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Top-quark mass measurements: Review and perspectives

Giorgio Cortiana

Max-Planck-Institut für Physik, Föhringer Ring 6, D-80805 München, Germany

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ABSTRACT

The top quark is the heaviest elementary particle known and its mass (m_{top}) is a fundamental parameter of the Standard Model (SM). The m_{top} value affects theory predictions of particle production cross-sections required for exploring Higgs-boson properties and searching for New Physics (NP). Its precise determination is essential for testing the overall consistency of the SM, to constrain NP models, through precision electroweak fits, and has an extraordinary impact on the Higgs sector, and on the SM extrapolation to high-energies. The methodologies, the results, and the main theoretical and experimental challenges related to the m_{top} measurements and combinations at the Large Hadron Collider (LHC) and at the Tevatron are reviewed and discussed. Finally, the prospects for the improvement of the m_{top} precision during the upcoming LHC runs are briefly outlined.

1. Introduction

Naturally complementing direct searches for new physics (NP) phenomena, precision measurements of the properties of the fundamental particles constitute an extremely successful path to refine our knowledge of high-energy physics and of its implications on the evolution of the Universe. In this context, the top quark plays a special role: its lifetime is extremely short ($\approx 10^{-25}$ s) and inhibits top-quark bound states and top-quark flavoured hadrons to be formed, offering a unique possibility to study the properties of the particle as a quasi-free quark (see Refs. [1,2] for recent reviews on the subject). The top quark is the heaviest elementary particle currently known and its mass (m_{top}) plays a fundamental role in high-energy physics. The value of m_{top} affects theory predictions of particle production cross-sections required for exploring Higgs-boson properties and searching for NP phenomena. Due to top-quark induced quantum-loop corrections, which modify the theory predictions for several physics observables, the precise determination of m_{top} is essential for testing the overall consistency of the Standard Model (SM) and to constrain NP models through precision electroweak fits. Fig. 1(a), from Ref. [3], displays the 68% and 95% confidence level (CL) contours for the indirect determination of the mass of the W boson (m_W) and m_{top} from global SM fits to electroweak precision data. The blue (grey) areas illustrate the fit results when including (excluding) the direct Higgs-boson mass measurements [4,5]. The contours are compared with the direct measurements of m_W and m_{top}, shown by the horizontal and vertical green bands, that are excluded from the fits.

In addition, owing to its large value, of the order of the electroweak symmetry breaking energy scale, m_{top} has a direct impact on the Higgs sector of the SM, and on extrapolations of the SM to high-energy scales [6,7]. With the discovery of a Higgs boson [4,5] at the Large Hadron Collider (LHC) with a mass of $m_H = 125.09 \pm 0.24$ GeV [8], precision measurements of the top-quark mass take a central role in answering the question of the stability of the electroweak vacuum: top-quark

E-mail address: cortiana@mppmu.mpg.de

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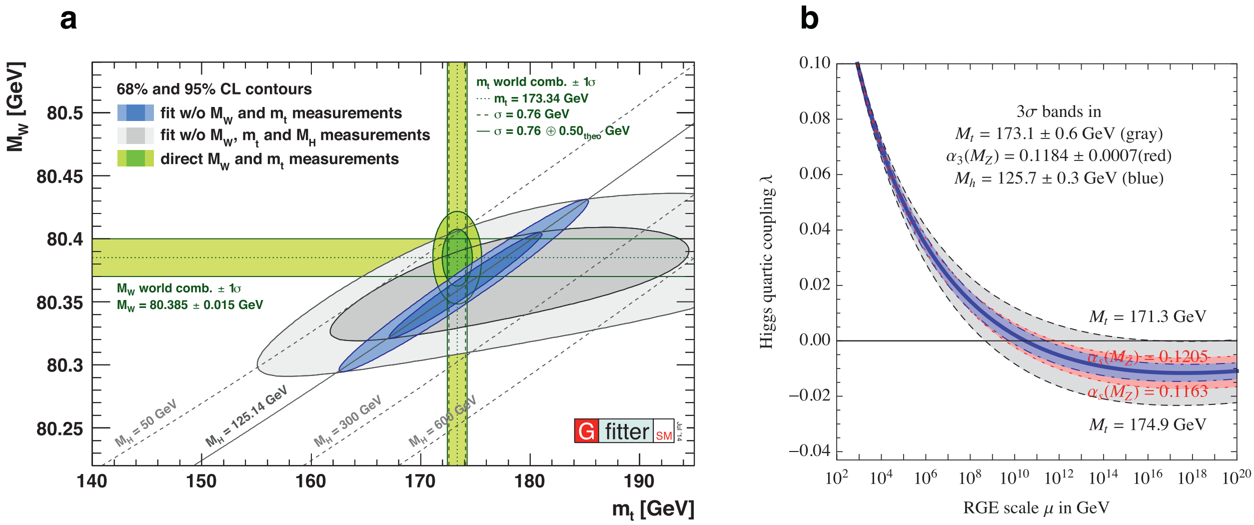

Fig. 1. (a) The 68% and 95% CL contours for the indirect determination of m_W and m_{top} from global SM fits to electroweak precision data (from Ref. [3]). (b) Evolution of the Higgs-boson self-coupling λ, within the renormalisation group equation (RGE), for the central values of $m_H = 125.7$ GeV, $m_{top} = 173.1$ GeV and $\alpha_S(m_Z) = 0.1184$ (solid curve), and variation of these central values by $\pm\, 3\sigma$ for the blue, grey and red, dashed curves, respectively (from Ref. [6]).

radiative corrections can drive the Higgs-boson self-coupling (λ) towards negative values, potentially leading to an unstable vacuum. The determination of the energy scale (μ) at which this happens, possibly requiring new physics at lower or comparable energies, is strongly influenced by the precision of the top-quark mass measurement and by the interpretation of m_{top} in a clear theoretical framework (μ varies by several orders of magnitude under a $\pm$ 1.8 GeV variation of m_{top}, as shown in Fig. 1(b), from Ref. [6]).

Currently, the most precise measurements of m_{top} are obtained from direct reconstruction of the top-quark decay final states and use calibrations based on Monte Carlo (MC) simulation to determine the top-quark mass value that best describes the data. In this approach, the measured top-quark mass corresponds to the parameter implemented in the MC (m_{top}^{MC}) which formally is not a renormalised field theory parameter, and must be used with care as input for precise theoretical predictions [9–11]. The top quark is colour charged and does not exist as an asymptotic state: the value of m_{top}, extracted from the experiments, depends on the theoretical definition of the mass, which varies according to the renormalisation scheme adopted: pole mass (m_{top}^{pole}) or running mass. As a result, the identification of m_{top}^{MC} with m_{top}^{pole} is currently subject to an uncertainty of the order of 1 GeV [10], comparable to the present experimental precision (see also Refs. [12,13] for previous recent reviews on m_{top}).

2. Top-quark pair production and signatures at the Tevatron and LHC

At Tevatron and LHC hadron colliders top quarks are mainly produced in pairs, through strong interactions, via gluon fusion and quark-antiquark annihilation processes. Depending on the collider centre-of-mass-energy ($\sqrt{s}$), and on the type of particle beams being utilised (proton-antiproton, $p\bar{p}$, or proton-proton, pp), the relative importance of the two processes varies. At the Tevatron $p\bar{p}$ collider, operating at $\sqrt{s} = 1.8 - 1.96$ TeV, approximately 85% of the top-quark pairs ($t\bar{t}$) are produced through quark-antiquark annihilation, whereas at all centre-of-mass-energies explored by the LHC pp collider, gluon fusion processes are dominant (80–90% for $\sqrt{s} = 7 - 14$ TeV). The top-quark pair production cross-section varies from $7.16^{+0.20}_{-0.23}$ pb at the Tevatron, to $172.0^{+6.4}_{-7.5}$ pb ($\sqrt{s} = 7$ TeV), $245.8^{+8.8}_{-10.6}$ pb ($\sqrt{s} = 8$ TeV) and $953.6^{+27.9}_{-38.3}$ pb ($\sqrt{s} = 14$ TeV) at the LHC [14]. The production of single-top quarks occurs via electroweak interactions and relates to a significantly lower (about one half) production cross-section than that for top-quark pairs.

After the discovery of the top quark in 1995 [15,16], the CDF and D0 experiments, operating at the Tevatron, have collected about 10 fb^{-1} of $\sqrt{s} = 1.96$ TeV $p\bar{p}$ collisions. The LHC experiments, ATLAS and CMS, in operation since 2010, have collected 5 fb^{-1} and 20 fb^{-1} of pp collisions data at the centre-of-mass-energies of 7 and 8 TeV, respectively (LHC Run-1). Within the planned LHC programme, about 100 fb^{-1} of $\sqrt{s} = 13 - 14$ TeV (LHC Run-2) and 200 fb^{-1} of $\sqrt{s} = 14$ TeV (LHC Run-3) pp collision data will be collected in the time period 2015–2022. An additional ten-fold increase of the integrated luminosity is expected within the LHC high-luminosity upgrade [17]. Correspondingly, the expected number of $t\bar{t}$ events that will be produced by the end of LHC Run-3 amount to about 300 Million, compared to 6 Million produced during the LHC operations at $\sqrt{s} = 7$ and 8 TeV, and 70k produced at the Tevatron at $\sqrt{s} = 1.96$ TeV. As we shall see in the following, this will open unprecedented opportunities for precise measurements of the properties of the top quark, and in particular of m_{top}.

In the SM, the top quark decays almost exclusively into a W boson and a b-quark ($t \to Wb$). The $t\bar{t}$ signatures are therefore determined by the W boson decay modes. In the "all-jets" channel, with a branching ratio (BR) of 46%, both W bosons decay into a quark-antiquark pair ($W \to q\bar{q}'$). In the "lepton+jets" channel (BR = 44%), one W boson from the top or antitop quark decays to a pair of charged and neutral leptons (e, μ, τ, and their corresponding neutrinos), while the other W boson decays into a quark-antiquark pair. Finally, the $t\bar{t}$ "di-lepton" channel corresponds to the case where both W bosons from the top and anti-top quarks decay leptonically, into a pair of charged and neutral leptons (BR = 10%) [18]. The experimental signatures associated to single-top quark production vary depending on the production mode (s-, t- and tW-channels). Currently, m_{top} measurements are available only for the t-channel, typically characterised by the presence of a detectable jet recoiling against the produced t (or $\bar{t}$) quark. To facilitate the event reconstruction and to distinguish the single-top quark production from the overwhelming background processes, the W boson associated to the top quark is required to decay leptonically ($W \to l\nu$).

3. Experimental setups, event selection and reconstruction

The CDF [19,20], D0 [21,22], ATLAS [23] and CMS [24] experiments utilise omnipurpose detectors that have been designed for the identification and reconstruction of the particles emerging from $p\bar{p}$ or pp collisions provided by the Tevatron and LHC accelerator complexes. Despite the different underlying technological choices, all detectors comprise three major subsystems. In the region close to the interaction point, tracking systems immersed in a magnetic field record precisely the trajectories and transverse momenta of charged particles. The energy and position of the electromagnetic and hadronic showers are measured by means of hermetic and finely grained calorimeter systems located immediately following the tracking systems. Finally, the outer part of the detectors comprises of dedicated muon systems providing precise momentum measurements for highly penetrating and energetic particles.

In general, the design and calibration of experimental physics analyses proceed via the use of MC simulated signal ($t\bar{t}$ or single-top quark) and background events. The generation of a primary hard interaction process (*e.g.* $q\bar{q}, gg \to t\bar{t}$), is accompanied by parton showers, and by non-perturbative processes that convert the obtained partonic final state into colourless hadrons. Subsequently, soft interactions compounding on the event of interest ("pile-up"[1]), are also included in the simulation [25]. The MC events are processed through experiment-specific simulation and reconstruction software, and the reconstructed final-state particles, originating from quarks and gluons evolving into collimated sprays of colourless hadrons, are clustered into jets, that can be associated with the final-state partons. While at CDF, D0 and ATLAS jets are reconstructed based on calorimeter only information, within CMS the particle-flow algorithm [26,27], combining the information from all detector sub-systems, is used.

Key ingredients for m_{top} analyses are the jet energy scale (JES) calibration procedures. These are applied after jet reconstruction, are meant to ensure the correct measurement of the average jet energy across the whole detector (intercalibration), and are designed to be independent of the pile-up conditions. Jet energy corrections account for the energy lost in un-instrumented regions between calorimeter modules, for differences between electromagnetically and hadronically interacting particles, as well as for calorimeter module irregularities. The calibration procedures use single hadron calorimeter response measurements, systematic MC simulation variations as well as in-situ techniques, where the jet transverse momentum (p_T) is compared to the p_T of a reference object, for example in γ+jets and Z+jets events [28–34]. Uncertainties on the JES vary from about 1% to 3% depending on the jet kinematic properties and flavour (u, d, c, s, b or gluon originated jets), and are typically among the largest sources of systematic uncertainty in m_{top} measurements.

