PROCEEDINGS OF SCIENCE

Top-quark mass at Tevatron and LHC

Stanislav Tokar[∗†] **on behalf of the ATLAS, CDF, CMS and D0 collaborations.**
Comenius University, Bratislava, Slovakia
E-mail: tokar@fmph.uniba.sk

The top-quark mass measurements carried out by the Tevatron and LHC experiments are summarized. Results of different approaches to the top-quark mass reconstruction are presented. Masses from different measurements are in good agreement within uncertainties. Precision of the measurements with the directly measured top-quark mass is now better than 0.5%. Progress in determination of the top-quark pole mass is reported and the relation between the directly measured top-quark mass and top-quark pole mass is discussed.

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∗Speaker.

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1. Introduction

The top quark is the heaviest particle of the Standard Model (SM) and its mass, $m_{\rm t}$, is an important SM parameter. Precise measurements of $m_{\rm t}$ provide critical inputs to fits of global electroweak parameters [1] that test the internal consistency of the SM. In addition, the value of $m_{\rm t}$ strongly affects the quartic coupling of the SM Higgs potential, which has cosmological implications [2]. Up to 2010 the top-quark mass measurements were performed exclusively by the CDF and D0 collaborations based on the Tevatron proton-antiproton ($p\bar{p}$) collision data. In 2011 the Tevatron accelerator was stopped having collected a data sample with an integrated luminosity of $\approx$ 10 fb^{-1} per experiment. Since 2010, measurements of $m_{\rm t}$ from the LHC by the ATLAS and CMS collaborations have become available. They are based on proton-proton (pp) collisions at a centre-of-mass energy of $\sqrt{s}$ = 7 and 8 TeV.

2. On top-quark mass

From theoretical point of view the top-quark pole mass is defined as the real part of the pole in the perturbative top-quark propagator. However, due to colour confinement the top quark is not asymptotically a free particle and thus the pole exhibits, due to the non-perturbative effects, an intrinsic ambiguity of order $\Lambda_{\rm QCD}$. From theory point of view it would be desirable to have the top-quark mass defined within a well-defined renormalization scheme and therefore it appears as prospective to analyze the measured top-quark mass within the concept of the short range mass (MSR) [3, 4]. Within this scheme only self-energy contributions above the scale R are absorbed into the MSR mass definition. Formally one can relate the MSR mass with the top-quark pole mass as $m_t^{\rm pole} = m_t^{\rm MSR}(R=0)$ and with the $\overline{\rm MS}$ mass as follows: $m_t^{\overline{\rm MS}} = m_t^{\rm MSR}(R=\overline{m})$. In this approach, reconstructed top-quark mass, $m_t^{\rm rec}$, is connected with $m_t^{\rm MSR}(R)$ taken at the scale of 1 GeV:

$$m_t^{\rm rec} = m_t^{\rm MSR}(R=1\,{\rm GeV}) + \Delta_t^{\rm MSR}(R=1\,{\rm GeV}), \quad \Delta_t^{\rm MSR}(R=1\,{\rm GeV}) \sim O(1\,{\rm GeV}). \tag{2.1}$$

The difference, $\Delta_t^{\rm MSR}$, between the reconstructed top-quark mass and the MSR mass is mainly related to the contributions coming from scales below Λ_s = 1 GeV. The MSR mass assumes full QCD calculations where perturbation theory gives corrections from below the scale R = 1 GeV and hadronization effects are included based on factorization [4].

Another important issue is the ambiguity of $m_t^{\rm pole}$. For this it is important to have a relation between $m_t^{\rm pole}$ and a running mass with a well defined renormalization scheme. Such a relation has been found in four loop approximation between $m_t^{\rm pole}$ and $\overline{\rm MS}$ mass ($\overline{m}$) [5]. The last term in the $m_t^{\rm pole}$ expansion is 195 MeV and though it is not known what will be the value of the next term in the expansion, the uncertainty connected with the non-perturbative effects has been already calculated – its value is 77 MeV [6] and can be considered as an ambiguity in $m_t^{\rm pole}$.

3. Top-quark mass reconstruction

Presently is the top-quark mass is inferred in two basic ways. The first approach is based on direct kinematical reconstruction of the invariant mass of the top-quark decay product via different techniques like matrix element methods, template methods, etc. The second approach employs the relation of the top-quark mass and the top-quark pair production cross section. Up to now the most precise results are obtained within the first (kinematic) approach, but in this approach the renormalization scheme is not well defined and thus it is not clear what is the relation between the measured mass and the mass parameter used in theoretical predictions. For this reason more and more attention is devoted to the second approach, where top-quark mass is inferred from the measured cross section of $t\bar{t}$ production. Here will be reported about both these approaches.

