Dark Neutrino Portal to Explain MiniBooNE Excess

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We present a novel framework that provides an explanation to the long-standing excess of electronlike events in the MiniBooNE experiment at Fermilab. We suggest a new dark sector containing a dark neutrino and a dark gauge boson, both with masses between a few tens and a few hundreds of MeV. Dark neutrinos are produced via neutrino-nucleus scattering, followed by their decay to the dark gauge boson, which in turn gives rise to electronlike events. This mechanism provides an excellent fit to MiniBooNE energy spectra and angular distributions.

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Introduction.—Neutrinos have been connected to anomalies in experimental data since their commencement in the realm of physics. From the problems with beta decays in the dawn of the twentieth century, that culminated with the proposal and subsequent discovery of the first of these remarkable particles, to the solar and atmospheric neutrino puzzles, that revealed the phenomenon of neutrino oscillations driven by masses and mixings, the neutrino road has been full of surprises. Some, however, like the 17-keV neutrino [1] or the superluminal neutrinos [2] turned out to be mere bumps on the road as they were resolved by explanations unrelated to new physics. As it happens, one never knows which *small clouds* hovering on the horizon of physics will eventually vanish and which will instead ignite a revolution.

Even today some peculiar data anomalies remain unsolved. On one hand, there is an apparent deficit of $\bar{\nu}_e$ in short-baseline reactor experiments [3] and of ν_e in radioactive-source experiments [4], both amounting to a 2.5–3σ discrepancy that many believe may be connected to unknown nuclear physics. On the other hand, the liquid scintillator neutrino detector (LSND) [5] and MiniBooNE neutrino experiments [6–9] have reported an excess of ν_e and $\bar{\nu}_e$ charge-current quasielastic (CCQE) events in their data. All these conundrums have been offered a number of exotic interpretations in the literature [10–14], typically invoking eV sterile neutrinos in schemes easily in tension with other neutrino data [15–17].

Recently, after 15 years of running, MiniBooNE updated their analysis revealing that the excess of electronlike events in the experiment [18], consistently observed in the neutrino and antineutrino modes, is now a 4.8σ effect. That makes the MiniBooNE result the most statistically relevant anomaly in the neutrino sector. The origin of such excess is unclear—it could be the presence of new physics, or a large background mismodeling. In this Letter, we propose a phenomenological solution to understand the MiniBooNE data [19].

Framework.—We introduce a new sector dark [20] composed by a new vector boson $Z_{\mathcal{D}}$ coupling directly solely to a dark neutrino $\nu_{\mathcal{D}}$, which mixes with the standard ones as

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}\nu_i + U_{\alpha 4}N_{\mathcal{D}}, \quad \alpha = e, \mu, \tau, \mathcal{D}, \tag{1}$$

where ν_i and ν_α are the neutrinos mass and flavor eigenstates, respectively. The new vector boson will, in general, communicate with the standard model (SM) sector via either mass mixing or kinetic mixing. The relevant part of the dark Lagrangian is

$$\mathcal{L}_{\mathcal{D}} \supset \frac{m_{Z_{\mathcal{D}}}^2}{2} Z_{\mathcal{D}\mu}Z_{\mathcal{D}}^{\mu} + g_{\mathcal{D}}Z_{\mathcal{D}}^{\mu}\bar{\nu}_{\mathcal{D}}\gamma_\mu\nu_{\mathcal{D}} + e\epsilon Z_{\mathcal{D}}^{\mu}J_\mu^{\text{em}} + \frac{g}{c_W}\epsilon' Z_{\mathcal{D}}^{\mu}J_\mu^Z, \tag{2}$$

where $m_{Z_{\mathcal{D}}}$ is the mass of $Z_{\mathcal{D}}$ and $g_{\mathcal{D}}$ is the coupling in the dark sector, e is the electromagnetic coupling, g/c_W is the Z coupling in the SM, while ϵ and ϵ' parametrize the kinetic and mass mixings, respectively. The electromagnetic and

