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(On behalf of the CDF Collaboration)

MEASUREMENT OF THE TOP QUARK MASS USING THE MINUIT FITTER IN DILEPTON EVENTS AT CDF

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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.

1. DATA SAMPLE AND EVENT SELECTION

In our analysis we used data collected from March 2002 to September 2003, corresponding to a total integrated luminosity of 193 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 $\Delta\phi > 20^\circ$. 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 13 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 top mass value for each event is returned from a kinematic event reconstruction procedure. This procedure is similar to that 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 (**R**) as known in order to constrain the kinematics and then vary the **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 **R**. For our analysis we chose the azimuthal angles of the neutrino momenta $\mathbf{R} = (\phi_{\nu 1}, \phi_{\nu 2})$ 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 correspond to the two way of associating 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.

2.1. Dilepton Candidates. We chose to split the $(\phi_{\nu 1}, \phi_{\nu 2})$ plane into 12×12 points. As it was noticed above for every point we have 8 solutions because of the sign 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 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:

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

The binned weight (probability) distributions for the 13 data events are shown in Figs. 1 and 2.

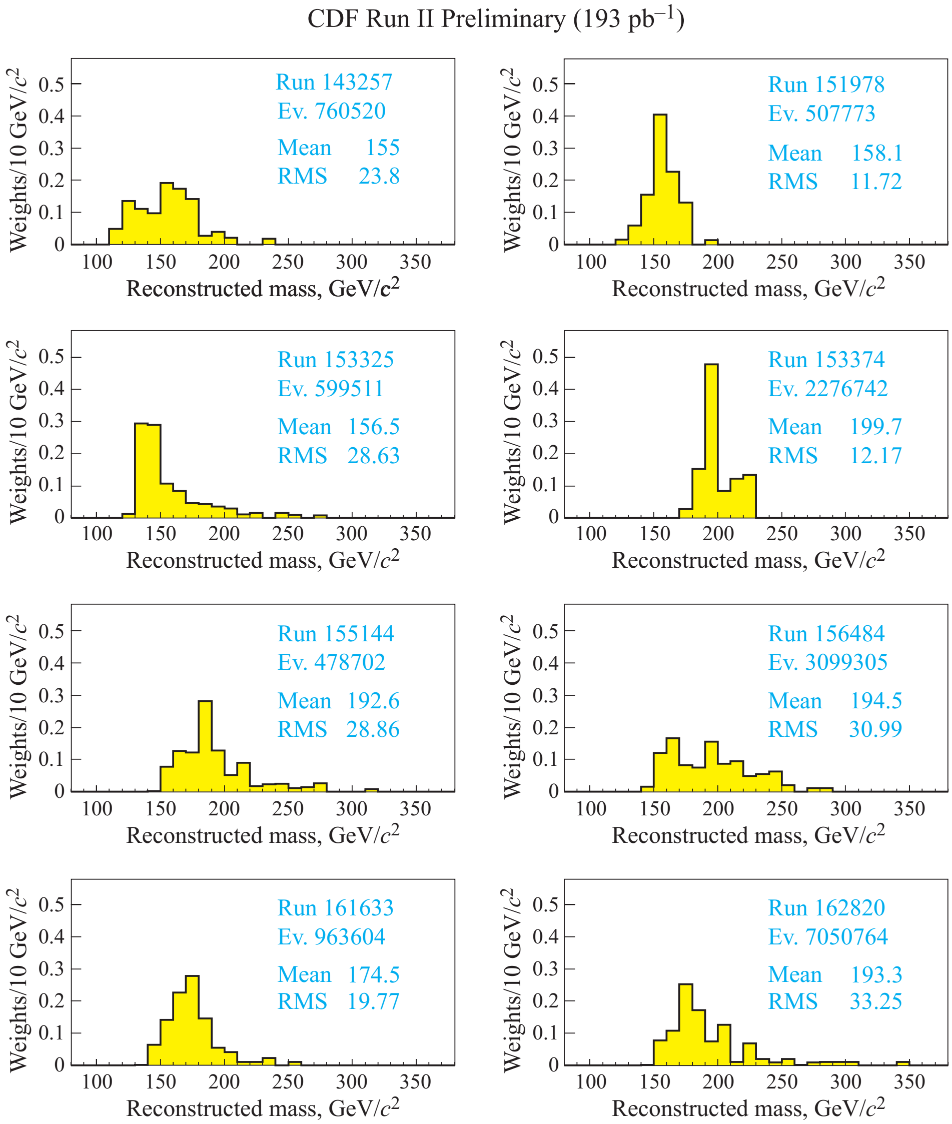

Fig. 1. Binned weight (probability) distribution for first 8 data events

2.2. Monte-Carlo Signal Templates. We created signal templates for input top masses in the $130 \div 230$ GeV range using Herwig–Monte-Carlo samples. The templates were parametrized as a sum of a gamma function and of a Gaussian comprising 6 parameters that depend linearly on the top mass.

