PROCEEDINGS OF SCIENCE

Search for Boosted Dark Matter in Super-Kamiokande with low-energy electrons

Nadège Iovine[1,*] **for the Super-Kamiokande collaboration**

[1] *Institute for Basic Sciences,*
55, Expo-ro, Yuseong-gu, Daejeon, South Korea

E-mail: niovine@ibs.re.kr

Despite efforts from numerous experiments to grasp the nature of dark matter, no convincing dark matter signal has been observed so far and the very properties of this invisible matter remain unknown. Nevertheless, strong constraints on these properties are set by current observations, particularly for GeV to TeV WIMP-like dark matter particles. In contrast, sub-GeV dark matter scenarios are largely unexplored and still offer promising prospects for dark matter detection. In this contribution, we conduct a search for low-energy electrons scattered by boosted dark matter particles in the Super-Kamiokande detector. In particular, a two-component dark matter scenario is considered, which results in a natural boosting of the non-secluded secondary dark matter particles produced by the decay or annihilation of the dominant cold dark matter component. This work focuses on boosted dark matter from the centre of our Galaxy, with scattered electron energies ranging from a few MeV to a few hundred of MeV. We present the first sensitivities of such low-energy boosted dark matter search using Super-Kamiokande.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

[*]Speaker

https://pos.sissa.it/

PoS(ICRC2023)1365

1. Introduction

A variety of overwhelming astrophysical observations support the existence of dark matter (DM) [1, 2]. Since its postulate, numerous experiments attempted to shed light on its nature, but so far the properties of this elusive matter remain largely unknown. Under the assumption that DM consists of Weakly Interacting Massive Particles (WIMPs) [3], searches for DM have been predominantly focused on the GeV to TeV mass scale. However, there has been a recent renewed interest in sub-GeV DM scenarios. When considering low-mass cold dark matter, its feeble interaction with SM particles leads to poor detection sensitivity. However, sub-GeV DM could undergo a boosting mechanism, which would make it energetic enough to knock electrons and hadrons out of the atoms [4]. Such boosted DM could exist as a subdominant relativistic DM component alongside the dominant cold DM particles making up the largest fraction of dark matter in our Universe. Several models propose the existence of boosted DM, such as cosmic-ray-boosted DM [5] or blazar-boosted DM [6]. Among these scenarios, the two-component DM model suggests that the dominant DM component could annihilate or decay into a second specie of DM particles, naturally boosting them to relativistic energies.

Boosted DM could be observed by looking for the recoil of electrons or nuclei in large-size terrestrial detectors. In this work, we present the sensitivities of a search for boosted DM with electrons in the Super-Kamiokande (SK) Cherenkov detector, considering recoiled energies between 10 and 100 MeV. As a large DM density is expected in the centre of galaxies [7], we focus on boosted DM from the centre of the Milky Way in order to optimise the signal expectation.

2. Flux of Boosted Dark Matter

For this search, DM is assumed to be naturally boosted by the annihilation of the DM particles A. The resulting differential flux of boosted DM B coming from the direction of the Galactic Centre can be expressed as:

$$\frac{\mathrm{d}\phi_B}{\mathrm{d}\Omega\,\mathrm{d}E_B} = \frac{1}{2}\,\frac{\langle\sigma_{A\bar{A}\to B\bar{B}}\,\upsilon\rangle}{4\pi m_B^2}\,\frac{\mathrm{d}N_B}{\mathrm{d}E_B}\int_{l.o.s}\rho_A^2(r(l,\theta,\Psi))\,\mathrm{d}l\ , \tag{1}$$

where m_B is the mass of the considered boosted DM particles and $\mathrm{d}N_B/\mathrm{d}E_B$ is the differential energy spectrum given by $2\delta(E_B - m_A)$. The corresponding spectrum of electron recoiled by boosted DM is obtained using the boosted DM module of GENIE [8] and can be seen in the left-hand of Figure 1 for a boosted DM mass of 200 MeV and several boosted DM energies. The thermally-averaged annihilation cross-section of the dominant DM specie A into the boosted DM particle B, $\langle\sigma_{A\bar{A}\to B\bar{B}}\,\upsilon\rangle$, is assumed to be equal to 5×10^{-26} cm^3/s. The remaining term Equation 2 is the differential J-factor, which is given by the integral over the line-of-sight of the density of the dominant DM specie A. The DM density distribution in our galaxy can be expressed as a function of the distance to the Galactic Centre, r, according to [9]:

