Simulation Study of Top Quark Reconstruction Near the $t\bar{t}$ Threshold

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Abstract. We present a result of a simulation study of top quark reconstruction in e^+e^- annihilation near the $t\bar{t}$ threshold. To probe new physics via precise measurement of the top quark property such as CP violation, precise measurement of the top quark momentum is required. In this report, a method to improve the precision by the kinematical fit is discussed.

INTRODUCTION

The discovery of the top quark at Tevatron has set the target energy of next experiments more clearly and enhanced the importance of the e^+e^- linear collider (LC) for precision measurements of the top quark properties. In fact rich physics with top quarks in LC has been studied and possible experimental strategies have been demonstrated [1,2].

As further studies, we focus on the study of top couplings, or the interaction form factors to see signs of new physics. Especially we consider tests of CP violation in top quark interactions.

In this study, we discuss that how precise we can reconstruct the momentum vector of top quark using kinematical fit which is key-measurement in some of CP-odd observables.

CP VIOLATION IN TOP QUARK

The CP violation in the top quark sector is extremely small within the Standard Model (SM). Therefore any CP violating effect observed in $e^+e^- \to t\bar{t}$ process means physics beyond the SM.

In this study, we focus on $t\bar{t}$ threshold region. In the threshold region, there are many theoretical advantages if the origin of the CP violation is chromo and weak electric dipole moment (EDM) [3,4]. There are also some experimental advantages: (1) Well-known kinematics, because effect of initial state radiation (ISR) and beamstrahlung is small. (2) Well-defined top rest frame, because top decays at rest. (3) Smaller background processes from multiple gauge boson processes such as $e^+e^- \to WWZ$.

For the observation of CP violation, a lot of CP-odd observable are proposed. In this study, we choosed an observable taking advantage of LC experiment as [3,4]:

$$< \vec{n} \cdot (\vec{n}_{\ell^+} + \vec{n}_{\ell^-}) >, \tag{1}$$

where $\vec{n}_{\ell^+}$ and $\vec{n}_{\ell^-}$ denote the directions of charged lepton ℓ^+ and ℓ^-, respectively and the basis $\vec{n}$ is defined from the e^- beam direction and the top momentum:

$$\vec{n}_{||} = \frac{\vec{p}_e}{|\vec{p}_e|}, \quad \vec{n}_N = \frac{\vec{p}_e \times \vec{p}_t}{|\vec{p}_e \times \vec{p}_t|}, \quad \vec{n}_\perp = \vec{n}_{||} \times \vec{n}_N. \tag{2}$$

In experiments the lepton-plus-4-jet mode of $t\bar{t}$ decay can be used to reconstruct the lepton momentum and the top quark three-momentum simultaneously. Here the electron beam direction and the lepton direction are generally well measured. Therefore good reconstruction of top quark momentum is very important. Thus we need to investigate how precise we can measure top quark momentum vector under realistic experimental conditions.

MONTE CARLO SIMULATION

Event Generation

We developed the event generator `physsim-2000a` [5] in which parton 4-momentum generation was carried out using `BASES/SPRING` [6] and `HELAS` [7]. This generator includes ISR and beamstrahlung and also includes S- and P-wave QCD $t\bar{t}$ threshold corrections.

For event generation, we set the center of mass energy 2GeV above $1s$ resonance of $t\bar{t}$ bound state and the polarization of electron beam assumed to be 80%. In this condition we expect 40k events with $100fb^{-1}$. The JLC detector with ACFA study parameters [8] was used in detector simulation.

Event Selection

In order to reconstruct the momentum vector of the top quark, we have to select event with a top quarks decays into 3jets while the other to a lepton, a neutrino and a bottom quark jet. The lepton-plus-4-jet mode selection first required the events with an isolated lepton. For remaining events, force four jets clustering was applied according to the Durham clustering algorithm. To reduce combinatorial background, double b-tagging based on the impact parameter method was applied. Then the remaining two jets are regarded as W boson candidate if the invariant mass of these is consistent with the W mass.

The remaining task is to choose the right combination of W boson and bottom quark jets comes from single top quark decays. In the $t\bar{t}$ threshold region, top quark pairs decay at very low velocity. In this configuration, the bottom quark and the W boson is expected to be back-to-back. Hence a cut on the acoplanarity of b-W system enhanced the correct assignment of W boson and bottom quark jet.

