The Legacy of LEP/SLC at the High Energy Frontier: CLIC

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The CLIC accelerating technology aims at delivering e^+e^- collisions in the multi-TeV regime. The physics opportunities of such a facility as well as experimental challenges are discussed.

1. Introduction

The closing of LEP marks the end of an era for CERN, and at the same time the start of a new one: the preparation for the LHC. LEP has produced a plethora of precision measurements putting the Standard Model (SM) to the test, but no firm evidence of new physics was discovered.

While the LHC is expected to be the machine that will break open the TeV scale and provide the first signals for physics beyond the SM, it has now been generally agreed that a future next high energy accelerator should be a linear e^+e^- collider. Much of the confidence in a lepton collider as a complementary machine to the LHC results from 12 years of experience with LEP.

The e^+e^- linear collider (LC) projects which are most advanced to date propose a machine that will operate with an initial center of mass system (CMS) energy of about 500 GeV, and will be upgradable to about 1 TeV [1].

CERN on the other hand has opted to study acceleration techniques to achieve beams for multi-TeV collisions. The physics case for the multi-TeV e^+e^- collider is driven by the following scenarios:

- The study of the Higgs
  For a light Higgs, a multi-TeV e^+e^- collider can access with high precision the triple Higgs coupling, and measure rare Higgs decays such as $H \to \mu\mu$. Heavy (e.g. SUSY) Higgses can be discovered and measured up to and beyond 1 TeV.

- Supersymmetry
  If discovered, precise measurements of sparticles properties (flavor, mass, width, couplings) will be needed to fully pin down and test the underlying theory. In many scenarios sparticles with masses larger than 500 GeV are predicted. Polarized beams will help disentangle mixing parameters and aid CP studies. Ultimately we *need* to measure all sparticles as precisely as possible.

- New resonances
  If new resonances appear in the TeV region, as anticipated by many alternative models (e.g. new gauge bosons, Kaluza-Klein resonances, or W_LW_L resonances), a multi-TeV collider becomes a particle factory, similar to LEP for the Z.

- No new particles
  If *no* new particles, apart from the Higgs at the LHC/Tevatron, are observed directly, then a multi-TeV collider will probe new physics indirectly (extra dimensions, Z', contact interactions) at 300-400 TeV scales via precision measurements.

- Unexpected phenomena
  Perhaps Nature has chosen a road as yet not explored (extensively) by our imagination. Recent examples of new ideas are string quantum gravity effects, non-commutative effects, black hole formation...

The CLIC project at CERN is studying the feasibility of an e^+e^- linear collider optimized for a CMS energy of 3 TeV with $\mathcal{L} \cong 10^{35}\text{cm}^{-2}\text{s}^{-1}$, using a novel technique called two-beam acceleration [2]. High luminosity is required due to the $1/s$ dependence of the cross sections of s-channel processes. Fusion processes will actually often be dominant in the multi-TeV region.

At CLIC a so called drive beam of low energy but high current is decelerated, and its energy is transferred to the main low current beam, which gets accelerated with gradients in the range of 100-200 MV/m. With an upgrade program a maximum energy of 5 TeV is foreseen.

Several test facilities (CTF1, CTF2) [4] have been built over the past 5 years which have succeeded in demonstrating the principle of two beam acceleration. So far, in CTF2 one has reached gradients of 70 MV/m (15 ns pulses), and 150 MV/m (3 ns pulses). A new test facility, CTF3 [5], is proposed for 2002-2006 to test the drive beam generation concept, after which one can plan for a full technical design of the accelerator. CLIC, if decided to be built, is likely to start off at lower energy, possibly with a Higgs factory in $\gamma\gamma$ mode as proposed in [6]. A CLIC collider will also include the e^-e^-, $e\gamma$ and $\gamma\gamma$ collider options, and polarized beams.

