Eur. Phys. J. C (2024) 84:172
https://doi.org/10.1140/epjc/s10052-024-12515-0

THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Regular Article - Theoretical Physics

Searching for a leptophilic Z' and a 3-3-1 symmetry at CLIC

A. Alves[1,a], **G. Gil da Silveira**[9,b], **V. P. Gonçalves**[6,7,c], **F. S. Queiroz**[2,3,4,d], **Y. M. Oviedo-Torres**[3,8,e], **J. Zamora-Saa**[2,5,f]

[1] Departamento de Física, Universidade Federal de São Paulo, UNIFESP, Diadema, São Paulo, Brazil
[2] Millennium Institute for Subatomic Physics at High-Energy Frontier (SAPHIR), Fernandez Concha 700, Santiago, Chile
[3] International Institute of Physics, Universidade Federal do Rio Grande do Norte, Campus Universitario, Lagoa Nova, Natal, RN 59078-970, Brazil
[4] Departamento de Física, Universidade Federal do Rio Grande do Norte, Natal, RN 59078-970, Brazil
[5] Center for Theoretical and Experimental Particle Physics-CTEPP, Facultad de Ciencias Exactas, Universidad Andres Bello, Fernandez Concha 700, Santiago, Chile
[6] Institut für Theoretische Physik, Westfälische Wilhelms-Universität Münster, Wilhelm-Klemm-Straße 9, 48149 Münster, Germany
[7] Institute of Physics and Mathematics, Federal University of Pelotas, Postal Code 354, Pelotas, RS 96010-900, Brazil
[8] Departamento de Física, Universidade Federal da Paraíba, Caixa Postal 5008, João Pessoa, PB 58051-970, Brazil
[9] Instituto de Física, Federal University of Rio Grande do Sul, Av. Bento Gonçalves, 9500, Porto Alegre CEP 91501-970, Brazil

Received: 13 September 2023 / Accepted: 3 February 2024 / Published online: 19 February 2024

Abstract We derive the discovery potential of a leptophilic Z', and a Z' rising from a $SU(3)_C \times SU(3)_L \times U(1)_N$ symmetry at the Compact Linear Collider (CLIC), which is planned to host e^+e^- collisions with 3 TeV center-of-mass energy. We perform an optimized selection cut strategy on the transverse momentum, pseudorapidity, and invariant mass of the dileptons in order to enhance the collider sensitivity. We find that CLIC can potentially reach a 5σ signal of a $1-5$ TeV leptophilic Z' with less than 1 fb^{-1} of integrated luminosity in the most favorable cases. As for the Z' belonging to a 3-3-1 symmetry, CLIC will offer a complementary probe with the potential to impose $M_{Z'} > 3$ TeV with $\mathcal{L} = 2$ fb^{-1}.

1 Introduction

The Compact Linear Collider (CLIC) represents a high-luminosity, TeV-scale linear e^+e^- collider under vigorous development by global collaborations, centered at CERN [1]. In order to maximize its physics potential, a staged construction is foreseen. CLIC will operate at center-of-mass energies of 380 GeV, 1.5 TeV, and 3 TeV. The total site length is projected to vary between 11 km and 50 km. Considerable advancements in recent years have been made, both in terms of technical development and system testing for the CLIC accelerator, which have greatly reduced its building cost and improved its physics potential. The first beams are planned to occur by 2035, thereby initiating a physics program expected to span over 25 to 30 years. Given our successful experience with the Large Electron Positron collider [2–4], with its larger luminosity and center-of-mass CLIC promises to be a unique opportunity to probe physics Beyond the Standard Model (BSM). It will facilitate direct searches and enable a comprehensive range of precision measurements of Standard Model processes. This potential will be particularly valuable for studying the Higgs boson and extended scalar sectors as well as new gauge bosons.

Several theories extending beyond the Standard Model (SM) rely on the existence of neutral gauge bosons that feature coupling to leptons. These theories provide potential explanations for unresolved phenomena, such as dark matter (DM), neutrino masses, the muon anomalous magnetic moment, among others. Such neutral bosons are often associated with a new Abelian gauge symmetry which is spontaneously broken, generating a Z' boson with mass around the new physics scale. Non-Abelian gauge symmetries can also give rise to a Z' boson. Such a Z' boson can be produced at Hadron and Lepton colliders producing a high-mass dilepton resonance. To the experimentalist, a Z' boson is, at the end of the day, a resonance more massive than the SM Z boson. Conversely, for a theorist, a Z' field represents a new force

[a] e-mail: aalves@unifesp.br
[b] e-mails: gustavo.silveira@ufrgs.br; gustavo.silveira@cern.ch
[c] e-mail: barros@ufpel.edu.br
[d] e-mail: farinaldo.queiroz@ufrn.br
[e] e-mail: ymot@estudantes.ufpb.br (corresponding author)
[f] e-mails: jilberto.zamora@unab.cl; jilberto.zamorasaa@cern.ch

carrier, which holds the secret to the road of physics beyond the Standard Model (SM).

Motivated by the importance of Z' bosons in theoretical constructions, we will assess the CLIC potential to discover a leptophilic Z' using a simplified model, and a Z' rising in extended gauge sectors with a $SU(3) \times SU(3) \times U(1)_N$ symmetry, 3-3-1 for short. A leptophilic Z' emerges in simple gauged lepton number theories [5–16], and or in more complex setups [17–23]. The $SU(3)_C \times SU(3)_L \times U(1)_N$ symmetry has featured in a multitude of papers in the literature because it could help to solve neutrino masses [24–32], flavor puzzles [33,34], dark matter [35–60], among others.

In the context of linear colliders, there have been leptophilic Z' studies in the past [6,22,23,61–66]. Although, none of them were focused on a sequential leptophilic Z' boson, which has couplings to SM lepton equal to the Z-boson, with no interaction with quarks. A sequential Z' is often the target of several collider searches at the LHC. If tree level couplings to quarks are turned off,[1] a sequential leptophilic Z' arises and could be a benchmark model at CLIC. Obviously, in the presence of sizeable couplings to quarks, the LHC reach is significantly better than CLIC. However, in the absence (or strong suppression) of interactions with quarks, CLIC stands out as a promising probe. Moreover, CLIC can also serve as a precision machine once a Z' boson is discovered at LHC or the High-Luminosity LHC. In our work, we will concentrate on the Z' phenomenology. Its mass should stem from a Stueckelberg mechanism [67,68] or from spontaneous symmetry breaking of the extra gauge symmetry. In the latter case, there will be a scalar field breaking the gauge symmetry, but it is assumed to be sufficiently heavy, yielding no impact on the Z' decay width into leptons [69]. The phenomenology of such a scalar is out of the scope of this manuscript.