Z currents are denoted by $J_\mu^{\rm em}$ and J_μ^Z. For simplicity, we assume the mass mixing between the Z and the $Z_\mathcal{D}$ boson to be negligible. We resort to kinetic mixing between $B_{\mu\nu}$ and $B'_{\mu\nu}$ [28], the SM hypercharge and the dark field strengths, as a way to achieve a naturally small coupling between the $Z_\mathcal{D}$ and the electromagnetic current $J_\mu^{\rm em}$. We will take $m_{N_\mathcal{D}} > m_{Z_\mathcal{D}}$, so the dark neutrino can decay as $N_\mathcal{D} \to Z_\mathcal{D} + \nu_i$, and $m_{Z_\mathcal{D}} < 2m_\mu$ so the $Z_\mathcal{D}$ can only decay to electrons and light neutrinos. The dark neutrino decay width into $Z_\mathcal{D} + \nu$'s is simply

$$\Gamma_{N_\mathcal{D}\to Z_\mathcal{D}+\nu'{\rm s}} = \frac{\alpha_\mathcal{D}}{2}|U_{D4}|^2(1-|U_{D4}|^2)\frac{m_{N_\mathcal{D}}^3}{m_{Z_\mathcal{D}}^2} \times\left(1-\frac{m_{Z_\mathcal{D}}^2}{m_{N_\mathcal{D}}^2}\right)\left(1+\frac{m_{Z_\mathcal{D}}^2}{m_{N_\mathcal{D}}^2}-2\frac{m_{Z_\mathcal{D}}^4}{m_{N_\mathcal{D}}^4}\right), \quad (3)$$

while the $Z_\mathcal{D}$ decay width into e^+e^- and light neutrinos are, respectively,

$$\Gamma_{Z_\mathcal{D}\to e^+e^-} \approx \frac{\alpha\epsilon^2}{3} m_{Z_\mathcal{D}} \quad (4)$$

and

$$\Gamma_{Z_\mathcal{D}\to\nu\nu} = \frac{\alpha_\mathcal{D}}{3}(1-|U_{D4}|^2)^2 m_{Z_\mathcal{D}}. \quad (5)$$

We observe that as long as $\alpha\epsilon^2 \gg \alpha_\mathcal{D}(1-|U_{D4}|^2)^2$, $Z_\mathcal{D}$ will mainly decay into e^+e^- pairs.

For simplicity, we focus on the case in which both $N_\mathcal{D}$ and $Z_\mathcal{D}$ decay promptly. Taking the typical energy $E_{N_\mathcal{D}}, E_{Z_\mathcal{D}} \sim 1$ GeV, and assuming for simplicity $|U_{e4}|^2, |U_{\tau 4}|^2 \ll |U_{\mu 4}|^2$, we can estimate $\gamma c\tau_{N_\mathcal{D}} \approx 4\times10^{-8} m_{Z_\mathcal{D}}^2[{\rm MeV}^2]/(m_{N_\mathcal{D}}^4[{\rm MeV}^4]\alpha_\mathcal{D}|U_{\mu4}|^2)$ cm and $\gamma c\tau_{Z_\mathcal{D}} \approx 6\times10^{-8}/(m_{Z_\mathcal{D}}^2[{\rm MeV}^2]\alpha\epsilon^2)$ cm. So for $\alpha_\mathcal{D}\sim0.25$, $|U_{\mu4}|^2\sim10^{-8}$ and $\alpha\epsilon^2\sim2\times10^{-10}$, 5 MeV $\lesssim m_{Z_\mathcal{D}} < m_{N_\mathcal{D}}$ would guarantee prompt decay for both particles. We will see shortly that $m_{N_\mathcal{D}}$ and $m_{Z_\mathcal{D}}$ between a few tens to a few hundreds of MeV is exactly what is needed to explain the experimental data.

Analysis and results.—The MiniBooNE experiment is a pure mineral oil (CH_2) detector located at the booster neutrino beam line at Fermilab. The Cherenkov and scintillation light emitted by charged particles traversing the detector are used for particle identification and neutrino energy reconstruction, assuming the kinematics of CCQE scattering. MiniBooNE has observed an excess of 381 ± 85.2 (79.3 ± 28.6) electronlike events over the estimated background in neutrino (antineutrino) beam configuration in the energy range $200 < E_\nu^{\rm rec}/{\rm MeV} < 1250$ corresponding to 12.84×10^{20} (11.27×10^{20}) protons on target [18].

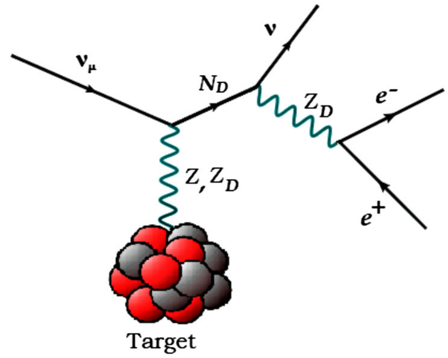

FIG. 1. Contributions to the cross section that in our model gives rise to MiniBooNE's excess of electronlike events.

