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Top / EW / SM Report

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A series of recent results obtained by the ATLAS and CMS experiments at the LHC, on the Top and Electroweak sectors of the Standard Model, are presented. Given that these are very broad topics, only a selection of highlighted results are discussed.

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1. Introduction

The data samples collected with the ATLAS [1] and CMS [2] experiments have been used to perform a large number of studies allowing to test the Standard Model (SM). Such tests are being performed for rare processes, as well as for differential and/or precision measurements. Indeed, good agreement between the SM and the measurements has been observed for many processes, covering over 15 orders of magnitude of the production cross-section. Almost all the studies presented here use the full accumulated luminosity during the Run 2 of the LHC, with pp collisions at $\sqrt{s} = 13$ TeV. They greatly benefit from the excellent reconstruction and calibration performance results for the various physics objects.

2. Electroweak studies

The vector boson scattering (VBS) and vector boson fusion (VBF) are processes that are particularly interesting to study in order to probe the interactions of gauge bosons. Indeed, in addition to the Electroweak (EW) and QCD contributions [1], effects from potential physics beyond the SM may occur. The Higgs boson also plays a special role in the weak boson scattering, regularizing the cross-section at high energies, ensuring evolution operator unitarity.

The VBS / VBF topologies are characterised by the presence of two energetic forward-backward tagging jets, a large mass and rapidity separation for the dijet system, as well as little hadronic activity between tagging jets in fully leptonic final states. In practice, one always measures the EW+QCD production and multivariate analysis techniques are often used in order to isolate the EW-production.

CMS has used the full Run 2 luminosity of 137 fb^{-1} to study the $W^{\pm}Zjj$ and $W^{\pm}W^{\pm}jj$ final states [3]. A simultaneous maximum likelihood fit to WW and WZ signal regions and background control regions was used to extract the EW $W^{\pm}W^{\pm}$, EW WZ, QCD WZ contributions. This yields an observed (expected) significance for the EW production of 6.8σ (5.3σ) in the WZ channel, well above 5σ in the $W^{\pm}W^{\pm}$ channel. For comparison, with 36 fb^{-1}, ATLAS has observed significances for the EW production amounting to 5.3σ in the WZ channel [4] and 6.5σ for $W^{\pm}W^{\pm}$ [5]. CMS also performed inclusive and differential (absolute and normalised) cross-section measurements as a function of several observables, which were then also used to set limits on potential contributions from anomalous quartic gauge couplings [3].

The polarisation of the W bosons in the $W^{\pm}W^{\pm}jj$ final state is correlated with their direction and hence their transverse momenta. The CMS collaboration has used a boosted decision tree (BDT) based on a series of different kinematic observables to distinguish between the various helicity eigenstates in the center of mass frames of either the $W^{\pm}W^{\pm}$ or of the initial state partons (see Figure 1) [6]. In the former frame, for example, an observed (expected) upper limit of 1.17 (0.88) fb at 95% CL has been set on the cross-section of the process $W^{\pm}_L W^{\pm}_L$. Distinguishing between the three possible helicity eigenstates (especially the $W^{\pm}_L W^{\pm}_L$) is a high priority component of the high luminosity LHC program, in order to probe the EW symmetry breaking.

The EW production of the $ZZjj$ final state has been studied by both ATLAS [7] and CMS [8]. Both analyses use events with four charged leptons in the final state ($lll'l'$), while the ATLAS study also uses events with two charged leptons and two neutrinos ($ll\nu\nu$). The separation of the EW signal

[1] A measurement probing, at leading order, purely EW interactions will be discussed below.

