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 particles 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.

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 100-200 MeV and $\phi$-Higgs mixing parameter is set by a very early displaced decay of $\phi$, 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 $\phi$ particles rather than disappearance experiments searching for $\phi$ 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 $\phi$. It utilizes cosmic rays as the beam, earth’s atmosphere as the target, and earth itself as the shielding region. In this picture, $\phi$ 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 $\phi$ 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 $h$,

$$\phi = \cos \theta \, s + \sin \theta \, h,$$

where $\theta$ 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 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 $K^\pm$ and $K_L$ particles is about $2:1$, as expected.

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 baryogenesis mechanisms [5, 6], precision physics of the Standard Model [7, 8], and, perhaps, naturalness [9]. In its minimal incarnation, the Higgs portal scalar is introduced for exploring the dark universe [1-4], facilitating baryogenesis mechanisms [5, 6], precision physics of the Standard Model [7, 8], and, perhaps, naturalness [9].
The $\phi$ 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 [23–25]

$$\text{Br}(K^\pm \to \pi^\pm \phi) \simeq 2\tau_{K^\pm} |V_{td}|^2 G_F^2 m_K m_{K^\pm}^2 p_{\phi\text{CM}} \theta^2 / 2048 \sqrt{2\pi^5} ,$$

$$\text{Br}(K_L \to \pi^0 \phi) \simeq 2\tau_{K_L} |\text{Re}(V_{td}^* V_{ts})|^2 G_F^2 m_K m_{K^0}^2 m_{\phi}^2 m_{\phi\text{CM}} \theta^2 / 2048 \sqrt{2\pi^5} ,$$

where the decay momentum in the center-of-mass (CM) frame is $p_{\phi\text{CM}} = \lambda(m_K^2, m_{\phi}^2, m_{\pi}^2)/2m_{K^\pm}$, and $\lambda$ is the Källén function. In small $m_{\phi}$ limit, $\text{Br}(K_L \to \pi^0 \phi)/\text{Br}(K^\pm \to \pi^\pm \phi) \simeq 3.7$ [26]. In the lab frame, the ratio of the final state $\phi$ energy to that of kaon is

$$\frac{E_{\phi}}{E_K} = \frac{E_{\phi\text{CM}}}{m_K} + \frac{p_{\phi\text{CM}}}{m_K} \sqrt{1 - \frac{m_{\phi}^2}{E_K^2}} \cos \vartheta_{\text{CM}} ,$$

where $E_{\phi\text{CM}} = \sqrt{p_{\phi\text{CM}}^2 + m_{\phi}^2}$ and $\vartheta_{\text{CM}}$ is the relative angle between $\phi$’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 distribution in their rest frame is isotropic. For given energy $E_K$, the values of $E_{\phi}$ distribute evenly between its extremes, corresponding to $\cos \vartheta_{\text{CM}} = \pm 1$. The resulting differential flux of $\phi$ can be calculated using

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

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

It is worth pointing out the above is a conservative approach of simulating atmospheric $\phi$ production. In order for the parton picture used by PYTHIA to be valid, we restrict the CM energy of $pp$ and $pm$ scatterings to be above $\sim 6$ 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 $\phi$ particles.

After being produced in the atmosphere, the $\phi$ 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 $\phi$ decay. These requirements led us to consider Hyper-K.

To calculate the $\phi$ 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 $\varphi$ and $\alpha$ are related by

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

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

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

An infinitesimal area on the source sphere is

$$dS = 2\pi (R + h)^2 d\cos \alpha = \frac{2\pi (R + h) L(\varphi)^2}{L(\varphi) - R \cos \varphi} d\cos \varphi .$$
We assume cosmic ray showers on the earth atmosphere to be isotropic, and so is the resulting $\phi$ 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 $\phi$ particles decaying inside this volume is, regardless of its shape,

$$R_{\text{event}} = V \sum_{\phi} \int_0^{\pi} \sin \varphi d\varphi \frac{R + h}{L(\varphi) - R \cos \varphi} \times \int dE_{\phi} \frac{d\Phi_{\phi}}{dE_{\phi}} \frac{1}{\gamma \beta \tau_{\phi}} e^{-\frac{L(\varphi)}{\gamma \beta \tau_{\phi}}},$$

