

Signatures of supersymmetry and a $L_\mu - L_\tau$ gauge boson at Belle-II

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We propose that the $\gamma + \cancel{E}$ signal at the Belle-II detector will be a smoking gun for supersymmetry (SUSY) in the presence of a gauged $U(1)_{L_\mu - L_\tau}$ symmetry. A striking consequence of breaking the enhanced symmetry appearing in the limit of degenerate (s)leptons is the nondecoupling of the radiative contribution of heavy charged sleptons to the $\gamma - Z'$ kinetic mixing. The signal process, $e^+ e^- \rightarrow \gamma Z' \rightarrow \gamma + \cancel{E}$, is an outcome of this ubiquitous feature. We take into account the severe constraints on gauged $U(1)_{L_\mu - L_\tau}$ models by several low-energy observables and show that any significant excess in all but the highest photon energy bin would be an undeniable signature of such heavy scalar fields in SUSY coupling to Z' . The number of signal events depends crucially on the logarithm of the ratio of stau to smuon mass in the presence of SUSY. In addition, the number is also inversely proportional to the $e^+ - e^-$ collision energy, making a low-energy, high-luminosity collider like Belle-II an ideal testing ground for this channel. This process can probe large swathes of the slepton mass ratio vs the additional gauge coupling (g_X) parameter space. More importantly, it can explore the narrow slice of $M_{Z'} - g_X$ parameter space still allowed in gauged $U(1)_{L_\mu - L_\tau}$ models for superheavy sparticles.

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I. INTRODUCTION

The standard model (SM) of particle physics fails to explain many experimental observations like neutrino mass, presence of dark matter, the baryon asymmetry of the universe, and the anomalous magnetic moment of muon, among others. There is little doubt that we need physics beyond the standard model to address these issues. One of the most celebrated extensions of the SM is its minimal supersymmetric extension, popularly called MSSM [1]. However, MSSM with R-parity conservation still cannot explain the nonzero tiny masses of the neutrinos and their nontrivial mixing pattern.

At the same time, given the upward trend of the lower bounds on supersymmetry (SUSY) particle masses, it is also becoming increasingly difficult to accommodate the results from the muon ($g - 2$) experiment in MSSM. Supersymmetric particle searches from the 35.9 fb^{-1} data, collected by CMS experimental collaborations at the LHC at a center-of-mass energy, $\sqrt{s} = 13 \text{ TeV}$, have found no

significant excess in signal over the expected SM background. Results from the CMS experiment [2] extend the gluino mass limit to 2.0 TeV, and the limits on top squark masses reach 1.14 TeV. For simplified models and a massless lightest neutralino, limits on the first two generations' left-handed slepton masses are set at 450 GeV, whereas the limits on the right-handed slepton masses are set at 330 GeV [3]. The searches by ATLAS experiment [4] under similar assumptions set an exclusion limit of 2.03 TeV on the gluino mass and 1.55 TeV on squark masses (first two generations) corresponding to an integrated luminosity of 36.1 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$. Masses up to 500 GeV [5] are excluded for sleptons, assuming three generations of mass degenerate sleptons.

There are other models that address the issue of neutrino masses along with one or more of the observations not in tune with the SM. One class of models that has generated considerable interest of late is that with an additional gauged $U(1)_{L_\mu - L_\tau}$ symmetry [6,7]. It has been implemented to explain the muon anomalous magnetic moment [8–10], neutrino masses and mixing [9,11–13], dark matter [13–21], Higgs boson flavor violating decays [22,23], and B-decay anomalies [14,22,24–26]. The possibility of detecting the gauge boson of $U(1)_{L_\mu - L_\tau}$ symmetry at the Belle-II experiment has been discussed [27,28]. In addition, constraints on the mass and the coupling of the new gauge boson in this model from neutrino trident production [29], neutrino beam experiments [27], lepton flavor violating τ

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decays [30], and rare Kaon decays [31] severely restrict its parameter space. The situation in supersymmetric versions of $U(1)_{L_\mu-L_\tau}$ is more relaxed and has been studied in the context of muon anomalous magnetic moment, neutrino masses and mixing, charged lepton flavor violating decays [32], dark matter [33,34], and flavor anomalies [34].

