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Searches for the Dark Photon at Fixed Target Experiments

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Recent astrophysical observations provided indirect evidences for sub-GeV, light, dark-matter (DM). A new gauge particle in this mass range could exist as an extra $U(1)$ gauge particle, called the dark photon. The dark photon can mix weakly with a ordinary photon and can mediate interactions of DM. If the dark photon is massive enough, it can decay into a pair of standard-model (SM) particles or DM particles. Light dark-matter particles in the MeV to GeV mass range, as well as in other mass ranges, have not been the subjects of intensive experimental researches. Large statistics is needed to search for dark-photon-mediated interactions. Therefore, high-power accelerators can be used to look for the dark photon. In this article, we review the current status of the experimental searches at various fixed-target experiments and the experiments planned in the near term future.

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I. INTRODUCTION TO DARK PHOTON

In 2008, PAMELA experiment reported on the rise of the positron to electron ratio in cosmic rays starting from 10 GeV onwards, subsequently confirmed by FERMI LAT and AMS-02 experiments [1–3]. In standard cosmic ray propagation models, it was expected that this ratio would decrease with increasing energy. Also, the 511 keV γ rays from electron positron annihilation was seen to occur at galactic center [4]. These evidences point to a possibility of a light DM with MeV to GeV mass light mediator of interaction with strong coupling to DM could explain these experimental observations and be consistent with the observed relic density as well as the $(g-2)_\mu$ anomaly [5].

Experimental and theoretical efforts in understanding the DM problem have mainly focused on the Weakly Interacting Massive Particles (WIMPs) or axions. Both the axion DM and WIMP DM are theoretically well-motivated models. The searches for WIMPs concentrate on masses above 10 GeV, while for axions, below 1 eV are the regions of interest. Depending on the mass ranges, different experimental techniques are required. For the WIMP DM, high-energy accelerators, such as the LHC, are required to extend the mass reach and to have sufficiently high production cross-sections. Assuming the WIMPs are still abundant in the universe today, they could interact when they pass through the earth with small probability. Numerous deep underground experiments look for a signature of WIMP recoiling in the detector. In the absence of direct experimental detection, one must look elsewhere.

The model of dark photon has sparked the interest as a viable model and due to its simplicity. In a dark photon model, an extra gauge symmetry $U_D(1)$ is assumed with a gauge particle that can mix with the SM photon through so-called "kinetic mixing".

$$\delta\mathcal{L} = \frac{\epsilon}{2} F^{Y\mu\nu} F^D_{\mu\nu} \tag{1}$$

This gauge particle is supposed to mediate interactions among DM particles. After the mixing, however, the dark photon (A') can interact with the electrically charged SM particles weakly with coupling strength of ϵe.

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Important features of the dark photon, relevant for experimental searches are as follows.

- The dark photon is assumed to be massive and its mass $m_{A'}$ is a free parameter of the theory. The full theory should have a symmetry breaking mechanism to give the dark photon its mass. We assume that such details occur at high enough masses to have little impact on phenomenology of dark photon interactions.
- The dark photon can decay into a pair of SM charged particles (leptons or hadrons). The branching fractions depend on the mass of the dark photon $m_{A'}$.
- The dark photon mediates interaction between DM particles. The mass of the dark matter particle (m_χ), coupling to dark photon ($\alpha_D = g_D^2/4\pi$) are free parameters. If $m_{A'} > 2m_\chi$, then dark photon can decay into a pair of DM particles. Details depend on whether the dark matter is a fermion or a boson.
- The life time of A' depends on $(m_{A'}, \epsilon)$ if only SM decays are allowed. While, for the case DM decays are allowed, the life time becomes a function of $(m_{A'}, \epsilon, m_\chi, \alpha_D)$.

II. PRODUCTION AND DECAYS OF THE DARK PHOTON

The features summarized in the previous section allows for experimental searches using accelerators. Sub-GeV massive particles is kinematically accessible in many existing lepton and hadron accelerators.

1. Production of Dark Photon in Accelerators

Since the dark photon mixes with SM photon, A' can be produced by a similar mechanism that can generate SM photons, but with reduced rate, determined by $m_{A'}$ and ϵ. In electron accelerators, Bremsstrahlung photons can be produced when electrons are stopped in fixed-targets made of a high-Z material. A' can be produced by a similar diagram, but whose cross section is suppressed by $\epsilon^2/m_{A'}^2$.

