

# Search for a Hidden Sector Scalar from Kaon Decay in the Dimuon Final State at ICARUS

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We present a search for long-lived particles (LLPs), produced in kaon decays, that decay to two muons inside the ICARUS neutrino detector. This channel would be a signal of hidden sector models that can address outstanding issues in particle physics such as the strong CP problem and the microphysical origin of dark matter. The search is performed with data collected in the Neutrinos at the Main Injector (NuMI) beam at Fermilab corresponding to  $2.41 \times 10^{20}$  protons-on-target. No new physics signal is observed, and we set world leading limits on heavy QCD axions, as well as for the Higgs portal scalar among dedicated searches. Limits are also presented in a model-independent way applicable to any new physics model predicting the process  $K \rightarrow \pi + S(\rightarrow \mu\mu)$ , for a LLP  $S$ . This result is the first search for new physics performed with the ICARUS detector at Fermilab. It paves the way for the future program of LLP searches at ICARUS.

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**Introduction**—Several beyond standard model physics models predict processes by which a kaon ( $K^\pm$  or  $K_L^0$ ) decays to a long-lived particle (LLP), which in turn decays to a  $\mu^+\mu^-$  pair. Two such processes are the Higgs portal scalar (HPS) [1], a dark sector model for dark matter [2], and a heavy QCD axion, or axionlike particle (ALP) [3,4], an  $\mathcal{O}(\text{GeV})$  resolution to the strong-CP problem [5]. Under these scenarios kaons created in the target of the Neutrinos at the Main Injector (NuMI) beam at Fermilab would produce (pseudo)scalars that could then propagate into the ICARUS detector and decay into dimuon pairs. ICARUS sits 800 m downstream of the NuMI target at a  $5.75^\circ$  far-off-axis position.

The ICARUS liquid argon time projection chamber (LArTPC) neutrino detector has been operational at Fermilab since 2022 [6–9], taking data as part of the

Short-Baseline Neutrino (SBN) Program [10,11]. ICARUS consists of two cryostat modules, both containing two TPCs with a common cathode. Each constituent TPC identifies neutrino interactions through the detection of ionization charge deposited in tracks and electromagnetic showers by charged particles produced in neutrino-argon interactions. The ionization charge is used to reconstruct charged particle trajectories with good calorimetry and precise ( $\sim\text{mm}$ ) spatial resolution.

Calorimetric, topological, and kinematic features distinguish dimuon decays in ICARUS from neutrino backgrounds. The primary residual neutrino background, from muon neutrino charged current coherent pion production ( $\nu_\mu\text{CC-Coh}\pi$ ) [12,13], is tuned from external data and further fit to a sideband in the analysis. The analysis searches for dimuon decays in a fiducial volume where both muons are contained in the detector. An excess above the expected neutrino background in a narrow region of invariant mass consistent with a resonance peak would be a signature of new physics. The results are interpreted through the Higgs portal scalar and heavy axion benchmark models. A model independent interpretation applicable to any model predicting the process  $K \rightarrow \pi + S(\rightarrow \mu\mu)$  is also included.

**LLP models**—

**Higgs portal scalar:** The Higgs portal scalar extends the standard model (SM) with a real, neutral scalar  $S$  with mass  $m_S$  that mixes with the SM Higgs boson with a mixing angle  $\theta_S$ . Such a scalar is a candidate portal between the SM and a dark matter particle that would enable dark matter to be thermally produced in the early universe [2],

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while preventing the overabundance that would result if the dark matter particle were light (its mass less than a few GeV) and coupled to the electroweak bosons [14]. In the mass region of interest ( $2m_\mu < m_S < m_K - m_\pi$ ), the scalar is produced in decays of charged ( $K^\pm$ ) and neutral ( $K_L^0$ ) kaons and predominantly decays to pairs of muons and pions [1].

**Heavy QCD Axion:** The axion is a solution to the strong-CP problem, the experimental observation that the CP-violating QCD coupling is very small ( $\lesssim 10^{-10}$ ) despite no symmetry in the SM requiring it to be at that scale [5]. The traditional QCD axion model implies the existence of a light axion particle with a very large decay constant [15,16] and suffers from the quality problem [17,18]. Extended axion models, such as those incorporating a larger gauge group [19–30], or a mirror symmetry [31–34], avoid the quality problem by engineering a heavier axion particle with a smaller decay constant.

Such an ALP can be introduced through a low-energy effective Lagrangian independent of the UV physics:

$$\mathcal{L} \supset \frac{c_3 \alpha_s a}{8\pi f_a} G\tilde{G} + \frac{c_2 \alpha_2 a}{8\pi f_a} W\tilde{W} + \frac{c_1 \alpha_1 a}{8\pi f_a} B\tilde{B} + \frac{c_\mu \partial_\nu a}{2f_a} \bar{\mu} \gamma^\nu \gamma_5 \mu,$$

where  $f_a$  is the axion decay constant and  $\alpha_s, \alpha_2, \alpha_1$  are given by the SM gauge couplings ( $\alpha_i = g_i^2/4\pi$ ) to the gluons ( $G$ ),  $SU(2)$  gauge field ( $W$ ), and  $U(1)$  gauge field ( $B$ ), respectively [3,4]. The axion couples to each gauge field through the coupling  $c_i$ , as well as to the muon by a coupling  $c_\mu$ . The muon coupling can be included at tree level [3], or induced indirectly from the renormalization group flow from the axion decay constant scale ( $f_a$ ) to the mass scale ( $m_a$ ) [4,35,36]. For this result, we consider the popular “codominance” model where there is no tree-level muon coupling and the gauge boson couplings are equal:  $c_1 = c_2 = c_3 = 1$ .

In this case, axions are produced in charged kaon decay [37–39]. Production in neutral kaon decay is suppressed: for  $K_L^0$  by CP-violation and for  $K_S^0$  by the short lifetime of the particle. The axions decay predominantly to  $\gamma\gamma$  and  $\mu\mu$  final states. The  $ee$  decay is suppressed by the small mass of the electron, while (semi)hadronic axion decays are not significant for  $m_a \lesssim 0.4$  GeV [40], in the mass region of interest. The di-gamma decay depends on the effective axion-photon coupling ( $c_\gamma$ ), for which we apply a computation based on vector meson dominance [4,40].

