A Proposal to Search for Dark Sectors with the EMCal Upgrade of the SeaQuest Experiment at Fermilab*

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Abstract

In 2017, the parasitic dark sector physics search experiment SeaQuest/E1067 successfully installed and commissioned a new displaced dark photon di-muon trigger along with 10-fold improvement in SeaQuest DAQ bandwidth during the last run of the SeaQuest/E906 experiment. This upgrade allows the SeaQuest experiment to search for dark photons (and, more in general, for new displaced dark particles decaying into muons) in the mass range from 200 MeV to about 10 GeV, in a parasitic operation mode with the E906 and the upcoming E1039 experiments. Given the recent stage-II approval of the E1039 polarized fixed target experiment and the success of the dark photon trigger upgrade, we propose to further expand the dark sector physics program to particles with a mass below 200 MeV (di-muon mass limit) down to about 1 MeV, a two orders of magnitude improvement. This will be achieved via adding a new electromagnetic calorimeter (EMCal), recycled from the PHENIX experiment at BNL, before the station-4 muon identification absorber for electron identification. With this EMCal upgrade, SeaQuest will have an unprecedented discovery reach for a large set of New Physics models predicting resonant and non-resonant electron signatures. Leveraging the existing SeaQuest experiment, we will be able to carry out a very broad dark sector physics program, first parasitically with the E1039 polarized fixed target experiment at Fermilab in 2019-2021, and second with a dedicated experiment after the EMCal upgrade. These two phases of the experiment will produce world best and most timely searches for uncharted models with new dark particles in the mass range from about 1 MeV to 10 GeV.

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1 Introduction

The LHC discovery of the Higgs Boson in 2012 has been a milestone for our understanding of fundamental physics. For the first time we have a self-consistent description of Nature, the Standard Model (SM) of particle physics.

At the same time, cosmological and astrophysical observations indicate that the SM particles accounts for less than 5% of the total mass and energy of the Universe, while the remaining unknown 95% arises from the so called dark energy and dark matter (DM). The existence of dark matter has been only inferred from its gravitational effects on visible matter, radiation and the large-scale structure of the Universe, but dark matter has never been directly detected, which makes its nature one of the most mysterious unanswered question in both astrophysics and high energy physics.

The last few years have seen tremendous progress in experimental searches for weakly interacting (WIMP) DM with masses of O(100 GeV). The precision has reached levels where DM candidates are, in certain cases, already excluded from interacting appreciably with the Higgs, putting pressure on the WIMP paradigm. Thus, there is an increased urgency to explore theories in which DM belongs to an extended dark (or hidden) sector. In this case, DM is neutral under the SM gauge symmetries, but thermalizes thanks to its interactions with additional hidden sector particles (the so called "mediators"). Dark sector theories are particularly motivated for DM masses below ∼10 GeV, for which new degrees of freedom (i.e. new dark particles) are needed such to provide an efficient DM annihilation to obtain the observed DM relic abundance.

Recently, there has been a huge and vibrant community effort in exploring dark sector models from a model-building, phenomenological, as well as experimental perspective [1, 2]. This has spurred a worldwide low-mass dark matter search at the LHC, RHIC, Fermilab, JLab, Babar/SLAC, Belle/KEK and other facilities. Additionally, several new experiments have been proposed with the scope of probing specific dark sector "thermal targets" (see Section 1.1).

Many dark sector models naturally predict the presence of long-lived dark mediators. The most suitable experiments to test long-lived dark sectors at around the GeV scale are fixed target beam-dump experiments. CERN is particularly involved in this effort leveraging its Super Proton Synchrotron (SPS) high-energy proton beam: there is a plan to run the NA62 experiment in beam-dump mode in ∼2023 after the completion of its kaon physics program [3]. Additionally, there has been a proposal for the SHiP experiment to start running in ∼2027 and accumulate 2×10^{20} protons on target (POT) [4, 5]. The physics program of these experiments is broad, ranging from testing long-lived dark photons, dark scalars, and axion like particles (ALPs) that decay to electrons, muons, and photons. However, dark particles with relatively short life times (O(10 cm–1 m)) will be elusive in these experiments, due to the long distance between the dump and the detector.

The parasitic SeaQuest/E1067 experiment at Fermilab will be able to spearhead a dark sector program in a relatively short time scale (several crucial results are expected before the NA62 experiment in 2023, see the timeline in Fig. 10) and filling the gap for shorter lived dark particles.

In this proposal, we present a unique opportunity at Fermilab to search for GeV-scale mediator particles in high-energy proton-nucleus collisions using existing detectors from SeaQuest (E906/E1039) [6] with modest upgrades. The existing SeaQuest spectrometer allows direct detection of dark particles only through the $\mu^+\mu^-$ final state [7]. We propose to extend its capability to e^+e^-, $\pi^+\pi^-$, and $\gamma\gamma$ final states by installing an electromagnetic calorimeter (EMCal). This proposal will not only greatly extend the sensitivity region to much lower masses by two orders of magnitude, but also allows to search for novel dark sector models, which have never been experimentally explored in the region of interest before. If a positive signal is observed, the impact on both particle physics and cosmology would be enormous and would open up an entire new field of research; otherwise a further exclusion of the uncharted dark matter phase space would provide vital input in shaping the future dark matter search effort and give input to future CERN fixed target experiments, such as the SHiP experiment.

The SeaQuest dark sector physics search program in the "visible mode" (where a dark sector particle decays into SM visible particles) will complement the one being pursued by the Fermilab short baseline neutrino facilities looking for the "invisible mode" (a dark sector particle decays into other dark particles and escapes direct experimental detection, but can be identified when the daughter dark particles interact with a detector) [8]. One can also explore the "visible mode" to search for long-lived dark particles at the neutrino program, but the accessible phase space will be very different from what SeaQuest will cover due to different kinematics acceptance and different baselines.

1.1 Physics Goals

The Standard Model gauge symmetries allow several types of "portal" interaction between a generic hidden sector and the SM particles at the renormalizable level: the dark photon portal ($\frac{\epsilon}{2\cos\theta_w}A'_{\mu\nu}B^{\mu\nu}$, where θ_w is the Cabibbo angle), the Higgs portal ($\kappa|H|^2|S|^2$), and the neutrino portal ($yHLN$), where A', S, and N are dark sector mediators, the dark photon, the dark Higgs, and the dark fermion, respectively. These portal couplings can play a key role in realizing the dark matter abundance, as eg. via the thermal freeze-out mechanism. SeaQuest will cover an essential role in probing the dark sector mediators.

Similarly to WIMP models, freeze-out models imply well defined targets in coupling space. Particularly, models where DM is the lightest state of the dark sector require a specific relation between the DM mass and the product of the dark sector and the portal couplings. Secluded models [9], where DM is heavier than some other particle of the dark sector, also require a large enough portal coupling such to obtain thermalization between the SM and the dark sector in the early universe (see eg. [10]). As we will discuss in Section 3, these target couplings will be broadly explored by the SeaQuest experiment with the EMCal upgrade.