In a Bremsstrahlung proess, photon is expected to carry almost all the energy of the incoming electron. Also the outgoing photon is collimated in the direction of the electron beam. Therefore, the dark photon can be considered almost mono-energetic and highly collimated. These characteristics allow one to design a compact experiment.

In hadron accelerators, copious amounts of secondary hadrons are produced when the beam hits a fixed target. Among these, π^0, η, and η' decay to $\gamma\gamma$, hence a source of photons. These neutral mesons can also decay into $\gamma A'$, as long as $m_{A'}$ is smaller than the mass of the meson. This practically limits the masses that can be covered to less than about 270 MeV. For very high energy proton accelerators of a few hundred GeV, proton Bremsstrahlung can be a source of A', in which case, larger mass A' is accessible.

2. Decays of Dark Photons in Fixed-Target Experiments

Design of the experiment has to take into account the particles to be detected. For $m_e < m_{A'}/2 < m_\mu, m_\chi$, A' decays exclusively to e^+e^-. Therefore, detection and measurement of the momenta of e^- and e^+ is necessary. One must take into account the lifetime of A', which is proportional to $1/(\epsilon m_{A'})^2$. The experiment would be sensitive to dark photons decaying after the target, but before the detector and whose decay products are in the acceptance of the detector. For $m_{A'} > 2m_\mu$, A' can decay into $\mu^+\mu^-$, however, such as massive $m_{A'}$ would have smaller production cross section in a Bremsstrahlung process, and muons would have wide opening angles, so, wider acceptance is needed.

If $m_{A'}/2 > m_\chi$, then A' can decay into pair of (stable) DM particles. The branching fraction to DM pair depends not only on the couping α_D, but also ϵ, m_χ and $m_{A'}$. However, since α_D is not constrained yet from existing data, it can even be large, $\alpha_D \gg \alpha_{em}$, in which case, this could be the dominant decay mode of A'. The lifetime goes as α_D^{-1}, hence, the dark photons can be rather short-lived. Even if the χ's are produced inside the target, they can reach the detector, since the χ has very small probability of interaction with matter.

III. FIXED TARGET EXPERIMENTS FOR THE DARK PHOTON SEARCH

In this section, we review some of the recent results that provide the most stringent limits. For a more comprehensive review and discussions, consult [6].

1. Dark Photon Search Experiments using Fixed Targets at Electron Accelerators – Visibly Decaying A' case

In fixed target experiments at electron accelerators, monoenergetic electrons are incident on a target, where the Bremsstrahlung process is the main production mechanism of A'. And the mass reach of A' is set by the incident electron energy. Production cross section of A' through Bremsstrahlung is proportional to $\epsilon^2/m_{A'}^2$.

For the visible mode, only the A' that decays into a pair of oppositely charged particles behind the target can be detected directly. The mean decay length is proportional to $E_e/m_{A'} \times 1/(\epsilon m_{A'})^2$. All experiments in this category detect and measure the momenta of the decay products. Since this would allow us to reconstruct the mass of A'.

In experiments using lower-energy electron beams, thin foils are used as targets followed by high-precision spectrometers, to measure the momenta of decay products. Since the expected interaction rate probability in a thin foil is small and the spectrometers have limited acceptance, large beam current is needed. APEX at JLab [7] and A1 at MAMI [8] experiments fall into this category. Since the targets are thin, these experiments are sensitive to promptly decaying A', covering large $m_{A'}$ and large ϵ parameter space (Fig. 1).

For more energetic electron beams, total absorption thick targets are used. In this case, phase space where the decay length of A' is smaller than the thickness of target is inaccessible. Experiments in the between 1980's and 1990's at SLAC(E141 [10], E137 [11]), Fermilab(E774 [9]), KEK [12], Orsay [13], searched for long-lived neutral particles decaying into e^+e^-. These experiments had target thicknesses ranging from 0.12 m to 179 m, with the detector in the range of 2 m to 204 m behind the target.

