DØNote 5347-CONF

Measurement of the Top Quark Mass in Dilepton Events with Neutrino Weighting in Run II at DØ

The DØ Collaboration
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A measurement of the mass of the top quark, $m_{\rm top}$, is presented in dilepton final states from top quark pair production. Expected neutrino rapidity distributions are used to solve an otherwise under-constrained kinematic fit. Distributions are generated from event weights obtained from comparing the calculated and reconstructed missing transverse energy. The first two moments extracted from these weight distributions, which are the mean value and the root mean square, are used to obtain a top quark mass measurement in data. The top quark mass is extracted by an unbinned maximum likelihood method. Ensemble tests are performed to demonstrate the correct extraction of $m_{\rm top}$ and to obtain the expected statistical uncertainty. A data sample of approximately 1 fb^{-1} of DØ Run-II data in the $e\mu$, ee, and $\mu\mu$ channels is used for this analysis. The top quark mass extracted from 57 dilepton candidate events is measured to be

$$m_{\rm top} = 172.5 \pm 5.8 \text{ (stat.) } \pm 3.5 \text{ (syst.) GeV.}$$

Preliminary Results for Summer 2007 Conferences

Contents

I. INTRODUCTION

In the Standard Model, mass is generated from the spontaneous breaking of electroweak symmetry via the Higgs mechanism. A precision measurement of the mass of the top quark provides information about the Higgs boson mass via corrections to the W boson mass. In this analysis, the top quark mass is measured in dilepton decays ($e\mu$, ee, $\mu\mu$) of $t\bar{t}$ events; that is, events in which each top quark decays to a b quark and a W boson, and in which both W bosons decay either into an electron and a neutrino or into a muon and a neutrino.

The top quark mass is measured for events collected at DØ between April 2002 and March 2006 of Run II at the Tevatron, comprising approximately 1 fb^{-1} of data. The DØ detector is described in detail in [1].

II. METHOD

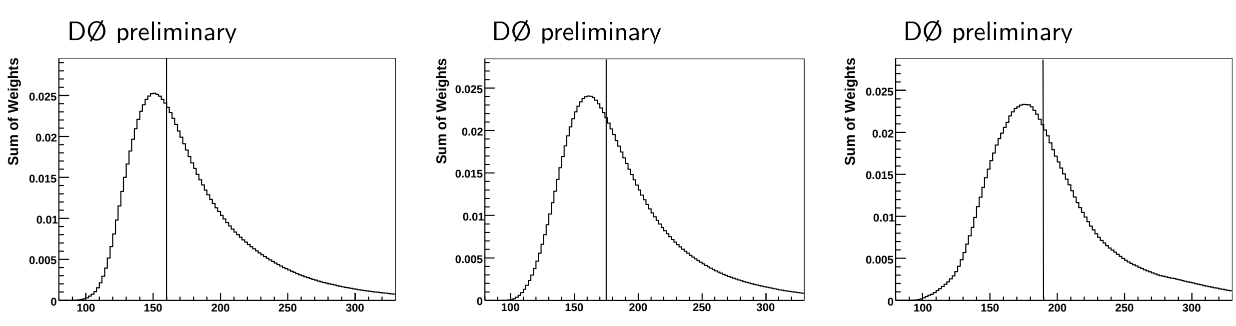
In dilepton decays, the final state consists of six particles: two charged leptons, two jets from b quarks, and two neutrinos. The mass of each final particle is known *a priori*, so this results in 18 independent kinematic quantities in the final state. Fourteen of these parameters – the momenta of the charged leptons and jets and the transverse energy components of the neutrino pair – are measured directly in the detector. Three additional constraints are added by requiring that the invariant mass of each lepton and neutrino pair equal the W boson mass and that the mass of the top and anti-top quarks be equal. This leads to a total of seventeen constraints, which is one constraint short of allowing a solution for the system.

