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Quark Charge Measurement with an ILC Vertex Detector

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Capability to correctly measure the vertex charge in heavy flavour jets is one of the benchmarks in vertex detector design for the International Linear Collider (ILC). An improved reconstruction method for vertex charge is described. The inclusive distributions for monoenergetic 100 GeV jets from $e^+e^- \to b\bar{b}$ obtained from this method are presented along with the resulting purity for discerning b- from $\bar{b}$-quarks. Further performance indicators, the leakage rates, which measure the probability of obtaining a wrong charge value, are introduced and plotted for charged and neutral hadrons as function of b-tag efficiency.

1. INTRODUCTION

The Linear Collider Flavour Identification (LCFI) collaboration is developing a vertex detector for the International Linear Collider, a 1 TeV linear e^+e^--collider intended to start operation in approximately 2015. The LCFI programme covers three areas of R&D: simulation and physics studies, development of a low mass, mechanically stable vertex detector design and sensor development. The aim of the physics studies is to both optimise the design of the detector and to evaluate its physics performance.

The most interesting new physics processes to be tested at the ILC, such as Higgs physics and supersymmetry, will be rich in heavy quarks. Quantities based on vertex detector information, such as the vertex topology and effective mass of the decay products, allow b- and c-quarks to be distinguished from each other and from the light-quark background. Excellent tagging of low energy charm jets is for instance needed for scalar top production $e^+e^- \to \tilde{t}_1\bar{\tilde{t}}_1 \to c\tilde{\chi}_1^0\bar{c}\tilde{\chi}_1^0$ with small mass difference between the neutralino and the scalar top [1].

By reconstructing the decay vertex charge, one can further distinguish between neutral and charged hadrons, and for the charged hadrons directly infer whether the heavy flavour parton contained is a quark or an antiquark. This information is for example needed when measuring the left-right forward-backward asymmetry, A_{FB}^{LR}, in $e^+e^- \to b\bar{b}$ or $e^+e^- \to c\bar{c}$, (where left-right refers to the polarisation of the colliding electrons and positrons, respectively). This quantity is sensitive to new physics phenomena beyond the direct energy reach of the ILC and the LHC, such as Z', leptoquarks, R-parity violating scalar particles and extra spatial dimensions [2]. Its reconstruction relies particularly on the detector performance at the ends of the polar angle range, where tracks traverse the vertex detector layers at an oblique angle, resulting in degradation of precision due to multiple scattering and elongation of cluster shapes.

Other effects sensitive to vertex detector performance include spin-parity analysis of SUSY particles and top-quark polarisation; for a more detailed discussion cf. [3] and the references therein.

2. THE VERTEX DETECTOR UNDER DEVELOPMENT

The baseline vertex detector design developed by LCFI [4] envisages five concentric detector layers of length 100 mm for the innermost and 250 mm for the outer layers, respectively, with radii ranging from 15 mm to 60 mm, thus providing angular coverage to $\cos\theta = 0.96$. In order to minimise multiple scattering, a material contribution of 0.064% of a radiation length per layer is aimed at. Besides, a point resolution of 3.5 μm is assumed.

