Detecting light long-lived particle produced by cosmic ray

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We investigate the possibility of detecting light long-lived particle (LLP) produced by high energy cosmic ray colliding with atmosphere. The LLP may penetrate the atmosphere and decay into a pair of muons near/in the neutrino telescope. Such muons can be treated as the detectable signal for neutrino telescope. This study is motivated by recent cosmic electron/positron observations which suggest the existence of O(TeV) dark matter and new light O(GeV) particle. It indicates that dark sector may be complicated, and there may exist more than one light particles, for example the dark gauge boson $A'$ and associated dark Higgs boson $h'$. In this work, we discuss the scenario with $A'$ heavier than $h'$ and $h'$ is treated as LLP. Based on our numerical estimation, we find that the large volume neutrino telescope IceCube has the capacity to observe several tens of di-muon events per year for favorable parameters if the decay length of LLP can be comparable with the depth of atmosphere. The challenge here is how to suppress the muon backgrounds induced by cosmic rays and atmospheric neutrinos.

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I. INTRODUCTION

The pursuit of new light boson (LB) with mass much lighter than W and Z bosons in the standard model (SM) has a long history. A well known example is a light gauge boson under an extra $U(1)$ gauge group beyond the SM gauge group $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$. However such kind of new LB is stringently constrained since the current precise measurements are in excellent agreement with the SM predictions. Obviously the interaction between the new LB and SM sector should be tiny to evade current constraints. With the same reason detecting LB experimentally is a very challenging task.

Recently the LB attracts more attention due to the new cosmic observations by PAMELA [1], ATIC [2] and Fermi [3]. PAMELA collaboration reported excess in the positron fraction from 10 to about 100 GeV but absence of anti-proton excess [4]. It is still consistent with the results released by ATIC [2] or Fermi [3] experiments. The afterwards investigations suggested that these new observations need new source of electron/positron which may come from the dark matter (DM). The DM particles might annihilate or decay into electron/positron in the halo today. Moreover man began to realize the possible connection between the heavier DM at O(TeV) and the LB at O(GeV). If the annihilating DM produces the extra electron/positron, there is a mismatch between the DM annihilation cross section expected in the epoch of freeze-out and that required to account for recent new observations. Namely the present DM annihilation cross section is too small. The new O(GeV) LB, via the so-called Sommerfeld enhancement, can fill the gap. Moreover, in order to be consistent with only electron/positron excess, LB decays preferably into charged leptons [4].

Generally speaking such new boson may be scalar, pseudoscalar or gauge boson. The interactions between the LB and SM sector could arise from the mixing between the LB and photon or Higgs. It is quite interesting to investigate how to detect such kind of LB. Many authors have studied how to produce such LB and detect them at colliders, namely low-energy collider, large hadron collider or fix-target experiment. For the collider search, one often requires the life time of LB is short, as a consequence the charged leptons as the LB decay products could be observed at the detector. Such charged leptons could be clearly and easily identified. The construction of realistic model of dark sector showed that dark sector can be more complicated. The assumption that LB is short-lived might be incorrect. If dark sector contains an array of LBs besides a light gauge boson, some lighter ones may be long-lived due to the suppressed interaction with SM sector. Several recent works provided an interesting approach to search such long-lived particle (LLP) [5–8]. The DM trapped inside the Sun/Earth would annihilate into LBs. If the LB has a long lifetime, it can travel through the Sun/Earth and decay into gamma rays or charged leptons which could be observed.

In this paper we point out another possible way to search such kind of LLP via the high energy cosmic rays. The high energy cosmic rays interact with atmospheric nucleons every second and can be treated as a natural and costless high energy hadron collider. If a proton with energy of $E \sim 10^4$ GeV in cosmic ray collides with an atmosphere nucleon, the center-of-mass energy $\sqrt{s}$ is approximately $\sqrt{2E_{\text{p}}N_E} \sim 10^2$ GeV. Such mechanism can copiously produce LLPs through pN collisions. If the lifetime of LLP is appropriate, it can penetrate the atmosphere and arrive at the neutrino telescope. The subsequently decay of LLP into a pair of muons can be observed by the telescope [9, 10].