In summary, we consider a leptophilic sequential Z' inspired by the CMS and ATLAS collaborations which adopt the sequential Z' as a benchmark. In this case, the gauge coupling is fixed allowing us to draw more concrete predictions. On the theoretical side, there should be a symmetry involving lepton number to explain the exclusive couplings to leptons and extra chiral fermions to cancel the gauge anomalies. This reasoning is also applicable to the Sequential Z' model adopted in ATLAS and CMS analyses. Anyway, our goal in this work is to assess CLIC potential to discover a Z' boson that resembles in some way the Z boson.

It is important to emphasize that, using LHC data, collider bounds on the Z' bosons belonging to a 3-3-1 symmetry have been derived in the past, excluding Z' masses below 4 TeV. However, if the Z' is leptophilic, the relevant collider constraints mainly come from LEP, and masses larger than 200 GeV are not excluded, which motivates the searching at future e^+e^- colliders. We have no data at the moment, thus we can only assess CLIC sensitivity reach. We will see that with less than 1 fb^{-1} of luminosity, CLIC can discover such a Z' boson. Therefore, despite not being able to produce on-shell Z' bosons with masses larger than 3 TeV, CLIC will be able to constrain better the couplings and properties of any new gauge boson that has sizeable couplings to leptons. In this spirit, we will perform a phenomenological analysis based on optimized cuts that yield better signal efficiency for discovery and exclusion for a given luminosity in the $e^+e^- \to e^+e^-$ channel. Although our focus is on the impact of a leptophilic Z' in the $e^+e^- \to e^+e^-$ process, we will also present, for comparison and completeness of our analysis, the predictions from the 3-3-1 model.

This paper is organized as follows. In the next Section we will describe the details of our analysis. In particular, we briefly present the CLIC experiment and the models considered. Moreover, the Monte Carlo simulation and cuts assumed in the analysis will be discussed. In Sect. 3 we present our results for the total and differential cross sections derived considering a leptophilic Z'. The predictions associated to the 3-3-1 model are also presented for comparison. The best kinematic cuts are obtained and the luminosity required to exclude (or discover) a Z' at CLIC is estimated considering distinct values for the Z' mass. Finally, in Sect. 4, we summarize our main conclusions.

2 Details of the analysis

Our goal in the present analysis is to estimate the impact of a Z' on the $e^+e^- \to e^+e^-$ process. Such a boson can contribute to the direct electron–positron annihilation (Drell-Yan), represented in the left panel of Fig. 1, as well can be present in the t-channel diagram (right panel). The main Standard Model backgrounds are represented by these same diagrams but with the exchange of a photon or a Z boson. Vector boson fusion (VBF) contributions are negligible after requiring only two same-flavor opposite-sign leptons in the final state. Moreover, VBF processes are $\mathcal{O}(\alpha^4)$, two orders ahead of the main SM backgrounds. We will focus on e^+e^- collisions at CLIC and assume a leptophilic Z'. Having in mind the new physics potential of CLIC and the reasonable hypothesis of Z' fields in theoretical constructions, in what follows we will briefly discuss the Compact Linear Collider and describe the models that we investigate in this work.

2.1 The Compact Linear Collider

The Compact Linear Collider (CLIC), currently under the development auspices of the CLIC accelerator collaboration,

[1] Effective quark couplings can be generated at loop level though, but they are naturally suppressed compared to the tree-level ones involving leptons.

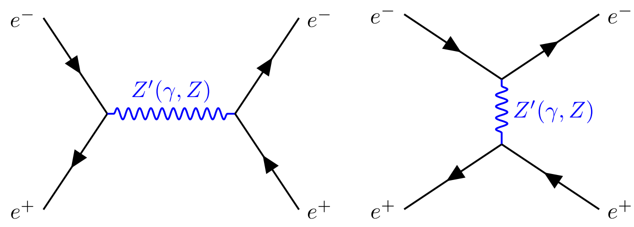


Fig. 1 Feynman diagrams for the signal and background processes relevant for the Z' search at the CLIC. In the left panel, the Drell-Yan contributions, and in the right panel, the Babbha scattering ones

is a high-luminosity linear collider capable of reaching multi-TeV energies. The Conceptual Design Report (CDR) for the CLIC was released in 2012 but recent updates to the initial proposal were presented [1,70–72]. A pioneering feature of the CLIC is its utilization of the two-beam acceleration technique, which employs novel accelerating structures functioning within the range of 80–100 MV/m.

The primary objective of this report was to substantiate the viability of the CLIC accelerator at elevated energies of 3 TeV. Furthermore, it was crucial to affirm that the presence of particles from beam-induced backgrounds and the characteristics of the luminosity spectrum would not inhibit the performance of high-precision physics measurements [1,73,74]. In the same way that LEP and SLAC were important to test various SM predictions, the CLIC hopes to collect more stringent electroweak precision measurements and signals of new physics for a period of 27 years in three different but complementary stages [75]. Moreover, based on a novel acceleration system, CLIC plans to progressively reach energies of up to $\sqrt{s} = 3$ TeV and an integrated luminosity of 5 ab^{-1} [76–79] in a sequence of stages. For the first stage of the CLIC operation, beams are expected to be delivered at an energy of $\sqrt{s} = 380$ GeV and a luminosity of 1 ab^{-1}. In the second and third stages, operations are aimed at elevated energies with beams at $\sqrt{s} = 1.5$ TeV with $\mathcal{L} = 2.5$ ab^{-1}, and $\sqrt{s} = 3$ TeV with $\mathcal{L} = 5$ ab^{-1}, respectively. In each of these operation stages, the CLIC program aims to improve electroweak precision measurements of SM parameters and find, either indirect or direct, indications of new physics (NP) [80].

These stages of the CLIC operation will be adjusted based on the results obtained by the HL-LHC. In particular, the center-of-mass energy can be increased by extending the length of the accelerator or by improving acceleration technology. In this way, the novel acceleration technology of the CLIC opens the possibility of carrying out studies with high center-of-mass energy and luminosity, accessing production mechanics at far higher energy than those observed at LEP.

2.2 The Models

2.2.1 Leptophilic Z'

A sequential Z' is a benchmark model at the LHC. It refers to the case where the Z' field couples to SM fermions in the same way the Z boson does [81,82]. With that in mind, we propose searching for a leptophilic Z' with sequential couplings to SM leptons. In other words, it is a Z' that features only couplings to SM leptons identical to the Z boson. Therefore, the neutral current reads,

$$\mathcal{L} = \frac{-g}{2\cos\theta_W} \sum_i \bar{\psi}_i \gamma^\mu (g_V^i - \gamma_5 g_A^i) \psi_i Z'_\mu \qquad (1)$$

where $\theta_W = \tan^{-1}(g'/g)$, $g_V^i = \tau_{3L}(i) 2 Q_i \sin^2\theta_W$, and $g_A^i = \tau_{3L}$. In this case, i=1,2,..6; with ψ_i running over all six lepton flavors. This new boson can potentially couple new particles but we hypothesize that these new particles are too heavy to be produced at CLIC via Z' exchange. The lagrangian above is, therefore, the relevant one for phenomenological studies.

