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Beauty and charm to study new physics at future linear colliders

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b and c hadrons are instrumental to the identification and study of the Higgs sector and new physics at a future lepton collider. This paper reviews highlights of b and c physics for the linear collider programs and the directions of ongoing R&D on pixellated Si sensors for its vertex tracker.

1. INTRODUCTION

An e^+e^- linear collider (LC) has emerged as possibly the most practical and realistic way towards collisions of elementary particles at constituent energies matching those of the LHC with high luminosity. The attainable beam energy depends on the available accelerating gradient and the luminosity on the beam power and its emittance at the interaction point (IP). Two projects, which aim at different collision energies with different acceleration technologies, are presently being developed. The ILC project is based on the use of superconducting RF cavities providing gradients of $\simeq$ 30 MV/m to produce collisions at centre-of-mass energies $\sqrt{s}$ = 0.25 - $\simeq$ 1 TeV [1]. In order to achieve higher energies the CLIC project develops a new acceleration scheme where a low-energy, high current drive beam is used to accelerate the main beam through high-frequency transfer structures, which have achieved gradients of $\simeq$ 100 MV/m [2]. In a farther future, plasma wake-fields accelerators using high-power laser pulses can provide gradients of 1-10 GV/m [3,4].

Heavy flavour identification and decay reconstruction is essential for the physics program of the next generation of high energy e^+e^- colliders. Because b and t are the two heaviest quarks, they will be preferentially produced by particles with large couplings to massive fermions including, but not limited to, the Higgs boson(s). Because b, c and t can, in principle, be identified with high efficiency and purity, they will also enable the selection of well-defined exclusive hadronic final states, for example in the study of precision electro-weak observables. This paper discusses the role of heavy hadron identification and reconstruction in the framework of the linear collider physics program and presents some highlights of the R&D program towards the next generation of vertex trackers, matched to the linear collider physics requirements.

2. HEAVY FLAVOURS AND THE LINEAR COLLIDER PHYSICS PROGRAM

The detailed study of the Higgs profile is possibly the centre-piece of the e^+e^- linear collider physics program at $\sqrt{s}$ = 0.25-0.5 TeV, in particular if the Higgs boson, h^0, is light, i.e. its mass is below the W^+W^- threshold, so that its dominant decay is $h^0 \to b\bar{b}$ [5]. Not only tagging the b jets is instrumental for studying its production, even more importantly the identification of b, c and light hadrons in its decay products is an essential test of the Higgs mechanism of mass generation. If this is indeed responsible for generating the fermion masses, in addition to those of the gauge bosons, the couplings of the Higgs boson to b and c quarks must scale proportionally to their masses. If the Higgs sector is embedded into an extended model of New Physics, such as

Supersymmetry (SUSY), these relations receive important corrections. Couplings to up-like and down-like fermions are shifted compared to their Standard Model (SM) predictions. In addition, in SUSY models sbottom-gluino and stop-higgsino loops may shift the effective b-quark mass in the hbb coupling. It is therefore essential to accurately determine these couplings by measuring the branching fractions of the Higgs boson decays in the corresponding fermions pairs. From $M_H = 115$ GeV, just above the LEP-2 lower mass limit, to $M_H = 185$ GeV, the SM upper mass limit from precision electro-weak observables, the branching fraction BR($H^0 \to b\bar{b}$) varies from 0.71 to $3.8{\times}10^{-3}$, i.e. from being the dominant process to becoming a rare decay. For a light Higgs boson, with mass $\simeq 120$ GeV the accessible fermionic final states are $b\bar{b}$, $c\bar{c}$ and $\tau^+\tau^-$. These decays need to be distinguished among them and from the top-loop mediated $H \to gg$ decay, which yields jets with light hadrons. This motivates by efficient and pure jet flavour tagging, which is best done by using a topological reconstruction of the decay chain [6]. Detailed studies have demonstrated that the effective couplings of an 120 GeV Higgs boson to $b\bar{b}$, $c\bar{c}$ and gg can be measured with a relative statistical accuracy of 0.005, 0.06 and 0.04, respectively, with 250 fb^{-1} of statistics collected at $\sqrt{s} = 250$ GeV [7]. Figure 1 shows the Higgs mass peak obtained in the $c\bar{c}$ channel with the ILD detector concept [8]. As the Higgs mass increases, the W^+W^- process becomes dominant. Still, measuring the $b\bar{b}$ final state is essential for verifying the fermion mass generation mechanism. Given the low event rate, this measurement is best performed at $\sqrt{s} =$ 1 TeV, or above, where the $e^+e^- \to \nu\bar{\nu}H^0$ fusion production process offers larger cross section compared to the associated production with the Z^0, typically exploited at $\sqrt{s} = 250$ - 500 GeV [9,10]. The main challenge presented by this measurement is the identification of relatively soft b jets in the forward region, i.e. at polar angles below 25°.