Beyond minimal models in which DM annihilates thanks to some of the portal coupling, the dark sector can be populated by several additional dark particles that participate to the mechanism of DM freeze-out. Very well motivated examples are models of Inelastic DM (iDM) [11] and models of Strongly Interacting Massive Particles (SIMPs) [12]. Unveiling the existence of these non-minimal dark sectors will be a prime target of the SeaQuest experiment in the coming years.

1.2 Proposed Upgrade

In 2017, a dedicated displaced di-muon dark photon trigger was successfully installed and commissioned at SeaQuest. This system will take data parasitic with the SeaQuest polarized target run (E1039). In this proposal, we advocate to expand the physics search capability by including di-electron channel to access the lower mass region below 200 MeV (di-muon mass limit), and to test many additional dark sector models predicting electron (pion and photon) signatures. This can be achieved by adding one EMCal detector behind the Station-3 (St-3) chambers. An existing EMCal detector has been identified from the previous PHENIX experiment at BNL and can be used for this purpose. The EMCal upgrade will be the first stage of a long-term dedicated dark sector physics program at Fermilab.

As shown in Fig. 1, the SeaQuest spectrometer [13] consists of a high precision tracking system (St-1/2/3 tracking), a muon identification system (absorber and St-4 muon ID), and a high-speed vertex trigger detector (forward/backward dark photon detector), and is capable of precisely measuring both the momentum and vertex of a charged particle. The 5m thick iron beam dump/magnet (FMag) bends and stops most of the SM particles (other than neutrinos and high energy muons) produced by proton-iron interactions. However, a dark particle, which interacts only weakly with normal matter, can travel a significant distance from the creation point before decaying into a pair of leptons or hadrons. This feature, combined with an unprecedented high luminosity (250k fb^{-1} per year), gives us great power to make the world's most sensitive dark matter search with the SM background suppressed to negligible level.

As detailed in Section 4, we propose to install the EMCal between the St-3 tracking and absorber (see the brown dashed open box in Fig. 1) during the 2021 summer shutdown, after the completion of E1039. This will allow two full years of beam time with the EMCal between the end of E1039 and the start of the long shutdown for PIP-II. Based on the beam parameters planned for E1039, this guarantees an integrated luminosity of 1.44×10^{18} protons on target.

Typically, such an EMCal detector would cost more than $1M to build. However, a great opportunity has emerged as the PHENIX experiment [14] at Brookhaven National Laboratory (BNL) started decommissioning in 2016 and their EMCal fits perfectly for our purposes. We successfully secured two sectors of the PHENIX EMCal, which will allow to extend the dark sector SeaQuest program with a much smaller cost.

We envision further upgrades to the SeaQuest spectrometer during the PIP-II long shutdown, which will increase SeaQuest's sensitivity to dark sector physics and add sensitivity to additional models. Upgrades to the tracking detectors will allow SeaQuest to operate at the full beam intensities enabled by PIP-II, with a corresponding increase in sensitivity. In Sec. 3 of our proposal we will also discuss the physics reach for several dark sector models after having accumulated a larger luminosity (the so called high-luminosity stage). As a benchmark scenario to show the potential of a long-run SeaQuest program, we choose a luminosity of 10^{20} POT (this is a luminosity similar to the one proposed for the SHiP experiment at CERN).

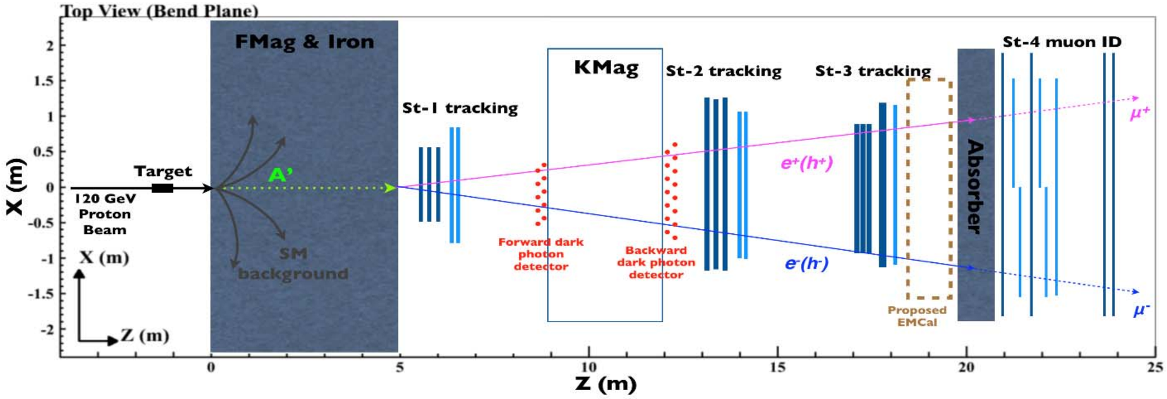


Figure 1: A schematic view of dark photon, A', decays into a pair of leptons/hadrons at the SeaQuest spectrometer. The displaced vertex trigger hodoscopes (installed in 2017) are on either side of KMag, and the proposed EMCal is between Station-3 and the absorber wall.

2 Experimental Plan and Recent Accomplishments

Adding an EMCal to the SeaQuest spectrometer serves two essential purposes. First, the EMCal provides a generic trigger for non-MIP particles. A simple energy threshold will reject the muons that penetrate the FMag beam dump, and trigger only on pions, electrons, and photons produced after the beam dump. Second, matching cluster energies in the EMCal to track momenta allows particle identification, which is necessary for rejecting backgrounds. Misidentification of $K_L^0 \to \pi^\pm e^\mp \nu_e$ as $A' \to e^+e^-$ is expected to be the dominant physics background, with $O(1000)$ such decays in the $(5-6)$ m) fiducial region, after having accumulated 1.44×10^{18} POT (see Sec. 3.1). An EMCal pion rejection factor of 1% or better reduces this background to $O(10)$ events, which can be further attacked using mass resolution and pointing cuts [15].

The EMCal upgrade builds on the recent effort to add $A' \to \mu^+\mu^-$ sensitivity to SeaQuest with a displaced di-muon trigger. The LANL team has led the project of upgrading the SeaQuest spectrometer, trigger and data acquisition (DAQ) systems to search for dark photons via their di-muon decay mode [16]. A GEANT4-based simulation package has been developed to study the trigger rate and background level in the di-muon channel. The data collected during a commissioning run in 2017 agrees very well with the rate simulation. We also developed the reconstruction tool for the dark photon search in the di-muon channel, which can be directly applied to the proposed work.

2.1 Preliminary Studies and Displaced Di-muon Trigger Performance

The displaced di-muon trigger was built, installed, and commissioned in 2017. This trigger uses two hodoscope planes of extruded scintillators, as shown in Fig. 2. These hodoscopes have good position resolution (1 cm and 2 cm segmentation) in contrast to the original SeaQuest hodoscopes. The

Figure 2: Left: One of eight hodoscope quadrants built for the 2017 displaced di-muon trigger upgrade. Right: The downstream hodoscope after installation.