The machine parameters [2] needed to achieve these energy and luminosity values lead to operate the machine in the high beamstrahlungs region, presenting important challenges for experiments at CLIC. The beam-beam effects result in considerable backgrounds and a distortion of the luminosity spectrum. E.g. the effective luminosity available with 1% of the peak energy is only 30% for a 3 TeV CLIC.

Based mostly on the experience at LEP/SLC, detectors for e^+e^- LCs have been conceptually designed [7]. The lessons from LEP/SLC dictate us to put sufficient emphasis on tracking resolution, jet flavor tagging, energy flow, hermeticity, precise vertexing, and high calorimeter granularity. However the multi-TeV high energy frontier leads to new challenges such as timing (<1 ns distance between bunches), energy flow (many highly collimated jets), and flavor tagging. Table 1 shows that at $\sqrt{s} = 3$ TeV the B mesons produced in $b\bar{b}$ events decay on average a distance of 9.0 cm from the primary vertex! For the CLIC studies a technique based on multiplicity increase versus distance from the vertex has been developed [8] to search for B-decays, with high efficiency. Furthermore at LCs the background in the interaction region requires the use of a mask. For CLIC the mask will cover the region below 120 mrad; electron/photon tagging will be possible down to 40 mrad with detectors in the mask.

$\sqrt{s}$ (TeV)	0.09	0.2	0.5	3.0	
	Z^0	HZ	HZ	H^+H^-	bb
d_{space} (cm)	0.3	0.3	0.85	2.5	9.0

Table 1
B-decay length (distance) at different CMS energies, and for several processes.

The CLIC physics working group has developed a set of tools for physics studies The CLIC luminosity spectrum is generated with CALYPSO [9]. The hadronic background from $\gamma\gamma$ events (4 events/bunch crossing) is generated with HADES [9]. The SIMDET-CLIC fast simulation package is used (based on the package for the TESLA Detector [10]). Most of the studies discussed in this paper use these tools.

2. Higgs Physics

Within the SM the circumstantial evidence for a light Higgs is accumulating, offering TeV class LCs an exciting physics program to study in detail the Higgs properties. In its last days of operation, an intriguing glimpse of a possible Higgs signal was observed at LEP. At its best moment in November 2000, the significance of the signal reached 2.9 σ, with a most likely mass around 115 GeV, but the significance has finally settled to about 2 σ since then.

The certainty of the existence of a light Higgs would certainly enhance the physics case for a TeV class e^+e^- collider dramatically. However – perhaps at first sight surprisingly – a multi-TeV collider can add important information on a light Higgs.

A final proof of the Higgs mechanism is the accurate reconstruction of the potential of the Higgs field, which can be studied through triple and quartic Higgs couplings. An accurate measurement would probe the extended nature of the Higgs sector, and is therefore of fundamental importance.

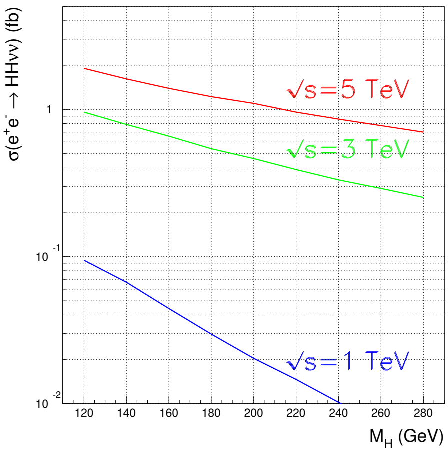

Figure 1. $\sigma_{HH\nu\nu}$ as function of M_H for a LC with $\sqrt{s} = 1, 3$ and 5 TeV.

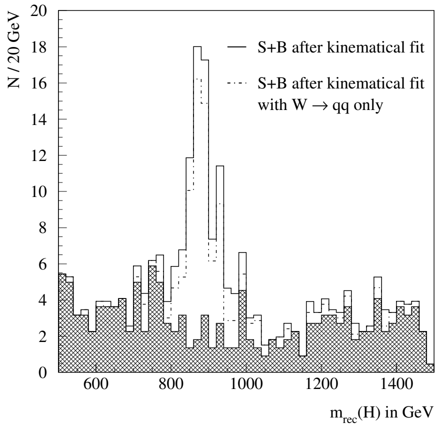

Figure 2. Reconstructed $H^{\pm} \rightarrow tb$ invariant mass for an integrated luminosity of 3 ab^{-1}. The hatched distribution is the $t\bar{b}\bar{t}b$ background.