3.1. Event selection

Event selection requirements, targeted at the $t\bar{t}$ (or t) signature under study, rely on the number of well-reconstructed physics objects in the detector, jets and charged leptons (typically electrons and muons), and on their properties. The presence of identified b-quark jets (by means of b-tagging algorithms, based on the properties of secondary vertexes and low p_T leptons reconstructed within the jets [35–40]), and of significant missing transverse energy (E_T^{miss}) from the undetected neutrino(s), are in general also required. The experimental signature, referred to as "E_T^{miss}+jets" channel, selects events solely based on E_T^{miss} and jet related information rather than on explicit charged lepton identification criteria thus achieving high acceptance to $W \to \tau\nu$ decays.

3.2. Event reconstruction

In the $t\bar{t} \to$ lepton+jets channel, selected events are typically subject to a kinematic fit aimed at extracting the full information from the underlying $t\bar{t}$ decay. Despite implementation differences, the available algorithms, p_T-max, χ^2- or likelihood-based (see Ref. [41] for a comparison of their performance), relate the measured kinematics of the reconstructed objects to the leading-order representation of $t\bar{t}$ decay, and return the best jet-to-parton association, according to the experimental resolution, to be used in the analyses for example in the calculation of the top-quark and W-boson invariant

[1] Pile-up is the term given to the extra signal produced in the detector by $p\bar{p}$ or pp interactions other than the primary hard scattering.

masses ($m_{\rm top}^{\rm reco}$, $m_W^{\rm reco}$). Missing information, related to the longitudinal boost of the escaping neutrino(s), can be recovered by additional constraints to the event kinematics: exploiting the known W-boson mass (and requiring $m_{q\bar{q}'} = m_{l\nu} = m_W$) and by imposing the top- and antitop-quark masses to be equal.

In the $t\bar{t} \to$ di-lepton channel, due to the presence of two escaping neutrinos, the full kinematic configuration of the event cannot be resolved unless additional assumptions are made. A possible solution is to construct $m_{\rm top}$-sensitive observables only using the available information (neglecting the presence of neutrinos), and measure $m_{\rm top}$ based on the kinematics of the identified (b-)jets and charged leptons in the event. For example $m_{\rm top}$ can be determined exploiting its correlation to the invariant mass of the charged lepton and b-jet system, m_{lb}. A similar approach can be followed for the $m_{\rm top}$ analyses based on single-top quark signatures. Alternatively, more elaborate methods, *e.g.* "neutrino weighting" [42,43] or "analytical matrix weighting" [44] techniques, targeted at obtaining information about the complete $t\bar{t}$ kinematics, can be exploited. The neutrino weighting approach steps through different hypotheses for the pseudo-rapidity of the two neutrinos in the final state, and for the underlying $m_{\rm top}$. For each hypothesis, the algorithm calculates the full event kinematics and assigns a weight to the resulting reconstructed top-quark mass based on the agreement between the calculated and measured $E_{\rm T}^{\rm miss}$. The solution corresponding to the maximum weight is selected to represent the event and the underlying $t\bar{t}$ decay. Similarly to the neutrino weighting case, in the analytical matrix weighting technique the full reconstruction of the event kinematics is done under different $m_{\rm top}$ assumptions. For each event, the most likely $m_{\rm top}$ hypothesis, fulfilling $t\bar{t}$ kinematic constraints, is obtained by assigning weights that are based on probability density functions for the energy of the charged leptons taken from simulation, which are applied in the solution of the kinematic equations [44].

In the $t\bar{t} \to$ all-jets and $t\bar{t} \to E_{\rm T}^{\rm miss}$+jets channels the general idea of the $t\bar{t} \to$ lepton+jets kinematic fit is extended to events with no reconstructed charged lepton. While the kinematic configuration is fully specified for $t\bar{t} \to$ all-jets events, in the $t\bar{t} \to E_{\rm T}^{\rm miss}$+jets channel, the leptonically decaying W boson is treated as missing particle as a whole.

4. Overview of the $m_{\rm top}$ measurements

The top-quark mass is measured using various techniques and in different decays channels by the CDF, D0, ATLAS and CMS experiments. The latest and most precise results are summarised in Fig. 2, and compared to the results of the first Tevatron+LHC $m_{\rm top}$ combination [45]. The measured $m_{\rm top}$ values (left panel), their total uncertainty and the (relative) importance of the main uncertainty categories (right panel) are provided. Two main classes of measurements can be distinguished:

- Direct $m_{\rm top}$ measurements, exploiting information from the kinematic reconstruction of the measured top-quark decay products, and their corresponding combinations (summarised in this Section).
- Indirect determinations of $m_{\rm top}$, based on the comparison of inclusive or differential $t\bar{t}$ production cross-section to the corresponding theory calculations, thus sensitive to $m_{\rm top}^{\rm pole}$ (detailed in Section 5).

4.1. Methodology

The methods exploited for the measurement of $m_{\rm top}$ directly using the kinematic properties of the $t\bar{t}$ (or single-top quark) decay products can be categorised in the following groups.

4.1.1. Template method

In the "template method", based on a full ($t\bar{t} \to$ lepton+jets, $t\bar{t} \to$ all-jets, and $t\bar{t} \to E_{\rm T}^{\rm miss}$+jets) or partial ($t\bar{t} \to$ di-lepton, and single-top quark) reconstruction of the kinematics underlying the top-quark(s) decay, probability density functions (templates) for observables sensitive to the underlying $m_{\rm top}$, and to additional parameters, are constructed based on MC simulation. As an example, the templates may be the distribution of the top-quark masses ($m_{\rm top}^{\rm reco}$) reconstructed from a kinematic fit in MC samples generated using different input $m_{\rm top}$. The templates can be subsequently mapped to continuous functions of $m_{\rm top}$, either through a non-parametric kernel-density estimator [46], or by fitting an analytic function that interpolates between the discrete input values of $m_{\rm top}$, and then used in a maximum-likelihood fit to the data. As illustration, Fig. 3(a) reports the $m_{\rm top}^{\rm reco}$ sensitivity to $m_{\rm top}$ in the $t\bar{t} \to$ lepton+jets analysis from Ref. [47], and the result of the template parametrisation. Depending on the number of input distributions utilised, one-, two- or multi-dimensional template fits are performed to determine $m_{\rm top}$ along with possible additional parameters, *e.g.* a global jet-energy scale factor (JSF), targeted at reducing the impact of the experimental systematics stemming from the JES [48]. In this case, additional (uncorrelated) event observables like the reconstructed hadronically decaying W-boson mass ($m_W^{\rm reco}$, Fig. 3(b)), are exploited. The template method, originally exploited for the $m_{\rm top}$ measurements in the top-quark observation papers [15,16], is widely used for $m_{\rm top}$ analyses, and constitutes the reference technique for the latest CDF and ATLAS $m_{\rm top}$ results.

4.1.2. Matrix element method

The "matrix element method" is based on the likelihood to observe a sample of selected events in the detector. For each event a probability is calculated as a function of the assumed values of each parameter to be measured (*e.g.* $m_{\rm top}$ and JSF), using a leading-order matrix element incorporating the differential cross-sections of the physics processes relevant to the analysis (see Ref. [50] for a discussion of the possible impact of the use of leading-order as opposed to next-to-leading-order matrix elements in $m_{\rm top}$ analyses). All possible assignments of reconstructed jets to final-state partons are used, each

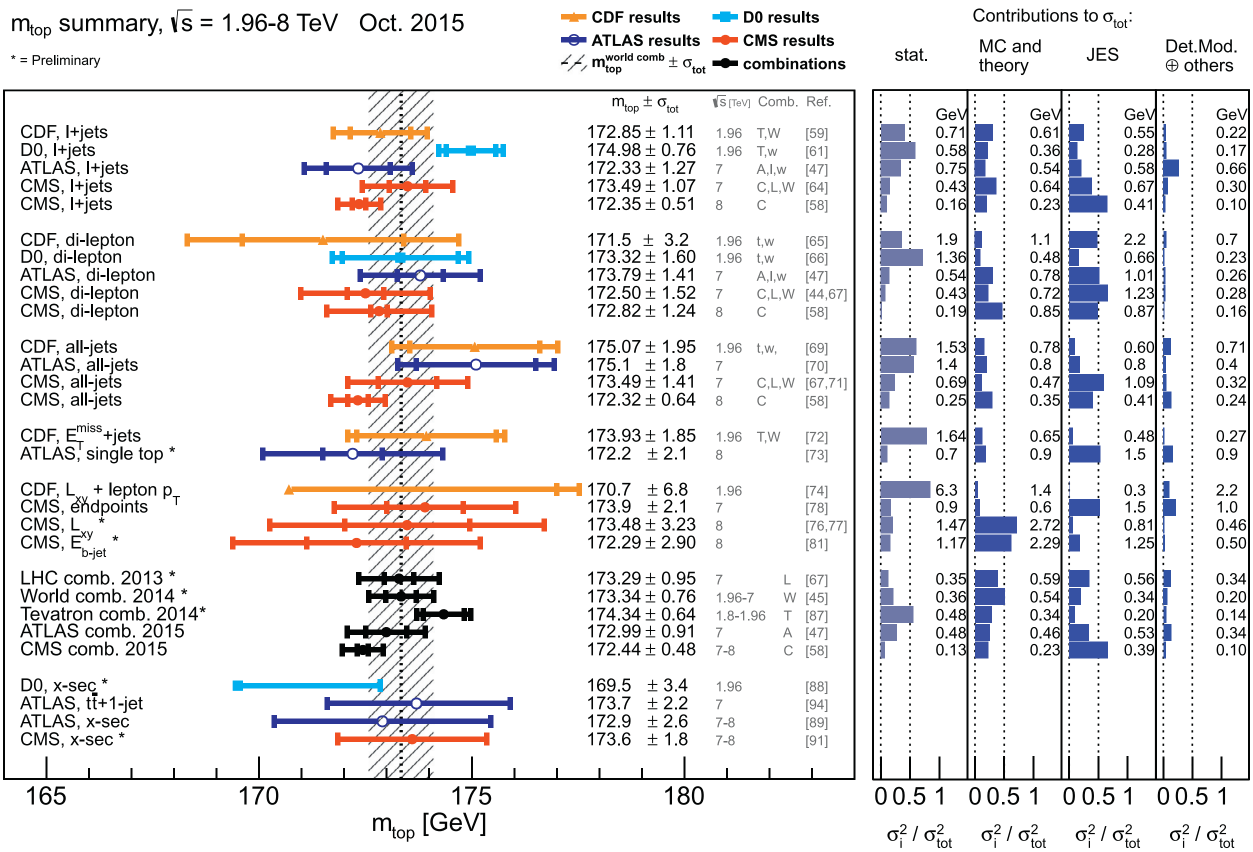

Fig. 2. (left panel) Summary of the latest m_{top} measurements and combinations. The total m_{top} uncertainty (in all cases symmetrised), the relative importance (defined as $\sigma_i^2/\sigma_{tot}^2$) and the size (in GeV) of the main uncertainty contributions are provided (right panel). All measurements are compared to the result of the world (Tevatron+LHC) combination [45]. For the m_{top} results based on L_{xy} and lepton p_T (CDF) and on the inclusive $t\bar{t}$ production cross section (D0) only the upper error bars are shown. Preliminary measurements are indicated with a $*$. Measurements input to the ATLAS, CMS, LHC, Tevatron or World combinations are marked by A, C, L, T, or W, respectively (upper/lower case characters indicate whether the corresponding published/preliminary result is used).

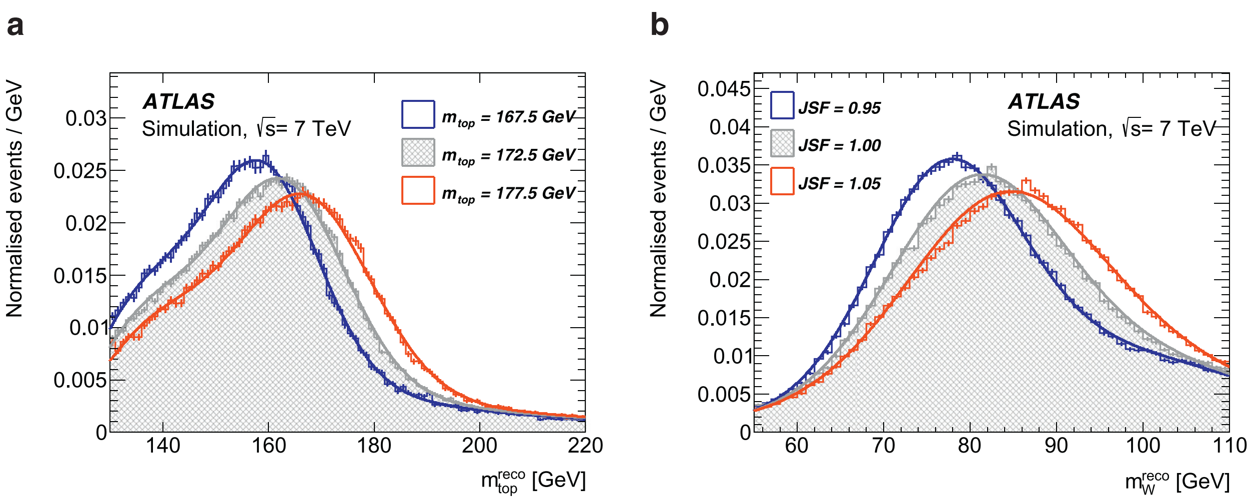

Fig. 3. Example template distributions of m_{top}^{reco} (a) and m_W^{reco} (b) in the $t\bar{t} \rightarrow$ lepton+jets analysis from Ref. [47]. The sensitivities of the templates to m_{top} and to the variation of a global jet-energy scale factor (JSF) are reported.

