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A perspective of High Energy Physics from precision measurements
La physique des Hautes Energies du point de vue des mesures de précision

Top quark physics at the LHC

La physique du quark top au LHC

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Abstract. An overview of the measurements and searches in the top quark sector at the LHC is presented. Due to the large amount of data recorded by the ATLAS and CMS experiments at a centre-of-mass energy of 13 TeV, top quark properties and couplings in production and decay can be studied with an unprecedented precision and compared to predictions of the standard model to shed light on the possible presence of new physics.

Résumé. Cet article donne un aperçu des mesures et des recherches au LHC dans le secteur du quark top. La grande quantité de données enregistrées par les expériences ATLAS et CMS à une énergie dans le centre de masse de 13 TeV, permet d'étudier avec une précision sans précédent les propriétés et les couplages du quark top lors de sa production et de sa désintégration. Les comparaisons avec les prédictions du modèle standard permettent de tester l'éventuelle présence d'une nouvelle physique.

Keywords. Top quark, LHC, Collisionner, Standard model, Couplings.

Mots-clés. Quark top, LHC, Grand collisionneur de hadrons, Modèle standard, Couplages.

1. Setting the top scene

The top quark was the last standard model (SM) fermion to be discovered in 1995. This up-type third-generation quark was first observed by the CDF and D0 Collaborations at the Tevatron collider. It is the heaviest SM particle and its mass plays a key role in the predictive power of the SM, e.g. in the consistency fits of the electroweak observables (see the article on the $W^{\pm}$ and Z^0 bosons physics), as well as in our understanding of the stability of the universe, i.e. the lifetime of the electroweak vacuum. Furthermore, the top quark is the only quark that decays before hadronisation, making top quark physics a unique playground to study a bare quark.

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Initial studies of the top quark production cross sections and the top quark properties have been performed at the Tevatron collider at a centre-of-mass energy $\sqrt{s} = 1.96$ TeV. The precision of these measurements was quickly surpassed when the LHC started colliding protons at $\sqrt{s} =$ 7 TeV.

In proton collisions at the LHC top quarks are dominantly produced via the strong interaction, resulting in a top quark-antiquark pair ($t\bar{t}$). In the SM the top quark decays almost 100% of the time to a b quark and a W^+ boson ($t \to bW^+$). The W boson will subsequently decay to either two quarks ($W \to q\bar{q}'$), which are observed as jets of particles, or to a charged lepton and a neutrino ($W \to l\nu$). Typically three final state topologies are defined for $t\bar{t}$ events: $t\bar{t} \to bW^+\bar{b}W^- \to bl^+\nu\bar{b}l^-\bar{\nu}$ (dilepton), $t\bar{t} \to bW^+\bar{b}W^- \to bq\bar{q}'\bar{b}l^-\bar{\nu}$ or $l^+\nu\bar{b}q\bar{q}'\bar{b}$ (lepton+jets), and $t\bar{t} \to bW^+\bar{b}W^- \to bq\bar{q}'\bar{b}q_1\bar{q}_2$ (all-jets). In the following the charges of the particles will be omitted and charge conjugation will be implicitly assumed.

There are three main modes for producing single top (anti)quarks, which have all been observed. The s-channel (and t-channel) production mode has only been observed at the Tevatron. The t-channel and tW-channel production modes have been observed at the LHC. For the studies based on single top quark events the leptonic decay of the W boson is typically considered.

2. Top quark production and modelling at the LHC

2.1. *Production of $t\bar{t}$ events*

The total $t\bar{t}$ production cross section has been measured in proton collision data at the LHC at four different centre-of-mass energies as shown in Figure 1, where the measurements are compared to the state-of-the-art prediction [1]. This prediction includes next-to-next-to-leading-order (NNLO) quantum chromodynamics (QCD) corrections supplemented with soft-gluon resummation with next-to-next-to-leading logarithmic (NNLL) accuracy. The scale uncertainty, which is used to estimate the impact of missing higher-order contributions, typically dominates the total uncertainty in the predictions. For the measurements the uncertainty is dominated by the systematic uncertainty for all considered final states. For the most precise measurements the uncertainty due to the luminosity is of the same size as all the other systematic uncertainties combined. The LHCb experiment observed the production of $t\bar{t}$ events in the forward region at different centre-of-mass energies. For the latest measurement the statistical and systematic uncertainties are of comparable size [2].

Apart from measuring the total $t\bar{t}$ production cross section, the accurate prediction and measurement of specific processes is crucial for precision physics. An example is the production of $t\bar{t}b\bar{b}$. Precise knowledge of this process is particularly important for studying the coupling between the top quark and the Higgs boson, which can be measured through the production cross section of $t\bar{t}H$ with the decay of the Higgs boson to $b\bar{b}$ being the dominant decay channel. Theoretically, the $t\bar{t}b\bar{b}$ process is challenging to compute because of the number of partons in the final state and the very different scales playing a role in producing the top and bottom quark pairs. There are several strategies to generate the $t\bar{t}b\bar{b}$ process. A first option is to use a next-to-leading-order (NLO) matrix element for the top quark pair and let the parton shower (PS) produce the bottom quark pair via gluon splitting. If the bottom quark pair is produced through gluon splitting the b quarks are assumed to be massless. This is referred to as the 5-flavour scheme (5FS). Another option is to generate $t\bar{t}$ events at NLO with up to two additional jets, thereby also including b quark jets. In this scheme the additional jets are produced through radiation and hence the 5FS is used. The third option is to use a $t\bar{t}+b\bar{b}$ matrix element at NLO. This last option assumes massive b quarks and is referred to as the 4FS. Typically the uncertainty in the predictions is of the order of 30%. The $t\bar{t}b\bar{b}$ events generated via the different options yield similar distributions for the final-state observables within the uncertainties [4]. The $t\bar{t}b\bar{b}$ production cross section was measured at

