

Probing the pair production of first-generation vectorlike leptons at future e^+e^- colliders

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This work explores the discovery potential of the first-generation weak-isosinglet vectorlike leptons, denoted by $E^\pm$, via pair production at future electron-positron colliders. Our analysis adopts a comprehensive framework that incorporates beam polarization configurations and leverages detailed detector simulations. We focus on two distinct multilepton signatures: the $2\ell + 2j + \cancel{E}_T$ and $3\ell + 2j + \cancel{E}_T$ final states ($\ell = e, \mu$). Both signatures arise from the decay $E^\pm \rightarrow Ze^\pm/W^\pm\nu_\ell$ and are distinguished by the decay patterns of the associated gauge bosons. By applying optimized selection criteria to both signal and background events, we establish exclusion sensitivities and discovery prospects across the vectorlike lepton mass spectrum. Our findings demonstrate that, for integrated luminosities of 25, 90, and 1000 fb⁻¹ at corresponding center-of-mass energies of 1, 1.5, and 3 TeV, the accessible mass range extends to approximately 490, 740, and 1440 GeV, respectively, which represents a substantial improvement over the detection limits of existing hadron collider experiments.

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I. INTRODUCTION

Vectorlike leptons (VLLs) are among the most promising candidates for physics beyond the Standard Model (BSM), appearing naturally in many theoretical extensions of the SM. They offer potential solutions to several fundamental problems in particle physics, including the hierarchy problem through new Higgs sector dynamics [1], viable dark matter candidates [2–5], electroweak (EW) vacuum stabilization [6,7], and explanations for some precision anomalies. The latter encompass the electron and muon $g - 2$ discrepancies [8–13] and observed deviations in the $W^\pm$ -boson mass [14,15]. The theoretical appeal of VLLs is further strengthened by their natural realization in extra-dimensional scenarios [16,17], supersymmetric frameworks [18–22], compositeness [23], and various other SM extensions [24–27].

A defining characteristic of VLLs is indeed their vectorlike nature: Both left- and right-handed components

transform identically under the SM gauge group. This property allows for gauge-invariant mass terms independent of the Higgs mechanism, distinguishing them from chiral SM fermions. Consequently, VLLs face less stringent constraints from EW precision observables [28,29] and Higgs sector measurements [30–32], while generating rich collider phenomenology (see, e.g., Refs. [33–56]). VLLs that mix with first-, second-, or third-generation SM leptons ($\ell = e, \mu, \tau$) are referred to as vectorlike electrons, muons, or tauons, respectively. This work focuses specifically on the first-generation scenario, so that our VLL is denoted by $E^\pm$, which exhibits unique phenomenological features compared to its heavier counterparts. Experimental searches at the Large Hadron Collider (LHC) have primarily targeted VLL pair production with decays involving third-generation leptons and gauge bosons [57–63]. Recent ATLAS results [64] establish stringent 95% confidence level mass limits for vectorlike electrons (muons), excluding doublet scenarios up to 1220 GeV (1270 GeV) and singlet scenarios up to 320 GeV (400 GeV). These limits highlight the particular challenge in detecting singlet VLLs at hadron colliders.

In fact, the search for weak-isosinglet VLLs faces significant challenges at hadron colliders because of large QCD backgrounds [65], motivating the exploration of future e^+e^- colliders such as the International Linear

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Collider (ILC) [66,67] and Compact Linear Collider (CLIC) [68,69], which offer clean experimental conditions for VLL searches [70–78]. This work examines the pair production of an electron-type weak-isosinglet VLL ($E^\pm$) with minimal mixing to SM electrons at c.m. energies of $\sqrt{s} = 1, 1.5$, and 3 TeV, focusing on the dominant decay channels $E^\pm \rightarrow W^\pm \nu_e$ and $E^\pm \rightarrow Z^\pm e$. By performing comprehensive signal and background simulations, we establish 2σ exclusion limits and 5σ discovery reaches, demonstrating that e^+e^- colliders can probe $E^\pm$ masses well beyond current LHC sensitivities, approaching the kinematic threshold at each energy stage and exploring previously inaccessible parameter space.

This paper is organized as follows. Section II introduces the theoretical framework for the singlet VLL model, in order to specify its interactions with SM particles and to compute the pair-production cross sections at e^+e^- colliders, including the effects of polarized beams. Section III presents a detailed collider analysis for the chosen final states, evaluating signals and backgrounds. We conclude with a summary in Sec. IV.

II. SINGLET VLL MODEL FRAMEWORK

A. Theoretical setup

We consider a minimal extension of the SM by introducing a weak-isosinglet VLL, denoted $E^\pm$, as mentioned, which mixes with the first-generation SM leptons. Under the SM gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$, the VLL transforms as

$$E_L, E_R^\dagger \sim (\mathbf{1}, \mathbf{1}, -1), \quad (1)$$

where both chiral components share the same gauge quantum numbers, permitting a gauge-invariant Dirac mass term.

In the singlet VLL model for the first generation, the fermion mass terms and electron mixing with the Standard Model lepton can be obtained from the Lagrangian written in two-component fermion form as

$$-\mathcal{L} = m_E E \bar{E} + \epsilon H L_e \bar{E} + y_e H L_e \bar{e} + \text{c.c.}, \quad (2)$$

where H is the SM Higgs complex doublet scalar field, $L_e = (e, \nu_e)_L$ is the SM first-family lepton doublet in the gauge eigenstate basis, y_e is the SM electron Yukawa coupling, and ϵ is the mixing Yukawa coupling. The field E ($\bar{E}$) denotes the left-handed (right-handed) two-component spinor of the vectorlike electron.

After EW symmetry breaking, the mass matrix for the charged leptons in the basis (e, E) is

$$\mathcal{M} = \begin{pmatrix} y_e v & 0 \\ \epsilon v & M \end{pmatrix}, \quad (3)$$

where $v \approx 174$ GeV is the Higgs vacuum expectation value. The mixing between the SM electron and the VLL is characterized by a small mixing angle θ_L , given to leading order (LO) by

$$\sin \theta_L \approx \frac{\epsilon v}{M}. \quad (4)$$

The physical mass eigenvalues are

$$m_e \approx y_e v \left(1 - \frac{\epsilon^2 v^2}{2M^2} + \dots \right), \quad (5)$$

$$M_E \approx M \left(1 + \frac{\epsilon^2 v^2}{2M^2} + \dots \right). \quad (6)$$

The mixing angle is severely constrained by current experimental data from EW precision tests, Z-pole observables, and direct VLL searches. Recent LHC results [64] require $\sin \theta \lesssim 0.03$ for VLL masses in the few hundred GeV range, while low-energy precision measurements impose even tighter constraints at lower masses. In this work, we adopt a value of $\epsilon = 0.01$. This choice is sufficiently small to enable a perturbative treatment of mixing effects while being large enough to ensure the prompt decay of $E^\pm$ within the detector volume [44]. For smaller mixing parameters that induce displaced decays, dedicated searches targeting long-lived charged particles become applicable, as investigated in Refs. [53,54,79].

B. Pair production at e^+e^- colliders

The pair production of singlet VLLs proceeds primarily through s -channel exchange of EW gauge bosons. The LO interaction Lagrangian for the vectorlike electron $E^\pm$, retaining terms up to $\mathcal{O}(\epsilon)$, is given by

$$\mathcal{L}_{\text{int}} = \frac{gs_W^2}{c_W} Z_\mu (E^\dagger \bar{\sigma}^\mu E - \bar{E}^\dagger \bar{\sigma}^\mu \bar{E}) - e A_\mu (E^\dagger \bar{\sigma}^\mu E - \bar{E}^\dagger \bar{\sigma}^\mu \bar{E}), \quad (7)$$

where e denotes the electromagnetic coupling, g is the $SU(2)_L$ gauge coupling, and θ_W is the Weinberg angle plus $s_W \equiv \sin \theta_W$ and $c_W \equiv \cos \theta_W$ with $e = gs_W$.

