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MEASUREMENT OF THE TOP QUARK MASS USING NEUTRINO ϕ WEIGHTING METHOD IN DILEPTON EVENTS AT CDF

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Беллеттини Дж. и др. E1-2005-129
Измерение массы топ-кварка в дилептонных событиях
на CDF с помощью метода взвешивания
по азимутальным углам нейтрино

Измерена масса топ-кварка в дилептонном канале $t\bar{t}$ в протон-антипротонных взаимодействиях при $\sqrt{s} = 1{,}96$ ТэВ. Интегральная светимость данных составила 340 пб$^{-1}$. В рамках гипотезы $t\bar{t}$-событий было отобрано и восстановлено 33 события. При фитировании массы топ-кварка (в предположении, что число фоновых событий составляет $11{,}6 \pm 2{,}1$) было получено значение $M_{\rm top} = 169{,}8^{+9{,}2}_{-9{,}3}$ (стат.) ГэВ/c^2. Систематическая погрешность оценена нами в $\pm 3{,}8$ ГэВ/c^2.

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Measurement of the Top Quark Mass
Using Neutrino ϕ Weighting Method in Dilepton Events at CDF

We report on a measurement of the top quark mass in the dilepton channel of $t\bar{t}$ events from $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The integrated luminosity of the data sample is 340 pb^{-1}. 33 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 11.6 ± 2.1 events expected from background) we measured $M_{\rm top} = 169.8 \pm^{9.2}_{9.3}$ (stat.) GeV/c^2. The estimate of systematic error is ± 3.8 GeV/c^2.

The investigation has been performed at the Dzhelepov Laboratory of Nuclear Problems, JINR.

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INTRODUCTION

One of the main physics goals of CDF [1] in Run II is the study of top quark properties. First observed by the CDF and D0 collaborations in 1995 [2], the top quark is very massive, more than 35 times heavier than b quark. The top mass is one of the fundamental parameters of the Standard Model (SM). Within the SM its precise measurement together with W mass gives a constraint on the Higgs boson mass.

In the CDF Run II we study proton–antiproton collisions at a center-of-mass energy 1.96 TeV. Top quarks are mostly produced in pairs ($t\bar{t}$) from quark–antiquark annihilations ($\sim 90\%$) or gluon–gluon fusion. According to the SM, both top quarks decay almost exclusively as $t \to Wb$. The channels of $t(\bar{t})$-decay are classified according to the decay modes of the W boson. The *dilepton* channel, when both W decay to leptons gets only 5% of decays, but has the best signal-to-background ratio (S/B). Near 30% of decays go to the *lepton + jets* channel, with one W producing an electron or a muon, and the other decaying into a quark pair and producing 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 paper we report a measurement of top quark mass in the dilepton channel [3].

1. DATA SAMPLE AND EVENT SELECTION

In our analysis we used data collected between March 2002 and August 2004, corresponding to a total integrated luminosity of 340 pb^{-1}.

We select 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 $\not{\mathbf{E}}_T$ and the nearest lepton or jet is $\Delta\phi > 20°$. The 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 also required. Events with cosmic ray, conversion or Z are eliminated.

After these selection cuts 33 events were left, which were reconstructed according to the $t\bar{t}$ hypothesis. The same cuts were applied to the Monte-Carlo generated signal or background events.

2. BRIEF DESCRIPTION OF THE METHOD

The estimated top mass value for each event is returned from a kinematic event reconstruction procedure. This procedure is similar to that used in the lepton + jets case [4]. 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 ($\mathbf{R}$) as known in order to constrain the kinematics and then vary the $\mathbf{R}$ to determine a set of solutions. In addition, we attach a χ^2-dependent weight to each solution.

The minimal requirement in the case of -1C kinematics is to use a two-dimensional vector as $\mathbf{R}$. For our analysis we chose the azimuthal angles of the neutrino momenta $\mathbf{R} = (\phi_{\nu 1}, \phi_{\nu 2})$ and create a net of solutions in the $(\phi_{\nu 1}, \phi_{\nu 2})$ plane. In practice we do not need to cover full $(\phi_{\nu 1}, \phi_{\nu 2})$ plane by the net. Taking into account the symmetry of the solutions for $\phi'_{\nu 1,\nu 2} = \phi_{\nu 1,\nu 2} + \pi$ it is enough to use the points in quadrant $(0 < \phi_{\nu 1} < \pi, 0 < \phi_{\nu 2} < \pi)$.

