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Top quark mass measurements at the Tevatron

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Summary. — The latest measurements of the top quark mass in various decay channels of top quark pair production are presented. A brief introduction to the measurement techniques is given. The measurements are performed on data samples of up to 4.8 fb^{-1} of integrated luminosity acquired by the CDF and DØ experiments in Run II of the Tevatron $p\bar{p}$ collider at a centre-of-mass energy of $\sqrt{s} = 1.96$ TeV. The Tevatron combination using up to 5.6 fb^{-1} of data results in a preliminary world average top quark mass of $m_{\mathrm{top}} = 173.3 \pm 1.1$ GeV. This corresponds to a relative precision of about 0.6%.

PACS `14.65.Ha` – Top quarks.

1. – Introduction

The top quark was discovered in 1995 by the CDF [1] and DØ [2] experiments at the Fermilab Tevatron proton-antiproton collider. The mass of the top quark, which is about 40 times heavier than the b quark, plays an important role in electroweak radiative corrections and therefore in constraining the mass of the Higgs boson. Precise measurements of the top quark mass provide a crucial test of the consistency of the standard model (SM) and could indicate a hint of physics beyond the SM.

2. – Tevatron's top quark sample

At the time of writing, Fermilab's Tevatron is still the only experimental collider providing a large sample of top quark events for precision measurements. At the Tevatron, top quarks are mostly produced in pairs via the strong interaction, in about 85% of the cases via $q\bar{q}'$ annihilation and in about 15% via gluon-gluon fusion. At the time of the conference, about 7.5 fb^{-1} of integrated luminosity per experiment were recorded by CDF and DØ, which corresponds to about 50k produced $t\bar{t}$ pairs.

Table I. – *Typical ball park signal-to-background ratios ($S:B$) and the number of combinatorial degrees of freedom (no. of permut.) for various decay topologies and number of b tags.*

	Dilepton		Lepton+jets		all-jets	
No. of b tags	$S:B$	no. of permut.	$S:B$	no. of permut.	$S:B$	no. of permut.
≥ 0	$1:4$	2	$<\ 1:1$	12	–	–
≥ 1	$4:1$	2	$3:1$	6	$1:4$	30
≥ 2	–	–	$10:1$	2	$4:1$	6

3. – Top quark decay channels and their experimental challenges

In the framework of the SM, the top quark decays to a W boson and a b quark nearly 100% of the time, resulting in a $W^+W^-b\bar{b}$ final state from top quark pair production. One of the challenges in measuring the top quark mass is the assignment of reconstruced leptons, jets, and missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}}$ to partons, which, in the absence of jet charge and flavour identification, can lead to several possible combinations. Both experiments use dedicated algorithms to identify jets which are likely to come from b quarks, *i.e.* to b tag them. This is done using properties of tracks associated to jets. The b tagging information can be used to identify jets as b quark jets, thus reducing the number of combinatoric possibilities.

$t\bar{t}$ events are classified according to the W boson decay channels. An event is referred to as “dileptonic” if both W bosons decay into leptons, “all-jets” if both W bosons decay into hadrons, and “lepton+jets” channel if one of the W bosons decays into an electron or muon alongside the corresponding neutrino, and the other one into a hadron:

- The *dileptonic channel* provides a clean event topology with two leptons and two jets. However it has a SM branching ratio (BR) of only about 5% for $\ell\ell$ modes, where ℓ corresponds to an electron or a muon. Furthermore, the jet assignment to b and $\bar{b}$ quarks as well the combination of the transverse momenta of the two neutrinos to $E_{\mathrm{T}}^{\mathrm{miss}}$ introduce additional challenges.

- The *all-jets channel* features the largest BR of about 46%, and has the advantage that all decay products can, in principle, be measured. Its major challenges are the large backgrounds from QCD multijet production and the large number of combinatoric possibilities.

- The *lepton+jets channel*, with a BR of about 29%, combines the advantages of the other two channels: it has a fairly clean topology with a relatively low number of combinatoric possibilities on the one hand, and a manageable level of background from $W+$ jets and QCD multijet production events on the other hand.