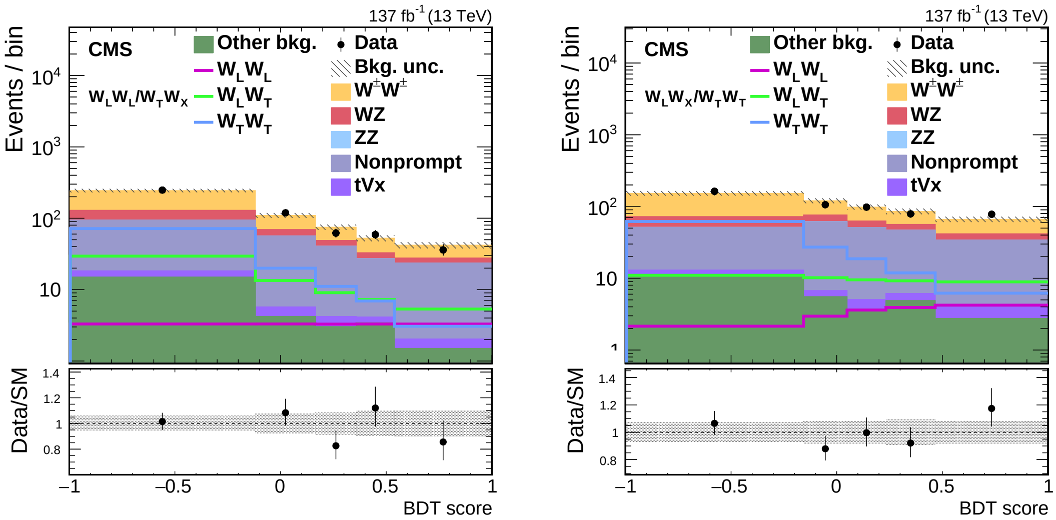

Figure 1: Distributions of the output score of the signal BDT used by CMS for the cross-section measurements for various polarisation configurations of the $W^{\pm}W^{\pm}$ pairs [6].

from the background (e.g. QCD ZZ) is performed using a multivariate analysis (ATLAS) and a matrix-element likelihood (CMS). The observed (expected) significance for the EW production amounts to 5.5σ (4.3σ) for ATLAS and 4.0σ (3.5σ) for CMS. The corresponding fiducial cross-sections are also found to be in good agreement between the measurements and the SM predictions.

With these recent results, all the $VVjj$ channels (with heavy bosons) have now been observed.

ATLAS measured unfolded differential cross-sections of Zjj VBF-like events, as a function of the mass, rapidity separation and the rapidity-ordered difference of the azimuthal angles of the dijet system, as well as the transverse momentum of the dilepton system [9]. Both inclusive-Zjj and EW-Zjj measurements are performed, using an EW signal region and three control regions. A data-driven estimate of the QCD Zjj component is performed on a bin-by-bin basis, in order to avoid biasing the shape of the EW distributions. The measurements are precise enough to distinguish between state-of-the-art predictions and interpretation studies in terms of EFT constraints were also performed.

Based on an idea described originally in Ref. [10], ATLAS has studied collisions of photons [11], which is a pure quantum field theory effect. Pb ions are used as intense sources of quasi-real photons and the luminosity that is currently available allows to go from the first observations to differential cross-section measurements [11].

ATLAS has observed and measured lepton pairs produced via the photon fusion mechanism and reconstructed by the central ATLAS detector. Events of pp collisions, where at least one of the protons stays intact and is detected by the ATLAS Forward Proton spectrometer, are used in this study [12]. The fractional proton energy lost is related to the kinematic properties of the dilepton system, which allows to extract a clear signal. After a data-driven background subtraction, the signal is observed with significances of 9.7 (13.3)σ for the ee ($\mu\mu$) channels respectively. ATLAS performed a proton-tagged fiducial cross-section measurement using high luminosity data, for the first time at the LHC. This result also allows to test proton soft-survival models.

A similar technique is used by CMS, in events with the two protons staying intact and be-

