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Physics opportunities with multi-TeV e^+e^- collisions

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Summary. — Multi-TeV e^+e^- collisions offer unique opportunities to perform particle physics experiments at constituent centre-of-mass equivalent to those of the LHC with elementary probes of well-defined initial energy and quantum numbers. The anticipated physics program and experimental challenges of the CLIC linear collider project are discussed including those scenarios which test the relations between particle physics and cosmology through dark matter.

PACS `29.20.Ej` – Linear accelerators.
PACS `14.80.-j` – Other particles (including hypothetical).

1. – Introduction

The last two generations of experiments at both e^+e^- colliders, LEP, SLC and the B-factories, and hadron colliders, the Tevatron, have confirmed the validity of the Standard Model (SM) to an increasing degree of accuracy and in different sectors of the theory. Now, with the start of operation at the LHC, we do expect that enough data collected at increasing proton energies will eventually unveil signals of the last missing piece of the SM, the Higgs sector, and, possibly, of New Physics (NP) beyond. The confirmation of the existence of the Higgs field, the determination of the mass of the Higgs boson and an indication of the nature and mass scale of New Physics will also offer us the inputs we need to plan towards the next large-scale facility in accelerator particle physics. Since more than two decades intense programs of studies and R&D for a linear e^+e^- collider and, to a lesser extent, for a high-energy muon collider have been pursued.

Most of this work has addressed the technical problems and physics issues related to an e^+e^- collider with centre-of-mass energies, $\sqrt{s}$, ranging from $\simeq 250\,\mathrm{GeV}$, just above that of LEP-2, up to $\simeq 1\,\mathrm{TeV}$, but with major emphasis on $\sqrt{s} = 0.5\,\mathrm{TeV}$ and has resulted in the development of the ILC project [1]. Despite the fact that we do not know of any resonance or physics process specific for this energy, 0.5 TeV has been adopted as the confluence of physics and technical considerations. Given the gradients attainable with conventional RF cavities and a manageable tunnel length, a machine able to deliver collisions at $\simeq 0.5\,\mathrm{TeV}$ with high luminosity appears technically feasible.

TABLE I. – *Main CLIC parameters (from* [3] *and updates).*

$\sqrt{s}$ (TeV)	3
Total Luminosity ($\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$)	6×10^{34}
Linac rep. rate (Hz)	5
No. of e^-/bunch (10^{10})	0.37
No. of bunches/pulse	312
Linac RF frequency (GHz)	11.994
Gradient unloaded/loaded (MV/m)	120/100
Total site length (km)	48.3
Bunch separation (ns)	0.5
Beam size at IP (x, y) (nm)	45, 0.9
Beamstrahlung momentum spread, δ_B	29%
No. of photons/e^-, n_γ	2.2
No. of coherent pairs/BX	3.8×10^8
No. of incoherent pairs/BX	3.0×10^5
No. of $\gamma\gamma \to$ hadrons/BX	3.3

The CLIC (Compact LInear Collider) project, started at CERN around 1987. Its original goal was an e^+e^- collider with $\sqrt{s} = 1$ TeV and luminosity of $1.1 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ [2]. By now CLIC has developed into an international collaboration with thirty-three institutions from eighteen countries and it aims to increase the beam energy into the multi-TeV region by replacing the conventional RF cavities with a two-beam acceleration scheme, where a low-energy, high current drive beam is used to accelerate a lower intensity main beam. CLIC transfer structures have already attained gradients in excess of 100 MV/m and significant R&D is now providing proofs of principles of the remaining open issues. The main parameters for a 3 TeV linear collider based on the CLIC scheme [3] are given in table I. In a farther future, plasma wake-field acceleration may become an attractive solution for an high energy e^+e^- collider [4], by providing even higher gradients.

2. – New Physics in multi-TeV e^+e^- collisions

Approval and construction of a new collider at multi-TeV energies will most likely occur only after the LHC results will have clearly indicated that new physics exists at a mass scale of $\mathcal{O}(1\,\mathrm{TeV})$ with a significant phenomenology to be explored at the new machine. In preparation for that, physics and detector studies are assessing the physics potential of a multi-TeV collider with the CLIC parameters for a broad variety of scenarios, develop performant yet robust event reconstruction algorithms to cope with the anticipated experimental conditions and contribute to the optimisation of the machine parameters. The physics case for a multi-TeV e^+e^- collider was already outlined in a study carried out in 2001-2003 [5]. Those results represent the basis for the current investigation of the experimental issues of multi-TeV physics through a program of studies performed on detailed simulation and reconstruction of physics processes and realistic backgrounds.