The triple Higgs coupling can be studied in the fusion process $e^+e^- \rightarrow HH\nu\nu$ at multi-TeV colliders. The cross section as a function of the Higgs mass is shown in Fig. 1: it depends very strongly on the CMS energy. Together with the large luminosity of a multi-TeV collider, event samples could be up to a factor of 100 larger at CLIC than at a TeV class collider.

The statistical precision on g_{HHH} with 5 ab^{-1} and a CMS energy of 3 TeV from a measurement of the $HH\nu\nu$ cross section for $M_H = 120(180)$ GeV is $\delta g_{HHH}/g_{HHH} = 0.094(0.140)$ [11]. By making use of the scalar nature the Higgs decay this accuracy can be further improved to $\delta g_{HHH}/g_{HHH} = 0.070(0.080)$ for $M_H = 120(180)$ GeV.

Apart from the Higgs potential, a multi-TeV collider also provides the opportunity to measure rare decay modes of the Higgs. For example, the decay $H \rightarrow \mu\mu$ has a branching ratio of about 10^{-4} in the SM for a light Higgs. For 5 ab^{-1} at 3 TeV, 2.7×10^6 Higgs bosons with $M_H = 120$ GeV will be produced, of which 650 will decay into muons [12]. The measurement of this cross section can be combined with an independent measurement of the Higgs production cross section, e.g. via the b or W decay modes, to extract $g_{H\mu\mu}$. The statistical accuracy on the coupling $g_{H\mu\mu}$ would be $\delta g_{H\mu\mu}/g_{H\mu\mu} = 0.040$, 0.062, and 0.106, for Higgs masses of 120, 140, and 150 GeV, respectively. Hence the anticipated accuracy of this measurement is comparable to that predicted at a muon collider[13], and better than present expectations for a VLHC at 200 TeV [14].

CLIC is also an ideal tool to produce and study heavy Higgs partners as e.g. predicted in minimal SUSY scenarios, if their masses are larger than 500-700 GeV. The process $e^+e^- \rightarrow H^+H^-$ with $M_H = 880$ GeV has been studied. The decay channel $H^{\pm} \rightarrow tb \rightarrow Wbb \rightarrow qqbb$ was analysed in which eight jets are expected in the final state [15]. The result is shown in Fig. 2, for a study including 15 overlaid $\gamma\gamma$ bunch crossings. A total of 47 reconstructed events of the type $e^+e^- \rightarrow H^+H^- \rightarrow (t\bar{b})(\bar{t}b)$ is expected in the mass region of 2.5σ around the peak, with both Higgs particles reconstructed. A 5σ discovery can be made at a 3 TeV collider with 3 ab^{-1} for a Higgs mass up to about 1.1 TeV.

In short a multi-TeV collider can add new, substantial information on the Higgs potential, rare Higgs decays, and heavy Higgs states.

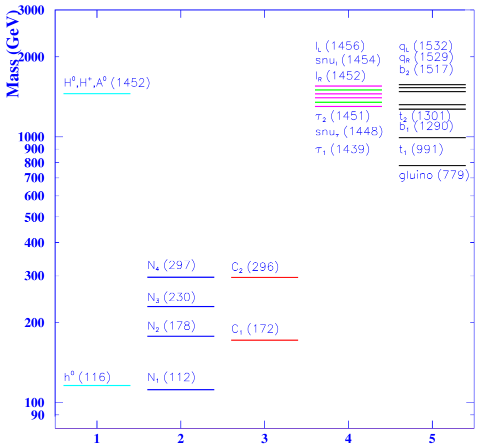

Figure 3. SUSY sparticle mass spectrum for point E of [16].