For polarized e^+e^- collisions with beam polarizations P_{e^-} and P_{e^+} , the partonic cross section takes the form

$$\bar{\sigma}(e^+e^- \rightarrow E^+E^-) = \frac{2\pi\alpha^2}{3} (\hat{s} + 2m_E^2) \sqrt{1 - 4m_E^2/\hat{s}} [|a_L|^2(1 - P_{e^-})(1 + P_{e^+}) + |a_R|^2(1 + P_{e^-})(1 - P_{e^+})], \quad (8)$$

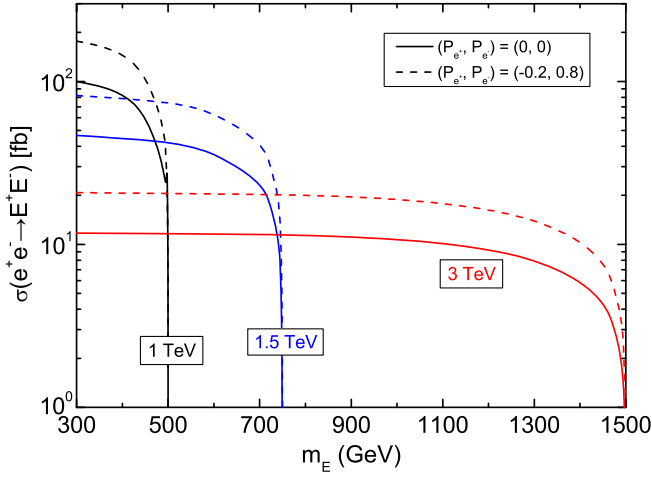


FIG. 1. Production cross sections for $e^+e^- \rightarrow E^+E^-$ as a function of m_E at $\sqrt{s} = 1, 1.5$, and 3 TeV, using the beam polarization configuration $(P_{e^+}, P_{e^-}) = (-0.2, 0.8)$.

with the chiral amplitude coefficients

$$a_L = \frac{1}{\hat{s}} + \frac{s_W^2 - 1/2}{c_W^2} \frac{1}{\hat{s} - M_Z^2}, \quad a_R = \frac{1}{\hat{s}} + \frac{s_W^2}{c_W^2} \frac{1}{\hat{s} - M_Z^2}. \quad (9)$$

Our analysis employs a single optimized beam polarization configuration across all collider scenarios, using +80% right-handed electrons and -20% left-handed positrons. This choice follows the technical design reports for future linear colliders [66] and maximizes the production cross section due to the hierarchy $|a_L| < |a_R|$ at high energies. The polarization values adhere to the standard convention where $P = +1$ ($P = -1$) corresponds to a fully right-handed (left-handed) particle.

The production cross sections for E^+E^- pairs, $\sigma(e^+e^- \rightarrow E^+E^-)$, are plotted as a function of m_E in Fig. 1 for three proposed collider configurations: $\sqrt{s} = 1$ (ILC), 1.5, and 3 TeV (CLIC). A distinct threshold behavior is observed, while optimized beam polarization yields a substantial enhancement in the cross section. With such optimization, the cross section reaches approximately 114, 20, and 7.8 fb for m_E values of 450 GeV, 740 GeV, and 1.45 TeV, respectively, at the corresponding c.m. energies.

C. Decay properties

The singlet first-generation VLL $E^\pm$ predominantly decays into SM particles through its small mixing with the SM electron. The main decay channels are the charged-gauge-current decay $E^\pm \rightarrow W^\pm \nu_e$, the neutral-gauge-current decay $E^\pm \rightarrow Z e^\pm$, and the SM Higgs-mediated decay $E^\pm \rightarrow h e^\pm$. The corresponding partial decay widths are given by

$$\Gamma(E^\pm \rightarrow W^\pm \nu_e) = \frac{e^2}{32\pi} m_E (1 + 2r_W)(1 - r_W)^2, \quad (10)$$

$$\Gamma(E^\pm \rightarrow Z e^\pm) = \frac{e^2}{64\pi} m_E (1 + 2r_Z)(1 - r_Z)^2, \quad (11)$$

$$\Gamma(E^\pm \rightarrow h e^\pm) = \frac{e^2}{64\pi} m_E (1 - r_h)^2, \quad (12)$$

where $r_X = m_X^2/m_E^2$ for $X = W^\pm, Z, h$.

In the high-mass regime ($m_E \gg m_W, m_Z, m_h$), the branching ratios (BRs) approach the characteristic pattern

$$\text{BR}(E \rightarrow W^\pm \nu_e) : \text{BR}(E \rightarrow Z e^\pm) : \text{BR}(E \rightarrow h e^\pm) = 2 : 1 : 1, \quad (13)$$

providing a distinctive signature for VLL identification and discrimination from other BSM scenarios.

III. COLLIDER ANALYSIS AND SIGNAL SENSITIVITY

We assess the discovery potential through comprehensive Monte Carlo (MC) simulations of both the signal and relevant SM backgrounds. The analysis focuses on the dominant decay channels of the singlet vectorlike electron: $E^\pm \rightarrow W^\pm \nu_e$ and $E^\pm \rightarrow Z e^\pm$. Considering the subsequent W -boson decays $W^\pm \rightarrow jj$ and $W^\pm \rightarrow \ell^\pm \nu_\ell$ as well as Z -boson decays $Z \rightarrow \ell^+ \ell^-$ and $Z \rightarrow jj$, the event samples for our search are categorized into the following two topologies:

- (i) *case 1.* $e^+e^- \rightarrow E^+E^- \rightarrow Z(\rightarrow jj)e^+W^-(\rightarrow \ell^-\bar{\nu}_\ell)\nu_e \rightarrow 2\ell + 2j + \cancel{E}_T$; and
- (ii) *case 2.* $e^+e^- \rightarrow E^+E^- \rightarrow Z(\rightarrow \ell^+\ell^-)e^+W^-(\rightarrow jj)\nu_e \rightarrow 3\ell + 2j + \cancel{E}_T$.

where $\ell = e, \mu, j$ denotes light-flavor jets and $\cancel{E}_T$ represents missing transverse energy. The corresponding Feynman diagrams are shown in Fig. 2.

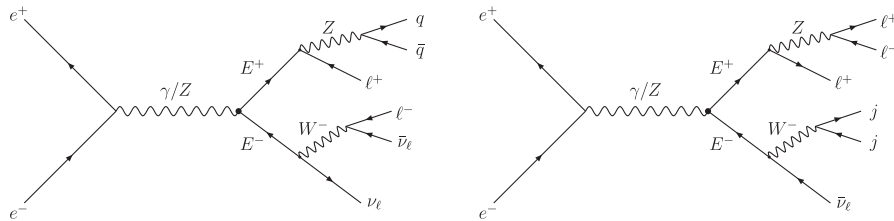


FIG. 2. Characteristic Feynman diagrams illustrating the signal processes for cases 1 (left) and 2 (right) discussed in the text.

TABLE I. SM background cross sections under the beam polarization configuration $(P_{e^+}, P_{e^-}) = (-0.2, 0.8)$. The values in parentheses denote the cross section ratio $\sigma_{\text{pol}}/\sigma_{\text{unpol}}$.

Process	Cross section (fb)		
	$\sqrt{s} = 1 \text{ TeV}$	$\sqrt{s} = 1.5 \text{ TeV}$	$\sqrt{s} = 3 \text{ TeV}$
$e^+e^- \rightarrow ZW^+W^-$	9.95 (0.17)	10.72 (0.21)	6.73 (0.21)
$e^+e^- \rightarrow t\bar{t}Z$	2.70 (0.59)	1.91 (0.54)	0.88 (0.53)
$e^+e^- \rightarrow t\bar{t}$	130 (0.78)	53 (0.70)	13.5 (0.70)

Signal and SM background events are generated at LO using MadGraph5_aMC@NLO [80], followed by parton showering and hadronization with Pythia 8.20 [81]. Detector effects are simulated using Delphes 3.4.2 [82] with the international large detector card for ILC studies and the CLIC detector card [83] for CLIC studies. The event analysis is carried out within the MadAnalysis5 framework [84,85].

To test the scope of future e^+e^- colliders in testing our VLL scenario, we choose three benchmark configurations of it, with the $E^\pm$ mass spanning values from the EW to the TeV scale. They are identified as follows, depending on the collider c.m. energy:

- (i) $m_E = 350, 400, \text{ and } 450 \text{ GeV}$ at $\sqrt{s} = 1 \text{ TeV}$;
- (ii) $m_E = 500, 600, \text{ and } 700 \text{ GeV}$ at $\sqrt{s} = 1.5 \text{ TeV}$;
- (iii) $m_E = 800, 1100, \text{ and } 1400 \text{ GeV}$ at $\sqrt{s} = 3 \text{ TeV}$.

The dominant SM backgrounds include $ZW^\pm$, $t\bar{t}Z$, and $t\bar{t}$ production. Table I summarizes their cross sections including polarization effects at e^+e^- colliders, with ratios $\sigma_{\text{pol}}/\sigma_{\text{unpol}}$ given in parentheses. We find that the adopted beam polarization setup effectively suppresses SM backgrounds, thereby enhancing the sensitivity to our VLL signals.

