Exotic leptons at future linear colliders

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Doubly charged excited leptons determine a possible signature for physics beyond the standard model at the present Large Hadron Collider. These exotic states are introduced in extended isospin multiplets and they can be treated either within gauge or contact effective interactions or a mixture of those. In this paper we study the production and the corresponding signatures of doubly charged leptons at the forthcoming linear colliders and we focus on the electron-electron beam setting. In the framework of gauge interactions, the interference between the $t$ and $u$ channel is evaluated that has been neglected so far. A pure leptonic final state is considered ($e^{-}e^{-} \rightarrow e^{-}e^{-}\nu\bar{\nu}$) that experimentally translates into a like-sign dilepton and missing transverse energy signature. We focus on the standard model irreducible background and we study the invariant like-sign-dilepton mass distribution for both the signal and background processes. Finally, the 3 and 5-sigma statistical significance exclusion curves in the model parameter space are provided.

I. INTRODUCTION

The Standard Model (SM) of particle physics is nowadays well tested within a plethora of low and high-energy experiments. The recent discovery of a particle compatible to the missing fundamental scalar [1, 2], the Higgs boson, establishes the last great success of the SM. Of course the theoretical and experimental frontiers are just moved onto some further questions and issues. Among those, let us consider the so-called hierarchy problem or the question why the Higgs boson is light after including loop corrections to the Higgs mass. Indeed, the Higgs mass receives quantum corrections from all heavy SM particles (Higgs, gauge bosons and top-quark). Such divergences are quadratic in a generic cut off scale and not protected by any chiral symmetry like the fermion masses are. Moreover, any possible new physics scale lying between the electroweak and the Planck scale might push higher the cut-off scale. Unless a fine tuning is considered as a satisfactory answer, a deeper understanding is desirable.

Certainly several beyond the standard model scenarios have been considered in the literature. Supersymmetry, extra-dimensions partial compositeness and compositeness are just a few of them. An active search for supersymmetric particles has been carried out at the Large Hadron Collider (LHC) with no positive outcome until now [3, 4]. This brings to a quite narrow window for the minimal supersymmetric model even though many non-minimal realizations are still under investigation and not excluded by the current data. The compositeness approach is somewhat complementary to supersymmetry and no experimental evidence has been provided either. New unknown particles are supposed to be the constituents of the Higgs boson and its mass is generated by some internal dynamics as a meson mass is generated by an interacting quark anti-quark pair [5]. On the same footing, composite models also concern about the proliferation of the SM leptons and quarks collected in the three different generations. One of the main consequence of a further substructure is the possibility to observe excited fermions that would produce signatures to be studied at colliders [6]. Indeed, many experimental analysis at colliders have been performed about the direct or indirect search of excited fermions, especially in the framework of four-fermion contact interactions. The stronger bounds are nowadays provided by the LHC experiments [7, 8].

In this paper, we focus on excited leptons and in particular on those having an exotic charge $Q = 2e$. These states appear in the context of phenomenological models that rely on isospin-invariance and magnetic type interaction [9]. Doubly charged leptons appear also in string inspired models [10] and in supersymmetric extensions of left-right symmetric models [11, 12]. Not prompt decaying doubly charged leptons have been also considered as a viable candidate for cold dark matter [13].

The production cross section and relevant signatures for the excited doubly charged leptons have been studied in some detail for both the contact and gauge interactions in the LHC framework [14, 15]. In this work, we address the phenomenology of doubly charged leptons in the context of the forthcoming electron-positron linear colliders. In particular, we aim to investigate the signatures produced by the doubly charged leptons at the linear colliders facilities and the interplay with the corresponding SM irreducible background. The International Linear Collider (ILC) [16] and the Compact Linear Collider (CLIC) [17, 18] proposal will offer the possibility to have $e^{-}e^{-}$ beams. Here we will focus on this particular beam option besides the standard one ($e^{+}e^{-}$) because it allows for the single production channel. Indeed, at tree level, the $e^{+}e^{-}$ configuration allows only pair production of the excited leptons and the available phase space would be very limited due to the large excited lepton mass. We
consider a pure leptonic final state as follows:

\[ e^- e^- \rightarrow E^- \nu e \rightarrow W^- e^- \nu e \rightarrow (e^- e^-) \tilde{\nu} e_e. \]  

(1)

Since we want to shape the main features of the process we fix the flavour of the final state leptons within the first generation (electron flavour).

