Vertex Detection for a Charm Tag in $e^+e^- \rightarrow W^+W^-$ at a High Energy Electron-Positron Linear Collider

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The study of the process $e^+e^- \rightarrow W^+W^-$ at Linear Collider energies presents a good opportunity to investigate anomalous triple gauge boson couplings and $W^+_L W^-_L$ rescattering. The helicity analysis of the $e^+e^- \rightarrow W^+_L W^-_L$ decays will benefit if the charm quark containing jet can be identified for events which contain one hadronic $W$ boson decay to a charm and another quark. A JAVA implementation of the SLD collaboration’s topological vertex finding algorithm (ZVTOP) in the linear collider analysis framework has been used to extract charm tag efficiencies and purities based on vertex multiplicities.

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I. MOTIVATION

The next $e^+e^-$ linear collider will provide a good opportunity to study strong electroweak symmetry breaking in the process $e^+e^- \rightarrow W^+W^-$, which is predominant at center-of-mass energies of 500 GeV and higher. Strong electroweak symmetry breaking is expected to be seen as deviations from the standard model in two possible ways: either anomalous couplings at the $W^+W^+\gamma$ and $W^+W^-Z$ vertices will be introduced or $W_L^+W_L^-$ final state rescattering effects may occur [1].

Studies of strong electroweak symmetry breaking effects [2] make use of a helicity angle analysis technique for the $W^+W^-$ state and employ a maximum likelihood method to fit alternatively for the two coefficients describing anomalous couplings or the complex form factor $F_T$ in the case of final state rescattering. These analyses are usually carried out with one $W$ decaying leptonically, the other hadronically. In the absence of flavor tagging, the latter decay introduces an ambiguity in the measurement of two of the five helicity angles entering the maximum likelihood fit. The determination of the flavor of one of the two hadronic jets will enhance the sensitivity by an equivalent luminosity gain of up to a factor 1.8 as shown in Figure 1. The study presented here attempts to quantify the possible gain if flavor tagging is employed in $e^+e^- \rightarrow W^+W^-$ decays using the current linear collider detector (LCD) design models as suggested in [3].

II. MONTE CARLO FAST SIMULATION AND ANALYSIS TECHNIQUE

Monte Carlo Data Samples for the process $e^+e^- \rightarrow W_L^+W_L^-$ of 10000 events each were generated with the generator PANDORA-PYTHIA [4, 5] for three center-of-mass system (CMS) energies at 500 GeV, 1000 GeV and 1500 GeV and for both LCD options [6, 7], the large gaseous detector (LD) and the Silicon detector (SD). The events generated with a TechniRho of 1600 GeV mass according to the model described in [8] have a more central polar angle distribution than Standard Model $e^+e^- \rightarrow W^+W^-$ events because of their enhanced $F_T$ amplitude. Only events with one $W$ decaying leptonically and the other hadronically are produced. Fast Monte Carlo track smearing is applied using the JAVA based LCD analysis software [9].

In order to not confuse hadrons stemming from different $W$s, only events with am electron or muon in the leptonic $W$ decay are selected. The $W$ production angle is restricted to $|\cos \Theta_W| < 0.90$ yielding typically 6000 to 6500 events. After the charged lepton track has been removed the DURHAM jetfinder [10] is employed to divide the event into two jets. The smeared charged tracks and neutral particle vectors created from Monte Carlo truth information are used as input to the jetfinder. Each jet is associated with one of the primary $W$ decay quarks by angular proximity of the respective momentum vectors. According to the quark type the jet is associated with, jets are classified as either up-type or down-type jets.

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FIG. 1: Equivalent luminosity gain as a function of the charm tag efficiency [2]. The tagging efficiency includes possible mistags. (The two separate data points above the curve are obtained for the low energy theorem (LET) limit.)

