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# ELECTRO-WEAK FITS AT CLIC *

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**Abstract**

The aim of the future linear colliders is to extend the sensitivity to new physics beyond the reach of the LHC. Several models predict the existence of new vector resonances in the multi-TeV region. We review the existing limits on the masses of these new resonances from LEP/SLC and TEVATRON data and from the atomic parity violation measurements, in some specific models. We study the potential of a multi-TeV $e^+e^-$ collider, such as CLIC, for the determination of their properties and nature.

## 1 Introduction

If new physics exists at the TeV scale it will be discovered at the LHC and the precision measurements at a linear collider (LC) will be crucial for revealing the character of the new phenomena. One of the most striking manifestations of new physics will come from the sudden increase of the $e^+e^- \to f\bar{f}$ cross section indicating the direct s-channel production of a new particle. New neutral vector gauge bosons characterise several extensions of the Standard Model (SM) and may represent the main phenomenology beyond 1 TeV. A first class consists of models with extra gauge bosons such as a new neutral $Z'$ gauge boson. This is common to both GUT-inspired $E_6$ models and to Left-Right (LR) symmetric models. Additional resonances are also introduced by recent string theories in the form of Kaluza-Klein (KK) graviton

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and gauge boson excitations. We discuss here a five dimensional extension of the Standard Model. Present bounds are derived from precision electro-weak data and from the atomic parity violation (APV) measurements. Beyond discovery, it will be essential to accurately measure the mass, width, production and decay properties of the new resonance to determine its nature and identify which kind of new physics it manifests. This could be the task of a multi-TeV $e^+e^-$ collider such as CLIC. Besides, CLIC will also probe mass scales much beyond the kinematic threshold for the production of the new vector gauge bosons. To establish the sensitivity reach to indirect effects of new vectors as $Z'$ gauge bosons and KK excitations of the photon and of the $Z^0$ boson, we consider cross sections, $\sigma_{f\bar{f}}$, and forward-backward asymmetries, $A_{FB}^{f\bar{f}}$, for $\mu^+\mu^-$, $b\bar{b}$ and $t\bar{t}$ at 1 TeV< $\sqrt{s}$ <5 TeV.

## 2 New Vector Resonances: $Z'$ and KK Excitations

One of the best motivated extensions of the SM is given by the extra $U(1)$ models which predict an extra gauge boson $Z'$ associated to an additional $U(1)$ symmetry. This extra symmetry, whose breaking scale is close to the Fermi scale, is for example foreseen in some grand unified theories. Popular models are parameterized by specific values of the angle $\theta_6$, which defines the embedding of the extra $U(1)$ factor in $E_6$. The $\chi, \psi$ and $\eta$ models correspond to the values $\theta_6$=0, $\theta_6 = \pi/2$ and $\theta_6 = -\tan^{-1}\sqrt{5/3}$ respectively. An extra neutral gauge boson is also predicted by the Left-Right (LR) models in which the gauge group $SO(10)$ is broken down to the standard gauge group plus an additional $SU(2)_R$ factor. Finally, a useful reference is represented by the so-called sequential standard model (SSM), which introduces an extra $Z'$ boson with the same couplings of the SM $Z^0$ boson.
There exist several constraints on the properties of new neutral vector gauge bosons. Direct searches for a new $Z'$ boson set lower limits on the masses from $\sigma(pp \to Z')B(Z' \to ll)$. The 95% CL bounds on $M_{Z'}$ for $\chi$, $\psi$, $\eta$, LR and SSM models are 595, 590, 620, 630, 690 GeV respectively (CDF data [1]). An extra $Z'$ naturally mixes with the SM $Z^0$ boson. The present precision electro-weak data constrain the mixing angle, $\theta_M$, within a few mrad [2]. They also constrain the $Z'$ mass. From the average of the four LEP experiments, for $\theta_M = 0$, the 95% CL limit on $M_{Z'}$ for $\chi$, $\psi$, $\eta$, LR and SSM models are 673, 481, 434, 804, 1787 GeV respectively [3]. A third class of constraints is derived from the atomic parity violation (APV) data [4]. In [5] these bounds are updated. The old analysis was based on the 1999 result of weak charge $Q_W$ in the Cesium atomic parity experiment which indicated

