PROCEEDINGS OF SCIENCE

Top physics in ATLAS and CMS

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A selection of recent results of top quark production performed by the ATLAS and CMS Collaborations at the LHC is presented. The results include measurements of top quark pair production, including inclusive and differential cross sections, as well as cross sections for $t\bar{t}$ production in association with additional heavy-quark jets or additional bosons. The production of single top quarks via t-channel, tW associated production, and in association with a Z boson is also discussed. The results discussed are mostly obtained using data collected in proton-proton collisions at centre-of-mass energies of 8 and 13 TeV.

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1. Introduction

The top quark is the heaviest known elementary particle and the only quark that decays before hadronisation, and thus gives direct access to its properties. With its large mass, it plays a crucial role in electroweak loop corrections, providing indirect constraints on the mass of the Higgs boson. Top quark measurements also provide important input to QCD calculations. Moreover, various scenarios of physics beyond the standard model (SM) expect the top quark to couple to new particles.

In hadron colliders, top quarks are mostly produced in pairs ($t\bar{t}$) via the strong interaction. At the LHC energies, the dominant mechanism is gluon-gluon fusion, corresponding to ~85% of the generation process at a centre-of-mass energy of 13 TeV. Top quarks can also be produced singly, via electroweak interaction. The three modes of single top quark production are t-channel, tW associated production and s-channel.

Top quarks decay almost exclusively via the $t \to bW$ and it is the decay of the W bosons that defines the final state. Therefore, $t\bar{t}$ signatures can be classified according to the combinatorics of the W boson decay. The $t\bar{t}$ measurements presented are performed using the final states that include events with two leptons, two neutrinos and two b jets (dilepton decay channels) and one lepton, one neutrino and four jets, out of which two arise from b quarks (lepton+jets), and requiring additional jets, leptons or a photon, depending on the process under study. The most recent results by the ATLAS [1] and CMS [2] experiments are discussed.

2. $t\bar{t}$ inclusive cross sections

Measurements of the $t\bar{t}$ inclusive cross section are performed using data collected with the CMS and ATLAS experiments in proton-proton collisions at centre-of-mass energies of 7, 8 and 13 TeV. The data are compared with the predictions from perturbative QCD (pQCD) calculations at full Next-to-Next-to-Leading-Order + Next-to-Next-to-Leading-Log (NNLO+NNLL) accuracy. The large $t\bar{t}$ data samples allowed to reach the high precision regime, with total uncertainties below 4%, of the same order of the precision of the full NNLO calculation. Additionally, the first measurement with 5.02 TeV has been published [3]. The results are in excellent agreement between the different channels and with the NNLO+NNLL predictions, see Fig. 1 [4].

3. $t\bar{t}$ differential cross sections

Differential measurements of $t\bar{t}$ cross section as a function of top quark related kinematic quantities are tests of pQCD and probe a variety of different properties, for instance the $p_{T}^{t\bar{t}}$ distribution is sensitive to higher order effects like initial-/final-state radiation of quarks or gluons. Moreover, possible deviations in the shapes of all distributions can hint at physics beyond the SM. ATLAS and CMS have performed numerous differential measurements of $t\bar{t}$ production, such as the cross section as a function of kinematic quantities of the top quark itself, both in the boosted and the resolve regimes, the $t\bar{t}$ system and its decay products, as well as exclusive measurements of $t\bar{t}$ pairs produced in association with other physics objects. The measurements are corrected for detector and hadronisation effects back to parton or particle level, using a regularised unfolding procedure, and

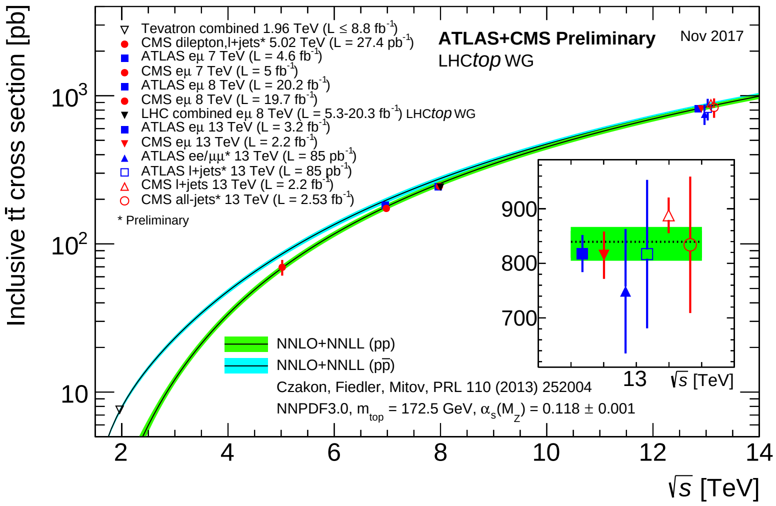

Figure 1: Summary of LHC and Tevatron measurements of the $t\bar{t}$ production cross section as a function of the centre-of-mass energy compared to the NNLO QCD calculation complemented with NNLL resummation (top++2.0) [4]. The theory band represents uncertainties due to renormalisation and factorisation scale, parton density functions and the strong coupling. The measurements and the theory calculation are quoted at m_t=172.5 GeV.

they are absolute or normalised, so that systematic uncertainties correlated between all bins cancel in the ratio. Figure 2 shows examples of those distributions compared to different theoretical models [5, 6].

