

Constraints and sensitivities for dipole-portal heavy neutral leptons from ND280 and its upgrade

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We report new constraints and sensitivities to heavy neutral leptons (HNLs) with transition magnetic moments, also known as dipole-portal HNLs. This is accomplished using data from the T2K ND280 near detector in addition to the projected three-year dataset of the upgraded ND280 detector. Dipole-portal HNLs have been extensively studied in the literature and offer a potential explanation for the 4.8σ MiniBooNE anomaly. To perform our analysis, we simulate HNL decays to e^+e^- pairs in the gaseous time projection chambers of the ND280 detector and its upgrade. Recasting an ND280 search for mass-mixed HNLs, we find that ND280 data places world-leading constraints on dipole-portal HNLs in the 390–743 MeV mass range, disfavoring the region of parameter space favored by the MiniBooNE anomaly. The addition of three years of ND280 upgrade data will be able to disfavor the MiniBooNE solution at the 5σ confidence level and extend the world-leading constraints to dipole-portal HNLs in the 148–860 MeV mass range. Our analysis suggests that ND280 data excludes dipole-portal HNLs as a solution to the MiniBooNE excess, motivating a dedicated search within the T2K collaboration and potentially highlighting the need for alternative explanations for the MiniBooNE anomaly.

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I. INTRODUCTION

Heavy neutral leptons (HNLs) are massive gauge-singlet fermions that naturally couple to Standard Model neutrinos via mixing. They are a leading candidate for physics beyond the Standard Model (BSM), potentially explaining the origin of neutrino masses [1–5], the nature of dark matter [6–8], and the matter-antimatter asymmetry in the Universe [9–11]. In the minimal mass-mixing scenario, the HNL mass scale is unconstrained and typically determined by the Majorana mass scale of these additional right-handed states. The most effective experimental probe of HNLs changes with the mass scale [12]; eV-scale HNLs are probed by neutrino oscillation experiments [13–15], keV-scale HNLs by β -decay searches and γ /x-ray spectra [16,17], MeV-scale HNLs by rare pion and kaon decay searches [18–20] and supernova (SN) production [21], and GeV-to-TeV-scale HNLs by rare heavier meson decay

searches and collider experiments [22–24]. Dipole-portal HNLs are an extension of mass-mixed HNLs characterized by a dimension-five effective transition magnetic moment coupling to photons and Standard Model neutrinos. In the $\mathcal{O}(10\text{--}100)$ MeV mass regime, HNLs with a nonzero dipole coupling to muon neutrinos have been explored as an explanation to the longstanding excess of electronlike events observed by the MiniBooNE experiment [25–30]. Specifically, the single-photon decay channel of these HNLs can mimic the single-electron signature of a ν_e charged-current interaction in MiniBooNE. It has been shown that dipole-portal HNLs alone cannot explain the angular distribution of the MiniBooNE excess [31,32]. However, Refs. [33,34] showed that dipole-portal HNLs in combination with a small contribution from eV-scale sterile neutrino oscillations can explain the angular distribution of the excess without suffering from significant tension in global sterile neutrino data.

The T2K near detector, ND280, provides an ideal environment to search for rare neutrino interactions due to its proximity to the high-intensity J-PARC neutrino source [35–40]. It includes three low-density gaseous time projection chambers (TPCs), which can perform powerful low-background searches for dilepton decays of HNLs. There are also fine-grained detectors (FGDs) comprised of segmented scintillator strips. Dipole-portal HNLs can decay to e^+e^- pairs through an off-shell photon, motivating

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a search for these HNLs in the ND280 TPC data. This search can be improved in the upgraded ND280 detector, which will have five gaseous TPCs and a new super FGD comprised of scintillator cubes [39].