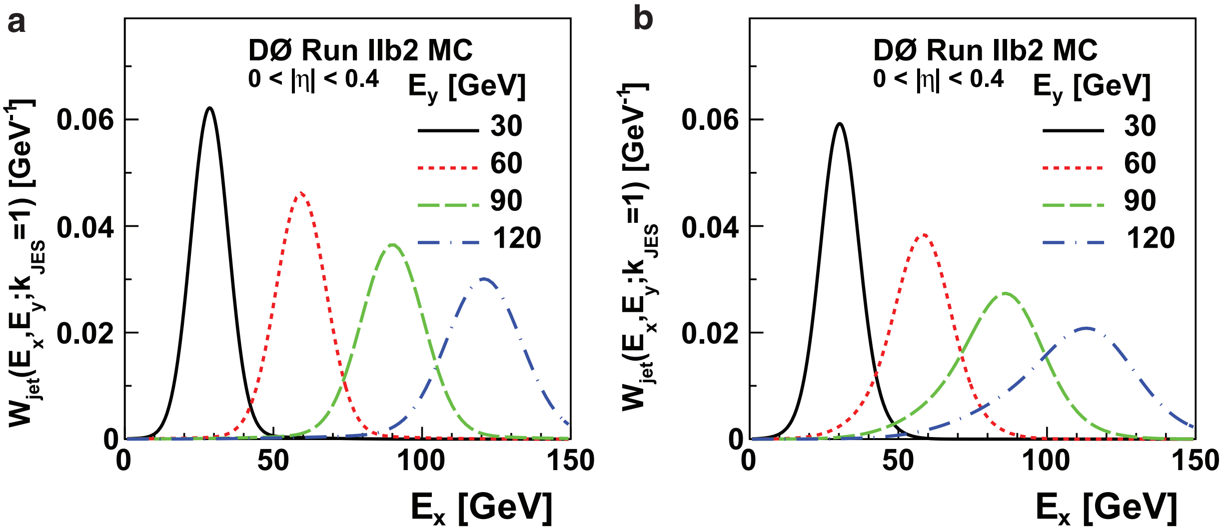

Fig. 4. Example of transfer functions (W_{jet} with $k_{JES} = JSF = 1$) for light- (a) and b-quark (b) originated jets as a function of the measured jet energy (E_x) and for different parton energies (E_y) (from Ref. [49]).

weighted by a probability determined from the matrix element. The correspondence between measured four-vectors and parton-level four-vectors is taken into account using probabilistic transfer functions (see Refs. [51,52] for comprehensive reviews of the method). As illustration, Fig. 4, from Ref. [49], reports examples of transfer functions (W_{jet}) for light- (a) and b-quark (b) originated jets. These represent the probability that the jet energy E_x measured in the detector corresponds to a matrix-element parent quark of energy E_y. The matrix element approach maximises the statistical power of the considered data sample at the cost, however, of a high computational demand. As a consequence, this technique is best suited for the Tevatron data sets, for event samples obtained by means of very tight selection criteria, or exploiting exclusive $t\bar{t}$ decays with reduced branching ratios.

4.1.3. Ideogram method

The "ideogram method" [53] combines some of the features of the above two techniques, and can be considered a computational effective approximation of the matrix element method. After a kinematic fit of the decay products to a $t\bar{t}$ hypothesis (Section 3.2), MC-based likelihood functions are exploited for each event (ideograms) that depend only on the parameters to be determined from the data. The ideograms reflect the compatibility of the kinematics of the event with a given decay hypothesis. As in the case of the template and matrix element methods, ideograms can be generalised in multiple dimensions depending on the number of input observables used.

4.2. Uncertainties affecting the m_{top} measurements

4.2.1. Statistical uncertainties

Statistical uncertainties on m_{top} arise from the finite size of the data samples available for the measurements. For Tevatron and LHC Run-1 analyses the statistical uncertainty constitutes a sizable contribution to the total uncertainty, especially for measurements exploiting multidimensional fits to the data, to determine simultaneously m_{top} and additional parameters designed to reduce the impact of the JES uncertainty on the measurement (see Section 4.2.3 and 4.3).[2] The statistical uncertainty component is expected to be reduced by up to one order of magnitude for the upcoming LHC analyses exploiting the full Run-2,3 data.

4.2.2. MC/theory related uncertainties (MC/theory)

Theory based uncertainties are related to the simulation of top-quark pair (or single-top quark) signal events, to the event modelling and to the description of the hard scattering environment. Choices to be made in the simulation are the proton (antiproton) parton distribution functions (PDFs), the MC generator and the hadronisation model. On the event modelling side, important ingredients are the description of the underlying event (UE) via MC tunes, and the settings adopted for the modelling of colour re-connection (CR), extra initial- or final-state QCD radiation (ISR/FSR) and the description of additional interactions accompanying the hard scatter (pile-up). Modelling effects are particularly relevant in relation to the

[2] In the present work, the full statistical uncertainty of the fit is quoted, including the contributions from the simultaneous determination of additional parameters along with m_{top}.

top-quark colour charge: to form colour-neutral stable particles, the top-quark decay products necessarily connect to additional coloured partons in the event. As a result, the full reconstruction of the $t\bar{t}$ kinematics is affected by the interplay between the hard scattering and the underlying event, and by their colour connection.

Whenever possible, MC modelling uncertainties are constrained using data. At the Tevatron, the MC parameters excursion used to evaluate the impact of ISR/FSR effects on $m_{\rm top}$ is determined in Drell-Yan events, which share the same initial state as most of the $t\bar{t}$ pairs, by studying the kinematic properties of the di-lepton pairs [48,49]. Constraints to the ISR/FSR systematics are obtained at the LHC by exploiting "gap-fraction" ("jet-veto") observables and the properties of extra jets accompanying the $t\bar{t}$ system [54,55]. Additional studies, currently statistically limited, based on jet-shapes [56], on the study of the UE and CR kinematics in $t\bar{t}$ events [57], and of the dependence of the $m_{\rm top}$ results as a function of the event kinematics [58], will become more sensitive and eventually be able to discriminate different MC models. These investigations are expected to play a crucial role in improving the MC/theory uncertainties in $m_{\rm top}$ analyses exploiting the data from the upcoming LHC runs.

4.2.3. Experimental uncertainties: Jet Energy Scale and Detector Modelling (JES and Det. Mod.)

Experimental uncertainties stem from the modelling of the physics objects used for the event reconstruction and from the description of the detector response. These are related to the identification, reconstruction and calibration of charged leptons, jets, and $E_{\rm T}^{\rm miss}$. The main systematic uncertainty contributions to the measurements typically originate from the jet energy scale for light-quark (u, d, c, s or gluon) and b-quark originated jets (JES and bJES), and from the uncertainty related to the modelling of the performance of the b-tagging algorithms in data relative to the MC. Additional detector modelling uncertainties, including trigger efficiencies, uncertainties on the data to MC modelling of the charged leptons identification, reconstruction and energy scale, as well as uncertainties stemming from the $E_{\rm T}^{\rm miss}$ and pile-up effects, are typically subdominant. Profiting from the large $t\bar{t}$-enriched data sets that have become available, the potentially large $m_{\rm top}$ systematics from detector modelling effects is substantially mitigated by the application of analysis techniques in which $m_{\rm top}$ is determined simultaneously with additional in-situ parameters exploiting information of jet energy scale sensitive distributions (Section 4.3). For example and as shown in Fig. 3(b), a global jet energy scale factor (JSF), defined as a multiplicative factor to be applied in addition to the standard jet energy corrections, can be constrained by the response of light-quark jets using the kinematic information in $W \to q\bar{q}'$ decays (referred to as in-situ $t\bar{t}$ jet energy calibration).

Finally, uncertainties on the background normalisation and differential distributions can affect the measured top-quark properties. For the analyses in the lepton+jets and di-lepton channels, in particular at the LHC, these uncertainties contribute only marginally to the total uncertainty of $m_{\rm top}$.

4.3. Individual results

In the following, individual $m_{\rm top}$ results are summarised and presented according to the final state exploited.

4.3.1. $t\bar{t} \to$ lepton+jets channel

The lepton+jets channel yields the most precise $m_{\rm top}$ measurements across all experiments. This final state profits from a good signal to background ratio, and the possibility to fully reconstruct the event kinematics, despite the presence of one neutrino from the W boson decay ($W \to l\nu$). Although different techniques (template, ideograms or matrix element, see Section 4.1) are applied to measuring the top-quark mass, all recent analyses mitigate the systematic uncertainty due to JES uncertainty by a simultaneous in-situ fit to global jet energy scale factor (JSF) sensitive distributions (Fig. 3).

The CDF $t\bar{t} \to$ lepton+jets analysis [59] is based on the template method, and uses 8.7 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} =$ 1.96 TeV. Events are reconstructed by means of a χ^2-based kinematic fit which determines the best jet-to-parton assignments. To increase the statistical power of the analysis, two $m_{\rm top}$-related invariant masses ($m_{\rm top}^{\rm reco}$, $m_{\rm top}^{\rm reco2}$), corresponding to the best and second best jet-to-parton assignments and the invariant mass of the two jets from the hadronically decaying W boson ($m_{q\bar{q}'}$, sensitive to JSF) are fit to the data. The jet energy calibrations are improved using an artificial neural network to achieve a better b-jet energy resolution. In a way similar to what is described in Ref. [60], this algorithm incorporates precision tracking and secondary vertex information, in addition to standard calorimeter measurements. The final $m_{\rm top}$ result, $m_{\rm top} = 172.85 \pm 1.11$ GeV, is obtained from a simultaneous fit to five event sub-samples defined according to the b-tagged jet multiplicity and properties, and is determined along with a JSF via a three-dimensional template method. The overall $m_{\rm top}$ uncertainty receives comparable contributions from the statistical, the MC/theory and JES uncertainties (Fig. 2).

The D0 $t\bar{t} \to$ lepton+jets analysis [49,61] rests on the matrix element technique and utilises the full $p\bar{p}$ data set at $\sqrt{s} =$ 1.96 TeV provided by the Tevatron, corresponding to an integrated luminosity ($\mathcal{L}$) of 9.7 fb^{-1}. The analysis profits from updated JES calibrations [29] and an improved implementation of the matrix element method [62,63]. The latter reduces the computational demand by two orders of magnitude, allowing a substantial increase of the number of simulated MC events used for the method calibration, and the evaluation of systematic uncertainties. A simultaneous fit to the data is performed to obtain $m_{\rm top}$ and JSF, and results in the most precise Tevatron $m_{\rm top}$ measurement: $m_{\rm top} = 174.98 \pm 0.76$ GeV, where the largest contribution to the total uncertainty is statistical in nature (0.58 GeV).

A recent extension of the template method in the $t\bar{t} \to$ lepton+jets channel has been proposed and exploited by ATLAS, where $m_{\rm top}$ is determined simultaneously with a JSF from $W \to q\bar{q}'$ decays and a separate b-to-light-quark energy scale

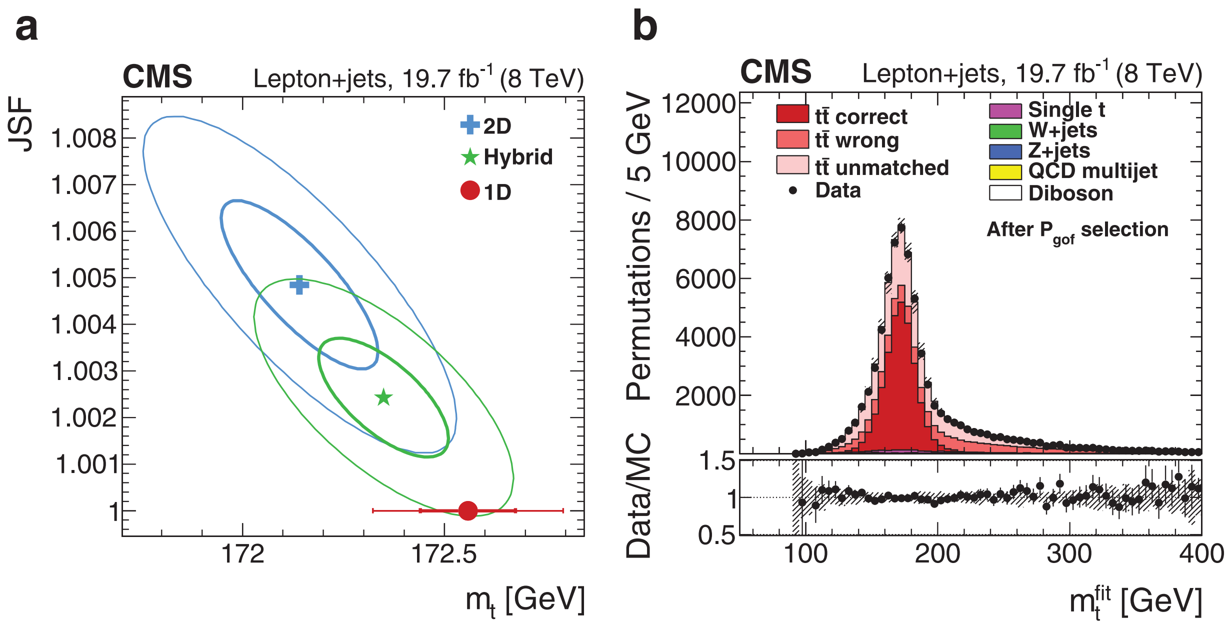

Fig. 5. (a) The (statistical only) likelihood contours corresponding to the two-dimensional (2D), hybrid, and one-dimensional (1D, JSF fixed to unity) fits to the data, in the CMS 8 TeV $t\bar{t} \rightarrow$ lepton+jets analysis. (b) Distribution of the reconstructed m_{top} values in data compared to the simulation (both figures from Ref. [58]).

factor (bJSF) [47]. The bJSF sensitive observable, R_{bq}, is defined in terms of a ratio of the scalar sums of the p_{T} of the b-tagged and light-quark jets present in the event. The JSF and bJSF account for differences between data and simulation in the light-quark and in the relative b-to-light-quark jet energy scale, thereby mitigating the corresponding systematic uncertainties. The result, $m_{\mathrm{top}} = 172.33 \pm 1.27$ GeV, is based on 4.6 fb^{-1} of LHC pp collision data at $\sqrt{s} = 7$ TeV, and has a sizable contribution from the statistical uncertainty (0.75 GeV), due to the dimensionality of the fit. This is expected to be greatly reduced when applying the method to the four-fold larger 8 TeV data set.

