Physics Potential of Vertex Detector as Function of Beam Pipe Radius

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At the International Linear Collider (ILC), b quark sign selection will be a powerful physics tool, enabling e.g. the measurement of otherwise inaccessible asymmetries. For the 40% of b-quarks hadronising to yield charged hadrons, the quark sign can be obtained via measurement of the vertex charge. Studies based on the fast Monte Carlo (MC) simulation SGV allow a direct comparison of different detector designs. The influence of the beam pipe radius on the performance has been quantified as function of polar angle for jet energies from 25 to 250 GeV. In addition, a preliminary comparison of the vertex detectors of the three ILC detector concepts is presented.

1. INTRODUCTION

The International Linear Collider (ILC), a 500 to 1000 GeV linear e^+e^- collider to start operation in ∼2015, will allow unique studies of new physics at the TeV scale, such as Higgs physics, supersymmetry (SUSY) or physics involving extra spatial dimensions. Since this new physics is expected to be rich in heavy-flavour jets, a high-precision vertex detector, providing flavour tagging of unprecedented purity and efficiency, will be crucial. In addition, it will allow quark sign selection via vertex charge reconstruction and the charge dipole technique, developed at SLD. The information on whether a jet stems from a quark or an antiquark is needed for instance for unfolding cross sections, as for example necessary for the study of modifications of angular distributions in $e^+e^- \rightarrow b\bar{b}$ due to virtual interactions of gravitons in models with extra spatial dimensions [1], where the low cross section in the backward region is sensitive to the parameter characterising different variants of the model. The main background to a measurement of that backward region cross section comes from neutral b-hadrons from the forward region that are misreconstructed as being charged, with the incorrect quark charge sign. Therefore the quality of the quark sign selection has a direct impact on the precision of the measurement.

Quark sign selection is also a vital tool for various measurements based on multi-jet processes such as analysis of the top quark polarisation via the $\bar{s}$-jet direction in $e^+e^- \rightarrow t\bar{t}$, $\bar{t} \rightarrow bW$, $W \rightarrow c\bar{s}$, the measurement of spin correlations in $e^+e^- \rightarrow \tilde{\chi}^0_2\tilde{\chi}^0_1$ or the angular analysis of $e^+e^- \rightarrow ZHH$; for a more detailed discussion of sensitive channels cf [2].

The Linear Collider Flavour Identification (LCFI) collaboration is performing an extensive R&D programme aimed at the development of a vertex detector that meets the stringent requirements of ILC physics. The design and test of the sensors and readout electronics and the study of adequate support structures and the mechanical detector design are closely linked with the work on simulation and physics studies, which serves the optimisation of the detector parameters, the assessment of the detector performance and the development of the vertex-based analysis tools required for the ILC physics programme.

2. VERTEX DETECTOR DESIGNS UNDER STUDY

The ILC vertex detector will be a highly pixellated device of $\sim 10^9$ pixels of $20\times20\,\mu\mathrm{m}^2$, attaining a point resolution of $\sim 3.5\,\mu$m. The pair-background on the innermost detector layer implies a fast readout of the detector (within $50\,\mu$s, hence 20 times per bunch train of 1 ms duration). The need to reduce multiple scattering while maintaining mechanical stability results in a targeted layer thickness of 0.1 % of a radiation length per layer. The baseline detector design [3], referred to as 'standard detector' in what follows, comprises 5 cylindrical detector layers, the innermost layer of 100 mm length, the outer layers 250 mm long, situated at radial positions ranging from 15 mm to 60 mm. The studies were made with the vertex detector embedded in the overall TESLA detector as described in [3].