3.1 Kinematic approach

The kinematic approach for the reconstruction of $m_{\rm top}$ employs observables sensitive to top-quark mass. It can be e.g. the invariant mass m_t reconstructed from top-quark decay products.

Template method. The essence of the template method [9, 10] is in a comparison of the distribution of an observable sensitive to top-quark mass reconstructed from data with modeled distributions (templates) of the sensitive observable obtained by simulation of signal and background. The reconstructed data distribution is compared to a combination of background template and signal templates with different input top-quark masses and the combination giving the best agreement between the data distribution and the simulated one, found by the likelihood fit, determines the top-quark mass. As a first step a kinematic fit is usually applied to each of the selected $t\bar{t}$-candidate events and, as a result of this, a reconstructed top-quark mass, m_t, is obtained for each event. The signal template is parametrized by a function $f_s\left(m_t, m_{\rm top}, \vec{\alpha}\right)$, where $m_{\rm top}$ is the input top-quark mass and $\vec{\alpha}$ is a vector of parameters known from simulation. The background template is also parametrized, but here the function does not depend on $m_{\rm top}$: $f_b\left(m_t, \vec{\beta}\right)$. The likelihood function is constructed using the signal and background templates, and taking into account the background normalization uncertainties as well as the uncertainties in the parameters of signal and background parametrizations – see details e.g. in Ref. [10] .

Matrix elements method. This method was proposed by K. Kondo, see details in Ref.[11], and is based on the full event kinematics. Each event can be represented by a set of variables, $\vec{x}$, that characterizes the event reconstructed objects, e.g. four-momenta of the final state particles. For each event probabilities that its kinematics comes from signal, i.e. for $t\bar{t}$ production ($P_{t\bar{t}}$), and background ($P_{\rm bkg}$) are estimated. The signal probability reads

$$P_{t\bar{t}} = \frac{1}{\sigma_{t\bar{t}}} \sum_{\rm flavors} \int dq_1 dq_2 \frac{d\sigma\left(p\bar{p} \to t\bar{t} \to \vec{y}\right)}{d\vec{y}} \cdot f\left(q_1\right) f\left(q_2\right) \cdot W\left(\vec{x}, \vec{y}\right), \tag{3.1}$$

where $\sigma_{t\bar{t}}$ is the total cross section of $t\bar{t}$ production, $\vec{x}$ ($\vec{y}$) are the reconstructed (partonic) four momenta of the final state particles (partons), $f\left(q_1\right)$ and $f\left(q_2\right)$ are parton distribution functions (PDFs) of colliding protons, and $W\left(\vec{x}, \vec{y}\right)$ is the detector transition function giving the probability that partons characterized by $\vec{y}$ will be reconstructed as final state objects characterized by $\vec{x}$. A similar expression can also be written for $P_{\rm bkg}$. The top-quark mass is extracted by maximalizing the likelihood based on the signal and background probabilities $P_{t\bar{t}}$ and $P_{\rm bkg}$.

Ideogram method. This method [12, 13] combines matrix elements and template approaches. It is based on an event-by-event likelihood which is constructed mass using templates for signal and background and includes all parton-jet assignments with the corresponding weights.

Other kinematic methods. There is a series of methods proposed to avoid using calorimetric information aiming at suppression of the systematics connected with jet energy scale. In these methods top-quark mass sensitive observables not connected with jets are used [14, 15]. Among them are b-decay transverse distance, L_{xy}, lepton p_{T}, etc.

The choice of the method used in the analysis depends on the type of $t\bar{t}$ events used. There are three basic channels classified according to the type of decay of the W bosons: Lepton + jets channel: $t\bar{t} \to WbW\bar{b} \to (\ell\nu_\ell)(jj)b\bar{b}$ (one of the W bosons decays leptonicaly and the other hadronicaly), Dilepton channel: $t\bar{t} \to WbW\bar{b} \to (\ell\nu_\ell)(\ell\nu_\ell)b\bar{b}$ (both W bosons decay leptonicaly), All jets (all hadronic) channel: $t\bar{t} \to WbW\bar{b} \to (jj)(jj)b\bar{b}$ (both W bosons decay hadronicaly). Note that the $t\bar{t}$ events with τ leptons are not discussed here.

3.2 Top-quark mass reconstructed at Tevatron

The Tevatron experiments in their second phase (Run II) worked with colliding beams of proton and anti-protons ($p\bar{p}$) at a center-of-mass energy $\sqrt{s} = 1.96$ TeV and the final accumulated statistics is around 10 fb^{-1} per experiment. Practically all the above mentioned techniques of top-quark mass reconstruction have their origin at the Tevatron experiments. Despite the fact that the Tevatron accelerator was stopped in 2011, results of the data analysis are coming and in many respects are competitive with the LHC results.