We highlight that the ATLAS and CMS collaborations have recently provided lower bounds on the mass of long lived multi-charged particles. In particular the ATLAS collaboration excludes particles up to 430 GeV based on the run at \( \sqrt{s} = 7 \) TeV and with \( L = 5 \) fb\(^{-1}\)\cite{20}. Similarly the CMS collaboration sets lower mass limits up to 685 GeV within the run at \( \sqrt{s} = 8 \) TeV and with \( L = 18.8 \) fb\(^{-1}\)\cite{20}. These exclusion limits do not directly apply to our case because Drell-Yan-like pair production is assumed for the multicharged particle in the experimental analysis and the doubly charged lepton considered here promptly decays. The production of excited fermions at linear electron-positron and electron-proton colliders has been addressed already long ago\cite{21},\cite{22}. A more recent phenomenological study on excited fermions at linear colliders can be found in \cite{23}, where fermion state with spin 1/2 and 3/2 have been considered.

In Sec. II we address the production cross section for the doubly charged lepton in the context of gauge mediated interactions, whereas Sec. III is dedicated to the production cross section via contact interactions. In Sec. IV we study the SM irreducible background and we carry out the analysis of the relevant kinematic distributions for the signal and the dominant SM background processes. Finally we summarize our conclusions and outlook in Sec. V.

II. PRODUCTION CROSS SECTION VIA GAUGE INTERACTIONS

In this section we focus on the production cross section for doubly charged leptons via gauge interactions. These exotic leptons were first introduced in the context of compositeness and weak isospin invariance\cite{9}. Higher isospin multiplets, namely \( I_W = 1 \) and \( I_W = 3/2 \), are added to the standard ones \( (I_W = 0 \) and \( I_W = 1/2) \). Exotic electromagnetic charges for the fermions are then allowed \( (Q = 4/3 e, 5/3 e \) for quarks and \( Q = 2 e \) for leptons). The exotic electromagnetic charges, not present in the SM, may lead to interesting signature to investigate at colliders.

At variance of contact interactions, the gauge interactions enrich the phenomenology with the sensitivity to angular distributions and to different weak isospin multiplets. As a drawback, the production cross section derived from gauge interactions are rather smaller than the ones predicted by contact interactions for the same value of the parameters \((m^*, \Lambda)\). Here, \( m^* \) is the mass of the excited doubly charged lepton and \( \Lambda \) the compositeness scale. We compare them in Fig. 1 for the process of interest \( e^- e^- \rightarrow E^- \nu e \).

In the following, we show that the production cross section for the doubly charged lepton is different depending on \( E^- \in I_W = 1 \) or \( I_W = 3/2 \). The production cross sections of excited fermions via gauge interactions for the different multiplets were already evaluated in \cite{23}. In particular the process \( q_a q_b \rightarrow F F^* \) has been addressed, where \( q_a \) and \( q_b \) are two generic SM quark and anti-quark, \( F \) stands for a SM fermion and \( F^* \) for an excited fermion. The authors give general expressions for the process at the parton level and they neglect the interference between the different kinematic channels. Here, we add the study of the interference between the t and u channel depicted in Fig. 1 diagrams c and d respectively, relevant for the present study. Indeed, the t – u interference vanishes in the \( I_W = 1 \) case but it plays a role when considering \( I_W = 3/2 \). The difference is determined by the chiral projector involved in the vertex that couples the excited fermion to a SM one. We recall the relevant Lagrangian for this section, that reads

\[ \mathcal{L}_{GI} = g \int \frac{f}{\Lambda} \bar{\psi} E \sigma_{\mu \nu} (i \partial^{\nu} W^\mu) P_R \psi e_e + g \int \frac{f}{\Lambda} \bar{\tilde{\psi}} E \sigma_{\mu \nu} (i \partial^{\nu} W^\mu) P_L \psi e_e + h.c., \]  