2.2.2 3-3-1 Model

The 3-3-1 model refers to the $SU(3)_C \times SU(3)_L \times U(1)_Y$ symmetry [83–85]. An obvious consequence of enlarging SM gauge group is the appearance of new vector bosons. Particularly, within the 331 models we have three new gauge bosons, six new fermions (three leptons and three quarks), and six new scalars. In these models, to avoid chiral anomalies and reproduce the correct SM interactions, leptons are accommodated in the triplet representations. In the quark sector, the first two generations transform under the triplet representation and the third generation transforms under the anti-triplet representation. Right-handed fermions transform in the singlet representation, as usual. Fermion masses are obtained through a two-step spontaneous symmetry breaking using three scalar triplets. There is freedom in the choice for the third component of the fermion triplet, and this freedom gives rise to different particle contents. We will focus on the 331RHN and 331LHN models [86], where the third component of the lepton triplet is a right-handed neutrino or a heavy and neutral fermion, respectively. In both 331 RHN and LHN models, the lagrangian that describes the interaction between fermions and the Z' boson is the same lagrangian presented in Eq. (1), where g_V^i and g_A^i are the vector and axial couplings whose values are shown in Table 1. Again, we will tacitly assume that the new fermions and scalars of the 331

Table 1 Vector and Axial couplings of the Z' boson with fermions in the 331RHN and 331LHN models

Z' Interactions with the SM fermions in the 3-3-1 model		
Interaction	g_V^i	g_A^i
$Z'\ \bar{u}u, \bar{c}c$	$\frac{-3+8\sin^2\theta_W}{6\sqrt{3-4\sin^2\theta_W}}$	$-\frac{1}{2\sqrt{3-4\sin^2\theta_W}}$
$Z'\ \bar{t}t$	$\frac{-3-2\sin^2\theta_W}{6\sqrt{3-4\sin^2\theta_W}}$	$-\frac{1-2\sin^2\theta_W}{2\sqrt{3-4\sin^2\theta_W}}$
$Z'\ \bar{d}d, \bar{s}s$	$\frac{-3+2\sin^2\theta_W}{6\sqrt{3-4\sin^2\theta_W}}$	$-\frac{3-6\sin^2\theta_W}{6\sqrt{3-4\sin^2\theta_W}}$
$Z'\ \bar{b}b$	$\frac{-3+4\sin^2\theta_W}{6\sqrt{3-4\sin^2\theta_W}}$	$-\frac{1}{2\sqrt{3-4\sin^2\theta_W}}$
$Z'\ \bar{\ell}\ell$	$\frac{1-4\sin^2\theta_W}{2\sqrt{3-4\sin^2\theta_W}}$	$\frac{1}{2\sqrt{3-4\sin^2\theta_W}}$
$Z'\ \overline{\nu_\ell}\nu_\ell$	$\frac{-\sqrt{3-4\sin^2\theta_W}}{18}$	$-\frac{\sqrt{3-4\sin^2\theta_W}}{18}$

models are heavier than the Z' so the interactions above are the only ones relevant for a Z' search at CLIC.

2.3 Simulation

All signal and background events were simulated using `FeynRules` [87], `MadGraph5` [88], `Pythia8` [89], and `Delphes3` [90]. In our analysis, we generate, in each case, 80k signal events for each of ten Z' mass hypotheses: from 0.5 to 5 TeV with intervals of 500 GeV, and 200k for backgrounds.

We simulate e^+e^- collisions at CLIC employing the `clic3000ll` Parton Distribution Function (PDF) set which takes initial state radiation effects at Leading Order+Leading Log approximation and also a parametrized implementation of beamstrahlung [91]. In this study, we assume that the new particle spectrum is heavy such that the decay of the Z' into BSM particles is kinematically forbidden. The interactions that we are considering are those corresponding to the Z' to SM fermions where the couplings to leptons are equal to the SM Z boson, but Z' does not couple to quarks, in the case of the leptophilic new gauge boson, as defined in Eq. (1). In the case of 331 models, couplings to quarks diminish the branching fraction of the Z' into SM leptons and increase the total width compared to the leptophilic case for the same $M_{Z'}$. In both models, we expect to observe sharp peaks in the e^+e^- invariant mass but the leptophilic model will produce narrower resonances.

The SM background and the signal have s and t-channel diagrams exchanging a Z, γ and Z', respectively, as depicted in panels (a) and (b) of Fig. 1. To avoid collinear divergences and suppress VBF backgrounds, we selected events with only one identified e^+e^- pair that satisfy the following basic

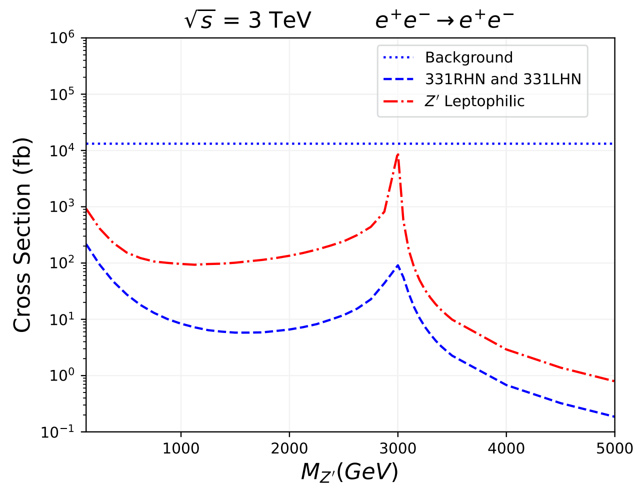


Fig. 2 The $e^+e^- \to e^+e^-$ cross section for the leptophilic (red dashed lines) and 3-3-1 models (blue dashed lines) for Z' masses up to 5 TeV. The SM background is displayed as a dotted blue curve. The basic cuts of Eq. (2) were required in all cases

selection requirements

$$p_T > 100 \text{ GeV}, \quad |\eta| < 3\,, \tag{2}$$

for the electron and the positron of the event.

3 Results and discussions

In Fig. 2, we present our results for the $e^+e^- \to e^+e^-$ cross section as a function of the Z' mass, derived considering the cuts discussed in the previous section and assuming the Leptophilic and 3-3-1 models for Z' masses up to 5 TeV. For masses much smaller than the collider energy, the t-channel diagram dominates as the Z' is produced off its mass-shell, but heavier Z' bosons tend to be produced more in the mass-shell increasing the cross section towards $M_{Z'} = 3$ TeV. By their turn, 331 bosons present a smaller cross section once, in this case, there are more options for the Z' to decay into, contrary to the case of the leptophilic ones. In 331 and leptophilic models, $BR(Z' \to e^+e^-) = 2.4\%$, and 11%, respectively, for the masses range we are considering in this work. The SM cross section for the $e^+e^- \to e^+e^-$ process is 13.2 pb, represented by the blue dotted line in Fig. 2.