where $\gamma$ is the boost factor of $\phi$ with energy $E_{\phi}$ and $\beta$ is the corresponding velocity. The sum over $\phi$ is performed on an event-by-event basis in our simulation. $d\Phi_{\phi}/dE_{\phi}$ is given by Eq. (4). The lifetime of $\phi$ is dictated by the Higgs portal. For mass of $\phi$ below twice the muon mass, it mainly decays into a $e^+ e^-$ pair. The corresponding decay length without boost factor is (assuming $m_\phi \gg m_e$)

$$\tau_{\phi} = \frac{8\pi}{\sqrt{2} G_F m_e^2 m_\phi \theta^2} \simeq 30 \text{ km} \left(\frac{m_\phi}{0.15 \text{ GeV}}\right) \left(\frac{\theta}{5 \times 10^{-7}}\right)^2,$$

where the benchmark values of $\theta$ and $m_\phi$ lie within the KOTO favored region. It is worth noting that the small electron mass appearing in the decay rate does not suppress the $\phi$ production rate (see Eq. (2)). 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 $\phi$ decay. We focus on fully contained events where the $\phi$ decay vertex emerges from inside the detector.

Our main result is shown in Fig. 3, in the $\theta$ versus $m_\phi$ 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 $\phi$ 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 $21.6 \times 10^3 \text{ m}^3$ (diameter = 70.8 m and height = 54.8 m) [27]. 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 understood, it is straightforward to derive an expected limit using our result. It is worth noting that in the $\phi$ decay signal, the invariant mass of the $e^+ e^-$ pair is always given by the decaying $\phi$ mass. This coincidence provides a useful cut for suppressing the background. In the same plot, the red contours correspond to constant decay lengths of $\phi$ assuming it travels near the speed of light but with the boost factor neglected.

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 $K^\pm \rightarrow \pi^\pm \phi$ at E949 [18] and NA62 [19], displaced visibly-decaying $\phi$ search at CHARM [15, 20], and searches for $B \rightarrow K \mu^+ \mu^-$ at LHCb [28, 29]. 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.

Moreover, there is important information about the lifetime and mass of $\phi$ 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 $\phi$ particles arriving at the Hyper-K detector, for two sets of parameters. They exhibit very different behaviors, which can be understood by comparing the $\phi$ 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, $m_\phi = 150\text{ MeV}$, $\theta = 5 \times 10^{-4}$, lies in the center of the KOTO region. In this case, $\gamma\beta\tau_\phi \sim 100\text{ km}$, for a typical boost factor (see Fig. 1), whereas $L(\varphi) \sim 10^4, 300, 10\text{ km}$ for $\varphi = 0, \pi/2, \pi$, respectively. Clearly, if a $\phi$ 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 $\phi$ 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 $\theta$ leading to a much longer lived $\phi$, $\gamma\beta\tau_\phi \sim 10^4\text{ km}$, thus $\phi$ could also arrive from directions below the horizon. However, smaller $\theta$ means fewer $\phi$ being produced from the atmosphere and such a point is beyond the reach of Hyper-K. Similarly, as $m_\phi$ 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 $\phi$ to reach Hyper-K, unless $\theta$ 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 $\phi$ decays, for $m_\phi = 150\text{ MeV}$. The result peaks around $\theta_{e^+e^-} \sim 30^\circ$, which is expected from the peak of $\phi$ energy distribution in Fig. 1, using $\theta_{e^+e^-} \sim 2m_\phi/E_\phi$. We find a sizable fraction of events have sufficiently large $e^+e^-$ opening angle for the double ring signature to be resolved once they occur inside the Hyper-K detector.

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 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 $\phi$ particles, one would find most of $\phi$ are arriving from directions above the detector’s horizon. The Hyper-K reach reported here for Higgs portal scalar similarly applies to light axion-like particles 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, although it is unlikely that Super-K fully probes the KOTO favored region given its smaller detector volume [30].

There have been recent proposals of searching for light particles such as the Higgs portal scalar at accelerator neutrino facilities [24, 31, 32], such as the DUNE near detector complex. In comparison, the atmospheric $\phi$ 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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