(2)

where \( f, \tilde{f} \) are couplings that parametrize the effective interaction for the \( I_W = 1 \) and \( I_W = 3/2 \), \( g \) is the SU(2) coupling, \( P_L = (1 - \gamma^5)/2 \) and \( P_R = (1 + \gamma^5)/2 \) are the chiral projectors, \( \sigma^{\mu \nu} = i [\gamma^\mu, \gamma^\nu]/2 \) are the field of \( \psi_F \) stands for the doubly charged lepton either for the case

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**FIG. 1.** Diagrams for the the process \( e^- e^- \rightarrow E^- \nu e \) induced by the contact interaction Lagrangian (a and b) and gauge interaction Lagrangian (c and d). Solid lines stand for electrons and electron neutrinos, wiggled lines for the \( W \) boson and solid double lines for the doubly charged lepton. We label with different momenta, \( p_1 \) and \( p_2 \), the incoming electrons.
ν_e \to E^- \nu_e$. In the left panel the total cross section against the center of mass energy is displayed for the different isospin multiplets. In particular, the solid blue line stands for $E^- \in I_W = 1$, the dashed red one for $E^- \in I_W = 3/2$ with the interference contribution taken into account. At variance, the orange dot-dashed curve is the result when the interference is not considered. The effect is not negligible.

The right panel shows the total cross section against mass. Also here the curves for different multiplets are displayed. The compositeness parameters are set to $(m^* = 0.5 \text{ TeV}, \Lambda = 5 \text{ TeV})$. The green dots stand for the CalcHEP output.

Also here the curves for different multiplets are displayed.

For $I_W = 1$ or $I_W = 3/2$, $\psi_e$ and $\psi_\nu$ are the electron and electron neutrino field respectively. The constants $f$ and $\tilde{f}$ are usually set to one in the literature and we keep this choice as well. The effective Lagrangian in (2) is made of dimension five operators and hence one inverse power suppression in the new physics scale $\Lambda$ is there.

In the following, we express the differential cross sections in terms of the Maldestam variables. According to Fig. 1 one has to take into account the $t$ and $u$ channels and the interference amongst the two. We list the result as follows

$$
\left( \frac{d\sigma}{dt} \right)_{I_W = 1} = \frac{1}{4s^2\Lambda^2} \frac{g^4f^2}{16\pi} \frac{t}{(t - M_W^2)^2} \left[ m^2(t - m^2) + 2su + m^2(s - u) \right] + \frac{1}{4s^2\Lambda^2} \frac{g^4\tilde{f}^2}{16\pi} \frac{u}{(u - M_W^2)^2} \left[ m^2(u - m^2) + 2st + m^2(s - t) \right], \quad (3)
$$

$$
\left( \frac{d\sigma}{dt} \right)_{I_W = 3/2} = \frac{1}{4s^2\Lambda^2} \frac{g^4f^2}{16\pi} \frac{t}{(t - M_W^2)^2} \left[ m^2(t - m^2) + 2su - m^2(s - u) \right] + \frac{1}{4s^2\Lambda^2} \frac{g^4\tilde{f}^2}{16\pi} \frac{u}{(u - M_W^2)^2} \left[ m^2(u - m^2) + 2st - m^2(s - t) \right] + \frac{1}{8s^2\Lambda^2} \frac{g^4\tilde{f}^2}{16\pi} \frac{1}{(t - M_W^2)} \left( 2stu + \frac{3}{4} utm^2 \right). \quad (4)
$$

where $M_W$ is the $W$ boson mass. Let us remark some features of the above expressions. One may obtain the cross section for the $u$ channel from the $t$ one just by crossing symmetry, namely $t \to u$. Therefore, the second line in eqs. (3)-(4) is obtained from the first one by performing the exchange between the Maldestam variables $t$ and $u$. The cross sections for the different isospin multiplets differ from the third term in the square brackets, flip of sign, and the interference term that is only present in eq. (4). The differences are inherited from the chiral projector that enters the Lagrangian in (2). $P_R$ for $E^- \in I_W = 1$ and $P_L$ for $E^- \in I_W = 3/2$. We compute explicitly the interference term and we show that it accounts for a relevant effect in the integrated cross section for $E^- \in I_W = 3/2$ as shown in Fig. 2. Indeed, the cross section is reduced by a factor of one third at $\sqrt{s} = 1 \text{ TeV}$. The result for the integrated total cross section reads as follows