Top-quark mass at CDF. Here it will be mention only the latest CDF measurement obtained in dilepton channel and the summary of all CDF top-quark mass measurements carried out in Run I and II. The top-quark mass measurement, carried out in the dilepton channel using a data sample of 9.1 fb^{-1}, employs a template method [16]. The applied technique uses two observables. One of them is M_t^{reco} – an invariant mass of the top-quark decay products ($\ell\nu b$), and the second observable is the so-called alternative mass: $M_{\ell b}^{\mathrm{alt}} = \sqrt{(l_1 \cdot b_1)(l_2 \cdot b_2)/E_{b_1}E_{b_2}}$, where $l_{1(2)}$ and $b_{1(2)}$ are four-momenta of leptons and b-jets, respectively. To account for the unconstrained kinematics of the top-quark dilepton channel, the phase space of the azimuthal angles of both neutrino momenta was scanned and for each point the top-quark mass was reconstructed by minimizing a χ^2 function for the $t\bar{t}$ final state hypothesis and a weight was assigned to it. The mass, M_t^{reco}, with the highest weight is taken for each event. The signal and background templates were created for an observable, M^{hyb}, which was a combination of M_t^{reco} and $M_{\ell b}^{\mathrm{alt}}$: $M^{\mathrm{hyb}} = wM_t^{\mathrm{reco}} + (1-w)M_{\ell b}^{\mathrm{alt}}$ with the weight w found by minimizing the total uncertainty ($w = 0.6$). The top-quark mass is extracted from a likelihood fit, where the likelihood expression is based on the signal and background M^{hyb} templates. Main source of systematics still comes from jet energy scale (2.2%). The total systematic uncertainty is 2.5% and the statistical one is 1.9%. The extracted mass is:

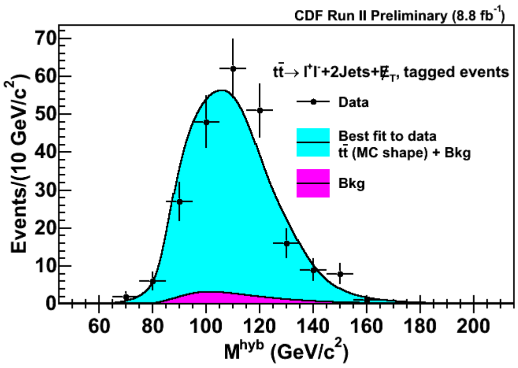

Figure 1: Likelihood fit to the dilepton data, b-tagged events. Background (purple) and signal+background (cyan) p.d.f.'s are superimposed to the M^{hyb} distribution from data (points).

$$m_t = 171.5 \pm 1.9 \text{ (stat) } \pm 2.5 \text{ (syst) GeV.}$$

This result improves the previous CDF result measured in the dilepton channel [17].

The CDF collaboration summarized its top-quark measurements performed in Run I and Run II [18]. The summary contains a combination of eight measurements and also the top-quark masses in the ℓ+jets, all jets, $\ell\ell$ and MET decay channels. Considering correlations of the uncertainties, and combining the statistical and systematic uncertainties, the resulting CDF average mass of the top quark was found to be $m_t = 173.16 \pm 0.93$ GeV, corresponding to a relative precision of 0.54%. The channel masses are:

$$m_t^{\ell+\text{jets}} = 172.51 \pm 1.02 \text{ GeV}$$
$$m_t^{\ell\ell} = 169.40 \pm 2.76 \text{ GeV}$$
$$m_t^{\text{allJ}} = 174.99 \pm 1.90 \text{ GeV}$$
$$m_t^{\text{MET}} = 173.64 \pm 1.79 \text{ GeV}$$

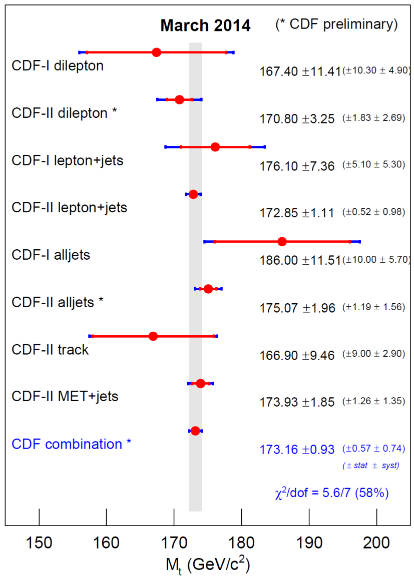

Figure 2: Summary of the CDF measurements and resulting combination of the top-quark mass. The red (blue) lines correspond to the statistical (total) uncertainty.

