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Combination of CDF and DØ Results on the Mass of the Top Quark

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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 recent preliminary Run II (2001-present) measurements using up to 3.6 fb^{-1} of data per experiment. Taking correlated uncertainties properly into account the resulting preliminary world average mass of the top quark is $M_{\mathrm{t}} = 173.1 \pm 0.6$ (stat.) $\pm$ 1.1 (syst.) GeV/c^2, assuming Gaussian systematic uncertainties. Adding in quadrature yields a total uncertainty of 1.3 GeV/c^2, corresponding to a relative precision of 0.75% on the top-quark mass.

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1 Introduction

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, M_{t}. The pioneering measurements were based on about 100 pb^{-1} of Run I (1992-1996) data [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12] and include results from the $t\bar{t} \to qq'bqq'\bar{b}$ (all-j), the $t\bar{t} \to \ell\nu qq'b\bar{b}$ (l+j), and the $t\bar{t} \to \ell^+\nu b\ell^-\overline{\nu}\bar{b}$ (di-l) decay channels[2]. The Run II measurements summarized here are the most recent results in the l+j, di-l, and all-j channels using $1.9-3.6$ fb^{-1} of data and improved analysis techniques [13, 14, 15, 16, 17, 18, 19, 20].

This note reports the world average top-quark mass obtained by combining five published Run I measurements [2, 3, 5, 7, 10, 11], with one DØ Run II published measurement [17], four preliminary Run II CDF results [13, 14, 15, 16] and two preliminary Run II DØ results [18, 19, 20]. The combination takes into account the statistical and systematic uncertainties and their correlations using the method of references [21, 22] and supersedes previous combinations [23, 24, 25, 26, 27, 28, 29]. The current result corresponds to an increase of approximately one inverse fb in integrated luminosity.

Since the last combination of summer 2008 CDF and DØ collaborations worked together on the review of the systematic uncertainties and establishing common procedures of their evaluation where possible. Both CDF and DØ experiments added an uncertainty coming from the color reconnection modeling in the $t\bar{t}$ event generation. The DØ experiment included the uncertainties associated with the initial and final state radiation modeling following the method used by CDF and evaluated uncertainties from the different hadronization models and higher order corrections to the $t\bar{t}$ matrix element calculation. Inclusion of more uncertainties resulted in the same size of the total uncertainty on the combined mass as in summer 2008 despite the decrease of statistical uncertainties.

The input measurements and error 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 world average top-quark mass is given in Section 5. A summary and outlook are presented in Section 6.

2 Input Measurements

For this combination eleven measurements of M_{t} are used: five published Run I results, and six preliminary Run II results, all reported in Table 1. In general, the Run I measurements

[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.

all have relatively large statistical uncertainties and their systematic uncertainty is 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 in-situ $W \rightarrow qq'$ decays. Residual JES uncertainties associated with η and p_T 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 is using the JES determined from the external calibration derived using γ+jets events as an additional Gaussian constraint to the in-situ calibration. Therefore the total resulting JES uncertainty has been split into the part coming solely from the in-situ calibration and the part coming 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 ref. [21, 22] that would use only the external calibration so that the combination gives the actual total JES uncertainty. The splitting obtained in this way is used to assess the iJES and part of dJES uncertainty coming from the external calibration constraint [30].

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 could offer a nice cross-check of the top-quark mass that's largely independent of the dominant JES systematic uncertainty which plagues the other measurements. 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 measurement [17] with 1 fb^{-1} of data and the preliminary result obtained with 2.6 fb^{-1} Run IIb dataset [18].

The DØ Run II di-l result is itself a combination of two results using different techniques analyzing dilepton data sets with no overlap [19, 20].