If LLP decays near the detector, the difficult task is to distinguish the signal muon pair from the huge muon
backgrounds which are produced by high-energy cosmic rays through hadron (for example π) decays and/or QED process. Provided that the time information of muon is precisely recorded, one can identify two signal muons which are supposed to arrive at detector at the same time, not heavily polluted by two irrelevant coincident parallel muon events. In order to suppress the muon backgrounds, the analysis focused on quasi-horizontal events might be important [11, 12]. A more optimistic case is that LLP decays inside the detector with an ‘obvious’ decay vertex. The challenge here is how to distinguish almost parallel di-muon from the single muon. Another possible case is that for a single collision between cosmic ray particle and atmosphere nucleon, more than one LLP are produced. In this case the multi muon pairs appear in detector at the same time will be a significant signal.

In this work, we assume the LB has a long lifetime to penetrate through the atmosphere, some mechanisms which satisfy this requirement will be discussed. We consider the LB production by the cosmic rays and simulate di-muon events from LB decay. In order to detect such high energy muons, we focus on the large volume neutrino telescope IceCube [13] which will reach an effective detecting area in square kilometers. The detector are installed under the ice surface in a depth of 1.4 km in order to suppress muon backgrounds produced in atmosphere. Moreover, there is a extension of IceCube namely DeepCore which is still under construction [14]. DeepCore will be installed in the more deeper location which will suffer less above-mentioned muon backgrounds.

This paper is organized as following. In the section II, we describe two classes of models which contain LLPs, discuss the main LLP production processes and calculate the LLP production cross section in pN collision. We utilize PYTHIA to do the calculation and simulate the LLP events. In Section II, we also investigate the LLP production flux produced by primary cosmic ray. We find that for a LLP production process with O(10) pb, the production rate of LLP can reach to O(10^4) per square kilometer and per year. In Section III, we investigate the possibility to detect di-muon signal from LLP decay in the neutrino detector. The conclusions and discussions are given in the last section.

II. THE PRODUCTION OF LLP

A. The model

In the models discussed in Ref. [13, 14], the dark sector includes both weakly-interacting-massive-particle (WIMP) and LB under a certain new gauge group. For the simplest case with an extra U(1) group, the dark sector can interact with SM sector though kinetic mixing, namely a new U(1) gauge field A'_μ could mix with U(1)_Y field A_μ in the SM. In addition there is another possible mixing between the SM Higgs field H and scalar h' which will break extra U(1) group to induce mass to A'. The Lagrangian can be written as,

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 + \frac{\kappa}{2}F'_{\mu\nu}F'^{\mu\nu} + |D_{\mu}h'|^2 - V(h') + \lambda_{h'H}h'H + V_{DM} + V_{SM}. \quad (1)$$

Here κ and λ_{h'H} are the two mixing parameters which will be determined (constrained) by experiments. V_{DM} is the lagrangian of DM which includes the O(TeV) DM kinetic and mass terms and its gauge interaction.

After the spontaneous breaking of extra U(1) group, the A' and h' will get the mass of m_{A'} and m_{h'}. If scalar mixing λ_{h'H} is neglected, the lifetime of LB is determined by m_{LB} and gauge kinetic mixing parameter κ. For light gauge boson mainly decay into charged leptons, the travel distance can be approximately estimated as l = γcτ ∼ γc/(ακ^2 m_{A'}) ∼ 10^{-5} m (γ/10^3)(κ/10^{-3})^{-2}(m_{A'}/1GeV)^{-1}. Typically the light gauge boson is not a long-lived particle. However for the dark Higgs boson and provided that m_{A'} > m_{h'}, dark higgs will decay into SM fermions through the triangle diagrams. The decay width is suppressed by a factor of κ^{-4}. Therefore the dark higgs can be a typical long-lived particle (LLP) with the decay length as large as 10^7 km. In such kind of models, the main LLP production mode is scalar-strahlung process pp → A' + X → A'h' + X (X denotes anything)