In this work, we show that the signature of supersymmetry as well as $L_\mu - L_\tau$ gauge boson can be seen at the Belle-II experiment [35] by studying the process $e^+e^- \rightarrow \gamma + \mathcal{E}$, which hinges on the presence of kinetic mixing between the photon and the extra gauge boson. Such a kinetic mixing is an unavoidable feature in any model with an additional $U(1)$ gauge symmetry. Here we consider a scenario where this mixing is absent at the tree level but arises radiatively at the one-loop level. As a result, the kinetic mixing is not constant but depends on the extra gauge coupling, the mass ratio of smuon and stau defined as $r = \frac{m_{\tilde{\mu}}}{m_{\tilde{\tau}}}$, and the momentum carried by the photon and the Z' . When r is 1, the supersymmetric contribution to the kinetic mixing vanishes, and the results resemble those for the nonsupersymmetric gauged $U(1)_{L_\mu-L_\tau}$ model. However, when the ratio is greater than or less than 1, the supersymmetric contribution could be significant, and the results are distinctly different from those of the nonsupersymmetric model.

As the results do not depend on the absolute mass scales, the signature of SUSY may be observed at the Belle-II experiment through this channel even when the sparticles are extremely massive. On the other hand, when all the SUSY particles are very heavy, the contribution to muon ($g-2$) at one loop comes only from the loop involving the Z' gauge boson. The allowed region of parameter space in the $(M_{Z'} - g_X)$ plane in such a scenario is severely restricted by other experiments. On top of that, the proposed signal at Belle-II can explore additional regions of the parameter space.

Another important feature emerges from the number of events histogram against the photon energy. We show that, when the correction to muon anomalous magnetic moment is given entirely by the Z' contribution, an excess in only the highest energy bin is possible. This means that, if an excess is observed in any but the highest energy bin, it would be a signature of SUSY particles contributing to the radiative kinetic mixing. This also indicates that an additional source of muon anomalous magnetic moment is required beyond the Z' contribution.

II. $U(1)_{L_\mu-L_\tau}$ MODEL IN SUSY

We extend the MSSM with a new $U(1)$ gauge symmetry, $U(1)_{L_\mu-L_\tau}$, where the (s)muon and (s)tau fields with their corresponding (s)neutrinos couple to the additional Z' with equal and opposite charge. Because our focus in this work is mainly on the gauge kinetic mixing, we shall not provide much details of the model here. Rather, we concentrate on

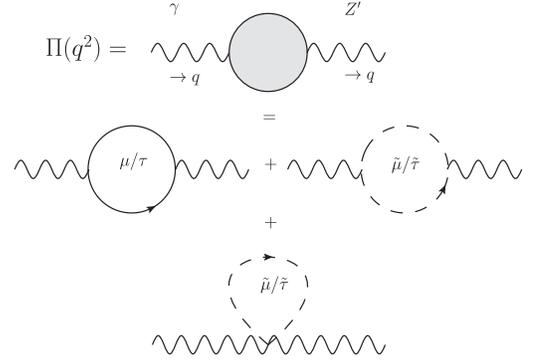


FIG. 1. Diagrams showing how $\gamma - Z'$ kinetic mixing arises radiatively at the one-loop level.

how the kinetic mixing involving the photon and the Z' appears radiatively in our setup and its consequences at the Belle-II experiment.

We shall assume that the kinetic mixing between $U(1)_{em}$ and $U(1)_{L_\mu-L_\tau}$ given by

$$\mathcal{L}_{\text{kin-mix}} = \frac{\epsilon}{2} (\hat{W}^{(em)\alpha} \hat{W}_\alpha^{L_\mu-L_\tau})_F \quad (1)$$

