FERMI NATIONAL ACCELERATOR LABORATORY

FERMILAB-TM-2466-E
TEVEWWG/top 2010/07
CDF Note 10210
DØ Note 6090
July 2010

Combination of CDF and DØ results on the mass of the top quark using up to 5.6 fb^{-1} of data

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Abstract

We summarize the top-quark mass measurements from the CDF and DØ experiments at Fermilab. We combine published Run I (1992–1996) measurements with the most precise published and preliminary Run II (2001-present) measurements using up to 5.6 fb^{-1} of data. Taking uncertainty correlations properly into account, and adding in quadrature the statistical and systematic uncertainties, the resulting preliminary Tevatron average mass of the top quark is $m_{top} = 173.3 \pm 1.1$ GeV/c^2.

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1 Introduction

This note reports the Tevatron average top-quark mass obtained by combining the most precise published and preliminary measurements of the top-quark mass, $\mathrm{m_{top}}$.

The experiments CDF and DØ, taking data at the Tevatron proton-antiproton collider located at the Fermi National Accelerator Laboratory, have made several direct experimental measurements of the top-quark mass, $\mathrm{m_{top}}$. The pioneering measurements were based on about 100 pb^{-1} of Run I data [1 - 12] collected from 1992 to 1996, and include results from the $t\bar{t} \to W^+bW^-\bar{b} \to qq'bqq'\bar{b}$ (all-j), $t\bar{t} \to W^+bW^-\bar{b} \to \ell\nu bqq'\bar{b}$ (l+j)[2], and $t\bar{t} \to W^+bW^-\bar{b} \to \ell^+\nu b\ell^-\overline{\nu}\bar{b}$ (di-l) decay channels. Several more measurements have been performed in Run II (2001 - present) in all decay modes. The Run II measurements considered here are the most recent results in the l+j, di-l, and all-j channels using $1.9 - 5.6$ fb^{-1} of data and improved analysis techniques [13 – 20].

With respect to the March 2009 combination [21], the preliminary Run II CDF measurement in the l+j channel has been updated using 5.6 fb^{-1} of data, and improved analysis technique [14]. The now published Run II CDF measurement in the di-l channel [22] has been substituted with a more precise preliminary result that uses 4.8 fb^{-1} of data [13]. Also, the Run II measurements in the all-j channel, and the measurement based on charged particle tracking have been published [15, 16]. The DØ Run II measurements are unchanged. The Tevatron average top-quark mass is thus obtained by combining five published Run I measurements [2, 3, 5, 7, 10, 11] with two published Run II CDF results [15, 16], two preliminary Run II CDF results [13, 14] and two preliminary Run II DØ results [18 – 20]. The combination takes into account the statistical and systematic uncertainties and their correlations using the method of Refs. [23, 24] and supersedes previous combinations [25, 26, 27, 28, 29, 30, 31, 21]. The definition and evaluation of the systematic uncertainties and the understanding of the correlations among channels, experiments, and Tevatron runs, is the outcome of many years of joint work between the CDF and DØ collaborations.

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

[2] Here $\ell = e$ or μ. Decay channels with explicit tau lepton identification are presently under study and are not yet used for measurements of the top-quark mass. Decays with $\tau \to e, \mu$ are included in the direct $W \to e$ and $W \to \mu$ channels.

2 Input Measurements

For this combination eleven measurements of m_{top} are used: five published Run I results, two published Run II results, and four preliminary Run II results, all reported in Table 1. In general, the Run I measurements all have relatively large statistical uncertainties and their systematic uncertainties are dominated by the total jet energy scale (JES) uncertainty. In Run II both CDF and DØ take advantage of the larger $t\bar{t}$ samples available and employ new analysis techniques to reduce both these uncertainties. In particular, the Run II DØ analysis in the l+j channel and the Run II CDF analyses in the l+j and all-j channels constrain the response of light-quark jets using the kinematic information from $W \to qq'$ decays (*in situ* calibration). Residual JES uncertainties associated with p_T and η dependencies as well as uncertainties specific to the response of b-jets are treated separately. The Run II CDF and DØ di-l measurements and the CDF measurement of Ref. [16] use a JES determined from external calibration samples. Some parts of the associated uncertainty are correlated with the Run I JES uncertainty as noted below.

The DØ Run II l+j analysis uses the JES determined from the external calibration derived from γ+jets events as an additional Gaussian constraint to the *in situ* calibration. Therefore the total resulting JES uncertainty is split into one part emerging from the *in situ* calibration and another part emerging from the external calibration.