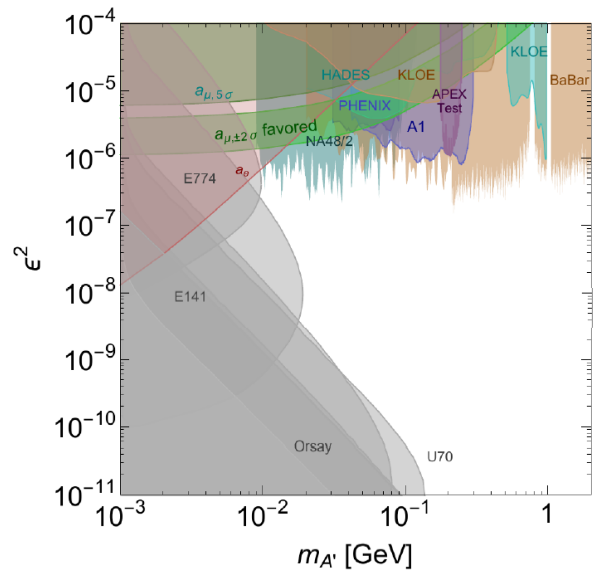

Fig. 1. (Color online) Exclusion limits from various fixed target experiments (see text) as well as e^+e^- collider (BaBar) in the $(m_{A'}, \epsilon)$ parameter space of the dark photon model, assuming there are no invisible decays [20–22].

Since these searches were model independent, reinterpretations of the results in terms of the dark photon model have been done. In the $(m_{A'}, \epsilon)$ plane, these experiments carve out the small $m_{A'}$ and small ϵ (Fig. 1). Since the large ϵ and small $m_{A'}$ is the region of high production cross sections, that region is excluded first in an experiment and as data is accumulated, the reach extends to the larger $m_{A'}$ and smaller ϵ. Going from top right to the bottom left region, the decay length of A' becomes longer, so for E137 experiment, which had a target thickness of 179 m, it is able to probe furthest in the lower left region of the paramater space.

2. Dark Photon Search Experiments using Fixed Targets at Electron Accelerators – Invisibly decaying A' case

For the cases where $A' \to \chi\chi$ is allowed, the requirements of the experiment is different. The production of the A' is the same as before. The opening angle of the χ with respect to the incident electron direction is less than $m_{A'}/E_e$. Therefore, transversely compact experiment is still possible, though the longitudinal depth should be sizable in order to have sensitivity. Usually,

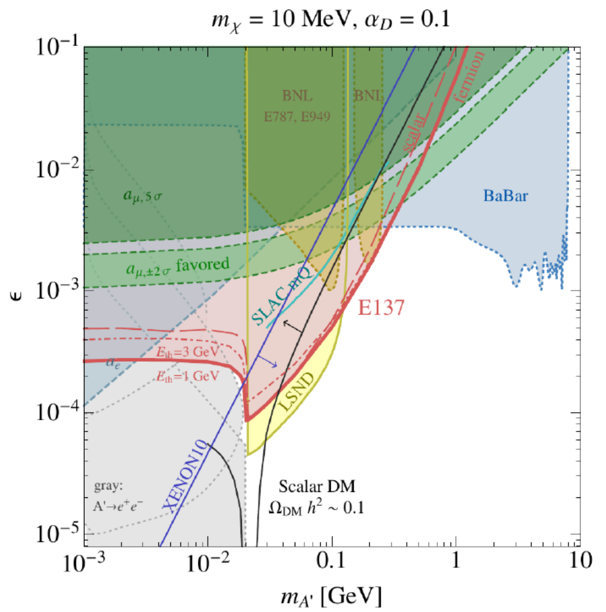

Fig. 2. (Color online) Exclusion limits from rare Kaon decay search experiments from BNL, LSND neutrino experiment, E137 electron beam dump experiment, and $^+e^-$ collider BaBar experiment in the $(m_{A'}, \epsilon)$ parameter space of the dark photon model for DM decaying case. The exclusion plot depends on the assumption of DM mass (m_χ) and coupling of DM to A' (α_D).

high-current accelerators are needed. Strong constraint comes from E137 experiment, where absence of e recoil event in the detector was interpreted as absence of $e-\chi$ scattering (Fig. 2).

3. Dark Photon Searches using Fixed Targets at Proton Accelerators – Visibly decaying case

In proton fixed-target experiments, large amounts of hadrons are created. Relevant to the dark photon searches are the π^0, η and η' mesons. Since they decay into pair of photons. Therefore, a channel of production of A' in proton fixed targets is through $\pi^0, \eta, \eta' \to \gamma A'$. Subsequently, search for A' proceeds in the decay channel $A' \to e^+e^-$.