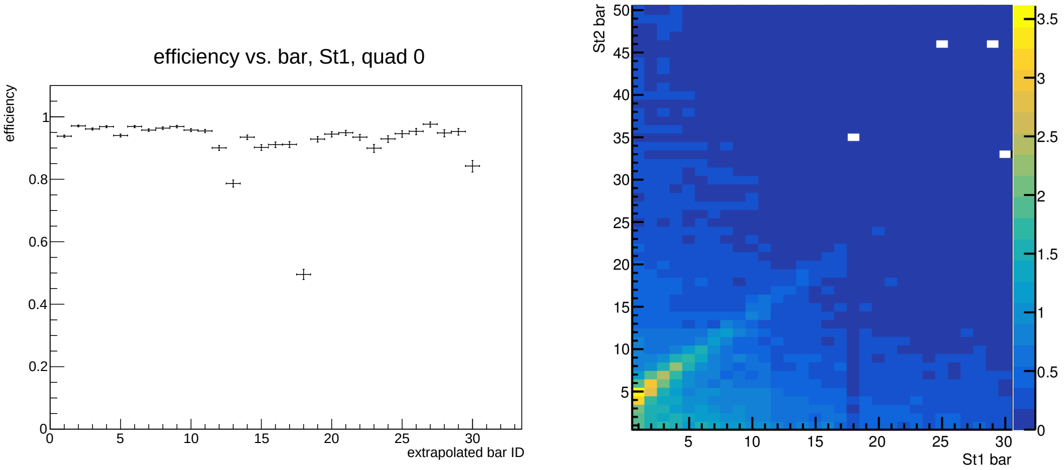


Figure 3: Left: Efficiency per bar for one quadrant. The bars with low efficiency will be repaired in summer 2018. Right: Hit correlations between the upstream and downstream hodoscopes show a diagonal band from muons created in the SeaQuest target or the upstream portion of the beam dump. Muons from further downstream would appear above this band.

hodoscopes are read out using wavelength-shifting fibers and silicon photomultipliers, and monitored using LEDs that are coupled to the bars using fiber splitters. The experience gained from this system will be essential for commissioning the new EMCal. The trigger logic uses FPGAs to recognize hit coincidences that correspond to muons originating from downstream of the beam dump. This trigger relies on the triple coincidence of the two new hodoscopes and the Station-4 hodoscope (downstream of the absorber wall), so it is only sensitive to di-muons.

The short commissioning run in 2017 proves that this trigger works. The hodoscope efficiency is excellent, about 95% on average, as shown in Fig. 3-left. Fig. 3-right shows that the combination of the two hodoscopes has sufficient resolution to distinguish particles originating from different points along the beam axis. This system is ready for extended data taking in fall 2018, and will operate parasitically with the E1039 polarized target run.

The new EMCal upgrade will make use of the hardware developed for the displaced di-muon trigger. The displaced vertex hodoscopes will be used in the event reconstruction to reject misreconstructed tracks; if the trigger rate for an EMCal-only trigger is too high, the FPGA logic for the displaced di-muon trigger can be extended to match EMCal clusters with hodoscope hits (i.e., di-electron trigger).

On the theory front, the dark photon search at SeaQuest has drawn significant interest from active theorists in this field (including several of the authors of this proposal) because of its unique sensitivity and approved beam time in 2019-2021. In addition to the channels explored in this proposal, there have been other potential dark matter signatures that are being actively pursued by our collaborating theorists [17, 18, 19].

2.2 Methods, Technical Challenges & Alternatives

The PHENIX EMCal [20] is a shashlik-type sampling calorimeter made of alternating tiles of lead and scintillator. The basic building block shown in Fig. 4-left is a module consisting of four towers which could be read out either individually or combined. The scintillation light from each tower is collected by wavelength-shifting fibers and detected by a phototube. A “leaky fiber” runs through the center of each module and is used to inject laser light for calibration. Thirty-six modules form a supermodule, and eighteen supermodules make a sector, a flat 2×4 m^2 plane with a rigid steel frame. One sector will cover 90% of the acceptance of the SeaQuest spectrometer, with no gaps.

The energy resolution for electrons has been measured to be $8.1\%/\sqrt{E(\mathrm{GeV})} + 2.1\%$. A typical electron from a potential dark photon decay has a momentum range of 2–20 GeV, which corresponds to 4–8% energy resolution. Fig. 4-right shows the different energy deposition spectra when the EMCal is exposed to electrons, pions, and protons. The MIP peak at 0.25 GeV is well separated from the electron peak, which demonstrates clean triggering on electrons. The separation of the peaks from 2 GeV pions and electrons is large enough to allow pions to be identified with a veto from the St-4 muon ID system.

The R&D for the EMCal readout must address several challenges. First, since this detector was built more than 20 years ago, aging of the phototubes and electronics is a concern. Second, the existing electronics for the PHENIX EMCal was operated at 10 MHz (RHIC clock), whereas at SeaQuest the bunch interval is 53 MHz (Fermilab clock). Last, the EMCal must interface with the SeaQuest trigger and DAQ. We are examining two options: reuse of the existing PHENIX readout (Section 2.2.1), or a new readout system (Section 2.2.2).

We will also redesign the calibration and monitoring system. The original system, consisting of a UV laser and a series of splitters, is not available. We plan to replace it with an LED-based system based on a design for the sPHENIX EMCal.

Besides the hardware R&D effort, we will also develop the simulation, reconstruction and particle identification software for the EMCal in the SeaQuest environment to analyze the data and understand the systematic uncertainties.

2.2.1 Refurbished PHENIX Readout

The default plan is to keep the original PHENIX readout. We were able to choose the two sectors (W0 and W1 shown in Fig. 5) with the fewest bad channels, and since we only need one sector, we can also select the best-performing phototubes and frontend modules. As shown in Fig. 5, there were only

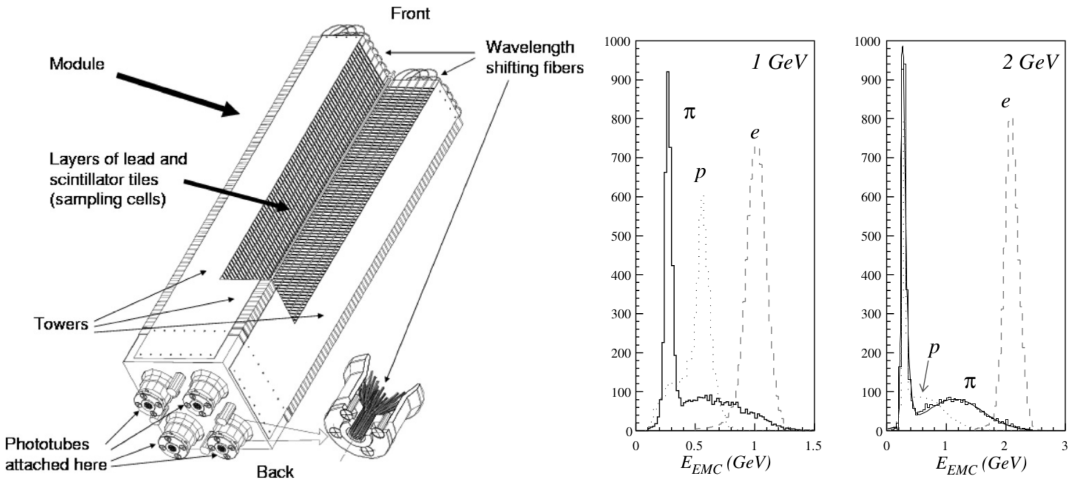


Figure 4: Left: Cutaway view of a PHENIX EMCal module showing a stack of scintillator and lead plates, with wavelength shifting fiber readout. Right: The measured energy spectra when the EMCal is exposed to electrons, pions and protons at 1 and 2 GeV.

a few bad channels at the end of PHENIX run in June 2016, after which these detectors have been safely stored at BNL. Previous PHENIX EMCal experts (A. Durum *et. al.*) have recently joined our effort to lead the operation and maintenance of these detectors. The PHENIX readout measures hit time to better than 1 ns resolution, and occupancy at SeaQuest is low enough that we do not expect pileup to be a problem.

