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Measurement of the Top Quark Mass using Quantities with Minimal Dependence on the Jet Energy Scale

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We present three measurements of the top quark mass in the lepton plus jets channel with $1.9 fb^{-1}$ of data using quantities with minimal dependence on the jet energy scale in the lepton plus jets channel at CDF. One measurement uses the mean transverse decay length of b-tagged jets (L2d) to determine the top mass, another uses the transverse momentum of the lepton (LepPt) to determine the top mass, and a third measurement uses both variables simultaneously.
Using the L2d variable we measure a top mass of $(176.7^{+10.0}_{-8.9}(stat) \pm 3.4(syst))\ GeV/c^2$, using the LepPt variable we measure a top mass of $(173.5^{+8.9}_{-9.1}(stat) \pm 4.2(syst))\ GeV/c^2$, and doing the combined measurement using both variables we arrive at a top mass result of $(175.3 \pm 6.2(stat) \pm 3.0(syst))\ GeV/c^2$. Since some of the systematic uncertainties are statistically limited, these results are expected to improve significantly if more data is added at the Tevatron in the future, or if the measurement is done at the LHC.

1. Introduction

This analysis grew out of a measurement of the top mass using the transverse decay length of b-jets in the lepton plus jets channel with 695 pb^{-1} of data [1]. Since the measurement relies almost exclusively on tracking, very different event information is used compared to conventional mass measurements, and so the result is expected to have small correlation with other measurements. Further, the jet energy scale systematic, which is the largest uncertainty on the world average top mass, should have a minimal effect on the results. However, the statistical resolution on the top mass is poor relative to more conventional, reconstruction based top mass measurements. To improve statistics, in addition to incorporating more than double the data of the previous measurement, it was decided that a second variable should be included to further reduce the uncertainty.

The second variable, originally proposed by C. S. Hill et. al. [2], was the transverse momentum of the leptons (transverse energy as measured in the calorimeter for electrons), which are correlated to the top mass through the momentum of the W bosons. Measuring the top mass using the lepton transverse momentum has a similar statistical power to the the decay length technique, and has the advantage of being almost completely uncorrelated statistically. Since the distribution of both these variables is approximately that of a decaying exponential over most of their range, the shapes are largely specified by the mean of the distributions. Thus, to keep the analysis simple, we use only the means and not the shapes of these distributions to evaluate the top mass.

2. Data Sample & Event Selection

The data for this analysis are collected with an inclusive lepton trigger that requires an electron (muon) with E_T (P_T) > 18 GeV. From this inclusive lepton dataset we select events offline with a reconstructed isolated lepton with E_T (P_T) > 20 GeV. All leptons used are required to be isolated and have a well resolved track in the central tracking chambers.

The total missing transverse energy (MET) in the event is required to be greater than 20 GeV, and a minimum of three jets must also be identified with reconstructed transverse energies greater than 20 GeV. b-jets are identified