Typical signal-to-background ratios and the number of combinatorial degrees of freedom are summarised in table I. The most important experimental challenges for the top quark mass measurements common to all channels are the absolute calibration of the jet energy scale (JES), which maps the energies of reconstructed jets to particle or parton level objects, the transverse momentum resolution and identification efficiency of jets and leptons, as well as the modeling of signal and background. More details on top quark production at the Tevatron can be found in [3].

4. – Analysis techniques: An overview

4˙1. *Template method.* – One of the most widely used techniques for top quark mass measurements is the so-called template method. The basic concept is simple and intuitive: one or more quantities sensitive to the top quark mass are identified, and their distributions are derived for simulated Monte Carlo (MC) events for various top quark masses. These distributions are commonly referred to as "templates". The top quark mass is then extracted by comparing the templates for various m_{top} to the data, for example with a maximum likelihood fit. Common choices for quantities sensitive to the top quark mass are: the reconstructed top quark mass and the transverse momenta of the leptons and jets in the event. The advantages of this method are that it makes relatively few assumptions, its conceptual simplicity, and the ease of combination between channels.

4˙2. *Matrix element method.* – The analysis technique that has yielded the most precise top quark mass measurements to date is the Matrix Element (ME) method, which was pioneered by DØ in Run I of the Tevatron using the lepton+jets channel [4]. In this method, a probability $\mathcal{P}_i$ is calculated for each event i as a function of the top quark mass:

$$\mathcal{P}_i(\vec{x}_i, m_{\text{top}}) = \mathcal{A}_{\text{norm}} \cdot \int f_{\text{transfer}}(\vec{x}_i|\vec{y}_i)\, \mathrm{d}\sigma(\vec{y}_i, m_{\text{top}}).$$

The dependence on m_{top} is explicitly introduced by the differential cross section term $\mathrm{d}\sigma(\vec{y}_i, m_{\text{top}}) \propto |\mathcal{M}|^2(m_{\text{top}})$, where $\mathcal{M}$ is the leading order (LO) matrix element for top quark pair production. $\mathrm{d}\sigma(\vec{y}_i, m_{\text{top}})$ is defined for a set of parton-level kinematic quantities $\vec{y}_i$, whereas the per-event probabilities $\mathcal{P}_i$ are given for detector-level reconstructed kinematic quantities $\vec{x}_i$. The mapping between $\vec{y}_i$ and $\vec{x}_i$ is introduced by means of a transfer function $f_{\text{transfer}}(\vec{x}_i|\vec{y}_i)$, which accounts for detector resolutions and cuts. A joint likelihood is constructed from the per-event probabilities: $\mathcal{L}(m_{\text{top}}) = \prod_i \mathcal{P}_i(\vec{x}_i, m_{\text{top}})$. This allows for the best m_{top} estimate together with its uncertainty Δm_{top} to be extracted with a maximum likelihood fit. The power of the ME technique stems from the fact that the full topological and kinematic information in the event is used in the form of 4-momenta, resulting in a superb statistical sensitivity. Furthermore, the combinatoric problem resolved by assigning a per-event weight to each permutation. This weight is constructed based on the consistency of each jet-quark assignment with the b quark jet identification by b tagging algorithms. The drawback of this method is the high computational demand for numerical integration of $\mathrm{d}\sigma(m_{\text{top}})$.

4˙3. *Alternative methods.* – Besides the main methods yielding the highest precision, alternative methods can be used. For instance, the production cross section of $t\bar{t}$ events is correlated to the top quark mass, which can be utilised to extract m_{top} assuming the validity of the SM. The advantage of this method over the main ones is that the value of the top quark mass can be extracted using the most complete to-date, fully inclusive theoretical predictions in higher-order QCD including soft gluon resummations. Moreover, these calculations are performed using the theoretically well-defined pole mass, whereas the main methods utilise LO MC generators, where the definition of the top quark mass has some uncertainty due to the renormalisation scheme. This particular measurement is presented in [3]. Other prominent alternative methods used at the Tevatron are template methods utilising the decay length of b quark jets and/or the transverse momentum of leptons [5, 6]. They are important cross checks since they are independent of some systematic uncertainties present in the main methods.

