Letter of Intent for a Direct Search for Dark Photon and Dark Higgs Particles with the SeaQuest Spectrometer in Beam Dump Mode

Co-Spokespersons: Ming X. Liu (LANL) and Paul E. Reimer (ANL)

Collaboration:

M. S. Daugherity, L. D. Isenhower, R. S. Towell, T. S. Watson
Abilene Christian University, Abilene, TX 79699
J. Arrington, D. Geesaman, K. Hafidi, R. J. Holt, P. E. Reimer, B. G. Tice
Argonne National Laboratory, Argonne, IL 60439
J. Huang
Brookhaven National Laboratory, Upton, NY 11973
Y. Zhang
Caltech, Pasadena, CA 91125
E. Kinney, P.-J. Lin
University of Colorado, Boulder, CO 80309
C. Brown, D. Christian, J.-Y. Wu
Fermi National Accelerator Laboratory, Batavia IL 60510
B. Dannowitz, M. Diefenthaler, B. Kerns, N. Makins, R. E. McClellan, J.-C. Peng, S. Prasad
University of Illinois, Urbana, IL 61081
W.-C. Chang, S.-Y. Wang
Institute of Physics, Academia Sinica, Taiwan
S. Sawada
KEK, Tsukuba, Ibaraki 305-0801, Japan
S. Gardner, W. Korsch
University of Kentucky, Lexington, KY 40506
T. Bhattacharya, M. Brooks, V. Cirigliano, C. da Silva, M. Graesser, R. Gupta, X. Jiang, Z. B. Kang, A. Klein, D. Kleinjan, K. Liu, M. Liu, M. McCumber, P. McGaughey, M. Snowball, Ivan Vitev, R. G. Van de Water, H. van Hecke, H. Xing
Los Alamos National Laboratory, Los Alamos, NM 87545
E. Beise, Y.-C. Chen
University of Maryland, College Park, MD 20742
C. Aidala, W. Lorenzon, R. Raymond, B. Roe, J. G. Rubin
University of Michigan, Ann Arbor, MI 48109-1040
K. P. Adhikari, J. A. Dunne, D. Dutta, L. El Fassi
Mississippi State University, Mississippi State, MS 39762
T. Badman, E. Long, K. Slifer, R. Zielinski
University of New Hampshire, Durham, NH 03824
D. Fields
University of New Mexico, Albuquerque, NM 87131
S. Pate, V. Papavassiliou, X.R. Wang
New Mexico State University, Las Cruses, NM 88003
R.-S. Guo, G. Wang
National Kaohsiung Normal University, Taiwan

Y. Mao, H. Yu
Peking University, China
Y. Goto
RIKEN, Wako, Saitama 351-01, Japan
R. Gilman, K. Myers, R. Ransome, A. Tadepalli
Rutgers University, Rutgers NJ 08544
Y. Zhong
SUNY Stony Brook University, Stony Brook, NY 11794
J.-P. Chen
Thomas Jefferson National Accelerator Facility, Newport News, VA 23606
S. Miyasaka, K. Nagai, K. Nakano, T.-A. Shibata
Tokyo Institute of Technology, Tokyo 152-8551, Japan
D. Crabb, D. Day, D. Keller, O. Rondon
University of Virginia, Charlottesville, VA 22904
Y. Miyachi, S. Nara
Yamagata University, Yamagata, 990-8560 Japan

Abstract:

There is a worldwide race in the search for dark photons and dark Higgs particles. If dark photons (dark Higgs) were observed, they would revolutionize our understanding of the fundamental structures and interactions of our universe. There is a unique opportunity today at Fermilab to search directly for dark photon and dark Higgs production in a highly motivated parameter space in high-energy proton-nucleus collisions using the existing SeaQuest (E906/E1039/E1027) dimuom spectrometer. This search can be accomplished with parasitic data taking with the upcoming E1039 experiment. The resulting data would provide the world's best sensitivity to dark photon (dark Higgs) masses between 0.2 – 10 GeV/c^2 for the next decade. Only a relatively minor upgrade of the existing SeaQuest dimuon spectrometer and trigger system is required to improve the acceptance and reduce the trigger rate to an acceptable level.

1. Physics motivation

The discovery of the Higgs boson at the LHC has completed the Standard Model of Particle physics (SM). 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 only accounts for approximately 4.9% 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**" [1]. 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 dark matter candidates. Recently, the physics of a possible "dark sector" has attracted much attention from both the experimental and theoretical communities.

In general, there are several types of mediator particles that can accommodate renormalizable interactions between the dark matter and the SM sectors. One popular example is a vector boson of a dark $U_D(1)$ gauge interaction, dubbed the "***dark photon"***, which can possess a kinetic mixing with the regular photon. Another possibility is a scalar boson ϕ, dubbed the "***dark Higgs"***, which is a gauge singlet under the standard model gauge group, and it mixes with the SM Higgs boson.

There is a unique opportunity today at Fermilab to search directly for a dark photon and dark Higgs in high-energy proton-nucleus collisions using existing detectors. With a moderate upgrade of the current SeaQuest/E906 dimuon spectrometer to add a new dark photon (dark Higgs) displaced decay vertex trigger, we would be well positioned to carry out this discovery science at Fermilab.

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 $U_D(1)$ gauge boson mediating abelian gauge interactions in the dark sector, SU(3) x SU(2) x $U_Y(1)$ x $U_D(1)$. 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 $\mathbf{m_{A'}}$ and $\boldsymbol{\varepsilon}$, the dimensionless parameter controlling kinetic mixing with the photon, with the interaction Lagrangian given by [2],

$$\mathcal{L}_{\rm mix} = \frac{\epsilon}{2} F^{\rm QED}_{\mu\nu} F^{\mu\nu}_{\rm Dark} \quad (1)$$

where $F^{\rm QED}_{\mu\nu}$ and $F^{\mu\nu}_{\rm Dark}$ are the tensors of the SM photon and dark photon fields, respectively.

Depending on the underlying messenger mechanism, **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. Dark matter phenomenology models and the muon *g-2* anomalous magnetic moment point to a likely dark photon mass from 1 MeV/c^2 to 10 GeV/c^2 [2-5]. That conclusion spurred a vibrant worldwide dark photon search in recent years at the LHC, RHIC, Fermilab, JLab, BaBar/SLAC, Belle/KEK and other facilities.

