Sector 30 Transfer Line and Linac to End Station A:

Community Statements on Science Opportunities

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Executive Summary

This document summarizes the scientific applications for the Sector 30 Transfer Line (S30XL) and Linac to End Station A (LESA), and community support for this program and facility. S30XL-LESA[1] is a staged concept to **provide an upgradeable near-CW beam of multi-GeV electrons at 46.5 MHz to the SLAC End Station A for experiments in particle physics requiring pA to 25 nA currents,** by extracting unused bunches from the LCLS-II linac to a transfer line connecting to an existing beamline. The capability to deliver CW electron beam is unique within the HEP laboratory complex, and has wide applications for HEP experiments that can: address major systematic effects in lepton-nuclear scattering relevant to DUNE; offer unique discovery potential for light dark matter; exploit LESA's high rate for test beam studies; and address questions in beam physics and strong-field QED. Leveraging LCLS-II allows the delivery of this beam, enabling a broad and high-impact physics program, for under 10M$.

This document comprises an overview of S30XL & LESA capabilities; 17 Statements of Interest describing experiments and test beam studies for which S30XL capabilities are especially well-suited; and five letters of support from neutrino experiment spokespeople and LHC upgrade coordinator. These statements were gathered in Spring 2019 over a two-month period, for an initial version of this document that was sent to DOE-OHEP in support of the S30XL AIP. Though some minor updates have been made, this document does not fully reflect progress in the science since Spring 2019. Our hope is that sharing it with the HEP community will spur growing awareness of the LESA facility, and new ideas for applications, in addition to further development of the ideas discussed here.

We now briefly summarize the two stages of S30XL-LESA and their scientific applications:
The first stage ("the S30XL AIP" or "S30XL Stage A") comprises a kicker and septum magnet to extract dark current bunches from the LCLS-II dump beamline in the Beam Switchyard, and a short transfer line directed towards a low-power dump located in the linac enclosure. Before dumping the beam, it can be used for experiments that require only a small space (on the scale of $1m^2$ transverse size), and do not demand precise beam tuning or frequent access. These include studies to characterize the injector dark current, strong-field QED experiments using one (or few) electron at a time in an undulator, and a test run for the Light Dark Matter eXperiment using a small prototype detector. The S30XL AIP was funded in FY20 and is under construction.

The second stage ("LESA", formerly "S30XL Stage B") adds an additional ~150m of beamline, connecting the S30XL beamline to the existing End Station A beamline, which transports the dark current beam to End Station A. A 46 MHz laser system based on the existing LCLS-II

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[1] In Spring 2019 when the first version of this document was assembled, LESA was referred to as "S30XL Stage B" and the S30XL AIP as "S30XL Stage A". The statements that follow generally adopt this terminology. Earlier references have also used the name "Dark Sector Experiments at LCLS-II (DASEL)" for the same concept.

oscillator can be added if necessary to increase the available current and improve its stability and tunability relative to the natural dark current. These features, together with the spoiler and collimators already existing on the End Station A line, allow sufficiently flexible beam and adequate floor space for a decade-scale, multi-use experimental program. Three key applications have been identified to date, which are described in the accompanying statements: Electron-nuclear scattering experiments to address key systematics for DUNE and other neutrino oscillation experiments; missing momentum experiments, which offer the only avenue to date to probe sub-GeV thermal dark matter irrespective of its spin; and a range of test-beam applications — benefitting ATLAS and CMS upgrades, detector R&D, and many other experiments across HEP and NP – that exploit the high rate, short pulse length, and tunability of the LESA beam.

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Sector 30 Transfer Line at SLAC: Overview

Tor Raubenheimer, Anthony Beukers, Alan Fry, Carsten Hast, Thomas Markiewicz, Yuri Nosochkov, Nan Phinney, Philip Schuster, Natalia Toro (SLAC National Accelerator Laboratory)

We describe the concept for a transfer beamline at Sector 30 to provide a near-CW beam of multi-GeV electrons at 46.5 MHz to the SLAC End Station A for experiments in particle physics requiring pA to μA currents. As described below, the Sector 30 Transfer Line can be used as a test beam, in support of intensity-frontier fixed target experiments measuring electron-nucleus scattering properties vital to the DUNE precision neutrino program, and to enable fixed-target searches for dark matter and new forces.

The Sector 30 Transfer Line delivers such beam at low cost by exploiting the 4 GeV superconducting RF linear accelerator under construction for the LCLS-II X-ray Free Electron Laser (FEL) [1,2]. Unused RF buckets between the LCLS-II electron bunches are filled with sub-μA current, extracted by a fast kicker in sector 30, and diverted via a transfer beamline towards End Station A. Because the beam is out of time with the FEL kickers and extracted downstream of the LCLS-II linac-to-undulator beamlines, it does not affect LCLS-II operations.

The scientific impact of multi-GeV, CW electron beams is underscored by the high demand for beam time at Jefferson Lab's CEBAF (the only facility in the world delivering such a beam) from both Nuclear and High-Energy Physics experiments. CEBAF is optimized for the needs of the NP community, such as exquisite beam polarization and precise, tunable beam energy. The Sector 30 Transfer Line is well equipped to meet the needs of HEP fixed-target experiments that may call for longer run-times than are practicable at CEBAF as well as flexible test beams for detector development. The Sector 30 Transfer Line can host these experiments in a cost-effective manner and provide new capabilities at SLAC.

In the following, we provide a brief overview of the science program for Sector 30 Transfer Line (this will be edited significantly to summarize the scope of statements of interest – but we provide this draft version to give some idea of what we think a range of practicable and motivated applications are). We then summarize the design and capabilities of the Sector 30 Transfer Line, provide a notional schedule for construction and operations, and comment on the complementarity of the Sector 30 Transfer Line with JLab's CEBAF .

1 APPLICATIONS

The Sector 30 Transfer Line would enable the following HEP science:

- **Neutrino Physics:** Accurate modeling of neutrino-nucleus scattering is key to inferring neutrinos' energy distribution from their scattering products, which is a limiting source of systematic uncertainty in measurements of neutrino oscillation parameters (see e.g. [3,4]). Numerous measurements of pions, neutrons, and protons in electron-nuclear scattering off Argon and its mirror nucleus Titanium are necessary to validate this modeling. The Sector 30 Transfer Line's 4 GeV energy (comparable to DUNE's neutrino energy) is well matched to this physics, and the low-current beam is especially suited to supporting high-acceptance and forward experiments complementary to lower-acceptance measurements performed with CLAS or Hall A equipment at JLab [5,6].

- **Test Beam and QED Physics with few-electron pulses:** The Sector 30 Transfer Line can be used as a test beam to study detector response with low-charge electron pulses (down to single electrons) with precise timing (well below any detector resolution). The high repetition rate of the beam, similar to the timing of the LHC and other next-generation experiments in HEP, BES, and NP, enables a broad range of new critical studies, such as out-of-time pileup. Single-electron pulses are also relevant to measurements of quantum effects in undulator radiation.
- **Dark Matter Physics**: Extending the search for dark matter to masses below a GeV requires new measurements in fixed-target electron scattering at multi-GeV energies [7]. The Sector 30 Transfer Line is well suited to supporting missing momentum (MM) measurements (as proposed by LDMX [8,9] for example). Such measurements would provide sensitivity to both light dark matter and dark matter mediator particles over the uncharted keV to GeV mass range.
- **Searches for New Forces:** Missing momentum experiments like LDMX can also search for long-lived new force carriers (e.g. dark photons) [8]. Next generation searches for shorter-lived new force carriers (for example, the "Super-HPS" concept using two silicon telescopes) could also be pursued at S30XL, if future gun laser improvements are made to allow operation at higher currents and repetition rates.

In practice, the detector needs of the above applications share a great deal of overlap. For example, the LDMX detector concept is compatible with a multi-use program, and could for example be (modestly) reconfigured to collect electron-nuclear scattering data for neutrino physics or to search for new forces.

Table 1 Examples of experiments in each of the science areas above, realizable with the two construction stages of S30XL and with a possible future upgrade to gun laser

Construction Stages	Examples of Realizable Experiments by Science Area				
	Dark Matter	New Force Searches	Neutrinos	Test Beam	Beam physics & Accelerator R&D
Stage A: dark current to BSY				• LDMX test • Undulator 1*e*	• Dark current characterization • Long-pulse kicker studies
Stage B: 46 MHz to ESA	• Missing Mom. (MM) • MM hi-lumi?		• MM- or TPC-based eN measurements	• Detector R&D • Detector tests • Undulator 1*e*	
Laser upgrade (FY25+)	• MM higher-lumi?	• SuperHPS	• Higher-current eN experiment?		

2 SCOPE, TIMELINE, DESIGN OVERVIEW, AND CAPABILITIES

This section summarizes the concept for using the SLAC LCLS-II linac to provide a low-current, quasi-continuous beam to small-scale experiments in the beam switch-yard (Stage A) and eventually a more flexible current to an experimental area in End Station A (Stage B).

The LCLS-II is an x-ray free electron laser based on a 4.0 GeV superconducting linac [1,2], fed by an RF gun [10] operating at up to 186 MHz. The baseline LCLS-II design has a maximum bunch rate of 929 kHz. These bunches are diverted from the dump line to an undulator line by high-speed kickers. The Sector 30 Transfer Line takes advantage of up to 200 "empty" RF buckets between LCLS-II bunches. These are populated at some (unknown) level by dark current originating from the gun; in addition, the existing 46-MHz laser oscillator could be used to produce a well-defined, low-current beam within a ~600 ns macro-pulse between LCLS-II primary bunches. The Sector 30 Transfer Line improvements comprise (1) a long-pulse kicker and septum magnet to divert current in these bunches off the LCLS-II dump line, (2) a 250m long transfer line from the kicker in Sector 30 to the existing A-line, (3) minor improvements in the existing End Station A infrastructure, and possibly (4) a 46-MHz laser oscillator that augments the dark current with a well-defined, low-current beam within a ~600 ns macro-pulse between LCLS-II primary bunches.

2.1 STAGING AND TIMELINE

We propose to build this beamline in two stages to minimize risk, with small efforts in beam physics, test beam, and QED supported by **Stage A**, and most of the science program being pursued in **Stage B**. We also consider a possible future upgrade to the gun laser system, (5) replacing the 46-MHz gun laser with a new 186 MHz laser completely independent of the LCLS-II gun laser, which could allow operation at higher currents and repetition rates.

- **Stage A** comprises the kicker, Lambertson septum, and about 100 m of beamline with three refurbished magnets, which will extract dark current bunches from the LCLS-II dump beamline. The diverted beam will be directed towards a low-power dump located in the linac housing or beam switchyard. This stage demonstrates the extraction system (kicker and septum) and the required diagnostics, and will measure the characteristics of the LCLS-II dark current. S30XL Stage A can also support experiments that are sufficiently small in physical size (roughly <1 m^3), do not require major infrastructure or frequent access, and do not require tight control over beam current. Examples of such experiments include test beams studies (for example, to study the performance of LDMX prototype trigger system, ECal, and HCal) and study of QED effects in undulators (e.g. multi-electron quantum interference and few-photon correlations in spontaneous undulator emission, representing a high-energy extension of the IOTA physics program). Assuming timely funding starting in late FY19, Stage A construction and commissioning could be completed in mid CY 2021.
- **Stage B** adds an additional ~150m of beamline with 14 refurbished dipole and quadrupole magnets, connecting the new S30XL beamline to the existing End Station A line, which transports the dark current beam to End Station A. A 46 MHz laser system based on the existing LCLS-II oscillator can be added if necessary to increase the available current and improve its stability and tunability, relative to the baseline achievable using the natural

dark current. High-impact physics studies in each the first 3 categories described above (neutrino physics, test beam, and dark matter physics) will be enabled by this 2nd stage. Assuming funding starting in FY20, this stage could be completed by mid CY 2022. Stage B is expected to operate for several years, and so the Stage B science case is the primary focus of this report.

- After several years of Stage B operation, a possible minor upgrade may be motivated, to support additional experiments that call for higher currents and/or repetition rates – such as an upgraded missing momentum experiment or a dedicated dark photon search. Whereas the Stage B laser system relies on the LCLS-II laser oscillator, which operates at 46 MHz, these considerations would motivate an independent laser oscillator, ideally at the gun RF frequency of 186 MHz. Such a laser system could produce currents at the 1 μA scale within the macro-pulse diverted to S30XL, while still representing only a percent-level increase to the power required of the linac. The notional schedule in Figure 4 shows such an upgrade in FY26, but this document does not further address its motivation.

2.2 DESIGN OVERVIEW

The baseline LCLS-II design has a maximum bunch rate of 929 kHz, corresponding to a bunch separation of 1,400 1.3-GHz RF buckets. Two high-speed kickers can deflect FEL bunches towards either the soft x-ray (SXR) or hard x-ray (HXR) undulators; unused beam travels to a high-power dump in the Beam Switch Yard (BSY). In initial operation, the LCLS-II linac accelerates up to 250 kW (nominally 62 μA at 4.0 GeV) of electrons to the BSY; an upgrade to the RF system can increase the beam current to 300 μA and the power to 1,200 kW. An energy upgrade to 8 GeV is also foreseen.

The Sector 30 Transfer Line takes advantage of the “empty” RF buckets between LCLS-II bunches. These RF buckets are populated by a 46-MHz laser oscillator to produce a well-defined, low-current beam with 21.6 ns bunch spacing within a ~600 ns macro-pulse between the LCLS-II primary bunches. These bunches are diverted to the transfer line by a new third high-speed kicker. A new 250-meter long beamline takes these bunches from the kicker/septum system to the existing End Station A beamline, where a spoiler/collimation system can be used to control the charge delivered to experiments. This is parasitic to LCLS-II operation, since the secondary beam is low-current (<1μA compared to 62 μA nominal LCLS-II current), well-separated in time from LCLS-II bunches, and extracted downstream of the kickers that direct the primary beams to the undulators. The layout of the proposed extraction is shown in Figure 1; the extraction concept is illustrated in Figure 2; the macro-pulse structure is illustrated in Figure 3.

The new gun laser shares the LCLS-II RF gun 46 MHz laser oscillator, but has a separate amplifier, UV conversion, and transport, all of which operate at much lower average laser power than the LCLS-II systems and are commercially available.

