**W** boson mass, dark matter and $(g - 2)_\mu$ in ScotoZee neutrino mass model

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We present a model of radiative neutrino masses, Scotogenic model with a singly charged scalar (ScotoZee model), which resolves recently reported deviations in $W$ boson mass as well as lepton $g - 2$, and naturally admits a scalar or a fermion dark matter. We find that the mass splitting, of $\sim 100$ GeV among the inert doublets fields, required by the shift in $W$ boson mass can be evaded by introducing a singlet scalar, which also is a key to resolving $(g - 2)_\mu$ (also, $(g - 2)_{\mu\tau}$) anomaly with in $1\sigma$. We show consistency of this framework with dark matter relic abundance, while satisfying constraints from charged lepton flavor violation, direct detection as well as collider constraints. We show that the model gives predictions for the lepton flavor violating processes testable in upcoming experiments.

**Introduction:** The CDF collaboration at Fermilab [1] reported a precision measurement of $W$ boson mass, $M_W^{CDF} = (80.4335 \pm 0.0094)$ GeV, which is in tension with the Standard Model (SM) prediction, $M_W^{SM} = (80.357 \pm 0.004)$ GeV [2] with an excess at $7\sigma$ level, which may be an indication of new physics (NP) beyond the Standard Model (SM). Some possible explanations to the $W$ boson mass shift that break custodial symmetry can arise at tree level [3–18], or at loop level [19–35], along with the prospect of reconciling one or more discrepancies [36–54] such as flavor anomalies and dark matter. Several other papers [55–83] also examine the consequence of the CDF $M_W$ anomaly on new physics scenarios.

Independently, muon $(g - 2)$ collaboration at Fermilab [84] has confirmed the long standing discrepancy in the anomalous magnetic moment (AMM) of muon measurement at BNL in 2006 [85] at a combined $4.2\sigma$ deviation, $\Delta a_{\mu}^{exp} = (2.51 \pm 0.59) \times 10^{-9}$, from the SM prediction [86]. In addition to these recent anomalies, astrophysical and cosmological observations [87–89] has provided a compelling evidence for the existence of dark matter (DM), for which the SM fails to provide an explanation. Moreover, one of the major shortcomings of the SM is its inability to explain the origin of non-zero neutrino mass substantiated by several experiments [90].

In this work we show that by a simple extension of the Scotogenic model [91] with the charged singlet (ScotoZee model) can simultaneously address all the puzzles previously mentioned. Our novel ScotoZee model\(^1\) is the simplest model that furnish a direct link between neutrino mass generation, dark matter, AMM of muon and also provide an upward mass shift in $W$ boson in agreement with the CDF measurement. Additionally, the presumed anomaly in the AMM of electron [96–98] can also be addressed within the same framework. We explore the parameter space of the ScotoZee model spanned by both the bosonic and fermionic DM candidates, while being consistent with the current experimental constraints.

**Model:** The proposed ScotoZee model is a simple charged singlet $S^+ (1, 1; -)$ extension of the Scotogenic [91] model, which contains Majorana singlet fermions $N_{R_i} (1, 0; -)$ and the scalar doublet $(\eta^+, \eta^0) \equiv \eta (2, 1/2; -)$, under the gauge group $SU(2)_L \times U(1)_Y \times Z_2$. Note that all the new particles are odd under $Z_2$, whereas the SM particles are even which guarantees the stability of the DM candidate, the lightest among the new neutral $Z_2$-odd particles. The charged scalar singlet $S^+$ not only gives rise to anomalous magnetic moment of muon and electron via mixing with charged doublet, but also serve as portal to generate correct relic abundance for fermionic DM. This naturally interlink the AMM of lepton and dark matter with the small Majorana neutrino masses generated at one-loop order. The effective Yukawa Lagrangian in the extended model can be written as

$$Y_{ij} \bar{L}_i \bar{\eta} N_{R_j} + f_{ij} \bar{\tau}_{R_i} S - \bar{N}_{R_j} + h.c.$$  \hspace{1cm} (1)

The $Z_2$ symmetry, being exact, prevents $\eta^0$ from obtaining a non-zero vacuum expectation value (VEV) and neutrinos remain massless at tree level. Moreover, the SM Higgs $h$ is decoupled from the new $CP$-even $(Re(\eta^0) \approx H)$ and -odd $(Im(\eta^0) \approx A)$ scalars. The charged scalars $\{\eta^+, S^+\}$ mix giving rise to mass eigenstates $\{H^+_1, H^+_2\}$.