For every point of the $(\phi_{\nu 1}, \phi_{\nu 2})$ plane we have 8 solutions. Double ambiguity corresponds to the two ways of associating the two charged leptons to the two leading jets (which are supposed to be b-jets). The four solutions are generated from the possibility for every neutrino to have two p_z momenta 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.

Averaging the reconstructed masses with taking into account the weights we get an estimation for the top mass from each single event. Furthermore we take for the averaging only those masses which fall into the bins with content above 30% of the maximum value for a weighted mass distribution. This cut was optimized with respect to the expected statistical errors.

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 (templates) are obtained using Monte-Carlo samples with full detector simulation.

2.1. Dilepton Candidates. The binned weight (probability) distributions for first 8 data events are shown in Fig. 1. The red arrow corresponds to the estimated top mass of the event. The dashed line is our cut (30% of maximum).

Here we chose to split the quadrant $(0 < \phi_{\nu 1} < \pi, 0 < \phi_{\nu 2} < \pi)$ into 12×12 points. As it was noticed above for every point we have 8 solutions because of the ambiguity of the neutrino longitudinal momenta and the ambiguity in assignment of the two jets to the two leptons. For every event we have 1152 1C

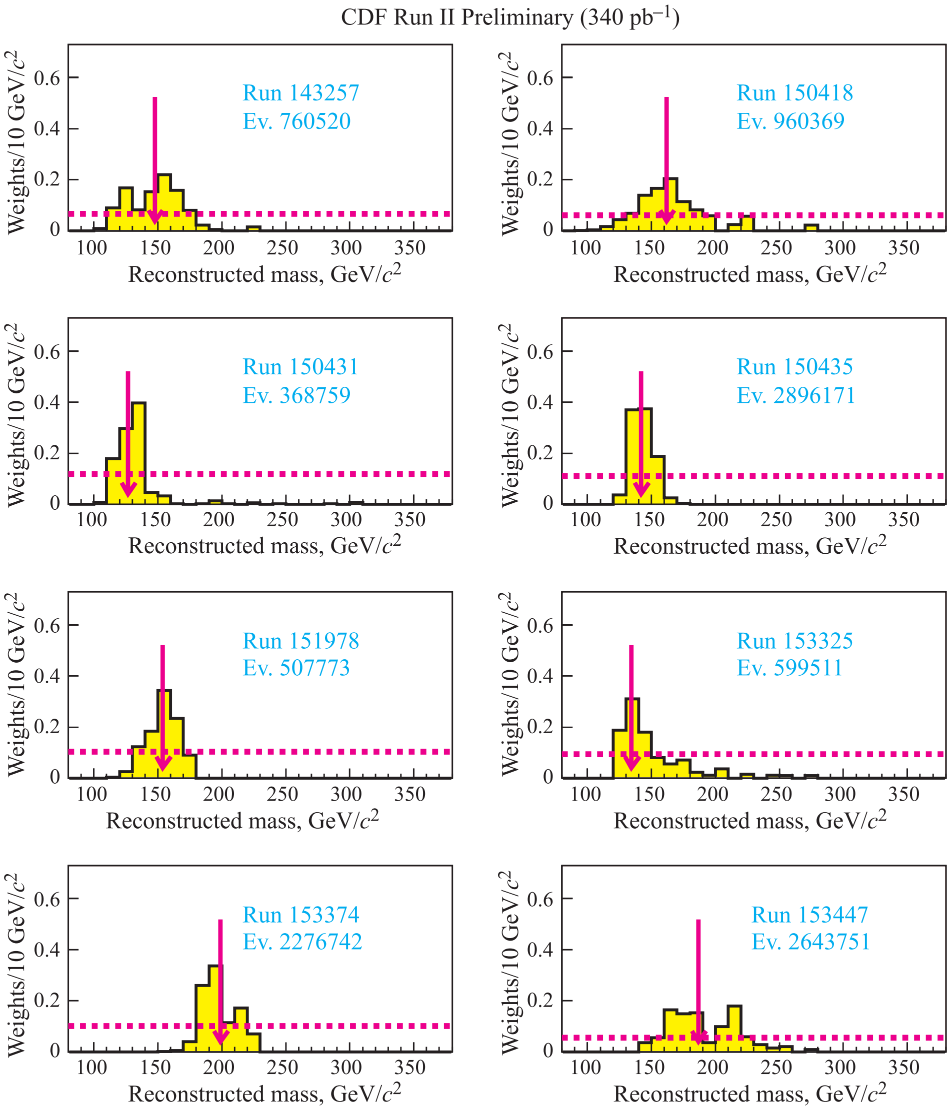

Fig. 1. Binned weight (probability) distributions for first 8 data events. The red arrow corresponds to the estimated top mass of the event. The dashed line shows our cut (30% of maximum)