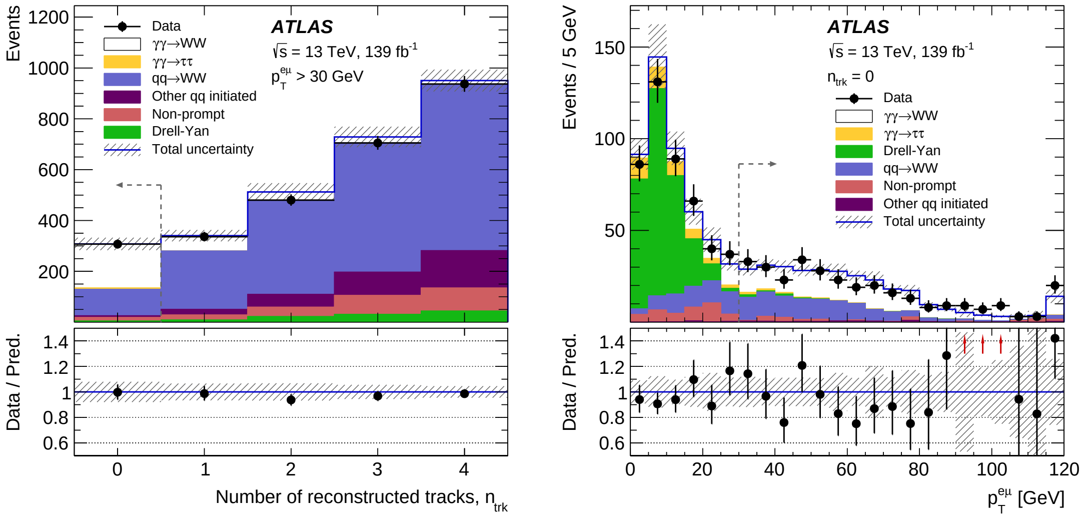

Figure 2: Left: the distribution of the number of tracks associated with the interaction vertex. Right: the distributions of $p_T^{e\mu}$ for $n_{\text{track}} = 0$. The $\gamma\gamma \to WW$ signal region requires a selection of $n_{\text{track}} = 0$ and $p_T^{e\mu} > 30$ GeV, as indicated by the arrows. The fitted normalisation factors and nuisance parameters have been used. The figures are reprinted from Ref. [14].

ing tagged by TOTEM, to search for potential contributions from new physics at high diphoton mass [13]. Here also, the kinematic matching between reconstructed diphoton system and scattered protons is used to suppress coincidences between inclusive diphotons and pile-up protons. A good agreement is found between the experimental spectrum and the background expectation. An upper limit is set on the light-by-light fiducial cross-section, which is then interpreted in terms of the first limits on four photons quartic gauge couplings.

ATLAS performed an observation of photon-induced W^+W^- production in pp collisions [14]. This is especially interesting, since at first order these events probe purely EW interactions. Protons radiate ISR photons and either stay intact or dissociate. The signal reconstruction requires an opposite-sign $e\mu$ pair, no tracks near the vertex of the leptons and a transverse momentum of the lepton pair larger than 30 GeV (which is a missing transverse momentum (MET) proxy) (see Figure 2). The main background originates from QCD-induced WW events with no extra tracks. The central challenge for this measurement originates from the physics modeling of events with few or no tracks, to account for the number of pile-up tracks near leptons, the number of tracks for background underlying event and the efficiency of the requirement to have no tracks near the vertex of the leptons. An observation with a significance of 8.4σ is achieved and a fiducial cross-section measurement is performed.

ATLAS performed differential unfolded cross-section measurements, in 4-lepton events, for numerous distributions [15]. The $4e$, $2e2\mu$ and 4μ channels have been considered. The branching fraction of $Z \to 4l$ was extracted and found to be in good agreement with the SM prediction. The measured cross-sections also have the potential to constraint possible contributions from new physics beyond the SM.

Before presenting the recent top quark studies, we discuss two analyses where the top quark is used to tag the events.