The dark sector could be more complicated. As discussed in Ref. [15, 16], if the dark sector has a more complex gauge group configuration, there might exit a series of LBs including the LLP. In such case, the high energy pN collisions may copiously produce the extra gauge boson A' and the production rate depends on the mixing parameter κ and m_{A'}. A' subsequently decays quickly into LLP, namely the dark Higgs boson h'. The process can be depicted as pp → A' + X → h'a' + X (a' represents another light gauge boson or light pseudo scalar which we do not discuss further its feature here. For simplicity we take the mass of h' and a' to be equal). If LLP propagates some distance which depends on its lifetime and decays into charged leptons as motivated by cosmic electron/positron data, we can utilize neutrino telescope to observe such kind of muons. Note that the LLP interacts with usual matter weakly, it can penetrate into the Earth without loss of energy.

In this case, we do the calculation as model-independent as possible and the input parameters are chosen as kinetic mixing κ and the mass of extra gauge boson m_{A'}. We assume A' production rate, mass m_{a'} and lifetime τ of h'. Typically branching ratio of A' into dark sector is much bigger than that into SM sector. Thus in our numerical simulation we assumed that A' decays only into h'. We also assume the branching ratio of h' into muon pair is 1. In fact, such branching ratios are calculable in the model we mentioned above, the detailed calculations can be found in the Ref. [13, 14]. Here we just treat them as free parameters, and our results could be adjusted to satisfy specific model by multiplying a factor of Br(A' → h')Br(h' → μ^+μ^-).
B. Simulation of LLP production

![Cross section of LLP production in pp collision as a function of cosmic primary proton energy](image)

**FIG. 1:** Cross section of LLP production in pp collision as a function of cosmic primary proton energy. The dash lines and the dashed-dot lines represent process $q\bar{q} \rightarrow A'$ and $q\bar{q} \rightarrow A''$ respectively. We utilize **PYTHIA** to simulate the LLP production events and calculate the cross section. The main free parameters are the mass of $A'$ and $h'$, kinetic mixing parameter $\kappa$, and dark sector gauge coupling $\alpha'$ for the Higgs-strahlung process. Here we choose three benchmark points $(m_{A'}, m_{h'}) = (1.2$ GeV, $0.4$ GeV), $(2.1$ GeV, $0.7$ GeV), $(3.0$ GeV, $1.0$ GeV) respectively.

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For the scalar-strahlung process, the cross section at parton level is given by (neglecting the mass of parton),

$$\hat{\sigma}(\hat{s})|_{q\bar{q} \rightarrow A'h'} = \frac{8\pi Q_q^2 \alpha' \kappa^2}{9} \frac{k^2 + 3m_{A'}^2}{\sqrt{\hat{s}}(\hat{s} - m_{A'}^2)^2},$$  \hspace{1cm} (2)

where $\hat{s} = x_1x_2s$ is the center of mass energy of partons with momentum fractions of $x_1$ and $x_2$, $k = \sqrt{(\hat{s} - m_{A'}^2 - m_{h'}^2)^2 - 4m_{A'}^2m_{h'}^2/(2\sqrt{\hat{s}})}$ is the momentum of $A'$ in the center of mass frame. The total cross section is

$$\sigma_{pN} = \int dV \sum_q f_p^Q(x_1)f_N^q(x_2)\hat{\sigma}(\hat{s})|_{q\bar{q}},$$ \hspace{1cm} (3)

where $dV$ represents $dx_1dx_2$, $q$ denotes sum over all the quark and anti-quark and $f$ is the parton distribution function (PDF). We use the CTEQ6M PDF here and set the factorization scale $Q^2 = \hat{s}$. To do a Monte Carlo calculation, the variables $x_1, x_2$ are randomly chosen within the ranges $(m_{A'} + m_{h'})^2/\hat{s} \leq x_1 \leq 1$, $(m_{A'} + m_{h'})^2/(x_1\hat{s}) \leq x_2 \leq 1$. In order to improve the convergence, we technically define new integration variables as $dV' = d\ln x_1d\ln x_2$. The integration is then transformed into

