Event generation and reconstruction of cross sections and asymmetries for $t\bar{t}$ semi-leptonic decay.

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1 Introduction

International Linear Collider (ILC) and Compact Linear Collider (CLIC) are two of the possible future projects for building a new e^+e^- collider. At the lowest energy stage the CLIC would be able to produce 380 GeV center-of-mass energy collisions and the ILC would be able to collide e^+e^- with 500 GeV center-of-mass energy. For the ILC and CLIC the electron polarization is expected to be around 80%, and for the ILC, also the positrons are to be polarized to around 30%. For both of the colliders, the integrated luminosity is expected to reach 500 fb^{-1}.

The detector of these colliders would be cylindrical in shape. To describe events in the detector, a spherical coordinate system is used with the origin in the center of the detector, z axis along the beam direction and two angles describing direction: polar angle θ and azimuthal angle ϕ.

Among other things, these Future Linear Colliders would allow before unprecedented precision measurements of t quark properties. In my work, I am interested in $t\bar{t}$ production in the e^+e^- collision. Furthermore, I am observing only the semi-leptonic decay, characterized by a branching ratio of $BR_{sl} = 43.4\%$ (Figure 1).

In the production of $t\bar{t}$ events, there is a forward-backward asymmetry A_{FB} for the t quark. That is, the produced t quark has a tendency to be moving more towards one side of the detector rather than other. A_{FB} can be defined as

$$A_{FB} = \frac{N(cos\theta_{top} > 0) - N(cos\theta_{top} < 0)}{N(cos\theta_{top} > 0) + N(cos\theta_{top} < 0)} \tag{1}$$

For the Monte Carlo simulations of the events MadGraph5_aMC@NLO was used, along with PYTHIA 6.428 for parton hadronization and showering, and Delphes 3.4.1 for fast detector simulation.

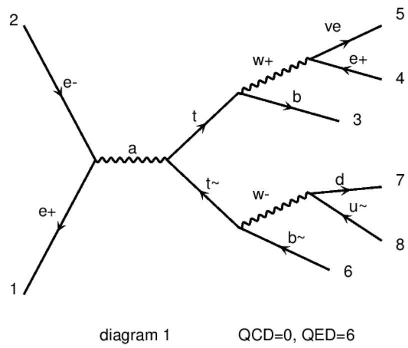

Figure 1: Feynman diagrams generated by MadGraph of the production and semi-leptonic decay of $t\bar{t}$ in an e^+e^- collision.

2 Event reconstruction

In the semi-leptonic decay four jets from the four decay quarks of the $t\bar{t}$ would be expected to be seen in the detector. Using b-tagging, it is possible to distinguish b and $\bar{b}$ jets from the others. This allows reconstruction of the hadronically decaying W boson. For the leptonically decaying W reconstruction, the detected lepton and missing transverse energy can be used. The lepton charge can also be used to determine which of the $t\bar{t}$ decayed hadronically and which leptonically. Since b-tagging does not distinguish between b and $\bar{b}$, all combinations of them and the reconstructed W bosons can be considered and the one that minimizes the following χ^2 chosen to be the right one:

$$\chi^2 = \left(\frac{m_{rec} - m_{top}}{\sigma_m}\right)^2 + \left(\frac{E_{rec} - E_{beam}}{\sigma_E}\right)^2 + \left(\frac{p^*_{b\ rec} - p^*_b}{\sigma_{p^*_b}}\right)^2 + \left(\frac{cos(Wb)_{rec} - cos(Wb)}{\sigma_{cos(Wb)}}\right)^2 \tag{2}$$

Here the rec subscript corresponds to the reconstructed values. $m_{top} = 273GeV$ is the t quark mass used in the simulation, E_{beam} is the energy of colliding electron (or positron), $p^*_b = 68GeV$ is the momentum of the b quark in the t quark rest frame and $cos(Wb)$ is the cosine of the angle between W boson and the b quark (at the detector rest frame).

In the χ^2 function, the variables need to be weighted by their dispersion. Because of this, they are iteratively fitted with a Gaussian and its standard deviation is used as the weight in the χ^2 for the next iteration (Figure 2). The leptonic branch of the $t\bar{t}$ decay gave reconstructed results that were closer to the generated ones. Thus, the fitting was done on the leptonic decay reconstruction. For the expected $cos(Wb)$ value, the same procedure is used.