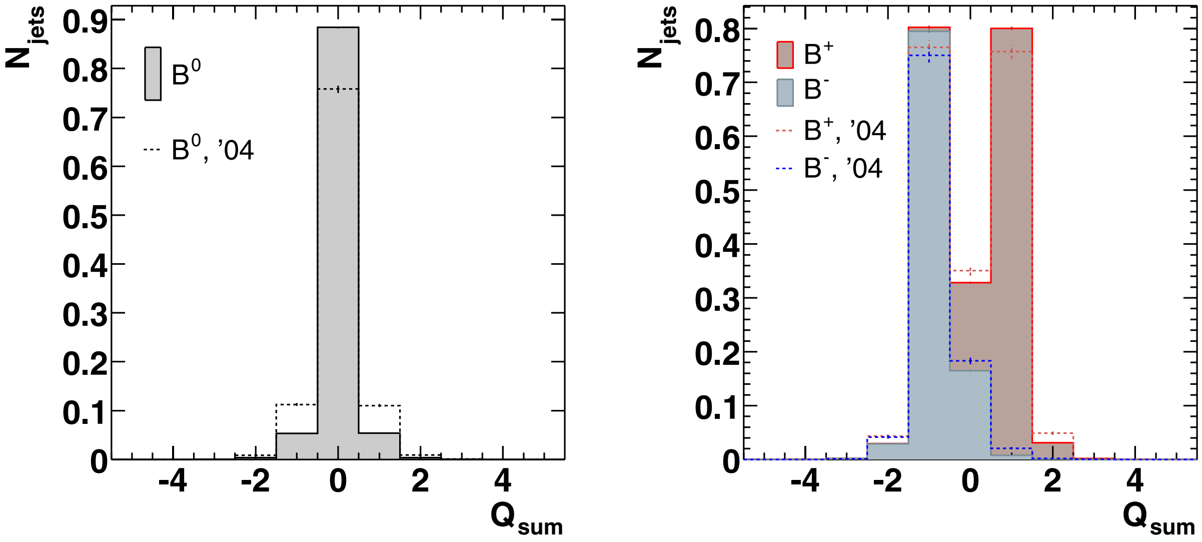
Future studies will evaluate the effects of varying these and other detector parameters, as well as aspects of the overall vertex detector design such as the arrangement of sensors in the layers and the overlap of the barrel staves, influencing the alignment capabilities. They will also cover the investigation of parameters that affect other subsystems of the ILC detector and accelerator, such as the strength of the B-field and the radius of the beam-pipe.

Contributions to the material budget from beam-pipe, sensors, electronics and support structure will be varied, paying particular attention to the ends of the polar angle range. Besides, an accurate description of particle energy loss and of charge transport and collection in the silicon sensors will be required, as well as simulation of data sparsification in the readout chip, taking realistic signal and background hit densities into account.

3. VERTEX CHARGE RECONSTRUCTION

The fast simulation program *Simulation a Grande Vitesse* (SGV) [5] interfaced to the PYTHIA version 6.1.52 event generator [6] was used to simulate $e^+e^- \to \gamma, Z \to b\bar{b}$ events at a centre of mass energy of 200 GeV. The JADE algorithm [7] with y_{cut} set to 0.04 was run to find jets. Two-jet events were selected, requiring the jets to be sufficiently back-to-back, $\cos\theta_{12} < -0.95$ with θ_{12} the angle between the jet momenta. Besides, a thrust angle cut was applied to ensure the jets were contained in the detector acceptance region, $20^\circ < \theta_{\mathrm{thrust}} < 160^\circ$.

For each jet the vertex finder ZVTOP [8] was then run on tracks passing the following quality criteria: Tracks had to have at least 20 hits in the main tracker, assumed to be a TPC, or 3 hits in the forward tracker or 3 hits in the vertex detector. Their momentum had to exceed 100 MeV/c and their impact parameters in z and $R\phi$ had to be below 2 cm and below 1 cm, respectively. Tracks stemming from the decay of K_S and Λ particles were excluded using Monte Carlo (MC) generator information, assuming that identification of such tracks will be possible with a high efficiency at the ILC.



(a)

(b)

Figure 1: Distributions of the sum charge Q_{sum} for (a) neutral and (b) charged B hadrons. Full histograms correspond to the current reconstruction method, dashed lines to the reconstruction used in [9].

Once vertices were found, the vertex axis was determined. It is given by the axis pointing from the interaction point (IP) to the vertex furthest away from it, the so-called seed vertex. Tracks were assigned to the B hadron decay chain, if they were either contained in a vertex other than the primary vertex or if they passed the following cuts: $T < 1$ mm, where T is the three-dimensional impact parameter at the point of closest approach (POCA) of the track to the vertex axis, $0.16 < L/D < 2.5$ with D and L the distances of the seed vertex and the POCA from the IP, respectively. With the sum charge Q_{sum} defined as the sum of the charges of all tracks assigned to the B decay chain, the vertex charge is given by $Q_{\mathrm{vtx}} = \pm 1$ for $Q_{\mathrm{sum}} = \pm 1$ or $Q_{\mathrm{sum}} = \pm 2$ and identical to Q_{sum} otherwise.