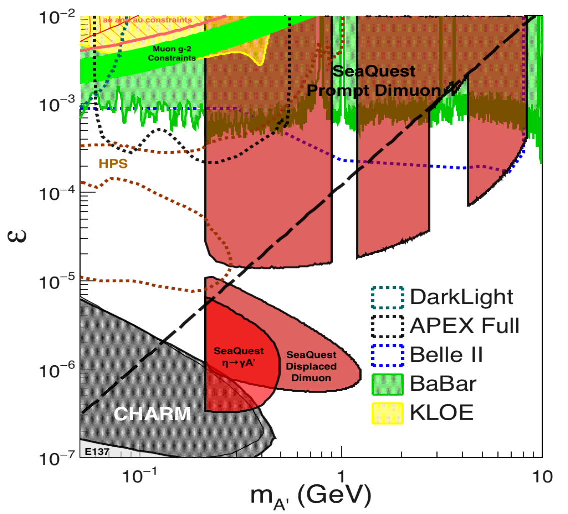

Figure 1. Current and projected future experimental limits on dark photon search [5]. The red and brown areas are the 95% exclusion zones from this LOI, a parasitic run with E1039, 1.44x10^{18} POT. The JLab-12 future experiments, APEX, HPS and DarkLight [10], are limited to low-mass region below 500 MeV. The LHC experiments are mostly sensitive to high-mass (>10GeV/c^2) and large coupling (ε > 10^{-3}) region. The black dashed curve is a theoretically motivated ($m_{A'}$, ε) relation, $m_{A'} \sim \sqrt{\varepsilon}\, m_Z$. Note that only BELLE-II (blue-dotted line) at KEK (2023) has the potential to probe part of the mass and coupling region that are covered by this LOI. Gaps around M~1GeV and M~3GeV are the phi, J/Psi and Psi' resonance regions excluded in current preliminary physics sensitivity studies.

As discussed in detail below, the SeaQuest spectrometer offers a great opportunity to search for dark photons at Fermilab with unprecedented sensitivity in a mass range of 0.2-10 GeV/c^2, probing values of **ε** as low as 10^{-7}, *3 orders of magnitude below the current experimental limit*. This sensitivity is very exciting because: (i) it probes new territory in the **ε-$m_{A'}$** parameter space, and thus has great discovery potential (see Figure. 1); (ii) it tests the relation **$m_{A'} \sim \sqrt{\varepsilon}\, m_Z$**, which in models with light dark matter (mass << Z^0 boson mass) naturally predicts a DM-nucleon cross-section that is consistent with observational hints [2-5]. Figure 2 shows the Drell-Yan like dimuon channel that we propose to explore the dark photon search at Fermilab.

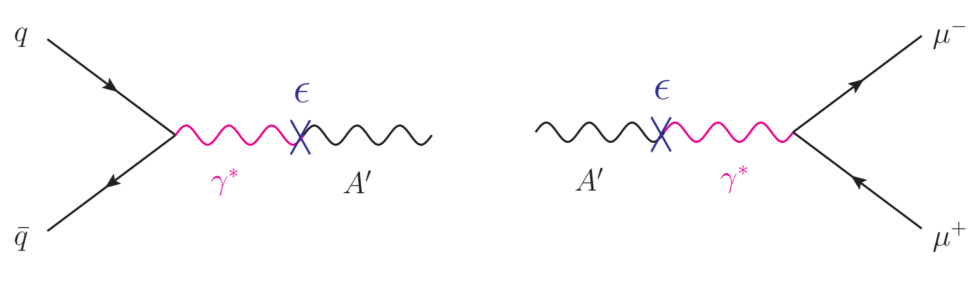

Figure 2. Feynman diagrams for dark photon production (left) and its decay into a muon pair (right). A dark photon of mass $m_{A'}$ is produced via kinetic mixing with a virtual photon produced through quark and antiquark annihilation in a high-energy proton-nucleus collision with a coupling constant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

At the LHC high-energy frontier, CMS and ATLAS are leading the search. They are best suited for the discovery of dark photons at a high-mass scale (> 10 GeV/c^2) with relatively large coupling constant, $\boldsymbol{\varepsilon} > 10^{-3}$, due to the limited integrated beam 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, $\mathbf{m_{A'}}$ < 500 MeV/c^2, and there are already three major dark photon search experiments approved — APEX, HPS and Dark-Light [6], as illustrated in Figure 1. The other high-energy physics centers for dark photon searches are the B-factories at SLAC and KEK. Recently the BaBar/SLAC, PHENIX/RHIC and NA48(2)/CERN experiments set new limits on the dark photon direct search [7,8], shown as the green region in Figure 1. Fermilab has already conducted a dark photon search with the MiniBooNE 2014 beam-dump run [9]. In the MiniBooNE case, the search was for a dark photon decaying into dark matter (invisible modes), which is allowed if the dark photon mass is greater than twice the daughter dark matter mass. The searches for visible and invisible modes of the dark photon compliment each other.

In this LOI, we explore the uncharted $\boldsymbol{\varepsilon}$-$\mathbf{m_{A'}}$ parameter space covering masses from 0.2 GeV (minimum mass of a muon pair) to 10 GeV and coupling constants from 10^{-2} down to 10^{-7}, see Figure 1. Note that a full study of our dark photon sensitivity at low mass is presently underway and that the lower $\boldsymbol{\varepsilon}$ limit could move somewhat. We will use the existing SeaQuest/E906 spectrometer to detect dark photon decays to muon pairs at the Fermilab Intensity Frontier Facility (the Main Injector). The E906 experiment, currently utilizing only ~5% of the available proton beam from the Main Injector, uses 1 pulse of $5\text{x}10^{12}$ protons every minute with a slow spill duration of 4 seconds. The E906 Cherenkov beam-monitoring detector typically vetoes about 50% of the beam due to large beam intensity fluctuations in each RF bucket that may cause high hit rates in the dimuon spectrometer. Assuming similar beam conditions in a future run, in an ideal case, we expect to have $1.44\text{x}10^{18}$ protons interacting in the dump in 2 years of parasitic data taking with the E1039 experiment, which is equivalent to an integrated luminosity of 35,000 fb^{-1}. This is two orders of magnitude larger than the projected integrated luminosity of 300 fb^{-1} expected at the LHC-14 by 2025, and similar to the projected BELLE-II Super-B-Factory integrated luminosity of 50,000 fb^{-1} at KEK by 2023 [10]. Higher sensitivity could possibly be achieved with dedicated runs in the future with further optimized detectors.

Physics of the Dark Higgs

In recent years, models with the dark Higgs as a mediator to dark matter have become the focus of many theoretical studies. The discovery of the Higgs boson at the Large Hadron Collider, the first fundamental scalar 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 theorized in many BSM models with an extended Higgs sector [11]. 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 to SM particles.