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

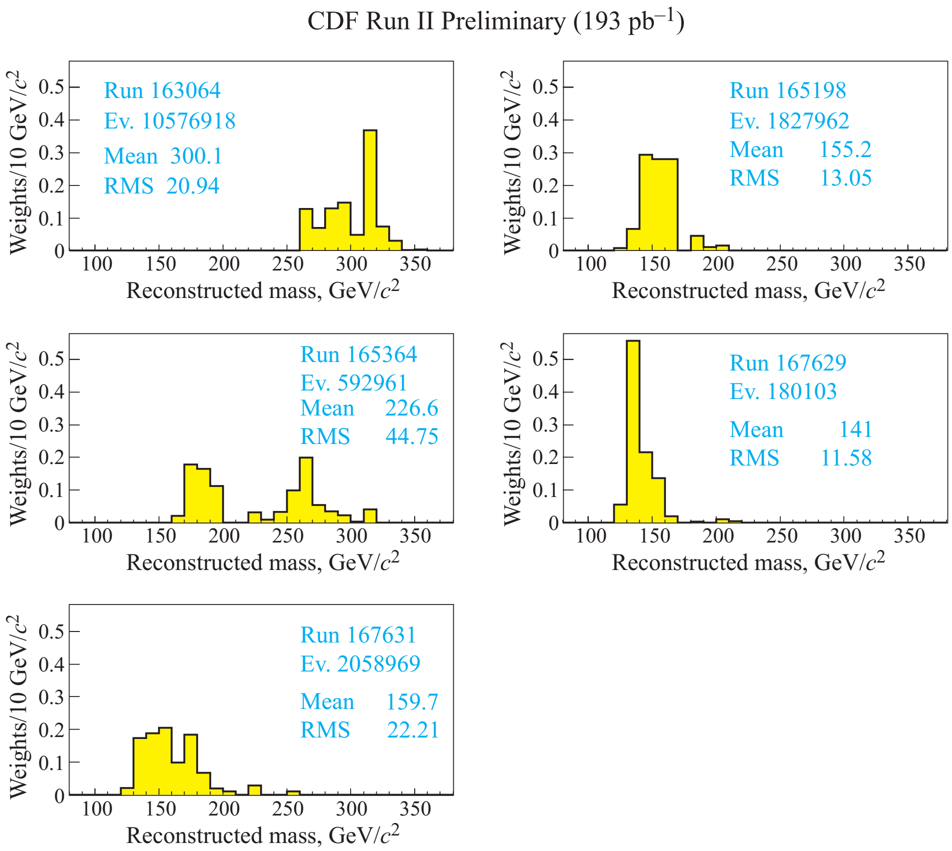

Fig. 2. Binned weight (probability) distribution for the additional 5 data events

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. These templates are presented in Figs. 3 and 4.

2.3. Background Templates. Templates for the 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 were combined together according to the expected number of events as derived by the $t\bar{t}$ cross-section group. We obtained the «fake» lepton sample from the Monte-Carlo generated $W+3$ or 4-parton events which passed all the selection cuts. The background templates are parametrized with the gamma function (the second term in 2), but with $M_{\rm top}$-independent parameters. The result for the combined background template is shown in Fig. 6.