$$\rho_{\mathrm{DM}}(r) = \frac{\rho_0}{\left(\delta + \frac{r}{r_s}\right)^{\gamma}\left[1 + \left(\frac{r}{r_s}\right)^{\alpha}\right]^{(\beta-\gamma)/\alpha}}\ , \tag{2}$$

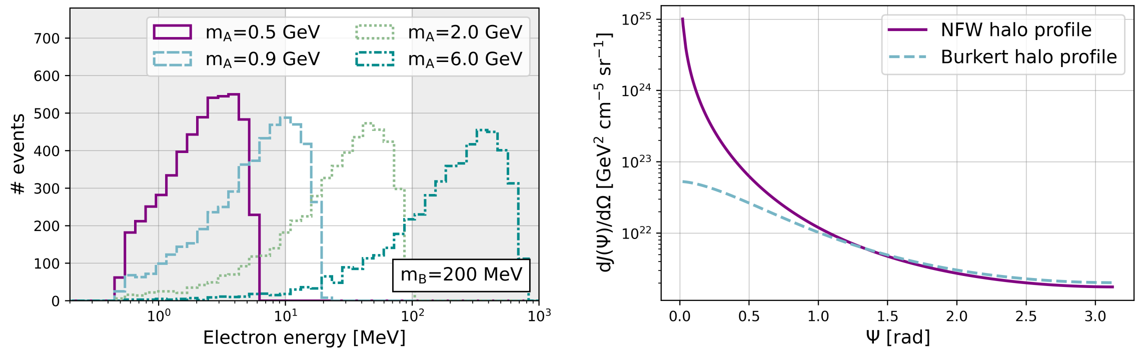

Figure 1: Left: Recoiled electron spectra for a boosted DM mass (m_B) of 200 MeV shown as a function of the electron energy for various BDM energies (m_A). **Right:** Differential J-factor ($\mathrm{d}J/\mathrm{d}\Omega$) presented with respect to the opening angle to the Galactic Centre (Ψ) for both the NFW and Burkert halo profiles.

with the scale radius, r_s, and normalisation density, ρ_0, taken from [10]. As the spatial distribution of boosted DM strongly depends on the shape of the DM halo, several models will be considered in this analysis to account for this important source of systematics. In this contribution, we present the sensitivities obtained for the Navarro-Frenk-White profile (NFW) [11] for which the parameters $(\alpha, \beta, \delta, \gamma)$ take the values (1,3,0,1). The right plot of Figure 1 shows the corresponding differential J-factor of this "cuspy" DM halo profile alongside the distribution of a less optimistic "cored" scenario, known as the Burkert halo profile [12].

3. Event Selection

The current event selection consists of simple cuts dedicated to select single-electron events contained in the fiducial volume of the Super-Kamiokande neutrino telescopes [13]. Super-Kamiokande is an underground Cherenkov detector located in the Gifu prefecture of Japan. It is composed of a 50 kT cylindrical water tank split into an inner and an outer section. The inner detector (ID) contains 11,129 inward-facing photo-multiplier tubes (PMTs), for a total of 32 kT with a 22.5 kT fiducial volume. The outer detector (OD) consists of a 2 m water layer around the ID equipped with 1,885 outward-facing PMTs. Events are tagged as fully-contained (FC) if all related hits were recorded solely in the ID. In addition to the selection of FC events, cuts on the Cherenkov cone opening angle is applied in order to select events leaving a single-ring signature in the detector. A cut on the energy of the recoiled electrons is also implemented, selecting events with energies between 10 and 100 MeV. A total livetime of 583.3 days is considered for the sensitivity computation, with events recorded during the SK-VI data-taking period extending from 2020 to 2022.

