Recent measurements of the top-quark mass and Yukawa coupling using the ATLAS and CMS detectors at the LHC

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An overview of recent measurements of the mass and Yukawa coupling of the top quark is presented. The measurements are made by the ATLAS and CMS Collaborations, exploiting $pp$ collisions at the center-of-mass energies of $\sqrt{s} = 13$ TeV in the Large Hadron Collider at CERN.

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1. Introduction

In the Standard Model (SM) of particle physics, the top quark is the elementary particle with the largest mass and the largest Yukawa coupling with the Higgs boson. Its mass \( m_t \) is a fundamental parameter of the SM: it allows to assess the internal consistency of the SM at the electroweak scale \([1]\) and, assuming the validity of the SM up to very high energy scales, it has a key role in the assessment of the stability of the universe \([2]\).

The mass of the top quark can be measured only through the comparisons of some observables, whose distributions depend on \( m_t \), with their theoretical expectations, and is currently measured with an uncertainty at the sub-GeV level for single measurements and reaching about half-GeV in combinations. However, the theoretical interpretation of the measured \( m_t \) is related to the measurement technique. In “direct” measurements, \( m_t \) is obtained from the comparison of measured distributions, such as the invariant mass of the decay products of the top quark or other quantities particularly sensitive to \( m_t \), and their expectations obtained from Monte Carlo (MC) simulation samples generated using different \( m_t \) values. In this way the “MC mass” \( (m_t^\text{MC}) \) is measured. “Indirect” measurements aim to determine \( m_t \) from a measured cross-section that can be compared with its theoretical value, computed from first principle calculations. In this way the pole mass \( (m_t^\text{POLE}) \) or the mass in the modified minimal subtraction (\( \text{MS} \)) renormalization scheme \( (m_t^\text{MS}) \), depending on the theoretical scheme that is adopted in the calculation, can be measured. The relation between \( m_t^\text{POLE} \) and \( m_t^\text{MS} \) is calculated to 4-loop precision in QCD \([3]\); the relation between \( m_t^\text{MC} \) and \( m_t^\text{POLE} \) is not well established and their difference, believed to be at the level of a few hundreds of MeV, is still under debate (see for example Refs. \([4, 5]\) and references therein).

In the SM, fermions acquire their mass \( m_f \) through a Yukawa interaction with the Higgs field, with coupling strength \( g_f = \sqrt{2} m_f / v \), where \( v \) is the vacuum expectation value of the Higgs field. The top quark has the largest Yukawa coupling with the Higgs boson \( g_t^\text{SM} \approx 1 \). Possible deviations of \( g_t \) from the expected value may indicate new physics effects that come into play to modify the effective coupling between the top quark and the Higgs field.

In the following we present an overview of some recent measurements of the mass and Yukawa coupling of the top quark, obtained by the ATLAS \([6]\) and CMS \([7]\) experiments, exploiting \( pp \) collisions at the CERN Large Hadron Collider at the center-of-mass energies \( \sqrt{s} = 13 \) TeV.

2. Direct top-quark mass measurements

Jets originated by \( b \) quarks can be identified by the presence of a “soft” muon inside the jet, coming from the semi-leptonic decay of a \( b \)-hadron. For \( t\bar{t} \) events in which only one of the \( t \) or \( \bar{t} \) decays leptonically\(^1\) (\( l+\text{jets} \) channel), that also contain one soft-muon tagged jet, the invariant mass distribution of the pair of leptons (the soft one and the one from the leptonic top-quark decay), can be used to determine the top-quark mass. This technique has the advantage of using a fully leptonic quantity that does not require the complete reconstruction of a top-quark, therefore reducing the uncertainty related to hadronic calibration and the modeling of the top-quark kinematics. The top-quark mass measured by the ATLAS Collaboration exploiting this technique, using 36.1 fb\(^{-1}\)

\(^1\)The top-quark always decays in a \( bW^+ \) pair. The “leptonic” or “hadronic” top quark decay is defined depending on the subsequent \( W^+ \to l^+\nu \) or \( W^+ \to q\bar{q}' \) decay, respectively (charge conjugation is implied in this definition).
of data at $\sqrt{s} = 13$ TeV [8], is $m_t^{MC} = 174.48 \pm 0.40$ (stat) $\pm 0.67$ (syst) GeV, in which the main contribution to the uncertainty is due to the modelling of the $b$ fragmentation and decay.

