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# The physics benchmark processes for the detector performance studies of the CLIC CDR

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**Abstract**

This note describes the physics benchmark processes used in the CLIC conceptual design report (CDR) to assess the performance of the CLIC_ILD and CLIC_SiD detector concepts.

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# 1 Introduction

The Compact Linear Collider (CLIC [1]) is an $e^+e^-$ project aiming at collisions with energies up to 3 TeV and with high luminosity. The anticipated physics potential of such a collider is broad and extends from precision tests of the Higgs sector to detailed studies of new phenomena through new particle spectroscopy, coupling measurements and to sensitivity to new physics beyond the machine centre of mass energy through precision studies of electroweak observables.

A set of key processes needs to be defined in order to establish the minimal requirements of the performance of a general purpose detector at CLIC, as well as to assess the achievable accuracies for physics observables while accounting for the realistic machine-induced background conditions, detector response and event reconstruction.

The challenging detector requirements imposed by the physics aims at $e^+e^-$ colliders were addressed for the 500 GeV ILC [2] in the validated ILD [3] and SiD [4] detector concepts. In the CLIC case, a number of benchmark physics processes were chosen in summer 2010, each addressing a particular aspect of the detector performance, selected to be complementary in assessing the full scope of detector capabilities of measuring physics observables. The majority of the benchmark processes have been chosen at 3 TeV, which is the reference energy for the machine design and optimisation, to emphasise the experimental issues of multi-TeV physics due to both the event kinematics and the machine induced-backgrounds.

The benchmark processes comprise 5 processes at 3 TeV (production of light Higgs, heavy Higgs, right-handed squarks, of chargino and neutralino, and of sleptons), and in addition the $t\bar{t}$ production at 500 GeV, for comparison with previous ILC studies. These processes, which serve as basis for the CLIC CDR [1], are described in the next sections.

The purpose of this note is to present the 6 chosen benchmark processes, together with their underlying physics model parameters, and the principal detector performance aspects they address. The actual full detector simulation and analysis for each of the 6 individual benchmark processes will be described in separate LCD notes and in the CLIC CDR.

The spectra of supersymmetric particles have been calculated using `Softsusy3.1.3` [5]. The sparticles decay branching fractions have been computed with `SDECAY1.1` [6] and the Born-level cross sections with `Madgraph4` [7]. The neutralino relic dark matter density has been computed using `micrOmegas2.2` [8] and points in the parameter space have been required to be compatible with the results from Cosmic Microwave background. Events of the benchmark signal processes have been generated with `Whizard` [9], and the hadronization was done with `Pythia6` [10].

# 2 Light Higgs production

The first process to be considered is the production of a light Higgs, with mass $m_h = 120$ GeV:

$$e^+e^- \to h\nu_e\bar{\nu}_e \tag{1}$$

At $\sqrt{s} = 3$ TeV, the dominant production process is through $WW$ fusion, which results in a large cross-section, thus opening up the possibility to study rare decays. The first CLIC detector benchmark is the measurement of the ratio of $BR(h \to \mu^+\mu^-)/BR(h \to b\bar{b})$. The observation of the rare decay $h \to \mu^+\mu^-$, with a branching ratio of $\mathcal{O}(10^{-4})$, relies on the ability to reconstruct the Higgs mass from the two decay muons with sufficiently good mass resolution to distinguish the Higgs decays from the large and irreducible background from, for example, $e^+e^- \to \mu^+\mu^-e^+e^-$. Observation of this rare decay thus requires excellent momentum resolution.

| | |
|---|---|
| Process: | $e^+e^- \to h\nu_e\bar{\nu}_e$ |
| Particle mass : | $m_h = 120$ GeV |
| Final states: | $h \to \mu^+\mu^-$ |
| | $h \to b\bar{b}$ |
| | $h \to c\bar{c}$ |

Table 1: The used mass and final states in the light Higgs production.

Due to the dominant fusion process, the Higgs bosons are preferentially produced in the forward direction. Therefore the reconstruction of the $h \to b\bar{b}$ and $h \to c\bar{c}$ final states at $\sqrt{s} = 3$ TeV challenges the ability to identify heavy flavour in the forward region (where there is non-negligible beam induced background). It also requires sufficient jet energy resolution to distinguish Higgs decays from $Z$ decays.

Thus this benchmark channel probes the detector performance for:

- muon momentum resolution;
- flavour-tagging in the forward region;
- jet energy reconstruction for forward jets.

# 3 Heavy Higgs production

Supersymmetric extensions of the SM result in a rich Higgs sector. The study of heavy Higgs pair production at CLIC requires the reconstruction of high mass, multi-jet final states and thus forms a suitable detector benchmark channel.