In this letter, we use data from the 2019 T2K search for mass-mixed HNLs in ND280 [41], which includes $12.34(6.29) \times 10^{20}$ protons-on-target (POT) in (anti)neutrino mode, to place constraints on dipole-portal HNLs. Additionally, we forecast the sensitivity of the ND280 upgrade, for which we assume 2×10^{22} POT in total [42]. Reference [43] excluded HNLs produced via mass-mixing in kaon decays in the ND280 decay pipe and detected via dipole-portal decays to single photons. We use the same detection mechanism, but instead consider production via dipole-portal upscattering of neutrinos in the ND280 detector and upstream bedrock. This was not possible in the prior study due to the lack of a detailed ND280 simulation. However, in this study, we use SIREN [44] to simulate the interactions of HNLs with a dipole-portal coupling to muon neutrinos, $d_{\mu\mathcal{N}}$, within a detailed model of the detector geometry. We show that constraints from ND280 data disfavor the region of dipole-portal HNL parameter space preferred in the oscillation-plus-decay solution to the MiniBooNE anomaly introduced in Ref. [33].

The rest of this paper is organized in the following way. In Sec. II, we describe the minimal HNL model and its dipole extension; in Sec. III, we introduce the ND280 detector and its upgrade; in Sec. IV, we describe the SIREN-based simulation of our signal events. We present our main results in Sec. V. Finally, in Sec. VI, we offer some parting words of wisdom from this study.

II. DIPOLE PORTAL HEAVY NEUTRAL LEPTONS

An HNL is a right-handed neutrino, $\mathcal{N}$, that transforms as a singlet under the Standard Model (SM) gauge group. The minimal HNL model interacts with the SM through mass-mixing. This model is typically considered in the context of the seesaw mechanism, which offers an explanation to the smallness of neutrino masses [3,5]. In the dipole extension, the HNL couples to the SM lepton doublet, $L_\alpha = (l_\alpha, \nu_\alpha)$, and electroweak gauge fields $B_{\mu\nu}$ and $W_{\mu\nu}^a$ via a dimension-six operator suppressed by a high-energy scale Λ . The relevant Lagrangian is given by

$$\mathcal{L} \supset \frac{1}{\Lambda^2} \bar{L}_\alpha \tilde{H} \sigma^{\mu\nu} \mathcal{N} (C_B^\alpha B_{\mu\nu} + C_W^\alpha W_{\mu\nu}^a \sigma_a) + \text{H.c.}, \quad (1)$$

where α is the SM flavor index, σ_a the Pauli matrices, $\tilde{H} = i\sigma_2 H^*$ the conjugated Higgs field, and C_B^α, C_W^α dimensionless coefficients. Here we assume a single HNL field for simplicity. After electroweak symmetry breaking, this generates a dimension five *transition magnetic moment* (TMM) term, or dipole-portal operator,

$$\mathcal{L} \supset d_{\alpha\mathcal{N}} \bar{\nu}_\alpha \sigma_{\mu\nu} F^{\mu\nu} \mathcal{N} + \text{H.c.}, \quad (2)$$

where $d_{\alpha\mathcal{N}} = (v_h/\sqrt{2})(C_W^\alpha C_B^\alpha + C_W^\alpha s_W)/\Lambda^2$ and v_h is the Higgs vacuum expectation value. This term couples the HNL to photons, enabling electromagnetic signatures. While couplings to W and Z are possible, their large masses suppress these channels. In this work, we consider the scenario in which the dipole operator in Eq. (2) dominates over the mass mixing operator [30,45], such that the interactions of the HNL are primarily electromagnetic. This study focuses on a Dirac HNL with a dominant TMM coupling to muon neutrinos, $|d_{e\mathcal{N}}|, |d_{\tau\mathcal{N}}| \ll |d_{\mu\mathcal{N}}|$. There are thus two parameters relevant to this study: the HNL mass $m_{\mathcal{N}}$ and the TMM coupling $d_{\mu\mathcal{N}}$.

In the dipole model, HNLs produce two experimental signatures. The first is the electromagnetic decay $\mathcal{N} \rightarrow \nu_\mu \gamma$, observable via pair production off a nucleus. The second is a virtual-photon decay yielding an e^+e^- pair at the vertex. For $m_{\mathcal{N}} = 100, \text{MeV}$, the branching ratio is $\text{BR}(\mathcal{N} \rightarrow \nu_\mu (\gamma^* \rightarrow e^+e^-)) \sim 0.7\%$ [43]. Both ND280 and its upgrade can reconstruct this channel via two charged tracks in the TPCs [41,43]. FGDs can detect on-shell photons, but face significant $\pi^0 \rightarrow \gamma\gamma$ backgrounds. The POD can observe single photons, though is limited by low-energy backgrounds. In contrast, the gaseous TPCs offer low-background environments, making them ideal for detecting e^+e^- decays. We exploit this to constrain dipole-portal HNLs via $\mathcal{N} \rightarrow \nu_\mu (\gamma^* \rightarrow e^+e^-)$ in the TPCs. HNLs are primarily produced via Primakoff-like upscattering, $\nu_\mu A \rightarrow \mathcal{N} A$, off nuclear targets in the bedrock and detector.