The masses of the scalar fields in the physical basis are:

$$m_h = \lambda_1 v^2, \quad m_{H(A)}^2 = \mu_a^2 + \frac{v^2}{2} (\lambda_3 + \lambda_4 \pm \lambda_5),$$  \hspace{1cm} (2)

$$m_{H^+_1}^2 = \frac{1}{2} \left( \mu_2 + \mu_3 \pm \sqrt{(\mu_2 - \mu_3)^2 + 2\mu_1^2 v^2} \right),$$

where, $\mu_2 = \mu_{\eta}^2 + \frac{\lambda_2}{2} v^2$, $\mu_3 = \mu_{S}^2 + \frac{\lambda_3}{2} v^2$. Here $\mu_{\eta,S}, \lambda_i$,
and $\mu$ are the bare-mass terms, quartic couplings, and cubic coupling. The mixing angle between the charged scalar fields is given by

$$\sin 2\theta = \frac{-\sqrt{2}\mu v}{m_H^2 - m_\eta^2}.$$  

with the VEV $v \simeq 246$ GeV. In this work, we comply with the perturbative and vacuum stability conditions [99, 100] constraining the scalar couplings. The Majorana mass term $\frac{1}{2} M_N N_i N_i$ along with the scalar quartic term $\frac{\lambda}{8} \{ (\phi^\dagger \eta)^2 + \text{h.c.} \}$ breaks the lepton number by two units, allowing for the one-loop generation of neutrino mass $M_\nu$ as given in Fig. 1 (top). This can be expressed as

$$(M_\nu)_{ij} = \sum_k Y_{ik} \Lambda_k Y^*_{kj},$$

$$\Lambda_k = \frac{M_N}{16\pi^2} \left[ \frac{m_H^2}{m_H^2 - M_N^2} \log \frac{m_H^2}{M_N^2} - (m_H \leftrightarrow m_A) \right].$$

Here the lightest mass eigenstates $\{H, A\}$ and $N_i$ can serve as viable bosonic and fermionic DM candidates. It is important to point out that unlike the Scotogenic model, where $M_N$ can be at canonical seesaw scale of $10^9$ GeV or the Yukawa coupling $Y$ arbitrarily small, the $(g-2)_\mu$ in the model requires the scale to be in the (sub) TeV range along with $O(0.1 - 1.0)$ Yukawa coupling. Thus, a successful explanation of $m_\nu \sim 0.1$ eV would naturally require $m_H$ to be nearly degenerate with $m_A$.

**Correction to W boson mass:** The shift in W boson mass [101] can be evaluated as a function of the oblique parameters, $S$, $T$ and $U$ [102, 103] that quantify the deviation of a new physics model from the SM through radiative corrections arising from shifts in gauge boson self-energies. The oblique parameters in our model get corrections from the extended Higgs sector which is same as in Zee model [104] except for the $\mathbb{Z}_2$ charges preventing the mixing between the SM and the extra Higgs doublets. So we use the expressions for $S$, $T$ and $U$ given in [105] under the alignment limit [106]. The corrections to $U$ at one-loop level is suppressed compared to $S$ and $T$.

With the new precision measurement of $M_W$ by CDF, it is reasonable to expect some electroweak (EW) observables to suffer from new tensions. We incorporate the global EW fit performed by Ref. [4] with the new CDF data to quote the $2\sigma$ allowed ranges of oblique parameters. We confirm the necessity of mass splitting in 2HDM [24, 25] to accommodate the recent CDF results and show that the introduction of the charged singlet scalar allows the components of the inert doublet fields to be degenerate as can be seen from Fig 2, opening up the parameter space for scalar DM. The splitting $\delta_H = m_{H^+} - m_H$ depends on the mixing angle, for instance, it can be at most $\sim 140$ GeV for $\sin \theta = 0.2$.

