Higgs Portal From The Atmosphere To Hyper-K

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A light Higgs portal scalar could be abundantly produced in the earth's atmosphere and decay in large-volume neutrino detectors. We propose broadening the purpose of the Hyper-Kamiokande detector to search for such particle that can account for recent KOTO measurements of rare kaon decays. The signal is electron-positron pair creation that manifests as a double-ring appearing from the same vertex. Most of pairs originate from zenith angles above the detector's horizon. This search can be generalized to other new light states and is highly complementary to beam experiments.

A Standard Model gauge singlet scalar that mixes with the Higgs boson, sometimes also referred to as the "dark Higgs", is a simple new physics candidate. It has been introduced for exploring the dark universe [1–4], facilitating baryogengesis mechanisms [5, 6], precision physics of the Standard Model [7, 8], and, perhaps, naturalness [9]. In its minimal incarnation, the Higgs portal scalar is produced in laboratories and decays into Standard Model particles via the same mixing parameter with the Higgs boson. These makes it a well-motivated and well-defined target of searches in a number of experiments. Constraints have been set for a wide range of its mass [10–12]. In particular, if the scalar is lighter than $\sim$ GeV, leading constraints come from the measurement of rare K and B meson decays where the mixing parameter must be smaller than $\sim 10^{-3}$.

Recently, Higgs portal scalar has been revisited to understand a new experimental finding. In 2016-18, the KOTO experiment at J-PARC performed a search for the flavor-changing decay process $K_L \to \pi^0 \nu\bar{\nu}$, in final states with two energetic photons plus a missing transverse momentum. Three candidate events were identified while Standard Model predicts nearly none [13]. Although this might simply be due to an underestimate of background, it has triggered the study of a variety of potential new physics candidates, heavy and light. Among them, a light Higgs portal scalar ϕ stands out as the simplest explanation [14] (see also [15–17]). The signal is explained as $K_L \to \pi^0\phi$ decay where ϕ is long lived and escapes the detector. Viable parameter space corresponds to a ϕ mass between 100-200 MeV and ϕ-Higgs mixing parameter of a few $\times 10^{-4}$.

Given such a simple explanation, it is worthwhile exploring how the target parameter space could be tested in other experiments. An obvious place to check is the isospin related decay mode, $K^+ \to \pi^+\nu\bar{\nu}$. Indeed, this channel has been searched for at the E949 [18] and NA62 [19] experiments where upper limits are set on the mixing parameter of the Higgs portal scalar. However, both limits feature a gap when the scalar mass is around the pion mass, due to the enormous $K^+ \to \pi^+\pi^0$ background. In this mass window, an upper limit on the mixing parameter is set by a very early beam dump experiment, CHARM [20], in the search for displaced decay of ϕ, although this limit is not yet competitive. The above contrast points to the direction to proceed. In order to cover the KOTO favored parameter space, one should resort to appearance experiments hunting the visible decay of long lived ϕ particles rather than disappearance experiments searching for ϕ as missing momentum. As a further useful observation, the decay length of a KOTO favored Higgs portal scalar is of order hundreds of kilometers (even longer if boosted). This gives motivation to imagine large experiments operating at length scales beyond those beam-based ones built entirely within the laboratories.

In this Letter, we propose using a nature-made experimental setup to probe the Higgs portal scalar ϕ. It utilizes cosmic rays as the beam, earth's atmosphere as the target, and earth itself as the shielding region. In this picture, ϕ particles originate from the decay of kaons, with the latter being abundantly produced in the cosmic-ray-atmosphere fixed-target collisions, together with charged pions that make the atmospheric neutrinos [21]. If long lived enough, the ϕ particles travel a long distance across the earth before decaying inside a human-made detector. We focus on the Hyper-Kamiokande (Hyper-K) experiment which, at least for the foreseeable future, has the largest detector volume and a suitably low energy threshold to capture the scalar decays.

