PROCEEDINGS OF SCIENCE

Pair production of charged IDM scalars at high energy CLIC

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The Compact Linear Collider (CLIC) is an e^+e^- collider proposed as the next energy frontier infrastructure at CERN. It will allow for precise measurements of the Higgs boson and top quark properties at its first running stage, at $\sqrt{s} = 380\,\text{GeV}$. The subsequent energy stages, at 1.5 TeV and 3 TeV, will mainly focus on searches for Beyond the Standard Model (BSM) phenomena. The Inert Doublet Model (IDM) is a simple extension of the Standard Model, introducing an additional Higgs doublet that brings in four new scalar particles. The lightest of the IDM scalars is stable and is a good candidate for a dark matter (DM) particle. The potential of discovering the IDM scalars in the experiment at CLIC has been tested for two high-energy running stages, at 1.5 TeV and 3 TeV centre-of-mass energy. The CLIC sensitivity to pair-production of the charged IDM scalars was studied using the full detector simulation for selected high-mass IDM benchmark scenarios and the semi-leptonic final state. To extrapolate the results to a wider range of IDM benchmark scenarios, the CLIC detector model in Delphes was modified to take into account the $\gamma\gamma \to$ had. beam-induced background. Results of the study indicate that heavy charged IDM scalars can be discovered at CLIC for most of the considered benchmark scenarios, up to masses of the order of 1 TeV. Results included in this paper supersede results presented previously in [1].

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1. Introduction

In addition to the comprehensive programme of precision studies, CLIC [2] offers diverse possibilities to search for new physics phenomena. Its two high-energy operating stages, at 1.5 TeV and 3 TeV, provide a discovery reach that is comparable to, and in many cases exceeds, that of the LHC [3]. This contribution presents results of the study [4] on the CLIC potential to detect new heavy particles predicted by the Inert Doublet Model (IDM).

The IDM [5] is a very simple extension of the SM scalar sector, where an “inert” doublet is introduced, containing four new scalar fields: $H^{\pm}$, A, and H. The lightest of them, H, is stable due to the imposed Z_2 symmetry, making it a natural DM candidate. Five free parameters are left in the model after the electroweak symmetry breaking and fixing of the SM parameters: three masses of the IDM scalars and two coupling constants.

We consider 23 scenarios with high dark scalar masses, selected from the two sets of benchmark points proposed in [6]. They cover all interesting regions of the parameter space in the context of future lepton collider studies and respect all current constraints, both theoretical and experimental. The benchmarks correspond to different values of the IDM scalar masses and couplings. They provide a range of production cross sections that depend almost entirely on the scalar masses (the influence of couplings is marginal). The production of pairs of charged and neutral scalar particles are the two dominant production channels in the e^+e^- colliders:

$$\begin{aligned} e^+e^- &\rightarrow \mathrm{H}\ \mathrm{A}\,, \\ e^+e^- &\rightarrow \mathrm{H}^+\mathrm{H}^-\,. \end{aligned}$$

Scalar $H^{\pm}$ mainly decays into $W^{\pm}$ and H, while A into Z and H. Depending on the scalar mass differences in both channels, the gauge bosons produced in these decays can be virtual or real.

2. Strategy and the analysis

A generator-level study [7] has previously analysed the possible detection of IDM scalars at CLIC. However, it showed a limited sensitivity to cross sections of approximately 1,fb (for scalar production and decay in the final state considered), with the discovery possible only up to $m_A + m_H \sim 550\,\mathrm{GeV}$ and $m_{H^{\pm}} \sim 500\,\mathrm{GeV}$ and many of the analysed benchmarks out of reach. Therefore, in this analysis, we consider the semi-leptonic final state, with one W decaying into a lepton and neutrino and another into jets. This signature offers cross sections almost an order of magnitude higher but is possible only for the charged production channel.

We used Whizard 2.7.0 [8] for the event generation, assuming −80% electron beam polarisation and taking into account the CLIC beam spectra. The CLIC sensitivity was studied for five selected scenarios using full detector response simulation, based on packages Geant4 [9] and DD4hep [10]. To further analyse a wide range of scenarios and still take into account the detector response, Delphes [11] fast simulation package, with dedicated CLIC detector (CLICdet) cards [12], was used to consider the full set of 23 benchmark points.