III. THE ND280 DETECTOR AND ITS UPGRADE

The ND280 near detector of the T2K experiment is located 284.9 meters downstream from the J-PARC neutrino beam target. The T2K experiment initially took data from 2010 to 2021. In 2023, the ND280 detector was upgraded for the T2K-II run, scheduled from 2023 to 2026. This upgrade increased the neutrino beam intensity by an order of magnitude, resulting in a projected 2×10^{22} POT by the end of T2K-II [42].

We briefly review the ND280 detector and its upgrade. Both configurations share three downstream TPCs and two FGDs. The TPCs, filled with an argon-based gas, enable precise tracking and momentum measurement via curvature in a 0.2 T dipole magnetic field [46]. The FGDs serve as neutrino targets: FGD1 consists of alternating vertical and horizontal scintillator bars, while FGD2 includes water layers between scintillator planes [47]. In our analysis, the FGDs serve as upscattering targets for HNL production, with decays reconstructed in the downstream TPCs. The original ND280 includes the POD upstream, which also acts as an upscattering target due to its high- Z material. In the upgrade, the POD is replaced by the SuperFGD,

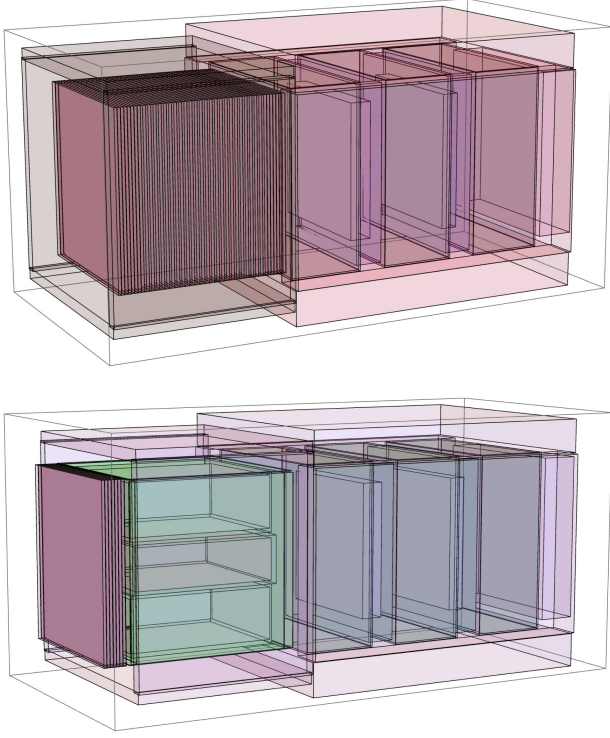


FIG. 1. Geometrical layout of the SIREN implementation of the nominal ND280 detector (top) and the upgraded detector (bottom). The beam direction is from left to right. Both detectors share three downstream TPCs and two FGDs. In ND280, the upstream region houses the POD. The upgrade replaces the POD with the sFGD, sandwiched by two high-angle TPCs (HA-TPCs).

sandwiched by two HA-TPCs [39]. The SuperFGD serves as an HNL production target, while the HA-TPCs extend angular coverage for charged particle tracking [48–50], increasing the fiducial volume for HNL decays. Six surrounding ToF panels [51] also serve as additional upscattering targets. Detector models, including geometry and material composition, were implemented using the SIREN simulation package [44,52] and are shown in Fig. 1.