a $\simeq 2.6\sigma$ discrepancy w.r.t. the SM prediction. A series of theoretical papers have since improved the prediction of $Q_W$, by including the effect of the Breit interaction among electrons and by refining the calculation of radiative corrections [6]. The present value of $Q_W$ extracted from the Cesium data differs only $\simeq 0.8\sigma$ from the SM prediction. Models involving extra neutral vector bosons can modify the $Q_W$ value significantly. Assuming no $Z^0 - Z'$ mixing, we can evaluate the contribution to the weak charge due to the direct exchange of the $Z'$ and derive bounds on $M_{Z'}$. The 95% CL limit from APV on $M_{Z'}$ for the $\chi$, $\eta$, LR and SSM models are 627, 476, 665 and 1010 GeV respectively (no bounds can be set on the $\psi$ model by the APV measurements). They are less stringent than, or comparable to those from LEP experiments. However, as these bounds are very sensitive to the actual value of $Q_W$ and its uncertainties, further determinations may improve the situation.
The LHC will push the direct sensitivity to new vector gauge bosons beyond the TeV threshold. With an integrated luminosity of 100 fb$^{-1}$, ATLAS and CMS are expected to observe signals from $Z'$ bosons for masses up to 4-5 TeV depending on the specific model [7]. A future linear $e^+e^-$ collider with c.o.m. energy below threshold can put lower bounds on $M_{Z'}$ by measuring cross sections and asymmetries in the fermionic channels. Both high luminosity and polarization of the electron and the positron beams are effective in increasing the reach. For example the sensitivity to the $\chi$ model at a 500 GeV LC with $L = .5$ ab$^{-1}$ will be of 5 TeV by assuming $P_{e^+}$=.6 and $P_{e^-}$=.8 [8]. Extra-$U(1)$ models can be accurately tested at a linear collider operating in the multi-TeV region, such as CLIC. The observation of a $Z'$ signal is granted but the accuracy that can be reached in the study of its properties depends on the quality of the accelerator beam energy spectrum and on the detector response, including accelerator induced backgrounds. $M_{Z'}$, $\Gamma_{Z'}/\Gamma_{Z^0}$ and $\sigma_{peak}$ can be extracted by a resonance scan. The dilution of the analysing power due to the beam energy spread is appreciable. Still, the relative statistical accuracies can be better than $10^{-4}$ on the mass and $5 \times 10^{-3}$ on the width [9].

Theories of quantum gravity have considered the existence of extra-dimensions for achieving the unification of gravity at a scale close to that of electro-weak symmetry breaking. String theories have recently suggested that the SM could live on a $3 + \delta$ brane with $\delta$ compactified large dimensions while gravity lives on the entire bulk. The corresponding models lead to new signatures for future colliders ranging from Kaluza-Klein (KK) excitations of the gravitons to KK excitations of the SM gauge fields with masses in the TeV range. We consider here a five-dimensional extension of the SM with fermions on the boundary. This predicts KK excitations of the SM gauge bosons with fermion couplings $\sqrt{2}$ larger compared to those of the

