

# 1 Search for the production of Higgs-portal scalar bosons in the NuMI beam using the 2 MicroBooNE detector

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We present the strongest experimental limits to date on the mixing angle,  $\theta$ , with which a new scalar particle,  $S$ , mixes with the Higgs field in the mass range  $110 \text{ MeV} < m_S < 155 \text{ MeV}$ . This result uses the MicroBooNE liquid argon time projection chamber to search for decays of these Higgs-portal scalar particles through the  $S \rightarrow e^+e^-$  channel with the decays of kaons in the NuMI neutrino beam acting as the source of the scalar particles. The analysis uses an exposure of  $2.01 \times 10^{21}$  protons on target of NuMI beam data including periods when the beam focusing system was configured to focus positively charged hadrons and separate periods when negatively charged hadrons were focused. The analysis searches for scalar particles produced from kaons decaying in flight in the beam's decay volume and at rest in the target and absorber. At  $m_S = 125 \text{ MeV}$  ( $m_S = 150 \text{ MeV}$ ) we set a limit of  $\theta < 3.19 \times 10^{-4}$  ( $\theta < 2.79 \times 10^{-4}$ ) at the 95% confidence level.

## I. INTRODUCTION

The exceptional imaging and particle-identification capabilities of liquid-argon time projection chambers (LArTPCs) enable a broad program of searches for physics beyond the Standard Model (SM) [1–10]. The existence of dark matter (DM) [11, 12] motivates many models of new physics. With the absence of direct observations of weakly interacting massive particles [13–15] as dark matter candidates, models are being developed that propose additional sectors of DM particles that couple to the SM through new forces [16–18]. In this paper, we use the MicroBooNE detector [19], exposed to the Neutrinos from the Main Injector (NuMI) beam [20], to test a model in which the Higgs field acts as a portal to a new sector of particles [21, 22].

The Higgs-portal model predicts the existence of an invisible sector of particles, which can act as DM candidates. This invisible sector couples to the SM only through the Higgs terms in the SM Lagrangian. This coupling proceeds through a new scalar singlet state  $S$ , which mixes with the SM Higgs boson through a mixing angle  $\theta$ . The mixing angle  $\theta$  and the mass of the scalar,  $m_S$ , are free parameters of the model.

We assume that the scalar particle  $S$  is produced in the decays of  $K$  mesons in the NuMI beam before it then decays in the MicroBooNE detector (Fig. 1). Both the branching ratio for the production of the  $S$  and the lifetime of the  $S$  are proportional to  $\theta^2$  [22]. In this analysis, we search for the decay  $S \rightarrow e^+e^-$ . Since the  $S$  would be produced in  $K \rightarrow \pi S$  decays, the kinematic limits for this decay channel are  $2m_e < m_S < m_K - m_\pi$ . In this analysis, we restrict our search range to  $100 \text{ MeV} < m_S <$

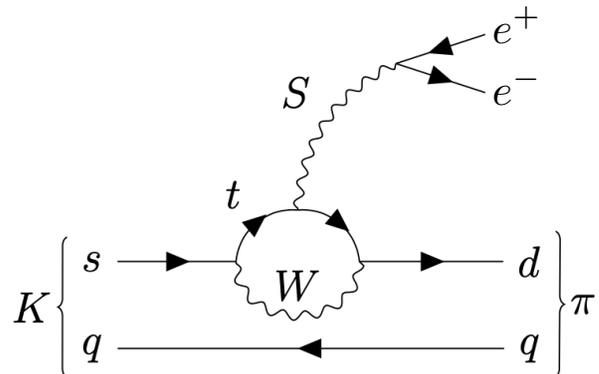


FIG. 1. The dominant production channel for Higgs-portal scalar particles,  $S$ , is from kaon decays in the NuMI beam [22]. The  $e^+e^-$  decay mode of  $S$  is the search mode of interest for this study. Here  $q = u, d$  as both charged and neutral kaons contribute to production, and  $u, d, s, t$  refer to the up, down, strange and top quarks.

211 MeV, since the E949 [23] and NA69 [24] collaborations have published strong exclusions for lower masses, and the dominant decay mode in the range  $m_S > 2m_\mu$  is  $S \rightarrow \mu^+\mu^-$ , which leaves the  $e^+e^-$  decay mode less sensitive.

## II. MICROBOONE IN THE NUMI BEAM

The MicroBooNE LArTPC [19] has an active volume of  $2.3 \times 2.6 \times 10.4 \text{ m}^3$ . We define a fiducial volume at a distance of 10 cm from each edge of the active volume and only analyze decay vertices within this fiducial volume. We use the Pandora pattern recognition package [25] to reconstruct candidates coincident in time with a NuMI