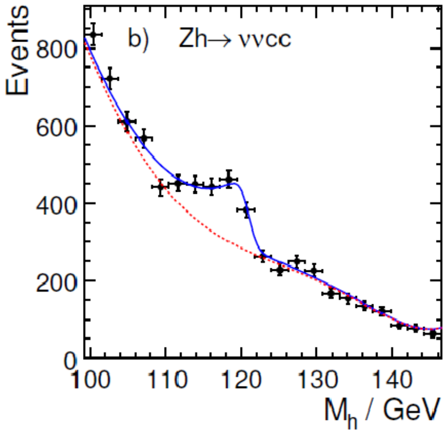

Figure 1. $c\bar{c}$ invariant mass distribution showing the $e^+e^- \to Z^0h^0 \to \nu\bar{\nu}c\bar{c}$ signal above the SM background for $M_h = 120$ GeV at $\sqrt{s} = 250$ GeV. A c-tagging efficiency of 29% is obtained. The result is obtained with full simulation and reconstruction of the ILD detector concept at ILC (from [8]).

Measurements of Higgs couplings to fermions accurate enough to be sensitive to the mass scale of heavy states, such as the SUSY Higgs sector, require not only high statistical accuracy but also precise theory predictions. Then, the interpretation of these measurements crucially depends on the precision of inputs, such as m_b, m_c and α_s, currently being obtained by lower energy accelerator experiments [11]. Figure 2 shows the change in sensitivity to the mass of the supersymmetric CP-odd A^0 boson when assuming only the experimental accuracies and also adding the uncertainties on heavy quark masses and α_s. If the linear collider $\sqrt{s}$ energy is sufficient, heavy Higgs bosons from SUSY, or other models with an extended Higgs sector, can be directly pair produced. These bosons are expected to couple predominantly to t and b quarks and their study would represent a genuine feast for b-tagging and reconstruction. The CP-odd and the heavy CP-even neutral Higgs bosons, A^0 and H^0 give mostly $e^+e^- \to H^0A^0 \to b\bar{b}b\bar{b}$ and $b\bar{b}\tau^+\tau^-$, while charged bosons would predominantly give $e^+e^- \to H^+H^- \to t\bar{b}\bar{t}b$. The study of these processes is of special relevance for establishing the connection between particle physics and cosmology through dark matter. In fact, the A^0 boson plays a special role in the study of the relic density

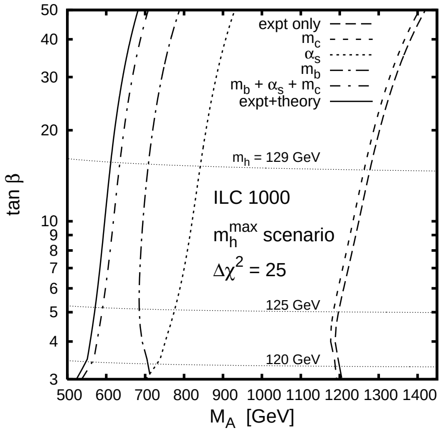

Figure 2. Contributions of different sources of parametric uncertainties to the sensitivity to M_A from measurements of the h^0 couplings in SUSY (from [11]).