Our proposal to explain MiniBooNE's low energy excess from the production and decay of a dark neutrino relies on the fact that MiniBooNE cannot distinguish a collimated e^+e^- pair from a single electron. Muon neutrinos produced in the beam would up-scatter on the mineral oil to dark neutrinos, which will subsequently lead to $Z_\mathcal{D}\to e^+e^-$ as shown schematically in Fig. 1. If $N_\mathcal{D}$ is light enough, this up-scattering in CH_2 can be coherent, enhancing the cross section. To take that into account, we estimate the up-scattering cross section to be

$$\frac{d\sigma_{\rm total}/dE_r}{\rm proton} = \frac{1}{8}F^2(E_r)\frac{d\sigma_{\rm C}^{\rm coh}}{dE_r} + \left(1-\frac{6}{8}F^2(E_r)\right)\frac{d\sigma_p}{dE_r}, \quad (6)$$

where $F(E_r)$ is the nuclear form factor [29] for carbon, while $\sigma_{\rm C}^{\rm coh}$ and σ_p are the elastic scattering cross sections on carbon and protons, which can be easily calculated. For carbon, $F(E_r)$ is sizable up to proton recoil energies of few MeV.

To obtain the spectrum of events, a simplified model was implemented in FeynRules [30] in which carbon and protons were taken to be an elementary fermion and events were generated in MadGraph5 [31]. Since MiniBooNE would interpret $Z_\mathcal{D}\to e^+e^-$ decays as electronlike events, the reconstructed neutrino energy would be incorrectly inferred by the approximate CCQE formula (see, e.g., Ref. [32])

$$E_\nu^{\rm rec} \simeq \frac{m_p E_{Z_\mathcal{D}}}{m_p - E_{Z_\mathcal{D}}(1-\cos\theta_{Z_\mathcal{D}})}, \quad (7)$$

where m_p is the proton mass, and $E_{Z_\mathcal{D}}$ and $\theta_{Z_\mathcal{D}}$ are the dark $Z_\mathcal{D}$ boson energy and its direction relative to the beam line. The fit to MiniBooNE data was then performed using the χ^2 function from the collaboration official data release [18], which includes the ν_μ and $\bar\nu_\mu$ disappearance data, reweighting the Monte Carlo events by the ratio of our cross section to the standard CCQE one, and taking into account the wrong sign contamination from Ref. [33]. Note that the official covariance matrix includes spectral data in

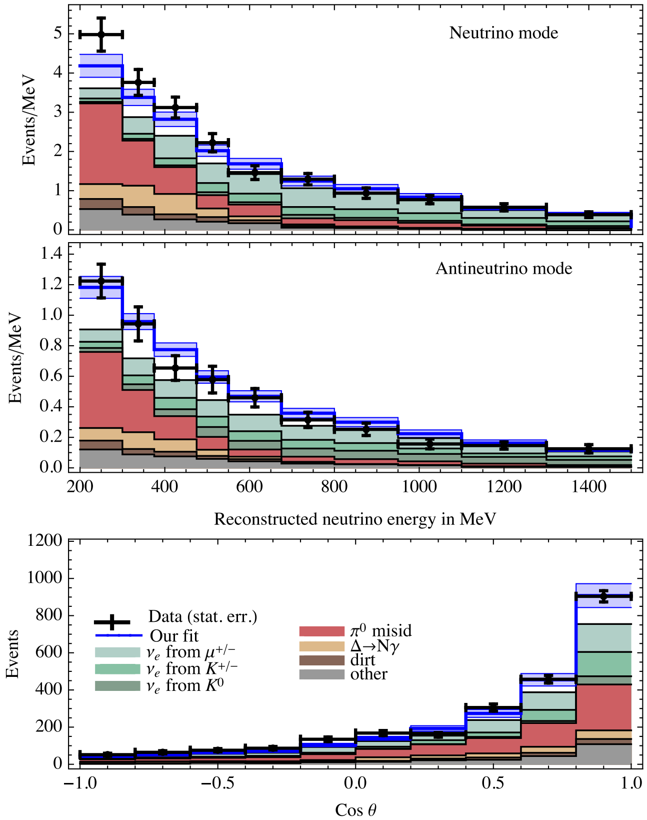

FIG. 2. The MiniBooNE electronlike event data [18] in the neutrino (top panel) and antineutrino (middle panel) modes as a function of $E_\nu^{\rm rec}$, as well as the $\cos\theta$ distribution (bottom panel) for the neutrino data. Note that the data points have only statistical uncertainties, while the systematic uncertainties from the background are encoded in the light blue band. The predictions of our benchmark point $m_{N_\mathcal{D}} = 420$ MeV, $m_{Z_\mathcal{D}} = 30$ MeV, $|U_{\mu 4}|^2 = 9\times 10^{-7}$, $\alpha_\mathcal{D} = 0.25$, and $\alpha\epsilon^2 = 2\times 10^{-10}$ are also shown as the blue lines.

