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Measurement of the Top Quark Mass using the Minuit Fitter in Dilepton Events at CDF

The CDF Collaboration
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We report on a measurement of the top quark mass in the dilepton channel of $t\bar{t}$ events from $p\bar{p}$ collisions at $\sqrt{s}$ =1.96 TeV. The integrated luminosity of the data sample is 193 pb^{-1}. 13 events were reconstructed according to the $t\bar{t}$ hypothesis and fitted as a superposition of signal and background. Using the background constrained fit (with 2.7±0.7 events expected from background) we measure M_{top} = 170.0 ±16.6 (stat) GeV/c^2. The estimate of systematic error is ±7.4 GeV/c^2.

I. INTRODUCTION

One of the major physics goals of CDF [1] in Run II is study of top quark properties. First observed by CDF and D0 collaborations in 1995 [2], top quark appears very massive, more than 35 times heavier then b quark. Top mass is one of the fundamental parameters of the Standard Model (SM), and its precise measurement together with W-mass gives a constraint on the Higgs boson mass, provides important test of the SM consistency, as well as sensitivity to physics beyond the SM.

On CDF, we study proton-antiproton collisions at a center-of-mass energy 1.96 TeV. Top quarks are produced in pairs ($t\bar{t}$) from quark-antiquark annihilations ($\sim$90%) or gluon-gluon fusion. According to the SM, both top quarks almost exclusively decay as $t \to Wb$, the channels of $t(\bar{t})$-decay are classified by decay modes of the W boson. The *dilepton* channel, when both W decay to leptons gets only 5% of decays, but it has the best signal-to-background ratio (S/B). Near 30% of decays go to $lepton + jets$ channel, with one W producing electron or muon, and other decaying into quark pair, produsing jets. The *all-hadronic* decay channel collects 44% of events, but has a large QCD background with S/B ratio of the order 1:10.

In this note we report a measurement of top quark mass in dilepton channel.

II. DATA SAMPLE & EVENT SELECTION

In our analysis we used data collected between March 2002 - September 2003 corresponding to a total integrated luminosity of 193 pb^{-1}.

We require events with two high E_T leptons of opposite charge, one of which must be isolated. Missing transverse energy must be $\not{E}_T > 25$ GeV indicating the presence of neutrino. If $\not{E}_T < 50$ GeV we additionally require that the angle between $\vec{\not{E}_T}$ and the nearest lepton or jet is $\Delta\phi > 20^o$. Transverse energy sum, H_T, has to be more than 200 GeV. Two (or more) jets with corrected $E_T > 15$ GeV and $|\eta| < 2.5$ are required in each event. Events with cosmic ray, conversion or Z are eliminated.

13 events were reconstructed according to the $t\bar{t}$ hypothesis after all selection cuts. The same cuts were applied to the Monte-Carlo generated signal or background events.

III. BRIEF DESCRIPTION OF THE METHOD

The top mass value for each event is returned from a kinematic event reconstruction procedure. This procedure is similar to the one used in the lepton+jets case [3]. In brief, event reconstruction is the result of minimization of the chisquare functional (χ^2) by the MINUIT routines. This chisquare functional has resolution terms related to the measured physical variables and constrained terms to take into account kinematic equations.

In contrast to the lepton+jets mode, for the dilepton case due to the existence of two neutrinos we have a non-constrained kinematics. The number of independent variables is one more than the number of kinematic constraints ($-1C$ kinematics). Obviously, it is impossible to pick up directly only one solution per event. We must assume some of the event parameters ($\vec{R}$) as known in order to constrain the kinematics and then vary the $\vec{R}$ to determine the variety of solutions. In addition, every solution must have a weight attached to it.

The minimal requirement in the case of $-1C$ kinematics is to use a two dimensional vector as $\vec{R}$. For our analysis we chose the azimuthal angles of the neutrino momenta $\vec{R} = (\phi_{\nu 1}, \phi_{\nu 2})$ and we create a net of solutions in the $(\phi_{\nu 1}, \phi_{\nu 2})$ plane.

For every point of the $(\phi_{\nu 1}, \phi_{\nu 2})$ plane we have 8 solutions. Two of them are generated due to the different possibilities to associate the two charged leptons to the two leading jets (which are supposed to be b-jets). The four other solutions are generated from the possibility for every neutrino to have two p_z momenta of opposite sign satisfying the $t\bar{t}$ kinematics. We select the minimal χ^2 solution for every point of the net for further use in our analysis.