The best motivated NP scenario for these studies is Supersymmetry (SUSY). Not only SUSY provides solutions to the limitations of the Standard Model, but it also offers us a viable candidate for dark matter. SUSY has been extensively used as a template for New Physics scenarios with a rich spectroscopy and a conserved quantum number. One of the main issues we face discussing SUSY at a future collider is the vast parameter space available, even when restricting ourselves to highly constrained models, such as the cMSSM. In recent years there has been a great effort to identify regions of this parameter space which appear to be most likely, given the data collected so far, both at particle colliders and at satellites [6,7]. By combining the electroweak results from LEP, SLC and Tevatron with lower energy experiments, the limits from direct searches at LEP-2 and the Tevatron and requiring the lightest neutralino, to be responsible for relic dark matter, as measured by the WMAP satellite [8], only narrow regions of the parameters are compatible with data. Still, this does not fix the expected SUSY mass scale. Solutions with heavy new particles are in fact compatible with collider and cosmology data. Some of the scenarios with high likelihood include rather light new particles, which should be observed at the LHC with $\simeq 1\,\mathrm{fb}^{-1}$, or less. However, mass spectra extending up to 1 TeV and beyond are also likely to exists. For example ref. [7] uses fifteen observables (electroweak, B physics, $(g-2)_\mu$ and Ωh^2) to determine the most likely SUSY spectrum in the cMSSM and NUHM1 models. The cMSSM spectrum has all the gauginos, Higgs bosons and sleptons lighter than 500 GeV but that of the NUHM1 model has the $\chi^0_{3,4}$ and $\chi^\pm_2$ with masses around 900 GeV. In another SUSY scenarios where the lightest SUSY particle is the gravitino, long-lived staus may form metastable states with nuclei which affect the Big Bang Nucleosynthesis. By taking the parameters of this model which yield the ^{6}Li and ^{7}Li abundances in the range favoured by astrophysical observations, the authors of ref. [9] obtain sleptons and gauginos with masses well above 1 TeV. More in general, since only gauginos and higgsinos need to be relatively light to achieve unification and provide a dark matter candidate, sfermions can be chosen to be heavy and decouple. These models are known as split-SUSY and represent a major challenge for both hadron and lepton colliders [10]. This motivates the continuing efforts towards accelerators able to deliver e^+e^- collisions at the highest energies.

The analytical power of CLIC has been studied for a specific high mass SUSY scenario compatible with neutralino dark matter. This scenario, point K$'$ of ref. [11], is characterised by rather heavy particles, with kinematic thresholds for pair production around 2.5 TeV for sleptons and between 2 and 3 TeV for charginos and neutralinos. Squarks and the gluino are even heavier and thus inaccessible in 3 TeV collisions, as well as at the LHC. Percent to few per-mil accuracy on the supersymmetric particle masses can be obtained at CLIC by combining data at the highest energy with dedicated scans of at least some of the pair production thresholds (see fig. 1). The use of beam polarisation, for which we could expect $\mathcal{P}_- \simeq 80\%$ and $\mathcal{P}_+ \simeq 60\%$, enhances the signals and/or suppresses some of the dominant SM backgrounds and also acts as an analyser in the operation at the highest energy. In order to be predictive of the neutralino relic density, measurements of gaugino and slepton masses need to be supplemented by a precise determination of the mass, and possibly the width, of the A^0 Higgs boson. This is achieved by studying the pair production process H^0, $e^+e^- \to H^0A^0$. For the chosen benchmark point, $M_A = 1.14$ TeV and the production cross-section is $\simeq 0.3$ fb at $\sqrt{s} = 3$ TeV. The dominant decays into $b\bar{b}$ pairs give the signal a very distinctive signature with four b-jets in spherical events. With $3\,\mathrm{ab}^{-1}$ of integrated luminosity, the A^0 mass can be determined to a relative accuracy of 0.3–0.5% when accounting for machine-induced backgrounds, provided adequate detector time stamping capabilities (see fig. 4).