For low energy proton fixed-target experiments, shielding for short-lived particles is not present. The detector has acceptance for forward going mesons and full event reconstruction of $\pi^0, \eta, \eta' \to \gamma A' \to \gamma e^+e^-$ is performed. A peak would be expected in the e^+e^- mass spectrum if $A' \to e^+e^-$ occurs in sufficient numbers. CERN NA48/2 experiment results impose a stringent limit on the $A' \to e^+e^-$ from 1.7×10^7 fully reconstructed $\pi^0 \to \gamma e^+e^-$ event sample (Fig. 1) [20].

CHARM and NOMAD neutrino experiments [14–17] searched for a neutral particle decaying into e^+e^-. Although they did search for neutral mesons decaying into $\gamma A'$, the most stringent limit comes from the searches for heavy neutrino search $\nu_h \to \nu e^+e^-$. Since these experiments have shieldings of a few hundred meteres in length they are sensitive to small ϵ parameter space, similar in reach to the E137 experiment (Fig. 1) [18,19].

4. Dark Photon Searches using Fixed Targets at Proton Accelerators – Invisibly decaying A' case

Direct and indirect detection of $A' \to \chi\chi$ are possible in fixed-target experiments using proton beams. Neutrino detection experiments such as LSND [32] and MiniBoone are able to detect recoil electrons in $e-\chi$ scattering. On the other hand, experiments such as BNL E787 [23] and E949 [24] looking for rare Kaon decays, $K^+ \to \pi^+\nu\bar{\nu}$, can search for $K^+ \to \pi^+ A'$ where A' decays invisibly is a source of missing energy (Fig. 2).

IV. PROSPECTS FOR DARK PHOTON SEARCHES

Due to the lack of direct experimental detection of the DM particles in LHC or deep underground searches, it becomes more important to probe the unexplored parameter space of the dark photon model. The phase space to explain the $(g-2)_\mu$ anomaly is closed in the visible decay mode. Still, there are largely unexplored phase space available. And for the invisible decaying A', the parameter is still available. Numerous experiments have recently been proposed and approved in the search for the A'.

1. Prospects for Searches in Electron Beam search experiments Fixed-Target Experiments

Along the electron fixed-target experiments, most notable of the recently approved experiments are APEX,

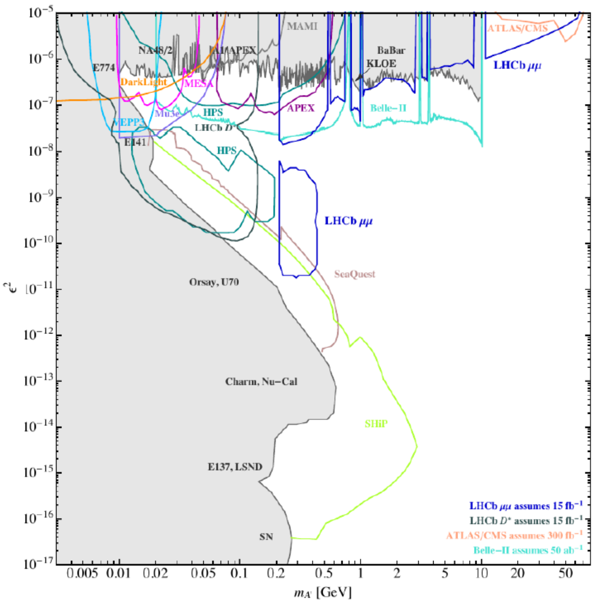

Fig. 3. (Color online) Present and expected exclusion limits in the $(m_{A'}, \epsilon)$ parameter space of the dark photon model, assuming there are no invisible decays [31]. Below the $2m_\mu$, almost all of the available parameter space will be explored.