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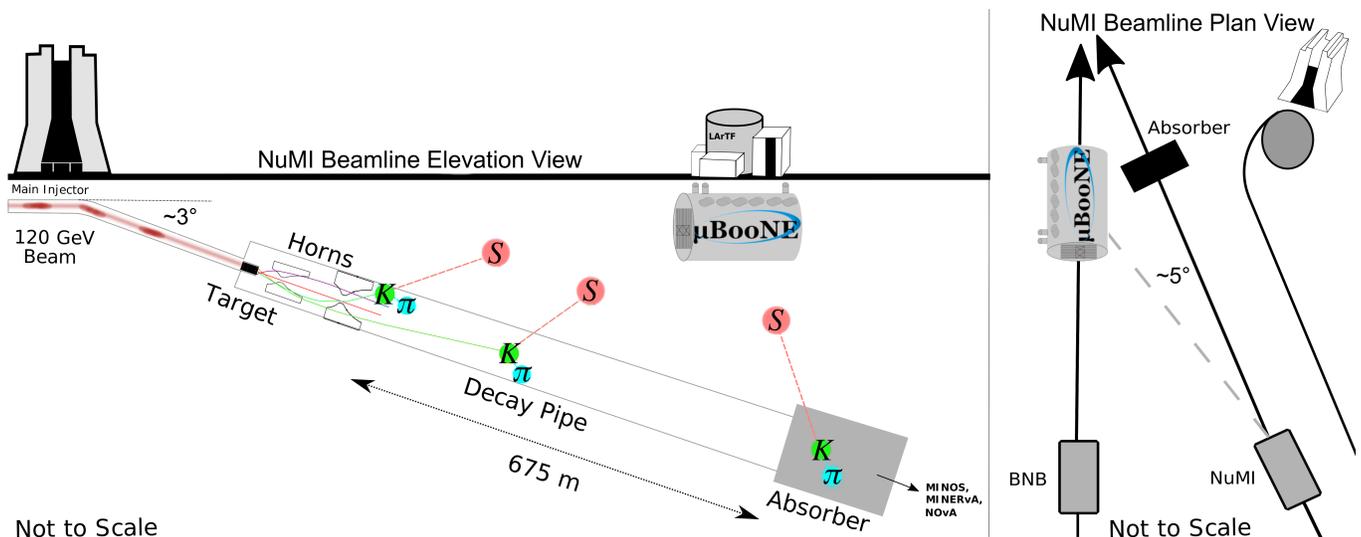


FIG. 2. A schematic of the NuMI beamline, showing the location of the MicroBooNE detector with respect to the NuMI target, decay pipe, and hadron absorber. The schematic on the left shows an elevation view; the right schematic shows a plan view. Figure adapted from Ref. [3].

113 beam spill that passes a trigger selection based on the  
 114 detector's optical system. During MicroBooNE's third  
 115 running period (Run 3), a cosmic ray tagger (CRT) sys-  
 116 tem of scintillator panels surrounding the LArTPC was  
 117 commissioned, and its data was used to aid in vetoing  
 118 cosmic muons.

119 A schematic of the NuMI beamline [20], located at  
 120 the Fermi National Accelerator Laboratory (Fermilab),  
 121 is shown in Figure 2. Protons with an energy of 120 GeV  
 122 are incident on a graphite target resulting in the produc-  
 123 tion of hadrons. Two magnetic horns focus the charged  
 124 hadrons along a 675 m long helium-filled decay pipe.  
 125 Hadrons that reach the end of the decay pipe before de-  
 126 caying are stopped by an aluminium, steel, and concrete  
 127 absorber of 5.6 m height, 5.5 m width, and 8.5 m depth.  
 128 This analysis uses  $8.97 \times 10^{20}$  protons-on-target of expo-  
 129 sure in which the NuMI focusing horns were configured  
 130 to focus positively charged hadrons along the decay pipe  
 131 (FHC), as well as  $1.12 \times 10^{21}$  POT of data in which the  
 132 NuMI focusing horns were configured to focus negatively  
 133 charged hadrons along the decay pipe (RHC).

134 Figure 3 shows event displays of the simulated decays  
 135 in the MicroBooNE detector of scalar particles produced  
 136 in three locations in the NuMI beamline. Depending on  
 137 their production point along the beamline, these particles  
 138 will enter the detector from different directions. Scalar  
 139 particles from a kaon decay at rest (KDAR) in the NuMI  
 140 target will arrive at an angle of  $8^\circ$ , and those originating  
 141 from KDAR in the NuMI absorber will arrive at  $\sim 120^\circ$ .  
 142 Particles from kaon decay in flight (KDIF) in the decay  
 143 region downstream of the target will arrive at an angle  
 144 between  $8^\circ$  and  $\sim 120^\circ$ . KDIF events are concentrated  
 145 towards smaller angles because the charged mesons are  
 146 focused down the NuMI beamline, so scalars reaching  
 147 MicroBooNE are predominantly from less off-axis kaons.

148 Scalar production by KDAR is spherically symmetric,  
 149 meaning a large number of scalars originate from the  
 150 nearby absorber, located a distance of 100 m from the  
 151 detector, whereas a smaller number of scalars originate  
 152 from the NuMI target, located a distance of 680 m from  
 153 the detector.

154 Simulation of the NuMI beam flux at MicroBooNE has  
 155 been described in detail elsewhere [26]. The flux of neu-  
 156 trinos through the MicroBooNE detector, which forms  
 157 the main background for this search, is predicted by a  
 158 GEANTv4.9.2 [27, 28] simulation of the NuMI beamline,  
 159 adjusted by the PPFx package [29]. Updates to the NuMI  
 160 flux model are discussed in [30], including an update to  
 161 GEANTv4.10.4 and target hall geometry, but are not in-  
 162 cluded in this work. Simulation of the scalar particle flux  
 163 uses the same GEANT4 simulation as for the kaon parents,  
 164 and kaon decays to scalar particles are simulated accord-  
 165 ing to the kinematics as described in Ref. [22].

