Snowmass Letter of Interest: Topic area – RF6

DarkQuest and LongQuest at the 120 GeV Fermilab Main Injector

Brian Batell[1], **Asher Berlin**[2], **Nikita Blinov**[3], **Zeynep Demiragli**[4], **Jared Evans**[5], **Stefania Gori**[6], **Phil Harris**[7], **Christian Herwig**[3], **Dustin Keller**[12], **Kun Liu**[8], **Ming Liu**[8], **Petar Maksimovic**[9], **Cristina Mantilla Suarez**[9], **Omar Moreno**[10], **Timothy Nelson**[10], **David Sperka**[4], **Nhan Tran**[3], **Yu-Dai Tsai**[3], **and Sho Uemura**[11]

[1]University of Pittsburgh
[2]New York University
[3]FNAL
[4]Boston University
[5]University of Cincinnati
[6]University of California Santa Cruz
[7]MIT
[8]LANL
[9]JHU
[10]SLAC
[11]Tel Aviv University
[12]University of Virginia

ABSTRACT

Expanding the mass range and techniques by which we search for dark matter is an important part of the worldwide particle physics program which has been specifically emphasized in the DOE Basic Research Needs for Dark Matter New Initiatives report.* Accelerator-based searches for dark matter are a uniquely compelling part of this program as a way to both create and detect dark matter in the laboratory and explore the dark sector by searching for mediators and excited dark matter particles. This proposal focuses on developing the DarkQuest experimental concept and related enhancements collectively referred to as LongQuest. DarkQuest is a proton fixed-target experiment with particular sensitivity to an array of visible dark sector signatures in the MeV-GeV mass range. Because it builds off of existing accelerator and detector infrastructure, it offers a powerful but low-cost experimental initiative that can be realized on a short timescale.

1 Goals

DarkQuest is a proton fixed target beam dump spectrometer experiment that would operate on the neutrino-muon beamline of the Fermilab Accelerator Complex and receive a high intensity beam of 120 GeV protons from the Main Injector. DarkQuest will directly search for the decays of unstable mediators and dark states to visible Standard Model particles, providing complementary coverage of a broad range of unexplored parameter space in the MeV-GeV mass range (1). This region is of high interest to many future and proposed experimental initiatives. DarkQuest distinguishes itself amongst other experimental initiatives in that it can cover a unique parameter space of dark matter scenarios as a compact beam dump spectrometer detector; and it can cover this parameter space before many competing experiments opportunistically with a very modest amount of resources. DarkQuest takes advantage of a long history of investment by the DOE Nuclear Physics (NP) and High Energy Physics (HEP) programs in the existing E906/E1039 SeaQuest/SpinQuest spectrometer experiments at Fermilab.

This letter describes a program to extend the SeaQuest/SpinQuest detector capability and launch a dedicated dark matter and dark sector search program on the timescale of 2023-2024 and beyond. Such a program will leverage the significant existing infrastructure and past investment in both the beamline and detectors. To gain full sensitivity to dark sector searches, we extend the functionality of existing detectors by reusing sectors from the decommissioned electromagnetic calorimeter (EMCal) of the PHENIX experiment to extend the DarkQuest detection capability to electrons, pions, and photons. By recycling the EMCal, we significantly reduce the overall cost and allow for efficient prototyping and installation.

LongQuest is a collection of potential enhancements to the DarkQuest program by adding additional particle detectors beyond the aforementioned EMCal for DarkQuest. The two main additional detectors would be: (1) a particle ID detector to enhance sensitivity by discriminating between pions, electrons, protons, and kaons and (2) a longer baseline detector approximately 40m from the beam dump for more displaced signatures in a cleaner detector environment. An illustration of the DarkQuest and LongQuest experimental setups are shown in Fig. 1.