4. Analysis Method

The idea behind this analysis is to search for an excess of recoiled electrons pointing in the direction of the Galactic Centre, with energies distributed according to the signal predictions. A binned likelihood method is used to compare data to what is expected from the background and signal probability density functions (PDFs).

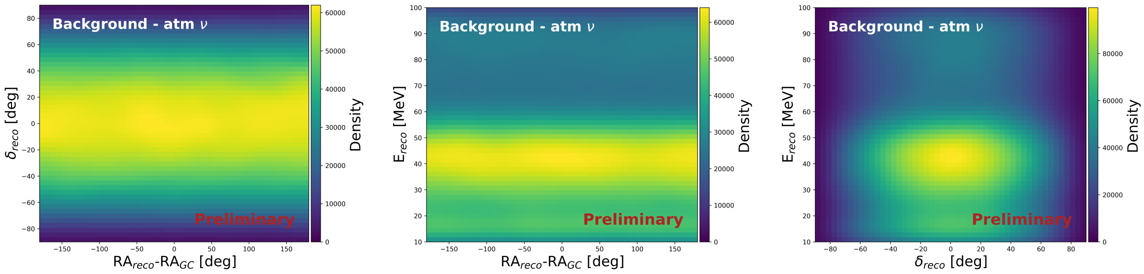

Figure 2: Two-dimensional projections of the Background PDF, with the three dimensions being the right ascension (RA), the declination (dec), and the energy (E) of the events.

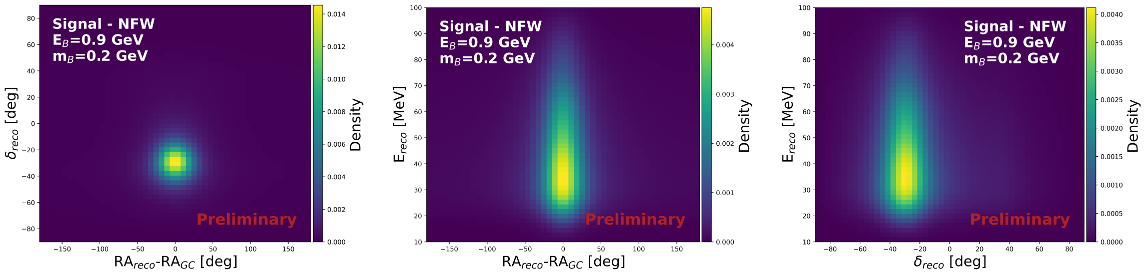

Figure 3: Two-dimensional projections of the signal PDF in assuming a BDM mass of 200 MeV, BDM-dark photon coupling of 0.5 for a dark photon of 20 MeV mass, for the NFW profile

The background distribution is estimated from Monte Carlo (MC) simulations weighted with an atmospheric neutrino flux [14]. In order to obtain a smooth distribution of the background, a Kernel Density Estimation (KDE) method is applied to the three-dimensional distribution of the events in right ascension (RA), declination (δ), and energy (E). The probability density function is estimated by applying a Gaussian kernel with a bandwidth optimised using a cross-validation method. The subsequent distribution is then binned with 50 bins in each dimension. The two-dimensional projections of the resulting binned background PDF can be seen in Figure 2.

Similarly, the signal PDFs are built from MC electron simulations weighted according to the signal predictions for several combinations of BDM mass and energies. The number of electrons expected to be recoiled by BDM in the Super-Kamiokande detector can be computed from:

$$N_{\text{recoil}} = T_{\text{livetime}}\ N_{\text{target}}\ \phi_B\ \sigma_{Be^- \to Be^-}\ , \tag{3}$$

where T_{livetime} is the livetime considered for the experiment. The number of targets, N_{target}, corresponds to the number of electrons that can be found in the detector volume. Information about the source morphology and the energy spectrum is encoded in ϕ_B, obtained from Equation 2. The number of expected recoiled electrons also depends on the interaction cross-section between boosted DM particles and electrons $\sigma_{Be^- \to Be^-}$, on which we can set a constraint if no signal electrons were to be found. The resulting signal distribution for a boosted DM mass of 200 MeV and boosted DM energy of $E_B = m_A = 1$GeV is shown in Figure 3, assuming the NFW halo distribution.