The object reconstruction adopts the following baseline selection criteria:

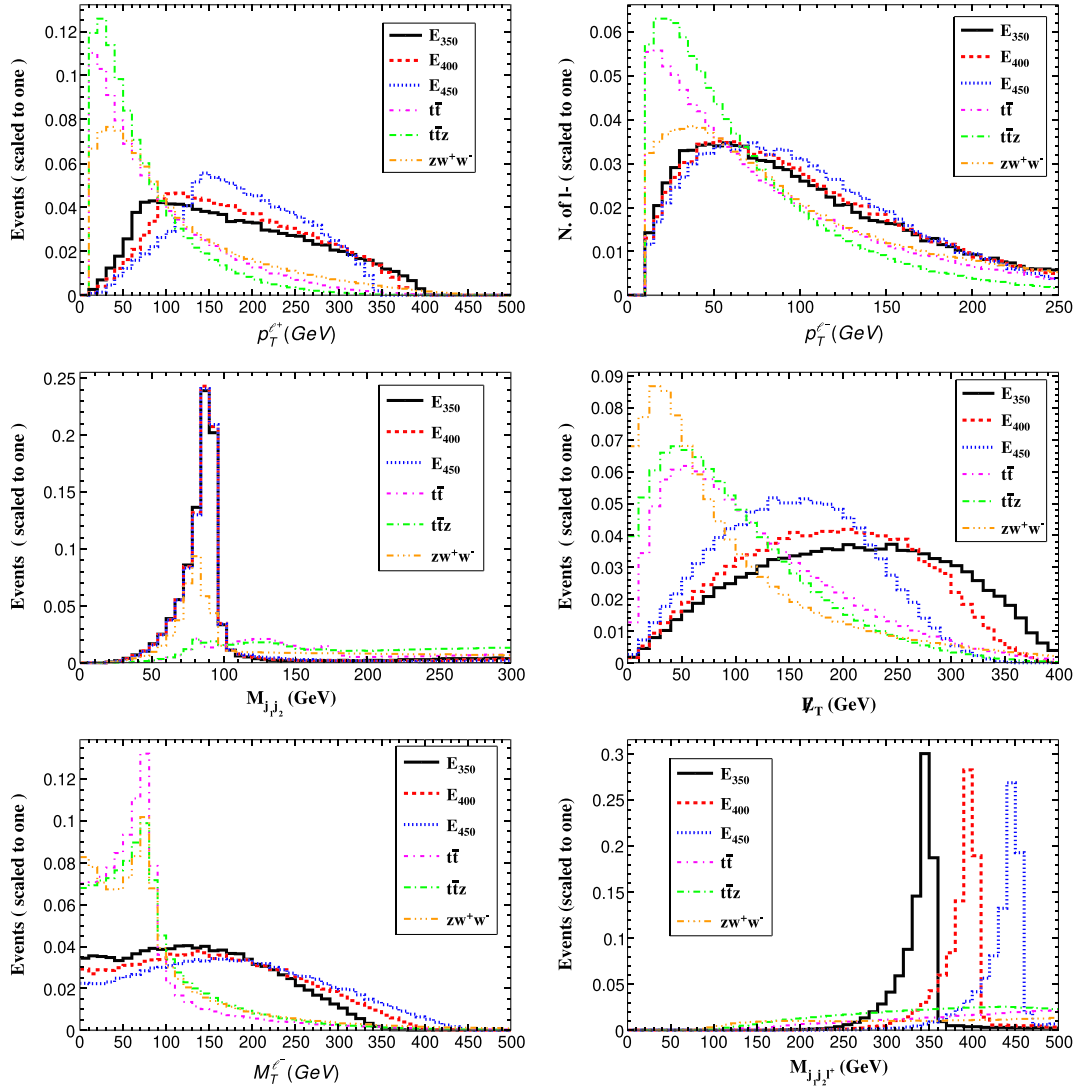
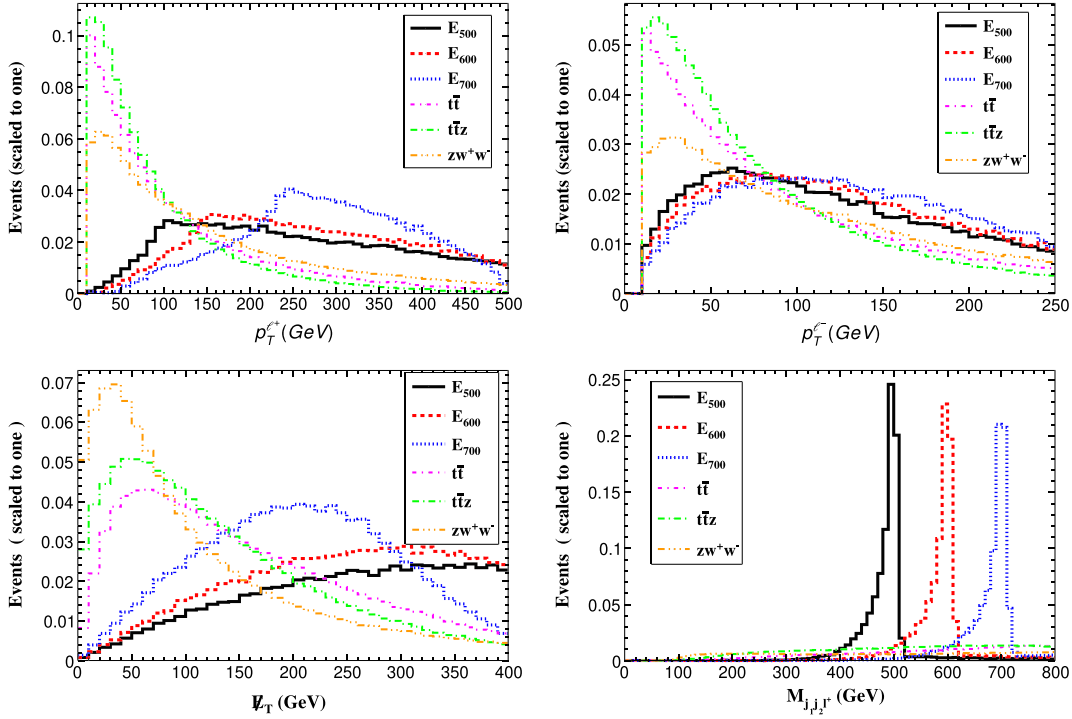


FIG. 3. Comparison of normalized distributions between signal processes and relevant SM backgrounds at $\sqrt{s} = 1 \text{ TeV}$ for case 1.

FIG. 4. The same as Fig. 3 but for $\sqrt{s} = 1.5$ TeV.

$$p_T^{\ell/j} > 10 \text{ GeV}, \quad |\eta_{\ell/j}| < 3, \quad \Delta R_{xy} > 0.4, \quad (14)$$

where $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ represents the spatial separation in the $\eta - \phi$ plane and the indices x and y refer to different final state particles, such as leptons and jets.

A. Case 1: $2\ell + 2j + \cancel{E}_T$ analysis

For the $2\ell + 2j + \cancel{E}_T$ signal channel (case 1), the dominant SM backgrounds stem from $e^+e^- \rightarrow ZW^+W^-$ and $e^+e^- \rightarrow t\bar{t}$ production. Signal events are characterized by two opposite-sign leptons ℓ_1 and ℓ_2 that are explicitly nonresonant with the Z boson, along with at least two jets consistent with a Z -boson decay. All jets are treated generically, without distinguishing between b jets and light jets. Furthermore, for the decay chain $E^- \rightarrow W^- (\rightarrow \ell^- \bar{\nu}_\ell) \nu_e$ and $E^+ \rightarrow Z (\rightarrow jj) e^+$ (and charged conjugate), the invariant mass $M_{j_1 j_2 e^+}$ can be utilized to reconstruct distinctive mass peaks.

Based on the distinct kinematic features of signal and background events, we show normalized differential distributions in Figs. 3–5 for the aforementioned signal benchmarks. The distributions are compared with those from the dominant SM backgrounds and include the following observables: the transverse momenta of the two leading leptons $p_T(\ell_1, \ell_2)$, the dijet invariant mass $M_{j_1 j_2}$, the missing transverse energy $\cancel{E}_T$, the reconstructed VLL mass $M_{j_1 j_2 e^+}$, and the transverse mass $M_T^{\ell^-}$. While the hadronic Z boson is typically reconstructed from dijet events, in high-energy

environments such as the $\sqrt{s} = 3$ TeV scenario, its hadronic decay usually produces a highly boosted single jet rather than a resolved dijet event, prompting the additional inclusion of the transverse momentum $p_T^{j_1}$ and invariant mass M_{j_1} of the leading fat jet. These kinematic observables provide effective discrimination between signal and background processes, particularly through the characteristic VLL mass peaks and distinctive missing transverse energy patterns inherent to the weak-isosinglet VLL signature.