Top-quark mass at D0. Here will be mentioned the latest D0 top-quark mass measurements performed in dilepton and ℓ+jets channels. Both measurements were carried out using the full D0 data sample of 9.7 fb^{-1}. In the case of the dilepton analysis [19] a matrix element technique was applied. This technique associates to each event a probability

$$P\left(\vec{x}, f_{t\bar{t}}, m_{\text{top}}\right) = f_{t\bar{t}} P_{t\bar{t}}\left(\vec{x}, m_{\text{top}}\right) + \left(1 - f_{t\bar{t}}\right) P_{\text{bkg}}\left(\vec{x}\right), \tag{3.2}$$

where $\vec{x}$ is a set of the observables: p_{T}, η and ϕ for event jets and leptons; $f_{t\bar{t}}$ is the fraction of $t\bar{t}$ events in data and $P_{t\bar{t}}$ (P_{bkg}) is the probability that observables $\vec{x}$ correspond to signal (background).

To extract m_t and $f_{t\bar{t}}$ a likelihood fit, with the likelihood function based on the event probability P, is performed to data. The fit leads to the mass:

$m_t = 173.93 \pm 1.61$ (stat) ± 0.88 (syst) GeV.

Here the statistical uncertainty dominates and the most significant systematic uncertainty comes from b-jet energy scale. This result is comparable with the previous D0 dilepton results obtained using the neutrino weighting technique [20]. The most precise measurement of the top-quark mass carried out at Tevatron was done by D0 in ℓ+jets channel using the matrix element method [21]. Extraction of m_t via likelihood technique using the signal and background probability densities was obtained via the matrix element method for each event. In addition, the signal fraction f_{sig} and jet energy scale factor k_{JES} are also extracted. A two-dimensional likelihood fit in the plane (f_{sig}, k_{JES}) to the data events leads to the extracted mass:

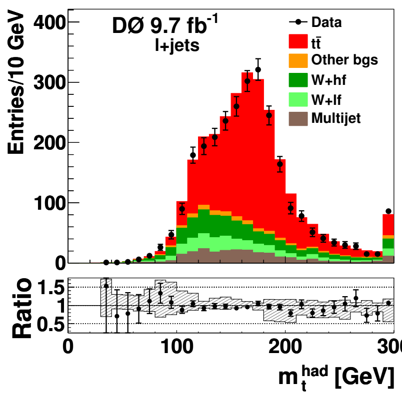

Figure 3: Invariant mass of the trijet system matched to the hadronic decay of the top quark in ℓ+jets final states.

$m_t = 174.98 \pm 0.58$ (stat+JES) ± 0.49 (syst) GeV.

The most significant sources of systematic uncertainties are effects of hadronization, underlying event and residual jet energy scale.

Top-quark mass – Tevatron combination. The Run I and Run II results of CDF and D0 experiments on the top-quark mass were combined
The resultant Tevatron combined value for the top-quark mass is

$$m_t = 174.34 \pm 0.58\ \text{(stat)} \pm 0.52\ \text{(syst) GeV}.$$

using the BLUE method [22] taking into account correlations between the sources of uncertainties. The theoretical uncertainties associated to the background modelling are taken to be 100% correlated among all measurements in the same channel. The uncertainties associated to the data driven background estimates are taken to be 100% correlated among all measurements in the same channel and same run period, but uncorrelated between the experiments. The global correlation between the CDF and D0 uncertainties is 25% and the experiment average top-quark masses are:

$$m_t^{\mathrm{CDF}} = 173.12 \pm 0.92\ \text{GeV},$$
$$m_t^{\mathrm{D0}} = 175.03 \pm 0.74\ \text{GeV}.$$

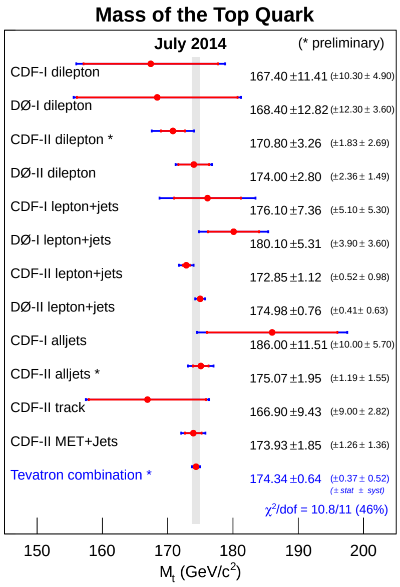

Figure 4: Summary of the input measurements and resulting Tevatron average mass of the top quark.

3.3 Top-quark mass reconstructed at LHC

In the LHC Run I the experiments ATLAS and CMS have measured the top-quark mass at center-of-mass energies $\sqrt{s} = 7$ and 8 TeV using samples with integrated luminosities of approximately 5 and 20 fb^{-1}, respectively.