**Muon’s Magnetic Moment:** The charged scalar contributions to anomalous magnetic moment at one-loop [107] as shown in Fig. 1 (bottom) is

$$\Delta a_\mu^{H_1^+} = \frac{m_\ell^2}{16\pi^2} \left( |Y_\ell| \sin^2 \theta + |f_\ell|^2 \cos^2 \theta \right) G[m_{H^+}, 2] + \frac{M_N}{m_\ell} \text{Re}(Y_\ell f_\ell^*) \sin 2\theta G[m_{H^+}, 1],$$

where,

$$G[M, \varepsilon] = \int_0^1 \frac{x^\varepsilon (x - 1)}{m_\ell^2 x^2 + (M^2 - m_\ell^2)x + M_N^2 (1 - x)}$$

![FIG. 1: Radiative neutrino mass generation at one-loop (top). The dominant correction to AMMs arising through the chiral enhancement (bottom). The cross (×) represents mass insertion whereas $\ell = e, (\mu)$ for electron (muon) AMM.](image1)

![FIG. 2: Mass splitting between the components of doublet scalar required by the new CDF measurement of W boson mass using 2σ ranges for S and T from Ref. [4]](image2)
and $\Delta \alpha^\mu_3 = \Delta \alpha^H_3 (\theta \rightarrow \frac{\pi}{2} + \theta)$. The dominant contribution to $\Delta \alpha^\mu_3$ comes from the Majorana neutrino mass enhancement aided by the mixing of the charged scalar mediators as shown in Fig. 1 (b). The sign of the product of Yukawa couplings and the mixing angle can be chosen independently of each other. This in turn allows for the simultaneous explanations of $\Delta \alpha^\ell_3 (\ell = \mu, e)$. Any choice of $Y_{i\ell} f^{\pm}_{i\ell}$ can explain $(g-2)_\mu$. Moreover, we find the upper limit on mass of Majorana neutrino (charged scalar) from $\Delta \alpha^\mu_3$ is of order 15 (6.5) TeV by allowing the Yukawa of $f, Y \leq 1$. The mass limit is more relaxed in the case of $(g-2)_e$.

Note that the Yukawa couplings and the masses of charged scalars are severely restricted by the cLFV processes such as radiative decay $\ell \rightarrow \ell \gamma$ [108]; such processes are enhanced in our model by the mass insertion of Majorana neutrinos. Moreover, though trilepton decay such $\mu \rightarrow 3e$ do not occur at tree-level, they can occur at the loop-level and contribute large branching ratios as shown in Ref. [109]. The same is also true for $\mu - e$ conversion in the nuclei. We impose these constraints in our parameter scan.

**DM Phenomenology:** In addition to explaining $W$ boson mass shift and $\Delta \alpha^\ell$, the proposed model can easily accommodate both the scalar (lightest of $H$ and $A$) and fermionic (lightest among $N_i$) dark matter candidates ($\chi$). We consider both options and analyze the parameter space by implementing the model in **SARAH** [113] and numerically evaluating the relic abundance using the software **MicrOMEGAs** [114]. The relic density of DM is achieved through standard thermal freeze-out mechanism.

For the case of Majorana fermion as a DM ($\chi \equiv N$) candidate, the annihilation channel which determines the observed relic density are DM self-(co-)annihilation into charged leptons $\ell^+_\alpha \ell^-_\beta$ (light neutrinos $\nu_\alpha, \nu_\beta$) through $t$-channel processes mediated by the $Z_2$-odd scalars, $H^\pm_1$ ($H, A$) via Yukawa couplings $Y$ and/or $f$. Note that neutrino masses and oscillations determine the flavor structure of $Y$, thus it is natural to take $Y$ relatively small and doublet scalar $\eta$ mass heavy $\sim \mathcal{O}$ (TeV), such that LFV constraints are automatically satisfied. Thus, we chose $f_{ii} = 1$ ($i = 1, 2$) and degenerate $N_i$ to maximize the contribution to annihilation of $\chi \chi \rightarrow \ell \ell$ via $S^+$; the allowed region of parameter space in the mass plane can be seen in Fig 3 (top) along with allowed region for muon AMM for specific choice of $\kappa = Y^* f \sin \theta = 0.015$.