2.2.2 New SiPM-Based Readout

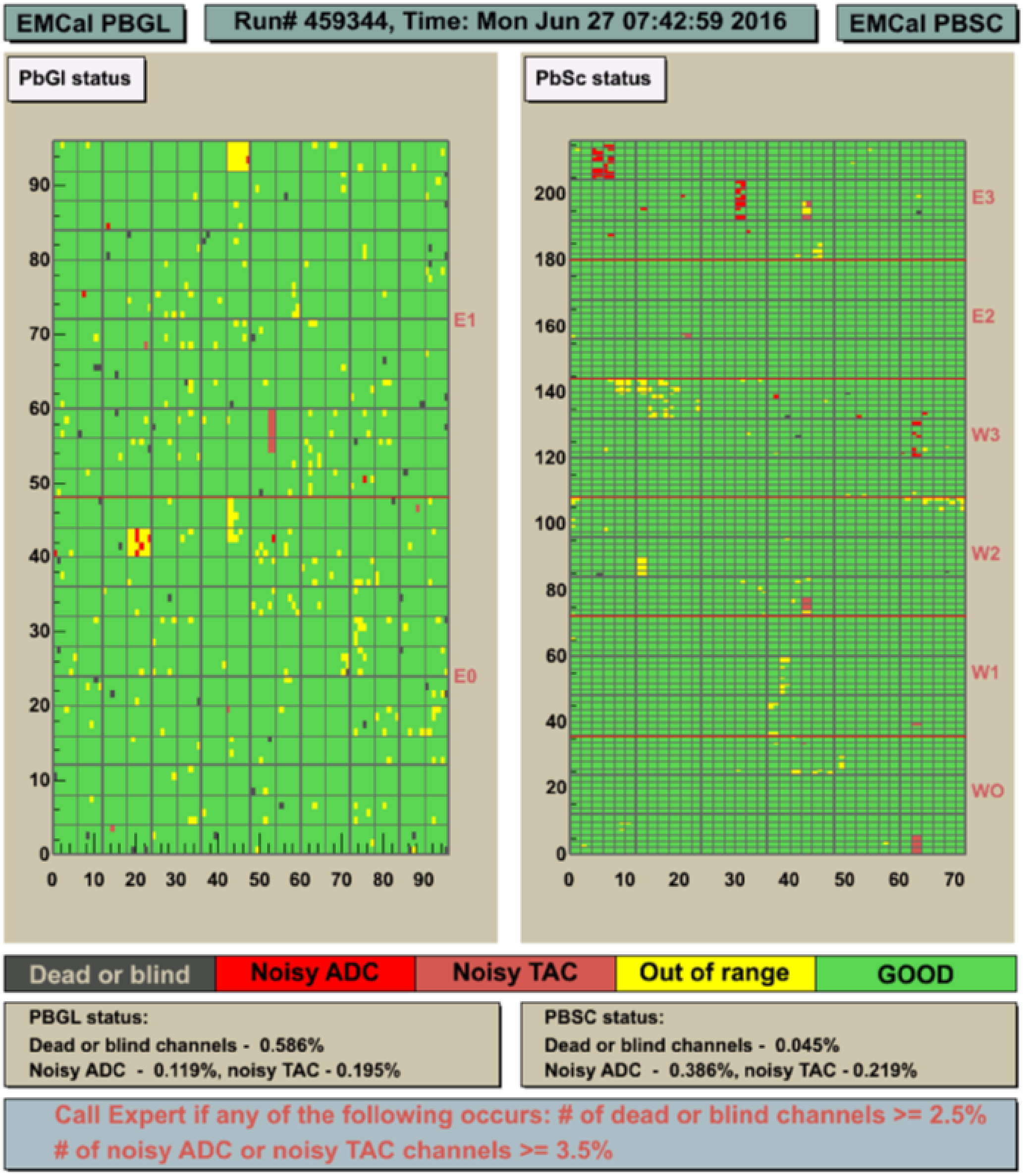
An alternative plan is also being explored through a collaboration with the STAR experiment at RHIC, which plans to use the same PHENIX EMCal modules for a forward calorimeter upgrade at STAR [21]. Their development is in an advanced stage: new SiPM-based frontend electronics (FEE) and new readout electronics (Detector Electronics Platform, DEP) have been prototyped and demonstrated in test beams at STAR. The proven performance of this system is a good match for our requirements. The DEP is designed to sample the analog waveform at 75 MHz (eight times the RHIC clock), and can be adapted to operate at the 53 MHz Fermilab clock. The DEP is designed to be flexible, and we will be able to reconfigure its FPGA to communicate with the SeaQuest DAQ. A new joint proposal is under discussion with STAR forward upgrade group to fund the readout electronics for SeaQuest EMCal upgrade.

3 Expected Reach and Future Opportunities

In this section, we present the reach for a broad set of dark sector models at the SeaQuest experiment, after the EMCal upgrade with the two benchmark luminosities 1.44×10^{18} POT and 10^{20} POT. Particularly, we will highlight the impact of the proposed calorimeter-upgraded experiment in testing dark sectors, compared to the present SeaQuest setup with the displaced di-muon trigger. First, we will focus on e^+e^- resonant (see Section 3.1.1) and non-resonant signatures (see Section 3.1.2). Second, we will emphasize the existence of many additional signatures that could be looked for at the upgraded SeaQuest experiment (see Section 3.2), such as, for example, $\gamma\gamma$ signatures.

3.1 Reach for Electron Signatures

A well-motivated new force carrier is the hypothetical dark photon, A', the gauge boson of a new broken $U(1)_D$ symmetry. The dark photon couples to the SM through kinetic mixing with the hypercharge



PBGL status:
Dead or blind channels - 0.586%
Noisy ADC - 0.119%, noisy TAC - 0.195%

PBSC status:
Dead or blind channels - 0.045%
Noisy ADC - 0.386%, noisy TAC - 0.219%

Call Expert if any of the following occurs: # of dead or blind channels >= 2.5%
# of noisy ADC or noisy TAC channels >= 3.5%

Figure 5: An online screenshot of PHENIX EMCal performance at the end of the run in June 2016. Two best performed PbSc EMCal detectors, W0 and W1, are secured for SeaQuest upgrade. Minimal work is expected to fix a few bad channels, most likely just replacing bad PMTs and/or frontend electronics boards.