Meanwhile, in the dark sector, a dark Higgs mechanism can spontaneously break the dark $U_D(1)$ gauge group and generate the dark photon mass [12]. In particular, the resulting dark Higgs-dark photon-dark photon coupling leads to potentially very interesting experimental signatures for the searches. In principle, these two perspectives can be considered separately. However, the combination of the two leads 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 [13],

$$\mathcal{L}_{\rm mix} = \mu\phi|H^\dagger H| \tag{2}$$

where H is the standard model Higgs doublet (another possible Lagrangian is also discussed in Appendix 2). The electroweak breaking generates a mixing between ϕ and the Higgs boson H. The mixing angle θ is related to the parameter μ by, $\theta = \mu\, v/m_h^2$, where v is the electroweak scale. 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.

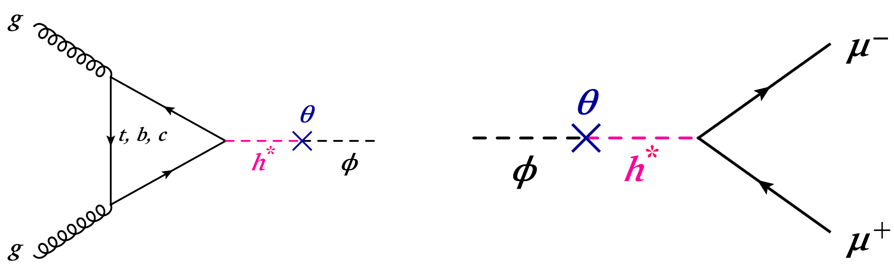

Figure 3. Feynman diagrams for dark Higgs production and its decay into a muon pair through the Higgs portal. Note that, different from the dark photon case, the dark Higgs is predominantly produced through gluon fusion process at Fermilab's beam energy.

The discovery of the Higgs boson is a strong motivation to explore this scenario. There are also motivations from cosmology and astrophysics, including the dark matter relic density, indirect detection and structure formation on galaxy scales. A dark Higgs with mass in the MeV/c^2 to GeV/c^2 window is of particularly interest and can be probed at Fermilab. Dark matter interacting with a mediator (dark Higgs, or dark photon) can offer new insights into these questions [14,15] and makes new predictions for dark matter bound states [16-18] that could be also tested in the future.

The current experimental constraints on this model are mainly from B and K meson decays [13,19,20]. For m_ϕ less than a few GeV/c^2, the upper bound on θ is around 10^{-2}-10^{-3}. There is also an earlier fixed target experiment CHARM [21] (in the 1980s) that has set the strongest bound for m_ϕ in the range 0.1-0.4 GeV/c^2, excluding the allowed θ range down to the 10^{-4}-10^{-5} level.

A proposal was submitted recently (4/19/2015) from the CERN SHiP Collaboration to develop a new fixed target experiment, similar to that in this LOI to search for dark particles at the Super Proton Synchrotron (SPS) [23]. There are some significant overlaps between the SHiP proposal and ours in the covered phase space. It is clear that we are in quite strong competition for discovering new physics in the overlapped regions. However, **we have a great advantage now since we already have a running experiment that only requires a moderate upgrade to accomplish the same goals.** SHiP will not begin taking data until at least 2025. If we want to win the opportunity for a possible major discovery at Fermilab, it is critical for the SeaQuest Collaboration to start the dark particle search in a timely manner, using a stable high quality and high intensity beam from the Main Injector. If a dark photon (dark Higgs) were observed, it would bring a revolution to our understanding of fundamental structures and interactions of our universe.

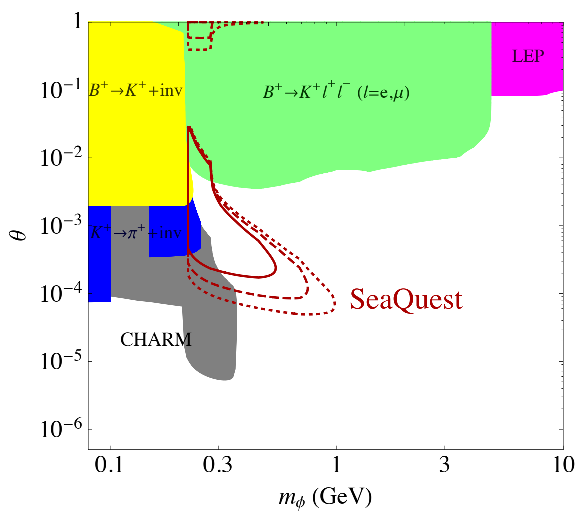

Figure 4. **Current limits and the projected 95% sensitivity on dark Higgs search from this LOI. The red solid curves correspond to the constraint with ϕ to $\mu^+\mu^-$ decay tagged through displaced vertex 2.0m downstream of the beam dump from the initial parasitic run with E1039, 1.44×10^{18} POT; the dashed line is for 5x initial statistics; the dotted curve is the optimistic case of 25x initial statistics.**

We can make the world's most sensitive search for dark photon and dark Higgs in a mass region of 0.2 ~ 10 GeV/c^2 for at least the next decade, as shown in Figures 1 and 4.

2. Proposed measurements and facility upgrade

We propose to carry out a new direct search for dark photons (equally applicable to the dark Higgs search) using the existing SeaQuest/E906 spectrometer in beam dump mode at Fermilab, by colliding the 120 GeV proton beam from the Main Injector with the 5m thick iron beam dump. We propose the addition of a new dedicated dark photon displaced vertex trigger into the SeaQuest spectrometer and to take data parasitically with the upcoming E1039 experiment in 2017-2019 in order to carry out a preliminary search. Without such a trigger, most of the dark photon/Higgs events will be lost. Figure 5 shows the current SeaQuest/E906 spectrometer setup.