Events associated with off-mass-shell Z' bosons (masses above 3 TeV) are also expected but with increasingly suppressed production rates, as we can see in Fig. 2. Notwithstanding, assuming an integrated luminosity of a few inverse attobarns will lead to hundreds of signal events even for 5 TeV bosons. On the other hand, we should expect a somewhat more difficult selection of signal events compared to the bosons that produce a peak in the invariant mass. Yet, the mass of the new boson can be read from the trans-

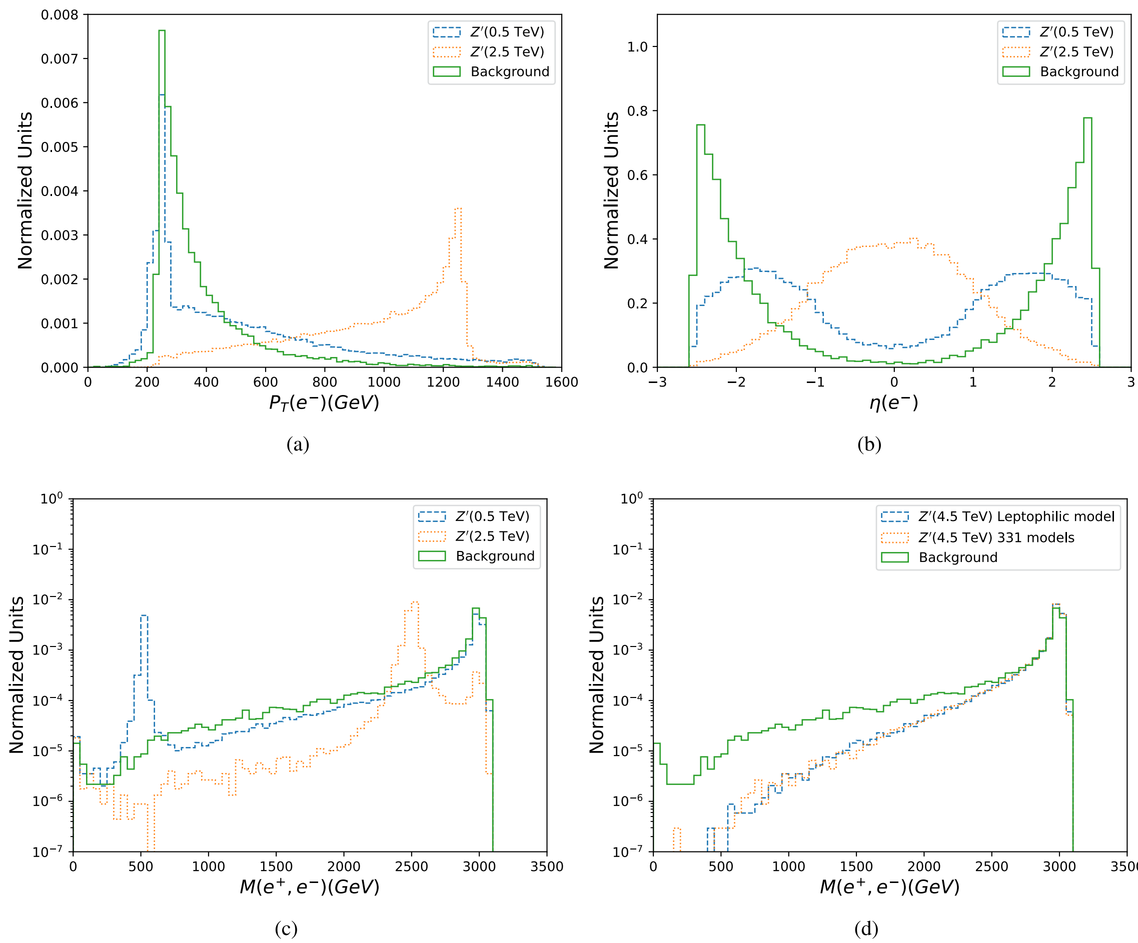


Fig. 3 The left(right) upper panel depicts the transverse momentum(rapidity) distribution of electrons of the SM background and signals corresponding to Z' masses of 0.5 and 2.5 TeV. The lower panels show the e^+e^- invariant masses distribution of background and signals for on-mass-shell (left), and an off-mass-shell (right) 4.5 TeV Z', respectively. All signals correspond to leptophilic Z' model. The distributions of 331 signals are similar

verse momentum distributions, which peak at approximately $M_{Z'}/2$.

The signal and background distributions of the electron transverse momentum, $p_T(e^-)$, electron rapidity, $\eta(e^-)$, and the e^+e^- invariant mass, $M(e^+, e^-)$, are shown in Fig. 3, for leptophilic Z' signals. The 331 Z' distributions are similar. As we see, the signal and background features are very distinctive, especially for heavy Z' bosons. Nonetheless, for lighter Z', the peaks in e^+e^- invariant mass still denounce the presence of signals, making the distinction against the smooth background spectrum an easy task. Concerning the rapidity distributions, lighter Z' and the SM backgrounds display a similar behavior with the majority of events hitting the high rapidity regions of the detector, while heavy Z' produced electrons and positrons at central rapidities. This is due to the competition between the s and t-channel amplitudes, where the t-channel contribution is amplified when the final state lepton is collinear with the initial state one, while the s-channel produces high-p_T yields.

In the case of off-mass-shell bosons, the transverse momentum and rapidity distributions still bear the distinctive marks of the heavy Z' bosons, but the peak in the e^+e^- invariant mass is lost. Instead, a sharp peak occurs at the collider energy, the same region where the backgrounds accumulate, as we see in the lower right panel of Fig. 3. This causes a decrease in the signal selection efficiency.

To remove backgrounds and increase the statistical significance of the signal, we searched for the kinematic cuts on p_T, η, and $M(e^+, e^-)$ that maximize the signal efficiency and minimize the background one. As discussed in the next section, the background efficiencies after optimization were found to be very small for Z' masses from 10 GeV to 5 TeV. We compute the signal significance as follows

Table 2 The best kinematic cuts for representative Z' masses in the 331 models. The transverse momentum and e^+e^- mass are given in GeV. In the two rightmost columns, we display the signal and background efficiencies after (1st cut)[1st+2nd cuts]all cuts in %

$M_{Z'}$	$p_T >$	$\|\eta\| <$	$\|M_{ee} - M_c\| < \delta_M$	$\epsilon_S(\%)$	$\epsilon_B(\%)$
500	207	2.23	458 ± 57	(98.4)[82.7]1.9	(98.4)[30.5]0.005
1500	641	2.65	1554 ± 52	(54.7)[54.7]17	(8)[8]0.005
2500	1032	1.96	2391 ± 84	(50)[49.8]10	(1.5)[1.5]0.005
3500	1481	0.90	3057 ± 64	(5.2)[5.2]4.1	(0.02)[0.02]0.005
4500	1481	1.56	3066 ± 73	(4.8)[4.8]3.8	(0.02)[0.02]0.005

Table 3 The best kinematic cuts for representative Z' masses in the leptophilic model. The transverse momentum and e^+e^- mass are given in GeV. In the two rightmost columns, we display the signal and background efficiencies after (1st cut)[1st+2nd cuts]all cuts in %