As of today, the vast majority of $m_t$ measurements have been done using $t\bar{t}$ events. Thanks to the large data samples now collected by the LHC experiments, $m_t$ measurements using single top quark production in the $t$-channel have become competitive and useful in combinations with other measurements, that are obtained in complementary phase spaces and dominated by different sources of uncertainty. Using 35.9 fb$^{-1}$ of data at $\sqrt{s} = 13$ TeV, the CMS Collaboration obtained a sample of single top-quark events in the leptonic channel with $\sim 60\%$ purity by means of a boosted decision tree discriminator, used to separate $t$-channel single top-quark events from backgrounds, built using variables whose correlation with $m_t$ is small or absent [9]. The top-quark mass is extracted by means of a maximum likelihood fit to the reconstructed $\ln m_t$, where the logarithm helps in the definition of appropriate parametric templates for the signal and background by reducing the skewness of the $m_t$ distribution. It is observed in MC simulated events that the peak of the reconstructed $m_t$ distribution does not correspond to the $m_t$ value used in the generator, mainly because a mis-reconstruction of the longitudinal momentum of the neutrino originated in the top-quark decay, therefore an “offset calibration” is applied to correct for this effect. With this technique, $m_t$ is determined in single top-quark events to be $m_t^{MC} = 172.13^{+0.76}_{-0.77}$ GeV, in which the uncertainty is dominated by the modeling of signal and $t\bar{t}$ events. The top quark-antiquark mass difference and mass ratio are also measured, by using the two sub-samples containing positive and negative leptons separately, to be $m_t - m_\tau = 0.83^{+0.77}_{-1.01}$ GeV and $m_\tau/m_t = 0.995^{+0.005}_{-0.006}$, in line with the SM expectations.

3. Indirect top-quark mass measurements

The first investigation of the running of the top-quark mass in the $\overline{\text{MS}}$ scheme was done by the CMS Collaboration using 35.9 fb$^{-1}$ of data at $\sqrt{s} = 13$ TeV [10]. In this analysis, a set of $t\bar{t}$ simulated events is divided in four sub-samples, corresponding to four intervals of the invariant mass of the $t\bar{t}$ pair determined at parton-level, which are treated as independent samples at the scales $\mu_k$ ($k = 1,4$) defined as the average $m_{t\bar{t}}$ in each interval. A maximum-likelihood unfolding is then applied to determine the true number of events at each scale from the observed one, which is needed to correct for reconstruction and resolution effects. For the determination of $m_t^{\overline{\text{MS}}}$, measurements are compared with theoretical predictions at NLO in the $\overline{\text{MS}}$ scheme as implemented in MCFM v6.8 [11]. The top-quark mass value at the $m_t$ scale, $m_t(m_t)$, is determined independently in each $m_{t\bar{t}}$ interval, and the calculation of the corresponding $m_t(\mu_k)$ is done at one loop precision using CRunDec v3.0 [12]. The measured running mass is found to agree with the expected evolution from $m_t(m_t) = 162.9 \pm 1.6$(fit + extr + PDF + $\alpha_S$)$^{+2.5}_{-3.0}$(scale) GeV.

4. Interpretation of the Monte Carlo top-quark mass

The difference between $m_t^{MC}$ and $m_t^{\text{pole}}$ is expected to be of the order of 0.5 GeV, due to non-perturbative QCD effects that affect the top-quark mass determination [4,5]. A study to relate $m_t^{MC}$ to mass definitions adopted in well-defined theoretical schemes, such as $m_t^{\text{pole}}$ and $m_t^{\text{MSR}}$, is done by the ATLAS Collaboration using MC simulated $t\bar{t}$ events originated from $pp$ collisions at $\sqrt{s} = 13$ TeV [13]. The MSR mass scheme is similar to the $\overline{\text{MS}}$ scheme but depends on an energy scale [14], which
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The mass of the top quark is a fundamental parameter of the SM. Its measurement at a precision of a few hundreds of MeV at the LHC poses interesting experimental and theoretical challenges. Different experimental techniques may require different theoretical interpretations, whose relations require further investigations, such as the one between \( m_t^{\text{MC}} \) and \( m_t^{\text{pole}} \) or \( m_t^{\text{MS}} \).

Measurement of the top-quark Yukawa coupling using \( t\bar{t} \) events are potentially sensitive to new physics effects that contribute to loop corrections. A recent measurement of the coupling strength \( Y_t = 1.16^{+0.07}_{-0.08} \text{(stat)}^{+0.23}_{-0.34} \text{(syst)} \) shows no deviations with respect to the SM expectations.
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References


