Modern Physics Letters A
Vol. 32, No. 10 (2017) 1730008 (16 pages)

DOI: 10.1142/S0217732317300087

Prospects of direct search for dark photon and dark Higgs in SeaQuest/E1067 experiment at the Fermilab main injector

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Published 14 March 2017

In this review, we present the current status and prospects of the dark sector physics search program of the SeaQuest/E1067 fixed target dimuon experiment at Fermilab Main Injector. There has been tremendous excitement and progress in searching for new physics in the dark sector in recent years. Dark sector refers to a collection of currently unknown particles that do not directly couple with the Standard Model (SM) strong and electroweak (EW) interactions but assumed to carry gravitational force, thus could be candidates of the missing Dark Matter (DM). Such particles may interact with the SM particles through "portal" interactions. Two of the simple possibilities are being investigated in our initial search: (1) dark photon and (2) dark Higgs. They could be within immediate reach of current or near future experimental search. We show there is a unique opportunity today at Fermilab to directly search for these particles in a highly motivated but uncharted parameter space in high-energy proton–nucleus collisions in the beam-dump mode using the 120 GeV proton beam from the Main Injector. Our current search window covers the mass range 0.2–10 GeV/c^2, and in the near future, by adding an electromagnetic calorimeter (EMCal) to the spectrometer, we can further explore the lower mass region down to about ~ 1 MeV/c^2 through the di-electron channel. If dark photons (and/or dark Higgs) were observed, they would revolutionize our understanding of the fundamental structures and interactions of our universe.

Keywords: Dark photon; dark Higgs; SeaQuest.

PACS Nos.: 12.60.-i, 12.90.+b

1. Introduction

This review of dark photon and dark Higgs search at Fermilab is partially based on our ongoing work at the SeaQuest experiment and the Letter of Intent we submitted to Fermilab PAC in 2015.[1] We first show the success and challenges of the Standard Model (SM) and the motivations for the Dark Sector Physics, followed by more detailed discussions of our experimental approaches at Fermilab — mainly directly detect long-lived dark photons (or dark Higgs) produced in the SeaQuest/E1067 targets or the 5-m thick iron beam-dump and subsequently decay into dimuons downstream of the target/beam-dump. A dedicated dark photon displaced vertex trigger is being developed for this search, accompanied with a tenfold improvement in Data Acquisition (DAQ) bandwidth and will be ready for data collection by late spring 2017. This new trigger/DAQ upgrade will allow us to trigger on these rare events parasitically that are otherwise impossible to be collected in current and future fixed target data-taking mode. At the end, we will also briefly discuss a possibility to further expand our dark photon search window in the near future by adding di-electron capability through a moderate detector upgrade. This upgrade can be achieved at relatively low cost by using an electromagnetic calorimeter (EMCal) recycled from other experiment, such as the EMCal from the recently completed PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) in Long Island, New York. A proposal has already been favorably discussed with the PHENIX collaboration to bring their EMCal to Fermilab SeaQuest/E1067 experiment.

The discovery of the Higgs boson at the LHC has completed the SM of particle physics. While the SM has been successfully tested over a wide range of energy scales, it fails to account for some key properties of the observed universe, such as Dark Matter (DM) and dark energy. The matter we know of today only accounts for approximately 5% of the total energy density of the universe, and the nature of the remaining energy and matter remains unknown. In the 2014 U.S. High Energy Physics P-5 Report, *Identify the new physics of dark matter*, is highlighted as a Top Five Science Driver of the field, and it is recommended that *several medium and small projects in areas especially promising for near-term discoveries and in which the U.S. is, or can be, in a leadership position, will move forward under all budget scenarios*, see Ref. 2. New physics beyond the SM may exist at a high-energy scale or in a low-energy but weakly coupled "dark sector", which may naturally contain light new DM candidates.

Dark sector refers to a collection of currently unknown particles that do not directly couple with the SM strong and electroweak (EW) interactions but assume to carry gravitational force. Such particles may interact with the SM particles through "portal" interactions. In general, there could be several types of mediator particles that can accommodate renormalizable interactions between the DM and the SM sectors. The physics of a possible "dark sector" has attracted much attention from both the experimental and theoretical communities in recent years. In the SeaQuest/E1067 experiment, we first focus on exploring two simple possibilities: (1) dark photon — the mediator that couples with the "vector portal" and (2) dark Higgs — the one that couples with the "scalar portal". Other possible portals, such as "Neutrino portal" and "Axion portal", are currently under active investigation for the future program and will not be discussed here. If dark photons (or dark Higgs) were observed, they would revolutionize our understanding of the fundamental structures and interactions of our universe.