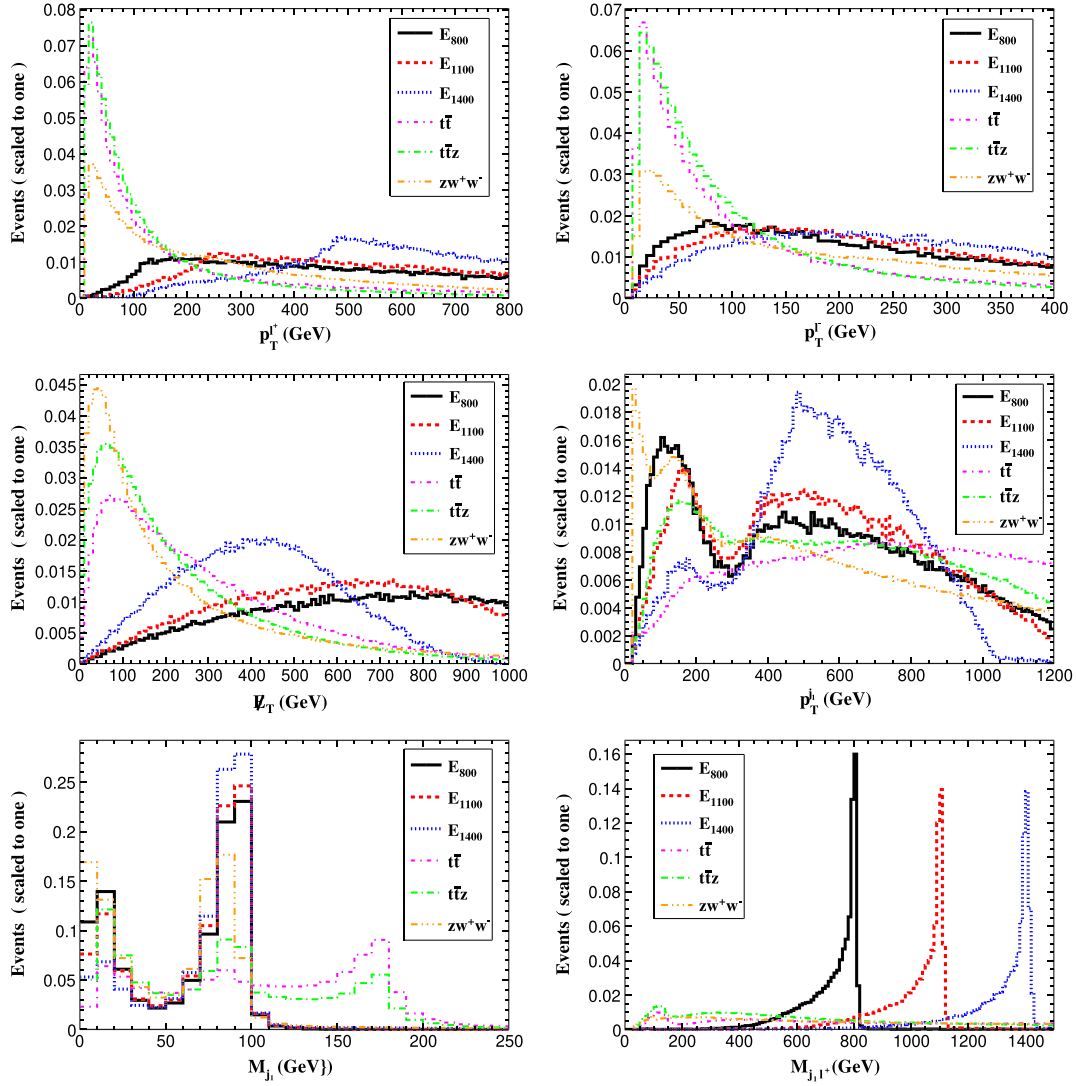
The event selection strategy employs three sequential cut stages.

(i) Cut 1: lepton selection.

- Selection of exactly two isolated leptons (e or μ) with opposite electric charges.
- Positive lepton transverse momentum thresholds: $p_T^{\ell^+} > 50$ GeV at $\sqrt{s} = 1$ TeV, > 100 GeV at 1.5 TeV, and > 160 GeV at 3 TeV.
- Negative lepton transverse momentum thresholds: $p_T^{\ell^-} > 25$ GeV at $\sqrt{s} = 1$ TeV, > 50 GeV at 1.5 TeV, and > 80 GeV at 3 TeV.
- Z -boson veto: $|M_{\ell\ell} - m_Z| > 10$ GeV.

(ii) Cut 2: missing transverse energy and transverse mass requirements.

- Missing transverse energy thresholds: $\cancel{E}_T > 100$ GeV at $\sqrt{s} = 1$ TeV, > 150 GeV at 1.5 TeV, and > 200 GeV at 3 TeV.
- Transverse mass requirement: $M_T(\ell^-) > 100$ GeV (applied uniformly across all energy configurations).

FIG. 5. The same as Fig. 3 but for $\sqrt{s} = 3$ TeV.(iii) *Cut 3: invariant mass selection.*

- For $\sqrt{s} = 1$ and 1.5 TeV: requirement of at least two jets with dijet invariant mass $|M_{jj} - m_Z| < 20$ GeV, combined with minimum $M_{jj\ell^+}$ thresholds of > 300 GeV at 1 TeV and > 400 GeV at 1.5 TeV.
- For $\sqrt{s} = 3$ TeV: requirement of at least one fat jet with $p_T^{j_1} > 300$ GeV and $60 \text{ GeV} < M_{j_1} < 110 \text{ GeV}$,

along with a minimum $M_{j_1\ell^+}$ threshold of > 600 GeV.

The cutflow results for our signal benchmarks with the three chosen E masses and dominant SM backgrounds are summarized in Tables II–IV for c.m. energies of 1, 1.5, and 3 TeV, respectively. The cross sections after each sequential selection are computed as $\sigma_{\text{cut}} = \sigma_0 \times \epsilon_{\text{cut}}$, where σ_0 denotes the initial cross section and ϵ_{cut} represents the

TABLE II. Cross sections (in fb) for our three signal benchmarks (with different m_E) and SM backgrounds in case 1 at $\sqrt{s} = 1$ TeV. Values in parentheses show the selection efficiency after the corresponding cut is applied.

Cuts	Signal (m_E in GeV)			Background		
	350	400	450	$t\bar{t}$	$t\bar{t}Z$	ZW^+W^-
Basic	2.97	2.57	1.95	40	0.97	3.63
Cut 1	1.86 (61%)	1.62 (61%)	1.23 (61%)	1.87 (4.7%)	0.037 (3.8%)	0.20 (5.5%)
Cut 2	1.07 (35%)	0.98 (37%)	0.76 (38%)	0.38 (1.0%)	0.008 (0.8%)	0.032 (0.9%)
Cut 3	0.64 (21%)	0.63 (24%)	0.52 (26%)	5.4×10^{-3} (0.014%)	4.4×10^{-4} (0.045%)	0.01 (0.3%)

TABLE III. The same as Table II but for $\sqrt{s} = 1.5$ TeV.