These selection criteria provide clean sample of top quarks. However it is not enough to reconstruct the momentum vector of top quark. The rejection of events with energetic missing neutrinos is necessary. A cut on the 3-jet invariant mass of the reconstructed top quark was applied. This cut has applied with care because the invariant mass cut biases the momentum measurement. The detection efficiency was 8% including the branching fraction to the lepton-plus-4-jet mode.

Kinematical Fitting

To improve the angular resolution of top quark and the selection efficiency, a kinematical fitting was applied. For lepton-plus-4-jet events, there are 8 unknown parameters; energy of four jets and 4-momentum of the neutrino. The direction of each jet is fixed to jet-finder output. If we apply constraint of three-momentum conservation and the neutrino mass, number of free parameters are reduced to 4 which are energy of each jet. Then we define the likelihood function as follows;

$$L = (\prod_{f=jet1}^{jet4} P_{E_f}(E_f^{meas.}, E_f)) \cdot P_{\Gamma_{W+}} \cdot P_{\Gamma_t} \cdot P_{\Gamma_{W-}} \cdot P_{\Gamma_{\bar{t}}} \cdot P_{\sqrt{s}} \quad , \tag{3}$$

where P_{E_f} is Gaussian distribution of the detector energy resolution. P_{Γ_W} and P_{Γ_t} are Breite-Wigner function of the W boson and the top quark, respectively. $P_{\sqrt{s}}$ is a weight function coming from ISR and beamstrahlung effect.

To make sure the algorithm works, we turned off ISR and beamstrahlung and also went slightly above $t\bar{t}$ threshold ($2m_t$+2GeV) to avoid complication due to off-shell top quarks. Fig. 1 shows energy resolutions of leptonic decayed W bosons, hadronic decayed W bosons and bottom quark jets, respectively. We see good improvement for these observables. Because the reconstruction of top quark direction is affected these observables, the fitting results in appreciable improvement

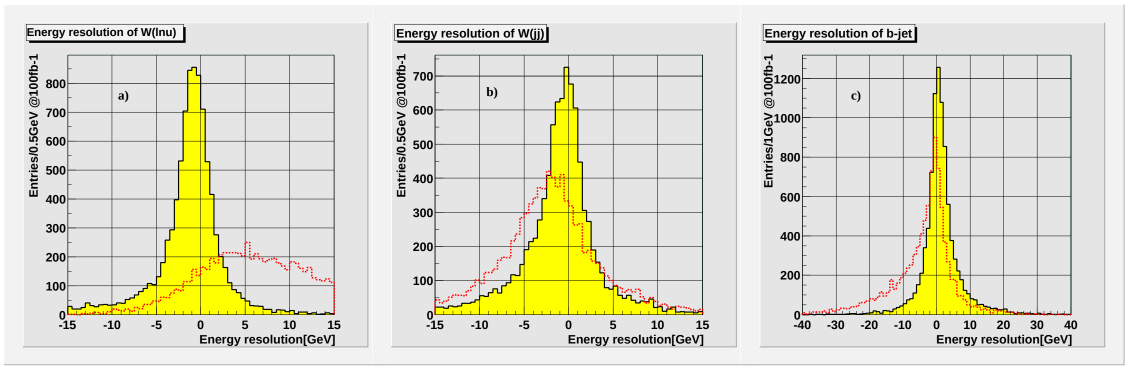

FIGURE 1. Energy resolution of a) leptonic decayed W boson, b) hadronic decayed W boson and c) bottom quark jet. Dashed and solid line show before and after kinematical fitting, respectively.

of top quark direction. If we are to achieve the same angular resolution for top quark momenta by tight top mass cuts, 35 % gain in the selection efficiency by this kinematical fitting.

SUMMARY

The top quark reconstruction in the lepton-plus-4-jet mode has been studied under realistic experimental condition of $e^+e^- \to t\bar{t}$ process near the $t\bar{t}$ threshold. In order to reconstruct the momentum vector of top quark efficiently, a kinematical fitting algorithm has been developed. The missing energy carried away by neutrinos from hadron decays in jets has been recovered by the kinematical fitting. The appreciable improvement of top quark direction has been also seen.

However more simulation study is necessary to extend the algorithm to below $t\bar{t}$ threshold region where top and anti-top quarks cannot be simultaneously on-shell.

It is also realized we need better jet clustering strategy instead of force 4-jet clustering for drastic improvements of kinematical fit performance.

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