The beam diversion system for the transfer line consists of a septum magnet and a vertical deflecting magnetic kicker, located downstream of the LCLS-II HXR and SXR extraction points. The transfer-line kicker is a variation on the LCLS-II kicker design, operating at the same rate but with a longer pulse, lower amplitude and looser tolerances. The septum magnet is identical to the LCLS-II HXR and SXR Lambertson septum magnets.

The transfer line itself is a 250 m beamline connecting the kicker at the end of the SLAC linac to the existing A-line leading into End Station A (ESA) as illustrated in Figure 1. The beamline uses magnets already available at SLAC or, in the case of the kicker and septum, existing magnet designs. The detailed layout has been examined to ensure non-interference with other parallel beamlines.

For a missing momentum experiment and test-beam operations, the beam must be degraded from ~25 nA in the linac to a desired current between 100 fA and 125 pA, corresponding to between 1 and approximately 500 electrons per μs, or a maximum of 0.5 Watts of electron beam power at 4 GeV. This is achieved by degrading the beam using a spoiler in the A-line (PR10), and then collimating the secondary beam and tuning the A-line to transport electrons of an energy slightly lower than the primary beam energy. This procedure increases the beam emittance which generally results in a beam spot size on the scale of several mm^2 to 1 cm^2. Where an even more diffuse beam is required, as for missing momentum, defocusing quadrupoles in the End Station will be used to spread the beam over areas up to O(10) cm^2.

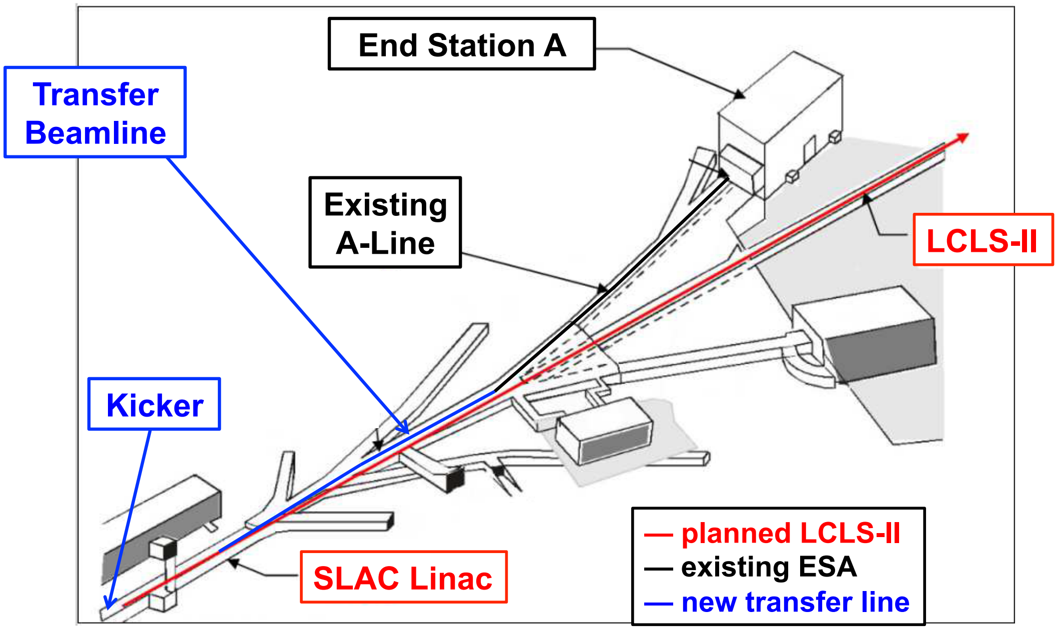

Figure 1. Layout illustrating SLAC linac, the LCLS / LCLS-II beamline, and End Station A with the newly proposed kicker and transfer line connecting to the existing A-Line.

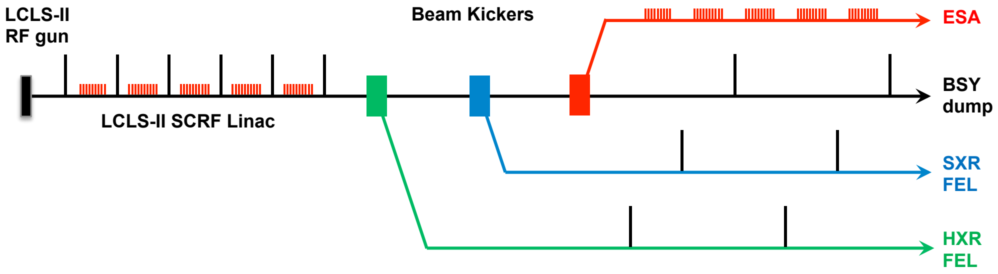

Figure 2. Schematic of the secondary bunches' time structure in the LCLS-II superconducting linac and their extraction to the new transfer line, downstream of the extractions to the LCLS-II undulators.

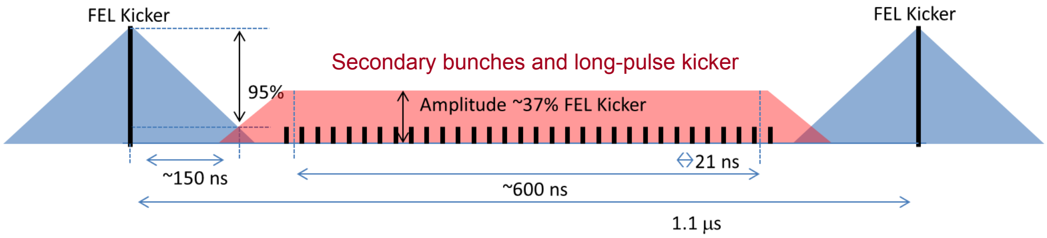

Figure 3. LCLS-II pulse structure showing primary pulses with 4x10^{8} e^{-} and secondary bunches from the gun with ~3000 e^{-} per bunch. The time structure of the FEL kickers and long-pulse kicker for the transfer beamline are also shown.

2.3 KEY PARAMETERS

The parameters of the beam delivered to End Station A by S30XL Stage B are listed in Table . Three categories of parameters are listed: beam at the experiment, beam in the End Station A beamline with the spoiler/collimator system, and beam in the LCLS-II accelerator. Parameters are listed for two scenarios in Stage B: primary low-current beam delivered to the End Station, and degraded beam (as envisioned for both missing momentum and test beam applications). Primary beam parameters achievable with a future laser upgrade are also included in the table, although degraded beam could also be used. Stage A is not included in the table because the properties of the dark current cannot be reliably predicted.

Table 2. S30XL electron beam parameters for Stage B (in the case of both primary and degraded beam), and for a future laser upgrade. For Stage B, the properties of degraded beam at both 4 and 2 GeV have been studied.

Experiment Parameters	**Stage B**		**Potential laser upgrade (Primary beam parameters)**
	Primary Beam	**Degraded beam**	
Energy	4.0 GeV (possible to upgrade to 8.0 GeV)	Up to 4.0 GeV (possible to upgrade to 8.0 GeV)	4.0 GeV (possible to upgrade to 8.0 GeV)
Bunch spacing	21.5 ns	21.5 ns	5.4 ns

Bunch charge	3000 e– (0.5 fC)	0.04 – 20 e– at 4 GeV (0.04 – 0.2 e– at 2 GeV)	70,000 e- (10 fC)
Macro pulse beam current	25 nA	0.1 – 150 pA at 4 GeV (0.1–1.5 pA at 2 GeV)	2 uA
Duty cycle	55% (600 ns out of 1.1 us)	55% (600 ns out of 1.1 us)	55% (600 ns out of 1.1 us)
Beam norm. emittance (rms)	~1 um	~100 um; < 1000 um	~1 um
Bunch energy spread	<1%	<1%	<1%
IP spot size	<250 um including jitter	4 cm x 4 cm	<250 um including jitter
Max beam power	55 W	0.5 W	5 kW
ESA Spoiler Parameters			
Charge reduction	N/A	0 – 99.99%	N/A
Emittance increase	N/A	100 - 1000x	N/A
Max beam power	N/A	55 W	N/A
Spoiler thickness	N/A	0 – 0.5 r.l.	N/A
Accelerator Parameters			
Macro pulse beam current	0 – 25 nA	0 – 25 nA	2 uA
Beam norm. emittance (rms)	~1um; < 25 um	~1um; < 25 um	~1um; < 25 um
Beam admittance (edge)	<50 nm, defined by LCLS-II collimators	<50 nm, defined by LCLS-II collimators	<50 nm; defined by LCLS-II collimators
Bunch energy spread (FWHM)	<2 %	<2 %	<2 %
Bunch length (rms)	<1 cm	<1 cm	<1 cm
Max beam power	55 W	55 W	5 kW

3 SCHEDULE

3.1 CONSTRUCTION

The construction schedule for the three phases of the Sector 30 Transfer Line is strongly dependent on both funding profile and the LCLS/LCLS-II schedules –installation will be done when scheduled LCLS downs allow access to the linac housing and BSY, and commissioning will need to be done parasitically to LCLS-II commissioning and operations. Assuming funding for Stage A beginning late in FY19, and continuing in FY20, the target timeframe for installation of Stage A is an anticipated LCLS-II down late in FY20. This would allow commissioning early in FY21, allowing useful operations in early CY21. FY21-22 funding for Stage B would allow installation (commissioning) of the beamline late in FY21 (early FY22), and of the new laser amplifier approximately one year later, for initial science in mid FY23, or perhaps earlier depending on opportunities for access. A notional timeline for construction and operations under this scenario is illustrated in Figure 4. The timing of a laser upgrade is more uncertain; contingent on the programmatic need for such an upgrade, installation in the mid- to late-2020's could be reasonable.

3.2 OPERATIONS

Figure 4 illustrates a notional schedule for LCLS-II operations, for the construction of the Sector 30 Transfer Line, and for the use of S30XL by multiple experimental programs. Installation and commissioning of S30XL will be parasitic and therefore will be scheduled around the down times established by the LCLS/LCLS-II program.

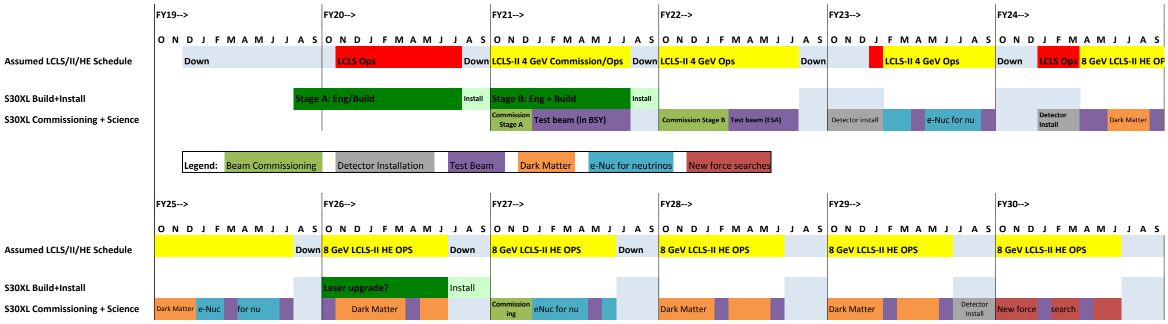

Figure 4: Construction and installation schedule for Sector 30 Transfer Line, assuming initial funding in mid-FY19, followed by a notional operations schedule through FY30. Operations are color-coded by science objective. Test beam operations (in purple) will be interspersed with the operation of larger experiments.

4 COMPLEMENTARITY TO CEBAF CAPABILITIES

The capabilities of the proposed S30XL are somewhat similar to those of Jefferson Lab's Continuous Electron Beam Accelerator Facility (CEBAF) — both facilities use superconducting linacs to provide CW electron beams at multi-GeV energies to user experiments. CEBAF is currently the only facility in the world delivering such a beam, and in high demand from both Nuclear and High-Energy Physics experiments. We summarize here both technical and operational differences, of which the latter seem more prominent for the suite of experimental directions currently envisioned.

TECHNICAL COMPARISON

There are technical differences in capabilities of the two facilities, which are quite important for some experiments. The most obvious of these favor CEBAF: CEBAF can deliver primary beam at a range of beam energies (from roughly 2 to 12 GeV), with different energies delivered to multiple experimental halls simultaneously. Moreover, CEBAF can deliver polarized beam with a high degree of polarization, and excellent reliability. Though crucial to the JLab nuclear physics program, these capabilities are less relevant to HEP concepts presented here (as well as to the HEP proposals that have been pursued at JLab).

Indeed, many of the S30XL experimental concepts considered here rely on beam characteristics that are most readily obtained with a secondary beam: very low current (at the level of one or a few electron per pulse) and a large beam spot. The layout of the SLAC A-line presents two advantages for secondary beam production: the long transport lends itself to generation far upstream of the End Station, and beam transport around the arc allows for very narrow energy definition. Indeed, the ESTB program used secondary beams routinely and with great success.

OPERATIONAL COMPARISON

For the experimental concepts considered here, the most important differences are not the machines' detailed technical capabilities (for which tolerances are quite high) but practical considerations of beam time and operating cost.

CEBAF's operating budget has allowed for roughly 20 weeks of operation per year, with a typical efficiency of about 50% (or roughly 70 PAC days per year in each hall). As of the 46th PAC meeting in July 2018, the laboratory had a backlog of 67.8 remaining approved experiments across four experimental halls, totaling 2733 remaining approved PAC days of operation, after combining experiments into run groups to improve efficiency [11]. In short, Halls A-C have roughly a 10-year backlog of approved proposals, with a 5-year backlog in Hall D.

In this environment, securing beam in a timely manner for HEP experiments has proved challenging. Running an HEP experiment precludes NP running in one of the halls for the duration of data-taking; depending on scheduling, time needed for installation may also come out the available beam time. With the high demand for beam time from nuclear physics experiments, and with Nuclear Physics paying for accelerator operations, this environment has proved quite challenging for scheduling even month-scale runs of HEP experiments that received the JLab PAC's highest scientific ratings.

S30XL, by contrast, will be able to operate parasitically throughout LCLS-II operations, which is nominally 5000 hours/year. The incremental cost of accelerating an additional 25nA in the LCLS-II linac are modest, so operations costs for S30XL are expected to be dominated by personnel, maintenance of the transport line, and user support. It is therefore expected that ~36 weeks of beam-time would be available per year, with high priority given to HEP programs.