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

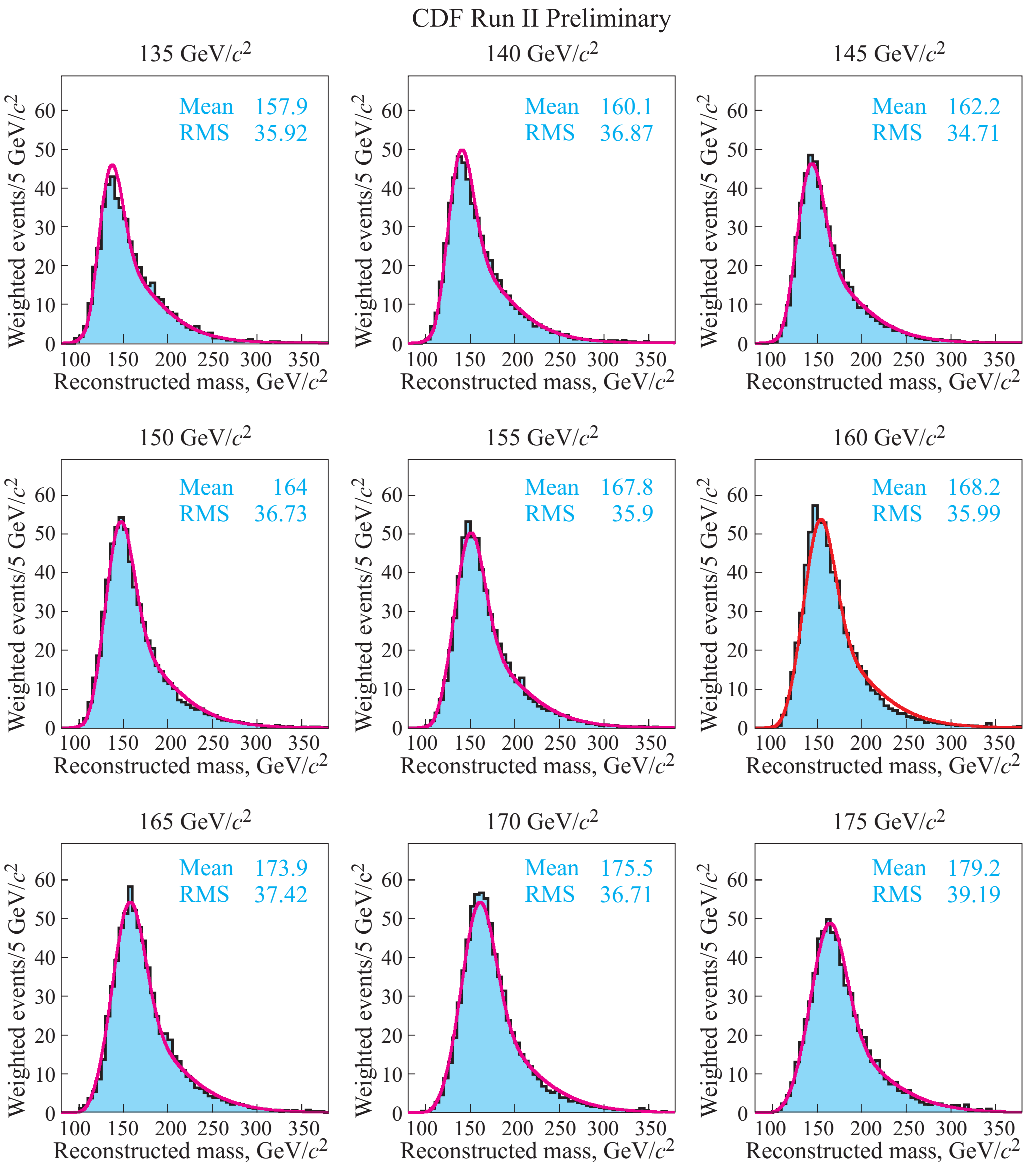

Fig. 3. Signal templates for top masses in the $135 \div 175$ GeV$/c^2$ range. The curves from the global fit (2) are also shown

with the superposition of signal and background. The used likelihood form is as follows:

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

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

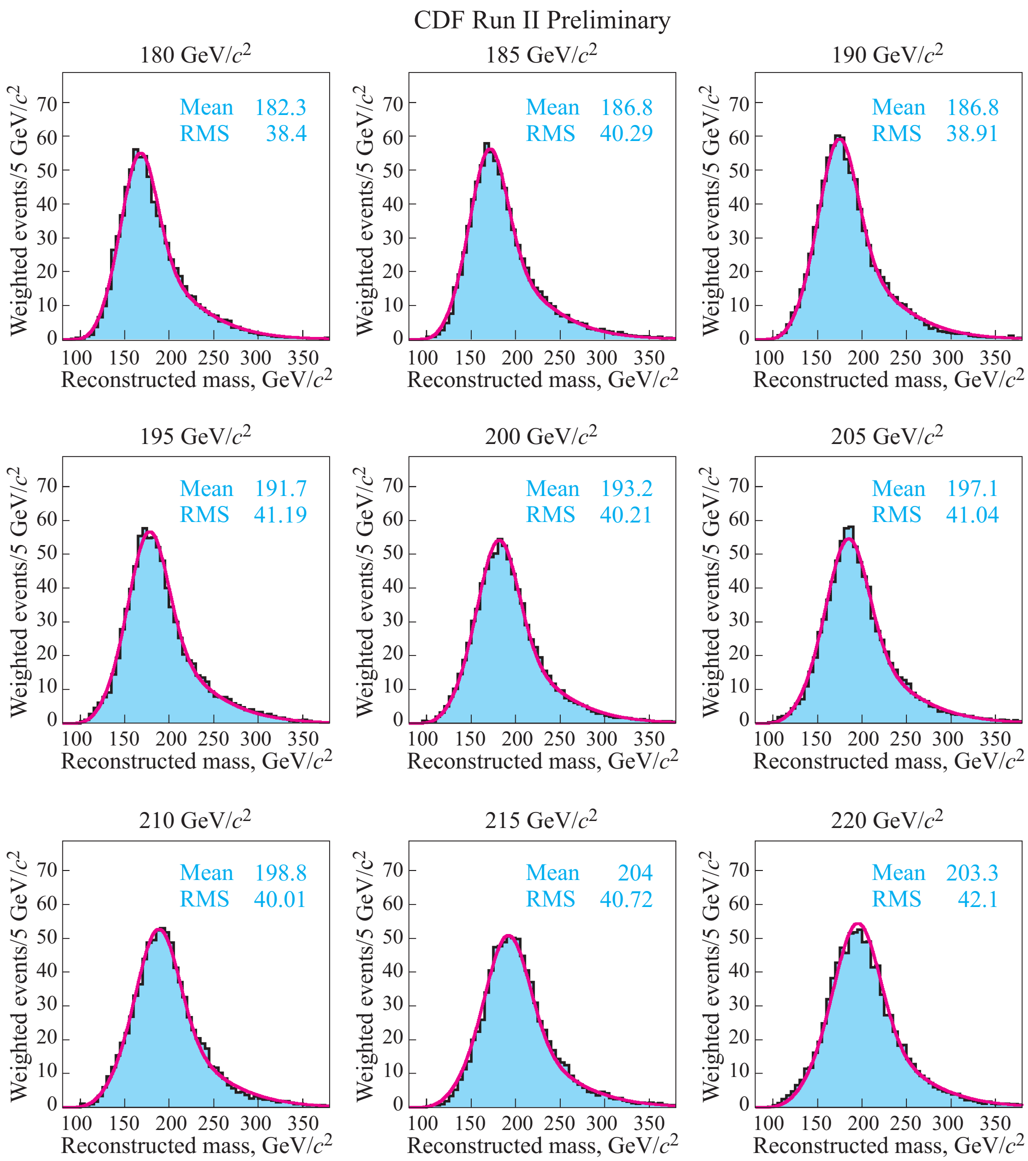

Fig. 4. Signal templates for top masses in the $180 \div 220$ GeV/c^2 range. The curves from the global fit (2) are also shown

where β_s is the expected signal fraction in the dilepton data sample. The additional terms L_{backgr} and L_{param} were added to constrain the number of background events and the value of the $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$ parameters obtained from the signal and background template parametrization.

$$L_{\text{backgr}} = \exp\left(\frac{-(N_b - (1-\beta_s)\cdot N_{\text{ev}})^2}{2\sigma_{N_b}^2}\right), \qquad (6)$$