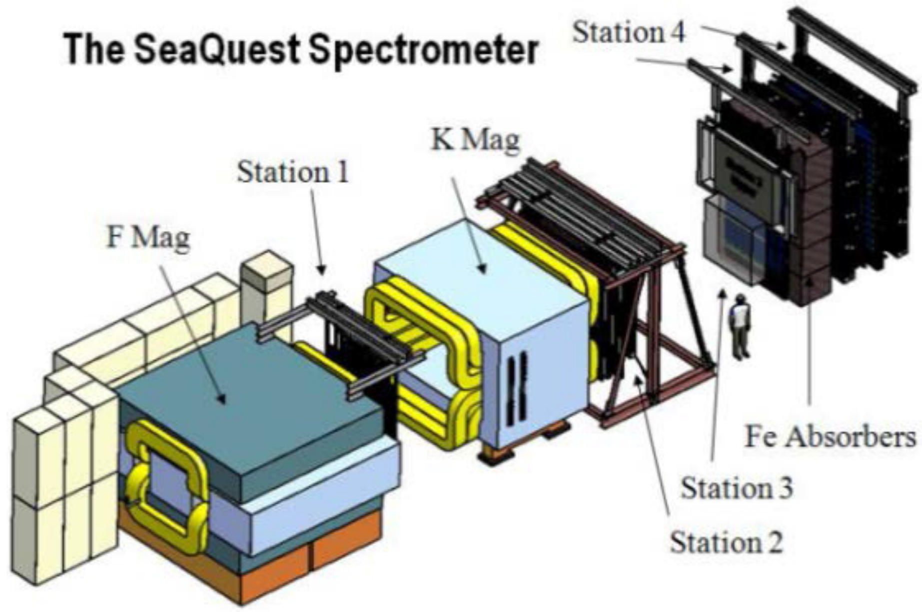

Figure 5. The SeaQuest/E906 25m long dimuon spectrometer, showing the two dipole magnets, F-Mag (also a beam dump, 5m thick solid iron block) and K-Mag (air core), 3 tracking stations and also the station-4 muon identifier located behind the last 1m thick iron absorber. Not shown on the left side are the targets (typically ~10% nuclear interaction length) that are located about 130cm upstream from the front face of F-Mag. The 120 GeV proton beam comes from the left.

The SeaQuest/E906 experiment is designed to measure high-mass (mass >4 GeV/c^2) Drell-Yan production in p+p, p+d and p+A with various nuclear targets, H, D, C, Fe and W. E906 will complete data taking in the summer 2016. The dimuon spectrometer will then be used by a new experiment, E1039, to study the internal quark structure of the polarized proton with a new polarized proton target (NH_3). Installation of the polarized target will begin in the summer of 2016, and E1039 plans to begin recording data in spring 2017, for 2 years. The spectrometer configuration will be the same as E906, except that the polarized target will be located further upstream, about 5 m from F-Mag. The target is about 6% nuclear interaction length, slightly shorter than the ones used in E906.

Figure 6 (left) shows a dimuon mass spectrum reconstructed from E906, based on a fraction of the data collected in 2014. Events with dimuon mass less than 2.5 GeV/c^2 were deliberately suppressed by the E906 trigger and event selection. The right-hand plot shows the reconstructed dimuon event vertex distributions from all dimuons produced from targets and the beam dump. The beam dump is located in Z from 0 to 500cm. Note that there are no events observed beyond Z > 200cm 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 > 200cm region is used as the search window for long-lived dark photons (dark Higgs).

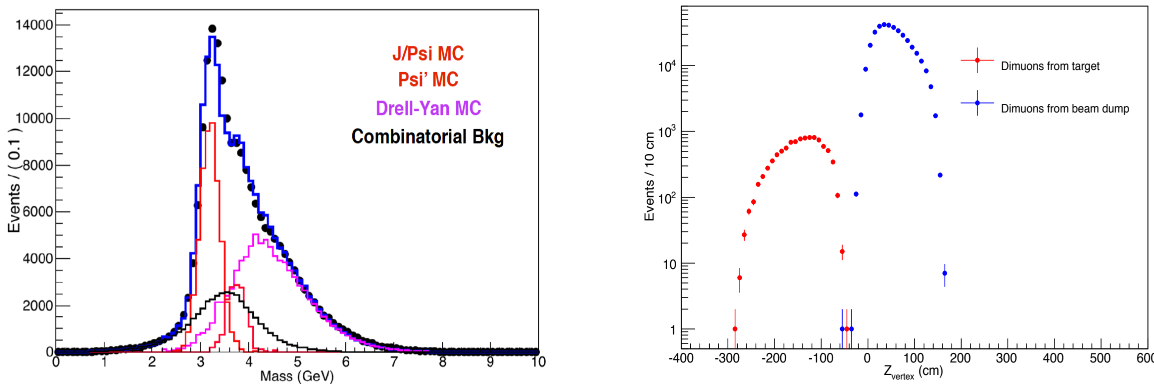

Figure 6. Left: Dimuon mass spectra from E906 Run-2 data, from dump events. Low-mass dimuons below 2.5GeV/c^2 are intentionally suppressed by the trigger and event selections. Right: reconstructed dimuon vertex distributions from target (red) and beam dump (blue). The offline Z-vertex resolution is about 30cm. After event selection, no dimuon events are observed at Z-vertex beyond 200 cm from the Run-2 data set.

As shown above, the SeaQuest/E906 spectrometer can measure both the dimuon mass and dark photon decay vertex. The 5m thick solid iron beam dump/magnet stops most of the SM particles (other than neutrinos and high energy muons) produced from 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 Figures 1 and 2). The displaced decay point gives us a great advantage to suppress the SM background in the dark photon (dark Higgs) search, compared to other on-going and proposed measurements. 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[9].

For the dark photon (dark Higgs) search in a parasitic running mode with E1039, the thin polarized NH3 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 and produce most of the dark photons (dark Higgs) within the first ~3 nuclear interaction length (~50cm) inside the beam dump. These dark photons (dark Higgs) will subsequently decay into oppositely charged muon pairs and be detected by the SeaQuest dimuon spectrometer.

The dark photon (dark Higgs) signal can be identified with two unique experimental observables, as illustrated in Figure 7,

1) A sharp dark photon (dark Higgs) mass peak in the reconstructed dimuon invariant mass continuum spectrum, and/or
2) Dark photon (dark Higgs) decay vertices displaced downstream of the beam dump.

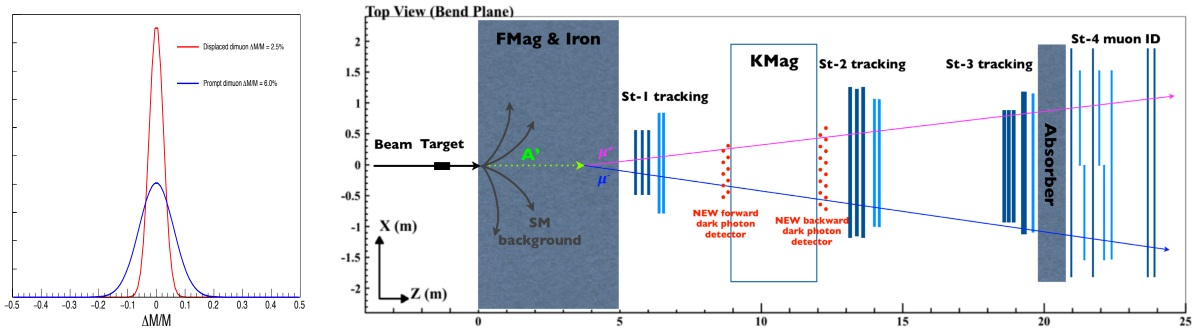

Figure 7. Left: Simulated dark photon dimuon invariant mass resolutions for "short-lived"(blue) and "long-lived"(red) dark photons with the E906 spectrometer; Right: A schematic view for a dark photon decay into a dimuon downstream of the E906 iron beam dump (and focusing magnet) at Fermilab. The dimuon trigger roads are reconstructed in the non-bend plane to determine the decay Z-vertex with a resolution about 30cm.

