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Measuring the top quark mass using the dilepton decay modes

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We demonstrate a new likelihood method for extracting the top quark mass from events of the type $t\bar{t} \rightarrow bW^{+}(\text{lepton}+\nu)\bar{b}W^{-}(\text{lepton}+\nu)$. This method estimates the top quark mass correctly from an ensemble of dilepton events. The method proposed by Dalitz and Goldstein is shown to result in a systematic underestimation of the top quark mass. Effects due to the spin correlations between the top quark and top antiquark are shown to be unimportant in estimating the mass of the top quark. [S0556-2821(97)06105-5]

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I. INTRODUCTION

The $t\bar{t}$ dilepton decay channels in which both W's decay into leptons and neutrinos are underconstrained with respect to the reconstruction of the top quark mass due to the presence of the two missing neutrinos. Nevertheless, as Dalitz and Goldstein [1] and independently Kondo *et al.* [2] have shown, it is possible to extract mass information from these events using a likelihood method. For each event, solutions are obtained for the kinematic quantities for a range of top quark masses. Each solution is weighted by a product of structure functions which estimates the probability of producing a $t\bar{t}$ pair consistent with the event at that top quark mass and a decay probability factor which neglects the polarization of the top quark. In this paper we show that the Dalitz-Goldstein weighting scheme leads to a systematic underestimation of the top quark mass. We propose a likelihood scheme which involves no kinematic weighting that is shown to estimate the top quark mass correctly. Finally we show that *not* allowing for the spin correlations in the decay of top quarks in the Dalitz-Goldstein scheme does not further bias the mass estimate significantly.

With the proposed luminosity upgrades of the Fermilab Tevatron [3], it is possible to acquire thousands of events of the type $t\bar{t} \rightarrow bW^{+}(\text{lepton}+\nu)\bar{b}W^{-}(\text{lepton}+\nu)$, where both the b quark jets are identified. The number of jet permutations in these channels is smaller than the lepton + jets decay modes of the top quark. It may then become possible to measure the top quark mass using the dilepton channels with the least amount of systematic error.

II. METHOD

Each dilepton event is characterized by 14 measurements, namely, the three vectors of the two b jets, leptons, and the missing E_T vector of the event. We denote these measurements collectively by the configuration vector c. Kinematically, each event is characterized by 18 variables, namely, the three vectors of the b jets, leptons, and the two missing neutrinos. For any given top quark mass, there are four constraints that constrain the lepton and neutrino pairs to the W mass and the W and b pairs to the top quark mass. Given a top quark mass, this enables one to solve for the neutrinos. This results in a pair of quadratic equations for the transverse components of each neutrino [2]. The solution involves finding the intersection of two ellipses. This can yield zero, two, or four solutions for a given top quark mass. The likelihood $P(m|c)$ of a solution for a top quark mass m, given the observed configuration vector c, is obtained by using Bayes' theorem:

$$P(m|c)=\frac{P(m)P(c|m)}{\int P(m)P(c|m)dm}, \tag{2.1}$$

where $P(m)$ is the *a priori* probability distribution of the top quark mass. $P(c|m)$ is the probability of observing the configuration vector c, for a given top quark mass m. If after each event is analyzed $P(m)$ is updated by $P(m|c)$ iteratively, one gets the familiar multiplicative rule for combining likelihoods. Dalitz and Goldstein [1,4] use the prescription

$$P(c|m)=\Sigma_{\text{partons}}F(x_1)F(x_2)D(l_1,m)D(l_2,m), \tag{2.2}$$

where $F(x_1)$ and $F(x_2)$ are the probabilities of finding partons with momentum fraction x_1 and x_2 in the colliding beam particles consistent with producing the event in question and $D(l_1,m)$ $[D(l_2,m)]$ is the probability of observing a lepton of energy l_1 $[l_2]$ in the rest frame of the top quark [top antiquark]. The expression for $D(l,m)$ as given in [1] neglects the top quark polarization, but treats the subsequent W decays according to the standard model. In reality spin correlations are present and the two decays are correlated.