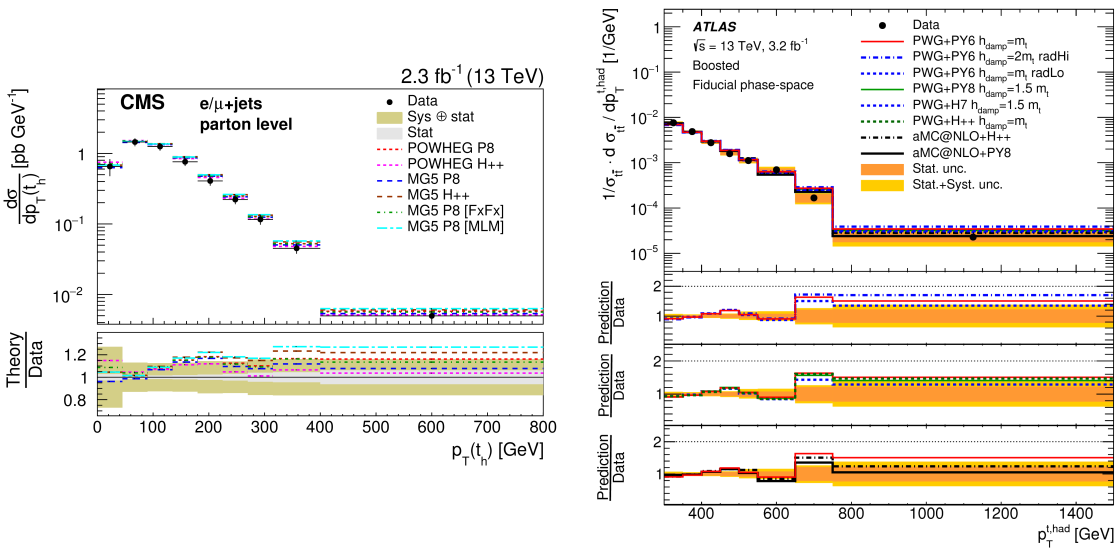

Figure 2: Differential $t\bar{t}$ cross sections as a function of top quark p_T at 13 TeV measured in the lepton+jets channel [5, 6].

4. $t\bar{t}$+jets

At the LHC energies, the fraction of $t\bar{t}$ events with additional hard jets ($t\bar{t}$+jets) in the final state is large, about half of the total number of $t\bar{t}$ events. The understanding of these processes is relevant to test higher order QCD calculations, in which contributions from initial- and final-state radiation are taken into account to achieve a good quantitative description of multijet processes. The correct description of these events is important not least because multijet processes constitute important backgrounds for many new physics searches and the associated production of $t\bar{t}$ with a Higgs boson ($t\bar{t}$H).

CMS and ATLAS have performed several measurements of $t\bar{t}$+jets in the dileptonic and l+jets channels, such as the cross section as a function of the jet multiplicity and properties of the jets in different kinematic ranges in $t\bar{t}$+jets topologies [7, 8, 9]. Typically the measurements are performed in a fiducial volume to minimise model dependencies. Figure 3 (left) shows an example of the differential cross section as a function of the number of additional jets in the event [7], compared to different generators at LO with additional hard partons and with NLO matrix element computations. These measurements are used to improve the modelling of the $t\bar{t}$ simulation [8, 9].

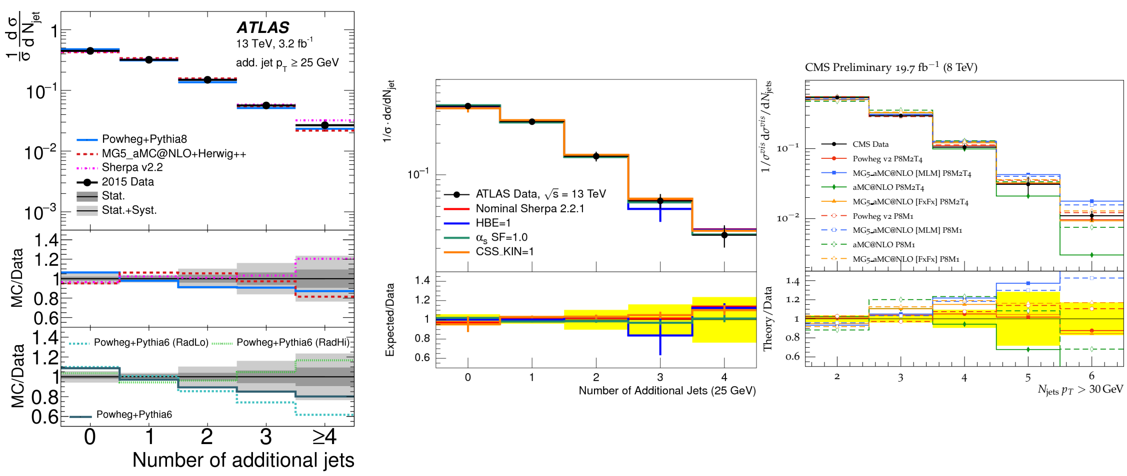

Figure 3: Differential $t\bar{t}$ cross sections as a function of additional jet multiplicity in the event (left, middle) [7, 8] compared to predictions of POWHEG, MG5_aMC@NLO and SHERPA interfaced with PYTHIA8, and cross section as a function of jet multiplicity compared to the predictions of POWHEG, MG5_AMC@NLO either with MLM matching or FXFX merging, and aMC@NLO. For each case the parton shower simulation is done by PYTHIA 8 with the CUETP8M1 and the newer CUETP8M2T4 event tunes [9].