$$
\sigma_{I_W = 1} = \frac{\alpha^2f^2\pi}{s^2\Lambda^2\sin^2\theta_w} \left[ -2 (s - m^2) + (s - m^2 + 2M_W^2) \ln \left( 1 + \frac{s - m^2}{M_W^2} \right) \right], \quad (5)
$$

$$
\sigma_{I_W = 3/2} = \frac{\alpha^2\tilde{f}^2\pi}{s^2\Lambda^2\sin^2\theta_w} \left[ -2s + m^2 \left( 1 + \frac{M_W^2}{s - m^2 + M_W^2} \right) + (s + 2M_W^2) \ln \left( 1 + \frac{s - m^2}{M_W^2} \right) \right] + \frac{\alpha^2\tilde{f}^2\pi}{8s^2\Lambda^2\sin^2\theta_w} \left( 8s + 3m^2 \right) \left[ -s + m^2 + 2M_W^2 \ln \left( 1 + \frac{s - m^2}{M_W^2} \right) \right], \quad (6)
$$

FIG. 2. The plot shows the total cross sections for the process $e^-e^- \to E^-\nu_e$. In the left panel the total cross section against the center of mass energy is displayed for the different isospin multiplets. In particular, the solid blue line stands for $E^- \in I_W = 1$, the dashed red one for $E^- \in I_W = 3/2$ with the interference contribution taken into account. At variance, the orange dot-dashed curve is the result when the interference is not considered. The effect is not negligible.

The right panel shows the total cross section against mass. Also here the curves for different multiplets are displayed. The compositeness parameters are set to $(m^* = 0.5 \text{ TeV}, \Lambda = 5 \text{ TeV})$. The green dots stand for the CalcHEP output.

In the following, we express the differential cross sections in terms of the Maldestam variables. According to Fig. 1 one has to take into account the $t$ and $u$ channels and the interference amongst the two. We list the result as follows
where we introduce the sine of the Weinberg angle to make the QED coupling constant appear in the expressions. Their behaviour near threshold, $s \rightarrow m^2$, may be parametrized as follows:

$$\sigma_{I_{W1}} = K \frac{x^4}{m^4 M_{W}^2}, \quad \sigma_{I_{W2}} = 3/2 - \frac{\bar{K} x^2 + O(x^2)}{m^2}, \quad (7)$$

where we define $x = s - m^2$, $K = (\alpha^2 f^2 \pi)/(6 \Lambda^2 \sin^2 \theta_W)$ and $\bar{K} = (11 \alpha^2 f^2 \bar{\pi}/(8 \Lambda^2 \sin^2 \theta_W)$. The result for the total cross section for the different multiplets is cross-checked with the CalcHEP [25] output of the model in Fig. 3.

### III. PRODUCTION CROSS SECTION VIA CONTACT INTERACTIONS

In this section we show the results for the production cross section in the case of contact interactions. The effective vertex is a four-fermion interaction and it is obtained after high energy modes of order $\Lambda$, the compositeness scale, have been integrated out. The underlying theory is indeed not specified and an effective Lagrangian is set up in order to study the interaction between excited fermions and SM particles. We consider the general contact interaction Lagrangian to be

$$\mathcal{L}_{CI} = \left( \frac{g^2}{2 \Lambda^2} \right) j^\mu j_\mu, \quad (8)$$

where the current reads [26]

$$j_\mu = (\eta \bar{f}_{L} \gamma_\mu f_{L} + \eta \bar{f}_{R} \gamma_\mu f_{R} + \eta' \bar{f}_{L}^{*} \gamma_\mu f_{L}^{*} + h.c.) + (L \rightarrow R). \quad (9)$$