Top-quark mass at ATLAS. ATLAS has measured the top-quark mass using different approaches at $\sqrt{s}$ =7 and 8 TeV. Here are reported the measurements performed at 7 TeV in ℓ+jets, $\ell\ell$ and all-jets channels and at 8 TeV in $\ell\ell$ channel. One of the measurements, carried out at 7 TeV with a sample of 4.6 fb^{-1}, employed a 3D template method for the ℓ+jets channel and a 1D-template method for the $\ell\ell$ channel [23]. In the ℓ+jets case the signal and background templates of three observables, $m_{\mathrm{top}}^{\mathrm{reco}}$, m_W^{reco}, and R_{bq}^{reco} are used in an unbinned fit to the selected data events. The observable $m_{\mathrm{top}}^{\mathrm{reco}}$ is the reconstructed invariant mass of top-quark decay products, m_W^{reco} is the invariant mass of the hadronically decaying W boson, and R_{bq}^{reco} is the ratio of the transverse momentum of the b-tagged jet to the average transverse momentum of the two jets of the hadronic W boson decay. The observable $m_{\mathrm{top}}^{\mathrm{reco}}$ is sensitive to m_t, the two other observables, m_W^{reco} and R_{bq}^{reco}, are

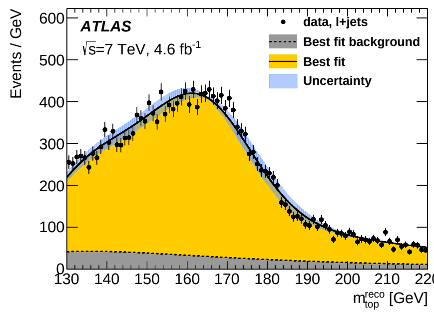

Figure 5: The fitted distribution of $m_{\mathrm{top}}^{\mathrm{reco}}$ and the fitted probability density functions for the background alone and for signal+background.

sensitive to JES and bJES, respectively. The likelihood function is constructed on the base of the signal and background templates of the above-mentioned observables. The output of the likelihood fit are the reconstructed top-quark mass, m_t, the jet energy scale factor (JES), and a relative b-jet energy scale factor (bJSF). As a representative fit result, in Fig. 5 it is shown the fitted distribution in the data, showing a $m_{\rm top}^{\rm reco}$ distribution. The fitted probability density functions for the background alone and for signal-plus-background are also shown. The extracted top-quark mass is

$$m_t^{\ell+\rm jets} = 172.33 \pm 0.75 \text{ (stat+JSF+bJSF)} \pm 1.02 \text{ (syst) GeV},$$

In the dilepton case the 1D template method was used with the sensitive observable $m_{\ell b}^{\rm reco}$, i.e. the $\ell - b$-jet invariant mass. An unbinned likelihood fit to data was based on $m_{\ell b}^{\rm reco}$ signal and background templates and the output of the fit were the top-quark mass, $m_t^{\ell\ell}$, and the background fraction, $f_{\rm bkg}$. The extracted $m_t^{\ell\ell}$ and its combination with $m_t^{\ell+\rm jets}$, using the BLUE method, is

$$m_t^{\ell\ell} = 173.79 \pm 0.54 \text{ (stat)} \pm 1.50 \text{ (syst) GeV}, \qquad m_t^{\rm comb} = 172.99 \pm 0.91 \text{ GeV}.$$

The relative precision of the combined result is 0.53%.

The template method is also used for the measurement of the top-quark mass in all-jet channel. The sensitive observable is $R_{3/2} = m_{\rm jjj}/m_{\rm jj}$, where $m_{\rm jjj}$ ($m_{\rm jj}$) is the three (two) jet invariant mass corresponding to the top-quark (W boson) decay products. $R_{3/2}$ is used rather than the reconstructed top-quark mass ($m_{\rm jjj}$) to reduce the systematic effects common to reconstructed top-quark and W boson masses. The large multijet background was determined by dividing the event sample into six disjoint sets according to the number of b-tagged jets and the $p_{\rm T}$ of the sixth jet.

ATLAS measured the top-quark mass also at 8 TeV in the dilepon channel using the sample of 20.3 fb^{-1} [24]. The same strategy and template method as at 7 TeV with the observable $m_{\ell b}^{\rm reco}$ was used, but the event selection was refined and the singly produced top quarks with the same lepton final states were also included. The top-quark mass, $m_t^{\ell\ell}$, extracted from the likelihood fit to data and its combination with the 7 TeV ℓ+jets and $\ell\ell$ channels results are:

$$m_t^{\ell\ell} = 172.99 \pm 0.41 \text{ (stat)} \pm 0.74 \text{ (syst) GeV}, \qquad m_t^{\rm comb} = 172.84 \pm 0.70 \text{ GeV}.$$

The relative precision of the combined result is 0.40%.