**Simulation and event selection**—A Monte Carlo simulation developed for ICARUS includes models of the NuMI neutrino and cosmic backgrounds, as well as the scalar signal. The cosmic ray flux is simulated with the CORSIKA generator [41]. The NuMI flux is simulated with G4NuMI [42], a Geant4 [43] based hadron production and particle propagation simulation of NuMI proton beam on the full NuMI beamline geometry. Hadron production data from NA49 [44,45] are used to correct hadron production cross sections [46]. Neutrino interactions are simulated by the

GENIE framework (v3.0.6 Ar23.20i) [47,48]. The dominant background component in the signal region consists of muon neutrino charged current coherent pion production. We have tuned the GENIE implementation of the Berger-Sehgal  $\nu_\mu$ CC-Coh $\pi$  model [13] to a measurement of the process performed by MINERvA [49] (see the Appendix). Energy depositions from particles traversing the detector are simulated using Geant4 [43]. The response of the ICARUS TPC is simulated by the Wire-Cell framework [50], with the ionization signal shapes tuned to ICARUS data [51]. The HPS [1] and ALP [4] signal models are simulated based on the kaon flux extracted from the NuMI  $\nu$  flux simulation. The scalar flux peaks at  $E_S \sim 0.5$  GeV with a broad tail out to a few GeV.

Ionization depositions in the detector recorded by the TPC are reconstructed into “events.” The reconstruction is performed by the Pandora framework [52,53], which groups ionization hits into events consisting of tracklike and showerlike objects and an interaction vertex. This analysis identifies candidate dimuon decays as Pandora events with two tracks, where the track start point is inside the fiducial volume and both tracks stop inside a containment volume inside the detector. The fiducial volume is defined with an inset of 10 cm from the active volume in the vertical and drift ( $\hat{x}$  and  $\hat{y}$ ) directions, 15 cm at the front in the beamline ( $\hat{z}$ ) direction, and 1 m at the back. The containment volume is the same except it is at an inset of 15 cm at the back of  $\hat{z}$ . Problematic regions of the detector are also removed from both volumes.

Candidate track pairs are subjected to topological and calorimetric cuts which require consistency with muonlike energy deposition patterns. First, the muon momentum reconstructed by the stochastic multiple-Coulomb-scattering (MCS) along the track [54] is compared to the muon momentum reconstructed by the track range [55]. The track range identifies the momentum with a resolution of  $\sim 3\%$ , whereas MCS obtains a resolution of 8–20% depending on the track length. A cut is made such that the momentum determined by MCS is not greater than 50% above the range-based momentum. This cut rejects proton tracks, which are typically straighter than muons and are reconstructed with a much larger MCS momentum than their track range would indicate.

Second, calibrated ionization energy depositions reconstructed along the last 25 cm of the track are compared to the muon and proton expectation to build  $\mu$ -like and  $p$ -like particle identification (PID) scores [56,57]. Muon energy loss in this track range forms a Bragg peak, which distinguishes stopping muons from protons and interacting pions. The PID cuts accept 76% of scalar-induced muons while rejecting 55% of neutrino-induced pions and protons.

A signature of dimuon decays is that, unlike neutrinos, there is no nuclear target, and thus no source for hadronic (highly ionizing) energy depositions below the tracking threshold or additional charge deposits around the vertex.

To leverage this, cuts are applied on large charge depositions close to the candidate decay vertex. These cuts reject protons in an energy range  $15 \lesssim \text{proton K.E.} \lesssim 50 \text{ MeV}$ , below the current Pandora tracking threshold in ICARUS.

Kinematic cuts further distinguish dimuon decay events. The momenta of the predicted scalars is such that the dimuon products have a small opening angle. A cut is made at  $70^\circ$  on the reconstructed dimuon opening angle. Kaons generally decay near the NuMI target, thus the momentum vector for most scalars points along the direction from the NuMI target to the ICARUS detector. The angle between these two vectors ( $\theta_{\text{NuMI}}$ ) is reconstructed as the angle between the summed dimuon momentum vector (obtained from the track direction and range) and the known direction from the NuMI target to the ICARUS detector. The pointing resolution on this angle for scalar decays is  $\sim 2^\circ$ , while the distribution for neutrino interactions is much broader and peaks at about  $20^\circ$ . The full  $\theta_{\text{NuMI}}$  range is used in the analysis. Events where  $\theta_{\text{NuMI}} > 5^\circ$  are used to characterize the background, while the  $\theta_{\text{NuMI}} < 5^\circ$  region defines the final signal selection.

The signal selection identifies signal scalar events with an efficiency of 9–18% (depending on the scalar mass). All cosmic activity and 99.96% of beam induced neutrino interactions within the fiducial volume are rejected in a simulated sample equivalent to roughly  $100\times$  data exposure. The dimuon invariant mass is reconstructed with a resolution of 2–5%, depending on the scalar mass. The binning of the dimuon mass spectrum is optimized to match this resolution.

*Systematic uncertainties and statistical procedure*—Systematic uncertainties from the models used in the Monte Carlo simulation (flux, interaction cross sections, particle propagation, and detector response) influence the predicted event rates for signal and background channels. The size of their impact is summarized in Table I. These uncertainties, in combination with the simulation, have

TABLE I. Uncertainty on the total event rate in the signal region for scalar signals and neutrino backgrounds. The scalar signal uncertainty is taken as the mean across the sampled mass points. It is nearly independent of the mass.

Systematic	Scalar sig. [%]	Neutrino bkg. [%]
Total detector uncertainty	11.0	20.2
Detector model variations	9.9	17.6
Cathode aplanarity	5.5	5.6
Energy scale	1.8	8.2
Flux	12.3	12.0
$\nu_\mu$ CC-Coh $\pi$ x-sec	...	62.9
Other $\nu$ interactions x-sec	...	4.1
Particle propagation	...	5.6
MC. statistics	...	4.6
Total	16.5	67.7

been validated by comparisons of data and simulation in sideband regions in the analysis.