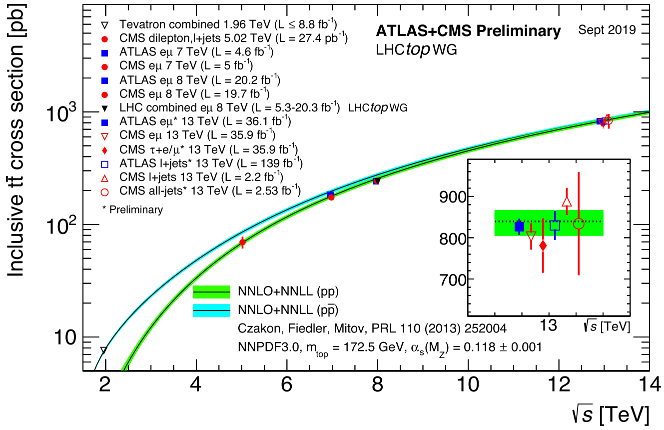

Figure 1. The $t\bar{t}$ production cross section at different centre-of-mass energies [3]. The prediction uses the NNPDF3.0 set for the parton distribution functions (PDFs), a top quark pole mass m_t^{pole} of 172.5 GeV, and a strong coupling $\alpha_S(m_Z)$ of 0.118 ± 0.001.

$\sqrt{s} = 13$ TeV in each of the three $t\bar{t}$ decay channels [5–7]. The precision on these measurements is around 30% including both statistical and systematic uncertainties and the measured cross section is a factor 1.3–1.5 larger than the predictions.

The large amount of data also allows for precise differential cross section measurements and simultaneous measurements of the cross section and m_t^{pole} or α_S. Specific examples will be discussed in later sections.

2.2. *Production of events with a single top quark*

The cross sections for singly produced top quarks have been measured at the LHC at $\sqrt{s} = 7, 8$ and 13 TeV. These measurements are summarised in Figure 2. The s-channel process has not yet been observed at the LHC. However, evidence for this process has been achieved at the LHC in proton collisions at $\sqrt{s} = 8$ TeV [8]. For the t- and tW-channels, the amount of collected events is large enough so that differential cross section measurements are performed. The collected t-channel events are also used to measure properties, such as the top quark mass. The prediction for the t-channel production mode is at NNLO precision, while for the other modes, predictions are at NLO precision complemented with soft-gluon resummation at NNLL accuracy. The precision in the measured cross section is better than 20% for the tW-channel and 10% for the t-channel at $\sqrt{s} = 8$ TeV. The collision data to be analysed and/or to be collected will help to further constrain the systematic uncertainty at $\sqrt{s} = 13$, which limits the precision of the measurements.

The single top quark production cross section is particularly interesting to constrain new physics that would alter the tWb coupling, which is a purely left-handed coupling in the SM, or change the production cross section when new particles or interactions are introduced. The single top quark production cross section is directly proportional to the square of the CKM matrix element V_{tb} provided that there are no significant contributions from the tWs and tWd couplings. The size of the tWb coupling can thus be directly measured using the single top quark production cross section measurements. In particular, the following quantity is measured: $|f_{\text{LV}} V_{tb}| = \sqrt{\sigma_{\text{meas}}/\sigma_{\text{theo}}(V_{tb} = 1)}$, where f_{LV} parametrises the possible presence of anomalous left-handed vector couplings ($f_{\text{LV}} = 1$ in the SM), σ_{meas} and σ_{theo} are respectively the measured and predicted cross sections with the latter being calculated assuming $V_{tb} = 1$. In the expression, $|f_{\text{LV}} V_{tb}|$ does not depend on the unitarity of the CKM matrix nor on the assumed number

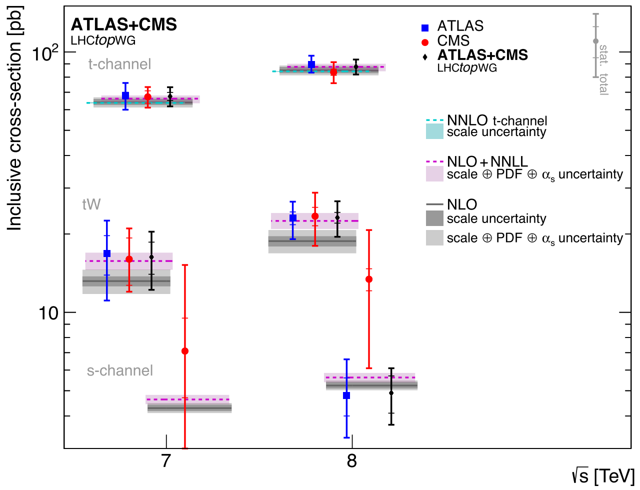

Figure 2. Single top quark production cross sections at different centre-of-mass energies [9].

of quark generations. The combination across experiments and centre-of-mass energies yields $|f_{\mathrm{LV}} V_{tb}| = 1.02 \pm 0.04(\mathrm{meas}) \pm 0.02(\mathrm{theo})$ [9], which is fully consistent with the SM expectation. The t-channel production mode dominates the precision of the combination.