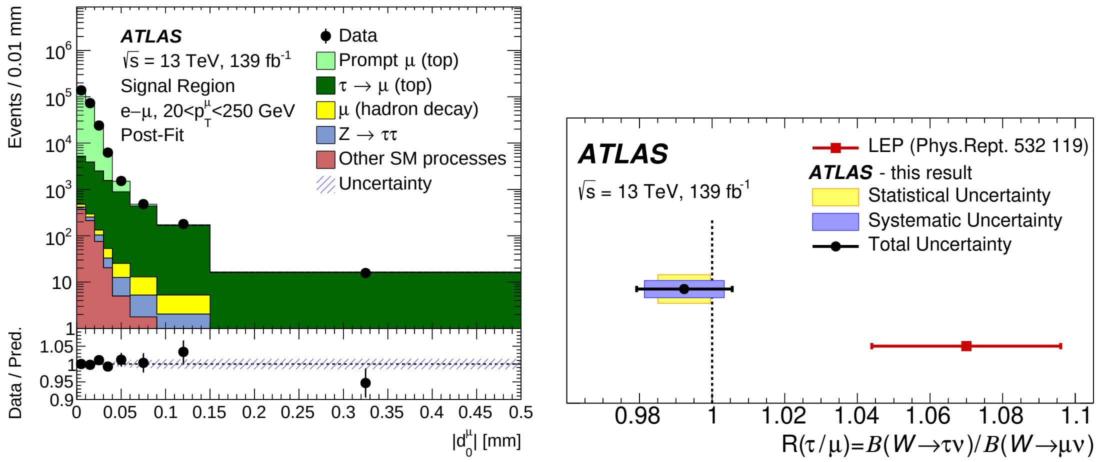

Figure 3: Left: the $|d_0^\mu|$ distribution for the $e-\mu$ channel for probe muons with $20 < p_T^\mu < 250$ GeV. The plot is shown after the fit has been performed. Right: the measurement of $R(\tau/\mu)$ (black circular marker) compared with the previous LEP result (red square marker). The statistical and systematic uncertainties are shown separately as well as the total uncertainty of the measurement. The vertical dashed line indicates the Standard Model prediction. The figures are reprinted from Ref. [17].

CMS performed a search for $W^\pm \to \pi^\pm\gamma$ decays, in $t\bar{t}$ events [16]. Leptonic top decays are used as tag, while requiring an isolated π and γ on the probe side. A BDT based on several kinematic observables is used to discriminate between signal and background. Good agreement is observed between the data and the expected background, which allows to use the $m_{\pi\gamma}$ distribution to set observed (expected) 95% CL upper limits on the $B(W^\pm \to \pi^\pm\gamma)$ at the level of 1.51×10^{-5} $(8.6^{+5.2}_{-2.9} \times 10^{-6})$.

ATLAS measured the ratio of branching ratios $B(W \to \tau\nu)/B(W \to \mu\nu)$ in $t\bar{t}$ events [17]. This measurement is especially interesting as it probes the universality of the W coupling to charged leptons, which is a fundamental property of the SM. Dilepton $(e\mu, \mu\mu)$ $t\bar{t}$ events provide a sample of probe W-bosons, where one triggers on the electron or the muon on the opposite side of the event. The transverse momentum (p_T^μ) and the transverse impact parameter $(|d_0^\mu|)$ of the muon (see Figure 3, left) are used to differentiate between $W \to \tau\nu \to \mu\nu\nu\nu$ and $W \to \mu\nu$ decays. A profile likelihood fit to the 2D distribution of p_T^μ and $|d_0^\mu|$ indicates good agreement between the $e-\mu$ and $\mu-\mu$ channels and yields for the global result:

$$R(\tau/\mu) \equiv B(W \to \tau\nu)/B(W \to \mu\nu) = 0.992 \pm 0.013[\pm 0.007\ (\text{stat}) \pm 0.011\ (\text{syst})].$$

This confirms the SM expectation, with the best precision achieved for such measurement up to now, “solving” the LEP discrepancy (see Figure 3, right).

3. Top quark studies

Even if a large number of top quarks are produced at the LHC (which can hence be considered a “top factory”), some events like the $t\bar{t}t\bar{t}$ production are still rare. ATLAS has found evidence for this process [18], which is sensitive to the top Yukawa coupling and to potential contributions from