A solution is found by ignoring the observed missing transverse energy $\not\!\!E_T$ from the neutrinos and instead assuming a top quark mass and a pseudorapidity for each neutrino. From this information, the four-momentum of each neutrino may be determined. The measured missing energy is then used to assign a weight, ω, to the solution, based on the agreement of the calculated transverse momentum of the neutrinos with the observed missing transverse energy:

$$\omega = \frac{1}{N_{\rm iter}} \sum_{i=1}^{N_{\rm iter}} \exp\left(\frac{-(\not\!\!E_{x,i}^{\rm calc} - \not\!\!E_x^{\rm obs})^2}{2\sigma^2_{\not E_x}}\right) \exp\left(\frac{-(\not\!\!E_{y,i}^{\rm calc} - \not\!\!E_y^{\rm obs})^2}{2\sigma^2_{\not E_y}}\right), \quad (1)$$

where the sum over $N_{\rm iter}$ indicates the sum over all solutions for all neutrino η assumptions and all permutations. The resolution $\sigma_{\not E_{x,y}}$ is a parameter of the method and affects the sensitivity on the top quark mass. It has been studied with $Z \to ee + jj$ events in data and with simulated events.

This procedure is repeated for 10 pseudorapidity choices of each neutrino at the assumed top quark mass. The bins of pseudorapidities are chosen in a way that they are filled with equal statistics. A weight is formed by summing over the weights for each neutrino choice. At each mass, the jets and lepton momenta are smeared 150 times within detector resolutions, and the solution algorithm is repeated for each smearing. The weights for all smearings are summed together to form a total event weight at the assumed top quark mass. Weights are calculated in 2 GeV increments for top quark masses between 80 and 330 GeV. When these weights are summed over a large number of Monte Carlo events, the distributions produce a peak near the input top quark mass, as shown in Fig. 1.



(a) (b) (c)

FIG. 1: Sum of event weights for a few thousand $t\bar{t}$ Monte Carlo events with top quark mass of (a) 160, (b) 175, and (c) 190 GeV. The vertical lines indicate the mass of the Monte Carlo top quarks.

III. EVENT SELECTION

The data used in this measurement are collected using the same triggers as in Ref. [2]. After events passing the trigger requirement are reconstructed, we impose the identical selection criteria as in Ref. [2] to isolate the dilepton candidates. These selection requirements yield 57 candidate events. Tabels I to III summarize the expected and observed event yields for each dilepton channel [2].

TABLE I: Expected and observed $e\mu$ event yield from background and signal $\sigma_{t\bar{t}=7.0\text{ pb}}$ processes after all cuts are applied.

$t\bar{t} \to e\mu$	WW	$Z \to \tau\tau$	fakes	total	observed
$28.58^{+2.12}_{-2.39}$	$1.37^{+0.59}_{-0.59}$	$3.57^{+0.67}_{-0.81}$	$0.30^{+0.17}_{-0.14}$	$35.31^{+2.82}_{-3.18}$	32

TABLE II: Expected and observed ee event yield from background and signal $\sigma_{t\bar{t}=7.0\text{ pb}}$ processes after all cuts are applied.

$t\bar{t} \to ee$	WW	$Z \to ee$ (fake $\not{E}_T$)	fake e	total	observed
9.75 ± 0.10	0.36 ± 0.04	1.12 ± 0.03	0.22 ± 0.07	12.87 ± 1.31	16

TABLE III: Expected and observed $\mu\mu$ event yield from background and signal $\sigma_{t\bar{t}=7.0\text{ pb}}$ processes after all cuts are applied.

$t\bar{t} \to \mu\mu$	WW	$Z \to \mu\mu$	$Z \to \tau\tau$ ($\tau \to \mu$)	fakes	total	observed
$5.80^{+0.38}_{-0.40}$	0.28 ± 0.12	$2.19^{+0.81}_{-1.56}$	$0.52 \pm {}^{+0.22}_{-0.25}$	0.37 ± 0.13	$9.35^{+0.93}_{-1.63}$	9

IV. PROBABILITY DENSITY FUNCTIONS

For each event, a weight distribution as function of the hypothesized top quark mass is generated from the weighted neutrino solutions (Neutrino Weighting Method) described earlier. Two parameters to characterize the weight distribution per event are chosen, namely the mean and root-mean-square (rms). The normalized three-dimensional distribution of mean, rms, and top quark mass yields a signal probability function $f_s(\text{mean}, \text{rms}, \text{m}_{\text{top}})$. The background probability density function $f_b(\text{mean}, \text{rms})$ is obtained as the normalized two-dimensional distribution of mean and rms of simulated background events. Relative weights are assigned to events of different background sources corresponding to the relative expected background yields. Statistical fluctuations in the signal and background probability density functions are smoothed by a three or two-dimensional fit, respectively.