A. Measurement errors

The expression for $P(c|m)$ in Eq. (2.2) must be further modified to take into account measurement errors. If the measured configuration vector is c_m of a true configuration vector c, we can write

$$P(c_m|m)=\int P(c|m)R(c,c_m,\sigma)dc, \tag{2.3}$$

where the function $R(c,c_m,\sigma)$ is the resolution function of the experiment, denoting the probability of observing the configuration vector c_m given a true configuration vector c. The resolution of each of the components of c is contained in the resolution vector σ. In practice, it is possible to choose the configuration vector c such that $R(c,c_m,\sigma)$is Gaussian. Because of the symmetric nature of the Gaussian in c and c_m, we can reexpress Eq. (2.3) as

$$P(c_m|m)=\int P(c|m)R(c_m,c,\sigma)dc. \tag{2.4}$$

This Gaussian integration can be carried out by smearing the measured configuration c_m repeatedly in a Gaussian fashion with standard deviations σ such that, for N smeared configurations,

$$\frac{dN}{N}=R(c_m,c,\sigma)dc. \tag{2.5}$$

The Monte Carlo integration then yields

$$P(c_m|m)=\frac{1}{N}\Sigma_{\text{configurations}}P(c|m). \tag{2.6}$$

B. Choice of the configuration vector

In what follows, we will assume that both the leptons are electrons. We choose the three quantities, energy, pseudorapidity, and azimuth (E,η,ϕ) to define the three vectors of the leptons and jets. The electrons are smeared with a typical collider detector fractional resolution of $15\%/\sqrt{(E)}$ in energy and the jets with a fractional energy resolution of $80\%/\sqrt{(E)}\oplus 0.05$. We ignore the fluctuations in direction, as these are dwarfed by the energy fluctuations. The p_T of the rest of the event after removing the leptons and jets is also a measured quantity and is smeared as though it were a small jet. The $\vec{\not{E}}_T$ is a deduced quantity from the measured quantities listed. The case when one or both of the leptons is a muon is handled by smearing the inverse momentum of the muon as a Gaussian, but will not be further discussed here.

We do not *a priori* know which lepton is associated with which b quark. We consider both combinations and add the likelihoods from either combination to form the total likelihood for each event, which is normalized to unity when integrated over the top quark mass m.

C. Combining likelihoods

We generate the likelihood spectrum for each event in the top quark mass range of 100–250 GeV/c^2 at intervals of 1 GeV/c^2.

The combined likelihood for an ensemble of events is obtained by multiplying the likelihoods of the individual events. The likelihood for an individual event can be zero for some values of the top quark mass due to the fact that we have used a narrow resonance approximation for the W mass in finding the solutions and due to the finite number of smears done per event. In order to prevent the combined likelihood having zeros in some bins due to these effects, we add a uniform floor probability distribution that integrates to 1%, in the top quark mass interval 100–250 GeV/c^2, to the likelihood distribution of each event and renormalize it. The final mass values are insensitive to the exact value of the floor.

The individual event likelihoods are sampled at top quark mass intervals of 1 GeV/c^2. The combined likelihood mass errors can fall below 1 GeV/c^2. We interpolate the individual event likelihoods at mass intervals of 0.25 GeV/c^2 so that the final combined event likelihood can span several bins in mass.