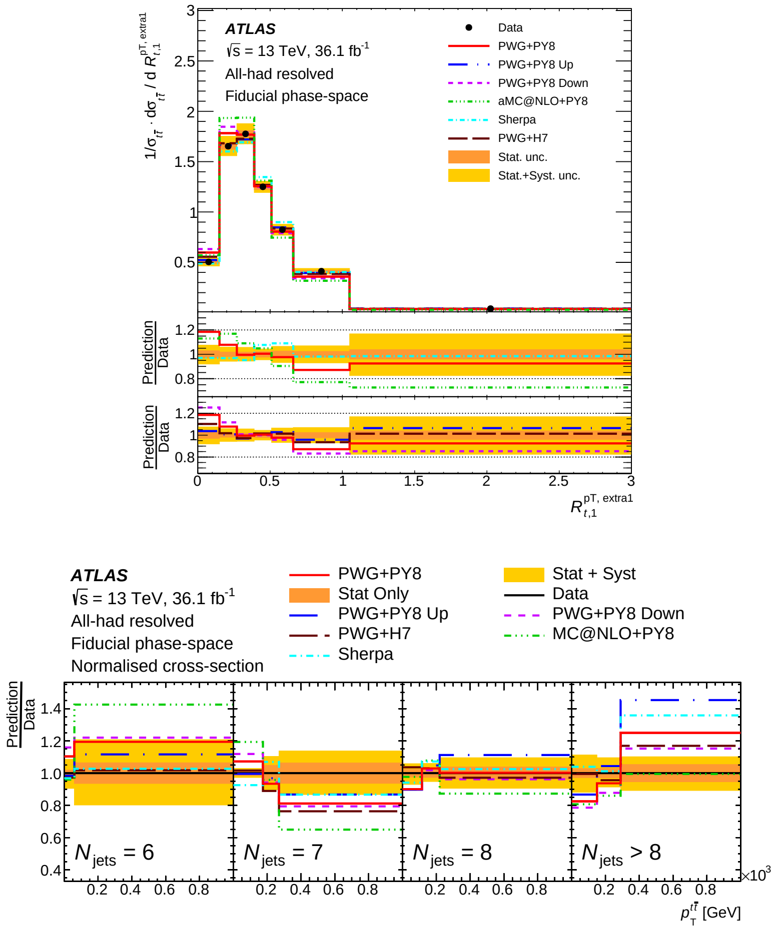

Figure 4: Top: particle-level single-differential normalised cross-section as a function of the ratio of the leading 'extra jet' p_{T} to the leading top-quark p_{T}. Bottom: ratio of the measured particle-level double-differential normalised cross-section to different MC predictions, as a function of the $t\bar{t}$ system transverse momentum $p_{\mathrm{T}}^{t\bar{t}}$, in bins of the jet multiplicity. The figures are reprinted from Ref. [20].

physics beyond the SM (due to the high energy scales that are involved). The event selection requires either two same sign leptons or at least three charged leptons, as well as high jet multiplicities and at least two b-tagged jets. A BDT is used to discriminate between signal and background, and the dominant backgrounds are evaluated using data-driven approaches. A profile likelihood fit to discriminant variables in the signal region and four control regions yields an observed (expected) significance of 4.3 (2.4) σ. The corresponding measured fiducial cross-section is somewhat larger than the expected one based on NLO QCD with EW corrections. For the same process, CMS obtained an observed (expected) significance of 2.6 (2.7) σ [19].

ATLAS measured the fiducial and full phase-space $t\bar{t}$ production cross-sections, in the all hadronic final state [20]. The measurement performed in this fully reconstructed final state was done inclusively, as well as for unfolded simple- and double-differential distributions, including also information on extra jets in the events (see Figure 4). A χ^2 discriminant, based on constraints on the reconstructed top quark and W masses, was used for the event reconstruction. A data-driven