There is no precedent for an HEP experiment receiving multiple consecutive months of dedicated beam time at JLab, as is required for the larger-scale neutrino and dark matter search experiments considered here. It is not at all clear that these experiments could be scheduled at JLab on a timescale commensurate with their scientific interest or competitive with international efforts. There is also no precedent for use of JLab as a test beam with the short turn-around time needed for useful detector development. Thus, **beam availability alone is a powerful argument for pursuing S30XL**, where the multi-faceted science program being presented here could realistically be completed within a 5-to-10 year operations period.

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STATEMENTS OF INTEREST DESCRIBING SCIENCE OPPORTUNITIES AT S30XL AIP (aka S30XL Stage)

Section Editor: Tor Raubenheimer

This section summarizes the scientific opportunities that have been identified for experiments at the SS30XL Stage A, in three categories:

- **Characterization of dark current in the injector**, relevant both to LCLS-II operations and to improved understanding of dark current effects for future applications of high-power CW linacs
- **Single- and few-electron studies in undulators**, offering a clean probe to explore QED phenomena and a natural follow-up opportunity to single-electron studies at IOTA
- **Test beam for LDMX,** a proposed light dark matter search that also proposes a science run at LESA/S30XL Stage B. An LDMX science run would address Priority Research Direction #1 identified by the Dark Matter Small Projects New Initiatives BRN[1].

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[1] Basic Research Needs for Dark Matter Small Projects New Initiatives https://science.energy.gov/~/media/hep/pdf/Reports/Dark_Matter_New_Initiatives_rpt.pdf

Characterization of Dark Current in a High Power CW Linac

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High power CW linacs have many potential applications including Free Electron Lasers [1], Energy Recovery Linacs [2], particle sources for particle and nuclear physics [3], and ultimately transmutation and ADS [4]. One of the critical issues in a CW linac is to understand the captured field emission and injector-produced dark current. When produced at low energy, the 'dark' current can be hard to separate from the nominal beam and even low currents can have damaging effects after being accelerated to high energy. Understanding dark current has been a topic of interest in most high powered linacs [5, 6, 7, 8, 9].

There have been limited measurements of dark current in CW injectors. The LCLS-II has set a specification on the maximum permissible dark current from the rf gun and first rf cavities of 400 nA at 100 MeV [10] with the assumption that most of this current would have large amplitude and would be collimated by the transverse collimation systems well before reaching GeV-scale energy. Most other dark current sources are expected to be collimated by the energy collimation systems at BC1, BC2, and the dogleg to the Bypass line [11]. Using a uniform source model from the cathode and the idealized collimation system design, only 6% of the initial dark current survives from the 100 MeV location into the Bypass line; this would correspond to 25 nA if the initial current were 400 nA. However, understanding the transverse and longitudinal phase space of the captured dark current is critical for LCLS-II where, to prevent radiation damage to the permanent magnet undulators, the losses are limited to 3 pA in the undulator region, a small fraction of the possible dark current.

The S30XL beamline is being designed to transport and measure very low beam currents. The electron beam is extracted from the LCLS-II beamline with a long pulse kicker so the measurements of the beam will not impact LCLS-II operation. The S30XL will provide the ability to fully characterize the phase space of the captured dark current. The transverse beam size will be measured on sensitive profile monitors and the phase space can be measured using the quad scan technique. The energy spectrum will be measured at a point of large horizontal dispersion and can be fine tuned by scaling the septum and dipole magnets without impact to LCLS-II.

These measurements will allow (1) characterization and understanding of the sources of dark current as the current can be studied while varying the injector parameters; (2) characterization of the dark current that might be sent towards the undulators and thereby providing a layer of protection to avoid irradiating the undulator magnets; and (3) the ability to study and tune the collimation system to approach the design performance and identify limitations of the design. Such measurements will be very important for LCLS-II and they will be important to aid the design and specification of other high-power CW linacs.

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Single (few) electron experiments at S30XL

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Quantum Electro-Dynamics (QED), which describes how light and matter interact, is a theory of the quantum electromagnetic and Dirac fields. Although the theory provides excellent agreement with measurement over a huge parameter range, there are regimes where the understanding is less clear. Quantum electromagnetic processes generally can be classified by two quantum parameters: $\chi = B / B_{cr}$, where B_{cr} is critical Schwinger field intensity, and $\xi = A^{\mu}A_{\mu}$, which is also known as a_0 parameter in the laser community and K parameter in the undulator community.

To date, most experiments aimed at exploring high field QED are carried out at a high energy and field intensities, probing non-linear non-perturbative QED effects and known high energy physics processes by means of colliding laser photons with tens-GeV scale electron beams [1]. Such processes include quantum recoil effects, e.g. electron spin flip, mass field dressing effects, non-linear Compton scattering, Breit-Wheeler electron-positron pair production, etc. [1-3]. All these effects happen in the regime where both quantum parameters are larger than 0.1. While such processes are extremely important in high energy science, they are generally not realized under the conditions inside current generation electron accelerator-based light sources, where the intensity parameter ξ is large but the field parameter χ is small or negligible.

In an accelerator, electrons are subject to interaction with external electromagnetic fields via Compton scattering, and collective interaction via electromagnetic forces. Both effects can be theoretically described, in the leading order, by using a classical electromagnetic Hamiltonian, as shown by Glauber [4]. Under such conditions, electrons, in the leading order, may be assumed to be spin-less charged scalar particle-like objects or classic currents in dressed Volkov states [5]. However, due to the improvement of electron beam manipulation techniques, magnets, and SRF technology, particle accelerators can enter new regimes where collective quantum effects start to play a key role. For instance, new acceleration technologies involving interaction with plasma, laser fields inside dielectric structures, and solid state acceleration, may involve electron current densities and acceleration gradients that alter quantum mechanical states. In addition, when sent to a very short-period undulator, e.g. an optical undulator, with large K parameter, the process of undulator radiation cannot be fully explained by means of classical perturbation theory and require complete non-perturbative quantum mechanical treatment Dirac electron states [6-7].

A path to getting a better understanding of the nonperturbative effects in accelerators is to experimentally study the behavior of a single electron. Examples of such studies include operation of a storage ring with single electron (IOTA, Fermilab), single electron source for dark matter search (proposed S30XL experiment at SLAC), low emittance dielectric laser accelerators, searches for anomalous electron dipole moment, single electron quantum dots, and ultra-precise nano-assembly [8-12]. With the development of fourth and fifth generation X-ray light sources around the world, it becomes increasingly important to learn about the quantum nature of electrons and their interaction with electromagnetic fields.

Currently, an experimental capability of single electron beam production exists at Fermilab's IOTA storage ring at energies of 100-150 MeV. Combined with a conventional undulator of K = 1, it will reach the value of quantum field parameter up to $B/B_{cr} = 10^{-6}$. This experiment could be complemented by the high-energy 4 GeV single electron beamline S30XL, proposed for construction at SLAC, which can possibly reach higher quantum field parameter up to $B/B_{cr} = 10^{-4}$, therefore improving the statistics of observed quantum effects.

For the first round of experiments, at the Fermilab IOTA ring and SLAC S30XL, two interesting topics may be targeted: the radiation formation region and the electron wave-packet localization in an undulator. An electron, placed in a "bath" of field photons in an undulator, will constantly undergo quantum mechanical interactions [13] and associated electron wave function reduction. So far, no conclusive experimental measurements of single electron wave packet localization in an undulator has been performed. One possible approach to probe the wavefunction is to utilize the multi-photon Compton effect and analyze the time of arrival correlations and the spectra of the produced secondary photons [14]. In a very strong undulator or wiggler, such as available for XLEAP-II experiment at SLAC, the arrival time of multi-photons intrinsically carries information on the electron wave-packet size and photon formation region. When two and more photons are born in the same formation region, they possess multi-photon concurrence in polarization, angular, and spectral domains associated with strong field effects [15].

After the 1st experiments are complete, there is another set of experiments that are considered important. In particular, understanding the spectral-angular distribution of the undulator multi-photons is potentially relevant to the operation of a quantum FEL. Both IOTA and S30XL can probe this with electron-undulator, electron-wiggler and electron-laser interactions in a 'single' electron experimental configuration. Finally, precise control of a small number of electrons, such as that provided by the S30XL beamline, may also shed light on collective quantum interference and collective recoil of electron wave-packets [16, 17].

Ultimately, a single electron in an accelerator is free of collective effects, therefore is the "cleanest" probe of non-perturbative QED. The higher beam energy and higher duty cycle at the S30XL beamline will provide an opportunity to extend the experimental programs planned at IOTA and other facilities aimed at exploring QED.

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Statement Of Interest: Light Dark Matter eXperiment (LDMX) Test Run at S30XL

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Abstract

LDMX, the Light Dark Matter Experiment, is a small-scale accelerator experiment having broad sensitivity to both direct dark matter and mediator particle production in the sub-GeV mass region. LDMX leverages well-established technologies where possible, but achieving the best sensitivity motivates the use of some technologies still under development for CMS upgrades and Mu2e. Operation of a small slice of LDMX in a test

run with Stage A of the Sector 30 Transfer Line (S30XL) would allow the verification of key performance parameters in advance of the assembly of the full experiment, as well as providing valuable test-beam data for these developing technologies. In addition, such a test run would serve as an important integration test for the data acquisition and trigger systems for the experiment, and would help prepare the experiment to take physics quality data from the time of first beam in End Station A.

Motivation and Science Goals Many of the subsystems of the LDMX experiment propose to use well-established detector technologies to minimize risk and cost [1, 2]. However, the calorimeters required to cope with high event rates and veto rare processes use more aggressive technologies. The electromagnetic calorimeter (ECal) is a high-granularity silicon-tungsten calorimeter using technology from the CMS HGCal upgrade and the hadronic calorimeter (HCal) is an extruded scintillator and steel sampling calorimeter with SiPM readout adapted from the Mu2e detector. While both of these are at an advanced R&D stage and will soon be deployed in major experiments, neither has a long operational history that can be used to pin down the key performance parameters that will be applicable in LDMX. Furthermore, the task that these detectors must perform in LDMX is quite different, making extrapolation of test beam results from CMS and Mu2e to performance in LDMX difficult or impossible. Operation of near-final prototypes of a small slice of the LDMX calorimetry in 4 GeV beam from Stage A of S30XL that closely mimics the beam conditions for LDMX in End Station A would be extremely useful in verifying the performance of these subsystems in advance of the completion of LDMX. Furthemore, operation of S30XL with dark current will produce beam pulses at 186 MHz, four times higher rate than S30XL will deliver beam in End Station A for Phase I of LDMX, and the ultimate goal for LDMX Phase II. Testing the detector - especially the ECal - in this environment will provide valuable data about operation of these technologies at very high repetition rates. This provides information important for planning Phase II of LDMX, as well as the general application of these technologies in similar physics environments.

In addition to testing the performance of key subsystems, the operation of a slice of the LDMX apparatus as a test run is a critical test of system integration. In particular, the operation of the data acquisition system and testing of the trigger strategy are an important step in readiness to run the full apparatus. The simple addition of a thin trigger scintillator completes the set of inputs to the trigger, and would allow full integration of the TDAQ and the verification of expected rates.

LDMX Test Detector Concept The layout in the Beam Switchyard (BSY) - where Stage A of S30XL will terminate - is shown in Figure 1. Other beamlines and supporting structures allow for an apparatus with a cross section of approximately 1 m×1 m and well over a meter long.

This is large enough to install a support stand holding the central stack of the LDMX ECal with a small HCal prototype behind and the trigger scintillator in front. A similar setup has been run with early prototypes of the CMS HGCal at both CERN and FNAL with much higher energy beam. Although space is tight for services on the apparatus itself, there is an adjoining tunnel adjacent to the S30XL beamline along this

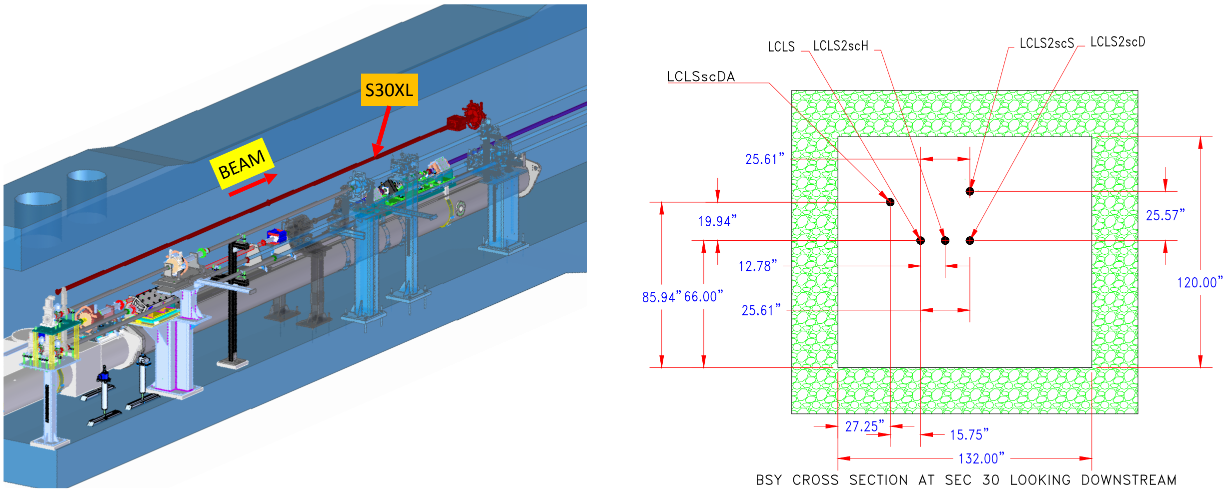

Figure 1: On the left, the area in the beam switchyard (BSY) where S30XL will terminate in Stage A, showing other beamlines and support elements. On the right, the cross section of beamlines in this region looking downstream, with S30XL labeled at LCLSacDA. An apparatus with a cross section of approximately 1 m×1 m can be placed along this line without interfering with other elements. In particular, the beam can be launched through a vacuum window to a region just downstream where there is an adjoining tunnel on the S30XL side of the BSY to allow support and services that are not intertwined with the other lines.

section of the BSY tunnel that is convenient for the location of the DAQ, power, and other services.