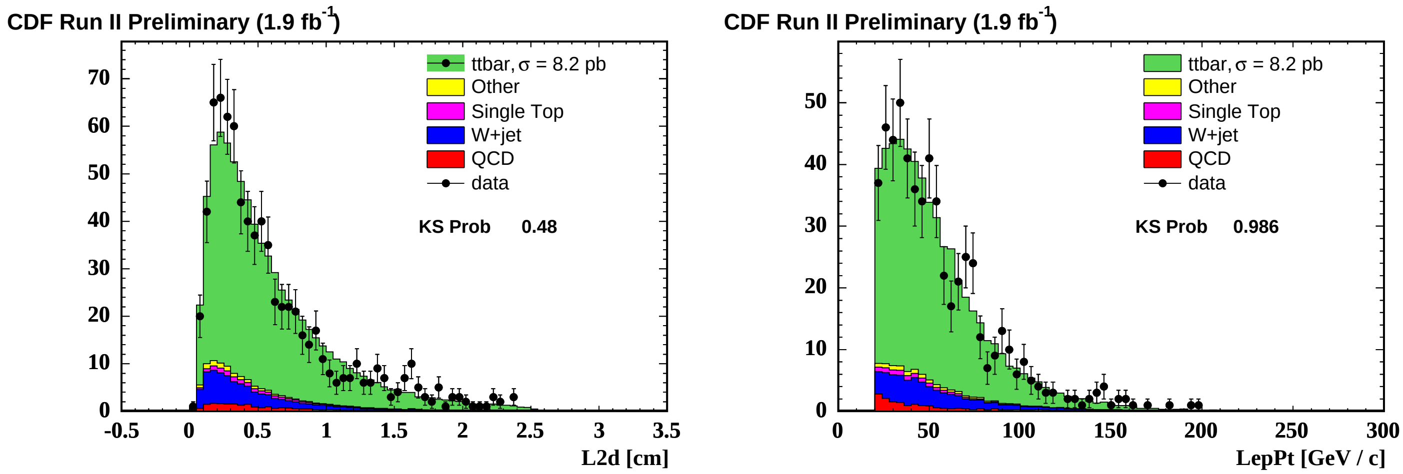

Figure 1: Left: Signal, background, and data for the L2d distribution using hypothesis top mass M=178 GeV/c^2. Right: Signal, background, and data for the LepPt distribution using hypothesis top mass M=173 GeV/c^2.

(tagged) using the SecVtx algorithm [3]. This algorithm identifies tracks that are displaced from the primary vertex and attempts to reconstruct a secondary vertex from them. If the secondary vertex is well resolved and has a sufficient transverse decay length from the primary vertex, the jet is tagged as a b. Note that this decay length is also directly used later to measure the top mass. In order for the event to pass selection, at least one jet must be tagged as a b for events with four or more jets of E_T greater than 20 GeV, and at least two jets must be tagged as a b for events with exactly three jets of E_T greater than 20 GeV.

3. Event Composition and Corrections

The $t\bar{t}$ signal Monte Carlo is generated in Pythia using the CTEQ5L [5] parton distribution function. Since this analysis is sensitive to inaccuracies in event kinematics, the events are reweighted to match the more accurate CTEQ6M [6] parton distribution function, and to match the expected (mass dependent) gluon fusion fractions. Further corrections (a scale factor) are applied to compensate for Monte Carlo mismodeling of the average b-jet decay length.

Aside from the signal, the largest contributions come from W+jets and QCD events. The QCD background is evaluated from data by altering the lepton selection criteria to make the events much more likely to contain fake leptons, and the W+jets events are evaluated from ALPGEN Monte Carlo that is showered with Pythia. Expected signal and background distributions for the L2d and LepPt variables are shown with data in Figure 1.

4. Method

Pseudoexperiment events are drawn separately from signal and background samples and combined according to the measured $t\bar{t}$ cross section in the greater than three jet bins (8.2 pb). This is done separately for 24 hypothesis top mass values ranging from a top mass of 130 GeV/c^2 to a top mass of 220 GeV/c^2. For each pseudoexperiment the total number of events is fixed to the value observed in the data. The total number of background events is fluctuated within statistical and systematic uncertainties, and the rest of the events are considered to be signal.

To evaluate the top mass results for each individual measurement (before L2d and LepPt are combined), the means and RMS's of the pseudoexperiment results are determined and are fit to quadratic polynomials as shown in Figure 2. Given the mean L2d and LepPt in data, the corresponding x-values of the central fit give us our expected mass, and the value of the shifted fits give us our ± one sigma asymmetric statistical uncertainties.