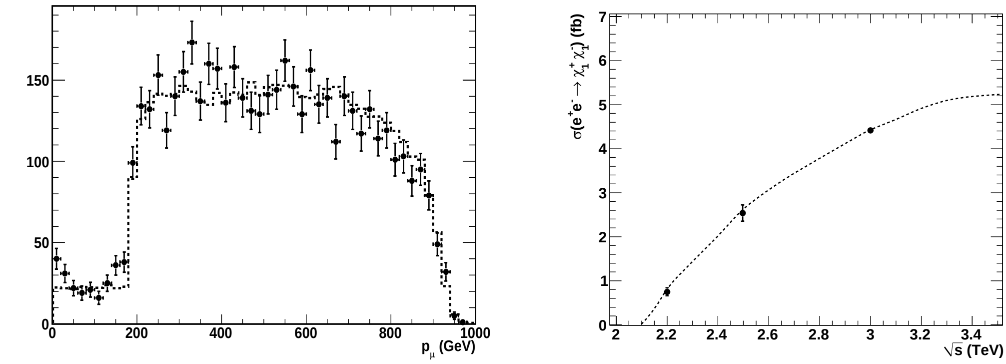

Fig. 1. – Momentum distribution for $\tilde{\mu}$ decays at 3 TeV and cross-section for $\chi_1^\pm$ pair production as a function of the $\sqrt{s}$ energy for the SUSY benchmark point K′. The combination of fits to the kinematic distributions at the highest energy with threshold scan provide accurate determination of SUSY particles, including the lightest neutralino.

The tiny cross-sections of supersymmetric particle pair production in this scenario underline the crucial importance of high total luminosity, the availability of beam polarisation and the flexibility of operation at energies below the maximum design value. By combining the results from this preliminary study, we estimate the statistical accuracy with which neutralino relic density, $\Omega_\chi h^2$, can be predicted to $\simeq 0.11$, which is comparable to those obtained for other SUSY benchmarks of lower mass [12].

Operation at the highest $\sqrt{s}$ energy offers sensitivity also to new resonances over a broad mass range, through auto-scan with the beamstrahlung tail of the luminosity spectrum. These are expected in scenarios with extra gauge bosons or with Kaluza-Klein excitations of the SM particles from extra-dimensions. Figure 2 shows an example of one of such signals in the the $\mu^+\mu^-$ invariant mass spectrum corresponding to $1\,\mathrm{ab}^{-1}$ of statistics taken at $\sqrt{s} = 3\,\mathrm{TeV}$ for a 4-site Higgs-less model with two additional neutral

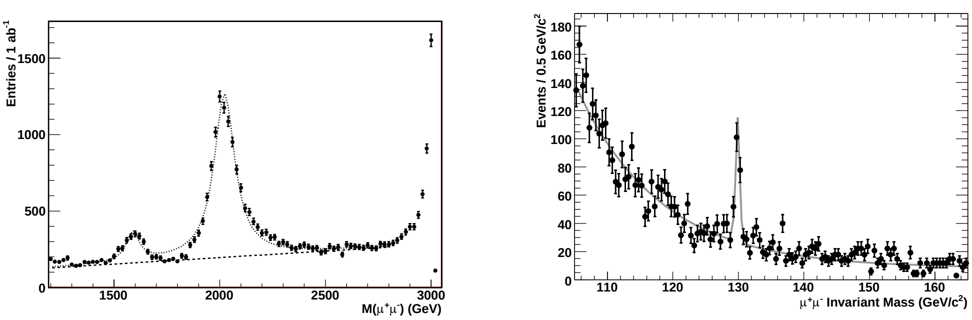

Fig. 2. – Signals at CLIC in the di-muon invariant-mass spectrum at 3 TeV. (Left) Signal of two Z' resonances obtained by auto-scan. The values of the two masses are extracted from a fit to the spectrum giving $\pm 3.5\,\mathrm{GeV}$ and $\pm 1.2\,\mathrm{GeV}$ statistical accuracy. (Right) $H^0 \to \mu^+\mu^-$ signal over the $\mu^+\mu^- + E_{\mathrm{missing}}$ background for $M_H = 130\,\mathrm{GeV}$ and $5\,\mathrm{ab}^{-1}$ of integrated luminosity (from [16]).

gauge bosons, Z'_1 and Z'_2 [13, 14]. If any of such resonances were observed, a program resembling the Z^0 physics runs at LEP would follow to determine the nature of the observed particle(s). In this program, the study of electroweak observables such as the A_{FB} and A_{LR} asymmetries in two fermions final states would be crucial. Even if no new resonance is detected, the study of these electroweak observables at the highest available energy would be important to indirectly probe NP at scales of 20–100 TeV.