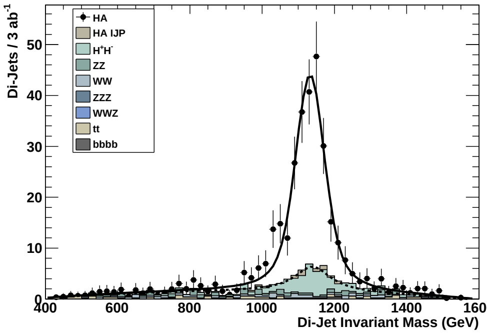

Figure 3. $b\bar{b}$ invariant mass distribution showing the $e^+e^- \to H^0A^0 \to b\bar{b}b\bar{b}$ signal above the SM and SUSY backgrounds for $M_A = 1.14$ TeV at $\sqrt{s} = 3$ TeV and assuming a b-tagging efficiency ϵ_b=0.85. The result is obtained with full simulation and reconstruction of a detector at CLIC (from [12]).

of Supersymmetric dark matter in the universe. For a precise study of dark matter, the observation of the heavy Higgs bosons at colliders and the measurement of their properties is essential. If $M_A \simeq 2M_{\chi_1^0}$, the neutralino annihilation process in the early universe is significantly enhanced through the A^0 pole, $\chi_1^0\chi_1^0 \to A^0 \to b\bar{b}$, which results in a large reduction of its relic density, Ω_χ. For the relic density calculation, the measurement of the A^0 mass and width removes a major source of uncertainty. For dark matter direct detection, these are equally important for calculating the scattering cross section, since the dominant contribution comes most often from Higgs boson exchange diagrams. The analysis of H^0A^0 has to identify the 4-b jets with high efficiency, since the expected cross section is $\mathcal{O}(1$ fb$)$ and, with four jets to tag, the efficiency is $\propto \epsilon_b^4$, and small misidentification, since the expected background-to-signal ratio is $\mathcal{O}(5 \times 10^3)$. A linear collider is expected to directly observe these states almost up to the kinematical limit. Detailed studies have been performed assuming various collider energies and boson masses. For boson masses in the range $400 < M_A < 1100$ GeV, an ϵ_b efficiency of $\simeq 0.80$, or more, is desirable (see Figure 3).

SUSY loop contributions from $\tilde{t}$, $\tilde{b}$ and $\tilde{g}$ may induce sizable CP asymmetries in charged Higgs boson decays [13]. These can be observed by studying the observable $\delta CP = \frac{\Gamma(H^- \to b\bar{t}) - \Gamma(H^+ \to \bar{b}t)}{\Gamma(H^- \to b\bar{t}) + \Gamma(H^+ \to \bar{b}t)}$. For this measurement the heavy quark must be distinguished from its antiquark. This can be done either by looking at the charge of the leptons from semileptonic decays or from the vertex charge, which requires excellent control of the reconstruction of charged decay products [6].

Finally, a linear collider of sufficient energy offers a unique opportunity to study the Higgs potential through the measurement of the Higgs self-coupling. Simulation studies have shown that the role of an hadron collider in this study is marginal, unless it reaches several ab^{-1} of integrated luminosity or collision energies of $\mathcal{O}(100$ GeV$)$ [14,15]. At a linear collider the Higgs self coupling, g_{hhh}, can be accessed by measuring the cross section of the $h^0h^0Z^0$ and $h^0h^0\nu\bar{\nu}$ processes from 0.5 to 3 TeV [16]. Isolating the $h^0h^0Z^0$ signal (σ=0.18 fb at $\sqrt{s} = 0.5$ TeV) from $t\bar{t}$ (530 fb), $Z^0Z^0Z^0$ (1.1 fb), $t\bar{b}\bar{t}b$ (0.7 fb) and $t\,\bar{t}Z^0$ (1.1 fb) will be a genuine experimental tour-de-force. Again, b tagging is essential for background suppression, provided high efficiency is attained, given the tiny signal cross section. Preliminary studies performed at 0.5 TeV for the $h^0h^0Z^0$ channel have shown that once a realistic simulation of signal and backgrounds is performed the results are less optimistic, compared to those obtained with parametric simulations. A multi-TeV collider is in principle advantageous for this measurement, since the cross section for the $h^0h^0\nu\bar{\nu}$ process at 3 TeV is larger by a factor of seven and can be further increased by operating with polarised beams. Still the $W^+W^-\nu\bar{\nu}$ (125 fb), $Z^0Z^0\nu\bar{\nu}$ (54 fb), $W^+W^-Z^0$ (32 fb) and $Z^0Z^0Z^0$ (0.34 fb) backgrounds are significant. Further, most of the sensitivity to g_{hhh} is in the forward region, which poses challenges in terms of reconstruction.

