Probing Relatively Heavier Right-Handed Selectron at the CEPC, FCCee and ILC

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We employ the low energy Minimal Supersymmetric Standard Model (MSSM) to explore the parameter space associated with Z-pole and Higgs-pole solutions. Such parameter spaces can not only saturate the cold dark matter relic density bound within 5σ set by the Planck 2018, but also satisfy the other standard collider mass bounds and B-physics bounds. In particular, we show that the right-handed selectron can be light. Thus, we propose a search for the relatively heavier right-handed selectron at the future lepton colliders with the center-of-mass energy $\sqrt{s} = 240$ GeV and integrated luminosity 3000 fb$^{-1}$ via mono-photon channel: $e^+_\mu e^-_\mu \rightarrow \chi^0_1(bino) + \chi^0_1(bino) + \gamma$. We show that for the Z-pole case the right-handed selectron will be excluded up to 180 GeV and 210 GeV respectively at 3σ and 2σ, while the right-handed selectron will be excluded up to 140 GeV and 180 GeV respectively at 3σ and 2σ in case of Higgs-pole.

I. INTRODUCTION

Despite the fact that the Suppersymmetric Standard Models (SSMs) are the best bet for the new physics beyond the standard model (BSM) but no concrete evidence has been found. The SSMs predict the unification of the gauge couplings of the hypercharge (or say electromagnetic), weak and strong interactions [1–6], provide the natural solution to gauge hierarchy problem, and have the lightest supersymmetric particle (LSP) as a good cold dark matter candidate [7, 8]. It is also interesting to note that the minimal SSM (MSSM) also predicts the mass range of the Higgs boson [100,135] GeV [9]. This is why Supersymmetry (SUSY) has been one of the main targets of the searches being done to look for the BSM physics beyond the standard model (BSM) but no concrete evidence has been found. The SSMs predict the unification of the gauge couplings of the hypercharge (or say electromagnetic), weak and strong interactions [1–6, 15–17], where the squarks and/or gluinos are around a few TeV while the sleptons, sneutrinos, Bino and Wino are within about 1 TeV. The Higgsinos (or say the Higgs bilinear $\mu$ term) can be either heavy or light. Especially, the EWSUSY can be realized in the Generalized Minimal Supergravity (GmSUGRA) [18, 19].

Apart from high energy collision experiments such as the LHC, the BSM physics is also being probed at the low energy. Recently, the Fermi-Lab Collaboration has announced the results for the measurement of the anomalous magnetic moment of the muon. Combining with the previous results by the Brookhaven National Lab (BNL) experiment, we have 4.2σ deviation from the SM [20]

$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{th} = (25.1 \pm 5.9) \times 10^{-10}. \quad (I.1)$$

This finding suggests the new physics around 1 TeV and have generated flurry of activity [21–58].

In parallel to LHC and low energy physics experiments for the BSM physics, high energy physics community also have plans to build lepton colliders such as Circular Electro-Positron Collider (CEPC) in China [59, 60], Future Circular Collider (FFCee) at CERN [61, 62], and International Linear Collider (ILC) [63, 64]. We know that in lepton collider such as $e^+e^-$, initial states are well defined $(E, p)$ with known polarization and less background particles are produced after collision. They are ideal machines for high-precision measurements. If we take CEPC as an example, it is a collider with a circumference of 100 km which is designed to operate at center-of-mass energy $\sqrt{s} = 240$ GeV, 91.2 GeV, and around 160 GeV as Higgs factory, Z factory or Z-pole and $W - W$ threshold scan respectively. It will produce large samples of Higgs, $W$ and $Z$ bosons to allow precision measurements of their properties as well as searches for the BSM physics.