In the case of scalar dark matter, which we choose to be the CP-even $H \equiv \chi$ (nearly degenerate with $A$ and $\lambda_5 < 0$), pair of DM can annihilate to $W^+W^-$, $ZZ$, $\nu_\alpha\nu_\beta$, $h h$, $\ell \ell$, and $q\bar{q}$. The low mass regime suffer a strong constraint form LEP [112] which can be fulfilled if one assumes $m_\chi > M_Z/2$, $m_{H^+_1} > M_W/2$ and $m_{H^+_1} + m_\chi > M_W$. For larger DM mass, it dominantly annihilates to pair of $W^+W^-, ZZ$, for which the allowed region is $m_\chi > 500$ GeV and mass splitting $\delta_{H^+} = m_{H^+_1} - m_\chi \lesssim 30$ GeV as shown in Fig. 3 (bottom). This can be relaxed by making the Higgs quartic coupling larger $\gtrsim 1$, however, such a choice is strongly constrained by direct detection bound [116–119].

In this work we take the $\lambda_3 + \lambda_4 + \lambda_5 \ll 1$ to automatically satisfy direct detection bound obtained from DM interacting with nucleus through tree level Higgs $h$ boson. Moreover, it is favoured to take couplings $Y_{\alpha\beta}$ small and

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2 The mass splitting is of order $\mathcal{O}(100)$ keV [115] to evade direct detection.
FIG. 4: Biased scattered plot assuming the fermionic DM with the same parameter space given in Fig. 3 (top). Colored shaded regions are the current exclusion limit [120], where as dotted-dashed line represents the future projected sensitivity [121]. Green dots correspond to solutions that satisfies $(g - 2)_{\mu}$, observed relic density as well as neutrino oscillation observables with in their $2\sigma$ measured values [122].

$M_N$ to be large from neutrino fit, which implies that the model is indistinguishable from the known inert doublet model (IDM). It turns out that the CDF measurement disfavours simple Scotogenic/IDM while simultaneously satisfying the correct relic abundance. However, the mixing of the charged doublet with the new charged singlet scalar evades this complication in our model, allowing the $CP$-even $H$ to be a viable DM candidate, as shown in Fig. 3 (bottom).

**Neutrino Fit/ Lepton Flavor violation:** The neutrino mass formula of Eq. (4), muon $g - 2$ and the dark matter analysis have close-knit correlation through Yukawa matrix $Y$, Majorana fermion, and new scalars. As mentioned before, simultaneous explanation of muon $g - 2$ and neutrino mass fixes the upper bound on the doublet scalar masses, there by forcing the parameter space in the region $m_A \simeq m_H$. In order to check the consistency with the neutrino oscillation data and efficiently probe the model with LFV observables, we adopt Casas-Ibarra parametrization from Ref. [123] to rewrite the Yukawa matrix $Y$ of Eq. (4) in terms of neutrino mass parameters

$$Y = \sqrt{\Lambda}^{-1} R \sqrt{M_{\nu}^{\text{diag}}} U_{\text{PMNS}}^\dagger,$$

