Standard model parameters from top quark measurements at LHC with ATLAS and CMS

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Theoretical predictions for standard model (SM) processes involving top quarks, such as top quark-antiquark pair or single top production, depend on fundamental SM parameters like the strong coupling constant or the top quark mass. By confronting predictions with measurements performed at the ATLAS and CMS Collaboration using data collected at the CERN LHC in the second data taking period, these parameters can be determined precisely. In these proceedings, recent results measuring SM and top quark properties are presented.

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1 Introduction

At the CERN LHC, top quarks are predominantly produced in top quark-antiquark pair (t\bar{t}) production via the gluon fusion mechanism. But with the increased data set available from the second data taking period (LHC Run II) (2015-2018) at a center-of-mass-energy of 13 TeV, also processes like single top \(t\)-channel production can be studied in experiments with high precision. Properties of the top quark, such as its large mass or its Yukawa coupling close to unity to the Higgs boson, imply that the top quark plays a special role within the standard model (SM), especially in the electroweak symmetry breaking. Further, theoretical predictions at higher order involving top quarks depend on them or further SM parameters, allowing for their precise extraction from measurements of the production cross section or kinematic observables. Recent measurements by the ATLAS [1] and CMS [2] Collaborations reach compatible or higher precision than corresponding theoretical predictions and are presented here in these proceedings.

2 Top quark mass measurements

The value of the top quark mass can be measured in multiple ways, depending on its definition and the experimental procedure used. They can be classified into two distinct major categories. For example, the mass can be measured by reconstructing the energy of top quark decay products or extracting it from measured distributions of kinematic observables at detector level by comparison to predictions of multi-purpose Monte-Carlo (MC) generators. Measurements of this type are commonly classified as direct measurements, and the mass value measured is often referred to as MC top quark mass (\(m_t^{MC}\)). They lack a clear theoretical interpretation compared to indirect measurements, where the top quark mass is extracted in a well defined renormalization scheme such as the pole or modified minimal subtraction (\(\overline{\text{MS}}\)) scheme by comparing sensitive observables to theoretical calculations at fixed order. Usually, \(m_t^{MC}\) is related to be close or equal to the mass as defined in the pole mass scheme, with an additional uncertainty of the order of 1 GeV coming from the usage of probabilistic MC generators [3, 4].

The first sub-GeV precision measurement of the top quark mass in a single top phase space was achieved recently by the CMS Collaboration analyzing single top \(t\)-channel events using 35.9 fb\(^{-1}\) of pp collision data [5]. Events have been categorized by the charge and flavor of the selected lepton of the subsequent top quark decay and a simultaneous parametric fit was performed to determine the top quark mass. Additionally, a multivariate discriminator was used to enhance the purity of the selected signal events, and two additional fits were performed to determine also the quark and antiquark masses separately. The result of the simultaneous fit is shown in
Figure 1 left, and the best fit value for the top quark/antiquark mass yields $172.13 \pm 0.7$ GeV. The extracted mass ratio between the quark and antiquark is found to be $0.995 \pm 0.006$, and their difference is $0.83^{+0.77}_{-1.01}$ GeV. Both values are in agreement with the SM expectation.

By using the mass of jets in the boosted regime in the $t\bar{t}$ topology [6], connections between direct and indirect measurements can be probed [7]. Such a measurement was performed by the CMS Collaboration using the same amount of pp collision data as in the previous analysis. The normalized differential cross section as a function of the boosted jet mass is measured and unfolded to the particle level. By comparing the unfolded data to theoretical predictions, the value for $m_{t}^{MC}$ is extracted to be $172.6 \pm 1.9$ GeV (see Figure 1 right). With respect to previous iterations of the same measurement, the resolution of the measured jet mass distribution and thus the precision of the extraction is significantly improved by the use of the XConE jet clustering algorithm for the first time at the LHC.
for the difference between $m_t^{\text{MC}}$ and $m_t^{\text{pole}}$. A scale of $R = 1$ GeV is chosen because of the numerical similarity to the pole mass ($m_t^{\text{MSR}}(R = 1 \text{ GeV}) \approx m_t^{\text{pole}}$).

CMS investigated for the first time the scale dependence (running) of the top quark mass in the $\overline{\text{MS}}$ scheme using $t\bar{t}$ events reconstructed in the dileptonic final state using 35.9 fb$^{-1}$ of collision data. By performing a profiled maximum likelihood fit to final state observables, the measured invariant mass spectrum of the reconstructed $t\bar{t}$ pair ($m_t$) is unfolded to the parton level. The running is probed up to a scale of 1 TeV by comparing the measured differential cross section to theoretical predictions and is found to be in agreement with the SM within 1.1σ (see Figure 2 right).