Using the χ^2 value from a minimization we weight the selected solutions by $\exp(-\chi^2/2)$. This is done in order to suppress the solutions which have worse compliance with the fit hypothesis.

The final extraction of the top quark mass from a sample of dilepton candidates is provided by the likelihood fit. The expected signal and background distributions are obtained using Monte Carlo samples with full detector simulation.

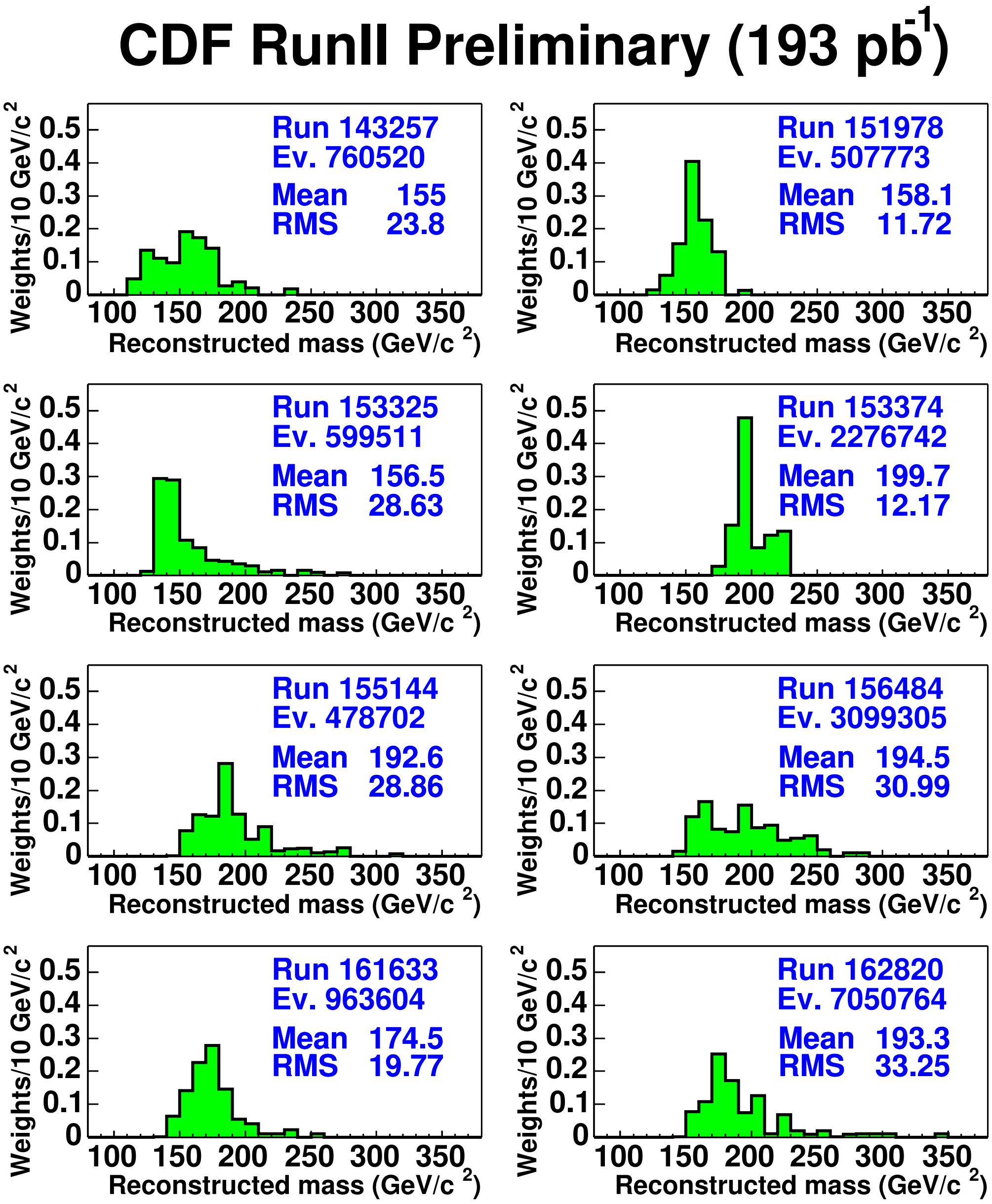

FIG. 1: Binned weight (probability) distribution for first 8 data events

A. Dilepton Canididates

For the $(\phi_{\nu 1}, \phi_{\nu 2})$ plane the net is chosen to have 12x12 points. As it was noticed above for every point we have 8 solutions from the ambiguity of the $p_z^{\nu 1,\nu 2}$ and jet assignment. For every event we have 1152 $1C$ minimizations with an output χ^2_{ijk} and m^{rec}_{ijk} ($i = 1, 12$; $j = 1, 12$; $k = 1, 8$). We selected the minimal χ^2_{ijk} for every point (i, j-fixed; $k = 1, 8$). The final output from this procedure was an array of 144 χ^2_{ij} and m^{rec}_{ij} ($i, j = 1, 12$). The overall normalization of the weight distribution is chosen to be one. The expression for the weight is:

$$w_{ij} = \frac{exp(-\chi^2_{ij}/2)}{\sum_{i=1}^{12}\sum_{j=1}^{12} exp(-\chi^2_{ij}/2)}. \tag{1}$$

Binned weight (probability) distribution for 13 data events are shown in Fig. 1, 2.

B. Monte Carlo Signal Templates

We created signal templates for input top masses in the 130÷230 GeV range using the Herwig generated Monte-Carlo samples. Then the templates obtained were parametrized as a sum of a Gamma function and of a Gaussian comprising 6 parameters that depend linearly on the top mass.

$$f_s(m_t|M_{top}) = \frac{(1-p_6)}{\sqrt{2\pi}p_5}e^{-0.5(\frac{m_t-p_4}{p_5})^2} + \frac{p_6 p_3^{(1+p_2)}}{\Gamma(1+p_2)}(m_t-p_1)^{p_2}e^{-p_3(m_t-p_1)} \tag{2}$$

The parameters of the Gaussian and Gamma distributions are themselves linear functions of the input top mass M_{top}:

$$p_k = \alpha_k + \alpha_{k+6} \cdot M_{top} \tag{3}$$

The set of signal MC templates is fitted to obtain the 12 α_k parameters. These templates are presented in Figs. 3, 4.

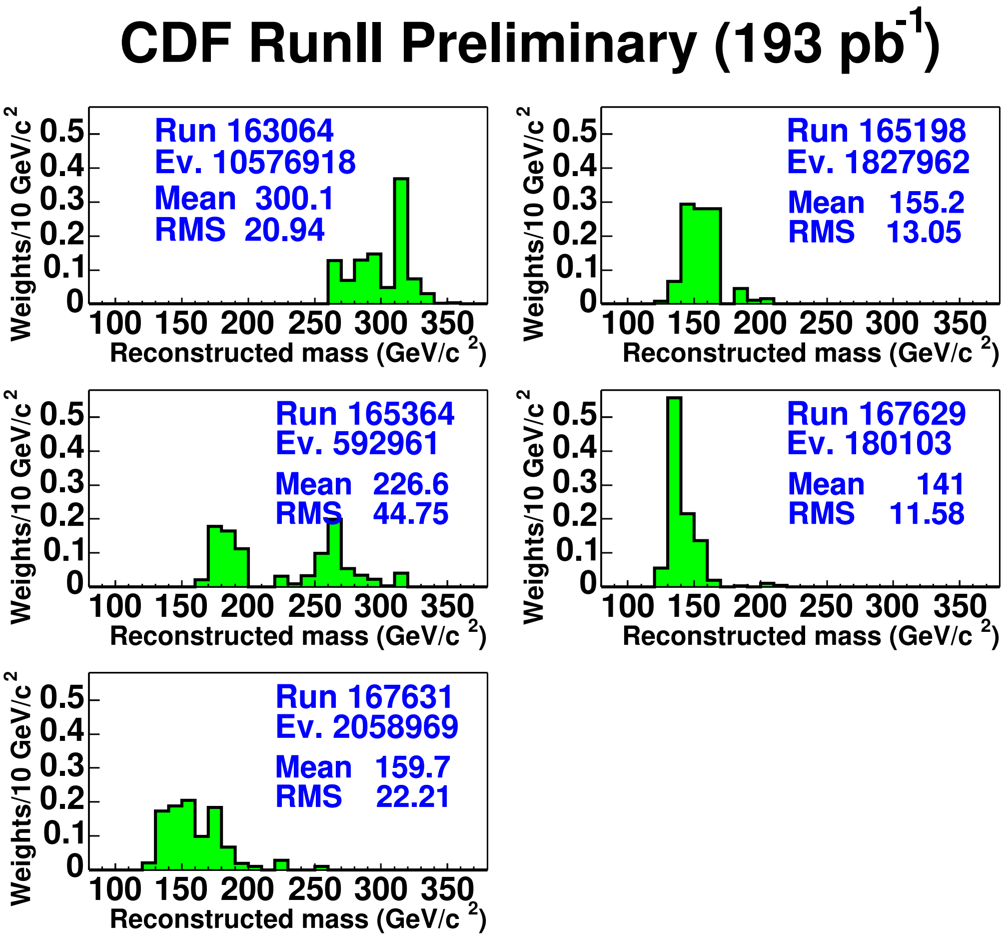

FIG. 2: Binned weight (probability) distribution for last 5 data events

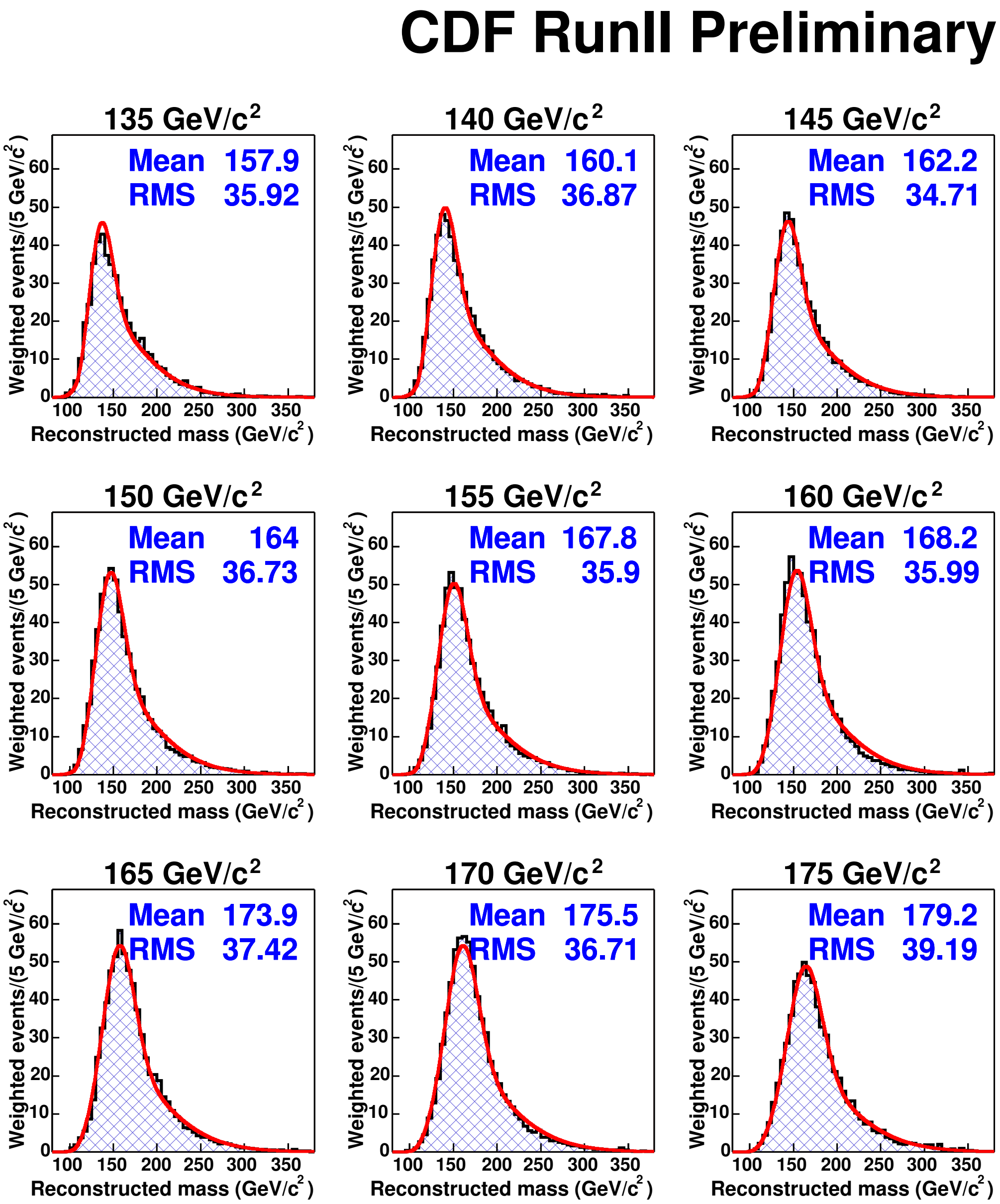

FIG. 3: Signal templates for top masses in the 135÷175 GeV/c^2 range. The curves from the global fit (2) are also shown.