3. Supersymmetry

A strong candidate for new physics, which would explain the hierarchy problem, is supersymmetry, predicting a partner for each know particle, a "sparticle". Since no sparticles have been observed so far supersymmetry is broken at the electroweak scale, and there are many models proposed for the supersymmetry breaking mechanism. All of these models predict a different phenomenology, including different mass spectra for the supersymmetric partners. Sparticles can be potentially discovered at an e^+e^- machine so long as direct production is kinematically allowed.

The direct searches at LEP have not revealed any signal of supersymmetric particles. Hence their masses are generally higher than roughly 100 GeV. But we still do not have any definite hint where to look for these sparticles.

Recently a new set of benchmark points has been suggested in [16], based on the constrained MSSM model taking into account the experimental search limits on sparticles, Higgs bosons, $\tan\beta$, $b \to s\gamma$ results, the compatibility with Dark Matter ($0.1 < \Omega h^2 < 0.3$), and, for some points, the compatibility with $g-2$. All of the scenarios proposed in [16] are found to have sparticles with masses larger than 500 GeV. Thus, a LC with an energy above 1 TeV would be needed to study all sparticles in e^+e^- collisions. An example of the mass spectrum is shown in Fig. 3 for a point (E) of [16], corresponding to $m_{1/2} = 300$ GeV, $m_0 = 1450$ GeV, $\tan\beta = 10$, sign of $\mu > 0$ and $A = 0$. For this point the heavy Higgses, sleptons and squarks have masses lager than 700 GeV. Sooner or later the need will arise to measure as precisely as possible *all* members of the sparticle spectrum, in order to disentangle or verify the underlying theory and (SUSY breaking) dynamics as completely as possible. Knowing the masses to a precision of 1% rather than a 10% level (typical for the LHC) is an great help for bottom-up approaches to reconstruct the SUSY breaking mechanism [17]. Furthermore initial state beam polarization can be used to single out newly produced states of definite helicity, and further disentangle SUSY parameters [18]. A recent study [19] shows that for smuons mass measurements with a precision to $O(1\%)$ are possible at CLIC.

Note however that in order to cover all points proposed in [16] –which does not necessarily give the upper limit of the possible sparticle mass range– an e^+e^- collider of 8 TeV would be necessary, and the luminosity would need to be increased by a factor 2-5 to produce measurable samples of all sparticles.

Hence these initial studies indicate that if SUSY is realized, and sparticles have masses in the anticipated range, then a multi-TeV e^+e^- collider would be the ideal tool to complete the sparticle spectrum measurements.

4. Signals in Alternative Scenarios

There is a wide range of new physics scenarios predicting the existence of new vector particles with masses in the TeV range. One of the simplest extensions of the SM consists in the introduction of an additional $U(1)$ gauge symmetry, whose breaking scale is close to the Fermi scale. Models for the production of new Z' bosons are studied for CLIC [20]. LEP and Tevatron data tell us that such bosons must have masses larger than about 600 GeV. At a LC these bosons would be s-channel produced and appear as resonances

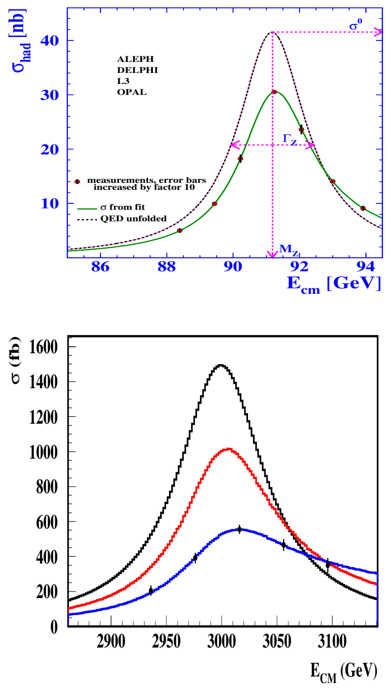

Figure 4. (Top) Z^0 line shape measurement. (Bottom) Production of $Z^{'} \rightarrow l^+l^-$ shown at the Born level, with ISR (middle) and with smearing due to the luminosity spectrum (lower curve).

in the two fermion cross sections, as the Z at LEP. The LHC may detect such resonances directly in the range up to several TeV, but most likely will not have the statistical power to measure in detail their properties.

