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The physics benchmark processes for the detector performance studies used in CLIC CDR Volume 3

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Abstract

This note describes the detector benchmark processes used in volume 3 of the CLIC conceptual design report (CDR), which explores a staged construction and operation of the CLIC accelerator. The goal of the detector benchmark studies is to assess the performance of the CLIC_ILD and CLIC_SiD detector concepts for different physics processes and at a few CLIC centre-of-mass energies.

Contents

1 Introduction

The Compact Linear Collider (CLIC [1]) is an $e^+ e^-$ collider under development aiming at collision energies up to 3 TeV. A total luminosity of $5.9{\cdot}10^{34}$ cm^{-2}s^{-1} is foreseen. The anticipated physics potential of such a collider is broad and extends from precision tests of the Higgs and top sector to detailed studies of new phenomena through new particle spectroscopy, coupling measurements, threshold scans, measurements of spins and other quantum numbers, and to sensitivity to new physics beyond the machine centre-of-mass energy through precision studies of electroweak observables.

The challenging detector requirements imposed by the physics aims and the beam conditions at CLIC are addressed in [1]. The majority of the benchmark processes have been chosen at 3 TeV, which is the reference energy for the machine design and optimisation for the CDR, to emphasise the experimental issues of multi-TeV physics due to both the event kinematics and the beam-induced backgrounds.

When actually building such a machine it will most likely be constructed in successive energy stages. A strategic document, referred to as volume 3 of the CLIC CDR study, is in preparation and describes an example of such a staged construction approach. In this example the construction of CLIC is envisaged in three stages. Starting with a centre-of-mass energy of 500 GeV, followed by an intermediate stage of 1.4 TeV, and subsequently the full energy of 3 TeV. Table 1 shows the integrated luminosity assumed for each of the stages in the detector benchmark studies. For dedicated studies of the Higgs and top sector the first stage (500 GeV) is also operated at a centre-of-mass energy near 350 GeV. For these two analyses performed at 350 GeV an integrated luminosity of up to 100 fb^{-1} for the top quark scan and 500 fb^{-1} for the Higgs study is used.

The purpose of this note is to present the selected benchmark processes for the staged approach, in a similar way as was done for the benchmark studies at 3 TeV [2]. The actual full detector simulation and analysis for each of the individual benchmark processes will be described in separate LCD notes, and the results will be summarised in volume 3 of the CLIC CDR.

Table 1: Energy and expected integrated luminosity for each stage.

Stage	Energy [GeV]	Integrated Luminosity [ab^{-1}]
1	500 (350)	0.5
2	1400	1.5
3	3000	2

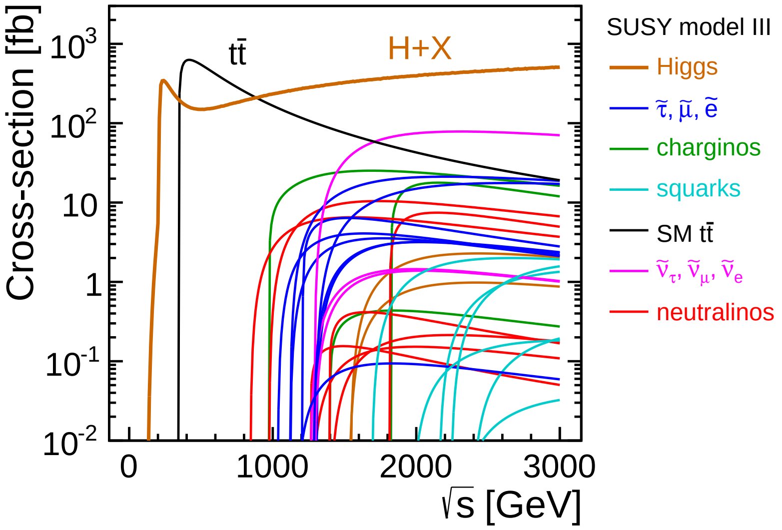

Figure 1: Cross sections for the production of $t\bar{t}$, H + X and pairs of supersymmetric particles in *model III* as a function of collider centre-of-mass energy.

To study supersymmetry a specific example model has been selected. The chosen model referred to as *SUSY model III* produces final states compatible with current direct sparticle searched at the LHC. The relevant GUT scale parameters of the SUSY model are given in Table 2. It is used for all SUSY benchmark processes presented here. The cross-sections for pairs of superpartners as function of the centre-of-mass energy are shown in Figure 1. The spectrum of supersymmetric particles has been calculated using `Softsusy 3.2.0` [3]. Events of the benchmark signal processes have been generated with `Whizard 1.95` [4], and the hadronisation was done with `Pythia 6.422` [5].

Table 2: The input parameters at the gauge coupling unification scale and sparticle masses of *SUSY model III*.