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

	Run I published					Run II preliminary					
	CDF			DØ		CDF				DØ	
	all-j	l+j	di-l	l+j	di-l	l+j	di-l	all-j	trk	l+j	di-l
$\int \mathcal{L}\, dt$	0.1	0.1	0.1	0.1	0.1	3.2	1.9	2.9	1.9	3.6	3.6
Result	186.00	176.10	167.40	180.10	168.40	172.14	171.15	174.80	175.30	173.75	174.66
iJES	0.00	0.00	0.00	0.00	0.00	0.74	0.00	1.64	0.00	0.47	0.00
aJES	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.91	1.32
bJES	0.60	0.60	0.80	0.71	0.71	0.38	0.40	0.21	0.00	0.07	0.26
cJES	3.00	2.70	2.60	2.00	2.00	0.32	1.73	0.49	0.60	0.00	0.00
dJES	0.30	0.70	0.60	0.00	0.00	0.08	0.09	0.08	0.00	0.84	1.46
rJES	4.00	3.35	2.65	2.53	1.12	0.40	1.90	0.21	0.10	0.00	0.00
lepPt	0.00	0.00	0.00	0.00	0.00	0.18	0.10	0.00	1.10	0.18	0.32
Signal	1.80	2.60	2.80	1.11	1.80	0.34	0.78	0.23	1.60	0.45	0.65
MC	0.80	0.10	0.60	0.00	0.00	0.51	0.90	0.31	0.60	0.58	1.00
UN/MI	0.00	0.00	0.00	1.30	1.30	0.00	0.00	0.00	0.00	0.00	0.00
BG	1.70	1.30	0.30	1.00	1.10	0.50	0.38	0.35	1.60	0.08	0.08
Fit	0.60	0.00	0.70	0.58	1.14	0.16	0.60	0.67	1.40	0.21	0.51
CR	0.00	0.00	0.00	0.00	0.00	0.41	0.40	0.41	0.40	0.40	0.40
MHI	0.00	0.00	0.00	0.00	0.00	0.09	0.20	0.17	0.70	0.05	0.00
Syst.	5.71	5.28	4.85	3.89	3.63	1.35	2.98	1.99	3.11	1.60	2.43
Stat.	10.00	5.10	10.30	3.60	12.30	0.94	2.67	1.70	6.20	0.83	2.92
Total	11.51	7.34	11.39	5.30	12.83	1.64	4.00	2.61	6.94	1.80	3.80

Table 1: Summary of the measurements used to determine the world average M_{t}. Integrated luminosity ($\int \mathcal{L}\, dt$) is in fb^{-1}, and all other numbers are in GeV/c^2. The error categories and their correlations are described in the text. The total systematic uncertainty and the total uncertainty are obtained by adding the relevant contributions in quadrature.

3 Error Categories

We employ the same error categories as used for the previous world average [29], plus two new categories (CR and MHI). They include a detailed breakdown of the various sources of uncertainty and aim to lump together sources of systematic uncertainty that share the same or similar origin. For example, the "Signal" category discussed below includes the uncertainties from ISR, FSR, and 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 sub-divided into several components in order to more accurately accommodate our best estimate of the relevant correlations. Each error category is discussed below.

Statistical: The statistical uncertainty associated with the M_{t} 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-h measurements and DØ Run II l+j measurements. Residual JES uncertainties, which arise 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 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 taken to be 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 semi-leptonic branching fraction, b-fragmentation modeling, and for CDF the 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 into the dJES category.

dJES: That part of the JES uncertainty which originates from limitations in the calibration data samples used 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 η- and p_T-dependent JES corrections and from the constraint using Run II γ+jet data samples.

rJES: The remaining part of the JES uncertainty which is correlated between all measurements of the same experiment independent of data-taking period, but 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 into 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 modeling of the $t\bar{t}$ signal 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 comparison of MC@NLO [31] and ALPGEN [32] $t\bar{t}$ MC samples, both with Herwig hadronization model.