Fig. 4 shows one of the most celebrated results of LEP, namely the Z^0 line shape measurements, and its uncanny precision with which the parameters have been determined: $\delta M_Z/M_Z \sim 2.5 \cdot 10^{-5}$ and $\delta\Gamma_Z/\Gamma_Z \sim 1 \cdot 10^{-3}$. A study simulating a similar resonance scan was performed for CLIC, assuming a $Z^{'}$ with a mass $M_{Z'}$ of 3.0 TeV and a width $\Gamma(Z^{'})/M_{Z'} \simeq \Gamma(Z^0)/M_{Z^0}$. A scan of the cross section with five points (Fig. 4) for 1 ab^{-1}, including the luminosity spectrum smearing gives the following fit accuracy: $\delta M_Z'/M_Z' \sim 10^{-4}$ and $\delta\Gamma_Z'/\Gamma_Z' \sim 3 \cdot 10^{-3}$. Despite being somewhat less precise than at LEP, the accuracy is still very appreciable.

Particularly challenging will be the measurement and disentangling of degenerate resonances, as predicted e.g. in the degenerate BESS Model. A study of an energy scan of degenerate narrow resonances shows that CLIC can distinguish resonances with a mass difference down to 13 GeV.

Also the Left-Right symmetric model has been studied, in particular the production of a Z' with a mass of 3 TeV which decays into heavy Majorana neutrinos. This leads to multi-jet plus lepton final states. The large number of $Z' \rightarrow N_e N_e$ events allows to determine the masses of these new particles with an accuracy of 0.01% for the Z' and 0.19% for the heavy neutrino [21].

If no Higgs boson exists with a mass less than about 700 GeV, then the $W^{\pm}, Z$ bosons are expected to develop strong interactions at scales of order 1-2 TeV. Generally one expects an excess of events above SM expectation, and, possibly, resonance formation.

The resonance formation in $e^+e^- \rightarrow \nu\overline{\nu}W_L^+W_L^-$ at 3 TeV was studied. Using the electro-weak Chiral Langrangian approach and taking for the values of the parameters which represent new physics in $\alpha_4 = 0.0$ and $\alpha_5 = -0.002$, a broad resonance is produced at 2 TeV in the WW invariant mass. The big advantage of an e^+e^- collider is the clean final state, which allows to use the hadronic decay modes of the $W's$ to select and reconstruct events. Four jets are produced in the decay of the two $W's$. However due to the boost from the decay of the heavy resonance, the two jets of a W are very collimated, and close to each other. With the present assumptions on the energy flow in SIMDET, the resolution to reconstruct the W, Z mass is about 7%. Heavy resonances in WW scattering can be detected at CLIC. The signal is not heavily distorted by detector resolution and background [22].

5. Precision Measurements

Apart from the direct observation of new particles, signals of new physics higher energy scales beyond the CMS energy can be discovered in precision measurements of e.g. two fermion production processes. The search reach using several observables successfully studied at LEP, such as $\sigma_{f\bar{f}}$, $A_{FB}^{f\bar{f}}$ and $A_{LR}^{f\bar{f}}$, has been analysed for CLIC, using the statistical accuracies determined in [20].