Cuts	Signal (m_E in GeV)			Background		
	500	600	700	$t\bar{t}$	$t\bar{t}Z$	ZW^+W^-
Basic	1.26	1.08	0.69	12.7	0.63	3.53
Cut 1	0.67 (51%)	0.62 (55%)	0.41 (56%)	0.26 (2.0%)	0.01 (1.6%)	0.14 (4.0%)
Cut 2	0.43 (33%)	0.42 (37%)	0.27 (37%)	0.04 (0.3%)	0.002 (0.3%)	0.02 (0.6%)
Cut 3	0.22 (17%)	0.21 (19%)	0.15 (21%)	5.8×10^{-4} (0.005%)	7.8×10^{-5} (0.012%)	4.6×10^{-3} (0.13%)

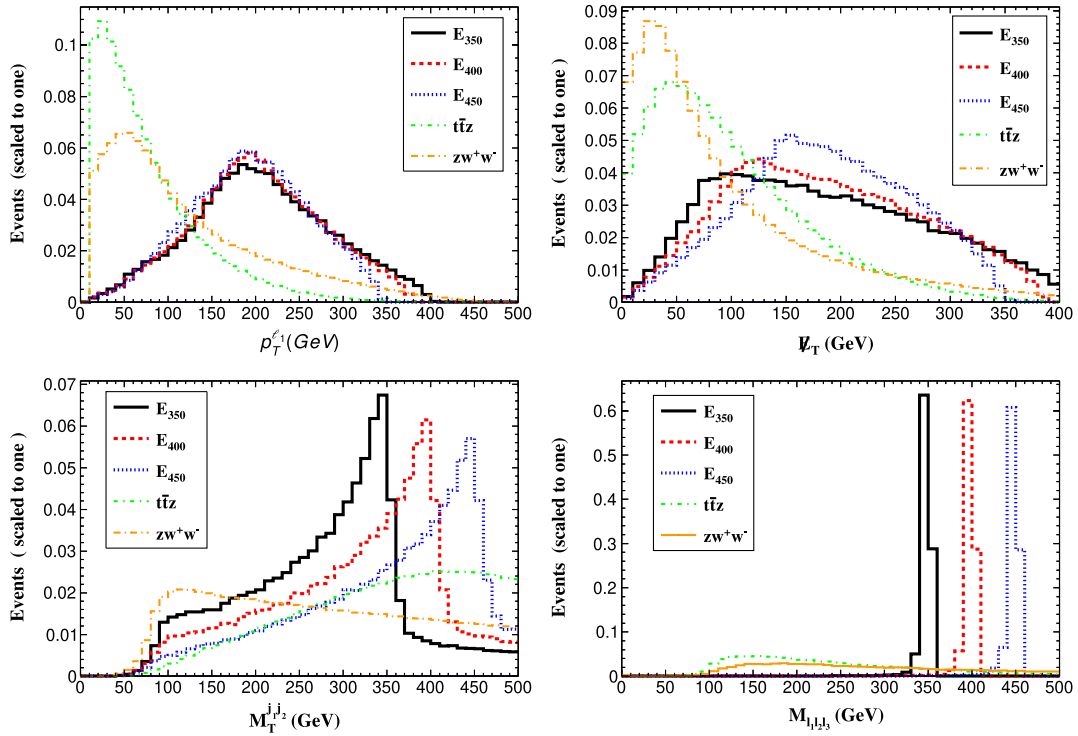
TABLE IV. The same as Table II but for $\sqrt{s} = 3$ TeV.

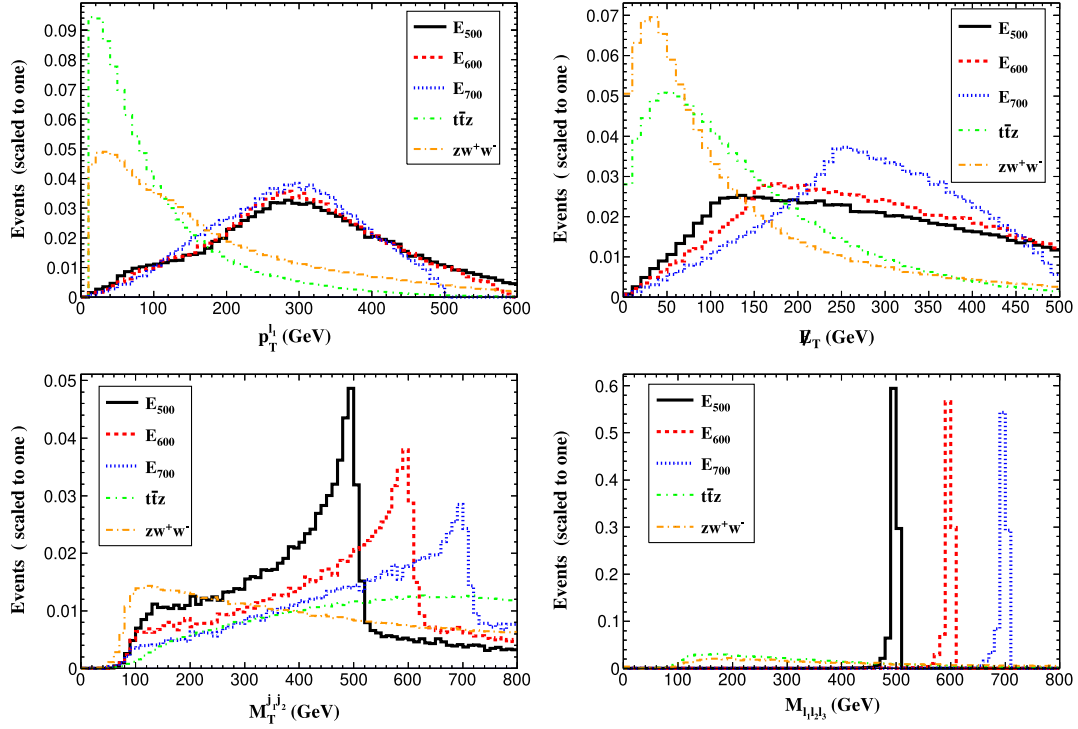
Cuts	Signal (m_E in GeV)			Background		
	800	1100	1400	$t\bar{t}$	$t\bar{t}Z$	ZW^+W^-
Basic	0.32	0.28	0.17	2.82	0.28	2.15
Cut 1	0.14 (41%)	0.14 (47%)	0.086 (49%)	0.037 (1.3%)	0.003 (1.1%)	0.074 (3.4%)
Cut 2	0.10 (30%)	0.10 (35%)	0.058 (33%)	0.0083 (0.29%)	0.00078 (0.28%)	0.011 (0.51%)
Cut 3	0.058 (17%)	0.068 (23%)	0.046 (26%)	8.6×10^{-4} (0.03%)	2.2×10^{-4} (0.079%)	5.1×10^{-3} (0.24%)

cumulative efficiency up to that stage. The efficiency for each individual cut is determined from the ratio of successive cross section values. Upon completion of the full selection procedure, the total SM background cross sections are suppressed to 3.3×10^{-3} fb at $\sqrt{s} = 1$ TeV, 1.5×10^{-3} fb at $\sqrt{s} = 1.5$ TeV, and 0.9×10^{-3} fb at $\sqrt{s} = 3$ TeV, confirming efficient background rejection across all considered collision energies.

B. Case 2: $3\ell + 2j + \cancel{E}_T$ analysis

The dominant SM backgrounds for the $3\ell + 2j + \cancel{E}_T$ final state (case 2) are $e^+e^- \rightarrow ZW^+W^-$ and $e^+e^- \rightarrow t\bar{t}Z$. In signal events, the highest- p_T isolated lepton (ℓ_1) originates from the decay $E^\pm \rightarrow Ze^\pm$, while an opposite-sign same-flavor lepton pair (ℓ_2, ℓ_3) comes from the Z-boson decay whereas the two jets arise predominantly from hadronic $W^\pm$ -boson decays. Reconstructible mass

FIG. 6. Normalized distributions for the signals and relevant SM backgrounds at $\sqrt{s} = 1$ TeV for case 2.

FIG. 7. The same as Fig. 6 but for $\sqrt{s} = 1.5$ TeV.

peaks emerge in $M_{\ell_1\ell_2\ell_3}$ and $M_T^{j_1j_2}$ for the processes $E^\mp \rightarrow W^\mp \nu_e$ and $E^\pm \rightarrow Ze^\pm$. At $\sqrt{s} = 3$ TeV, the W boson from heavy $E^\pm$ decay is highly boosted, causing its hadronic decay products to merge into a single fat jet; accordingly, the transverse momentum and invariant mass distributions of the leading fat jet j_1 are included in the analysis.

Based on the kinematic differences between signal and background processes, we show in Figs. 6–8 the differential distributions for the signals and relevant SM backgrounds. These observables offer distinctive features for signal identification and background suppression.

The event selection is performed through three sequential cut stages.

(i) *Cut 1: lepton selection.*

- Exactly three isolated leptons (e or μ) are required: $N_\ell = 3$.
- The leading lepton must satisfy the transverse momentum thresholds of $p_T^{\ell_1} > 120$ GeV at $\sqrt{s} = 1$ TeV, > 150 GeV at 1.5 TeV, and > 250 GeV at 3 TeV.
- At least one opposite-sign same-flavor lepton pair must be consistent with a Z -boson decay: $|M_{\ell\ell} - m_Z| < 10$ GeV.

(ii) *Cut 2: missing transverse energy and jet requirements.*

- The missing transverse energy must satisfy $\cancel{E}_T > 80$ GeV at $\sqrt{s} = 1$ TeV, > 100 GeV at 1.5 TeV, and > 300 GeV at 3 TeV.

