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Combination of CDF and D0 results on the mass of the top quark using up to 9.7 fb^{-1} at the Tevatron

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Abstract

We summarize the current top quark mass (m_t) measurements from the CDF and D0 experiments at Fermilab. We combine published results from Run I (1992–1996) with the most precise published and preliminary Run II (2001–2011) measurements based on $p\bar{p}$ data corresponding to up to 9.7 fb^{-1} of $p\bar{p}$ collisions. Taking correlations of uncertainties into account, and combining the statistical and systematic contributions in quadrature, the preliminary Tevatron average mass value for the top quark is $m_t = 174.30 \pm 0.65$ GeV/c^2, corresponding to a relative precision of 0.37%.

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More information can be found at `http://tevewwg.fnal.gov`.

1 Introduction

This note reports the averaged mass of the top quark ($m_{\rm t}$) obtained by combining the most precise Tevatron measurements of its mass at the Tevatron $p\bar{p}$ Collider at Fermilab, and updates the combination presented in Refs. [1] and [2]. Reference [2] also provides a detailed description of the systematic uncertainties. The CDF and D0 Tevatron experiments, and the ATLAS and CMS LHC experiments, also provided a combination of their most precise top-quark mass measurements [3].

The CDF and D0 collaborations have performed several direct measurements of the top-quark mass. The pioneering measurements were first based on approximately 0.1 fb^{-1} of Run I data [4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15] collected from 1992 to 1996, that included results from $t\bar{t} \to W^+bW^-\bar{b} \to qq'bqq'\bar{b}$ (all–jets), $t\bar{t} \to W^+bW^-\bar{b} \to \ell\nu bqq'\bar{b}$ (ℓ+jets or lepton+jets), and $t\bar{t} \to W^+bW^-\bar{b} \to \ell^+\nu b\ell^-\bar{\nu}\bar{b}$ ($\ell\ell$ or dilepton) channels, where ℓ refers to electrons or muons (all charge-conjugate final states are considered in the analyses). Decays of $W \to \tau\nu_\tau$ followed by leptonic $\tau \to e$ or μ decays are included in the direct leptonic $W \to e$ and $W \to \mu$ decay channels. Run II (2001–2011) had a variety of $m_{\rm t}$ measurements, and those considered in this paper are the most recent results in these channels, using up to 9.3 fb^{-1} of data for CDF (corresponding to all the CDF Run II data) [16, 17, 18, 19, 20], and using 9.7 fb^{-1} of data for D0 (corresponding to all the D0 Run II data) [21, 22, 23, 24, 25]. The CDF analyses based on charged-particle tracking for exploiting the transverse decay length of b-tagged jets (L_{XY}) and the transverse momentum of electrons and muons from W boson decays ($p_T^{\rm lep}$), using data corresponding to a luminosity of 1.9 fb^{-1} [16], are not expected to be updated

The latter analysis is not included in the combination because of a statistical correlation with other samples.

The Tevatron average $m_{\rm t}$ is obtained by combining five published Run I measurements [5, 6, 8, 10, 13, 14] with six published Run II results [16, 17, 18, 19, 20, 21, 22] and with the preliminary D0 combination [25] of Run II dilepton measurements [23, 24]. This combination supersedes the previous combinations of Refs. [1, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36].

Compared to the Summer 2014 Tevatron combination of Ref. [1]:

- The Run II D0 measurements in the $\ell\ell$ channels have been updated based on the entire Run II data, using a neutrino weighting technique [23] and a matrix element method [24]. The former measurement is published and the latter has been accepted for publication in Phys. Rev. D. Both measurements use the same data and are therefore correlated. Their combination, discussed in Ref. [25], is used as input to the present combination.
- The Run II CDF measurements in the $\ell\ell$ [20] and all–jets channels [19] are now published, while they were preliminary in Summer 2014. The published $\ell\ell$ measurement does not differ significantly from its preliminary version. The published all–jets measurement is identical to its preliminary version.

The definition and evaluation of the systematic uncertainties and of the correlations among channels, experiments, and Tevatron runs is the outcome of many years of joint effort between the CDF and D0 collaborations that is described in Ref. [2]. The measurements in the present combination are calibrated through the input values of m_{t} in the Monte Carlo (MC). It is expected that the difference between the MC mass definition and the pole mass of the top quark is < 1 GeV/c^2 [37].

The input measurements and uncertainty categories used in the combination are discussed in Sections 2 and 3, respectively. The correlations assumed in the combination are discussed in Section 4, and the resulting Tevatron average top-quark mass is given in Section 5. A summary is presented in Section 6.

2 Input Measurements

The twelve measurements of m_{t} used in this combination are shown in Table 1. The Run I measurements all have relatively large statistical uncertainties and their systematic uncertainties are dominated by the uncertainty in jet energy scale (JES). In Run II both CDF and D0 take advantage of the larger $t\bar{t}$ samples, and employ new analysis techniques to reduce the uncertainties. In particular, the Run II D0 analysis in the ℓ+jets channel and the Run II CDF analyses in the ℓ+jets, all–jets, and MEt channels constrain the response of light-quark jets using the kinematic information from $W \to qq'$ decays (the so-called in situ calibration) [10, 38]. Residual JES uncertainties associated with p_T and η dependence, as well as uncertainties specific to the response of b jets, are treated separately. The Run II D0 $\ell\ell$ measurements use the JES determined in the ℓ+jets channel through the in situ calibration [23, 24]. The D0 Run II ℓ+jets result is the most accurate single result from the Tevatron [21, 22]. Unlike the other inputs, the CDF all–jets measurement [19] uses a next-to-leading order generator as default program to model $t\bar{t}$ events (POWHEG [39]).

Table 1 lists the individual uncertainties in each result, subdivided into the categories described in the next Section. The correlations between the inputs are described in Sec. 4.

3 Uncertainty Categories

We employ uncertainty categories similar to those used for the previous Tevatron combination [1, 2], with small modifications to better account for their correlations. They are divided into sources of same or similar origin that are combined as in Ref. [2]. For example, the *Signal modeling* (*Signal*) category discussed below includes the uncertainties from different systematic sources that are correlated due to their origin in the modeling of the simulated signal.

Table 1: Summary of the measurements used to determine the Tevatron average $m_{\rm t}$. Integrated luminosity ($\int \mathcal{L}\, dt$) has units of fb^{-1}, and all other numbers are in GeV/c^2. The uncertainty categories and their correlations are described in Section 3. The total systematic uncertainty and the total uncertainty are obtained by adding the relevant contributions in quadrature. The symbols "n/a" stands for "not applicable", "n/e" for "not evaluated".