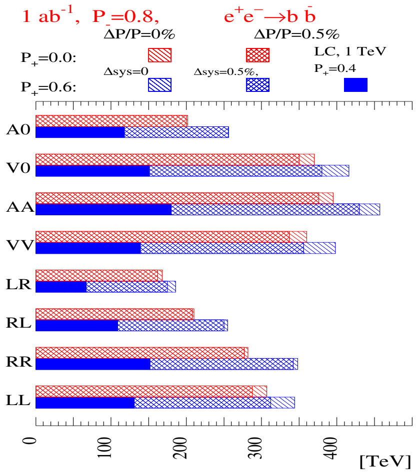

Figure 5. Limits on the scale Λ of contact interactions in $ee \to b\bar{b}$ for CLIC operating at 3 TeV (dashed histogram) compared to a 1 TeV LC (filled histogram) for different models. The electron polarisations $\mathcal{P}_-$ is taken to be 0.8 and the positron $\mathcal{P}_+$ to be 0.6; the upper bars show the sensitivity achieved without positron polarisation.

Results are given in Fig. 5 in terms of lower limits on Λ which can be excluded at 95% C.L. High luminosity e^+e^- collisions at 3 TeV can probe Λ scales in the range 200-400 TeV for 1 ab^{-1}. For comparison, the corresponding results expected for a LC operating at 1 TeV are also shown [20].

The expected gain in reach for Λ for 5 ab^{-1} and a 5 TeV (10 TeV) e^+e^- collider would be 400-800 GeV (500-1000) TeV. If the Higgs particle is indeed light, i.e. below 130 GeV or so, then the Standard Model cannot be stable up to the GUT or Planck scale, and a new mechanism is needed

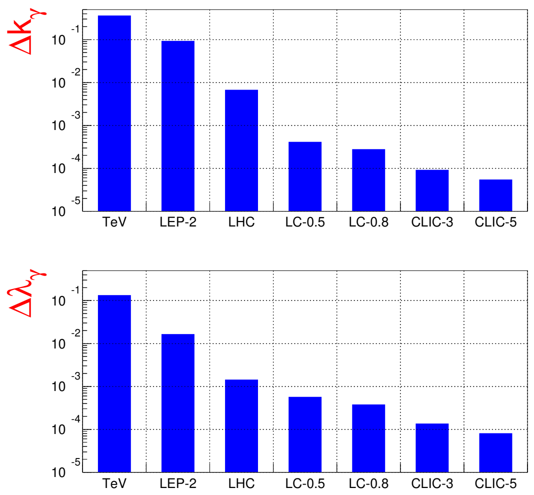

Figure 6. Precision of triple gauge coupling measurements at different accelerators.

to stabelize it [23]: only a narrow corridor up to the Planck scale is allowed for Higgs masses around 180 GeV. E.g. for a Higgs with a mass in the region of 115-120 GeV, the SM will hit a region of electro-weak unstable vacuum in the range of 100-1000 TeV. Hence if the Higgs is as light as 120 GeV, the signature of the new physics cannot escape a multi-TeV collider! If – in the worst case of scenarios – this new physics would have 'evaded' measurements at the LHC and the TeV class LC up to then, but will finally have to show up at CLIC.

Another example of precision measurements is the determination triple Gauge boson couplings, studied e.g. in $e^+e^- \to W^+W^-$. Deviations from the SM expectations in these couplings are a sign of new physics. An initial study, without taking into account background and detector effects, suggest that the sensitivity of the anomalous $\Delta\lambda_\gamma$ and $\Delta\kappa_\gamma$ couplings for CLIC at 3 (5) TeV amount to roughly $1.3 \cdot 10^{-4}(0.8 \cdot 10^{-4})$ and $0.9 \cdot 10^{-4}(0.5 \cdot 10^{-4})$ respectively, for 1 ab^{-1} of data [24] (see Fig. 6), i.e. a factor 2-4 more precisely than a TeV class LC.