The CMS collaboration reports m_{top} measurements in the $t\bar{t} \rightarrow$ lepton+jets channel based on the full LHC Run-1 data sets ($\mathcal{L} = 5.0\,\mathrm{fb}^{-1}$ and $\mathcal{L} = 19.7\,\mathrm{fb}^{-1}$) collected at $\sqrt{s} = 7$ TeV and 8 TeV [58,64]. In both analyses, m_{top} is derived simultaneously with a JSF from $t \rightarrow Wb\,(W \rightarrow q\bar{q}')$ decays, employing a two-dimensional ideogram method. While in the 7 TeV analysis a simultaneous fit to m_{top} and JSF is performed assuming no prior knowledge of the JSF, a JSF constrained fit is applied to the 8 TeV data set (referred to as “hybrid” method in Ref. [58] and Fig. 5). This procedure incorporates the prior knowledge about the JES and its uncertainty [34], applying a Gaussian constraint to JSF. The hybrid approach is found to reduce both the statistical and systematic uncertainties compared to the unconstrained two-dimensional fit, yielding a total uncertainty improvement of about 20%. The likelihood contours, corresponding to the two-dimensional (2D), hybrid, and one-dimensional (1D, in which the JSF is fixed to unity) fits to the data are shown in Fig. 5(a) together with the distribution of the reconstructed m_{top} value in data compared to the simulation (b). The measured m_{top} values are: $m_{\mathrm{top}} = 173.49 \pm 1.07$ GeV and $m_{\mathrm{top}} = 172.35 \pm 0.51$ GeV for the 7 and 8 TeV analyses, respectively, where the overall uncertainties are driven by residual JES and MC/theory based systematic uncertainties. The CMS 8 TeV $t\bar{t} \rightarrow$ lepton+jets result constitutes the most precise m_{top} measurement to date.

4.3.2. $t\bar{t} \rightarrow$ di-lepton channel

In the di-lepton channel, the signal to background ratio is typically very good, and the kinematics is under constrained due to the presence of at least two neutrinos in the final state. As a result, direct in-situ fits to global jet energy scale factors are inhibited and the corresponding JES uncertainties are larger than for the lepton+jets results (the JES contribution accounts typically for 50–60% of the total uncertainty on m_{top}, Fig. 2). In addition, due to the relatively small branching ratio, Tevatron m_{top} analyses exploiting this decay mode are characterised by fairly large statistical uncertainties (1.4–1.9 GeV).

The CDF $t\bar{t} \rightarrow$ di-lepton analysis [65] uses 9.1 fb^{-1} of 1.96 TeV $p\bar{p}$ collisions, and exploits templates of a special observable, m^{hyb}, for an optimal reduction of the dominant JES systematic uncertainty. The m^{hyb} is constructed as a linear combination of the top-quark mass obtained from the neutrino-weighting algorithm and m_{lb}^{alt}, a variable defined based on the ratio of the invariant masses of the lepton and b-jet systems, and the corresponding b-jets energies, to minimise the sensitivity to the JES. The result yields $m_{\mathrm{top}} = 171.5 \pm 3.2$ GeV, where the total uncertainty receives comparable contributions from the statistical (1.9 GeV) and systematic (2.5 GeV) uncertainties.

The latest $t\bar{t} \rightarrow$ di-lepton D0 result [66], is based on 9.6 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. It features a comprehensive optimisation of the neutrino weighting method and fitting parameters to minimise the statistical uncertainties. In

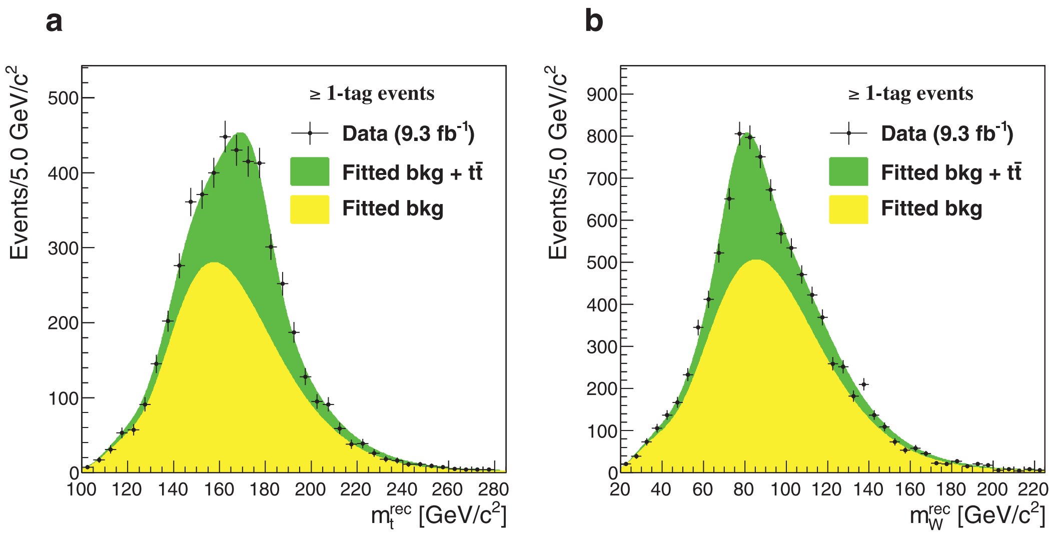

Fig. 6. The distribution of m_{top}^{reco} (a) and m_W^{reco} (b) exploited in the CDF $t\bar{t} \to$ all-jets m_{top} analysis (from Ref. [69]).

addition, it profits from a JSF recalibration based on the results the $t\bar{t} \to$ lepton+jets analysis [61], which reduces the otherwise limiting JES systematic uncertainty, but introduces correlations between the $t\bar{t} \to$ lepton+jets and $t\bar{t} \to$ di-lepton m_{top} measurements. The observables used to determine m_{top} via a two-dimensional template method are the first moments, mean and standard deviation, of the m_{top}^{reco} distributions obtained from the neutrino weighting algorithm. The resulting $m_{top} = 173.32 \pm 1.60$ GeV constitutes the best di-lepton result from the Tevatron and is competitive with the results from the LHC.

The ATLAS $t\bar{t} \to$ di-lepton analysis is based on a one-dimensional template method. Instead of attempting a full kinematic reconstruction, templates are obtained for the m_{lb} observable, defined as the per-event average invariant mass of the two lepton (either electron or muon) plus b-jet pairs from the decay of the top quarks [47]. In contrast to D0, to keep the correlation to the $t\bar{t} \to$ lepton+jets result minimal, thereby maximising the gain in the ATLAS m_{top} combination, the jet energy scale factors (JSF, bJSF) measured in the $t\bar{t} \to$ lepton+jets channel are not propagated to di-lepton analysis. The final result, $m_{top} = 173.79 \pm 1.41$ GeV, is obtained from a simultaneous fit to the sub-samples of events defined according to the b-tagged jet multiplicity, and has an overall correlation of $\rho_{tot} = -7\%$ to $t\bar{t} \to$ lepton+jets m_{top} result.

Measurements of m_{top} in the di-lepton channel are available from the CMS collaboration based on the LHC Run-1 data sets at $\sqrt{s} = 7$ TeV [44,67] and 8 TeV [58] corresponding to integrated luminosities of 5.0 fb^{-1} and 19.7 fb^{-1}, respectively. The top-quark mass is reconstructed with the analytical matrix weighting technique, and the m_{top} measurements use distributions derived from MC signal samples, generated at different input m_{top} values, and backgrounds, in binned likelihood fits to the data. While different templates are used according to the b-tagged jet multiplicity of the event in the 7 TeV analysis, as a result of an optimisation procedure to minimise the total uncertainty, only events with two b-tagged jets are used for the 8 TeV results. The resulting top-quark masses are $m_{top} = 172.50 \pm 1.52$ GeV and $m_{top} = 172.82 \pm 1.24$ GeV for the 7 and 8 TeV analyses, respectively.[3]

4.3.3. $t\bar{t} \to$ all-jets channel

In the all-jets channel a full reconstruction of the event kinematics is possible without the ambiguity due to neutrino momenta, however the signal to background ratio is significantly poorer due to the severe QCD multijets background, whose production cross-section exceeds that of $t\bar{t}$ by several orders of magnitude. Despite this underlying limitation, and the particular attention required to precisely estimate and control the background contributions via data-driven techniques, the final m_{top} precision obtained in this channel is comparable to that of the lepton+jets and di-lepton results.

CDF measures m_{top} in the $t\bar{t} \to$ all-jets channel using 9.3 fb^{-1} of $p\bar{p}$ collision data at $\sqrt{s} = 1.96$ TeV [69]. To strongly suppress the background, the event selection is complemented by a multivariate algorithm, containing multiple kinematic and jet-shape variables (to distinguish between quark- and gluon-originated jets) as input. Using a two-dimensional template method, a top-quark mass of $m_{top} = 175.07 \pm 1.95$ GeV is measured along with a JSF exploiting information from the hadronically decaying W boson, and incorporating a prior based on the external JES uncertainty. The m_{top}^{reco} and m_W^{reco} distributions exploited in the analysis are reported in Fig. 6.

[3] In addition, an alternative m_{top} result in the $t\bar{t} \to$ di-lepton channel is presented in Ref. [68] based on the $\sqrt{s} = 8$ TeV data set and exploiting the m_{lb} observable ($m_{top} = 172.3 \pm 1.3$ GeV). The analysis setup is also used to extract the top-quark mass using different theory predictions, MC simulations as well as a fixed-order QCD calculations.

With the ATLAS $t\bar{t} \to$ all-jets analysis based on 3.5 fb^{-1} of pp collisions at $\sqrt{s} = 7$ TeV [70], the top-quark mass is obtained from a one-dimensional template fit to the ratio of three-jet to di-jet mass ($R_{3/2} = m_{jjj}/m_{jj} = m_{q\bar{q}'b}/m_{q\bar{q}'}$). The three-jet mass is calculated from the jets associated via a kinematic likelihood fitter [41] to a top-quark decay. Using these three jets the di-jet mass is obtained from the two jets assigned to the W boson decay. While retaining sensitivity to the underlying m_{top}, the $R_{3/2}$ observable allows a cancellation of systematic effects common to the m_{jjj} and m_{jj} masses, thus minimising the impact of the JES uncertainty on m_{top} in a complementary way with respect to a simultaneous determination of m_{top} and JSF. The measurement yields $m_{\mathrm{top}} = 175.1 \pm 1.8$ GeV, and the total uncertainty receives similar contributions from the statistical (1.4 GeV) and systematic (1.2 GeV) uncertainties.

The CMS measurements in the $t\bar{t} \to$ all-jets channel, using 7 and 8 TeV, are based on the ideogram method [58,67,71]. Within the 7 TeV analysis only m_{top} is extracted from a fit to the data (one-dimensional ideogram method). The analysis setup with a simultaneous determination of m_{top} and JSF is found to be subject to comparable total systematic uncertainties: due to the tight jet selection criteria applied, the reduction of the JES uncertainty via a two-dimensional ideogram method is compensated by the increased statistical uncertainty (two versus one parameter fit), and by an enhanced sensitivity to MC modelling effects. A similar situation is observed for the 8 TeV analysis [58], where, similarly to the corresponding $t\bar{t} \to$ lepton+jets case, the fit employs an hybrid method with a constrained JSF. The resulting measured m_{top} values are: $m_{\mathrm{top}} = 173.49 \pm 1.41$ GeV and $m_{\mathrm{top}} = 172.32 \pm 0.64$ GeV for the 7 and 8 TeV analyses, respectively.