FIG. 2: Displaced charm vertex as reconstructed by ZvTopVertexer (side view). The coordinate errors shown are enlarged by a factor 100.
Finally, ZvTopVertexer [], the JAVA implementation of SLD’s topological vertexing algorithm [], is used to reconstruct vertices from the charged tracks of each jet (see Figure 2). Since the multiplicity of vertices found in a jet depends on the lifetime of the W decay particles, jets induced by a charm quark are expected to have higher vertex multiplicities. The simple charm tag applied in this study requires at least two reconstructed vertices \(N_{\text{vert}}\) for the jet in question after rejecting \(K_0^0\) decay vertices by a cut on the invariant vertex mass \((|m_{\text{vert}} - m_{K_0^0}| < 25\text{ MeV})\) applied to the furthest outlying vertex.

The resulting efficiencies and purities for correctly tagged jets for event samples at three different LC CMS energies are collected in Table I and Table II for the LD and SD design options, respectively. The efficiencies at a level 61% and the purities at about 90% only show a slight dependence on the CMS energy. The later causes only minor differences between the two LCD design options exist. Figure 3 points to the importance of the discriminating variables, possibly in a neural net based technique, will be required.

### III. RESULTS

| LC \(E_{\text{CMS}}\) | 500 GeV | 1000 GeV | 1500 GeV |
|---------------------|---------|---------|---------|
| \(\varepsilon_c\)   |         |         |         |
| 59.6 ± 0.9%         | 61.2 ± 0.8% | 62.6 ± 0.8% |
| \(p_c\)             |         |         |         |
| 86.9 ± 0.4%         | 89.6 ± 0.4% | 92.1 ± 0.3% |
| \(A\)               |         |         |         |
| 73.9%               | 79.3%   | 84.3%   |
| \(Q\)               |         |         |         |
| 32.5%               | 38.5%   | 44.4%   |

**TABLE I:** Results on the \(c\)-tag efficiency \(\varepsilon_c\) and purity \(p_c\), the analyzing power \(A = 2p_c - 1\) and the effective tagging efficiency \(Q = \varepsilon_c A^2\) for the LD detector design.

| LC \(E_{\text{CMS}}\) | 500 GeV | 1000 GeV | 1500 GeV |
|---------------------|---------|---------|---------|
| \(\varepsilon_c\)   |         |         |         |
| 60.1 ± 0.9%         | 61.5 ± 0.8% | 62.5 ± 0.8% |
| \(p_c\)             |         |         |         |
| 87.8 ± 0.4%         | 89.6 ± 0.4% | 90.9 ± 0.4% |
| \(A\)               |         |         |         |
| 75.5%               | 79.2%   | 81.8%   |
| \(Q\)               |         |         |         |
| 34.3%               | 38.6%   | 41.8%   |

**TABLE II:** Results on the \(c\)-tag efficiency \(\varepsilon_c\) and purity \(p_c\), the analyzing power \(A = 2p_c - 1\) and the effective tagging efficiency \(Q = \varepsilon_c A^2\) for the SD detector design.

The resulting efficiencies and purities for correctly tagged jets for event samples at three different LC CMS energies are collected in Table I and Table II for the LD and SD design options, respectively. The efficiencies at a level 61% and the purities at about 90% only show a slight dependence on the CMS energy. The latter causes the increase of the effective tagging power \(Q\) with energy from about 33% to 43%. As can be seen in Figure 3 only minor differences between the two LCD design options exist. Figure 3 points to the importance of the \(K_S^0\) decay vertex veto in order to reach a high purity level. While the charm tag efficiency is only decreased by a few percent, the purity is enhanced by 10% or more.

Achieving charm tag efficiencies of approximately 61% and purities of approximately 90% (in absence of other backgrounds than \(W \rightarrow u\nu\) decays) with a simple vertex multiplicity tag is encouraging. However, in order to obtain the effective charm tagging efficiency necessary to substantially increase the sensitivity of the helicity measurement, additional measures to enhance the charm vertex reconstruction as well as the use of additional discriminating variables, possibly in a neural net based technique, will be required.
FIG. 5: C-tag efficiency (lower red circles) and purity (upper blue squares) without the $K_0^S$ vertex veto for LD and SD designs at various CMS energies.

FIG. 6: C-tag efficiency (lower red circles) and purity (upper blue squares) without the $K_0^S$ vertex veto for LD and SD designs at various CMS energies.

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