The neutrino flux uncertainty is estimated from hadron production data [44,45], assumed to be 40% outside of data coverage. Focusing and operational uncertainties associated with the NuMI beamline are estimated by simulating fluxes with alternate geometry configurations [46]. An additional flat normalization uncertainty of 8.6% is added in quadrature to account for uncertainties in the extended NuMI target hall geometry that are particularly relevant for the ICARUS far-off-axis location. The flux uncertainty for kaon-induced scalars is computed from the components of the neutrino flux uncertainty relevant for kaon production. The flux uncertainty is treated as correlated between the neutrino background and scalar signal.

The uncertainty on the  $\nu_\mu$  CC-Coh $\pi$  cross section, which is the dominant background uncertainty, is derived from a tuning procedure detailed in the Appendix. The cross section uncertainty from all other processes is obtained from GENIE [47]. Uncertainties on particle propagation account for uncertainties in  $\pi$ -Ar and  $p$ -Ar interaction cross sections and are computed by the Geant4-Reweight package [58]. They are relevant only for the neutrino background.

Uncertainties on the detector response arise from three sources: detector model variations, reconstructed energy scales, and cathode aplanarity. Aspects of the detector model such as the effective channel gain, noise level, and ionization signal shape are varied by the size of the variation of each quantity across the runtime of the ICARUS experiment. Separate simulations with each of the detector model variations are performed, and the change in the number of events entering the signal region is propagated as a normalization uncertainty on the rate. The energy scale uncertainties are relevant for the two reconstructed energy scales used in the event selection: the MCS momentum and the calorimetric ionization energy. The uncertainty is implemented by varying the reconstructed energies in Monte Carlo simulation by an amount prescribed by the calibration. Finally, there is an uncertainty to address the aplanarity of the cathode plane in both ICARUS cryostats.

The analysis of dimuon-like events is performed as a search for an excess above background or “bump hunt” within the reconstructed dimuon invariant mass spectrum. It makes use of the BumpHunter test statistic [59,60], which is defined as  $-\log p_{\min}$ , where  $p_{\min}$  is the minimum local p-value among a set of windows over the binned dimuon invariant mass spectrum.

The signal region search is performed in three steps. First, the dimuon mass window with the greatest excess above the nominal background in the signal region ( $\theta_{\text{NuMI}} < 5^\circ$ ) is identified by the BumpHunter algorithm. Second, a scale factor on the  $\nu_\mu$  CC-Coh $\pi$  background template is fit to data in a larger  $\theta_{\text{NuMI}}$  region ( $\theta_{\text{NuMI}} < 10^\circ$ ), excluding the invariant mass range identified in the first step. Third, the BumpHunter algorithm is rerun to identify the



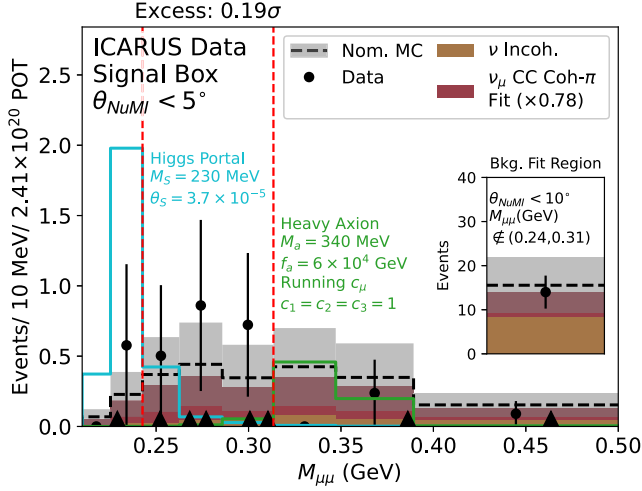


FIG. 1. Signal box result of the search. A scale factor on the  $\nu_\mu$  CC-Coh $\pi$  background is obtained from a fit region shown in the inset. A bump hunt search in the data against the scaled background prediction obtains an insignificant excess with a global significance of  $0.19\sigma$ , in the range  $0.24 < M_{\mu\mu} < 0.31$  GeV. The reconstructed mass of the eight data events are shown with a caret on the bottom of the figure. Spectra of two example model points excluded at the 90% CL (see Fig. 2) are shown.

largest excess in the signal region above the scaled background. The global significance of the BumpHunter test statistic output from the final step is obtained using the null hypothesis BumpHunter test statistic distribution as computed with 10,000 toy experiments. In each toy experiment, systematic and statistical uncertainties on the neutrino rate are thrown, and the full three-step procedure is run to obtain the sampled test statistic value.

**Results**—The search is performed with data corresponding to  $2.41 \times 10^{20}$  protons-on-target (POT) with the NuMI beam in the forward horn current (FHC) configuration, taken between June 2022 and July 2023. Beam quality cuts, based on those developed by NO $\nu$ A [61], are applied to the data. The result of the search is shown in Fig. 1. A scale factor of 0.78 on the  $\nu_\mu$  CC-Coh $\pi$  component of the background is obtained from the template fit. The initial background expectation in the signal box region is  $7.8 \pm 5.0(\text{syst}) \pm 2.8(\text{stat})$ , fit to 6.4 events by the scale factor. Eight data events are observed. The largest excess is found in the mass window  $0.24 < M_{\mu\mu} < 0.31$  GeV, with a global significance of  $0.19\sigma$  when compared to the null hypothesis. The excess is not statistically significant, and limits are set with the CL $_s$  method at the 90% confidence level (CL) [62]. The obtained scale factor is consistent within the prior uncertainty on the  $\nu_\mu$  CC-Coh $\pi$  rate (62.9%), especially noting that it is subject to a significant statistical uncertainty, and biased downward by the bump estimate procedure.