4. RESULTS

4.1. Inclusive sum charge distributions

Distributions of the sum charge for neutral and charged B hadrons are shown in Fig. 1, and compared to the results corresponding to the status presented at the previous LCWS workshop [9]. A clear improvement is seen for both charged and neutral B hadrons, which yield the correct sum charge for almost 90 % of all jets. This improvement is due to an optimisation in the lower cut value on L/D and the assignment to the B decay chain of tracks contained in reconstructed 'inner vertices', i.e. vertices other than the primary vertex that are closer to the IP than the seed vertex.

4.2. Quark charge purity for charged hadron decays

While the inclusive distributions in Fig. 1 already give an indication of the high performance of the reconstruction algorithm, any physics analysis using this method would require to first distinguish b-quark jets from charm- and light quark jets. Any such selection cuts result in a smaller sample size, described by the b-tag efficiency ϵ_b, and a corresponding change in the quality of reconstruction when only taking the resulting subsample into account, which is measured by the purity $\Pi(b)$.

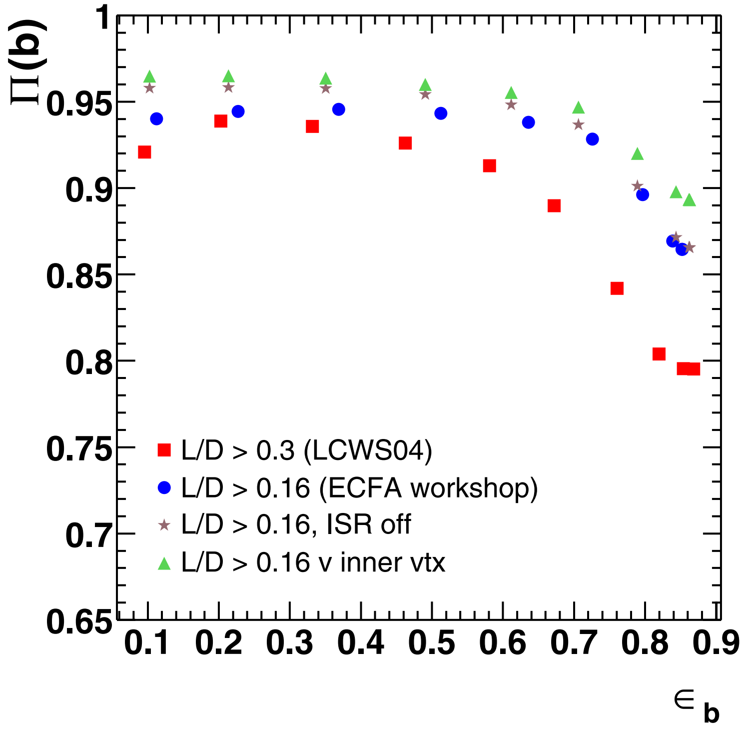


Figure 2: Quark charge purity for jets stemming from charged hadrons as function of b-tag efficiency. The current reconstruction method, as described in section 3, indicated by the triangles, is compared to the result from [9], shown as squares. The effects of only optimising L/D and of additionally switching off the simulation of initial state radiation are also shown.

With N_{tot} the number of jets passing the selection cuts described in section 3 and $N(M_{\mathrm{Pt,cut}})$ the number of jets, for which additionally the seed vertex decay length exceeds $300\,\mu$m and the P_t-corrected vertex mass M_{Pt} is in the range $M_{\mathrm{Pt,cut}} < M_{\mathrm{Pt}} < 5.5\,\mathrm{GeV}$, the b-tag efficiency is defined as

$$\epsilon_b(M_{\mathrm{Pt,cut}}) = \frac{N(M_{\mathrm{Pt,cut}})}{N_{\mathrm{tot}}}. \tag{1}$$

Distinction between b-quarks and other flavours is achieved by the lower cut on M_{Pt}, a typical cut value being $M_{\mathrm{Pt}} = 2\,\mathrm{GeV}$, corresponding to an efficiency of $\epsilon_b \approx 70\%$.

The purity $\Pi(b)$ of correctly identifying the quark charge for jets containing a charged B hadron is given by the ratio

$$\Pi(b) = \frac{N_{\mathrm{b,r=g}}}{N(M_{\mathrm{Pt,cut}})}, \tag{2}$$

where $N_{\mathrm{b,r=g}}$ is the number of jets, for which the quark charge inferred from the Q_{vtx}-value is correct.