166 The rate of KDAR in the NuMI absorber uses the pre-  
 167 diction from the MiniBooNE collaboration, and was cho-  
 168 sen because this prediction is consistent with the Mini-  
 169 BooNE measured KDAR charged current  $\nu_\mu$  rate [31].  
 170 Between the MiniBooNE and MicroBooNE operating pe-  
 171 riods, the NuMI beam changed from a 96 cm to 120 cm  
 172 graphite target, reducing the rate of KDAR at the ab-  
 173 sorber. To account for this, an additional scaling factor  
 174 is introduced. Production of scalar particles with a mass  
 175 of 150 MeV is shown for each horn current configuration  
 176 in Figure 4. In RHC mode, KDAR produces 54% of the  
 177 simulated flux of scalar particles, with KDAR producing  
 178 the remaining 46%, and similarly for FHC.

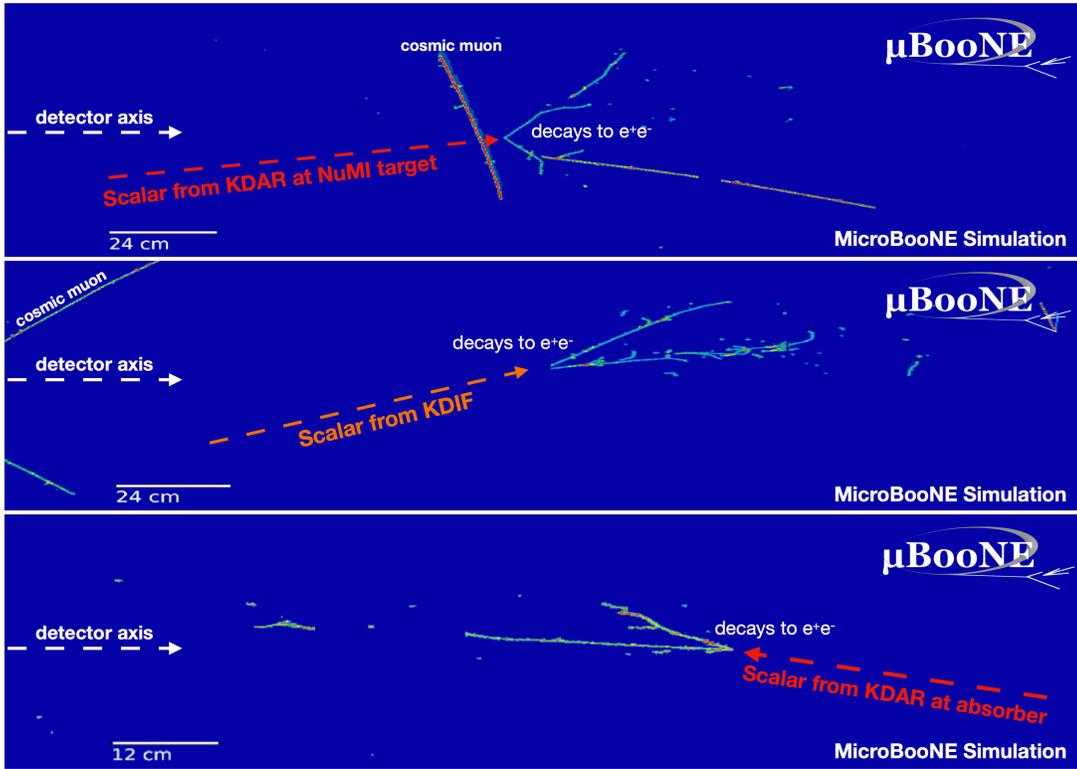


FIG. 3. Three simulated decays of Higgs-portal scalar particles with masses of 200 MeV into  $e^+e^-$  pairs. Top: a scalar produced from kaon decay at rest in the NuMI target. Middle: a scalar produced from kaon decay in flight in the NuMI decay pipe. Bottom: a scalar produced from kaon decay at rest in the NuMI hadron absorber.

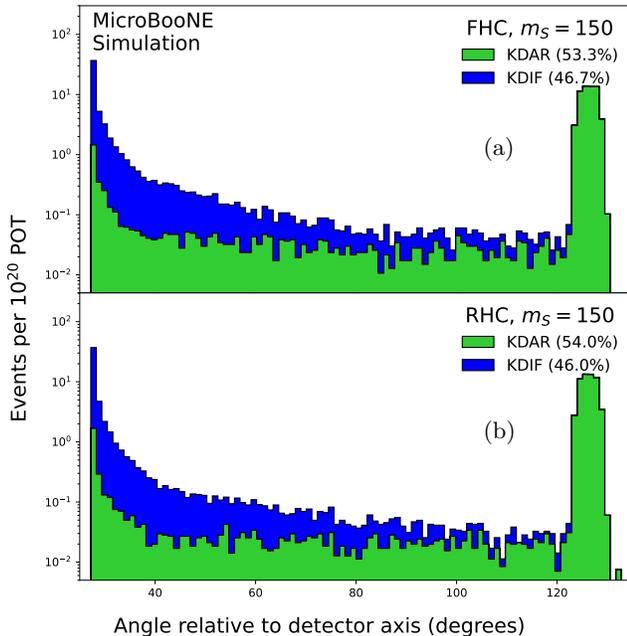


FIG. 4. The production mechanism of simulated Higgs-portal scalar particles ( $m_S = 150$  MeV) for (a) Forward Horn Current (FHC) in which the NuMI horns are configured to focus positively charged mesons; (b) Reverse Horn Current (RHC), in which the NuMI horns are configured to focus negatively charged mesons.