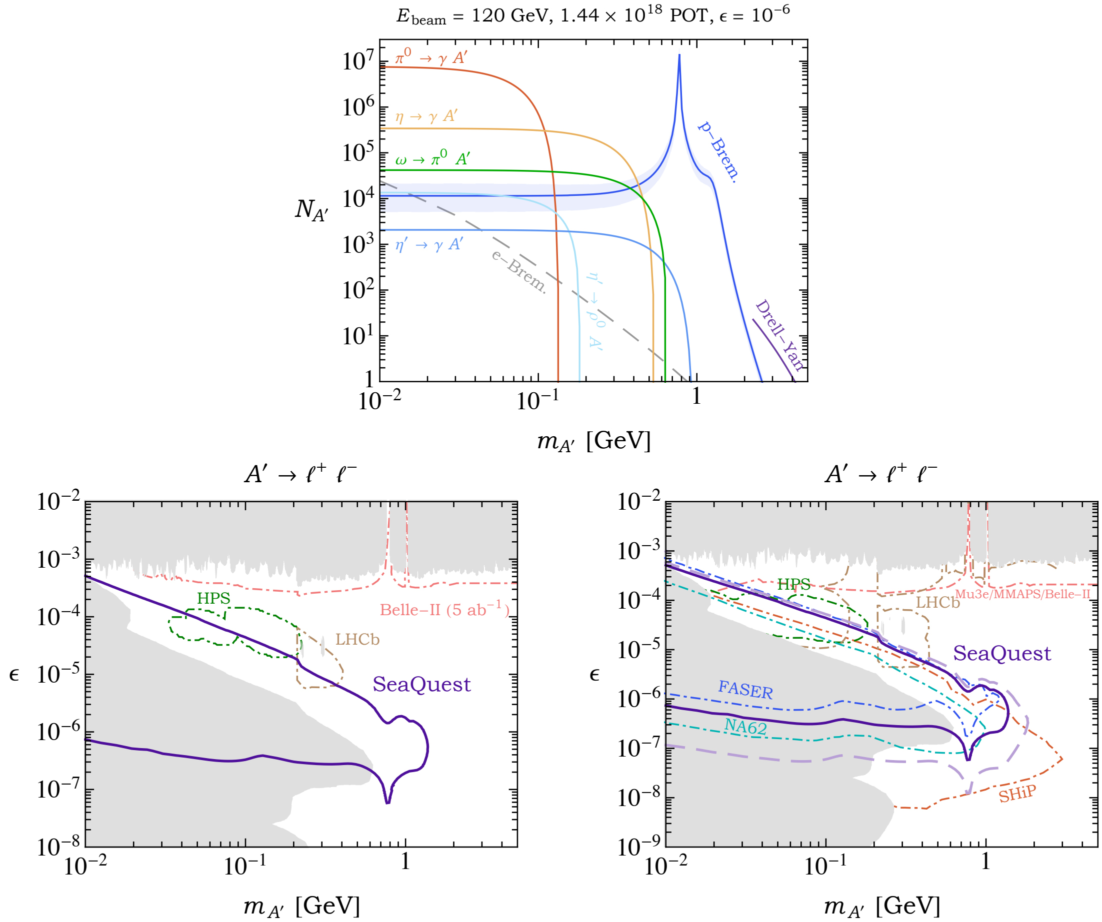


Figure 6: Top: Number of dark photons (solid color) produced at SeaQuest in various production channels for $\epsilon = 10^{-6}$. For comparison, we also show the analogous production rate for electron Bremsstrahlung (dashed gray), assuming a 120 GeV electron beam, the same luminosity, and production within the first radiation length of a tungsten target. Lower left: the projected sensitivity of SeaQuest to displaced electron decays of dark photons, for the fiducial decay region of $(5-6)$ m and for 1.44×10^{18} POT. Also shown are existing constraints (solid gray), as well as the projected reach of experiments running before 2023 (dot-dashed): Belle-II, LHCb (di-muon analysis), as well as HPS. From [15]. Lower right: the same but adding the Seaquest reach with 10^{20} POT (dashed purple curve) and the reach of planned and proposed future experiments beyond 2023.

gauge boson, controlled by the dimensionless parameter, ϵ (see Section 1.1). Dark photons are efficiently produced at SeaQuest from the collisions of the high-energy protons with nuclei in the iron dump, through Drell-Yan production, the Bremsstrahlung mechanism, and the decay of SM mesons (pions, eta, ...). In the upper panel of Fig. 6, we show the number of dark photon produced at SeaQuest, after collecting 1.44×10^{18} POT, having fixed $\epsilon = 10^{-6}$. Even for such a small value of the portal coupling, ϵ, one would expect more than 100,000 dark photons produced up to masses ~ 1.5 GeV! This rate is much larger than the corresponding rate at electron fixed target experiments (see the dashed gray line in the plot).

3.1.1 Minimal Dark Photon Model

In minimal secluded models, the dark photon can only decay back to SM particles thanks to the portal coupling, ϵ. Its branching ratio to electrons and muons is sizable and of $\mathcal{O}(10\%)$ for all masses above threshold ($m_{A'} > 2m_e \simeq 1$ MeV for electrons, and $m_{A'} > 2m_\mu \simeq 200$ MeV for muons). The dark photon proper lifetime is macroscopic ($\gtrsim$ cm) for $\epsilon \sim 10^{-6} \times (m_{A'}/\mathrm{GeV})^{-1/2}$. Therefore, a search for displaced electron and muon decays at SeaQuest will constitute an efficient probe of this model.

The lower left panel of Fig. 6 shows the projected reach of SeaQuest assuming an upgraded sensitivity to electron final states and an integrated luminosity of 1.44×10^{18} POT, having required a dark photon decaying in the conservative fiducial decay region $(5-6)$ m after the target[1]. In this fiducial region, we expect only a few background events, mainly coming from $K_L^0 \to \pi^\pm e^\mp \nu_e$. Plenty of open parameter space will be probed (regions in gray are the only regions already probed by past experiments). For $m_{A'} \lesssim 200$ MeV, an EMCal upgrade would enable SeaQuest to be competitive with the HPS experiment running in the summer of 2019 and the coming years (the pre-2023 reach has been taken from [1]), while at larger masses, SeaQuest will have an unprecedented opportunity to test displaced dark photons with a mass up to ~ 1.5 GeV. In the future, this reach will be further extended by the SeaQuest high-luminosity stage (see the dashed purple line in the right lower panel of Fig. 6 for the reach with 10^{20} POT). This reach will be complementary to the reach of the CERN-based proposed beam-dump experiment, SHiP (see the orange line in the figure), that, if approved, will start running in 2027 (for details, see [15]) and to the NA62 beam-dump mode experiment running in 2023 (see the cyan line in the figure).

Without an EMCal, SeaQuest could possibly have a similar reach only for 200 MeV $\lesssim \mathrm{m_{A'}}$, where the dark photon decays to $\mu^+\mu^-$ with a similar branching ratio (see also [18]). This is true only on condition of being able to reduce the SM background from large-angle scatters of di-muons in the beam dump to a negligible level, which is still being studied. Without the EMCal upgrade, SeaQuest will not be able to probe minimal dark photon models for $m_{A'} \lesssim 200$ MeV. As we can see from the lower left panel of Fig. 6, the EMCal-upgraded SeaQuest experiment will be the first in probing this region at the relatively sizable values of ϵ where the displacement of A' decays is small.