is absent at the tree level, i.e., $\epsilon = 0$. Here $\hat{W}^{(em)\alpha}$ and $\hat{W}_\alpha^{L_\mu-L_\tau}$ are the corresponding SUSY field strengths. The subscript ‘‘F’’ indicates F-term contribution. However, such a kinetic mixing can still be generated at the one-loop level involving muon, tau, smuon, and stau in the loops as shown in Fig. 1. The absence of kinetic mixing at the tree level can be justified using some symmetry arguments. One possibility is that the kinetic mixing is forbidden by a discrete symmetry, $\mu \leftrightarrow \tau$, $\tilde{\mu} \leftrightarrow \tilde{\tau}$, $\hat{W}^{(em)\alpha} \rightarrow \hat{W}^{(em)\alpha}$, and $\hat{W}_\alpha^{L_\mu-L_\tau} \rightarrow -\hat{W}_\alpha^{L_\mu-L_\tau}$ in the limit of $m_\mu = m_\tau$ and $m_{\tilde{\mu}} = m_{\tilde{\tau}}$. Breaking the symmetry softly by $m_\mu \neq m_\tau$ and $m_{\tilde{\mu}} \neq m_{\tilde{\tau}}$ generates a finite kinetic mixing radiatively.

Another possibility is to consider the $U(1)_{L_\mu-L_\tau}$ gauge factor embedded within an unbroken nonabelian gauge symmetry (such as $SU(2)$). This would forbid the kinetic mixing. However, when the $U(1)$ gauge factor comes out from the breaking of the full nonabelian gauge symmetry, the mass degeneracy of the states within the nonabelian multiplets will be lost, leading to nonzero kinetic mixing generated at the one-loop level [36].

As the decoupling theorem does not apply if the heavy (s)particle masses break symmetries [37,38], in this case, nondecoupling effects will be present. This will be elaborated in the subsequent discussion. Note also that the superpartner soft masses break supersymmetry and hence may give rise to nondecoupling corrections [38].

As discussed, coupling of the photon with Z' appears at the one-loop level and is given by¹

¹Note that it is sufficient to consider kinetic mixing between $U(1)_{em}$ and the $U(1)_{L_\mu-L_\tau}$ as long as $M_{Z'}/M_Z^2 \ll 1$.

$$\epsilon \equiv \Pi(q^2) = \frac{8eg_X}{(4\pi)^2} \int_0^1 x(1-x) \ln \frac{m_\tau^2 - x(1-x)q^2}{m_\mu^2 - x(1-x)q^2} dx + \frac{2eg_X}{(4\pi)^2} \int_0^1 (1-2x)^2 \ln \frac{m_{\tilde{\ell}}^2 - x(1-x)q^2}{m_{\tilde{\mu}}^2 - x(1-x)q^2} dx, \quad (2)$$

where the contributions come from the loop diagrams in Fig. 1. Here e is the electromagnetic charge, m_ℓ and $m_{\tilde{\ell}}$ are the masses of charged lepton ℓ and charged slepton $\tilde{\ell}$, q is the momentum carried by γ and Z' , and g_X is the gauge coupling corresponding to $U(1)_{L_\mu - L_\tau}$. Here, for simplicity of the analysis, we have considered identical masses for $m_{\tilde{\ell}_L}$ and $m_{\tilde{\ell}_R}$. In general, these masses can be different, and in such cases, one must define other ratios involving only left-handed sleptons or right-handed sleptons.

III. CONSTRAINTS AND SIGNATURE AT BELLE-II

At the Belle-II experiment, we shall consider the signal process $e^+e^- \rightarrow \gamma Z'$ and then Z' decaying to $\nu\bar{\nu}$, leading to a final state $e^+e^- \rightarrow \gamma + \cancel{E}$. The kinetic mixing parameter is a function of $q^2 = M_{Z'}^2$ (for on-shell production of the Z' boson) and r . It is the dependence on r that makes the model predictions very different compared to what is obtained in gauged $L_\mu - L_\tau$ models with no supersymmetry. In our analysis, the kinetic mixing parameter, ϵ , that is generated radiatively never exceeds 10^{-4} .

At this stage, it is worth mentioning that the gauged $L_\mu - L_\tau$ model was first introduced to address the discrepancy between the experimental measurement and the SM predictions of muon $(g-2)$, and this is given by [39]

$$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (28.7 \pm 8.0) \times 10^{-10}, \quad (3)$$

where $a_\mu \equiv (g_\mu - 2)/2$.

