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Jet Flavour Identification at the CLIC Multi-TeV e^+e^- Collider

Marco Battaglia

CERN, CH-1211 Geneva 23 Switzerland

Abstract. Jet flavour identification in multi-TeV e^+e^- collisions is expected to provide insights on new phenomena at scales beyond those probed by the LHC. The anticipated high track density and jet collimation represent a new challenge to jet tagging algorithms. A method, based on the sampling of the jet charged multiplicity, sensitive to the long decay length and large decay multiplicity of heavy flavour hadrons is proposed and the expected performances for the tagging of $e^+e^- \to b\bar{b}$ events at $\sqrt{s}$ = 3 TeV are discussed.

I INTRODUCTION

The physics programme of future high energy linear colliders (LC), designed to deliver e^+e^- collisions at centre-of mass energies $\sqrt{s}$ = 0.1-5 TeV with luminosities in excess to $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, largely relies on the ability to identify the flavour of final state fermions with high efficiency and purity. A first phase will be devoted to the accurate study of the Higgs profile, if a relatively light Higgs boson exists as suggested by theory, electro-weak data and the signals reported at LEP-2, to the precise determination of the top mass and to complement the LHC program in searching for signals of new physics at the TeV mass scale. In a second phase, a multi-TeV LC is expected to break new grounds by studying in detail the properties of new physics established by the LHC or the lower energy LC and by exploring the mass scale beyond 10 TeV for new phenomena. The CLIC concept aims for a linear collider providing collisions at centre-of-mass energies beyond the TeV frontier with a luminosity of $10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at $\sqrt{s}$ = 3 TeV, based on the two-beam acceleration scheme [1].

If a new resonance has been detected at the TeV scale, either at the LHC or at a lower energy e^+e^- collider, CLIC will be able to copiously produce it and provide with accurate determinations of its couplings to establish its nature. If no evidence for new particles has been obtained by the LHC and the LC, CLIC will probe the energy domain beyond 10 TeV by indirect searches, relying on accurate determinations of flavour-specific electro-weak data ($\Gamma_{f\bar{f}}$, $A_{FB}^{f\bar{f}}$, A_{LR}) sensitive to virtual processes and vertex corrections from new particle contributions [2].

Tagging and anti-tagging of t, b and τ final states will also be instrumental in refining the knowledge of the Higgs sector by isolating signals of heavy Higgs bosons, which occur in SM extensions such as Supersymmetry, and by testing the Higgs potential by measuring multiple Higgs production ($ZHHH$ and $\nu_e\bar{\nu}_e HH(H)$) cross sections and of Supersymmetry. These analyses may require the high energy and luminosity of CLIC in order to access pair produced heavy bosons and to collect enough statistics in the low cross-section processes testing the Higgs triple and quartic couplings. The signal final states are expected to be characterised by large b jet multiplicity in processes such as $e^+e^- \to H^+H^- \to t\bar{b}\bar{t}b \to W^+b\bar{b}W^-\bar{b}b$ and $e^+e^- \to \nu_e\bar{\nu}_e HH(H) \to \nu_e\bar{\nu}_e b\bar{b}b\bar{b}(b\bar{b})$.

II THE VERTEX TRACKER AT CLIC

Several solutions for the design and the silicon sensor technology have been proposed for the LC vertex tracker. These consist of either a multi-layered detector, based on CCD or CMOS sensor technology, with stand-alone tracking capabilities or a three-layered hybrid pixel detector. At CLIC, the anticipated background from e^+e^- pairs produced in the interaction of the colliding beams will limit the approach to the interaction region to about 3.0 cm compared to $\simeq$ 1.5 cm foreseen for the lower energy projects [3]. This is compensated by the increase of the short-lived hadron decay length due to the larger boost. At $\sqrt{s} = 3$ TeV, the average decay distance of a B hadron is 9.0 cm, in the two-jet process $e^+e^- \to b\bar{b}$, and 2.5 cm in multi-parton $e^+e^- \to H^+H^- \to t\bar{b}\bar{t}b \to W^+b\bar{b}W^-\bar{b}b$ decays. Due to the large boost and large hadronic multiplicity, the local detector occupancy in $e^+e^- \to b\bar{b}$ events is expected to increase by almost a factor of ten, to > 1 particle mm^{-1} from $\sqrt{s} = 0.5$ TeV to $\sqrt{s} = 3.0$ TeV. This indicates the need to design a large vertex tracker based on small area pixel sensors, able to accurately reconstruct the trajectories of secondary particles originating few tens of centimetres away from the beam interaction point and contained in highly collimated hadronic jets. There are other background issues relevant to the conceptual design of a vertex tracker for CLIC. These are the rate of $\gamma\gamma \to$ hadrons events, estimated at 4.0 BX^{-1}, and the neutron flux, possibly of the order of 10^{10} 1 MeV-equivalent n cm^{-2} year^{-1}. The need to reduce the number of $\gamma\gamma$ events overlapped to a e^+e^- interaction requires fast time stamping capabilities while the neutron induced bulk damage has to be considered in terms of sensor efficiency reduction.

A vertex tracker consisting of seven concentric Si layers located from 3.0 cm to 30 cm from the beam interaction point and based on hybrid pixel sensors, with 20 ns time stamping and radiation hardness capabilities, demonstrated for their LHC applications has been considered in this study. The layer spacing has been chosen to optimally sample the heavy hadron decay length, resulting in a closer spacing for the innermost layers (see Figure 1). A model of this tracker has been implemented in GEANT; $e^+e^- \to b\bar{b}$ events and pair background have been passed through the GEANT simulation assuming a solenoidal field B of 6 T.