Fig. 2 shows the purity as a function of b-tag efficiency, where $M_{\mathrm{Pt,cut}}$ has been varied from 0 to 4.5 GeV in steps of 0.5 GeV. At the typical cut value of 2 GeV, purity has increased by 5.7 % to 94.7 % as compared to the results presented at the previous LCWS workshop [9]. Purities of almost 90 % are now reached up to the largest efficiency considered.

4.3. Leakage rates - new performance indicators

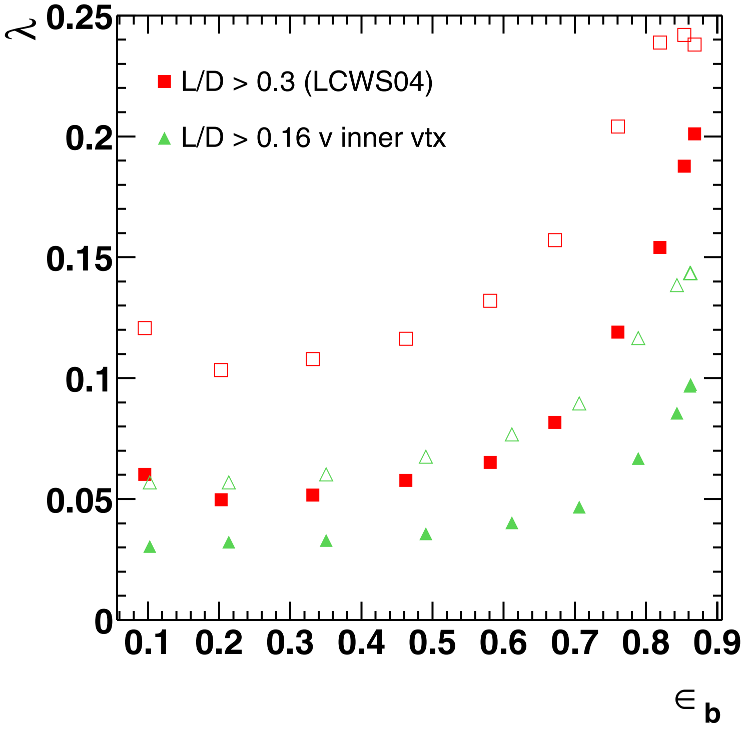


Figure 3: Leakage rates found for the reconstruction method described in section 3 and for that from [9] Full symbols indicate the probability λ_{pm} of wrongly reconstructing a charged hadron, open symbols the probability λ_0 of finding a neutral hadron to be charged.

Once should note that wrongly reconstructing a charged B hadron reduces the efficiency, while wrongly reconstructing a neutral B reduces the purity. To disentangle these two effects, new performance indicators, the leakage rates λ_0 and λ_{pm} are defined as probabilities of obtaining a wrong vertex charge value from the reconstruction for hadrons that are neutral and charged at the MC generator level, respectively.

Leakage rates are plotted as function of b-tag efficiency in Fig. 3. The values λ_{pm} for charged hadrons are lower, because a wrongly assigned or missing track in the B decay chain may result in a sum charge $Q_{\mathrm{sum}} = \pm 2$, still yielding the correct vertex charge $Q_{\mathrm{vtx}} = \pm 1$, whereas for neutral hadrons any single mistake in the track assignment will result in Q_{vtx} being wrongly reconstructed.

5. SUMMARY AND FUTURE PLANS

The ILC physics programme depends on excellent vertex detector performance. The reconstruction algorithm for one of the vertex detector benchmarks, the quark charge, has been improved to yield a purity $\Pi(b) = 94.7\,\%$ at a typical b-tag efficiency $\epsilon_b \approx 70\,\%$ for a pure $e^+e^- \rightarrow b\bar{b}$ sample at a centre of mass energy of 200 GeV.

The leakage rates for charged and neutral hadrons, corresponding to the probabilities of finding the wrong quark charge from the reconstruction, complement the information contained in the purity.

In the future, these studies will be extended to explore the limits of polar angle coverage, to a range of jet energies and to other quark flavours. The effects of varying detector design parameters will then be evaluated in terms of flavour-tagging and vertex charge reconstruction capabilities, both independently and in the context of the analysis of benchmark physics processes.

References

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