After the simulation and reconstruction stages, in each event we required the presence of an electron or muon and a pair of jets, which corresponds to the expected final state signature. Based on the distributions of the kinematic variables that describe the system, a simple cut-based preselection

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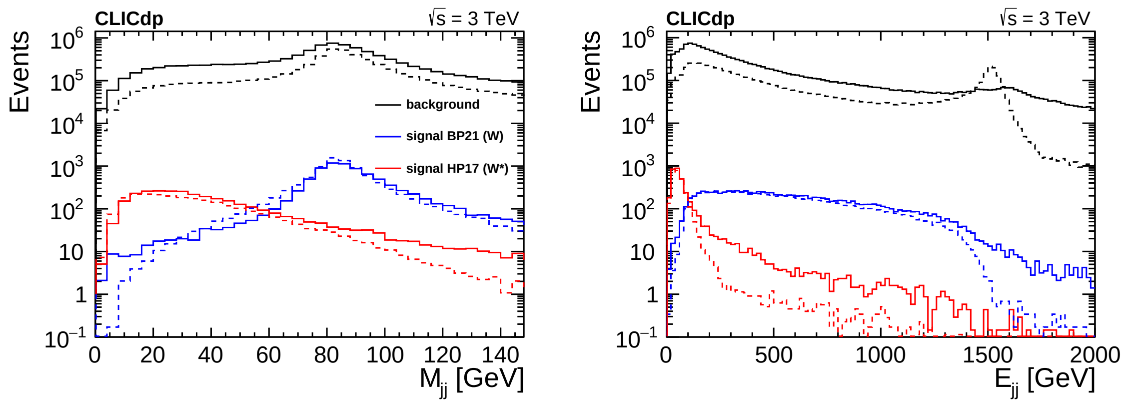

Figure 1: Histograms of the mass (left) and the energy (right) of a dijet system corresponding to full simulation of the HP17 (red) and BP23 (blue) signal scenarios at the 3 TeV CLIC. The black histogram is the sum of all SM background channels. Dashed histograms correspond to the fast simulation. Distributions are normalized to the number of events expected in the actual experiment.

was also imposed. The distributions of mass and energy of a dijet system, corresponding to the full simulation for the two signal scenarios (HP17 and BP23) and the SM background, are shown in Figure 1. The respective histograms, presented for comparison, result from the fast simulation (and include the $\gamma\gamma \to$ had. contribution; see Sec. 3). The significant difference visible between the two signal scenarios results from the mass splitting, $m_{H^\pm} - m_H$, which is small in the HP17 scenario (the produced $W^\pm$ boson is highly virtual) and large in BP23 ($W^\pm$ boson is on shell).

Events that had passed the preselection were considered in the event classification procedure, based on the Boosted Decision Trees (BDTs) and implemented in the TMVA toolkit [13]. Trainig was performed separately on the two datasets: one containing signal scenarios with virtual $W^\pm$ bosons and another composed of the remaining samples with real $W^\pm$ production.

3. Influence of the overlay events

Because of the high bunch repetition rate and beam intensity, beam-induced backgrounds need to be taken into account at CLIC. From the point of view of event reconstruction, the most important are the so-called “overlay events” – the $\gamma\gamma$ interactions producing soft hadrons. In the case where the mass splitting between IDM scalars is small, there is a strong influence of $\gamma\gamma \to$ had. processes on the reconstruction of low-energy jets and leptons from highly virtual W boson decays.

The standard procedure aimed to reduce the contribution of the overlay events, implemented in the full simulation, is to apply cuts on the time stamps of reconstructed Particle Flow Objects (PFOs). However, the CLICdet model for Delphes does not include an implementation of timing cuts. To mimic the timing cuts on the PFO level, we applied an additional generator-level selection to the $\gamma\gamma \to$ had. samples before overlying them on the generated signal and background events. The impact of this procedure on the reconstruction of the jet and dijet mass in the HP17 scenario (with small $m_{H^\pm} - m_H$) is presented in Fig. 2. The respective distributions produced using the full simulation and Delphes, with and without the overlay contribution, are compared. After including $\gamma\gamma$ interactions, a clear improvement in signal modelling can be achieved for fast simulation.