Top-quark mass at CMS. The CMS experiment measured the top-quark mass at $\sqrt{s} = 7$ and 8 TeV. Here are presented the measurements at $\sqrt{s}$ = 8 TeV performed in the ℓ+jets, all-jets and $\ell\ell$ channels, as well as the combined 7 and 8 TeV result. The ℓ+jets measurement carried out at $\sqrt{s}$ = 8 TeV using the data sample of 19.7 fb^{-1} employs an ideogram technique [25]. The applied technique is based on a joint maximum likelihood fit to data. The fit output is the top-quark mass, m_t, and (optionally) the jet energy scale factor, JSF. The likelihood fit is based on an event likelihood created using $m_t^{\rm fit}$ and $m_W^{\rm reco}$ templates obtained from simulation for different m_t and JSF. The observables for measuring m_t and JSF are the masses $m_t^{\rm fit}$ and $m_W^{\rm reco}$ corresponding to top quark

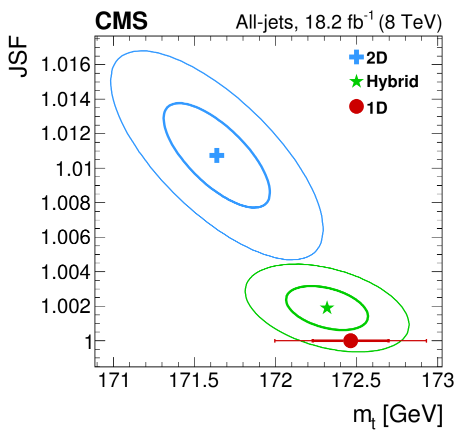

Figure 6: The two-dimensional likelihood ($-2\Delta log(L)$) for the ℓ+jets channel for the 2D, hybrid, and 1D fits (see text).

and W boson, respectively, which are estimated by a kinematic fit for each event and different parton-jet assignments. Three approaches are used to reconstruct the top-quark mass: *2D approach* with a simultaneous fit to m_t and JSF, *1D approach* with a fit only to m_t (JSF = 1) and *hybrid approach* with a prior knowledge about JES used but a Gaussian constraint applied centered at 1 with the variance depending on the JES uncertainty. In Fig. 6 are shown the contours of likelihood, $-2\Delta log(L)$, corresponding to one (two) statistical standard deviation(s) of m_t for the 2D and hybrid fits. For the 1D fit, the thick (thin) lines correspond to the one (two) σ of statistical uncertainty. The extracted top-quark masses are
m_t^{2D} = 172.14 $\pm$ 0.19 (stat+JSF) $\pm$ 0.59 (syst) GeV, m_t^{1D} = 172.56 $\pm$ 0.12 (stat) $\pm$ 0.62 (syst) GeV, m_t^{hyb}= 172.35 $\pm$ 0.16 (stat) $\pm$ 0.48 (syst) GeV.
The most precise results is obtained in the hybrid approach where the total uncertainty is 0.51 GeV, i.e. a relative precision of 0.30%.

The same ideogram technique using the mentioned three approaches was used also at the measurement carried out in the all-jets channel ($\sqrt{s} = 8$ TeV, $\int Ldt = 19.7$ fb^{-1}) [25]. The reconstructed top-quark masses using these approaches are
m_t^{2D} = 171.64 $\pm$ 0.32 (stat+JSF) $\pm$ 0.95 (syst) GeV, m_t^{1D} = 172.46 $\pm$ 0.23 (stat) $\pm$ 0.62 (syst) GeV, m_t^{hyb}= 172.35 $\pm$ 0.25 (stat) $\pm$ 0.59 (syst) GeV.

In the dilepton case an analytical matrix weighting technique (AMWT) - see details in Ref. [25] was employed. The background in the $\ell\ell$ is very small and the main systematic uncertainties comes from the factorization and renormalization scales. The likelihood fit to the data gives

$$m_t^{\ell\ell} = 172.82 \pm 0.19 \text{ (stat)} \pm 1.22 \text{ (syst) GeV}.$$

CMS combined its top-quark measurements at 7 and 8 TeV taking into account correlations between the measurements. The obtained value is

$$m_t = 172.44 \pm 0.48 \text{ GeV}.$$

The relative precision of the result is 0.28% – it is the most precise measurement to date.

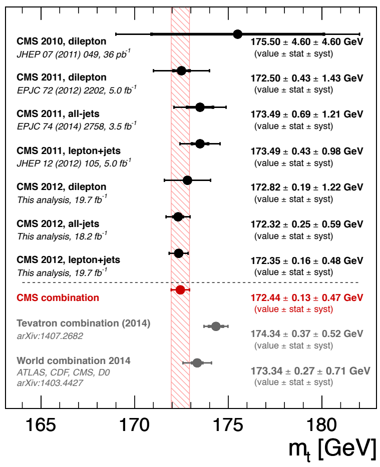

Figure 7: Summary of the CMS measurements in Run I performed at $\sqrt{s}$ = 7 and 8 TeV, including the combination.