minimizations with an output χ^2_{ijk} and $m^{\rm rec}_{ijk}$ $(i = 1, 12;\ j = 1, 12;\ k = 1, 8)$. 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 $m^{\rm rec}_{ij}$ $(i, j = 1, 12)$. The overall normalization of the weight distribution is chosen to be one. The expression for the weight is

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

2.2. Monte-Carlo Signal Templates. We created signal templates for input top masses in the $140 \div 230$ GeV$/c^2$ range with 5 GeV$/c^2$ steps using Herwig–Monte-Carlo samples. The templates were parametrized as a sum of a Gamma function and of a Gaussian comprising 6 parameters

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

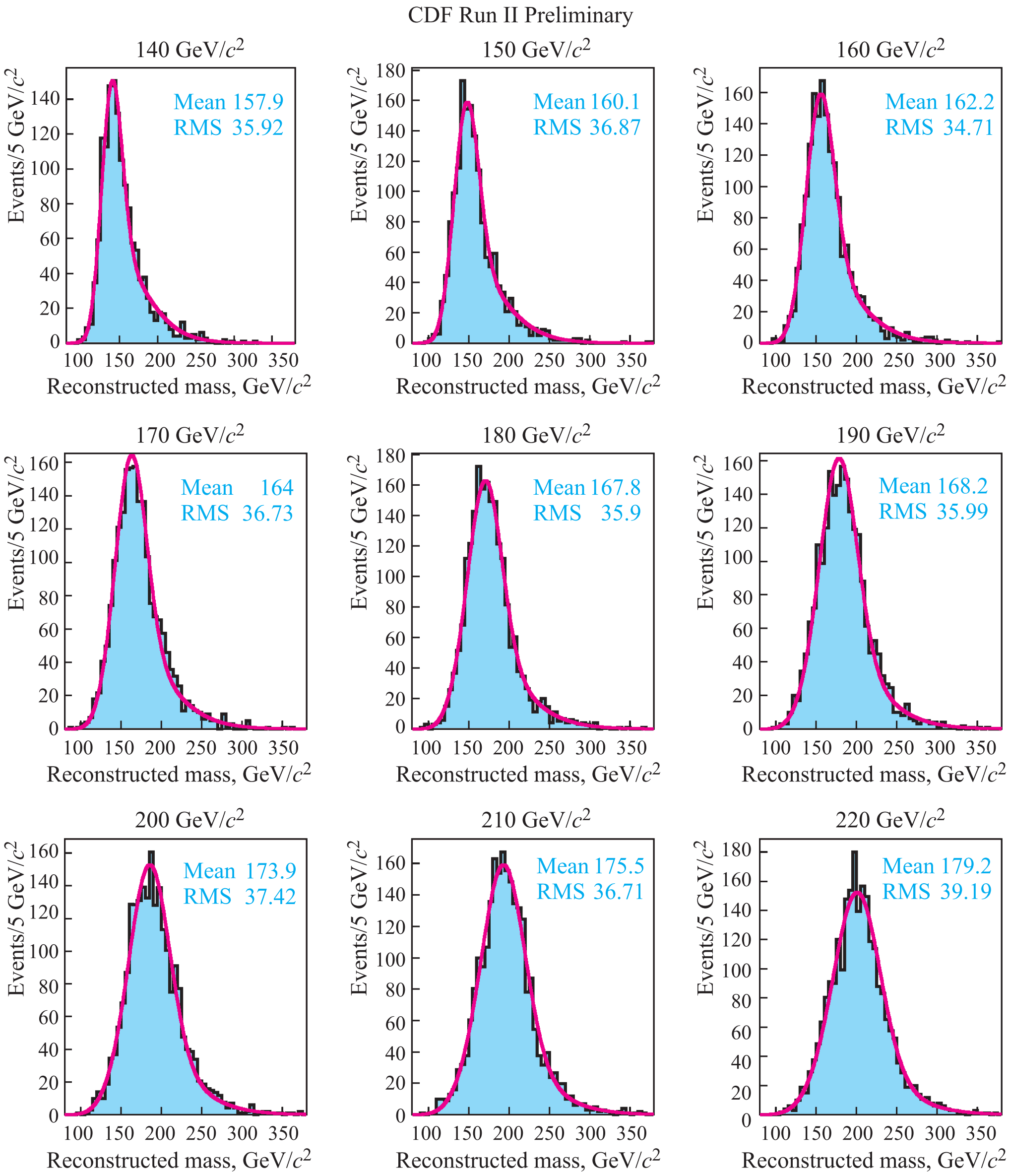

Fig. 2. Arbitrarily selected signal templates for top masses in the $140 \div 220$ GeV$/c^2$ range. The curves from the global fit (2) are also shown

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

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

The set of signal MC templates is fitted to obtain the 12 α_k parameters. Some of these templates are presented in Fig. 2.

2.3. Background Templates. Templates for the background processes ($WZ \to ll$, $WW \to ll$, Drell–Yan, $Z \to \tau\tau$ and fake lepton) were created from the official Monte-Carlo samples and were combined together according to the expected number of events as derived by the $t\bar{t}$ cross section group. The combined background template was also parameterized by (2), but with $M_{\rm top}$-independent parameters. The templates of the individual background processes along with the combined background template are shown in Fig. 3.