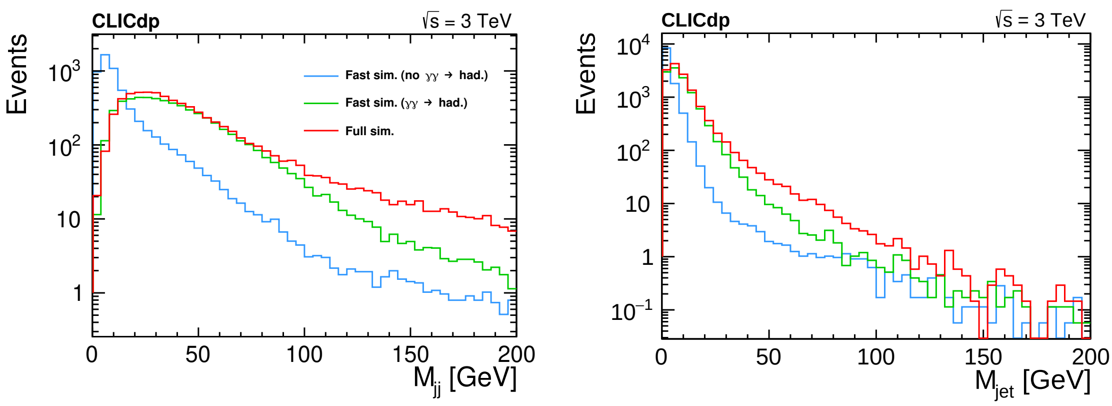

Figure 2: Histograms of the mass of a di-jet system (left) and a single jet (right), for signal HP17 at $\sqrt{s}$ = 3 TeV, obtained using different simulation methods: the full simulation (red), fast simulation (azure) and fast simulation with overlay contribution (green).

4. Results

After the BDT selection, the expected statistical significance of deviations from the SM background predictions was obtained for each signal scenario. The results obtained with the full simulation at $\sqrt{s}$ =3 TeV are presented in Fig. 3 (left), compared with the outcome of fast simulation both with and without the overlay background contribution. The BDTs were trained on each scenario separately here, both for the fast and the full simulations, on the one hand to perform a correct validation of the Delphes results, but also to avoid uncontrolled bias in such small datasets. The reliability of the results obtained using fast simulation has visibly improved after including the overlay background.

This can be seen also on the right in Fig. 3, where ratios of the results from the two simulation methods are shown, with and without the overlay contribution. However, the residual discrepancy has still remained due to other possible systematic effects. It was addressed by introducing an additional correction factor, depending only on the dark scalar mass splitting. A functional form of the correction was fitted to the points corresponding to fast simulation with the $\gamma\gamma \rightarrow$ had. events included, which is also shown in Fig. 3.

The obtained function was used to scale the expected significances for the 23 benchmark scenarios considered in the study, for both CLIC high-energy stages. The final results are presented as a function of $2m_{H^\pm}$ and $m_{H^\pm} - m_H$ in Fig. 4. They are based on fast simulation with overlay events included and BDTs trained concurrently for all signal scenarios, as described in Sec. 2. To account for the arbitrary choice of functional form and all possible systematic effects, we assumed 100% uncertainty on the applied correction, which is shown with the error bars on the presented plots. The results show that charged IDM scalars can be observed at CLIC, with high statistical significance reaching 40 σ and for masses up to about 1 TeV.