4. Top-quark pole mass

The dependence of $t\bar{t}$ cross section (inclusive or $t\bar{t}$+jet one) on the top-quark pole mass, m_t^{pole}, is used to infer this mass. The m_t^{pole} is used in the theoretical predictions and though it exhibits some ambiguity, as mentioned above, it is theoretically a well-defined mass unlike the directly reconstructed top-quark mass. A big progress in the $t\bar{t}$ cross section calculations – now they are known at NNLO including NNLL soft gluon resummations [29], makes the idea of determination of m_t^{pole} very attractive.

Top-quark pole mass at ATLAS. For the extraction of m_t^{pole} the ATLAS experiment used the inclusive $t\bar{t}$ cross section measurements at 7 and 8 TeV performed in dilepton e/μ channel with electron and muon as decay products [26]. The pole mass can be extracted from the predicted NNLO+NNLL dependence of inclusive $t\bar{t}$ cross section, $\sigma_{t\bar{t}}$, on m_t^{pole}. In Fig. 8 are shown the predicted NNLO+NNLL $t\bar{t}$ production cross sections at 7 and 8 TeV as a function of m_t^{pole}, showing the central values (solid lines) and total uncertainties (dashed lines) with several PDF sets, and are compared to the measurements of $\sigma_{t\bar{t}}$ with their dependence on the assumed value of m_t through acceptance. Combining the results at 7 and 8 TeV the extracted top-quark pole mass reads

$$m_t^{\text{pole}} = 172.9\,^{+2.5}_{-2.6}\ \text{GeV}.$$

The main analysis systematics comes from $t\bar{t}$ modelling and QCD scale, from PDFs, lepton efficiencies, and jets and b-tagging.

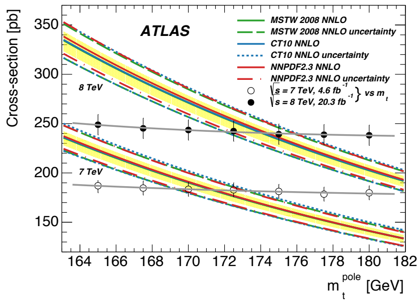

Figure 8: Predicted NNLO+NNLL $\sigma_{t\bar{t}}$ at 7 and 8 TeV as a function of m_t^{pole} with several PDF sets is compared with the measured $\sigma_{t\bar{t}}$.

Top-quark pole mass at CMS. The CMS collaboration has also extracted the top-quark pole mass, m_t^{pole}, using the inclusive $t\bar{t}$ cross section ($\sigma_{t\bar{t}}$) measurements at 7 and 8 TeV performing the measurements in dilepton e/μ channel [27]. The predicted NNLO+NNLL $t\bar{t}$ production cross sections, employing NNPDF3.0 and $\alpha_S = 0.118 \pm 0.001$, were compared to the measured $\sigma_{t\bar{t}}$ at $\sqrt{s}$ = 7 and 8 TeV as a function of m_t^{pole}. The pole mass was extracted at each value of $\sqrt{s}$. Combining the results at 7 and 8 TeV, the extracted top-quark pole mass reads

$$m_t^{\text{pole}} = 173.8\,^{+1.8}_{-1.7}\ \text{GeV}.$$

The extracted masses using the CT14 and the MMHT2014 PDF sets give, within uncertainties, compatible results. The main analysis systematics comes from $t\bar{t}$ modelling and QCD scale, from PDFs, lepton efficiencies, and jets and b-tagging.

Top-quark pole mass at D0. The D0 collaboration extracted the top-quark pole mass utilizing the $t\bar{t}$ cross section measurement at $\sqrt{s}$ = 1.96 TeV combining the lepton+jets and dilepton top-quark decay channels using the data sample with an integrated luminosity of 9.7 fb^{-1} [28]. The predicted NNLO+NNLL $t\bar{t}$ production cross section [30] is compared with the measured one as a function of m_t^{pole}. From this comparison, the D0 top-quark pole mass was extracted:

$$m_t^{\text{pole}} = 172.8\,^{+3.4}_{-3.2}\ \text{GeV}.$$

The uncertainty corresponds to a precision of 1.9%. The obtained mass is within uncertainties compatible with the ATLAS and CMS ones. The main analysis systematics comes from $t\bar{t}$ modelling and QCD scale, from PDFs, lepton efficiencies, and jets and b-tagging.