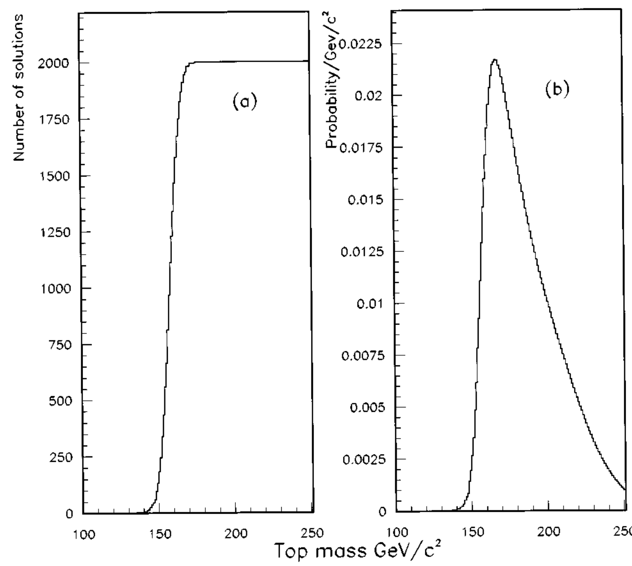

FIG. 1. (a) shows the number of solutions versus top quark mass for a typical event generated with top quark mass of 175 GeV/c^2. (b) Probability distribution for that event obtained according to the Dalitz-Goldstein prescription.

In general Monte Carlo events have weights associated with them. These were normalized so that the average weight in the event sample was unity. Events with weights outside the window 0.3–3.0 were rejected. The likelihood distribution for each event was raised to the power given by its weight before being used to form the combined likelihood.

D. Event selection criteria

We select only those events with $E_T>15$ GeV for both the leptons and jets and $\not{E}_T>25$ GeV. We demand that both b jets be explicitly identified by a tagging algorithm. While smearing, we only admit smeared configurations that satisfy the same criteria as the event selection.

In what follows we smear each Monte Carlo–generated event once to simulate the measurement process and subsequently 1000 times to do the Monte Carlo integration.

III. RESULTS

We generate Monte Carlo events with a top quark mass of 175 GeV/c^2. We neglect top quark polarization in generating these events, but treat the subsequent W decays according to the standard model [5]. No final state or initial state radiation is included in this initial set of events. The events have $t\bar{t}$ pairs produced according to the standard QCD processes (dominated at Fermilab energies by valence quark fusion and s-channel gluon exchange). The top quark polarization is neglected after production. The W's are decayed correctly according to the standard model, mimicking the assumptions going into the Dalitz-Goldstein weighting scheme. We call this the uncorrelated sample.

Figure 1(a) shows the unweighted distribution of solutions found for the $\approx$1000 smeared configurations for a typical such event. The solutions turn on at a mass of 140 GeV/c^2 and stay turned on until the end of the mass range at 250

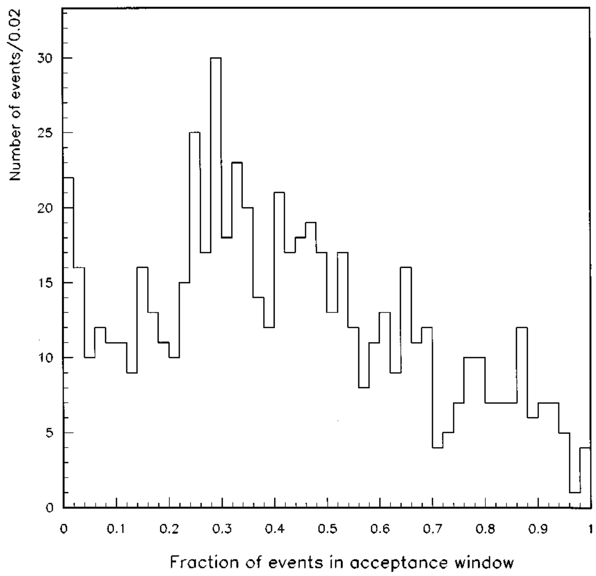

FIG. 2. Histogram of the fraction of the number of solutions $\mathcal{R}$ in a window $\pm$ 35 GeV/c^2 of the generated top quark mass.