To effectively detect the dark photon (dark Higgs) events over the full mass range 0.2 - 10 GeV/c^2 covered by the dimuon spectrometer, a moderate upgrade of the E906 trigger system is required to improve the DAQ acceptance for dimuons below 2.5GeV/c^2, as shown in Figure 8. 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 background, as illustrated in Figure 9.)

LANL, in collaboration with the E906 DAQ group, will develop and install a new finely-segmented displaced vertex trigger into the SeaQuest/E906 dimuon spectrometer in late 2016. Initial studies show that two 80cm x 80cm scintillating-strip tracking detectors situated between the E906 Station-1 and Station-2 tracking chambers would fulfill the requirements for both triggering on displaced dimuon vertices and rejecting low-mass combinatorial dimuon background, as illustrated in the diagram in Figure 7 (right).

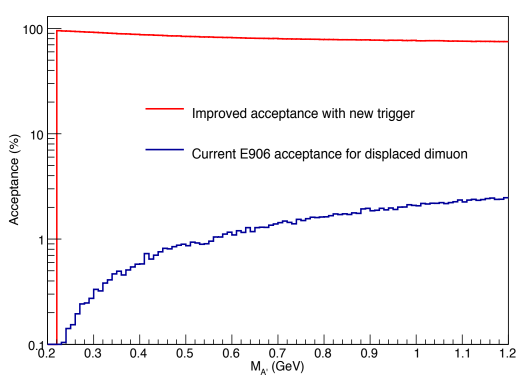

Figure 8. Expected significantly improved event acceptance within the current DAQ bandwidth as enabled by the new trigger for low-mass dimuons from the beam dump. The E906 trigger was specifically designed to reject low-mass dimuons that did not come from the target. The red line is the improved acceptance for low-mass dimuons with the new trigger; the blue curve is the current efficiency due to limited DAQ bandwidth with the current E906 trigger.

Most importantly, the new trigger will be capable of identifying a displaced dark photon decay Z-vertex with a resolution ~30cm for dimuons in the mass range of 0.2 - 2 GeV/c^2, which are otherwise rejected by the current E906 trigger due to a limited DAQ bandwidth. This new trigger is expected to have a high background rejection power from an FPGA based precision muon road finding algorithm and to use less than 10% of the current E906 DAQ bandwidth (~1 KHz). That would allow us to run the dark photon (dark Higgs) search parasitically with the upcoming E1039 experiment. Figure 8 shows the expected large improvement of the low-mass dark photon acceptance with the new trigger.

This finely-segmented new trigger will also help to select “prompt dimuons” in the trigger road finder by rejecting fake muon roads formed from random combinations of hits from different tracks, through precision vertexing and opening angle measurement of two muon tracks. A preliminary study with full Monte Carlo (MC) simulation shows the overall beam dump dimuon trigger rate is about a factor of 5~10 above current DAQ limits of 1 kHz (assuming 40K protons per RF bucket; this is twice the current average proton beam intensity). The new trigger is expected to provide an additional rejection power of 10~100, since our current trigger roads are mostly from random combinatorial of hits rather than real tracks. This allows us to take most of the prompt low-mass dimuons even with the limited E906 DAQ bandwidth. Figure 9 shows a simulated “prompt” dark photon signal calculated at LO (see Appendix 1) with mass 1.5 GeV/c^2, assuming we can record all of the dimuon events. In a preliminary study, we estimated the background with next-to-leading order (NLO) Drell-Yan calculation for masses above 1 GeV/c^2, and extrapolated them down to 200 MeV with a polynomial function fit. More detailed simulation study and preparation of dedicated short test runs are in progress to fully evaluate various background contributions.

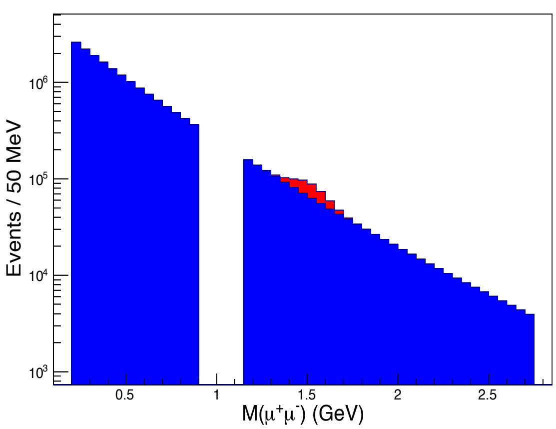

Figure 9. A simulated dark photon signal (red) at mass $m_{A'} = 1.5$GeV/c^2 and $\varepsilon = 2.7\times10^{-4}$, following $m_{A'} = \sqrt{\varepsilon}\, m_Z$, on top of the Drell-Yan continuum (Blue). The significance of the signal (red) above the Drell-Yan background, defined as $S/\sqrt{(N_{BG} + S)}$, is about 22 with the expected statistics from 2 years of parasitic run with E1039 polarized Drell-Yan experiment. The gap around M~1 GeV/c^2 represents phi meson resonance peak region which is excluded in a current preliminary study for simplicity. The width of the excluded region is determined by detector dimuon mass resolution.

3. Preliminary studies and expected results

E906 is expected to complete data taking in the summer of 2016. After that, a new experiment – E1039, will take over the SeaQuest/E906 dimuon spectrometer and run a new physics program with a polarized proton target for 2 years. The goal of E1039 is to measure the high-mass (mass > 4 GeV/c^2) Drell-Yan dimuons’ transverse single spin asymmetry with a polarized NH_3 target.

To study the sensitivity of the dark photon and dark Higgs search, we assume parasitic data taking with E1039 from 2017 to 2019. The expected total number of protons on target is about 1.44 x 10^{18}, under the assumption of running the experiment with the same beam conditions currently seen by E906. For this, new dark photon (dark Higgs) trigger detectors will be installed and ready for data taking parasitically with E1039 in early 2017. Development of the new trigger detectors can take place in parallel with the E906 experiment.

Dark photon search:

By combining these two unique experimental techniques discussed above, we could dramatically expand the current dark photon search region ($\mathbf{m_{A'}}$, $\boldsymbol{\varepsilon}$) by as much as 3 orders of magnitude for the coupling constant in a mass range of 0.2-10 GeV/c^2, as illustrated in Figure 1. None of the current or near future approved experiments has the capability to explore this region, due to either limited beam energy or luminosity [8-11]. The BELLE-II experiment at KEK, could reach a similar high-mass region in 2023 after a major upgrade, but still with less sensitivity in coupling constant, $\boldsymbol{\varepsilon} > 10^{-4}$, than what we proposed here [11].