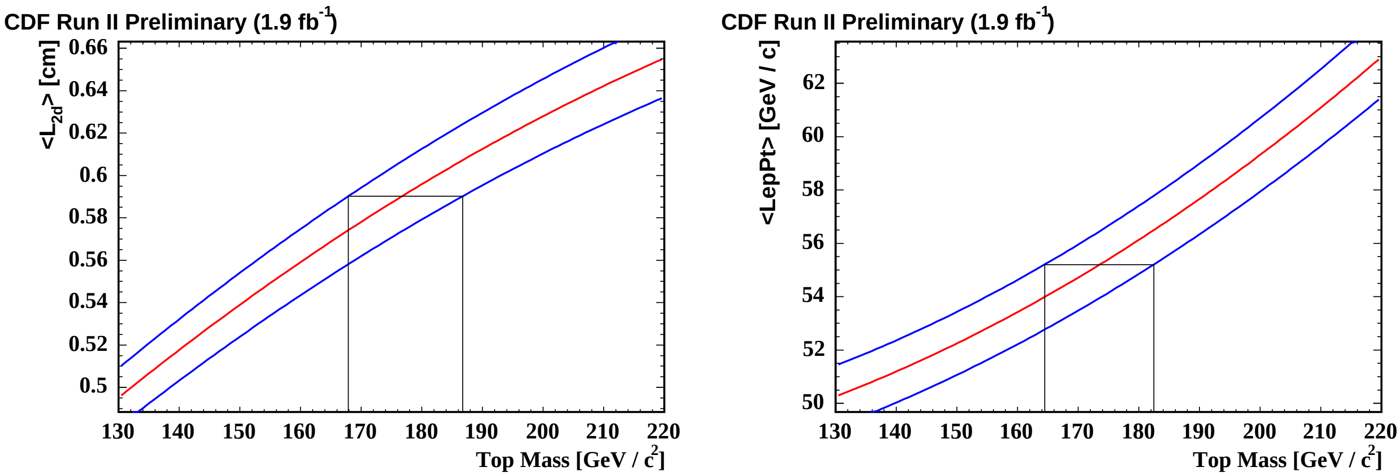

Figure 2: Left: Expected central values and one sigma confidence intervals of L2d mean results depending on top mass. Right: Expected central values and one sigma confidence intervals of LepPt mean results depending on top mass. The black lines show the plus and minus one sigma statistical uncertainties from data.

5. Combination

A joint top mass measurement using both the L2d and LepPt is also performed using pseudoexperiments. For each of the pseudoexperiments thrown for the L2d and LepPt measurements, the means are recorded. For a given top mass sample, these pseudoexperiments form an ellipse in the mean L2d versus mean LepPt plane. When results are measured in the data, they are compared to each of these hypothesis mass ellipses. The consistency of the mass hypothesis is evaluated based on the "distance" the data means are from the expected results (the ellipse center). This distance is evaluated from Equation 1:

$$D = \sqrt{(\frac{\delta P_t}{\sigma_{Pt}})^2 + (\frac{\delta L_{2d}}{\sigma_{L2d}})^2} \tag{1}$$

Here, δP_t is the difference between the mean LepPt of the data and the hypothesis value, and σ_{Pt} is the size of the RMS of the hypothesis LepPt means from pseudoexperiments, etc. If a given mass hypothesis represents the true value of the top mass, then the probability that a given pseudoexperiment will be at least as discrepant as the data is given by the fraction of pseudoexperiments with a larger value of D than the data. These fractions are evaluated along with uncertainties (dictated by number of pseudoexperiments and finite Monte Carlo statistics) and are fit to a Gaussian. Results for the data are shown in Figure 3. This fit provides us with our mass result and our statistical uncertainty. These fits have been shown to be without bias and to properly produce Gaussian statistical uncertainties in nineteen Monte Carlo samples, ten of which were blinded in advance.

6. Results

Using $1.9 fb^{-1}$ of CDF data, we find 576 events passing our selection. From these events we measure a mean LepPt of $55.2 \pm 1.3\ GeV/c$ and a mean L2d of $0.596 \pm 0.017\ cm$ (after application of the L2d scale factor, PDF, and gluon fusion reweightings, as explained previously). The associated top mass results and statistical uncertainties come out to $176.7^{+10.0}_{-8.9}\ GeV/c^2$ for L2d and $173.5^{+8.9}_{-9.1}\ GeV/c^2$ for LepPt. Under the combined measurement the fit result shown in Figure 3 returns us a top mass of $(175.3 \pm 6.2(stat))\ GeV/c^2$.

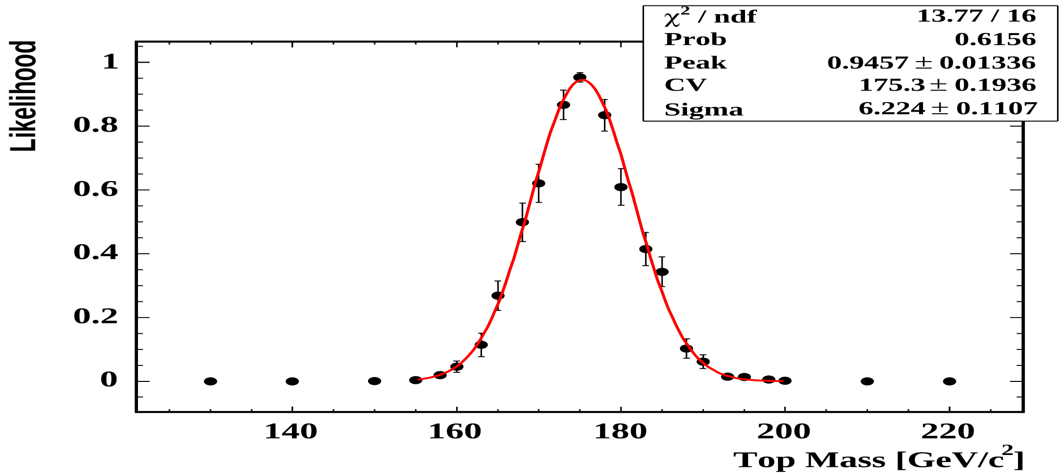

Figure 3: Likelihood fit results for data under the combined measurement.