### 179 III. IDENTIFYING SCALAR BOSON DECAYS 180 IN THE MICROBOONE DETECTOR

181 The  $e^+e^-$  topology should result in two shower-like  
182 clusters of activity, as shown in Fig. 3. However, fewer  
183 than half of simulated scalar boson decays result in two  
184 separate showers reconstructed by *Pandora*. In a signifi-  
185 cant fraction of cases the two showers overlap and are  
186 reconstructed as a single shower. We therefore divide  
187 our beam-like interactions into two samples: those with  
188 two reconstructed shower-like clusters and those with one  
189 reconstructed shower-like cluster. Interactions with no  
190 reconstructed showers are rejected.

191 Neutrino interactions that mimic the  $e^+e^-$  topology  
192 are the main source of background. A further signifi-  
193 cant source of background are cosmic-ray muons passing  
194 through the detector. Due to the considerable cosmic  
195 flux, a number of muons mimic the single reconstructed  
196 shower signal topology, and to a lesser extent the two-  
197 shower topology. The *Pandora* pattern recognition pack-  
198 age assigns a score to each candidate interaction that  
199 indicates whether it is cosmic-like or beam-like. We use  
200 this score, along with information from the CRT system  
201 when available, to isolate a sample of beam-like interac-  
202 tions.