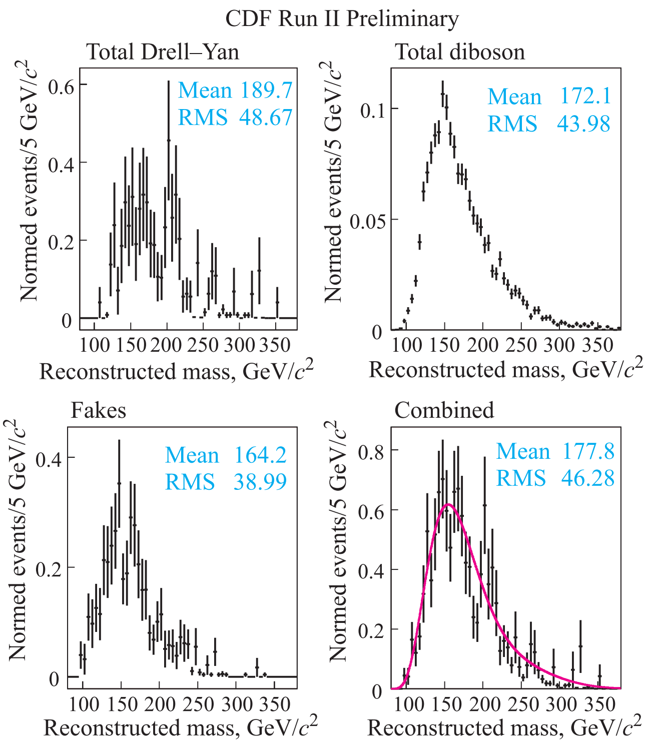

Fig. 3. The templates of background processes Drell–Yan (coupled with $Z \to \tau\tau$), $WW + WZ$, fake lepton and the combined background template. The red curve for combined background shows the fit result

2.4. 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:

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

Here

$$L_{\text{shape}} = \frac{e^{-(n_s+n_b)} \cdot (n_s+n_b)^N}{N!} \cdot \prod_{n=1}^{N} \frac{n_s \cdot f_s(m_n|M_{\text{top}}) + n_b \cdot f_b(m_n)}{n_s+n_b} \tag{5}$$

where parameters n_s and n_b are the expected signal and background numbers in the dilepton data sample. N is the total number of events observed in the data. Also the additional terms were added to constrain number of the background events and to constrain $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$ parameters, obtained from the signal and background template parameterization

$$L_{\text{backgr}} = \exp\left(\frac{-(n_b - n_b^{\text{exp}})^2}{2\sigma_{n_b}^2}\right), \tag{6}$$

$$L_{\text{param}} = \exp\{-0.5[(\boldsymbol{\alpha}-\boldsymbol{\alpha}_0)^T U^{-1}(\boldsymbol{\alpha}-\boldsymbol{\alpha}_0) + (\boldsymbol{\beta}-\boldsymbol{\beta}_0)^T V^{-1}(\boldsymbol{\beta}-\boldsymbol{\beta}_0)]\}. \tag{7}$$

Here U and V are the covariance matrices for $\boldsymbol{\alpha}_0$ and $\boldsymbol{\beta}_0$, respectively. Thus with this likelihood form we have two free parameters: M_{top} and n_s.