For the heavy Higgs benchmark study, a SUSY model with the GUT scale parameters given in Table 2 was chosen. (For an explanation of the SUSY model parameters, see for example [11].) Other relevant particle masses are given in the footnote[2)]. In this model, the heavy Higgs bosons predominantly decay to heavy quarks, with the remaining decay modes being dominated by $\tau$-leptons in the final state. For later reference, this model is called *SUSY model I*.

Note this is not a CMSSM model, since it has non-unified gaugino masses. This allows sleptons to be relatively heavier compared to squarks than the ratio found in mSUGRA within the stau-coannihilation region. These parameters were chosen to be consistent with current data.

[2] $m_{\tilde{\chi}^0_{1,2,3,4}} = 328.3,\ 701.8,\ 760.2,\ 816.2$ GeV, $m_{\tilde{\chi}^\pm_{1,2}} = 701.6,\ 816.1$ GeV, $m_{\tilde{\tau}_1} = 330.2$ GeV, $m_{\tilde{\tau}_2} = 674.3$ GeV, $m_{\tilde{\nu}_\tau} = 666.8$ GeV, $m_{\tilde{t}_1,\tilde{t}_2} = 739.4,\ 1121.8$ GeV, $m_{\tilde{b}_1,\tilde{b}_2} = 1043.3,\ 1096.0$ GeV, $m_{\tilde{e}_R} = 422.8$ GeV, $m_{\tilde{e}_L} = 696.1$ GeV, $m_{\tilde{\nu}_e} = 691.3$ GeV, $m_{\tilde{u}_R,\tilde{u}_L} = 1125.7,\ 1257.7$ GeV, $m_{\tilde{d}_R,\tilde{d}_L} = 1116.1,\ 1260.0$ GeV, $m_{\tilde{g}} = 1239.7$ GeV

| | |
|---|---|
| Processes: | $e^+e^- \to H^+H^-$ <br> $e^+e^- \to H^0A^0$ |
| Particle masses: | $m_h = 119.13$ GeV <br> $m_{A^0} = 902.6$ GeV <br> $m_{H^0} = 902.4$ GeV <br> $m_{H^\pm} = 906.3$ GeV |
| Final states: | $H^+H^- \to tb\bar{t}\bar{b}$ (and possibly $tb\tau\nu_\tau$) <br> $H^0A^0 \to b\bar{b}b\bar{b}$ (and possibly $b\bar{b}\tau^+\tau^-$) |
| Branching ratios: | $H^+ \to t\bar{b}$ (81.8%), $\tau^+\nu_\tau$ (18.2%) <br> $H^0 \to b\bar{b}$ (81.8%), $\tau^+\tau^-$ (17.3%), $t\bar{t}$ (0.9%) <br> $A^0 \to b\bar{b}$ (81.7%), $\tau^+\tau^-$ (17.3%), $t\bar{t}$ (1.0%) |
| Model parameters | $M_1 = 780$ GeV, $M_2 = 940$ GeV, $M_3 = 540$ GeV <br> $A_0 = -750$ GeV, $m_0 = 303$ GeV, $\tan\beta = 24$, $\mu > 0$ <br> $m_t = 173.3$ GeV, $M_b(M_b) = 4.25$ GeV, $\alpha_S(M_z) = 0.118$ |

Table 2: The used particle masses, final states, branching ratios and the model parameters in the heavy Higgs production (*SUSY model I*).

In particular, the contribution to the muon magnetic moment anomaly, $a_\mu$, is $\Delta a_\mu = 6 \times 10^{-10}$ and they result in $BR(b \to s\gamma) = 3.0 \times 10^{-4}$.

It should be noted that for the purpose of the benchmark of the detector performance, the exact nature of the model parameters is not critical. The essential feature of this model is that it gives rise to a heavy SUSY Higgs sector.

The reconstruction of the heavy Higgs mass and width in the processes $e^+e^- \to H^+H^- \to t\bar{b}\bar{t}b$ and $e^+e^- \to H^0A^0 \to b\bar{b}b\bar{b}$ is chosen as the second benchmark physics process.

This physics benchmark probes the detector performance for:

- flavour-tagging for high energy jets;
- invariant mass reconstruction of high mass states in a high multiplicity environment.

# 4 Production of right-handed squarks

The production and decay of right-handed squarks in the process:

$$e^+e^- \to \tilde{q}_R\bar{\tilde{q}}_R \qquad (2)$$

results in a simple topology of two high energy jets and missing energy and is chosen as the third benchmark process.