203 To select signal-enhanced samples for analysis, a num-  
204 ber of boosted decision trees (BDTs) are used. These

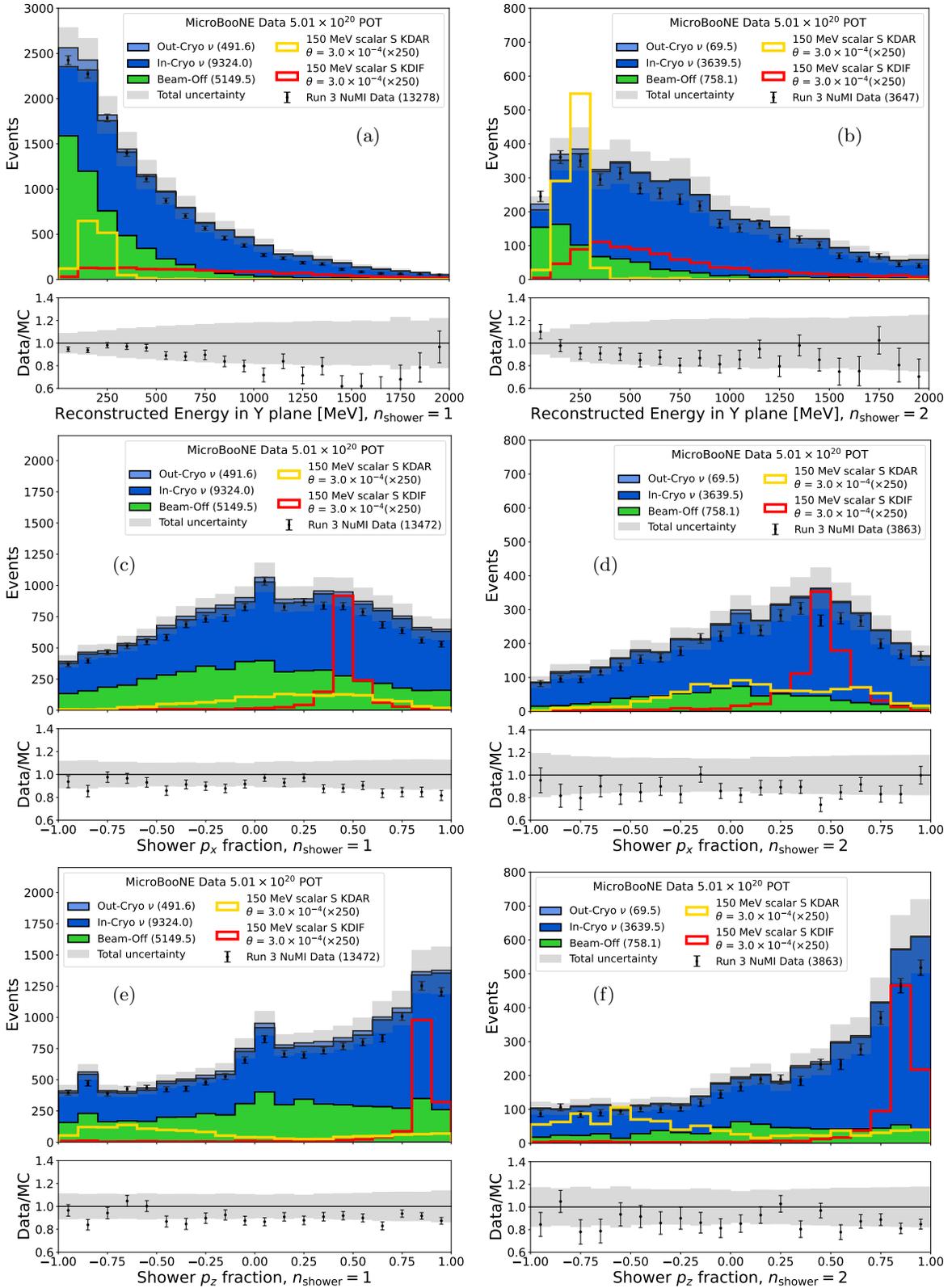


FIG. 5. Three of the BDT input variables, shown for events in Run 3 trained for a scalar mass of 150 MeV. (a) The reconstructed energy recorded in the TPC collection plane, the wires of which are oriented in the in the  $y$ -direction, for one-shower events. (b) The reconstructed energy recorded in the TPC collection plane for two-shower events. (c) The momentum fraction, in the  $x$ -direction, of the shower for one-shower events. (d) The momentum fraction, in the  $x$ -direction, of the highest-energy shower for two-shower events. (e) The momentum fraction, in the  $z$ -direction, of the shower for one-shower events. (f) The momentum fraction, in the  $z$ -direction, of the highest-energy shower for two-shower events.

BDTs are trained on a full Monte Carlo simulation of the MicroBooNE detector with separate simulated samples of background neutrino interactions and signal Higgs-portal scalar decays. Onto both of these simulated samples are overlaid data events taken with no beam passing through the detector in order to provide the simulations with realistic cosmic muons and detector noise. The interactions of neutrinos in the detector are simulated with the GENIEv3.0.6 G18\_10a\_02\_11a [32, 33] generator modified with a custom tune of the interaction cross-sections on argon [34]. Particles exiting the simulated nucleus are propagated through a detector simulated with GEANTv4.10.3.p03c [27, 28]. The decays of Higgs-portal scalar particles in the detector are simulated with custom-written code, and the particles resulting from the decay are, as for the case of neutrino interactions, propagated through the same detector simulation, implemented in LArSoft [35].

We train separate BDTs to discriminate KDIF and KDAR topologies from background using information such as the direction of the interaction. For each scalar mass under investigation (given in Tab. I), eight separate BDTs are trained according to beam polarity and signal topology:

- FHC, two-shower KDIF topology,
- FHC, two-shower KDAR topology,
- FHC, one-shower KDIF topology,
- FHC, one-shower KDAR topology,
- RHC, two-shower KDIF topology,
- RHC, two-shower KDAR topology,
- RHC, one-shower KDIF topology, and
- RHC, one-shower KDAR topology.

A pre-training is performed using a large number of variables to select 28 variables with the highest importance weights. Each BDT is then trained using these 28 variables, and the relative importance of the variables in each BDT will depend on the target topology. Figure 5 shows the agreement between data and simulation for three variables that are typically the most important: the reconstructed energy recorded by the TPC collection plane, and the momentum fraction of the leading shower in the  $x$  and  $z$  directions, where  $z$  is the direction of the detector axis,  $y$  points vertically upwards, and  $x$  points from the anode to the cathode of the TPC. These three distributions show the distinguishing power between signal and background of these variables and illustrate the good agreement between data and simulation. The signal distributions are shown separately for scalar particles from KDAR and KDIF to illustrate why separate BDT trainings are performed to discriminate KDIF and KDAR topologies. The samples are primarily distinguished by the mono-energetic nature of scalars from KDAR and the

differing incoming angle distributions. KDIF scalars are produced close to the target, whereas KDAR scalars are produced predominantly at the absorber.

Figure 6 shows the four BDTs trained for the search in the Run 3 sample at a scalar mass of 150 MeV. Good agreement is observed between the data and the background simulation across the full range of BDT values. The BDT can be seen to provide good separation between simulated signal and background events, particularly for the two-shower samples. The consistency between data and background prediction show no evidence of scalar decays within the MicroBooNE detector. Therefore this analysis will set limits on the Higgs-portal scalar parameter space.

In comparison to the previous MicroBooNE search for Higgs-portal scalar particles decaying into  $e^+e^-$  pairs [2], which used an exposure of  $1.93 \times 10^{20}$  POT of data from the NuMI beam in the Run 1 period, this analysis uses significantly more data. The previous search considered only mono-energetic scalar particles produced from KDAR in the NuMI absorber, whereas in this work we consider mono-energetic scalar particles produced from KDAR in both the NuMI target and absorber as well as scalar particles produced from KDIF in the NuMI decay volume, which will have a range of energies. The previous analysis was a purely topological search, while the study presented here uses significant additional information such as the reconstructed energy of the showers, and uses improved selection algorithms that rely on Pandora-based tools [25] to identify shower-like objects using the new BDTs described above to suppress background.

#### IV. SYSTEMATIC UNCERTAINTIES

The dominant sources of systematic uncertainty at MicroBooNE arise from the modeling of the NuMI beam flux, neutrino background cross sections, modeling of the propagation of particles within the detector volume, and modeling of the detector response. The PPFX package [29], used to predict the flux of hadrons in the NuMI beam, provides uncertainties on that flux arising from uncertainties on the production of hadrons in the NuMI target and the geometry of the beam focusing system. The full suite of uncertainties is applied to the simulated neutrino-induced background.