IV. SIMULATING HEAVY NEUTRAL LEPTONS IN ND280 AND ITS UPGRADE

Monte Carlo simulations of dipole-portal HNL interactions within the detectors were performed using the SIREN package [44], adapted from the LeptonInjector framework [55]. SIREN models cascades of particle interactions with its `InteractionTree` object, allowing us to simulate both the production of HNLs via Primakoff upscattering and their decay to single photons. We use the `DarkNews` interface of SIREN [56] to compute total and differential upscattering cross sections on various nuclear targets, and the total and differential HNL decay width. See Ref. [33] and references therein for the full expressions of the cross section and decay width. The detailed detector model interface of SIREN allows us to consider all of the different subcomponents of

ND280 and its upgrade outlined in Sec. III. This is essential for properly estimating the upscattering rate within each detector.

Each event is generated by first considering a muon (anti)neutrino traveling along the beamline with energy sampled according to the T2K ν_μ ($\bar{\nu}_\mu$) flux reported in Refs. [57,58]. The upscattering location is sampled based on interaction probability within each detector subcomponent along the neutrino’s path. We include upscattering up to three HNL decay lengths upstream of the TPCs, accounting for interactions in the bedrock for long-lived HNLs. The kinematics of the outgoing HNL in the upscattering interaction are determined by sampling the differential cross section. SIREN then samples the decay position using the lab-frame decay length and determines decay kinematics by sampling the differential width. To optimize efficiency, SIREN enforces HNL decays within the TPC fiducial volume when possible. We use SIREN to compute the physical weight of each upscattering-and-decay event. From these weights, we can determine the total rate of single photons from HNL decays within ND280 and its upgrade.

We inject 10^5 neutrino events at a set of discrete points in $(d_{\mu\mathcal{N}}, m_{\mathcal{N}})$ parameter space. Figure 2 shows the distribution of upscattering locations within ND280 and its upgrade for three of these points. The upscattering occurs almost entirely on the high-density materials in each detector, as opposed to the low-density gaseous TPCs. Further, since the HNL decay length decreases as the mass increases ($\Gamma_{\mathcal{N} \rightarrow \nu\gamma} \propto m_{\mathcal{N}}^3$), most of the upscattering events for higher mass HNLs leading to single photons in the TPCs occur within the detector itself rather than in the (not shown) upstream bedrock. In Fig. 3 we show the median lab frame decay length of HNLs in our simulation across the parameter space. There are two competing effects that will impact the sensitivity to dipole-portal HNLs. Sensitivity decreases at both short and long decay lengths: short-lived HNLs decay before reaching the TPC, while long-lived ones are less likely to decay within it.

The single photons produced in HNL decays will not typically convert to e^+e^- pairs inside the gaseous TPCs; therefore, we must rely on dipole-portal decays directly to e^+e^- pairs. To do this, we rescale the contribution from each event in our simulation according to the branching ratio $\text{BR}(\mathcal{N} \rightarrow \nu_\mu(\gamma^* \rightarrow e^+e^-))$ [43]. We sample the kinematics of the e^+e^- pair according to Eq. (A4) of Ref. [43]. The event selection applies the following criteria: (1) the opening angle $\Delta\Phi$ between the two tracks satisfies $\Delta\Phi < 90^\circ$, and (2) the polar angle θ of the incoming HNL is aligned with the beam direction ($\cos\theta > 0.992$). We assume the e^+e^- tagging efficiency for dipole-portal HNL decays matches that for minimal HNLs reported by T2K [41], varying with HNL mass and peaking at $\sim 10\%$. We note that the efficiency depends on the e^+e^- opening angle, which differs between dipole-portal and mass-mixed

