Optimization of timing selections at 380 GeV CLIC

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Abstract

The Compact Linear Collider (CLIC) is a proposed high-luminosity linear electron-positron collider at the energy frontier. It is foreseen to be built and operated in three stages, with a centre-of-mass energy ranging from a few hundred GeV up to 3 TeV. The main beam-induced background impacting CLIC physics analyses is produced by beamstrahlung radiation from the electron and positron bunches traversing the high field of the opposite beam and converting to hadrons, $\gamma \gamma \rightarrow$ hadron events. The timing selections are a powerful tool to discriminate signal from background events at CLIC. For each CLIC stage, three sets of selections, \textit{Loose}, \textit{Selected}, and \textit{Tight}, are defined to allow the analysis of different signal topologies. The selections are defined depending on the particle type and the reconstructed polar angle of each particle flow object reconstructed using the particle flow analysis. As a first step, the performance of the timing selections currently defined for the CLIC 380 GeV energy stage are evaluated using a $t\bar{t}$ sample decaying mainly into light quarks as signal and $\gamma \gamma \rightarrow$ hadron events as background. As a result, after applying the selections the level of background is significantly reduced, down to few GeV, while the shift of the signal peak to lower energy is kept within a few percent. The cuts in the \textit{Loose} selection are then relaxed to search for possible improvements: in one of the options considered, the signal component is partially recovered but also the background energy mean remains unchanged with respect to not applying any cuts. In conclusion, no change is foreseen on the timing selections.

This work was carried out in the framework of the CLICdp Collaboration
1 Introduction

The Compact Linear Collider (CLIC) is a proposed high-luminosity linear electron–positron collider at the energy frontier [1, 2]. It is foreseen to be built and operated in three stages with increasing centre-of-mass energies. In the first stage, CLIC will mainly operate at a centre-of-mass energy of 380 GeV with the aim of measuring the properties of the top quark and the Higgs boson with high precision. The accelerator parameters for the first stage are reported in Table 1. The background at CLIC is produced by beamstrahlung radiation from the electron and positron bunches traversing the high field of the opposite beam. Photons then convert to two main types of background, incoherent $e^+e^-$ pairs and $\gamma\gamma \rightarrow \text{hadron}$ events. At the 380 GeV energy stage, 0.18 $\gamma\gamma \rightarrow \text{hadron}$ interactions occur on average per bunch crossing with centre-of-mass energy more than 2 GeV [3].

To face the challenge of the beam-induced background and to fulfil the physics requirements, a detector model with a highly segmented calorimetry system optimized for particle flow techniques and timing capabilities has been defined and optimized using a dedicated software suite [4]. The CLICdet layout follows the typical collider detector scheme: the innermost part is composed of a silicon pixel vertex detector and a silicon tracker; surrounding them, an electromagnetic and hadronic calorimeter are placed, all embedded inside a superconducting solenoid providing a 4 T field; in the outermost part an iron yoke is interleaved with muon chambers. A longitudinal cross section of CLICdet is shown in Figure 1.

CLICdet will operate in a triggerless readout mode, i.e. the entire bunch train composed of 352 bunches at the 380 GeV energy stage will be read out every 20 ms. In the bunch train, the bunches are separated by 0.5 ns. At most, one hard $e^+e^-$ physics interaction in an entire bunch train will be produced, while most of the bunch crossings will only produce background particles. To obtain excellent detector performance in this triggerless readout mode, the subdetectors must provide a precise hit timing information. This can be achieved with a time-stamping capability of 10 ns for all silicon tracking elements and a hit time resolution of 1 ns for all calorimeter hits. Studies have shown [1] that at the highest energy stage of CLIC, the timing information coming from the subdetectors combined with additional $p_T$ information can help to mitigate the impact of the $\gamma\gamma \rightarrow \text{hadrons}$ background. In the context of a 380 GeV CLIC collider, a preliminary set of timing selections are already defined but the performance is studied precisely for the first time in this note. Therefore, as a first step the performance of the timing selections currently used for the first CLIC stage are evaluated in terms of absolute acceptance of the signal and rejection of the background; while in a second step, the loosest selection available is relaxed to check if further optimization is possible. Since a precise measurement of the top quark is one of the most important parts in the CLIC physics programme at the first stage, a pair of top quarks produced at the $e^+e^-$ interaction point is used as the signal.