	Run I published					Run II published						Run II prel.
	CDF			D0		CDF					D0	D0
	ℓ+jets	$\ell\ell$	all–jets	ℓ+jets	$\ell\ell$	ℓ+jets	L_{XY}	MEt	$\ell\ell$	all–jets	ℓ+jets	$\ell\ell$
$\int \mathcal{L}\, dt$	0.1	0.1	0.1	0.1	0.1	8.7	1.9	8.7	9.1	9.3	9.7	9.7
$M_{\rm t}$	176.10	167.40	186.00	180.10	168.40	172.85	166.90	173.93	171.50	175.07	174.98	173.50
In situ light-jet calibration (iJES)	n/a	n/a	n/a	n/a	n/a	0.49	n/a	1.05	n/a	0.97	0.41	0.47
Response to $b/q/g$ jets (aJES)	n/a	n/a	n/a	0.00	0.00	0.09	0.00	0.10	0.16	0.01	0.16	0.28
Model for b-jets (bJES)	0.60	0.80	0.60	0.71	0.71	0.16	0.00	0.17	0.26	0.20	0.09	0.13
Out-of-cone correction (cJES)	2.70	2.60	3.00	2.00	2.00	0.21	0.36	0.18	1.47	0.37	n/a	n/a
Light-jet response (1) (rJES)	3.35	2.65	4.00	n/a	n/a	0.48	0.24	0.40	1.56	0.42	n/a	n/a
Light-jet response (2) (dJES)	0.70	0.60	0.30	2.53	1.12	0.07	0.06	0.04	0.37	0.09	0.21	0.31
Lepton modeling (LepPt)	n/e	n/e	n/e	n/e	n/e	0.03	0.00	n/a	0.41	n/a	0.01	0.08
Signal modeling (Signal)	2.62	2.86	1.97	1.10	1.80	0.61	0.90	0.63	1.01	0.53	0.35	0.43
Jet modeling (DetMod)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.14
b-tag modeling (b-tag)	0.40	0.00	0.00	0.00	0.00	0.03	0.00	0.03	0.05	0.04	0.10	0.22
Background from theory (BGMC)	1.30	0.30	0.00	1.00	1.10	0.12	0.80	0.00	0.24	0.00	0.06	0.00
Background based on data (BGData)	0.00	0.00	1.70	0.00	0.00	0.16	0.20	0.15	0.31	0.15	0.09	0.08
Calibration method (Method)	0.00	0.70	0.60	0.58	1.14	0.05	2.50	0.21	0.20	0.87	0.07	0.14
Offset (UN/MI)	n/a	n/a	n/a	1.30	1.30	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Multiple interactions model (MHI)	n/e	n/e	n/e	n/e	n/e	0.07	0.00	0.18	0.27	0.22	0.06	0.07
Systematic uncertainty (syst)	5.30	4.85	5.71	3.89	3.63	0.99	2.82	1.35	2.51	1.55	0.63	0.84
Statistical uncertainty (stat)	5.10	10.30	10.00	3.60	12.30	0.52	9.00	1.26	1.91	1.19	0.41	1.31
Total uncertainty	7.35	11.39	11.51	5.30	12.83	1.12	9.43	1.85	3.15	1.95	0.75	1.56

Some systematic uncertainties have been separated into multiple categories to accommodate specific types of correlations. For example, the jet energy scale (JES) uncertainty is subdivided into six components to more accurately accommodate our best understanding of the relevant correlations among input measurements.

In this note we use the new naming scheme described in Ref. [2]. The previous names of the systematic uncertainties are given in parentheses.

Statistical uncertainty (Statistics): The statistical uncertainty associated with the m_{t} determination.

In situ light-jet calibration (iJES): That part of the JES uncertainty that originates from in situ calibration procedures and is uncorrelated among the measurements. In the combination reported here, it corresponds to the statistical uncertainty associated with the JES determination using the $W \to qq'$ invariant mass in the CDF Run II ℓ+jets, all–jets, and MEt measurements, and in the D0 Run II $\ell\ell$ and ℓ+jets measurements. Residual JES uncertainties arising from effects not considered in the in situ calibration are included in other categories. For the D0 Run II $\ell\ell$ measurement, the uncertainty coming from transferring the ℓ+jets calibration to the dilepton event topology is quoted in the *Light-jet response (2) (dJES)* category described below.

Response to $b/q/g$ jets (aJES): That part of the JES uncertainty that originates from average differences in detector electromagnetic over hadronic (e/h) response for hadrons produced in the fragmentation of b-quark and light-quark jets.

Model for b jets (bJES): That part of the JES uncertainty that originates from uncertainties specific to the modeling of b jets and that is correlated across all measurements. For both CDF and D0 this includes uncertainties arising from variations in the semileptonic branching fractions, b-fragmentation modeling, and differences in the color flow between b-quark jets and light-quark jets. These were determined from Run II studies but back-propagated to the Run I measurements, whose *Light-jet response (1)* uncertainties (*rJES*, see below) were then corrected to keep the total JES uncertainty constant.

Out-of-cone correction (cJES): That part of the JES uncertainty that originates from modeling uncertainties correlated across all measurements. It specifically includes the modeling uncertainties associated with light-quark fragmentation and out-of-cone corrections. For D0 Run II measurements, it is included in the *Light-jet response (2) (dJES)* category.

Light-jet response (1) (rJES): The remaining part of the JES uncertainty that covers the absolute calibration for CDF's Run I and Run II measurements. It also includes small contributions from the uncertainties associated with modeling multiple interactions within a single bunch crossing and corrections for the underlying event.

Light-jet response (2) (dJES): That part of the JES uncertainty that includes D0's Run I and Run II calibrations of absolute response (energy dependent), the relative response (η-dependent), and the out-of-cone showering correction that is a detector effect. This uncertainty term for CDF includes only the small relative response calibration (η-dependent) for Run I and Run II.

Lepton modeling (LepPt): The systematic uncertainty arising from uncertainties in the scale and resolution of lepton transverse momentum measurements. It was not considered as a source of systematic uncertainty in the Run I measurements.