2.3. *Modelling of events with top quarks*

The large amount of data collected at the LHC allows for (multi)differential cross section measurements as a function of a wide variety of observables. These measurements are then confronted with various state-of-the-art predictions from Monte Carlo (MC) event generators interfaced with a parton showering algorithm and hadronisation model. The events simulated in this way are typically at NLO accuracy. Deviations between the simulation and the measured distributions need to be carefully studied since observed differences could either be related to a mismodelling in the simulation, e.g. parameters that need further tuning or missing higher order corrections, or effects from new physics beyond the SM (BSM). Examples of how the differential cross section measurements are used to study specific top quark properties or search for new physics effects are presented in later sections. In this section we focus on comparisons of data with various predictions.

Differential cross section measurements are performed both for $t\bar{t}$ and single top quark production in the t- and tW-channels. In general all the MC predictions agree well with the data, with a well-studied exception the differential cross section of the top quark transverse momentum, p_{T}^{t}. For the latter case, almost all MC predictions tend to be harder than the data as a function of p_{T}^{t}. This has been observed by both experiments in different $t\bar{t}$ decay channels and at $\sqrt{s} = 8$ and 13 TeV [10–15]. The same trend is also seen in the single top t-channel at $\sqrt{s} = 8$ TeV by the ATLAS experiment [16], although it is noted that the NLO+NNLL prediction describes the data better than the MC predictions which are typically at NLO accuracy. The differential p_{T}^{t} cross section measurement in the single top t-channel performed by the CMS Collaboration at $\sqrt{s} = 13$ TeV [17] does not fully confirm the trend although it is worth noting in this context that both experiments use a different parton shower algorithm for their measurements. Similar measurements are also performed in the boosted top quark regime at 8 and 13 TeV [18–20]. It is clear that the description is improved with higher order MC predictions and that the uncertainties are still large in this part of the phase space. Measurements with more data and

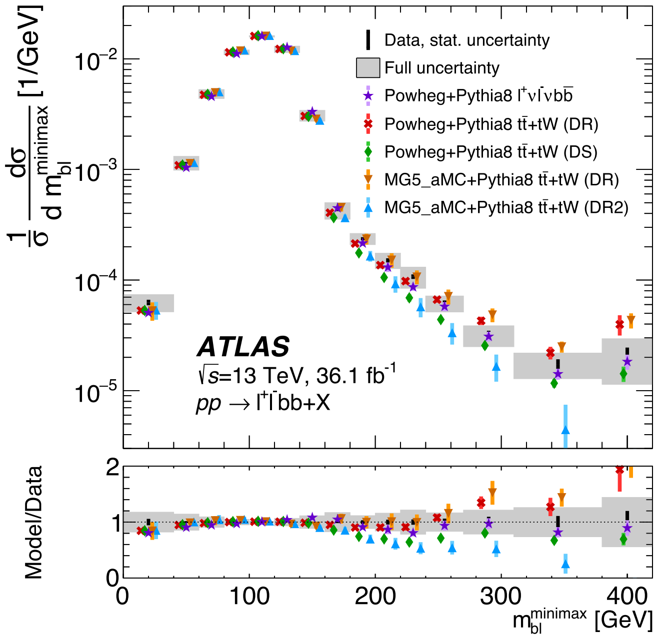

Figure 3. The differential m_{bl}^{minimax} cross section compared with theoretical predictions with various implementations of interference effects. Uncertainties for each of the MC predictions correspond to variations of the parton distribution functions set and renormalisation and factorisation scales [21].

reduced systematic uncertainties are required to get a better understanding on whether this is a modelling issue for all top quark events, regardless of the production mode, and in the full phase space. Theoretical predictions will also continue to improve and be tested for this particular distribution.

When performing differential cross section measurements in the $t\bar{t}$ or tW production channels, it is particularly important to correctly subtract the tW or $t\bar{t}$ background, respectively. A different strategy would be to use differential cross section measurements to confront various prescriptions for modelling the interference between $t\bar{t}$ and tW production with the data. In this perspective a study was performed in the dilepton decay channel and reconstructing the invariant mass of the b-quark jet and charged lepton stemming from the same top quark decay. The ambiguity between the jets and the leptons is resolved by defining $m_{bl}^{\text{minimax}} = \min(\max(m_{b1,l1}, m_{b2,l2}), \max(m_{b1,l2}, m_{b2,l1}))$. The study demonstrates that the various prescriptions describe the unfolded normalised differential m_{bl}^{minimax} cross section reasonably well [21] and the prediction that naturally incorporates the interference effects describes the data best. This can be seen from Figure 3. With more data it will become possible to constrain certain interference models and hence steer future model tuning and development.

Differential cross section measurements are also used to study the underlying event in $t\bar{t}$ events [22]. In that case, the normalised differential cross section is measured as function of the multiplicity and kinematic observables of charged-particle tracks. No deviation is observed from the hypothesis that underlying event is universal while tested here at high energy scales. An additional study was performed to tune the phenomelogical parameters and the value of α_S used in the simulation to the data [23]. This study showed that a lower value of α_S is preferred in the simulation. This was confirmed by a measurement of jet substructure observables [24] and resulted in a new set of underlying event tunes presented in [25].

Neutral strange particle production has been studied at $\sqrt{s}$ = 7 TeV in $t\bar{t}$ events in the dilepton decay channel [26] and compared to MC simulations with different hadronisation and fragmentation schemes, colour reconnection models and different tunes for the underlying event. The kinematic distributions are found to be well described by the MC models for strange particle production within jets, but not for strange particles produced outside jets.

Some initial studies on the jet fragmentation in top quark events have been performed at the LHC [27,28]. These studies show that the different fragmentation models adequately describe the proton collision data collected at $\sqrt{s}$ = 7 or 8 TeV. However, it is also clear that with more data the sensitivity will be significantly larger, which will allow constraining the fragmentation parameters in the near future.