It is important to note that the radiation and background environment in this region will be much more challenging that LDMX will face when operating in End Station A. While this makes some studies more difficult, it enables others. In particular, this test can provide useful data regarding the robustness of the SiPMs used to read out the trigger scintillator in LDMX, which are relatively sensitive to radiation.

Science Deliverables In addition to acting as an integration test for the DAQ and trigger and a critical first test of the ECal, HCal and Trigger Scintillator subdetectors for LDMX, a number of other studies would be enabled by a test run of LDMX with Stage A of S30XL. Many of these are important inputs for LDMX physics, while some are also of general interest to the instrumentation community. Examples include:

Beam Studies: Operating a slice of LDMX with S30XL will enable studies of the S30XL beam that are relevant to accelerator physics:

- Characterization of dark current in SRF structures under different operational conditions
- Testing low-current beam diagnostics
- Detailed studies of kicker operation
- Collimation and Optics for S30XL

ECal: Operating silicon-tungsten calorimetry with 186 MHz dark current uniquely enable studies of high rate operation and reconstruction.

- Operation of silicon-tungsten calorimetry at high repetition rates and at a range of particle arrival phases relative to the electronics timing
- Reconstruction and resolution for spatially overlapping showers in silicon-tungsten calorimetry.
- Reconstruction and resolution for temporally overlapping showers in silicon-tungsten calorimetry.

HCal: Operating the hadronic calorimeter at S30XL will enable studying the detector in a high rate and high radiation environment.

- Study distribution of energy observed transversely from a stack of ECal modules during normal electromagnetic showers
- Reconstruction and separation of temporally overlapping hadronic showers in the calorimeter and tuning of the Monte Carlo simulation to reproduce the data.
- Study the radiation effects on the readout electronics.

Trigger Scintillator: Operation of the trigger scintillator with 186 MHz dark current beam and in the environment of the BSY provides important information for use of this technology in LDMX and elsewhere.

- MIP counting and single-bunch tagging at high rates in thin scintillator with integrated SiPM readout.
- Studies of radiation effects in plastic scintillator with SiPM readout.
- Study use of trigger scintillator timing information to correct trigger amplitude information from the ECal based on amplifier pulse shape

While these are representative of the topics expected to be studied in an LDMX test run that are of broader R&D interest, they are by no means complete - more ideas for basic detector R&D with this apparatus are anticipated as plans develop. Finally, while it is not expected that a test run of LDMX with Stage A of S30XL will produce physics results, analysis tools and techniques that will be important to producing physics with LDMX can be developed and tested on data from a test run. In general, an LDMX test run with Stage A of S30XL is an effective way to ensure that the experiment is ready to efficiently take and analyze data upon taking first beam in End Station A.

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STATEMENTS OF INTEREST
DESCRIBING SCIENCE OPPORTUNITIES
AT S30XL Stage B (aka LESA)

This section summarizes the scientific opportunities that have been identified for experiments at S30XL-LESA, in three categories:

- **Electronuclear scattering measurements for neutrinos:** includes an overall scientific overview, contributions describing two potential detector concepts, and supporting letters from the spokespeople of accelerator-based neutrino experiments
- **Light dark matter searches:** includes a contribution from the LDMX experiment, which addresses Priority Research Direction #1 identified by the Dark Matter Small Projects New Initiatives BRN[1].
- **Test beam applications**: includes 9 statements from the HEP community describing applications of S30XL Stage B as a test beam. These applications span basic detector R&D; characterization of detector responses to single particles, large particle fluxes, and/or pile-up for application to HEP experiments; and studies of electromagnetic radiation damage.

We note that these statements were prepared in Spring 2019, with only partial updates to include a few additional references and signatories who have more recently contributed to ongoing efforts described here.

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[1] Basic Research Needs for Dark Matter Small Projects New Initiatives https://science.energy.gov/~/media/hep/pdf/Reports/Dark_Matter_New_Initiatives_rpt.pdf

Electronuclear Scattering Measurements For Neutrinos: Introduction

Section editors: A. Friedland, P. Schuster, N. Toro, H. Tanaka

This section provides several different perspectives on the motivations and prospects for electron-nuclear scattering measurements at LESA.

The three statements that follow describe the overall motivation for a program of inclusive electron-nuclear scattering data, and the prospects for such measurements with two different small-scale detector concepts: LDMX and a dedicated large-acceptance TPC. These statements were developed in part through the workshop "Electron-Nuclear Scattering Prospects at S30XL [1]".

Following the statements are four short letters of support from leaders in the neutrino experimental community.

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[1] https://indico.slac.stanford.edu/event/102/

Neutrinos at S30XL

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(Dated: April 2019)

Electron-nucleus scattering data can play a valuable role in validating models of neutrino-nucleus interactions, which are in turn a key ingredient for the success of all aspects of the broad physics program at DUNE. A recent workshop at SLAC [1] explored open problems in today's neutrino event generator codes, the scientific role of an electron-nucleus scattering program, the potential contributions of experiments at S30XL to this program, and the match between the needed data and the capabilities of current detector concepts. This report draws on the presentations at the workshop to describe the neutrino case for a dedicated program at S30XL in support of DUNE, the key measurements that such a program should enable, and two "straw-man" concepts for suitable low-cost detectors.

The Nobel-prize-winning discovery of neutrino masses and flavor mixing represents a breakthrough in the search for physics beyond the Standard Model. As the field of neutrino physics enters the precision era, neutrino oscillation experiments are taking center stage in the US HEP domestic portfolio. A central role for the next decade and beyond will be played by the Deep Underground Neutrino Experiment, or DUNE. A $1B+ undertaking, it is being actively developed by an international collaboration of over a thousand researchers from 30+ countries.

DUNE will use an intense neutrino beam and a large, state-of-the-art detector employing Liquid Argon Time-Projection Chamber (LArTPC) technology. Central to DUNE's success is its ability to precisely measure neutrino oscillation probabilities as a function of energy. For example, a mismodeling of the detector's energy scale (resolution) leads to inaccurate reconstruction of the locations (magnitudes) of oscillation features, and therefore to systematic errors in neutrino mass splittings (mixing angles). Near detector measurements alone can reveal the presence of discrepancies, but may not be able to distinguish among their sources—such as specific physical processes in neutrino-nucleus interactions, mismodeling of the neutrino flux, or various detector systematics.

This problem has come into sharp relief in the last ten years, as precision results from modern experiments—such as NOνA, MINERvA, T2K, and MiniBooNE—have revealed serious deficiencies in today's event generator codes, such as GENIE, which is used by all Fermilab-based experiments. DUNE will feel the effects of these deficiencies more acutely than the past experiments, such as MINOS or NOνA, as it strives for much greater precision.

Moreover, compared to T2K and MiniBooNE, DUNE operates at higher energies, 1–4 GeV, where the event rate is dominated by various inelastic (pion-producing) physical processes and modeling is especially challenging.

At first glimpse, calorimetric energy reconstruction at DUNE may seem a completely different physics problem than the modeling of final states in electron-nuclear scattering — but in fact, the two are closely related. Effects contributing to energy loss in DUNE include subthreshold particles, charge recombination, and nuclear breakup (caused mostly by neutrons) [2]. To infer the missing energy, one must rely on a model for neutrino-nucleon interactions within the argon nucleus, combined with a model for the final state interactions (FSI) affecting all hadrons produced at the primary vertex. Many facets of this physics can be explored in electron-scattering experiments, with greater statistics, precision, and control than can be achieved using a broad-band neutrino beam [3]. Indeed, while present electron-scattering data has only scratched the surface of these effects, it has already revealed substantial disagreements between data and event generators such as GENIE. Specifically, available inclusive electron-nucleus datasets show 50% and greater discrepancies with GENIE cross sections in regions of phase space relevant to DUNE (see Figure 1). The discrepancies are worst precisely where sizable incident energy is carried by hadrons: in this case, understanding the distribution of these hadrons (e.g. the fraction of energy carried by neutrons vs. pions) and their spectrum is key to modeling DUNE energy reconstruction.

Measuring outgoing hadrons in electron-nucleus scattering with a low-threshold, wide-acceptance detector can provide a key dataset for improving and validating these aspects of neutrino generators. To date, no such data analysis has yet been carried out. The JLab "Electrons for Neutrinos" (e4nu) proposal [4, 5], which will use the existing CLAS12 detector, represents a promising start to such a program. S30XL presents an opportunity to repurpose or design a low-cost experiment with a focus on capabilities – such as neutron reconstruction, angular coverage, and low kinematic thresholds – that complement CLAS12 capabilities and enable important measurements for modeling of neutrino-nucleus interactions [3].

A March 2019 workshop at SLAC [1] reviewed the status of the models in today's event generators, the case for a dedicated electron scattering experiment to improve the models, the prospects from recently proposed experiments, and the opportunities presented at the S30XL beamline at SLAC. These discussions made clear that the program of validation and improvement for neutrino generator physics is essential for the success of the DUNE program, and that additional data is needed to carry out this program. This report summarizes the physics case for such a program and outlines two detector concepts that were presented at the workshop and can be considered as "straw-men" for low-cost approaches to electron-nucleus scattering measurements, with complementary capabilities that exceed those available at JLab in some important ways. These concepts are described in more detail in subsequent reports by their proponents.

I. MOTIVATION

While is it by now universally recognized that the physics of neutrino-nuclear interactions, as implemented for example in GENIE, must be better understood, the situation is less clear about what improvements are most urgent to assure that DUNE meets its science goals. The issue, once again, comes down to the richness of physics involved. Should one focus on the nuclear structure of argon, or on the hadronic physics of pion production? On two-nucleon currents, or the transition between resonant and deep-inelastic scattering (DIS) regimes?

While improvements on all these fronts are, in theory, desirable, in practice we do not want to treat our cancer patient for the cold (that she might also have). Correct diagnosis is thus the key first step. As discussed in Sections II and III, current electron scattering data points towards the production of hadrons and their in-medium propagation as the parts of the model in dire need for improvement.

The second key step is to ensure that the proposed treatment is, in fact, a cure. In other words, we need to be certain that proposed changes in the generator codes are indeed physically valid and are not just phenomenological parameter adjustments in what is, fundamentally, an unsound model. The latter possibility should be a serious concern: while for any given neutrino dataset it may well be possible to achieve superficial agreement by phenomenological generator tuning, if the underlying model is not valid, the problems are likely to reappear in different distributions of events, in a different kinematic regime, or in a different nucleus.

Thus, extensive validation efforts are necessary for all generator changes. Such validation requires availability of high-quality experimental data over a range of scattering conditions. One is then led to the idea of a program of ancillary experimental measurements, designed specifically to ensure and improve the performance of DUNE. By moving beyond inclusive cross-section measurements to measurements of the hadronic system, electron-scattering experiments can play a very important role both in diagnosing the problem and in assuring its successful cure. We begin by describing how electron scattering data already demonstrates problems with current cross section models (Section II), using GENIE as an example, and how such modeling errors impact the DUNE oscillation program (Section III). We then argue how dedicated electron-scattering studies at S30XL can help validate and improve the physics models implemented in GENIE and other generators.

II. TESTING NEUTRINO EVENT GENERATORS WITH ELECTRON SCATTERING DATA

The value of electron scattering data for neutrino experiments stems from the fact that much of the physics is common between electron- and neutrino-nucleus scattering models. This includes, for example, the properties of the initial nuclear state, including the distributions of nucleon's momenta and energies, the development of the intra-nuclear cascade as the produced hadrons travel through the nucleus, etc [18]. This connection enables one to leverage numerous advantages of electron scattering, such as: monochromatic and adjustable beams of precisely known energy (precision $\mathcal{O}(0.1\%)$), specific final states with known kinematics (scattering angle, energy transfer), and cross sections higher by several orders of magnitude then for neutrinos. Hence, electron scattering data can be used to efficiently test different aspects of the interaction model, so long as the same physics is used in the generator to treat both electron and neutrino cases.

As an illustration, let us consider recently collected at Jefferson Laboratory data for electron-carbon scattering [6]. The initial electron energy was $E_e^{\text{init}} = 2.2$ GeV, and the energies of the final electrons E_e^{fin} were measured at 15.5-degree scattering angle. The results are shown in the left panel of Fig. 1. The horizontal axis shows the energy transferred to the hadronic system, $\omega \equiv E_e^{\text{init}} - E_e^{\text{fin}}$. The Figure clearly shows the richness of physics in this energy regime, with several processes making comparable contributions to the overall scattering event rate.

The prominent feature seen in the $\sim$ 100–300 MeV range is *the quasielastic peak*, which is formed by the interactions that leave the nucleon intact, $e+N \rightarrow e+N$. The finite width of this feature arises from the Fermi motion of the nucleons in carbon and is captured in GENIE by the Relativistic Fermi Gas (RFG) model. In fact, despite the seeming simplicity of the RFG model, the experimental data is seen to be in passable agreement with the generator predictions in this range, especially if the MEC (Meson-Exchange Current) contribution were to be removed.

On the other hand, beyond the quasielastic peak, the generator predictions are in a striking disagreement with the data. The processes occurring in this regime correspond mainly to various modes of pion production. In particular, the broad maximum in the data should correspond to creation of the hadronic Δ resonance. It is clear that the location of maximum for the predicted Δ resonance is off. Also off is the predicted cross section for larger values of ω, where the contribution of higher hadronic resonances gradually transitions to the DIS (Deep Inelastic Scattering) regime. In fact, this finding is not specific to the kinematic regime of the Jefferson Laboratory experiment—it generally persists for other values of initial electron energies, scattering angles, and targets. As the second illustration, in the right panel of Fig. 1 we show a comparison for $E_e^{\text{init}} = 4.045$ GeV, at a larger 30.0° scattering angle for deuterium [7]. These conditions allow us to test the generator predictions deeper in the pion-producing regime. Moreover, deuterium is a much simpler nucleus, with well-understood properties and minimal FSI effects. Once again, however, the discrepancies between data and GENIE predictions are apparent.