3. 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 33 with expected number of background events 11.6 ± 2.1. The output m_{top} (median) vs. input M_{top} is shown in Fig. 4 (top). The shift of the output m_{top}

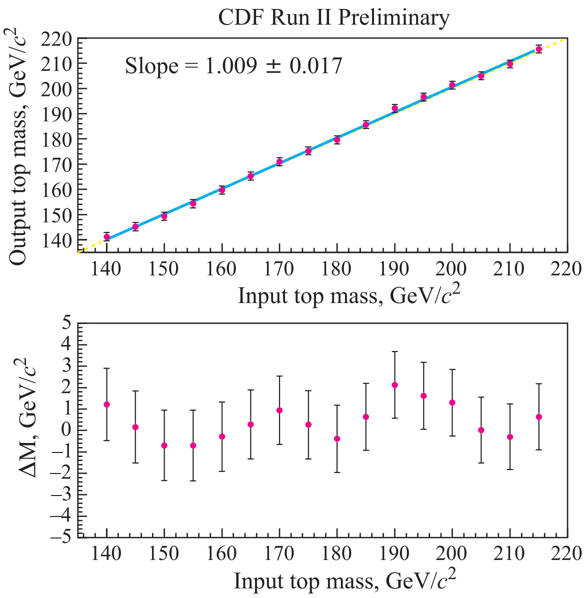

Fig. 4. Top: Median top mass returned by pseudo-experiments with 33 events each as a function of input mass. The result of a linear fit is also shown. The green dashed line is drawn with a slope of 1.0. Bottom: Shift of median top mass from input mass as a function of input mass

from input M_{top} as function of input M_{top} are also shown in Fig. 4 (bottom) for better visualization. A linear fit yielded a slope of 1.009 ± 0.017. The mean and width of the pull distributions as a function of input top mass are shown in Fig. 5. From the pull width distribution we understand that we are underestimating our statistical errors by about 5.1%. We take into account this effect by scaling the returned errors by 1.051.

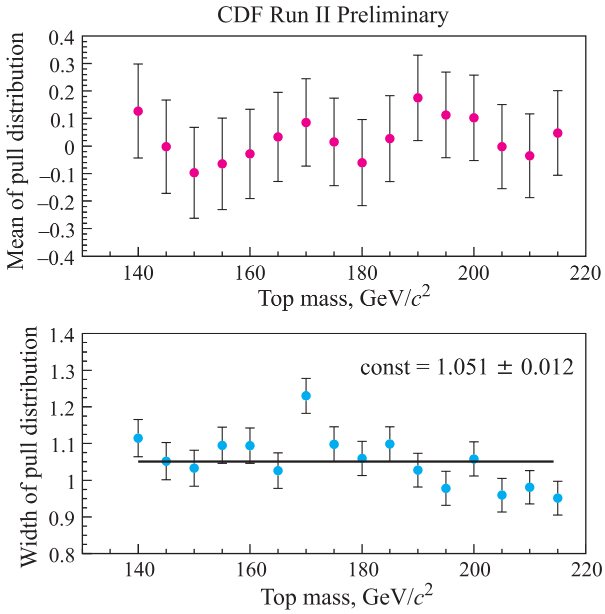

Fig. 5. Mean (top) and width (bottom) of pull distributions determined from the pseudo-experiments as a function of input top mass

4. 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 radiations, c) shape of the background template, d) parton distribution functions, e) approximations made by Monte-Carlo generators, and f) b-jet energy scale. The magnitudes of uncertainties were estimated using large Monte-Carlo samples generated only for the systematic studies.

The procedure for estimating the systematic uncertainty is similar for all sources. For each source we varied the input value as appropriate (by 1σ, or changing PDF, etc.) and evaluated the impact on the returned top mass. This was done by simulating a large number of pseudo-experiments (PE) with the nominal assumption and with the alternate assumption. Each PE had the same number of events as in the data. The likelihood procedure was the same as for the data. The obtained mass value was entered into an ensemble of results of simulated experiments. The systematic uncertainty assigned to our measurement is the difference in the average of these result distributions for the nominal and shifted ensembles.