Moving away from the Higgs sector, b quarks remain a leading signature for several scenarios of new physics. A class of SUSY models with large hierarchy between the scalars and the gauginos, the so-called split Supersymmetry, have recently been studied in detail [17]. In these models quarks and sleptons are heavy enough that charginos and neutralinos decay exclusively into $W^{\pm}$, Z^0 and h^0 bosons and lighter χ states. In particular, decays of the kind $\chi^0_{2,3,4} \to h^0\chi^0_{1,2}$ and $\chi^{\pm}_2 \to h^0\chi^{\pm}_1$, followed by $h^0 \to b\bar{b}$ may be dominant [18]. These features are also common to mSUGRA models with large values of m_0, $m_{1/2}$ and $\tan\beta$. All these give remarkable events with four b-jets and large missing energy, which would be the gaugino sector counterpart of the events from heavy Higgs decays discussed above.

The study of precision electro-weak observables in two-fermion production opens an window on phenomena at mass scales well above the collider collision energy. The $e^+e^- \to b\bar{b}$ and $e^+e^- \to t\bar{t}$ processes are important in this respect because they allow us to select samples of down- and up-type quarks selected with good purity. In addition, models of warped extra dimensions with bulk SM fields have excitations strongly coupled to quarks of the third generation. These excitation may be heavier that the $\sqrt{s}$ energy of the collider [19]. In this case, deviations to the cross section and forward-backward asymmetries in the $b\bar{b}$ and $t\bar{t}$ two-fermion processes, should be detectable at a multi-TeV linear collider up to masses of $\mathcal{O}(10\text{ TeV})$

In summary, the b- and c-tagging efficiency has to be large for most of the anticipated studies, which are characterised by large jet multiplicity and low signal-to-background ratios. The systematics coming from input parameters in the theory predictions and the efficiency of the jet flavour tagging also need to be minimised. Heavy quark masses play a major role in the interpretation of the Higgs sector data. Heavy hadron production and decay properties, in particular charged decay multiplicities ands fragmentation functions, are crucial to jet flavour tagging, which is based on the topology and kinematics of charged particle tracks. For this part, the linear collider program will largely rely on results obtained at lower energy heavy flavour experiments.

3. VERTEX TRACKERS FOR HEAVY FLAVOUR TAGGING

The crucial role of heavy flavour tagging at a linear collider has motivated the significant attention that the design of a vertex tracker and the choice of sensor technologies has received in the last decade. Vertex trackers at a future e^+e^- linear collider will face new and different challenges compared to those at LEP and LHC. The distinctive feature of linear collider physics is its anticipated accuracy for a large variety of measurements (spectroscopy, searches, rare decays, electro-weak observables, ...) to be performed over a broad energy range. The target performance for the track extrapolation resolution is $\sigma_{IP} = 5\mu\text{m} \oplus \frac{10\mu\text{m GeV}^{-1}}{p_t}$ for operation below 1 TeV and $5\mu\text{m} \oplus \frac{20\mu\text{m GeV}^{-1}}{p_t}$ for a multi-TeV collider, where the larger particle boost and energy is expected to compensate at least in part the larger distance of the detector from the beam, dictated by beam-induced backgrounds. This performance makes possible the detailed reconstruction of the decay topology in hadronic jets containing a b or a c quark. This reconstruction allows us to identify not only b jets with high efficiency, $\epsilon_b = 0.80$ with a misidentification probability of 0.02 and 0.25 for u, d, s and c quarks, respectively, but also c jets with high purity, even when the main background consists of b jets, $\epsilon_c = 0.30$ with 0.07 misidentification probability for b [6]. This is the case of the $h^0 \to c\bar{c}$ decay for $M_h = 120$ GeV, where the dominant $h^0 \to b\bar{b}$ decays constitute the main background, giving a signal-to-background ratio of 0.05. The asymptotic track extrapolation resolution can be obtained with a single point resolution of $\simeq 3$ μm and the multiple scattering term implies a single layer thickness of $\simeq 0.1$ % X_0. The single point resolution corresponds to a pixel size of 10-30 μm with binary or analog readout. The layer material budget requires $\simeq 50$ μm-thick sensors and puts significant constraints on the chip power dissipation, which should be kept compatible with passive cooling. Data can be readout either continuously during the train of colliding bunches to keep the detector occupancy low, corresponding to a readout time of 25-50 μs at the ILC, or stored locally with a time stamp and readout in between trains, depending on the pixel granularity and the read-out architecture chosen. In the case of CLIC, where the bunch spacing is only 0.5 ns, time stamping to $\simeq$10-20 ns is likely required to keep the occupancy low and to identify tracks from $\gamma\gamma \to$ hadrons produced outside of the time bucket of the main e^+e^- collision of interest.