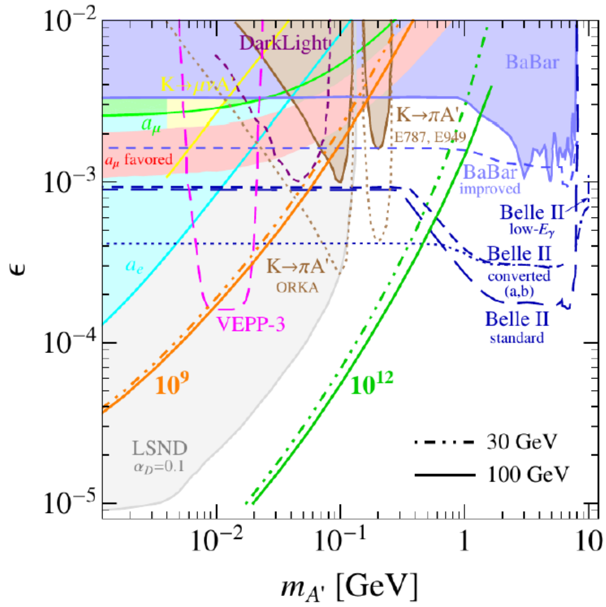

Fig. 4. (Color online) Present and expected exclusion limits in the $(m_{A'}, \epsilon)$ parameter space of the dark photon model invisible decays [34]. The orange and green curves are the expected exclusions by NA64 experiment with the given number of protons on target. ORKA, which was forseen as an upgrade of E949 experiment, has recently been canceled.

BDX, DarkLight, and Heavy Photon Search (HPS) at JLab. These three experiments use complementary techniques and beam energies to probe a large parameter space (Fig. 3).

APEX experiment uses pre-existing pair of low-momentum spectrometers to measure $A' \to e^+e^-$ from 2.26 GeV e^- beam on thin Ta foil. At the end of each spetrometer arm is a gas Cherenkov detector and calorimeters for particle identification and energy measurement to complement the momentum measurement by the analyzing dipole. The experiment will be sensitive in the $m_{A'}$ region between 65 MeV and 525 MeV, with the mass resolution expected to be about 1 MeV. The experiment has analyzed the test data, with its preliminary result showing promise. It is planning a full run, lasting 34 days, during 2016 or 2017 [25].

The HPS experiment employs a dipole magnetic field to steer away the electrons after the thin foil targets. On the other hand, the dark photon, if created, will move in a straight line before decaying into e^+e^-. A silicon vertex tracker can measure the vertex position with 1 mm precision. With this vertexing capability, it is able to probe smaller regions of ϵ than other JLab experiments. Behind the tracker is an electro-magnetic calorimeter, whose energy measurement together with tracking information gives 1 MeV mass resolution. This experiment has taken data in spring of 2016 using 2.3 GeV electron beams, and is expected to complete with periodic running up to year 2020 [27].

DarkLight experiment is somewhat unconventional in that the detector sits in the beamline of recirculating 100 MeV 10mA electron accelerator used to generate free electron laser. The 100 MeV e^- hits a thin hydrogen gas target inside a 0.5 T solenoidal magnetic field. Inside the solenoid magnet are the Silicon precision tracking and GEM time projection chambers (TPC) allowing measurement of low momentum charged particles with small dE/dx loss. It will undergo a proof-of-principle test in 2016 with partial acceptance coverage [26]. An important difference with the other two experiments is that this will be sensitive to invisible decays of A', by reconstructing the full event kienatics $e^- + p \to e^- p +$ missing momenta (Fig. 4).

BDX experiment is designed exclusively to probe the dark sector [28]. It aims to be sensitive to $\chi - p$ quasi-elastic scattering and $\chi - e$ elastic scattering. About 350 C/year of beam will be delivered to Hall A of Jlab,