The Higgs portal scalar is defined as a mass eigenstate and a linear combination of a Standard Model gauge singlet s and the Higgs boson h,

$$\phi = \cos\theta\, s + \sin\theta\, h \ , \tag{1}$$

where θ is a real mixing parameter. The cosmic rays near us are dominated by protons while the elements in the earth's atmosphere are dominated by nitrogen and oxygen, comprised of equal numbers of protons and neutrons. We simulate fixed target proton-proton and proton-neutron collisions using `PYTHIA 8` [22] for various incoming proton energies, which is further convoluted with the incoming cosmic proton spectrum [23] to derive the differential energy spectrum of kaons (most relevant for this study, $K^\pm$ and K_L), $d\Phi/dE_K$. Their sum is shown as the blue histogram in Fig. 1. The ratio of $K^\pm$

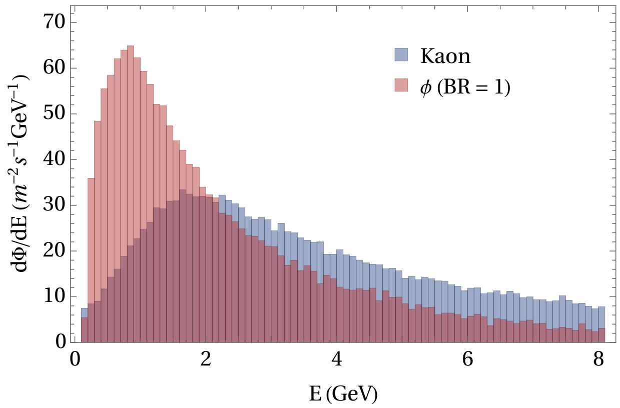

FIG. 1. Energy distribution of atmospheric kaons ($K^\pm$ and K_L added together) and ϕ particles, for $m_\phi = 150\,\mathrm{MeV}$, obtained from the atmospheric simulation described in the text. For illustration purpose, the flux of ϕ has been rescaled by assuming the $K \to \pi\phi$ decay branching ratios are equal to 1.

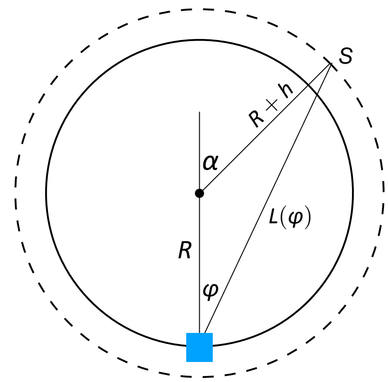

FIG. 2. Geography of earth and detector. The blue box indicates the location of the Hyper-K detector. The dashed circle represents a sphere where the cosmic-ray-atmosphere reactions mainly occur that produce light ϕ particles. h is given by the height of this sphere plus the depth of detector underground, and φ is the zenith angle in view of the detector.

and K_L particles is about $2:1$, as expected.

The ϕ particles are produced from rare kaon decays, $K^\pm \to \pi^\pm\phi$ and $K_L \to \pi^0\phi$. The corresponding branching ratios are [24–26]

$$\mathrm{Br}(K^\pm \to \pi^\pm\phi) \simeq \frac{9\tau_{K^\pm}|V_{ts}V_{td}^*|^2 G_F^3 m_t^4 m_{K^\pm}^2 p_{\phi\mathrm{CM}}\theta^2}{2048\sqrt{2}\pi^5}, \quad (2)$$

$$\mathrm{Br}(K_L \to \pi^0\phi) \simeq \frac{9\tau_{K_L}[\mathrm{Re}(V_{ts}V_{td}^*)]^2 G_F^3 m_t^4 m_{K^\pm}^2 p_{\phi\mathrm{CM}}\theta^2}{2048\sqrt{2}\pi^5},$$

where the decay momentum in the center-of-mass (CM) frame is $p_{\phi\mathrm{CM}} = \lambda(m_K^2, m_\pi^2, m_\phi^2)/2m_{K^\pm}$, and λ is the Källén function. In small m_ϕ limit, $\mathrm{Br}(K_L \to \pi^0\phi)/\mathrm{Br}(K^\pm \to \pi^\pm\phi) \simeq 3.7$ [27]. In the lab frame, the ratio of the final state ϕ energy to that of kaon is

$$\frac{E_\phi}{E_K} = \frac{E_{\phi\mathrm{CM}}}{m_K} + \frac{p_{\phi\mathrm{CM}}}{m_K}\sqrt{1 - \frac{m_K^2}{E_K^2}}\cos\vartheta_{\mathrm{CM}}\ , \quad (3)$$

where $E_{\phi\mathrm{CM}} = \sqrt{p_{\phi\mathrm{CM}}^2 + m_\phi^2}$ and ϑ_{CM} is the relative angle between ϕ's three-momentum in the kaon rest frame and the boost direction of the kaon. Because $K^\pm$ and K_L are scalars, the angular ϕ distribution in their rest frame is isotropic. For given energy E_K, the values of E_ϕ distribute evenly between its extremes, corresponding to $\cos\vartheta_{\mathrm{CM}} = \pm 1$. The resulting differential flux of ϕ can be calculated using