Signal modeling (Signal): The systematic uncertainty arising from uncertainties in $t\bar{t}$ modeling that is correlated across all measurements. This includes uncertainties from variations of the amount of initial and final state radiation and from the choice of parton density function used to generate the $t\bar{t}$ Monte Carlo samples that calibrate each method. When appropriate it also includes the uncertainty from higher-order corrections evaluated from a comparison of $t\bar{t}$ samples generated by MC@NLO [40] and ALPGEN [41], both interfaced to HERWIG [42, 43] for the simulation of parton showers and hadronization. In this combination, the systematic uncertainty arising from a variation of the phenomenological description of color reconnection (CR) between final state particles [44, 45] is included in the *Signal modeling* category. The CR uncertainty is obtained by taking the difference between the PYTHIA 6.4 tune "Apro" and the PYTHIA 6.4 tune "ACRpro" that differ only in the CR model. In the latest analysis in the ℓ+jets channel, D0 uses the following samples: PYTHIA with Perugia 2011 versus Perugia 2011NOCR tunes to estimate the uncertainty due to the CR model. This uncertainty was not evaluated in Run I since the Monte Carlo generators available at that time did not allow for variations of the CR model. These measurements therefore do not include this source of systematic uncertainty. Finally, the systematic uncertainty associated with variations of the MC generator used to calibrate the mass extraction method is added. It includes variations observed when substituting PYTHIA [46, 47, 48] (Run I and Run II) or ISAJET [49] (Run I) for HERWIG [42, 43] when modeling the $t\bar{t}$ signal.

Jet modeling (DetMod): The systematic uncertainty arising from uncertainties in the modeling of jet interactions in the detector in the MC simulation. For D0, this includes uncertainties from jet resolution and identification. Applying jet algorithms to MC events, CDF finds that the resulting efficiencies and resolutions closely match those in data. The small differences propagated to $m_{\rm t}$ lead to a negligible uncertainty of 0.005 GeV/c^2, which is then ignored.

b-tag modeling (b-tag): This is the part of the uncertainty related to the modelling of the b-tagging efficiency and the light-quark jet rejection factors in the MC simulation with respect to the data.

Background from theory (BGMC): This systematic uncertainty on the background originating from theory (MC) takes into account the uncertainty in modeling the background sources. It is correlated between all measurements in the same channel, and includes uncertainties on the background composition, normalization, and shape of different components, e.g., the uncertainties from the modeling of the W+jets background in the ℓ+jets channel associated with variations of the factorization scale used to simulate W+jets events.

Background based on data (BGData): This includes, among other sources, uncertainties associated with the modeling using data of the QCD multijet background in the all–jets, MEt, and ℓ+jets channels and the Drell-Yan background in the $\ell\ell$ channel. This also includes effects of trigger uncertainties which are determined using data. This part is uncorrelated between experiments.

Calibration method (Method): The systematic uncertainty arising from any source specific to a particular fit method, including the finite Monte Carlo statistics available to calibrate each method.

Offset (UN/MI): This uncertainty is specific to D0 and includes the uncertainty arising from uranium noise in the D0 calorimeter and from the multiple interaction corrections to the JES. For D0 Run I these uncertainties were sizable, while for Run II, owing to the shorter calorimeter electronics integration time and in situ JES calibration, these uncertainties are negligible.

Multiple interactions model (MHI): The systematic uncertainty arising from a mismodeling of the distribution of the number of collisions per Tevatron bunch crossing owing to the steady increase in the collider instantaneous luminosity during data-taking. This uncertainty has been separated from other sources to account for the fact that it is uncorrelated between experiments.

These categories represent the current preliminary understanding of the various sources of uncertainty and their correlations. We expect these to evolve as we continue to probe each method's sensitivity to the various systematic sources with improving precision.

4 Correlations

The following correlations are used for the combination:

- The uncertainties in the *Statistical uncertainty (Stat)* and *Calibration method (Method)* categories are taken to be uncorrelated among the measurements.
- The uncertainties in the *In situ light-jet calibration (iJES)* category are taken to be uncorrelated among the measurements except for D0's $\ell\ell$ and ℓ+jets measurements, where this uncertainty is taken to be 100% correlated since the $\ell\ell$ measurement uses the JES calibration determined in ℓ+jets channel.
- The uncertainties in the *Response to b/q/g jets (aJES)*, *Light-jet response (2) (dJES)*, *Lepton modeling (LepPt)*, *b-tag modeling (b-tag)*, and *Multiple interactions model (MHI)* categories are taken to be 100% correlated among all Run I and all Run II measurements within the same experiment, but uncorrelated between Run I and Run II and uncorrelated between the experiments.
- The uncertainties in the *Light-jet response (1) (rJES)*, *Jet modeling (DetMod)*, and *Offset (UN/MI)* categories are taken to be 100% correlated among all measurements within the same experiment but uncorrelated between the experiments.

Table 2: The matrix of correlation coefficients used to determine the Tevatron average top-quark mass.

	Run I published					Run II published						Run II prel.
	CDF			D0		CDF					D0	D0
	ℓ+jets	$\ell\ell$	all–jets	ℓ+jets	$\ell\ell$	ℓ+jets	L_{XY}	MEt	$\ell\ell$	all–jets	ℓ+jets	$\ell\ell$
CDF-I ℓ+jets	1.00											
CDF-I $\ell\ell$	0.29	1.00										
CDF-I all–jets	0.32	0.19	1.00									
DØ-I ℓ+jets	0.26	0.15	0.14	1.00								
DØ-I $\ell\ell$	0.11	0.08	0.07	0.16	1.00							
CDF-II ℓ+jets	0.49	0.29	0.30	0.22	0.11	1.00						
CDF-II L_{XY}	0.07	0.04	0.04	0.05	0.02	0.08	1.00					
CDF-II MEt	0.26	0.16	0.16	0.12	0.07	0.32	0.04	1.00				
CDF-II $\ell\ell$	0.52	0.31	0.35	0.25	0.13	0.51	0.06	0.28	1.00			
CDF-II all–jets	0.27	0.17	0.18	0.14	0.07	0.30	0.04	0.18	0.31	1.00		
DØ-II ℓ+jets	0.19	0.12	0.08	0.13	0.07	0.28	0.05	0.17	0.16	0.14	1.00	
DØ-II $\ell\ell$	0.11	0.08	0.05	0.07	0.04	0.16	0.03	0.10	0.10	0.08	0.43	1.00

- The uncertainties in the *Backgrounds estimated from theory (BGMC)* category are taken to be 100% correlated among all measurements in the same channel.
- The uncertainties in the *Backgrounds estimated from data (BGData)* category are taken to be 100% correlated among all measurements in the same channel and same run period, but uncorrelated between the experiments.
- The uncertainties in the *Model for b jets (bJES)*, *Out-of-cone correction (cJES)*, and *Signal modeling (Signal)* categories are taken to be 100% correlated among all measurements.