C. Background Templates

Templates for the following background processes $WZ \to ll$, $WW \to ll$, Drel-Yan, $Z \to \tau\tau$ and "fake" lepton, were created from the MC samples (Fig. 5), and then were combined together according to the expected number of events as derived by the $t\bar{t}$ cross section group. We obtained "fake" lepton sample from the Monte-Carlo generated W+3 or 4-parton events, which passed all the selection cuts. The background templates are parameterized with the Gamma function (second term in 2), but with M_{top}-independent parameters. The result for the combined background template is shown in Fig. 6.

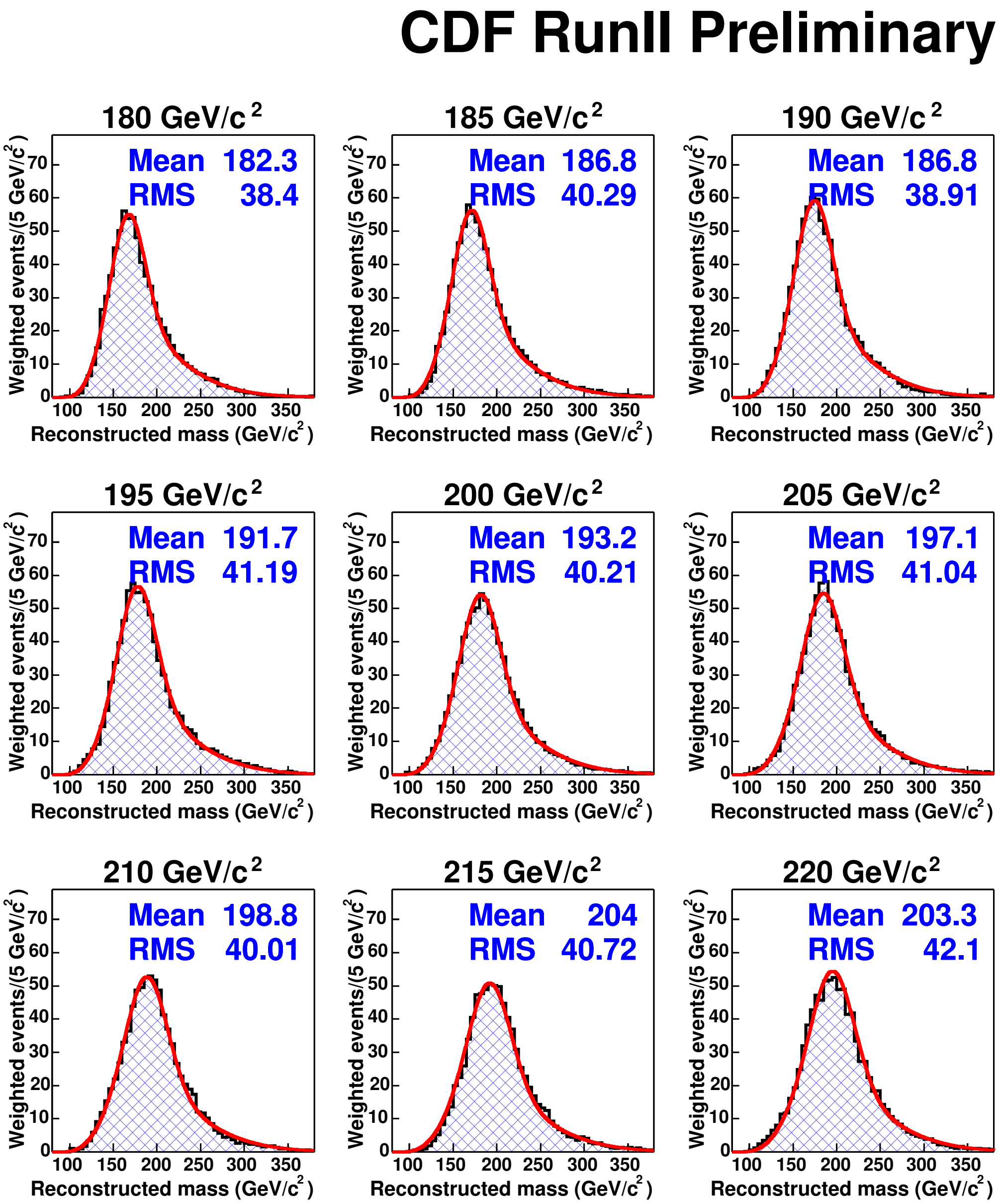

FIG. 4: Signal templates for top masses in the 180÷220 GeV/c^2 range. The curves from the global fit (2) are also shown.