4˙4. *Method calibration.* – Each of the above methods makes simplifying assumptions, which can potentially introduce biases in the top quark mass extraction. A typical example is the use of the LO matrix element in the ME method. These biases need to be corrected for by performing a calibration of the method with simulated MC events. Typically, this is done using the so-called ensemble tests, where the top quark mass is extracted in many pseudo-experiments made up of MC events according to the composition of the data sample. This is done for various $m_{\rm top}$ points. This way, a mapping between $m_{\rm top}^{\rm measured}$ and $m_{\rm top}^{\rm generated}$ can be established, which can be used for calibration. In a similar fashion, the estimated statistical uncertainty can be calibrated using the pull $\equiv \frac{m_{\rm top}-\langle m_{\rm top}\rangle}{\Delta m_{\rm top}}$ distribution.

4˙5. *In situ JES calibration.* – One of the major uncertainties on the top quark mass measurement is introduced by the limited precision of the absolute value of the JES. This uncertainty can be reduced by means of an *in situ* calibration of the JES in the lepton+jets and all-jets channels by constraining the invariant dijet mass of the jet pair(s) assigned to the hardonic W boson decay(s) to the very precisely known m_W value. Thus, a simultaneuos measurement of $m_{\rm top}$ and JES can be performed, explicitly correlating these two quantities and reducing the overall uncertainty on $m_{\rm top}$.

5. – Review of top quark mass measurements at the Tevatron

Given the large number of top quark mass measurements at the Tevatron it is impossible to cover all of them in detail. Therefore, only some of the most important measurements channel by channel are presented in the following. An overview summarising recent top quark results is given on the web pages of CDF [7] and DØ [8].

5˙1. *Lepton+jets channel.* – The most precise top quark mass measurements by both Tevatron experiments are performed with the ME method in the lepton+jets channel.

The measurement of $m_{\rm top}$ by DØ [9] is made on a data sample of $\ell + 4\,$jets, $\ell = e,\ \mu$ events with one or more b tags selected from $3.6\,{\rm fb}^{-1}$ of data. For the calculation of signal probabilities the full LO ME for the $q\bar{q}' \to t\bar{t}$ process is used, while the background probabilities are calculated using a LO ME for $W+$jets processes from VECBOS [10]. The fraction of signal events $f_{\rm sig}$ in the sample is determined with the ME method itself by maximising the likelihood with respect to $f_{\rm sig}$. This determination of $f_{\rm sig}$ is calibrated with pseudo-experiments featuring a known sample composition, as demonstrated in fig. 1 for the $\mu+$jets channel. Furthermore, an *in situ* calibration of the JES with the W boson mass is applied. The extraction of the top quark mass and the JES value are calibrated with simulated MC events featuring known $m_{\rm top}$ and JES values. The resulting calibration curves for $m_{\rm top}$ and JES are shown in fig. 1. DØ applies this method independently to $1\,{\rm fb}^{-1}$ and $2.6\,{\rm fb}^{-1}$ of data and obtains $m_{\rm top} = 173.7 \pm 0.8$ (stat) $\pm$ 1.6 (syst) GeV after combining the results. The likelihood in $m_{\rm top}$, JES, as well as the corresponding expected statistical+JES uncertainty are shown in fig. 2.

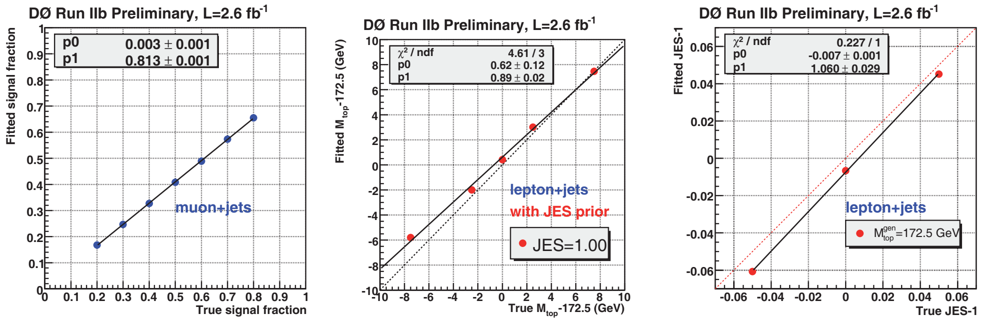

Fig. 1. – The calibration of the extraction of: fraction of signal events in the μ+jets channel (left), top quark mass (middle), and jet energy scale (right) for 2.6 fb^{-1} of DØ's 3.6 fb^{-1} measurement of m_{top} with the ME method in the lepton+jets channel [9].