7. Systematic Uncertainties

We evaluate the mean LepPt and L2d for data and compare to our background estimations in the one and two jet bins as cross checks for our background modeling. To be conservative, we take the larger of the shifts between the expected and the observed results for the one and two jet bins as the systematic uncertainty on our backgrounds. A number of factors are taken into account in evaluating uncertainties on the signal. QCD radiation uncertainties are evaluated using Pythia Monte Carlo samples generated with initial and final state radiation simultaneously tuned up or down. The larger of the shifts between the central value and the alternate radiation samples is taken as the systematic uncertainty. For the LepPt measurement this comes out to a surprisingly large number. This is because both the samples with more and less QCD radiation end up having a larger mean LepPt than the nominal sample. To get a handle on other uncertainties related to the generator, the top mass is evaluated again using a Herwig Monte Carlo sample instead of Pythia. Using the Herwig sample alters a number of properties, including how the QCD fragmentation is performed, the QED radiation (which in Herwig is added in at the leptonic W-decay vertices using the PHOTOS algorithm [4]), the transverse Fermi motion of the colliding partons, and spin correlations between the top quarks. The full shift between the top mass results for the Pythia and Herwig samples is taken as a conservative estimate of the uncertainties due to these different generators. The parton distribution function systematic is evaluated by reweighting to the twenty 90% CTEQ6M [6] eigenvector PDFs and adding the shifts in quadrature (allowing gluon fractions to vary). Since these eigenvectors do not account for uncertainties on the strong coupling constant, this extra uncertainty is determined by reweighting to the CTEQ6A and CTEQ6B PDFs [7]. These samples are similar to the nominal CTEQ6M NLO PDF, but with altered values of the strong coupling constant.

As mentioned in 3, the mean L2d results are corrected to account for differences in the Monte Carlo modeling of the decay length compared to data. The uncertainty on this correction (scale factor uncertainty) is significant, but will improve with statistics. A similar uncertainty is determined for the LepPt measurement due to uncertainty in the lepton transverse momentum. This uncertainty is found by fitting the Z-mass peak in data and Monte Carlo using electrons and muons separately. The observed shift is not corrected for. Rather, to be conservative, the weighted average of the full shift between the lepton types is taken as a systematic uncertainty. The jet energy scale is the dominant uncertainty for many other top mass measurements. In our case, the only possible way for the jet energy scale to have any effect is in the way it changes event selection (based upon which jets pass selection, and whether the MET passes the cut). It turns out that the LepPt measurement is only minimally effected by the jet energy scale, however the L2d measurement suffers a larger shift. This is because tagged jets near the 20 GeV threshold have a significantly lower than normal average decay length. At such low energies, the jet energy scale uncertainty is entirely dominated by uncertainties in out-of-cone effects on the jet energy scale. Improvements in the understanding of out-of-cone effects would help reduce this systematic. This systematic can also be reduced at the cost of statistics by cutting out low decay-length jets in the event selection. A summary of the systematic uncertainties is shown in Table I.

Table I: Systematic Results

Systematic	L2d	LepPt	Combination
QCD Radiation	0.9	2.3	1.5
PDFs	0.3	0.6	0.5
Generator	0.7	1.2	0.6
L2d Scale Factor	2.9	0	1.4
LepPt scale	0	2.3	1.1
Bkg Shape	1.0	2.3	1.6
Out of Cone JES	1.0	0.3	0.6
Total	3.4	4.2	3.0

8. Conclusion

We have performed three measurements of the top quark mass using variables with minimal correlation to the jet energy scale and combined them. Under an integrated luminosity of $1.9 fb^{-1}$ we measure a top quark mass of $(176.7^{+10.0}_{-8.9}(stat) \pm 3.4(syst))\ GeV/c^2$ using the decay length method, $(173.5^{+8.9}_{-9.1}(stat) \pm 4.2(syst))\ GeV/c^2$ using the lepton transverse momentum, and $(175.3 \pm 6.2(stat) \pm 3.0(syst))\ GeV/c^2$ in combination. If updated, the results of this method will improve, but will continue to be limited by statistics for the rest of Run II. However, if this analysis is done at the LHC statistics will no longer be an issue. Further, since some of the dominant systematics are statistically limited, the results of these techniques could well become competitive with conventional top mass analyses, and due to their reduced correlation with conventional top measurements they should help reduce the uncertainty on the world average top mass in a combination.

8.1. References

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