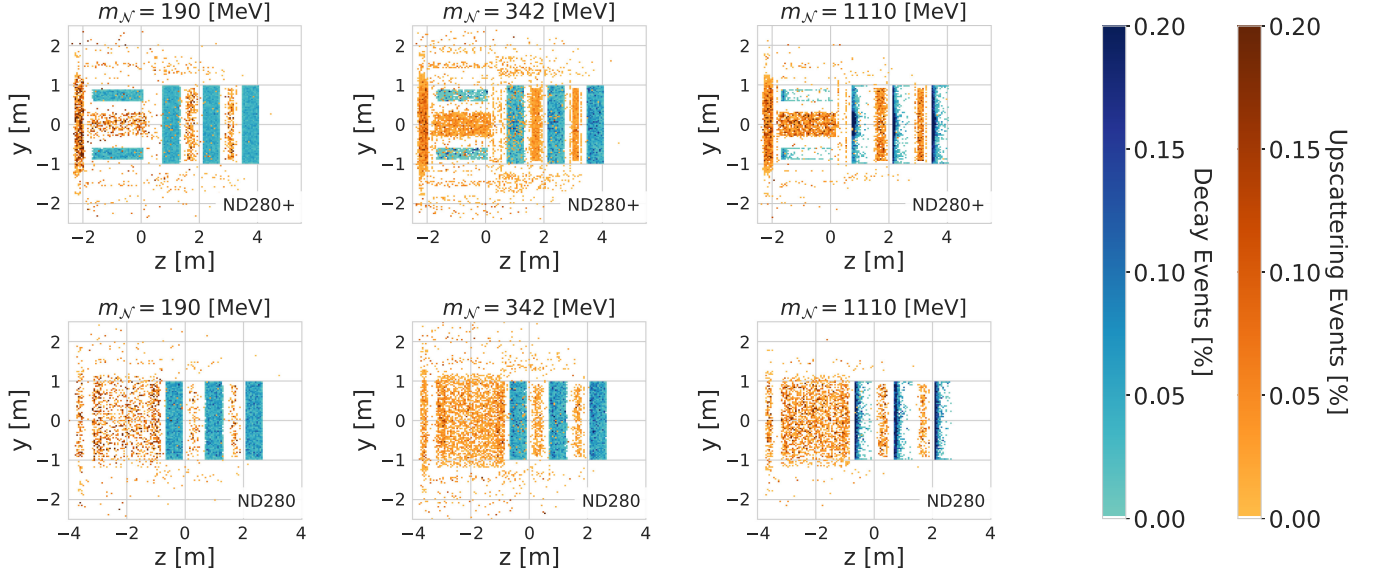


FIG. 2. Decay and up-scattering vertex of dipole-portal HNLs in ND280 and its upgrade for three different HNL masses. The two color scales are proportional to the weighted rates of HNLs whose decay products reach the fiducial volume. The top row is the ND280 upgrade, while the bottom is the ND280 detectors. All events are simulated assuming a dipole coupling of $d_{\mu\mathcal{N}} = 3.87 \times 10^{-7}$. As the HNL mass increases from left to right, the effective decay length decreases, such that most of the signal comes from upscattering in the nearby detector subcomponents. The T2K neutrino beam propagates along the z -axis.

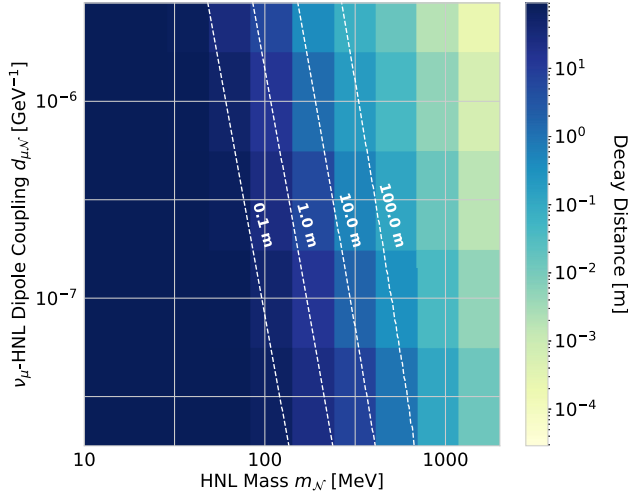


FIG. 3. The median decay distance of dipole-portal HNLs in ND280 at different points in the parameter space. The color axis reflects the prediction from the simulation described in Sec. IV. The dashed lines are calculated analytically using the HNL decay width and the T2K flux.

HNL decays. A detailed efficiency evaluation for dipole-portal HNLs is left for future work.

Finally, we apply a fiducial volume cut in the TPCs using the geometry from Ref. [59].

