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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.

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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" (ℓ+jets), or "all–jets". Single top production contributes significantly at the LHC through the $qg \to q'tb̄$ 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 μ) of opposite charge, missing transverse momentum $E_{\mathrm{T}}^{\mathrm{miss}}$ due to neutrinos, and ≥ 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 ℓb 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 ℓb 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 $m_t = 172.99 \pm 0.41(\mathrm{stat}) \pm 0.74(\mathrm{syst})$ GeV. Tevatron's most precise single measurement in the $\ell\ell$ channel of $m_t = 173.32 \pm 1.36(\mathrm{stat}) \pm 0.85(\mathrm{syst})$ 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 ℓ+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

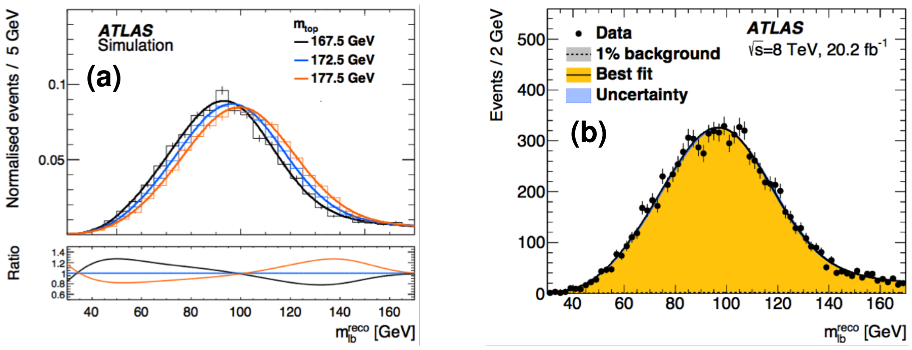

Figure 1: **(a)** Expected dependence of the $m_{\ell b}$ distribution of processes involving top quarks on m_t from Monte Carlo simulations at $\sqrt{s} = 8$ TeV with the ATLAS detector [11]. **(b)** The distribution in $m_{\ell b}$ in 20.3 fb^{-1} of data at $\sqrt{s} = 8$ TeV with the ATLAS detector. The predictions correspond to the best-fit values.

background hypotheses, as a function of m_t. This probability is calculated *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, $E_{\mathrm{T}}^{\mathrm{miss}}$, and exactly four jets with at least one b-tag. A new JES calibration from exclusive γ+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_{JES} is calibrated *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_{JES}) as shown in Fig. 2 (a), and $m_t = 174.98 \pm 0.58(\mathrm{stat+JES}) \pm 0.49(\mathrm{syst})$ GeV is obtained. The most precise m_t result from the CDF Collaboration in the ℓ+jets channel of $m_t = 172.85 \pm 0.71(\mathrm{stat+JES}) \pm 0.85(\mathrm{syst})$ 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 ℓ+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_{JES}). However, this probability is not calculated *ab initio*, but is obtained from MC simulations, in analogy to the template method. The final result of $m_t = 172.35 \pm 0.16(\mathrm{stat+JES}) \pm 0.48(\mathrm{syst})$ 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 $m_t = 172.33 \pm 0.75(\mathrm{stat+JES}) \pm 1.02(\mathrm{syst})$ GeV [16].