The interesting question is whether we can probe the relatively heavier sparticles at the future lepton colliders. In this article, we study the EWSUSY parameter space via the low scale MSSM boundary conditions. Especially, we have the Z-pole $(m_{\chi}^0 \approx 1/2m_Z)$ and Higgs-pole $(m_{\chi}^0 \approx 1/2m_h)$ solutions where $m_{\chi}^0$ is the Bino like LSP neutralino mass. These solutions satisfy the Higgs mass bounds, B-physics bounds, and sparticle mass bounds, and have the correct cold dark matter relic density given by Planck 2018. We also present a few benchmark points
to show the parameter space. In addition to it, making
the most of the opportunity of the $Z$-pole and Higgs-pole
parameter space, for the first time we propose a new
search for the relatively heavier right-handed selectron
at future lepton colliders with the center-of-mass energy
$\sqrt{s} = 240$ GeV and integrated luminosity 3000 fb$^{-1}$ via
mono-photon channel: $e^+e^- \rightarrow \overline{\chi}^0_1(bino) + \gamma$. In this analysis, we consider
$e_Re_R \rightarrow \nu\bar{\nu}\gamma$ as the SM background and neglect the events involving $W^\pm$ as me-
diator due to the right-handed selectron search. We find
that for the $Z$-pole case, the right-handed selectron can be
excluded up to 180 GeV and 210 GeV at 3$\sigma$ and 2$\sigma$, re-
spectively, while the right-handed selectron will be ex-
cluded up to 140 GeV and 180 GeV at 3$\sigma$ and 2$\sigma$ in case
of Higgs pole, respectively.

The rest of the paper is organized as follows. We de-
scribe the input parameter and the ranges for scan in
section II, display results of scans in section III, discuss
our collider study in section IV, and conclude in section
V.

II. SCANNING PROCEDURE AND
PHENOMENOLOGICAL CONSTRAINTS

We have employed SPHeNo 4.0.3 package [65, 66] gener-
ated with SARAH 4.13.0 [67, 68] to perform the focused
scans to explore the parameter space having $Z$-resonance
and Higgs-resonance solutions. During our focus scan, we
therefore adopted the following (universality) condi-
tions to impose on the parameter space of the MSSM at
the EW scale:

$$
M_f \equiv M_{Q_{1,2,3}} = M_{U_{1,2,3}} = M_{D_{1,2,3}},
T_f \equiv T_i = T_b = T_\tau,
$$

where $M_{Q_{1,2,3}}$, $M_{U_{1,2,3}}$, and $M_{D_{1,2,3}}$, are the squared soft
masses of the fermions. The parameter $T_f$ corresponds to
fermion trilinear couplings; usually these are taken to be
proportional to the Yukawas, such that $T^{ij}_{f} = Y^{ij}_{u} A_f$,
where $i, j$ are generation indices. In our numerical code,
we fixed all the elements of $T_f$ to small values (1 GeV
for the diagonal terms and zero otherwise), except for
$T^{(3,3)}_f = T^{(3,3)}_i = T^{(3,3)}_b = T^{(3,3)}_\tau$, which we left as a free
parameter to be scanned over an extended range. We also
consider non universal gauginos and slepton masses. To
generate the particle spectrum for a given configuration
of the final set of the free parameters,

$$
M_1, M_2, M_3, T_f, \tan\beta, M_f, m_A, \mu, M_{L_{1,2,3}}^2, M_{E_{1,2,3}}^2
$$

In order to calculate $\Omega_{\chi_1^0} h^2$ and other DM observ-
ables for each sampled parameter space, we also pro-
duced a CalcHEP [69] model file for the MSSM with
SARAH, which was then embedded in the public code
MicrOmegas-v5.2.4 [70–72].

In scanning the parameter space, we use the SSP [73]
Mathematica package and link with SPHeno and Mi-
crOmegas. The data points collected all satisfy the re-
quirement of REWSB, with the neutralino being the LSP.
After collecting the data, we require the following bounds
(inspired by the LEP2 experiment) on sparticle masses.

**LEP constraints:** We impose the bounds that the
LEP2 experiments set on charged sparticle masses ($\gtrsim$ 100
GeV) [74].

**Higgs Boson mass:** The experimental combination
for the Higgs mass reported by the ATLAS and CMS
Collaborations is [75]

$$
m_h = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.}) \text{ GeV}.
$$

Due to the theoretical uncertainty in the Higgs mass cal-
culations in the MSSM – see e.g. [76, 77] – we apply the
constraint from the Higgs boson mass to our results as:

$$
122 \text{ GeV} \leq m_h \leq 128 \text{ GeV}.
$$

**Rare B-meson decays:** Since the SM predictions are
in a good agreement with the experimental results for the
rare decays of $B$-meson such as the $B_s \rightarrow \mu^+\mu^-$, $B_s \rightarrow X_s\gamma$, where $X_s$ is an appropriate state including a
strange quark, the results of our analyses are required to be
consistent with the measurements for such processes.
Thus we employ the following constraints from B-physic-
ics [78, 79]:

$$
\begin{align*}
1.6 \times 10^{-9} & \leq \text{BR}(B_s \rightarrow \mu^+\mu^-) \leq 4.2 \times 10^{-9}, \\
2.99 \times 10^{-4} & \leq \text{BR}(b \rightarrow s\gamma) \leq 3.87 \times 10^{-4}, \\
0.70 \times 10^{-4} & \leq \text{BR}(B_u \rightarrow \tau\nu_\tau) \leq 1.5 \times 10^{-4}.
\end{align*}
$$