Using the inputs from Table 1 and the correlations specified here, the resulting matrix of total correlation coefficients is given in Table 2.

The measurements are combined using a program implementing two independent methods: a numerical χ^2 minimization and the analytic best linear unbiased estimator (BLUE) method [50, 51]. The two methods are mathematically equivalent. It has been checked that they give identical results for the combination. The BLUE method yields the decomposition of the uncertainty on the Tevatron m_t average in terms of the uncertainty categories specified for the input measurements [51].

5 Results

The resulting combined value for the top-quark mass is

$$m_t = 174.30 \pm 0.35\,(\text{stat}) \pm 0.54\,(\text{syst})\ \text{GeV}/c^2.$$

Adding the statistical and systematic uncertainties in quadrature yields a total uncertainty of 0.65 GeV/c^2, corresponding to a relative precision of 0.37% on the top-quark mass. The combination has a χ^2 of 10.8 for 11 degrees of freedom, corresponding to a probability of 46%, indicating good agreement among all input measurements. The breakdown of the uncertainties is shown in Table 3.

This result is almost identical to the Summer 2014 combination [1]: the total statistical uncertainty is reduced by 20 MeV/c^2, the total systematic uncertainty is increased by 20 MeV/c^2, and the central value is 40 MeV/c^2 lower.

The pull and weight for each of the inputs obtained from the combination using the BLUE method are listed in Table 4. The full set of input measurements and the resulting Tevatron average mass of the top quark are summarized in Fig. 1. A similar figure with only Run II measurements, excluding CDF L_{XY} measurement which has a much larger uncertainty than the others, is shown in Fig. 2

The weights of some of the measurements are negative, which occurs if the correlation between two measurements is larger than the ratio of their total uncertainties. In these instances the less precise measurement will acquire a negative weight. While a weight of zero means that a particular input is effectively ignored in the combination, channels with a negative weight affect the resulting central value of m_t and help reduce the total uncertainty [50]. To visualize the weight that each measurement carries in the combination, Fig. 3 shows the absolute values of the weight of each measurement divided by the sum of the absolute values of the weights of all input measurements. Negative weights are represented by bins with a different (grey) color. We note that due to correlations between the uncertainties, the relative weights of the different input channels may be significantly different from what would be expected from the total accuracy of each measurement represented by error bars in Fig. 1.

None of the inputs shows a pull larger than 2 in absolute value, which indicates no anomalous behavior. Nevertheless, it is still interesting to determine the mass separately in the all–jets, ℓ+jets, $\ell\ell$, and MEt channels (leaving out the L_{XY} measurement). We use the same methodology, inputs, uncertainty categories, and correlations as described above, but fit the four physical observables, $m_t^{\text{all-jets}}$, $m_t^{\ell+\text{jets}}$, $m_t^{\ell\ell}$, and m_t^{MEt} separately. The results of these combinations are shown in Fig. 4 and Table 5.

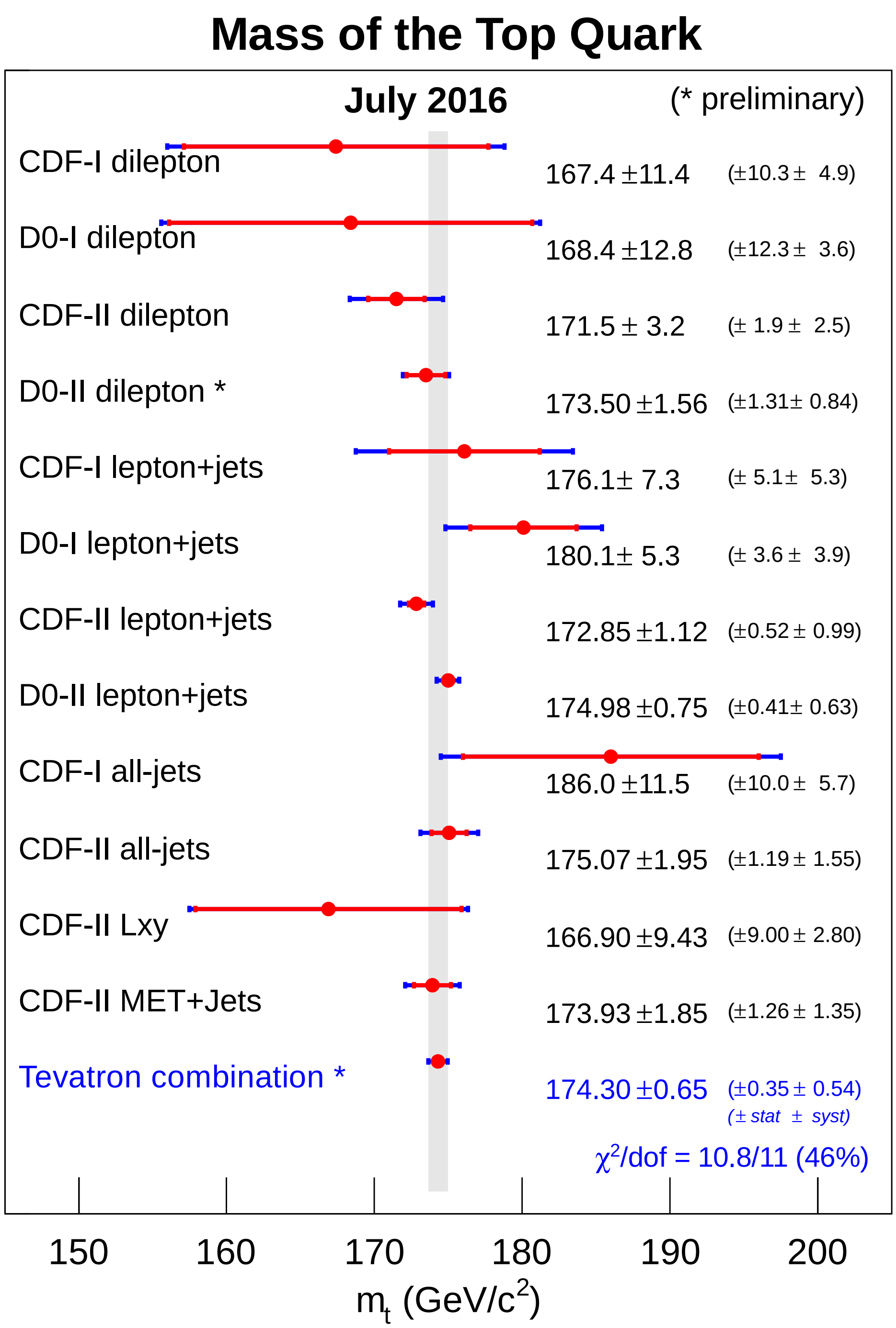

Figure 1: Summary of the input measurements and resulting Tevatron average mass of the top quark. The red lines correspond to the statistical uncertainty while the blue lines show the total uncertainty.