Using these background and signal distributions, the likelihood function is built as the product of the Poisson probabilities to observe n^i_{obs} events in a particular bin i:

$$\mathcal{L}(\mu) = \prod_{i=min}^{max} \frac{\left(n_{\rm obs}^{\rm tot}\, f^i(\mu)\right)^{n_{\rm obs}^i}}{n_{\rm obs}^i!} e^{-n_{\rm obs}^{\rm tot}\, f^i(\mu)}\,, \tag{4}$$

with $n_{\rm obs}^{\rm tot}$ being the total number of events and $\mu \in [0, 1]$ being the fraction of signal events in the sample. The portion of events in each bin is given by:

$$f^i(\mu) = \mu\, f_s^i + (1-\mu)\, f_{\rm bg}^i\,, \tag{5}$$

where f_s and $f_{\rm bg}$ are the signal and background PDFs, respectively. By maximising the likelihood, $\mathcal{L}(\mu)$, one obtains the best estimate on the signal fraction. For values of μ consistent with the background-only hypothesis, the 90% confidence level (CL) upper limit, μ_{90}, is drawn following the likelihood interval method [15]. The 90% CL sensitivity, $\hat{\mu}_{90}$, is obtained by taking the median value of the upper limits computed using 100,000 pseudo-experiments sampled from the background-only PDF. The sensitivities on the boosted DM-electron cross-section, $\sigma_{Be^- \to Be^-}$ can be deduced using the ratio between the total number of events in the sample and the expected number of signal events for each combination of boosted DM mass and energies.

5. Sensitivities

The 90% CL sensitivities were computed for a boosted DM mass of 200 MeV and boosted DM energies ranging from 600 MeV to 10 GeV, assuming the NFW halo profile. This particular boosted DM scenario is the one considered for the Super-Kamiokande search presented in [16] and was chosen here to demonstrate the potential of a low-energy search with respect to previous SK analyses. In Figure 4, the resulting sensitivities are expressed in terms of the BDM-electron cross-section as a function of the BDM energy, m_A. Using integration described in [4], one can then obtain the sensitivities on the coupling of dark photons to the standard model, ϵ. The sensitivities

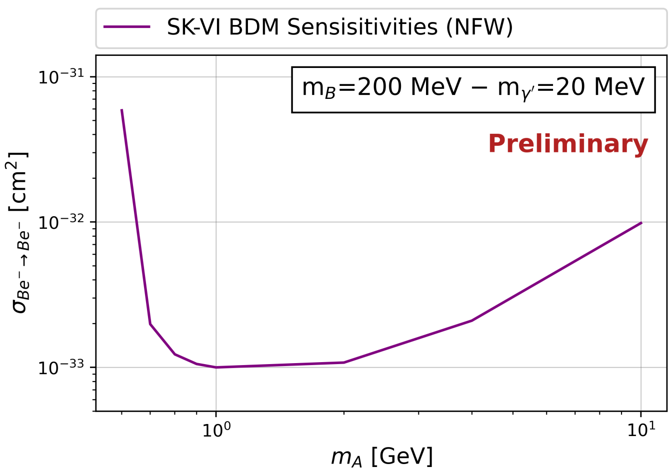

Figure 4: 90% CL Sensitivity on the BDM-electron interaction cross-section ($\sigma_{Be^- \to Be^-}$) for a BDM mass of 200 MeV, BDM-dark photon coupling of 0.5 for a dark photon of 20 MeV mass, when considering the DM halo distribution following the NFW profile.