Another interesting study is the differential cross section measurements of so-called jet-pull observables [29]. These observables are sensitive to the colour connections between the partons produced in the collision. The observables are measured at $\sqrt{s}$ = 13 TeV for the lepton+jets $t\bar{t}$ decay channel and for two dijet systems, i.e. the jets from the hadronic W boson decay and the two b-quark jets from the top-quark decays. From the measured distributions it is clear that none of the current predictions is fully describing the data for all observables.

With the large amount of data still to be collected at the LHC more detailed studies will follow by both the ATLAS and CMS collaborations, which in turn will lead to significant progress for the modelling of top quark events.

3. Top quark properties

3.1. *Mesmerising mass*

One can not discuss the status of the top quark mass measurements without entering the discussion on how to interpret the mass measurements. Indeed, in quantum field theory the concept of mass has no absolute meaning. Quantum corrections affect the meaning of parameters such as the mass. To come to a physically meaningful definition divergent high-energy corrections need to be absorbed into the mass definition. This is achieved through so-called renormalisation techniques, for which several schemes exist. The mass parameter is thus dependent on the scheme. Masses in various schemes can be related to each other through a perturbative series. The so-called pole mass, m_t^{pole}, is conceptually closest to the rest mass of a classical particle, and it contains corrections from all energy scales down to zero momentum. Because of large corrections from QCD at low energies, m_t^{pole} contains an intrinsic ambiguity of 110–250 MeV [30, 31]. Other mass schemes have been introduced to avoid this ambiguity. These schemes define so-called short-distance masses and do not resum contributions from energy scales below some scale R, which implies that short-distance masses depend on the scale R. To avoid the ambiguity, the scale R is taken to be larger than $\Lambda_{\text{QCD}} \sim \mathcal{O}(200 \text{ MeV})$, which is the characteristic scale of confinement in QCD.

The most precise top quark mass measurements rely on the direct (partial) kinematic reconstruction of the top quark based on its decay products. A wide variety of techniques exists to extract the top quark mass from the decay products with different sources of systematic uncertainties limiting the precision of the measurements. The techniques rely on the simulated distributions of observables that are sensitive to the top quark mass parameter in the MC generator. In general terms one typically estimates the top quark mass from the peak position or the kinematic endpoint of these observable distributions. The direct measurements are thus limited by the accuracy of the MC generator for modelling these distributions and the corresponding conceptual meaning of the top quark mass parameter used in the MC generator, m_t. The CMS and ATLAS Collaborations have measured m_t with a precision of about 500 MeV [32, 33]. In these measurements the modelling uncertainties in the $t\bar{t}$ simulation are dominant. These are for instance the uncertainty in the colour reconnection model, the final-state radiation and the fragmentation, both of which impact the jet energy scale of light-quark-flavour and b quark jets. In general the various m_t measurements performed at the LHC agree very well with each other with m_t being around 172.5 GeV. There is however one exception. The measurement performed using $t\bar{t}$ events in the lepton+jets channel based on a template fit to the invariant mass from the isolated charged lepton and the lepton required to be present in the decay chain of the beauty hadron in the b quark jet yields $m_t = 174.48 \pm 0.40(\text{stat}) \pm 0.67(\text{syst})$ GeV [34]. This measurement provides an agreement at the level of about 2.2 standard deviations with other measurements performed at the LHC. The systematic uncertainty is dominated by the modelling of $t\bar{t}$ production and of the b quark fragmentation and decay.

The high precision achieved by direct top quark mass measurements today, forces the debate on the interpretation of m_t into a more quantitative discussion. To make quantitative statements, the questions that are raised are to which renormalisation scheme the extracted m_t corresponds or how m_t is related to standard schemes such as m_t^{pole}. In principle the top quark mass scheme used in the MC generators is fixed by the structure and theoretical precision of the PS algorithm. For example, the state-of-the-art PS algorithms are designed in the approximation of a stable top quark, i.e. the narrow width approximation. In addition, the PS algorithms are not uniformly precise for all observables, even with NLO matching. Recently a few studies have been performed to understand how some of these approximations affect m_t [35–37]. Moreover, since the PS algorithms are developed in the collinear approach, i.e. in the boosted regime, a top quark mass measurement performed using boosted top quarks would be more straight-forward to interpret. Recently a measurement has been performed at $\sqrt{s} = 13$ TeV yielding $m_t = 172.56 \pm 2.47$ GeV [38].

A different approach is to use the $t\bar{t}$ production cross section to determine the top quark mass. Indeed, the $t\bar{t}$ production cross section is sensitive to the value of the top quark mass in a theoretically well-defined scheme, e.g. m_t^{pole}. This dependence can be calculated up to next-to-next-leading order (NNLO), including NNLL corrections in the production, and electroweak corrections in the production and the decay. Comparing the measured cross section with the calculated top quark mass dependence, the extracted top quark mass is achieving a precision of around 1.6 GeV for m_t^{pole} [39–41]. Recently, a precision of less than 1 GeV was achieved using multidifferential cross section measurements [42]. It is worth noting that since the measurements of the cross section rely on MC generators for the selection of the event requirements, to determine the efficiency of these criteria, and for the extrapolation of the fiducial cross section to the full phase space, also these measurements are to some small extent model dependent and thus the extracted mass can not be fully unambigiously interpreted as m_t^{pole} [43].

Over the last years, significant progress has been made from the theoretical side in an attempt to relate the m_t measurements with m_t^{pole} [44–46]. This progress is very promising and it is not unlikely that the question will be solved in the next decade.

Recently also the running of the top quark mass has been studied experimentally [47]. The measured running is probed up to a scale of the order of 1 TeV and found to be compatible with the scale dependence predicted by the renormalisation group equation.