The software framework and event simulation used in this study is briefly described in Section 2. In Section 3 an introduction to the timing selections is given with particular emphasis on those used for the first CLIC stage. Further possible optimizations for the loose selection are described in Section 4. In Section 5 this study is summarized and conclusions are given.

2 Simulation and reconstruction

The CLICdet detector geometry is described with the DD4HEP software framework [6] and simulated in GEANT4 [7] via the DDG4 [8] package of DD4HEP.

The simulated events are generated mostly using the WHIZARD [9, 10] program assuming zero polarization of the electron and proton beam. The initial states are created in the GUINEAPIG [11] simulation of the CLIC collisions. The performance of the timing selections for the 380 GeV CLIC stage is assessed using a 6-fermion production, comprising predominantly $t\bar{t}$ events from hard Standard Model $e^+e^-$ interactions. The six fermions in the final state correspond to $d\bar{d}u\bar{y}y$, where $y$ can be $b$, $d$ or $s$ quarks. The simulation of the parton showering, hadronisation and fragmentation is performed using
2 Simulation and reconstruction

Table 1: Parameters for the first stage of CLIC.

| Parameter                                      | Stage 1 |
|------------------------------------------------|---------|
| Centre-of-mass energy [GeV]                    | 380     |
| Main tunnel length [km]                        | 11.4    |
| Repetition frequency [Hz]                      | 50      |
| Number of bunches                              | 352     |
| Bunch separation [ns]                          | 0.5     |
| Number of particles per bunch [10^9]           | 5.2     |
| IP beam size (horizontal) [nm]                 | ≃149    |
| IP beam size (vertical) [nm]                   | 2.9     |
| Bunch length [µm]                              | 70      |
| Total luminosity [10^{34} cm^{-2} s^{-1}]      | 1.5     |
| Luminosity above 99% of √s [10^{34} cm^{-2} s^{-1}] | 0.9   |
| Number of beamstrahlung photons per beam particle | 1.4   |
| Number of γγ → hadron events per BX (√s > 2 GeV) | 0.18   |

Figure 1: Longitudinal cross section of CLICdet [5].
PYTHIA [12]. This component of the event is called signal. The $\gamma \gamma \rightarrow \text{hadron}$ events are hadronized in PYTHIA and the amount correspondent to 30 bunch crossings (BX) is included. This component of the event is referred to as background.

The reconstruction software is implemented in the linear collider MARLIN-framework [13]. The first step of the reconstruction is to overlay the signal event with the expected number of $\gamma \gamma \rightarrow \text{hadron}$ background events for 30 bunch crossings. The signal event is placed in bunch crossing 11 at $t = 0$ ns. At this stage, only the energy deposits inside the timing window of 10 ns after the signal event are selected. This time window matches the expected detector timing resolutions and integration times. In the next step, the positions of the energy deposits in the tracking detectors are smeared and the energy of the calorimeter hits are scaled with the calibration constants. At this point the tracking algorithms are run to obtain reconstructed tracks and the particle flow approach by PANDORAPFA [14–16] is used to build calorimeter clusters and match them to tracks. All visible particles are reconstructed by PANDORAPFA using both reconstructed tracks and calorimeter hits. The particles are called particle flow objects (PFOs). A PFO is marked as signal if any hit in its cluster are coming from a MC Particle of the $t\bar{t}$ event. If this requirement is not satisfied, it is marked as background. A more detailed description of the reconstruction of single particles and more complex events is given in [5].