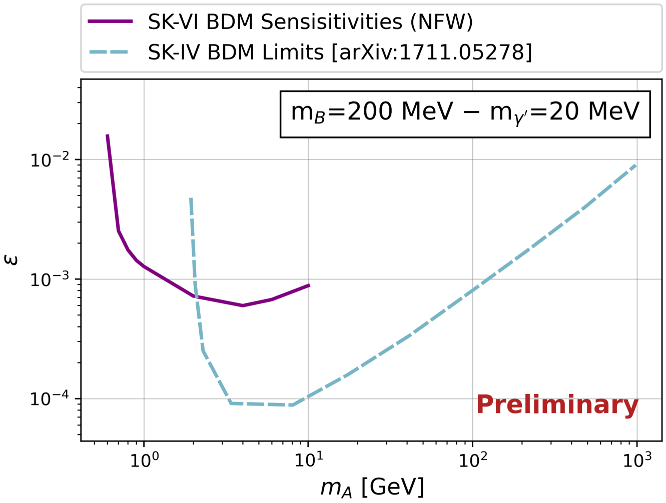

Figure 5: 90% CL Sensitivity on the dark photon-electron coupling (ϵ) for a BDM mass of 200 MeV, BDM-dark photon coupling of 0.5 for a dark photon of 20 MeV mass, when considering the DM halo distribution following the NFW profile. The limits obtained by the previous Super-Kamiokande BDM search with recoiled electrons are also shown [16].

in terms of ϵ are shown in Figure 5, along with previous Super-Kamiokande limits from a similar search using SK-IV data.

By considering low-energy recoiled electron events, this analysis is able to extend the search for boosted DM to lower energies than the previous SK boosted DM search with electrons. It has to be noted that the sensitivities of this analysis are obtained with SK-VI data with a limited livetime of 583.3 days, while the limits shown in Figure 5 are computed from SK-IV data for a total livetime of 2,628.1 days. The boosted DM mass and energy combinations are also sub-optimal for this analysis as the majority of the signal falls outside of the 10 MeV to 100 MeV electron energy range, affecting the signal efficiency. We expect this low-energy search to be more competitive for lower boosted dark matter masses and energies.

6. Conclusion and outlooks

The preliminary sensitivities computed for this boosted DM search from the centre of our galaxy with low-energy electrons show encouraging improvements for the future of this analysis. By considering lower recoiled electron energies, an enhancement of the sensitivities can be seen for boosted DM energies below a few GeV. In the current state of this work, only a few years of data are considered. The next step would thus be to consider the full livetime of the Super-Kamiokande detector in order to gain in sensitivity. The event selection also needs to be improved by optimising the applied cuts and considering further selection tools, such as Boosted Decision Trees (BDT).

With the emphasis set on low-energies, the improvement will be most marked for lower boosted dark matter masses. The plan is therefore to scan more masses of boosted DM, going from a few MeV to a few tenths of MeV, for an extended boosted DM range. Finally, it would also be enviable to extend the analysis to higher electron energies in order to consistently cover the entire energy range of the Super-Kamiokande detector.

References

[1] G. Bertone and D. Hooper *Rev. Mod. Phys.* **90** no. 4, (2018) 045002.

[2] **Planck** Collaboration, P. A. R. Ade *et al.* *Astron. Astrophys.* **571** (2014) A16.

[3] G. Steigman and M. S. Turner *Nucl. Phys. B* **253** (1985) 375–386.

[4] K. Agashe, Y. Cui, L. Necib, and J. Thaler *JCAP* **10** (2014) 062.

[5] C. Xia, Y.-H. Xu, and Y.-F. Zhou *JCAP* **02** no. 02, (2022) 028.

[6] J.-W. Wang, A. Granelli, and P. Ullio *Phys. Rev. Lett.* **128** no. 22, (2022) 221104.

[7] A. V. Kravtsov, A. A. Klypin, J. S. Bullock, and J. R. Primack *Astrophys. J.* **502** (1998) 48.

[8] J. Berger *arXiv:1812.05616 [hep-ph]* (2018) .

[9] J. An and H. Zhao *Mon. Not. Roy. Astron. Soc.* **428** (2013) 2805–2811.

[10] F. Nesti and P. Salucci *JCAP* **07** (2013) 016.

[11] J. F. Navarro, C. S. Frenk, and S. D. M. White *Astrophys. J.* **462** (1996) 563–575.

[12] A. Burkert *Astrophys. J. Lett.* **447** (1995) L25.

[13] **Super-Kamiokande** Collaboration, Y. Fukuda *et al.* *Nucl. Instrum. Meth. A* **501** (2003) 418–462.