In gauged $L_\mu - L_\tau$ models without supersymmetry, the extra contribution to $(g_\mu - 2)/2$ comes solely from a one-loop diagram involving Z' and is given by [8,9]

$$a_\mu^{Z'} = \frac{g_X^2}{8\pi^2} \int_0^1 \frac{2m_\mu^2 x^2 (1-x)}{x^2 m_\mu^2 + (1-x)M_{Z'}^2} dx. \quad (4)$$

In addition, the most stringent constraints on the $U(1)_{L_\mu - L_\tau}$ parameter space come from neutrino trident production (CCFR [40]), neutrino-electron elastic scattering (BOREXINO [41]), and the light Z' search through $e^+e^- \rightarrow \mu^+\mu^-Z'$, $Z' \rightarrow \mu^+\mu^-$ by the BABAR Collaboration [42]. The CCFR collaboration reported a strong adherence of the observed cross section to the SM prediction, which strongly constrains a large section of the $M_{Z'} - g_X$ parameter space [29]. The observation of ${}^7\text{Be}$ solar neutrino scattering rates at Borexino disfavors any additional contribution that is 8% or more above the SM prediction [43,44]. For a recent

discussion on other constraints, see Ref. [45]. Taking them into account, a thin slice of the $M_{Z'} - g_X$ parameter space,

$$10 \text{ MeV} \lesssim M_{Z'} \lesssim 210 \text{ MeV}, \quad 4 \times 10^{-4} \lesssim g_X \lesssim 10^{-3}, \quad (5)$$

is left to explain the muon $(g-2)$ anomaly. However, it was shown in [32] that once SUSY is taken into consideration the allowed parameter range satisfying muon $(g-2)$ is larger depending on the choice of SUSY parameters.

In case of superheavy sparticles, the allowed parameter range is the same as that in non-SUSY $L_\mu - L_\tau$ [given in Eq. (5)]; however, their contribution to kinetic mixing is nondecoupling. Hence, one would still be able to discern their signatures at Belle-II through the signal process.

Belle-II experiment [35,46] is an electron-positron collider with a center-of-mass energy of $\sqrt{s} = 10.58 \text{ GeV}$ and is expected to reach an integrated luminosity of 50 ab^{-1} . The signal process $e^+e^- \rightarrow \gamma + \cancel{E}$ under study results from the associated production of a monoenergetic photon and a light Z' [see Fig. 2(a)] and subsequent decay of Z' into a $\nu\bar{\nu}$ pair. The $\gamma - Z'$ kinetic mixing depends on the momentum q carried by Z' as well as the ratio of smuon and stau masses. The cross section of Z' production $e^+e^- \rightarrow \gamma + Z'$ in the center-of-mass frame is given by [47]

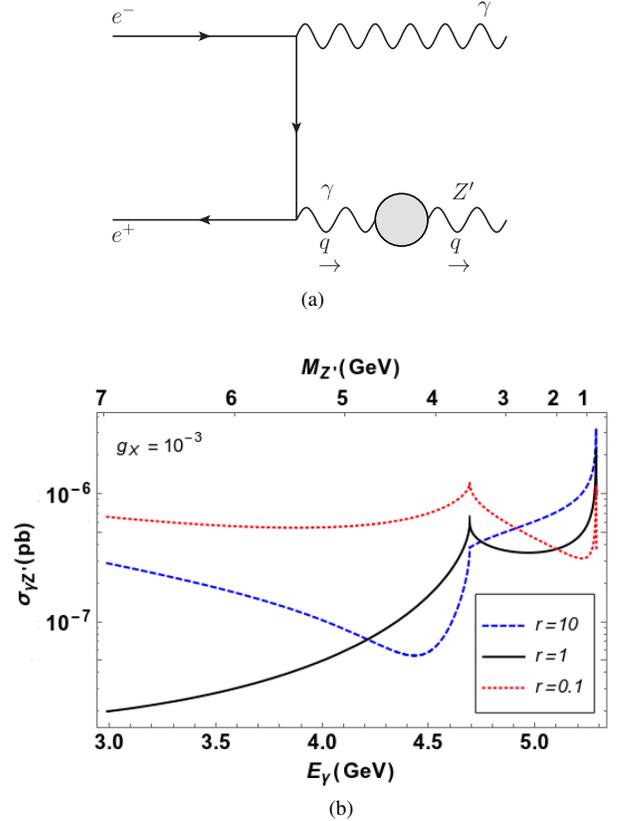


FIG. 2. (a) Feynman diagram for $\gamma - Z'$ production at Belle-II. (b) Variation of the cross section for this process with changing E_γ and $M_{Z'}$.