$$\sigma_{pN} = \frac{1}{N_{total}} \sum_i \left[ \sum_q x_1f_p^Q(x_1)x_2f_N^q(x_2)\hat{\sigma}(\hat{s})|_{q\bar{q}}dV' \right],$$ \hspace{1cm} (4)

where $i$ denotes $i$-th configuration of cross section.

For the single $A'$ production which is a $2 \rightarrow 1$ process, the cross section contains one $\delta$ function which fixes $\hat{s} = m_{A'}^2$. We transform integration variables $x_1, x_2$ to $s, y$ through $dx_1dx_2 = dsdy/s$ and integrate out the $\delta$ function. The total cross section can be written as

$$\sigma|_{pN \rightarrow A'N} = \int \frac{4\pi^2 Q_q^2 \alpha \kappa^2}{3m_{A'}^2} x_1f_p^Q(x_1)x_2f_N^q(x_2)dy$$ \hspace{1cm} (5)

where $x_1 = m_{A'e^0}/\sqrt{s}$ and $x_2 = m_{A'e^{-0}/\sqrt{s}}$. From $x_{1,2} \leq 1$, we choose $y$ in the range of $-\ln(\sqrt{s}/m_{A'}) \leq y \leq \ln(\sqrt{s}/m_{A'})$.

We show the LLP production cross sections for the pp collision in Fig. 1. From the figures we can see that the scalar-strahlung process cross sections are much smaller than those of $A'$ resonance process. It is simply because the scalar-strahlung process is the $2 \rightarrow 2$ process which has more power of coupling and smaller phase space. Numerically in the energy region of O(100) GeV, the single $A'$ production is several orders of magnitude larger than that the scalar-strahlung process. From the Fig. 1 we can also conclude that cross section is very sensitive to the mass of $A'$. This is quite understandable provided the quick rise of $q\bar{q}$ luminosity for the lower mass $A'$.

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In our simulations, we randomly generate muon pairs in the $h'$ rest frame, then boost them to the $A'$ rest frame and lab frame.

C. Flux of long-lived particle produced by high energy cosmic rays

In this subsection, we evaluate the LLP production rate by high energy cosmic ray. From several GeV to energy range above $10^6$ GeV, the flux of primary nucleons in the cosmic rays is approximately written as

$$\Phi_N(E) \approx 1.8(E/\text{GeV})^{-\alpha} \frac{\text{nucleons}}{\text{cm}^2 \text{s sr} \text{GeV}},$$ \hspace{1cm} (6)

where the differential spectral index $\alpha$ is 2.7 under $10^6$ GeV, 3.0 from $10^6$ GeV to $10^{10}$ GeV, and finally 2.7 above $10^{10}$ GeV. The main component of primary cosmic nucleons is proton. To produce energetic LLP, the energy...
of cosmic rays is required to be as high as or above $10^2$ GeV. For secondary hadrons induced by such energetic cosmic ray, the interaction length may be smaller than the decay length in the atmosphere. Thus the collisions between the atmosphere nucleons and secondary mesons induced by primary cosmic hadrons are important. The flux of new LLP particles can be estimated by [11]

$$\Phi_{h'} = \sum_h \int_{E_{min}}^{E_{max}} dE \Phi_h(E) \mathcal{P}_{h'}(E),$$

where $h$ denotes the primary cosmic hadrons and secondary nucleons, pion and kaon, $\Phi_h$ is the flux of hadron, and $\mathcal{P}_{h'}(E)$ is the probability of producing LLP $h'$ in one collision. $\Phi_h(E)$ is approximated as $\mathcal{P}_{h'}(E) \approx A \sigma_{hN}^{h'} / \sigma_T$, where $A \sim 14.6$ is the average nucleon number of a nuclei in air, $\sigma_{hN}^{h'}$ is the cross section to produce $h'$, and $\sigma_T$ is the total cross section of cosmic hadrons in atmosphere about $O(10^2)$ mb which is approximately parameterized as $\sigma_T \approx C_0^h + C_1^h \ln(E/GeV) + C_2^h \ln^2(E/GeV)^2$. Requiring final muons from LLP decay with large energy and flux, we choose the cosmic ray energy region from $10^2$ GeV to $10^7$ GeV.