Uncertainties on the production of kaons impact the simulation of the Higgs-portal scalar signal. The PPFX package provides an energy-dependent uncertainty on kaons produced in the NuMI target. On charged kaons produced downstream of the target, a 40% uncertainty is assigned based on model spreads in the absence of data. Approximately 30% of the Higgs-portal scalar flux arises from  $K_L^0$  decays.

The PPFX prediction uses isospin symmetry to infer the neutral kaon flux based on charged kaon data [36] but assigns no uncertainty. To conservatively account for the systematic uncertainty introduced by the charged

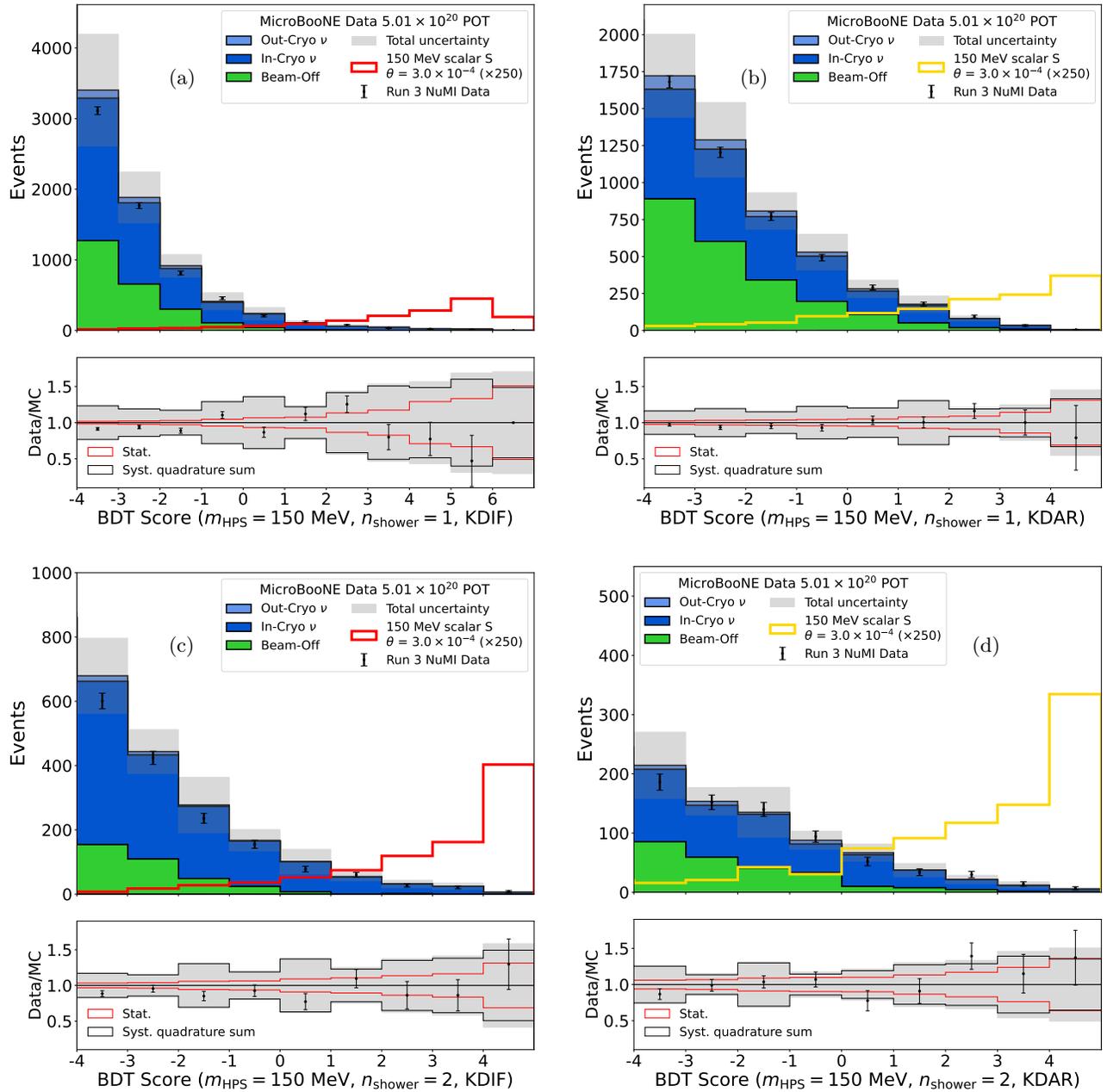


FIG. 6. The distributions of BDT scores for the four BDTs trained to search for Higgs-portal scalar (HPS) particles with masses of 150 MeV in the Run 3 dataset. The quadrature sum of the uncertainties on the background prediction is shown by the gray band, where red indicates the MC statistical uncertainty, and black indicates systematic uncertainty. The simulated signal is shown at a normalization corresponding to  $\theta = 3.0 \times 10^{-4}$ , scaled up by a factor of 250. Overflow events are also included in the right-most bin of each BDT score distribution. (a) The BDT trained to distinguish KDIF topologies in the one-shower sample. (b) The BDT trained to distinguish KDAR topologies in the one-shower sample. (c) The BDT trained to distinguish KDIF topologies in the two-shower sample. (d) The BDT trained to distinguish KDAR topologies in the two-shower sample.