Radiation conditions are significantly lower compared to those faced by the LHC detectors and novel sensor technologies can be exploited. The main path of R&D to match the linear collider requirements is towards detectors which have substantially lower material budget and higher space, or space-time granularity, compared to those developed for the LHC. This can be achieved with monolithic technologies, where the sensitive volume and at least part of the signal processing electronics are implemented in the same Si wafer. CMOS active pixel sensors have demonstrated several appealing properties and have been adopted as baseline for detailed designs [20]. Beam hodoscopes made of pixel sensors of various technologies, developed for linear collider application have been successfully operated and demonstrated tracking performances meeting the LC requirements under realistic conditions [21,22,23,24] (see Figure 4). Some of these technologies have now reached a degree of maturity and reliability that makes them well suited for application in near-term projects. Vertex detector based on pixel sensors, originally developed for the ILC are currently under construction for the HFT upgrade of STAR at RHIC [25] and for Belle-2 at KEKB [26], based on the CMOS and DEPFET technologies, respectively. However, these still have limitations in readout speed and in amount of data processing performed directly in pixel. New technologies, potentially more performant and which may accommodate more advanced functionalities have recently emerged. Silicon-On-Insulator (SOI) with a high resistivity handle wafer brings together electronics in low feature size CMOS processese with a fully depleted sensitive substrate [27,28]. Multi-tier vertical integration techniques make possible to integrate heterogeneous technologies by stacking several thin layers with small pitch interconnect. This gives maximum freedom of choice for the use of optimal technologies for the various functions of the detector [29]. Both technologies are moving through the stages of a generic R&D exploring feasibility and issues of their use for particle

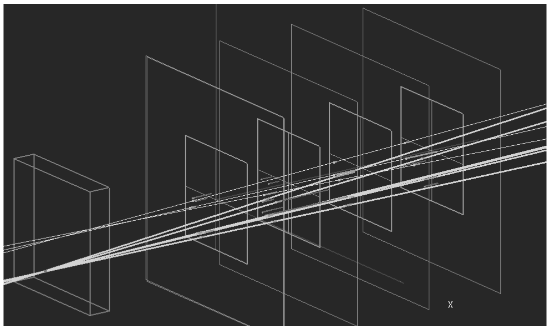

Figure 4. Display of a six-prong vertex from the interaction of an 120 GeV proton in a Cu target reconstructed with a beam hodoscope made of thin CMOS pixel sensors in the T966 beam test experiment at FNAL. The average resolution of the vertex position along the beam axis has been measured to be (260±10) μm, which corresponds to the vertexing resolution expected for a detector at CLIC (from [21]).

detection and design optimisation.

Sensor R&D motivated by the linear collider program has already found important applications in other project in HEP as well as fields of science outside of accelerator particle physics. Thin CMOS sensors with small, radiation tolerant pixels are successfully used in imaging in transmission electron microscopy, where their thin sensitive volume and high pixellisation is very advantageous and provides point spread function performances superior to photographic films at a frame rate of $\simeq$ 100 f/s [30]. DEPFET sensors have excellent energy resolution and are being developed for soft X-ray detection in planetary imaging [31] and XFEL [32] experiments.