We can firstly estimate the LLP production rate in order of magnitude as

$$\phi_{h'} \sim 10^3 \left( \frac{\sigma_{hN}^{h'}}{100 \text{mb}} \right) \left( \frac{\sigma_T}{300 \text{mb}} \right)^{-1} \left( \frac{E_{min}}{100 \text{GeV}} \right)^{-1.7} \text{km}^{-2} \text{yr}^{-1} \text{sr}^{-1}.$$  

The formula indicates that for the single $A'$ production cross section of 10 pb, the cosmic ray will produce at least $10^4$ LLPs per year and per square kilometer. In Fig. 2 we show the results of LLP differential rate as a function of cosmic ray energy. From the figure we can see that the event rate can reach $O(10^3)$ to $O(10^4)$ $\text{km}^{-2} \text{yr}^{-1} \text{sr}^{-1}$. However for the scalar-strahlung process, the event rate is very low from $O(10^{-1})$ to $O(10)$ due to the small cross section and we do not discuss this process below.

### III. Detecting Long-Lived Particle at High Energy Neutrino Detector

In this section we will discuss the possibility of detecting such LLP at neutrino detector. If the LLP penetrates through atmosphere and decays into muons near or inside detector, this signal can be observable at neutrino telescope. In the last section, we have evaluated the $h'$ production rate. For simplicity, we assume that all $h'$s are produced at the upper atmosphere. Moreover, the $h'$ flux can be treated as isotropic due to the isotropy of cosmic ray. The long-lived $h'$ interacts with SM particle weakly, thus it is safe to neglect the energy loss before it decays into muon pair. The lifetime of $h'$ is model-dependent, and it is treated as a free parameter here. The probability of a particle decays between two point is given by [3]:

$$P_{\text{decay}} = e^{-D/l} - e^{-(D+d)/l} = e^{-D/l}(1 - e^{-d/l}),$$

where $D$ is the distance between the production point and entry point, $d$ is the distance between two point, $l = \gamma \tau$ is the decay length of particle. Here $D$ is approximately $10 \sim 20$ km, and it is the depth of atmosphere plus distance from detector to horizon; $d$ is the neutrino telescope’s size (if the detector has the capacity to recognize LLP decay events nearby, $d$ can be larger). If $D$ is far larger than $d$ and $l$, the decay probability is roughly $e^{-D/l}$; if the decay length $l$ is far larger than $D$ and $d$, the decay probability is $d/l$. Therefore, it is difficult to observe the LLP decay if the decay length of LLP is too large or too small. The most promising case is that the decay length $l$ is comparable with $D$.

As mentioned in the introduction if LLP decays outside the neutrino detector, the atmosphere muon background is huge. These muons are generated mainly from secondary charged pion and kaon decay. Most muons are in lower energy regime due to the relatively large cosmic ray flux in this energy region and energy lost in matter. The formula of atmosphere muon flux is similar to that
of cosmic ray which is approximately given by \[ \phi_\mu(E_\mu) \approx \frac{0.14 E_\mu^{2.7}}{cm^2 s sr GeV^2} \left( \frac{1}{1 + \frac{1.1 E_\mu \cos \theta}{115 GeV}} + \frac{0.054}{850 GeV} \right) \]