SM [10]. Masses of the KK excitations of $W$, $Z^0$ and $\gamma$ are given by $M_n \simeq nM$, for large value of the fifth dimension compactification scale, $M$. The KK excitations of $W^{\pm}$, $Z^0$ and $\gamma$ mix with the SM gauge bosons. This mixing is parameterized by the angle $\beta$.
Indirect limits from electro-weak measurements are derived by considering the modifications in the electro-weak observables at the $Z^0$ peak and at low energy [11]. An update of the lower bounds on the compactification scale derived from a recent determination of the $\epsilon$ parameters and from the latest APV results is given in [5]. The 95% CL limits from high energy experiments range from $M > 2.5$ TeV for $\sin\beta = 0$ to $M > 4.5$ TeV for $\sin\beta = 1$. The ones from APV turn out to be significantly below the corresponding high energy bounds.
Non observation of deviations in lepton pair production at LHC can set limits on the compactification scale $M$. For example by considering an effective luminosity of 5 fb$^{-1}$ one gets a bound of $M = 6.7$ TeV [12]. At CLIC, the lowest excitations $Z^{(1)}$ and $\gamma^{(1)}$ could be directly produced. Results for the $\mu^+\mu^-$ cross sections and forward-backward asymmetries at the Born level and after folding the effects of the beam spectrum are given in [5].

## 3 Indirect Sensitivity to $Z'$ and KK Excitations at CLIC

Precision electro-weak measurements performed in multi-TeV $e^+e^-$ collisions can push the mass scale sensitivity for scenarios beyond the SM beyond the 10 TeV frontier. We consider here the $\mu^+\mu^-$, $b\bar{b}$ and $t\bar{t}$ production cross sections $\sigma_{f\bar{f}}$ and forward-backward asymmetries $A_{FB}^{f\bar{f}}$.
As a general property, at a LC the indirect sensitivity to the mass of a new vector resonance such a $Z'$, can be parameterized in terms of the available integrated luminosity $L$, and c.o.m energy, $\sqrt{s}$. In fact a scaling law for large $M_{Z'}$ can be obtained by considering the effect of the $Z'-\gamma$ interference in the cross section. For $s << M_{Z'}^2$ and assuming that the uncertainties $\delta\sigma$ are statistically dominated, we get that the range of mass values giving a significant difference from the SM prediction can be derived from: $|\sigma^{SM} - \sigma^{SM+Z'}|/\delta\sigma \propto \sqrt{sL}/M_{Z'}^2 > \sqrt{\Delta\chi^2}$. This means that the sensitivity to the $Z'$ mass scales as: $M_{Z'} \propto (sL)^{1/4}$. This relationship shows that there is a direct possible trade-off between $\sqrt{s}$ and $L$, which should be taken into account when optimizing the parameters of a high energy $e^+e^-$ linear collider.
At the CLIC design c.o.m. energies, the relevant $e^+e^- \to f\bar{f}$ cross sections are significantly reduced and the experimental conditions at the interaction region need

to be taken into account in validating the accuracies on electro-weak observables. Since the two-fermion cross section is of the order of only 10 fb, it is imperative to operate the collider at high luminosity. This can be achieved only in a regime where beam-beam effects are important and primary $e^+e^-$ collisions are 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. This is due to the inclusion of spurious charged particles in the jet which spoils the correlation between the jet and the quark charge. These experimental conditions require efficient and robust algorithms to ensure sensitivity to flavour-specific $f\bar{f}$ production. The statistical accuracies for the determination of $\sigma_{f\bar{f}}$ and $A_{FB}^{f\bar{f}}$ have been studied using a realistic simulation [13, 14]. The results are summarized in terms of the relative statistical accuracies on the 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 [5]: $\delta\sigma_{\mu^+\mu^-}/\sigma_{\mu^+\mu^-} = \pm 0.010$, $\delta\sigma_{b\bar{b}}/\sigma_{b\bar{b}} = \pm 0.012$,$\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} = \pm 0.014$, $\delta A_{FB}^{\mu\mu}/A_{FB}^{\mu\mu} = \pm 0.018$, $\delta A_{FB}^{b\bar{b}}/A_{FB}^{b\bar{b}} = \pm 0.055$, $\delta A_{FB}^{t\bar{t}}/A_{FB}^{t\bar{t}} = \pm 0.040$. The $\sigma_{f\bar{f}}$ and $A_{FB}^{f\bar{f}}$ ($f = \mu,\ b,\ t$) values have been computed, for 1 TeV $< \sqrt{s} <$ 5 TeV, both in the SM and including the corrections due to the presence of a $E_6 - Z'$ boson with 10 TeV $< M_{Z'} <$ 40 TeV. Predictions have been obtained by implementing these models in the COMPHEP program [15]. 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 probability of less than 5%. This probability has been defined as the minimum of the global probability computed for all the observables and that for each of them, taken independently. This sensitivity has been determined, as a function of the $\sqrt{s}$ energy and integrated luminosity $L$ and compared to the previous scaling law. Results for the SSM and for the $\chi$ model are summarized in Figure 1. For the $\eta$ model the sensitivity is lower: for example to reach a sensitivity of $M_{Z'}$=20 TeV, more than 10 ab$^{-1}$ of data at $\sqrt{s}$=5 TeV would be necessary.

