An emergent $Z'$ from the Higgs shadow

Waleed Abdallah,1,* Anjan Kumar Barik,2,† Santosh Kumar Rai,2,‡ and Tousik Samuj2,§

1Department of Mathematics, Faculty of Science, Cairo University, Giza 12613, Egypt
2Regional Centre for Accelerator-based Particle Physics, Harish-Chandra Research Institute, HBNI, Chhatnag Road, Jhunsi, Prayagraj (Allahabad) 211019, India

We show in this work how a sub-100 GeV $Z'$ in a $U(1)$ extension of the Standard Model (SM) can emerge through Higgs mediated channels at the Large Hadron Collider (LHC). The light $Z'$ has minimal interaction with the SM sector as well as vanishing kinetic mixing with $Z$ boson which allows it to be light and below the SM gauge boson masses. Interestingly such a light $Z'$ is very difficult to observe in the standard production modes. We show that it is possible to observe such a gauge boson via scalar mediators that are responsible for the symmetry breaking mechanism of the model. The model also provides a dark matter candidate whose compatibility with the observed relic density is established due to the light $Z'$. We also comment on other interesting possibilities such as a light $Z'$ may present for other observables.

The new century while welcoming the discovery of a 125 GeV scalar [1, 2] which completed the Standard Model (SM) picture of observed particle spectrum, also opened us to the realm of the unknown structure beyond it. Despite the remarkable success of the SM, several unexplained observations from experiments, be it the neutrino mass or the existence of dark matter (DM) have always hinted at the possibility of new physics beyond the SM (BSM). However the sole discovery of the Higgs boson and nothing else at the Large Hadron Collider (LHC) has cast a shadow on what that exact possibility may be. In addition, the true nature of the observed scalar and its confirmation of being the SM Higgs will only be possible, once its interactions are precisely measured leaving its confirmation of being the SM Higgs only will be possible, once its interactions are precisely measured leaving us with the possibility of new physics within the scalar sector itself. Another fact that cannot be wished away on the non-observation of any other new physics signal could be the possibility of very weakly interacting particles hidden in the LHC data which may emerge in channels yet to be looked at by the experiments. In this work we shall try to highlight signals of such a symmetry which may be lurking under the shadow of the Higgs discovery while providing a solution to both the neutrino mass problem as well as DM signals.

We consider the neutrinophilic $U(1)_X$ model [3] studied in an earlier work featuring multi-lepton signals at the LHC through heavy neutrino production. A crucial part in that analysis was played by the non-vanishing gauge kinetic mixing (GKM) of the SM $U(1)_Y$ with the new $U(1)_X$ symmetry, $g_x$. However, in the vanishing GKM limit we highlight an interesting signal that could directly probe $Z'$ and provide a robust signal within the reach of future runs of the LHC. In addition, the vanishing GKM also leads to the possibility of the $Z'$ in the model to become dominantly leptophilic. This happens when the decay of $Z'$ is driven by one-loop contributions over the tree-level mode, provided we choose a conducive set of values for a few parameters. Thus one can summarise several interesting possibilities in a common framework:

- A light sub-100 GeV $Z'$ signal at the LHC via Higgs production.
- A compatible fermionic DM with the correct relic density ensured by the presence of the light $Z'$.
- Neutrino mass generation via inverse-seesaw mechanism [3].
- Lepton flavor violating (LFV) signal at one-loop through $Z'$ decay and possible contribution to lepton anomalous magnetic moments.

We focus on the first two aspects of the model in this work while commenting on LFV signals at experiments with some initial observations. The search for $Z'$ boson put strong limits on its mass and interaction properties [4, 5]. In our case, an interesting scenario arises where the $Z'$ can be lighter than SM gauge boson masses and can evade bounds from the existing $Z'$ search due to vanishing interactions with the SM fermions. For such a $Z'$ we show that the most promising mode becomes the Higgs mediated production, where the scalar responsible for the $U(1)_X$ breaking and the SM Higgs responsible for electroweak (EW) symmetry breaking mix with each other. As the $U(1)_X$ symmetry is broken by a singlet scalar, its admixture with the observed scalar at the LHC leaves a significant parameter space of this neutrinoophilic model allowed by existing constraints, which can lead to $Z'$ production at the LHC. A similar production mechanism in the context of $U(1)_{B-L}$ for a $Z'$ has been looked at in Refs. [6, 7]. However, to obtain a light $Z'$ in that model and to avoid LHC constraints, the gauge coupling $g_{B-L}$ is restricted to unnaturally small values. In our case, the new gauge coupling ($g_x$) remains naturally large with $g_2 \sim g_1 \sim g_x$, where $g_2, g_1$ are gauge