where $\theta$ is zenith angle (here $\theta \leq 70^\circ$), and this formula is valid when the probability of the muon decay can be neglected (i.e. $E_\mu > 100/\cos \theta$ GeV). From the Eq. (10), we can see that in the energy region $O(10^2)$ GeV the atmospheric muon flux is only one order of magnitude smaller than primary cosmic ray, while the LLP flux is about ten orders smaller. Requiring that two muons arrive at detector in a tiny time window could effectively reduce background which contains two uncorrelated muons. Note that lots of SM processes can produce muon pair events directly [24]. For example, one single shower contains many hadrons, and muons from two hadrons decay may be treated as a pair of muons. In addition the electro-weak Drell-Yan process can also produce muon pair directly. In a word, if the LLP does not decay inside the detector, it is very challenging to distinguish signal from the atmospheric di-muon backgrounds.

However there is still hope to detect muon pair from LLP decay near the detector. The energy of LLP is typically less than 1 TeV. In such energy region, most of the atmospheric muons are absorbed in the solid/liquid matter. For example, for 10, 10$^2$ and 10$^3$ GeV muons, the muon range is 0.05, 0.41 and 2.45 km.w.e respectively [25]. The neutrino detector is often installed in deep underground with shield of several km.w.e. rock/water/ice. Such shield can prohibit the low-energy atmospheric muons to arrive at the detector, especially for direction with large zenith angle and even quasi-horizontal direction. Detecting LLP decay in these directions is more promising. Thus if the LLP decays not far from detector, the resulting di-muon may be identified.

To detect the clean LLP signal, we expect that LLP happens to decay inside the detector and we can observe a pair of "suddenly" appeared muons. In order to recognize di-muon event, we require that the energy of muons must be above the detector’s threshold energy. Moreover, because the high energy atmospheric neutrino may produce single high energy muon when traveling through the detector, we also require that the two tracks of di-muon should be identified separately 3. In our simulations, we require that the angle between two muon tracks is greater than $O(10^{-4})$.

It needs to mention another background arising from atmospheric neutrino, which can induce di-muon events inside the detector through inelastic $\nu N$ collision. $\nu N$ collision can produce muon plus charm hadron and the charm hadron will subsequently induce another muon via semi-leptonic decay [26]. Such two muons will be identified as a di-muon event. Such di-muon event rate may be larger than the LLP decay due to large atmospheric neutrino flux (for example, the atmospheric muon neutrino flux around 100 GeV is about $O(10^{-4})m^{-2}s^{-1}sr^{-1}GeV^{-1}$). However, associated hadronic shower in $\nu N$ collision could be utilized to suppress such backgrounds.

\[ FIG. 3: \text{Di-muon event rate as a function of di-muon energy. The dash lines and the solid lines correspond to different energy threshold of 3.2 GeV for Super-Kamiokande and 100 GeV for IceCube respectively. For the lines with same shape, the upper and lower one represent three benchmark point (m$_{A'}$, m$_{\mu'}$) = (1.2 GeV, 0.4 GeV), (2.1 GeV, 0.7 GeV), (3.0 GeV, 1.0 GeV) respectively.} \]

\[ FIG. 4: \text{Di-muon event rate as a function of separation angle between two muons. The notations are same as Fig. 3.} \]

\[^{3}\text{The authors of Ref. [8] have pointed out that it is possible to distinguish di-muon signal from single muon even the separation of di-muon is not large enough. They provided two handles to identify di-muon signal with energy above critical energy utilizing the different characteristics of Cherenkov radiation.} \]
muon energy and the separation angle. Here we assume all the LLPs decay in the detector. We take the each muon energy threshold of IceCube to be 50 GeV and the separated angle of di-muon greater than $10^{-4}$. For comparison, we also show the rate of di-muon events with energy above 3.2 GeV which corresponds to the threshold at the Super-Kamiokande detector. From Fig. 3 we find that di-muon event rate with energy larger than 100 GeV could be $O(10^5)$ per square kilometer, per year. From Fig. 4 we find that the separated angle of most di-muons is about $O(10^{-2})$. For the Super-Kamiokande detector with $R = 16.9$ m, $H = 36.2$ m and energy threshold 1.6 GeV, it is suitable for detecting the low energy di-muon events with large flux. However it is difficult to distinguish the di-muon events from single muons due to the limited volume.