4.1 Top-quark pole mass from $t\bar{t}+$ one jet

From NLO calculations [31] follows that the m_t^{pole} dependence of the $t\bar{t}+$ 1 jet cross section is enhanced with respect to that of the inclusive $t\bar{t}$ cross section. The pole mass can be extracted from the normalised differential distribution:

$$R\left(m_t^{\text{pole}}, \rho_s\right) = \frac{1}{d\sigma_{t\bar{t}+1\text{jet}+\text{X}}} \frac{d\sigma_{t\bar{t}+1\text{jet}+\text{X}}}{d\rho_s}\left(m_t^{\text{pole}}, \rho_s\right), \tag{4.1}$$

where $\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}j}}}$, m_0 (= 170 GeV) is an arbitrary value, and $s_{t\bar{t}j}$ is the invariant mass of the system $t\bar{t}+$ jet. Due to the normalization many experimental and theoretical uncertainties are canceled.

ATLAS performed its measurement using the 7 TeV data with an integrated luminosity of 4.6 fb^{-1} [31]. The R-distribution, after the background subtraction, was unfolded to parton level using corrections for detector and hadronization effects. The extracted top-quark pole mass is

$$m_t^{\text{pole}} = 173.7 \pm 1.5(\text{stat}) \pm 1.5(\text{syst})\ ^{+1.8}_{-1.7}\ (\text{theory})\ \text{GeV}.$$

The dominant experimental uncertainties are due to the jet energy calibration and the initial and final-state radiation modelling. The theoretical uncertainties include the uncertainty due to missing higher orders in the perturbative NLO calculation, as well as uncertainties due to the PDF and α_S used in the calculation.

A similar analysis based on the observable ρ_s has been carried out by CMS using the dilepton data at 8 TeV with an integrated luminosity of 19.7 fb^{-1} [32]. The extracted pole mass is

$$m_t^{\text{pole}} = 169.9 \pm (\text{stat})\ ^{+2.5}_{-3.1}\ (\text{syst})\ ^{+3.6}_{-1.6}\ (\text{theory})\ \text{GeV}.$$

The precision is mostly limited by the systematic uncertainties arising from modelling sources and the theory uncertainties in the POWHEG $t\bar{t}$+jet simulation.

4.2 Top-quark mass measurements using alternative topologies

There is a series of measurements of the top-quark mass proposed and performed with aim to avoid using (b-)jet energy scale. A classical measurement in this direction was the measurement of CDF [14] where the top-quark mass was measured exploiting the transverse decay length of b-jets (L_{xy}) and isolated lepton p_T. Both L_{xy} and p_T depend approximately linearly on top-quark mass. Using the invariant mass of system formed by secondary vertex and isolated lepton, as an observable, at $\sqrt{s} = 1.96$ TeV using an integrated luminosity of 1.9 fb^{-1}, the mass was extracted:

$$m_t = 170.7 \pm 6.3\ (\text{stat}) \pm 2.6\ (\text{syst})\ \text{GeV}.$$

A similar procedure, based on an invariant mass of the secondary vertex and lepton, was applied by CMS to the data at $\sqrt{s} = 8$ TeV with an integrated luminosity of 19.7 fb^{-1} [33] and obtained:

$$m_t = 173.68 \pm 0.20\ (\text{stat})\ ^{+1.58}_{-0.97}\ (\text{syst})\ \text{GeV}.$$

An interesting approach used by CMS employs the exclusive decay channel $t \to (W \to \ell\nu)(b \to J/\psi + X \to)$ [34]. Once again the data sample at $\sqrt{s} = 8$ TeV with an integrated luminosity of 19.7 fb^{-1} was used and the observable used to infer the top-quark mass was invariant mass of J/ψ and isolated lepton ($J/\psi + \ell$). The extracted mass was

$$m_t = 173.68 \pm 3.0\ (\text{stat}) \pm 0.9\ (\text{syst})\ \text{GeV}.$$

For determination of the top-quark mass can be used also the single top-quark production $t \to (W \to b,\ W\ell\nu)$. This alternative was studied by CMS using the data sample at $\sqrt{s} = 8$ TeV with an integrated luminosity of 19.7 fb^{-1} [35]. The investigated observable was $M_{\ell\nu b}$ – the invariant mass of the leptonic branch top-quark decay products. The measured top-quark mass was

$$m_t = 172.6 \pm 0.77\ (\text{stat})\ ^{+0.97}_{-0.93}\ (\text{syst})\ \text{GeV}.$$

The obtained masses are in good agreement with the results of the standard approaches.

5. Summary

The top-quark mass measurements carried out by experiments of Tevatron (CDF, D0) and LHC (ATLAS, CMS) have achieved an unprecedented precision. The uncertainty of the top-quark mass is well below 1 GeV and approaches to Λ_{QCD}. As the nonperturbative aspects of the strong interaction prevent us to extract unambiguously the top-quark pole mass from experiment, it is inevitable to continue effort for better understanding of relation between the measured top-quark mass and the top-quark pole mass, as well as for better understanding of ambiguities in the top-quark pole mass itself. From experimental point of view it is needed to try different approaches for a better understanding of systematic effects.

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