In the simulation, the number of jets differed from 4 both on the generator level and on the detector level. As can be seen in Figure 3, the jets on the generator level tend to split up from the original four. However, on the detector level,

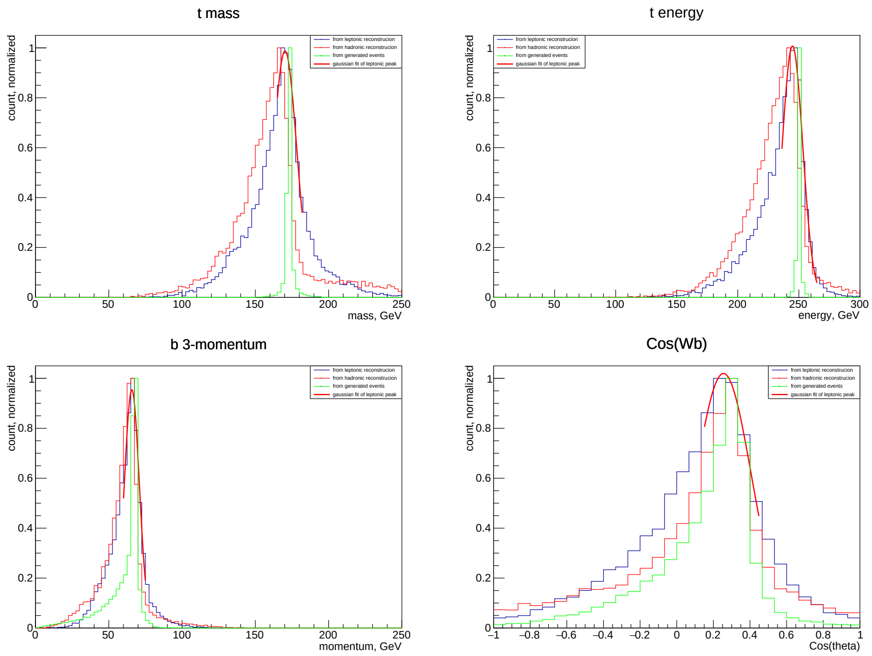

Figure 2: The parameters used in χ^2: the mass of the t quark; the energy of the t quark; the b quark momentum at t quark rest fram; the angle between W boson and b quark. Collider energy: 500 GeV. $e^+; e^-$ polarization: -0.3;0.8.

in most of the events, some jets are merged together. For the reconstruction two cuts were used:

1. The number of detected jets in the event has to be 4 or greater.

2. The number of b-tagged jets among the jets has to be exactly 2.

All the jets that were not b-tagged are used in the W reconstruction.

In Figure 3 it can be seen that a substantial number of jets that were 4 on the generator level got detected as 3. Because of this, an attempt was made to relax the first cut. By examining only those events that had exactly 3 jets on the detector level, it was seen that they produced a W with the mass many times too small, and correspondingly gave bad results in the t quark reconstruction (Figure 4 left side). To mitigate this, the mass of the reconstructed W was manually set to 80 GeV (the value used in the Monte Carlo simulation), while keeping the momentum unchanged. That way the t reconstruction results were improved (Figure 4 right side). In the end, however, the cut was not relaxed because the results attained this way still were noticeably worse than the ones where the cut was in place.

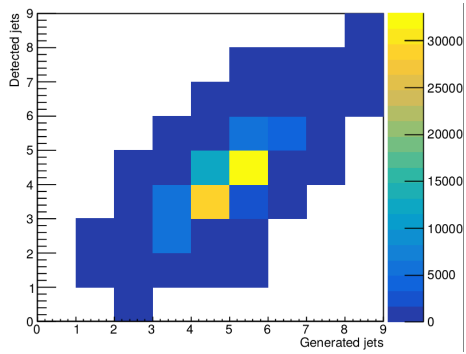

Figure 3: The number of generated and corresponding detected jets. Collider energy: 500 GeV. $e^+;e^-$ polarization: -0.3;0.8. Number of events: 100000.

3 Results

The reconstruction was done on four Monte Carlo samples - for both polarizations of e^+e^- and for the energies corresponding to CLIC and ILC. For each sample, the reconstruction efficiency was calculated, that is, the fraction of events, that "survived" the cuts. From the simulations, the e^+e^- to $t\bar{t}$ cross section σ was extracted. With that, the expected number of reconstructed events in the real detector could be estimated:

$$N = L \cdot \sigma \cdot BR_{sl} \cdot efficiency \tag{3}$$

where $L = 500fb^{-1}$ is the integrated luminosity of the detector. The forward-backward asymmetry of the t quark A_{FB} was calculated.

The reconstructed forward-backward asymmetry of t was compared to the generated one. And for the cross section and the forward-backward asymmetry, the statistical errors were determined $\delta_{stat} = RMS/\sqrt{N}$, which for the A_{FB} can be written as:

$$\delta A_{FB} = \sqrt{\frac{1 - A_{FB}^2}{N}} \tag{4}$$

and for the cross section:

$$\delta\sigma = \frac{\sigma}{\sqrt{N}} \tag{5}$$

The results are shown in Table 1.

The hadronic reconstruction showed worse results leading to think that the misdetection of the non-b-tagged jets are causing some problems in the reconstruction process. To test this, the 4-momenta of non-b-tagged jets were increased and decreased by 1% and 5%, and the reconstruction was repeated. The resulting A_{FB} changes can be seen in Table 2, and the relative A_{FB} changes can be seen in Table 3.