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* We ignore the possibility of generating neutrino mass radiatively in this study.
coulomb strengths for the SM $SU(2)_L$ and $U(1)_Y$ gauge symmetries, respectively.

The model is an extension of the SM with an extra $U(1)_X$ gauge group and four new fields, including two chiral sterile neutrinos ($N_L, N_R$) added for each generation, an additional Higgs doublet ($H_2$) and a scalar singlet ($S$). All the new fields are charged under $U(1)_X$ while all SM particles are neutral. The charge assignments of the new particles along with the first Higgs doublet ($H_1$) are listed in Table I. The new charge-neutral fermions are the only spin-1/2 fields which carry a $U(1)_X$ charge. This leads to coupling of the new gauge boson with neutrinos after symmetry breaking. With the assigned charges, the new Lagrangian added to the SM is given by (neglecting the kinetic terms)

$$\mathcal{L}_S \supset -\mu_1 H_1^+ H_1 - \mu_2 H_1^+ H_2 - \mu_3 S^\dagger S + \{\mu_{12} H_1^+ H_2 + \text{h.c.}\}$$

$$- \lambda_1 (H_1^+ H_1)^2 - \lambda_2 (H_2^+ H_2)^2 - \lambda_3 (S^\dagger S)^2 - \lambda_{12} |H_1^+ H_2|^2$$

$$- \lambda_{12} |H_1^+ H_1|^2 |H_2|^2 - \lambda_{13} |H_1|^2 |H_2^+ S|^2 - \lambda_{23} |H_2|^2 |S|^2,$$

$$\mathcal{L}_Y \supset -(Y_{\nu} L H_2 N_R + Y_{R} S N_R N_L^C + Y_L S N_L N_L^C + \text{h.c.}),$$

$$\mathcal{L}_M \supset -\tilde{M}_N (\tilde{N}_L N_R + \tilde{N}_R N_L).$$

(1)

We refer the readers to Ref. [3] for more details on the model Lagrangian, the mass and mixing of the fermions, scalars and gauge bosons. After the spontaneous breaking of EW and $U(1)_X$ symmetries, we are left with three CP even neutral Higgses, a charged Higgs and a pseudoscalar Higgs with mass $m_A = \sqrt{\mu_{12}^2 + \mu_{13}^2 + \mu_{23}^2}$, where $v = \sqrt{v_1^2 + v_2^2} \approx 246 \text{ GeV}$ ($v_{(2)}$) being the vacuum expectation value (VEV) of $H_{1(2)}$ while $\mu_{12}$ is the coefficient of the soft-breaking term\(^2\) in the scalar potential to avoid a massless pseudoscalar. In this work we only focus on the CP-even scalars which play a crucial role for $Z'$ signal.

The CP-even scalar mass matrix in the $(\rho_1 \rho_2 \rho_3)^T$ basis [3] is given by

$$M_H^2 = \begin{pmatrix} 2\lambda_{12} v_1^2 + \mu_{12} v_1 v_2 & \lambda_{12} & \lambda_{13} v_1 v_3 \\ \lambda_{12} & 2\lambda_{23} v_2^2 + \mu_{13} v_1 v_2 & \lambda_{23} v_2 v_3 \\ \lambda_{13} v_1 v_3 & \lambda_{23} v_2 v_3 & 2\lambda_{23} v_3^2 \end{pmatrix},$$

(2)

where $\lambda_{12} = (\lambda_{12} + \lambda_{13}^2) v_1 v_2 - \mu_{12}$. We identify the three CP-even mass eigenstates ($h_1, h_2$ and $h_3$) as linear combinations of the flavor states and can be written as $h_i = Z_{ij}^h \rho_j$, where $Z_{ij}^h$ represents the mixing matrix for the CP-even states. For our analysis we identify $h_1$ as the 125 GeV SM Higgs boson observed at the experiments and treat $h_2$ as the singlet dominated scalar. The other CP-even state along with the pseudoscalar and charged Higgs (belonging primarily to the $H_2$ doublet) are taken to be degenerate in mass and very heavy ($> 3 \text{ TeV}$). We shall work in the limit $\tan \beta \ll 1$ where $\tan \beta = v_2/v_1$ such that the only relevant admixture that $h_1$ has is from the singlet scalar which is parametrised by the mixing matrix component $Z_{13}^h$.