Limits on the Higgs portal scalar and heavy QCD axion models are shown in Fig. 2. This Letter obtains world leading limits on the heavy axion decay constant, covering

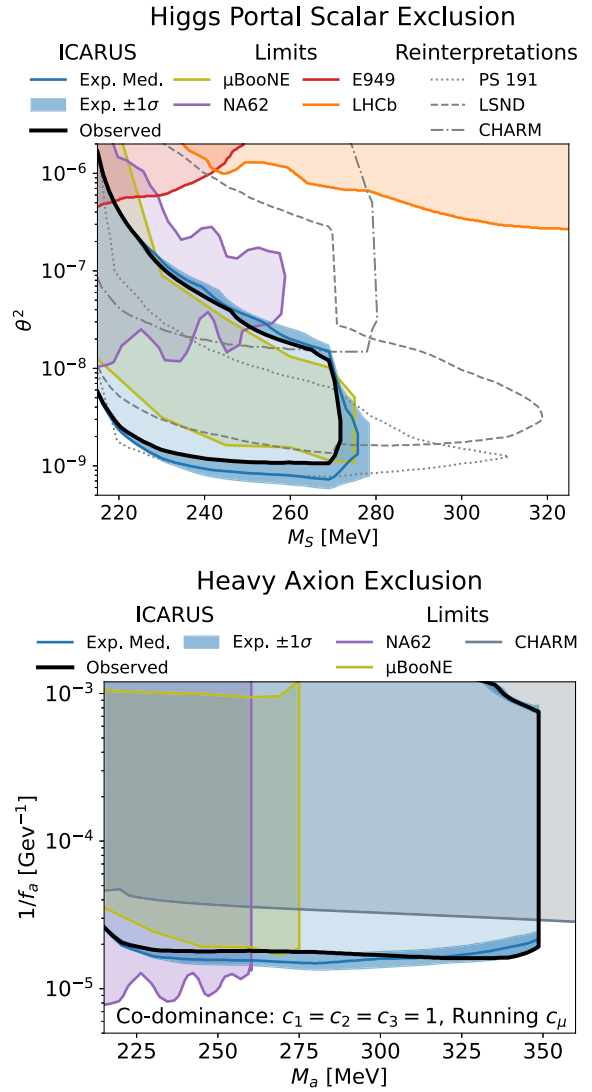


FIG. 2. Limits on the Higgs Portal scalar (top) and heavy axion (bottom) models. Exclusions are computed with the CL $_s$  method at the 90% CL. The HPS limit is compared to direct searches [63,71–74] and reinterpreted limits on the model [64,67–70,75]. The ALP limit is compared to other limits on the particle [4,64,71,72,76].

lower values of  $1/f_a$  in the axion mass range  $260 \text{ MeV} \lesssim M_a < m_K - m_\pi$ . The limits from this search also extend to larger (tree-level) axion-muon couplings up to  $c_\mu \approx 10^{-4} - 10^{-1}$  and are complementary to prior searches for muon-coupled axions [3,63–66]. This measurement also extends the limits on the Higgs portal scalar mixing angle amongst dedicated searches in the mass range  $2m_\mu < m_S \lesssim 270 \text{ MeV}$ . Reinterpretations of measurements from LSND [67,68] and PS191 [69,70] extend further but are based on reanalyses of other measurements performed outside of both experiments. The observed exclusions for both models are consistent with the range of expected sensitivity.

Model independent limits are shown in Fig. 3. The model independent scenario interprets the reach of the

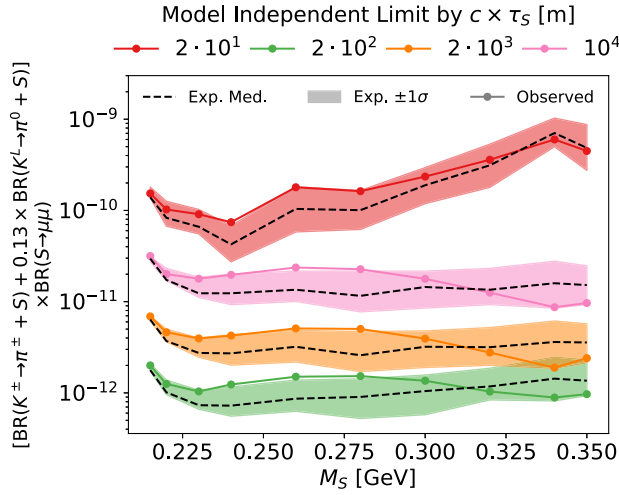


FIG. 3. Model independent limits (at the 90% CL) on the process  $K \rightarrow \pi + S(\rightarrow \mu\mu)$ , for a LLP  $S$ . Contours are shown as a function of the branching ratio of the process and the particle mass, for a few example values of the particle lifetime. Limits in the full three-dimensional space are available in the Supplementary Material [77].

search for a general branching ratio of the process, scalar lifetime  $\tau_S$ , and scalar mass  $M_S$ . Both charged  $K^\pm$  and  $K_L^0$  contribute to scalar production. They produce scalars with essentially the same energy spectrum and do so at a relative rate,  $1K^\pm : 0.13K_L^0$ , independent over the sampled scalar mass points. Thus, the combined branching ratio  $[\text{BR}(K^\pm \rightarrow \pi^\pm S) + 0.13 \times \text{BR}(K_L^0 \rightarrow \pi^0 S)] \times \text{BR}(S \rightarrow \mu\mu)$  is a model independent parameter that defines the reach of the search. In Fig. 3, the combined branching ratio is plotted for a few choices of the scalar lifetime. The limits in the full three-dimensional model independent space are available as Supplementary Material [77].

**Conclusion**—We have presented a search for a dimuon resonance produced in kaon decay performed with the ICARUS neutrino detector with  $2.41 \times 10^{20}$  POT in the NuMI beam in its FHC configuration. The search finds no significant excess above the expected neutrino background. World leading limits are set on heavy QCD axions for various choices of the muon and gauge boson couplings including the codominance scenario, and leading limits among dedicated searches are set for the Higgs portal scalar in the mass range  $2m_\mu < m_S \lesssim 270$  MeV. The search is also interpreted in a model independent framework applicable to any new physics model predicting the process  $K \rightarrow \pi + S(\rightarrow \mu\mu)$ , for a long-lived scalar  $S$ .

This search is the first result with the ICARUS neutrino detector at Fermilab. It paves the way to a future program of hidden sector searches at ICARUS, as well as the broader set of measurements planned as part of the SBN program.