3 Timing selections

To reject the beam-induced background without impacting the physics performance, the time-stamping capabilities of CLICdet described in Section 1 are used. Simply imposing tight timing selections at the hit level does not provide a final solution due to the fact that it does not take into account the hadronic shower development time and the time-of-flight corrections for lower momentum particles. Only the combination of both timing capabilities of the high-granularity calorimeters and particle flow reconstruction allows one to obtain a precise time-stamp for the calorimeter clusters. Once the particle flow clustering is finished, $p_T$ dependent timing selections are applied. The timing selections are therefore also called $p_T$ vs. time selections and their main aim is to reduce the background at the minimum possible while keeping invariant the signal. They are imposed to each reconstructed PFO and are defined depending on the particle type and its reconstructed polar angle. The reconstructed polar angle is shown in Figure 2 for both the signal and the $\gamma \gamma \rightarrow \text{hadrons}$.

PFOs are divided into three exclusive categories – photons, neutral hadrons and charged particles – and accepted or rejected based on the time of the calorimeter clusters and their reconstructed transverse momentum. The cluster time is computed using the truncated energy weighted mean time of its calorimeter hits. By default, the cluster time is computed using HCAL clusters. ECAL clusters are used only in the following cases:

- if the PFO is a photon;
- if the number of ECAL hits reconstructed for the PFO is more than five;
- if the number of ECAL hits reconstructed for the PFO is more or equal than half of the number of HCAL hits.

The cluster time is corrected using the time-of-flight information coming from the associated track in the case of a charged particle, and the time-of-flight of a straight path in the case of neutrals.

In Figure 3 the cluster time as a function of the $p_T$ of the three particle categories for both the signal and the background components of $t\bar{t}$ events is shown for the 380 GeV CLIC collider. Given the large overlap of the signal and background distributions, it is clear that the search for highly performant selections is a challenging task. Three sets of $p_T$ vs. time selections are therefore created to allow the analysis of different signal topologies: Loose, Selected, and Tight. In all selections, no photon or neutral hadron with $p_T$ more than 2 GeV is rejected, and no timing cut is applied on charged particles if their $p_T$ is more...
4 Optimization of timing selections for the 380 GeV CLIC stage

To check for possible optimizations, the following relaxed Loose selections are applied:

- increasing the time cut from 5 ns to 6 ns in the charged PFO category, referred to as time+;
- increasing the time cut from 5 ns to 8 ns in the charged PFO category, referred to as time++;
- decreasing the \( p_T \) cut from 0.75 GeV to 0.5 GeV for all categories, referred to as \( p_T^- \);
- decreasing the \( p_T \) cut from 0.75 GeV to 0 GeV for all categories, referred to as \( p_T^{--} \).

They are compared to the case where no selection is applied and to the Loose selections listed in Table 2, also referred to as vanilla selections.

The comparison of the energy mean of the relaxed cuts to the vanilla one can be found in Figure 8 for all PFOs contained in each \( t\bar{t} \) event and in Figures 9 and 10 for the three particle categories divided

Figure 2: Reconstructed polar angle of all PFO reconstructed in the event, marked as signal (blue) and the \( \gamma\gamma \rightarrow \text{hadrons} \) (red).

than 4 GeV in the case of Loose and Selected selections, and more than 3 GeV in the case of Tight one. The three selections for the 380 GeV CLIC stage are listed in Tables 2 to 4. The effect of the three timing selections on the reconstructed energy for both the signal and the background components of \( t\bar{t} \) events with overlay of 30 BX of \( \gamma\gamma \rightarrow \text{hadrons} \) background is shown in Figure 4.