The next relevant mixing term which is of importance is the GKM which allows $Z'$ to directly interact with the SM fermions. A vanishing value for this mixing would imply that the $Z'$ would couple very weakly to any of the SM fermions, making its direct production very difficult at a collider experiment such as the LHC [3]. We show in Eq. (3) the $Z-Z'$ mixing angle as a function of the gauge couplings and VEVs [3],

$$\tan 2\theta' = \frac{2g_2 (g'_s v_2^2 + 2g_x v_2 v_3^2)}{g_2^2 v_2^2 + 4g_x^2 v_3^4 + 4g_2^2 (v_2^2 + 4v_3^2) - g_4^2 v_2^2},$$

(3)

A natural choice of the mixing between $Z$ and $Z'$ is to choose it to be vanishingly small, such that it does not modify the $Z$ boson couplings with the SM fields. This can be easily achieved for $\tan \beta \ll 1$ and $g'_s \simeq 0$, which in turn allows the $U(1)_X$ gauge coupling $g_x$ to be relatively large.

The main highlight of this work is to show how the Higgs sector of the model can play a crucial role in producing the otherwise hidden $Z'$. To do that we need to however ensure that the scalar sector still satisfies constraints including that of the observed Higgs boson mass and its decay probabilities [8, 9]. The publicly available packages, HiggsSignals [10] and HiggsBounds [11, 12] provide us with compatible points. The model can also accommodate a DM candidate by appropriately choosing one of the Yukawa couplings ($\nu_4$ and $\nu_5$) to be very small. In order to ensure that we have a DM in the model, we find that a pair of the heavy neutrinos ($\nu_4$ and $\nu_5$), degenerate in mass become stable if the Yukawa coupling $Y_{\nu_1} \sim 10^{-27}$ and $Y_{\nu_3} = Y_{\nu_1} = 0$. This makes the decay lifetime of the heavy fermions larger than the age of the Universe. This however also makes the DM coupling to any of the SM states very weak, leading to an overabundant DM. The viability of the DM with the correct relic density is re-enforced with the spectrum having non-SM lighter states to which the DM can annihilate into. This easily motivates us to choose the singlet scalar and $Z'$ much lighter than the DM particle such that the dominant annihilation channels for the DM become $\nu_4 \nu_5 \rightarrow h_2 Z'$ (t-channel via $\nu_4$ and $\nu_5$),

\(^2\) This term can be generated dynamically by adding new scalars to the model.
FIG. 1. The relic density $\Omega h^2$, the SD and SI DM-nucleus scattering cross sections as a function of DM mass and gauge coupling $g_x$.

| $\lambda_1$ | $\lambda_2$ | $\lambda_{12}$ | $\lambda_{24}$ | $\mu_{12}$ (GeV)$^2$ | $v_4$ (GeV) | $g_x$ | $\tan \beta$ | $m_{h_1}$ (GeV) | $m_{h_2}$ (GeV) |
|-------------|-------------|-------------|-------------|-----------------|------------|-----|---------|----------------|----------------|
| 0.12875     | 1.0         | 0.005      | 0.005      | 10^4            | 100        | 10^{-3} | 125.0   | 144.5          |

TABLE II. Scalar sector parameters and masses consistent with all experimental constraints.