3.2. *Width*

The top quark width Γ_t can be measured indirectly using the t-channel production cross section for single top quarks and the ratio of the branching fraction to b quarks to the branching fraction to any quark. The most precise indirect measurement corresponds to $\Gamma_t = 1.36 \pm 0.02(\text{stat})^{+0.14}_{-0.11}(\text{syst})$ GeV [48]. Both the ATLAS and CMS Collaborations also performed direct measurements of Γ_t. Among those, the most precise direct measurement is obtained using $t\bar{t}$ events in the dilepton final state collected at 13 TeV and results in $\Gamma_t = 1.9 \pm 0.5$ GeV for

m_t = 172.5 GeV [49]. Both the direct and indirect measurements are fully consistent with the SM prediction at NLO, Γ_t = 1.35 GeV, which has an uncertainty below 1% and which assumes m_t = 173.3 GeV and α_S = 0.118 [48].

Given the large amount of data, a more natural strategy would be to measure the top quark mass and width simultaneously, which would allow taking into account the correlation between the width and the mass. However, in order to be able to clearly interpret these measurements the narrow width approximation in the PS algorithms would need to be lifted, as mentioned in the previous section.

3.3. *Spin correlations and polarisation*

The lifetime of the top quark ($\sim 10^{-25}$ s) is shorter than the hadronisation time ($\sim 10^{-23}$ s) and much shorter than the spin decorrelation time ($\sim 10^{-21}$ s). Therefore the top quark decays before hadronisation and its spin information is directly transferred to its decay products. This gives a unique opportunity to study the spin properties of a bare quark. Top quark pair production in QCD is parity invariant so at LO the top quarks and antiquarks produced at the LHC are not expected to be polarised. However, their spins are predicted to be correlated with an amount of correlation depending on the $t\bar{t}$ invariant mass, $m_{t\bar{t}}$. The amount of spin correlation in $t\bar{t}$ events could be affected by BSM physics, like e.g. the presence of scalar supersymmetric top squarks. To study spin correlations experimentally it is relevant to note that not all decay particles carry the same degree of spin information. The charged leptons arising from leptonically decaying W bosons carry almost the full spin information of the parent top quark and spin correlation measurements are therefore often performed in the dilepton channel. The simplest sensitive observable that can be studied is the azimuthal opening angle, $\Delta\phi$, between the two charged leptons measured in the laboratory frame. The spin correlation is extracted from the absolute and normalised $t\bar{t}$ differential cross section measured as a function of $\Delta\phi$ in four bins of $m_{t\bar{t}}$ corrected for detector resolution and acceptance effects back to parton level [50]. The spin correlation measured by the ATLAS Collaboration inclusively over all the $m_{t\bar{t}}$ bins is found to be significantly higher than the NLO prediction including PS (see Figure 4). While NLO predictions including electroweak effects agree with data within its large scale uncertainties, the agreement disappears at NNLO in QCD. This observation is not confirmed by the CMS Collaboration [51]. It is clear that further measurements and developments for state-of-the-art predictions are required to understand the origin of the disagreement. Instead of using a single observable, it is also possible to measure the full spin density matrix, leading to 15 polarisation and spin correlation coefficients. In this case the top quark and antiquark kinematics need to be fully reconstructed, which gives rise to large uncertainties in the dilepton channel. The measured coefficients are found to be compatible with the SM expectation [51,52] and are used to set limits on hypothetical BSM scenarios.

In single top quark production the SM assumes a Wtb vector-axial-vector coupling leading to the production of highly polarised top quarks. The differential cross section of the top quark polarisation angle in the t-channel is studied and found to be in agreement with the SM predictions quoting a measurement with a 14% precision [54].

3.4. *Asymmetry*

At LO in QCD the top quark-antiquark production is symmetric under charge conjugation. However at NLO, interference in the amplitudes of the $q\bar{q}$ initiated processes lead to an asymmetry in t versus $\bar{t}$ production. The qg processes are also asymmetric (but to a smaller extent) while the $t\bar{t}$ production through gluon fusion remains symmetric at all orders. The consequence of this

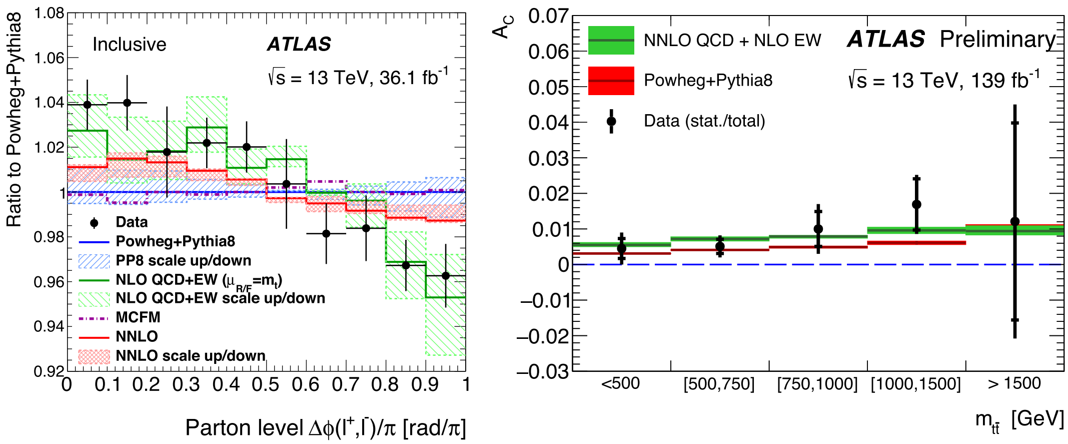

Figure 4. Comparison of the unfolded $\Delta\phi$ distribution normalised to the predictions from Powheg+Pythia with other theoretical predictions [50] (left). Measurement of the charge asymmetry as a function of $m_{t\bar{t}}$ compared to the SM predictions at different orders [53] (right).