Detailed studies show that this situation persists across a wide range of scattering angles. Discrepancies as large as ±50% or more between the measured inclusive scattering rate and

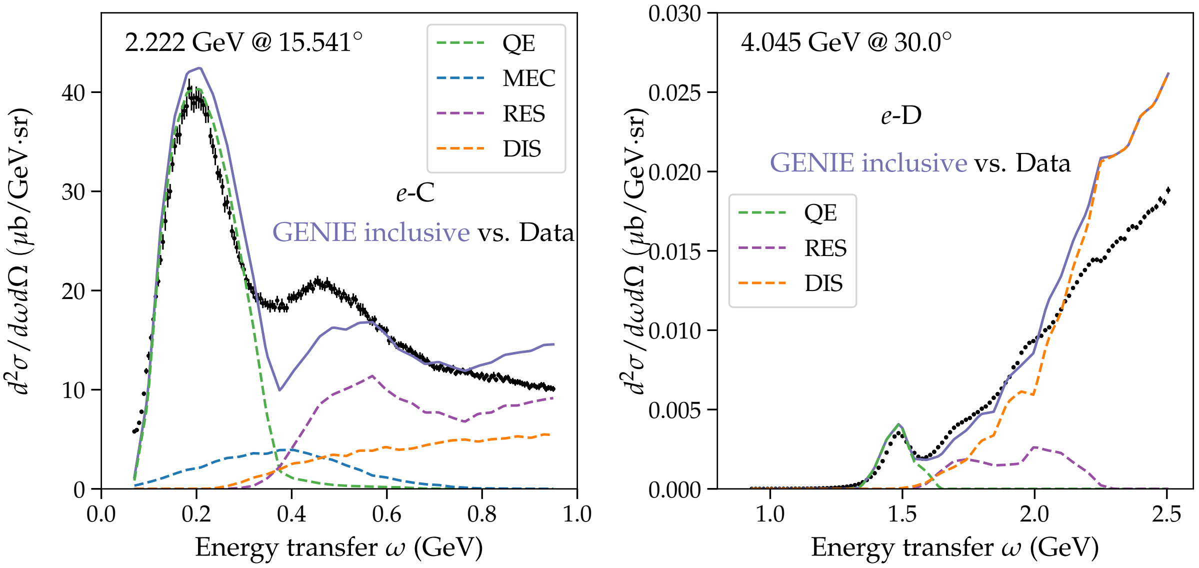

FIG. 1: *Left*: Comparison of the inclusive GENIE prediction (solid line) to data for electron scattering off carbon at beam energy 2.2 GeV and 15.5° [6], an example of kinematics relevant to DUNE. The individual components contributing to the GENIE cross section are also shown (dashed lines). Large discrepancies beyond the quasielastic peak are apparent. *Right*: Comparison of GENIE inclusive predictions (solid line) to data for a 4.045 GeV electron scattering off deuterium at 30° [7], where pion-producing processes dominate.

GENIE predictions are not uncommon. We also stress that comparably large, quantitatively consistent discrepancies exist in deuterium, where nuclear effects are much less important. This reaffirms the point already indicated by the kinematics at which the discrepancies are greatest: that they involve primarily errors in modeling of hadronic physics. Of course, for precision modeling, various nuclear effects are also important to take into account. These include the nuclear binding energy affecting the position of the quasielastic and delta peaks, two-nucleon currents, etc. However, even with all these effects accurately accounted for, unless the model describing pion-producing reactions is also improved, the large discrepancies plainly evident in Fig. 1 will persist.

III. CONNECTIONS TO NEUTRINO OSCILLATION EXPERIMENTS

The main lesson so far can be summarized as follows: *When comparing the inclusive electron-scattering rates in the energy range of 1–4 GeV relevant to DUNE, large discrepancies with the predictions of GENIE are observed; these are primarily due to how GENIE models hadronic inelasticities.* This finding has direct implications for the neutrino program. Let us see how this works.

First of all, we note that inelastic (pion-production) processes dominate the event rate at DUNE, comprising about 2/3 of all events. This affects even events that appear quasi-elastic—some of them could be in fact pion production, where pion gets reabsorbed in the argon nucleus. This case is clearly articulated in [8], where it is also noted that this important topic received too little attention so far, compared, for example, with the two-nucleon currents (so-called $2p2h$ MEC) phenomenon.

Second, failure to correctly model inelastic processes leads to mismodeling of the properties of the hadronic system. In turn, accurate prediction of the hadronic system is essential for the reconstruction of energy at DUNE. In fact, this goes to the heart of how cross section uncertainties enter the performance of DUNE and of other similar experiments (e.g., NOνA). Let us discuss this important point in some detail.

The starting observation is that DUNE measures neutrino energy using the calorimetric method. This requires detecting all final-state particles and summing up their energies. If this could be done faithfully, there would be no need for cross-section physics—one would simply compare the event distributions with respect to measured energies for the near and far sites, in order to infer the oscillation probability. In reality, however, DUNE is not a perfectly hermetic detector, and has a number of energy-loss channels, including subthreshold particles, charge recombination, and nuclear breakup (caused mostly by neutrons) [2]. This is where event generator predictions come in: they are needed to fill in the missing energy information in all channels. If the generator systematically mis-predicts the unobserved properties of the hadronic system, the inferred values of total energy will be incorrect, and this problem cannot be diagnosed using neutrino data alone.

While inclusive electron scattering data, described before, mostly probe hadronic effects at the primary neutrino-nucleon interaction vertex, to correctly predict exclusive hadronic final state, one also has to accurately model the FSI effects, specifically, the development of the intra-nuclear hadronic cascade. This is another rich physics problem, with different generators giving very disparate answer.

To get a sense of how uncertain the predictions for the hadronic-system composition are, we can compare predictions of two event generators on the market: GENIE and GiBUU [3]. In Fig. 2, we consider 4-GeV electron scattering off the argon target and impose event

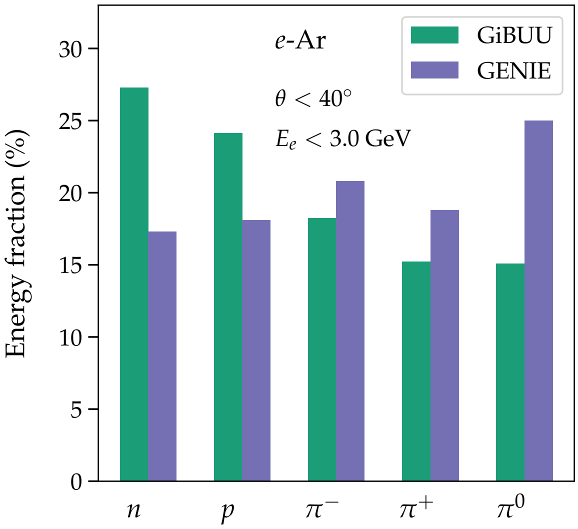

FIG. 2: Generators have very different underlying physics, leading to different compositions of the outgoing hadronic system. Shown are the energy fractions carried by various hadron types according to the GiBUU and GENIE generators, in the scattering of 4-GeV electrons on an argon target. The event selection criteria here are: electron energy loss of at least 1 GeV and detected final-state particles go into a 40° forward cone. This angular selection is inspired by the capabilities of the LDMX detector, but similar trends are seen with other kinematic selections.

selection criteria motivated by the realistic capabilities of the LDMX detector (as described in the caption). We can see that, compared to GENIE, GiBUU predicts ∼40% less energy carried in electromagnetic showers caused by neutral pions and ∼50% more energy carried in neutrons, the latter being particularly difficult to measure. Such large discrepancies will result in large uncertainties on the inferred neutrino energy, with the exact numbers dependent on the performance of the event reconstruction procedure [2].

The consequences of failing to accurately reconstruct neutrino energy are well known. Roughly speaking, accurate determination of the *energies* corresponding to oscillation minima/maxima translates into precise determination of neutrino-mass splittings, while precise determination of the *magnitudes* of these features translates into precise determination of mixing angles. Hence, inaccuracy of the neutrino-energy scale determination affects the extracted mass splittings, while inaccuracy of the estimated energy resolution introduces a bias in the determined mixing angles. As a concrete illustration here, one may consider the evolution of results from the NOνA experiment [9–11]. In 2016, the measurements seemed to indicate exclusion of maximal mixing for the atmospheric oscillation channel at the 2.5σ level [10]. As the energy reconstruction procedure was refined, however, this exclusion got significantly weakened in most recent analyses [11].

Moreover, since neutrino cross sections depend on E_ν, energy mis-reconstruction can lead one to incorrectly infer the appearance probability in the $\nu_\mu \to \nu_e$ or $\bar{\nu}_\mu \to \bar{\nu}_e$ modes. This can spoil the measurements of the CP-violating phase, $\delta_{\rm CP}$, or introduce apparent contradictions between different pieces of data [2]. Even more impetus for accurate energy determination arises if one relaxes the no-BSM-physics assumption in the oscillation analysis.

In this case, various degeneracies between parameters may arise that are broken if one measures the appearance probability over a range of energies.

With the stakes being so high, it is clear that a program of validation and improvement for the generator physics is essential for the success of the DUNE program. Once again, electron scattering experiments can help, as we describe next.

IV. CURRENT DATA, PROSPECTS, AND THE OPPORTUNITY AT S30XL

The problem of understanding neutrino-nucleus interactions and final-state compositions has already motivated several electron-scattering measurements. We summarize these below, then comment on how the S30XL facility could enable a more flexible and comprehensive program.

A recent experiment, E12-14-012, in Hall A at Jefferson Lab used the High Resolution Spectrometers (HRSs) to measure the inclusive (e, e') and exclusive $(e, e'p)$ cross sections of argon and its mirror nucleus, titanium, at beam energy 2.2 GeV [6, 12]. The experimental proposal was motivated by the need of improving the description of nuclear effects in DUNE [13]. Making use of the HRSs' excellent precision, the experiment E12-14-012 investigated the ground-state properties of the argon and titanium nuclei, from the measurements of single proton knockout detected in coincidence with electron scattering. For limited kinematics, corresponding to scattering angle 15.5°, that experiment has reported the inclusive cross sections [6, 12], which are in fact used by us in Fig. 1 (left panel). However, systematic studies of final-state configurations involving pions or more than one nucleons are beyond the scope of that experiment, and so is exploring the full range of kinematic conditions relevant to DUNE.

A second experiment, named "Electrons for Neutrinos" ($e4\nu$), has been proposed and approved for Jefferson Lab Hall B, which will use the CLAS12 detector [4, 5]. The $e4\nu$ proposal will take 20 days of production data, spanning 4 beam energies (1.0–6.6 GeV) and 5 target nuclei ($^{4}_{2}$He, $^{12}_{6}$C, $^{16}_{8}$O, $^{40}_{18}$Ar, and $^{120}_{50}$Sn). CLAS12 has broad acceptance in both angle and momentum, and therefore can detect a recoiling electron as well as hadronic final states above a threshold momentum. The $e4\nu$ proposal has been approved by the JLab PAC, and is scheduled to run in summer 2021.

The aims of a S30XL neutrino program are to extend and complement the $e4\nu$ proposal, by enabling extended data-taking for experiments that can make a rich set of hadronic final-state measurements *simultaneous with* precise reconstruction of the recoiling electron [3]. Specifically, S30XL can improve on the currently proposed program in the following ways:

- The prerequisite for an electron-beam program relevant to neutrino physics is the use of a continuous-wave electron beam at energies comparable to the multi-GeV neutrino energies at DUNE. Currently, the only such beam is at JLab, which is highly oversubscribed by the NP program (Hall B alone has over 1000 days of approved experiments) and so HEP-motivated experiments receive limited priority in scheduling. An HEP-owned facility would allow considerably more flexibility and beam-time to realize this program.

  Moreover, the theoretical understanding of how different physics effects will affect DUNE's systematic uncertainties is still evolving; given the priority of the neutrino program within the US HEP enterprise, the ability to mount new experiments with a short turn-around time, to address these questions as they arise, is imperative.

- The S30XL facility can host detectors that are repurposed, reconfigured, or designed specifically to accomplish this physics. This allows greater flexibility than is afforded by the CLAS12 detector.

  This flexibility is required because, as described below, the program of measurements motivated by neutrino physics calls for precise reconstruction of far-forward physics, broad angular acceptance with low detection thresholds, and neutron detection capabilities. This motivates going beyond the CLAS and Hall A programs at JLab, which *requires* the flexibility for installing new detectors that would be enabled by a dedicated, HEP-managed beamline.

  In particular, (i) CLAS12 lacks a calorimeter thick enough to contain neutron showers, and has poor neutron detection efficiency beyond 40° production angle; (ii) The CLAS12 momentum threshold $\sim$300 MeV/c [14] exceeds the characteristic momenta of pions expected at DUNE based on MINERvA data [15]; (iii) CLAS12 covers a limited range of polar angle, and cannot detect particles emitted at backward ($\theta > 143°$) or very forward ($\theta \lesssim 8°$) angles; and (iv) CLAS12 has substantial gaps in azimuthal coverage; these gaps introduce considerable challenges for data analysis, which have been a limiting factor for analysis of existing CLAS6 data [14]. An experiment with enhanced capabilities in any combination of these directions will not just identify modeling errors in hadronic effects and FSI, but also provide a powerful calibration for improved modeling *that matches cleanly to the kinematics relevant for DUNE energy reconstruction.*

With respect to the last point, it may not be practical to build a detector that surpasses CLAS12 on *all* of the above simultaneously. Nonetheless, the two low-cost "straw-man" detectors presented at the workshop, and discussed in Statements of Interest that follow, already represent substantial improvements in a subset of these areas. For example, repurposing the **LDMX** detector for electronuclear measurements offers excellent forward coverage, 2π azimuthal coverage, and excellent neutron detection with somewhat reduced momentum thresholds comparable to those of CLAS12, but limited capabilities for charged particles produced at polar angles > 45°. A second concept would use a **low-cost TPC to achieve nearly 4π coverage**, with low detection thresholds but limited neutron-detection capability; limited forward coverage could be made up by using the TPC in conjunction with a forward tracker. Each of these concepts will be presented in a statement of interest accompanying this report. Clearly, the next step in developing this program would require a more thorough study to understand what detector capabilities are most important, and how to balance these capabilities against each other in a cost-effective manner.