$$\sigma(e^+e^- \rightarrow \gamma + Z') = \frac{2\pi\alpha^2 |\Pi(M_{Z'}^2)|^2}{s} \left[1 - \frac{M_{Z'}^2}{s} \right] \left[\left\{ 1 + \frac{2sM_{Z'}^2}{(s - M_{Z'}^2)^2} \right\} \ln \frac{(1 + \cos\theta_{\max})(1 - \cos\theta_{\min})}{(1 - \cos\theta_{\max})(1 + \cos\theta_{\min})} - \cos\theta_{\max} + \cos\theta_{\min} \right]. \quad (6)$$

Here we have $\cos\theta_{\min} < \cos\theta < \cos\theta_{\max}$, with $\cos\theta_{\min} = -0.821$ and $\cos\theta_{\max} = 0.941$, which corresponds to the range of the coverage of the electromagnetic calorimeter [28]. The angle θ is the angle between the electron beam axis and the photon momentum. The cross section is plotted in Fig. 2(b), where the final state photon energy E_γ is related to q^2 in the center-of-mass frame as

$$E_\gamma = \frac{s - q^2}{2\sqrt{s}}. \quad (7)$$

The maximum value of E_γ is $\sqrt{s}/2$ (5.29 GeV at Belle-II) that corresponds to $M_{Z'}^2 = 0$ for an on-shell Z' . At Belle-II, this process can probe the Z' gauge boson of mass $\lesssim 6$ GeV, which corresponds to a maximum g_X of 4×10^{-3} [48]. The decay mode of the Z' boson into two muons is possible for $M_{Z'} > 2m_\mu$ and results in $\gamma\mu^+\mu^-$ signal which is cleaner. However, it cannot probe the crucially important range of Z' mass that can still explain muon $(g-2)$ in the absence of additional SUSY contribution.

The decay width of the additional gauge boson is much less than its mass for this parameter space, which justifies the use of the narrow width approximation. The value of the gauge coupling g_X has been taken to be 10^{-3} in Fig. 2(b) to correspond to a region where muon $(g-2)$ may still be satisfied even when the superpartners are very heavy.

One can see from this figure that the cross section increases for higher values of E_γ , which corresponds to lower $M_{Z'}$. The $r = 1$ curve corresponds to the case where the slepton masses are equal and hence their contribution to the radiative kinetic mixing drops out. We consider a hierarchy between the sleptons to the tune of a factor of 10 at its maximum extent. It is not difficult to translate this choice into a realistic situation where the lighter of the two sleptons are at about 1 TeV, whereas the other is close to 10 TeV. The two different ratios, 0.1 and 10, then represent two very different phenomenological situations, one where the stau is much lighter than the smuon and the other the opposite, respectively. In Fig. 2(b), a heavier stau mass ($r > 1$) leads to a larger cross section at higher photon energies. The charged slepton contribution to ϵ interferes destructively with the charged lepton contribution when $r < 1$ in this region, resulting in a smaller cross section. However, the same may not be said for the lower photon energies. In fact, for a large part of the photon energy spectrum, a lighter stau mass results in a larger cross section.

The SM background comes from the $2 \rightarrow 3$ process $e^+e^- \rightarrow \gamma\nu\bar{\nu}$ involving W and Z bosons in the propagator. The differential scattering cross section in the center-of-mass frame can be found in Ref. [28]. We have assumed that the electromagnetic calorimeter does not miss any event if the photon is within the detector range. We also do not consider the situation where one of the photons in a $\gamma\gamma$ final state or an e^+e^- pair in radiative Bhabha scattering is missed and contributes to the background.