Model parameters	$M_1 = 840$ GeV, $M_2 = 600$ GeV, $M_3 = 450$ GeV
	$A_0 = -800$ GeV, $\tan\beta = 20$
	$\mu = +902$ GeV , $m_{A^0,\mathrm{pole}} = 765$ GeV
	$m_{\tilde{Q}_{1,2}} = m_{\tilde{u}_{1,2}} = m_{\tilde{d}_{1,2}} = 2000$ GeV
	$m_{\tilde{Q}_3} = m_{\tilde{u}_3} = m_{\tilde{d}_3} = 900$ GeV
	$m_{\tilde{L}_{1,2,3}} = m_{\tilde{e}_{1,2,3}} = 500$ GeV
Spectrum in GeV	
Neutralinos ($\tilde{\chi}^0_1$,$\tilde{\chi}^0_2$, $\tilde{\chi}^0_3$, $\tilde{\chi}^0_4$) =	357, 487, 904, 911
Charginos ($\tilde{\chi}^\pm_1$, $\tilde{\chi}^\pm_2$) =	487, 911
Sleptons ($\tilde{e}^-_R$, $\tilde{e}^-_L$, $\tilde{\nu}_e$) =	559, 650, 644
($\tilde{\tau}_1$,$\tilde{\tau}_2$, $\tilde{\nu}_\tau$) =	517, 642, 630
Gluino ($\tilde{g}$) =	1114
Squarks ($\tilde{t}_1$, $\tilde{t}_2$, $\tilde{b}_1$, $\tilde{b}_2$) =	844, 1120, 1078, 1191
($\tilde{d}_R$, $\tilde{u}_R$,$\tilde{d}_L$, $\tilde{u}_L$) =	2167, 2181, 2197, 2196
Heavy Higgses (h, A^0, H^0, $H^\pm$)	118, 765, 765, 769

2 Energy Stage 1: 500 GeV

2.1 Higgs mass

The first process to be considered is the production of a light Standard Model Higgs via the process $e^+e^- \to HZ$. As the study was started before the discovery of a new particle with a mass of 125 GeV at the LHC, a mass of m_H=120 GeV was assumed. Although cross sections and branching ratios are slightly different for the higher Higgs mass the analysis procedure remains the same and the results of this benchmark study will qualitativly not be much different. The analysis uses the model-independent recoil method to extract the Higgs mass by studying the Z decay to electrons and muons as listed in Table 3.

Thus this benchmark channel probes the detector performance for:

- muon and electron identification;
- muon and electron momentum resolution.

The study is performed at 500 GeV as well as at 350 GeV, both with CLIC_ILD [6].

Table 3: The Higgs mass, final states and cross sections used in the SM Higgs production study.

Process:	$e^+e^- \rightarrow HZ$
Particle mass :	$m_H = 120$ GeV
Final states:	$HZ \rightarrow X\mu^+\mu^-$ @ 350 GeV
	$HZ \rightarrow Xe^+e^-$ @ 350 GeV
	$HZ \rightarrow q\bar{q}q\bar{q}$ @ 500 GeV
	$HZ \rightarrow \nu\bar{\nu}b\bar{b}$ @ 500 GeV
Cross section:	$\sigma(HZ \rightarrow X\mu^+\mu^-) = 4.9$ fb @ 350 GeV
	$\sigma(HZ \rightarrow q\bar{q}q\bar{q}) = 34.3$ fb @ 500 GeV
	$\sigma(HZ \rightarrow \nu\bar{\nu}b\bar{b}) = 80.7$ fb @ 500 GeV

Table 4: The final states used for the study of $t\bar{t}$ production.

Process:	$e^+e^- \rightarrow t\bar{t}$
Particle mass:	$m_t = 174$ GeV in the 1S mass definition
Final states:	$t\bar{t} \rightarrow (bq\bar{q})(\bar{b}q\bar{q})$ (via W decay), i.e. 6 jets
	$t\bar{t} \rightarrow (bq\bar{q})(\bar{b}l\nu_l)$, where $l = e, \mu$, i.e. 4 jets $+ 1 + \not{E}$
Branching ratios:	$tt \rightarrow bWbW \rightarrow qqqqbb$ (45.7%)
	$tt \rightarrow bWbW \rightarrow qql\nu bb$ (29.2%) without τ
Cross section:	$\sigma = 392$ fb at $\sqrt{E} = 348$ GeV (from TOPPIK NNLO with $\alpha_s = 0.1180$)

2.2 $t\bar{t}$ threshold scan

A threshold scan would be useful for measuring the mass of the top quark. Such a threshold scan for the top quark can be performed at CLIC using the 500 GeV stage of the machine running at $\sim 2\,m_t$. Table 4 summarises the main parameters for this benchmark study.

This benchmark channel provides a test of:

- jet and missing energy reconstruction in multi-jet final states
- flavour tagging
- impact of the CLIC beam energy spectrum on threshold scans at low energy

Top quarks produced at rest need to be reconstructed, with the goal of measuring the top mass very precisely. The study is performed with CLIC_ILD.

Table 5: The particle masses, final states and branching ratios used in the study of chargino and neutralino production for *SUSY model III*.