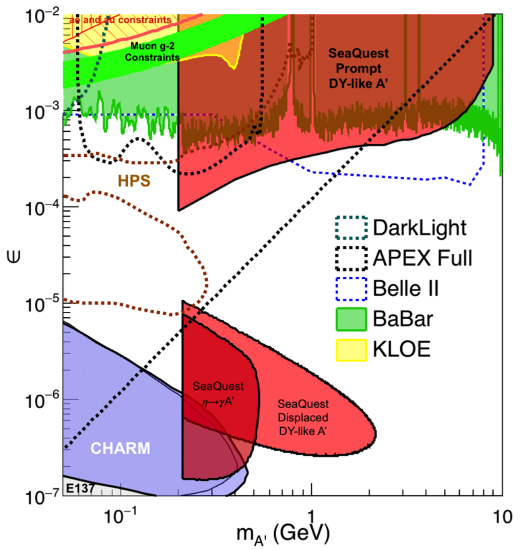

Fig. 1. (color online) Current and projected future experimental limits on dark photon search.[6] The dark-red areas are the projected preliminary 95% exclusion zones for the Fermilab SeaQuest/E1067 experiment, assuming a parasitic run with other fixed target experiments to accumulate beam on target 1.4×10^{18} Proton on Target (POT). Due to the ϕ, J/ψ and ψ' resonances, gaps are expected in the dimuon mass around $M \sim 1$ GeV/c^2 and $M \sim 3$ GeV/c^2 in the large coupling prompt-decay region but not shown in current preliminary physics sensitivity plots as detector and tracking optimization is still underway. The JLab-12 experiments, APEX, HPS and DarkLight,[7] are most sensitive to dark photons in the low-mass region below ~ 500 MeV/c^2. The LHC experiments are mostly sensitive to high-mass dark photons ($> \sim 10$ GeV/c^2) at large coupling ($\epsilon > 10^{-3}$) region. The black dashed curve is a theoretically prejudiced ($m_{A'}, \epsilon$) relation, $m_{A'} \sim \sqrt{\epsilon} m_Z$. Also plotted are sensitivity regions from BaBar (Green) and BELLE-II projection expected ~ 2023 (blue-dotted line) after its upgrade.

1.1. *Physics of the dark photon*

One of the most interesting and motivated portals to the dark sector is given by the mixing of the photon with the so-called dark photon (A'), a new $\mathrm{U}_D(1)$ gauge boson mediating Abelian gauge interactions in the dark sector, $\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}_Y(1) \times \mathrm{U}_D(1)$. In this model, dark photons (A') interact feebly with normal matter via kinetic mixing with the regular photons. This dark photon scenario is characterized by two parameters: the dark photon mass $m_{A'}$ and the coupling constant ϵ, the dimensionless parameter controlling kinetic mixing with the photon, with the interaction Lagrangian given by Eq. (1),[3]

$$L_{\mathrm{mix}} = \frac{\epsilon}{2} F^{\mathrm{QED}}_{\mu\nu} F^{\mu\nu}_{\mathrm{Dark}}\,, \tag{1}$$

where $F^{\mathrm{QED}}_{\mu\nu}$ and $F^{\mu\nu}_{\mathrm{Dark}}$ are the tensors of the SM photon and dark photon fields, respectively. Depending on the underlying messenger mechanisms, ϵ can range between 10^{-10} and $O(1)$, while $m_{A'}$ can take values from 10^{-18} eV/c^2 to tens of TeV/c^2. Recent development in DM phenomenology models and the muon $(g-2)$ anoma-

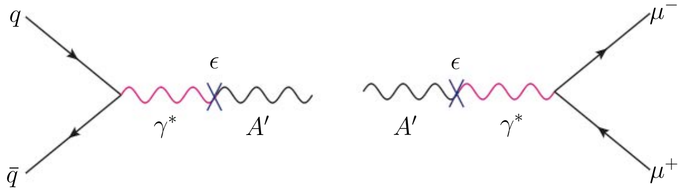

Fig. 2. Feynman diagrams for dark photon production (left) and its decay into a muon pair (right). A dark photon of mass $m_{A'}$ is produced via kinetic mixing with an SM virtual photon produced in the quark and antiquark annihilation process in a high-energy proton–nucleus collision with a coupling constant ϵ. The dark photon subsequently decays into a muon pair through kinetic mixing into another virtual photon.

lous magnetic moment point to a likely dark photon mass from $\sim O(1)$ MeV/c^2 to $\sim O(10)$ GeV/c^2.[3–6] This conclusion spurred a vibrant worldwide dark photon search in recent years at the LHC, RHIC, Fermilab, JLab, SLAC, KEK and other major accelerator facilities.

As illustrated in Fig. 1, for the coming decade, CMS, ATLAS and LHCb are expected to lead the search at high-energy frontier at LHC. They are best suited for the discovery of dark photons at a high-mass scale (> 10 GeV/c^2) with relatively large coupling constant, $\epsilon > 10^{-3}$, for their high beam energy but limited integrated luminosity (~ 300 fb^{-1} expected circa 2025 with LHC-14). At the low-energy high-intensity frontier, the JLab-12 GeV upgrade allows for high precision searches for dark photons in the low-mass region, $m_{A'} < 500$ MeV/c^2. There are already three major dark photon search experiments approved at JLab-12: APEX, HPS and Dark-Light.[7] The other high-energy physics centers for dark photon searches are the B-factories at SLAC and KEK. The BaBar (SLAC), PHENIX (RHIC) and NA48 (CERN) experiments recently set new limits on the dark photon search,[8,9] shown as the green region in Fig. 1. At Fermilab, two accelerator-based direct search experiments are being pursued for dark photons in the intermediate mass range $O(1)$ MeV/c^2 $\sim$ $O(10)$ GeV/c^2: a dark photon search in the invisible mode with the MiniBooNE detector[10] and a direct search in the visible mode at SeaQuest fixed target experiment in the beam-dump mode (this review). In the MiniBooNE case, the search was for a dark photon decaying into DM (invisible modes), which is allowed if the dark photon mass is greater than twice the daughter DM mass. The searches for visible and invisible modes of the dark photon compliment each other. Figure 2 shows how a dark photon is produced and detected in the dimuon channel in a Drell–Yan-like process in p + A interactions in the SeaQuest/E1067 experiment at Fermilab.