CDF's top quark mass measurement [11], performed on 4.8 fb^{-1} of $\ell + 4$ jets events with one or more b tags, is similar to the one by DØ. In the following, I only outline the main differences. CDF uses transfer functions not only to map the transverse momenta of partons to reconstructed jets, but also their orientation in $\eta \times \phi$ space, where $\eta = -\ln\{\tan{}^{\theta}/_{2}\}$ is the pseudorapidity. This is necessitated by lower angular resolution of CDF's coarse hadronic calorimeter compared to DØ. Another difference is that this analysis applies a neural network (NN) to separate signal from background, and also uses the background fraction corresponding to the NN value of a given event to scale the average background likelihood value when calculating the total likelihood of the sample. Moreover, CDF applies a cut on the peak value of the individual event likelihoods to reduce the contribution from badly reconstructed candidate events. The resulting

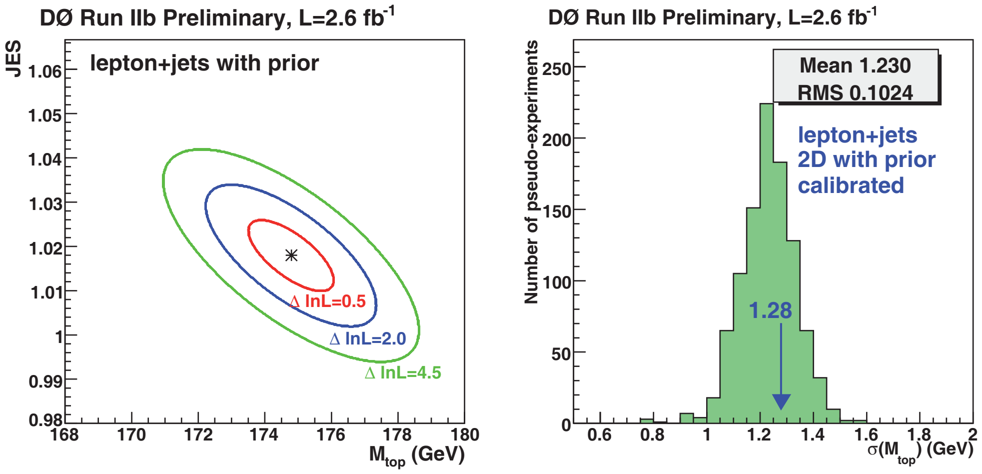

Fig. 2. – The measured likelihood in m_{top} and JES with statistical uncertainty contours (left) and the distribution of the expected statistical+JES uncertainty on m_{top} with the measured Δm_{top} value (right) for 2.6 fb^{-1} of DØ's 3.6 fb^{-1} measurement of m_{top} with the ME method in the lepton+jets channel [9].

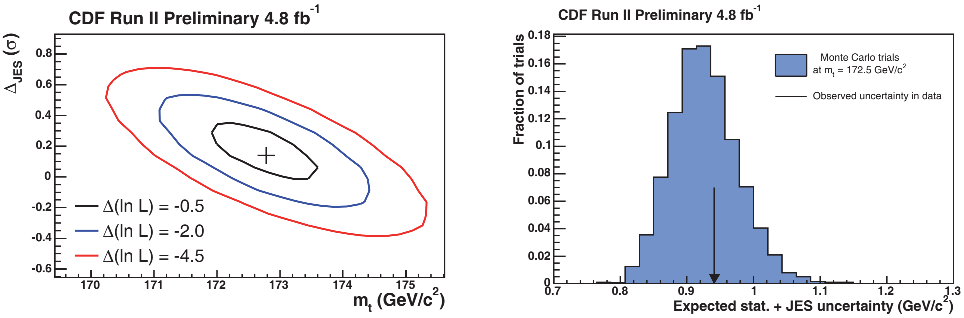

Fig. 3. – The measured likelihood in m_{top} and JES with statistical uncertainty contours (left) and the distribution of the expected statistical+JES uncertainty on m_{top} with the measured Δm_{top} value (right) for CDF's $4.8\,\text{fb}^{-1}$ measurement of m_{top} with the ME method in the lepton+jets channel [11].