$M_{Z'}$	$p_T >$	$\|\eta\| <$	$\|M_{ee} - M_c\| < \delta_M$	$\epsilon_S(\%)$	$\epsilon_B(\%)$
500	189	2.00	485 ± 65	(96.8)[96.8]11.1	(98.9)[30.5]0.005
1500	444	0.92	1461 ± 88	(78.3)[26]20.1	(22)[1.8]0.01
2500	991	0.45	2547 ± 64	(52.2)[22.8]15	(1.8)[0.4]0.01
3500	1481	1.02	3072 ± 78	(5.1)[5.1]3.9	(0.02)[0.02]0.005
4500	1482	0.48	3086 ± 91	(4.6)[4.6]3.5	(0.02)[0.02]0.005

$$N_\sigma = \frac{L \times \epsilon_S \sigma_S}{\sqrt{L \times \epsilon_B \sigma_B + (\varepsilon_B^{sys} \times L \times \epsilon_B \sigma_B)^2}}, \quad (3)$$

where $\sigma_S(\epsilon_S)$ and $\sigma_B(\epsilon_B)$ represent the cross section (selection efficiency) of the signal and the backgrounds, respectively. The integrated luminosity is denoted by L, while ε_B^{sys} is the systematic uncertainty in the background rate.

The best cuts along with the cut-flow for some representative Z' masses are shown in Table 2 for the Z' leptophilic model and in Table 2 for the 331 models. The cut in the e^+e^- mass was performed by searching for the best window around the signal peak to select the events. For each Z' mass, 4×10^5 random searches were performed in the cut thresholds space of $p_T(l)$, $|\eta(l)|$, and e^+e^- window around the signal peak. The search is agnostic of the Z' mass, and the algorithm is able to identify the resonance peak without any previous information about the model parameters.

The background efficiencies are tiny for each Z' mass, while the signal efficiency increases from light towards heavy Z' bosons, reaching a maximum at 2.5 TeV mass, approximately, in all models. Tables 2 and 3 show that higher signal efficiencies are achieved by hardening the p_T threshold and selecting more centrally produced events in the detector. As anticipated, the signal efficiencies drop to $\sim$ 4%, or less, when the boson's mass is above the energy collider.

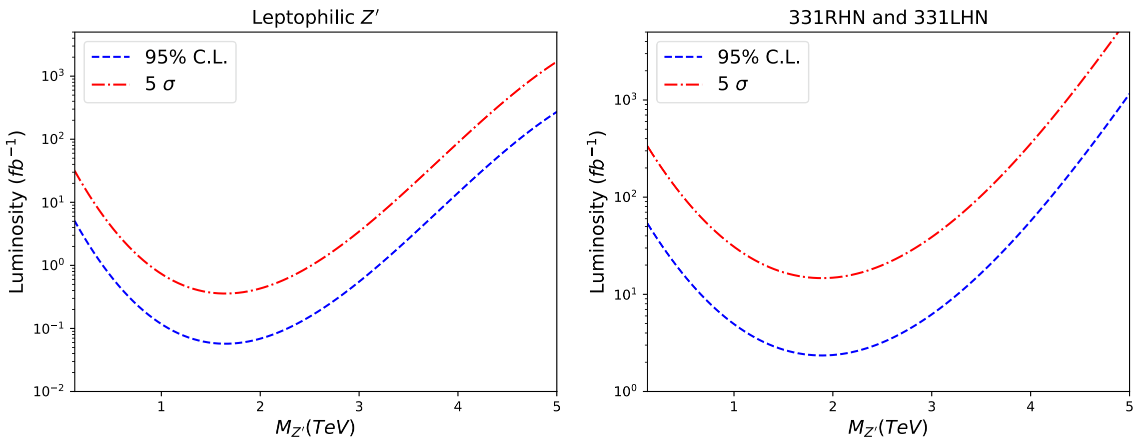
We show, in Fig. 4, the luminosity required to exclude a Z' at 95% confidence level (CL) or to discover its signal in the 3 TeV CLIC. A 3-3-1 Z' will demand around one order of magnitude more data compared to leptophilic ones. Yet, 1 ab^{-1} will suffice for the less promising case, while luminosities as low as 100 pb^{-1} will be needed for the most promising scenarios. It is known that LHC already places $M_{Z'} > 4$ TeV [86]. CLIC will also present discovery potential for masses above 4 TeV as shown in Fig. 4 for these models. Nevertheless, it is worth pointing out that in the Multi-TeV Z' mass regime, CLIC has the potential to discover such a boson with less than 1 fb^{-1} of data (See Fig. 4b). This clearly shows that even if LHC happens to discover a Z' boson with a mass larger than CLIC's center-of-mass energy, CLIC will still play an important role in constraining its properties in a similar vein to LEP back in time.

Anyway, there is room for improvement if we combine the signal for final state muons [18], which should nearly double the signal cross section after cuts depending on the Z' mass. One can discriminate the leptophilic from the 3-3-1 hypothesis by looking for a resonance at different channels, such as dijets.

An interesting possibility is that the Z' mediates the interactions between dark matter and the SM spectrum. In that case, due to the diminished branching ratio into leptons, the integrated luminosity to reach the sensitivity we forecast here will be larger but, given these excellent prospects for discovery and exclusion, observing this new boson at CLIC will probably remain viable. We plan to investigate the Z' phenomenology at CLIC in scenarios with a dark matter candidate in the future.

4 Conclusions

In this work, we investigate the prospects of the 3 TeV CLIC to unravel new physics associated with a new weak interaction coupling to electrons and positrons. If this new interac-



(a) (b)

Fig. 4 The required luminosity, in fb^{-1}, for 95% CL exclusion and 5σ discovery, in 3 TeV CLIC, of the leptophilic (left panel) and 331RHN/331LHN Z' boson (right panel)

tion couples feebly to quarks, then an e^+e^- collider is the suitable machine to search for that leptophilic interaction. We found that an optimized kinematics cuts strategy search for $e^+e^- \rightarrow e^+e^-$ benefits from resonant and non-resonant contributions from a Z' improving the mass reach of the collider.

In the leptophilic case, Z' masses from 100 GeV up to 5 TeV can be excluded at 95% C.L. with less than 10fb^{-1} if the strength of couplings with leptons is similar to the SM Z boson, and with up to 100fb^{-1} for a discovery. By their turn, LHN and RHN 3-3-1 models will need more data once couplings to quarks compete for the branching ratios of the Z'. Yet, CLIC will surely complement searches performed at the LHC for 3-3-1 models.

In summary, we proposed that in the same way the sequential Z' boson is a benchmark model for LHC collaboration, a leptophilic Z' with sequential couplings to leptons be for the CLIC. We justified this argument by assessing the CLIC discovery potential, which reaches a 5σ detection with less than 1fb^{-1} of integrated luminosity for $M_{Z'} = 1 - 3$ TeV.