3.1.2 Inelastic and Strongly Interacting Dark Matter

iDM. In models of inelastic dark matter (iDM), a pseudo-Dirac pair of nearly degenerate Majorana particles (χ_1 and χ_2 with $m_1 \lesssim m_2$) couple off-diagonally to the dark photon with a strength controlled by the $U(1)_D$ fine-structure constant, α_D. The fractional mass-splitting is denoted as $\Delta = \frac{m_2 - m_1}{m_1} \ll 1$. The lighter state, χ_1 is cosmologically stable and can constitute the dark matter of the universe at late times. Furthermore, if the dark photon is heavier than $\chi_{1,2}$, a viable cosmology for sub-GeV thermal dark matter is possible, thanks to the co-annihilation $\chi_1\chi_2 \to A'^* \to f\bar{f}$, where f is a SM fermion.

In this set of models, the dark photon promptly decays to a $\chi_1\chi_2$ pair. χ_1 leaves the detector registering as missing momentum. χ_2, on the other hand, undergoes a 3-body decay through an off-shell A', $\chi_2 \to \chi_1 \ell^+\ell^-$ (see Feynman diagrams in the upper panel of Fig. 7). Generically, for not too large mass splittings, Δ, χ_2 travels macroscopic lengths before decaying. A search for displaced non-resonant leptons at SeaQuest would have unprecedented reach for such models.

In the upper left panel of Fig. 8, we show the projected sensitivity of SeaQuest to the cosmologically-motivated parameter space of inelastic dark matter in the $\alpha_D - m_1$ plane for fiducial decay regions of

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[1] Further improvements by a factor of ~ 2 in the ϵ reach could be achieved via searching for dark photons decaying in the $(5-9)$ m fiducial region, on condition of being able to suppress SM backgrounds (see [15]).

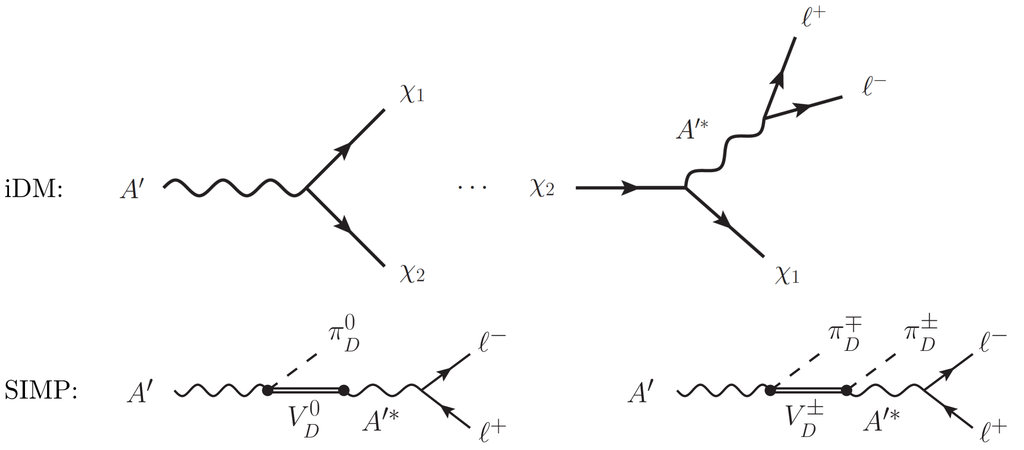

Figure 7: Feynman diagrams for the decay of a dark photon, A', in iDM models (upper panel) and in SIMP models (lower panels). χ_2 and χ_1 are the excited DM and DM states in iDM models. π_D and V_D are the dark pions and vectors in SIMP models.

$(5-6)$ m, $(5-9)$ m, and $(5-12)$ m (solid, dashed, and dotted line, respectively), using the electron signature ($\chi_2 \to \chi_1 e^+ e^-$), after accumulating 1.44×10^{18} POT luminosity. For each point in parameter space, we fix the kinetic mixing parameter, ϵ, to guarantee that the relic abundance of χ_1 agrees with the observed dark matter energy density. Existing constraints are shown in gray. The upper right panel shows the corresponding reach in the $(5-6)$ m fiducial region with 1.44×10^{18} POT (solid) compared to the reach with 10^{20} POT for the $(5-6)$ m, $(5-9)$ m, and $(5-12)$ m fiducial regions (from darker to lighter purple). SeaQuest could *definitely* test cosmologically-motivated regions of model-space for DM masses, $m_1 \lesssim 4$ GeV even in the almost-background-free $(5-6)$ m fiducial region! (see [22] for the complementarity with other fixed target and neutrino experiments). Because of kinematic thresholds, an analogous muon final-state search by SeaQuest would have similar sensitivity only in the very restricted mass range of 2 GeV $\lesssim m_1 \lesssim 4$ GeV, under the very optimistic assumption of zero background. This shows the necessity of the EMCal upgrade for broadly testing iDM models.

SIMP. Similar signals arise from models in which dark matter is the lightest stable pseudo-Goldstone, π_D, of a strongly interacting hidden sector, analogous to the pions of SM QCD. A dark photon portal between such a hidden sector and the SM is directly motivated to guarantee a viable cosmology of light dark matter. In addition to dark matter pion-like states, these models also give rise to hidden sector analogues of spin-1 vector mesons, V_D, similar to the ρ, ϕ, and ω of the SM. In these models, the dark photon generically decays to a stable (either neutral or charged) pion, π_D, and an unstable (either neutral or charged) vector, V_D, which subsequently decays to SM leptons with some displacement (see Feynman diagrams in the lower panel of Fig. 7).

The lower left panel of Fig. 8 shows the projected sensitivity of SeaQuest to models of strongly interacting dark matter in the $\epsilon - m_{A'}$ plane for fiducial decay regions of $(5-6)$ m, using the electron signature, after collecting 1.44×10^{18} POT. Along the black contours, the hidden sector pion abundance agrees with the observed dark matter energy density for different choices of the vector meson to pion mass ratio, $m_V/m_\pi = 1.6, 1.8$ (our "thermal targets") In gray, we show the regions of parameter space already probed by past experiments. On the left of the vertical dotted lines, the model is in conflict with bounds on DM self-interaction. The lower right panel shows the comparison of the reach with 1.44×10^{18} POT (solid line) and 10^{20} POT (dashed line). As shown in the figure, the EMCal-upgraded SeaQuest experiment will be able to *definitely* test the SIMP scenario for masses up to $m_{A'} \lesssim 5$ GeV. Because of kinematic thresholds, the corresponding di-muon search would probe only masses $m_{A'} \gtrsim 500$ MeV, under the optimistic assumption of zero background.