$$\frac{d\Phi_\phi}{dE_\phi} = \sum_{K=K^\pm, K_L} \mathrm{Br}(K \to \pi\phi)\int_{E_{K\mathrm{min}}(E_\phi)}^{E_{K\mathrm{max}}(E_\phi)} dE_K \frac{d\Phi_K}{dE_K} \times \frac{m_K}{2p_{\phi\mathrm{CM}}\sqrt{E_K^2 - m_K^2}}\ , \quad (4)$$

where $E_{K\mathrm{max,min}}$ is the largest (smallest) kaon energy that satisfies Eq. (3), for given E_ϕ. In the limit $E_K \gg m_K$, $E_{K\mathrm{max,min}} \simeq E_\phi m_K/(E_{\phi\mathrm{CM}} \mp p_{\phi\mathrm{CM}})$. In Fig. 1, the red histogram shows the energy distribution of atmospheric ϕ particles, for $m_\phi = 150\,\mathrm{MeV}$. Its energy is peaked $\sim 700\,\mathrm{MeV}$.

It is worth pointing out the above is a conservative approach of simulating atmospheric ϕ production. In order for the parton picture used by `PYHTIA` to be valid, we restrict the CM energy of pp and pn scatterings to be above $\sim 6\,\mathrm{GeV}$. We also neglected secondary reactions of kaons in the atmosphere before they decay, keeping in mind that the earth's atmosphere is dilute. These approximations leave out lower energy processes that could also make kaons, and in turn, more ϕ particles.

After being produced in the atmosphere, the ϕ particles can travel through the earth to decay inside human-made detectors, provided they have sufficiently long lifetimes. Clearly, the larger the detector the better to capture such a signal. Its energy threshold should be low enough to see sub-GeV energy deposits from the ϕ decay. These requirements led us to consider Hyper-K.

To calculate the ϕ flux at Hyper-K detector, we consider the geometric picture shown in Fig. 2. We assume all cosmic-ray-atmosphere reactions occur on a sphere with fixed height above the ground. This height plus the depth of the underground Hyper-K detector, denoted by h, is taken to be 10 km. The angles φ and α are related by

$$\cos\alpha = [L(\varphi)\cos\varphi - R]/(R+h)\ , \quad (5)$$

where $L(\varphi)$ is the distance ϕ travels,

$$L(\varphi) = R\cos\varphi + \sqrt{h^2 + 2Rh + R^2\cos^2\varphi}\ . \quad (6)$$

An infinitesimal area on the source sphere is

$$d\mathcal{S} = 2\pi(R+h)^2 d\cos\alpha = \frac{2\pi(R+h)L(\varphi)^2}{L(\varphi) - R\cos\varphi}d\cos\varphi\ . \quad (7)$$