Background: The systematic uncertainty arising from uncertainties in modeling the dominant background sources and correlated across all measurements in the same channel. These include uncertainties on the background composition and shape. In particular uncertainties associated with the modeling of the QCD multi-jet background (all-j and l+j) for CDF which is correlated between Run I and Run II, uncertainties associated with the modeling of the Drell-Yan background (di-l), 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 multi-jet background determined from data which is uncorrelated with CDF as it depends on detector related effects.

Monte Carlo (MC): The systematic uncertainty associated with variations of the physics model used to calibrate the fit methods and correlated across all measurements. It includes variations observed when substituting PYTHIA [33, 34, 35] (Run I and Run II) or ISAJET [36] (Run I) for HERWIG [37, 38] 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 integration time and in-situ JES determination, 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 [39] taking the difference between PYTHIA 6.4 tune Apro and PYTHIA 6.4 tune ACRpro that only includes a change in the color reconnection model. Monte Carlo generators which explicitly include CR models for hadron collisions have recently become available [39] and allow us to quantify this systematic for the first time. This was not possible in Run I and these measurements do not include this source of systematic uncertainty.

This systematic source was not considered in the previous measurements and is added here for the first time.

Multiple Hadron Interactions (MHI): The systematic uncertainty arising from a mismodeling of the distribution of number of collision per bunch crossing due to the change in the collider instantaneous luminosity during data-taking. It has been separated from other sources to account for the fact that it is uncorrelated between the two 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 ever improving precision. Variations in the assignment of uncertainties to the error 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 all negligibly effect ($\ll 0.1\text{GeV}/c^2$) the combined M_{t} and total uncertainty.

4 Correlations

The following correlations are used when making 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 on 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 on 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.
- 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 co-efficients is given in Table 2.

		Run I published					Run II preliminary					
		CDF			DØ		CDF				DØ	
		l+j	di-l	all-j	l+j	di-l	l+j	di-l	all-j	trk	l+j	di-l
CDF-I	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	l+j	0.33	0.18	0.20	0.20	0.07	1.00					
CDF-II	di-l	0.46	0.28	0.33	0.22	0.11	0.36	1.00				
CDF-II	all-j	0.15	0.10	0.12	0.10	0.05	0.17	0.19	1.00			
CDF-II	trk	0.16	0.08	0.07	0.12	0.05	0.20	0.12	0.06	1.00		
DØ-II	l+j	0.10	0.08	0.06	0.07	0.04	0.23	0.15	0.10	0.11	1.00	
DØ-II	di-l	0.07	0.06	0.04	0.04	0.03	0.16	0.11	0.07	0.07	0.52	1.00

Table 2: The resulting matrix of total correlation coefficients used to determined the world average top quark mass.

The measurements are combined using a program implementing a numerical χ^2 minimization as well as the analytic BLUE method [21, 22]. The two methods used are mathematically equivalent, and are also equivalent to the method used in an older combination [40], and give identical results for the combination. In addition, the BLUE method yields the decomposition of the error on the average in terms of the error categories specified for the input measurements [22].

5 Results

The combined value for the top-quark mass is:

$$M_{\mathrm{t}} = 173.1 \pm 1.3 \ \mathrm{GeV}/c^2 \,, \tag{1}$$

with a χ^2 of 6.3 for 10 degrees of freedom, which corresponds to a probability of 79%, indicating good agreement among all the input measurements. The breakdown of the uncertainties is shown in Table 3. The total JES is ± 0.73 GeV/c^2 with ± 0.48 GeV/c^2 coming from its statistical and ± 0.55 GeV/c^2 from non-statistical component.

	Tevatron Combined
Result	173.12
iJES	0.48
aJES	0.33
bJES	0.23
cJES	0.19
dJES	0.30
rJES	0.13
lepPt	0.11
Signal	0.30
MC	0.49
UN/MI	0.03
BG	0.26
Fit	0.16
CR	0.41
MHI	0.07
Syst.	1.07
Stat.	0.65
Total	1.25

Table 3: Summary of the Tevatron combined world average M_{t}. The error categories are described in the text. The total systematic uncertainty and the total uncertainty are obtained by adding the relevant contributions in quadrature. All numbers are in units of GeV/c^2.