asymmetry at NLO is that the top quarks (antiquarks) are produced preferentially in the direction of the incoming quark (antiquark). At the LHC which is a proton–proton collider, the colliding beams are symmetric so there is no preferential direction for the incoming quarks or antiquarks. Nevertheless due to the difference in the proton PDFs, the valence quarks carry on average a larger fraction of the proton momentum than the antiquarks from the sea. This results in top quarks being produced preferentially with higher absolute rapidity while top antiquarks are more centrally produced. Since the fraction of $q\bar{q}$ initiated $t\bar{t}$ production is only around 10% at $\sqrt{s} = 13$ TeV, this effect is predicted to be very small in the SM. Several BSM processes such as production of axigluons or heavy Z' bosons can enhance this asymmetry expecially in specific kinematic regions like large $m_{t\bar{t}}$ or large longitudinal boost of the $t\bar{t}$ system. A $t\bar{t}$ charge asymmetry is defined counting the number of events N as:

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)},$$

where $\Delta|y| = |y_t| - |y_{\bar{t}}|$ is the absolute rapididy difference between the top quark and antiquark. Both the ATLAS and CMS Collaborations measured this quantity using data collected at 7 and 8 TeV. The inclusive and differential results obtained by both experiments in the lepton+jet channel have been combined [55], but the statistical uncertainties in the high $m_{t\bar{t}}$ region still limit the achievable precision. While the amount of $t\bar{t}$ events produced through $q\bar{q}$ annihilation is smaller at 13 TeV than at lower centre-of-mass energies, the large amount of data, especially in the boosted regime, permits to study the charge asymmetry more profoundly. The charge asymmetry is measured in the lepton+jets channel using a fully Bayesian unfolding method to correct for detector and acceptance effects simultaneously in the resolved and boosted topologies (see Figure 4) [53]. The methodology allows to constrain the larger systematic uncertainties in situ. The inclusive and differential measurements are found to be consistent with the SM predictions. The measured inclusive asymmetry differs from zero by 4 standard deviations. The differential cross sections measurements in the dilepton final state as a function of $\Delta|y| = |y_t| - |y_{\bar{t}}|$ at parton and particle levels can also be used to extract A_C [15]. The measurements as a function of the lepton pseudo-rapidity $\Delta\eta_\ell = |\eta_\ell| - |\eta_{\bar{\ell}}|$ can be exploited to construct a similar asymmetry based only on the lepton angles. Such asymmetry is diluted compared to when using the reconstructed

$t\bar{t}$ event but it does not require the reconstruction of the top quark or antiquark kinematics. Both these measured observables are consistent with the SM expectations. Since the $q\bar{q}$ initiated production is enhanced in the forward region, it is expected that the LHCb Collaboration will provide interesting asymmetry measurements in the top quark sector at high luminosity [56]. The b quark from the top quark decay can also be used to build other kind of asymmetries sensitive to CP violation [57]. So asymmetries in the top quark sector are still interesting to explore in the years to come.

4. Top quark couplings and rare processes

The large amount of data collected by the LHC at 13 TeV allows to establish and study top quark processes that were not accessible so far. With predicted cross sections around 1 pb or below, the production of top quarks in association with bosons (W, Z, H or γ) becomes a tool to scrutinise the top quark couplings searching for any deviations from the SM expectations. The Wtb coupling is for instance studied by measuring the W helicity fractions with $\sqrt{s} = 8$ TeV data [58, 59]. The potential deviations from SM predictions are often parametrised within the framework of an effective field theory (EFT) in terms of Wilson coefficients of BSM dimension 6 operators [60]. Studies of the coupling between the top quark and Higgs boson are discussed in the Higgs Chapter.

4.1. *Top quark couplings to bosons*

Measurements of $t\bar{t}$ production in association with a Z or a W boson provide a direct probe of the weak couplings of the top quark. These couplings could be modified by the presence of BSM physics. Events containing two leptons of same charge (SS) are used to extract the $t\bar{t}W$ signal, while events with three or four charged leptons that include a same-flavour lepton pair compatible with the decay of a Z boson are usually used to measure the $t\bar{t}Z$ cross section. In these channels, the efficiency of the trigger and of the isolated lepton selection requirements are crucial. The $t\bar{t}W$ signal is much more difficult to isolate than $t\bar{t}Z$ events because the SS dilepton final state suffers from a significant background from leptons with misidentified charge and from non-prompt leptons from hadron decays, photon conversions or jets misidentified as leptons. These type of backgrounds are evaluated using data driven techniques and validated in control regions. The main background in the $t\bar{t}Z$ analyses comes from at least one top quark produced in association with one or multiple W, Z, or Higgs bosons. The signal regions are split according to jet multiplicity and the number of b-tagged jets in the events. In the dilepton channel, a multivariate discriminant is introduced to further separate signal and background events. The amount of $t\bar{t}W$ and $t\bar{t}Z$ events are fitted in the signal and control regions to extract the individual cross sections as well as the 68 and 95% confidence level 2-dimensional contours. The latest $t\bar{t}W$ measurements [61, 62] reach a precision of around 22% still dominated by statistical uncertainties, while the inclusive $t\bar{t}Z$ cross section is now measured with a precision of 8% with equal contributions from statistical and systematic uncertainties [63]. For the first time, the large amount of data permits to measure absolute and normalised differential $t\bar{t}Z$ cross sections using signal-enriched regions [63]. These differential measurements are performed as a function of the transverse momentum of the Z boson (see Figure 5) and other relevant kinematic observables. After correcting for detector and acceptance effects the distributions agree with the SM predictions and could then be used to put more stringent constraints on anomalous interactions.