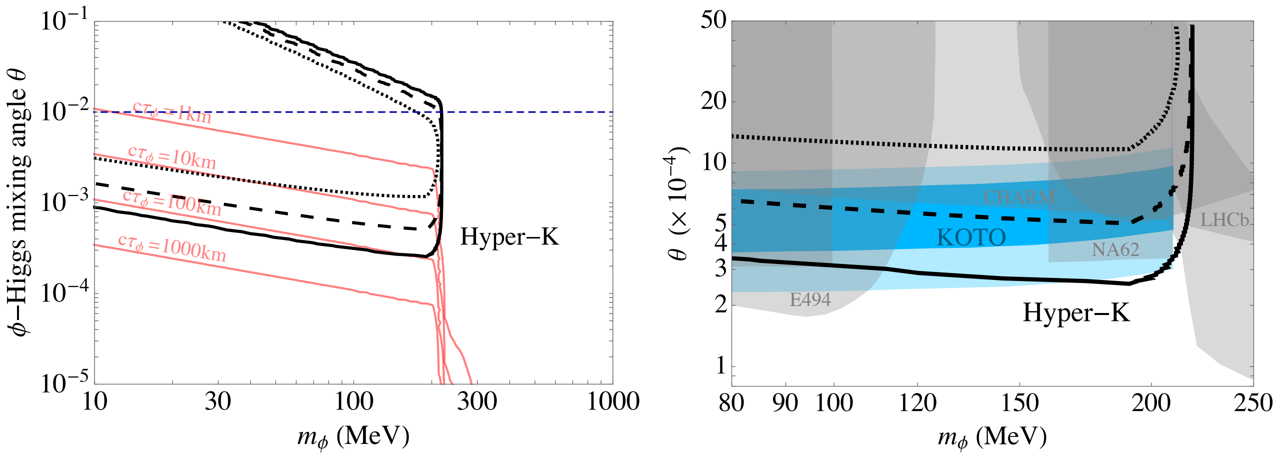

FIG. 3. **Left:** Using Hyper-K detector to search for long lived Higgs portal scalar ϕ produced from the atmosphere. The (solid, dashed, dotted) black contours correspond to 10, 100, 1000 signal events after ten years of exposure. The red curves corresponds to constant values of $c\tau_\phi$, the lifetime of ϕ times the speed of light. **Right:** The region of parameter space favored by the KOTO anomaly is shown in blue (dark and light blue correspond to 1 and 2σ favored regions, respectively), in together with exclusion by existing experiments (from E494, NA62, CHARM, LHCb) shown in gray. Like the left panel, the black curves corresponds to fixed number of signal events using Hyper-K to hunt atmospheric ϕ particles.

We assume cosmic ray showers on the earth atmosphere to be isotropic, and so is the resulting ϕ angular distribution within the hemisphere pointing towards the center of the earth. If the Hyper-K detector volume is denoted as V, the event rate of ϕ particles decaying inside this volume is, regardless of its shape,

$$R_{\rm event} = V\int_0^\pi \sin\varphi d\varphi \frac{R+h}{L(\varphi)-R\cos\varphi} \times \int dE_\phi \frac{d\Phi_\phi/dE_\phi}{\gamma\beta\tau_\phi} e^{-\frac{L(\varphi)}{\gamma\beta\tau_\phi}} , \quad (8)$$

where γ is the boost factor of ϕ with energy E_ϕ and β is the corresponding velocity. $d\Phi_\phi/dE_\phi$ is given by Eq. (4). The lifetime of ϕ is dictated by the Higgs portal. For mass of ϕ below twice the muon mass, it mainly decays into a e^+e^- pair. The corresponding decay length without boost factor is (assuming $m_\phi \gg m_e$)

$$c\tau_\phi = \frac{8\pi}{\sqrt{2}G_F m_e^2 m_\phi \theta^2} \simeq 30\,{\rm km}\left(\frac{0.15\,{\rm GeV}}{m_\phi}\right)\left(\frac{5\times10^{-4}}{\theta}\right)^2 , \quad (9)$$

where the benchmark values of θ and m_ϕ lie within the KOTO favored region. It is worth noting that the small electron mass appearing in the decay rate does not suppress the ϕ production rate (see Eq. (2)).[1] Once produced from the atmosphere, it is able to penetrate the earth above deep underground detectors. In water Cherenkov detectors like Hyper-K, the final state e^+e^- manifest as a double-ring signature, where the two rings originate from the same primary vertex of ϕ decay. We focus on fully contained events where the ϕ decay vertex emerges from inside the detector.

Our main result is shown in Fig. 3, in the θ versus m_ϕ plane. In the left panel, the black solid, dashed, and dotted curves corresponds to observing 10, 100, and 1000 e^+e^- pair events due to ϕ decay in the Hyper-K detector, after 10 years of data taking. To derive these curves, the volume of the Hyper-K detector used is $216\times10^3\,{\rm m}^3$ (diameter $=$ 70.8 m and height $=$ 54.8 m) [29]. Here, we only present contours for certain signal events. They indicate the region of parameter space that potentially could be covered with the Hyper-K detector. Once the backgrounds is fully understood, it is straightforward to derive an expected limit using our result.[2] It is worth noting that in the ϕ decay signal, the invariant mass of the e^+e^- pair is always given by the decaying ϕ mass. This coincidence provides a useful cut for suppressing the background. In the same plot, the red contours correspond to constant values of $c\tau_\phi$, the lifetime of ϕ times the speed of light.

[1] This is in sharp contrast with the case of dark photon where the same parameter controls both the production and decay. In fact, Ref. [28] found that the atmospheric production cannot provide a competitive constraint for dark photon.

[2] A potential background for our signal is from atmospheric neutrinos undergoing neutral-current interaction with a π^0 radiation by the nuclear target. The two photons from π^0 decay could also manifest as a double ring in water Cherenkov detectors. A zenith angle distribution analysis (see below) could be useful for background discrimination. A detailed simulation of the atmospheric neutrino induced background is beyond the scope of this work.