4.3.4. Alternative final states and techniques for direct m_{top} determination

Total m_{top} uncertainties comparable with those of the analyses in the di-lepton and all-jets channels can be achieved by exploiting alternative final states ($E_{\mathrm{T}}^{\mathrm{miss}}$+jets or single-top quark enriched), as well as techniques based mostly on tracking information (L_{xy} and lepton p_{T}), or on different observables (kinematic endpoints and b-jet energy spectra).

The CDF m_{top} measurement in the $E_{\mathrm{T}}^{\mathrm{miss}}$+jets channel [72] uses 8.7 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, and focuses on events with large $E_{\mathrm{T}}^{\mathrm{miss}}$ and jets, vetoing identified charged leptons. Although no identified leptons are present, the measurement is sensitive to all W-boson leptonic decays, including $W \to \tau\nu$, which constitute approximately 40% of the signal sample. After selection, events are reconstructed by means of a modified χ^2-based kinematic fit, allowing for two missing particles (the charged lepton and the neutrino associated to the W boson). Similarly to the $t\bar{t} \to$ lepton+jets result [59], the analysis is based on templates of the $m_{\mathrm{top}}^{\mathrm{reco}}$, $m_{\mathrm{top}}^{\mathrm{reco2}}$ and $m_{q\bar{q}'}$ (m_W^{reco}) distributions which are fit to the data. This results in a m_{top} value of $m_{\mathrm{top}} = 173.93 \pm 1.85$ GeV, where the main contribution (1.64 GeV) to the total uncertainty is statistical in nature.

Using 20.3 fb^{-1} of pp collision data at $\sqrt{s} = 8$ TeV, ATLAS measures m_{top} based on a single-top quark enriched final state [73]. Selected events, targeted at the t-channel, contain one charged lepton, $E_{\mathrm{T}}^{\mathrm{miss}}$, and two jets, one of which is required to be b-tagged, resulting in a statistically independent data set with respect to other ATLAS m_{top} analyses. In addition, the ambiguities related to the jet-to-parton assignment are minimised in this channel, and the sensitivity to MC modelling effects is complementary to that of $t\bar{t}$-based m_{top} methods, due to the different colour connection patterns and momentum transfer scales involved. A one-dimensional template method is used, based on the invariant mass of the lepton and the b-tagged jet as estimator (m_{lb}), and yields $m_{\mathrm{top}} = 172.2 \pm 2.1$ GeV, where the total uncertainty is dominated by the uncertainties on the JES (1.5 GeV).

The CDF collaboration, using a partial $p\bar{p}$ data set ($\mathcal{L} = 1.9\,\mathrm{fb}^{-1}$) at $\sqrt{s} = 1.96$ TeV, developed m_{top} analysis techniques using observables with minimal dependence on the JES [74]. These are based on the transverse decay length of b-tagged jets (L_{xy}), the p_{T} of electrons and muons from W-boson decays, or a combination of both [75]. Events are selected in the $t\bar{t} \to$ lepton+jets channel, and the top-quark mass measurement is performed through comparisons with the mean L_{xy} and mean lepton p_{T} from MC simulations performed for a variety of top-quark mass hypotheses. The analysis is sensitive to different event characteristics than typical m_{top} measurements, and requires ad-hoc data-driven calibrations of the observables and of the boost of the top quarks. The combination of the m_{top} results obtained by the individual L_{xy} and lepton p_{T} observables yields $m_{\mathrm{top}} = 170.7 \pm 6.8$ GeV, where the precision is limited by the statistical uncertainty (accounting for 6.3 GeV).

At the LHC, the L_{xy} technique is exploited in the $t\bar{t} \to$ lepton+jets and $t\bar{t} \to$ di-lepton channels by the CMS collaboration, and applied to the pp data sets collected at $\sqrt{s} = 8$ TeV, corresponding to $\mathcal{L} = 19.3 - 19.6\,\mathrm{fb}^{-1}$ [76,77]. The m_{top} is obtained using the median of the L_{xy} distribution reconstructed in data, compared to the result of MC simulations performed at different input m_{top}. The result is $m_{\mathrm{top}} = 173.48 \pm 3.23$ GeV and the achieved precision is limited by the uncertainties in the modelling of the p_{T} of the top quark (2.6 GeV). As in the case of the corresponding CDF analysis, however, the JES uncertainty contributes only marginally to the total uncertainty of m_{top}, signalling the high level of complementarity of tracking based methods with respect to the standard analyses described in the previous sections.

The CMS collaboration reports a measurement of m_{top} exploiting the endpoints of kinematic distributions, based on 5.0 fb^{-1} of pp data at $\sqrt{s} = 7$ TeV [78]. The method, originally developed to determine possible NP particle masses in decay chains with undetected particles and unconstrained kinematics, suits well the case of $t\bar{t} \to$ di-lepton decays and is based on the "stransverse mass", m_{T2} [79]. To fully determine the di-lepton kinematic, the two multistep $t \to Wb \to l\nu b$ decay chains are split and their elements grouped in independent ways, either using only charged lepton or b-jet information, or a combination of the two in the form of an m_{lb}-like invariant mass. In a demonstrative effort, motivated primarily by future applications to NP scenarios, in addition to the top-quark mass, the masses of the W boson and the neutrino (m_ν^2) are determined. These are however constrained ($m_\nu^2 = 0$ and $m_W = 80.4$ GeV) to achieve the best m_{top} precision. The result: $m_{top} = 173.9 \pm 2.1$ GeV, has a limited dependence on the MC simulation, and brings complementary information with respect to conventional m_{top} analyses.

Finally, following a recent theoretical proposal [80], the top-quark mass is measured by the CMS collaboration in the $t\bar{t} \rightarrow$ di-lepton channel ($ll = e\mu$) , using 19.7 fb^{-1} of pp collisions at $\sqrt{s} = 8$ TeV, based on the position of the peak of the energy spectrum of the b-jets [81]. Under the hypothesis that top quarks are produced unpolarised [82], the chosen observable is independent of the Lorentz boosts and can be related to the energy of the b-quark in the rest frame of the top quark, in turn depending on m_{top}. After calibration for event selection, reconstruction, and background contamination effects, the top-quark mass is measured to be $m_{top} = 172.29 \pm 2.90$ GeV, where the dominant sources of systematic uncertainty stem from the modelling of the hard scattering process (MC/theory) and to a lesser extent from the JES.[4]

4.4. Top-quark mass combinations

Individual m_{top} results resting on various techniques and $t\bar{t}$ (or single-top quark) decay channels, have different sensitivities to statistical and systematic effects, and to the details of the MC simulation (right panel of Fig. 2). To exploit the full physics potential of the available measurements, and to profit from their diversity and complementarity, they are combined, thereby further increasing our knowledge on m_{top}. Input to all combinations are the individual results with a detailed breakdown of the uncertainties as well as the assumed correlations between individual sources. The tasks of each combination is to determine a mapping between corresponding uncertainty sources, to understand the correlations in each of the categories across different analyses and experiments, and evaluate the compatibility of the input results. Alongside with independent and experiment-specific combinations [47,58], multi-experiment working groups[5] are responsible for carrying out m_{top} combinations using measurements from different collaborations, and to provide various sets of recommendations aimed at refining and harmonising the statistical and systematic uncertainty treatment in current and future measurements. The Best Linear Unbiased Estimator method (BLUE) [84–86] is used to perform the m_{top} combinations. It determines the coefficients (weights) to be used in a linear combination of the input measurements by minimising the total uncertainty of the combined result. In the algorithm both statistical and systematic uncertainties and the measurement correlations are taken into account, while assuming that all uncertainties are independent and distributed according to Gaussian probability density functions.

A selection of the available m_{top} measurements is used in the recent Tevatron, LHC, and Tevatron+LHC combinations. The current LHC and Tevatron combinations yield $m_{top} = 173.29 \pm 0.95$ GeV and $m_{top} = 174.34 \pm 0.64$ GeV, and correspond to a precision improvement of 10% and 16% with respect to the most precise input measurement, respectively [67,87]. The first Tevatron+LHC m_{top} combination (also referred to as “world” combination) results in $m_{top} = 173.34 \pm 0.76$ GeV [45] and improves the overall m_{top} precision by 28% with respect to the most precise input. In general, the systematic uncertainties stemming from the JES (and bJES) and the MC/theory modelling dominate the total uncertainties of the combined m_{top} results. Except for the latest CMS combination resulting in $m_{top} = 172.44 \pm 0.48$ GeV [58], the present ATLAS, LHC, Tevatron and Tevatron+LHC m_{top} combinations do not include all recently improved individual measurements (Fig. 2). Among these are the latest $t\bar{t} \rightarrow$ di-lepton results from CDF and D0 [65,66] for the Tevatron combination; and the ATLAS 7 TeV $t\bar{t} \rightarrow$ all-jets [70] and single-top quark results [73] for the ATLAS combination ($m_{top} = 172.99 \pm 0.91$ GeV [47]). Updated inputs to the LHC m_{top} combination include the final ATLAS 7 TeV [47,70] and CMS 8 TeV results [58] as well as the ATLAS 8 TeV m_{top} result based on single-top enriched signatures [73]. Finally, the conceivable inclusion of the individual measurements [47,58,61,65,66,70,73], as well as possible refinements of the intra-experiments correlation assumptions described in Ref. [47] (see also Section 6), are expected to result in major overall uncertainty improvements in future world m_{top} combinations. For example in the case of the ATLAS combination, the precision improvement with respect to the most precise input m_{top} result is increased from 8% [67] to 28% [47] when taking into account anti-correlations effects on m_{top} systematics, introduced by the different analyses techniques (one- versus three-dimensional templates).

5. Alternative m_{top} measurement methods

The standard techniques to measure the top-quark mass, as described in the previous sections, make use of observables obtained via a kinematic reconstruction of the top-quark decays. As anticipated in the introduction, all measurements of this type rely on MC simulation for their calibration, and m_{top}^{MC} may differ by up to $O(1\,\text{GeV})$ from the theoretically well-defined top-quark pole-mass, m_{top}^{pole} [10]. As described in the following, alternative techniques are targeted at allowing a better theoretical interpretation of the measured m_{top}, often approaching the precisions of the standard results.

[4] Another interesting and complementary proposal, not yet exploited by the experiments, is represented by the “weight function” method [83]. Based on the normalised energy distribution of the charged lepton emitted from the parent top-quark in the laboratory frame, the sensitivity to m_{top} is obtained via weight functions constructed such that their integral $I(m)$ vanishes for $m = m_{top}$.

[5] The Tevatron Electroweak (TEV-EW-WG) and the LHC Top Physics (LHC-TOP-WG) working groups. More information at http://tevewwg.fnal.gov and http://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWG.

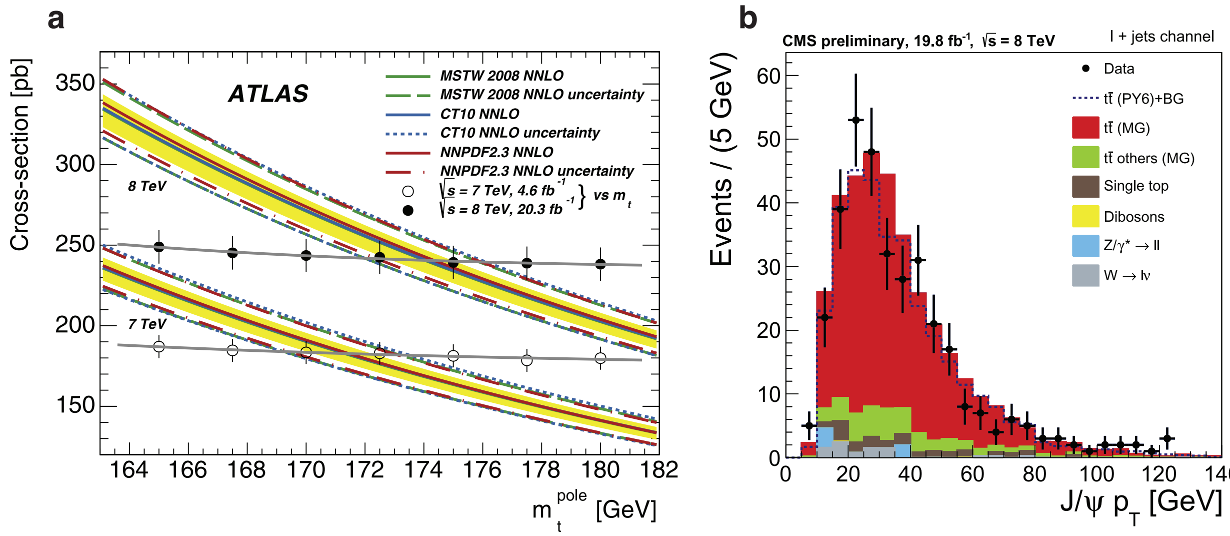

Fig. 7. (a) Predicted $t\bar{t}$ production cross-sections (and their uncertainty) at $\sqrt{s}=7$ and 8 TeV for different PDF sets, as a function of $m_{\rm top}^{\rm pole}$. The measurements of $\sigma_{t\bar{t}}$ from the ATLAS di-lepton analysis are overlaid, with their dependence on the assumed value of $m_{\rm top}^{\rm MC}$ (from Ref. [89]). (b) Comparison of data and MC simulated distributions of the transverse momentum of J/ψ candidates in $t\bar{t} \to$ lepton+jets events from the CMS $\sqrt{s}=8$ TeV collision data (from Ref. [57]).