REFERENCES

1. J. Brau *et al.*, SLAC-R-857 (2007).
2. R. W. Assmann *et al.*, CERN 2000-008.
3. C. G. R. Geddes *et al.*, Nature **431** (2004) 538.
4. A. G. R. Thomas *et al.*, Phys. Rev. Lett. **98** (2007) 095004 [arXiv:physics/0701186].
5. M. Battaglia and K. Desch, AIP Conf. Proc. **578** (2001) 163 [arXiv:hep-ph/0101165].
6. D. Bailey *et al.* [LCFI Collaboration], Nucl. Instrum. Meth. A **610** (2009) 573 [arXiv:0908.3019 [physics.ins-det]].
7. T. Kuhl and K. Desch, Note LC-PHSM-2007-001.
8. H. Stoeck *et al.*, The ILD Letter of Intent, 2009.
9. M. Battaglia and A. De Roeck, arXiv:hep-ph/0211207.
10. T. L. Barklow, arXiv:hep-ph/0312268.
11. A. Droll and H. E. Logan, Phys. Rev. D **76** (2007) 015001 [arXiv:hep-ph/0612317].
12. M. Battaglia and P. Ferrari, CERN-LCD-2010-006, arXiv:1006.5659 [hep-ex].
13. E. Christova *et al.*, Nucl. Phys. B **639** (2002) 263 [Erratum-ibid. B **647** (2002) 359] [arXiv:hep-ph/0205227].
14. U. Baur, T. Plehn and D. L. Rainwater, Phys. Rev. D **67** (2003) 033003 [arXiv:hep-ph/0211224].
15. U. Baur, T. Plehn and D. L. Rainwater, Phys. Rev. D **69** (2004) 053004 [arXiv:hep-ph/0310056].
16. M. Battaglia, E. Boos and W. M. Yao, in *Proc. of the APS/DPF/DPB Summer Study on the Future of Particle Physics (Snowmass 2001)* ed. N. Graf, E3016, [arXiv:hep-ph/0111276].
17. N. Arkani-Hamed *et al.*, Nucl. Phys. B **709** (2005) 3 [arXiv:hep-ph/0409232].
18. N. Bernal, A. Djouadi and P. Slavich, JHEP **0707** (2007) 016 [arXiv:0705.1496 [hep-ph]].
19. R. Contino *et al.*, JHEP **0705** (2007) 074 [arXiv:hep-ph/0612180].
20. R. De Masi *et al.*, to appear on Nucl. Instrum. Meth. A (2010), doi:10.1016/j.nima.2010.06.339.
21. M. Battaglia *et al.*, Nucl. Instrum. Meth. A **593** (2008) 292 [arXiv:0805.1504 [physics.ins-det]].
22. J. J. Velthuis *et al.*, IEEE Trans. Nucl. Sci. **55** (2008) 662.
23. P. Roloff, Nucl. Instrum. Meth. A **604** (2009) 265.
24. J. Baudot *et al.*, IEEE Trans. Nucl. Sci. **56** (2009) 1677.
25. L. Greiner *et al.*, Nucl. Instrum. Meth. A **589** (2007) 675.
26. L. Andricek *et al.*, to appear on Nucl. Instrum. Meth. A (2010), doi:10.1016/j.nima.2010.02.191.
27. Y. Arai *et al.*, to appear on Nucl. Instrum. Meth. A (2010), doi:10.1016/j.nima.2010.02.190.
28. M. Battaglia *et al.*, Nucl. Instrum. Meth. A **604** (2009) 380 [arXiv:0811.4540 [physics.ins-det]].
29. R. Yarema *et al.*, Nucl. Instrum. Meth. A **617** (2010) 375.
30. M. Battaglia *et al.*, to appear on Nucl. Instrum. Meth. A (2010), doi:10.1016/j.nima.2010.07.066.
31. J. Treis *et al.*, to appear on Nucl. Instrum. Meth. A (2010), doi:10.1016/j.nima.2010.03.173.
32. M. Porro *et al.*, to appear on Nucl. Instrum. Meth. A (2010), doi:10.1016/j.nima.2010.02.254.