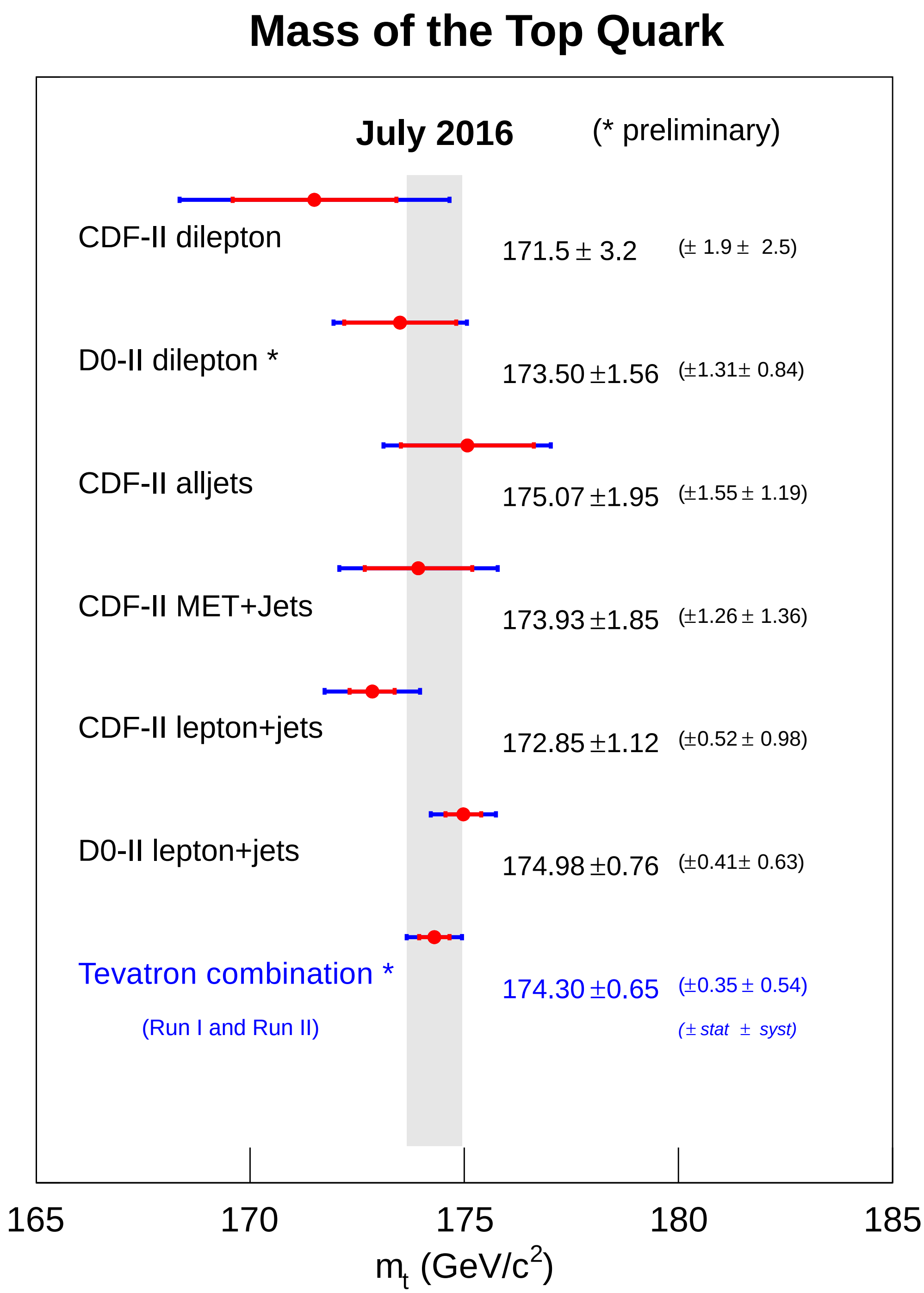

Figure 2: Summary of the input Run II measurements and resulting Tevatron average mass of the top quark.

Table 3: Summary of the Tevatron combined average m_t and its uncertainties. The uncertainty categories are described in the text. The total systematic uncertainty and the total uncertainty are obtained by adding the relevant contributions in quadrature.

	Tevatron combined values (GeV/c^2)
M_t	174.30
In situ light-jet calibration (iJES)	0.31
Response to $b/q/g$ jets (aJES)	0.11
Model for b-jets (bJES)	0.10
Out-of-cone correction (cJES)	0.03
Light-jet response (1) (rJES)	0.05
Light-jet response (2) (dJES)	0.14
Lepton modeling (LepPt)	0.01
Signal modeling (Signal)	0.36
Jet modeling (DetMod)	0.05
b-tag modeling (b-tag)	0.07
Background from theory (BGMC)	0.04
Background based on data (BGData)	0.07
Calibration method (Method)	0.07
Offset (UN/MI)	0.00
Multiple interactions model (MHI)	0.06
Systematic uncertainty (syst)	0.54
Statistical uncertainty (stat)	0.35
Total uncertainty	0.65

Using the results of Table 5 we calculate the following values including correlations: $\chi^2(\ell+\text{jets}-\ell\ell) = 1.79/1$, $\chi^2(\ell+\text{jets}-\text{all–jets}) = 0.61/1$, $\chi^2(\ell+\text{jets}-\text{MEt}) = 0.00/1$, $\chi^2(\ell\ell-\text{all–jets}) = 2.12/1$, $\chi^2(\ell\ell-\text{MEt}) = 0.64/1$, and $\chi^2(\text{all–jets}-\text{MEt}) = 0.35/1$. These correspond to probabilities of 18%, 43%, 99.8%, 15%, 43%, and 56%, respectively, indicating that the top-quark mass determined in each decay channel is consistent in all cases.