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

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. 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 central value and helps reduce the total uncertainty. See reference [21] for further discussion of negative weights.

The color reconnection systematic uncertainty evaluated in the current result negligibly affects the central value of the top quark mass combination and increases its total uncertainty by 70 MeV/c^2. Further studies on color reconnection effects are ongoing.

Although the χ^2 from the combination of all measurements indicates that there is good agreement among them, and no input has an anomalously large pull, 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, error categories, and correlations as described above, but fit for

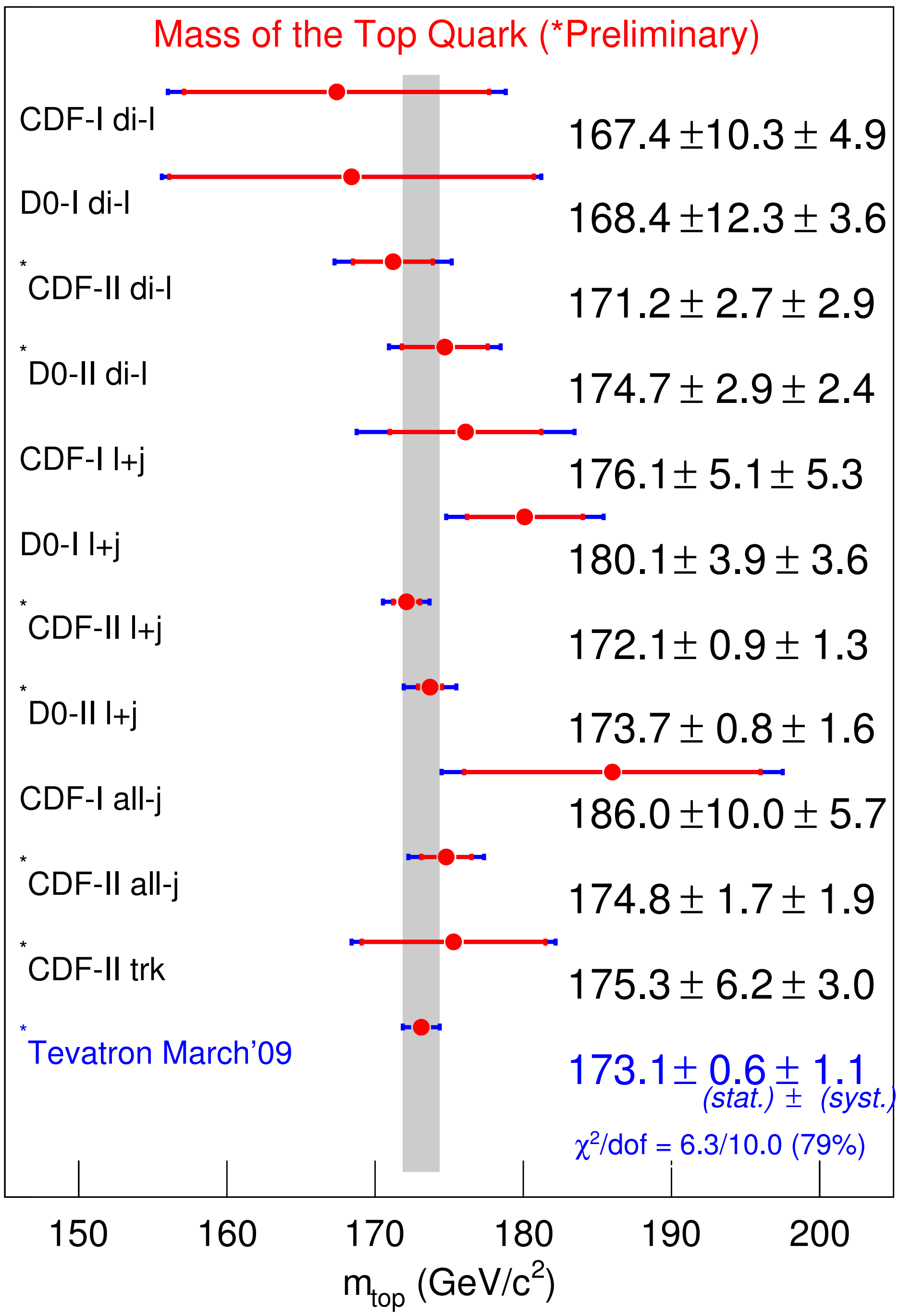

Figure 1: A summary of the input measurements and resulting world average mass of the top quark.

	Run I published					Run II preliminary					
	CDF			DØ		CDF				DØ	
	l+j	di-l	all-j	l+j	di-l	l+j	di-l	all-j	trk	l+j	di-l
Pull	+0.4	−0.5	+1.1	+1.4	−0.4	−0.9	−0.5	+0.7	+0.3	0.5	+0.4
Weight [%]	−2.4	−0.5	−0.6	+2.0	+0.3	+47.4	+0.7	+16.2	−0.1	+39.8	−2.7

Table 4: The pull and weight for each of the inputs used to determine the world average mass of the top quark. See Reference [21] for a discussion of negative weights.

Parameter	Value (GeV/c^2)	Correlations		
$M_{\mathrm{t}}^{\mathrm{all-j}}$	175.1 ± 2.6	1.00		
$M_{\mathrm{t}}^{\mathrm{l+j}}$	172.7 ± 1.3	0.20	1.00	
$M_{\mathrm{t}}^{\mathrm{di-l}}$	171.4 ± 2.7	0.19	0.50	1.00

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-jets, lepton+jets, and di-lepton channels.

the three physical observables, $M_{\mathrm{t}}^{\mathrm{all-j}}$, $M_{\mathrm{t}}^{\mathrm{l+j}}$, and $M_{\mathrm{t}}^{\mathrm{di-l}}$. The results of the fit to the three top mass observables are shown in Table 5 and have χ^2 of 5.0 for 8 degrees of freedom, which corresponds to a probability of 76%. These results differ from a naive combination, where only the measurements in a given channel contribute to the M_{t} determination