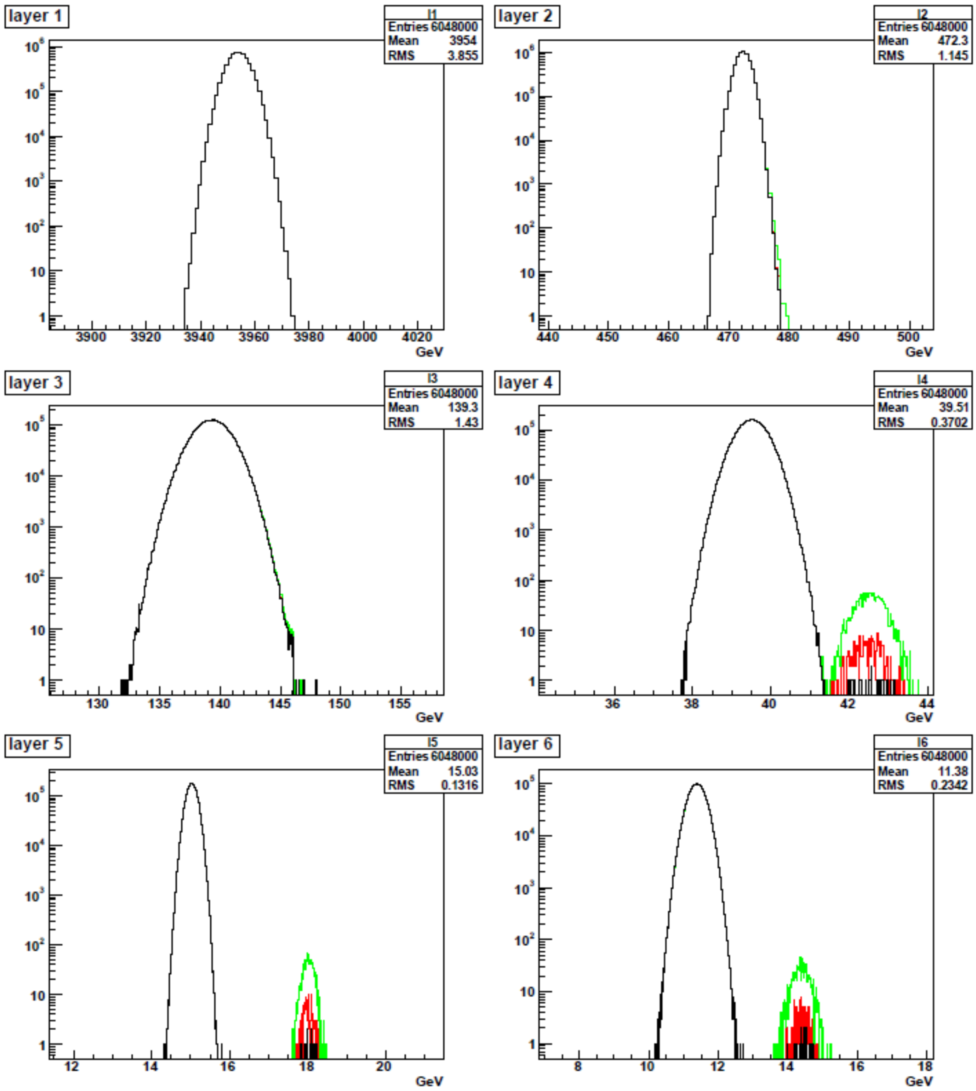

Fig. 5. (Color online) Energy deposited in the six 10 cm CsI scintillators in 7 days of data collection, with 10 (black), 100 (red), 1000 (green) signal events injected.

its primary site candidate for the experiment. It will reuse BaBar CsI(Tl) scintillation crystals with length of 2 m and total volume of 0.5 m^3. The detector R&D is ongoing and a full proposal will be prepared [29].

NA64 experiment at CERN aims to search for invisibly decaying dark photon by dumping 100 GeV electron beam onto an electromagnetic calorimeter [34]. If the invsibly decaying A' is produced in the calorimeter, very little energy will be carried by the scattered electron. The experiment looks for small energy depositions, the "missing E_T" as its signature. It is expected to explore new region of parameter space in a very short amount if time (Fig. 4). NA64 has been approved in 2016 and will take data between July 2016 – October 2016.

2. Prospects for Searches in Proton Beam Fixed-Target Experiments

Several proton fixed-target experiments have recently been approved. Most notable is the SHiP experiment using SPS beams at CERN. The details of the SHiP experiment will be discusssed elsewhere in this volume. E1067 is an experiment running parasitically with E906 SeaQuest using Fermilab Muon Injector 120 GeV proton beams (Fig. 3).

E1067 experiment will be able to probe not only the dark photon in the visible mode, but also the dark Higgs portal. Due to the muon spectrometers, it is able to search for a massive neutral particle decaying into $\mu^+\mu^-$, hence, probing regions where $m_{A'} > 2m_\mu$. Its expected reach largely overlaps with that of SHiP, but covers some complementary regions of the parameter space. However it is expected to take data in 2017–2019 and will explore the parameter space several years before SHiP. There is a possible detector upgrade in 2020 [30].