V. MAXIMUM LIKELIHOOD

After having modeled the smoothed signal probability density function $f_s(\text{mean}, \text{rms}, \text{m}_{\text{top}})$ and smoothed background probability density function $f_b(\text{mean}, \text{rms})$, the top quark mass is extracted using a maximum likelihood method. The likelihood $\mathcal{L}$ consists of three parts. The first part is a constraint that requires that the fitted sum of the number of signal events n_s and the number of background events n_b agrees within Poisson fluctuations with the number of observed events N:

$$\mathcal{L}_{\text{poisson}}(n_s + n_b, N) \equiv \frac{(n_s + n_b)^N e^{-(n_s+n_b)}}{N!}. \tag{2}$$

The second part is a Gaussian constraint that requires agreement between the fitted number of background events n_b and the number of expected background events $\bar{n}_b$ within Gaussian fluctuations, where the width of the Gaussian is given by the uncertainty σ_b on $\bar{n}_b$:

$$\mathcal{L}_{\text{gaus}}(n_b, \bar{n}_b, \sigma_b) \equiv \frac{1}{\sqrt{2\pi}\sigma_b} e^{[-(n_b-\bar{n}_b)^2/2\sigma_b^2]}. \tag{3}$$

The third part contains the direct dependence on the top quark mass. The total likelihood is given by:

$$\mathcal{L}(\mathrm{mean}_i, \mathrm{rms}_i, \bar{n}_b, N \mid m_{\mathrm{top}}, n_s, n_b) =$$
$$\mathcal{L}_{\mathrm{gaus}}(n_b, \bar{n}_b, \sigma_b)\mathcal{L}_{\mathrm{poisson}}(n_s + n_b, N) \prod_{i=1}^{N} \frac{n_s f_s(\mathrm{mean}_i, \mathrm{rms}_i \mid m_{\mathrm{top}}) + n_b f_b(\mathrm{mean}_i, \mathrm{rms}_i)}{n_s + n_b}.$$

The result of minimizing $-\log\mathcal{L}$ is our top quark mass estimate $\hat{m}_{\mathrm{top}}$. Its statistical uncertainty $\hat{\sigma}_{m_{\mathrm{top}}}$ is given by half of distance between the mass values at which the $-\log\mathcal{L}$ value is 0.5 units greater than its minimum value. This is calculated by minuit [4, 5].

The combination of all three dilepton channels is done by multiplying the likelihoods of every channel. This is equivalent to adding up the negative log likelihoods of every channel:

$$-\log\mathcal{L} = \sum_c (-\log\mathcal{L}^c) \quad , \tag{4}$$

where c denotes the dilepton channel: $c \in \{e\mu, ee, \mu\mu\}$. The combined negative log likelihood $-\log\mathcal{L}$ is minimized simultaneously with respect to seven variables: m_{top}, n_s^c, and n_b^c. The performance of the three dilepton channels and the combination is evaluated using ensemble testing techniques: the top quark mass m_{top} is extracted in 300 pseudo-experiments performed on ensembles of the size of the corresponding data sample. The events are chosen randomly from the signal and background Monte Carlo samples, so that the average number of background events per source matches the expected yield.

Figures 2 and 3 show a good agreement between the output and input top quark mass and demonstrate the reliability of the statistical uncertainty estimation with widths of pull distributions near their expected value of 1.0. The linear fits in Figures 2 and 3 are used to calibrate the results from data, mapping the output minimum to an input top quark mass.

The results of the fits are summarized in Table IV.

Channel	slope	offset [GeV]	⟨pull width⟩	$\langle\sigma_{m_{\mathrm{top}}}\rangle$ [GeV]
$e\mu$	0.99 ± 0.02	-0.1 ± 0.2	1.05 ± 0.02	8.4
ee	0.96 ± 0.02	-1.2 ± 0.2	1.01 ± 0.02	10.7
$\mu\mu$	1.08 ± 0.05	1.2 ± 0.5	1.15 ± 0.02	16.0
combined	1.02 ± 0.01	0.1 ± 0.1	1.02 ± 0.02	6.0

TABLE IV: Slope and offset of the calibration curves in Figures 2 and 3, the pull width after calibration, and the mean value of the statistical uncertainty after calibration and correction for the non-unit pull width for all channels.