V. A PROGRAM OF KEY MEASUREMENTS

The physics program for an electronuclear experiment at S30XL has two components [3]:

a. Inclusive measurements of event rate vs. electron kinematics, over a range of beam energies, allowing characterization of the nuclear response well beyond existing data, and overlapping a region where existing models are significantly discrepant with data. Figure 3 illustrates the density of DUNE events in leptonic phase-space (Q^2 vs. energy transfer ω). The coverage of existing data for argon and titanium at kinematics relevant to DUNE is currently limited to one dataset per nucleus [6, 12]. Even for carbon, the best-studied nucleus, existing data misses most of the DIS region [16]. The blue and green contours in

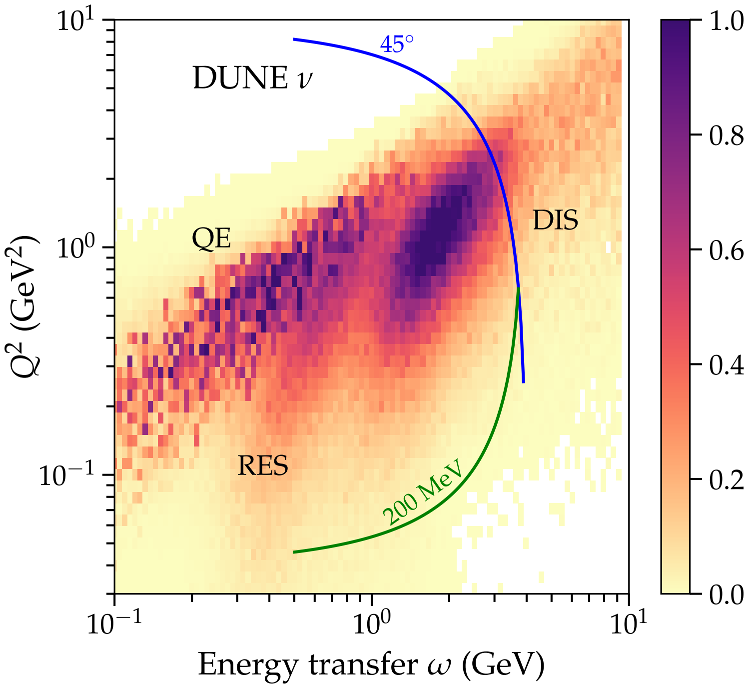

FIG. 3: The color map shows the kinematics of neutrino event distribution in DUNE, with different physical processes marked. The blue curve shows a contour of 45° final-state lepton scattering angle, while the green curve shows a contour of constant $p_T = 200$ MeV. The region to the left of these curves can be covered by the LDMX detector.

Fig. 3 illustrate that the bulk of this uncovered phase space is in a relatively accessible region for a broad-acceptance experiment at S30XL with a 4 GeV beam: the electron typically falls within a 45° cone has transverse momentum exceeding 200 MeV. Additional phase space could be explored using other beam energies. More importantly, data could be collected for argon and titanium.

In addition to the DIS region of GeV-scale energy transfer being poorly explored to date, the rates and physics of these reactions are not yet adequately understood (even at lower energy transfer). Figures 1 and 2 illustrate two different aspects of this modeling uncertainty: not only are there 20-50% discrepancies between generators and inclusive data (a discrepancy that persists in more extensive surveys of the literature [16, 17]), but the balance of hadronic energy between pions and nucleons in the high-energy-transfer events also differs across generators by $> 50\%$. The first type of discrepancy can be quantified with inclusive rate measurements alone, but addressing the second type of discrepancy requires a new class of measurements — one that can only be done with wide-acceptance detectors — which we discuss below.

b. Hadronic measurements, simultaneous with electron reconstruction are needed to disentangle the roles of different kinds of processes, breaking the degeneracy between inequivalent models illustrated in Fig. 2 and to improving the modeling of each hadron production mechanism relevant to neutrino scattering. This motivates measurements of hadron kinematics within detector acceptance, as well as characterization of the hadron *multiplicity* within some broad phase-space acceptance, as a function of the outgoing electron kinematics.

In the domain of a few hundred MeV energy transfer, the distributions of hadrons at 100 MeV scale kinetic energy provide valuable probes of the relative rates and kinematics for quasielastic reactions, resonance production, and meson-exchange interactions, as well as of the modeling of final state interactions (FSI) within the nucleus. These are essential for accurately modeling the low-energy particles in the neutrino final state that will be easiest to miss in DUNE energy reconstruction.

The domain of GeV-scale energy transfer, dominated by deep inelastic scattering (DIS), will become increasingly important to neutrino physics in the DUNE era. However, even the most inclusive measurements have not yet fully probed this domain. Characterizing the more energetic, forward hadrons produced in electron DIS will help to validate models of neutrino DIS. While it is true that electron scattering data, not probing the axial content of the nucleon, cannot be directly translated to neutrino modeling, measuring DIS reactions of electrons on a range of target nuclei *will* provide an important probe of FSI for the produced energetic hadrons. This calls for a rather demanding measurement: simultaneous reconstruction of (i) the outgoing electron to identify total energy transfer to the hadronic system, (ii) the energetic hadrons in the forward direction produced in DIS reactions, and (iii) the softer hadrons expected to arise from FSI emitted from nuclei over a wide range of angles.

VI. CONCLUSION

In summary, electron-scattering experiments are an important tool in constraining the nuclear physics uncertainties that plague the neutrino-oscillation program. Such experiments can help to test and improve modeling of both the primary lepton-nucleon scattering process and the development of the intra-nuclear hadronic cascade that are both essential for neutrino-oscillation measurements. The monochromatic incoming beam and larger interaction rate compared to neutrinos make this program complementary to direct measurements of charged-current interactions, either in near detectors or with auxiliary neutrino experiments [16].

All of these considerations motivate an electron-nucleus scattering program, which could be effectively carried out at S30XL [3]. Dedicated running at S30XL would allow for a rich program of measurements to validate nuclear modeling in neutrino generators. The beamline offers considerable flexibility to repurpose, reconfigure, or specifically design a detector to accomplish this physics; a detailed detector study has not yet been performed, and is a natural next step. The two "straw-man" detectors presented below offer excellent proofs of concept that an experiment with significant scientific relevance could be done at S30XL.

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[18] A notable exception here has to be made for the axial contribution to the interaction at the primary vertex, which needs to be studied separately.

Electron-nucleon measurements with LDMX at S30XL

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Abstract

LDMX is an electron fixed-target experiment designed to search for sub-GeV dark matter using the missing momentum technique. It can also be used to perform unique measurements of electron-nucleon interactions which are important for the future neutrino oscillation program. LDMX, in its baseline dark matter configuration, is particularly capable of probing the DIS region of the DUNE neutrino-nucleon phase space which is not well-constrained. As a 2π detector with excellent tracking and good hadronic acceptance, LDMX can measure the correlation between the electron and pions, protons, and neutrons from the recoiling hadronic system. We compare three electron-nucleon generators (GENIE, GiBUU, GEANT4) to study kinematic distributions of the electron and correlated pion and neutrons. We find that LDMX improves constraints of electron-nucleon modeling and provides valuable input to the simulation of lepton-nucleon interactions. We also briefly discuss potential extensions of the LDMX experiment which could further enhance the electron-nucleon physics program.

1 Introduction

LDMX (Light Dark Matter eXperiment) is a fixed-target experiment that is designed to search for sub-GeV dark matter employing a high repetition rate, low current electron beam [1]. For the studies described below, we assume a 4 GeV incoming electron beam and a dataset of 1×10^{14} EoT (electrons on target).

In Fig. 1, we illustrate the experimental signature of dark matter in LDMX. The incoming electron beam loses a significant fraction of its energy at the target and there is no other detectable energy from dark matter production. From this illustration, by replacing the dark matter signal with recoiling visible particles, one can see how LDMX can make measurements of electron-nucleon scattering processes.

The baseline detector configuration for LDMX detector is optimized for the dark matter search. The tagging tracking system and the target are housed inside of a 1.5 T dipole magnet while the recoil tracker is in the fringe magnetic field. The target is currently envisioned to be Tungsten and 0.1 X_0 thick, though different target materials and thicknesses are possible. These provide robust measurements of incoming and outgoing electron momentum. The tracking systems not

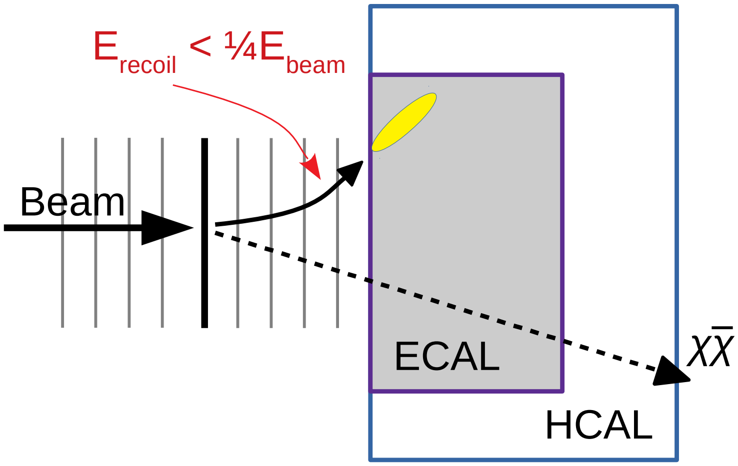

Figure 1: Schematic of the LDMX experimnent for dark matter

only enable missing momentum to be calculated, but allow for critical handles, such as the angle of recoil electrons, that will be important for characterizing any potential signals. The ECal is surrounded by the HCal to provide large angular coverage downstream of the target area to efficiently detect byproducts of target interactions which are critical to discriminating signal from SM backgrounds.

2 LDMX and DUNE

Within this baseline detector configuration, LDMX already has the potential to perform valuable electron-nucleon measurements. While the final detector design is still under development, we describe a coarse set of detector capabilities which are particularly relevant for electron-nucleon measurements.

- Electrons: We estimate the electron energy resolution to be between 5-10% and the p_T resolution to be < 10 MeV. The tracker acceptance is approximately 45 degrees in the polar angle where the $\hat{z}$ axis is defined along the beamline. Charged particles can be measured down to a kinetic energy of approximately 60 MeV. The estimate of tracking angular and energy acceptance is shown in Fig. 2.
- Charged pions and protons: We estimate the energy and p_T resolutions and tracking acceptance to be similar for charged pions and protons and electrons. The recoil tracker and ECal detectors can be used to do particle ID to separate charged pions and protons for kinetic energies < 1.5 GeV.
- Neutrons: We estimate the HCal to have an energy resolution of $5\% \oplus 40\%/\sqrt{E}$ and a polar angular acceptance of 65 degrees

Figure 3 shows the neutrino event distribution in the DUNE near detector according to the Monte Carlo generator GiBUU [2].

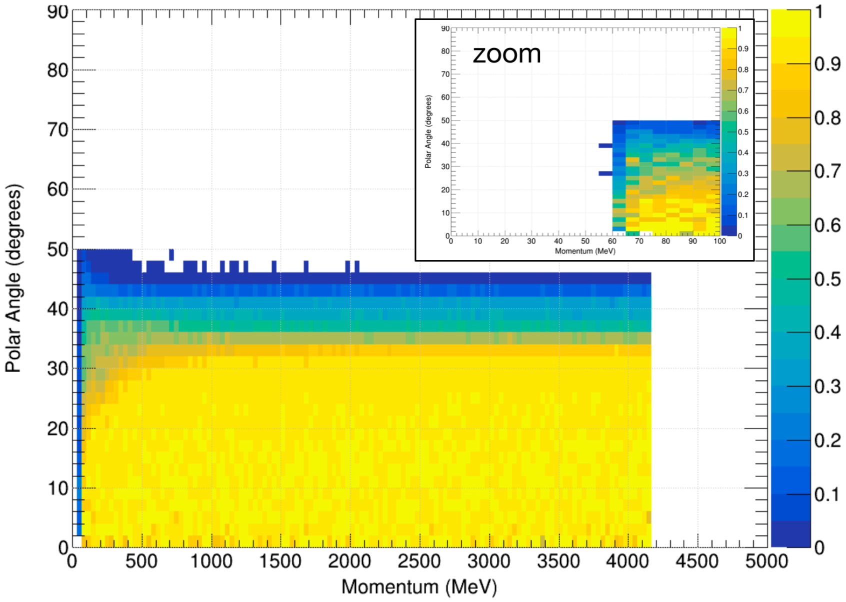

Figure 2: The color map shows the acceptance of a charged (pion) track as a function energy and angle. The acceptance is defined as a charged particle which leaves 4 hits in the recoil tracking system

Overlaid on it are iso-contours of electron scattering angle and transverse momentum. The iso-contours corresponding to a 45° scattering angle and to a p_T of 10 MeV (which lies below the scale of the plot) carve out the phase space that LDMX can probe. Within this space, and thanks to its great statistics, LDMX can map out all of the interaction channels: quasi-elastic, meson-exchange current, resonance production (RES), and deep inelastic scattering (DIS). The most easily accessible regions for LDMX are the transition region between RES to DIS and the DIS region with $\omega \gtrsim 1$ GeV. These regions have been the least explored by existing electron-scattering experiments, even at the inclusive level. Because they correspond to the highest event rates in DUNE, the measurements performed by LDMX are crucial to fully understand the results from DUNE.

The superb detection capabilities of LDMX also enable it to record almost all of the available information about its events. The unique capability to correlate the lepton and the system of hadronic recoils will enable LDMX to make the first exclusive measurement that is directly relevant to the long-baseline neutrino program. The high neutron detection efficiency is a crucial requirement for mapping out the full hadronic system. Fully characterizing the hadronic system will provide valuable information for cross-section modeling. Potential spectral features due to final-state interactions can be directly measured due to the fine energy resolution. Charged-pion and proton separation not only allows to distinguish interaction channels, but also is relevant for understanding neutrino energy reconstruction in long-baseline neutrino experiments.