$\nu_4\nu_4 \rightarrow Z'Z'$ ($h_2 h_2$), $\nu_3\nu_5 \rightarrow Z'Z'$ ($h_2 h_2$), all interacting via the unsuppressed $g_x$ coupling strength. We fix our scalar parameters such that the $h_1$ is SM-like with mass $m_{h_1} \approx 125$ GeV and the singlet $S$ dominated $h_2$ has mass $m_{h_2} \approx 144.5$ GeV, while the others are very heavy. As our focus lies in showing the scenario where a light $Z'$ could be observed at the LHC through the Higgs mediated channel, the relevant parameters that take center stage in our analysis are the gauge coupling $g_x$ that affects the $Z'$ mass and the quartic coupling $\lambda_{14}$ which would affect the scalar sector mixing between the $H_1$ and $S$ components. We therefore scan over the parameters and show the DM relic and the corresponding spin-dependent (SD) and spin-independent (SI) direct detection cross sections in Fig. 1. The parameter choices and the relevant scalar masses are shown in Table II. Quite clearly we can find a wide range of values for the DM in the model to satisfy the relic density requirements of $\Omega h^2 = 0.120 \pm 0.001$ at 90% CL [13] which is also allowed by XENON1T [14, 15] constraints on direct detection cross section, notwithstanding the fact that the indirect detection constraints are easily satisfied in the given range due to the suppressed couplings with SM particles.

We are now ready to analyse the light $Z'$ signal at the LHC based on the choice of parameters given in Table II. Note that the mixing $Z'_{13}$ plays a crucial role in the pair production of $Z'$ at the LHC via scalar mediators as it dictates how much of the singlet admixture is required to have a substantial production cross section for $Z'$ pair. This interplay of $Z'$ coupling with the singlet scalar with gauge coupling $g_x$ strength while the two scalars being produced through the gluon-gluon fusion gives us a unique opportunity to study a $Z'$ which hardly interacts with the SM fermions and therefore cannot be produced directly at the experiments. The scalar responsible for giving a mass to it becomes the mediator that would eventually produce it and help in its detection at experiments. Therefore we focus on the process

$$pp \rightarrow h_{1,2} \rightarrow Z'Z'$$

at the LHC to show how this can help in detecting a light $Z'$. Such a light $Z'$ could have easily evaded direct searches in the absence of GKM ($g'_{x} \lesssim 10^{-5}$) and small $\theta \lesssim 10^{-5}$ since the production of $Z'$ via fermion interaction is rendered negligible at the LHC.

We show the $Z'$ pair production cross section at the LHC in Fig. 2. A clear feature emerges from the scan over the light $Z'$ mass ($75 \text{ GeV} > M_{Z'} > 20 \text{ GeV}$) and the mixing parameter ($0.12 > |Z'_{13}| > 0$) in the Higgs sector. An upper bound on the allowed deviations in the SM Higgs branching to new modes (including invisible) gives us a corresponding upper bound on $Z'$ pair production via the Higgs mediators which is highlighted as the hatched region obtained using HiggsSignals in Fig. 2. Note that the relevant part of the bound only applies to the region where the SM Higgs is produced on-shell and then decays to a pair of $Z'$. However, the value of $Z'_{13}$ which indirectly affects the SM Higgs data would still extend the bound on the cross section beyond the on-shell $h_1$ production, encompassing the full range of $M_{Z'}$ as shown in the figure. This exclusion is more on the allowed mixing between the $h_1$ and $h_2$ states via $|Z'_{13}| > 0.12$ which then transcends to an exclusion on the cross section. The SM-like Higgs is the major contributor for $Z'$ production when $M_{Z'} \leq m_{h_1}/2$ while the singlet dominant $h_2$ becomes the dominant contributor beyond this mass range. Note that the contribution from the singlet dominated $h_2$ is more or less constant for $M_{Z'} \leq m_{h_2}/2$ since the decay branching of $h_2 \rightarrow Z'Z'$ is 100%. The off-shell contributions to the production...
fall rapidly for both $h_1$ and $h_2$ as evident from Fig. 2, although it could be a region of interest for the High Luminosity LHC (HL-LHC). We however must underline the importance of this production channel as this might be the only relevant channel of observation for a light $Z'$ which has no meaningful coupling with the quarks and charged leptons that could help in its direct production.