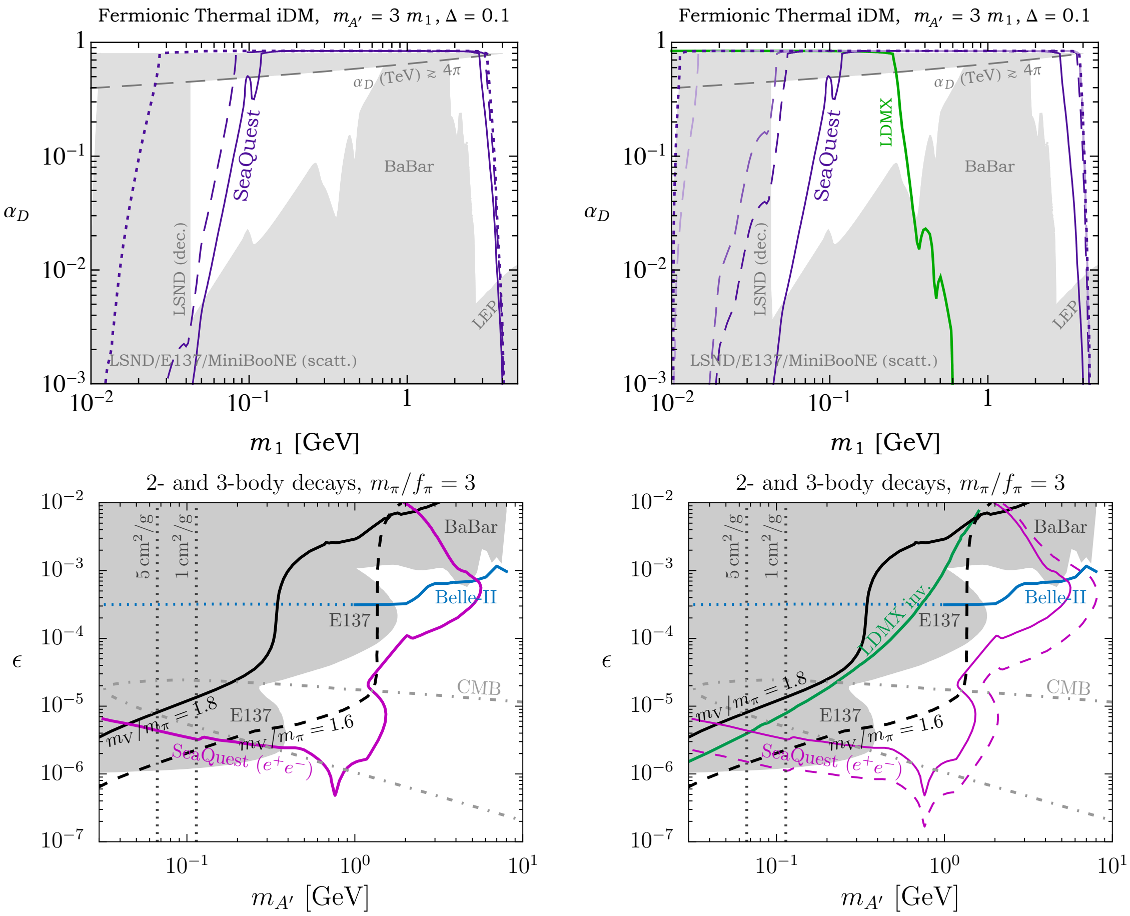

Figure 8: Upper panels: SeaQuest reach for the iDM model (in purple). Lower panels: SeaQuest reach for the SIMP model (purple lines). Upper left: The projected sensitivity of SeaQuest to the cosmologically-motivated parameter space of inelastic dark matter model, assuming 1.44×10^{18} POT for the fiducial decay region of $(5-6)$ m (solid), $(5-9)$ m (dashed), and $(5-12)$ m (dotted). Also shown are existing constraints (solid gray). Upper right: the reach in the $(5-6)$ m fiducial region with 1.44×10^{18} POT (solid) compared to the reach with 10^{20} POT for the $(5-6)$ m, $(5-9)$ m, and $(5-12)$ m fiducial regions (from darker to lighter purple). From [15]. Lower left: The SeaQuest sensitivity to models of strongly-interacting dark matter assuming 1.44×10^{18} POT for the fiducial decay region of $(5-6)$ m, and having fixed $m_{A'} = 3m_{\pi_D}$. The “thermal goal" for the two benchmark scenarios $m_V/m_\pi = 1.8$ and $m_V/m_\pi = 1.6$ is shown in solid black and dashed black, respectively. Also shown are existing constraints (solid gray) and the expected bound from Belle-II (in blue). Finally, light dot-dashed gray contours denote regions excluded by measurements of the CMB. Lower right: comparison of the reach with 1.44×10^{18} POT (solid) and with 10^{20} POT (dashed) in the $(5-6)$ m fiducial region. In this plot, we also include the reach of the proposed LDMX experiment (in green). From [23].

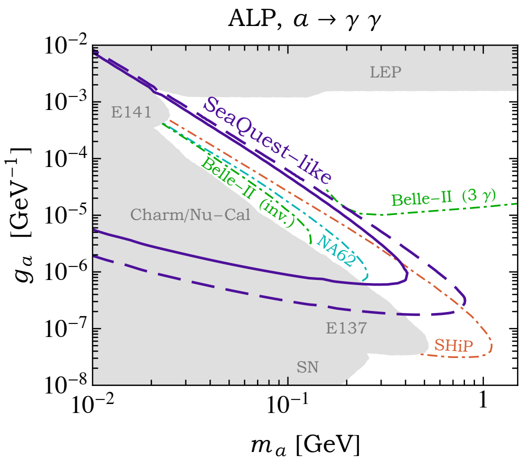

Figure 9: Sensitivity to axion-like particles in the displaced diphoton channel at the upgraded SeaQuest with 1.44×10^{18} POT (solid purple) and with 10^{20} POT (dashed purple), corresponding to 10 signal events. We conservatively fix the fiducial decay region to 7 m - 8 m. The gray region denotes the parameter space that is already excluded by past experiments. Also shown are the projected reach of Belle-II (green) [24], a beam dump run of NA62 in 2023 (cyan) [25], and the proposed SHiP experiment (red) [25]. From [23].

3.2 Additional Signatures and Future Opportunities

In addition to the models discussed in the previous section, many additional dark sector models will be tested by the EMCAl-upgraded SeaQuest experiment via looking for resonant and non-resonant e^+e^- signatures. Examples are models with light scalars, hidden valley models, models with leptophilic scalars (see [15]).

Furthermore, the EMCal upgrade will allow to test a huge array of additional signatures that can not be properly studied with the present SeaQuest setup. Examples are photon signatures, as obtained in eg. models with axion-like particles (see [15]), pion or Kaon signatures as obtained in eg. models with dark Higgs bosons, and lepton-meson signatures as obtained in models with sterile neutrinos. In Table 1, we list some of the signatures that the upgraded SeaQuest experiment will be able to search for and the corresponding dark sector model that will be uniquely probed by this experiment. This serves to demonstrate the incomparable broad program that will be pursued by SeaQuest after its EMCal upgrade.

Some of these signatures may benefit from additional upgrades to the SeaQuest spectrometer. For example, backgrounds for the $\gamma\gamma$ signature for axion-like particles could be suppressed by adding a preshower detector to the EMCal or additional iron shielding. As an example, in Fig. 9, we show the reach for axion-like particles decaying into two photons with 1.44×10^{18} POT (solid purple) and with 10^{20} POT (dashed purple), at a SeaQuest-like experiment with 7m iron shielding. We will develop simulations to better understand backgrounds and sensitivity with different changes to the SeaQuest spectrometer.