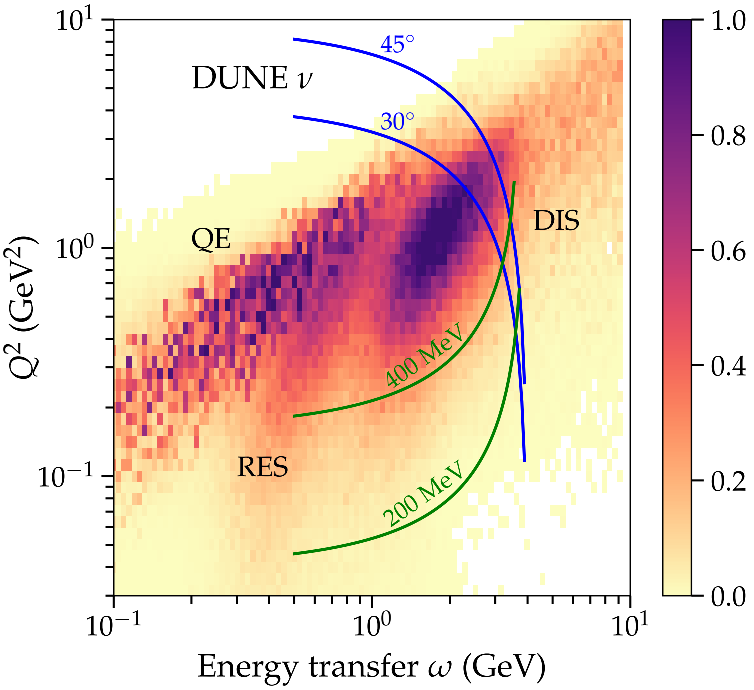

Figure 3: The color map shows neutrino event distribution in DUNE. Blue lines show contours of constant electron scattering angle. Green lines show contours of constant p_T.

3 Electron-nucleon measurements and generator comparison

Considering the baseline detector configuration, we study the potential for LDMX to make measurements of electron-nucleon processes which can be used to improve Monte Carlo generators. We study the modeling of electron-Tungsten interactions using three Monte Carlo generators: GENIE (v2.12.8) [3, 4], Geant4 (v4.10.p3) [5], GiBUU (v2017). The modeling of electro-nuclear interactions in Geant4 uses the Bertini cascade model [6] with improvements as described in [1].

In order to compare predictions for each of the different Monte Carlo generators, we define a common set of kinematic selections.

- $Q_e^2 > 0.03$ GeV^2 where Q is 4-momentum transfer of the electron before and after the target; a moderate selection is needed to define a phase space where the generators are physically valid
- $p_{T,e} > 0.2$ GeV and $\omega > 1$ GeV where $p_{T,e}$ is transverse momentum of the outgoing electron; this defines a selection where the electron has lost a significant amount of energy with respect to detector resolutions and is synergistic to the LDMX dark matter phase space

These kinematic selections are simply representative and not meant to be taken as strict detector limitations. Before performing these kinematic selections, we apply parametric angular and momentum/energy smearing of electron, charged hadron, and neutral hadron according to the expected detector resolutions described above. We also apply angular acceptance criteria according to the detector acceptance described above. We do *not* apply detector reconstruction identification efficiency effects since they are not yet defined. However, we expect them to be an $\mathcal{O}(1)$ effect.

In Fig. 4, we illustrate the energy transfer distribution of the electron (ω) for two different selections on the electron polar angle θ. These distributions are made after the common kinematic selections described above. The number of events in these figures are the expected number of events for a dataset of 1×10^{14} EoT. The distributions for the 3 generators are quite different both in overall rate and also their distribution. GiBUU produces less overall rate of events because it predicts a softer electron energy recoil distribution that passes the $\omega > 1$ GeV selection. The relative difference of each of the generators also varies strongly with the electron angle, θ. For example, in the $\theta = 10° - 20°$ selection GEANT4 and GENIE are somewhat similar, but are quite different in the $\theta = 20° - 30°$ selection.

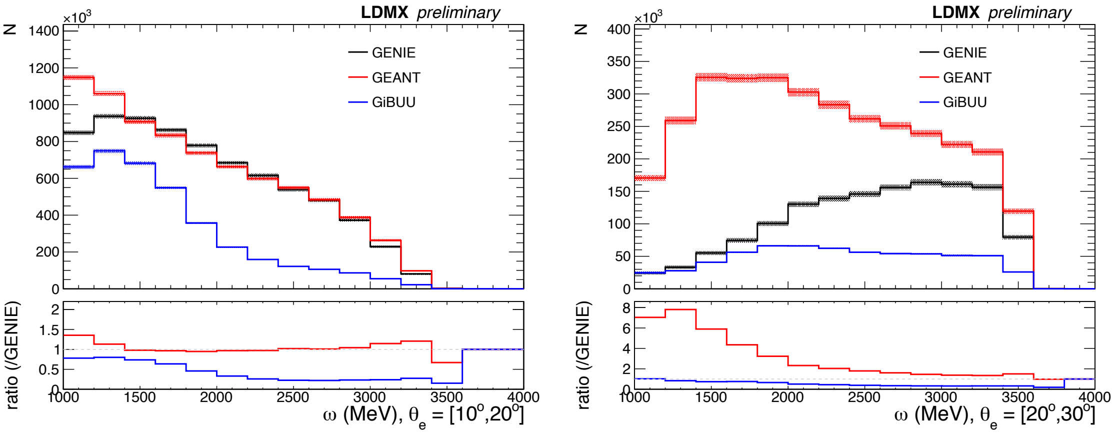

Figure 4: Electron energy transfer (ω) for an electron angle of $10° - 20°$ (left) and $20° - 30°$ (right).

The unique capability of LDMX to measure correlated information between the recoiling electron and hadronic recoil from nuclei is illustrated by the distributions shown in Fig. 5. In making the distributions, only events that pass the kinematic selections described above are considered. The distribution on the left shows the kinetic energy of all charged pions in an event. After accounting for the acceptance and energy resolution of the tracker, LDMX can measure the charged pion kinetic energy down to $\sim$60 MeV. On the right, the angular distribution of all neutrons in an event within the acceptance of the calorimeter and with (smeared) kinetic energies greater than 500 MeV is shown. The distributions are serve to illuminate the striking differences between the generators. The lower rate of GiBUU events is due to the selection on the electron energy transfer but the kinetic energy distribution of the charged pions is very different below 1 GeV. For the neutrons, GEANT4 produces a large fraction of forward (low θ) neutrons while GiBUU has a large fraction of high angle neutrons.

From representative distributions we have shown for the electron and hadronic recoil (pions, neutrons) kinematics, it is clear that there are large deviations in the predictions of electron-nucleon interactions from various state-of-the-art generators. Understanding the modeling of not only the recoiling lepton, but also the hadronic system is vital to understanding neutrino-nucleon interactions and event reconstruction at DUNE.

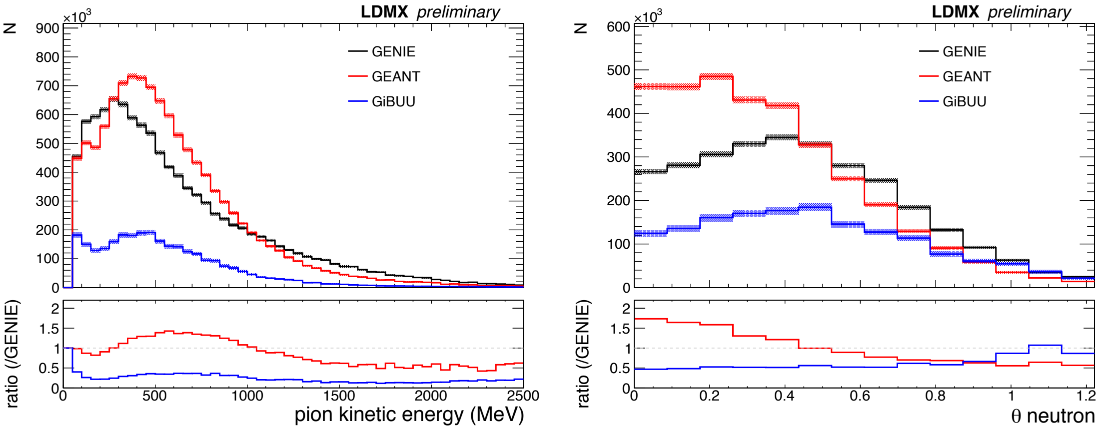

Figure 5: Charged pion kinetic energy distribution (left) and neutron polar angle distribution (right).

4 Potential Extensions

In the baseline dark matter configuration and nominal running, LDMX has the potential to perform valuable measurements of electron-nucleon processes of both the leptonic and recoiling hadronic systems. Beyond this nominal program, there is potential to extend the physics program. While some are more challenging to realize than others, we enumerate a few possibilities:

- The nominal physics selections can be extended to smaller energy transfer ω to fully cover the resonance production and meson-exchange current region. However, there are challenges with triggering on this topology (prescaling is a possibility) and eventually also issues of detector resolution. More study is left to future work to understand the impact of such measurements.
- We assume a 4 GeV electron beam in our studies above, but there is potential for different beam energies. Larger beam energies, in particular 8 GeV electron beams from higher energy LCLS-II, will move the LDMX acceptance contours to the right in Fig. 3. This would allow LDMX to cover more of the DIS phase space with relatively little change in the detector configuration.
- Varying the target material would provide more data for nuclear modeling. For example, scintillator of primarily Carbon and Hydrogen and Titanium (mirror nuclei of Argon) are target materials which can be particularly interesting to the neutrino community. In certain cases, this would conflict with the dark matter program and require dedicated beam time.
- In order to improve energy acceptance for low energy charged particles, the dipole magnetic field can be reduced. The effect of a reduced magnetic field on the reconstruction of higher energy particles is left to study in future work.
- Additional detector systems such as improved silicon tracking or high-angle scintillating detectors could improve the angular acceptance of LDMX for electron-nucleon measurements. However, much study is still needed to understand the benefits and potential costs including the effect on the dark matter program.

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Statement of interest: TPC with almost 4π electron scattering acceptance for neutrino cross-section studies

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As discussed in previous section, the next and current generation of neutrino oscillation spectrum requires unprecedent precision in the reconstruction of the neutrino energy in an event by event bases. Current neutrino experiments realize this energy reconstruction with two approaches. In water Cherenkov detectors such as SuperKamikande or HyperKamiokande, the energy is reconstructed based on the assumption of the neutrino interaction at the nucleon level and the assumption of the conservation of energy and momentum. In Calorimetric detectors such as Nova or Dune, the reconstruction is based on the addition of all the visible energy of the event. In both approaches, the identification of hadrons in the final state is critical to select the proper interaction channel or to sum the proper energy to the event. The interaction final states are affected by the initial nuclear state such as Fermi momentum or nuclear pair correlations and by final states such as Coulomb corrections, Pauli blocking and Final state interactions. See reference [1] for a more complete review of the situation. These nuclear phenomena are common to both neutrinos and electron scattering. Electron scattering experiments, opposite to neutrino experiments, allow us to control the initial state projectile. These experiments open the possibility of more detail modelling of the underlying nuclear physics.

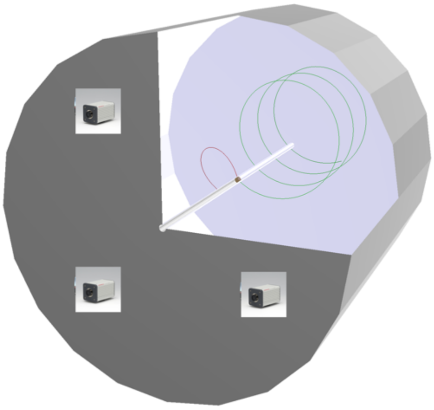

Figure 1. Artistic representation of the TPC showing two tracks, high and low momentum, emerging from the target inside the detector. Ionization electrons are transformed into light at the anode and read by cameras located at the cathode.

The main purpose of this experiment is to simulate neutrino interaction reconstructions with electron beams. This goal can be achieved by measuring all the final state particles regardless the particle momentum or angle. The detection of almost all the final states will enable the study of the nuclear contributions to the reactions by measuring transverse and longitudinal missing momentum, angular and momentum correlation, track multiplicities and the identification of the final state particles. These electron scattering experiments need to be carried out in a detector with almost full acceptance. This experiment does not require the precision on momentum and angle reconstruction of the electron scattering experiments such as the ones carried out in JLAB or MAMI. A moderate resolution of the order of few per cent with full acceptance will reproduce the capabilities of neutrino detectors without the need of very sophisticated technology. These studies might also provide results interesting to the nuclear physics community through the study the initial state correlation pairs inside the nucleus.

One possible realization of this experiment is an atmospheric pressure TPC surrounding a target located outside of the gas volume as depicted in Fig.1. The TPC is embedded in a magnetic field in the direction of the electron beam and the TPC field. The field will curve particles according to its transverse momentum so the strength is moderate, and it can be build using conventional technology. The TPC is expected to have around 1 m diameter and a length of 1 to 2 meters. Numbers need to be determined by simulations. The inner tube is one of the main challenges since it has to have the smallest diameter provided the beam transverse size, the multiple scattering in the target station of the incoming beam and the engineering limitations. The inner wall of the TPC can be very thin when operating the TPC at atmospheric pressure and allowing low momentum particles to enter in the active TPC volume. To reduce costs, the TPC can be readout by light following several developments in the field. The concept is based on the light emission of the gas mixture in the anode. This light is focused by an optical system and recorded with a photosensor. Several options are possible: from CCD’s, to multipixel MPPC’s or even the TimePix[2] readout at CERN. This last device is very convenient due to the large number of readout pixels (65000) at a moderate cost (~5000 $). Its time sampling capabilities that fits the TPC readout requirements. Similar optical readout system has been operated in the past at Berkeley and University of Geneva [3] and recently at Liverpool University [4]. The optical system allows to a demagnification which will allow to read large areas of the anode with few sensors. As a reference, an optical system with magnification x10 and the TimePix sensor will allow to read and area of 14x14 cm^2 with a pixel pitch of 500 um. The cost of such detector is normally driven by the field cage construction and readout. By using the light-based readout, the cost can be severely reduced to levels that be constructed by small collaborations.