Miniboone experiment collected data with 1.86×10^{20} protons-on-target in 2014, lasting 10 months, to search for scattering of DM particle inside the detector [33]. Since neutrino scattering events could be backgrounds, protons were steered away from the usual neutrino target/horn, and onto an iron beam stop target. Data analysis is ongoing and results are expected soon.

3. Posssibility of a Dark Photon Search Experiment in Korea

Existing accelerators in the few GeV energy range can be used to produce the sub-GeV dark photons. Electron accelerators in Pohang Accelerator Laboratory (PAL) have enough energy to produce the sub-GeV dark photon. The PLSII LINAC which has been in operation since 2012, has 3 GeV beam energy with a short 1ns pulse width. The charge per pulse is 0.5 nC with a repetition rate of 10 Hz. The area after the beam dump is accessible to perform detection measurements.

Recently commissionned PAL XFEL has a 10 GeV energy electron LINAC with 20% higher average beam current. the beam dump area was constructed without regard for possible experiment behind it. As long as Bremsstrahlung can occur and the energy of the electron is higher than $m_{A'}$, the average current, rather than the total power is more relevant. Hence, PAL PLSII is good enough for the dark photon search experiment. One disadvantage of using PAL PLSII, is that while it is being used to top up the electron storage ring, it cannot be used to perform beam dump experiment.

For this study, we use GEANT4 to study the preliminary feasibility of a beam-dump experiment at PAL PLSII 3 GeV electron linear accelerator (LINAC). The beam-dump target is 30 cm thick iron followed by 10 cm tungsten. This is followed by CsI scintillator bars with 10 cm in length and 5 cm in width and height.

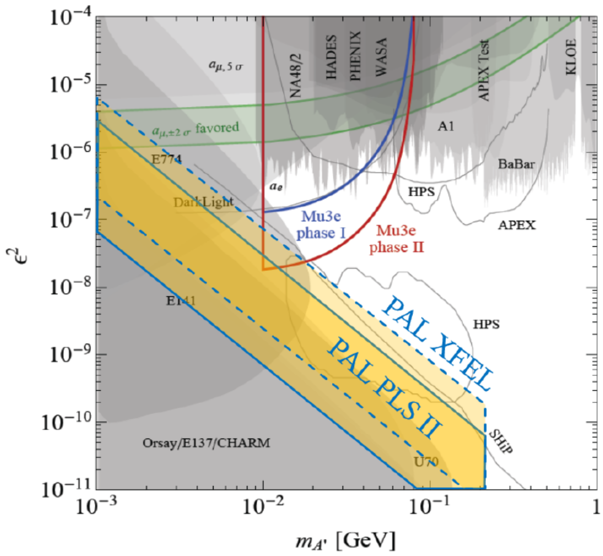

Fig. 6. (Color online) Expected sensitivity with 7 days of data collection at PAL PLSII and PAL XFEL electron linear accelerator beams.

A total of 6 bars are placed behind the target and shielding. Since each beam pulse delivers 3×10^9 electrons, the secondary particles reaching the detector is not negligible. Fig. 5 shows the distribution of energy deposited in 7 days of data collection, The large gaussian peak is energy deposited by secondaries, most of which are soft photons and energetic charged particles, such as muons and protons. If there is signal due to energy deposited by $A' \to e^+e^-$, it will show up as a peak 3 GeV away from the large peak due to backgrounds. Shown on the figure is what would happen if there are 10 (black), 100(red), 1000(green) $A' \to e^+e^-$ events during those 7 days of data taking.

Based on this preliminary study, we can see that the first 3 scintillators are swamped by background noise, while for the last 3 scintillators, signal is visible. From this, the expected sensitivity is shown in Fig. 6. Even with small amount of data collection, previously unexplored parameter space can be explored. Further optimizations of target and detector geometry would improve the situation.

V. CONCLUSION

There is world-wide effort in the search for the light dark matter and dark photons using fixed-target experiment techniques. High intensity rather than the highest energy accelerator is what is needed to perform the searches. For visibly decaying dark photon, the experiment can be compact and low-cost compared to other modern partcle experiments. Dark photon search experiment seems feasible using PAL electron LINACs and merits further study.

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