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- [1] B. Batell, J. Berger, and A. Ismail, Probing the Higgs portal at the Fermilab short-baseline neutrino experiments, *Phys. Rev. D* **100**, 115039 (2019).
- [2] G. Krnjaic, Probing light thermal dark-matter with a Higgs portal mediator, *Phys. Rev. D* **94**, 073009 (2016).
- [3] R. T. Co, S. Kumar, and Z. Liu, Searches for heavy QCD axions via dimuon final states, *J. High Energy Phys.* **02** (2023) 111.
- [4] J. Berger and G. Putnam, Sensitivity to kaon decays to ALPs at fixed target experiments, *Phys. Rev. D* **110**, 055035 (2024).
- [5] G. 't Hooft, Symmetry breaking through Bell-Jackiw anomalies, *Phys. Rev. Lett.* **37**, 8 (1976).
- [6] S. Amerio *et al.* (ICARUS Collaboration), Design, construction and tests of the ICARUS T600 detector, *Nucl. Instrum. Methods Phys. Res., Sect. A* **527**, 329 (2004).
- [7] L. Bagby *et al.* (ICARUS-T600 Collaboration), Overhaul and installation of the ICARUS-T600 liquid Argon TPC electronics for the FNAL short baseline neutrino program, *J. Instrum.* **16**, P01037 (2021).
- [8] L. Bagby *et al.* (ICARUS/NP01 Collaboration), New read-out electronics for ICARUS-T600 liquid Argon TPC. Description, simulation and tests of the new front-end and ADC system, *J. Instrum.* **13**, P12007 (2018).
- [9] P. Abratenko *et al.* (ICARUS Collaboration), ICARUS at the Fermilab short-baseline neutrino program: Initial operation, *Eur. Phys. J. C* **83**, 467 (2023).
- [10] R. Acciarri *et al.* (MicroBooNE, LAr1-ND, and ICARUS-WA104 Collaborations), A proposal for a three detector short-baseline neutrino oscillation program in the Fermilab booster neutrino beam, *arXiv:1503.01520*.
- [11] P. A. Machado, O. Palamara, and D. W. Schmitz, The short-baseline neutrino program at Fermilab, *Annu. Rev. Nucl. Part. Sci.* **69**, 363 (2019).
- [12] D. Rein and L. M. Sehgal, Coherent  $\pi^0$  production in neutrino reactions, *Nucl. Phys.* **B223**, 29 (1983).
- [13] C. Berger and L. M. Sehgal, PCAC and coherent pion production by low energy neutrinos, *Phys. Rev. D* **79**, 053003 (2009).
- [14] B. W. Lee and S. Weinberg, Cosmological lower bound on heavy neutrino masses, *Phys. Rev. Lett.* **39**, 165 (1977).

- [15] R. D. Peccei and H. R. Quinn, *CP* conservation in the presence of instantons, *Phys. Rev. Lett.* **38**, 1440 (1977).
- [16] R. D. Peccei and H. R. Quinn, Constraints imposed by *CP* conservation in the presence of instantons, *Phys. Rev. D* **16**, 1791 (1977).
- [17] S. B. Giddings and A. Strominger, Loss of incoherence and determination of coupling constants in quantum gravity, *Nucl. Phys.* **B307**, 854 (1988).
- [18] S. R. Coleman, Why there is nothing rather than something: A theory of the cosmological constant, *Nucl. Phys.* **B310**, 643 (1988).
- [19] S. Dimopoulos, A solution of the strong *CP* problem in models with scalars, *Phys. Lett.* **84B**, 435 (1979).
- [20] V. A. Rubakov, Grand unification and heavy axion, *JETP Lett.* **65**, 621 (1997).
- [21] T. Gherghetta, N. Nagata, and M. Shifman, A visible QCD axion from an enlarged color group, *Phys. Rev. D* **93**, 115010 (2016).
- [22] S. Dimopoulos, A. Hook, J. Huang, and G. Marques-Tavares, A collider observable QCD axion, *J. High Energy Phys.* **11** (2016) 052.
- [23] P. Agrawal and K. Howe, Factoring the strong *CP* problem, *J. High Energy Phys.* **12** (2018) 029.
- [24] P. Agrawal and K. Howe, A flavorful factoring of the strong *CP* problem, *J. High Energy Phys.* **12** (2018) 035.
- [25] M. K. Gaillard, M. B. Gavela, R. Houtz, P. Quilez, and R. Del Rey, Color unified dynamical axion, *Eur. Phys. J. C* **78**, 972 (2018).
- [26] B. Lillard and T. M. P. Tait, A high quality composite axion, *J. High Energy Phys.* **11** (2018) 199.
- [27] C. Csáki, M. Ruhdorfer, and Y. Shirman, UV sensitivity of the axion mass from instantons in partially broken gauge groups, *J. High Energy Phys.* **04** (2020) 031.
- [28] T. Gherghetta, V. V. Khoze, A. Pomarol, and Y. Shirman, The axion mass from 5D small instantons, *J. High Energy Phys.* **03** (2020) 063.
- [29] T. Gherghetta and M. D. Nguyen, A composite Higgs with a heavy composite axion, *J. High Energy Phys.* **12** (2020) 094.
- [30] A. Valenti, L. Vecchi, and L.-X. Xu, Grand color axion, *J. High Energy Phys.* **10** (2022) 025.
- [31] Z. Berezhiani, L. Gianfagna, and M. Giannotti, Strong *CP* problem and mirror world: The Weinberg-Wilczek axion revisited, *Phys. Lett. B* **500**, 286 (2001).
- [32] A. Hook, Anomalous solutions to the strong *CP* problem, *Phys. Rev. Lett.* **114**, 141801 (2015).
- [33] A. Hook, S. Kumar, Z. Liu, and R. Sundrum, High quality QCD axion and the LHC, *Phys. Rev. Lett.* **124**, 221801 (2020).
- [34] H. Fukuda, K. Harigaya, M. Ibe, and T. T. Yanagida, Model of visible QCD axion, *Phys. Rev. D* **92**, 015021 (2015).
- [35] M. Chala, G. Guedes, M. Ramos, and J. Santiago, Running in the ALPs, *Eur. Phys. J. C* **81**, 181 (2021).
- [36] M. Bauer, M. Neubert, S. Renner, M. Schnubel, and A. Thamm, The low-energy effective theory of axions and ALPs, *J. High Energy Phys.* **04** (2021) 063.
- [37] M. Bauer, M. Neubert, S. Renner, M. Schnubel, and A. Thamm, Consistent treatment of axions in the weak chiral Lagrangian, *Phys. Rev. Lett.* **127**, 081803 (2021).
- [38] M. Bauer, M. Neubert, S. Renner, M. Schnubel, and A. Thamm, Flavor probes of axion-like particles, *J. High Energy Phys.* **09** (2022) 056.
- [39] C. Cornella, A. M. Galda, M. Neubert, and D. Wyler,  $K^\pm \rightarrow \pi^\pm a$  at next-to-leading order in chiral perturbation theory and updated bounds on ALP couplings, *J. High Energy Phys.* **06** (2024) 029.
- [40] D. Aloni, Y. Soreq, and M. Williams, Coupling QCD-scale axionlike particles to gluons, *Phys. Rev. Lett.* **123**, 031803 (2019).
- [41] D. Heck, J. Knapp, J. N. Capdevielle, G. Schatz, and T. Thouw, CORSIKA: A Monte Carlo code to simulate extensive air showers (1998).
- [42] L. Aliaga *et al.* (MINERvA Collaboration), Neutrino flux predictions for the NuMI beam, *Phys. Rev. D* **94**, 092005 (2016); **95**, 039903(A) (2017).
- [43] S. Agostinelli *et al.*, Geant4—A simulation toolkit, *Nucl. Instrum. Methods Phys. Res., Sect. A* **506**, 250 (2003).
- [44] C. Alt *et al.* (NA49 Collaboration), Inclusive production of charged pions in  $p + C$  collisions at 158-GeV/c beam momentum, *Eur. Phys. J. C* **49**, 897 (2007).
- [45] B. Baatar *et al.* (NA49 Collaboration), Inclusive production of protons, anti-protons, neutrons, deuterons and tritons in  $p + C$  collisions at 158 GeV/c beam momentum, *Eur. Phys. J. C* **73**, 2364 (2013).
- [46] A. P. Wood, The NuMI flux prediction at ICARUS, Ph.D. thesis, Houston University, 2024.
- [47] C. Andreopoulos *et al.*, The GENIE neutrino Monte Carlo generator, *Nucl. Instrum. Methods Phys. Res., Sect. A* **614**, 87 (2010).
- [48] L. Alvarez-Ruso *et al.* (GENIE Collaboration), Recent highlights from GENIE v3, *Eur. Phys. J. Special Topics* **230**, 4449 (2021).
- [49] M. A. Ramírez *et al.* (MINERvA Collaboration), Neutrino-induced coherent  $\pi^+$  production in C, CH, Fe, and Pb at  $\langle E_\nu \rangle \sim 6$  GeV, *Phys. Rev. Lett.* **131**, 051801 (2023).
- [50] C. Adams *et al.* (MicroBooNE Collaboration), Ionization electron signal processing in single phase LArTPCs. Part I. Algorithm description and quantitative evaluation with MicroBooNE simulation, *J. Instrum.* **13**, P07006 (2018).
- [51] P. Abratenko *et al.* (ICARUS Collaboration), Calibration and simulation of ionization signal and electronics noise in the ICARUS liquid argon time projection chamber, *J. Instrum.* **20**, P01032 (2025).
- [52] R. Acciarri *et al.* (MicroBooNE Collaboration), The Pandora multi-algorithm approach to automated pattern recognition of cosmic-ray muon and neutrino events in the MicroBooNE detector, *Eur. Phys. J. C* **78**, 82 (2018).
- [53] A. Abed Abud *et al.* (DUNE Collaboration), Reconstruction of interactions in the ProtoDUNE-SP detector with Pandora, *Eur. Phys. J. C* **83**, 618 (2023).
- [54] P. Abratenko *et al.* (MicroBooNE Collaboration), Determination of muon momentum in the MicroBooNE LArTPC using an improved model of multiple Coulomb scattering, *J. Instrum.* **12**, P10010 (2017).
- [55] R. L. Workman *et al.* (Particle Data Group), Review of particle physics, *Prog. Theor. Exp. Phys.* **2022**, 083C01 (2022).
- [56] P. Abratenko *et al.* (ICARUS Collaboration), Angular dependent measurement of electron-ion recombination in