To do that, the measurement without external JES constraint has been combined iteratively with a pseudo-measurement using the method of Refs. [23, 24] which uses only the external calibration in a way that the combination give the actual total JES uncertainty. The splitting obtained in this way is used to assess the statistical part of the JES uncertainty, and the part of the JES uncertainty coming from the external calibration constraint [32].

The analysis technique developed by CDF and referred to as "trk" uses both the mean decay-length from b-tagged jets and the mean lepton transverse momentum to determine the top-quark mass in l+j candidate events. While the statistical sensitivity is not as good as the more traditional methods, this technique has the advantage that since it uses primarily tracking information, it is almost entirely independent of JES uncertainties. As the statistics of this sample continue to grow, this method is expected to offer a cross-check of the top-quark mass largely independent of the dominant JES systematic uncertainty. The statistical correlation between an earlier version of the trk analysis and a traditional Run II CDF l+j measurement was studied using Monte Carlo signal-plus-background pseudo-experiments which correctly account for the sample overlap and was found to be consistent with zero (to within $<1\%$) independent of the assumed top-quark mass.

The DØ Run II l+j result is a combination of the published Run IIa (2002–2005) measurement [17] with 1 fb^{-1} of data and the preliminary result obtained with 2.6 fb^{-1} Run IIb (2006–2007) dataset.

Table 1: Summary of the measurements used to determine the Tevatron average m_{top}. Integrated luminosity ($\int \mathcal{L}\ dt$) has units in fb^{-1}, and all other numbers are in GeV/c^2. The uncertainty categories and their correlations are described in the Sec. 3. The total systematic uncertainty and the total uncertainty are obtained by adding the relevant contributions in quadrature. The new measurements utilized here are the two CDF preliminary results in the last column.

	Run I published					Run II published		Run II preliminary			
	CDF			DØ		CDF		DØ		CDF	
	all-j	l+j	di-l	l+j	di-l	all-j	trk	l+j	di-l	l+j	di-l
$\int \mathcal{L}\ dt$	0.1	0.1	0.1	0.1	0.1	2.9	1.9	3.6	3.6	5.6	4.8
Result	186.0	176.1	167.4	180.1	168.4	174.80	175.30	173.75	174.66	173.00	170.56
iJES	-	-	-	-	-	1.64	-	0.47	-	0.58	-
aJES	-	-	-	-	-	-	-	0.91	1.32	-	-
bJES	0.6	0.6	0.8	0.7	0.7	0.21	0.0	0.07	0.26	0.26	0.35
cJES	3.0	2.7	2.6	2.0	2.0	0.49	0.60	0.0	0.0	0.27	2.01
dJES	0.3	0.7	0.6	0.0	0.0	0.08	0.0	0.84	1.46	0.01	0.64
rJES	4.0	3.4	2.7	2.5	1.1	0.21	0.10	0.0	0.0	0.41	1.98
LepPt	0.0	0.0	0.0	0.0	0.0	-	1.10	0.18	0.32	0.14	0.31
Signal	1.8	2.6	2.8	1.1	1.8	0.23	1.60	0.45	0.65	0.21	0.36
Backgd	1.7	1.3	0.3	1.0	1.1	0.35	1.60	0.08	0.08	0.34	0.27
Fit	0.6	0.0	0.7	0.6	1.1	0.67	1.40	0.21	0.51	0.10	0.05
MC	0.8	0.1	0.6	0.0	0.0	0.31	0.60	0.58	1.00	0.37	0.57
UN/MI	-	-	-	1.3	1.3	-	-	-	-	-	-
CR	-	-	-	-	-	0.41	0.40	0.41	0.41	0.37	0.61
MHI	-	-	-	-	-	0.17	0.70	0.05	0.00	0.10	0.27
Syst	5.7	5.3	4.9	3.9	3.6	1.99	3.10	1.60	2.43	1.06	3.09
Stat	10.0	5.1	10.3	3.6	12.3	1.70	6.20	0.83	2.92	0.65	2.19
Total	11.5	7.3	11.4	5.3	12.8	2.61	6.94	1.80	3.80	1.24	3.79

The DØ Run II di-l result is itself a combination of two results using different techniques but partially overlapping dilepton datasets [19, 20].

Table 1 also lists the uncertainties of the results, subdivided into the categories described in the next Section. The correlations between the inputs are described in Section 4.