3. – Standard Model Physics in multi-TeV e^+e^- collisions

Despite the scale of electroweak symmetry breaking being $\mathcal{O}(100\,\text{GeV})$, there are good reasons to study the SM at multi-TeV energies. The first is that the cross-section of some processes, such as the Higgs boson production through gauge boson fusion, increases logarithmically with the energy. This makes Higgs coupling measurements already at 1 TeV potentially more precise than those at 0.35–0.5 TeV [15]. At 3 TeV, 5.5×10^5 (2×10^5) SM Higgs bosons with mass of 120 GeV (600 GeV) are produced per ab^{-1} of integrated luminosity with unpolarised beams, which exceeds the statistics achievable at 350 GeV by a factor of $\simeq 3.5$ for $M_H = 120\,\text{GeV}$. With a statistics of 10^6 Higgs bosons or more, depending on the availability of polarised beams, its rare decays can be studied with enough accuracy to perform sensitive tests of the SM. The first of such decays is $H^0 \to \mu^+\mu^-$. This process offers a unique opportunity to test the mechanism of mass generation in the charged lepton sector by comparing the ratio of the Higgs coupling constant to muons and taus, $g_{H\mu\mu}/g_{H\tau\tau}$, to that of their masses, M_μ/M_τ. The $g_{H\tau\tau}$ coupling for an 120 GeV Higgs boson can be measured to a relative accuracy of ± 0.035 at lower energies. For $M_H = 120$–$150\,\text{GeV}$, the mass interval favoured by electroweak observables, the branching fraction $\text{BR}(H^0 \to \mu^+\mu^-)$ varies from 2.6×10^{-4} to 6.5×10^{-5}. The LHC may only obtain a signal for the $H^0 \to \mu^+\mu^-$ decay with 3σ significance, even by combining the data of the ATLAS and CMS experiments for $300\,\text{fb}^{-1}$ of integrated luminosity at 14 TeV. Neither the ILC can obtain a significant signal at 0.5 TeV. At CLIC the signal is observable for masses up to $\simeq 155\,\text{GeV}$ and the $g_{H\mu\mu}$ coupling measurable with a relative statistical accuracy of 0.04-0.08, for $M_H = 120$–$150\,\text{GeV}$, with $3\,\text{ab}^{-1}$ of data (see fig. 2) [16].

If the Higgs boson is heavier, and the W^+W^- decay channel is accessible, the $b\bar{b}$ mode, dominant for lighter masses, quickly decreases in rate and becomes a rare mode with branching fraction of the order of 2×10^{-3} for $M_H = 200\,\text{GeV}$. In such a case, the measurement of the process $e^+e^- \to \nu\bar{\nu}H^0 \to \nu\bar{\nu}b\bar{b}$ offers the only opportunity to study the Higgs mechanism in the fermion sector, the decays to gauge bosons being dominant. The large Higgs sample which can be collected at 3 TeV makes in principle feasible for CLIC to observe the $b\bar{b}$ decay and accurately determine the g_{Hbb} coupling. Since the cross-section peaks in the forward region, good parton reconstruction and b-tagging down to small angles are required. Finally, double Higgs production has a favourable cross-section in multi-TeV collisions through the $e^+e^- \to H^0H^0\nu\bar{\nu}$ process for a light Higgs boson [17]. Again this represents a unique opportunity to test the Higgs potential through the determination of the triple Higgs coupling. In fact, the sensitivity to triple Higgs coupling appears marginal both at the LHC [18, 19] and, in the $H^0H^0Z^0$ process, at a 0.5 TeV linear collider. As for the case discussed above the main challenge at CLIC is in the requirement of good parton reconstruction and b-tagging down to small angles, since the part of the $HH\nu\bar{\nu}$ cross-section sensitive to the triple Higgs coupling is forward peaked.