Acknowledgements The authors thank Yoxara Villamixar for discussions and the anonymous referee for constructive suggestions. This work was supported by Simons Foundation (Award Number:1023171-RC), FAPESP Grant 2018/25225-9, 2021/01089-1, 2023/01197-4, ICTP-SAIFR FAPESP Grants 2021/14335-0, CNPq Grants 307130/2021-5, 311851/2020-7, 307317/2021-8, and ANID-Millennium Science Initiative Program ICN2019_044. Y.M.O.T. acknowledges financial support from CAPES under grants 88887.485509/2020-00. V.P.G. was partially supported by CNPq, CAPES, FAPERGS and INCT-FNA (Process No. 464898/2014-5).

Data Availability Statement This manuscript has no associated data or the data will not be deposited. [Authors' comment: all the studies in this paper are theoretical. No experiment has been done. So data sharing does not apply to this paper.].

Funded by SCOAP[3].

References

1. O. Brunner et al., (2022). arXiv:2203.09186 [physics.acc-ph]
2. R. Barate et al., LEP Working Group for Higgs boson searches, ALEPH, DELPHI, L3, OPAL. Phys. Lett. B **565**, 61 (2003). https://doi.org/10.1016/S0370-2693(03)00614-2. arXiv:hep-ex/0306033
3. J. Alcaraz et al., (ALEPH, DELPHI, L3(OPAL, LEP Electroweak Working Group), (2006). arXiv:hep-ex/0612034
4. S. Schael et al., ALEPH, DELPHI, L3, OPAL, LEP Electroweak. Phys. Rep. **532**, 119 (2013). https://doi.org/10.1016/j.physrep.2013.07.004. arXiv:1302.3415 [hep-ex]
5. J. Heeck, W. Rodejohann, Phys. Rev. D **84**, 075007 (2011). https://doi.org/10.1103/PhysRevD.84.075007. arXiv:1107.5238 [hep-ph]
6. F. del Aguila, M. Chala, J. Santiago, Y. Yamamoto, JHEP **03**, 059 (2015). https://doi.org/10.1007/JHEP03(2015)059. arXiv:1411.7394 [hep-ph]
7. N.F. Bell, Y. Cai, R.K. Leane, A.D. Medina, Phys. Rev. D **90**, 035027 (2014). https://doi.org/10.1103/PhysRevD.90.035027. arXiv:1407.3001 [hep-ph]
8. S.O. Kara, S. Akkoyun, T. Bayram, Int. J. Mod. Phys. A **29**, 1450171 (2014). https://doi.org/10.1142/S0217751X14501711
9. S. Patra, S. Rao, N. Sahoo, N. Sahu, Nucl. Phys. B **917**, 317 (2017). https://doi.org/10.1016/j.nuclphysb.2017.02.010. arXiv:1607.04046 [hep-ph]
10. J. Heeck, Phys. Lett. B **758**, 101 (2016). https://doi.org/10.1016/j.physletb.2016.05.007. arXiv:1602.03810 [hep-ph]