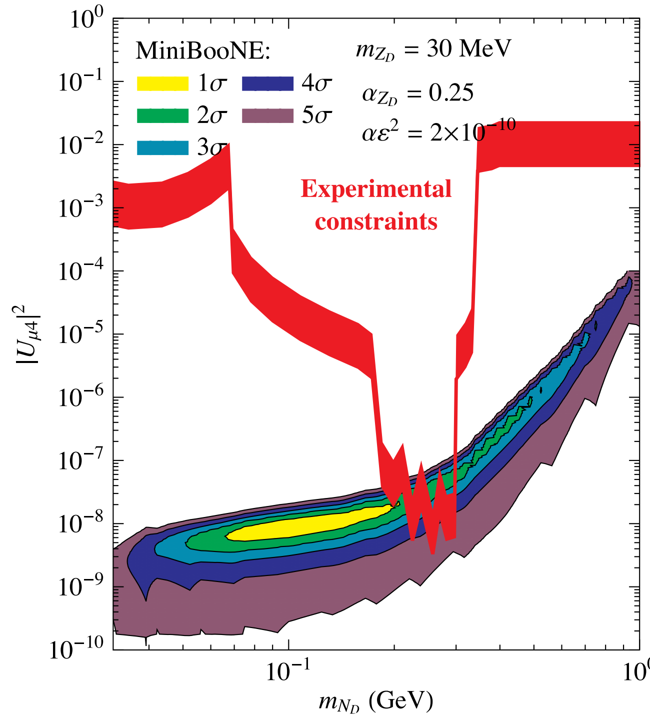

FIG. 3. Region of our model in the $|U_{\mu 4}|^2$ versus $m_{N_\mathcal{D}}$ plane satisfying MiniBooNE data at 1σ to 5σ C.L., for the hypothesis $m_{Z_\mathcal{D}} = 30$ MeV, $\alpha_{Z_\mathcal{D}} = 0.25$, and $\alpha\epsilon^2 = 2\times 10^{-10}$. The region above the red curve is excluded at 99% C.L. by meson decays, the muon decay Michel spectrum and lepton universality [35,36].

electronlike and muonlike events for both neutrino and antineutrino modes.

In Fig. 2 we can see the electronlike event distributions, including all of the backgrounds, as reported by MiniBooNE. We clearly see the event excess reflected in all of them. The neutrino (antineutrino) mode data as a function of $E_\nu^{\rm rec}$ is displayed on the top (middle) panel. The corresponding predictions of our model, for the benchmark point $m_{N_\mathcal{D}}=420$ MeV, $m_{Z_\mathcal{D}}=30$ MeV, $|U_{\mu 4}|^2 = 9\times 10^{-7}$, $\alpha_\mathcal{D} = 0.25$, and $\alpha\epsilon^2 = 2\times 10^{-10}$, are depicted as the blue lines. The light blue band reflects an approximated systematic uncertainty from the background estimated from Table I of Ref. [18]. On the bottom panel we show the $\cos\theta$ distribution of the electronlike candidates for the neutrino data, as well as the distribution for $\cos\theta_{Z_\mathcal{D}}$ for the benchmark point (blue line). The $\cos\theta$ distribution of the electronlike candidates in the antineutrino data is similar and not shown here and our model is able to describe it comparably well. We remark that our model prediction is in extremely good agreement with the experimental data. In particular, our fit to the data is better than the fit under the electron-Volt sterile neutrino oscillation hypothesis [18] if one considers the constraints from other oscillation experiments. We find a best fit with $\chi^2_{\rm bf}/{\rm dof} = 33.2/36$, while the background only hypothesis yields $\chi^2_{\rm bg}/{\rm dof} = 63.8/38$, corresponding to a 5.2σ preference for our model.

In our framework, as the dark boson decays dominantly to charged fermions, the constraints on its mass and kinetic mixing are essentially those from a dark photon [34]. In the mass range 20–60 MeV, the experiments that dominate the phenomenology are beam dump experiments and NA48/2. Regarding the dark neutrino, the constraints are similar but weaker than in the heavy sterile neutrino scenario with nonzero $|U_{\mu 4}|^2$ [35,36]. Since $N_\mathcal{D}\to\nu e^+e^-$ is prompt, limits from fixed target experiments like PS191 [37], NuTeV [21], BEBC [38], FMMF [39], and CHARM II [40] do not apply. Besides, $W\to\ell N\to\ell\nu e^+e^-$ in high energy colliders can constrain $|U_{\mu 4}|^2 >$ few $\times 10^{-5}$ for $m_{N_\mathcal{D}} > \mathcal{O}(\mathrm{GeV})$ [22]. Finally, we do not expect any significant constraints from the MiniBooNE beam dump run [41] due to low statistics.