1.2. *Physics of the dark Higgs*

Besides dark photons, models with the dark Higgs as a mediator to DM have also become the focus of many theoretical studies and experimental search in recent years. The discovery of the Higgs boson at the LHC, the first fundamental scalar

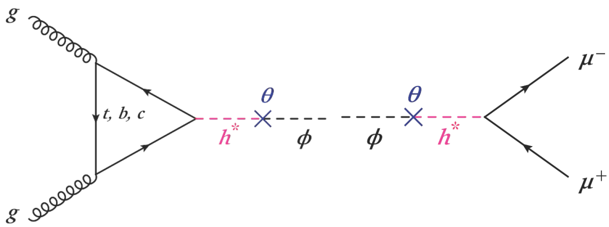

Fig. 3. Feynman diagrams for dark Higgs production (left) and its decay into a muon pair (right) through the Higgs portal. Note that different from the dark photon case, the dark Higgs is predominantly produced through gluon fusion process in the SeaQuest/E1067 experiment at Fermilab's Main Injector.

particle observed in nature, places the importance of the dark Higgs search on equal footing to that of the dark photon. The Higgs provides the only "Scalar Portal" in the SM to the dark sector. From the visible sector prospective, Higgs "siblings" have long been considered in many BSM models with an extended Higgs sector.[12] For example, a dark Higgs can be obtained from the EW symmetry breaking of the Higgs sector with additional scalar singlet. The mixing between the SM Higgs doublet and the additional singlet provides the portal for the dark Higgs coupling with SM particles.

Meanwhile, in the dark sector, a dark Higgs mechanism could also spontaneously break the dark $U_D(1)$ gauge group and generate the dark photon mass.[3,13] In particular, the resulting dark Higgs-dark photon coupling leads to potentially very interesting experimental signatures for the searches. In principle, these two perspectives can be considered separately. The combination of the two could lead to a richer phenomenology, for example, more complicated and rich cascade decays with multiple leptons in the final states.

For simplicity, we consider here a simple mixing scenario that is similar to the dark photon case. The Lagrangian responsible for the Higgs boson-dark Higgs mixing is given by Eq. (2),[14]

$$L_{\rm mix} = \mu\phi|H^\dagger H|\,, \tag{2}$$

where H is the SM Higgs doublet (for other possibilities, see Refs. 20 and 24, for example). The EW symmetry breaking generates a mixing between ϕ and the Higgs boson H. The mixing angle θ is related to the parameter μ by $\theta = \mu\nu/m_{h^2}$, where ν is the electroweak scale and m_h is the SM Higgs mass. Like the dark photon case, there are also two parameters controlling the experimental search for dark Higgs ϕ: the mixing angle θ and the dark Higgs mass m_ϕ. Figure 3 shows a dark Higgs is produced through a gluon–gluon fusion process and subsequently decays into a muon pair.

The discovery of the Higgs boson is a strong motivation to explore this scenario. There are also motivations from cosmology and astrophysics, including the DM relic density, indirect detection and structure formation on galaxy scales. DM interacting with a mediator (dark Higgs, or dark photon) can offer new insights into these

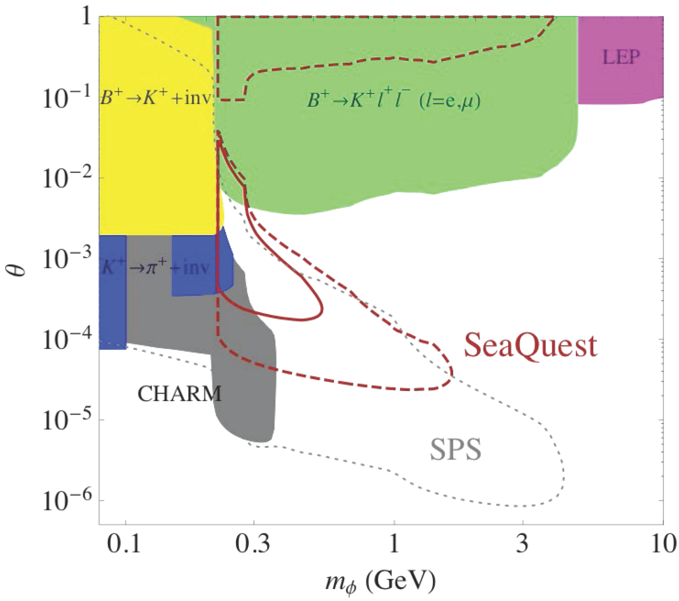

Fig. 4. (color online) Current limits and the projected 95% sensitivity on dark Higgs search from SeaQuest/E1067. The dark-red solid curves correspond to the constraint with $\phi \to \mu^+\mu^-$ decay tagged through displaced vertex 2.0 m downstream of the beam-dump from the initial parasitic runs with other fixed target experiments, assuming an integrated luminosity of 1.4×10^{18} POT collected over a two-year period; the dashed line is for 4×10^{20} POT, assuming the same integrated luminosity of SHiP projection of five-year operation; the light-dark dotted line is the SHiP projection.

questions[15,16] and makes new predictions for DM bound states[17,18] that could be also tested in the future at Fermilab.