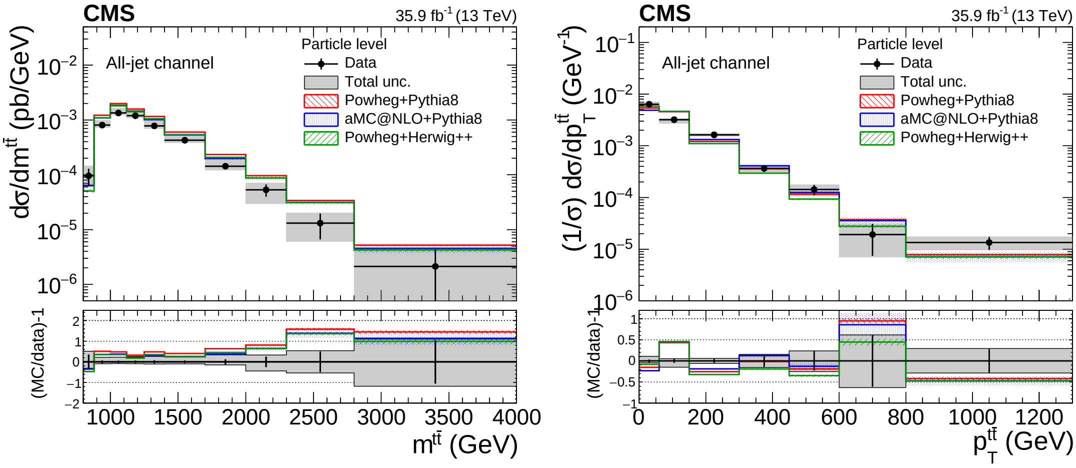

Figure 5: Differential cross-section unfolded to the particle level, absolute, as a function of $m^{t\bar{t}}$ (left) and normalized, as a function of $p_{\mathrm{T}}^{t\bar{t}}$ (right), measured by CMS in the all-jet channel [21].

method (ABCD) was used to estimate the dominant multijet background. Good agreement with the predictions is found for the inclusive fiducial cross-section. Monte Carlo simulations describe angular properties more consistently than the energy sharing between the final state objects. Two dimensional differential cross-sections are more discrepant than the one dimensional measurements. This result is qualitatively consistent with the lepton + jet and the boosted all hadronic measurements in the overlap regions.

CMS measured the boosted $t\bar{t}$ production cross-sections in the lepton + jets and the all hadronic final states [21]. The unfolded fiducial and full phase-space measurements are performed using boosted tops reconstructed using large-R jets in the hadronic channel and small-R jets for lepton+jets. The top tagging is performed using the N-subjettiness observable and the QCD multijet background is evaluated using a data-driven approach. Unfolded cross-sections are measured as a function of numerous observables, among which the mass and transverse momentum of the $t\bar{t}$ pairs (see Figure 5). While some normalisation differences are observed between data and theory, there is generally good agreement for the shapes of the distributions. ATLAS has also performed a fully hadronic boosted measurement, using a data sample corresponding to 36 fb^{-1} [22].

CMS measured the $t\bar{t}$ production cross-section with additional jets and b-jets [23], which is important for the ttH studies. The measurement was performed for both the dilepton and lepton+jets decay modes. A kinematic fit is used to remove combinatoric ambiguities. A two dimensional maximum likelihood fit using b-tagging discriminant variables for the first and second additional (non $t\bar{t}$) jets is used to extract the $t\bar{t}jj$ cross-section and its ratio to $t\bar{t}b\bar{b}$, in the visible phase-space. The measurement is then also extrapolated to the full phase-space, accounting for acceptance effects. Relatively good agreement between the measurements and the Standard Model predictions is observed. ATLAS also performed fiducial and differential production cross-section measurements of $t\bar{t}$ plus (heavy flavour) jets [24, 25].

ATLAS measured the fiducial and parton-level $t\bar{t}\gamma + tW\gamma$ cross-sections, in the electron plus muon final state [26]. The inclusive measurement is obtained through a profile likelihood fit of the scalar sum of transverse momenta. It has a relative uncertainty of 6.3% and is compatible with the

