with the standard model was observed with some excesses. This motivates improved NNLO calculations and monte-carlo (MC) simulation techniques, as well as further exploration in Run III, the HL-LHC and beyond. Overall, this diverse and impressive set of results show that the top-quark continues to be a very interesting tool to study the properties of the standard model and look for new physics in both precise measurements and rare searches.

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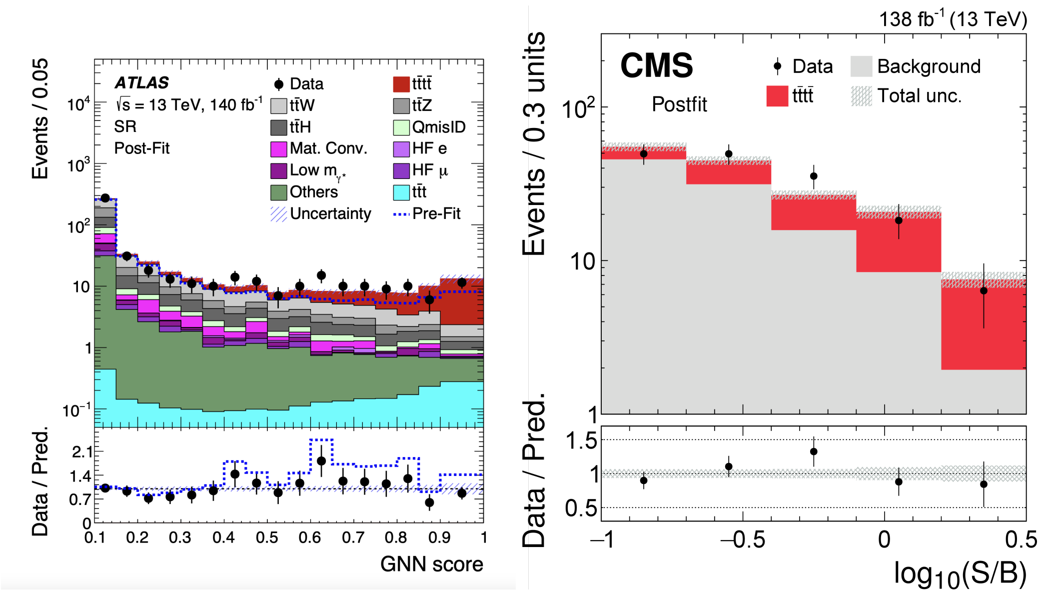

(a) **(b)**

Figure 5: (a) Comparison between data and the predictions after a fit to data for the GNN distribution in the SR for the ATLAS $t\bar{t}t\bar{t}$ observation[9]. The first bin contains underflow events. The ratio of the data to the total post-fit prediction is shown in the lower panel. The dashed blue lines show the pre-fit prediction in the upper panel and the ratio of the data to the total pre-fit prediction in the lower panel. (b) Comparison for all SRs included in the CMS $t\bar{t}t\bar{t}$ observation [11] combined as a function of $log_{10}(S/B)$, where S and B are evaluated for each bin of the fitted distributions as the predicted signal and background yields before the fit to data. The signal and background yields are shown with their best fit normalizations from the simultaneous fit to the data ("postfit"). Shaded bands represent the total post-fit uncertainty in the predictions in both figures.

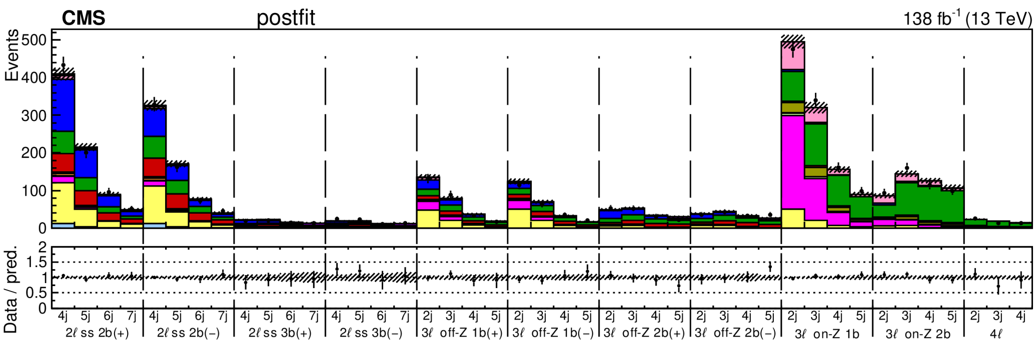

Figure 6: Observed data and expected yields in the and postfit scenario for top+leptons EFT measurement [12]. All kinematic variables have been combined, resulting in distributions for the jet multiplicity only. The postfit values are obtained by simultaneously fitting all 26 Wilson coefficients (WCs) and the nuisance parameters (NPs). The lower panel contains the ratios of the observed yields over the expected. The error bands are computed by propagating the uncertainties from the WCs and NPs.

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