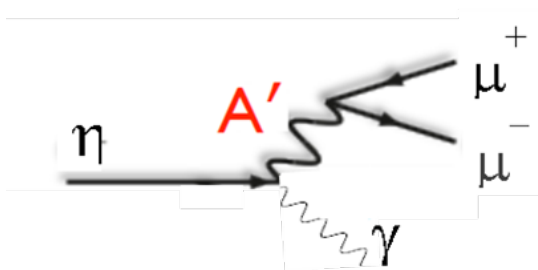

Figure 10. ***Feynman diagram of an η meson decaying to a photon (γ) and a dark photon, denoted by A', with a probability governed by the square of the coupling constant between light and dark sectors, ε^2. The A' can subsequently decay into a $\mu^+\mu^-$ pair with a decay lifetime proportional to ε^{-2}.***

Additional simple modifications to the experiment, such as adding electron identification detectors, could also greatly enhance the reach of this experiment. For example, with electron measurements, we can also search for dark photon in a mass region bellow 200MeV/c^2. Preliminary projections for the detection of e^+e^- from η decay and proton bremsstrahlung are compared with muon pair detection in Figure 11.

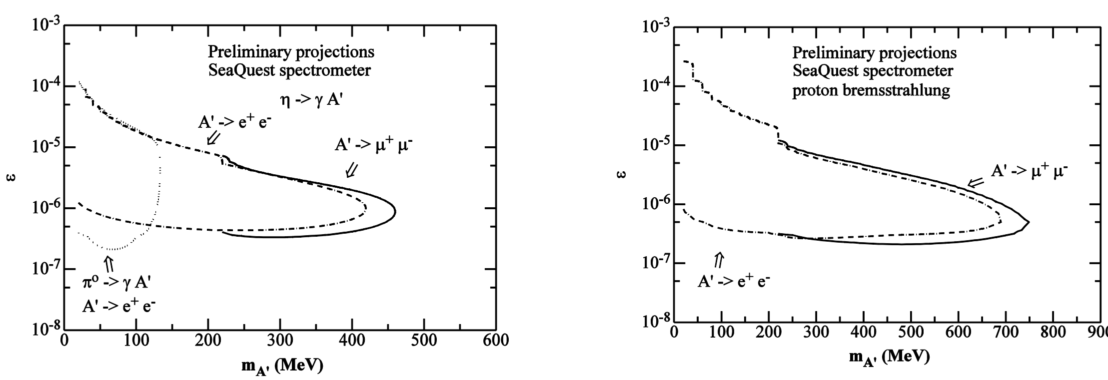

Figure 11. Left: Preliminary ***projections for an η meson decaying to a photon (γ) and a dark photon, denoted by A' [25]. The A' can subsequently decay into a $\mu^+\mu^-$ pair, solid curve, or an e^+e^- pair, dash-dot curve. The dotted curve represents the projected exclusion limit for π^0 decay. Right: Preliminary projections for proton bremsstrahlung to a dark photon, denoted by A'. The A' can subsequently decay into a $\mu^+\mu^-$ pair: solid curve, or an e^+e^- pair: dash-dot curve.***

Dark Higgs search:

For the dark Higgs search, we find that the SeaQuest dimuon spectrometer has excellent acceptance for a long-lived dark Higgs with a displaced decay vertex 2.0m downstream of its creation point and in this case we can extend the coverage down to $\theta<10^{-4}$ for dark Higgs mass m_ϕ up to about 1 GeV/c^2. Figure 4 shows our sensitivity in the dimuon channel to dark Higgs production under 3 different integrated luminosities scenarios.

Identifying a "prompt signal" at high-mass is more difficult, mainly because the production cross section of ϕ is intrinsically suppressed by the electroweak scale, making it much smaller than the Standard Model $\mu^+\mu^-$ background production via electromagnetic interactions. For m_ϕ>>2 m_μ, the dimuon channel is further suppressed by the branching ratio, because the Higgs portal implies that the decays into heavier final states (mesons) dominate the ϕ total decay rate. This is very different from the dark photon case.

Future possibilities for exotic physics with upgraded detectors:

Existing searches have focused on renormalizable connectors to a hidden sector, since a large new physics mass scale does not suppress these. Because the possibilities we discuss here are extremely sensitive to small mixing angles, it should also be possible to probe the existence of higher dimension portals as well. This opens a window to entirely new sorts of hidden sector dynamics, such as those mediated by non-Abelian (QCD-like) hidden sectors [25]. The latter would require the upgraded detectors that could detect charged pion final states.

As an example of a non-Abelian dark sector process, consider again η meson decay. In particular, we consider the case where the η meson could decay into a photon and a low-mass dark ρ' as indicated in Figure 12. Further, we assume that the dark ρ' subsequently decays into a charged pion pair. It is conceivable that the production probability could surpass that of the Abelian sector and estimates were made for 10x ε^2 and 100x ε^2 as shown in Figure 13. For the sake of a conservative estimate, it is assumed that decay rate to the pion pair is governed by ε^2.

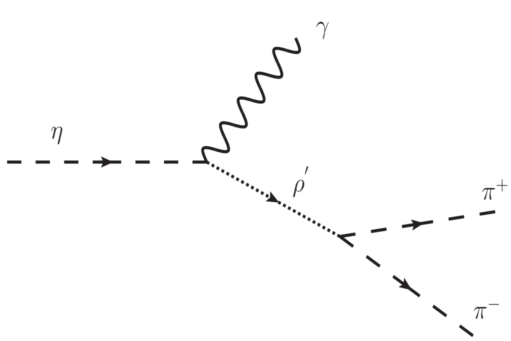

Figure 12. ***Feynman diagram of an η meson decaying to a photon (γ) and a dark ρ' , denoted by ρ', with a probability governed by the square of the coupling constant between light sector and the non-abelian dark sector [25]. The ρ' can subsequently decay into a $\pi^+\pi^-$ pair.***