3 Uncertainty Categories

We employ the same uncertainty categories as used for the previous Tevatron average [21]. They are divided such that sources of systematic uncertainty that share the same or similar origin are combined. For example, the "Signal" category discussed below includes the uncertainties from initial state ratiation (ISR), final state radiation (FSR), and parton density functions (PDF)—all of which affect the modeling of the $t\bar{t}$ signal. Some systematic uncertainties have been broken down into multiple categories in order to accommodate specific types of correlations. For example, the jet energy scale (JES) uncertainty is subdivided into six components in order to more accurately accommodate our best estimate of the relevant correlations.

Statistics: The statistical uncertainty associated with the $\mathrm{m_{top}}$ determination.

iJES: That part of the JES uncertainty which 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+j and all-j measurements and DØ Run II l+j measurement. Residual JES uncertainties arising from effects not considered in the *in situ* calibration are included in other categories.

aJES: That part of the JES uncertainty which originates from differences in detector electromagnetic over hadronic (e/h) response between b-jets and light-quark jets. This category also includes uncertainties associated with the jet identification and resolution, trigger and b-jets tagging. It is specific to the DØ Run II measurements and is uncorrelated with the DØ Run I and CDF measurements.

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

cJES: That part of the JES uncertainty which originates from modeling uncertainties correlated across all measurements. Specifically it includes the modeling uncertainties associated with light-quark fragmentation and out-of-cone corrections. For DØ Run II measurements, it is included in the dJES category.

dJES: That part of the JES uncertainty which originates from limitations in the data samples used for calibrations and which is correlated between measurements within the same data-taking period, such as Run I or Run II, but not between experiments. For CDF this corresponds to uncertainties associated with the η-dependent JES corrections which are estimated using di-jet data events. For DØ this includes uncertainties in the calorimeter response for light jets, uncertainties from p_T- and η-dependent JES corrections and from the sample dependence of using γ+jets data samples to derive the JES.

rJES: The remaining part of the JES uncertainty which is correlated between all measurements of the same experiment independently from the data-taking period, but which is uncorrelated between experiments. For CDF, this is dominated by uncertainties in the calorimeter response to light-quark jets, and also includes small uncertainties associated with the multiple interaction and underlying event corrections. For DØ Run II measurements, it is included in the dJES category.

LepPt: The systematic uncertainty arising from uncertainties in the scale of lepton transverse momentum measurements. This is an important uncertainty for CDF's track-based measurement. It was not considered as a source of systematic uncertainty in the Run I measurements.

Signal: The systematic uncertainty arising from uncertainties in the $t\bar{t}$ modeling which is correlated across all measurements. This includes uncertainties from variations in the ISR, FSR, and PDF descriptions used to generate the $t\bar{t}$ Monte Carlo samples that calibrate each method. For DØ it also includes the uncertainty from higher order corrections evaluated from a comparison of $t\bar{t}$ samples generated by MC@NLO [33] and ALPGEN [34], both interfaced to HERWIG [35, 36] for the simulation of parton showers and hadronization.

Background: Uncertainty in modeling the background sources. They are correlated between all measurements in the same channel, and include uncertainties on the background composition and shape. In particular uncertainties associated with the modeling of the QCD multijet background using data in the all-j and l+j channels, uncertainties associated with the modeling of the Drell-Yan background in the di-l channel, and uncertainties associated with variations of the factorization scale used to model W+jets background are included.

Fit: The systematic uncertainty arising from any source specific to a particular fit method, including the finite Monte Carlo statistics available to calibrate each method. For DØ this uncertainty also includes the uncertainties from modeling of the QCD multijet background determined from data and dominated by limited statistics.

Monte Carlo (MC): The systematic uncertainty associated with variations of the physics model used to calibrate the fit methods and which is correlated across all measurements. It includes variations observed when substituting PYTHIA [37–39] (Run I and Run II) or ISAJET [40] (Run I) for HERWIG [35, 36] when modeling the $t\bar{t}$ signal.

Uranium Noise and Multiple Interactions (UN/MI): This is specific to DØ and includes the uncertainty arising from uranium noise in the DØ calorimeter and from the multiple interaction corrections to the JES. For DØ 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.