V. DIPOLE PORTAL CONSTRAINTS

Prior to this work, several experiments have probed the region of dipole-portal HNL parameter space relevant

to T2K. Borexino sets limits on lower-mass HNLs ($m_{\mathcal{N}} \lesssim 10$ MeV) by detecting single-photon decays from neutrino upscattering within Earth, leveraging the large solar neutrino flux and the low energy threshold of the detector [60]. Similarly, Super-Kamiokande sets constraints on dipole-portal HNLs through the terrestrial upscattering of atmospheric neutrinos [61]. CHARM-II [62] indirectly constrains dipole-portal HNLs up to $m_{\mathcal{N}} \sim 100$ MeV through a measurement of the neutrino-electron elastic scattering cross section [62], and NOMAD directly constrains higher mass dipole-portal HNLs through a single photon search [63]. MINER ν A sets strong constraints in the $m_{\mathcal{N}} \in [63 \text{ MeV}, 486 \text{ MeV}]$ regime through the high dE/dx sidebands of their neutrino-electron elastic scattering analyses [33]. Astrophysical constraints on dipole-portal HNLs also exist, considering SN1987A cooling [30], excess neutrinos and photons from SN1987A [64], and the light curves of Type IIP supernovae [65]. These constraints assume flavor-universal dipole couplings, and it is not clear how they change within the scenario considered here, $d_{\mu\mathcal{N}} \neq 0$ and $d_{e\mathcal{N}} = d_{\tau\mathcal{N}} = 0$. We thus neglect astrophysical bounds going forward [66]. Finally, dipole-portal HNLs can potentially explain the long-standing excess of electronlike events observed by the MiniBooNE experiment [25–30, 34]. In this paper, we focus on the solution presented in Ref. [33], in which dipole-portal HNLs explain the bulk of the MiniBooNE excess alongside a smaller contribution from eV-scale sterile neutrino oscillations. Prior to this work, a portion of the preferred region from this solution at $m_{\mathcal{N}} \sim 500$ MeV remained unconstrained at the 95% confidence level (CL).

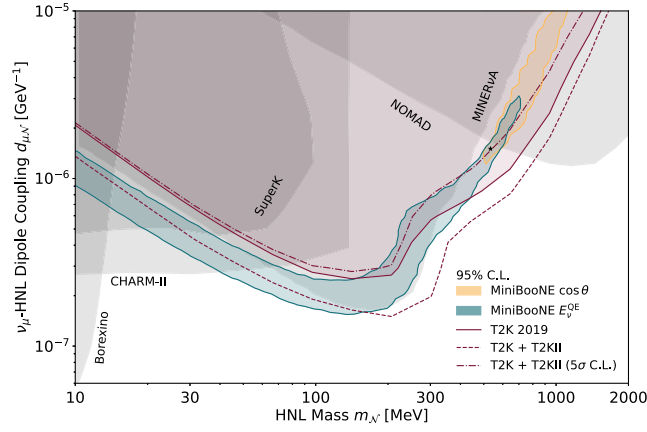


FIG. 4. Constraints and preferred regions at the 95% CL in dipole-portal HNL parameter space. The results of this study are shown in red; the filled contour shows our constraints using the 2019 ND280 data [41], while the dashed line shows the sensitivity of a combined analysis using the full ND280 dataset and three years of data from the upgraded ND280 detector. The preferred region to explain the energy and angular distributions of the MiniBooNE excess from Ref. [33] are also shown. Our constraints disfavor this solution at the 95% CL. Assuming no excess of e^+e^- events emerges, the full T2K + T2K-II analysis will be able to rule out the MiniBooNE solution at the 5σ CL. See the text for a description of the other constraints shown in the figures.

Figure 4 summarizes these constraints and preferred regions in dipole-portal HNL parameter space.

Using the simulation presented in Sec. IV, we calculate constraints and sensitivity to dipole-portal HNLs from ND280 and its upgrade, respectively. Following Ref. [41], we rely on the nonobservation of isolated e^+e^- pairs in the gaseous TPCs of these detectors. We can also search for single photons in the FGDs and SuperFGDs; however, their low event selection efficiency ($\sim 1.9\%$) and poor signal-to-background ratio ($> 1\%$) due to neutral pion decay backgrounds [67] render them less effective at constraining the parameter space. We find that constraints from FGDs and SuperFGDs are over ten times weaker than those from the TPCs. The gaseous TPCs, with their low single-shower backgrounds [41,67], provide the strongest constraints on dipole-portal HNLs.