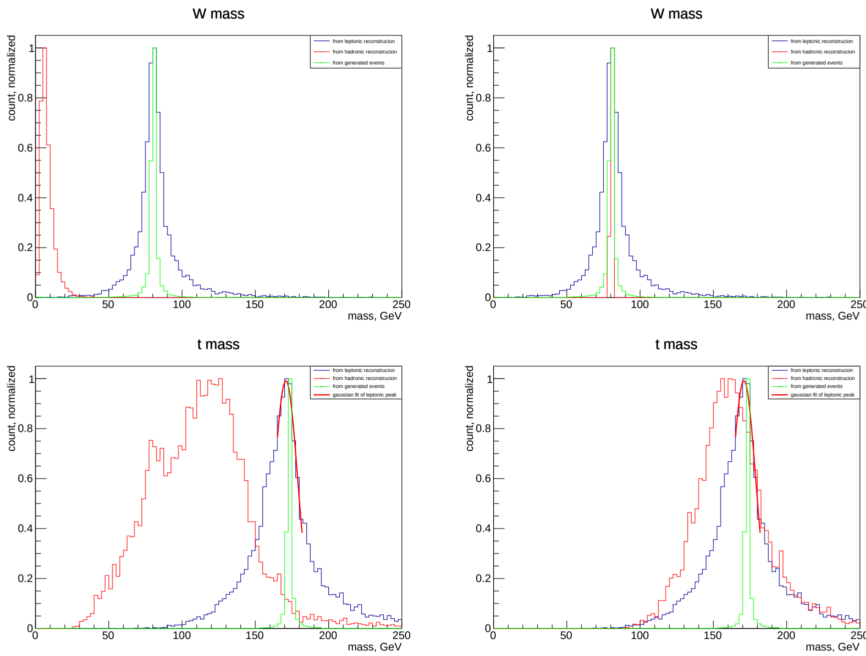

Figure 4: W and t mass in the case with exactly 3 jets on the detector level. Left side corresponds to unedited reconstructed data. Right side corresponds to reconstructed data with edited W mass. Collider energy: 500 GeV. $e^+; e^-$ polarization: -0.3;0.8.

4 Summary

- Using this reconstruction algorithm, only relatively small fraction of semi-leptonically decaying $t\bar{t}$ events (around 15%) pass the cuts.
- Despite it, the relative error of the cross section is quite small - below 2%.
- The cases with right-handed electrons produced a somewhat precise reconstructed A_{FB} as compared to the generated A_{FB} - around 5% deviation. This deviation, however, was in both cases towards the lower end.
- The cases with left-handed electrons produced noticeably worse reconstructed A_{FB} as compared to the generated A_{FB}. In the 0%;-80% e^+e^- polarization, the reconstructed A_{FB} is off by an astounding 68%. The cause of this failure in reconstruction could be investigated further.
- A small change in the non-b-tagged jet 4-momentum usually results in a several times smaller change in the reconstructed A_{FB}. This is not the case for the 0%;-80% e^+e^- polarization, where the reconstructed A_{FB} itself is quite small.

Table 1: Comparison of A_{FB} and σ for different beam polarizations and CLIC and ILC working energies. The collider energies are 500 GeV for the 30%;80% polarizations (ILC) and 380 GeV for the 0%;80% polarizations (CLIC).

$e^+;e^-$ pol., %	efficiency, %	N	σ, fb	$\frac{\delta\sigma}{\sigma}$, %
-30;80	16	4059	0.12	1.6
30;-80	15	8352	0.25	1.1
0;80	13	2779	0.10	1.9
0;-80	12	5378	0.21	1.4
$e^+;e^-$ pol., %	det. A_{FB}	gen. A_{FB}		$\frac{\delta A_{FB}}{A_{FB}}$, %
-30;80	0.45	0.47		3.1
30;-80	0.30	0.37		3.4
0;80	0.25	0.27		7.4
0;-80	0.07	0.20		18.5

Table 2: Comparison of A_{FB} for different beam polarizations and CLIC and ILC working energies and the change in non-b-tagged jet 4-momenta. The collider energies are 500 GeV for the 30%;80% polarizations (ILC) and 380 GeV for the 0%;80% polarizations (CLIC).

jet change / $e^+;e^-$ pol.		-5.00%	-1.00%	0.00%	1.00%	5.00%
-30;80		0.447	0.446	0.447	0.446	0.445
30;-80		0.303	0.302	0.303	0.304	0.307
0;80		0.248	0.249	0.250	0.251	0.247
0;-80		0.062	0.071	0.074	0.077	0.084

Table 3: Comparison of relative A_{FB} change for different beam polarizations and CLIC and ILC working energies and the change in non-b-tagged jet 4-momenta. The collider energies are 500 GeV for the 30%;80% polarizations (ILC) and 380 GeV for the 0%;80% polarizations (CLIC).

jet change / $e^+;e^-$ pol.		-5.00%	-1.00%	0.00%	1.00%	5.00%
-30;80		-0.08%	-0.11%	0.00%	-0.27%	-0.52%
30;-80		-0.13%	-0.30%	0.00%	0.21%	1.20%
0;80		-0.51%	-0.13%	0.00%	0.38%	-1.21%
0;-80		-15.93%	-2.96%	0.00%	4.10%	14.33%