The mean of the energy distribution for the overall distribution of signal and background is shown in Figure 5. The mean of the energy distribution after the selections is shown in Figures 6 and 7 for each particle category and polar angle group for the signal component and the overlay, respectively. It can be noted that for PFOs with \( \cos \theta > 0.975 \) the reduction of the background is obtained with almost no loss in the signal, in particular in the case of photons. The level of background is reduced more with the Tight selection than with the other two selections, but more signal is lost. In the case of the charged PFOs with \( \cos \theta \leq 0.975 \), the signal loss is almost 10 GeV in the extreme case of the Tight selection. When considering the Loose selection, the mean of the signal energy distribution is shifted less than 1 GeV in the case of photons and neutral hadrons, while in the case of charged PFOs it is almost 2 GeV. Therefore, in the next section, the \( p_T \) vs. time selections on the charged PFOs are modified in the attempt of recovering this loss.
4 Optimization of timing selections for the 380 GeV CLIC stage

Table 2: Loose selections used for the 380 GeV CLIC stage.

| | \(| \cos \theta | \leq 0.975 \) | | \(| \cos \theta | > 0.975 \) |
|---|---|---|---|
| **Photons** | **Neutral hadrons** | **Charged particles** |
| \( p_T \) range [GeV] | time cut [ns] | \( p_T \) range [GeV] | time cut [ns] | \( p_T \) range [GeV] | time cut [ns] |
| 0.75 \( \leq \) \( p_T \) < 2.00 | \( t \) < 10.0 | 0.75 \( \leq \) \( p_T \) < 2.00 | \( t \) < 2.00 | 0.75 \( \leq \) \( p_T \) < 2.00 | \( t \) < 10.0 |
| 0.00 \( \leq \) \( p_T \) < 0.75 | \( t \) < 2.50 | 0.00 \( \leq \) \( p_T \) < 0.75 | \( t \) < 1.00 | 0.00 \( \leq \) \( p_T \) < 0.75 | \( t \) < 5.00 |

Table 3: Selected selections used for the 380 GeV CLIC stage.

| | \(| \cos \theta | \leq 0.975 \) | | \(| \cos \theta | > 0.975 \) |
|---|---|---|---|
| **Photons** | **Neutral hadrons** | **Charged particles** |
| \( p_T \) range [GeV] | time cut [ns] | \( p_T \) range [GeV] | time cut [ns] | \( p_T \) range [GeV] | time cut [ns] |
| 0.75 \( \leq \) \( p_T \) < 2.00 | \( t \) < 5.0 | 0.75 \( \leq \) \( p_T \) < 2.00 | \( t \) < 2.0 | 0.75 \( \leq \) \( p_T \) < 2.00 | \( t \) < 4.0 |
| 0.00 \( \leq \) \( p_T \) < 0.75 | \( t \) < 1.0 | 0.00 \( \leq \) \( p_T \) < 0.75 | \( t \) < 1.0 | 0.00 \( \leq \) \( p_T \) < 0.75 | \( t \) < 2.0 |

Table 4: Tight selections used for the 380 GeV CLIC stage.

| | \(| \cos \theta | \leq 0.975 \) | | \(| \cos \theta | > 0.975 \) |
|---|---|---|---|
| **Photons** | **Neutral hadrons** | **Charged particles** |
| \( p_T \) range [GeV] | time cut [ns] | \( p_T \) range [GeV] | time cut [ns] | \( p_T \) range [GeV] | time cut [ns] |
| 0.75 \( \leq \) \( p_T \) < 2.00 | \( t \) < 1.0 | 0.75 \( \leq \) \( p_T \) < 2.00 | \( t \) < 2.0 | 0.75 \( \leq \) \( p_T \) < 2.00 | \( t \) < 2.0 |
| 0.00 \( \leq \) \( p_T \) < 0.75 | \( t \) < 1.0 | 0.00 \( \leq \) \( p_T \) < 0.75 | \( t \) < 1.0 | 0.00 \( \leq \) \( p_T \) < 0.75 | \( t \) < 2.0 |

| **Charged particles** |
| \( 0 \leq | \cos \theta | \leq 1 \) |
| \( p_T \) range [GeV] | time cut [ns] |
| 0.75 \( \leq \) \( p_T \) < 4.00 | \( t \) < 10.0 |
| 0.00 \( \leq \) \( p_T \) < 0.75 | \( t \) < 3.00 |

