Probing New Scales at a e^+e^- Linear Collider

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Extending the sensitivity to New Physics beyond the anticipated reach of the Lнс is a prime aim of future colliders. This paper summarises the potential of an e^+e^- linear collider, at and beyond 1 TeV, using a realistic simulation of the detector response and the accelerator induced background. The possible LC energy-luminosity trade-offs offered in probing multi-TeV scales for new phenomena with electro-weak observables are also discussed.

1. Introduction

The Lнс is expected to directly probe possible New Physics beyond the Standard Model (SM) up to a scale of a few TeV. While its data should provide answers to several of the major open questions in the present picture of elementary particle physics, it is important to start examining how this sensitivity can be further extended at a next generation of colliders. Today we have a number of indications that New Physics could be of supersymmetric nature. If this is the case, the Lнс will have a variety of signals to discover these new particles and the linear collider (LC) will be required to complement the probe of the SUSY spectrum with detailed measurements. However, beyond Supersymmetry there is a wide range of other scenarios invoking new phenomena at, and beyond, the TeV scale. They are aimed at explaininig the origin of electro-weak symmetry breaking, if there is no light elementary Higgs boson, at stabilising the SM, if SUSY is not realised in nature, or at embedding the SM in a theory of grand unification.

Many of such scenarios predict the existence of new particles that would be manifested as rather spectacular resonances in e^+e^- collisions, if the achievable centre-of-mass energy is sufficient. A high energy LC represents an ideal laboratory for studying this New Physics [1, 2]. It also retains an indirect sensitivity, through a precision study of the virtual corrections to electro-weak observables, when their mass exceeds the available centre-of-mass energy. This paper summarises the results of a series of studies aimed at quantifying the potential of a high energy, high luminosity e^+e^- LC in extending to high scales the probe for New Physics. While a significant activity has already addressed the issues related to a TeV-class collider, we now review the potential of a multi-TeV LC, such as Clic.

2. Electro-weak Observables at a Multi-TeV LC

The analysis of the Lep and Slc data has provided a significant experience in the extraction of electro-weak observables, optimising their statistical sensitivity and controlling their systematic uncertainties. At larger centre-of-mass energies, the relevant $e^+e^- \rightarrow f\bar{f}$ cross sections are significantly reduced and the experimental conditions at the interaction region need to be taken into account in validating the anticipated accuracies on the cross section $\sigma_{f\bar{f}}$, forward-backward

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Table I Relative statistical accuracies on electro-weak observables, obtained for 1 ab^{-1} of CLIC data at $\sqrt{s} = 3$ TeV, including the effect of $\gamma\gamma \to$ hadrons background.

Observable	Relative Stat. Accuracy $\delta\mathcal{O}/\mathcal{O}$ for 1 ab^{-1}
$\sigma_{\mu^+\mu^-}$	± 0.010
$\sigma_{b\bar{b}}$	± 0.012
$A_{FB}^{\mu\mu}$	± 0.018
A_{FB}^{bb}	± 0.055

asymmetries $A_{FB}^{f\bar{f}}$ and left-right asymmetries $A_{LR}^{f\bar{f}}$ determination at $\sqrt{s} = 1$ TeV $- 5$ TeV. Since the two-fermion cross section is of the order of only 10 fb, it is imperative to achieve high luminosity by reducing the beam-spot sizes. In this regime the beam-beam effects are important and the primary e$^+$e$^-$ collision is accompanied by several $\gamma\gamma \to$ hadrons interactions. Being mostly confined in the forward regions, this $\gamma\gamma$ background reduces the polar angle acceptance for quark flavour tagging and dilutes the jet charge separation using jet charge techniques. These experimental conditions require efficient and robust algorithms to ensure sensitivity to flavour-specific $f\bar{f}$ production. The statistical accuracy for the determination of $\sigma_{f\bar{f}}$, $A_{FB}^{f\bar{f}}$ and $A_{LR}^{f\bar{f}}$ has been studied, for $\mu^+\mu^-$ and $b\bar{b}$, taking the CLIC parameters at $\sqrt{s} = 3$ TeV. The SIMDET parametrised detector simulation has been used and the $\gamma\gamma \to$ hadrons background, corresponding to 10 overlayed bunch crossings, has been added to e$^+$e$^- \to \mu^+\mu^-$, $b\bar{b}$ events. $b\bar{b}$ final states have been identified using an algorithm based on the sampling of the decay charged multiplicity of the highly boosted b hadrons at CLIC energies [3]. Similarly to LEP analyses, the forward-backward asymmetry has been extracted from a fit to the flow of the jet charge Q^{jet} defined as

$$Q^{\text{jet}} = \frac{\sum_i q_i |p_i T|^k}{\sum_i |p_i T|^k},$$

where q_i is the particle charge, p_i its momentum, T the jet thrust axis and the sum is extended to all the particles in a given jet. Here the presence of additional particles, from the $\gamma\gamma$ background, causes a broadening of the Q^{jet} distribution and thus a dilution of the quark charge separation. The track selection and the value of the power parameter k needed to be optimised as a function of the number of overlayed bunch crossings. The results are summarised in terms of the relative statistical accuracies $\delta\mathcal{O}/\mathcal{O}$ in Table I. Another important issue is the accuracy on the luminosity determination, that needs to be controlled to 0.5%, or better.