In the same way, we can also fit two physical observables: the mass measured in CDF and the one measured at D0, m_t^{CDF} and m_t^{D0}, separately. The results of these combinations are shown in Table 6. The chi-squared value including correlations is $\chi^2(\text{CDF}-\text{D0}) = 3.4/1$, corresponding to a probability of 6.5%.

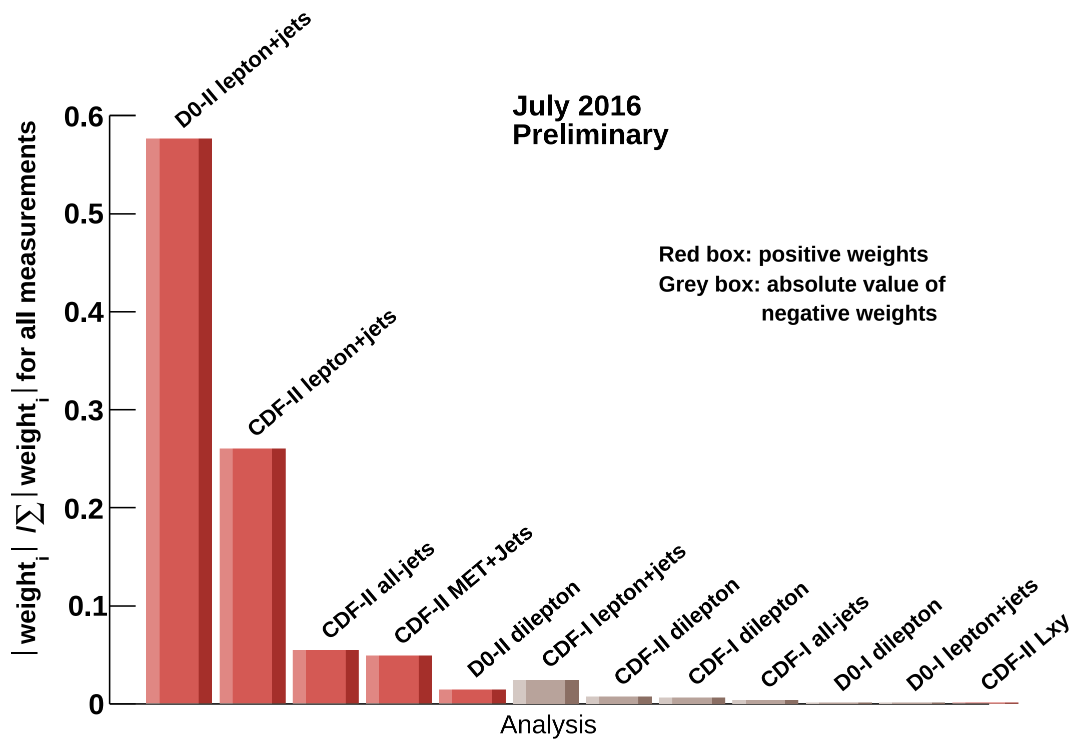

Figure 3: Relative weights of the input measurements in the combination. The relative weights have been obtained by dividing the absolute value of each measurement weight by the sum over all measurements of the absolute values of the weights. Negative weights are represented by their absolute value, but using a grey color.

Table 4: The pull and weight for each of the inputs obtained from the combination with the BLUE method used to determine the average top-quark mass.

	Run I published					Run II published						Run II prel.
	CDF			D0		CDF					D0	D0
	ℓ+jets	$\ell\ell$	all–jets	ℓ+jets	$\ell\ell$	ℓ+jets	L_{XY}	MEt	$\ell\ell$	all–jets	ℓ+jets	$\ell\ell$
Pull	0.25	−0.61	1.02	1.10	−0.46	−1.59	−0.79	−0.21	−0.91	0.42	1.75	−0.56
Weight	−0.03	−0.01	−0.00	−0.00	−0.00	0.29	0.00	0.05	−0.01	0.06	0.63	0.02

Table 5: Summary of the combination of the 12 measurements by CDF and D0 in terms of four physical quantities, the mass of the top quark in the all–jets, ℓ+jets, $\ell\ell$, and MEt decay channels.

Parameter	Value (GeV/c^2)	Correlations			
		$m_t^{\text{all-jets}}$	$m_t^{\ell+\text{jets}}$	$m_t^{\ell\ell}$	m_t^{MEt}
$m_t^{\text{all-jets}}$	175.66 ± 1.84	1.00			
$m_t^{\ell+\text{jets}}$	174.22 ± 0.66	0.19	1.00		
$m_t^{\ell\ell}$	172.61 ± 1.38	0.17	0.46	1.00	
m_t^{MEt}	174.23 ± 1.77	0.10	0.22	0.16	1.00

Table 6: Summary of the combination of the 12 measurements by CDF and D0 in terms of two physical quantities, the mass of the top quark measured in CDF and in D0.

Parameter	Value (GeV/c^2)	Correlations	
		m_t^{CDF}	m_t^{D0}
m_t^{CDF}	173.08 ± 0.92	1.00	
m_t^{D0}	174.96 ± 0.74	0.26	1.00

6 Summary

An update was presented of the combination of measurements of the mass of the top quark from the Tevatron experiments CDF and D0. This preliminary combination includes five published Run I measurements, six published Run II measurements, and one preliminary Run II measurement. Most of these measurements are performed with the full Tevatron data set. Taking into account the statistical and systematic uncertainties and their correlations, the preliminary result for the Tevatron average is $m_t = 174.30 \pm 0.35\,(\text{stat}) \pm 0.54\,(\text{syst})$ GeV/c^2. Adding in quadrature the statistical and systematic uncertainties yields a total uncertainty of 0.65 GeV/c^2. The mass of the top quark is measured with a relative precision of 0.37%, limited by the systematic uncertainties, which are dominated by the uncertainty on in situ jet energy scale calibration and signal modeling.

The central value is 40 MeV/c^2 lower than the Tevatron Summer 2014 average [1] of $m_t = 174.34 \pm 0.64\,\text{GeV}/c^2$ while the total uncertainty is almost identical. Compared to the world average [3], the central value of this combination is 1.00 GeV/c^2 higher and its precision is 16% better.