**Current LHC searches:** Based on [80–82], we con-
side the following constraints on gluino and first/second
generation squark masses

$$
(a) \quad m_{\tilde{g}} \gtrsim 2.2 \text{ TeV}, \quad m_{\tilde{q}} \gtrsim 2 \text{ TeV},
$$

**DM searches and relic density:** For the discussion
on the phenomenology of neutralino DM in our scenario,
we impose the following constraint for the LSP relic den-
sity, based on the current measurements of the Planck
satellite [83]:

$$
0.114 \leq \Omega_{\text{CDM}}h^2(\text{Planck2018}) \leq 0.126 (5\sigma).
$$

We use the current XENON1T with 2 t · y spin-
independent (SI) DM cross section with bounds [84]. All
points lying above these upper bounds have been ex-
cluded from the plots.

III. RESULTS OF FOCUSED SCANS

In this section we are focusing on the sparticle spec-
trum consistent with mass bounds and the constraints
discussed above.
FIG. 1: Parameter spaces in the $m_{\tilde{\chi}^0_1} - m_{\tilde{e}_1}$ and $m_{\tilde{\chi}^0_1} - m_{\tilde{e}_2}$ planes. Gray points are consistent with the REWSB and LSP neutralino. Green points satisfy the mass bounds including $m_h = 125 \pm 3$ GeV and the constraints from rare $B$-meson decays. Red points form a subset of green points and satisfy the $5\sigma$ Planck bounds on dark matter relic density.

FIG. 2: Parameter spaces in the $m_{\tilde{\chi}^0_1} - m_{\tilde{\chi}^0_1}$ and $m_{\tilde{\chi}^0_1} - \sigma^{SI} (\chi, p)$ planes. Color coding is same as in Fig. 1.

In Figure 1, we display plots in $m_{\tilde{\chi}^0_1} - m_{\tilde{e}_1}$ and $m_{\tilde{\chi}^0_1} - m_{\tilde{e}_2}$ planes. Note that here $\tilde{e}_1$ is the right-handed selectron while $\tilde{e}_2$ is left handed selectron. Gray points satisfy the REWSB and the LSP neutralino conditions. Green points satisfy the mass bounds and B-physics constraints. Red points form a subset of green points and satisfy the Planck 2018 bounds (mentioned above) on the relic abundance of the LSP neutralino within $5\sigma$ uncertainty. We see that from left panel the green points are almost everywhere. But when we demand the relic density bound, red solutions appear to be around $m_{\tilde{\chi}^0_1} \sim 45$ GeV and 62 GeV. These solutions represent well known the $Z$-pole ($m_{\tilde{\chi}^0_1} \approx 1/2m_Z$) and the Higgs-pole ($m_{\tilde{\chi}^0_1} \approx 1/2m_h$) solutions where two LSP neutralinos annihilate via s-channel exchange of a virtual particle, for example, a $Z$ or Higgs boson and the mass of the exchanged particle closely matches twice the LSP neutralino mass. The solid black horizontal line indicates the LEP bounds on sleptons [85–89] while the dashed black line represents the estimated exclusion limit for right handed selectron (we will discuss it in section IV). Note that though red points appear to be between 80 GeV to 360 GeV in our present
scans but we can increase the mass range by keep doing focus scans. In the left panel we see the similar situation for neutralino mass and we note that $\tilde{e}_l$ or the left handed slepton mass can be as heavy as 1100 GeV.

In Figure 2 left panel, we show plots for $m_{\tilde{\chi}^0_1} - m_{\tilde{\chi}^\pm_1}$ and $m_{\tilde{\gamma}} - \sigma_{SI}(\chi, p)$. Color coding is same as in Fig. 1. In the left panel we see that $m_{\tilde{\chi}^\pm_1}$ can be as heavy as 450 GeV for both Z-pole and Higgs-pole scenario but can be made heavy by focused scans. In the right panel display $m_{\tilde{\chi}^0_1} - \sigma_{SI}(\chi, p)$ plot. Her orange line represents the current XENON1T with $2 t \cdot y$ bounds. In this plot, the two dips around 45 GeV and 62 GeV indicate the Z-pole and Higgs-pole solutions. This plot clearly show that almost all of the red points are consistent with the current bounds set by XENON1T with $2 t \cdot y$.