likelihood in m_{top}, JES and the expected statistical+JES uncertainty are shown in fig. 3. This analysis finds $m_{\text{top}} = 172.8 \pm 0.7\ (\text{stat}) \pm 0.6\ (\text{JES}) \pm 0.8\ (\text{syst})\,\text{GeV}$.

The measurements of m_{top} in the $\ell +$ jets channel at the Tevatron are limited by systematic uncertainties, and substantial efforts are underway to gain an improved understanding of the dominating sources of systematic uncertainty: differences in the JES of b quark and light quark jets, the effect from the modeling of hadronisation, the underlying event, colour reconnection, initial and final state radiation; as well as others.

5˙2. *All-jets channel.* – The third most statistically significant contribution to the world average top quark mass at the time of the conference comes from a measurement in the all-jets channel by CDF using $2.9\,\text{fb}^{-1}$ of data [12]. This analysis applies the template method to the $6 \leq N_{\text{jets}} \leq 8$ final state to extract the top quark mass. Its main challenge is the high level of background from QCD multijet production. After a multijet trigger requirement and an offline preselection the $S : B$ level is about $1 : 430$. Therefore, a discrimination variable $\mathcal{D}_{\text{NN}}$ is constructed with a multilayered NN from kinematic variables of jets, and also jet shape variables which provide discrimination between quark and gluon jets, for example the second moment in η and ϕ. To enhance the purity of the sample and to reduce the number of combinatoric possibilities b tagging is applied. For each jet-parton assignment, a χ^2 is constructed which accounts for: the consistency of the two dijet pairs with the W mass, the consistency of the jjb combinations with the reconstructed top quark mass, and the consistency of the individual fitted jet momenta with the measured ones, all within experimental resolutions. The final sample for top mass extraction is defined by $\mathcal{D}_{\text{NN}} > 0.9$ (0.88) and $\chi^2 < 6$ (5) for events with 1 (≥ 2) b tags, yielding a signal-to-background ratio of $1 : 4$ ($1 : 1$). The template distributions for reconstructed m_{top} and m_W are shown in fig. 4, while the measured likelihood in m_{top} and JES, as well as the expected statistical+JES uncertainty are presented in fig. 5.

5˙3. *Dilepton channel.* – The fourth most significant contribution to the world average top quark mass at the time of the conference comes from the DØ experiment, and is done in the dilepton channel with the ME method. DØ uses all $\ell\ell b\bar{b}$, $\ell = e, \mu$ final states in $1.1\,\text{fb}^{-1}$ of data and the $e\mu b\bar{b}$ final state in $2.5\,\text{fb}^{-1}$ of data [13], and finds

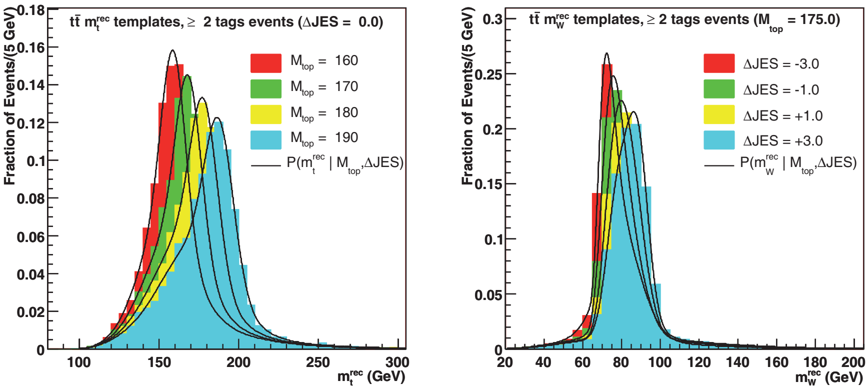

Fig. 4. – The template distributions for reconstructed m_{top} (left) and m_W (right) for CDF's 2.9 fb^{-1} measurement of m_{top} with the template method in the all-jets channel.