The challenge in production does not always manifest itself in the decay properties of such a particle, highlighted by the fact that even a decay width as small as $10^{-10}$ GeV would still lead to prompt decay of a weakly interacting particle in the detector. A similar scenario emerges for $Z'$, which at tree-level gets a total decay width of $\mathcal{O}(10^{-9} - 10^{-8})$ GeV for the given mass range in Fig. 2, leading to its prompt decay which is in fact driven by the GKM ($g_{Z'}^\nu$) as well as the choice of $\tan\beta$. Thus we expect $Z'$ to decay to visible charged lepton pair or dijet final states after being produced. The tree-level branching ratios for $Z'$ are shown in the right panel of Fig. 2. We assume the region of parameter space shown in Fig. 2 as representative points for the model and highlight the $Z'$ signal at the LHC and the prospect of its observation in the most sensitive 4$\ell$ channel. Although the 4$\ell$ channel is the most likely channel of observing the $Z'$ signal, other final states comprising of leptons and jets could also manifest as obvious channels of discovery. These channels are however likely to have a larger SM background to contend with, leading to lesser sensitivity. We use CheckMATE [16] to confirm how much of the region of interest is still allowed by experiments that have looked at leptonic final states with jets and missing transverse momentum. As the signal for $Z'$ would lead to signatures with $n\ell+m$ jets+$E_T^{miss}$ where $n=0-4$, $m=0-4$, we include the available analyses in CheckMATE to put an upper bound on the pair production cross section. This bound mainly arises out of the multi-lepton searches for supersymmetric electroweakinos [17] and is expectedly stronger as shown by the corresponding exclusion curve in Fig. 2. CheckMATE relies on the use of several relevant tools such as jet-finding algorithms [18, 19] in FastJet [20] and event reconstruction using Delphes-3 [21] to determine the exclusion conditions [22] on a model parameter space.

The most relevant and strongest bound however comes from a 4$\ell$ signal which was recently looked at by ATLAS [23]. The analysis gives a differential cross section measurement of the 4 lepton final state in the SM and has been included in the Rivet-3.1.4 [24, 25] package. This allows one to compare the experimental result directly with predictions of new physics models. We include our model output for the aforementioned final state and use the package Contur [26] to evaluate robust limits on the parameter space shown in Fig. 2. The robust search strategy presented in the ATLAS analysis can be also used to propose search sensitivity for $Z'$ and values of $Z_{13}'$ for high integrated luminosity options of the LHC. We have shown the sensitivity curves with 300 fb$^{-1}$ and 3000 fb$^{-1}$ integrated luminosity at the LHC, assuming a rather pessimistic view that similar efficiencies of the 13 TeV analysis could be applicable at the 14 TeV run. Note that we have not tried to present a study where we look for improvements in the existing ATLAS analysis as it covers nearly 50 different distributions in the relevant kinematic variables, which we believe is a very dynamic set for our scenario.

We have performed the analysis using the UFO files created by SARAH [27] where we follow the use of chain of packages MadGraph5@aMCNLO (v2.6.7) [28, 29] → Pythia 8 [30] → HepMC [31] → Rivet [24, 25] → Contur [26, 32]. The events for the analysis were generated using MadGraph5@aMCNLO and showered using Pythia 8. The HepMC output was then included in Rivet and run for the ATLAS analysis of Ref. [23]. The resulting YODA file that
contains the recast information of our model was then used by Contur to evaluate a likelihood fit and determine the exclusions on the model parameter space.