VI. RESULTS

The top quark mass is estimated by maximizing the likelihood for the selected data in each channel. The top quark mass estimates and uncertainties are corrected to account for the calibration from ensemble tests and the non-unit pull widths. The combined result is corrected by using the combined calibration curve.

After applying the measured top quark mass calibration, we find: 172.5 ± 5.8 GeV for the combination of all three channels.

A. Statistical Uncertainties

The statistical uncertainties quoted above are determined by the width of the $-\log\mathcal{L}$ distribution. The distributions of expected and observed statistical uncertainties are shown in Fig 4.

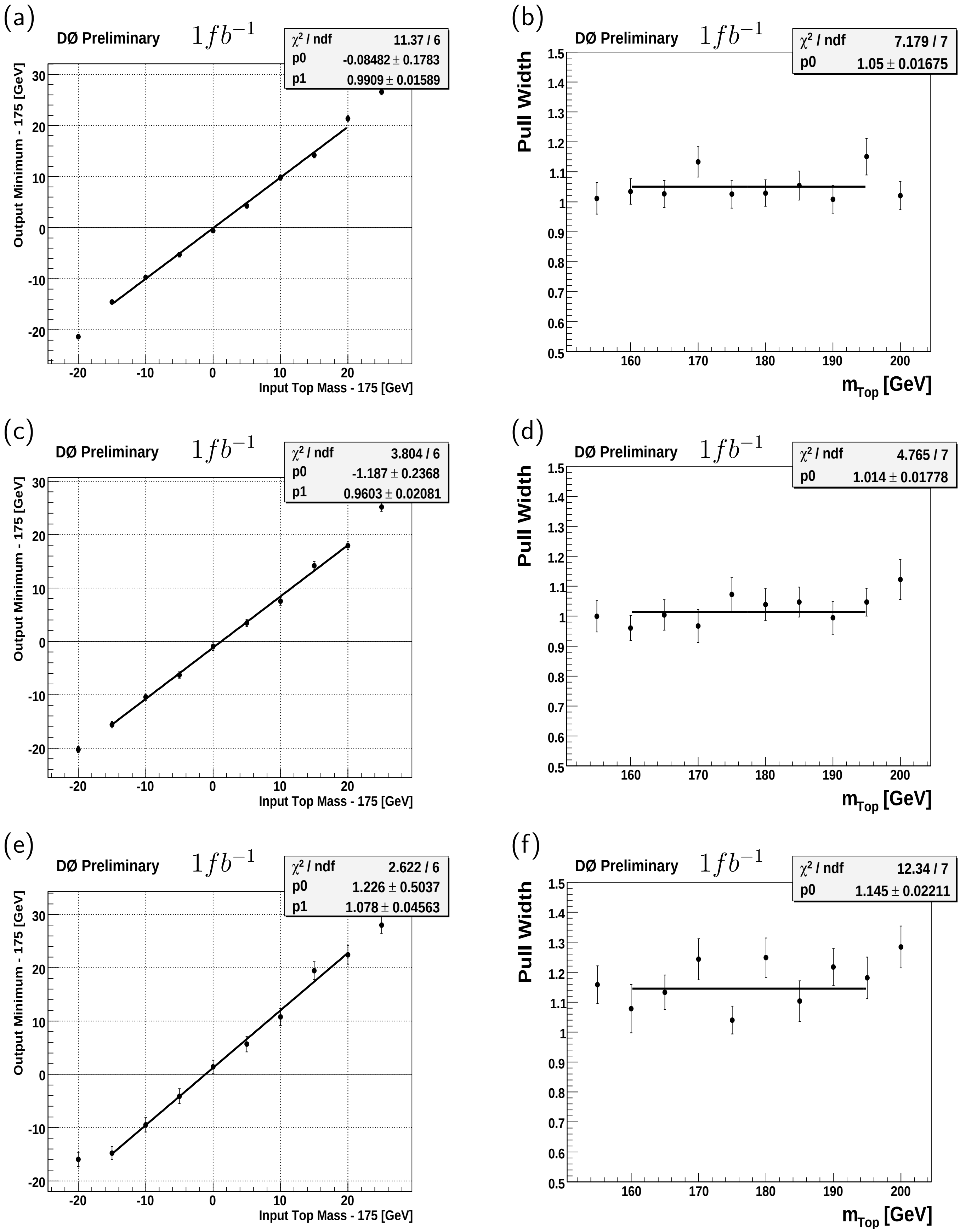


FIG. 2: Calibration curves: Top quark mass estimate as function of generated MC input top quark mass for the $e\mu$ (a), ee (c), and $\mu\mu$ (e) channels. Pull width distributions for the $e\mu$ (b), ee (d), and $\mu\mu$ (f) channels.