$m_{\mathrm{top}} = 174.7 \pm 2.9$ (stat) $\pm$ 2.4 (syst) GeV. The likelihood in m_{top} for the 2.5 fb^{-1} dataset is shown in fig. 6. The comparison of the statistical uncertainty found in data with the expected statistical distributions can be found in the same figure.

6. – Tevatron top quark mass combination and conclusion

The Tevatron Electroweak Working Group has combined the measurements of the top quark mass on the full Run I dataset (1992–96) and up to 5.6 fb^{-1} of the Run II dataset(started 2001) properly taking into account correlated uncertainties [14]. The resulting world average top quark mass assuming Gaussian systematic uncertainties is $m_{\mathrm{top}} = 173.3 \pm 0.6$ (stat) $\pm$ 0.9 (syst) GeV, which corresponds to a relative precision of

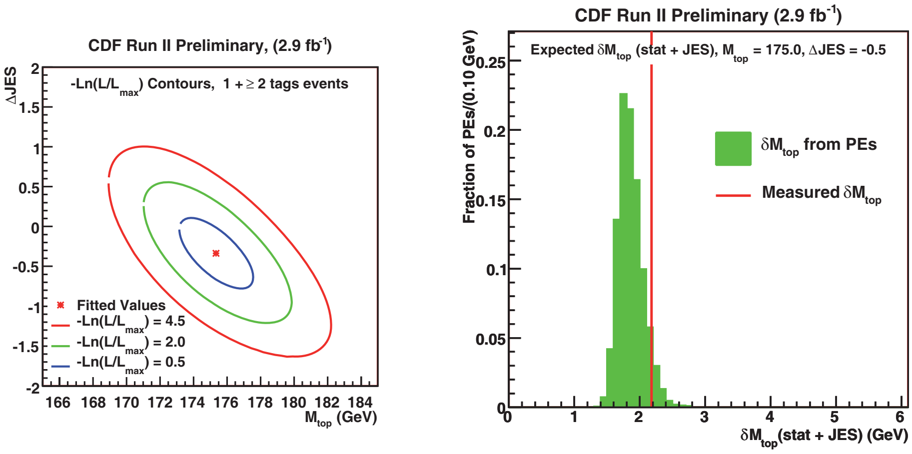

Fig. 5. – The measured likelihood in m_{top} and JES (left), as well as the expected statistical+JES uncertainty (right) for CDF's 2.9 fb^{-1} measurement of m_{top} with the template method in the all-jets channel [12].

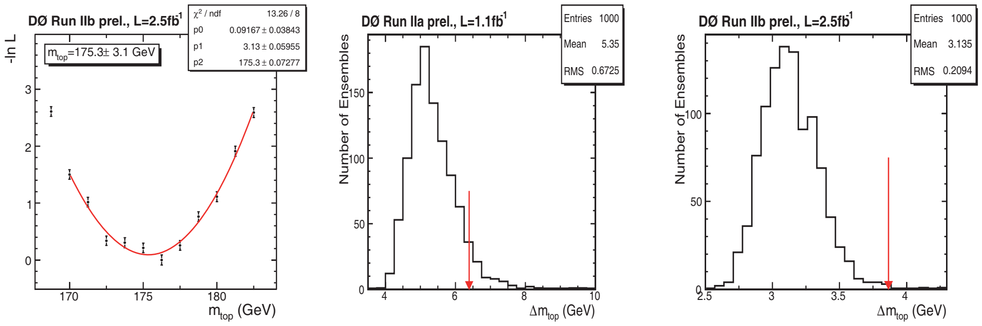

Fig. 6. – The measured likelihood in $m_{\rm top}$ (left) for 2.5 fb^{-1}of DØ's 3.6 fb^{-1} measurement with the ME method in the dilepton channel [13]. The expected statistical uncertainty distribution alongside with the uncertainty found in data is demonstrated for the 1.1 fb^{-1} (middle) and 2.5 fb^{-1} (right) datasets.

about 0.6%. The most precise measurements are systematically limited, and a substantial effort from both Tevatron experiments is directed towards a better understanding of systematic uncertainties.

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