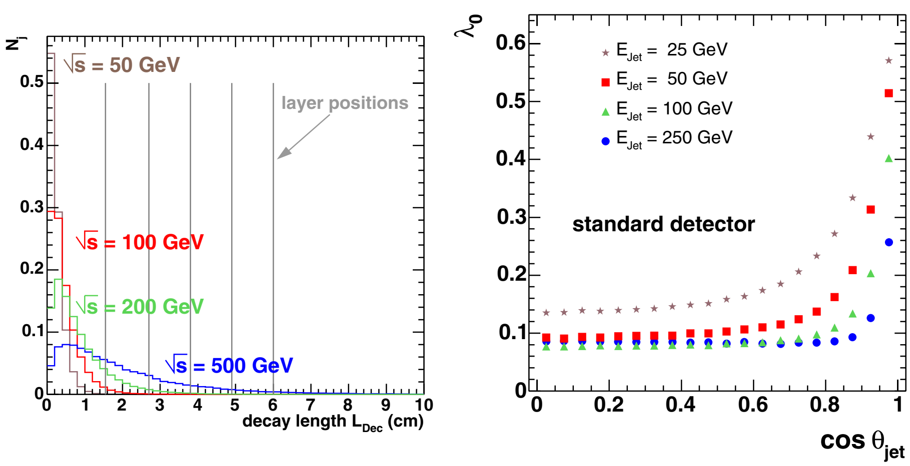
Variations of the detector that have been studied comprise a detector in which the innermost layer has been omitted, corresponding to a beam pipe radius $R_{\text{bp}} = 25$ mm with the beam pipe thickness increased from 0.4 mm to 1 mm for mechanical integrity, and a detector with the inner layer moved inwards corresponding to $R_{\text{bp}} = 8$ mm. In addition, current versions of the vertex detectors proposed within the SiD and GLD global detector concepts were inserted into the same global detector geometry for comparison.

3. VERTEX CHARGE RECONSTRUCTION

Vertex charge reconstruction was studied using jets from $e^+e^- \to b\bar{b}$ events generated using the fast simulation SGV [4], interfaced to PYTHIA version 6.1.52 [5]. The vertex finder ZVTOP [6] was run on all tracks assigned to a jet by the JADE algorithm [7] and the charges of the tracks assigned to the b-hadron decay chain were summed. The main cut for this track assignment was optimised for each detector configuration independently. Further details on the reconstruction procedure can be found elsewhere [8].

4. RESULTS

The dependence of vertex charge reconstruction on energy and polar angle has been studied for the 'standard detector' geometry described in section 2. With decreasing jet energy, one expects performance to degrade due to

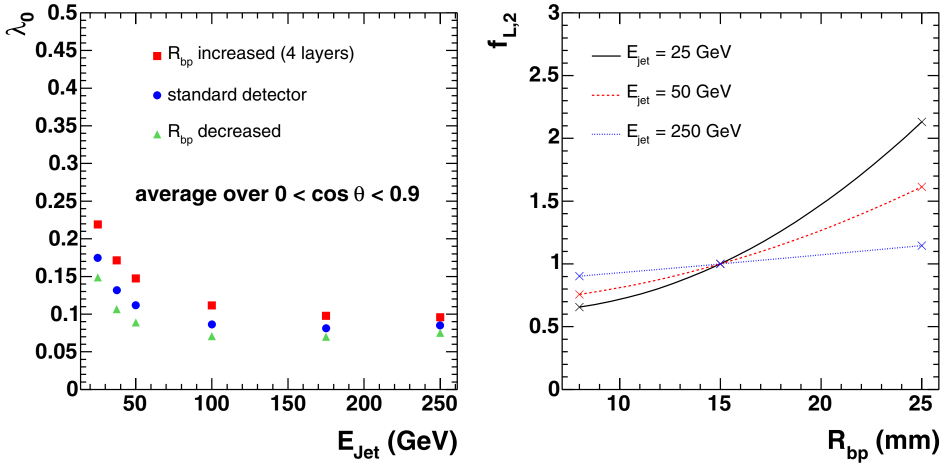


(a) (b)

Figure 1: (a) Decay length distribution for outermost reconstructed vertex in jets from $e^+e^- \to b\bar{b}$ events. (b) Probability λ_0 of misreconstructing neutral vertices as function of jet energy and polar angle.

more pronounced multiple scattering effects and the shorter average distance L_{Dec} of the outermost vertex from the interaction point (IP) as shown in Fig. 1 (a). MC studies show that for a jet energy of 250 GeV, in only $\sim 75\%$ of jets the b-hadron decays inside the beam pipe, while for 6% of all jets the subsequent c-hadron decay vertex lies outside the vertex detector.