Our 95% CL constraints on dipole-portal HNLs from the 2019 T2K data [41] are shown in red in Fig. 4. These are derived using the Poisson likelihood to observe zero events given the simulation-derived signal prediction. The primary source of background for this analysis is coherent pion production neutrino-argon interactions in the TPCs, though other neutrino interactions also contribute [41]. We ignore backgrounds in this calculation, which yields a less stringent limit given the under-fluctuation observed in the ND280 data. We find that the systematic uncertainties associated with the flux normalization and cross section

are small ($\sim 5\%$) and do not significantly impact our results [57]. Thus, we leave them for a dedicated analysis by the experimental collaboration since the impact of flux uncertainties is likely smaller than that of a detailed assessment of the experimental efficiencies. Two effects are apparent in Fig. 4. First, longer-lived HNLs in the lower mass regime are produced mostly through upscattering in the upstream bedrock. The constraint from this production channel turns over once the decay length of the HNL is on the order of the fiducial volume size, at $m_N \sim 200$ MeV. Beyond this point, HNL production occurs mostly through upscattering in the detector itself. This leads to the second “bump” in the observed constraint for $m_N \gtrsim 300$ MeV. Importantly, the constraint from this second region disfavors the dipole-portal HNL explanation for the MiniBooNE excess from Ref. [33] at the 95% CL, as shown in Fig. 4.

We also assess the capability of a full T2K + T2K-II analysis, using the full ND280 dataset as well as three years of data from the upgraded ND280 detector. To do this, we compute the Asimov sensitivity within a Poisson likelihood, assuming that the analysis observes exactly the predicted background. The search at the upgraded detector looks for e^+e^- pairs in the original three TPCs as well as the two additional upstream HA-TPCs. We assume that the background in the ND280 upgrade scales linearly with the POT and total TPC volume. This is a conservative choice, as the background rejection will likely improve in the upgraded detector. The dashed line in Fig. 4 shows the 95% CL Asimov sensitivity of the T2K + T2K-II search. Such an analysis is expected to exclude the MiniBooNE solution of Ref. [33] at a CL that corresponds to 5σ after three years of T2K-II data. It would also begin to probe previously unconstrained parameter space across a wide range of HNL masses.

VI. CONCLUSION

In this letter, we set new constraints on dipole-portal HNLs through a reinterpretation of data from a 2019 T2K search for e^+e^- pairs from mass-mixed HNLs [41]. We also evaluated the sensitivity of a combined T2K + T2K-II analysis using the full ND280 dataset as well as three years of data from the upgraded detector. We used the SIREN Monte Carlo simulation to estimate the rate of e^+e^- pairs from dipole-portal HNL decay inside the gaseous TPCs of ND280 and its upgrade. The detailed geometric treatment of our simulation enables the accurate calculation of the HNL production rate from Primakoff upscattering in the detector and upstream bedrock, an essential ingredient of the constraints and sensitivities presented here. Our main results, presented in Fig. 4, show that the 2019 T2K dataset world-leading constraints on the TMM coupling of HNLs with muon neutrinos, $d_{\mu N}$, in the $m_N \in [390 \text{ MeV}, 743 \text{ MeV}]$ region. Importantly, they disfavor the dipole-portal HNL solution to the MiniBooNE excess

presented in Ref. [33] at the 95% CL. Our sensitivity estimates further suggest that a full T2K + T2K-II analysis can set world-leading constraints on dipole-portal HNLs across a wider range of masses.

The results presented in this letter motivate an official search for dipole-portal HNLs within the T2K collaboration. The T2K + T2K-II sensitivity presented here reflects an accurate calculation of the rate of HNL decays to single photons in the fiducial volume; however, input from the T2K collaboration is necessary to properly evaluate the reconstruction performance on these events. Just as the collaboration successfully leveraged the favorable setup of ND280 to set strong limits on mass-mixed HNLs [41], so too can they use ND280 and its upgrade to reach untouched regions of dipole portal HNL parameter space. Furthermore, at the level to which our simulation accurately reflects the ND280 detector, our constraints motivate alternative solutions to the MiniBooNE anomaly. Studies like the one presented here are vital in paring down the expansive model space of MiniBooNE explanations [12]. Thus, this paper represents an important step toward determining the nature of the anomaly.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [68], embargo periods may apply.

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