Note that for the squarks production, the same supersymmetry model is used as for the heavy Higgs production, i.e. *SUSY model I* (see Section 3). Additional information is given in Table 3.

| | |
|---|---|
| Process: | $e^+e^- \to \tilde{q}_R\bar{\tilde{q}}_R$ |
| Squark masses: | $m_{\tilde{u}_R} = m_{\tilde{c}_R} = 1125.7$ GeV<br>$m_{\tilde{d}_R} = m_{\tilde{s}_R} = 1116.1$ GeV |
| Final states: | $\tilde{q}_R\bar{\tilde{q}}_R \to q\bar{q}\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \text{jets} + \not{E}$, i.e. inclusive jets and missing energy (possibly with $c$ and $s$ tagging) |
| Branching ratios: | $\tilde{q}_R \to q\tilde{\chi}_1^0$ (99.7%) |

Table 3: The used particle masses, final states and branching ratios in the production of right-handed squarks.

| | |
|---|---|
| Processes: | $e^+e^- \to \tilde{\chi}_i^+\tilde{\chi}_j^-$<br>$e^+e^- \to \tilde{\chi}_i^0\tilde{\chi}_j^0$ |
| Particle masses: | $m_{\tilde{\chi}^0_{1,2,3,4}} = 340.3,\ 643.1,\ 905.5,\ 916.7$ GeV<br>$m_{\tilde{\chi}^\pm_{1,2}} = 643.2,\ 916.7$ GeV<br>$m_h = 118.52$ GeV |
| Final states: | $\tilde{\chi}_1^+\tilde{\chi}_1^- \to W^+W^-\tilde{\chi}_1^0\tilde{\chi}_1^0$<br>$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to hh\tilde{\chi}_1^0\tilde{\chi}_1^0$<br>$\tilde{\chi}_2^0\tilde{\chi}_2^0 \to hZ\tilde{\chi}_1^0\tilde{\chi}_1^0$ |
| Branching ratios: | $\tilde{\chi}_1^\pm \to W^\pm\tilde{\chi}_1^0$ (100%)<br>$\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$ (90.6%), $Z\tilde{\chi}_1^0$ (9.4%)<br>$h \to b\bar{b}$ (68.8%), $\tau^+\tau^-$ (21.0%), $W^+W^-$ (11.8%), $ZZ$ (0.9%)<br>$W^\pm \to hadrons$ (67.6%) |
| mSUGRA parameters: | $m_{1/2} = 800$ GeV, $A_0 = 0$, $m_0 = 966$ GeV, $\tan\beta = 51$, $\mu > 0$ |

Table 4: The used particle masses, final states, branching ratios and the SUSY model parameters in the chargino and neutralino production (*SUSY model II*).

The reconstruction of the squark mass in the inclusive jets plus missing energy provides a test of:

- jet energy and missing energy reconstruction for high energy jets in a simple topology.

# 5 Chargino and neutralino pair production

Since the purpose of the benchmark channels is to demonstrate the detector capabilities for reconstructing typical final states at CLIC rather than providing a full demonstration of the physics reach of the machine, a SUSY model in which the lightest chargino and two lightest neutralinos are dominated by a single decay mode is used (see Table 4).

This model, which for later references is referred to as the *SUSY model II*, has 640 GeV wino-like states and 910 GeV higgsino-like states. Other relevant masses are given in the footnote[3)].

Since the $Z$, $W$ and $h$ have largest decay fractions to quarks, the signatures for chargino and neutralino production in this model are final states with four jets and missing energy. The reconstruction of the $Z$, $W$ and $h$ masses from the appropriate di-jet combinations is essential to disentangle the physics signatures. Hence chargino and neutralino production provides a benchmark for the reconstruction of hadronically decaying gauge bosons in a multi-jet environment. The fourth benchmark process is the reconstruction of the $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ masses in final states with four jets and missing energy from the processes given in Table 4.

This benchmark process addresses:

- jet energy and missing energy reconstruction in high energy decays;
- di-jet mass reconstruction and separation of $Z$, $W$ and $h$ hadronic decays.

# 6 Slepton production

The production of energetic leptons is a signature for many physics processes beyond the standard model, and thus the reconstruction of high energy electrons and muons is an essential aspect of a detector at CLIC. Hence the fifth physics benchmark channel, namely slepton production, focuses on lepton reconstruction. The same SUSY scenario as in the case of chargino and neutralino pair production, i.e. the *SUSY model II* (see Section 5) is used.