| **Charged particles** |
| \( 0 \leq | \cos \theta | \leq 1 \) |
| \( p_T \) range [GeV] | time cut [ns] |
| 0.75 \( \leq \) \( p_T \) < 3.00 | \( t \) < 4.0 |
| 0.00 \( \leq \) \( p_T \) < 0.75 | \( t \) < 2.00 |
Figure 3: Cluster time as a function of the $p_T$ of the three particle categories (photons at the top, neutral hadrons in the middle and charged PFOs at the bottom) for both the signal (left) and the background (right) components of $t\bar{t}$ events with overlay of 30 BX of $\gamma\gamma \rightarrow$ hadrons background for the 380 GeV CLIC stage.
Figure 4: Reconstructed energy distribution for all PFOs (solid line), and for PFOs passing the different timing cuts for signal (dashed line) and background (dotted line): without any selection (red), Loose (orange), Selected (green) and Tight (blue). t\bar{t} events are used with overlay of 30 BX of $\gamma\gamma \rightarrow$ hadrons background for the 380 GeV CLIC stage.

Figure 5: Signal and background reconstructed energy mean for different applied timing selections: without any selection (red), Loose (orange), Selected (green) and Tight (blue). t\bar{t} events are used with overlay of 30 BX of $\gamma\gamma \rightarrow$ hadrons background for the 380 GeV CLIC stage.

into signal and background. The effect of relaxing the cuts is an increase of the background component. The $p_T$ selection is the only one recovering the signal component but also leaving the level of background essentially unchanged with respect to not applying any cuts. This last observation is valid only for photons and neutral hadrons, but not for charged PFOs. In fact, part of the signal component of the charged PFOs suffers from a mis-correction of the PFO time in the case where the track and the calorimeter clusters associated with the charged PFO are not produced by the same simulated particle. Therefore, this signal component cannot be recovered with a simple modification to the $p_T$ vs. time selections. In conclusion, this study shows that no further optimization is possible on top of the Loose selections currently defined for the 380 GeV CLIC accelerator.
5 Conclusions

In this study the performance of the timing selections defined for the CLIC 380 GeV energy stage is evaluated. $t\bar{t}$ events coming from hard $e^+e^-$ interactions and decaying mainly into light quarks are simulated and reconstructed as signal. At the same time a realistic estimate of the $\gamma\gamma \rightarrow$ hadrons is included as background. The mean of the total energy reconstructed in all events is chosen as a figure-of-merit for this study. The results for the selection for the CLIC 380 GeV collider are found to be satisfactory: after applying the selections, the level of background is significantly reduced down to a few GeV, while the energy mean of the signal distribution is only few percent. In the extreme case of the Tight selection for example, the background is reduced from about 45 GeV down to about 8 GeV and less than 4% is lost in the signal energy mean. In a second step of this study, the cuts in the Loose selection are relaxed to search for possible improvements. Among all the options considered, only the $p_T$ -- relaxed selection partially recovers the signal component but also leaves the background energy mean unchanged with respect to not applying any cuts. Therefore, no change is foreseen on the timing selections for the CLIC 380 GeV energy stage.
Figure 7: Background reconstructed energy mean for the three particle categories (photons at the top, neutral hadrons in the middle and charged PFOs at the bottom) for different applied timing selections: without any selection (red), Loose (orange), Selected (green) and Tight (blue). $\bar{t}t$ events are used with overlay of 30 BX of $\gamma\gamma \rightarrow$ hadrons background for the 380 GeV CLIC stage.

Figure 8: Signal and background reconstructed energy mean for different relaxed cuts on the Loose selection: time+, time++, $p_T-$, $p_T--$, from left to right respectively. $\bar{t}t$ events are used with overlay of 30 BX of $\gamma\gamma \rightarrow$ hadrons background for the 380 GeV CLIC stage.
Energy Mean [GeV]

Figure 9: Signal reconstructed energy mean for the three particle categories (photons at the top, neutral hadrons in the middle and charged PFOs at the bottom) for different relaxed cuts on the Loose selection: time+, time++, p_T−, p_T−−, from left to right respectively. tt events are used with overlay of 30 BX of γγ → hadrons background for the 380 GeV CLIC stage.