in that channel, since the combination here fully accounts for all correlations, including those which cross-correlate the different channels. Using the results of Table 5 we calculate the chi-squared consistency between any two channels, including all correlations, as $\chi^2(dil - lj) = 0.3$, $\chi^2(lj - allj) = 0.8$, and $\chi^2(allj - dil) = 1.3$. These correspond to chi-squared probabilities of 57%, 36%, and 26%, respectively, and indicate that the determinations of M_{t} from the three channels are consistent with one another.

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 and six preliminary Run II measurements. Taking into account the statistical and systematic uncertainties and their correlations, the preliminary world-average result is: $M_{\mathrm{t}} = 173.1 \pm 1.3$ GeV/c^2, where the total uncertainty is obtained assuming Gaussian systematic uncertainties and adding them plus the statistical uncertainty in quadrature. While the central value is somewhat higher than our 2008 average, the averages are compatible as appreciably more luminosity and refined analysis techniques are now used.

The mass of the top quark is now known with a relative precision of 0.75%, limited by the systematic uncertainties, which are dominated by the jet energy scale uncertainty. This systematic is expected to improve as larger data sets are collected since new analysis techniques constrain the jet energy scale using in-situ $W \rightarrow qq'$ decays. It can be reasonably expected that with the full Run II data set the top-quark mass will be known to better than 0.75%. To reach this level of precision further work is required to determine more accurately the various correlations present, and to understand more precisely the b-jet modeling, Signal, and Background uncertainties which may limit the sensitivity at larger data sets. Limitations of the Monte Carlo generators used to calibrate each fit method also become more important as the precision reaches the ~ 1 GeV/c^2 level; these warrant further study in the near future.

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