4 Schedule and Milestones

We have successfully secured two PbSc based Electromagnetic Calorimeter detectors (each covers 2×4 m^2 in area, currently valued ∼US \$1M for each) for the SeaQuest upgrade. Both BNL management and DOE Nuclear Physics Program Office have approved the transfer of these \$2M EMCal detectors to LANL for the SeaQuest upgrade. The detectors are ready for shipping from BNL to Fermilab for the SeaQuest upgrade, and will be sent back to BNL for storage after the completion of SeaQuest dark sector physics search program.

We propose to ship these two PHENIX EMCal detectors from BNL to Fermilab in summer 2018

Signature	**Model**	**EMCal Needed?**
$\mu^+\mu^-$	dark photon dark Higgs	No
e^+e^-	light dark photon light dark Higgs leptophilic scalar	Yes
$\mu^+\mu^-\mu^+\mu^-$	Higgsed dark photon	No
$e^+e^-e^+e^-$	light Higgsed dark photon	Yes
$\mu^\pm\pi^\mp, \mu^\pm K^\mp, \cdots$	sterile neutrino	No
$e^\pm\pi^\mp, e^\pm K^\mp, \cdots$	light sterile neutrino	Yes
$\mu^+\mu^- + \text{MET}$	inelastic dark matter strongly interacting dark matter hidden valleys	No
$e^+e^- + \text{MET}$	inelastic dark matter with small mass-splittings light strongly interacting dark matter light hidden valleys	Yes
$\pi^+\pi^-, K^+K^-, \cdots$	dark Higgs	Yes
$\gamma\gamma$	axion-like particle	Yes

Table 1: Various experimental signatures and the relevant models that can be searched for at SeaQuest. For each scenario, we also comment on whether an EMCal upgrade would facilitate such a search.

(preferably in July or by early August as BNL needs to clear the current EMCal storage space for other planned activities). The refurbishment/replacement of the detector elements, including PMTs, optical couplings, and frontend electronics, will start once the detectors are received at Fermilab. For the readout, the default plan is to use the existing PHENIX readout electronics and integrate them into the SeaQuest DAQ system. There is also an ongoing (well-advanced) effort by other groups at BNL to develop SiPM-based readout system for the identical EMCal detectors (again recycled from the PHENIX experiment) for the STAR forward upgrade at RHIC. Their current schedule is to complete R&D and enter the mass production by the end of 2018. If schedule and budget allows, we could consider to switch to the new readout system for SeaQuest experiment.

We have already finished the mechanical support design and built the stand, and currently working on the LED-based calibration system (a very similar system was developed recently for the SeaQuest displaced dark photon trigger upgrade), and exploring options for back-end electronics integration to the SeaQuest DAQ system using existing electronics. We have the full PHENIX Timing and Control (GTM), and DAQ system (DCM) in operation at Fermilab. The full EMCal system will be ready for installation during the Fermilab summer shutdown in 2021.

We plan to conduct background studies and prototype tests at SeaQuest during the E1039 run. These studies will be parasitic with E1039 and will avoid interfering with E1039 data taking, similar to the di-muon trigger installation and operation.

During the E1039 run (2019–2021), we will prepare for the SeaQuest transition to the dark sectors program. We will attract new collaborators from the dark sectors community, soliciting participation in the EMCal upgrade, analysis of the di-muon data, and E1039 commissioning and data taking. We will also develop proposals to funding agencies for the extended dark sectors program and specific detector upgrades.

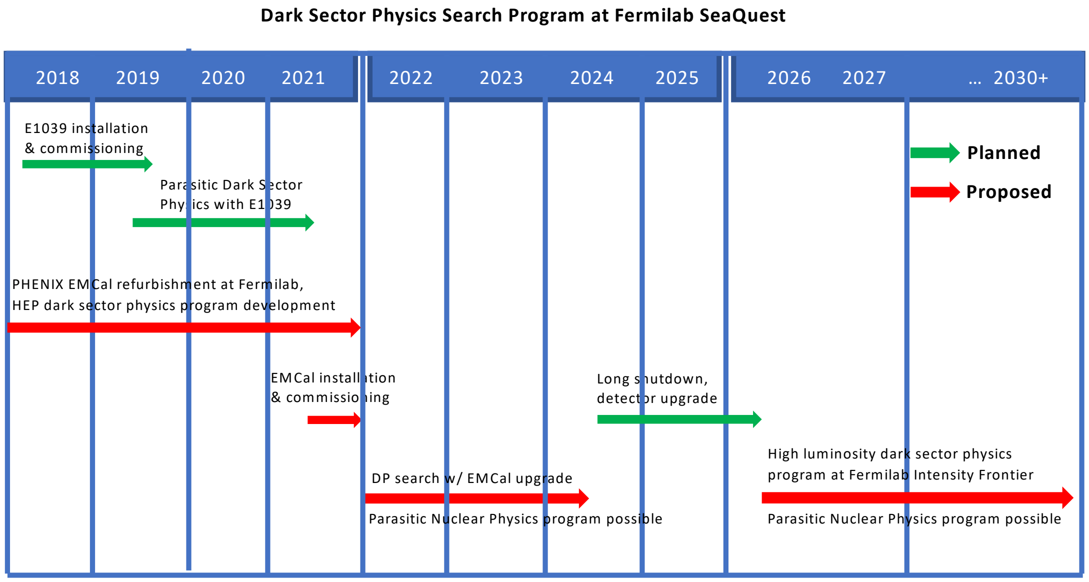

Figure 10: Projected timeline of dark sector physics search at SeaQuest. Exact dates could move depending on the actual E1039 operation schedule and future Fermilab upgrade plan. The EMCal detector will be installed in the SeaQuest experiment during the summer shutdown in 2021, after the completion of E1039, and will be ready for data taking in early 2022. A long-term high luminosity program could be carried out after the Fermilab long shutdown in 2026, with further upgrade of the SeaQuest detectors.

Appendices

A Facilities and Other Resources

This experiment will be carried out at Fermilab, using the SeaQuest spectrometer in the Main Injector. We will first collect data parasitically with SeaQuest/E1039 fixed target experiment which has been approved by DOE and Fermilab PAC 2019-2021. After 2021, we will run a dedicated dark sector physics search program at SeaQuest with updated EMCal detectors.

B Equipment

No special equipment is required beyond what is already available at Fermilab and the SeaQuest experimental hall, building NM4. The EMCal detectors used for the upgrade will be recycled from the PHENIX experiment at BNL. Each EMCal detector weights about 22 Tons(standard), and $2m \times 4m \times 1m$ in dimensions. After the SeaQuest experiment, these two EMCal detectors could be shipped back to BNL for storage. These detectors are safe for transportation on the public roads. See attached property transfer letter and radioactivity survey reports from BNL.

C Data Management Plan

All experimental data will be archived by the Fermilab Scientific Computing Division for the SeaQuest experiments. As this is a parasitic experiment with the E1039 experiment, we will store both the raw data and reconstructed data on the tape storage provided by Fermilab. In total we expect 50 TB of raw data from E1039 in 2 years of running, of which 1 TB will be from the detector and trigger built by this project.

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