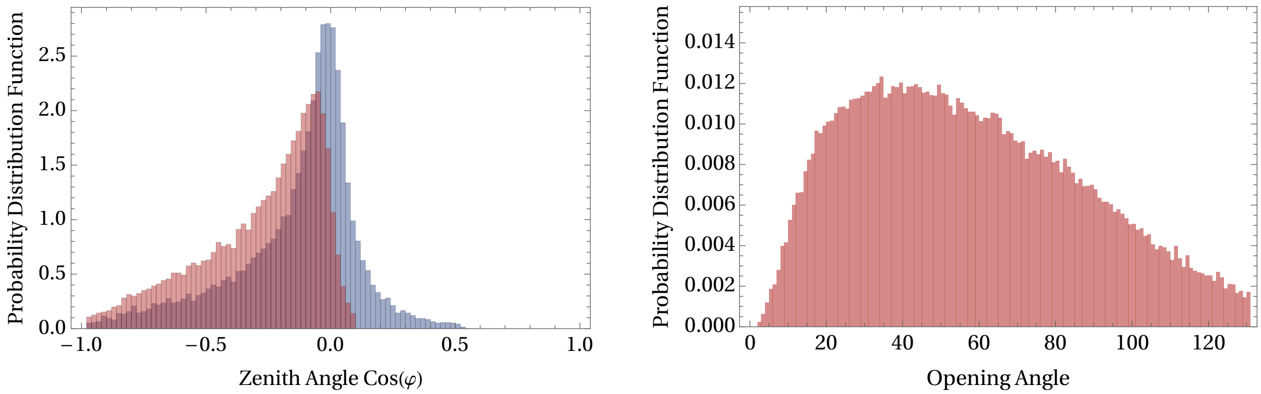

FIG. 4. Additional kinematical features of the ϕ decay signal. **Left:** Zenith angle φ distribution of the incoming into the Hyper-K detector for two sets of parameters, $m_\phi = 150\,\mathrm{MeV}$, $\theta = 5\times10^{-4}$ (red) and $m_\phi = 200\,\mathrm{MeV}$, $\theta = 10^{-4}$ (blue). The first point lies within the KOTO favored region and can leads to hundreds of ϕ decay events in Hyper-K. Most of the events are expected to arrive in directions above the detector's horizon. **Right:** electron-positron opening angle distribution from ϕ decay, for $m_\phi = 150\,\mathrm{MeV}$. The corresponding ϕ energy spectrum is shown in Fig. 1.

In the right panel of Fig. 3, we zoom in toward the KOTO favored (blue shaded) parameter space. Regions already excluded by existing searches are shaded in gray, including the measurement of $K^\pm \to \pi^\pm\phi$ at E949 [18] and NA62 [19], displaced visibly-decaying ϕ search at CHARM [14, 20], and searches for $B \to K\mu^+\mu^-$ at LHCb [30, 31]. Again, the Hyper-K coverage is indicated by the thick black curves, with solid, dashed and dotted corresponding to observing 10, 100 and 1000 e^+e^- pair events, respectively. Remarkably, they enclose almost the entire parameter space of interest to KOTO.

Another attenuation effect before ϕ reaches the Hyper-K detector is the scattering with the earth. The energy of atmospheric ϕ is peaked around GeV scale, which roughly coincides with the nucleon mass and the QCD scale for strong interactions. The corresponding scattering cross section of ϕ with the nucleon target can be estimated to be, $\sigma \sim \theta^2/\mathrm{GeV}^2 \sim 10^{-28}\theta^2\,\mathrm{cm}^2$. Given the earth nucleon density, $n \sim 10^{24}/\mathrm{cm}^3$, the free streaming length of ϕ is roughly, $l_F = 1/(n\sigma) \gtrsim 10^3\,\mathrm{km}\left(10^{-2}/\theta\right)^2$. In the left panel of Fig. 3, the region below the dark blue horizontal dashed line corresponds to $l_F > 10^3\,\mathrm{km}$, which is a sufficient condition for ϕ to travel to the Hyper-K detector from directions above the horizon (see discussions below). Clearly, this constraint is easily fulfilled for the region of parameter space of interest to KOTO (see Fig. 3 (right)).