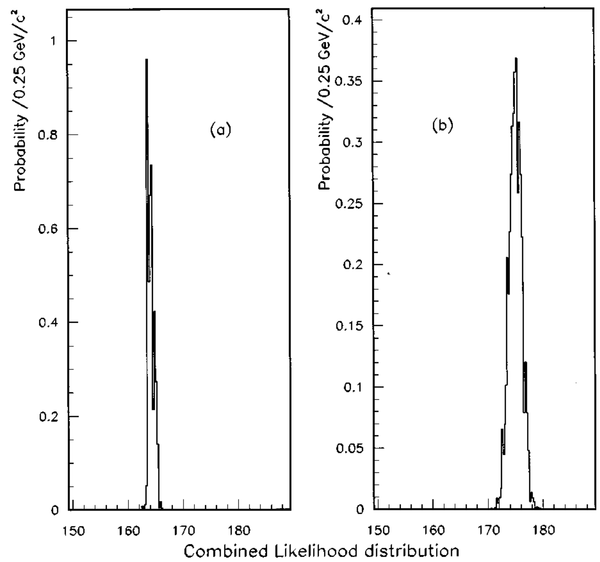

FIG. 3. For events generated with a top quark mass 175 GeV/c^2, (a) the combined likelihood distribution using the Dalitz-Goldstein weighting scheme yields a mean top quark mass 164.5 GeV/$c^2 \pm$ 0.5 GeV/c^2 and (b) using the new likelihood method proposed here yields a mean top quark mass 175.3 GeV/$c^2 \pm$ 1.1 GeV/c^2.

GeV/c^2. Figure 1(b) shows the probability distribution for this event using the Dalitz-Goldstein prescription of Eq. (2.2). The structure function weighting in Eq. (2.2) makes the high mass solutions less likely, yielding a likelihood distribution that has a distinct peak. We now proceed to analyze a sample of $\approx$1000 such Monte Carlo events that decay into dileptons. Because of measurement errors, not all of these events will give solutions consistent with a top quark in the mass range 100–250 GeV/c^2. Figure 2 is a histogram of the quantity $\mathcal{R}$ defined by

$$\mathcal{R}=\Sigma_{\text{window}}\frac{N_i}{\text{tot}_M\times N_{\text{smear}}}, \tag{3.1}$$

where N_i is the number of solutions for top quark mass i, tot_M is the total number of top quark masses considered, and N_{smear} is the total number of smears per event. The sum extends for top quark masses in a window $\pm$ 35 GeV/c^2 of the generated top quark mass. There is a peak in the histogram for values of $\mathcal{R}$ below 0.1. This is due to events that are so mismeasured that they have difficulty solving for a top quark mass in the window considered even when smeared a thousand times. We reject events with $\mathcal{R}<0.2$ since these will have very spiky likelihood distributions.

Figure 3(a) is the combined likelihood of 511 events which survive after event selection criteria and the $\mathcal{R}$ cut from an initial sample of 925 events, using the Dalitz-Goldstein weighting scheme [7].

The most likely top quark mass from the event sample is 164.5 ± 0.54 GeV/c^2. The Dalitz-Goldstein weighting scheme thus introduces a bias of 10.5 GeV/c^2 towards lower masses at this value of the top quark mass.

A. A Critique of the Dalitz-Goldstein weighting scheme

For a given event, the parton momenta (x_1,x_2) needed to produce it will decrease as the top quark mass m is decreased since $x_1x_2=m^2/s$, where s is the overall center-of-mass energy squared. This means that the Dalitz-Goldstein weighting scheme will tend to skew the likelihood distribution for each event toward lower top quark masses, since it is proportional to the product of the structure functions. We note that the top quark production cross section is also a product of such structure functions and decreases rapidly as the top quark mass increases, for the same reason. The likelihood scheme proposed by Kondo *et al.* [2] is proportional to the top quark production cross section and also suffers from this defect. It is this skewing of the likelihood distributions towards lower masses that produces a 10.5 GeV/c^2 bias in the Dalitz-Goldstein scheme. One can indeed ask why the top quark mass measurement has to be coupled to its production mechanism at all.