At multi-TeV energies, very heavy Higgs bosons, with masses in the range 500–900 GeV can be studied independently of their decay properties in the ZZ fusion

TABLE II. – *Scaling of SM event characteristics with* $\sqrt{s}$.

$\sqrt{s}$ (TeV)	0.2	0.5	1.0	3.0
$N_{\rm jets}$	4.2	4.8	5.6	6.4
$E_{\rm parton}$ (GeV)	32	64	110	240
d_B (cm)	0.3	0.9	3.0	9.0

channel $e^+e^- \to e^+e^-H^0 \to e^+e^-X$ by a reconstruction of the recoil mass of the e^+e^- final states. This process, which is the high-energy counterpart of the well-known Higgstrahlung process, makes it possible to detect and determine mass and width for Higgs bosons with non-standard couplings. In this analysis it is essential to reconstruct electrons within 100 mrad from the beam axis within the pair background.

The second set of measurements specific to collisions above 1 TeV is the study of the dynamics of WW scattering. If the electroweak symmetry breaking is not due to the Higgs mechanism, the $e^+e^- \to W^+W^-\nu\bar{\nu}$ and $e^+e^- \to Z^0Z^0\nu\bar{\nu}$ processes may reveal new dynamics of gauge boson interactions. The experimental signatures are represented by deviations of the $e^+e^- \to W_LW_L\nu\bar{\nu}$ cross-section from the SM prediction and the formation of vector resonances at masses above 1 TeV. Even if the Higgs boson exists, it is of great interest to study the $e^+e^- \to W^+W^-\nu\bar{\nu}$ cross-section as a function of the W^+W^- invariant mass to test that the Higgs mechanism removes the strong WW scattering.

4. – Experimental issues for multi-TeV e^+e^- collisions

Carrying out experimentation at multi-TeV energies implies a number of new issues, compared to a sub-TeV collider, which require careful consideration. These include event topologies with large hadronic jet multiplicities, collimated particles and long flying short-lived hadrons, higher machine-induced backgrounds and shorter separation between colliding bunches. Table II summarises some of the characteristics of SM events in terms of particle and jet multiplicities for e^+e^- collisions from LEP-2 to CLIC. Signal processes may be characterised by very large jet multiplicities up to the eight parton final state of $e^+e^- \to H^+H^- \to t\bar{b}\bar{t}b \to b\bar{b}q\bar{q}\bar{b}bq\bar{q}$, in Supersymmetry, or the twelve partons of $e^+e^- \to t\bar{t}t\bar{t} \to b\bar{b}q\bar{q}q\bar{q}b\bar{b}q\bar{q}q\bar{q}$, a signal for models of new physics with an extra Z' boson strongly coupled to the top quark, discussed in another contribution in this issue [20].

Machine-induced backgrounds, negligible at LEP, will become significant for the parameters of a 0.5 TeV collider and definitely important at CLIC at 3 TeV. There are three main sources of such backgrounds which affect the detector: incoherent pairs, $\gamma\gamma$ interactions and parallel muons. Incoherent pairs are produced in the intense electromagnetic interaction of the colliding beams and are deflected by the intense electric fields. Deflected pairs define the minimum radius of the beam pipe and of the innermost sensitive layer. At the 0.5 TeV ILC this radius is estimated $\simeq$ 16 mm and becomes $\simeq$ 32 mm at CLIC for $\sqrt{s} = 3$ TeV, where we expect on average $\simeq 0.02$ hits mm^{-2} BX^{-1}.