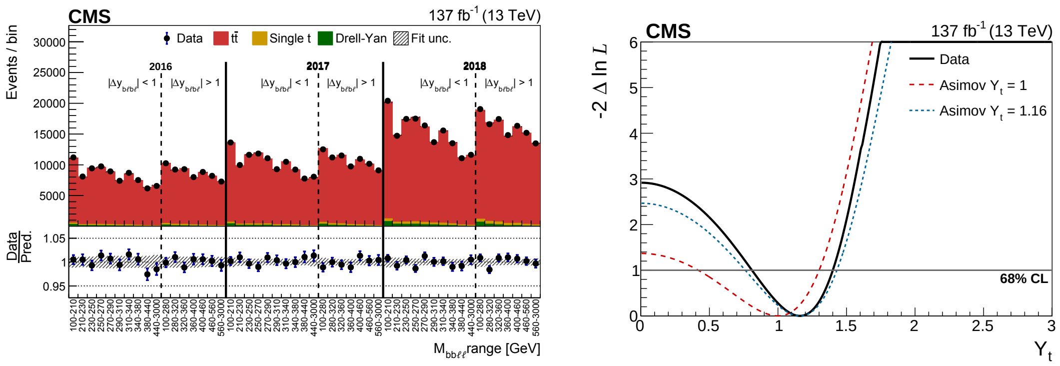

Figure 6: Left: the comparison between the CMS data and MC simulation at the best fit value of $Y_t = 1.16$ after performing the likelihood maximization, with shaded bands displaying the post-fit uncertainty. The solid lines separate the three data-taking periods, while the dashed lines indicate the boundaries of the two Δy_{blbl} bins in each data-taking period, with M_{blbl} bin ranges displayed on the x-axis. Right: the result of a profile likelihood scan, as a function of Y_t. The figures are reprinted from Ref. [29].

NLO-QCD prediction, which has a similar precision. Absolute and normalised unfolded differential measurements are performed for five kinematic and event topology observables. Generally good agreement is observed between these measurements and the theoretical predictions. In the case of the azimuthal angle between the two leptons, good agreement is observed for the NLO-QCD predictions, while the p-values obtained for the LO plus parton shower predictions are below 1%.

For the $t\bar{t}Z$ production cross-section, ATLAS performed inclusive and differential measurements (as a function of numerous observables), unfolded to both the particle and parton levels [27]. Such measurements are especially interesting due to the sensitivity to the top Yukawa coupling. The ATLAS study is focused on the most sensitive channels, with three and respectively four leptons in the final state. The inclusive cross-section is derived from a profile likelihood fit to six signal regions and the WZ/ZZ plus light jets control regions. It has a relative uncertainty of 10% and is compatible with the NLO+NNLL QCD prediction, which has a precision of 11%. There is also generally good agreement between the differential measurements and the predictions. CMS reports a measurement of the inclusive $t\bar{t}Z$ cross-section with a precision of 8% [28].

CMS performed an evaluation of the top Yukawa coupling, using $t\bar{t}$ kinematic distributions [29]. These are the mass of the system of two b-jets and two charged leptons and respectively the rapidity difference between the b-jet plus charged lepton systems associated to the top quarks (see Figure 6, left). They are proxies to the similar quantities computed for the top quarks, but avoid the sensitivity to the uncertainties related to the MET from the neutrinos. The measurement is performed for the di-lepton channel and the selection ensures a suppression of the Drell-Yan background. A two-dimensional likelihood fit yields $Y_t = 1.16^{+0.24}_{-0.35}$ (see Figure 6, right). This result is complementary to the direct measurement, which has a precision of about 12%.

CMS performed and extraction of the CKM matrix elements based on the single top t-channel production [30]. The production rates are measured in the electron and muon channels. The CKM matrix elements are extracted through a maximum likelihood fit for several event categories (based on the lepton type, the jet and b-jet multiplicities) and observables (the lepton plus (b-)jet mass, the MET), distinguishing also profiled and non-profiled uncertainties. Assuming the SM (i.e.

unitarity), this yields: $|V_{tb}| > 0.970$ and $|V_{td}|^2 + |V_{ts}|^2 < 0.057$, both at 95% CL.

CMS took a step towards a global EFT fit, by implementing a novel EFT approach in an analysis targeting single-top and $t\bar{t}$ production in association with W, Z or Higgs bosons [31]. This analysis selects events with b-jets and either two same-sign, or three, or four leptons. Event categories are defined based on the lepton, jet and b-jet multiplicities. The event yields for all the relevant processes are parameterized as a function of all the relevant Wilson coefficients. Confidence intervals are evaluated for each of these coefficients, by either fitting the other relevant Wilson coefficients too or by fixing them to the SM values.

4. Conclusion

The large luminosity collected during the Run 2 of the LHC allows ATLAS and CMS to indirectly study the EW symmetry breaking in boson scattering, study high energy photon collisions, produce heavy states of four top quarks with masses above 700 GeV, use $t\bar{t}$ events for precision measurements and for tag and probe studies. Through this vast programme, the fundamental aspects of the Standard Model are being tested and its EFT-based extensions are studied.

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