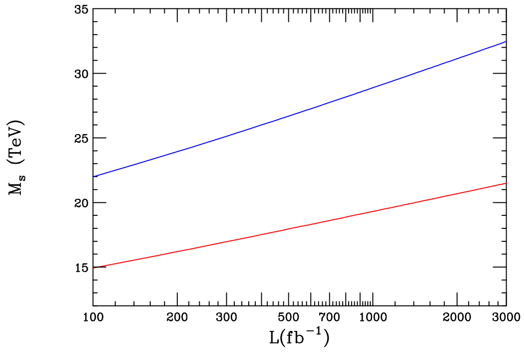

Figure 7. Search reach for the ADD model scale M_s at CLIC as a function of the integrated luminosity from the set of processes $e^+e^- \to f\bar{f}$ assuming $\sqrt{s} = 3$ (bottom) or 5 (top) TeV.

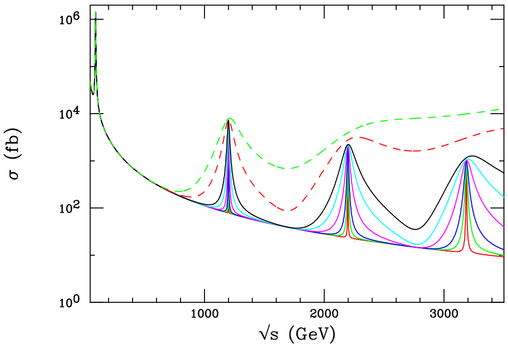

Figure 8. KK graviton excitations in the RS model produced in the process $e^+e^- \to \mu^+\mu^-$. From the most narrow to widest resonances the curves are for c in the range 0.01 to 0.2.

6. Recent New Ideas

For the past few years new and alternatives ideas have been proposed, in particular those which use elements of string theory and may imply measurable effects at TeV scales

A prime example is the idea of large extra dimensions at the TeV scale. These theories aim to solve the hierarchy problem by bringing the gravity scale closer to the electro-weak scale. (if you cannot get to the Planck scale, try to bring the Planck scale to you.) The hidden extra dimensions can dramatically change the strength of gravity, and bring the Planck scale down to the TeV region.

Extra dimensions signatures at future colliders, particularly at CLIC, have been discussed in detail in [25]. There is a large variety of models which can be basically classified in three groups: (*i*) the large extra dimensions scenario of Arkani-Hamed, Dvali and Dimopoulos(ADD)[26]; (*ii*) extra dimensions of TeV scale in size [27]; (*iii*) warped extra dimensions, such as the Randall-Sundrum Model(RS)[28]. High energy lepton colliders in the multi-TeV range with sufficient luminosity, such as CLIC, will be able to study both direct and indirect signals and make detailed studies of models in all three classes.

Fig. 7 shows the reach for indirect measurements in the channel $e^+e^- \to f\bar{f}$ as can be obtained at a multi-TeV collider, versus luminosity, from [25], for the ADD model. Similar results have been obtained for the other classes of models. In general a multi-TeV collider has a sensitivity to reach up to 20-80 TeV depending on the model.

Direct measurements can be made in the RS and TeV scale models, since these can produce resonances in the s-channel two fermion processes in e^+e^- interactions. In the RS model [28] TeV scale graviton resonances are expected in many channels. In its simplest version, with two branes and one extra dimension, and all of the SM fields remaining on the brane, the model has two fundamental parameters: the mass of the first resonance and the parameter $c = k/M_{\overline{Pl}}$ which should be less than but not to far away from unity. This parameter controls the effective coupling strength of the graviton and thus the width of the resonances. A spectrum for $e^+e^- \to \mu^+\mu^-$ is given in Fig. 8. Clearly the cross sections are huge and a putative signal cannot be missed by a LC with sufficient CMS energy. The LC will be a KK resonance factory, up to the kinematic limit, and can be used to measure the properties (M, c, branching ratios) and quantum numbers (spin) of the KK resonances.