- For $\sqrt{s} = 1$ and 1.5 TeV: the dijet transverse mass must exceed 250 and 350 GeV, respectively.

- For $\sqrt{s} = 3$ TeV: at least one fat jet is required with $p_T^{j_1} > 300$ GeV and invariant mass $60 \text{ GeV} < M_{j_1} < 110$ GeV.

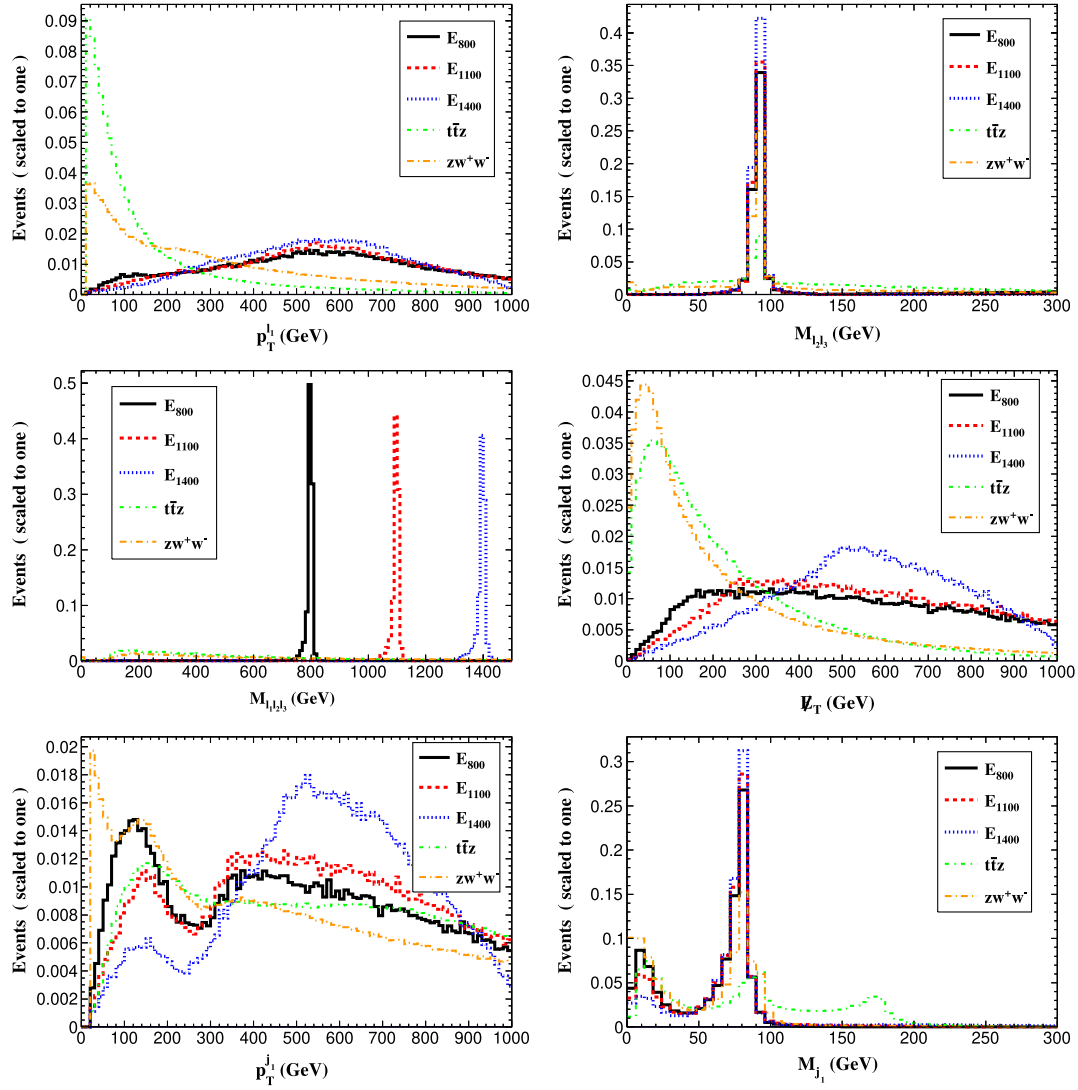
(iii) *Cut 3: tripleton invariant mass selection.*

- The minimum requirement for the tripleton invariant mass is $M_{\ell_1\ell_2\ell_3} > 300$ GeV at $\sqrt{s} = 1$ TeV, $M_{\ell_1\ell_2\ell_3} > 450$ GeV at $\sqrt{s} = 1.5$ TeV, and $M_{\ell_1\ell_2\ell_3} > 600$ GeV at $\sqrt{s} = 3$ TeV.

The cutflow data in Tables V–VII detail the evolution of cross sections and cumulative selection efficiencies for both the usual three signal benchmarks and the dominant SM backgrounds ($t\bar{t}Z$ and ZW^+W^-) in case 2 at c.m. energies of 1, 1.5, and 3 TeV, respectively, revealing that the signal efficiencies remain relatively stable (approximately 8%–20% after full selection) and are generally higher for heavier masses. In contrast, the background efficiencies are dramatically suppressed by several orders of magnitude, falling to as low as 10^{-5} for $t\bar{t}Z$ and 10^{-4} for ZW^+W^- after the final selection, thereby underscoring the exceptional effectiveness of the sequential cuts in enhancing the signal-to-background ratio.

C. Statistical analysis

The discovery ($\mathcal{Z}_{\text{disc}}$) and exclusion ($\mathcal{Z}_{\text{excl}}$) significances are calculated following the method in Ref. [86]:

FIG. 8. The same as Fig. 6 but for $\sqrt{s} = 3$ TeV.

$$\mathcal{Z}_{\text{disc}} = \sqrt{2 \left[(s+b) \ln \left(1 + \frac{s}{b} \right) - s \right]},$$

$$\mathcal{Z}_{\text{excl}} = \sqrt{2 \left[s - b \ln \left(1 + \frac{s}{b} \right) \right]}, \quad (15)$$

where s and b represent the expected numbers of signal and background events, respectively, for a given integrated luminosity.

TABLE V. Cross sections (in fb) for our three signal benchmarks (with different m_E) and SM backgrounds in case 2 at $\sqrt{s} = 1$ TeV. Values in parentheses show the selection efficiency after the corresponding cut is applied.

Cuts	Signal (m_E in GeV)			Background	
	350	400	450	$t\bar{t}Z$	ZW^+W^-
Basic	1.82	1.58	1.19	0.98	3.63
Cut 1	0.55 (30%)	0.48 (30%)	0.36 (30%)	0.0048 (0.17%)	0.036 (0.35%)
Cut 2	0.20 (11%)	0.22 (13.6%)	0.20 (16.7%)	3.3×10^{-4} (0.012%)	0.0034 (0.034%)
Cut 3	0.20 (11%)	0.22 (13.6%)	0.20 (16.7%)	1.2×10^{-4} (0.0046%)	0.002 (0.02%)

The combined sensitivity for both 2σ exclusion and 5σ discovery is presented in Fig. 9, which displays the required integrated luminosity as a function of m_E for both final states considered at $\sqrt{s} = 1, 1.5$, and 3 TeV. The contours clearly demonstrate that the integrated luminosity requirement grows gradually with increasing m_E and exhibits a steep rise near the kinematic threshold, mirroring the rapid decline in signal cross section as m_E approaches the

TABLE VI. The same as Table V but for $\sqrt{s} = 1.5$ TeV.

Cuts	Signal (m_E in GeV)			Background	
	500	600	700	$t\bar{t}Z$	ZW^+W^-
Basic	0.78	0.66	0.42	0.63	3.58
Cut 1	0.24 (30%)	0.20 (30%)	0.14 (33%)	0.0029 (0.15%)	0.035 (0.34%)
Cut 2	0.066 (8.3%)	0.068 (10%)	0.054 (12.5%)	6.4×10^{-5} (0.0034%)	0.0034 (0.017%)
Cut 3	0.066 (8.3%)	0.067 (10%)	0.054 (12.5%)	2.2×10^{-5} (0.0012%)	0.002 (0.01%)

TABLE VII. The same as Table V but for $\sqrt{s} = 3$ TeV.