- liquid argon for ionization calorimetry in the ICARUS liquid argon time projection chamber, *J. Instrum.* **20**, P01033 (2025).
- [57] C. Anderson *et al.*, The ArgoNeuT detector in the NuMI low-energy beam line at Fermilab, *J. Instrum.* **7**, P10019 (2012).
- [58] J. Calcutt, C. Thorpe, K. Mahn, and L. Fields, Geant4Re-weight: A framework for evaluating and propagating hadronic interaction uncertainties in Geant4, *J. Instrum.* **16**, P08042 (2021).
- [59] G. Choudalakis, On hypothesis testing, trials factor, hypertests and the BumpHunter, in PHYSTAT 2011 (2011), arXiv:1101.0390.
- [60] L. Vaslin, S. Calvet, V. Barra, and J. Donini, pyBumpHunter: A model independent bump hunting tool in Python for high energy physics analyses, *SciPost Phys. Codebases* **2023**, 15 (2023).
- [61] P. Adamson *et al.* (NOvA Collaboration), First measurement of muon-neutrino disappearance in NOvA, *Phys. Rev. D* **93**, 051104 (2016).
- [62] A. L. Read, Presentation of search results: The  $CL_s$  technique, *J. Phys. G* **28**, 2693 (2002).
- [63] R. Aaij *et al.* (LHCb Collaboration), Search for hidden-sector bosons in  $B^0 \rightarrow K^{*0} \mu^+ \mu^-$  decays, *Phys. Rev. Lett.* **115**, 161802 (2015).
- [64] F. Bergsma *et al.* (CHARM Collaboration), Search for axion like particle production in 400-GeV proton—copper interactions, *Phys. Lett.* **157B**, 458 (1985).
- [65] R. Acciarri *et al.* (ArgoNeuT Collaboration), First constraints on heavy QCD axions with a liquid Argon time projection chamber using the ArgoNeuT experiment, *Phys. Rev. Lett.* **130**, 221802 (2023).
- [66] J. R. Batley *et al.* (NA48/2 Collaboration), Searches for lepton number violation and resonances in  $K^\pm \rightarrow \pi \mu \mu$  decays, *Phys. Lett. B* **769**, 67 (2017).
- [67] S. Foroughi-Abari and A. Ritz, LSND constraints on the Higgs portal, *Phys. Rev. D* **102**, 035015 (2020).
- [68] L. B. Auerbach *et al.* (LSND Collaboration), Search for  $\pi^0 \rightarrow \nu_\mu \bar{\nu}_\mu$  decays in the LSND Detector, *Phys. Rev. Lett.* **92**, 091801 (2004).
- [69] D. Gorbunov, I. Krasnov, and S. Suvorov, Constraints on light scalars from PS191 results, *Phys. Lett. B* **820**, 136524 (2021).
- [70] G. Bernardi *et al.*, Further limits on heavy neutrino couplings, *Phys. Lett. B* **203**, 332 (1988).
- [71] E. Cortina Gil *et al.* (NA62 Collaboration), Measurement of the very rare  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  decay, *J. High Energy Phys.* **06** (2021) 093.
- [72] P. Abratenko *et al.* (MicroBooNE Collaboration), Search for long-lived heavy neutral leptons and Higgs portal scalars decaying in the MicroBooNE detector, *Phys. Rev. D* **106**, 092006 (2022).
- [73] R. Aaij *et al.* (LHCb Collaboration), Search for long-lived scalar particles in  $B^+ \rightarrow K^+ \chi (\mu^+ \mu^-)$  decays, *Phys. Rev. D* **95**, 071101 (2017).
- [74] A. V. Artamonov *et al.* (E949 Collaboration), Search for heavy neutrinos in  $K^+ \rightarrow \mu^+ \nu_H$  decays, *Phys. Rev. D* **91**, 052001 (2015); **91**, 059903(E) (2015).
- [75] M. W. Winkler, Decay and detection of a light scalar boson mixing with the Higgs boson, *Phys. Rev. D* **99**, 015018 (2019).
- [76] J. Jerhot, B. Döbrich, F. Ertas, F. Kahlhoefer, and T. Spadaro, ALPINIST: Axion-like particles in numerous interactions simulated and tabulated, *J. High Energy Phys.* **07** (2022) 094.
- [77] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/PhysRevLett.134.151801> for an annotated, machine readable text file containing the model-independent limit sampled across the three-dimensional parameter space.
- [78] H. G. Schlaile, Amplitude analysis of  $\pi^\pm - {}^{12}\text{C}$  elastic scattering, *Phys. Rev. C* **55**, 2584 (1997).
- [79] P. Stowell, C. Wret, C. Wilkinson, L. Pickering, S. Cartwright, Y. Hayato, K. Mahn, K. McFarland, J. Sobczyk, R. Terri, L. Thompson, M. Wascko, and Y. Uchida, NUISANCE: A neutrino cross-section generator tuning and comparison framework, *J. Instrum.* **12**, P01016 (2017).
- [80] A. A. Belkov and B. Z. Kopeliovich, Adler relation and neutrino production of single hadrons, *Sov. J. Nucl. Phys.* **46**, 499 (1987).
- [81] A. Kartavtsev, E. A. Paschos, and G. J. Gounaris, Coherent pion production by neutrino scattering off nuclei, *Phys. Rev. D* **74**, 054007 (2006).