| | |
|---|---|
| Processes: | $e^+e^- \rightarrow \tilde{\ell}^+\tilde{\ell}^-$, where $\tilde{\ell} = \tilde{e}$, $\tilde{\mu}$ or $\tilde{\nu}$ |
| Particle masses: | $m_{\tilde{e}_R} = m_{\tilde{\mu}_R} = 1010.8$ GeV<br>$m_{\tilde{e}_L} = m_{\tilde{\mu}_L} = 1100.4$ GeV<br>$m_{\tilde{\nu}_L} = 1097$ GeV |
| Final states: | $\tilde{\ell}_R^+\tilde{\ell}_R^- \rightarrow \ell^+\ell^-\tilde{\chi}_1^0\tilde{\chi}_1^0$, where $\ell = e$ or $\mu$<br>$\tilde{\ell}_L^+\tilde{\ell}_L^- \rightarrow \ell^+\ell^-\tilde{\chi}_2^0\tilde{\chi}_2^0$, where $\ell = e$<br>$\tilde{\nu}_e\bar{\tilde{\nu}}_e \rightarrow \ell^+\ell^-\tilde{\chi}_1^-\tilde{\chi}_1^+$ , where $\ell = e$ |
| Branching ratios: | $\tilde{\ell}_R \rightarrow \ell\tilde{\chi}_1^0$ (100%), where $\ell = e$ or $\mu$<br>$\tilde{e}_L \rightarrow e\tilde{\chi}_2^0$ (29%), $\tilde{e}_L \rightarrow e\tilde{\chi}_1^0$ (19%)<br>$\tilde{\nu}_{e,L} \rightarrow e\tilde{\chi}_1^{\pm}$ (56%) |
| mSUGRA parameters: | $m_{1/2} = 800$ GeV, $A_0 = 0$, $m_0 = 966$ GeV, $\tan\beta = 51$, $\mu > 0$ |

Table 5: The used particle masses, final states, branching ratios and the SUSY model parameters in the slepton production.

[3] $m_H = 742.0$ GeV, $m_A = 742.8$ GeV, $m_{H^\pm} = 747.6$ GeV, $m_{\tilde{\tau}_1} = 670.4$ GeV, $m_{\tilde{\tau}_2} = 973.7$ GeV, $m_{\tilde{\nu}_\tau} = 962.0$ GeV, $m_{\tilde{t}_1} = 1392.9$ GeV, $m_{\tilde{t}_2} = 1598.1$ GeV, $m_{\tilde{b}_1} = 1544.4$ GeV, $m_{\tilde{b}_2} = 1609.7$ GeV, $m_{\tilde{e}_R} = 1010.8$ GeV, $m_{\tilde{e}_L} = 1100.4$ GeV, $m_{\tilde{\nu}_e} = 1097.2$ GeV, $m_{\tilde{u}_R} = 1817.7$ GeV, $m_{\tilde{u}_L} = 1870.3$ GeV, $m_{\tilde{d}_R} = 1812.3$ GeV, $m_{\tilde{d}_L} = 1871.83$ GeV, $m_{\tilde{g}} = 1811.8$ GeV

The fifth CLIC detector benchmark is the reconstruction of slepton masses from the lepton energy distributions in the processes given in Table 5.

The main aspects of the detector performance which are addressed are:

- reconstruction and identification of high energy leptons;
- energy resolution for high energy electrons and muons, in two leptons, or two leptons plus 4 jets topology;
- boson mass resolution.

# 7 In addition: $t\bar{t}$ production at 500 GeV

The process of $e^+e^- \rightarrow t\bar{t}$ has been extensively studied for the ILC [3] at $\sqrt{s} = 500\,\text{GeV}$. It is possible that the construction of the CLIC accelerator will be staged in energy, with the exact construction path depending on the physics uncovered by the LHC. Given the different beam parameters for CLIC and ILC, the measurement of the top mass from direct reconstruction in $e^+e^- \rightarrow t\bar{t}$ at $\sqrt{s} = 500\,\text{GeV}$ is chosen as the sixth benchmark process, with the aim of assessing possible differences in physics sensitivity.

Both fully-hadronic and semi-leptonic final states are considered, as shown in Table 6.

| | |
|---|---|
| Process: | $e^+e^- \rightarrow t\bar{t}$ |
| Final states: | $t\bar{t} \rightarrow (bq\bar{q})(\bar{b}q\bar{q})$, i.e. 6 jets |
| | $t\bar{t} \rightarrow (bq\bar{q})(\bar{b}\ell\nu_\ell)$, where $\ell = e,\ \mu,$ i.e. 4 jets $+\ell+\not{E}$ |

Table 6: The studied final states in case of $t\bar{t}$ p production.

This benchmark channel provides a test of:

- mass reconstruction in a multi-jet final state for low energy jets;
- flavour tagging;
- impact of CLIC beam conditions at 500 GeV compared to those of the ILC.

# 8 Summary

In order to test the complementary requirements on a general purpose CLIC detector which are implied by the physics aims at a multi TeV scale, a set of benchmark processes was defined and presented in this note. The studies of these processes use full Geant4 simulations, including overlaid background, and serve to assess the physics performance in the CLIC CDR.

## References


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