11. W. Altmannshofer, C.-Y. Chen, P.S. Bhupal Dev, A. Soni, Phys. Lett. B **762**, 389 (2016). https://doi.org/10.1016/j.physletb.2016.09.046. arXiv:1607.06832 [hep-ph]
12. W. Altmannshofer, S. Gori, S. Profumo, F.S. Queiroz, JHEP **12**, 106 (2016). https://doi.org/10.1007/JHEP12(2016)106. arXiv:1609.04026 [hep-ph]
13. S. Sadhukhan, M.P. Singh, Phys. Rev. D **103**, 015015 (2021). https://doi.org/10.1103/PhysRevD.103.015015. arXiv:2006.05981 [hep-ph]
14. L.A. Anchordoqui, I. Antoniadis, X. Huang, D. Lust, T.R. Taylor, Phys. Lett. B **820**, 136585 (2021). https://doi.org/10.1016/j.physletb.2021.136585. arXiv:2105.02630 [hep-ph]
15. K. Asai, T. Moroi, A. Niki, Phys. Lett. B **818**, 136374 (2021). https://doi.org/10.1016/j.physletb.2021.136374. arXiv:2104.00888 [hep-ph]
16. T. Moroi, A. Niki, JHEP **05**, 016 (2023). https://doi.org/10.1007/JHEP05(2023)016. arXiv:2205.11766 [hep-ph]
17. P. Ko, Y. Omura, Phys. Lett. B **701**, 363 (2011). https://doi.org/10.1016/j.physletb.2011.06.009. arXiv:1012.4679 [hep-ph]
18. S.O. Kara, M. Sahin, S. Sultansoy, S. Turkoz, JHEP **08**, 072 (2011). https://doi.org/10.1007/JHEP08(2011)072. arXiv:1103.1071 [hep-ph]
19. B. Allanach, F.S. Queiroz, A. Strumia, S. Sun, Phys. Rev. D **93**, 055045 (2016) (Erratum: Phys.Rev.D 95, 119902 (2017)). https://doi.org/10.1103/PhysRevD.93.055045. arXiv:1511.07447 [hep-ph]
20. A.J. Buras, A. Crivellin, F. Kirk, C.A. Manzari, M. Montull, JHEP **06**, 068 (2021). https://doi.org/10.1007/JHEP06(2021)068. arXiv:2104.07680 [hep-ph]
21. Y.-Y. Li, C.-X. Yue, Y.-Q. Wang, X.-J. Cheng, Nucl. Phys. B **982**, 115899 (2022). https://doi.org/10.1016/j.nuclphysb.2022.115899
22. E.J. Chun, T. Mondal, JHEP **07**, 044 (2021). https://doi.org/10.1007/JHEP07(2021)044. arXiv:2104.03701 [hep-ph]
23. J. Li, W. Wang, X. Cai, C. Yang, M. Lu, Z. You, S. Qian, Q. Li, (2023) https://doi.org/10.1007/JHEP03(2023)190. arXiv:2302.02203 [hep-ph]
24. M.B. Tully, G.C. Joshi, Phys. Rev. D **64**, 011301 (2001). https://doi.org/10.1103/PhysRevD.64.011301. arXiv:hep-ph/0011172
25. J.C. Montero, C.ADe.S. Pires, V. Pleitez, Phys. Rev. D **65**, 095001 (2002). https://doi.org/10.1103/PhysRevD.65.095001. arXiv:hep-ph/0112246
26. N.V. Cortez, M.D. Tonasse, Phys. Rev. D **72**, 073005 (2005). https://doi.org/10.1103/PhysRevD.72.073005. arXiv:hep-ph/0510143
27. D. Cogollo, H. Diniz, C.A. de S. Pires, Phys. Lett. B **677**, 338 (2009). https://doi.org/10.1016/j.physletb.2009.05.060. arXiv:0903.0370 [hep-ph]
28. D. Cogollo, H. Diniz, C.A. de S. Pires, Phys. Lett. B **687**, 400 (2010). https://doi.org/10.1016/j.physletb.2010.03.066. arXiv:1002.1944 [hep-ph]
29. D. Cogollo, H. Diniz, C.A. de S. Pires, P.S. Rodrigues da Silva, Eur. Phys. J. C **58**, 455 (2008). https://doi.org/10.1140/epjc/s10052-008-0749-5. arXiv:0806.3087 [hep-ph]
30. H. Okada, N. Okada, Y. Orikasa, Phys. Rev. D **93**, 073006 (2016). https://doi.org/10.1103/PhysRevD.93.073006. arXiv:1504.01204 [hep-ph]
31. C.A. de Sousa Pires, F. Ferreira De Freitas, J. Shu, L. Huang, P. Wagner Vasconcelos Olegário, Phys. Lett. B **797**, 134827 (2019). https://doi.org/10.1016/j.physletb.2019.134827. arXiv:1812.10570 [hep-ph]
32. A.E. C. Hernández, L.T. Hue, S. Kovalenko, H.N. Long, An extended 3-3-1 model with two scalar triplets and linear seesaw mechanism (2021). arXiv:2001.01748 [hep-ph]
33. J.M. Cabarcas, J. Duarte, J.A. Rodriguez, 11th International Conference on Heavy Quarks and Leptons, PoS **HQL2012**, 072 (2012). https://doi.org/10.22323/1.166.0072. arXiv:1212.3586 [hep-ph]
34. L.T. Hue, L.D. Ninh, T.T. Thuc, N.T.T. Dat, Eur. Phys. J. C **78**, 128 (2018). https://doi.org/10.1140/epjc/s10052-018-5589-3. arXiv:1708.09723 [hep-ph]
35. D. Fregolente, M.D. Tonasse, Phys. Lett. B **555**, 7 (2003). https://doi.org/10.1016/S0370-2693(03)00037-6. arXiv:hep-ph/0209119
36. H.N. Long, N.Q. Lan, Europhys. Lett. **64**, 571 (2003). https://doi.org/10.1209/epl/i2003-00267-5. arXiv:hep-ph/0309038
37. C.A. de S. Pires, P.S. Rodrigues da Silva, JCAP **0712**, 012 (2007). https://doi.org/10.1088/1475-7516/2007/12/012. arXiv:0710.2104 [hep-ph]
38. J.K. Mizukoshi, C.A.S. Pires, F.S. Queiroz, P.S. Rodrigues da Silva, Phys. Rev. D **83**, 065024 (2011). https://doi.org/10.1103/PhysRevD.83.065024. arXiv:1010.4097 [hep-ph]
39. J.D. Ruiz-Alvarez, C.A.S. Pires, F.S. Queiroz, D. Restrepo, P.S. Rodrigues da Silva, Phys. Rev. D **86**, 075011 (2012). https://doi.org/10.1103/PhysRevD.86.075011. arXiv:1206.5779 [hep-ph]
40. S. Profumo, F.S. Queiroz, Eur. Phys. J. C **74**, 2960 (2014). https://doi.org/10.1140/epjc/s10052-014-2960-x. arXiv:1307.7802 [hep-ph]
41. P.V. Dong, T.P. Nguyen, D.V. Soa, Phys. Rev. D **88**, 095014 (2013). https://doi.org/10.1103/PhysRevD.88.095014. arXiv:1308.4097 [hep-ph]
42. P.V. Dong, H.T. Hung, T.D. Tham, Phys. Rev. D **87**, 115003 (2013). https://doi.org/10.1103/PhysRevD.87.115003. arXiv:1305.0369 [hep-ph]
43. D. Cogollo, A.X. Gonzalez-Morales, F.S. Queiroz, P.R. Teles, JCAP **1411**, 002 (2014). https://doi.org/10.1088/1475-7516/2014/11/002. arXiv:1402.3271 [hep-ph]
44. P.V. Dong, D.T. Huong, F.S. Queiroz, N.T. Thuy, Phys. Rev. D **90**, 075021 (2014). https://doi.org/10.1103/PhysRevD.90.075021. arXiv:1405.2591 [hep-ph]
45. P.V. Dong, N.T.K. Ngan, D.V. Soa, Phys. Rev. D **90**, 075019 (2014). https://doi.org/10.1103/PhysRevD.90.075019. arXiv:1407.3839 [hep-ph]
46. C. Kelso, H.N. Long, R. Martinez, F.S. Queiroz, Phys. Rev. D **90**, 113011 (2014). https://doi.org/10.1103/PhysRevD.90.113011. arXiv:1408.6203 [hep-ph]
47. Y. Mambrini, S. Profumo, F.S. Queiroz, Phys. Lett. B **760**, 807 (2016). https://doi.org/10.1016/j.physletb.2016.07.076. arXiv:1508.06635 [hep-ph]
48. P.V. Dong, C.S. Kim, D.V. Soa, N.T. Thuy, Phys. Rev. D **91**, 115019 (2015). https://doi.org/10.1103/PhysRevD.91.115019. arXiv:1501.04385 [hep-ph]
49. C.A.S. Pires, P.S. Rodrigues da Silva, A.C.O. Santos, C. Siqueira, Phys. Rev. D **94**, 055014 (2016). https://doi.org/10.1103/PhysRevD.94.055014. arXiv:1606.01853 [hep-ph]
50. A. Alves, G. Arcadi, P.V. Dong, L. Duarte, F.S. Queiroz, J.W.F. Valle, Phys. Lett. B **772**, 825 (2017). https://doi.org/10.1016/j.physletb.2017.07.056. arXiv:1612.04383 [hep-ph]
51. P.S. Rodrigues da Silva, Phys. Int. **7**, 15 (2016). https://doi.org/10.3844/pisp.2016.15.27. arXiv:1412.8633 [hep-ph]
52. C.D.R. Carvajal, B.L. Sánchez-Vega, O. Zapata, Phys. Rev. D **96**, 115035 (2017). https://doi.org/10.1103/PhysRevD.96.115035. arXiv:1704.08340 [hep-ph]
53. P.V. Dong, D.T. Huong, F.S. Queiroz, J.W.F. Valle, C.A. Vaquera-Araujo, JHEP **04**, 143 (2018). https://doi.org/10.1007/JHEP04(2018)143. arXiv:1710.06951 [hep-ph]
54. G. Arcadi, C.P. Ferreira, F. Goertz, M.M. Guzzo, F.S. Queiroz, A.C.O. Santos, Phys. Rev. D **97**, 075022 (2018). https://doi.org/10.1103/PhysRevD.97.075022. arXiv:1712.02373 [hep-ph]
55. J.C. Montero, A. Romero, B.L. Sánchez-Vega, Phys. Rev. D **97**, 063015 (2018). https://doi.org/10.1103/PhysRevD.97.063015. arXiv:1709.04535 [hep-ph]
56. D.T. Huong, D.N. Dinh, L.D. Thien, P. Van Dong, JHEP **08**, 051 (2019). https://doi.org/10.1007/JHEP08(2019)051. arXiv:1906.05240 [hep-ph]