A dark Higgs with mass in the range of $O(1)$ MeV/c^2 to $O(10)$ GeV/c^2 window is of particular interest and can be probed in the SeaQuest/E1067 experiment at Fermilab. The current experimental constraints on this model are mainly from B and K meson decays.[14,19,20] For m_ϕ less than a few GeV/c^2, the upper bound on θ is around 10^{-3}–10^{-2}. There is also an earlier fixed target experiment CHARM[21] (in the '80s) that has set the strongest bound for m_ϕ in the range of 0.1–0.4 GeV/c^2, excluding the allowed θ range down to the 10^{-5}–10^{-4} level. For the future, the Search for Hidden Particles (SHiP) collaboration submitted a proposal recently to develop a new fixed target experiment at CERN to search for dark particles using the 400 GeV proton beam at the Super Proton Synchrotron (SPS).[22] In several aspects, the proposed experiment is very similar to the Fermilab SeaQuest/E1067 experiment, and there are some significant overlaps between the SHiP and the SeaQuest/E1067 searches. SHiP is planned to take data in 2015, by that time, SeaQuest/E1067 should have completed its phase-I search program. Figure 4 shows the current dark Higgs excluded regions and projected sensitivity from SeaQuest/E1067.

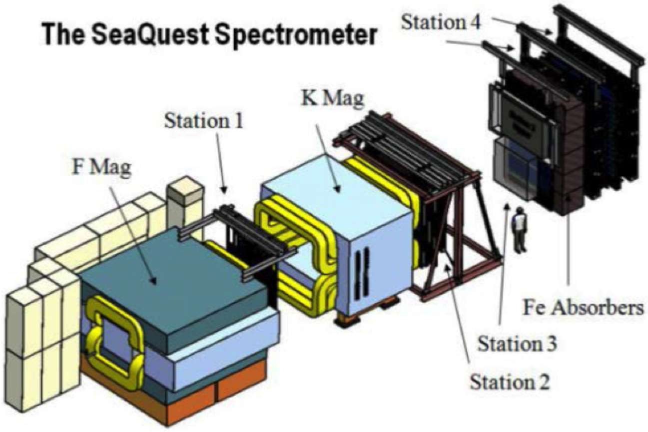

Fig. 5. The SeaQuest/E906 25 m long dimuon spectrometer, showing the two dipole magnets, F-Mag (also a beam-dump, 5-m thick solid iron block) and K-Mag (air core), three tracking stations and also the Station-4 muon identifier located behind the last 1-m thick iron absorber. Not shown on the left side are the targets (typically 10% nuclear interaction length) that are located about 130 cm upstream from the front face of F-Mag. The 120 GeV/c proton beam comes from the left.

2. Experimental Setup and Projected Sensitivities

As discussed above, we will carry out initial direct search for dark photons (equally applicable to the dark Higgs search) by parasitically taking data with other fixed target SeaQuest experiments (E906 and later with E1039) in a beam-dump mode, using the same SeaQuest dimuon spectrometer but looking for signals mainly produced in the beam-dump. The currently running SeaQuest/E906 experiment is designed to measure high-mass (mass$\,>4$ GeV/c^2) Drell–Yan produced in p + A collisions (A = H, D, C, Fe and W), with a typical target thickness of $\sim 10\%$ of nuclear interaction length. Figure 5 shows the current SeaQuest/E906 spectrometer setup. The E906 experiment will complete data collection in summer 2017. The dimuon spectrometer will then be used, without modification, by a new polarized fixed target Drell–Yan experiment, E1039, to study the internal quark structure of the polarized proton with a solid polarized proton target (NH_3 target). Installation of the polarized target could begin as early as the late 2017 with data collection starts in early 2018 and runs for two years. The E1039 spectrometer configuration will be the same as E906, except that the polarized target will be located further upstream, about 5 m from F-Mag (also the beam-dump). The thickness of the polarized target is about 6% of nuclear interaction length, slightly shorter than the ones used in E906.

For the dark photon (dark Higgs) search in a parasitic running mode with E1039 (similar with E906), the thin polarized NH_3 target and supporting materials will take away only about 6% of protons from the incoming beam, leaving 94% of the beam to interact directly with the iron beam-dump (the F-Mag in Fig. 5) and produce most of the dark photons (dark Higgs) within the first ~ 3 nuclear

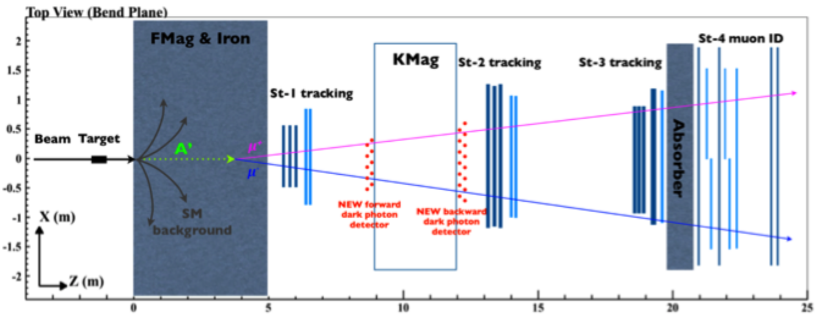

Fig. 6. A schematic view for a dark photon decay into a dimuon downstream of the E906 iron beam-dump (and focusing magnet F-Mag) at Fermilab. The dimuon trigger roads are reconstructed in the non-bend plane to determine the decay Z-vertex with a Z-resolution about 30 cm.