[14] M. Honda *et al.* *Phys. Rev. D* **92** no. 2, (2015) 023004.

[15] G. Cowan, K. Cranmer, E. Gross, and O. Vitells *Eur. Phys. J. C* **71** (2011) 1554. [Erratum: Eur.Phys.J.C 73, 2501 (2013)].

[16] **Super-Kamiokande** Collaboration, C. Kachulis *et al.* *Phys. Rev. Lett.* **120** no. 22, (2018) 221301.

Full Authors List: Super-Kamiokande Collaboration

K. Abe[1,46] C. Bronner[1] Y. Hayato[1,46] K. Hiraide[1,46] K. Hosokawa[1] K. Ieki[1,46] M. Ikeda[1,46] J. Kameda[1,46] Y. Kanemura[1] R. Kaneshima[1] Y. Kashiwagi[1] Y. Kataoka[1,46] S. Miki[1] S. Mine[1,6] M. Miura[1,46] S. Moriyama[1,46] Y. Nakano[1] M. Nakahata[1,46] S. Nakayama[1,46] Y. Noguchi[1] K. Sato[1] H. Sekiya[1,46] H. Shiba[1] K. Shimizu[1] M. Shiozawa[1,46] Y. Sonoda[1] Y. Suzuki[1] A. Takeda[1,46] Y. Takemoto[1,46] H. Tanaka[1,46] T. Yano[1] S. Han[2] T. Kajita[2,46,22] K. Okumura[2,46] T. Tashiro[2] T. Tomiya[2] X. Wang[2] S. Yoshida[2] P. Fernandez[3] L. Labarga[3] N. Ospina[3] B. Zaldivar[3] B. W. Pointon[5,49] E. Kearns[4,46] J. L. Raaf[4] L. Wan[4] T. Wester[4] J. Bian[6] N. J. Griskevich[6] S. Locke[6] M. B. Smy[6,46] H. W. Sobel[6,46] V. Takhistov[6,24] A. Yankelevich[6] J. Hill[7] S. H. Lee[8] D. H. Moon[8] R. G. Park[8] B. Bodur[9] K. Scholberg[9,46] C. W. Walter[9,46] A. Beauchene[10] O. Drapier[10] A. Giampaolo[10] Th. A. Mueller[10] A. D. Santos[10] P. Paganini[10] B. Quilain[10] T. Nakamura[11] J. S. Jang[12] L. N. Machado[13] J. G. Learned[14] K. Choi[15] N. Iovine[15] S. Cao[16] L. H. V. Anthony[17] D. Martin[17] N. W. Prouse[17] M. Scott[17] A. A. Sztuc[17] Y. Uchida[17] V. Berardi[18] M. G. Catanesi[18] E. Radicioni[18] N. F. Calabria[19] A. Langella[19] G. De Rosa[19] G. Collazuol[20] F. Iacob[20] M. Mattiazzi[20] L. Ludovici[21] M. Gonin[22] G. Pronost[22] C. Fujisawa[23] Y. Maekawa[23] Y. Nishimura[23] R. Okazaki[23] R. Akutsu[24] M. Friend[24] T. Hasegawa[24] T. Ishida[24] T. Kobayashi[24] M. Jakkapu[24] T. Matsubara[24] T. Nakadaira[24] K. Nakamura[24,46] Y. Oyama[24] K. Sakashita[24] T. Sekiguchi[24] T. Tsukamoto[24] N. Bhuiyan[25] G. T. Burton[25] F. Di Lodovico[25] J. Gao[25] A. Goldsack[25] T. Katori[25] J. Migenda[25] Z. Xie[25] S. Zsoldos[25,46] A. T. Suzuki[26] Y. Takagi[26] Y. Takeuchi[26,46] J. Feng[27] L. Feng[27] J. R. Hu[27] Z. Hu[27] T. Kikawa[27] M. Mori[27] T. Nakaya[27,46] R. A. Wendell[27,46] K. Yasutome[27] S. J. Jenkins[28] N. McCauley[28] P. Mehta[28] A. Tarant[28] Y. Fukuda[29] Y. Itow[30,31] H. Menjo[30] K. Ninomiya[30] J. Lagoda[32] S. M. Lakshmi[32] M. Mandal[32] P. Mijakowski[32] Y. S. Prabhu[32] J. Zalipska[32] M. Jia[33] J. Jiang[33] C. K. Jung[33] M. J. Wilking[33] C. Yanagisawa[33,*] M. Harada[34] Y. Hino[34] H. Ishino[34] Y. Koshio[34,46] F. Nakanishi[34] S. Sakai[34] T. Tada[34] T. Tano[34] T. Ishizuka[35] G. Barr[36] D. Barrow[36] L. Cook[36,46] S. Samani[36] D. Wark[36,41] A. Holin[37] F. Nova[37] B. S. Yang[38] J. Y. Yang[38] J. Yoo[38] J. E. P. Fannon[39] L. Kneale[39] M. Malek[39] J. M. McElwee[39] M. D. Thiesse[39] L. F. Thompson[39] S. T. Wilson[39] H. Okazawa[40] S. B. Kim[42] E. Kwon[42] J. W. Seo[42] I. Yu[42] A. K. Ichikawa[43] K. D. Nakamura[43] S. Tairafune[43] K. Nishijima[44] A. Eguchi[45] K. Nakagiri[45] Y. Nakajima[45,46] S. Shima[45] N. Taniuchi[45] E. Watanabe[45] M. Yokoyama[45,46] P. de Perio[46] S. Fujita[46] K. Martens[46] K. M. Tsui[46] M. R. Vagins[46,6] J. Xia[46] S. Izumiyama[47] M. Kuze[47] R. Matsumoto[47] M. Ishitsuka[48] H. Ito[48] Y. Ommura[48] N. Shigeta[48] M. Shinoki[48] K. Yamauchi[48] T. Yoshida[48] R. Gaur[49] V. Gousy-Leblanc[49,†] M. Hartz[49] A. Konaka[49] X. Li[49] S. Chen[50] B. D. Xu[50] B. Zhang[50] M. Posiadala-Zezula[51] S. B. Boyd[52] R. Edwards[52] D. Hadley[52] M. Nicholson[52] M. O'Flaherty[52] B. Richards[52] A. Ali[53,49] B. Jamieson[53] S. Amanai[54] Ll. Marti[54] A. Minamino[54] S. Suzuki[54]