The electroweak production of a single top quark in association with a Z boson (tZq) is even trickier to isolate from the diboson, $t\bar{t}Z$ and non-prompt lepton backgrounds. However this

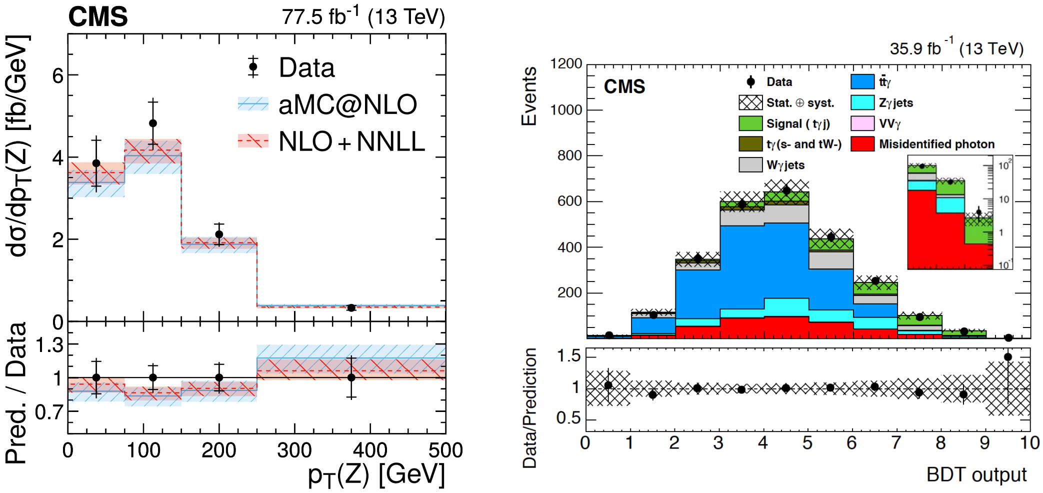

Figure 5. Measured differential $t\bar{t}Z$ production cross section in the full phase space as a function of the transverse momentum of the Z boson [63] (left), multivariate discriminant used to isolate the $t\gamma$ signal [64] (right).

process is interesting to study since it provides sensitivity to the WWZ triple-gauge coupling, which could be one of the production modes, and to modified interactions in a unique way. Final states where both the W boson from the top quark decay as well as the Z boson decay into leptons are explored leading to a three lepton signature. Events are categorised in different signal regions according to the number of jets and b-tagged jets. In each of the signal regions a multivariate discriminant is used to isolate tZq events and fit the cross section value. The tZq process has been observed with a significance of more than 5 standard deviations and is measured with an uncertainty of 15% [65, 66].

In order to probe the $t\gamma$ coupling, the production and kinematic properties of a top-quark pair produced in association with a photon ($t\bar{t}\gamma$) are studied. The inclusive and differential cross sections of this process are sensitive to BSM physics, for instance through anomalous dipole moments of the top quark affecting the transverse momentum spectrum of the γ or through some of the Wilson coefficients in the context of an EFT. Backgrounds arise from electrons or hadronic processes that are reconstrued as photons. Also off-shell production of $Wt\gamma$ results in the same final state. The latest $t\bar{t}\gamma$ measurement uses the $e\mu$ channel and a likelihood fit to the scalar sum over all transverse momenta in the event to extract the inclusive cross-section in a fiducial volume. Normalised and absolute parton level differential cross sections are measured as a function of different characteristic observables and compared to MC simulations and NLO predictions [67], which are found to be in agreement. The first evidence for single top quark production in association with a photon in the t-channel has been reported [64]. Events with a muon are selected and the top quark kinematics is reconstructed. The multivariate discriminant distribution shown in Figure 5 is used to isolate the signal from the large $t\bar{t}\gamma$ background. This result paves the way for more precise measurements using the large amount of available or to be collected data.

4.2. *Four-top quark production*

The production of four top quarks ($t\bar{t}t\bar{t}$) is one of the most spectacular processes predicted by the SM and that could be studied at the LHC. With a cross section of only roughly 12 fb, it has not yet been observed. Therefore this observation would be a milestone for measuring rare processes at the LHC. Four top quarks could be copiously produced in many BSM like models with gluinos, heavy scalar bosons, axigluons, colour scalars and top compositeness, even in cases where top quark pairs are not. In the framework of EFT, $t\bar{t}t\bar{t}$ production has a larger constraining power than the $t\bar{t}$ process on the $qqtt$ operators. Therefore, the $t\bar{t}t\bar{t}$ process offers complementary handles to search for deviations from the SM in the top quark sector. Searches for the $t\bar{t}t\bar{t}$ process are performed in two different final states that have very different challenges. The channel with one lepton or two leptons with opposite charge corresponds to a large branching fraction but suffers from a large background coming mainly from $t\bar{t}$+light jets and $t\bar{t}b\bar{b}$ events. This background is usually evaluated using data driven techniques or from MC simulation validated in control regions. As the uncertainty on these backgrounds is very large, data in control regions is used to constrain these uncertainties by profiling the corresponding nuisance parameters in a likelihood fit. The channels with two leptons with the same charge or with at least three leptons, on the other hand, have small branching fractions but benefit from a low level of background mainly coming from fake or non-prompt leptons or from $t\bar{t}$ production with additional electroweak bosons. This is the most sensitive channel. The $t\bar{t}t\bar{t}$ topology also features high jet multiplicity and high b-jet multiplicity as well as high overall energy that could be quantified with a large value for the scalar sum of the transverse momenta of all reconstructed objects in the event. These observables are used in multivariate techniques to separate signal and background and enhance the sensitivity. The ATLAS Collaboration obtains an observed (expected) significance for the $t\bar{t}t\bar{t}$ signal of 2.8 (1.0) standard deviations [68] by combining the two final states. The latest result from the CMS Collaboration uses an extended dataset in the multilepton channel reaching 2.6 (2.7) standard deviations [69] for the $t\bar{t}t\bar{t}$ process above the background-only hypothesis. More data will allow the observation of this process at the LHC, although we might have to wait until the end of the LHC Run 3 in case the SM prediction is correct.