4.1 $t\bar{t}$+heavy flavour

The production of $t\bar{t}$ in association with a pair of bottom quarks ($b\bar{b}$) is an irreducible background to the production of $t\bar{t}$H, where the Higgs boson decays to $b\bar{b}$. A precise measurement of $\sigma(t\bar{t}b\bar{b})$ has the potential to reduce the background uncertainty and thus, increase sensitivity. Both CMS and ATLAS Collaborations have measured the cross section ratio $\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$ using dilepton and l+jets decay channels. The CMS measurement at 13 TeV is performed by selecting dilepton events [10]. The relative contribution from $t\bar{t}b\bar{b}$ is determined with a simultaneous template fit to the measured b-tagging algorithm discriminant of the jets in the event. The result of the ratio is $\sigma(\mathrm{t\bar{t}b\bar{b}})/\sigma(\mathrm{t\bar{t}jj}) = 0.022 \pm 0.003\,(\mathrm{stat}) \pm 0.006\,(\mathrm{syst})$, for particle-level jets with $p_T > 20$ GeV. The individual cross sections are also measured, resulting $4.0 \pm 0.6\,(\mathrm{stat}) \pm 1.3\,(\mathrm{syst})$ pb for the $\mathrm{t\bar{t}b\bar{b}}$ process and $184 \pm 6\,(\mathrm{stat}) \pm 33\,(\mathrm{syst})$ pb for the $\mathrm{t\bar{t}jj}$ process, evaluated in the full phase space of the $\mathrm{t\bar{t}}$ system, see Fig 4.

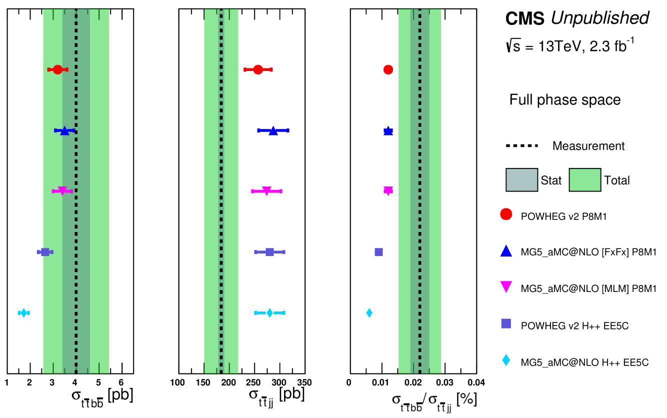

Figure 4: The measured cross sections for $\mathrm{t\bar{t}b\bar{b}}$ (left), $\mathrm{t\bar{t}jj}$ (middle) and their ratio (right) in the full phase space of the $\mathrm{t\bar{t}}$ system in comparison with the theoretical calculations [10]. The error bars of the Monte Carlo predictions correspond to the scale uncertainty.

5. $\mathrm{t\bar{t}}$ production in association with additional bosons

5.1 Measurement of $\mathrm{t\bar{t}}$+W/Z at 13 TeV

Measurements of the cross sections of $\mathrm{t\bar{t}}$+W/Z processes are the first step towards measuring the coupling to bosons. They are also relevant because they could be enhanced by beyond the SM (BSM) contributions as well as they represent an important background for BSM searches, as some searches for SUSY or $\mathrm{t\bar{t}H}$. The general strategy of the analyses by both the ATLAS and CMS Collaborations is described in the following. The event sample is divided in categories depending on the number of charged leptons (2, 3 or 4 leptons), which yield different admixtures of $\mathrm{t\bar{t}W}$ and $\mathrm{t\bar{t}Z}$ processes: Same-sign dilepton selections are enriched in $\mathrm{t\bar{t}}$+W, while trilepton and four-lepton topologies are dedicated to measure the $\mathrm{t\bar{t}Z}$ process. The signal is extracted simultaneously in a binned likelihood fit in the different signal categories. Additionally, the categories are further split depending on jet multiplicity, number of b-tagged jets, and other observables to increase sensitivity. The expected yields after the fit compared to data in the same-sign dilepton analysis performed by the CMS experiment are shown in Fig. 5 [11].