The constants in front of each vector current are usually put equal to one in the literature. In the following we do not consider the right-handed Lagrangian term in (9) for simplicity. The resulting effective Lagrangian in $\mathcal{L}_{CI}$ is made of dimension six operators and hence two inverse powers of the new physics scale $\Lambda$ appear. According to the processes $a$ and $b$ displayed in Fig. 1 we need the current as follows

$$j_\mu = \left( \frac{g^2}{2 \Lambda^2} \right) \left[ \bar{\psi}_\nu(x) \gamma_\mu P_L \psi_e(x) + \bar{\psi}_e(x) \gamma_\mu P_L \psi_e(x) + h.c. \right], \quad (10)$$

where the fields $\psi_\nu$, $\psi_e$ and $\psi_E$ are the electron neutrino, electron and excited lepton respectively, whereas $P_L = (1 - \gamma^5)/2$ is the chiral projector. The corresponding Lagrangian reads

$$\mathcal{L}_{CI} = \left( \frac{g^2}{\Lambda^2} \right) \left[ \bar{\psi}_\nu(x) \gamma_\mu P_L \psi_e(x) \bar{\psi}_e(x) \gamma_\mu P_L \psi_e(x) + h.c. \right]. \quad (11)$$

Two identical particles are incoming as initial state, namely two electrons. Hence, we have to consider the interference between the diagrams $a$ and $b$ in Fig. 1. The exchange of the incoming electrons is taken into account by a relative sign between the matrix elements of the contributing processes. Therefore, the matrix element squared is

$$|\mathcal{M}|^2 = |\mathcal{M}_a - \mathcal{M}_b|^2 = |\mathcal{M}_a|^2 + |\mathcal{M}_b|^2 - 2 Re(\mathcal{M}_a \mathcal{M}_b^*). \quad (12)$$

By using trace technology and summing up the three different contributions according to eq. (12), the total cross section reads

$$\sigma = \left( \frac{g^2}{\Lambda^2} \right)^2 \frac{s}{4 \pi} \left( 1 - \frac{m^2}{s} \right)^2 = \left( \frac{s}{\Lambda^2} \right)^2 \frac{4 \pi}{s} \left( 1 - \frac{m^2}{s} \right)^2, \quad (13)$$

where in the last step we set $g^2 = 4 \pi$, again keeping the usual choice found in the literature [26]. In eq. (13) $m^2$ stands for the excited lepton mass and the Maldestam variable $s$ for the square of the collider energy. In the case of contact interactions there is no angular dependence in the cross section. Therefore, we just write down the result for the integrated total cross section. The model embedding doubly charged leptons in the contact interaction framework has been implemented in CalcHEP in 15.

### IV. STANDARD MODEL BACKGROUND AND LSD INvariant MASS DISTRIBUTION

In this section we consider the signatures produced by the decay of the unstable doubly charged lepton and we focus on a pure final lepton state by considering the decay $E^{\pm} \rightarrow W^{-} e^{+} \rightarrow e^{+} l^{\mp} \nu_l$. In particular, the decay cascade determines the following final state event
$e^-e^- \rightarrow e^-e^-\nu_e\bar{\nu}_e$, where we only consider the electron flavour for sake of simplicity.

Such final particle set may be obtained either via contact or gauge interactions involved in the excited lepton production and decay process. Therefore, there are four different production-decay combinations. As shown in [14], the contact interactions mechanism is always dominant for the production of $E^-$ whereas the decay exhibits a dependence on the relative values of the parameters ($m^*, \Lambda$). Since the highest energy expected at the ILC will be 1 TeV, the ratio $m^*/\Lambda$ stays rather low. Indeed, we consider the compositeness scale to be at least 5 TeV. In this case, the decay of the doubly charged lepton is mainly driven by gauge interactions whereas the contact interaction model is used for the production of the heavy exotic particle.

The final state particle, $e^-e^-\nu_e\bar{\nu}_e$, translates experimentally into a like sign dilepton (LSD) and missing transverse energy ($E_T$) signature, due to the undetectable neutrino and anti-neutrino. In order to shape the detection strategy of such a signal, an estimate of the backgrounds in the $e^-e^-$ beam setting is necessary. We consider here only the irreducible SM background by using the CalcHEP generator. The contribution of additional beyond SM physics is not taken into account in the present work. According to previous studies carried out in [14] [15], the LSD invariant mass is an appropriate kinematic distribution to look at to discriminate between the background and the signal. However, we study also different kinematic variables in order to optimize the signal strength over the background by establishing useful cuts at the level of the CalcHEP generator.