where $R$ is an arbitrary complex orthogonal matrix. The neutrino oscillation parameters are scanned to within the $2\sigma$ allowed ranges from Ref. [122] to obtain the Yukawa matrix. As mentioned before, product of Yukawa couplings $Y_{ii}f_{ii}$ can explain $(g - 2)_{\mu}$, however $Y_{12}f_{2i}$ is severely constrained by $\mu \rightarrow e\gamma$ [124] due to the Majorana fermion mass enhancement. This chiral enhancement to $\mu \rightarrow e\gamma$ is avoided by choosing $f_{ii}(i = 1, 2)$ nonzero and $Y_{12} = Y_{21} = 0$. We then compute the branching fractions for $\ell_i \rightarrow \ell_j \gamma$ and $\ell_i \rightarrow 3\ell_j$ process at one-loop level as stated before. This allows us to check the consistency of our fit with LFV and make testable predictions for fermionic DM (see Fig. 4) whereas, in the case of scalar DM, since Yukawa coupling $f$ does not play any role in relic abundance, there is more freedom in the choice of parameters and yield no sizeable predictions.

**Conclusions:** In the light of recent experimental results confirming a $4.2\sigma$ discrepancy in the measurement of $(g - 2)_{\mu}$ and a possible $7\sigma$ excess in the mass of $W$ boson it is imperative to investigate new physics contributions for clarification. We propose the ScotoZee model, a simple charged singlet extension of the Scotogenic model, to show a direct correlation between these anomalies and the observed neutrino oscillation data as well as dark matter relic abundance. We explore the parameter space spanned by both the bosonic and fermionic dark matter candidates and provide a coherent resolution to the AMM and $M_W$ anomaly while evading dangerous LFV processes like $\mu \rightarrow e\gamma$ and $\mu \rightarrow 3e$, which are enhanced by the Majorana neutrino mass entering through the mixing of the charged scalars. In contrast to the simple Scotogenic/IDM models, where the small mass splitting $\Delta_{H^+} = m_{H^+} - m_H$ required for the production of observed relic abundance is disfavored by the CDF measurement, the scalar DM candidate in our model survives due to the presence of the extra charged singlet. This model predicts large rates for LFV process $\tau \rightarrow \ell \gamma$ which can be tested in the future experiments.

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**Appendix A: Scalar potential**

The most general renormalizable scalar potential of the ScotoZee model is given by:

$$V = \mu_\phi^2 \phi^\dagger \phi + \mu_\eta^2 \eta^\dagger \eta + \frac{\lambda_1}{2}(\phi^\dagger \phi)^2 + \frac{\lambda_2}{2}(\eta^\dagger \eta)^2 + \lambda_3(\phi^\dagger \phi)(\eta^\dagger \eta) + \lambda_4(\phi^\dagger \eta)(\eta^\dagger \phi) + \frac{\lambda_5}{2}(\phi^\dagger \phi)^2 + \text{h.c.}$$
$+ \frac{\lambda_6}{2} (S^- S^+)^2 + \lambda_7 (\phi^\dagger \phi)(S^- S^+) + \lambda_8 (\eta^\dagger \eta)(S^- S^+) + \frac{\mu_2}{2} [\varepsilon_{\alpha \beta} \phi^\alpha \eta^\beta S^- + \text{h.c.}]$. 

(8)

Appendix A: Oblique parameters

$\delta H_+ = 1 \text{ GeV}$

$\delta H_+ = 100 \text{ GeV}$

$\delta H_+ = 200 \text{ GeV}$

$\sin(\theta)$ as a function of charged scalar mass $m_{H^+}$ for different mass splitting between the doublet fields, $\delta_{H^+} = m_{H^+} - m_H$ (top) and mass of neutral scalars as a function of mass splitting between the doublet fields for different choices of charged singlet scalar mass (bottom). These plots show the parameter space required to explain the upward shift in $M_W$ reported by CDF measurement, consistent with the $2\sigma$ ranges of $S$ and $T$ from Ref. [29].

FIG. 5: Mixing angle $\theta$ as a function of charged scalar mass $m_{H^+}$ for different mass splitting between the doublet fields, $\delta_{H^+} = m_{H^+} - m_H$ (top) and mass of neutral scalars as a function of mass splitting between the doublet fields for different choices of charged singlet scalar mass (bottom). These plots show the parameter space required to explain the upward shift in $M_W$ reported by CDF measurement, consistent with the $2\sigma$ ranges of $S$ and $T$ from Ref. [29].

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