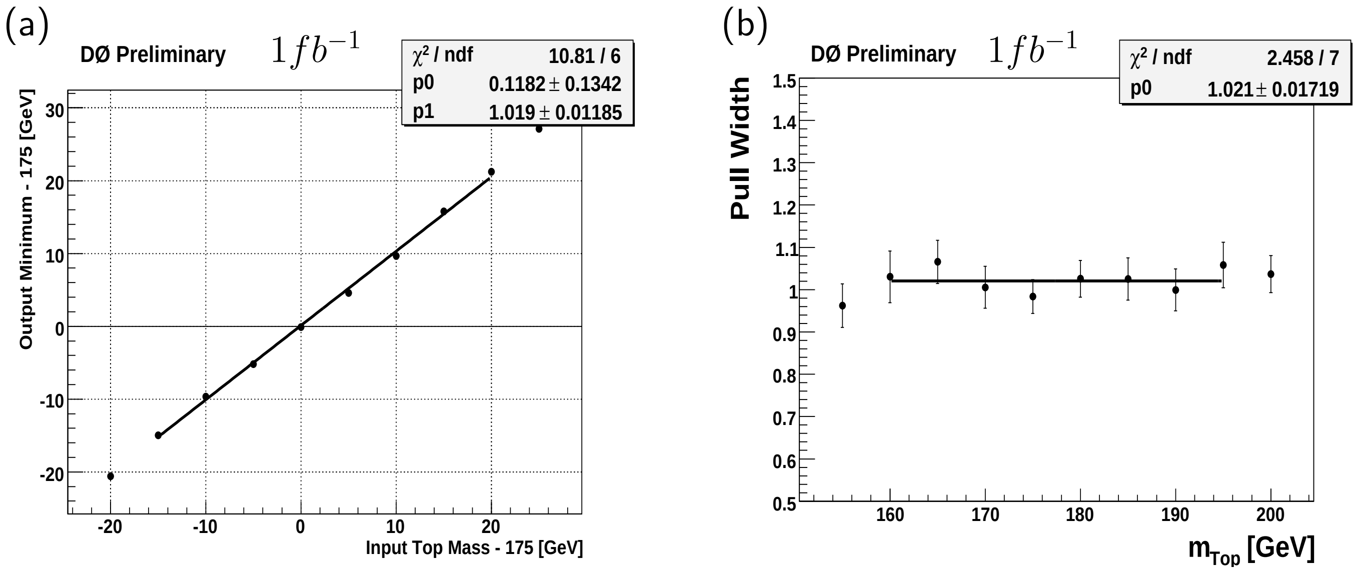


FIG. 3: Calibration curves: Top quark mass estimate as function of generated MC input top quark mass for the combined channel (a). Pull width distributions for the combined channel (b).

B. Systematic Uncertaintiess

A summary of all systematics is given below.

- *Jet Energy Scale.* The main systematic uncertainty is expected to arise from the uncertainty in the jet energy scale. It is estimated by repeating the ensemble testing with simulated events, where the jet energy scale is shifted up by one sigma. The total uncertainties on the jet energy scale are calculated from the statistical and systematic uncertainty on the jet energy scale in data and in Monte Carlo events:

$$\sigma^{\rm jes}_{\rm total} = \sigma^{\rm MC\,jes}_{\rm stat} \oplus \sigma^{\rm MC\,jes}_{\rm syst} \oplus \sigma^{\rm data\,jes}_{\rm stat} \oplus \sigma^{\rm data\,jes}_{\rm syst}$$

  The jet energy scale of the events used to estimate the probability densities remains unshifted. This uncertainty is found to be ± 2.5 GeV.

- *b-Jet Energy Scale.* The jet energy scale has been derived for inclusive jet flavors and is applied to the b-jets. The difference between the inclusive jet energy scale compared to a purely b-jet energy scale leads to a 1.5% uncertainty in the jet energies. This yields an uncertainty of ± 2.0 GeV on the top quark mass.