## End Matter

*Appendix:  $\nu_\mu$ CC-Coh $\pi$  modeling*—The Rein-Sehgal model [12] and the Berger-Sehgal model [13] are based on Adler’s partially conserved axial current relation, which predicts the  $\nu_\mu$ CC-Coh $\pi$  cross section to be proportional to the pion-nucleus ( $\pi - N$ ) elastic scattering cross section as

$$\begin{aligned} \frac{d\sigma^{CC}}{dQ^2 dy dt} &= \frac{G_F^2 \cos^2 \theta_C f_\pi^2 E}{2\pi^2 |q|^2} uv \left[ \left( G_A - \frac{1}{2} \frac{Q_{\min}^2}{Q^2 + m_\pi^2} \right)^2 \right. \\ &\quad \left. + \frac{y}{4} (Q^2 - Q_{\min}^2) \frac{Q_{\min}^2}{(Q^2 + m_\pi^2)^2} \right] \\ &\quad \times \frac{d\sigma(\pi^+ N \rightarrow \pi^+ N)}{dt}, \end{aligned} \quad (\text{A1})$$

where  $t$  is the momentum transfer to the nucleus,  $Q^2$  is the 4-momentum transfer squared,  $Q_{\min}^2 = m_\pi^2 y / (1 - y)$  is the high energy approximation to the true minimal  $Q^2$ ,  $y$  is the Bjorken inelasticity, and  $G_A$  is the axial vector form factor. The kinematic factors  $u$  and  $v$  are  $u, v = (E + E' \pm |\mathbf{q}|) / 2E$ . Constants  $G_F$ ,  $\theta_C$ , and  $f_\pi$  are the Fermi coupling constant, Cabibbo angle, and the pion decay constant, respectively. The two models differ in the way they calculate the  $\pi - N$  differential cross section. The Rein-Sehgal model derives it from the pion-nucleon ( $\pi - n$ ) cross section using the ansatz:

$$\frac{d\sigma(\pi N \rightarrow \pi N)}{dt} = A^2 \frac{d\sigma_{el}}{dt} \Big|_{t=0} e^{-bt} F_{abs}, \quad (\text{A2})$$