We have compared the number of events corresponding to the signal and the background processes in Fig. 3 for an integrated luminosity of 50 ab^{-1} . In these plots, the width of each energy bin is taken to be $\Delta E_\gamma = 0.1 \text{ GeV}$ [35], which is the detector resolution for the photon energy at Belle-II. The values of the coupling g_X have been taken to be 10^{-3} and 4×10^{-3} . The choice 4×10^{-3} is consistent with the latest measurement of $Z \rightarrow 4\mu$ at the LHC [48] as well as the results from the light Z' search by the BABAR Collaboration for $M_{Z'} \gtrsim 3 \text{ GeV}$ [42]. However, it requires additional SUSY contribution to the anomalous magnetic moment of the muon. The ratio r is allowed to take the values 0.1, 1, and 10. The statistical errors are estimated using $\sqrt{N_S + N_B}$, where N_S and N_B denote the number of signal events and background events, respectively. As we can see from the Figs. 3(a)–3(c), in the case of $r = 1$, i.e., when SUSY gives no contribution, the significance ($\equiv N_S/\sqrt{N_S + N_B}$) of the signal events compared to the SM background is larger than 3σ only in the highest energy bin for $g_X = 10^{-3}$. On the other hand, for a larger ratio, i.e., $r = 10$, the 3σ excess can be seen in the last two bins with an excess of around 5σ in the last bin, which is clearly different from the $r = 1$ case. However, no significant excess is observed in any of the bins for a smaller ratio, $r = 0.1$, at this value of g_X .

The result is more spectacular in the case of $g_X = 4 \times 10^{-3}$, as seen in Figs. 3(d)–3(f). We get more than 3σ excess in a large number of bins for all three choices of r , although the last four energy bins are ruled out in this case from the observations of the CCFR and BABAR Collaborations. These histograms are even more intriguing when analyzed from the vantage point of muon $(g-2)$. Note that any value of $M_{Z'}$ less than 1.38 GeV corresponds to $E_\gamma > 5.2 \text{ GeV}$ from Eq. (7). Hence, Eq. (5) restricts any observable excess to be only in the highest energy bin, irrespective of r , when all the sparticles are too heavy to contribute to $(g-2)_\mu$. This additional information, in conjunction with the result of Ref. [32], which shows that higher values of both $M_{Z'}$ and g_X may be allowed in a