Color Reconnection (CR): The systematic uncertainty arising from a variation of the phenomenological description of color reconnection between final state particles [41, 42]. This is obtained taking the difference between PYTHIA 6.4 tune “Apro” and PYTHIA 6.4 tune “ACRpro” that only differ only in the color reconnection model. Monte Carlo generators which explicitly include different CR models for hadron collisions have recently become available. This was not possible in Run I; these measurements therefore do not include this source of systematic uncertainty.

Multiple Hadron Interactions (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 with DØ measurements.

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 ever improving precision. Variations in the assignment of uncertainties to the uncertainty categories, in the back-propagation of the bJES uncertainties to Run I measurements, in the approximations made to symmetrize the uncertainties used in the combination, and in the assumed magnitude of the correlations, have all a negligible impact ($\ll 0.1\,\mathrm{GeV}/c^2$) in the combined $\mathrm{m_{top}}$ and total uncertainty.

4 Correlations

The following correlations are used for the combination:

- The uncertainties in the Statistical, Fit, and iJES categories are taken to be uncorrelated among the measurements.
- The uncertainties in the aJES, dJES, LepPt and 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 rJES and UN/MI categories are taken to be 100% correlated among all measurements within the same experiment but uncorrelated between the experiments.
- The uncertainties in the Background category are taken to be 100% correlated among all measurements in the same channel.

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

	Run I published					Run II published		Run II preliminary			
	CDF			DØ		CDF		DØ		CDF	
	l+j	di-l	all-j	l+j	di-l	all-j	trk	l+j	di-l	l+j	di-l
CDF-l+j	1.00	-	-	-	-	-	-	-	-	-	-
CDF-I di-l	0.29	1.00	-	-	-	-	-	-	-	-	-
CDF-I all-j	0.32	0.19	1.00	-	-	-	-	-	-	-	-
DØ-I l+j	0.26	0.15	0.14	1.00	-	-	-	-	-	-	-
DØ-I di-l	0.11	0.08	0.07	0.16	1.00	-	-	-	-	-	-
CDF-II all-j	0.15	0.10	0.12	0.10	0.05	1.00	-	-	-	-	-
CDF-II trk	0.16	0.08	0.07	0.12	0.05	0.06	1.00	-	-	-	-
DØ-II l+j	0.10	0.08	0.06	0.07	0.04	0.10	0.11	1.00	-	-	-
DØ-II di-l	0.07	0.06	0.05	0.04	0.03	0.07	0.07	0.52	1.00	-	-
CDF-II l+j	0.36	0.19	0.23	0.20	0.07	0.19	0.19	0.22	0.15	1.00	-
CDF-II di-l	0.48	0.28	0.35	0.23	0.11	0.21	0.12	0.11	0.08	0.43	1.00

- The uncertainties in the bJES, cJES, Signal, CR, and MC 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 [23, 24]. The two methods are mathematically equivalent, and are also equivalent to the method used in an older combination [43]. 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_{top} average in terms of the uncertainty categories specified for the input measurements [24].

5 Results

The combined value for the top-quark mass is: $m_{top} = 173.32 \pm 0.56$ (stat) ± 0.89 (syst) GeV/c^2. Adding the statistical and systematic uncertainties in quadrature yields a total uncertainty of 1.06 GeV/c^2, corresponding to a relative precision of 0.61% on the top-quark mass. Rounding off to two significant digits in the uncertainty, the combination provides $m_{top} = 173.3 \pm 1.1$ GeV/c^2. It has a χ^2 of 6.1 for 10 degrees of freedom, which corresponds to a probability of 81%, indicating good agreement among all the input measurements. The breakdown of the uncertainties is shown in Table 3. The total JES uncertainty is ± 0.61 GeV/c^2 with ± 0.46 GeV/c^2 coming from its statistical component and ± 0.40 GeV/c^2 from the nonstatistical component. The total statistical uncertainty is ± 0.56 GeV/c^2.

The pull and weight for each of the inputs are listed in Table 4. The input measurements and the resulting Tevatron average mass of the top quark are summarized in Fig. 1.

Table 3: Summary of the Tevatron combined average m_{top} . 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_{top}	173.32
iJES	0.46
aJES	0.21
bJES	0.20
cJES	0.13
dJES	0.19
rJES	0.15
LepPt	0.10
Signal	0.19
Background	0.23
Fit	0.11
MC	0.40
UN/MI	0.02
CR	0.39
MHI	0.08
Systematics	0.89
Statistics	0.56
Total	1.06

The weights of some of the measurements are negative. In general, this situation can occur if the correlation between two measurements is larger than the ratio of their total uncertainties.