Moreover, there is important information about the lifetime and mass of ϕ in the proposed signal, including the zenith angle and opening angle distributions of the final state e^+e^- pairs. In the left panel of Fig. 4, we plot the distribution of the zenith angle of ϕ particles arriving at the Hyper-K detector, for two sets of parameters. They exhibit very different behaviors, which can be understood by comparing the ϕ decay length, Eq. (9), and the distance it needs to travel before reaching the Hyper-K detector, $L(\varphi)$, given in Eq. (6). The first set of parameters, $m_\phi = 150\,\mathrm{MeV}$, $\theta = 5\times10^{-4}$, lies in the center of the KOTO region. In this case, $\gamma\beta\tau_\phi \sim 100\,\mathrm{km}$, for a typical boost factor (see Fig. 1), whereas $L(\varphi) \sim 10^4$, 300, 10 km for $\varphi = 0, \pi/2, \pi$, respectively. Clearly, if a ϕ particle travels to the detector from directions well below the horizon ($0 < \varphi < \pi/2$), the distance $L(\varphi)$ is too long compared to $\gamma\beta\tau_\phi$ for it to survive. As a result, most of the ϕ particles are expected to arrive from above the Hyper-K detector's horizon ($\pi/2 < \varphi < \pi$). For comparison, the second set of parameters has a much smaller θ leading to a much longer lived ϕ, $\gamma\beta\tau_\phi \sim 10^4\,\mathrm{km}$, thus ϕ could also arrive from directions below the horizon. However, smaller θ means fewer ϕ being produced from the atmosphere and such a point is beyond the reach of Hyper-K. Similarly, as m_ϕ increases beyond twice of the muon mass, it mainly decays into $\mu^+\mu^-$, via a much larger muon Yukawa coupling. The corresponding decay length is too short for ϕ to reach Hyper-K, unless θ is made much smaller, again resulting in a suppressed atmospheric production rate. In both latter cases, a larger detector would be needed.

In the right panel of Fig. 4, we plot the final state electron-positron opening angle distribution from ϕ decays, for $m_\phi = 150\,\mathrm{MeV}$. The result peaks around $\theta_{e^+e^-} \sim 30^\circ$, which is expected from the peak of ϕ energy distribution in Fig. 1, using $\theta_{e^+e^-} \sim 2m_\phi/E_\phi$. A sizable fraction of events have a large e^+e^- opening angle. This quantity is relevant for the double ring signature to be resolved once they occur inside the Hyper-K detector. In the main plot Fig. 3, we did not implement any cut on $\theta_{e^+e^-}$, which is straightforward to do once the threshold is established.

To summarize, we propose broadening the purpose of the Hyper-Kamiokande experiment though using it to hunt down long-lived Higgs portal scalar particles produced from the atmosphere. The target parameter space of this search is for the scalar mass below than twice the muon mass and has a strong overlap with that favored by the recent KOTO anomaly in the K_L rare decay measurement. The corresponding signal is electron-positron pair creations in the Hyper-K detector. We make approximations to the atmospheric production picture and derive a semi-analytical expression for the signal rate. In most events, the electron-positron opening angle is large enough for the double-ring signal to be resolved. If the double-rings are further used to reconstruct the decaying ϕ particles, one would find most of ϕ are arriving from directions above the detector's horizon. In the future, a more inclusive treatment of the ϕ production, better understanding of angular distribution measurement by the Hyper-K detector, as well as the background will be useful toward deriving a precise limit. The Hyper-K reach reported here for Higgs portal scalar similarly applies to light axion-like particles (of the DFSZ type [32, 33]) which couple to Standard Model fermions also through their masses. The presence of small electron Yukawa coupling in the decay rates naturally makes these particles long lived and suitable to be searched for at earth-sized experiments.

It could be exciting to explore the proposed signal using the existing Super-Kamiokande data. However, it is worth noting that the Super-K detector volume is about a factor of ten smaller than Hyper-K [34]. One could also consider searching for the signal at the future DUNE far detector which is made of liquid argon and is a few times smaller than Hyper-K in volume. This said, DUNE could be better at distinguishing $e^{\pm}$ from γ, which is useful for background discrimination. It is beyond the scope of this paper to quantitatively compare the performance between Hyper-K and DUNE.

There have been recent proposals of searching for long-lived light particles including the Higgs portal scalar at accelerator neutrino facilities using their near detectors [25, 35–37], as well as higher energy collider experiments with displaced detectors [10]. In comparison, the atmospheric ϕ particles carry relatively lower energies than their beam counterpart, thus the resulting e^+e^- opening angles are wider and easier for detection. Background is also much lower in the absence of a nearby intense beam. The very large Hyper-K detector volume partially compensates for the relatively lower atmospheric luminosity. All in all, there is excellent complementarity between the searches for long-lived particles of atmospheric and beam origins.

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