In total there are fourteen different background processes from the SM. Out of them, we select the four ones which have a higher cross section and dominate over the others. We list them as follows

\begin{align}
  e^-e^- &\rightarrow \gamma W W^* \rightarrow e^-e^-\nu_e\bar{\nu}_e \quad (14) \\
  e^-e^- &\rightarrow \gamma W^* \rightarrow e^-e^-\nu_e\bar{\nu}_e \quad (15) \\
  e^-e^- &\rightarrow \nu W W^* \rightarrow e^-e^-\nu_e\bar{\nu}_e \quad (16) \\
  e^-e^- &\rightarrow Z W W^* \rightarrow e^-e^-\nu_e\bar{\nu}_e \quad (17)
\end{align}

The intermediate particles in (14)-(17) are meant as internal propagating fields that radiate or decay, as one may see in Fig. 4 where we list the SM dominant background processes. We study the differences in the kinematic distributions of signal and background by means of CalcHEP. We consider the following kinematic variables: most energetic electron transverse momentum and pseudorapidity, less energetic electron transverse momentum and pseudorapidity and missing transverse energy. We expect that the transverse energy distribution is peaked to higher values in the signal with respect to the background. Indeed, the neutrino produced in association with the excited lepton has to balance the heavy exotic particle.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig4}
\caption{The diagrams show four of the SM background processes that we consider for a detailed kinematic analysis. They account for the higher cross sections out of the fourteen overall SM irreducible backgrounds. The internal propagating particles are used to label each process in (14)-(17).}
\end{figure}

In Fig. 8 we show the invariant LSD mass distribution for the signal and the background. Different values of the parameters ($m^*, \Lambda$) are considered and only the higher SM backgrounds are displayed. We add a fifth background process, namely $e^-e^- \rightarrow \gamma e Z^* \rightarrow e^-e^-\nu_e\bar{\nu}_e$, to show that the four processes in eqs. (14)-(17) are indeed the dominant ones. The other SM processes not shown in Fig. 8 are negligible and account for less than the 2% of the total background. In the upper panels the LSD invariant mass distribution is displayed with the base kinematic cuts taken into account as in table I. While the signal is evident in the case $\Lambda = 5 \text{ TeV}$, it is in turn scarcely visible already at $\Lambda = 8 \text{ TeV}$. In the lower panel we show the LSD invariant mass distribution after the improved cuts have been implemented (see table I). The background is rather reduced and the high mass values ($m^* \geq 0.8 \text{ GeV}$) are then more accessible despite the lower cross section for higher $m^*$ masses.

Finally we study the statistical significance for the signal at 3 and 5-sigma level. We address this aspect in order to assess the accessible parameter space ($m^*, \Lambda$) at linear colliders, at least in this particular beam setting and at the level of ideally reconstructed particles. At a given integrated luminosity $L$ and for any point in the parameter space ($m^*, \Lambda$), we can provide the expected number of events for the signal and the background as follows:

\begin{equation}
  N_s = L \sigma_s, \quad N_b = L \sigma_b,
\end{equation}

where the the cross section for the signal, $\sigma_s$, and the one for the background, $\sigma_b$, are provided by the CalcHEP.
Base Kinematic Cuts
\[ p_T(e^-) > 50 \text{ GeV} \quad |\eta(e^-)| < 2.5 \quad \Delta R(e^-, e^-) > 0.5 \]  
Improved Kinematic Cuts
\[ p_T^{\text{min}}(e^-) > 200 \text{ GeV} \quad -1 < \eta^{\text{max}}(e^-) < 2.5 \quad E_T > 200 \text{ GeV} \]

Table I. The base kinematic cuts and the optimized cuts are displayed. We adopt the first set in order to obtain the upper panel in Fig. 8 whereas the second set refers to the lower panel of the same figure.

\begin{tabular}{|c|c|}
\hline
\text{p} & \text{T} (\text{e}^-) > 50 \text{ GeV} \\
\hline
\text{p} & \text{T}^{\text{max}} (\text{e}^-) > 200 \text{ GeV} \\
\hline
\end{tabular}

\begin{tabular}{|c|c|}
\hline
\text{p} & \text{T} (\text{e}^-) < 2.5 \\
\hline
\text{p} & \text{T}^{\text{min}} (\text{e}^-) < 2.5 \\
\hline
\end{tabular}

\begin{tabular}{|c|c|}
\hline
\text{p} & \text{T} (\text{e}^-) > 0.5 \\
\hline
\text{p} & \text{T}^{\text{max}} (\text{e}^-) > 200 \text{ GeV} \\
\hline
\end{tabular}

\begin{tabular}{|c|c|}
\hline
\text{p} & \text{T} (\text{e}^-) < 2.5 \\
\hline
\text{p} & \text{T}^{\text{min}} (\text{e}^-) < 2.5 \\
\hline
\end{tabular}