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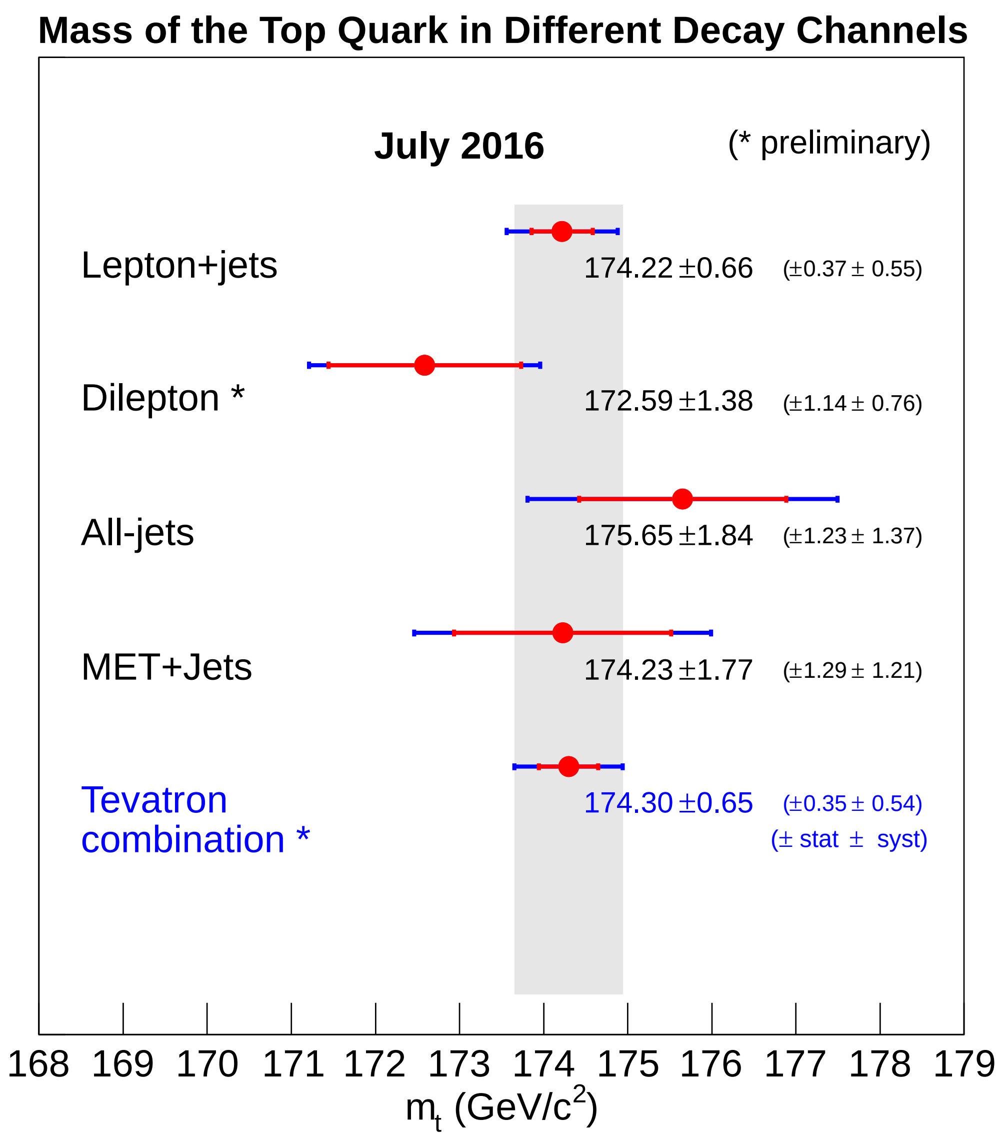

Figure 4: Summary of the combination of the twelve top-quark mass measurements by CDF and D0 for different final states. The red lines correspond to the statistical uncertainty while the blue lines show the total uncertainty.

References

[1] The CDF Collaboration, the D0 Collaboration and the 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`.

[2] T. Aaltonen *et al.* [CDF and D0 Collaborations], *Combination of the top-quark mass measurements from the Tevatron collider* Phys. Rev. D **86**, 092003 (2012).

[3] The ATLAS, CDF, CMS and D0 Collaborations, *First combination of Tevatron and LHC measurements of the top-quark mass*, `arXiv:1403.4427`.

[4] F. Abe *et al.* [CDF Collaboration], *Measurement of the top quark mass and $t\bar{t}$ production cross section from dilepton events at the Collider Detector at Fermilab*, Phys. Rev. Lett. **80**, 2779 (1998).

[5] F. Abe *et al.* [CDF Collaboration], *Measurement of the top quark mass with the Collider Detector at Fermilab*, Phys. Rev. Lett. **82**, 271 (1999). `hep-ex/9810029`.

[6] F. Abe *et al.* [CDF Collaboration], *Measurement of the top quark mass with the Collider Detector at Fermilab*, Erratum: Phys. Rev. Lett. **82** (1999) 2808.

[7] B. Abbott *et al.* [D0 Collaboration], *Measurement of the top quark mass using dilepton events*, Phys. Rev. Lett. **80**, 2063 (1998). `hep-ex/9706014`.

[8] B. Abbott *et al.* [D0 Collaboration], *Measurement of the top quark mass in the dilepton channel*, Phys. Rev. D**60**, 052001 (1999).

[9] F. Abe *et al.* [CDF Collaboration], *Measurement of the top quark mass*, Phys. Rev. Lett. **80**, 2767 (1998).

[10] T. Affolder *et al.* [CDF Collaboration], *Measurement of the top quark mass with the Collider Detector at Fermilab*, Phys. Rev. D **63**.

[11] S. Abachi *et al.* [D0 Collaboration], *Direct measurement of the top quark mass*, Phys. Rev. Lett. **79**, 1197 (1997).

[12] B. Abbott *et al.* [D0 Collaboration], *Direct measurement of the top quark mass at D0*, Phys. Rev. D **58**, 052001 (1998).

[13] V. M. Abazov *et al.* [D0 Collaboration], *A precision measurement of the mass of the top quark*, Nature **429**, 638 (2004).

[14] F. Abe *et al.* [CDF Collaboration], *First observation of the all hadronic decay of $t\bar{t}$ pairs*, Phys. Rev. Lett. **79**, 1992 (1997).

[15] V. M. Abazov *et al.* [D0 Collaboration], *Measurement of the top quark mass in alljet events*, Phys. Lett. B **606**, 25 (2005).

[16] T. Aaltonen *et al.* [CDF Collaboration], *Measurements of the top-quark mass using charged particle tracking*, Phys. Rev. D **81**, 032002 (2010).