The CMS measurement yields significances above 5σ over the background-only hypothesis for both $\mathrm{t\bar{t}W}$ and $\mathrm{t\bar{t}Z}$ processes. The measured cross sections, summarised in Fig. 6 left, result $\sigma(\mathrm{t\bar{t}W}) = 0.80^{+0.12}_{-0.11}(\mathrm{stat})^{+0.13}_{-0.12}(\mathrm{syst})$ pb and $\sigma(\mathrm{t\bar{t}Z}) = 1.00^{+0.09}_{-0.08}(\mathrm{stat})^{+0.12}_{-0.10}(\mathrm{syst})$ pb. These results are also used, in the context of effective field theory interpretations, to set constraints on the Wilson coefficients of 8 operators which would modify $\mathrm{t\bar{t}Z}$ and $\mathrm{t\bar{t}W}$ production, as illustrated in Fig. 6 right.

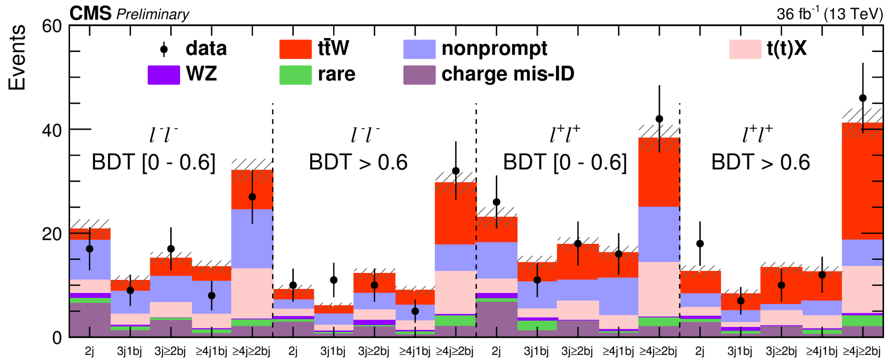

Figure 5: Post-fit predicted and observed yields in each analysis bin in the same-sign dilepton analysis. The hatched band shows the total uncertainty associated to signal and background predictions [11].

The results by the ATLAS Collaboration (with a partial data set) are: $\sigma(\mathrm{t\bar{t}W}) = 0.90 \pm 0.3$ pb and $\sigma(\mathrm{t\bar{t}Z}) = 1.5 \pm 0.8$ pb [12]. All measurements are consistent with SM calculations.

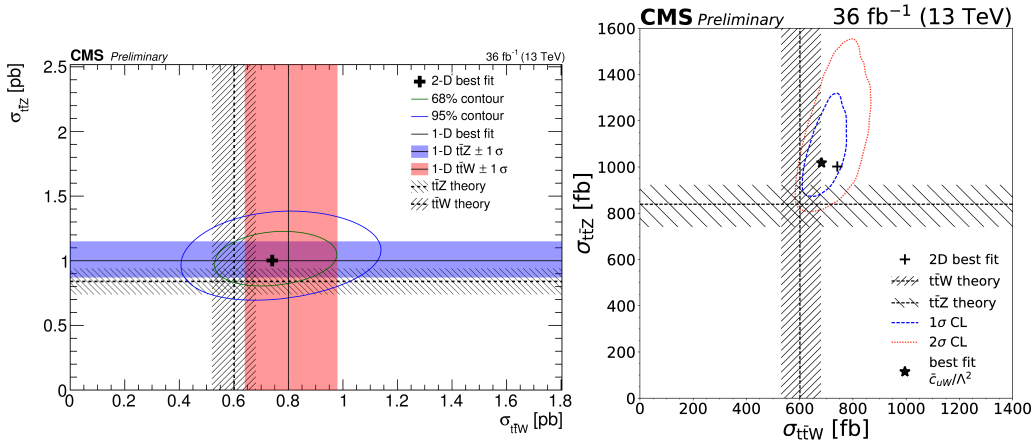

Figure 6: Left: Result of the simultaneous fit to the tt̄W and tt̄Z cross sections along with the 68% and 95% CL uncertainty contours. The result of this fit is superimposed with the separate tt̄W and tt̄Z cross section measurements. Right: The tt̄W and tt̄Z cross sections corresponding to the best-fit value of the coefficient $\bar{c}_{uW}$, shown as a star, along with the corresponding 1σ (red) and 2σ (blue) contours. Predictions from theory at NLO (dotted lines) and their uncertainties (hatches) are also shown [11].

5.2 Measurement of tt̄+γ at 8 TeV

The production cross section of tt̄ associated with a photon has been measured at $\sqrt{s}$ = 8 TeV by both collaborations [13, 14]. This process is sensitive to the tγ coupling and models with composite top quarks and excited top quark production ($\mathrm{t}^\star \to \mathrm{t}\gamma$). The $\mathrm{t\bar{t}} + \gamma$ measurement by the ATLAS Collaboration is performed in the l+jets decay channel. Events are selected by requiring a photon with high transverse energy, in addition to the tt̄ selection. Prompt photons are estimated from a template fit to the photon isolation variable. The transverse energy of the selected photons and the result of that template fit are shown in Fig. 7. The fiducial cross section is measured by ATLAS to be $\sigma_{\mathrm{t\bar{t}}+\gamma} \cdot BR = 139 \pm 7(\mathrm{stat}) \pm 17(\mathrm{syst}) \pm 1(\mathrm{lumi})$ fb, consistent with the SM expectation,

$\sigma(t\bar{t}+\gamma) = 151 \pm 24$ fb. In addition, differential cross sections in the fiducial region are measured as a function of the transverse momentum and pseudorapidity of the photon. The measurement by the CMS Collaboration yields $\sigma_{t\bar{t}+\gamma} \cdot BR = 127 \pm 27(\text{stat}+\text{syst})$ fb.

