Measurements of the top quark mass from the LHC and the Tevatron

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The mass of the top quark is a fundamental parameter of the standard model and has to be determined experimentally. In these proceedings, I review recent measurements of the top quark mass in $pp$ collisions at $\sqrt{s} = 7$, 8, and 13 TeV recorded by the ATLAS and CMS detectors at the LHC, and in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV recorded by the CDF and D0 experiments at the Tevatron. The measurements are performed in final states containing two, one, and no charged leptons. A relative precision of down to 0.3% is attained. In addition, recent measurements aiming to determine the top quark mass in the well-defined pole scheme using both inclusive $t\bar{t}$ and $t\bar{t} + 1$ jet production are presented.
1. Introduction

Since its discovery [1, 2], the determination of the top quark mass $m_t$, a fundamental parameter of the standard model (SM), has been one of the main goals of the CERN Large Hadron Collider (LHC) and of the Fermilab Tevatron Collider. Indeed, $m_t$ and masses of $W$ and Higgs bosons are related through radiative corrections that provide a consistency check of the SM [3, 4]. Furthermore, $m_t$ dominantly affects the stability of the SM Higgs potential [4, 5]. With $m_t = 173.34 \pm 0.76$ GeV, a world-average combined precision of 0.44% has been achieved [6].

In the SM, the top quark decays to a $W$ boson and a $b$ quark nearly 100% of the time. Thus, $t\bar{t}$ events are classified according to $W$ boson decays as “dileptonic” ($\ell\ell$), “lepton+jets” ($\ell+\text{jets}$), or “all–jets”. Single top production contributes significantly at the LHC through the $qg \rightarrow q't\bar{b}$ process. In the following, I will present representative measurements in the three channels; a full listing of $m_t$ results from the LHC and the Tevatron can be accessed through Refs. [7, 8, 9, 10].

2. Standard measurements of the top quark mass

The most precise single measurement of $m_t$ in the $\ell\ell$ channel is performed by the ATLAS Collaboration using 20.2 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 8$ TeV [11]. The selection requires two isolated leptons ($e$ or $\mu$) of opposite charge, missing transverse momentum $E_{T}^{\text{miss}}$ due to neutrinos, and $\geq 2$ jets, where at least one of which is identified as originating from a $b$ quark ($b$-tagged). A transverse momentum $p_{T,\ell b} > 120$ GeV is required for the average of the two $\ell b$ systems to reduce the dominant uncertainty from the jet energy scale (JES). The $m_t$ is extracted with the “template method”, which in this case fits the distribution in the average invariant mass of the $\ell b$ system to the expectations from Monte Carlo (MC) simulations for different $m_t$, shown in Fig. 1 (a). The best fit to data is shown in Fig. 1 (b), and results in $m_t = 172.99 \pm 0.41(\text{stat}) \pm 0.74(\text{syst})$ GeV. Tevatron’s most precise single measurement in the $\ell\ell$ channel of $m_t = 173.32 \pm 1.36(\text{stat}) \pm 0.85(\text{syst})$ GeV is performed by the D0 Collaboration using 9.7 fb$^{-1}$ of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV [12].

The most precise single measurement of $m_t$ from the Tevatron is performed by the D0 Collaboration using 9.7 fb$^{-1}$ of data in the $\ell+\text{jets}$ channel [13] with a “matrix element (ME) method”. This approach determines the probability of observing a given event under both the $t\bar{t}$ signal and
background hypotheses, as a function of $m_t$. This probability is calculated \textit{ab initio} using the respective MEs of the $t\bar{t}$ signal and dominant $W$+jets background, taking into account effects from parton showering (PS), hadronisation, and finite detector resolution. This selection requires the presence of one isolated lepton, $E_T^{\text{miss}}$, and exactly four jets with at least one $b$-tag. A new JES calibration from exclusive $\gamma$+jet, $Z$+jet, and dijet events is applied to account for differences in detector response to jets originating from a gluon, a $b$ quark, and $u,d,s,$ or $c$ quarks. The overall JES $k_{\text{JES}}$ is calibrated \textit{in situ} by constraining the reconstructed invariant mass of the hadronically decaying $W$ boson to $M_W = 80.4$ GeV. The likelihood over all candidate events is maximised in $(m_t, k_{\text{JES}})$ as shown in Fig. 2 (a), and $m_t = 174.98 \pm 0.58(\text{stat+JES}) \pm 0.49(\text{syst})$ GeV is obtained. The most precise $m_t$ result from the CDF Collaboration in the $\ell$+jets channel of $m_t = 172.85 \pm 0.71(\text{stat+JES}) \pm 0.85(\text{syst})$ GeV [14] is obtained with the template method.