B. A new likelihood method

Figure 1(a) shows the number of solutions for a typical event as a function of the top quark mass. We now make the radical proposal of not using any weights at all, but simply use a likelihood distribution that is shaped like the number of solutions as a function of the top quark mass. If one examines this distribution visually for an ensemble of top quark events, there exists a significant number of events where the likelihood distribution thus formed does show a peak and falls for large top quark masses. Using this scheme, one gets the combined likelihood of Fig. 3(b) which peaks at the input mass, but has a larger standard deviation. The larger standard deviation is due to the fact that we are not suppressing the high mass tail of the individual event likelihood distributions using a weighting scheme. This method does not use any extrinsic information of the top quark production mechanism to obtain the mass but relies solely on the measured kinematic quantities of the events in question. We refer to this scheme as the ‘‘no-weights’’ method.

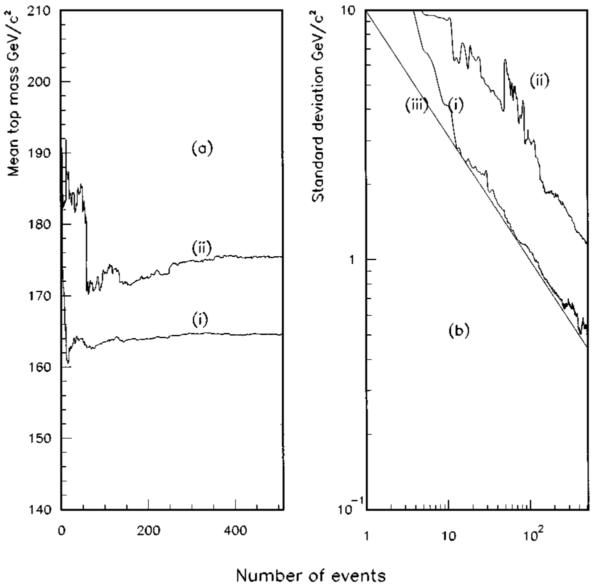

FIG. 4. Evolution of (a) the mean value and (b) standard deviation of the combined likelihood distribution as a function of the number of events for (i) Dalitz-Goldstein weighting scheme, (ii) the ''no-weights'' method, and (iii) curve showing $N^{-1/2}$ shape.

Figure 4(a) shows the evolution of the mean value of the combined likelihoods for the Dalitz-Goldstein method and the no-weights method as a function of the number of events. Figure 4(b) shows the evolution of the standard deviation [8] of the combined likelihoods using the two methods as a function of the number of events. An approximate $1/\sqrt{(N)}$ dependence on the number of events is evident.

The ''no-weights'' mass is slightly sensitive to the value of the $\mathcal{R}$ cut, since the events rejected by the $\mathcal{R}$ cut tend to favor lower top quark masses. It is possible to adjust the $\mathcal{R}$ cut so that the input top quark mass is returned by the ''no-weights'' algorithm. Once tuned at one generated top quark mass, the algorithm works well at all other masses with the cut unchanged. The Dalitz-Goldstein scheme cannot reproduce the generated mass for any value of the $\mathcal{R}$ cut. It should be noted that the window chosen around the generated mass in defining the $\mathcal{R}$ cut has to be symmetric about the generated mass to avoid bias. This can be done iteratively when dealing with data.