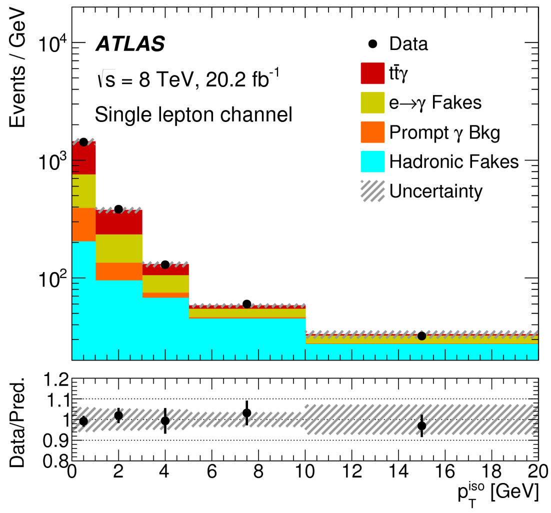

Figure 7: Results of the combined likelihood fit using the track-isolation distributions as the discriminating variable [13].

5.3 Evidence of SM $t\bar{t}$H production

The associated production of a Higgs boson with a $t\bar{t}$ is the best direct probe of the top quark - Higgs boson Yukawa coupling with minimal model dependence, a missing vital element to verify the SM nature of the discovered Higgs boson. A measurement of the $t\bar{t}$H production cross section also has the potential to distinguish the SM Higgs boson mechanism from alternative mechanisms to generate fermion mass. The large data samples being collected during Run-2 would allow to observe this process that was limited by statistics during Run-1.

The ATLAS and CMS Collaborations have performed searches in all Higgs boson decay channels, studying final states with photons, bottom quark-antiquark pairs or leptons via WW, ZZ and $\tau\tau$, claiming evidence of $t\bar{t}$H production [15, 16]. For illustration, the signal strength modifiers (μ), the ratio of the observed $t\bar{t}$H production cross section relative to the value expected for a 125 GeV SM Higgs boson, obtained in the multilepton channels are shown in Fig. 8.

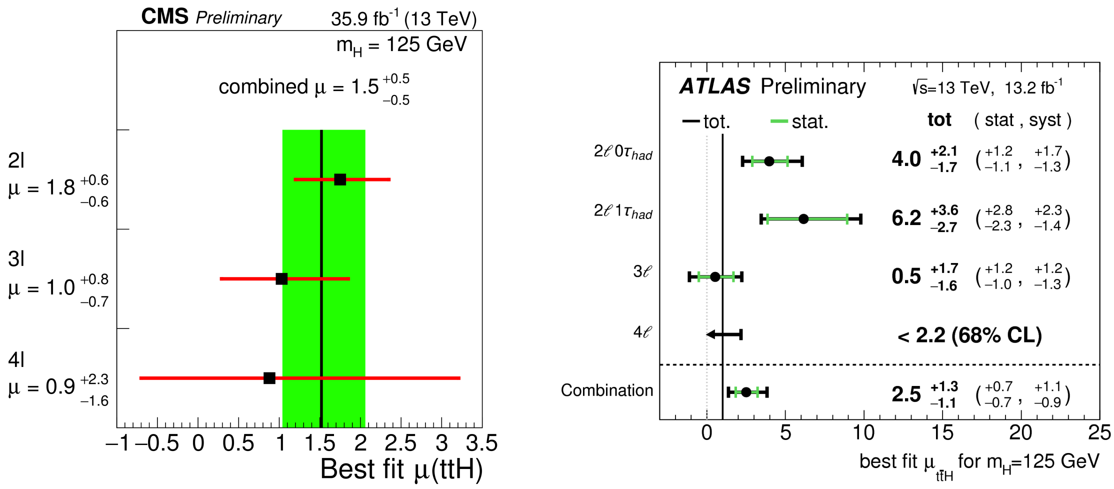

Figure 8: Summary of the signal strength measurements (the ratio of the measured $t\bar{t}$H signal cross section to the SM expectation) in the individual multilepton channels for CMS (left) and ATLAS (right) [15, 16].

6. Single top quark measurements

Single top quark processes are a direct probe of the Wtb coupling and of V_{tb} element of the CKM matrix. They represent an important background for Higgs boson searches in associated production W/ZH $\to$ qqbb. Moreover, they are sensitive to many models of new physics affecting the Wtb vertex like Flavor Changing Neutral Currents (FCNC) and anomalous couplings, or involving new particles such as W$'$ or charged Higgs bosons. In this section measurements of the inclusive cross section of the t-channel and tW associated production are presented, as well as the first measurement of the associated production with a Z boson.