Figure 2: Particle-level boosted jet mass distribution compared to best fit results for a NLL theory prediction using two top quark mass schemes (left) [8]. Measured scale dependence of the top quark mass as a function of the scale $\mu = m_t/2$ (right) [10].

The top quark mass was further measured by ATLAS analyzing events in which the $t\bar{t}$ pair decays semileptonically [11]. Here, the sensitivity of the shape of the invariant mass distribution of a lepton and a soft muon coming from a B hadron decay to the top quark mass is used. This particular analysis mitigates the dependence on typical uncertainties of top quark mass measurements coming from jet energy calibrations. The top quark mass is found to be $m_t = 174.48 \pm 0.78$ GeV.

3 Probing heavy quark fragmentation

Two measurements of differential distributions being sensitive to the modeling of bottom quark fragmentation function have been carried out by ATLAS [12] and CMS [13]. Bottom quarks play a vital role in many LHC measurements like in the top quark sector, and measuring the bottom quark fragmentation function is a fundamental test of perturbative QCD and the parton shower formalism. In both measurements, observ-
ables are defined based on charged-particle tracks that characterize the bottom-quark momentum relative to the momentum of the jet. In the ATLAS analysis, the measured distributions are corrected for detector effects via unfolding and are compared to predictions obtained from different MC generators. In the CMS measurement, the shape of the distributions is used to extract the best fit value for the Bowler-Lund bottom-quark fragmentation shape parameter $r_b$ for the first time at the LHC. It is found to be $0.858 \pm 0.037 \text{(stat)} \pm 0.031 \text{(syst)}$, which is in good agreement with measurements using $e^+e^-$ data performed at the CERN LEP.

4 Measurements of electroweak parameters

Electroweak contributions to $t\bar{t}$ production, like the exchange of massive bosons between the final state top quarks, allow to study the dependence of the differential production cross section on fundamental SM parameters such as the top quark Yukawa coupling $Y_t$. CMS has performed a measurement of $Y_t$ by performing a profiled likelihood fit to final state distributions using $137 \text{fb}^{-1}$ of collision data [14]. To mitigate the dependence of the missing transverse momentum resolution in the dileptonic decay channel, proxy variables are determined. The dependence of the shape of the distributions on different $Y_t$ assumptions are modeled using HATHOR [15] predictions. The best fit value for $Y_t$ is found to be $1.16^{+0.24}_{-0.35}$ and similarly an upper limit of $Y_t < 1.5$ is calculated at 95% CL.

By exploiting the dependence of the single top $t$-channel production cross section on the entries of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, their elements $V_{tb}$, $V_{td}$, and $V_{ts}$ can be extracted. This is done in the reported CMS analysis in a model independent and simultaneous way [16]. Events of pp collision data corresponding to an integrated luminosity of $35.9 \text{fb}^{-1}$ are separated using multivariate discriminators, and the individual signal strength parameters of different $t$-channel production modes are fitted simultaneously in a profiled maximum likelihood fit. For the interpretation, three different beyond the SM physics scenarios are assumed, and also the top quark decay width is constrained.

Finally, the reported measurement performed by ATLAS puts a fundamental assumption in the SM to test, probing the ratio of couplings strengths of different fermion generations to gauge bosons [17]. Using $139 \text{fb}^{-1}$ of data recorded with the ATLAS detector in pp collisions, the ratio of $R(\tau/\mu) = B(W \rightarrow \tau \nu_\tau)/B(W \rightarrow \mu \nu_\mu)$ is measured the first time at the LHC. Novel methods are used for this kind of measurement, and a value of $0.992 \pm 0.013[\pm 0.007 \text{(stat)} \pm 0.011 \text{(syst)}]$ is extracted through a template likelihood fit to the spectra of the impact parameter and transverse momentum of the muon. The measured value is found to be in agreement with the SM assumption of lepton universality and surpasses the precision of LEP for the same ratio by a factor of 2.
5 Summary

Using measurements of top quark production, fundamental parameters of the standard model QCD Lagrangian, like the top quark mass, or the electroweak sector, e.g., CKM matrix elements and the Yukawa coupling, can be measured. Similarly, heavy-quark fragmentation functions can be probed, and a better understanding of the parton shower formalism and Monte-Carlo multi-purpose generators can be gained. Significant progress was made by the ATLAS and CMS Collaborations using the data collected during LHC Run II at a center of mass energy of 13 TeV and recent measurements were presented.

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