In the case of the 5D SM, we have included only the effect of the exchange of the first KK excitations $Z^{(1)}$ and $\gamma^{(1)}$, neglecting that of the remaining excitations of the towers, which give only small corrections. The scaling law for the limit on the compactification scale $M$ can be obtained by considering the interference of the two new nearly degenerate gauge bosons with the SM photon in the cross section and taking the $s << M^2$ limit. The result is again $M \propto (sL)^{1/4}$. 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 sen-

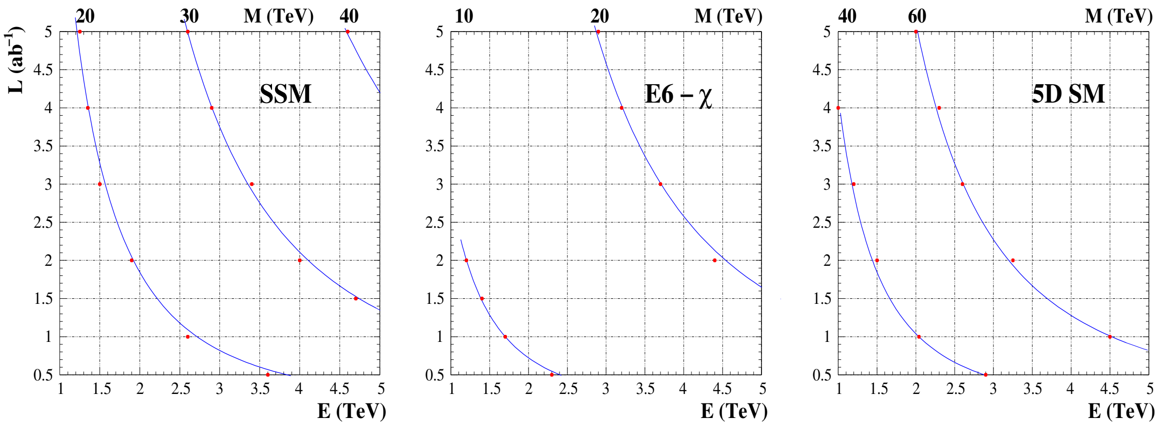


Figure 1: *The 95% CL sensitivity contours in the L vs. $\sqrt{s}$ plane for different values of $M_{Z'}$ in the SSM model (left), in the $E_6$-$\chi$ model (center) and in the 5D SM. The points represent the results of the analysis, while curves show the behaviour expected from the scaling $M_{Z'} \propto (sL)^{1/4}$.*

sitivity achievable on the compactification scale $M$ for an integrated luminosity of 1 ab$^{-1}$ in $e^+e^-$ collisions at $\sqrt{s}$ = 3-5 TeV is of the order of 40-60 TeV. Results for a similar analysis, including all electro-weak observables, are discussed in [16].

