Fermi National Accelerator Laboratory

FERMILAB-Conf-99/260

Top Quark Mass Measurement from $t\bar{t}$ DiLepton Events at Linear Collider

J. Antos

IEP Slovak Academy of Sciences
Slovakia and Academia Sinica, Taiwan

G.P. Yeh

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

October 1999

Published Proceedings of the *International Workshop on Linear Colliders, LCWS99*, Sitges, Barcelona, Spain, April 28-May 5, 1999

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy

FERMILAB-Conf-99/260
April, 1999

Top Quark Mass Measurement from $t\bar{t}$ DiLepton events at Linear Collider

J. Antoš

IEP, Slovak Academy of Sciences, Slovakia
and Academia Sinica, Taiwan

G. P. Yeh

Fermi National Accelerator Laboratory, USA
and Academia Sinica, Taiwan

The determination of the top quark mass can be achieved at the Linear Collider to the precision of 200 MeV/c^2 , which is an order of magnitude better than the expected precision at the hadron colliders. The top quark mass determination can be obtained from direct reconstruction of $t\bar{t}$ DiLepton events, with the center-of-mass energy at or above the $t\bar{t}$ production threshold.

1 Introduction

With the discovery of the top quark [1], many studies [2,3,4], have focused on the precise measurement of its mass and other properties. The top quark mass is an important parameter in the Standard Model. The large mass of about 175 GeV/c^2 may indicate that the top quark has a special role in electroweak symmetry breaking. Precision measurement of the top quark mass, together with the mass of the W boson, provide a constraint on the mass of the Higgs particle.

The top quark mass will be measured in the next 10 years at the Tevatron and at the Large Hadron Collider (LHC) to a precision of 1%. Studies [4] have shown that a precision of 200 MeV/c^2 of top quark mass may be achieved at the Linear Collider, from an energy scan near the $t\bar{t}$ production threshold.

We present the results of a study on the the determination of top mass from direct reconstruction of $t\bar{t} \to \ell^+\nu b\ell^-\bar{\nu}\bar{b}$ events. The production of $t\bar{t}$ pair and its subsequent decay into the final state with two leptons, ℓ^+ and ℓ^-, have been studied since the first CDF results [5] on the top quark, because the DiLepton events have small background and are simple to identify. The top mass measurement from the DiLepton channel already provides the smallest systematic uncertainty.

2 Method

For the top quark mass determination by direct reconstruction, the Linear Collider has an advantage over hadron colliders. While the momenta of incoming partons are unknown in hadronic collisions, the energy-momentum of the colliding e^+ and e^- particles are known to high precision. This provides additional kinematic constraints, and even the DiLepton channel of $t\bar{t}$ production with two neutrinos in the final state represents an over-constrained system.

At Linear Collider, the $t\bar{t}$ production cross-section is 0.7 pb at $\sqrt{s} = 500$ GeV and 0.2 pb at 1000 GeV. For the design luminosity of 5×10^{33} cm^{-2} s^{-1} and 10^{34} cm^{-2} s^{-1} at $\sqrt{s} = 500$ and 1000 GeV, respectively, on the order of 1000 $t\bar{t}$ DiLepton events are expected in one year of running with 50–100 fb^{-1}.

For the simulation of $e^+e^- \to t\bar{t} \to W^+bW^-\bar{b} \to \ell^+\nu b\ell^-\bar{\nu}\bar{b}$ events at center-of-mass energies of 355, 500, 1000 GeV, we use PYTHIA[6] version 5.7, and we simulate 1000 events for each energy. The beamsthralung is taken into account in leading log approximation. In this study, we assume that the b-jet resolution $\sigma(E_T) = 1.+0.045\times E_T$ can be achieved.

We neglect errors in the determination of kinematical characteristics of leptons, and we also assume that the top quark mass will have been determined [2] to 2-3 GeV/c^2 precision by the time the Linear Collider is operational. Therefore, the mass window (160,190) in which we will reconstruct top mass is sufficient.

The reconstruction of top mass is obtained from the full kinematical reconstruction of $t\bar{t} \to W^+bW^-\bar{b} \to \ell^+\nu b\ell^-\bar{\nu}\bar{b}$ events. We define a χ^2 functional:

$$\begin{aligned}\chi^2 \quad = \quad & \frac{((P_{\ell_1}+P_{\nu_1})^2 - M_w^2)^2}{\sigma_1^2} + \\ & + \frac{((P_{\ell_2}+P_{\nu_2})^2 - M_w^2)^2}{\sigma_2^2} + \\ & + \frac{((P_{\ell_1}+P_{\nu_1}+P_{b_1})^2 - (P_{\ell_2}+P_{\nu_2}+P_{b_2})^2)^2}{\sigma_3^2} + \\ & + \frac{(E_{cms} - (E_{\ell_1}+E_{\nu_1}+E_{b_1}+E_{\ell_2}+E_{\nu_2}+E_{b_2}))^2}{\sigma_4^2}\end{aligned}$$

where P_{ℓ_i}, P_{b_i} are the measured four momenta of the charged leptons and b-jets, respectively, and E_{cms} is total energy of colliding beams. E_{ℓ_i}, E_{b_i}, E_{ν_i} are energies of leptons, b-jets and neutrinos in the $t\bar{t}$ event, and σ_i are parameters set to take into account resolution and Breit-Wigner nature of top and W boson masses.