We find that a light $Z'$ which couples weakly to SM particles can lie hidden in the LHC data. The symmetry need not have an unnaturally small coupling to stay hidden but could simply be hidden due to its inability to interact directly with the SM sector. This kind of a structure not only allows a solution to the neutrino mass problem, as shown in an earlier work [3], but is also able to provide a viable thermal DM candidate without contriving to spoil the neutrino mass solution proposed in the model. In addition to these interesting possibilities we also comment on some far reaching consequences of arranging the Yukawa strength $Y_\nu$ to values of $\mathcal{O}(0.1)$. Note that the mixing of the light neutrino with heavy neutrinos is small and unlike the typical inverse seesaw-mechanism, the $\nu_\tau Z - \nu_j$ coupling as well as $\nu_j W - \ell$ coupling where $i = 1, 2, 3, j = 4 - 9$ remains very small due to the choice of very small tan $\beta$ values. This ensures that the lepton unitarity and corrections to the $W$ boson mass are easily satisfied. As we have argued earlier that the $U(1)_X$ gauge coupling can be naturally large ($\mathcal{O}(g_{_{\text{EW}}})$) in the model, radiative decays of $Z'$ become important since its tree-level couplings with SM fermions is small due to the small $Z$-$Z'$ mixing. The term $Y_\nu \ell \bar{l}_L H_2 N$ in the Lagrangian would determine whether the radiative corrections are meaningful or not. Note that for values of $Y_\nu \lesssim 10^{-3}$ and $g_{_{\text{EW}}} \sim 0.1$ the one-loop induced decays end up smaller to the tree-level decays. However, for $Y_\nu \sim 10^{-2}$ the loop induced decays as shown in Fig. 3 have amplitudes which are proportional to $Y_\nu^2$ and start becoming comparable to the tree-level modes. The one-loop contributions to the decay width of $Z'$ are in the range of $\sim \mathcal{O}(10^{-6} - 10^{-4})$ GeV as compared to the tree-level width of $\mathcal{O}(10^{-9} - 10^{-8})$ GeV for $Y_\nu \sim 0.1$. An immediate and interesting consequence of this result is that the $Z'$ behaves as a leptophilic boson with no decay to quarks. In a likely scenario of this happening, the $Z'$ decays to light neutrinos and charged leptons, contributing to the invisible decay mode of the SM-like Higgs when $M_{Z'} \leq m_{h_1}/2$. The invisible mode would render the search for such a $Z'$ at the LHC very challenging. The most likely place of discovery in such a scenario would be to look for it at future lepton colliders. A clever tuning of the Yukawa sector $Y_\nu$ however does spring the possibility of a LFV decay of $Z'$ via the loops, as considered in inverse seesaw models to search for LFV in Z decay [33–35]. We evaluate the one-loop decay width for $Z'$ where we keep all parameters consistent with the plot shown in Fig. 2 and only choose a $Y_\nu$ that reproduces the correct neutrino mass and the DM candidate as

$$Y_\nu = \begin{pmatrix} 10^{-27} & 0 & 0 \\ 0 & 0.21 & 0.08 \\ 0 & 0.08 & 0.19 \end{pmatrix}.$$ 

We find that the dominant decay, as one expects would be to the light neutrinos which constitutes nearly 80% of the branching probability while the rest go to the charged leptons $\mu^+\mu^-(7.9\%), \tau^+\tau^-(5.6\%)$ and $\mu^+\pi^-(6.5\%)$. The loop diagrams have been calculated with the help of Package-X [36] and LoopTools [37]. The branching probability to the exotic LFV modes could be arranged at the level of $5-10\%$ by suitably varying the $Y_\nu$ values. These LFV modes of $Z'$ could then clearly be observed at the LHC by focusing on the LFV searches in the Higgs decay which are of great interest [38]. A more promising scenario would be in machines vouched as Higgs factories [39–42] where the $h_1 \to Z'Z'$ mode can be looked at with more precision. A close examination of the parameter space that could lead to such possibilities is really very interesting but beyond the scope of this work, and we leave it for future studies.

To conclude, we have tried to show through this work that a light $Z'$ in a $U(1)_X$ extension of the SM can be easily hidden in the LHC data if the new symmetry does not speak to the SM sector directly. We motivate such a scenario through the neutrino sector by introducing a neutrino philic $U(1)$ which can also provide a DM candidate. The weakly interacting DM candidate gives the correct relic when $Z'$ is lighter. We then highlight how such a light $Z'$ can be produced at the LHC via the Higgs channel and existing LHC searches for such modes could be sensitive to a significant parameter space of such a model. An interesting consequence of the model is the decay of $Z'$ via one-loop. In the absence of direct coupling with the SM fields, the $Z'$ can decay via one-loop and behaves as a leptophilic gauge boson. The typically non-diagonal mixing in the light and heavy neutrino states and the structure of the $Y_\nu$, Yukawa coupling matrix can lead to LFV decays of $Z'$ which leads to interesting signatures of the model that can be looked for at the LHC and future lepton colliders.
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* awaleed@sci.cu.edu.eg
† anjanbarik@hri.res.in
‡ skrai@hri.res.in
§ tousiksamui@hri.res.in