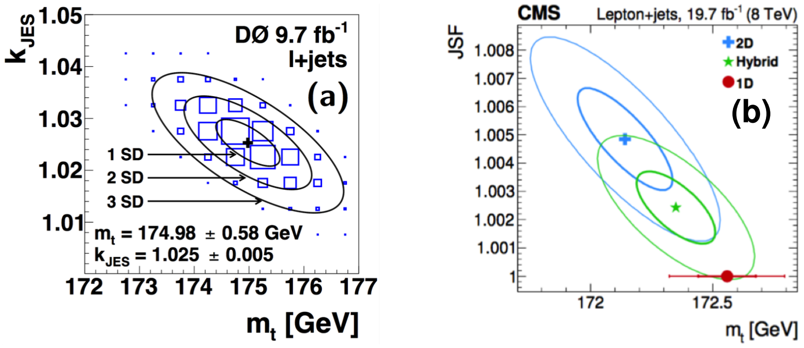

Figure 2: **(a)** The likelihood in (m_t, k_{JES}) in 9.7 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV recorded with the D0 detector [13]. Fitted contours of equal probability are overlaid as solid lines. The maximum is marked with a cross. **(b)** Same as (a), but in 19.5 fb^{-1} of pp collisions at $\sqrt{s} = 8$ TeV recorded with the CMS detector [15]. The central result corresponds to "Hybrid", and k_{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 χ^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 $m_t = 175.07 \pm 1.19(\mathrm{stat+JES}) \pm 1.55(\mathrm{syst})$ GeV. The most precise result in the all-jets channel at the LHC of $m_t = 172.32 \pm 0.25(\mathrm{stat+JES}) \pm 0.59(\mathrm{syst})$ 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].

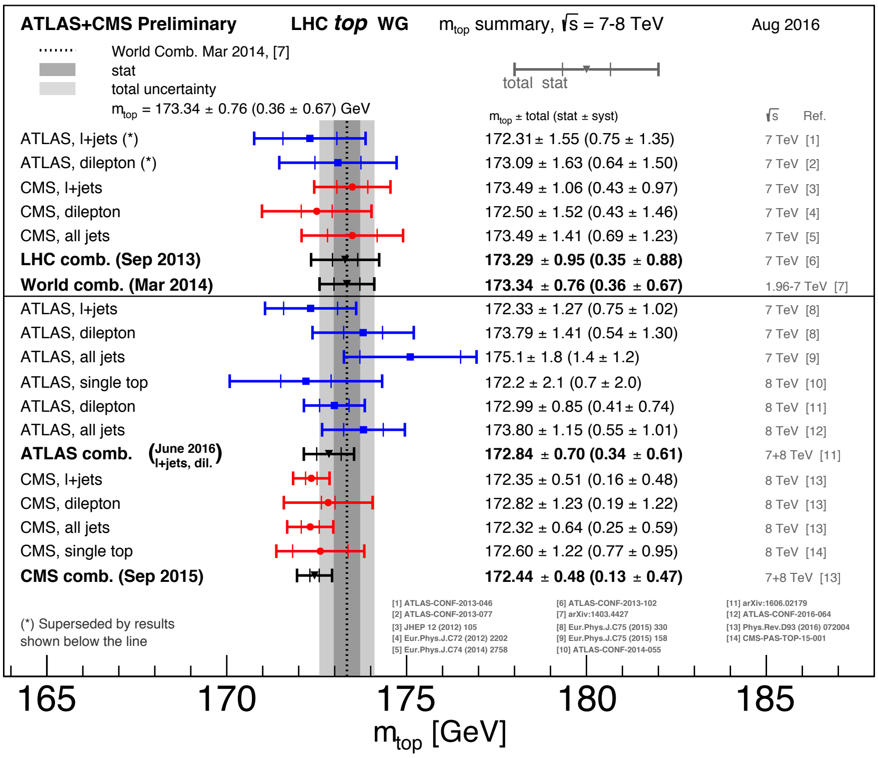

Figure 3: Overview of recent m_t measurements at the LHC [18]. References to the individual measurements are given at the bottom of the Figure.

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^{pole} in the SM Lagrangian within an uncertainty of $\lesssim$1 GeV [20].

The first LHC result on m_t at $\sqrt{s} = 13$ TeV is an extraction of m_t^{pole} from $\sigma_{t\bar{t}}$ performed by CMS in the ℓ+jets channel using 2.3 fb^{-1} of data [21]. This analysis exploits the dependence of $\sigma_{t\bar{t}}$ on m_t^{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 $\mathrm{d}\sigma/\mathrm{d}m_{\ell b}$ dependence between signal and background. The final result is $m_t^{\text{pole}} = 173.3^{+2.3}_{-2.0}(\text{stat}+\text{syst})\,^{+1.6}_{-1.1}(\text{theo})$ GeV.