[17] T. Aaltonen *et al.* [CDF Collaboration], *Top Mass Measurement in the Lepton+Jets Channel using a Matrix Element Method with quasi-Monte Carlo integration and in situ Jet Calibration with* $5.6\,\mathrm{fb}^{-1}$, Phys. Rev. Lett. **109**, 152003 (2012).

[18] T. Aaltonen *et al.* [CDF Collaboration], *Top-quark mass measurement in events with jets and missing transverse energy using the full CDF data set*, Phys. Rev. D **88**, 011101 (2013).

[19] T. A. Aaltonen *et al.* [CDF Collaboration], *Measurement of the Top-Quark Mass in the All-Hadronic Channel using the full CDF data set*, Phys. Rev. D **90**, 091101 (2014).

[20] T. Aaltonen *et al.* [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. D **92**, 032003 (2015)

[21] V. M. Abazov *et al.* [D0 Collaboration], *Precision measurement of the top-quark mass in lepton+jets final states*, Phys. Rev. Lett. **113**, 032002 (2014).

[22] V. M. Abazov *et al.* [D0 Collaboration], *Precision measurement of the top-quark mass in lepton+jets final states*, Phys. Rev. D **91**, 112003 (2015).

[23] V. M. Abazov *et al.* [D0 Collaboration], *Precise measurement of the top quark mass in dilepton decays using optimized neutrino weighting*, Phys. Lett. B **752**, 18 (2016).

[24] V. M. Abazov *et al.* [D0 Collaboration], *Measurement of the Top Quark Mass Using the Matrix Element Technique in Dilepton Final States*, Accepted by Phys. Rev. D, `arXiv:1606.02814` .

[25] V. M. Abazov *et al.* [D0 Collaboration], *Combination of the matrix element and neutrino weighting measurements of the top quark mass in dilepton final states*, D0 Conference Note 6484.

[26] The CDF Collaboration, the D0 Collaboration and the Tevatron Electroweak Working Group, `arXiv:1305.3929`.

[27] The CDF Collaboration, the D0 Collaboration and the Tevatron Electroweak Working Group, *Combination of CDF and D0 Results on the Mass of the Top Quark*, `arXiv:1107.5255`.

[28] The CDF Collaboration, the D0 Collaboration, and the Tevatron Electroweak Working Group, *Combination of CDF and D0 results on the top-quark mass*, `hep-ex/0404010`.

[29] The CDF Collaboration, the D0 Collaboration, and the Tevatron Electroweak Working Group, *Combination of CDF and D0 results on the top-quark mass*, `hep-ex/0507091`.

[30] The CDF Collaboration, the D0 Collaboration, and the Tevatron Electroweak Working Group, *Combination of CDF and D0 results on the top-quark mass*, hep-ex/0603039.

[31] The CDF Collaboration, the D0 Collaboration, and the Tevatron Electroweak Working Group, *Combination of CDF and D0 results on the top-quark mass*, hep-ex/0608032.

[32] The CDF Collaboration, the D0 Collaboration, and the Tevatron Electroweak Working Group, *Combination of CDF and D0 results on the top-quark mass*, hep-ex/0703034.

[33] The CDF Collaboration, the D0 Collaboration, and the Tevatron Electroweak Working Group, *Combination of CDF and D0 results on the mass of the top quark*, arXiv:0803.1683.

[34] The CDF Collaboration, the D0 Collaboration, and the Tevatron Electroweak Working Group, *Combination of CDF and D0 results on the mass of the top quark*, arXiv:0808.1089.

[35] The CDF Collaboration, the D0 Collaboration and the Tevatron Electroweak Working Group, *Combination of CDF and D0 Results on the Mass of the Top Quark*, arXiv:0903.2503.

[36] The CDF Collaboration, the D0 Collaboration and the Tevatron Electroweak Working Group, *Combination of CDF and D0 Results on the Mass of the Top Quark*, arXiv:1007.3178.

[37] A. Buckley *et al.*, *General-purpose event generators for LHC physics*, Phys. Rept. **504**, 145 (2011).

[38] V. M. Abazov *et al.* [D0 Collaboration], *Measurement of the top quark mass in the lepton+jets final state with the matrix element method*, Phys. Rev. D **74**, 092005 (2006).

[39] S. Frixione, P. Nason and G. Ridolfi, *A Positive-weight next-to-leading-order Monte Carlo for heavy flavour hadroproduction*, JHEP **0709**, 126 (2007).

[40] S. Frixione and B. Webber, *Matching NLO QCD computations and parton shower simulations*, JHEP **029**, 0206 (2002).

[41] M. L. Mangano, M. Moretti, F. Piccinini, R. Pittau, and A. D. Polosa, *ALPGEN, a generator for hard multiparton processes in hadronic collisions*, JHEP **07**, 001 (2003)

[42] G. Marchesini *et al.*, *HERWIG: A Monte Carlo event generator for simulating hadron emission reactions with interfering gluons. Version 5.1 - April 1991*, Comput. Phys. Commun. **67**, 465 (1992).

[43] G. Corcella *et al.*, *HERWIG 6: An event generator for hadron emission reactions with interfering gluons (including supersymmetric processes)*, JHEP **01**, 010 (2001).

[44] P. Z. Skands and D. Wicke, *Non-perturbative QCD effects and the top mass at the Tevatron*, Eur. Phys. J. C **52**, 133 (2007).

[45] P. Z. Skands, *The Perugia Tunes*, `arXiv:0905.3418`.

[46] H.-U. Bengtsson and T. Sjostrand, *The Lund Monte Carlo for hadronic processes: PYTHIA version 4.8*, Comput. Phys. Commun. **46**, 43 (1987).

[47] T. Sjostrand, *High-energy physics event generation with PYTHIA 5.7 and JETSET 7.4*, Comput. Phys. Commun. **82**, 74 (1994).

[48] T. Sjostrand *et al.*, *High-energy-physics event generation with PYTHIA 6.1*, Comput. Phys. Commun. **135**, 238 (2001).

[49] F. E. Paige and S. D. Protopopescu, *ISAJET: A Monte Carlo event generator for pp and $\bar{p}p$ interactions*, BNL Reports 38034 and 38774 (1986), unpublished.

[50] L. Lyons, D. Gibaut, and P. Clifford, *How to combine correlated estimates of a single physical quantity*, Nucl. Instrum. Meth. A **270**, 110 (1988).

[51] A. Valassi, *Combining correlated measurements of several different physical quantities*, Nucl. Instrum. Meth. A **500**, 391 (2003).