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 jet fragmentation. The initial and final state radiation (ISR and FSR) uncertainties are estimated using the Pythia [5] Monte-Carlo samples, in which QCD parameters for parton shower evolution are varied based on the CDF studies of Drell–Yan data. For the parton distribution functions (PDF) we considered two different groups of PDF (CTEQ and MRST), two sets of MRST for different Λ_{QCD} values, and 20 pairs of CTEQ6M uncertainty sets. The effect of using different top Monte-Carlo generators was checked by comparing the nominal Herwig [6] with alternate Pythia [5] samples. In addition, we have estimated the systematic uncertainty due to the background shape by comparing the combined shape and the shapes from individual background components ($WW + WZ$, Drell–Yan and fake lepton). Also the additional uncertainty for the b-jet scale due to heavy quark fragmentation, color flow effects, and more abundant semileptonic decays, were taken into account.

The systematic uncertainties are summarized in the Table. The total systematic uncertainty is estimated to be 3.8 GeV/c^2.

Systematic uncertainties as determined with the pseudo-experiments

CDF Run II Preliminary

Source	Uncertainty, GeV/c^2
Jet Energy Scale	3.3
Initial State Radiation	0.7
Final State Radiation	0.8
Parton Distribution Functions	0.9
Monte-Carlo Generators	1.0
Background Shape	0.7
b-jet Energy Scale	0.7
Total	**3.8**

5. RESULTS

The two-component background-constrained fit (with 11.6 ± 2.1 expected background events) for the obtained 33 dilepton candidates returns $M_{\mathrm{top}} = 169.8 \pm^{8.8}_{8.9}$ (stat.) GeV/c^2, with $23.4 \pm^{6.3}_{5.7}$ signal and 11.0 ± 2.1 background events. The left plot in Fig. 6 shows the fitted mass distribution. The insert shows the mass dependence of the negative log-likelihood function. The right plot is the

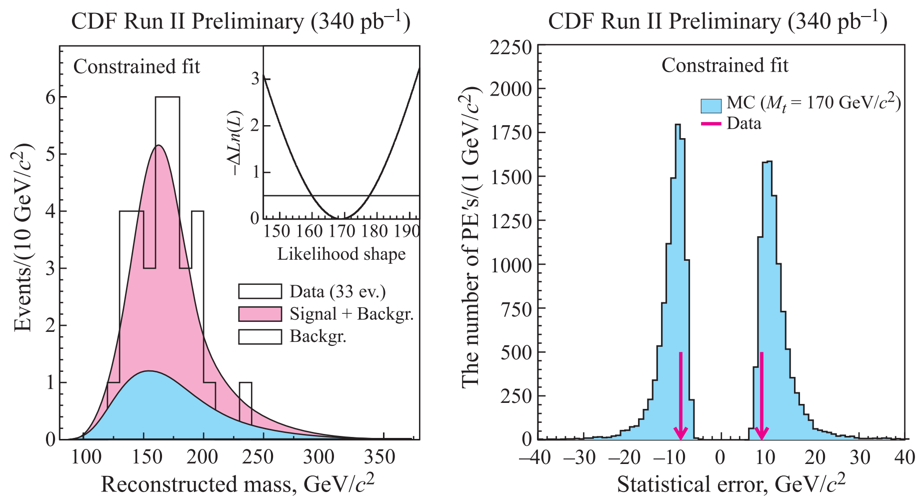

Fig. 6. Left: Two-component background-constrained fit to the dilepton sample. The blue shaded area corresponds to the background returned by the fit and the red line-shaded area is the sum of background and signal events. The insert shows the mass-dependent negative log-likelihood used in the fit. Right: Left/right error distributions returned by the PE's. The arrows indicate the errors returned by the fit to the data

expected statistical errors from Monte-Carlo sample, where the arrows indicate present result on the data events.

After the correction by factor of 1.051 (see Sec. 3), our preliminary result on the data sample with the integrated luminosity of 340 pb^{-1} is

$$M_{\text{top}} = 169.8 \pm^{9.2}_{9.3} \text{ (stat.)} \pm 3.8 \text{ (syst.) GeV}/c^2.$$

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