The most precise m_t^{pole} measurement is performed by the ATLAS Collaboration in the ℓ+jets channel using 4.6 fb^{-1} of data at $\sqrt{s} = 7$ TeV [23]. The m_t^{pole} is extracted from 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^{pole}. More precisely, the differential production cross section $\mathscr{R}(m_t^{\text{pole}}, \rho_s) \equiv 1/\sigma_{t\bar{t}+1\text{jet}} \cdot \text{d}\sigma_{t\bar{t}+1\text{jet}}/\text{d}\rho_s$ is compared to NLO calculations [24], where $\rho_s \equiv 2m_0/\sqrt{s_{t\bar{t}+1\text{jet}}}$, and the arbitrary constant m_0 is set to 170 GeV in this analysis. The selection is similar to other analyses in the ℓ+jets channel discussed in Sect. 2, and the correct jet-parton assignment is determined through a χ^2 kinematic fit. To reduce the total uncertainty, $p_\text{T} > 50$ GeV is required for the extra jet. The distribution in ρ_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^{pole} measurement is performed by the D0 Collaboration in the ℓ+jets channel using 9.7 fb^{-1} of data [25]. This analysis extracts m_t^{pole} by relating measured $\text{d}\sigma_{t\bar{t}}/\text{d}m_{t\bar{t}}(m_t)$ and $\text{d}\sigma_{t\bar{t}}/\text{d}p_{T,t/\bar{t}}(m_t)$ 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^{pole} extraction from an inclusive $\sigma_{t\bar{t}}$ measurement. The selection is similar to Ref. [13], and the correct jet-parton assignment is identified through a χ^2 kinematic fit. The resulting distributions are corrected for detector, PS, hadronisation effects, and the presence of background to obtain $\text{d}\sigma_{t\bar{t}}/\text{d}m_{t\bar{t}}(m_t)$ and $\text{d}\sigma_{t\bar{t}}/\text{d}p_{T,t/\bar{t}}(m_t)$, which are then directly compared to theory calculations to extract m_t^{pole}. The final result reads $m_t^{\text{pole}} = 169.1 \pm 2.5(\text{stat}+\text{syst}) \pm 1.5(\text{theo})$ GeV.

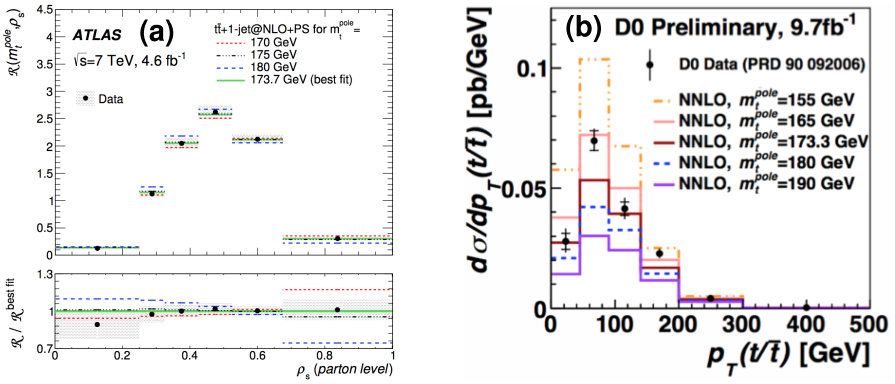

Figure 4: **(a)** The distribution $\mathscr{R} \equiv 1/\sigma_{t\bar{t}+1\text{jet}} \cdot \text{d}\sigma_{t\bar{t}+1\text{jet}}/\text{d}\rho_s$ in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector [23], compared to NLO predictions [24]. **(b)** The distribution of $\text{d}\sigma_{t\bar{t}}/\text{d}p_{T,t/\bar{t}}(m_t)$ 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 $m_t = 172.35 \pm 0.16(\text{stat+JES}) \pm 0.48(\text{syst})$ GeV and $m_t = 174.98 \pm 0.58(\text{stat+JES}) \pm 0.49(\text{syst})$ GeV are performed by the CMS and D0 Collaborations in the ℓ+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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