5.1. Top-quark mass from inclusive $t\bar{t}$ cross-section measurements

The theoretical dependence of the $t\bar{t}$ production cross-section ($\sigma_{t\bar{t}}$) on $m_{\rm top}$ can be exploited to extract the mass of the top quark, by comparing the measured cross-section to the corresponding theory calculation [14]. In this framework, the top-quark mass can be measured unambiguously within the renormalisation scheme adopted for the cross-section calculation (*e.g.* $m_{\rm top}^{\rm pole}$), provided that the $m_{\rm top}^{\rm MC}$ dependence introduced by the event selection in the experimental analysis is negligible. To date measurements of this type are obtained by the D0, ATLAS and CMS collaborations.

The D0 collaboration reports a measurement of $\sigma_{t\bar{t}}$ in 9.7 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s}=1.96$ TeV, using $t\bar{t} \to$ lepton+jets and $t\bar{t} \to$ di-lepton final states [88]. The analysis employs multivariate techniques to build efficient $t\bar{t}$ signal discriminants, exploiting the kinematic features of top-quark pair events along with b-tagging information. The measured $\sigma_{t\bar{t}}$, determined from a combination of the lepton+jets and di-lepton channels, has a total relative uncertainty of 7.3% and a relatively weak dependence on the $m_{\rm top}^{\rm MC}$ assumed for the calculation of the $t\bar{t}$ signal acceptance ($d\sigma_{t\bar{t}}/dm_{\rm top}^{\rm MC} \approx -0.6\%$/GeV around $m_{\rm top}^{\rm MC} =$ 172.5 GeV). Maximising a joint likelihood including the experimental and theoretical dependencies on $m_{\rm top}$ [14], along with their corresponding total uncertainties, the top-quark pole-mass is found to be $m_{\rm top}^{\rm pole} = 169.5^{+3.3}_{-3.4}$ GeV.

The corresponding ATLAS result [89] rests on the $t\bar{t}$ production cross-section measurements in the di-lepton $e\mu$ channel performed using $\mathcal{L} = 4.6$ and 20.3 fb^{-1} of $\sqrt{s}=7$ and 8 TeV LHC pp data. The numbers of events with one and two b-tagged jets are counted and used to simultaneously determine $\sigma_{t\bar{t}}$ and the efficiency to reconstruct and b-tag a jet from a top-quark decay, thereby minimising the associated systematic uncertainties. The total relative experimental uncertainties on $\sigma_{t\bar{t}}$ of 3.8% (7 TeV) and 4.3% (8 TeV), and the reduced dependence of the measured cross-section on $m_{\rm top}^{\rm MC}$ ($d\sigma_{t\bar{t}}/dm_{\rm top}^{\rm MC} = -0.28 \pm 0.03\%$/GeV), offer the possibility of performing a relatively precise $m_{\rm top}$ measurement in the pole-mass scheme. Results are obtained for each centre-of-mass energy and then combined to yield $m_{\rm top}^{\rm pole} = 172.9^{+2.5}_{-2.6}$ GeV, where the total uncertainty is dominated by uncertainties stemming from the choice of the PDFs (using the PDF4LHC prescriptions [90]) and from the variation of the factorisation and renormalisation scales used in the theoretical calculations [14]. The measured and predicted $t\bar{t}$ production cross-sections exploited in the analysis are reported in Fig. 7(a).

Using the full pp data set available at $\sqrt{s}=7$ and 8 TeV, corresponding to integrated luminosities of $\mathcal{L} = 5.0\,\text{fb}^{-1}$ and 19.7 fb^{-1}, CMS extracts $m_{\rm top}$ based on the $\sigma_{t\bar{t}}$ measurement in the di-lepton $e\mu$ channel [91]. The analysis is performed via a template fit of signal and background contributions to multi-differential distributions related to the b-jet multiplicity and the multiplicity and transverse momenta of the jets present in the event. The resulting $\sigma_{t\bar{t}}$ is measured with a total relative uncertainty of 3.5% and 3.8% for the 7 TeV and 8 TeV data sets. The experimental dependencies of $\sigma_{t\bar{t}}$ on $m_{\rm top}^{\rm MC}$ around $m_{\rm top}^{\rm MC} =$ 172.5 GeV, are approximately -0.38%/GeV and -0.55%/GeV for the 7 TeV and 8 TeV data sets, respectively. A weighted average of the $m_{\rm top}$ results extracted from each centre-of-mass energy is performed taking into account the correlations of the various systematic uncertainties, and yields $m_{\rm top}^{\rm pole} = 173.6^{+1.7}_{-1.8}$ GeV, where the uncertainty stemming from the PDF is evaluated based on the NNPDF3.0 set [92].

5.2. Top-quark mass from differential normalised cross-section measurements

One of the main disadvantages of the $m_{\rm top}$ extractions from the inclusive $t\bar{t}$ production cross-section measurements is connected to their relatively limited precision with respect to the direct methods. The current relative precision of the

$\sigma_{t\bar{t}}$ measurements at the LHC (ranging from 3.5% to 4.3%) is limited by “external” uncertainties sources (the luminosity and beam energy measurements, and the theoretical uncertainties related to the cross-section calculations [89]), and a variation of 5% of the measured $\sigma_{t\bar{t}}$ induces a change of 1% on the extracted m_{top}. To overcome this difficulty, a novel technique has been proposed [93]: it is based on the normalised production cross-section of $t\bar{t}$ pairs with an additional jet, differential in the (inverse) invariant mass of the final-state jets. The method shares the rigorous interpretation of the mass extracted from the inclusive $t\bar{t}$ cross-sections, with the advantage of a greater sensitivity (up to a factor five larger) and competitiveness relative to analyses based on the kinematic reconstruction of the top-quark decay products. The chosen observable inherits its sensitivity from the m_{top} dependence of gluon radiation off top-quarks, with enhanced effects in the phase-space region relatively close to the $t\bar{t}$+1-jet production threshold. The current result [94], based on 4.6 fb^{-1} of $\sqrt{s} = 7$ TeV pp data collected with the ATLAS detector, yields $m_{\text{top}}^{\text{pole}} = 173.7^{+2.3}_{-2.1}$ GeV, where the dominant contribution to the total uncertainty is statistical in nature (1.5 GeV), and is expected to be substantially reduced when extending the analysis to the 8 TeV data set ($\mathcal{L} = 20.3$ fb^{-1}).

6. Prospects and future investigations

6.1. Refinements of the detector and MC modelling

Systematic effects stemming from the jet energy measurements are among the dominant sources of experimental uncertainty in many physics analyses, and in particular the uncertainty on the jet energy scale associated with jets initiated by a b-quark (bJES) plays a critical role in m_{top} precision measurements. The largest contributions to the bJES uncertainty stems from the modelling of the fragmentation and hadronisation of b-jets. To reduce these, the LHC Run-2,3 data sets can be used to obtain precise in-situ measurements of the b-fragmentation [57], by exploiting the kinematic properties of charm meson candidates (*i.e.* D_0, $D^{\pm}$, J/ψ) within the decay products of the b-quark jets associated with top quarks (see Fig. 7(b)). In a complementary approach, the b-jet energy scale can be probed by comparing the measured jet energy to that of well calibrated reference objects using charged-particle tracks within jets in $t\bar{t}$ samples [30], and Z+b-jet events [95]. In addition, several complementary measurements using $t\bar{t}$-enriched data sets can be performed to substantially refine the performance of different MC generators and tunes, and to mitigate the MC/theory related systematic uncertainties affecting top quark physics analyses. These comprise the study of UE and CR kinematics in $t\bar{t}$ events similar to those proposed in Ref. [57], and improved constraints to the modelling of the ISR/FSR QCD radiation accompanying the production of top quarks using $t\bar{t}$+jets (differential) cross-section measurements [96,97], as well as jet-veto and jet-shape related observables [54–56].

6.2. Data unfolding and comparison with theoretical calculations

The m_{lb} observable in $t\bar{t} \to$ di-lepton events, and the differential and normalised $t\bar{t}$+1-jet cross-section as a function of the (inverse) invariant mass of the final-state jets, can be computed theoretically in perturbative QCD [93,98–100]. In a possible extension of the current analyses [47,68,94], the corresponding data distributions (corrected for experimental effects and background contamination) can be compared to: (i) MC templates, associated with $m_{\text{top}}^{\text{MC}}$; (ii) the corresponding theory predictions, obtained using unambiguously defined top-quark mass schemes, *i.e.* $m_{\text{top}}^{\text{pole}}$. This approach is expected to allow assessing the dependence of the extracted m_{top} on the different theoretical assumptions and implementations, as well as opening the possibility to determining experimentally, by comparing the results of (i) and (ii), the difference between $m_{\text{top}}^{\text{MC}}$ and $m_{\text{top}}^{\text{pole}}$. A substantially reduced uncertainty in the relation of the two quantities will allow the m_{top} precision achieved experimentally to be fully exploited in theoretical calculations, precision SM tests and NP searches.

6.3. Exclusive top-quark decays, $t \to Wb \to l\nu + J/\psi X$, and top-tagging techniques

The study of the production of $t\bar{t}$ pairs with a J/ψ in the final state offers an alternative method of measuring the top-quark mass [101]. In top-quark pair events with a least one leptonically decaying W boson and one of the b-quarks hadronising to J/ψ (with the subsequent $J/\psi \to \mu^+\mu^-$ decay), m_{top} can be measured, ideally with no or negligible systematic uncertainties stemming from the JES, by exploiting its correlation to the invariant mass, $m(lJ/\psi)$, of the charged lepton and $J/\psi \to \mu^+\mu^-$ system. Sensitivity studies have been performed within the ATLAS and CMS collaborations, and recent exploratory analyses based on 8 TeV pp data establish the first steps towards these measurements (see Refs. [57,102] and references therein). Currently and as exemplified in Fig. 7(b), within the limited size of the available data samples, the kinematic properties of the J/ψ candidates reconstructed in $t\bar{t}$ events are found to be in reasonable agreement with various Monte Carlo predictions. With additional statistics (LHC Run-2,3), these investigations are expected to significantly contribute to m_{top} precision measurements by either constraining systematic uncertainty sources related to the b-quark hadronisation and fragmentation modelling, or by enabling an alternative mass measurement method, with complementary uncertainty contributions with respect to the traditional results.

In addition, the centre-of-mass energy of the LHC gives access to a new kinematic regime featuring highly-boosted top quarks. Initially developed for NP physics searches, to efficiently identify large area “top-jets” including all top-quark decay products, top-tagging techniques have proven a very active research field, and their present performance are promising in view of future top-quark properties measurements [103–105]. Similarly to the case of the top-quark mass determination using single-top quark enriched topologies [73], a possible m_{top} result using highly boosted top quarks is expected to have complementary sensitivities to MC modelling effects, and feature peculiar colour connection patterns, interesting to further understanding the relation between m_{top}^{MC} and m_{top}^{pole}.

6.4. Indirect m_{top} determinations from flavour physics observables

The systematic use of flavour physics observables has been proposed as an alternative way to measure the mass of the top quark in a robust theoretical framework [106]. This approach exploits the large top-quark Yukawa coupling and its related impact on quantum-loop corrections to identify flavour physics processes with enhanced sensitivity to m_{top}, and infer the top-quark mass from their measurements. With the present data the obtained m_{top} precision is limited and amounts to about 8 GeV. However, the projected achievable total uncertainty on m_{top}, taking into account foreseeable theoretical and experimental progresses, indicates a reach of about 2 GeV. Among the studied observables the mass difference in the B_s system, Δm_{B_s}, and the measurement of the branching ratio of $B_s \to \mu^+\mu^-$ dominate the present and the projected sensitivities to the top-quark mass. Although the proposed methodology is unlikely to surpass the direct m_{top} determinations in precision, the comparison of the various results and approaches will carry essential information, further helping to disentangle the theoretical ambiguities in the extraction of m_{top}.

6.5. Future m_{top} combinations

The combination of the results of different analyses, within the same experiment, or across different collaborations allows to exploit the full physics potential of the input measurements, to profit from their diversity, complementarity and partially correlated uncertainties, to increase the precision of m_{top}. Continuing in-depth studies of the correlation of the m_{top} measurements from the various experiments, using different top-quark signatures and collision data sets, taking into account possible de-correlation or anti-correlation effects, are expected to enable significant precision improvements [47]. In addition, the use of common $t\bar{t}$ MC samples, processed through the experiment-specific detector simulations, is planned to precisely assess the systematic uncertainties related to the baseline MC choices, and to evaluate the level of compatibility between different strategies adopted to evaluate MC/theory related uncertainties. The results of these investigations, together with improvements on the individual measurements, will boost the understanding of inter-experiment correlations and is expected to substantially increase the final precision achievable from the combination of the available m_{top} results.