III B MULTIPLICITY TAG AT CLIC

The kinematics in multi-TeV e^+e^- collisions, suggests that the extensions of the reconstruction and tagging algorithms, pioneered at LEP and SLC and further developed for application at a lower energy LC, may need to be reconsidered. The high jet collimation and large b decay distance pose significant challenges to the track pattern recognition and reconstruction that may affect the accuracy of b and c identification by secondary vertex and impact parameter tagging. These are being addressed by studying tracking performances for different designs for the main tracker [4]. At the same time it is interesting to explore new quark tagging techniques, that profit from the kinematics of multi-TeV e^+e^- collisions. A b tagging algorithm based on the tag of the steps in particle multiplicity originating from the heavy hadron decay along its flight path has been developed and tested here. The principle adopted stems from a technique developed for charm photo-production experiments [5]. At a multi-TeV linear collider, such as CLIC, the signal of the production and decay of a b or c hadron can be obtained from an analysis of the number of hits recorded within a cone centred on the jet direction as a function of the radial position of the detector layer. In the present implementation of the algorithm, a cone of half-aperture angle $\psi = 40$ mrad, optimised to maximise the sensitivity in presence of background and fragmentation particles, defines the area of interest (AoI) on each detector layer. The decay of a highly boosted short-lived hadron is characterised by a step in the number of hits recorded in each AoI, corresponding to the additional charged multiplicity generated by the decay products. Since the average charged decay multiplicity of a beauty hadron is about 5.2 [6] and that of a charm hadron 2.3, the B decay signature can consists of either one or two steps, depending on whether the charm decay length exceeds the vertex tracker layer spacing. The number of background hits in the AoI is estimated to be 0.7, constant with the radius, the increase of the AoI surface being compensated by the background track density reduction due to the detector solenoidal field. This background density is measured, by sampling the region outside the AoI, and

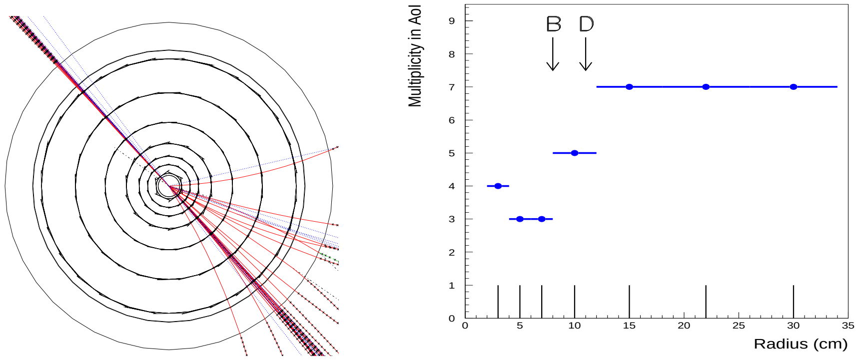

FIGURE 1. *Display of a $e^+e^- \to b\bar{b}$ event at $\sqrt{s} = 3$ TeV (left) with the detected hit multiplicity steps from the cascade decay of a long flying B hadron (right).*

subtracted. The effect of significant fluctuations of the number of these background hits and of low momentum curling tracks in the innermost layers can be further removed by rejecting those jets where the hit multiplicity decreases with increasing radius or fluctuates by more than two units. The multiplicity pattern of a tagged B decay is shown in Figure 1. Jets fulfilling the above criteria and with at least an upward multiplicity step larger than 1 and a total multiplicity increase larger than 2 have been considered. According to simulation 69%, 29% and 3% of these jets are due to b, c and light quarks respectively. The b jets have been further discriminated using a b likelihood based on the size, radial position and number of multiplicity steps, the fraction of the jet energy and the invariant mass of the tracks originating at the detected multiplicity steps. The resulting likelihood for b and lighter jets and the b efficiency and purity resulting from a cut on this discriminating variable are shown in Figure 2. By fitting that distribution for the $b\bar{b}$ content, $\sigma(e^+e^- \to b\bar{b})$ at $\sqrt{s} = 3$ TeV can be determined to ± 0.01 (stat) relative accuracy with an integrated luminosity of 1000 fb^{-1}, corresponding to one year of CLIC running at nominal luminosity.

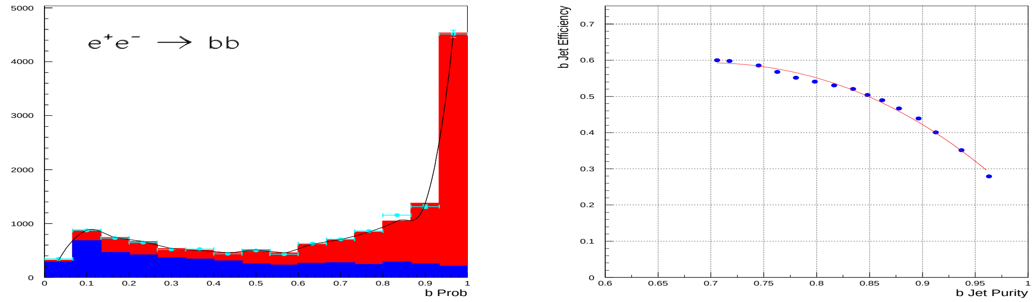

FIGURE 2. *The b likelihood for jets in $e^+e^- \to q\bar{q}$ events at $\sqrt{s} = 3$ TeV (left) with a multiplicity tag. The response for b (c and lighter) jets is shown in light (dark) grey. The b-jet efficiency is given as a function of the purity corresponding to different likelihood cut values (right).*

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