A scan similar to the one for the Z at LEP, folded with the CLIC luminosity spectrum, was made for an integrated luminosity of 1 ab^{-1}, and results in a precision to determine c to 0.2% and M to better than 0.1% [29]. Further it was demonstrated that the spin-2 nature of the graviton can be reconstructed and the ratio $BR(G \to \gamma\gamma)/BR(G \to \mu\mu) = 2$ can be determined to the percent level. If CLIC is so lucky that it has the first three resonances within its CMS range, it has the intriguing possibility to measure the graviton self-coupling in $G_3 \to G_1 G_1$ decay ($\sim 15\%$ of decays) [30]. The dominant decay mode is $G_1 \to$ gluon-gluon into jets. From the jet pairing the mass of G_1 can be well reconstructed [29].

Hence, if KK resonances are produced in the TeV region, then CLIC can be used to precisely determine the shape, mass, spin, and branching ratios of the objects. With such information the objects can be unambiguously identified as gravitons.

If the fundamental Planck scale is in the TeV range, then a natural consequence would be the possibility of production of black holes (BH) in the multi-TeV range, above the Planck scale. The cross section is $\sigma = \pi R_s^2 \sim 1\ \text{TeV}^{-2} \sim O(100)$ pb, hence very large. Here R_S is the Schwarzschild Radius. If $\sqrt{s}_{e^+e^-} > M_{BH} > M_{\text{Planck}}$ then the collider becomes a black hole factory. The lifetime of such a black hole is of order $\sim 10^{-25} - 10^{-27}$ sec, hence the black hole will evaporate before it could possible 'eat' any detector material. Hence these mini black holes are not dangerous for Mankind.

The decay of a black hole can be very complex and involve several stages [31,32]. If the dominating mode is Hawking radiation then all particles (quarks, gluons, gauge bosons, leptons) are expected to be produced democratically, with e.g. a ratio 1/5 between leptonic and hadronic activity. The multiplicity is expected to be large. The production and decay process have been included in the PYTHIA generator[32]. Fig. 9 shows a black hole event produced in a detector at CLIC, leading to spectacular multi-jet and lepton/photon signals. If this scenario is realized in Nature black holes will be produced at high rates at the LHC. CLIC can be very instrumental in precise measurements, e.g. the testing of Hawkings radiation, and the extraction of the number of underlying EDs. The large production cross section, low backgrounds and little missing energy would make BH production and decay a perfect laboratory to study strings and quantum gravity.

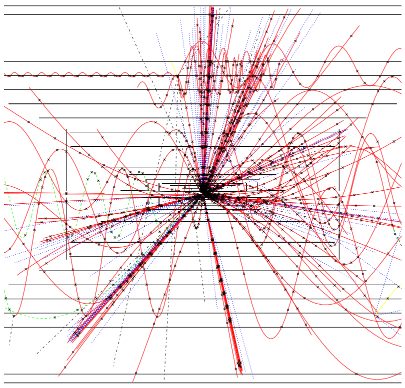

Figure 9. Black hole production in a CLIC detector.

Several other novel ideas include noncommutative theories; string quantum gravity effects in $e^+e^- \to e^+e^-$ and $\gamma\gamma$; brane fluctuation modes, (Nylons?); split Fermions in Extra Dimension; Extra Dimensions & Two supersymmetries...

7. Conclusion

Linear e^+e^- colliders operating in the multi-TeV energy range are likely to be based on the CLIC two-beam acceleration concept. CLIC will operate in the high beamstrahlung region, rendering experimentation at such a collider challenging. Studies so far indicate that precision measurements will be possible.

R&D on this two-beam accelerator technology will continue until 2006 at least, only after which one can plan for a full technical design of such a collider.

A multi-TeV collider has a large potential to push the high energy horizon up to scales of 1000 TeV, where – if the Higgs is light– new physics can no longer hide from experiment. A multi-TeV collider with high luminosity can be used for precision measurements in the Higgs sector. It can precisely measure the masses and couplings of heavy sparticles, thereby e.g. completing the SUSY spectrum. If extra dimensions or even black holes pop up in the multi-TeV range, such a collider will be a precision instrument to study quantum gravity in the laboratory.

In short a collider with $\sqrt{s} \simeq$ 3-5 TeV is expected to break new grounds, way beyond the LHC.

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