7. Conclusions

A review of the methodologies exploited for the measurements of m_{top} at the Tevatron and LHC hadron colliders has been presented, together with a discussion of the main theoretical and experimental uncertainties, and the prospects for their reduction in the course of the LHC Run-2,3. The application of complementary techniques, based either on the direct reconstruction of the top-quark decay products, or on the comparison of the experimental $t\bar{t}$ (differential) cross-section measurements with the corresponding theoretical calculations, will allow to reduce the theoretical uncertainties related to the identification of the m_{top}^{MC} parameter, used for the direct measurement calibrations, to well defined top-quark mass schemes (*e.g.* m_{top}^{pole}). This aspect, together with significant foreseeable improvements on the precision reach of individual m_{top} results, and optimised treatments of the measurement correlations in future multi-experiment m_{top} combinations, provide strong confidence that an overall m_{top} precision of the order of 200–300 MeV [107,108], comparable with the projections for the linear collider [109], can be achieved at the LHC. The unprecedented precision of the m_{top} results, and their unambiguous theoretical interpretation, will dramatically influence the predictions regarding the stability of the Higgs field and its effects on the evolution of the Universe, as well as the sensitivity of SM consistency tests and indirect NP searches.

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References

[1] K. Kröninger, A.B. Meyer, P. Uwer, Top-Quark Physics at the LHC, in: T. Schöorner-Sadenius (Ed.), The Large Hadron Collider: Harvest of Run 1, Springer, 2015, pp. 259–300, doi:10.1007/978-3-319-15001-7_7. arXiv: 1506.02800.
[2] E. Boss, et al., The top quark, Phys. Usp. 58 (2015) 1241–1269, doi:10.3367/UFNe.0185.201512a.1241. arXiv: 1509.03325.
[3] M. Baak, et al., The global electroweak fit at NNLO and prospects for the LHC and ILC, Eur. Phys. J. C74 (2014) 3046, doi:10.1140/epjc/s10052-014-3046-5. arXiv: 1407.3792.
[4] ATLAS Collaboration, Observation of a new particle in the search for the standard model Higgs boson with the ATLAS detector at the LHC, Phys. Lett. B 716 (2012) 1, doi:10.1016/j.physletb.2012.08.020. arXiv: 1207.7214.
[5] CMS Collaboration, Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, Phys. Lett. B 716 (2012) 30, doi:10.1016/j.physletb.2012.08.021. arXiv: 1207.7235.
[6] G. Degrassi, et al., Higgs mass and vacuum stability in the standard model at NNLO, J. High Energy Phys. 1208 (2012) 098, doi:10.1007/JHEP08(2012)098. arXiv: 1205.6497.

[7] F. Bezrukov, M. Shaposhnikov, Why should we care about the top quark Yukawa coupling? J. Exp. Theor. Phys. 120 (3) (2015) 335, doi:10.1134/S1063776115030152. arXiv: 1411.1923.
[8] ATLAS and CMS Collaborations, Combined measurement of the Higgs Boson mass in pp collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS experiments, Phys. Rev. Lett. 114 (2015) 191803, doi:10.1103/PhysRevLett.114.191803. arXiv: 1503.07589.
[9] S. Frixione, A. Mitov, Determination of the top quark mass from leptonic observables, J. High Energy Phys. 1409 (2014) 012, doi:10.1007/JHEP09(2014)012. arXiv: 1407.2763.
[10] A.H. Hoang, The Top Mass: Interpretation and Theoretical Uncertainties, 2014, arXiv:1412.3649.
[11] S. Weinzierl, Precision on the Top Mass, 2015, arXiv:1505.00630.
[12] A. Juste, et al., Determination of the top quark mass circa 2013: methods, subtleties, perspectives, Eur. Phys. J. C74 (2014) 3119, doi:10.1140/epjc/s10052-014-3119-5. arXiv: 1310.0799.
[13] S. Moch, et al., High Precision Fundamental Constants at the TeV scale, 2014, arXiv:1405.4781.
[14] M. Czakon, P. Fiedler, A. Mitov, Total top-quark pair-production cross section at hadron colliders through $O(\alpha_S^4)$, Phys. Rev. Lett. 110 (2013) 252004, doi:10.1103/PhysRevLett.110.252004. arXiv: 1303.6254.
[15] CDF Collaboration, Observation of top quark production in $\bar{p}p$ collisions, Phys. Rev. Lett. 74 (1995) 2626, doi:10.1103/PhysRevLett.74.2626. arXiv: hep-ex/9503002.
[16] D0 Collaboration, Observation of the top quark, Phys. Rev. Lett. 74 (1995) 2632, doi:10.1103/PhysRevLett.74.2632. arXiv: hep-ex/9503003.
[17] G. Apollinari, O. Brüning, L. Rossi, High Luminosity LHC Project Description, Technical Report, 2014. https://cds.cern.ch/record/1974419.
[18] K. Olive, et al., Review of particle physics, Chin. Phys. C38 (2014) 090001, doi:10.1088/1674-1137/38/9/090001.
[19] CDF Collaboration, Measurement of the J/ψ meson and $b-$hadron production cross sections in $p\bar{p}$ collisions at $\sqrt{s} = 1960$ GeV, Phys. Rev. D71 (2005) 032001, doi:10.1103/PhysRevD.71.032001. arXiv: hep-ex/0412071.
[20] CDF Collaboration, Measurements of inclusive W and Z cross sections in $p\bar{p}$ anti-p collisions at $\sqrt{s} = 1.96$ TeV, J. Phys. G34 (2007) 2457, doi:10.1088/0954-3899/34/12/001. arXiv: hep-ex/0508029.
[21] D0 Collaboration, The D0 detector, Nucl. Instrum. Method A338 (1994) 185, doi:10.1016/0168-9002(94)91312-9.
[22] D0 Collaboration, The upgraded D0 detector, Nucl. Instrum. Method A565 (2006) 463, doi:10.1016/j.nima.2006.05.248. arXiv: physics/0507191.
[23] ATLAS Collaboration, The ATLAS experiment at the CERN large hadron collider, JINST 3 (2008) S08003, doi:10.1088/1748-0221/3/08/S08003.
[24] CMS Collaboration, The CMS experiment at the CERN LHC, JINST 3 (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
[25] A. Buckley, et al., General-purpose event generators for LHC physics, Phys. Rep. 504 (2011) 145, doi:10.1016/j.physrep.2011.03.005. arXiv: 1101.2599.
[26] CMS Collaboration, Particle-Flow Event Reconstruction in CMS and Performance for Jets, Taus, and MET, Conference note, CMS-PAS-PFT-09-001, 2009. https://cds.cern.ch/record/1194487.
[27] CMS Collaboration, Commissioning of the Particle-flow Event Reconstruction with the first LHC collisions recorded in the CMS detector, Conference note, CMS-PAS-PFT-10-001, 2010. https://cds.cern.ch/record/1247373.
[28] A. Bhatti, et al., Determination of the jet energy scale at the collider detector at fermilab, Nucl. Instrum. Methods A566 (2006) 375, doi:10.1016/j.nima.2006.05.269. arXiv: hep-ex/0510047.
[29] D0 Collaboration, Jet energy scale determination in the D0 experiment, Nucl. Instrum. Methods A763 (2014) 442, doi:10.1016/j.nima.2014.05.044. arXiv: 1312.6873.
[30] ATLAS Collaboration, Jet energy measurement and its systematic uncertainty in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector, Eur. Phys. J. C75 (2015) 17, doi:10.1140/epjc/s10052-014-3190-y. arXiv: 1406.0076.
[31] ATLAS Collaboration, Jet energy measurement with the ATLAS detector in proton-proton collisions at $\sqrt{s} = 7$ TeV, Eur. Phys. J. C73 (2013) 2304, doi:10.1140/epjc/s10052-013-2304-2. arXiv: 1112.6426.
[32] CMS Collaboration, Determination of jet energy calibration and transverse momentum resolution in CMS, JINST. 6 (2011) P11002, doi:10.1088/1748-0221/6/11/P11002. arXiv: 1107.4277.
[33] CMS Collaboration, Jet Energy Scale Performance in 2011, Detector performance note, CMS-DP-2012-006, 2012. https://cds.cern.ch/record/1454659.
[34] CMS Collaboration, CMS JEC Run I Legacy Performance Plots, Detector performance note, CMS-DP-2015-044, 2015. https://cds.cern.ch/record/2052170.
[35] CDF Collaboration, Measurement of the $t\bar{t}$ production cross section in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV using lepton + jets events with secondary vertex b-tagging, Phys. Rev. D 71 (2005) 052003, doi:10.1103/PhysRevD.71.052003. arXiv: hep-ex/0410041.
[36] D0 Collaboration, b-Jet identification in the D0 experiment, Nucl. Instrum. Method A620 (2010) 490, doi:10.1016/j.nima.2010.03.118. arXiv: 1002.4224.
[37] ATLAS Collaboration, Measuring the Mistag rate with 5 fb^{-1} of Data from the ATLAS Detector, Conference note, ATLAS-CONF-2012-040, 2012. http://cds.cern.ch/record/1435194.
[38] ATLAS Collaboration, Measuring the b-tag Efficiency in a Sample of Jets Containing Muons with 5 fb^{-1} of Data from the ATLAS Detector, Conference note, ATLAS-CONF-2012-043, 2012. http://cds.cern.ch/record/1435197.
[39] ATLAS Collaboration, Calibration of b-tagging Using Dileptonic Top Pair Events in a Combinatorial Likelihood Approach with the ATLAS Experiment, Conference note, ATLAS-CONF-2014-004, 2014. http://cds.cern.ch/record/1664335.
[40] CMS Collaboration, Identification of b-quark jets with the CMS experiment, JINST 8 (2013) P04013, doi:10.1088/1748-0221/8/04/P04013. arXiv: 1211.4462.
[41] J. Erdmann, et al., A likelihood-based reconstruction algorithm for top-quark pairs and the KLFitter framework, Nucl. Instrum. Method A748 (2014) 18, doi:10.1016/j.nima.2014.02.029. arXiv: 1312.5595.
[42] D0 Collaboration, Measurement of the top quark mass in the dilepton channel, Phys. Rev. D 60 (1999) 052001, doi:10.1103/PhysRevD.60.052001. arXiv: hep-ex/9808029.
[43] CDF Collaboration, Measurement of the top quark mass using template methods on dilepton events in $p\bar{p}$ collisions at $\sqrt{s} = 1.96\tilde{}$ TeV, Phys. Rev. D 73 (2006) 112006, doi:10.1103/PhysRevD.73.112006. arXiv: hep-ex/0602008.
[44] CMS Collaboration, Measurement of the top-quark mass in $t\bar{t}$ events with dilepton final states in pp collisions at $\sqrt{s} = 7$ TeV, Eur. Phys. J. C72 (2012) 2202, doi:10.1140/epjc/s10052-012-2202-z. arXiv: 1209.2393.
[45] ATLAS, CDF, CMS and D0 Collaborations, First Combination of Tevatron and LHC Measurements of the Top-quark Mass, 2014. arXiv:1403.4427
[46] K. Cranmer, Kernel estimation in high-energy physics, Comput. Phys. Commun. 136 (2001) 198, doi:10.1016/S0010-4655(00)00243-5. arXiv: hep-ex/0011057.
[47] ATLAS Collaboration, Measurement of the top quark mass in the $t\bar{t} \to$ lepton+jets and $t\bar{t} \to$ dilepton channels using $\sqrt{s} = 7$TeV ATLAS data, Eur. Phys. J. C75 (2015) 330, doi:10.1140/epjc/s10052-015-3544-0. arXiv: 1503.05427.
[48] CDF Collaboration, Top quark mass measurement using the template method in the lepton+jets channel at CDF II, Phys. Rev. D 73 (2006) 032003, doi:10.1103/PhysRevD.73.032003. arXiv: hep-ex/0510048.
[49] D0 Collaboration, Precision measurement of the top-quark mass in lepton+jets final states, Phys. Rev. D91 (2015) 112003, doi:10.1103/PhysRevD.91.112003. arXiv: 1501.07912.
[50] T. Martini, P. Uwer, The matrix element method at next-to-leading order accuracy, Acta Phys. Pol. B46 (11) (2015) 2143, doi:10.5506/APhysPolB.46.2143. arXiv: 1511.07150.
[51] F. Fiedler, et al., The matrix element method and its application in measurements of the top quark mass, Nucl. Instrum. Method A624 (2010) 203, doi:10.1016/j.nima.2010.09.024. arXiv: 1003.1316.
[52] I. Volobouev, Matrix element method, in: HEP: Transfer Functions, Efficiencies, and Likelihood Normalization, 2011. arXiv: 1101.2259.
[53] DELPHI Collaboration, Measurement of the mass and width of the W boson in e^+e^- collisions at $\sqrt{s} = 161$ GeV-209 GeV, Eur. Phys. J. C55 (2008) 1, doi:10.1140/epjc/s10052-008-0585-7. arXiv: 0803.2534.