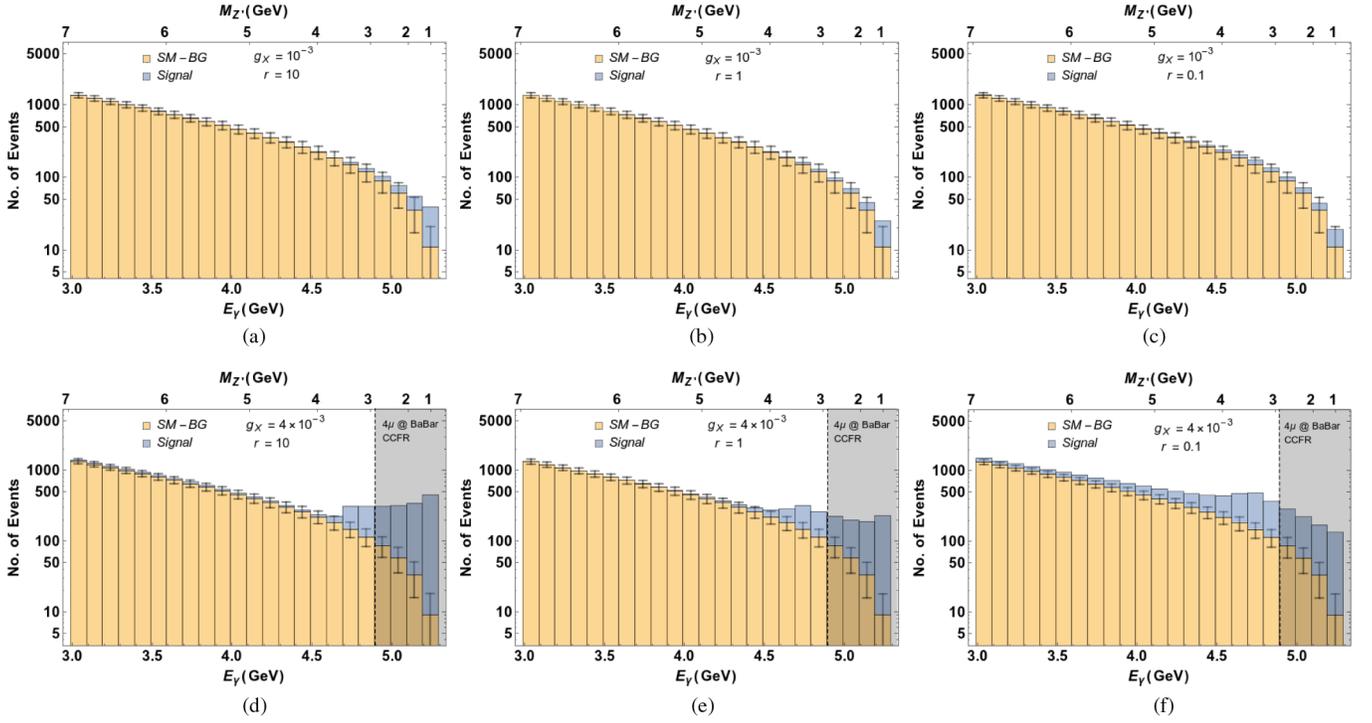


FIG. 3. E_γ distribution of event numbers in SUSY $L_\mu - L_\tau$ model for $e^+e^- \rightarrow \gamma E$ channel at the Belle-II experiment with $\sqrt{s} = 10.58$ GeV and an integrated luminosity of 50 ab^{-1} . The shaded regions are excluded from the observations of the CCFR [40] and BABAR [42] collaborations.

supersymmetric model, results in a very important inference. If Belle-II observes any significant excess in any of the energy bins apart from the last one, it would be an unmistakable signature of the sleptons contributing to the

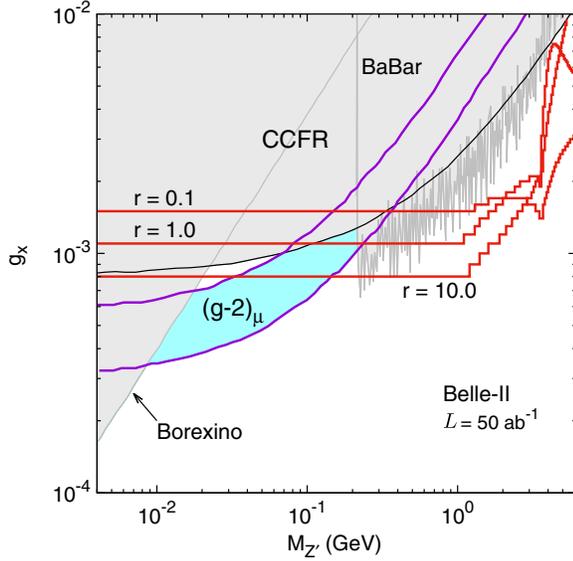


FIG. 4. 3σ exclusion plot in $M_{Z'} - g_X$ plane. Larger values of r exclude a larger region and vice versa. The exclusion region from BOREXINO is shown for $r = 1$ and depends very mildly on this ratio: a larger r excludes a larger region. Allowed region at 2σ from muon magnetic moment measurements is shown when the particles do not contribute to $(g-2)_\mu$.

$\gamma - Z'$ kinetic mixing² and an additional source of $(g-2)_\mu$ over the Z' contribution.

An excess in the last energy bin, while still a signature of $U(1)_{L_\mu - L_\tau}$, can be present even in the absence of SUSY. In that case, the maximum possible excess in the last bin comes for $g_X = 10^{-3}$. We can then define a ratio N_S/N_0 , where N_S is the number of signal events observed and N_0 is the maximum number of events in the absence of SUSY (i.e., for $g_X = 10^{-3}$). If a significant excess is observed in the last bin and this ratio is found to be greater than 1, then it would be a telltale signature of the presence of SUSY. In a supersymmetric scenario, this ratio depends on both r and g_X , and an observation would point towards a range of allowed values for them. An ambiguity would persist if this observed ratio is less than 1, although that would constrain the non-SUSY $L_\mu - L_\tau$ model very strongly ($9 \times 10^{-4} \lesssim g_X \lesssim 10^{-3}$).