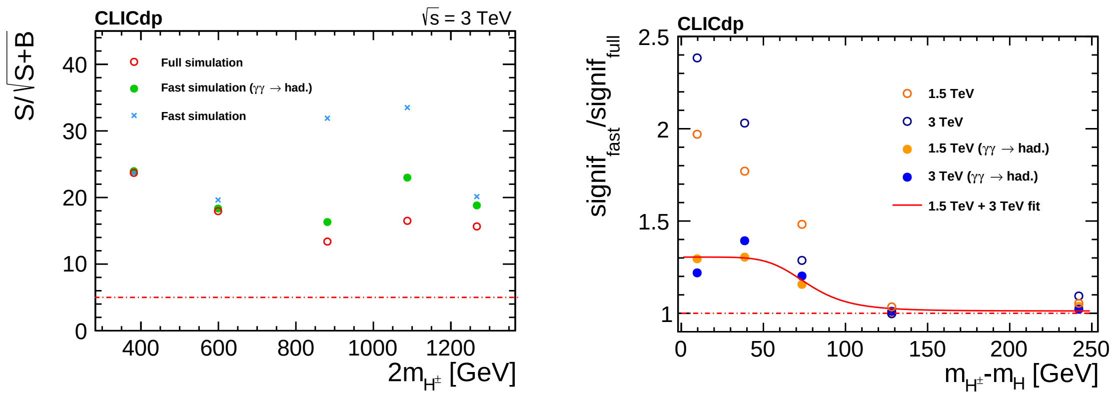

Figure 3: Statistical significance expected in the study, as a function of $2m_{H^\pm}$ and $m_{H^\pm} - m_H$. Left: the comparison of results obtained with different simulation methods for 3 TeV CLIC; the red dotted line shows the 5σ threshold. Right: ratios of the results from different simulation methods and a dependence of the remaining discrepancy, shown as a function of the scalar mass splitting. See text for more details.

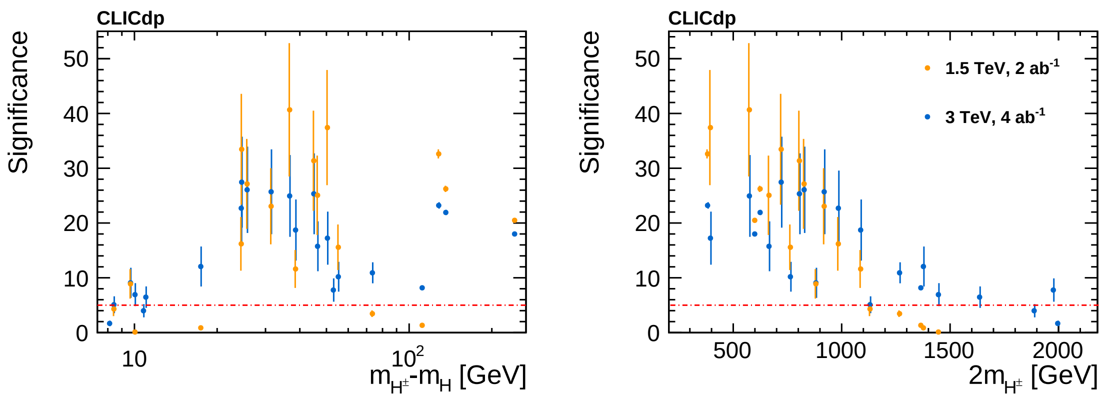

Figure 4: Expected statistical significance of IDM charged scalar pair-production observation as a function of the IDM scalar mass difference, $m_{H^\pm} - m_H$ (left) and of the total mass of the produced IDM scalars, $2m_{H^\pm}$ (right). Results of the Delphes fast simulation study are presented for CLIC running at 1.5 TeV (orange) and 3 TeV (blue points). Error bars indicate the systematic uncertainty, estimated from the observed difference between fast and full simulation results, see text for details. The red horizontal lines indicate the 5σ threshold.

5. Conclusion

The prospects for detecting heavy charged IDM scalar pair production at CLIC has been studied for five selected IDM signal scenarios using the Geant4-based full simulation. The large set of 23 benchmark scenarios was then analysed using Delphes fast simulation tool. As the influence of $\gamma\gamma \rightarrow$ had. overlay background on the reconstruction of the signal events cannot be neglected in the case of small scalar mass splittings, it was also included in the fast simulation. A dedicated correction was further applied to account for the residual discrepancies between the two simulation methods. We conclude that almost for all of the considered benchmark scenarios the observation of charged IDM scalar pair-production is possible, with their masses up to 1 TeV.

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