[54] ATLAS Collaboration, Measurement of $t\bar{t}$ production with a veto on additional central jet activity in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector, Eur. Phy. J. C72 (2012) 2043, doi:10.1140/epjc/s10052-012-2043-9. arXiv: 1203.5015.
[55] CMS Collaboration, Measurement of jet multiplicity in di-leptonic top pair events, Conference note, CMS-PAS-TOP-12-023, 2012. https://cds.cern.ch/record/1478672.
[56] ATLAS Collaboration, Measurement of jet shapes in top-quark pair events at $\sqrt{s} = 7$ TeV using the ATLAS detector, Eur. Phys. J. C73 (12) (2013) 2676, doi:10.1140/epjc/s10052-013-2676-3. arXiv: 1307.5749.
[57] CMS Collaboration, Study of the underlying event, b-quark fragmentation and hadronization properties in $t\bar{t}$ events, Conference note, CMS-PAS-TOP-13-007, 2013. https://cds.cern.ch/record/1600599.
[58] CMS Collaboration, Measurement of the top quark mass using proton-proton data at $\sqrt{s} = 7$ and 8 TeV, Phys. Rev. D93 (2016) 072004, doi:10.1103/PhysRevD.93.072004. arXiv:1509.04044.
[59] CDF Collaboration, Precision top-quark mass measurements at CDF, Phys. Rev. Lett. 109 (2012) 152003, doi:10.1103/PhysRevLett.109.152003. arXiv: 1207.6758.
[60] CDF Collaboration, Improved b-jet Energy Correction for $H \to b\bar{b}$ Searches at CDF(2011).
[61] D0 Collaboration, Precision measurement of the top-quark mass in lepton+jets final states, Phys. Rev. Lett. 113 (2014) 032002, doi:10.1103/PhysRevLett.113.032002. arXiv: 1405.1756.
[62] CDF Collaboration, Top quark mass measurement in the lepton + jets channel using a matrix element method and *in situ* jet energy calibration, Phys. Rev. Lett. 105 (2010) 252001, doi:10.1103/PhysRevLett.105.252001. arXiv: 1010.4582.
[63] O. Brandt, et al., Acceleration of matrix element computations for precision measurements, Nucl. Instrum. Method A775 (2015) 27, doi:10.1016/j.nima.2014.11.063. arXiv: 1410.6319.
[64] CMS Collaboration, Measurement of the top-quark mass in $t\bar{t}$ events with lepton+jets final states in pp collisions at $\sqrt{s} = 7$ TeV, J. High Energy Phys. 12 (2012) 105, doi:10.1007/JHEP12(2012)105. arXiv: 1209.2319.
[65] CDF Collaboration, Measurement of the top-quark mass in the $t\bar{t}$ dilepton channel using the full CDF Run II data set, Phys. Rev. D92 (2015) 032003, doi:10.1103/PhysRevD.92.032003. arXiv: 1505.00500.
[66] D0 Collaboration, Precise measurement of the top quark mass in dilepton decays using optimized neutrino weighting, Phys. Lett. B752 (2016) 18–26, doi:10.1016/j.physletb.2015.10.086. arXiv: 1508.03322.
[67] ATLAS and CMS Collaborations, Combination of ATLAS and CMS Results on the Mass of the Top Quark Using up to 4.9 fb^{-1} of Data, Conference notes, CMS-PAS-TOP-13-005 and ATLAS-CONF-2013-102, 2013. https://cds.cern.ch/record/1601811; https://cds.cern.ch/record/1603490.
[68] CMS Collaboration, Determination of the Top-quark Mass from the m(lb) Distribution in Dileptonic $t\bar{t}$ events at $\sqrt{s} = 8$ TeV, Conference note, CMS-PAS-TOP-14-014, 2014. http://cds.cern.ch/record/1966416.
[69] CDF Collaboration, Measurement of the Top-quark mass in the all-hadronic channel using the full CDF data set, Phys. Rev. D90 (2014) 091101, doi:10.1103/PhysRevD.90.091101. arXiv: 1409.4906.
[70] ATLAS Collaboration, Measurement of the top-quark mass in the fully hadronic decay channel from ATLAS data at $\sqrt{s} = 7$ TeV,, Eur. Phys. J. C75 (2015) 158, doi:10.1140/epjc/s10052-015-3373-1. arXiv: 1409.0832.
[71] CMS Collaboration, Measurement of the top-quark mass in all-jets $t\bar{t}$ events in pp collisions at $\sqrt{s}$=7 TeV, Eur. Phys. J. C74 (2014) 2758, doi:10.1140/epjc/s10052-014-2758-x. arXiv: 1307.4617.
[72] CDF Collaboration, Top-quark mass measurement in events with jets and missing transverse energy using the full CDF data set, Phys. Rev. D88 (2013) 011101, doi:10.1103/PhysRevD.88.011101. arXiv: 1305.3339.
[73] ATLAS Collaboration, Measurement of the Top quark Mass in Topologies Enhanced with Single Top-quarks Produced in the t-channel in $\sqrt{s} = 8$ TeV ATLAS data, Conference note, ATLAS-CONF-2014-055, 2014. http://cds.cern.ch/record/1951323.
[74] CDF Collaboration, Measurements of the Top-quark Mass Using Charged Particle Tracking, Phys. Rev. D81 (2010) 032002, doi:10.1103/PhysRevD.81.032002. arXiv: 0910.0969.
[75] C.S. Hill, J.R. Incandela, J.M. Lamb, A method for measurement of the top quark mass using the mean decay length of b hadrons in $t\bar{t}$ events, Phys. Rev. D71 (2005) 054029, doi:10.1103/PhysRevD.71.054029. arXiv: hep-ex/0501043.
[76] CMS Collaboration, Measurement of the Top Quark Mass Using the B-hadron Lifetime Technique, Conference note, CMS-PAS-TOP-12-030, 2013. http://cds.cern.ch/record/1563140.
[77] CMS Collaboration, Top Quark Mass Combinations Using the 2010, 2011 and 2012 Data, Conference note, CMS-PAS-TOP-13-002, 2013. http://cds.cern.ch/record/1599576.
[78] CMS Collaboration, Measurement of masses in the $t\bar{t}$ system by kinematic endpoints in pp collisions at $\sqrt{s} = 7$ TeV, Eur. Phys. J. C73 (2013) 2494, doi:10.1140/epjc/s10052-013-2494-7. arXiv: 1304.5783.
[79] M. Burns, et al., Using subsystem MT2 for complete mass determinations in decay chains with missing energy at hadron colliders, J. High Energy Phys. 03 (2009) 143, doi:10.1088/1126-6708/2009/03/143. arXiv: 0810.5576.
[80] K. Agashe, R. Franceschini, D. Kim, Simple “invariance” of two-body decay kinematics, Phys. Rev. D88 (2013) 057701, doi:10.1103/PhysRevD.88.057701. arXiv: 1209.0772.
[81] CMS Collaboration, Measurement of the Top-quark Mass from the b Jet Energy Spectrum, Conference note, CMS-PAS-TOP-15-002, 2015. http://cds.cern.ch/record/2053086.
[82] ATLAS Collaboration, Measurement of top quark polarization in top-antitop events from proton-proton collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector, Phys. Rev. Lett. 111 (2013) 232002, doi:10.1103/PhysRevLett.111.232002. arXiv: 1307.6511.
[83] S. Kawabata, et al., Weight function method for precise determination of top quark mass at large hadron collider, Phys. Lett. B741 (2015) 232, doi:10.1016/j.physletb.2014.12.044. arXiv: 1405.2395.
[84] L. LyonsD. Gibaut and P. Clifford, How to combine correlated estimates of a single physical quantity, Nucl. Instrum. Method A270 (1988) 110, doi:10.1016/0168-9002(88)90018-6.
[85] A. Valassi, Combining correlated measurements of several different physical quantities, Nucl. Instrum. Method A500 (2003) 391, doi:10.1016/S0168-9002(03)00329-2.
[86] R. Nisius, On the combination of correlated estimates of a physics observable, Eur. Phys. J. C74 (2014) 3004, doi:10.1140/epjc/s10052-014-3004-2. arXiv: 1402.4016.
[87] Tevatron Electroweak Working Group, Combination of CDF and D0 Results on the Mass of the Top Quark Using up to 9.7 fb^{-1} at the Tevatron, arXiv:1407.2682(2014).
[88] D0 Collaboration, Measurement of the Inclusive $t\bar{t}$ Production Cross Section in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV, Conference note, D0 Note 6453-CONF, 2015. http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/TOP/T106/.
[89] ATLAS Collaboration, Measurement of the $t\bar{t}$ production cross-section using $e\mu$ events with b -tagged jets in pp collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS detector, Eur. Phys. J. C74 (2014) 3109, doi:10.1140/epjc/s10052-014-3109-7. arXiv: 1406.5375.
[90] M. Botje, et al., The PDF4LHC Working Group Interim Recommendations, 2011, arXiv:1101.0538.
[91] CMS Collaboration, Measurement of the $t\bar{t}$ Production Cross Section in the $e\mu$ Channel in pp Collisions at 7 and 8 TeV, Conference note, CMS-PAS-TOP-13-004, 2015. http://cds.cern.ch/record/2048642.
[92] R.D. Ball, et al., Parton distributions for the LHC Run II, J. High Energy Phys. 04 (2015) 040, doi:10.1007/JHEP04(2015)040. arXiv: 1410.8849.
[93] S. Alioli, et al., A new observable to measure the top-quark mass at hadron colliders, Eur. Phys. J. C73 (2013) 2438, doi:10.1140/epjc/s10052-013-2438-2. arXiv: 1303.6415.
[94] ATLAS Collaboration, Determination of the top-quark pole mass using $t\bar{t} + 1$-jet events collected with the ATLAS experiment in 7 TeV pp collisions, J. High Energy Phys. 10 (2015) 121, doi:10.1007/JHEP10(2015)121. arXiv: 1507.01769.

[95] CMS Collaboration, Calculation of Residual Energy Correction for b Jets Using Z+b Events in 8 TeV pp Collisions, Conference note, CMS-PAS-JME-13-001, 2014. http://cds.cern.ch/record/1951028.

[96] ATLAS Collaboration, Measurement of the $t\bar{t}$ production cross-section as a function of jet multiplicity and jet transverse momentum in 7 TeV proton–proton collisions with the ATLAS detector, J. High Energy Phys. 01 (2015) 020, doi:10.1007/JHEP01(2015)020. arXiv: 1407.0891.

[97] CMS Collaboration, Measurement of $t\bar{t}$ production with additional jet activity, including b quark jets, in the dilepton channel using pp collisions at $\sqrt{s} = 8$ TeV, Eur. Phys. J. C (2016). (Accepted for publication).

[98] S. Biswas, K. Melnikov, M. Schulze, Next-to-leading order QCD effects and the top quark mass measurements at the LHC, J. High Energy Phys. 08 (2010) 048, doi:10.1007/JHEP08(2010)048. arXiv: 1006.0910.

[99] G. Heinrich, et al., NLO QCD corrections to $W^+W^-b\bar{b}$ production with leptonic decays in the light of top quark mass and asymmetry measurements, J. High Energy Phys. 06 (2014) 158, doi:10.1007/JHEP06(2014)158. arXiv: 1312.6659.

[100] J.M. Campbell, et al., Top-pair production and decay at NLO matched with parton showers, J. High Energy Phys. 04 (2015) 114, doi:10.1007/JHEP04(2015)114. arXiv: 1412.1828.

[101] A. Kharchilava, Top mass determination in leptonic final states with J/ψ, Phys. Lett. B476 (2000) 73, doi:10.1016/S0370-2693(00)00120-9. arXiv: hep-ph/9912320.

[102] ATLAS Collaboration, Reconstruction of J/ψ Mesons in $t\bar{t}$ final states in Proton–Proton Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Detector, Conference note, ATLAS-CONF-2015-040, 2015. http://cds.cern.ch/record/2046216.

[103] ATLAS Collaboration, Performance of jet substructure techniques for large-R jets in proton–proton collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector, J. High Energy Phys. 09 (2013) 076, doi:10.1007/JHEP09(2013)076. arXiv: 1306.4945.

[104] ATLAS Collaboration, Performance of Boosted Top Quark Identification in 2012 ATLAS Data, Conference note, ATLAS-CONF-2013-084, 2013. http://cds.cern.ch/record/1571040.

[105] CMS Collaboration, Boosted Top Jet Tagging at CMS, Conference note, CMS-PAS-JME-13-007, 2014. http://cds.cern.ch/record/1647419.

[106] G.F. Giudice, P. Paradisi, A. Strumia, Indirect determinations of the top quark mass, J. High Energy Phys. 11 (2015) 192, doi:10.1007/JHEP11(2015)192. arXiv: 1508.05332.

[107] CMS Collaboration, Projected Improvement of the Accuracy of Top-quark Mass Measurements at the Upgraded LHC, Conference note, CMS-PAS-FTR-13-017, 2013. https://cds.cern.ch/record/1605627.

[108] K. Agashe, et al., Working group report: top quark, in: Community Summer Study 2013: Snowmass on the Mississippi (CSS2013) Minneapolis, MN, USA, July 29-August 6, 2013, 2013. arXiv: 1311.2028.

[109] K. Seidel, et al., Top quark mass measurements at and above threshold at CLIC, Eur. Phys. J. C73 (2013) 2530, doi:10.1140/epjc/s10052-013-2530-7. arXiv: 1303.3758.