D. Likelihood

We use a maximum likelihood method to extract the top quark mass by comparing the reconstructed top mass distribution of the data with the superposition of signal and background. The used likelihood form is as follows:

$$L = L_{shape} \cdot L_{backgr} \cdot L_{param}; \tag{4}$$

$$L_{shape} = \prod_{n=1}^{N_{ev}} \prod_{i=1}^{12} \prod_{j=1}^{12} (\beta_s \cdot f_s(m_{ij}^{rec}|M_{top}) + (1-\beta_s) \cdot f_b(m_{ij}^{rec}))^{w_{ij}} \tag{5}$$

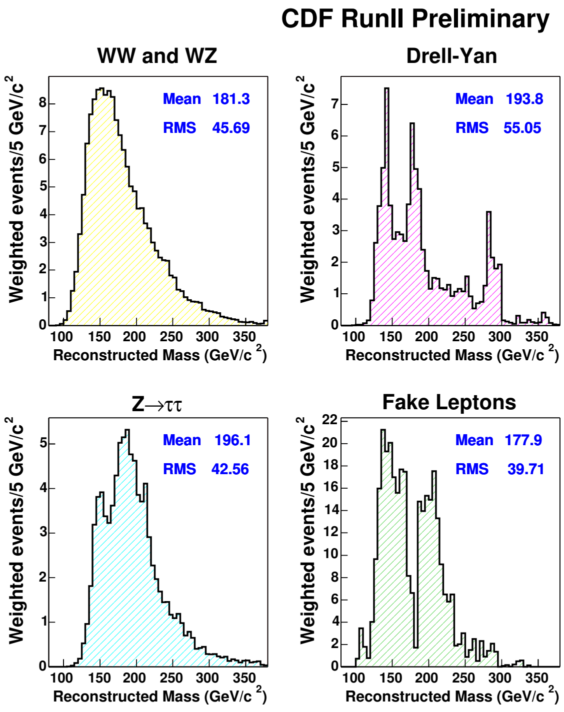

FIG. 5: Templates of background processes WW+WZ, Drell-Yan, $Z \to \tau\tau$ and "fake" lepton.

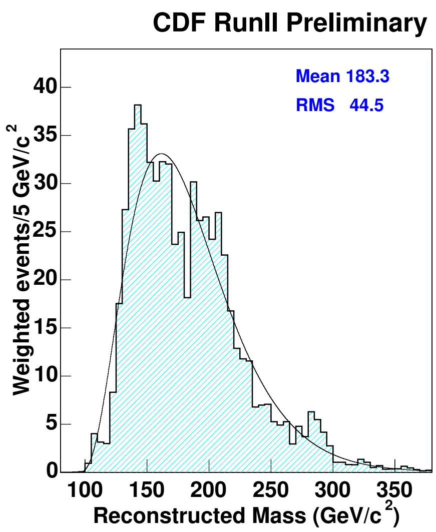

FIG. 6: Combined background template. The curve shows the fit result.

where β_s is the expected signal fraction in the dilepton data sample. Also the additional terms were added to constrain number of the background events and to constrain $\vec{\alpha}$, $\vec{\beta}$ parameters, obtained from the signal and background template parameterization.

$$L_{backgr} = exp(\frac{-(N_b - (1-\beta_s) \cdot N_{ev})^2}{2\sigma^2_{N_b}}), \tag{6}$$

$$L_{param} = exp\{-0.5[(\vec{\alpha} - \vec{\alpha_0})^T U^{-1}(\vec{\alpha} - \vec{\alpha_0}) + (\vec{\beta} - \vec{\beta_0})^T V^{-1}(\vec{\beta} - \vec{\beta_0})]\}. \quad (7)$$

Here U and V are the covariance matrices for $\vec{\alpha_0}$ and $\vec{\beta_0}$ respectively.