3. Sensitivity to a Z' Boson

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. This extra symmetry is for instance predicted in some grand unified theories. The extra Z' associated to this symmetry naturally mixes with the SM Z^0. The mixing angle is strongly constrained by precision electroweak data to be of the order of few mrad while direct searches at Tevatron for a new Z' boson set a lower mass limit around 600 GeV. Further improvements are expected by precision electro-weak data obtained at a GIGA-Z facility.

The search for such an extended gauge sector offers an interesting framework for studying the sensitivity to scales beyond those directly accessible, even at a multi-TeV collider. It also raises the issue of the ability to discriminate between different models. Main classes of models with additional Z' bosons include E_6 inspired models and the left-right models (LR) (for a recent review see [4]). Concerning the E_6 models, the Z' fermion couplings depend on the angle θ_6 which defines the embedding of the extra $U(1)$ in the E_6 group.

In this study we have considered the so-called η model with $\theta_6 = -\arctan\sqrt{5/3}$, the χ model with $\theta_6 = 0$ and, as a reference model, the so called sequential SM (SSM) which has an additional Z' boson with SM-like couplings.
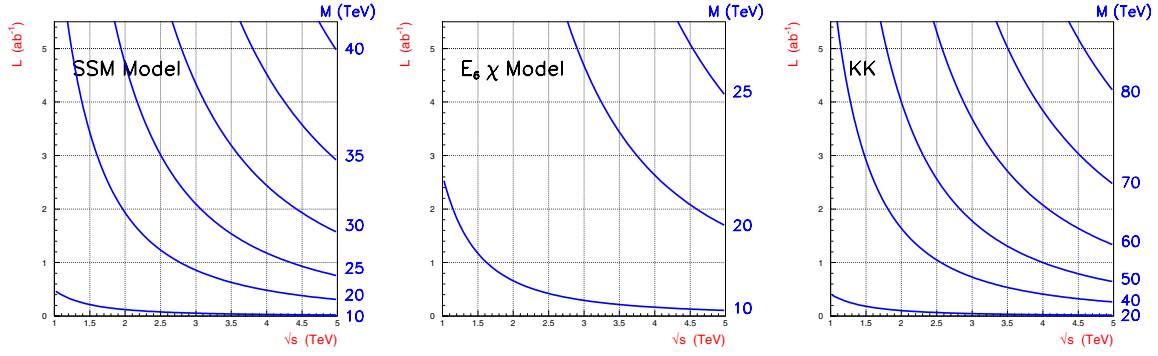
Figure 1: The 95% C.L. sensitivity contours in the L vs. $\sqrt{s}$ plane for different values of $M_{Z'}$ in the SSM model (left) and in the $E_6\,\chi$ model (center) and for different values of the compactification scale M in a five dimensional extension of the SM with fermions on the boundary (right).

There has been a significant interest in the LHC and LC potential in the search for a new Z' boson. At the LC, the indirect sensitivity to its mass, $M_{Z'}$, can be parametrised in terms of the available integrated luminosity $\mathcal{L}$, and centre-of-mass energy, $\sqrt{s}$. In fact the scaling law for large $M_{Z'}$ can be obtained by considering the effect of the $Z' - \gamma$ interference in the cross section σ. For $s << M_{Z'}^2$ and assuming that the uncertainties $\delta\sigma$ are statistically dominated, we get the range of mass values giving a significant difference:

$$\frac{|\sigma^{SM} - \sigma^{SM+Z'}|}{\delta\sigma} \propto \frac{1}{M_{Z'}^2}\sqrt{sL} > \sqrt{\Delta\chi^2} \tag{1}$$

and the sensitivity to the Z' mass scales as:

$$M_{Z'} \propto (sL)^{1/4} \tag{2}$$

This relationship shows that there is a direct trade-off possible between $\sqrt{s}$ and $\mathcal{L}$, which should be taken into account when optimising the parameters of a high energy LC.