Cuts	Signal (m_E in GeV)			Background	
	800	1100	1400	$t\bar{t}Z$	ZW^+W^-
Basic	0.19	0.17	0.10	0.28	2.17
Cut 1	0.055 (28%)	0.048 (28%)	0.032 (30%)	0.0015 (0.17%)	0.02 (0.3%)
Cut 2	0.023 (12%)	0.025 (14%)	0.021 (20%)	8.7×10^{-5} (0.01%)	0.0022 (0.032%)
Cut 3	0.023 (12%)	0.025 (14%)	0.021 (20%)	5.0×10^{-5} (0.0057%)	0.0013 (0.019%)

production limit. Case 2 consistently demands higher integrated luminosity compared to case 1 for both exclusion and discovery sensitivities. The $2\ell + 2j + \cancel{E}_T$ final state proves to be especially promising for probing singlet vectorlike leptons of electron flavor at future e^+e^- colliders. In particular, at $\sqrt{s} = 1$ TeV, masses up to $m_E \lesssim 490$ GeV can be explored with 25 fb^{-1} ; at $\sqrt{s} = 1.5$ TeV, the mass reach extends to $m_E \lesssim 740$ GeV with 90 fb^{-1} ; while at $\sqrt{s} = 3$ TeV masses up to $m_E \lesssim 1440$ GeV become accessible with 1000 fb^{-1} . The $3\ell + 2j + \cancel{E}_T$

signature can instead be used for signal consolidation purposes.

IV. SUMMARY

The clean experimental environment of high-energy e^+e^- colliders, together with beam polarization capabilities and well-defined initial states, offers distinct advantages in searches for VLLs over hadronic environments. In this work, we have performed a comprehensive analysis of the

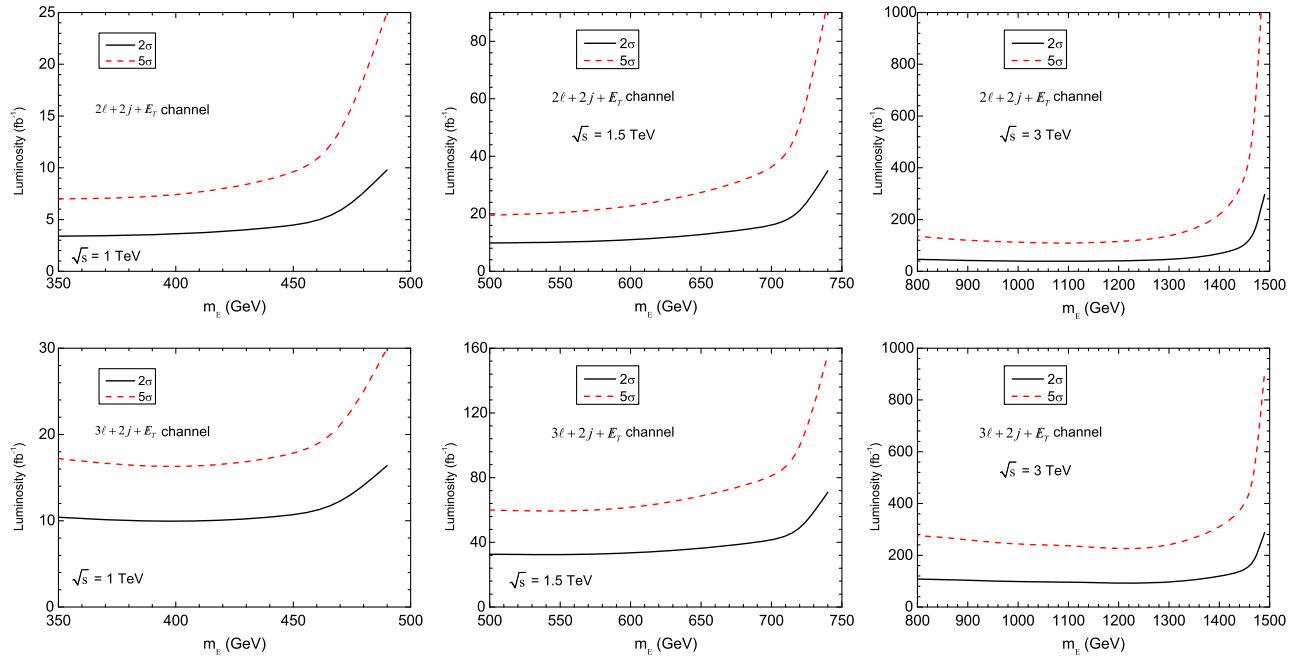


FIG. 9. 2σ exclusion limits (solid curves) and 5σ discovery prospects (dashed curves) are shown as a function of the heavy VLL mass m_E for case 1 (top) and case 2 (bottom), at three c.m. energies: 1 (left), 1.5 (middle), and 3 TeV (right).

pair production and decay patterns of weak-isosinglet VLL of electron flavor at future e^+e^- colliders. Using detailed MC simulations at c.m. energies of $\sqrt{s} = 1, 1.5$, and 3 TeV, including beam polarization effects, we have developed optimized search strategies targeting both $2\ell + 2j + \cancel{E}_T$ and $3\ell + 2j + \cancel{E}_T$ final states.

Upon adopting a variety of $E^\pm$ masses within the kinematic reach of the ILC and CLIC prototypes considered here, each with varying luminosity values, our results demonstrate that well-designed selection criteria can suppress SM backgrounds efficiently while retaining a high signal acceptance. The first channel is especially powerful for singlet VLL searches, owing to its sizable production cross section and favorable signal-to-background ratio. The projected discovery reaches at 5σ significance extend to $m_E \lesssim 490$ GeV at $\sqrt{s} = 1$ TeV with 25 fb^{-1} , $m_E \lesssim 740$ GeV at $\sqrt{s} = 1.5$ TeV with 90 fb^{-1} , and $m_E \lesssim 1440$ GeV at $\sqrt{s} = 3$ TeV with 1000 fb^{-1} ,

substantially exceeding the current mass limits from hadron colliders. The second channel is less sensitive in comparison but can be used for signal confirmation.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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- [1] N. Arkani-Hamed, K. Blum, R. T. D'Agnolo, and J. Fan, *J. High Energy Phys.* **01** (2013) 149.
 - [2] P. Schwaller, T. M. P. Tait, and R. Vega-Morales, *Phys. Rev. D* **88**, 035001 (2013).
 - [3] J. Halverson, N. Orlofsky, and A. Pierce, *Phys. Rev. D* **90**, 015002 (2014).
 - [4] S. Bahrami, M. Frank, D. K. Ghosh, N. Ghosh, and I. Saha, *Phys. Rev. D* **95**, 095024 (2017).
 - [5] S. Bhattacharya, P. Ghosh, N. Sahoo, and N. Sahu, *Front. Phys.* **7**, 80 (2019).
 - [6] M. L. Xiao and J. H. Yu, *Phys. Rev. D* **90**, 014007 (2014).
 - [7] K. Y. Cingiloglu and M. Frank, *Phys. Rev. D* **111**, 016025 (2025).
 - [8] G. Hiller, C. Hormigos-Feliu, D. F. Litim, and T. Steudtner, *Phys. Rev. D* **102**, 071901 (2020).
 - [9] A. S. De Jesus, S. Kovalenko, F. S. Queiroz, C. Siqueira, and K. Sinha, *Phys. Rev. D* **102**, 035004 (2020).
 - [10] M. Frank and I. Saha, *Phys. Rev. D* **102**, 115034 (2020).
 - [11] R. Dermisek, K. Hermanek, and N. McGinnis, *Phys. Rev. D* **104**, 055033 (2021).
 - [12] T. Brune, T. W. Kephart, and H. Päs, *Eur. Phys. J. C* **84**, 1254 (2024).
 - [13] G. Guedes and P. Olgoso, *J. High Energy Phys.* **09** (2022) 181.
 - [14] S. P. He, *Chin. Phys. C* **47**, 043102 (2023).
 - [15] J. Kawamura and S. Raby, *Phys. Rev. D* **106**, 035009 (2022).
 - [16] G. Y. Huang, K. Kong, and S. C. Park, *J. High Energy Phys.* **06** (2012) 099.
 - [17] K. Kong, S. C. Park, and T. G. Rizzo, *J. High Energy Phys.* **07** (2010) 059.
 - [18] P. W. Graham, A. Ismail, S. Rajendran, and P. Saraswat, *Phys. Rev. D* **81**, 055016 (2010).
 - [19] M. Endo, K. Hamaguchi, S. Iwamoto, and N. Yokozaki, *Phys. Rev. D* **85**, 095012 (2012).
 - [20] S. P. Martin and J. D. Wells, *Phys. Rev. D* **86**, 035017 (2012).
 - [21] M. Endo, K. Hamaguchi, K. Ishikawa, S. Iwamoto, and N. Yokozaki, *J. High Energy Phys.* **01** (2013) 181.
 - [22] W. Fischler and W. Tangarife, *J. High Energy Phys.* **05** (2014) 151.
 - [23] S. De Curtis, L. Delle Rose, S. Moretti, and K. Yagyu, *Phys. Lett. B* **786**, 189 (2018).
 - [24] H. J. He, T. M. P. Tait, and C. P. Yuan, *Phys. Rev. D* **62**, 011702(R) (2000).
 - [25] X. F. Wang, C. Du, and H. J. He, *Phys. Lett. B* **723**, 314 (2013).
 - [26] H. J. He, C. T. Hill, and T. M. P. Tait, *Phys. Rev. D* **65**, 055006 (2002).
 - [27] H. J. He and Z. Z. Xianyu, *J. Cosmol. Astropart. Phys.* **10** (2014) 019.
 - [28] F. del Aguila, J. de Blas, and M. Perez-Victoria, *Phys. Rev. D* **78**, 013010 (2008).
 - [29] K. Ishiwata and M. B. Wise, *Phys. Rev. D* **88**, 055009 (2013).
 - [30] J. Kearney, A. Pierce, and N. Weiner, *Phys. Rev. D* **86**, 113005 (2012).
 - [31] W. Altmannshofer, M. Bauer, and M. Carena, *J. High Energy Phys.* **01** (2014) 060.
 - [32] A. Falkowski, D. M. Straub, and A. Vicente, *J. High Energy Phys.* **05** (2014) 092.
 - [33] S. A. R. Ellis, R. M. Godbole, S. Gopalakrishna, and J. D. Wells, *J. High Energy Phys.* **09** (2014) 130.
 - [34] K. Ishiwata, Z. Ligeti, and M. B. Wise, *J. High Energy Phys.* **10** (2015) 027.
 - [35] R. Dermisek, A. Raval, and S. Shin, *Phys. Rev. D* **90**, 034023 (2014).