$\gamma\gamma$ collisions arise from photons radiated in the electromagnetic interactions of the colliding beams. Products of $\gamma\gamma$ interactions overlap with those from the main e^+e^- interaction creating a source of potential confusion for the event reconstruction, in particular in the forward region. At $\sqrt{s} = 0.5$ TeV there are on average $\simeq 0.1\gamma\gamma \to$ hadrons events/BX. At 3 TeV CLIC these become 3.3 events/BX in which $\simeq$ 33 particles/BX are

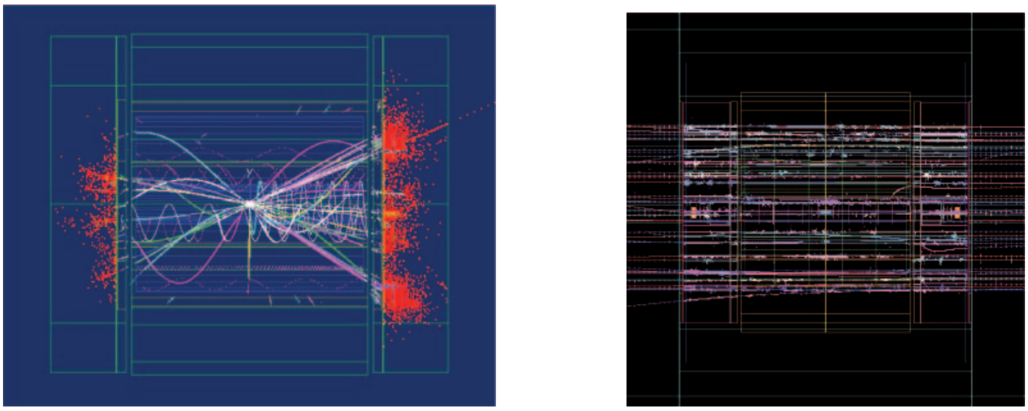

Fig. 3. – Machine-induced backgrounds at CLIC. $\gamma\gamma \to$ hadrons events overlayed to a simulated $e^+e^- \to \nu\bar{\nu}H^0 \to \nu\bar{\nu}b\bar{b}$ (left panel) and fifty simulated parallel muons tracked through the detector (right panel).

produced, depositing on average $\simeq 44$ GeV of energy per BX. Finally, the interactions of halo particles with the beam scrapers in the beam delivery region produce high-energy muons, mostly through the Bethe-Heitler process, which can reach the detector. The estimated flux of muons is 1.6×10^3 muons/BX for 2×10^{-4} of the electrons in the bunch to hit the spoilers. The average energy of these muons is $\simeq 200$ GeV and, due to their radial distribution, they are expected to affect most the calorimeters (see fig. 3). Their flux can be largely reduced by filling the tunnel with magnetised muon absorbers. However, the SLC operation experience has taught us that the amount of particles in the beam halo can be substantially larger than foreseen and the effect of a significant flux of parallel muons on the measured calorimetric energy and the muon tag purity has to be assessed.

The combination of increased background rates and very short spacing between bunches presents new challenges to experimentation. In particular, very good space-time granularity will be required for the detectors. Time granularity is needed primarily to mitigate the overlay of energy from $\gamma\gamma \to$ hadrons events (see fig. 3). A full pulse of CLIC bunch crossings deposits five times more energy in the detector in $\gamma\gamma$ background events than an e^+e^- collision. Space granularity is dictated by the high collimation of hadronic jets carrying energies up to that of the beams and the incoherent pair background. The fraction of particle tracks in $e^+e^- \to W^+W^-$ events which are closer than 2 mm from another track at a radius of 45 cm is 5×10^{-3} at 0.2 TeV, 1.5×10^{-2} at 0.5 TeV and becomes 7×10^{-2} at 3 TeV. In $e^+e^- \to W^+W^-\nu\bar{\nu}$ events at 3 TeV, 20% (35%) of the neutral clusters will have an energy deposition by a charged particle within 20 mm in the electromagnetic (hadronic) calorimeter. Due to these event characteristics, it is necessary to reassess the performance of particle flow for parton energy reconstruction. Most of the interesting SM processes are characterised by production cross-sections which are peaked in the forward region. In order to profit from the favourable cross-sections obtainable in multi-TeV collisions, it is essential to ensure good parton reconstruction and jet flavor tagging down to small angles.