6.1 t-channel

The cross section measurement using data at 13 TeV has been performed studying either the electron and muon channel [17] or the muon channel only [18, 19]. Events are identified by the presence of an isolated lepton, a central b-tagged jet and a forward light jet. The analysis strategy is based on multivariate discriminants. The measured cross sections result $\sigma^{ATLAS} = 247 \pm 46$ pb [17] and $\sigma^{\mathrm{CMS}} = 232 \pm 31$ pb [18]. The cross sections have been measured also differentially as a function of the top quark p_{T} and $|\eta|$ [19]. The results are in good agreements with SM predictions, see Fig. 9.

The t-channel process in pp collisions is characterised by the asymmetry in the production of top quarks and antiquarks, as the density of u quarks is almost twice than the density of d quarks. The measurement of this asymmetry can help to constrain the parton distribution functions of the proton. The analyses are also performed by a fit to the multivariate discriminant, in this case separated by lepton charge. The ratio $\sigma(\mathrm{t})/\sigma(\bar{\mathrm{t}})$ is in agreement with the SM prediction, see Fig. 9 right.

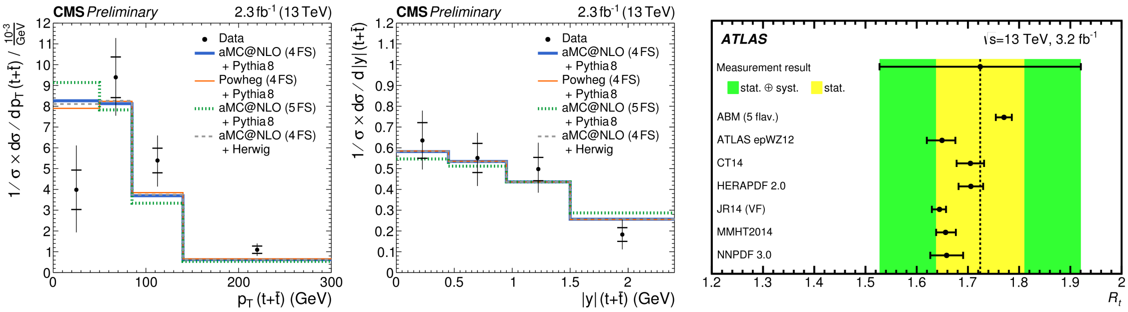

Figure 9: Normalised differential cross sections as a function of the top quark p_T (left) and $|\eta|$ (middle) [19] and measured ratio of t-channel single-top and single-antitop quark cross section (right), compared with the values obtained using different PDF sets [17]. The uncertainties include the factorisation and renormalisation scales and top quark mass uncertainties.

6.2 tW associated production

ATLAS achieved evidence of the associated production of a single top quark and W boson in pp collisions at 13 TeV [20]. The measurement is performed using events with two leptons and a jet originated from a b quark. A multivariate analysis based on kinematic properties is applied to separate the signal from the $t\bar{t}$ background, in different signal and background categories based on the number of jets and b-tagged jets in the event, see Fig. 10. The signal is observed at a significance of 4.5 standard deviation above the background-only hypothesis (expected significance 3.9 σ). The corresponding measured cross section value is: σ_{tW}=94$\pm$10(stat)$^{+28}_{-22}$(syst)$\pm$2(lumi) pb.

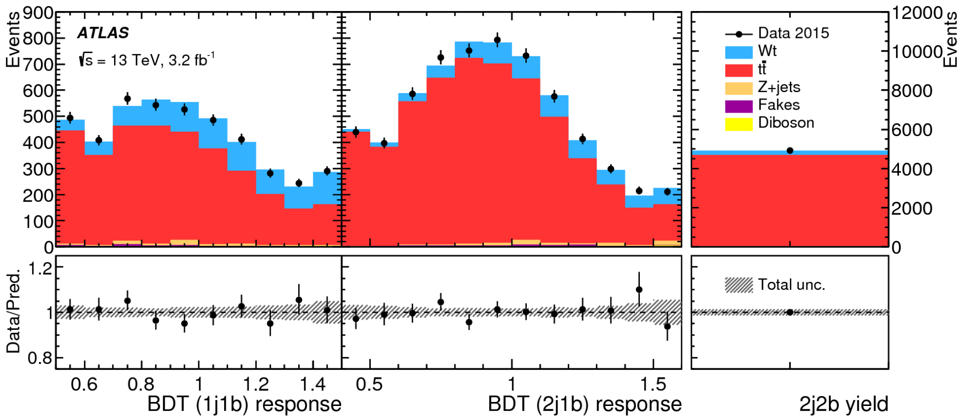

Figure 10: Post-fit distributions in the signal (1j1b) and control regions (2j1b and 2j2b). The error bands represent the total uncertainties in the fitted results. The upper panels give the yields in number of events per bin, while the lower panels give the ratios of the numbers of observed events to the total prediction in each bin [20].

A summary of the single top quark cross section results by the ATLAS and CMS Collaborations, including those at $\sqrt{s}$= 7, 8 and 13 TeV, is shown in Fig. 11 (left). The summary of the extractions of the CKM matrix element Vtb performed with a subset of those results is presented in Fig. 11 (right). The results in the single top quark production modes agree well among themselves and with the SM expectation.