312 kaon rates and the uncertainty due to assumptions made  
 313 in the flux calculation, an uncertainty of 100% is given  
 314 for Higgs-portal scalar particles produced by  $K_L^0$  decays.  
 315 A 30% uncertainty is assigned to the rate of KDAR in  
 316 the NuMI absorber. This is derived from the 30% model  
 317 spread between the MARS [37], FLUKA [38], and GEANT4 [27,  
 318 28] simulations as described in [31].

319 Uncertainties on the neutrino-induced background  
 320 arising from interaction cross-section modeling are de-  
 321 scribed in [34]. Uncertainties on particle propa-  
 322 gation through the detector are assessed using the  
 323 GEANT4Reweight package [39]. Uncertainties on the re-  
 324 sponse of the detector to ionization are simulated as de-  
 325 scribed in [40]. Uncertainties on the detector's electric  
 326 field map arising from a space charge effect and on charge  
 327 recombination are separately accounted for. The scintil-  
 328 lation light-yield uncertainty is estimated by modeling  
 329 a 25% decrease in light yield. An uncertainty on the  
 330 Rayleigh scattering length of argon is evaluated by vary-  
 331 ing this quantity from 60 cm to 90 cm. Uncertainties on  
 332 the attenuation length of scintillation light in argon are  
 333 accounted for based on an observed decline in light levels  
 334 over the course of detector operations. An uncertainty on  
 335 the background arising from neutrino interactions outside  
 336 the active detector region is also incorporated. All of the  
 337 aforementioned systematic uncertainties are summed in  
 338 quadrature, the total of which is shown in Fig. 6 as a  
 339 function of the BDT score.

## V. RESULTS

341 The limits on  $\theta$  are obtained using the semi-frequentist  
 342 CL<sub>S</sub> method [41, 42] as implemented in the pyhf limit-  
 343 setting software framework [43–45]. At each scalar-  
 344 particle mass, the pyhf package uses the six highest-  
 345 score bins from each of the eight BDT distributions,  
 346 and scales the signal contributions simultaneously across  
 347 these distributions to set limits on  $\theta$ . These limits are  
 348 shown in Figure 7 and Table I: when compared to the  
 349 expected limits, they are consistent with the  $\pm 1\sigma$  ex-  
 350 pectation. Table I also shows the numbers of observed  
 351 events and expected background events used in the limit  
 352 setting. Figure 8 compares the limits set in this work to  
 353 pre-existing limits from other experiments. We set the  
 354 strongest experimental limits to date on  $\theta$  in the mass  
 355 range  $110 \text{ MeV} < m_S < 155 \text{ MeV}$ : this is the region  
 356 around the  $\pi^0$  mass, in which the NA62 [24] and E949 [23]  
 357 limits are significantly weakened by  $\pi^0$  backgrounds. The  
 358 previous strongest direct limit in this region is that set by  
 359 a previous MicroBooNE search [2]. A reinterpretation of  
 360 PS191 data [46] also presents a competitive limit to this  
 361 work.

362 Previous limits on the existence of Higgs-portal scalar  
 363 particles have been set by the BELLE-II [47], E949 [23],  
 364 LHCb [48, 49], NA62 [24] and ICARUS [50] experiments,  
 365 and by the MicroBooNE experiment through the  $e^+e^-$  [2]  
 366 and  $\mu^+\mu^-$  [3] decay channels. The previous MicroBooNE

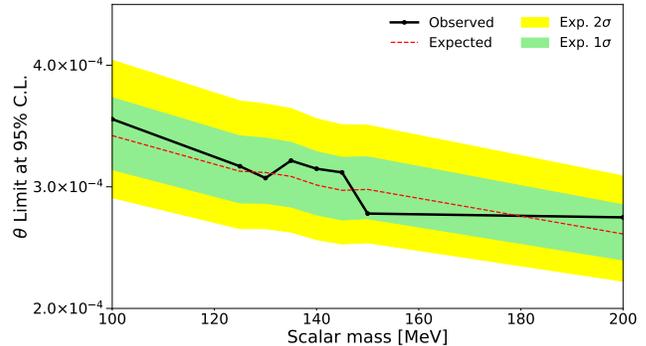


FIG. 7. Limits set by this analysis on the mixing angle  $\theta$  that governs the coupling of an invisible sector to the Higgs term in the SM Lagrangian. The limits are presented as a function of the mass,  $m_S$ , of the observable new scalar particle  $S$  that would result from such a coupling, and are compared with the expected limits.

TABLE I. Observed and expected limits on the mixing angle  $\theta$ , and the final observed and expected background events, given as a function of the mass,  $m_S$ , of the scalar particle  $S$ .