57. C.E. Alvarez-Salazar, O.L.G. Peres, Phys. Rev. D **103**, 035029 (2021). https://doi.org/10.1103/PhysRevD.103.035029. arXiv:1906.06444 [hep-ph]
58. D. Van Loi, C.H. Nam, P. Van Dong, Eur. Phys. J. C **81**, 591 (2021). https://doi.org/10.1140/epjc/s10052-021-09374-4. arXiv:2012.10979 [hep-ph]
59. M. Dutra, V. Oliveira, C.A. de S. Pires, F.S. Queiroz, JHEP **10**, 005 (2021). https://doi.org/10.1007/JHEP10(2021)005. arXiv:2104.14542 [hep-ph]
60. V. Oliveira, C.A.S. Pires, (2021). arXiv:2112.03963 [hep-ph]
61. D.V. Soa, H.N. Long, D.T. Binh, D.P. Khoi, J. Exp. Theor. Phys. **98**, 661 (2004). https://doi.org/10.1134/1.1757665. arXiv:hep-ph/0311287
62. J.-J. Blaising, J.D. Wells, (2012). arXiv:1208.1148 [hep-ph]
63. S. Spor, E. Gurkanli, M. Köksal, Nucl. Phys. B **979**, 115785 (2022). https://doi.org/10.1016/j.nuclphysb.2022.115785. arXiv:2203.02352 [hep-ph]
64. S.C. İnan, A.V. Kisselev, JHEP **10**, 121 (2021). https://doi.org/10.1007/JHEP10(2021)121. arXiv:2108.04478 [hep-ph]
65. E. Gurkanli, (2023). arXiv:2307.01326 [hep-ph]
66. A. Dasgupta, P.S.B. Dev, T. Han, R. Padhan, S. Wang, K. Xie, (2023). arXiv:2308.12804 [hep-ph]
67. E.C.G. Stueckelberg, Helv. Phys. Acta **11**, 225 (1938). https://doi.org/10.5169/seals-110852
68. H. Ruegg, M. Ruiz-Altaba, Int. J. Mod. Phys. A **19**, 3265 (2004). https://doi.org/10.1142/S0217751X04019755. arXiv:hep-th/0304245
69. K. Mekala, A.F. Zarnecki, B. Grzadkowski, M. Iglicki, SciPost Phys. Proc. **8**, 091 (2022). https://doi.org/10.21468/SciPostPhysProc.8.091. arXiv:2107.13903 [hep-ex]
70. M. Aicheler, P. Burrows, M. Draper, T. Garvey, P. Lebrun, K. Peach, N. Phinney, H. Schmickler, D. Schulte, N. Toge, *https://cds.cern.ch/record/1500095*, CERN Yellow Reports: Monographs (CERN, Geneva, 2012). https://doi.org/10.5170/CERN-2012-007
71. A. Robson, P.N. Burrows, N. Catalan Lasheras, L. Linssen, M. Petric, D. Schulte, E. Sicking, S. Stapnes, W. Wuensch, (2018). arXiv:1812.07987 [physics.acc-ph]
72. CLIC accelerator, arXiv:1903.08655
73. E. Aslanides et al., Tech. Rep. (2019) https://cds.cern.ch/record/2706890. arXiv:1912.13466
74. (CLIC Conceptual Design Report), https://doi.org/10.5170/CERN-2012-003. arXiv:1202.5940 [physics.ins-det]
75. A. Robson, P. Roloff, (2018). arXiv:1812.01644 [hep-ex]
76. R. Franceschini, Int. J. Mod. Phys. A **35**, 2041015 (2020). https://doi.org/10.1142/S0217751X20410158. arXiv:1902.10125 [hep-ph]
77. E. Sicking, R. Ström, Nat. Phys. **16**, 386 (2020). https://doi.org/10.1038/s41567-020-0834-8. arXiv:2001.05224 [physics.acc-ph]
78. A.F. Zarnecki (CLICdp, ILD concept group), PoS **CORFU2019**, 037 (2020). https://doi.org/10.22323/1.376.0037. arXiv:2004.14628 [hep-ph]
79. E. Accomando et al., (CLIC Physics Working Group), in *11th International Conference on Hadron Spectroscopy, CERN Yellow Reports: Monographs* (2004). https://doi.org/10.5170/CERN-2004-005. arXiv:hep-ph/0412251
80. J. de Blas et al. (CLIC), **3/2018** (2018). https://doi.org/10.23731/CYRM-2018-003. arXiv:1812.02093 [hep-ph]
81. V. Khachatryan et al., CMS. JHEP **04**, 025 (2015). https://doi.org/10.1007/JHEP04(2015)025. arXiv:1412.6302 [hep-ex]
82. M. Aaboud et al., ATLAS. JHEP **10**, 182 (2017). https://doi.org/10.1007/JHEP10(2017)182. arXiv:1707.02424 [hep-ex]
83. F. Pisano, V. Pleitez, Phys. Rev. D **46**, 410 (1992). https://doi.org/10.1103/PhysRevD.46.410. arXiv:hep-ph/9206242
84. R. Foot, O.F. Hernandez, F. Pisano, V. Pleitez, Phys. Rev. D **47**, 4158 (1993). https://doi.org/10.1103/PhysRevD.47.4158. arXiv:hep-ph/9207264
85. R. Foot, H.N. Long, T.A. Tran, Phys. Rev. D **50**, R34 (1994). https://doi.org/10.1103/PhysRevD.50.R34. arXiv:hep-ph/9402243
86. A. Alves, L. Duarte, S. Kovalenko, Y.M. Oviedo-Torres, F.S. Queiroz, Y.S. Villamizar, Phys. Rev. D **106**, 055027 (2022). https://doi.org/10.1103/PhysRevD.106.055027. arXiv:2203.02520 [hep-ph]
87. A. Alloul, N.D. Christensen, C. Degrande, C. Duhr, B. Fuks, "Feynrules", https://feynrules.irmp.ucl.ac.be/. Accessed 20 Sept 2021
88. J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.-S. Shao, T. Stelzer, P. Torrielli, M. Zaro, J. High Energy Phys. **2014**, 1 (2014). https://doi.org/10.1007/jhep07(2014)079. arXiv:1405.0301 [hep-ph]
89. T. Sjostrand, S. Mrenna, P.Z. Skands, Comput. Phys. Commun. **178**, 852 (2008). https://doi.org/10.1016/j.cpc.2008.01.036. arXiv:0710.3820 [hep-ph]
90. J. de Favereau, C. Delaere, P. Demin, A. Giammanco, V. Lemaître, A. Mertens, M. Selvaggi (DELPHES 3). JHEP **02**, 057 (2014). https://doi.org/10.1007/JHEP02(2014)057. arXiv:1307.6346 [hep-ex]
91. S. Frixione, O. Mattelaer, M. Zaro, X. Zhao, (2021). arXiv:2108.10261 [hep-ph]