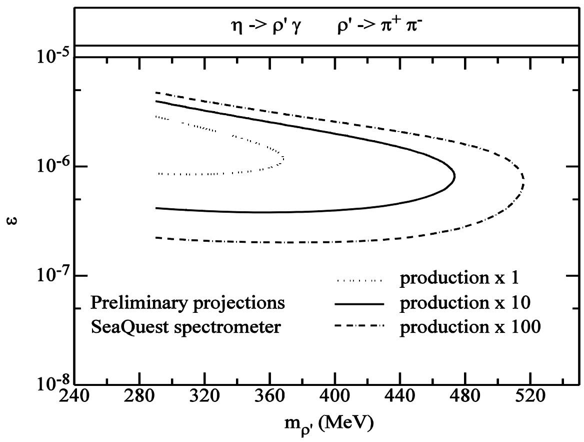

Figure 13. ***Preliminary projections for an η meson decaying to a photon (γ) and a dark ρ', denoted by ρ', with a probability governed by the square of the coupling constant between light and dark sectors of ε^2, dotted curve; $10x\varepsilon^2$, solid curve and $100x\varepsilon^2$, dash-dot curve [25]. The ρ' can subsequently decay into a $\pi^+\pi^-$ pair with a decay lifetime proportional to ε^{-2}.***

Preliminary Schedules

The parasitic run of this project fits the Fermilab beam schedule very nicely. The on-going E906 dimuon experiment will complete data taking in the summer 2016, followed by a new polarized fixed target Drell-Yan experiment E1039 which is approved for 2 years of beam time. The new polarized target installation and the target hall reconfiguration will take place between July 2016 and approximately March 2017, see Figure 14.

Year	FY2016	FY2017	FY2018	FY2019
Experiment	**Displaced trigger development & possible DAQ improvement**	**New trigger installation; Start parasitic data taking with E1039**	**Continue data taking and analysis; First results**	**Continue data taking. 1.5x10^{18} POT**
Theory	**Signal Cross sections at LO/NLO QCD background study**	**New model calculations**	**Data interpretation, first results Fully developed “dark sector” physics at Fermilab**	**Discovery or new limits**

Figure 14. Tentative timeline for the initial search program at Fermilab Intensity Frontier.

Integrated theoretical work is very important for the success of this search. We would like to fully explore the new physics search potentials at Fermilab and develop a new “dark sector” physics program at the Fermilab Intensity Frontier. First, we will carry out detailed calculations of the dark photon (dark Higgs) production cross-section in the parameter space that is relevant to this search at both LO and NLO and guide the optimization of the experimental approach. By combining the best calculations of the signal dark photon (dark

Higgs) production and the SM Drell-Yan like background yields, we will be able to clearly identify the discovery dark photon (dark Higgs) signals or set a new limit in the parameter space, see Appendix 2 for details.

4. Collaboration and required resources

The initial collaboration includes many people that have been heavily involved in both E906 and the future E1039 polarized target Drell-Yan experiment. A new group of people, including leading theorists that have been actively working on search for physics beyond the Standard Model, have expressed great interest to join our effort to further explore the discovery physics potential at Fermilab.

This experiment does require continuous support from Fermilab to provide high quality and high intensity proton beam to SeaQuest. Further improvement of delivered beam quality is desired but not necessary for the initial search in the parasitic running mode with E1039.

Preliminary discussions with the E906/E1039 collaborations show that they are extremely supportive of this effort and have agreed to let us run in parasitic mode during regular data taking. While we do not foresee any problems with running in parasitic mode alongside E1039, the spokespersons of SeaQuest collaborations have in principle agreed to provide dedicated beam time of up to a month to the dark photon search, contingent on FNAL management approval. Currently, E906 is helping us to study low-mass dimuon yields through a few short dedicated data takings with special triggers as part of its muon background evaluation effort.

Besides the trigger, we are also considering other possible upgrades that could benefit E906 and E1039 if upgrades can come online in time:

1) Minimize DAQ deadtime. Initial discussions lead us to believe that more than a factor of 10 improvement in DAQ throughput is possible with sufficient resources (both financial and effort). These resources will be identified within the collaboration.
2) Add charged pion and electron capabilities. We plan to use recycled EMCal and HCal detectors from other completed experiments at RHIC and JLab to help our coverage of particle identifications. We are exploring various options now to reach possible solutions by next summer.

Summary:

Today there is a unique opportunity at Fermilab to search directly for dark photon and dark Higgs production in highly motivated parameter space in high-energy proton-nucleus collisions using existing SeaQuest dimuom spectrometer. We will be able to see or exclude the existence of dark photons and dark Higgs over a wide region of phase space. If a dark photon and/or dark Higgs are observed, they will bring a revolution to our understanding of fundamental structures and interactions of our universe.

We request that Fermilab PAC:

1. Approve the inclusion of new elements necessary to make a dark sector trigger. The necessary equipment will be constructed and supplied by the collaboration.
2. Approve the parasitic collection of this data during E1039. In the unlikely situation that parasitic data collection during E1039 is not possible, approve a short, up to one month dedicated data collection period.

After the sensitivity has been demonstrated through parasitic running, we will consider non-parasitic running either at the conclusion of the Drell-Yan program or as opportunities present themselves depending on funding and schedule. *The request for non-parasitic beam time will be presented to the PAC at a later time.*

The approval of these points is necessary for the collaboration to continue on the path toward for the new trigger detectors and to obtain funding and effort for the DAQ improvements.

Appendix 1. Dark photon and dark Higgs rate estimates and expected statistics

In this appendix we provide some details on how we perform dark photon and dark Higgs rate estimates and expected statistics. Our calculations in the dimuon channel are carried out through leading order (LO) perturbative QCD computations in p+Fe collisions. We take the E906 configuration with the following assumptions: total number of protons on the beam dump ~ 1.44 x 10^{18}, accumulated over the first ~2 years of data taking with the E1039 experiment in 2017 – 2019 in parasitic mode. This is assuming that we continue data taking with the same beam conditions currently seen by E906: 5x10^{12} protons per minute (4 seconds beam time for every 60 second spill) with an effective 200 days of running with the current E906 efficiency.

Let us start with the dark photon production at LO, which is generated through quark-anti-quark annihilation followed by a kinetic mixing with a virtual photon as shown in Figure A.1.

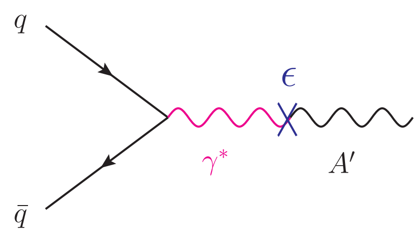

Figure A.1 Dark photon production in quark anti-quark annihilation channel

The dark photon differential cross section is given by

$$\frac{d\sigma}{dx_F}(p+p\to A'+X)=\sigma_0^{A'}\sum_q e_q^2 q(x_1)\bar{q}(x_2)\frac{x_1x_2}{x_1+x_2}$$

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

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

Once the dark photon is produced, such a *real* dark photon will likely pass through a significant amount of distance in our "beam dump" experiment, and will then decay. Here we only consider the scenario in which they decay into SM particles – the so-called visible decay modes, in which they could decay into possible lepton pair (e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$) as well as quark anti-quark pair (eventually into hadrons). For example, the dark photon decaying into dimons is illustrated in Figure. A.2.