IV. RESULTS FROM PSEUDO-EXPERIMENTS

We checked whether the fit with likelihood form (4) was able to return the correct mass by performing the "sanity check" pseudo-experiments for different input top mass values. The overall number of events in the pseudo-experiments was 13 with expected number of background events 2.7±0.7. The output m_{top} (median) vs. input M_{top} is shown in Fig. 7. A linear fit yielded a slope of 1.00±0.02. The mean and width of the pull distributions as a function of input top mass are shown in Fig. 8. From the latter follows that we are underestimating our statistical errors for about 5.8%. We take into account this effect by scalling obtained errors by 1.058. We have not considered first two points in Fig. 8 when determining this correction factor. We expect that the influence of the kinematical limit of ~100 GeV, which is set by W+jet invariant mass, is especially strong in the low mass region.

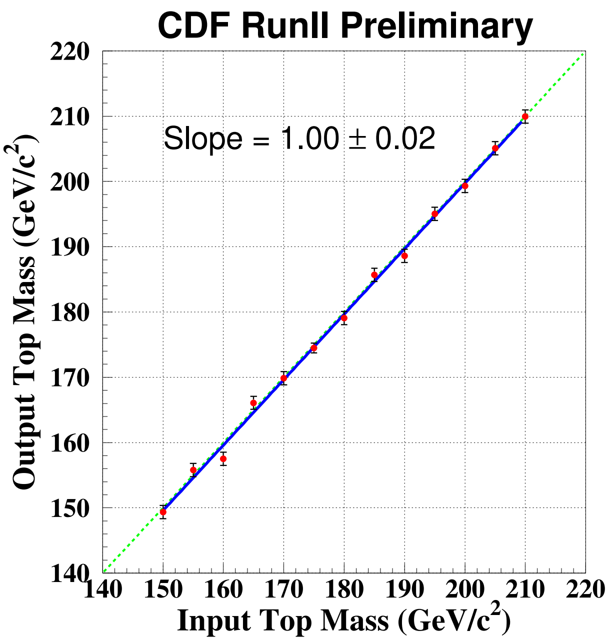

FIG. 7: Median top mass returned by pseudo-experiments with 13 events each as a function of input mass. The result of a linear fit is also shown. The green dashed line is drawn with a slope of 1.0.

V. SYSTEMATIC UNCERTAINTIES

We have considered the following sources of systematic uncertainties on the fitted mass value: a) jet energy scale, b) amount of initial and final state radiation, c) shape of the background template, d) parton distribution functions, and e) approximations made by Monte-Carlo generators. We have estimated each systematic uncertainty by performing a series of pseudo-experiments (PE) with $\pm 1\sigma$ systematic Monte-Carlo samples.

The largest contribution comes from the uncertainty in the jet energy measurement, which includes jet energy corrections for different calorimeter response (as a function of η), the absolute hadron energy scale, and fragmentation. The initial and final state radiation (ISR and FSR) uncertainties are estimated using the Pythia [4] Monte-Carlo samples, in which QCD parameters for parton shower evolution are varied based on the studies of CDF Drell-Yan data. For the parton distribution functions (PDF) we considered two different group of PDF (CTEQ and MRST), two sets of MRST for different Λ_{QCD} values, and 20 pairs of CTEQ6M uncertainty sets. In addition, we have estimated the systematic uncertainty due to the background shape (combined background and WW background), different Monte-Carlo generators (Pythia and Herwig [5]).

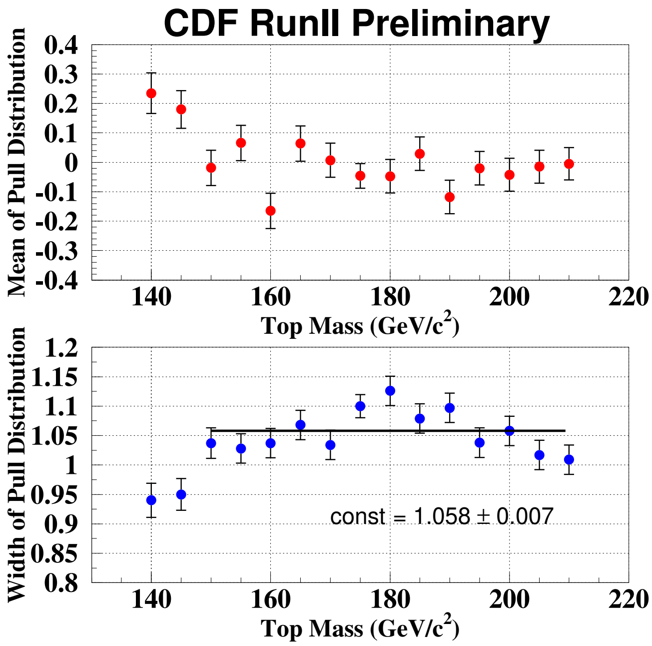

FIG. 8: Mean (above) and width (below) of pull distributions determined from the pseudo-experiments as a function of input top mass.