[1]Kamioka Observatory, Institute for Cosmic Ray Research, University of Tokyo, Kamioka, Gifu 506-1205, Japan
[2]Research Center for Cosmic Neutrinos, Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba 277-8582, Japan
[3]Department of Theoretical Physics, University Autonoma Madrid, 28049 Madrid, Spain
[4]Department of Physics, Boston University, Boston, MA 02215, USA
[5]epartment of Physics, British Columbia Institute of Technology, Burnaby, BC, V5G 3H2, Canada
[6]Department of Physics and Astronomy, University of California, Irvine, Irvine, CA 92697-4575, USA
[7]Department of Physics, California State University, Dominguez Hills, Carson, CA 90747, USA
[8]Institute for Universe and Elementary Particles, Chonnam National University, Gwangju 61186, Korea
[9]Department of Physics, Duke University, Durham NC 27708, USA
[10]Ecole Polytechnique, IN2P3-CNRS, Laboratoire Leprince-Ringuet, F-91120 Palaiseau, France
[11]Department of Physics, Gifu University, Gifu, Gifu 501-1193, Japan
[12]GIST College, Gwangju Institute of Science and Technology, Gwangju 500-712, Korea
[13]School of Physics and Astronomy, University of Glasgow, Glasgow, Scotland, G12 8QQ, United Kingdom
[14]Department of Physics and Astronomy, University of Hawaii, Honolulu, HI 96822, USA
[15]Center for Underground Physics, Institute for Basic Science (IBS), Daejeon, 34126, Korea
[16]Institute For Interdisciplinary Research in Science and Education, ICISE, Quy Nhon, 55121, Vietnam
[17]Department of Physics, Imperial College London , London, SW7 2AZ, United Kingdom
[18]Dipartimento Interuniversitario di Fisica, INFN Sezione di Bari and Universita e Politecnico di Bari, I-70125, Bari, Italy
[19]Dipartimento di Fisica, INFN Sezione di Napoli and Universita di Napoli, I-80126, Napoli, Italy
[20]Dipartimento di Fisica, INFN Sezione di Padova and Universita di Padova, I-35131, Padova, Italy
[21]INFN Sezione di Roma and Universita di Roma "La Sapienza", I-00185, Roma, Italy
[22]ILANCE, CNRS - University of Tokyo International Research Laboratory, Kashiwa, Chiba 277-8582, Japan
[23]Department of Physics, Keio University, Yokohama, Kanagawa, 223-8522, Japan
[24]High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan
[25]Department of Physics, King's College London, London, WC2R 2LS, UK
[26]Department of Physics, Kobe University, Kobe, Hyogo 657-8501, Japan
[27]Department of Physics, Kyoto University, Kyoto, Kyoto 606-8502, Japan
[28]Department of Physics, University of Liverpool, Liverpool, L69 7ZE, United Kingdom
[29]Department of Physics, Miyagi University of Education, Sendai, Miyagi 980-0845, Japan
[30]Institute for Space-Earth Environmental Research, Nagoya University, Nagoya, Aichi 464-8602, Japan
[31]Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya University, Nagoya, Aichi 464-8602, Japan
[32]National Centre For Nuclear Research, 02-093 Warsaw, Poland
[33]Department of Physics and Astronomy, State University of New York at Stony Brook, NY 11794-3800, USA
[34]Department of Physics, Okayama University, Okayama, Okayama 700-8530, Japan