The most precise single measurement of $m_t$ from the LHC is performed by the CMS Collaboration using 19.7 fb$^{-1}$ of data at $\sqrt{s} = 8$ TeV in the $\ell$+jets channel [15]. The analysis uses a similar selection to the D0 result and applies the “ideogramm method” to extract $m_t$. Similar to the ME method, this approach calculates the probability to observe a given event as a function of $(m_t, k_{\text{JES}})$. However, this probability is not calculated \textit{ab initio}, but is obtained from MC simulations, in analogy to the template method. The final result of $m_t = 172.35 \pm 0.16(\text{stat+JES}) \pm 0.48(\text{syst})$ GeV is represented in Fig. 2 (b). The most precise $m_t$ result from the ATLAS Collaboration is obtained with the template method using 4.7 fb$^{-1}$ of data at $\sqrt{s} = 7$ TeV and reads $m_t = 172.33 \pm 0.75(\text{stat+JES}) \pm 1.02(\text{syst})$ GeV [16].

![Figure 2: (a) The likelihood in $(m_t, k_{\text{JES}})$ in 9.7 fb$^{-1}$ of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV recorded with the D0 detector [13]. Fitted contours of equal probability are overlaid as solid lines. The maximum is marked with a cross. (b) Same as (a), but in 19.5 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 8$ TeV recorded with the CMS detector [15]. The central result corresponds to “Hybrid”, and $k_{\text{JES}}$ is denoted as “JSF”.

The all-jets channel is particularly challenging due to very high background from QCD multijets. Tevatron’s most precise single $m_t$ result in this channel comes from the CDF Collaboration using 9.3 fb$^{-1}$ of data [17]. A neural network and $b$-tagging enhance the signal-to-background ratio from $10^{-3}$ to about 1. The correct assignment of jets to partons is determined by minimising a $\chi^2$, which accounts for consistency of the two dijet systems with $m_W$, consistency of the two $jjb$ systems with each other, and consistency of the individual fitted jet momenta with measured ones, within experimental resolutions. The measured value is $m_t = 175.07 \pm 1.19(\text{stat+JES}) \pm 1.55(\text{syst})$ GeV. The most precise result in the all-jets channel at the LHC of $m_t = 172.32 \pm 0.25(\text{stat+JES}) \pm 0.59(\text{syst})$ GeV comes from the CMS Collaboration [15].
An overview of recent $m_t$ measurements at the LHC [18] is given in Fig. 3. A combination of $m_t$ measurements from Run I and II of the Tevatron considering statistical and systematic correlations yields $m_t = 174.30 \pm 0.35({\text{stat}}) \pm 0.34({\text{syst}})$ GeV [19].

![Figure 3: Overview of recent $m_t$ measurements at the LHC [18]. References to the individual measurements are given at the bottom of the Figure.](image)

### 3. Measurements of the top quark mass in the pole scheme

The standard measurements of $m_t$ from Sect. 2 are experimentally the most precise ones. However, they extract an $m_t$ parameter as implemented in MC generators, which is related to the pole mass scheme definition $m_t^{\text{pole}}$ in the SM Lagrangian within an uncertainty of $\leq 1$ GeV [20].

The first LHC result on $m_t$ at $\sqrt{s} = 13$ TeV is an extraction of $m_t^{\text{pole}}$ from $\sigma_{t\bar{t}}$ performed by CMS in the $\ell +$jets channel using 2.3 fb$^{-1}$ of data [21]. This analysis exploits the dependence of $\sigma_{t\bar{t}}$ on $m_t^{\text{pole}}$, which is now known with $\approx 3\%$ precision at NNLO with NNLL corrections [22]. The input measurement of $\sigma_{t\bar{t}}$ achieves a relative uncertainty of $\approx 4\%$ by constraining the dominant W+jets background through sidebands in low jet and $b$-tag multiplicities, and using the difference in $d\sigma/dm_{t\bar{t}}$ dependence between signal and background. The final result is $m_t^{\text{pole}} = 173.3^{+3.2}_{-2.3}({\text{stat+syst}})^{+1.6}_{-1.0}({\text{theo}})$ GeV.