The kinematical characteristics of neutrinos are not measured, but the following kinematical constraints apply: $E_{\nu_i} = \sqrt{P_{\nu_{i1}}^2 + P_{\nu_{i2}}^2 + P_{\nu_{i3}}^2}$ and $P_{\nu_{1j}} = -(P_{\ell_{1j}} + P_{b_{1j}} + P_{\ell_{2j}} + P_{b_{2j}} + P_{\nu_{2j}})$. The χ^2 is dependent on three components of momentum of neutrino $\vec{P_{\nu_2}}$, which can be determined by finding a minimum of χ^2. To find a minimum, either the standard general minimization packages e.g. MINUIT can be employed, or the solution can be obtained from a set of three nonlinear equations: $\frac{\delta\chi^2}{\delta P_{\nu_{21}}} = 0$; $\frac{\delta\chi^2}{\delta P_{\nu_{22}}} = 0$; $\frac{\delta\chi^2}{\delta P_{\nu_{23}}} = 0$. We employed this last method, because it proved to work much faster. For a solution to be accepted, it should pass a minimum χ^2 cut. There is a two-fold ambiguity in association of the lepton and b-jet from the same top decay. A decision based on smaller χ^2 provides 70%, 93%, 97% probability to find the correct choice for E_{cms}= 355, 500, 1000 GeV, respectively. The treatment of resolution is similar to a previous study [7] for CDF. As a top mass measurement for a given event, we take the most probable value of the convolution of reconstructed top masses over the resolution function.

3 Results

The reconstructed top mass distribution for E_{cms} = 355, 500, 1000 GeV is presented in Fig. 1. The uncertainty on the mean top mass, $\sigma/\sqrt{N}$, is less than 200 MeV/c^2 for each E_{cms}. The top mass was initially set to 175 GeV/c^2. For the lowest energy, the threshold behavior results in asymmetric distribution of reconstructed top mass.

In the region close to $t\bar{t}$ threshold, we expect some sensitivity of the distribution of reconstructed top mass due to the top width. Widths 0.5, 0.8, 1.2 and 1.5 times the nominal top width at the given top mass were considered. The sensitivity to the top width is at a level of 20 – 25%.

To see the effect of jet energy resolution, we degrade the jet energy resolution by a factor of 2. We also studied the resolution on the top quark mass when true (unsmeared) variables are used for reconstruction (no convolution). To see the effect of initial, final state radiation and beamstrahlung, we applied the same reconstruction on another sample with initial, final state radiation and beamstrahlung switched OFF. For most of this study, the top mass in PYTHIA was set to 175 GeV/c^2. We also studied the effects when the top mass was set to 170 GeV/c^2 or 180 GeV/c^2. From these studies [8], it can be summarized that a precision of about 200 MeV/c^2 on top mass determination can be achieved. Comparing this resolution with the result of an analysis [7] for CDF DiLepton top mass reconstruction (also for about 1000 $t\bar{t}$ DiLepton events), a factor of $\approx$ 6 improvement is achieved at the Linear Collider.

In Fig. 1, there is an $\approx$ 2 GeV mass shift from the top mass set at 175 GeV. There is no shift when unsmeared variables are used. The shift comes from the convolution over jet energy resolution. This mass shift is naturally eliminated when we calibrate the results obtained as a function of top mass.

Although physics at the Linear Collider has been explored[4] for about 10 years, studies of top quarks physics at the Linear Collider have concentrated on the $t\bar{t}$ threshold, and dependent on a threshold scan. In contrast, the top quark mass determination from direct reconstruction of $t\bar{t}$ events, is insensitive to uncertainties of luminosity measurement. The precision of the top mass determination from a threshold scan is also expected to be about 200 MeV/c^2. There has been active discussion and work on the theoretical uncertainties in the $t\bar{t}$ threshold studies.[9] The direct determination can be accomplished at any energy at or above the $t\bar{t}$ threshold, while other new physics are also being studied. In the course of this analysis, we noticed that the recent precision measurement of the mass M_w of the W boson by the four LEP experiments Aleph, Delphi, L3, Opal, have all been based on direct reconstruction of W^+W^- events, rather than by threshold scan.

4 Conclusion

At the Linear Collider, the top quark mass can be determined from direct reconstruction of $t\bar{t}$ DiLepton events, to a precision of 200 MeV/c^2, which is an order of magnitude better than what is expected to be achieved by hadron colliders. This method of top mass determination has not been fine tuned for the Linear Collider. Further improvement to this method can be made. The limitations will come from systematic uncertainties due to jet energy scale and gluon radiation.