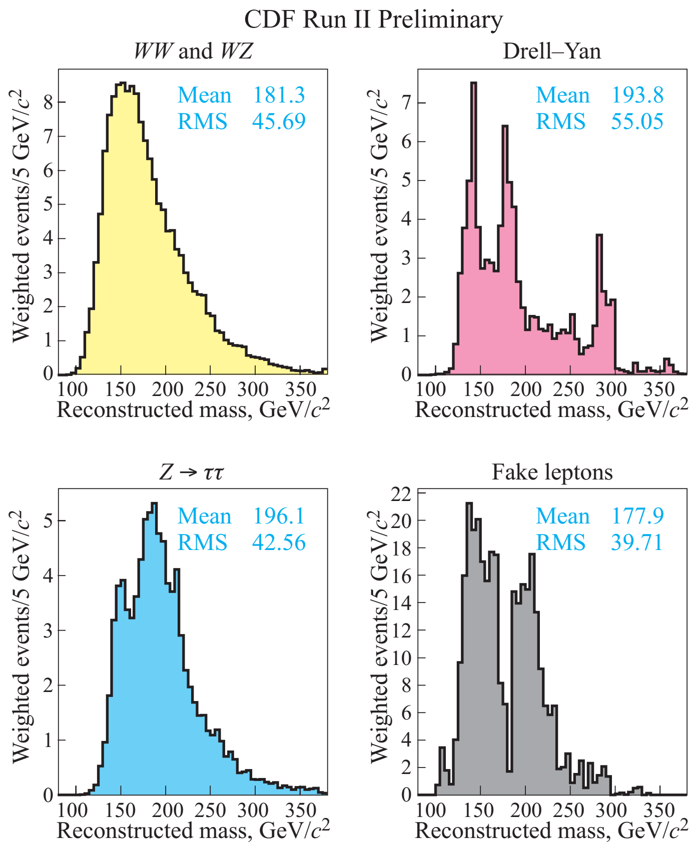

Fig. 5. Templates of background processes $WW + WZ$, Drell–Yan, $Z \to \tau\tau$ and «fake» lepton

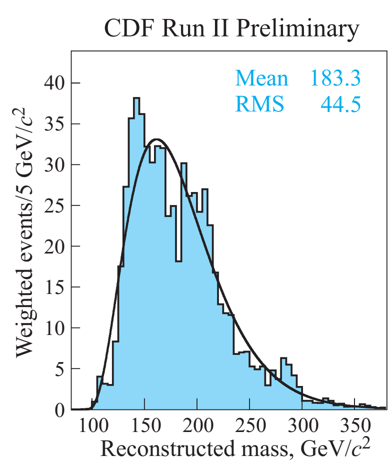

Fig. 6. Combined background template. The curve shows the fit result

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

Here U and V are the covariance matrices for $\boldsymbol{\alpha}_0$ and $\boldsymbol{\beta}_0$, respectively.

3. RESULTS FROM PSEUDO-EXPERIMENTS

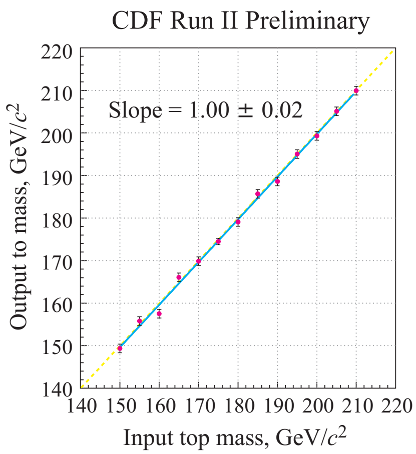

Fig. 7. Median top mass returned by pseudo-experiments with 13 events each as a function of input mass. The result of a linear fit is also shown. The green dashed line is drawn with a slope of 1.0

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 pull width distribution we understand that we are underestimating our statistical errors by about 5.8%. We take into account this effect by scaling the returned 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 the $W+$jet invariant mass, is very strong in the low-mass region.

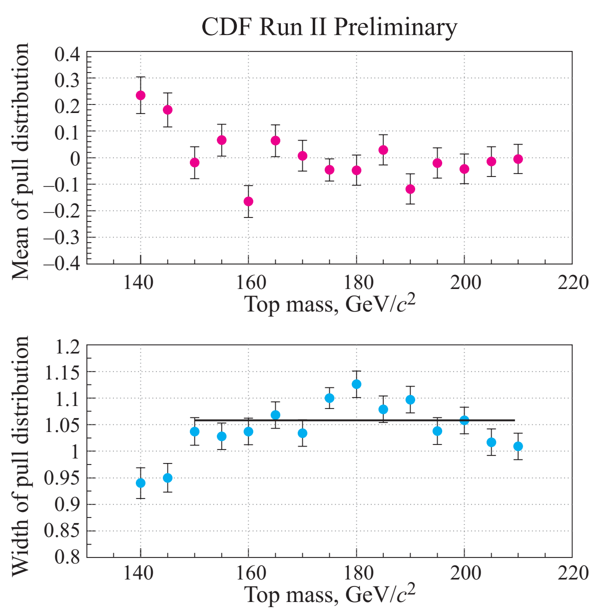

Fig. 8. Mean (top) and width (bottom) of pull distributions determined from the pseudo-experiments as a function of input top mass

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 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 jet 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 CDF studies of 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 $\Lambda_{\rm QCD}$ values, and 20 pairs of CTEQ6M uncertainty sets. In addition, we have estimated the systematic uncertainty due to the background shape (by comparing combined background and WW only background), different Monte-Carlo generators (Pythia and Herwig [5]).