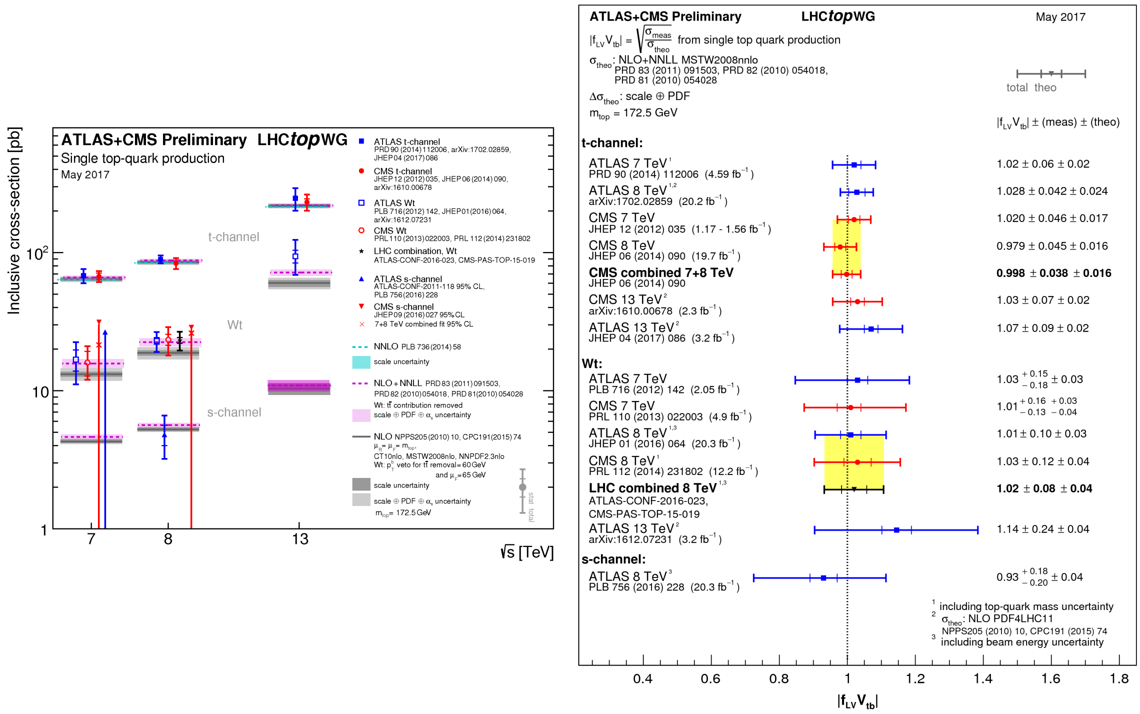

Figure 11: Left: Summary of single top quark cross section measurements by CMS and ATLAS, as function of centre-of-mass energy. The measurements are compared to theoretical calculations based on: NLO QCD, NLO QCD complemented with NNLL resummation and NNLO QCD (t-channel only) [4]. Summary of the ATLAS and CMS extractions of the CKM matrix element V_{tb} from single top quark measurements. For each result, the contribution to the total uncertainty originating from the uncertainty on the theoretical prediction for the single top production cross section is shown along with the uncertainty originating from the experimental measurement of the cross-section. [4].

6.3 Evidence for tZq

The large data samples collected at the LHC allow also searching for the associated production of a single top quark in the t-channel and a Z boson (tZq). The process is sensitive to the top quark coupling to the Z boson and to the triple gauge-boson coupling WWZ. The analysis [21] by the ATLAS Collaboration is performed selecting events that contain three identified leptons (electron and/or muon) and two jets, one of which is identified as a b-quark jet. The criteria are modified to define validation regions, which are used to check the modelling of the main background contributions. The major backgrounds come from diboson, $t\bar{t}$ and Z + jets production. A neural network is used to improve the background rejection and extract the signal. Figure 12 shows the discriminant in the signal region after the profile likelihood fit. The resulting significance of the signal is 4.2σ in the data and the expected significance is 5.4σ. The measured cross section is 600 ± 170 (stat)± 140 (syst) fb, in agreement with the SM predictions and the result by the CMS Collaboration in the same decay channel [22].

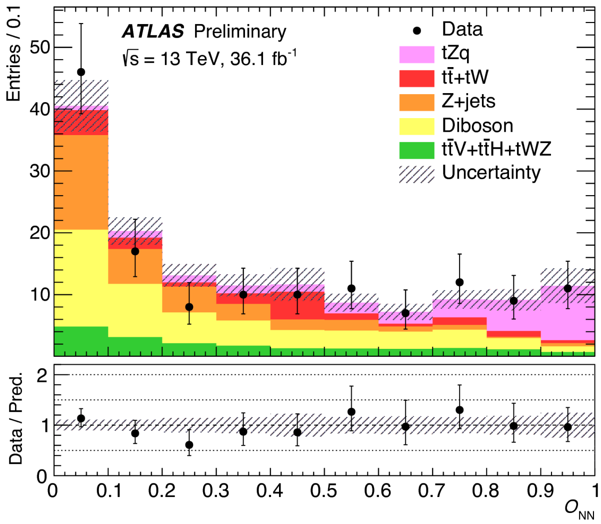

Figure 12: Post-fit neural-network output distribution in the tZq signal region. Signal and backgrounds are normalised to the expected number of events after the fit. The uncertainty band includes both statistical and systematic uncertainties as obtained by the fit [21].