The absence of any observed excess in this channel would exclude regions of the $M_{Z'} - g_X$ parameter space that are still allowed to explain muon $(g-2)$, as shown in Fig. 4. This exclusion region would depend on the ratio r and supersedes any existing bounds for much of the parameter space. We show the exclusion contours for

²Even when $r = 1$ i.e., when the sleptons do not contribute to the kinetic mixing, such an excess is impossible in a non-SUSY scenario if the muon $(g-2)$ observations are to be explained.

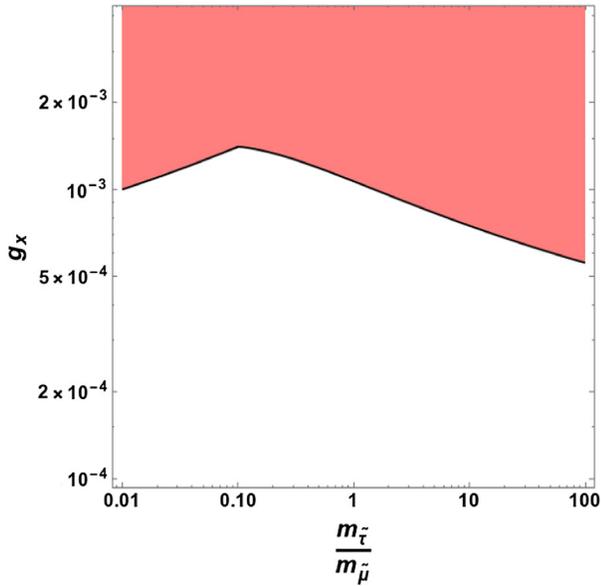


FIG. 5. 3σ exclusion plot in the $g_X - r$ plane for $M_{Z'} < 7$ GeV. Values of g_X above 4×10^{-3} are disallowed for this range in gauge boson mass from the constraints discussed in the text.

$r = 0.1$ and 10 , which makes the variation of the excluded region with r very clear. Parts of the additional unconstrained region in this plane, which may be available to explain $(g - 2)_\mu$ depending on SUSY parameters, are also excluded by the lack of observed excesses in the signal channel. As shown in Fig. 5, lack of any significant excess would also strongly constrain the hitherto free $g_X - r$ parameter space. This exclusion region corresponds only to values of Z' mass less than 7 GeV. Heavier Z' gauge boson parameter space would still remain unconstrained;

however, explaining muon $(g - 2)$ in such a scenario would require significant SUSY contribution.

IV. CONCLUSION

We have considered the possibility of an additional $L_\mu - L_\tau$ force within a supersymmetric framework. We demonstrated the exciting nondecoupling behavior of the contribution of sleptons to the $\gamma - Z'$ kinetic mixing in this class of models. This important observation begets the possibility of visible signatures of scalars like the smuon and stau, too heavy to have been detected at the LHC, in processes modified by the $\gamma - Z'$ mixing. We propose the channel $e^+e^- \rightarrow \gamma Z' \rightarrow \gamma \tilde{E} e^-$ to probe this effect and show that the Belle-II is ideally equipped to do so.

It is clear that, if Belle-II observes an excess beyond 3σ in any of the energy bins except the highest one, it would be an undeniable signature of heavy charged scalars, like those appearing in SUSY, contributing to the kinetic mixing. It would also indicate the need for additional contribution, beyond that from Z' , to accommodate muon anomalous magnetic moment measurements. Finally, if Belle-II observes no excess whatsoever over the SM in any of the energy bins, large chunks of both $M_{Z'} - g_X$ and $g_X - r$ parameter space would be excluded. Additionally, this feature and its analysis would remain unchanged for any model with an extra gauged $U(1)$ symmetry incorporating chiral superfields that have equal and opposite charge under it.

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