Table 4: The pull and weight for each of the inputs used to determine the Tevatron average mass of the top quark. See Reference [23] for a discussion of negative weights.

	Run I published					Run II published		Run II preliminary			
	CDF			DØ		CDF		DØ		CDF	
	l+j	di-l	all-j	l+j	di-l	all-j	trk	l+j	di-l	l+j	di-l
Pull	+0.38	−0.52	+1.11	+1.30	−0.39	+0.62	+0.29	+0.29	+0.37	−0.50	−0.76
Weight [%]	−2.5	−0.5	−0.7	+1.3	+0.2	+10.5	−0.5	+26.2	−2.1	+70.0	−1.8

Table 5: Summary of the combination of the 11 measurements by CDF and DØ in terms of three physical quantities, the mass of the top quark in the all-j m_{top}^{all-j}, l+j m_{top}^{l+j}, and di-l m_{top}^{di-l} decay channels.

Parameter	Value (GeV/c^2)	Correlations		
		m_{top}^{all-j}	m_{top}^{l+j}	m_{top}^{di-l}
m_{top}^{all-j}	175.2 ± 2.6	1.00		
m_{top}^{l+j}	173.0 ± 1.1	0.20	1.00	
m_{top}^{di-l}	171.1 ± 2.5	0.19	0.48	1.00

This is indeed the case here. In these instances the less precise measurement will usually acquire a negative weight. While a weight of zero means that a particular input is effectively ignored in the combination, a negative weight means that it affects the resulting m_{top} central value and helps reduce the total uncertainty.

Although no input has an anomalously large pull and the χ^2 from the combination of all measurements indicates that there is good agreement among them, it is still interesting to also fit for the top-quark mass in the all-j, l+j, and di-l channels separately. We use the same methodology, inputs, uncertainty categories, and correlations as described above, but fit the three physical observables, m_{top}^{all-j}, m_{top}^{l+j}, and m_{top}^{di-l}separately. The results of these combinations are shown in Table 5.

Using the results of Table 5 we calculate the chi-squared consistency between any two channels, including all correlations, as χ^2(di-l/l+j)=0.75, χ^2(l+j/all-j)=0.68, and χ^2(all-j/di-l)=1.58. These correspond to chi-squared probabilities of 38%, 68%, and 21%, respectively, and indicate that the determinations of m_{top} from the three different final states are consistent with each another.