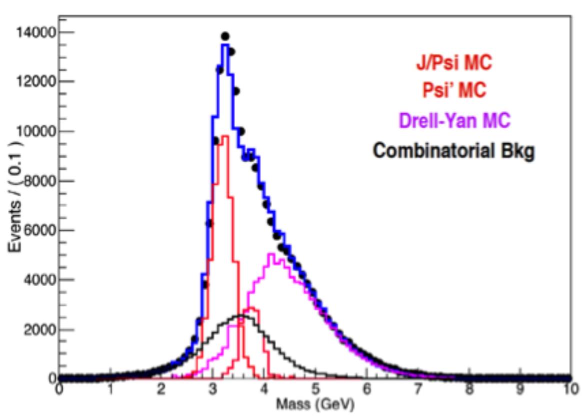

Fig. 7. Dimuon mass spectra from E906 Run-2 data. Low mass dimuons below 2.5 GeV/c^2 are intentionally suppressed by the trigger selection in order to maximally take signal high-mass dimuon events efficiently within the E906 DAQ limit.

interaction length ($\sim$50 cm) inside the beam-dump, from the same Run-2 data sample. These dark photons (dark Higgs) will subsequently decay into oppositely charged muon pairs detected by the SeaQuest dimuon spectrometer.

The dark photon (dark Higgs) signal will be identified with unique experimental observables: (1) A sharp dark photon (dark Higgs) mass peak in the reconstructed dimuon invariant mass spectrum, and/or (2) for a long-lived dark particle, a displaced dark photon (dark Higgs) decay vertices downstream of the beam-dump, as illustrated in Fig. 6.

Figure 7 shows an example of dimuon mass spectrum reconstructed from E906, based on a fraction of the data collected in 2014. Given limited DAQ bandwidth, background events with dimuon mass less than 2.5 GeV/c^2 were deliberately suppressed by the E906 trigger and event selection in order to maximally collect high mass Drell–Yan candidates.

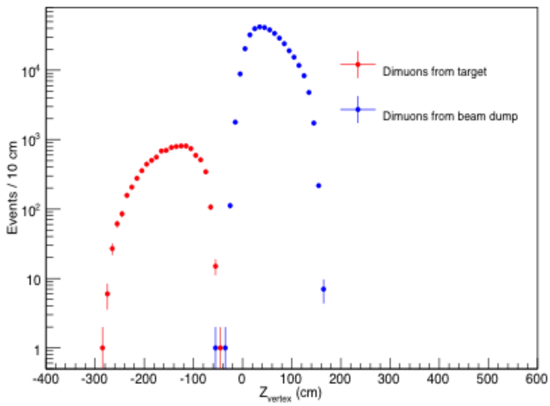

Fig. 8. (color online) Reconstructed dimuon vertex distributions from target (red) and beam-dump (blue). The offline Z-vertex resolution is about 30 cm for high-mass Drell–Yan events. After event selection, no dimuon events are observed at Z-vertex beyond 200 cm from the Run 2014 data set.

Figure 8 shows the reconstructed dimuon event vertex distributions from all dimuons produced in the targets and the beam-dump. The beam-dump (F-Mag) is located in Z from 0 cm to 500 cm, and targets are located upstream, with $\langle Z \rangle \sim 130$ cm. Note that there are no events observed beyond $Z > 200$ cm after beam-dump event selection [blue data points], indicating that very low backgrounds are possible for long-lived decays. In a preliminary study, this $Z > 200$ cm region is used as the search window for long-lived dark photon (dark Higgs) candidates.

To effectively detect the dark photon (dark Higgs) events over the full mass range of 0.2–10 GeV/c^2 covered by the SeaQuest dimuon spectrometer, a moderate upgrade of the SeaQuest/E906 trigger system is required to select low mass dimuons, mass < 2.5 GeV/c^2, at the trigger level. Ultimately, our goal is to collect not only the *long-lived* displaced dark photons (dark Higgs) that decay significantly downstream of the beam-dump, but also to take, within our DAQ limit, most of the *short-lived* dark photons (dark Higgs) that decay near the interaction points (identified via a sharp dimuon mass peak above the SM continuum dimuon background). Currently, the SeaQuest experiment is undergoing trigger and DAQ upgrade to install a new finely segmented displaced vertex dimuon trigger to be ready for data collection by early 2017, in combination with the tenfold improved DAQ bandwidth. A 80 cm $\times$ 80 cm (100 cm $\times$ 100 cm for Station-2 trigger plane) scintillating-strip triggering detector per quadrant situated near the E906 Station-1 (Station-2) tracking chambers will fulfill the requirements for both triggering on displaced dimuon vertices and rejecting low-mass combinatorial dimuon background, as illustrated in the diagram in Fig. 6. Without such a trigger, most of the low-mass dark photon/Higgs events will be lost.