In Fig. 3 we see the region in the plane $|U_{\mu 4}|^2$ versus $m_{N_\mathcal{D}}$ consistent with MiniBooNE data at 1σ to 5σ C.L., for the exemplifying hypothesis $m_{Z_\mathcal{D}} = 30$ MeV, $\alpha_{Z_\mathcal{D}} = 0.25$, and

$\alpha\epsilon^2 = 2 \times 10^{-10}$. Other values of these parameters can also provide good agreement with the data. We also show the combined nonoscillation bounds from meson decays, muon decay Michel spectrum, and lepton universality compiled in Refs. [35,36], which exclude the region above the red line. The ship hull shape region can be divided in two parts: a high mixing region at $|U_{\mu 4}|^2 \sim 10^{-4}$–$10^{-8}$, corresponding to $m_{N_\mathcal{D}} \gtrsim 300$ MeV, and a low mixing region for $|U_{\mu 4}|^2 \lesssim 10^{-8}$ and $m_{N_\mathcal{D}} \lesssim 200$ MeV. The latter seems to be favored by spectral data. As a side remark, we have checked that the typical opening angle $\theta_{e^+e^-}$ of the e^+e^- pair satisfy $\cos\theta_{e^+e^-} > 0.99$, ensuring that MiniBooNE will identify these events as electronlike.

The MicroBooNE experiment at Fermilab [42] is currently investigating the low energy excess of electronlike events observed by MiniBooNE. They can distinguish electrons from photon conversions into a e^+e^- pair by their different ionization rate at the beginning of their trajectory in the liquid argon detector. In addition our framework allows for the possibility of the experimental observation of the $K_L \to \nu_\mathcal{D}\nu_\mathcal{D}$, via off-shell $Z_\mathcal{D}$ exchange, by the KOTO or NA62 experiments as $\mathcal{B}(K_L \to \nu_\mathcal{D}\nu_\mathcal{D})$ can go up to $\mathcal{O}(10^{-10})$ for $m_{N_\mathcal{D}} < m_K$ [43].

We also have inquired into the possible effects of $N_\mathcal{D}$ and $Z_\mathcal{D}$ on oscillation experiments. While low energy sources, such as the Sun or nuclear reactors, do not have enough energy to produce these particles, they could be, in principle, produced in higher energy oscillation experiments. Typically ν_μ and $\bar{\nu}_\mu$ beams in accelerator neutrino experiments have an insurmountable $\mathcal{O}(1\%)$ contamination of $\nu_e + \bar{\nu}_e$, and atmospheric neutrinos have a large ν_e and $\bar{\nu}_e$ component. While Cherenkov detectors, like Super-Kamiokande, cannot distinguish between electrons and photons, detectors like MINOS, NOνA, or T2K would have a hard time seeing any signal over their neutral current contamination. That is particularly relevant at lower energies where one would expect the signal of new physics to lay.

In a different note, we do not foresee any issues with cosmological data, as the particles in the dark sector decay too fast to affect big bang nucleosynthesis, and the ν-ν self-interactions are too small to change neutrino free streaming. Supernova cooling would not constrain the model, as the $Z_\mathcal{D}$ is trapped due to the large kinetic mixing.

Finally, one may wonder if the phenomenological approach we propose here can arise in a UV-complete anomaly free model. We have checked that such realization is possible as follows. A gauge $U(1)_\mathcal{D}$ symmetry, under which the only charged fermions are the dark neutrinos, protects neutrino masses from the standard Higgs mechanism. An enlarged scalar sector is called upon to ensure nonzero neutrino masses, naturally leading to ν-$N_\mathcal{D}$ mixing, as well as the mass of the dark gauge boson. In this realization, both kinetic and mass mixing are unavoidable, but typically small. The model naturally connects neutrino masses with the new interaction [44]. We will explore the rich phenomenology of this model in detail elsewhere.

Conclusion.—We have shown that the low energy excess observed by MiniBooNE can by explained by a light dark sector to which neutrinos are a portal. The framework is elegant and no tuning is needed to fit the excess. We find an excellent agreement with spectral and angular data distributions, in both neutrino and antineutrino modes. This solution is consistent with all current experimental data and can be probed by liquid argon detectors in the near future.

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