C. Spin correlations and final state radiation effects

We now generate events where both the top quark and top antiquark polarizations are taken into account and all spin correlations are kept at the tree level [6]. We use the two weighting methods outlined above to determine the top quark mass. The results are presented in Table I. There is no apparent shift in the top quark mass between the two samples for either method. From this, we conclude that spin correlations do not affect the determination of the top quark mass in the dilepton channel in any significant way. The Monte Carlo samples used so far do not include additional jets due to initial and final state gluon radiation. We now generate $\approx$1000 events at top quark masses of 140, 160, 180, and 200 GeV/c^2 using the program ISAJET [9]. We demand that both the b quark jets be identified. Table I shows the results using either method. Once again, the Dalitz-Goldstein method underestimates the generated mass. The ''no-weights'' method can now be used to estimate the effects due to final state radiation as implemented in ISAJET. It can be seen that the net effect of the final state radiation is to systematically lower the measured value of the top quark mass. The amount of lowering increases with the top quark mass, due to the increased amount of final state radiation. At a top quark mass of 180 GeV/c^2, the effect of final state radiation is to lower the top quark mass by $\approx$5 GeV/c^2. Finally, we have also studied the effect of event selection E_T cuts for their effect on the result. We get results that are the same within errors, even when no E_T cuts are used.

TABLE I. Summary of top quark mass measurements on various Monte Carlo (MC) samples.

Top mass MC sample	Dalitz-Goldstein method (GeV/c^2)	No-weights method (GeV/c^2)
175 GeV/c^2 Spin uncorrelated	164.5 ± 0.54	175.3 ± 1.11
175 GeV/c^2 Spin correlated	164.8 ± 0.49	174.1 ± 1.05
140 GeV/c^2 ISAJET	131.8 ± 0.37	139.9 ± 0.7
160 GeV/c^2 ISAJET	147.6 ± 0.48	158.0 ± 1.02
180 GeV/c^2 ISAJET	163.7 ± 0.74	175.1 ± 0.92
200 GeV/c^2 ISAJET	179.7 ± 0.58	193.2 ± 1.08

IV. CONCLUSIONS

We have demonstrated a new likelihood method that determines the top quark mass in dilepton decays of the top quark that gives an unbiased estimate of the top quark mass. We demonstrate that weighting schemes that involve products of structure functions, such as the Dalitz-Goldstein scheme, give a downward bias to the measured value of the top quark mass. We demonstrate that spin correlation effects between the top quark and top antiquark decay products do not influence the outcome of the mass measurement. We estimate the effects due to final state radiation as implemented in ISAJET.

The statistical precision obtainable using 1000 top quark to dilepton fully tagged events using this method is of the order of 1 GeV/c^2 using this technique. Assuming that jet energy scale systematics in the upgraded Tevatron detectors can be controlled to this level, the dilepton channels provide an excellent means of measuring the top quark mass.

ACKNOWLEDGMENTS

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[1] R. H. Dalitz and G. R. Goldstein, Phys. Rev. D **45**, 1531 (1992); Nucl. Instrum. Methods Phys. Res. A **338**, 185 (1994).

[2] K. Kondo, T. Chikamatsu, and S-H. Kim, J. Phys. Soc. Jpn. **62**, 1177 (1993).

[3] ''Future of Electroweak Physics at the Fermilab Tevatron,'' Report of the tev_2000 Study Group, edited by D. Amidei and R. Brock, Report No. Fermilab-Pub-96/082 (unpublished).

[4] Strictly the method outlined here is an extension of the method used in [1] since they were working on one Collider Detector at Fermilab (CDF) event for which the $\not{E}_T$ was not known and as such had two additional missing variables.

[5] S. Parke (private communication).

[6] R. Kleiss and W. J. Stirling, Z. Phys. C **40**, 419 (1988).

[7] We use Eichten-Hinchliffe-Lane-Quigg (EHLQ) set I structure functions for this calculation. The results are largely insensitive to the structure function type.

[8] The standard deviation of the likelihood is an approximate measure of the error in the top quark mass, which becomes more accurate as the likelihood distribution becomes more Gaussian. We use it here, since it is readily calculated.

[9] F. Paige and S. Protopopescu, BNL Report No. BNL38034, 1986 (unpublished).