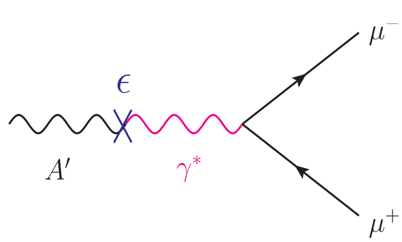

Figure A.2 Dark photon decay into dimons through a kinetic mixing with virtual photon

The decay width can be computed and the LO result is given by,

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

where e_f and m_f is 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 J. D. Bjorken et al [2]. With the results for both dark photon production and decay, we will be able to estimate the dimuon yields in our experiment configuration, which will be extremely useful in both planning the experiments and interpreting the results in the future. As an example, we provide the dark photon decay branching ratio here in Fig. A.3.

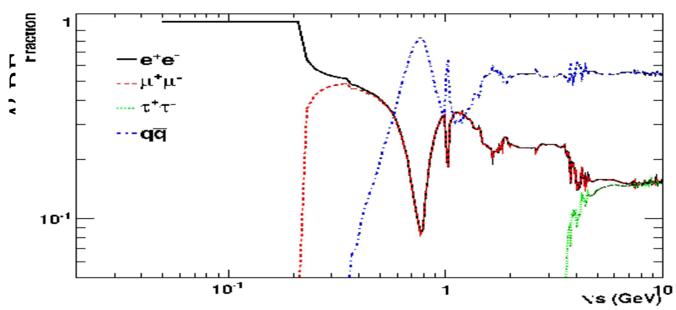

Figure A.3 Dark photon decay branching ratio in the visible decay mode

On the other hand, dark Higgs are generated at LO through gluon-gluon fusion channel. The LO cross section can be computed similarly and the result is given by,

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

where g(x) is the gluon distribution function. At the same time, dark Higgs decay in the visible mode has been extensively studied by D. Curtin et al [26]. We reproduce the branching ratio here in Fig. A.4.

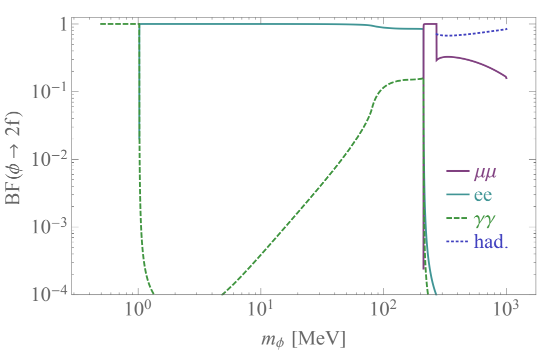

Figure A.4 Dark Higgs decay branching ratio in the visible decay mode

Other E906 groups have carried out independent checks and confirmed the preliminary results presented here. Latest discussions on dark photon search at E906 can be found in reference [24].

Appendix 2: A joint Experimental and Theoretical Effort for Discoveries

Our experimental research will involve tightly integrated theoretical components. The theory collaboration will provide critical guidance for our experimental search by computing the dimuon signal yield and the expected SM backgrounds. Once the data become available, they will help to interpret the experimental data and understand the implication for dark photon (dark Higgs) search, e.g., by mapping out the parameter space explored/constrained by our experiment.

Dark photons A' in proton-nucleus collisions are generated by quark-antiquark annihilation at leading order (LO), see Figure 1 (LH); and they could then decay into lepton pairs (e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$) as well as hadrons (first to quark-antiquark which then fragment into hadrons), see Figure 1 (RH). On the other hand, dark Higgs ϕ production can be generated through a mixing with SM Higgs via gluon-gluon fusion Higgs production, see Figure 2 (LH); and then it will decay through a mixing with the SM Higgs including dimuon as decay products, see Figure 2 (RH). We will study the production cross-sections for both dark photon and dark Higgs in proton-nucleus collisions at LO as well as NLO perturbative QCD approach. We will take into account the isospin effect as well as the modification of parton distribution functions inside the nucleus [22]. We will compute in great details these cross sections as functions of the relevant kinematic variables in our experiment as well as the model parameters: (ε, $m_{A'}$) for dark photon and (θ, m_ϕ) for dark Higgs.

We will further study the decay of dark photon and dark Higgs. Dark photons coupled to fermions through gauge couplings, and thus the decay width is more controlled by the phase space. On the other hand, dark Higgs couples to fermions through Yukawa couplings. The dominant decay channel is to the heaviest particles if kinematics is allowed. As a result, for the mass range of interest to our experiment, the branching ratio for the dark Higgs to e^+e^- final state is always negligible. On the other hand, for m_ϕ above GeV scale, it mainly decays into mesons rather than $\mu^+\mu^-$. Therefore, it is worth exploring the possible meson final states that could also yield a signal using effective field theories or lattice QCD. This could further extend the SeaQuest sensitivity to higher ϕ mass range with future upgrade of the detector to identify charged pions (or hadrons). We will carry out detailed studies for the decay width of both dark photon and dark Higgs.

With the production cross-section and the decay width at hand, we will be able to:

(1) Calculate the signal dimuon invariant mass distribution from both dark photon and/or dark Higgs channel, which will help our experimental search through the "mass peak" approach;

(2) Fold into the calculation of the expected dimuon signal as a function of distance from the collision point, which could help our experimental search through the "displacement vertex" approach;

Besides we may also be able to study:

(3) The decays of dark photon and dark Higgs (and in association with dark Z) can form complicated cascade decays and reach a final state characterized with multi-

lepton, highly collimated “lepton jets”. We would like to explore the existence and the evolution of the “lepton jet” in help of modern EW/QCD technique.

(4) The invisible decays of the dark photon or the dark Higgs opens a unique window to the non-WIMP light dark matter candidates (m_{DM}< 10 GeV). We would like to explore the possibility for detecting invisible decays at SeaQuest and place potential bounds on light dark matter mass and couplings to ordinary matter.

At the same time, the standard Drell-Yan dimuon production will be a major potential background for our dark photon A’ and/or dark Higgs ϕ search, particularly at high-mass and large coupling regime where the dark photon (dark Higgs) decay vertex is close to its creation point. It is critical to understand and remove the background in our experiment. To achieve this, we will implement our knowledge of Drell-Yan production, and calculate to the highest accuracy both the Drell-Yan cross-section and the dimuon background distribution for both promptly decay and displaced vertex searches. This component of the project will be essential to calculate our sensitivity to the parameters, and understand the implications for the dark photon (dark Higgs) search.

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