[35]Media Communication Center, Osaka Electro-Communication University, Neyagawa, Osaka, 572-8530, Japan
[36]Department of Physics, Oxford University, Oxford, OX1 3PU, United Kingdom
[37]Rutherford Appleton Laboratory, Harwell, Oxford, OX11 0QX, UK
[38]Department of Physics, Seoul National University, Seoul 151-742, Korea
[39]Department of Physics and Astronomy, University of Sheffield, S3 7RH, Sheffield, United Kingdom
[40]Department of Informatics in Social Welfare, Shizuoka University of Welfare, Yaizu, Shizuoka, 425-8611, Japan
[41]STFC, Rutherford Appleton Laboratory, Harwell Oxford, and Daresbury Laboratory, Warrington, OX11 0QX, United Kingdom
[42]Department of Physics, Sungkyunkwan University, Suwon 440-746, Korea
[43]Department of Physics, Faculty of Science, Tohoku University, Sendai, Miyagi, 980-8578, Japan
[44]Department of Physics, Tokai University, Hiratsuka, Kanagawa 259-1292, Japan
[45]Department of Physics, University of Tokyo, Bunkyo, Tokyo 113-0033, Japan
[46]Kavli Institute for the Physics and Mathematics of the Universe (WPI), The University of Tokyo Institutes for Advanced Study, University of Tokyo, Kashiwa, Chiba 277-8583, Japan
[47]Department of Physics,Tokyo Institute of Technology, Meguro, Tokyo 152-8551, Japan
[48]Department of Physics, Faculty of Science and Technology, Tokyo University of Science, Noda, Chiba 278-8510, Japan
[49]TRIUMF, 4004 Wesbrook Mall, Vancouver, BC, V6T2A3, Canada
[50]Department of Engineering Physics, Tsinghua University, Beijing, 100084, China
[51]Faculty of Physics, University of Warsaw, Warsaw, 02-093, Poland
[52]Department of Physics, University of Warwick, Coventry, CV4 7AL, UK
[53]Department of Physics, University of Winnipeg, MB R3J 3L8, Canada
[54]Department of Physics, Yokohama National University, Yokohama, Kanagawa, 240-8501, Japan

[*]also at BMCC/CUNY, Science Department, New York, New York, 1007, USA.
[†]also at University of Victoria, Department of Physics and Astronomy, PO Box 1700 STN CSC, Victoria, BC V8W 2Y2, Canada.