FIG. 5. The kinematic variables for the signal and the processes in (14) and (15) are shown. With \( p_T^{\text{max(min)}} \) we label the highest (lowest) energetic electron transverse momentum distribution, and with \( \eta^{\text{max(min)}} \) we label the highest (lowest) energetic electron pseudorapidity. The model parameters are \( (m^* = 0.5 \text{ TeV}, \Lambda = 5 \text{ TeV}) \).

The statistical significance is then a function of two parameters, namely \( m^* \) and \( \Lambda \) through the expected number of events for the signal and the background in (18). Performing the scanning over the parameter space we can derive the experimental evidence region \( (S \geq 3) \) and experimental discovery region \( (S \geq 5) \). The result are shown in Fig. 5. We consider two different cases for the luminosity, \( L = 500 \text{ fb}^{-1} \) and \( L = 1000 \text{ fb}^{-1} \), and two energies of the colliding electrons, \( \sqrt{s} = 1 \text{ TeV} \) and \( \sqrt{s} = 3 \text{ TeV} \). This choice possibly corresponds to the nominal luminosity and energy for the ILC [16] and CLIC [17, 18] facilities.

V. CONCLUSIONS AN OUTLOOK

In the paper we discuss the production of heavy exotic doubly charged leptons in the framework of forthcoming linear colliders. In particular we focus on the beam setting \( e^-e^- \), that allows for the production of a
single doubly charged lepton instead of the corresponding pair production. Since the excited doubly charged lepton mass is expected to be heavy, the $e^-e^-$ beam configuration determines a wider mass parameter space to explore with respect to the $e^+e^-$ beam setting.

We consider the production of the heavy exotic lepton both within contact and gauge interactions. In the latter case we study in some detail the production cross section in relation with the different isospin multiplets ($I_W = 1$ and $I_W = 3/2$). In particular, we take into account the interference between the $t$ and $u$ channels and we provide the expression for the differential cross sections. The interference effect has not been previously evaluated and it is there for $E^{--} \not\in I_W = 3/2$. Despite the production via contact interaction mechanism dominates over the gauge interaction one, the additional $t-u$ interference term produces a sizable contribution to the cross section in the gauge mediated case. It amounts to a reduction of the production cross section by a factor of one third at $\sqrt{s} = 1$ TeV.

By considering the decay cascade $E^{--} \rightarrow W^- e^- \rightarrow \bar{\nu}_e e^- e^-$, the following final state particle set is studied: $e^- e^- \bar{\nu}_e \nu_e$. Experimentally it translates into a LSD pair and missing transverse energy. We study the LSD invariant mass distribution to assess the detection strategy of the signal in the linear collider and $e^-e^-$ beam setting. Several SM background processes are there, fourteen in total, and we do not take into account other new physics sources besides the excited doubly charged lepton. Four dominant SM processes are studied in some details and we perform an analysis of their kinematic distribution by means of CalcHEP. We then suggest a sample of kinematic cuts to discard background events whereas keeping the signal strength still high. We apply those cuts to all the remaining SM background processes. We derive by means of CalcHEP the number of expected signal and background events taking into account some improved cuts. All the SM background processes are considered at this stage. Therefore, we provide the 3 and 5-sigma statistical significance exclusion curves in the $(m^*, \Lambda)$ parameter space.

Finally, CalcHEP allows to study kinematic distributions for particles which are ideally reconstructed. In order to better establish the possibility to observe such exotic leptons at linear colliders, it would be desirable to introduce the effects of detectors like the efficiency and resolution reconstruction of the physical objects.

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FIG. 9. Luminosity curves in the parameter space \((m^*, \Lambda)\) at 3 and 5-sigma values of the statistical significance. We show both cases of \(\sqrt{s} = 1\) TeV and \(\sqrt{s} = 3\) TeV. The solid (dashed) lines refer to the 3 (5)-sigma value of the statistical significance.

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