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Figure 10: Background reconstructed energy mean for the three particle categories (photons at the top, neutral hadrons in the middle and charged PFOs at the bottom) for different relaxed cuts on the Loose selection: time+, time++, $p_T^-$, $p_T^{--}$, from left to right respectively. $t\bar{t}$ events are used with overlay of 30 BX of $\gamma\gamma \rightarrow$ hadrons background for the 380 GeV CLIC stage.

References

[1] L. Linssen, et al (Eds), CLIC Conceptual Design Report: Physics and Detectors at CLIC (2012), CERN-2012-003, arXiv:1202.5940 [physics.ins-det].

[2] P. Burrows, et al (Eds), Updated baseline for a staged Compact Linear Collider (2016), CERN-2016-004, URL: http://dx.doi.org/10.5170/CERN-2016-004.

[3] CLIC beam-beam interactions documentation, URL: http://clic-beam-beam.web.cern.ch/clic-beam-beam/380gev_16_bx8mm.html (visited on 16/10/2018).

[4] N. Alipour Tehrani et al., CLICdet: The post-CDR CLIC detector model (2017), URL: http://cds.cern.ch/record/2254048.

[5] A detector for CLIC: main parameters and performance, CLICdp-NOTE-2018-005 (2018), To be published.
References

[6] M. Frank et al., *DD4hep: A Detector Description Toolkit for High Energy Physics Experiments*, J. Phys. Conf. Ser. **513** (2013) 022010.

[7] S. Agostinelli et al., *Geant4-a simulation toolkit*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **506** (2003) 250, ISSN: 0168-9002, DOI: https://doi.org/10.1016/S0168-9002(03)01368-8, URL: http://www.sciencedirect.com/science/article/pii/S0168900203013688.

[8] M. Frank et al., *DDG4: A Simulation Framework using the DD4hep Detector Description Toolkit*, J. Phys. Conf. Ser. **664** (2015) 072017.

[9] W. Kilian, T. Ohl, J. Reuter, *WHIZARD: Simulating Multi-Particle Processes at LHC and ILC*, Eur.Phys.J. C **71** (2011) 1741, arXiv: 0708.4233 [hep-ph].

[10] M. Moretti, T. Ohl, J. Reuter, *O’MegA: An optimizing matrix element generator*, 2001, arXiv: 0102195 [hep-ph].

[11] D. Schulte, *Study of Electromagnetic and Hadronic Background in the Interaction Region of the TESLA Collider*, PhD thesis, DESY, 1997, URL: http://inspirehep.net/record/888433/files/shulte.pdf.

[12] T. Sjostrand, S. Mrenna, P. Z. Skands, *PYTHIA 6.4 Physics and Manual*, JHEP **05** (2006) 026, DOI: 10.1088/1126-6708/2006/05/026, arXiv: hep-ph/0603175 [hep-ph].

[13] F. Gaede, *Marlin and LCCD: Software tools for the ILC*, Nucl. Instrum. Meth. **A559** (2006) 177.

[14] J. Marshall, M. Thomson, *The Pandora Software Development Kit for Pattern Recognition*, Eur.Phys.J. C **75** (2015) 439, DOI: 10.1140/epjc/s10052-015-3659-3, arXiv: 1506.05348 [physics.data-an].

[15] M. A. Thomson, *Particle Flow Calorimetry and the PandoraPFA Algorithm*, Nucl. Instrum. Meth. **A611** (2009), arXiv:0907.3577 25, DOI: 10.1016/j.nima.2009.09.009, arXiv: 0907.3577 [physics.ins-det].

[16] J. S. Marshall, A. Münnich, M. Thomson, *Performance of Particle Flow Calorimetry at CLIC*, Nucl. Instrum. Meth. **A700** (2013) 153, DOI: 10.1016/j.nima.2012.10.038, arXiv: 1209.4039 [physics.ins-det].