As shown above, the SeaQuest/E906 spectrometer can measure both the dimuon mass and dark photon (dark Higgs) decay vertex. The 5-m thick solid iron

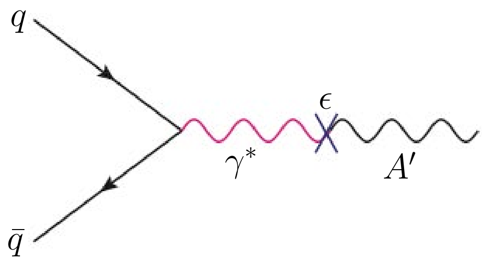

Fig. 9. Dark photon production in Drell–Yan like quark and antiquark annihilation process.

beam-dump (F-Mag) stops most of the SM particles (other than neutrinos and high energy muons) produced in proton–iron interactions. However, a dark photon (dark Higgs), which interacts feebly with normal matter, can travel a significant distance from the creation point before it decays into an oppositely charged muon pair in the so-called visible decay modes (shown in Fig. 1). The displaced decay point gives us a great advantage to further suppress the SM background beyond the invariant mass peak window in the dark photon (dark Higgs) search, compared to other on-going and proposed measurements. Figure 1 shows our projected exclusion regions based on two-year parasitic data collection with E1039 with integrated POT 1.4×10^{18}. We note that our approach is complimentary to the search in the invisible decay modes performed recently by the MiniBooNE beam-dump experiment at Fermilab with 1.86×10^{20} POT in 2014.[10]

2.1. *Dark photon and dark Higgs yield estimates*

In this session, we provide some details on how we estimate dark photon and dark Higgs yields at SeaQuest/E1067. Our calculations are carried out through leading order (LO) perturbative Quantum Chromodynamics (QCD) computations in $p + Fe$ collisions. We take the SeaQuest/E906 configuration with the following assumptions: total number of protons on the beam-dump $\sim 1.4 \times 10^{18}$, accumulated over the first two years of parasitic data collection with the E1039 experiment in 2018–2020. This assumes that we continue data collection with the same beam conditions currently seen by E906: 5×10^{12} protons per minute (4 s beam time for every 60 s spill) with an effective 200-day running with the current E906 data-taking efficiency.

Let us start with the dark photon production at LO in a Drell–Yan-like process, which is generated through quark–antiquark annihilation followed by a kinetic mixing with a virtual photon as shown in Fig. 9.

The LO dark photon differential cross-section is given by Eq. (3),

$$\frac{d\sigma}{dx_F}(p + p \to A' + X) = \sigma_0^{A'} \sum_q e_q^2 q(x_1)\bar{q}(x_2)\frac{x_1 x_2}{x_1 + x_2}\,, \tag{3}$$

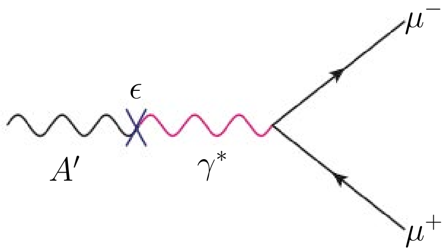

Fig. 10. A dark decay into a dimuon pair through a kinetic mixing with a virtual photon.

where x_F is the Feynman longitudinal momentum fraction of the dark photon, $x_{1,2}$ are quark momentum fractions with $q(x)$ quark distribution function and

$$\sigma_0^{A'} = \frac{4\pi^2 \alpha_{em} \epsilon^2}{N_c m_{A'}^2}, \qquad x_1 = \frac{x_F + \sqrt{x_F^2 + 4m_{A'}^2/s}}{2}, \qquad x_2 = \frac{-x_F + \sqrt{x_F^2 + 4m_{A'}^2/s}}{2}. \tag{4}$$

Once the dark photon is produced, such a real dark photon will likely pass through a significant amount of distance before decay in our "beam-dump" experiment. Here, we only consider a simple scenario in which they decay into SM particles only, in the so-called visible decay modes, in which they could decay into possible lepton pairs (e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$) as well as quark–antiquark pair (eventually into hadrons). For example, the dark photon decaying into a dimuon pair is illustrated in Fig. 10.

In this case, the decay width can be computed and the LO result is given by Eq. (5),

$$\Gamma(A' \to f + \bar{f}) = C \frac{\epsilon^2 m_{A'}}{3} e_f^2 \alpha_{em} \left(1 + \frac{2m_f^2}{m_{A'}^2}\right) \sqrt{1 - \frac{4m_f^2}{m_{A'}^2}}, \tag{5}$$

where e_f and m_f are the fractional electric charge and the mass of the fermion, respectively. The coefficient C is an overall normalization factor coming from the color of the decay products: $C = 1$ (N_C) for lepton (quark). The last two factors come from the phase space correction, without which it reduces to the well-known result given by Bjorken *et al.*[3] With the results for both dark photon production and decay, we estimate the dimuon yields in the SeaQuest/E1067 experiment configuration. We reproduce the dark photon decay branching ratio as a function of dark photon mass in Fig. 11,

On the other hand, at LO, dark Higgs particles are mostly generated through gluon–gluon fusion channel in hadronic interactions at SeaQuest/E1067. The LO

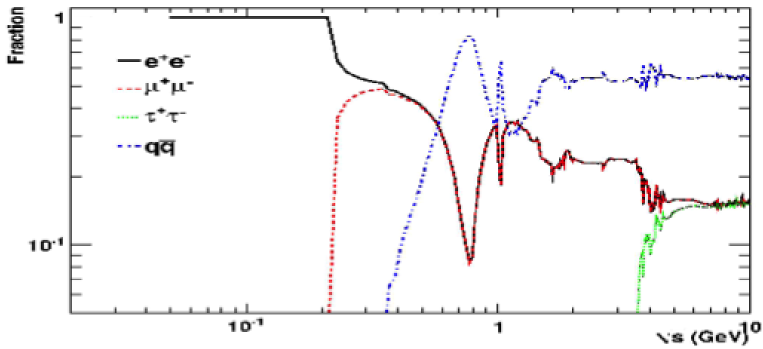

Fig. 11. Dark photon decay branching ratio in the visible decay mode.