- [36] A. Crivellin, F. Kirk, C. A. Manzari, and M. Montull, *J. High Energy Phys.* **12** (2020) 166.
- [37] M. Endo and S. Mishima, *J. High Energy Phys.* **08** (2020) 004.
- [38] N. Chakrabarty, *Eur. Phys. J. Plus* **136**, 1183 (2021).
- [39] G. Guedes and J. Santiago, *J. High Energy Phys.* **01** (2022) 111.
- [40] M. Raju, A. Mukherjee, and J. P. Saha, *Eur. Phys. J. C* **83**, 429 (2023).
- [41] X. Q. Li, Z. J. Xie, Y. D. Yang, and X. B. Yuan, *Nucl. Phys. B* **1006**, 116646 (2024).
- [42] R. Dermisek, J. P. Hall, E. Lunghi, and S. Shin, *J. High Energy Phys.* **12** (2014) 013.
- [43] R. Dermisek, E. Lunghi, and S. Shin, *J. High Energy Phys.* **02** (2016) 119.
- [44] N. Kumar and S. P. Martin, *Phys. Rev. D* **92**, 115018 (2015).
- [45] R. Dermisek, E. Lunghi, and S. Shin, *J. High Energy Phys.* **05** (2016) 148.
- [46] C. H. Chen and T. Nomura, *Eur. Phys. J. C* **76**, 353 (2016).
- [47] J. Kawamura, S. Raby, and A. Trautner, *Phys. Rev. D* **100**, 055030 (2019).
- [48] F. F. Freitas, J. Gonçalves, A. P. Morais, and R. Pasechnik, *J. High Energy Phys.* **01** (2021) 076.
- [49] A. Osman Acar, O. E. Delialioglu, and S. Sultansoy, *arXiv:2103.08222*.
- [50] J. Kawamura and S. Raby, *Phys. Rev. D* **104**, 035007 (2021).
- [51] C. Bonilla, A. E. Cárcamo Hernández, J. Gonçalves, F. F. Freitas, A. P. Morais, and R. Pasechnik, *J. High Energy Phys.* **01** (2022) 154.
- [52] F. Baspehlivan, B. Dagli, O. E. Delialioglu, and S. Sultansoy, *arXiv:2201.08251*.
- [53] Q. H. Cao, J. Guo, J. Liu, Y. Luo, and X. P. Wang, *Phys. Rev. D* **110**, 015029 (2024).
- [54] E. Bernreuther and B. A. Dobrescu, *J. High Energy Phys.* **07** (2023) 079.
- [55] J. Kawamura and S. Shin, *J. High Energy Phys.* **11** (2023) 025.
- [56] I. Bigaran, B. A. Dobrescu, and A. Russo, *Phys. Rev. D* **109**, 055033 (2024).
- [57] G. Aad *et al.* (ATLAS Collaboration), *J. High Energy Phys.* **09** (2015) 108.
- [58] G. Aad *et al.* (ATLAS Collaboration), *J. High Energy Phys.* **07** (2023) 118.
- [59] A. M. Sirunyan *et al.* (CMS Collaboration), *Phys. Rev. D* **100**, 052003 (2019).
- [60] A. Tumasyan *et al.* (CMS Collaboration), *Phys. Rev. D* **105**, 112007 (2022).
- [61] A. Tumasyan *et al.* (CMS Collaboration), *Phys. Lett. B* **846**, 137713 (2023).
- [62] A. Hayrapetyan *et al.* (CMS Collaboration), *Phys. Rep.* **1115**, 570 (2025).
- [63] S. Bißmann, G. Hiller, C. Hormigos-Feliu, and D. F. Litim, *Eur. Phys. J. C* **81**, 101 (2021).
- [64] G. Aad *et al.* (ATLAS Collaboration), *J. High Energy Phys.* **05** (2025) 075.
- [65] P. N. Bhattiprolu and S. P. Martin, *Phys. Rev. D* **100**, 015033 (2019).
- [66] H. Baer *et al.* (ILC Collaboration), *arXiv:1306.6352*.
- [67] A. Ayshev *et al.* (ILC International Development Team Collaboration), *arXiv:2203.07622*.
- [68] H. Abramowicz *et al.* (CLIC Detector and Physics Study Collaboration), *arXiv:1307.5288*.
- [69] R. Franceschini, *Int. J. Mod. Phys. A* **35**, 2041015 (2020).
- [70] B. Yang, J. Li, M. Wang, and L. Shang, *Phys. Rev. D* **104**, 055019 (2021).
- [71] L. Shang, M. Wang, Z. Heng, and B. Yang, *Eur. Phys. J. C* **81**, 415 (2021).
- [72] S. Bhattacharya, S. Jahedi, and J. Wudka, *J. High Energy Phys.* **05** (2022) 009.
- [73] L. Shang, J. Li, X. Jia, and B. Yang, *Nucl. Phys. B* **987**, 116071 (2023).
- [74] P. N. Bhattiprolu, S. P. Martin, and A. Pierce, *Phys. Rev. D* **109**, 035009 (2024).
- [75] C. X. Yue, Y. Q. Wang, H. Wang, Y. H. Wang, and S. Li, *Nucl. Phys. B* **1000**, 116482 (2024).
- [76] C. X. Yue, Y. Q. Wang, X. C. Sun, and X. Y. Li, *J. Phys. G* **52**, 025003 (2025).
- [77] J. F. Shen, Y. J. Zhang, and L. Han, *Chin. Phys. C* **49**, 113108 (2025).
- [78] R. P. Li, J. W. Lian, and Y. B. Liu, *Eur. Phys. J. C* **85**, 1429 (2025).
- [79] M. Aaboud *et al.* (ATLAS Collaboration), *Phys. Rev. D* **99**, 092007 (2019).
- [80] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.-S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, *J. High Energy Phys.* **07** (2014) 079.
- [81] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen, and P. Z. Skands, *Comput. Phys. Commun.* **191**, 159 (2015).
- [82] J. de Favereau, C. Delaere, P. Demin, A. Giammanco, V. Lemaître, A. Mertens, and M. Selvaggi (DELPHES 3 Collaboration), *J. High Energy Phys.* **02** (2014) 057.
- [83] E. Leogrande, P. Roloff, U. Schnoor, and M. Weber, *arXiv:1909.12728*.
- [84] E. Conte, B. Fuks, and G. Serret, *Comput. Phys. Commun.* **184**, 222 (2013).
- [85] E. Conte, B. Dumont, B. Fuks, and C. Wymant, *Eur. Phys. J. C* **74**, 3103 (2014).
- [86] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, *Eur. Phys. J. C* **71**, 1554 (2011); **73**, 2501(E) (2013).