7. Summary

Top quark measurements provide important information about the production process as described in QCD, as well as sensitivity to possible new physics phenomena. In the last years, the LHC has become a real *top factory* and the large top quark samples collected allowed to perform precise inclusive and differential tt̄ and single top quark cross section measurements, first measurements of tt̄ + heavy flavour processes, and the first observation of tt̄+W/Z/γ, as well as evidence for tt̄+H and rare single top quark processes such as tZq. The latter measurements will benefit from the data expected to be collected during the full LHC Run-2, which will allow to reduce the uncertainties significantly and thus to verify if couplings to the top quark are compatible with SM or altered by BSM effects.

References

[1] ATLAS Collaboration, The ATLAS Experiment at the CERN Large Hadron Collider, JINST 3 (2008) S08003.

[2] CMS Collaboration, The CMS experiment at the CERN LHC, JINST 3 (2008) S08004.

[3] CMS Collaboration, Measurement of the inclusive tt̄ cross section at $\sqrt{s} = 5.02$ TeV, CMS-PAS-TOP-16-023, https://cds.cern.ch/record/2258177.

[4] https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots

[5] CMS Collaboration, Measurement of differential cross sections for top quark pair production using the lepton+jets final state in proton-proton collisions at 13 TeV, Phys. Rev. D 95, 092001.

[6] ATLAS Collaboration, Measurements of top-quark pair differential cross-sections in the lepton+jets channel in pp collisions at 13 TeV using the ATLAS detector, JHEP 11 (2017) 191.

[7] ATLAS Collaboration, Measurement of jet activity produced in top-quark events with an electron, a muon and two b-tagged jets in the final state in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector, Eur. Phys. J. C (2017) 77: 220.

[8] ATLAS Collaboration, Studies on top-quark Monte Carlo modelling with. Sherpa and MG5_aMC@NLO, ATL-PHYS-PUB-2017-007, https://cds.cern.ch/record/2261938.

[9] CMS Collaboration, Investigations of the impact of the parton shower tuning in Pythia 8 in the modelling of $\mathrm{t\bar{t}}$ at $\sqrt{s}$=8 and 13 TeV, CMS-PAS-TOP-16-021, https://cds.cern.ch/record/2235192.

[10] CMS Collaboration, Measurements of $t\bar{t}$ cross sections in association with b jets and inclusive jets and their ratio using dilepton final states in pp collisions at $\sqrt{s}$ = 13 TeV, Phys. Lett. B **776** (2018) 355.

[11] CMS Collaboration, Measurement of top pair-production in association with a W or Z boson in pp collisions at 13 TeV, CMS-PAS-TOP-17-005, https://cds.cern.ch/record/2264544.

[12] ATLAS Collaboration, Measurement of the $\mathrm{t\bar{t}Z}$ and $\mathrm{t\bar{t}W}$ production cross sections in multilepton final states using 3.2 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector, EPJC 77 (2017) 40.

[13] ATLAS Collaboration, Measurement of the $\mathrm{t\bar{t}}+\gamma$ production cross section in proton-proton collisions at $\sqrt{s}$=8 TeV with the ATLAS detector, JHEP 11 (2017) 086.

[14] CMS Collaboration, Measurement of the semileptonic $\mathrm{t\bar{t}}+\gamma$ production cross section in pp collisions at $\sqrt{s}$ = 8 TeV, JHEP 10 (2017) 006.

[15] CMS Collaboration, Search for Higgs boson production in association with top quarks in multilepton final states at $\sqrt{s}$ = 13 TeV, CMS-PAS-HIG-17-004, https://cds.cern.ch/record/2256103.

[16] ATLAS Collaboration, Evidence for the associated production of the Higgs boson and a top quark pair with the ATLAS detector, submitted to Phys. Rev. D, arXiv:1712.08891.

[17] ATLAS Collaboration, Measurement of the inclusive cross-sections of single top-quark and top-antiquark t-channel production in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector, JHEP 04 (2017) 086.

[18] CMS Collaboration, Cross section measurement of t-channel single top quark production in pp collisions at $\sqrt{s}$ = 13 TeV, Phys. Lett. B 72 (2017) 752.

[19] CMS Collaboration, Measurement of the differential cross section for t-channel single-top-quark production at $\sqrt{s}$= 13 TeV, CMS-PAS-TOP-16-004, https://cds.cern.ch/record/2151074.

[20] ATLAS Collaboration, Measurement of the cross-section for producing a W boson in association with a single top quark in pp collisions at $\sqrt{s}$=13TeV with ATLAS, JHEP 01 (2018) 63.

[21] ATLAS Collaboration, Measurement of the production cross-section of a single top quark in association with a Z boson in proton-proton collisions at 13 TeV with the ATLAS detector, ATLAS-CONF-2017-052, https://cds.cern.ch/record/2273868.

[22] CMS Collaboration, Evidence for the standard model production of a Z boson with a single top quark in pp collisions at $\sqrt{s}$ = 13 TeV, CMS-PAS-TOP-16-020, https://cds.cern.ch/record/2284830.