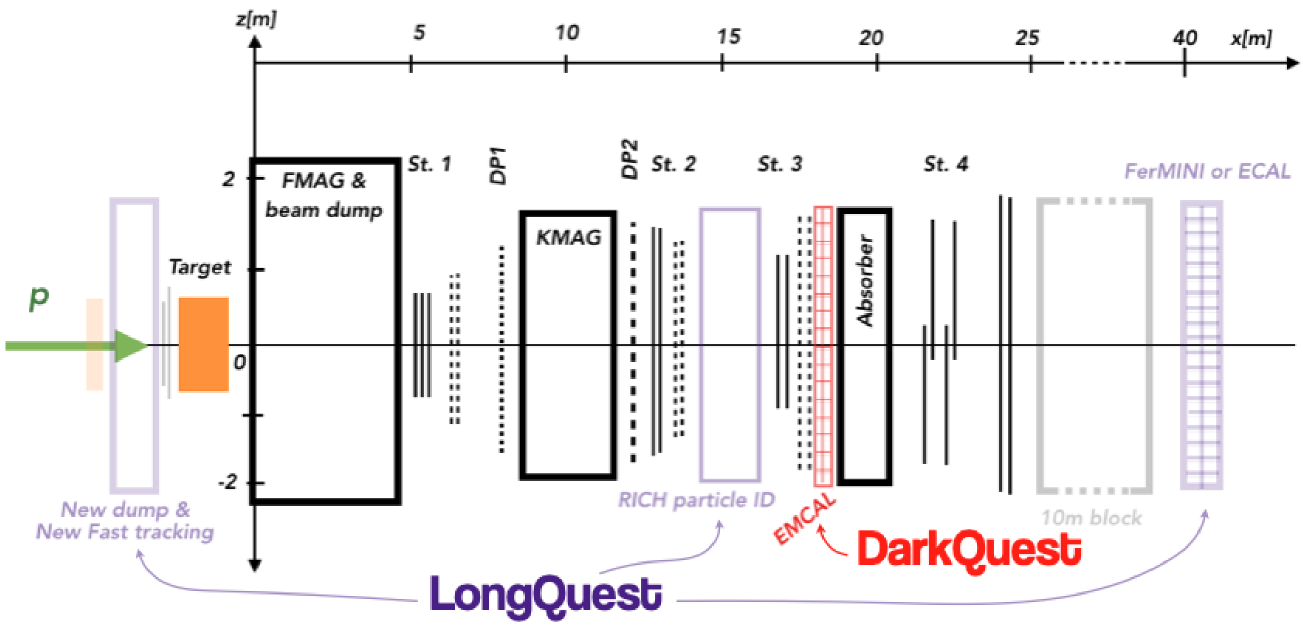

Figure 1. Schematic of the DarkQuest (red) and LongQuest (purple) detector upgrades

The DarkQuest/LongQuest experiment is an ideal laboratory for probing dark sectors through their production and decay into SM particles. All dark sector models tested at DarkQuest share the common feature of containing a "portal" interaction with the SM that connects the SM to the dark sector and a mediator that facilitates these interactions. DarkQuest can search for two broad classes of dark particles: (1) the mediators; (2) the dark particles participating in the process of thermalization and annihilation of DM in the early Universe (we will refer to these as "DM excited states"). In the first scenario, when the mediator is lighter than twice the mass of any particle within the hidden sector DarkQuest can search for the mediator decay into visible standard model particles. In the second scenario, the hidden sector contains additional particles (such as the DM itself and its excited states) at a similar mass scale as the mediator. In this case, DarkQuest can search for a rich set of signals from the DM excited state decay cascades. To enumerate further those potential signatures and final states to which DarkQuest is sensitive include: e^+e^- (dark Higgs, leptophilic scalars, dark photons and other gauge bosons); $e^+e^-e^+e^-$ (Higgsed Dark

Photon); $e^{\pm}\pi^{\mp}, e^{\pm}K^{\mp}$ (sterile neutrino (2)); $e^{+}e^{-}$+missing energy (strongly-interacting massive particles (3), inelastic DM, hidden valley); $\pi^{+}\pi^{-}, K^{+}K^{-}$ (dark Higgs); $\gamma\gamma$ (axion-like particle).

2 Status & Plans

The SpinQuest experiment is currently planning to run in FY21 and FY22 after which period DarkQuest could potentially run during FY23-FY24. Another potential scenario would be to have DarkQuest and LongQuest run after the PIP-II installation at Fermilab, which would occur after FY26.

In order to prepare for these timelines, this letter lays out the studies that we plan to complete for a Snowmass white paper in order to demonstrate the feasibility of the DarkQuest experiment as well as lay out design parameters for future LongQuest enhancements. We broadly describe these activities in these areas for DarkQuest:

- **Simulation of signal acceptance and reconstruction**: We will simulate at particle and GEANT level several dark sector signal scenarios including the baseline $e^{+}e^{-}$ benchmark dark photon model, right handed neutrino signatures, and axion-like particles. We will study the acceptance and rates for such signatures and how well we can reconstruct the particle masses.

- **Simulation of primary K_L^0 background rates**: The largest background to electron dark sector signatures will be from K_L^0 particles which make it through the beam dump and decay in the spectrometer. We will simulate such background events and understand their kinematics and potential background contributions.

- **Study of background data hit rates**: In order to understand detector occupancy from muon backgrounds, we will use unbiased data collected in the 2017 SpinQuest run. This will give us an understanding of hit rates in the detector in addition to what we may expect on top of a given dark sector signal process. Studying these events will help us to understand the degradation of the signal reconstruction from such backgrounds.

- **EMCal test stands** With EMCal prototype towers in hand, we can place these detectors in the experimental hall in order to detect the rate of EMCal hits in the DarkQuest experimental hall near the eventual detector position. This will help us to understand trigger rates for the EMCal and to what extent we can use the EMCal directly in the trigger.

Furthermore for LongQuest, we intend to develop a first conceptual design. This includes the technology and expected performance for a particle ID detector and a longer baseline displaced particle detector beyond the 10m iron absorber behind DarkQuest (4). Given the additional shielding, the LongQuest long-baseline detector can provide a cleaner environment to search for dark sector particles. The extra space also allows additional detectors to be installed, like the ones searching for millicharged particles (5) or studying neutrino interaction (6).

References

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