The $\sigma_{f\bar{f}}$ and $A_{FB}^{f\bar{f}}$ ($f = \mu$, b) values have been computed, for 1 TeV $< \sqrt{s} <$ 5 TeV, both in SM and including the corrections due to the presence of a Z' boson with 10 TeV $< M_{Z'} <$ 40 TeV, with the couplings predicted by the models mentioned above. This has been obtained by implementing them in the COMPHEP program. The relative statistical errors on the electroweak observables are obtained by rescaling the values of Table I for different energies and luminosities. The sensitivity has been defined as the largest Z' mass giving a deviation of the actual values of the observables from their SM predictions corresponding to a SM probability of less than 5%. This sensitivity has been determined, as a function of the $\sqrt{s}$ energy for an integrated luminosity $\mathcal{L}$ of 1 ab^{-1} and 5 ab^{-1}, and rescaled to other values of $\mathcal{L}$ using the formula (2) and assuming the uncertainties to be dominated by statistics. Results are summarised in Figure 1. For the η model the sensitivity is lower: for example to reach a sensitivity of $M_{Z'} = 20$ TeV, 10 ab^{-1} of data at $\sqrt{s} = 5$ TeV would be necessary.

4. Sensitivity to Kaluza-Klein Excitations in Theories with Extra-Dimensions

Theories of quantum gravity have considered the existence of extra-dimensions for achieving the unification of gravity at a scale close to that of electroweak symmetry breaking. String theories have recently suggested that the SM could live on a $3 + \delta$ brane with δ compactified large dimensions while gravity lives on the entire ten dimensional bulk. The corresponding models lead to new signatures for future colliders ranging from Kaluza-Klein (KK) excitations of the gravitons [5] to KK excitations of the SM gauge fields with masses in the TeV range [6].

Among the models with extra dimensions we have considered the five dimensional extension of the SM with fermions on the boundary which predicts KK excitations of the SM gauge bosons

with couplings $\sqrt{2}$ larger than those of the SM. KK masses are given by $M_n = nM$, with M the compactification scale of the fifth dimension. Indirect limits on $M \sim 4$ TeV from electroweak measurements already exist [7]. These models predict excitations of the Z^0 and of the photon which are almost degenerate in mass.

In this analysis we have included in the cross section calculations only the exchange of the first KK excitations $Z^{(1)}$ and $\gamma^{(1)}$, neglecting the effect of the remaining towers which give a small correction. The scaling law for the limit on M can be obtained by considering the interference of the two new nearly degenerate gauge bosons with the photon in the cross section and taking the $s \ll M^2$ limit. The result is the same as eq. (2). The analysis closely follows that for the Z' boson discussed above. In Figure 1 we give the sensitivity contours as a function of $\sqrt{s}$ for different values of M. We conclude that the sensitivity achievable for the compactification scale M for an integrated luminosity of 1 ab^{-1} in e$^+$e$^-$ collisions at $\sqrt{s}$ = 3 TeV - 5 TeV is of the order of 40–60 TeV. Results for a similar analysis, including all electro-weak observables are discussed in [8].

5. Sensitivity to Contact Interactions

The scenarios investigated above address specific models of New Physics beyond the SM.

Table II Definition of different models of contact interaction.

Model	LL	RR	LR	RL	VV	AA	V0	A0
η_{LL}	±1	0	0	0	±1	±1	±1	0
η_{RR}	0	±1	0	0	±1	±1	±1	0
η_{LR}	0	0	±1	0	±1	∓1	0	±1
η_{RL}	0	0	0	±1	±1	∓1	0	±1

Fermion compositeness or exchange of very heavy new particles can be described in all generality by four-fermion contact interactions [9]. These parametrise the interactions beyond the SM by means of an effective scale, Λ_{ij},

$$\mathcal{L}_{CI} = \sum_{i,j=L,R} \eta_{ij} \frac{g^2}{\Lambda_{ij}^2} (\bar{e}_i \gamma^\mu e_i)(\bar{f}_j \gamma^\mu f_j). \tag{3}$$

The strength of the interaction is set by convention as $g^2/4\pi = 1$ and models can be considered by choosing either $|\eta_{ij}| = 1$ or $|\eta_{ij}| = 0$ as detailed in Table II. The contact scale Λ can be interpreted as effect of new particles at a mass M_X, $1/\Lambda^2 \propto \lambda^2/M_X^2$.