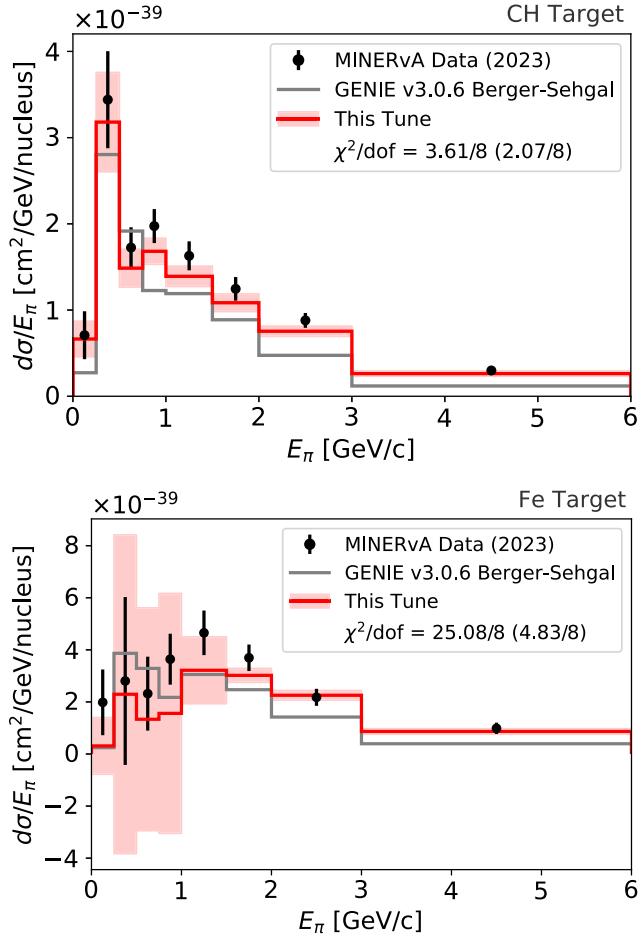


FIG. 4.  $\nu_\mu\text{CC-Coh}\pi$  differential cross section as a function of pion energy predicted by GENIE v3.00.06 and this tune, compared to the MINERvA measurement.

where  $b = \frac{1}{3}R_0^2A^{2/3}$ ,  $F_{abs} = \exp[-(9A^{1/3}/16\pi R_0^2)\sigma_{inel}]$ , and the forward elastic  $\pi - n$  differential cross section is given by the optical theorem as

$$\left. \frac{d\sigma_{el}}{dt} \right|_{t=0} = \frac{1}{16\pi} \left( \frac{\sigma_{tot}^{\pi^+p} + \sigma_{tot}^{\pi^-p}}{2} \right)^2, \quad (\text{A3})$$

with  $\sigma_{tot}^{\pi^{\pm}p}$  calculated from pion-deuterium scattering data. The Berger-Sehgal model uses a different ansatz for  $T_\pi < 1$  GeV:

$$\frac{d\sigma(\pi N \rightarrow \pi N)}{dt} = A_1 \left( \frac{A}{12} \right)^{4/3} e^{-b_1(A/12)^{2/3}t}, \quad (\text{A4})$$

where  $A_1$  and  $b_1$  are pion energy dependent constants obtained by fitting to pion-carbon scattering data [78]. Terms containing the nucleus mass number  $A$  models the  $A$ -dependence behavior.

We tune the GENIE v3.0.6  $\nu_\mu\text{CC-Coh}\pi$  model event generator to MINERvA cross section measurements on

TABLE II. Model parameter values and uncertainties from GENIE v3.00.06 and this tune.

Model parameter	Nominal value	Fit value
A-dependence factor	4/3	$0.91 \pm 0.46$
$\sigma(\pi N)$ scales		
$0 < E_\pi [\text{GeV}] < 0.25$	1	$2.9 \pm 1.1$
$0.25 < E_\pi [\text{GeV}] < 0.5$	1	$1.1 \pm 0.2$
$0.5 < E_\pi [\text{GeV}] < 0.75$	1	$0.7 \pm 0.1$
$0.75 < E_\pi [\text{GeV}] < 1.0$	1	$1.3 \pm 0.1$
$1.0 < E_\pi [\text{GeV}] < 1.5$	1	$1.1 \pm 0.1$
$1.5 < E_\pi [\text{GeV}] < 2.0$	1	$1.2 \pm 0.1$
$2.0 < E_\pi [\text{GeV}] < 3.0$	1	$1.5 \pm 0.1$
$3.0 < E_\pi [\text{GeV}] < 6.0$	1	$2.2 \pm 0.3$

the hydrocarbon (CH) and iron ( $^{56}\text{Fe}$ ) target. This fit uses the Berger-Sehgal framework for the  $\nu_\mu\text{CC-Coh}\pi$  process, but infers the  $\pi$ -Ar cross section from the MINERvA measurement. The tune was performed using the NUISANCE package [79] with the GENIE Reweight package, which together provide the infrastructure to fit the Monte Carlo simulation to data by varying model parameters in GENIE and extract fit uncertainties from systematic throws. The fit was performed in two steps: the A-dependence fit and the cross section scaling fit. First, the exponent of the first A-dependence term from Eq. (A4) was varied to fit the measurement of the CH/Fe total cross section ratio as a function of neutrino energy. This A-dependence tune enables realistic extension of the model to the argon nucleus to within the fit uncertainty ( $\sim 60\%$ ). Second, eight scaling factors that scale the  $\pi - N$  cross section for the eight pion energy bins in Fig. 4 were varied for a joint fit to the differential cross section with respect to pion energy for the CH and  $^{56}\text{Fe}$  targets. The fit tunes the Berger-Sehgal model to be based on the MINERvA data in place of the original pion-carbon scattering data, for which the information on measurement uncertainty or the covariance matrix is unavailable.

Fitted parameter values are summarized in Table II. A comparison of the tune result with the MINERvA data and GENIE v3.0.6 for the differential cross section with respect to the pion energy is shown in Fig. 4.  $\chi^2/\text{ndof}$  for  $d\sigma/dE_\pi$  is 3.61/8 for the CH target and 25.08/8 for the  $^{56}\text{Fe}$  target. With the fit uncertainty taken into account, the  $\chi^2/\text{ndof}$  becomes 2.07/8 for the CH target and 4.83/8 for the  $^{56}\text{Fe}$  target, which shows that the tuned result agrees well with the MINERvA data within the fit uncertainty.

The result of the fit and its uncertainty is taken as the central value and uncertainty of the  $\nu_\mu\text{CC-Coh}\pi$  cross section for the search. An additional uncertainty on the axial mass of the form factor of  $\pm 0.3$  GeV is also added in quadrature. This uncertainty is added to cover the range of predictions for the phenomenological form factor  $G_A$  (see, e.g., Refs. [13,80,81]). Its impact is subleading to

the uncertainties on the pion-argon cross section. The large uncertainty on the A-dependence parameter results in large uncertainties for targets other than carbon. In addition, large measurement uncertainties on low pion energy bins result in large fit uncertainties on corresponding cross

section scaling factors. Nonetheless, this tune provides a more reliable uncertainty than the flat 100% assigned by GENIE and includes realistic shape uncertainties on the kinematic variables relevant for  $\nu_\mu$  CC-Coh $\pi$  cross section modeling.