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

Table. **Systematic uncertainties as determined with the pseudo-experiments**

CDF Run II Preliminary

Source of systematics	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**

RESULTS

The two-component background-constrained fit (with 2.7 ± 0.7 expected background events) for the obtained 13 dilepton candidates returns $M_{\rm top} =$ $= 170.0 \pm ^{15.9}_{15.5}$ (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.

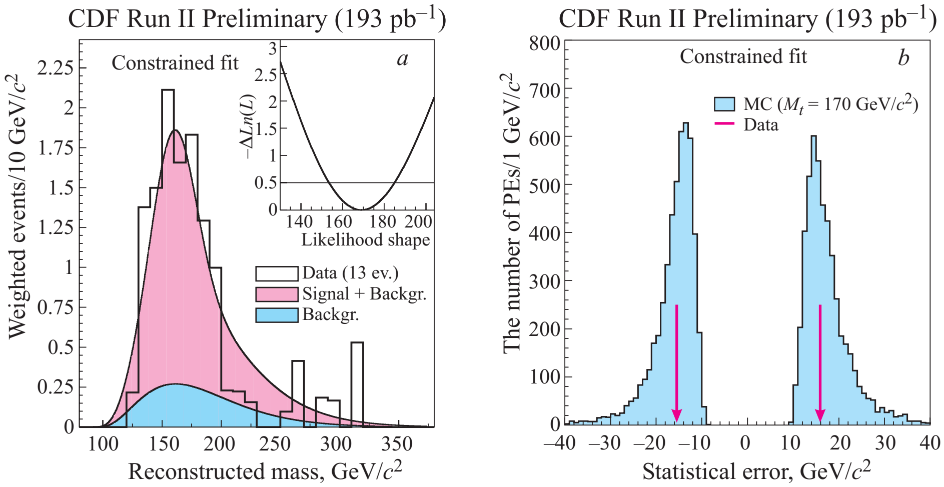

Fig. 9. *a*) Two-component background-constrained fit to the dilepton sample. The blue shaded area corresponds to the background returned by the fit and the red line-shaded area is the sum of background and signal events. The insert shows the mass-dependent negative log-likelihood used in the fit. *b*) Left/right error distributions returned by the PEs. The arrows indicate the errors returned by the fit to the data

After symmetrization of statistical errors and correction by factor of 1.058 (see Sec. 3), our preliminary result on the data sample with the integrated luminosity of 193 pb^{-1} is:

$$M_{\text{top}} = 170.0 \pm 16.6 \text{ (stat.) } \pm 7.4 \text{ (syst.) GeV}/c^2. \qquad (8)$$

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Измерение массы топ-кварка в дилептонных событиях на CDF с помощью программы MINUIT

Измерена масса топ-кварка в дилептонном канале $t\bar{t}$ в протон-антипротонных взаимодействиях при $\sqrt{s} = 1{,}96$ ТэВ. Интегральная светимость данных составила 193 пб$^{-1}$. В рамках гипотезы $t\bar{t}$-событий было отобрано и восстановлено 13 событий. При фитировании массы топ-кварка (в предположении, что число фоновых событий составляет $2{,}7 \pm 0{,}7$) было получено значение $M_{\mathrm{top}} = 170{,}0 \pm 16{,}6$ (стат.) ГэВ/c^2. Систематическая погрешность оценена нами в $\pm 7{,}4$ ГэВ/c^2.

Сообщение Объединенного института ядерных исследований. Дубна, 2005

Bellettini G. et al. (On behalf of the CDF Collaboration) E1-2005-18

Measurement of the Top Quark Mass Using the MINUIT Fitter 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 $p\bar{p}$ 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 $M_{\mathrm{top}} = 170.0 \pm 16.6$ (stat.) GeV/c^2. The estimate of systematic error is ± 7.4 GeV/c^2.

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