Processes:	$\mathrm{e^+e^-} \rightarrow \widetilde{\chi}_1^+\widetilde{\chi}_1^-$, σ = 15.3 fb
	$\mathrm{e^+e^-} \rightarrow \widetilde{\chi}_2^0\widetilde{\chi}_2^0$, σ = 5.4 fb
Final states:	$\widetilde{\chi}_1^+\widetilde{\chi}_1^- \rightarrow \mathrm{W^+W^-}\widetilde{\chi}_1^0\widetilde{\chi}_1^0$
	$\widetilde{\chi}_2^0\widetilde{\chi}_2^0 \rightarrow \mathrm{h(Z)h(Z)}\widetilde{\chi}_1^0\widetilde{\chi}_1^0$
Branching ratios:	$\widetilde{\chi}_1^\pm \rightarrow \mathrm{W^\pm}\widetilde{\chi}_1^0$ (100%)
	$\widetilde{\chi}_2^0 \rightarrow \mathrm{h}\widetilde{\chi}_1^0$ (94.6%), $\mathrm{Z}\widetilde{\chi}_1^0$ (5.1%)

3 Energy Stage 2: 1.4 TeV

3.1 Gauginos

Charginos and neutralinos are studied through the production and decay channels listed in Table 5. Since the Z, W and h bosons have large 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.

This benchmark process addresses:

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

The study is performed with CLIC_SiD [7] and uses similar techniques as in the 3 TeV case [8].

3.2 Stau Pair Production

The main parameters of the $\widetilde{\tau}_1$ pair production benchmark study are listed in Table 6. This channel requires the reconstruction of τ leptons in the presence of backgrounds. In order to limit the number of physics backgrounds to consider, only hadronic τ decays are selected. Since the cross section for this process is very low, good efficiency for τ reconstruction is required while maintaining high purity.

The stau mass and the cross section will be extracted from the τ-jet energy distribution. The main aspect of the detector performance which is addressed is:

- reconstruction of τ leptons.

The study is performed with CLIC_ILD.

Table 6: The particle masses, final states, branching ratios and cross section used in the stau production study for *SUSY model III*.

Process:	$e^+e^- \to \tilde{\tau}_1\tilde{\tau}_1$
Final state:	$\tau\tau\tilde{\chi}^0_1\tilde{\chi}^0_1$
Branching ratios:	$\tilde{\tau}_1 \to \tau\tilde{\chi}^0_1$ (99%)
	$\tau \to$ hadrons (64.8%), $\tau \to e\nu\nu$ (17.8%), $\tau \to \mu\nu\nu$ (17.4%)
Cross section:	$\sigma = 2.4$ fb

Table 7: The particle masses, final states and branching ratios used in the slepton production study for *SUSY model III*.

Processes:	$e^+e^- \to \tilde{\mu}^-_R\tilde{\mu}^+_R \to \mu^+\mu^-\tilde{\chi}^0_1\tilde{\chi}^0_1$, $\sigma = 1.1$ fb
	$e^+e^- \to \tilde{e}^-_R\tilde{e}^+_R \to e^+e^-\tilde{\chi}^0_1\tilde{\chi}^0_1$, $\sigma = 5.7$ fb
	$e^+e^- \to \tilde{\nu}_e\tilde{\nu}_e \to e^+e^-\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\sigma = 5.6$ fb
Final states:	$\tilde{l}^+_R\tilde{l}^-_R \to l^+l^-\tilde{\chi}^0_1\tilde{\chi}^0_1$, where $l = e$ or μ
	$\tilde{\nu}_e\tilde{\nu}_e \to e^+e^-\tilde{\chi}^+_1\tilde{\chi}^-_1 \to e^+e^-W^+W^-\tilde{\chi}^0_1\tilde{\chi}^0_1$
Branching ratios:	$\tilde{l}_R \to l\tilde{\chi}^0_1$ (100%), where $l = e$ or μ
	$\tilde{\nu}_{eL} \to e\tilde{\chi}^{\pm}_1$ (56%)

3.3 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. This physics benchmark channel, namely slepton production, focuses on lepton reconstruction under the conditions listed in Table 7.

Masses and cross section are extracted from the lepton energy distribution as in the 3 TeV case [9].

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

- reconstruction and identification of high energy leptons;
- energy resolution for high energy electrons and muons.

The study is performed with CLIC_ILD.

Table 8: The mass and final states used in the Higgs self-coupling study.

Process:	$e^+e^- \to HH\nu_e\bar{\nu}_e$
Particle mass :	$m_H = 120$ GeV
Final state:	$q\bar{q}q\bar{q}\nu\bar{\nu}$
Cross section:	$\sigma(HH\nu_e\bar{\nu}_e) = 0.16$ fb at 1.4 TeV
	$\sigma(HH\nu_e\bar{\nu}_e) = 0.63$ fb at 3 TeV

3.4 Higgs self-coupling (Stage 2 and 3)

The dominant process at 1.4 TeV for the study of the production of two Higgs bosons is $e^+e^- \to HH\nu_e\bar{\nu}_e$. The Standard Model Higgs is assumed to have a mass of $m_H = 120$ GeV. The analysis is performed on events with four jets and missing energy. The relevant cross section for the considered processes are listed in Table 8.

This benchmark process addresses:

- jet reconstruction;
- measurement of missing energy.

The study is performed with CLIC_SiD for both 1.4 TeV and 3 TeV.

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