In Fig. 3 and Fig. 4 we did not include effects of LLP decay. The Fig. 5 shows the di-muon rate as a function of the lifetime of LLP, where $(m_{A'}, m_{h'}) = (1.2$ GeV, 0.4 GeV), (2.1 GeV, 0.7 GeV), (3.0 GeV, 1.0 GeV) from top to bottom. The size of detector are taken as 1 km and the zenith angle is less than $\theta \leq 70^\circ$. We choose each muon energy threshold of detector to be 50 GeV and the separated angle of di-muon to be greater than $10^{-4}$.

IV. DISCUSSIONS AND CONCLUSIONS

In this paper, we investigated the possibility of searching long-lived particle (LLP) produced by high energy cosmic ray colliding with atmosphere. The LLP may penetrate the atmosphere and decay into a pair of muons near/in the neutrino telescope. Such muons can be treated as the detectable signal. This study is motivated by recent cosmic electron/positron observations by PAMELA/ATIC/Fermi. The new data suggests new source of electron/positron which may come from O(TeV) dark matter. In order to understand the dark matter thermal history, new light O(GeV) particles have been proposed. It is quite natural to conjecture that dark sector is complicated. There are more than one light particles in dark sector, for example the dark gauge boson $A'$ and associated dark Higgs boson $h'$. In this paper, we studied the scenario with $A'$ heavier than $h'$ and $h'$ is treated as LLP.

We have studied the LLP production processes and found that the promising process is single $A'$ production $q\bar{q} \rightarrow A'$, and $A'$ subsequently decays into $h'$ rather than into SM particles. Our numerical calculations show that for $A'$ with mass of $1$ GeV, the production rate can reach $10^{5} km^{-2}s^{-1}sr^{-1}$ and the final di-muon rate from $h'$ is serval tens for some favorable parameter region. We have assumed the $\kappa \sim 10^{-3}$, $\alpha' = \alpha$ and the branching ratio of $A' \rightarrow h' \rightarrow \mu^+\mu^-$ is 1. For different parameter selections, our results need to be multiplied by a factor of $(\kappa/10^{-3})^2 Br_{A'\rightarrow h'} Br_{h'\rightarrow \mu^+\mu^-}$. Here it is worth remarking that a complete analysis for LLP production needs QCD correction to production process and simulations of cosmic ray shower included secondary hadrons and nucleons. The LLP could also be produced from secondary meson decay directly if allowed by kinematics. These elements will increase LLP production rate efficiently.

We simulated the signal di-muon events and calculated the rate as functions of di-muon energy and the separation angle between two muons. Our numerical results showed that the large volume neutrino detector IceCube is suitable to detect LLP with lifetime about $10^{-8} \sim 10^{-4}$ s. It is worth to mention that such parameter region could be compatible with the constraints from fixed-target experiments. For example, the Ref. [8] has reported the constraints on LLP decay length $c\tau$ between 1 cm and $10^{8}$ cm by CHARM experiment result.

The scenario proposed in this paper could be cross-checked (tested) at the low energy $e^+e^-$ collider and/or large hadron collider. At the collider, the LLP will es-
cape from the detector and act as the missing energy. For example, the well promising process is the $\gamma A'$ associated production \([30]\). The $\gamma + E_T$ signal can be isolated from SM irreducible background $\gamma Z \rightarrow \gamma \nu \bar{\nu}$. If the LLP associated production with other light bosons which decay into charged leptons, the multi-$e^+e^-/\mu^+\mu^- + E_T$ is a cleaner signal. Moreover, the interaction between SM and dark sector may be induced via the mixing of Higgs fields. It implies that SM Higgs may decay into LLP. Such possible invisible decay modes can even change our search strategies of SM Higgs boson.

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