In our numerical simulation, Monte Carlo samples of signal and background events are generated by using MadGraph5 [90, 91] for hard scattering processes, PYTHIA8 [92] for parton showering and hadronization and DELPHES 3 [93] for jet clustering and detector simulation. We generate the signal events with the collision energy equal to 240 GeV and use the anti-$k_T$ algorithm to do the jet reconstruction with the radius $R = 0.4$. The beam polarization is set to be fully right-handed. All jets and particles within $|y| < 3.0$ will be recorded by simulation, otherwise it will be missed. In addition, we apply photon isolation techniques, which have been developed to filter out indirect photons that are produced from the fragmentation of quark and gluon partons. Photon isolation viable is defined as

$$I(P) = \sum_{i \neq P} \frac{p_{T}(i)}{p_{T}(P)},$$

where the denominator stands for the transverse momentum of photon, and the numerator is the sum of transverse momenta above $p_{T}^{min}$ of all particles that lie within a cone of radius $R_0$ around and except the photon. In our simulation, we require the isolation viable to be $I(P) < 0.12$ and $R_0 = 0.5$, $p_{T}^{min} = 0.5$ GeV.

The final states is quite simple with only MET and mono-photon to be detected. Therefore, in order to analyze the signal events, we make use of the following quantities and the threshold is chosen to maximize the Higgs signal significance of the CEPC:

- Missing transverse energy (MET) of all invisible particles: We require $E_{inv} < 80.0$. The distribution of MET is shown in the left panel of Fig. 4, where the green region stands for the background distribution and the blue/orange one stands for the

![FIG. 3: The Feynman diagrams for the background and signal events, respectively.](image-url)
Fig. 4: The distribution of missing transverse momentum (left) and the invariant mass of the missing momentum (right) for Higgs-pole case with $m_{\tilde{e}_R} = 100$ GeV and $m_{\tilde{e}_R} = 140$ GeV.

Higgs-pole case with slepton mass equal to 100 and 140 GeV respectively.

- Invariant mass of invisible particles: $m_{inv} = \sqrt{(E_{total} - E_{vis})^2 - p_{vis}^2}$, where $E_{total}$ = 240 GeV, $E_{vis}$ the total energy of all visible particles and $p_{vis}$ the visible particles. It should satisfy: $m_{inv} > 130.0$ GeV. Since for background events, two neutrinos come from an on-shell Z boson, so the invariant mass of two neutrinos is around Z boson mass as shown in the right panel in Fig. 4. In this panel, the color meaning is same as before, and as we can see, the distribution of Z-pole mass set an effective cut-off between signal events and background events.

Note that here we show our study for Higgs-pole only but more or less similar results true for Z-pole solutions.

Significance for signal events is calculated by $\sigma = S/\sqrt{B}$. In Fig. 5, we show the significance of signal events with the selectron mass ranging from 50 GeV to 400 GeV. For the Z-pole case, the right handed selectron will be excluded to 180 GeV and 210 GeV by $3\sigma$ and $2\sigma$ respectively. In the Higgs-pole scenario, the right handed selectron will be excluded to 140 GeV and 180 GeV by $3\sigma$ and $2\sigma$ respectively.

V. DISCUSSION AND CONCLUSION

In the low energy MSSM, we studied the EWSUSY parameter space associated with Z-pole and Higgs-pole solutions. Such parameter spaces can not only have the correct dark matter relic density within 5 $\sigma$ from the Planck 2018, but also escape the other standard collider mass bounds and B-physics bounds. Especially, the right-handed selectron can be light. Therefore, we proposed a search for the relatively heavier right-handed selectron at the future lepton colliders with the center-of-mass energy $\sqrt{s} = 240$ GeV and integrated luminosity 3000 fb$^{-1}$ via mono-photon channel: $e_R^{-}\bar{e}_R^{+} \rightarrow \tilde{\chi}_1^{0}(bino) + \tilde{\chi}_1^{0}(bino) + \gamma$. We showed that for the Z-pole case the right-handed selectron can be excluded up to 180 GeV and 210 GeV respectively at $3\sigma$ and $2\sigma$, while the right-handed selectron can be excluded up to 140 GeV and 180 GeV respectively at $3\sigma$ and $2\sigma$ in case of Higgs-pole.

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