4.3. *Search for flavour-changing neutral currents in the top quark sector*

In the SM, flavour-changing neutral currents (FCNC) are forbidden at tree level and are strongly suppressed at higher orders by the Glashow–Iliopoulos–Maiani (GIM) mechanism. The SM predicts branching fractions for top quark FCNC decays of the order of 10^{-12}–10^{-16}. However various extensions of the SM would result in a significant enhancement of the FCNC top quark decay rates. Hence any deviations from these heavily SM suppressed rates would be a sign of new physics. The anomalous vertices, tqH, $tq\gamma$, tqg and tqZ, could be probed at the production or in the decays of single top quark or top quark pair production. Many searches for deviations are performed at the LHC for all possible production and decay modes. Often the analyses concentrate on one of such cases at a time. The searches rely on the reconstruction of the event kinematics, including the top quark decaying through an FCNC, and often utilise multivariate discriminant to separate signal and background. The tqH vertex is probed with dedicated analyses for each signature according to the possible Higgs boson decay. In case of $H \to b\bar{b}$, the limits on the branching fraction of $t \to Hq$ are around 4×10^{-3} [70, 71], while they are tighter for $H \to \tau\tau$ [71], $H \to WW^*/ZZ^*$ [72] or $H \to \gamma\gamma$ [73], which are both around 1–2×10^{-3}. The $tq\gamma$ vertex has been considered both in production and decay in the photon and one lepton final state leading to an upper limit on the $t \to q\gamma$ branching fraction at the 95% confidence level of 2–6×10^{-5}, depending on whether the assumed coupling is left-handed or right-handed. The upper limit on the $t \to c\gamma$ branching fraction is around 20×10^{-5} [74]. The tqZ vertex is explored in the trilepton final state and constrained to an upper limit on the $t \to qZ$ branching fraction of 2–4×10^{-4} [75, 76]. The enormous amount of data expected in the high-luminosity phase of the LHC will permit to further improve these upper limits by at least an order of magnitude in case of no discovery [56].

Studying the top-quark couplings to bosons as well as rare processes involving the top quark is just at a start. These topics will be an important field of research in the coming years.

5. Perspectives

During the LHC Run 2 (2015–2018) an amount of proton–proton collisions corresponding to about 150 fb^{-1} has been collected at $\sqrt{s} = 13$ TeV. Currently, many of the Run 2 measurements use only a fraction of the collected data (36 fb^{-1}). During the LHC Run 3 (2021–2023) 200 fb^{-1} is expected to be collected at $\sqrt{s} = 13$–14 TeV. This means that by the end of Run 3, $\mathcal{O}(10)$ times more data will be available compared to what is used for the measurements today. This has two implications. First, some rare processes will potentially be observed for the first time at the LHC, e.g. the $t\bar{t}t\bar{t}$ process, leading to potentially new insights or constraints on beyond the standard model processes. Second, the uncertainty on all top quark precision measurements will be limited by systematic effects. For this reason, the focus is shifting towards reducing the systematic uncertainties, with the top quark mass and differential cross section measurements as the driving forces to achieve this goal. It is expected that significant progress will be made, both for the modelling of the top quark events in the simulation as for the prescription to assess the modelling uncertainties. After Run 3, the high-luminosity phase of the LHC is expected to deliver 3 ab^{-1} bringing measurements and searches in top quark physics yet to another level [56]. In parallel, the theory community is developing new MC generators and better predictions for processes involving top quarks. These studies and the legacy measurements from the high-luminosity phase of the LHC will be the reference point for accelerators beyond the LHC.

A potential future e^+e^- collider with $\sqrt{s} \geq 350$ GeV would enable to scrutinise the top quark properties with very high precision without suffering from significant uncertainties from PDF, QCD scales or collider luminosity. The precision of the theory predictions in leptonic collisions is around the per-mil level, allowing a comparison with measurements at the same level of precision. For instance, a scan of the top quark pair production cross section around the threshold will offer a precision in the top quark mass at the level of 25 MeV, including both statistic and systematic uncertainties. The theoretical uncertainty on the line shape prediction would allow a top quark mass extraction with a 50 MeV total theoretical uncertainty [77], providing the strong coupling constant is measured with sufficient precision. The precise measurement of the top quark mass and of other standard model parameters will be used in a global fit of the electroweak observables and provide the most stringent consistency test for the standard model. In addition, an e^+e^- collider with a sufficiently large centre-of-mass energy allows for measuring the top quark Yukawa coupling precisely using the $t\bar{t}H$ final state, studying the $t\bar{t}Z$ and $t\bar{t}\gamma$ vertices at the per-mil level, and constraining anomalous operators an order of magnitude more stringently than what can be done at the HL-LHC [78, 79].

Clearly, depending on the chosen successor of the LHC, the top quark properties and couplings can be measured very precisely, and/or new physics can be probed in the top quark sector, e.g. using EFTs at a proton collider operating at much higher centre-of-mass energies.

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