The most precise $m_t^{\text{pole}}$ measurement is performed by the ATLAS Collaboration in the $\ell +$jets channel using 4.6 fb$^{-1}$ of data at $\sqrt{s} = 7$ TeV [23]. The $m_t^{\text{pole}}$ is extracted from the production cross section of a $t\bar{t}$ system in association with a jet $\sigma_{t\bar{t}+1\text{jet}}$, since the radiation rate of a high-$p_T$ gluon off the $t\bar{t}$ system is proportional to $m_t^{\text{pole}}$. More precisely, the differential production
cross section $\mathcal{R}(m_t^{\text{pole}}, \rho_s) \equiv 1/\sigma_{t\ell+1\text{jet}} \cdot d\sigma_{t\ell+1\text{jet}}/d\rho_s$ is compared to NLO calculations [24], where $\rho_s \equiv 2m_0/\sqrt{s_{t\ell+1\text{jet}}}$ and the arbitrary constant $m_0$ is set to 170 GeV in this analysis. The selection is similar to other analyses in the $\ell+\text{jets}$ channel discussed in Sect. 2, and the correct jet-parton assignment is determined through a $\chi^2$ kinematic fit. To reduce the total uncertainty, $p_T > 50$ GeV is required for the extra jet. The distribution in $\rho_s$ is corrected for detector, PS, hadronisation effects, and the presence of background. The resulting distribution at parton level is given in Fig. 4 (a). The final result reads $m_t^{\text{pole}} = 173.1 \pm 1.50(\text{stat}) \pm 1.43(\text{syst})^{+0.93}_{-0.49}(\text{theo})$ GeV.

The second most precise $m_t^{\text{pole}}$ measurement is performed by the D0 Collaboration in the $\ell+\text{jets}$ channel using 9.7 fb$^{-1}$ of data [25]. This analysis extracts $m_t^{\text{pole}}$ by relating measured $d\sigma_{t\ell}/dm_{t\ell}(m_t)$ and $d\sigma_{t\ell}/dp_{T,\ell/j}(m_t)$ to recent NNLO and NLO calculations [26]. Differential cross sections allow for a more complete use of kinematic information, and thus a notably higher statistical precision than the $m_t^{\text{pole}}$ extraction from an inclusive $\sigma_{t\ell}$ measurement. The selection is similar to Ref. [13], and the correct jet-parton assignment is identified through a $\chi^2$ kinematic fit. The resulting distributions are corrected for detector, PS, hadronisation effects, and the presence of background to obtain $d\sigma_{t\ell}/dm_{t\ell}(m_t)$ and $d\sigma_{t\ell}/dp_{T,\ell/j}(m_t)$, which are then directly compared to theory calculations to extract $m_t^{\text{pole}}$. The final result reads $m_t^{\text{pole}} = 169.1 \pm 2.5(\text{stat} + \text{syst}) \pm 1.5(\text{theo})$ GeV.

![Figure 4](image.png)

Figure 4: (a) The distribution $\mathcal{R} \equiv 1/\sigma_{t\ell+1\text{jet}} \cdot d\sigma_{t\ell+1\text{jet}}/d\rho_s$ in $pp$ collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector [23], compared to NLO predictions [24]. (b) The distribution of $d\sigma_{t\ell}/dp_{T,\ell/j}(m_t)$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV with the D0 detector [25], compared to NNLO predictions [26]. Both distributions are shown at parton level, after corrections for detector, PS, and hadronisation effects.

4. Conclusions

I presented recent measurements of the top quark mass, a fundamental parameter of the SM. The most precise single measurements at the LHC and the Tevatron of respectively $m_t = 172.35 \pm 0.16(\text{stat}+\text{JES}) \pm 0.48(\text{syst})$ GeV and $m_t = 174.98 \pm 0.58(\text{stat}+\text{JES}) \pm 0.49(\text{syst})$ GeV are performed by the CMS and D0 Collaborations in the $\ell+\text{jets}$ channel, corresponding to a relative precision of 0.30% and 0.43%. The precision of $m_t$ measurements in the pole scheme is improved to 1.3% due to the advent of new theory calculations and experimental approaches.

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