In order to estimate the sensitivity of electro-weak observables to the contact interaction scale Λ, the statistical accuracies discussed in Section II have been assumed for the $\mu\mu$ and $b\bar{b}$ final states. The systematics of the assumed 0.5% include the contributions from model prediction uncertainties. Results are given in terms of the lower limits on Λ which can be excluded at 95% C.L., in Figure 2. It has been verified that, for the channels considered in the present analysis, the bounds for the different Λ_{ij} are consistent. High luminosity e$^+$e$^-$ collisions at 3 TeV can probe Λ at scales of 200 TeV, and beyond. For comparison, the corresponding results expected for a LC operating at 1 TeV are also shown. Beam polarisation represents an important tool in these studies. First, it improves the sensitivity to new interactions, through the introduction of the left-right asymmetries A_{LR} and the polarised forward-backward asymmetries A_{FB}^{pol} in the electro-weak fits. If both beams can be polarised to $\mathcal{P}_-$ and $\mathcal{P}_+$ respectively, the relevant parameter is the effective polarisation defined as

$$\mathcal{P} = \frac{-\mathcal{P}_- + \mathcal{P}_+}{1 - \mathcal{P}_- + \mathcal{P}_+}.$$

In addition to the improved sensitivity, the uncertainty on the effective polarization, can be made smaller than the error on the individual beam polarization measurements. Secondly, in the case of a significant deviation from the SM prediction would be observed, e$^-$ and e$^+$ polarization is
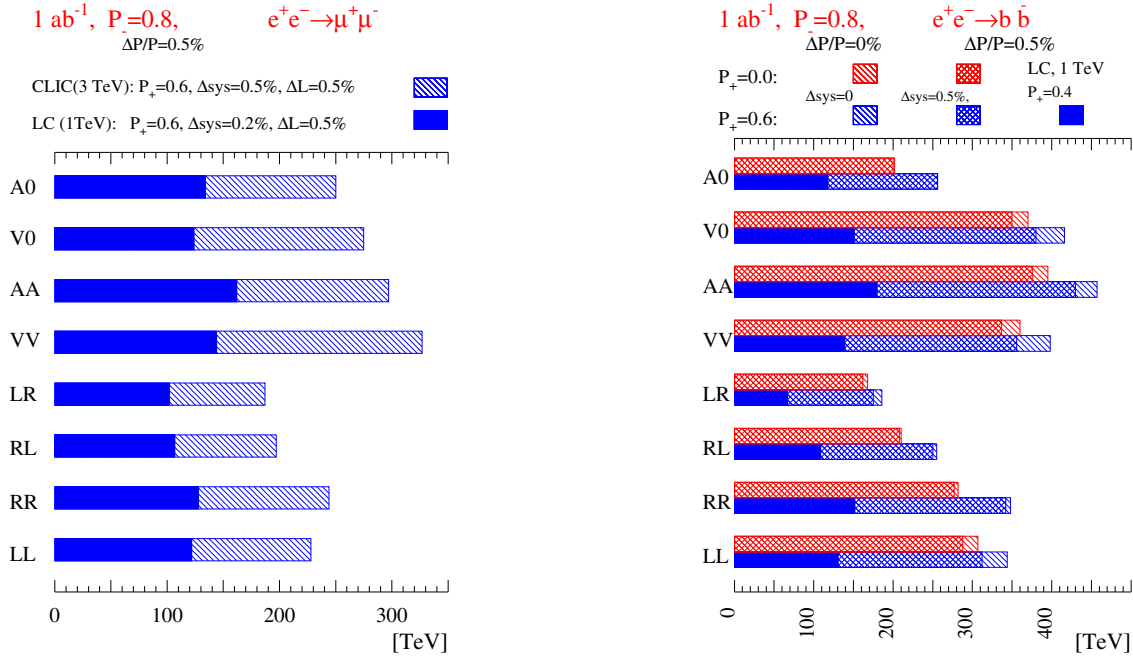
Figure 2: Limits on the scale Λ of contact interactions in $e^+e^- \rightarrow \mu^+\mu^-$, $b\bar{b}$ for CLIC operating at 3 TeV (dashed histogram) compared to a 1 TeV LC (filled histogram) for different models and the $\mu^+\mu^-$ (left) and $b\bar{b}$ (right) channels. The electron polarisations $\mathcal{P}_-$ is taken to be 0.8 and the positron $\mathcal{P}_+$ to be 0.6. For comparison the upper bars in the right plot show the sensitivity achieved without positron polarisation. The influence of systematic uncertainties is also shown.

greatly beneficial to determine the nature of the new interactions. This has been studied in details for a LC at 0.5–1.0 TeV [10] and those results also apply, qualitatively, to a multi-TeV collider.

6. Conclusions

Extending the sensitivity to New Physics beyond the anticipated reach of the LHC, is a prime aim of future colliders. By accurately measuring electro-weak observables, a LC able to achieve e^+e^- collisions at and beyond 1 TeV, with high luminosity, can indirectly probe scales extending from tens to several hundreds TeV.

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