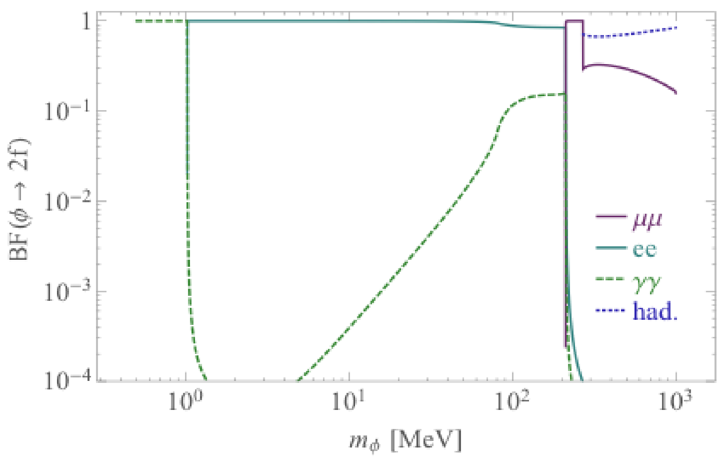

Fig. 12. Dark Higgs decay branching ratio in the visible decay mode.[24]

cross-section can be computed similarly and the result is given by Eq. (6),

$$\sigma(p + p \to \phi + X) = \int_0^1 \frac{dx}{x} g(x) g\left(\frac{m_\phi^2}{xs}\right) \frac{\alpha_s^2 G_F m_\phi^2}{288\sqrt{2}\pi s}\,, \tag{6}$$

where $g(x)$ is the gluon distribution function and m_ϕ the dark Higgs mass. Dark Higgs decays in the visible mode have been extensively studied[24] and we reproduce the branching ratio here in Fig. 12.

2.2. *Dark photon search*

The E906 experiment, currently utilizes only $\sim 6\%$ of the available proton beam from the Main Injector, taking 1 pulse of 5×10^{12} protons every minute with a slow spill duration of 4 seconds. Assuming similar beam conditions in the future runs, in an ideal case, we expect to sample 1.4×10^{18} protons interacting in the dump in two years of parasitic data collection, which is equivalent to an integrated $\mathrm{p} + \mathrm{p}$ luminosity of $\sim 35\ \mathrm{K\,fb}^{-1}$. This is two orders of magnitude larger than the projected integrated luminosity of $300\ \mathrm{fb}^{-1}$ expected at LHC by the end of 2025, and similar to the projected BELLE-II Super-B-Factory integrated luminosity of $\sim 50\ \mathrm{K\,fb}^{-1}$ at KEK (by 2023).[11] Higher sensitivity could possibly be achieved with dedicated runs in the future with further optimized detectors.

We estimate the projected dark photon search sensitivity based on the assumption discussed above. Figure 1 shows the production and decay of dark photons in the Drell–Yan-like dimuon channel probed in SeaQuest/E1067 at Fermilab. We note that besides the Drell–Yan-like process, dark photon could also be created through kinetic mixing with the SM regular photon produced from any other processes, such as η and π^0 decays as well as from incoming proton beam Bremsstrahlung radiation. Full detector GEANT simulation has been performed to evaluated accepted events and expected backgrounds. The kinematics of SeaQuest/E1067 experiment sets the accessible $\epsilon - m_{A'}$ parameter space: covering mass from 0.2 GeV/c^2 (minimal mass of a muon pair) to 10 GeV/c^2 (limited by the 120 GeV beam energy in the fixed target mode) and coupling constant from 10^{-2} down to 10^{-7}, see Fig. 1. The large coupling region is from bump-search of dark photon signal on top of the dimuon continuum, and the low coupling region is from displaced dark photon decay vertex search. Note that a full study of our dark photon sensitivity at low mass is presently underway and that the actual ϵ limit could move somewhat. This sensitivity is very exciting because: (i) it probes new territory in the $\epsilon - m_{A'}$ parameter space, and thus has great discovery potential; (ii) it tests the prejudiced relation $m_{A'} \sim \sqrt{\epsilon} m_Z$, which in models with light DM (mass $\ll Z^0$ boson mass) naturally predicts a DM-nucleon cross-section that is consistent with observational hints.[3–6]

2.3. *Dark Higgs search*

For the dark Higgs search, we follow the same approach taken for the dark photon search. We find that the SeaQuest dimuon spectrometer also has excellent acceptance for a long-lived dark Higgs with a displaced decay vertex 2.0 m downstream of its creation point. Preliminary study shows that we can extend the coupling constant coverage down to $\theta < 10^{-4}$, and for dark Higgs mass m_ϕ up to about 1 GeV/c^2. Figure 6 shows our sensitivity in the dimuon channel to dark Higgs production under two different integrated luminosities scenarios.