- *Jet Resolution Uncertainty* The jet resolution of simulated events is corrected to match the resolution in data by smearing and removal of simulated jets. To estimate the systematics due to this procedure, the resolution of simulated signal events has been shifted up and down by its uncertainty. The ensemble tests are repeated with the shifted events, but with the nominal probability densities. The jet resolution uncertainty is found to be ± 0.3 GeV.

- *Uncertainty in Radiation of Extra Jets* The uncertainty in the fraction of extra jets in top quark events arising, for example, from gluon radiation, is a source of systematics. The Monte Carlo modeling describes the data within uncertainties. However, the ratio of events with exactly two jets and events with more than two jets is 0.26 for simulated events and 0.14 in data. To account for this difference, the simulated events are reweighted such that this ratio is the same. Ensemble tests are performed with the reweighted events and a difference in the top quark mass of ± 0.14 GeV is observed and assigned as a systematic uncertainty.

- *Color Recombination* There is a systematic due to the modeling of the underlying event and color recombination. The simulated pythia events used in this analysis use the so-called "tune A". To estimate the effect of the choice of the tune, ensemble tests were performed using pythia events with "tune DW" [3]. Tune A is a set of parameters for the pythia generator associated with initial and final state radiation, underlying event, and hadronization that was tuned to reproduce distributions from the low-bias data acquired by the CDF collaboration. Tune DW is an update to this set of parameters incorporating high p_T jet data from the D0 collaboration (azimuthal decorrelations in dijet events) and the Z p_T spectrum measured by CDF. Tune DW has significantly less initial state radiation than tune A and corresponding increases in the other parameters to maintain agreement with the low-bias CDF data.