$m_S$ (MeV)	95% C.L. limit on $\theta$ ( $\times 10^{-4}$ )		Number of selected events	
	Observed	Expected	Observed	Background
100	3.57	$3.42^{+0.32}_{-0.28}$	8566	$8395^{+219}_{-219}$
125	3.19	$3.13^{+0.29}_{-0.26}$	10517	$10360^{+278}_{-278}$
130	3.08	$3.12^{+0.29}_{-0.25}$	10590	$10457^{+257}_{-257}$
135	3.23	$3.09^{+0.28}_{-0.25}$	10712	$10541^{+287}_{-287}$
140	3.16	$3.02^{+0.28}_{-0.25}$	10989	$10834^{+277}_{-277}$
145	3.14	$2.97^{+0.27}_{-0.24}$	10685	$10419^{+258}_{-258}$
150	2.79	$2.98^{+0.27}_{-0.24}$	11309	$11262^{+293}_{-293}$
200	2.76	$2.61^{+0.24}_{-0.21}$	15137	$15007^{+383}_{-383}$

367  $e^+e^-$  result is the direct predecessor to this analysis.  
 368 Additional constraints have been made by reinterpreting  
 369 data from the CHARM [51] and PS191 [46] experiments.  
 370 All these existing limits are shown in Fig. 8. Addition-  
 371 ally, not shown on the figure, some regions of small  $m_S$   
 372 and small  $\theta$  can be excluded from cosmological consider-  
 373 ations [52].

## VI. CONCLUSIONS

375 We have presented limits on the mixing angle  $\theta$  that  
 376 describes the coupling, through the Higgs mass term in  
 377 the SM Lagrangian, of an invisible sector that could pro-  
 378 vide a source of dark matter particles. These limits have  
 379 been set through a search for a new scalar singlet par-  
 380 ticle,  $S$ , that would be produced in kaon decays in the  
 381 NuMI beam and be detected through its decays to  $e^+e^-$

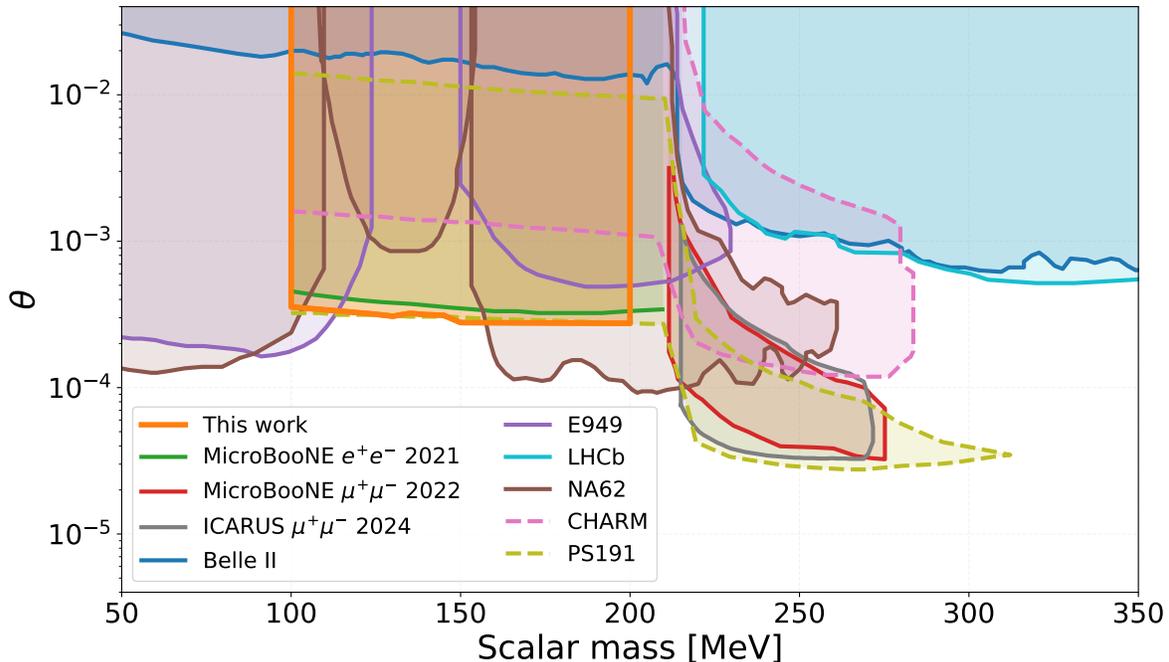


FIG. 8. The 95% C.L. limits on the mixing angle  $\theta$  set by this analysis, as previously shown in Fig. 7, compared to limits set by previous measurements. Shown are direct limits set by the Belle-II [47], E949 [23], LHCb [48, 49], NA62 [24] and ICARUS [50] experiments, and previous limits from MicroBooNE [2, 3]. Limits are also shown from reinterpretations of data from the CHARM [51] and PS191 [46] experiments. Limits from E949, NA62, PS191 and ICARUS, and the MicroBooNE  $\mu^+\mu^-$  limit, are at 90% C.L. All other limits are at 95% C.L.

382 pairs in the MicroBooNE LArTPC. This work uses kaons  
 383 decaying in flight within the beam's decay volume, at  
 384 rest in the target, and within the absorber. This ap-  
 385 proach significantly increases the expected scalar flux  
 386 compared to previous limits set by MicroBooNE [2, 3].  
 387 In this paper, we present the strongest experimental lim-  
 388 its to date on the mixing parameter  $\theta$  in the mass range  
 389  $110 \text{ MeV} < m_S < 155 \text{ MeV}$  corresponding to  $2.01 \times 10^{21}$   
 390 protons on target, the full NuMI beam dataset recorded  
 391 by MicroBooNE.

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