The systematic uncertainties are summarized in Table I. The total systematic uncertainty is estimated to be 7.4 GeV/c^2.

CDF RunII Preliminary

Source	Uncertainty (GeV/c^2)
Jet Energy Measurement	6.7
Initial State Radiation	1.8
Final State Radiation	0.7
Parton Distribution Functions	2.2
Monte-Carlo Generators	0.7
Background Shape	0.7
Total	**7.4**

TABLE I: Systematic uncertainties as determined with the pseudo-experiments.

VI. RESULTS

The two-component, background-constrained fit (with 2.7 ± 0.7 expected background events) for the obtained 13 dilepton candidates returns 170.0 $\pm^{15.9}_{15.5}$ (stat.) GeV/c^2, with 10.5±3.6 signal and 2.7±0.7 background events. The left plot in Fig. 9 shows the fitted mass distribution. The insert shows the mass dependence of the negative log-likelihood function. The right plot is the expected statistical errors from Monte-Carlo sample, where the arrows indicate present result on the data events.

After symmetrization of statistical errors and correction by factor of 1.058 (see section IV), our preliminary result on the data sample with the integrated luminosity of 193 pb^{-1} is:

$$\mathrm{M}_{top} = 170.0 \pm 16.6 \text{ (stat.) } \pm 7.4 \text{ (syst.) GeV/c}^2.$$

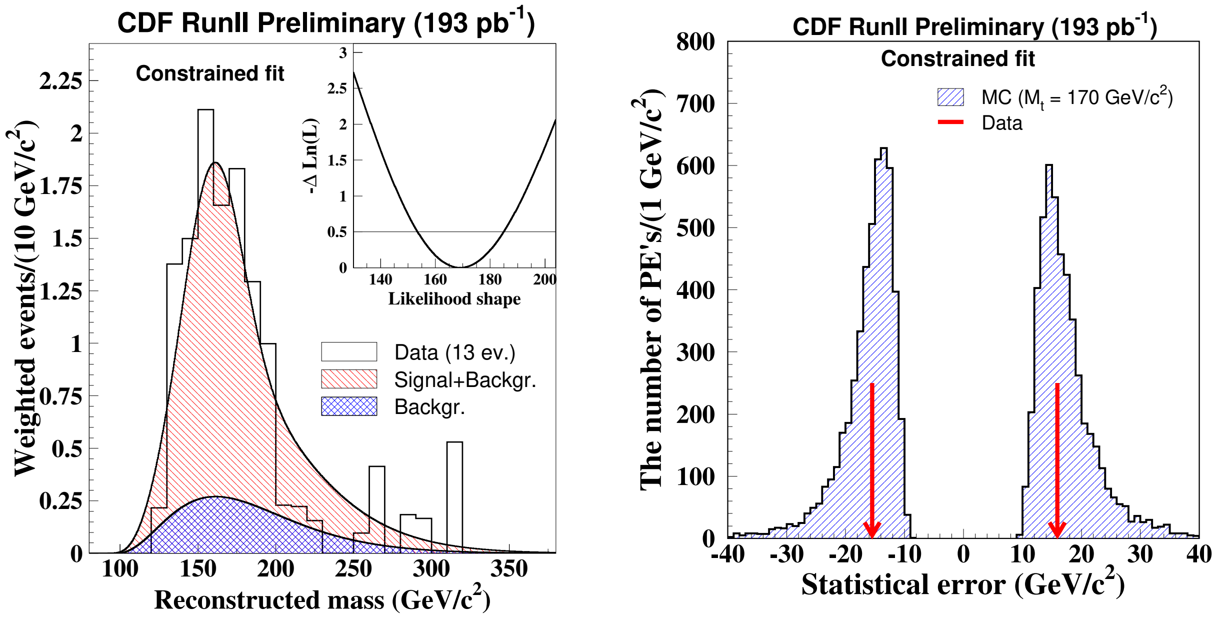

FIG. 9: Left: two-component, constrained fit to the dilepton sample. The blue shaded area corresponds to the background returned by the fit and the red line-shaded area is the sum of background and signal events. The insert shows the mass-dependent negative log-likelihood used in the fit. Right: left/right error distributions returned by the PE's. The arrows indicate the errors returned by the fit to the data.

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