An important issue concerns the ability to probe the models, once a significant discrepancy from the SM predictions would be observed. Since the model parameters and the mass scale are *a priori* arbitrary, an unambiguous identification of the scenario realized is difficult. However, some informations can be extracted by testing the compatibility of different models while varying the mass scale. Suppose that a particular model is realized in nature. By comparing the integrated $\chi^2$ distribution for the actual model and a different one, we can evaluate the confidence level at which the two models are distinguishable. Figure 2 shows an example of such tests. Taking $M$=20 TeV, $L$ = 1 ab$^{-1}$ of CLIC data at $\sqrt{s}$ = 3 TeV could distinguish the SSM model from the $E_6$-$\chi$ model at the 86% CL and from the 5D SM at the 99% CL. For a mass scale of 40 TeV, $L$ = 3 ab$^{-1}$ of CLIC data at $\sqrt{s}$ = 5 TeV, the corresponding confidence levels become 91% and 99% respectively. Further sensitivity to the nature of the gauge bosons could be obtained by studying the polarized forward-backward asymmetry $A_{FB}^{pol}$ and the left-right asymmetry $A_{LR}$ colliding polarized beams.

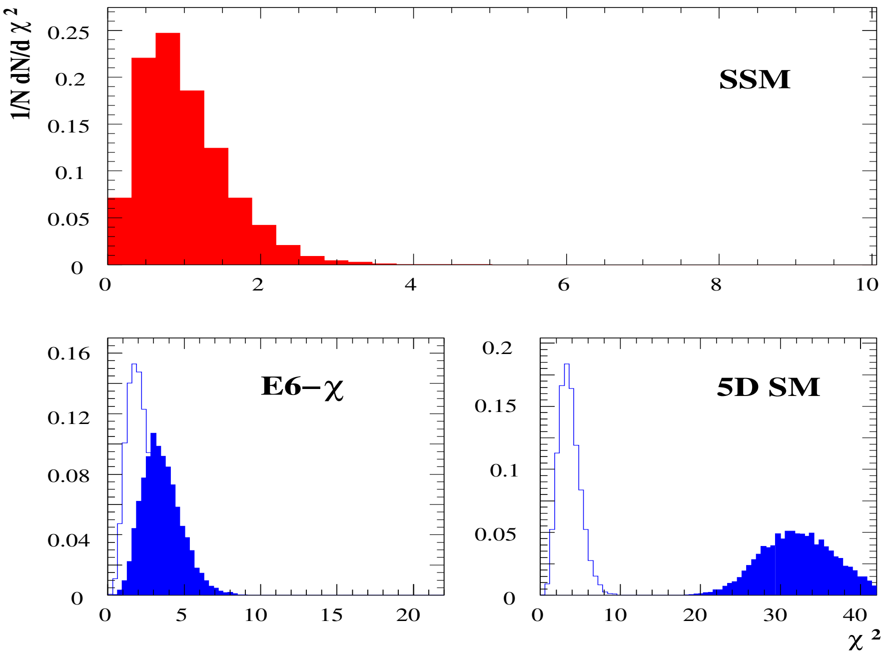


Figure 2: $\chi^2$ *distributions obtained for a set of pseudo-experiments (L = 1 ab*$^{-1}$ *of* Clic *data at* $\sqrt{s}$ *= 3 TeV) where the SSM is realized with a* $Z'$ *mass of 20 TeV (upper plot). The corresponding distributions for the* $E_6$-$\chi$ *and 5D SM for M=20 TeV (full histograms) and for M=40 TeV are shown in the lower panels.*

# 4 Conclusions

Accuracies achievable for the determination of the fundamental properties of new neutral vector resonances are discussed for different classes of models, using realistic assumptions for the experimental conditions at Clic. Even beyond the kinematical reach for s-channel production, a multi-TeV $e^+e^-$ collider could probe the existence of new vector resonances up to scales of several tens of TeV by studying the unpolarised electro-weak observables. Some information regarding the nature of these new resonances could still be gained and further sensitivity would be provided by the use of polarised beams.

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