Not only the detector needs to be adapted to the experimental conditions. Due to the energy overlayed by background events, also the strategies for reconstructing parton energy and direction through jet clustering needs to be revised. At LEP-2, and at a 0.5 TeV collider, a common reconstruction procedure is to force particles in the event into

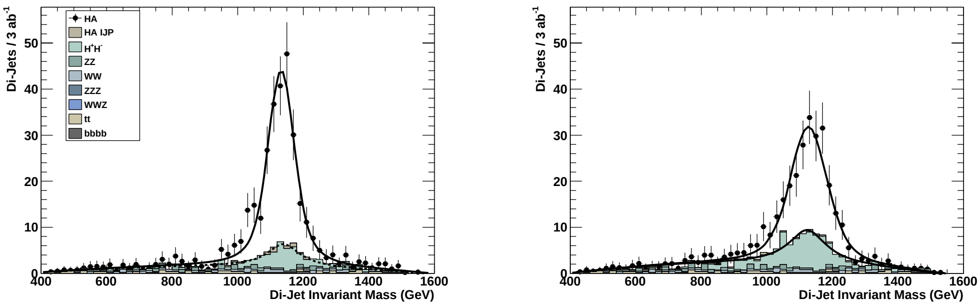

Fig. 4. – Di-jet invariant mass distribution for $e^+e^- \rightarrow H^0A^0 \rightarrow b\bar{b}b\bar{b}$ with no (left panel) and 40 BX (right panel) of overlayed $\gamma\gamma$ background for $3\,\mathrm{ab}^{-1}$ of integrated luminosity at $\sqrt{s} = 3\,\mathrm{TeV}$.

a number of jets which matches the number of partons expected for the process of interest. The values of the cut-off parameters at which the number of naturally reconstructed jets would change by ± 1 are then used to reject background events with more or fewer partons than the signal. If the number of $\gamma\gamma$ interactions overlayed to an e^+e^- event becomes significant, as we expect at CLIC, a more inclusive technique, accounting for the extra particles flowing in the event, needs to be applied. There are several paths which can be explored. In the presence of b jets, the b-hadron flight direction, which can be reconstructed topologically with a performant vertex tracker, can be used to seed the jet clustering. More generally, jet clustering algorithms developed for the LHC [21], which are more robust against underlying background events, may be usefully applied in multi-TeV e^+e^- events.

Preliminary results suggest that a time stamping of the order of 10–20 ns would be adequate to guarantee the precision of the CLIC measurements, at least for those processes contained in the barrel region. Figure 4 shows the di-jet invariant-mass distribution for the $e^+e^- \rightarrow H^0A^0 \rightarrow b\bar{b}b\bar{b}$ process discussed without and with $\gamma\gamma$ background overlayed. Due to the favourable kinematics of the signal events with no missing energy, balanced and energetic b-jets, the di-jet mass resolution can be significantly improved by performing a constrained kinematic fit, accounting for beamstrahlung. This fit also mitigates the impact of overlayed $\gamma\gamma$ background events up to $\simeq$ 30–40 BXs, corresponding to detector time stamping accuracies of 15–20 ns. Under these conditions, the heavy boson mass can be determined with a relative statistical accuracy of $\simeq 0.05$ [22].

5. – The work ahead: Studies and R&D

e^+e^- collisions at multi-TeV energies offer us the unique opportunities to probe physics with elementary particles of (rather) well-defined energy and quantum numbers over an unmatched energy range from $\simeq 0.5\,\mathrm{TeV}$ up to constituent energies matching those of the LHC. We expect this to open up new horizons through precision studies of both New Physics and the Standard Model, which may not be feasible elsewhere. In particular, CLIC data will be crucial for establishing the connection between Cosmology and New Physics, if the New Physics mass scale is of order of 1 TeV. The physics potential of a 1–3 TeV collider appears very rich. Preserving the event reconstruction accuracy, which has been a signature feature of e^+e^- experiments so far, will be a challenge, which needs to be addressed by a combined effort from physics benchmarking, detector R&D

and machine parameter optimisation. The R&D required for a detector optimised for multi-TeV collisions matches well the current efforts for a 0.5 TeV ILC, and for the LHC upgrades. Operation at multi-TeV energies further stresses issues already highlighted by the ILC R&D, such as high detector granularities, while new requirements emerge, in particular related to fast time stamping. The optimal balance between very high precision at high energy, as expected by the ILC, and high precision at very high energy, as promised by CLIC, can only be assessed with the LHC physics results at hand. Therefore, while waiting for these results, there is a compelling case for vigorously pursuing R&D and studies for CLIC, which offers an extremely appealing opportunity to attain multi-TeV e^+e^- collisions with high luminosity.

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