Unlike the dark photon case, identifying a "prompt signal" at high-mass turns out to be more difficult, mainly because the production cross-section of ϕ is intrinsically suppressed by the EW scale, making it much smaller than the SM $\mu^+\mu^-$ background produced via electromagnetic interactions. For $m_\phi \gg 2m_\mu$, the dimuon channel is further suppressed by the branching ratio because the Higgs portal implies that the decays into heavier final states (hadrons) dominate the ϕ total decay rate. We note that if dark particle is discovered, the dimuon angular distribution

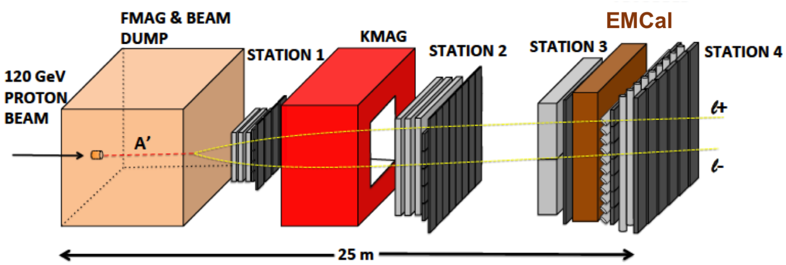

Fig. 13. A possible SeaQuest Spectrometer upgrade: A new EMCal located behind the Station-3 chambers could be used to identify and measure high-energy electron (possibly also hadron) pairs from long-lived dark photon decays.

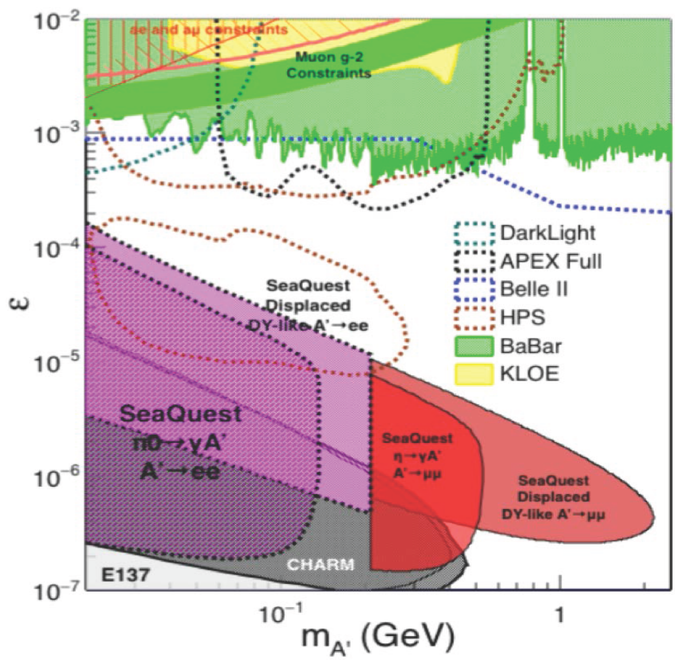

Fig. 14. By including di-electron channel probe through EMCal upgrade, SeaQuest can reach lower mass region below the dimuon limit, assuming POT 1.4×10^{18}.

can be used to further identify the property of this new dark particle: a scalar (dark Higgs) or a vector (dark photon).

2.4. *Future possibilities for exotic physics with upgraded detectors*

Current searches have been focused on using the dimuon probe to detect dark photon and dark Higgs signals. By adding a new EMCal behind the current Station-3 chambers, one could also identify and measure high-energy electron pairs from dark photon (or dark Higgs) decays, see Fig. 13.

Di-electron channel will allow us to access the dark photon (Higgs) mass below the dimuon mass limit, ~ 200 MeV/c^2, down to ~ 1 MeV/c^2. Figure 14 shows the preliminary result of much expanded coverage of the dark photon search space by including di-electron channel. Because electrons from the target area cannot penetrate the 5-m thick iron beam-dump, only these electrons from long-lived dark photon decays can reach the detectors.

With EMCal, one can also identify charged hadrons from electrons and muons. This will allow us to further explore other exotic hidden sector dynamics, such as those mediated by non-Abelian (QCD-like) hidden sectors.[23] The latter would require the upgraded detectors that could detect charged pion final states. Detailed MC simulation study is underway to further explore new physics opportunities with an upgraded EMCal in the future at SeaQuest.

3. Summary

We have shown there is a unique opportunity today at Fermilab to directly search for dark photon and dark Higgs production in highly motivated parameter space in high-energy proton–nucleus collisions in the SeaQuest/E1067 experiment. The displaced dark photon trigger and DAQ upgrade will allow us to take data parasitically with other fixed target experiments. In a two-year parasitic running with E1039, we will be able to see or exclude the existence of dark photons and dark Higgs over a wide region of phase space. If dark photon and/or dark Higgs are observed, they will not only shed light on the mystery of DM but also bring a revolution to our understanding of the fundamental structures and interactions of our universe.

Acknowledgments

The author would like to thank the generous support from Los Alamos National Laboratory (LANL) LDRD program, this work is supported by LDRD Grant 20160081ER, and also thank the Fermilab CAD for delivering excellent beam to the SeaQuest experiment. This work has been carried out in close collaboration with P. McGaughey, K. Liu, H. van Hecke, S. Uemura, S. Lim, A. Klein and R. Van de Water from LANL, Z.-B. Kang from UCLA/LANL, Y. Zhang from CalTech, J. Huang from BNL, Y. M. Zhong from StonyBrooks, R. Holt and P. Reimer from ANL, D. Christian from Fermilab and J. C. Peng from UIUC. The author also had very fruitful discussions with S. Gorri of University of Cincinnati, N. Torro and P. Schuster from SLAC and the Fermilab SeaQuest/E1067 collaboration.

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