Performance of vertex charge reconstruction is measured in terms of the leakage rate λ_0, defined as the probability of reconstructing a neutral vertex as charged, which determines the purity of the resulting jet sample. Fig. 1 (b) shows the performance as function of jet direction and energy. The degradation towards the detector edge indicates that performance is mainly driven by multiple scattering effects, which affect oblique tracks more strongly than tracks traversing the sensors in the central region of the detector with approximately normal incidence. At large $|\cos\theta|$ and low energy, where jets tend to be broader, it is also more likely that a track is lost at the detector edge.



(a) (b)

Figure 2: Comparison of detectors with different beam pipe radius: (a) in terms of their leakage rates and (b) in terms of the 2-jet luminosity factor compared to the standard design, see text.

Detectors with different beam pipe radii (see section 2) are compared in terms of their leakage rates, averaged over the polar angle range $0 < |\cos\theta| < 0.9$. The energy dependence, plotted in Fig. 2 (a), shows that the detector with smallest $R_{\rm bp}$ performs best at all jet energies, with the difference in performance increasing towards lower jet energies. This difference can be translated into a luminosity factor, defined as the factor by which the integrated luminosity needs to be changed to measure a signal with the same statistical significance as obtained from the standard detector. In particular, the 2-jet luminosity factor, $f_{\rm L,2}$, shown in Fig. 2 (b), is applicable to analyses in which the vertex charge needs to be reconstructed independently for two jets, such as the decay products of the two Higgs particles in ZHH events. This result indicates that a significant increase in integrated luminosity would be required to compensate for an increase in the beam pipe radius. It should be noted that the result shown in Fig. 2 (b) is based on a somewhat simplified method to estimate the required increase in luminosity, which assumes that the jets with a small distance $L_{\rm Dec}$ between outermost vertex and IP, which have the worst λ_0, are discarded in the analysis. In an actual analysis, one would not cut on $L_{\rm Dec}$ and hence disregard information, but weight jets according to their λ_0 value. A preliminary estimate using this modified procedure lowers the 2-jet luminosity factor for the large $R_{\rm bp}$ detector at 25 GeV jet energy from the value 2.14, shown in the plot, to $1.65 - 1.85$, depending on the background assumed. The conclusion - a significant advantage for physics of the detector with a smaller inner layer radius - is unchanged by this improvement of the procedure.

The comparison of the vertex detectors from the GLD and SiD concepts with the standard detector shows that the material at the end of the SiD short barrel staves compromises performance at large $|\cos\theta|$, while the GLD performance is affected by the larger inner layer radius compared to the standard detector. However, it should be noted that some effects that could be relevant to this comparison, such as possible mechanical instability of the barrel cylinders perpendicular to the beam line, which are more likely to occur for longer barrel structures, are the subject of the detector R&D programme and could not be taken into account in the present study.

5. SUMMARY AND CONCLUSIONS

At the ILC, b quark sign selection will be a powerful physics tool, which will greatly enhance sensitivity to new physics. It has been studied in the 40% of cases yielding charged b-hadrons, by measuring their vertex charge. Performance has been quantified by the probability of reconstructing a neutral b-hadron as charged. This measurement is sensitive to multiple scattering in the vertex detector. Vertex detectors with beam pipe radii ranging from 8 to 25 mm were compared. Estimates indicate that for channnels depending on quark sign selection, a significant increase in integrated luminosity would be required to compensate for an increase in beam pipe radius. It is therefore important that the final focus design should respect the baseline beam pipe radius of $12-15$ mm. R&D to reduce the beam pipe thickness to 0.4 mm and the vertex detector layer thickness to 0.1% of a radiation length per layer is important. A higher solenoid field would be an advantage, since acceptable pair background rates on the innermost vertex detector layer need to be achieved.

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