References

1. CDF Collaboration, F. Abe, *et al.*, Phy. Rev. Lett. **74**, 2626 (1995);
   D0 Collaboration, S. Abachi, *et al.*, Phy. Rev. Lett. **74**, 2632 (1995).
2. CDF Collaboration, CDF II Technical Design Report, Nov. 1996.
3. J. Parsons, "Top Studies for the LHC", http://lutece.fnal.gov/thinkshop/
4. Sumino, et. al., JLC Workshop 173 (1992); Phys. Rev. **D47**, 56 (1993);
   K. Fujii, T. Matsui, Y. Sumino, Phys. Rev. **D50**, 4341 (1994).
   Keystone Workshop: http://hep-www.colorado.edu/LC/workshop.html
   ECFA Workshop: http://www.desy.de/conferences/ecfa-desy-lc98.html
   ACFA Workshop: http://acfahep.kek.jp/china_workshop/index.html
5. G.P. Yeh, "Top Search Progress in CDF", Santa Monica, CA Feb. 23, 1989.
6. T. Sjostrand, Comp. Phys. Comm. **82**, 74 (1994).
7. J. Antos, Acta Phys. Slov. **49**, 127 (1999).
8. J. Antoš, G.P. Yeh, cdfnote 4912, http://www.cern.ch/Physics/LCWS99/
9. A. Hoang, J. Kuhn, Y. Sumino, T. Teubner, ... recent studies.

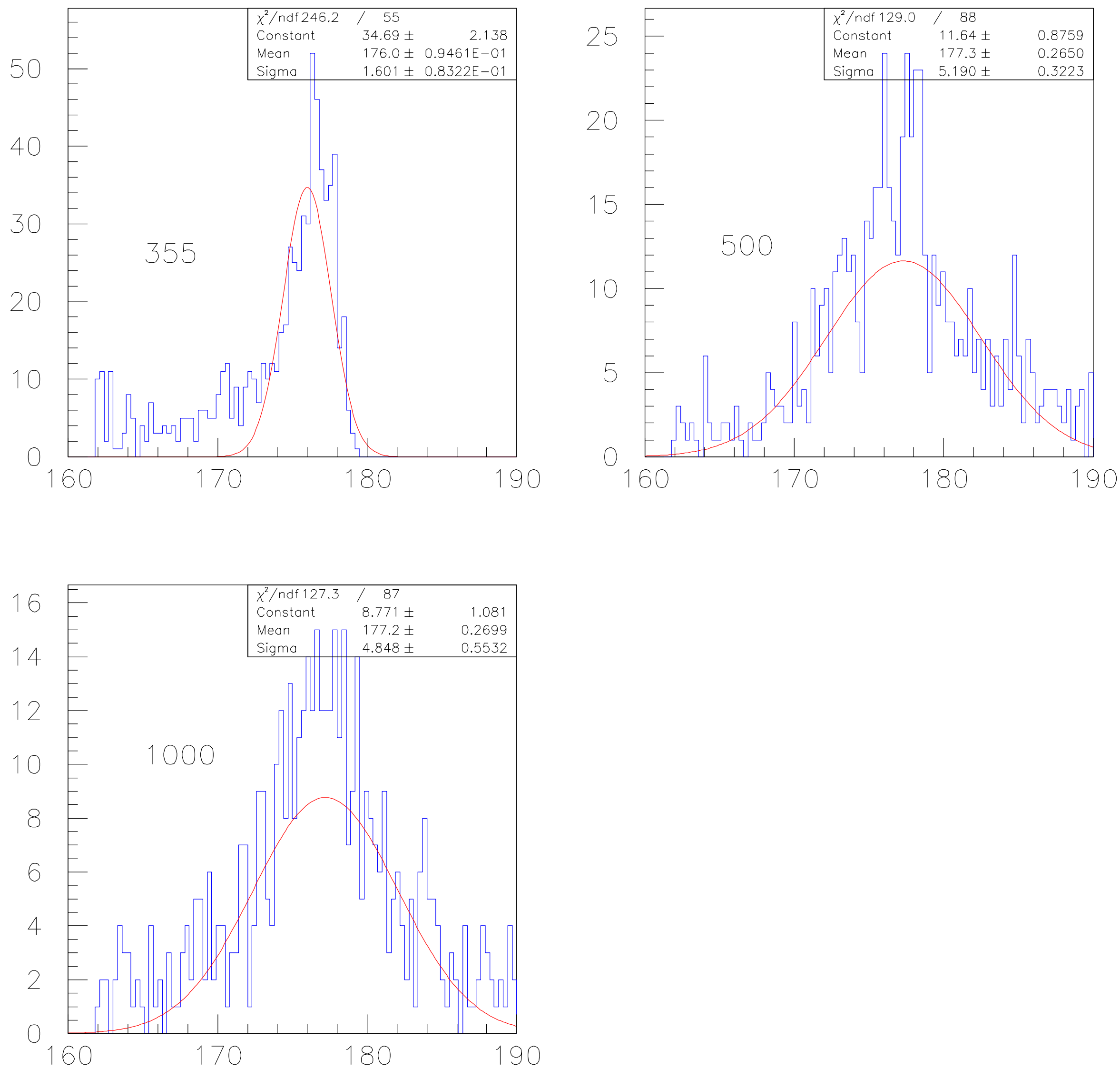

Figure 1: Reconstructed (raw) top mass distribution and Gaussian fit.