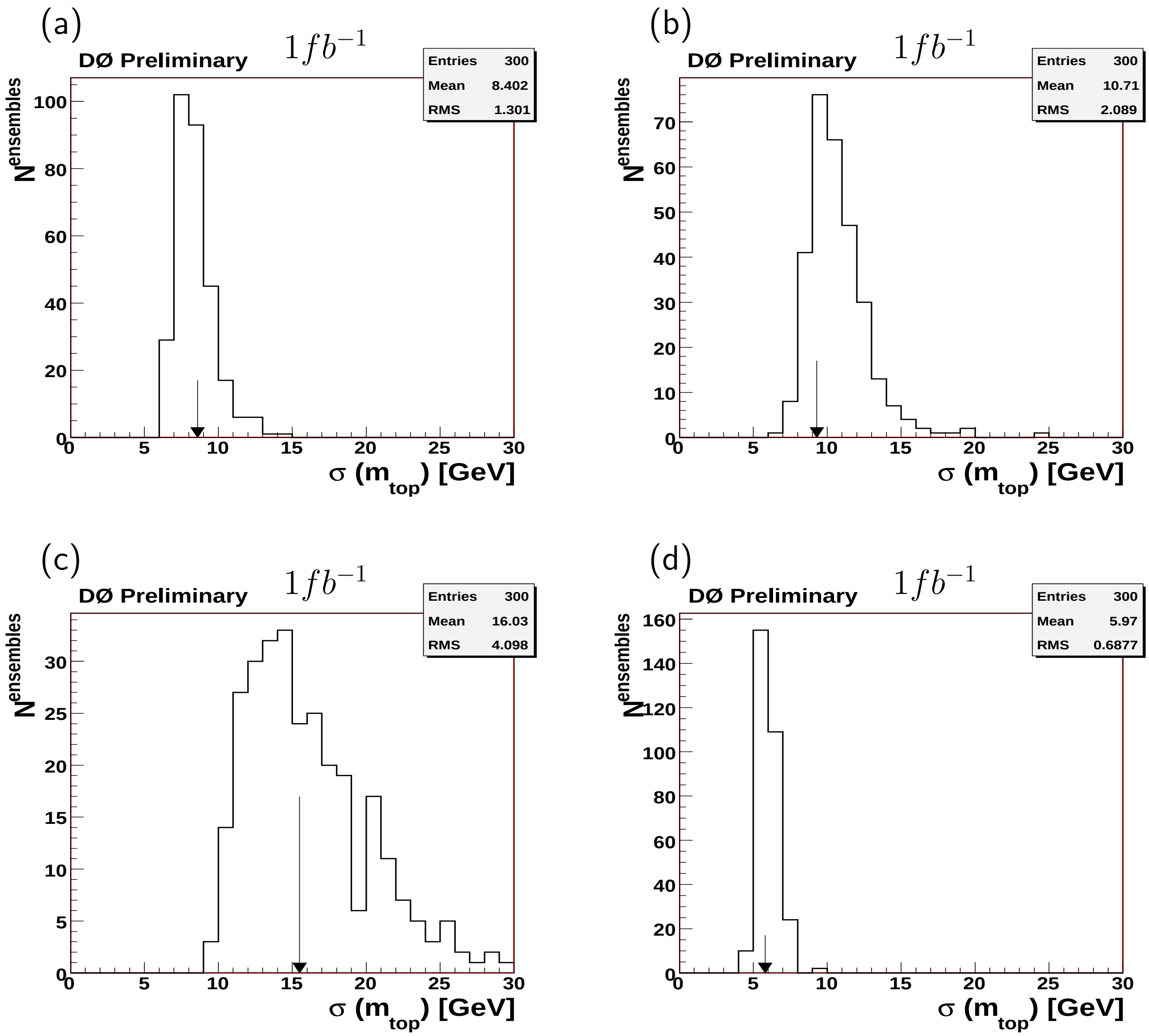


FIG. 4: Distribution of statistical uncertainties after correcting for the pull width for $m_{\rm top}^{\rm MC}$=170 GeV. Results are shown for the $e\mu$ (a), the ee (b), the $\mu\mu$ (c), and the combined (d) channels. The arrows mark the observed uncertainties in data.

A calibration curve in the range 160 to 185 GeV is obtained and the difference in the measured top quark mass is found to be ± 0.13 GeV.

- Estimates for systematic uncertainties are taken from [6].

A list of all evaluated systematic uncertainties appears in Table V. The systematic uncertainties are dominated by the jet energy scale uncertainties. All systematics are assumed uncorrelated and are combined in quadrature. The combined systematic uncertainty is ±3.5 GeV.

VII. CONCLUSION

In approximately 1 fb^{-1} of proton-antiproton collision data, we have used the neutrino weighting method to extract a top quark mass estimate from top quark events in the dilepton final state. The results for each channel and the

Source	Uncertainty (GeV)
Jet Energy Scale	±2.5
b-Jet Energy Scale	±2.0
Jet Resolution	±0.3
Muon Resolution	±0.4
$t\bar{t}$ + jets	±0.14
PDF variation	±0.7
Background Template Shape	±0.3
Template fit statistics	±0.9
Underlying event	±0.13
Total Systematic Uncertainty	±3.5

TABLE V: Summary of systematic uncertainties.

combination of all three channels are the following:

$$\begin{aligned} e\mu : m_{\rm top} &= 170.6 \pm \ \ 8.6\ ({\rm stat.}) \quad \pm 3.5\ ({\rm syst.})\, {\rm GeV} \\ ee : m_{\rm top} &= 173.9 \pm \ \ 9.3\ ({\rm stat.}) \quad \pm 3.5\ ({\rm syst.})\, {\rm GeV} \\ \mu\mu : m_{\rm top} &= 179.7 \pm 15.5\ ({\rm stat.}) \quad \pm 3.5\ ({\rm syst.})\, {\rm GeV} \\ {\rm combination} : m_{\rm top} &= 172.5 \pm \ \ 5.8\ ({\rm stat.}) \quad \pm 3.5\ ({\rm syst.})\, {\rm GeV} \end{aligned}$$

[1] V. M. Abazov *et al.*, (D0 Collaboration), “The Upgraded DØ Detector,” Nucl. Instrum. Methods Phys. Res. A **565**, 463 (2006).
[2] ”Measurement of the $t\bar{t}$ Production Cross Section at $\sqrt{s} = 1.96$ TeV”, conference notes, `http://www-d0.fnal.gov/Run2Physics/d0_private/eb/Run2EB_008/Run2EB_008_07.html`.
[3] T. Sjöstrand, L. Lönnblad, and Stephen Mrenna, ”PYTHIA 6.2 Physics and Manual,” arXiv:hep-ph/0108264.
[4] R. Brun and F. Rademakers, Nucl. Instrum. Meth. A **389**, 81 (1997).
[5] F. James and M. Roos, Comput. Phys. Commun. **10**, 343 (1975).
[6] D0 Collaboration, ”Measurement of m_{top} in $e\mu$ Events with Neutrino Weighting”, D0 Note 5171-CONF (2006) `http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/TOP/T34/`.

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