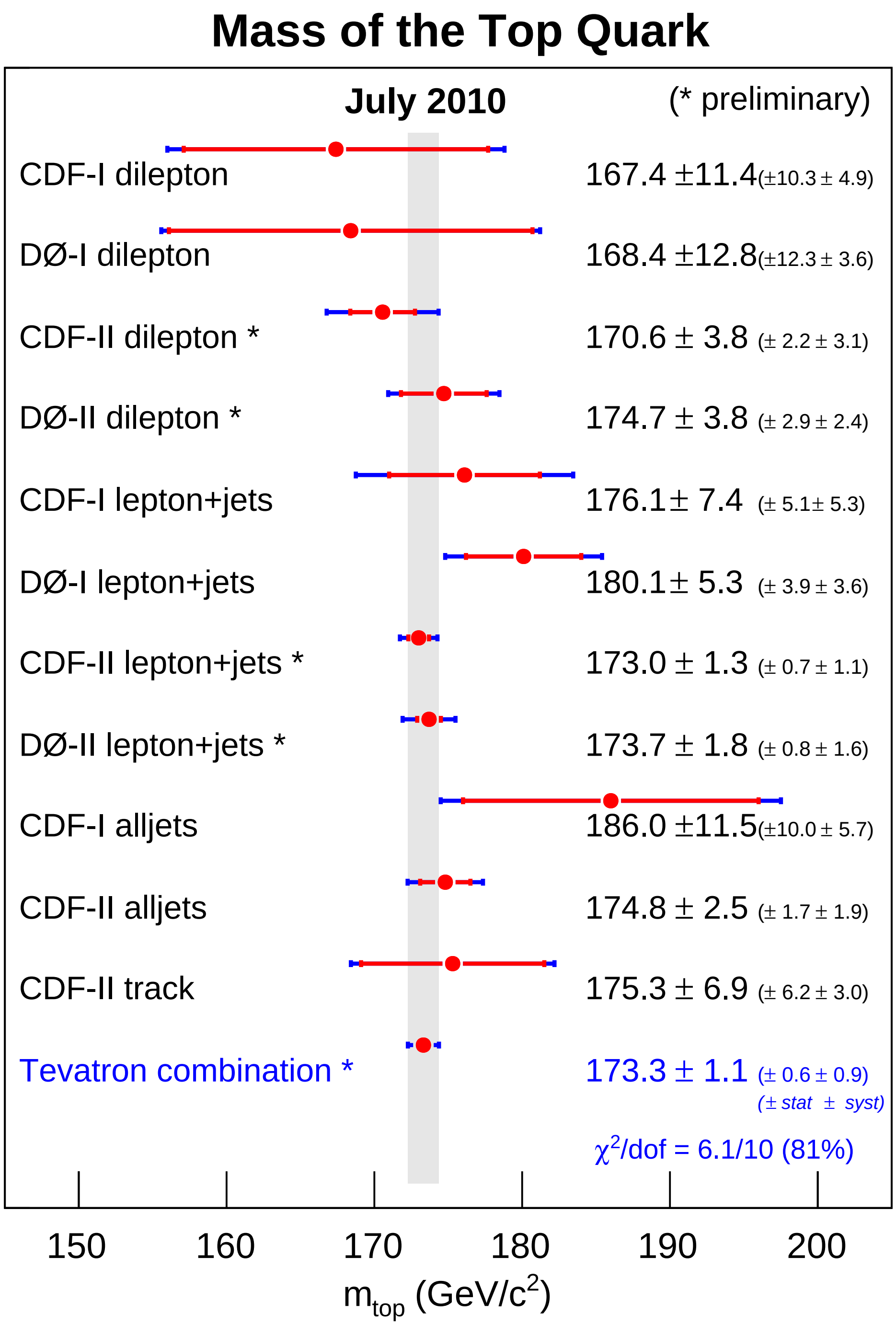

Figure 1: Summary of the input measurements and resulting Tevatron average mass of the top-quark.

6 Summary

A preliminary combination of measurements of the mass of the top quark from the Tevatron experiments CDF and DØ is presented. The combination includes five published Run I measurements, two published Run II measurements, and four preliminary Run II measurements. Taking into account the statistical and systematic uncertainties and their correlations, the preliminary result for the Tevatron average is: $m_{top} = 173.32 \pm 0.56$ (stat) ± 0.89 (syst) GeV/c^2, where the total uncertainty is obtained assuming Gaussian systematic uncertainties. Adding in quadrature the statistical and systematic uncertainties yields a total uncertainty of 1.06 GeV/c^2, corresponding to a relative precision of 0.61% on the top-quark mass. Rounding off the uncertainty to two significant digits, the combination provides $m_{top} = 173.3 \pm 1.1$ GeV/c^2.

The central value is 0.20 GeV/c^2 higher than our March 2009 average of $m_{top} = 173.12 \pm 1.26$ GeV/c^2, while the relative precision has improved by 15% with respect to the previous Tevatron average.

The mass of the top quark is now known with a relative precision of 0.61%, limited by the systematic uncertainties, which are dominated by the jet energy scale uncertainty. This source of systematic uncertianty is expected to improve as larger datasets are collected since analysis techniques constrain the jet energy scale using kinematical information from $W \to qq'$ decays. It can be expected that with the full Run II dataset the top-quark mass will be known to an accuracy better than the one presented in this paper. To reach this level of precision further work will be focuses on a better understanding of b-jet modeling, and in the uncertainties in the signal and background simulations.

7 Acknowledgments

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by DOE and NSF (USA), CONICET and UBACyT (Argentina), CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil), CRC Program, CFI, NSERC and WestGrid Project (Canada), CAS and CNSF (China), Colciencias (Colombia), MSMT and GACR (Czech Republic), Academy of Finland (Finland), CEA and CNRS/IN2P3 (France), BMBF and DFG (Germany), Ministry of Education, Culture, Sports, Science and Technology (Japan), World Class University Program, National Research Foundation (Korea), KRF and KOSEF (Korea), DAE and DST (India), SFI (Ireland), INFN (Italy), CONACyT (Mexico), NSC(Republic of China), FASI, Rosatom and RFBR (Russia), Slovak R&D Agency (Slovakia), Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010 (Spain), The Swedish Research Council (Sweden), Swiss National Science Foundation (Switzerland), FOM (The Netherlands), STFC and the Royal Society (UK), and the A.P. Sloan Foundation (USA).

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