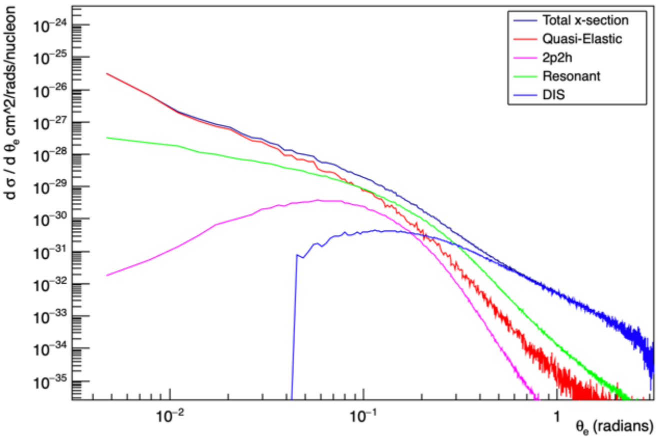

Figure 2. Scattering angle of 4 GeV electrons for different nuclear interactions.

The angular distribution of 4 GeV electrons scattered from the C nucleus as predicted by the GIBUU event generator [5] and shown in Figure 2. Requesting the electrons to traverse at least 25 cm inside the TPC (a fourth of the total length) with an inner TPC radius of 1cm, the minimum acceptance angle is around 40 milliradians. Most of the interactions below this value will be quasielastic and probably will not eject hadrons with a large transverse momentum. Electrons ejected below 40 milliradians can be detected with the LDMX forward calorimeter.

One of the drawbacks of TPC's is the low drift velocity in the gas, of the order of tenths of microseconds. According to the same GIBUU simulations, the integrated cross-section above 4 milliradians is of the order of 2 10^{-33} cm^2/nucleon. The interaction probability in a Carbon target with a density of approximately 2 g/cm^3 is of the order of 5 10^{-7} in a 1 mm thick target. At a 1 pA beam current, there will be ~3 interactions per second with the scattered electron above 40 milliradians. The event rates are within the TPC timing capabilities. Most of the interactions below 40 milliradians will leave no signature in the detector due to the low value of the momentum transfer. Targets thinner than 1mm will improve the performance, the lower interaction rate can be compensated with the high beam intensities and the target will affects less the hadrons produced in the interactions. A dedicated Monte Carlo study will be carried out to understand more precisely the capabilities of this design.

This project will also explore different nuclei targets and energies. To reach levels interesting to neutrino experiments based on the water Cherenkov technology, we will require electron beams with energies around 700 MeV. This energy can be achieved at other facilities such as MAMI in Mainz (Germany). Groups at the MAMI electron beam facility has already shown interest in the project.

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Letters Of Support
From The Broader Community

Attached are 4 letters of support we have received from spokespeople of neutrino experiments (DUNE, SBND, ANNIE, and MINERvA).

The letters attest support of the broader neutrino physics community for the overall goal of exploring neutrino-nuclear interactions at S30XL, but do not reflect an endorsement of more specific claims or proposals in the preceding statements, except as stated directly in the letters.

DEEP UNDERGROUND NEUTRINO EXPERIMENT

16 April 2019

We are writing in support of the proposal to study electron-nuclear scattering on Argon and/or Titanium nuclei at 2, 4, and 8 GeV using the proposed S30XL, to address the challenges described in the statement "Neutrinos at S30XL", for example using either the LDMX detector or a low-pressure TPC with nearly 4π coverage.

The DUNE experiment heralds an era of high precision neutrino physics. The experiment will compare neutrino and antineutrino oscillations to search for evidence of CP violation in the lepton sector. DUNE will use a broad-band beam, with neutrino energies up to 8 GeV.

To achieve the ultimate goals of the DUNE physics program, great emphasis is being placed on controlling systematic errors associated with many different aspects of the experiment, including the neutrino event energy reconstruction. The proposed efforts promise to produce data and data-generator comparisons that will prove useful in improving our understanding of neutrino-nucleus interaction in the energy range relevant for the DUNE program. In addition, the proposed data set is likely to be helpful in tuning the multi-nucleon, hadronically inelastic reactions, and FSI parts of the models used in DUNE.

While it is difficult to quantify the impact of the proposed measurements on DUNE, we believe it will provide data that will aid in improving neutrino interaction models and event generators.

Sincerely,

E C Blucher

Professor Edward C. Blucher
University of Chicago
Co-spokesperson of DUNE Collaboration

Stefan Söldner-Rembold

Professor Stefan Söldner-Rembold
University of Manchester
Co-spokesperson of DUNE Collaboration

Fermilab
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois, 60510

The University of Chicago
The Enrico Fermi Institute
5640 South Ellis Avenue
Chicago, Illinois 60637-1433

April 1, 2019

To Whom It May Concern:

We are writing, as representatives of the Short-Baseline Near Detector (SBND) neutrino experiment at Fermilab, to express our support for the developing proposal to study electron-nucleus scattering using the Sector 30 Transfer Line at SLAC. A major component of the SBND science program is the detailed study of the physics of neutrino-argon scattering using the millions of neutrino interactions that will be recorded in the SBND liquid argon time projection chamber (LArTPC) detector. The SBND dataset will be more than an order of magnitude larger than current neutrino-argon samples, and will provide the best opportunity for improving our understanding of these complicated interactions ahead of the DUNE long-baseline oscillation experiment, starting after 2026. The careful control of systematic uncertainties associated with neutrino-nucleus scattering will be paramount to achieving the precision physics goals of DUNE.

Multiple handles can provide a significant advantage for untangling the impacts of vector and axial currents as well as the dense nuclear environment in neutrino scattering. Electron-nucleus scattering data is complementary to neutrino data in this regard and can help in constraining the underlying models and could, therefore, enhance the efficacy of the neutrino data from SBND and other experiments. In our view, new data from a SLAC electron scattering experiment would contribute to our understanding of the physics of neutrino-nucleus scattering and benefit the ongoing effort to improve neutrino simulation codes and reduce systematic uncertainties for future neutrino experiments.

Sincerely,

SBND Collaboration Spokespersons:

Ornella Palamara

Ornella Palamara
Guest Scientist
Fermi National Accelerator Laboratory
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David W. Schmitz

David W. Schmitz
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IOWA STATE UNIVERSITY
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April 2, 2019

To Whom It May Concern,

We are writing to express the support of the ANNIE collaboration for the new proposal to study electron scattering using the Sector 30 Transfer Line at SLAC.

The field of neutrino oscillations studies is undergoing a major transition as we move from first ‘observations’ to high precision quantification of oscillation parameters and searches for new physics. One of the main sources of systematic uncertainties in neutrino oscillation analyses are neutrino-nucleus cross sections. The ANNIE collaboration is engaged in the study of neutrino-nuclear scattering with particular attention to final state neutrons. Our experiment benefits from the intense Booster Neutrino Beam. Even so, neutrino based scattering measurements like ours are limited by uncertainties in the underlying neutrino flux. The use of wide-energy neutrino beams, combined with the vector-axial nature of the neutrino interaction, makes reducing and quantifying this uncertainty a considerable challenge. Complementary data from electron scattering, bringing even higher statistics and a better-defined beam will be critical to the broader field and of high value to our own experiment. In particular, detailed measurements of final states from electron scattering, when combined with data collected by the ANNIE collaboration, will help to disentangle the vector and axial components of our data.

Neutrino nucleus scattering is a complex many-body problem that needs to be understood over a wide variety of target nuclei and energy. Neutrino experiments like ours will be able to measure specific aspects of the problem in the full context of a neutrino beam. However, the results of detailed electron scattering measurements such as this proposed work at SLAC can deliver broader scope and more control than are available to neutrino-based scattering experiments.

For these reasons we strongly endorse the proposed S30XLforNu measurements and look forward to incorporating their results in our own neutrino cross-section measurements.

Yours sincerely,

Matthew Wetstein

Matthew Wetstein
ANNIE Co-Spokesperson
Assistant Professor

Mayly Sanchez
ANNIE Co-Spokesperson
Cassling Family Professor

To Whom It May Concern,

We are writing in support of a new proposal to study electron scattering using the Sector 30 Transfer Line at SLAC.

The discovery of neutrino mass and mixing has inspired a new generation of neutrino oscillation experiments that impose stringent new requirements on our understanding of the impact of the nuclear environment on neutrino scattering. These same neutrino oscillation experiments have also given rise to intense neutrino beams, which in turn have allowed for a dedicated neutrino scattering experiment. The MINERvA experiment's goal is to measure and compare neutrino scattering cross sections on different nuclei using neutrinos in the few GeV range. We are writing on behalf of that collaboration to say that we very much encourage the electron scattering measurements coming from the S30XLforNu proposal, since they will be key to shedding light on these interactions.

To model neutrino interactions at oscillation experiments, many different effects must be parameterized and measured. At the moment, neutrino experiments have to disentangle uncertainties related to vector and axial currents and the impact of the nuclear environment. While some of these, such as the axial vector component of the neutrino-nucleon cross section, are best measured by neutrino experiments such as MINERvA, several other effects can be precisely measured in electron scattering experiments. The proposed S30XLforNu measurements will substantially improve the reach of MINERvA by constraining models of the vector current and impact of the nuclear environment, thus allowing us to use the full power of the MINERvA data to measure effects specific to neutrino scattering. While there are other electron scattering for neutrino efforts ongoing at JLAB, those experiments are hampered by very restricted beamtime. We strongly support the proposal for a dedicated electron scattering facility at SLAC, which will facilitate large and comprehensive datasets that are needed for developing and tuning neutrino interaction models.

Although near detectors are planned for all long-baseline oscillation experiments, they simply are not enough to constrain the models needed for the high precision predictions for the far detector. Part of the reason for this is that due to the large mixing angles, the far detector spectra are substantially different from the near detector spectra. The next goals in the field are associated with precise comparisons of electron neutrino and antineutrino appearance. One has simply to look at T2K's recent oscillation papers to understand how much oscillation experiments rely on external cross section measurements. This reliance will only increase as accelerator-based oscillation experiments become systematically dominated over the next decade.

Having a comprehensive set of electron scattering data with various final states obtained on a wide range of nuclei and beam-energies will not only significantly constrain our neutrino event generators, but will also allow MINERvA itself to make better measurements. We do our best to predict backgrounds using our own data but we too must extrapolate, in our case from other kinematic regions, and the better that extrapolation, the better our measurements will be.

Please contact us if you have any additional questions about how these data will support MINERvA's physics program.

Sincerely,
Laura Fields
Deborah Harris
MINERvA Spokespeople
on behalf of the MINERvA Collaboration

Statement Of Interest: Light Dark Matter eXperiment (LDMX) at S30XL

Torsten Åkesson[1], Asher Berlin[2], Nikita Blinov[3], Lene Bryngemark[4], Giulia Collura[5], Caterina Doglioni[1], E. Craig Dukes[6], Valentina Dutta[5], Bertrand Echenard[7], Ralf Ehrlich[6], Thomas Eichlersmith[8], Niramay Gogate[9], Vinay Hegde[9], R. Craig Group[6], Joshua Hiltbrand[8], David G. Hitlin[7], Joseph Incandela[5], Gordan Krnjaic[3], Amina Li[5], Dexu Lin[7], Jeremiah Mans[8], Phillip Masterson[5], Takashi Maruyama[10], Martin Meier[8], Sophie Middleton[7], Omar Moreno[10], Geoffrey Mullier[1], Timothy Nelson[10], James Oyang[7], Reese Petersen[8], Ruth Pöttgen[1], Stefan Prestel[1], Luis Sarmiento Pico[1], Philip Schuster[10], Lauren Tompkins[4], Natalia Toro[10], Nhan Tran[3], and Andrew Whitbeck[9]

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August 25, 2020

Abstract

If there is an interaction between light DM and ordinary matter, as there must be in the case of a thermal origin, then there is necessarily a production mechanism in accelerator-based experiments. The most sensitive way (if the interaction is not electron-phobic) to search for this production is to use a primary electron beam to produce DM in fixed-target collisions. LDMX, the Light Dark Matter Experiment, is a small-scale experiment employing a multi-GeV electron beam and a missing-momentum-and-energy signature to search for this dark matter production reaction, as well as mediator production, in the sub-GeV mass region. LDMX can explore dark-matter-electron couplings in uncharted regions that extend down to and below the level motivated by direct thermal freeze-out mechanisms. In contrast to any other dark matter detection scheme, LDMX can efficiently probe both scalar **and** fermion dark matter, including both spin-independent reactions and the spin-dependent and inelastic interactions typical of sub-GeV thermal fermion dark matter. LDMX would also be sensitive to a wide range of visibly and invisibly decaying dark sector particles, thereby addressing many of the science drivers highlighted in the 2017 US Cosmic Visions New Ideas in Dark Matter Community Report and strongly overlapping both thrusts of the Priority Research

Direction "Create and Detect Dark Matter at Accelerators" emphasized in the 2018 Basic Research Needs for Dark Matter New Initiatives DOE report. LDMX would achieve the required sensitivity by leveraging existing and developing detector technologies from the CMS, HPS and Mu2e experiments. Achieving this sensitivity relies crucially on access to a low-current, multi-GeV CW electron beam. The S30XL beam is very well matched to these running requirements and, in contrast with CEBAF, is better able to support the 6-to-24-month run times required for LDMX.

Motivation and Science Goals Discovering the particle nature of dark matter (DM) is perhaps the most pressing challenge facing elementary particle physics today. Among the simplest possibilities is one in which dark matter arose as a thermal relic from the hot early Universe, which only requires small non-gravitational interactions between dark and familiar matter, and is robustly viable over the MeV to TeV mass range. Testing the hypothesis that the dark matter abundance arises from weak boson-mediated interactions has been the primary focus of direct and indirect detection experiments to date, which are most sensitive to dark matter particles with masses ranging from a few GeV to a TeV. However, the lower mass range of MeV to GeV, where the most stable forms of ordinary matter are found, has remained stubbornly difficult to explore with existing experiments.

In recent years, powerful ideas to probe “light dark matter” (LDM) in the sub-GeV mass range have emerged from efforts to test the intriguing possibility that dark matter is part of a dark sector that is neutral under all Standard Model (SM) forces (see [4, 7] for recent reviews). As with Weakly Interacting Massive Particles (WIMPs), an attractive sensitivity milestone is motivated by the requirement that thermal freeze-out reactions give rise to an appropriate abundance of dark matter. This casts a spotlight on dark matter interactions with electrons that is only a few orders of magnitude beyond existing accelerator-based sensitivity [1]. To reach this goal, our aim is to use an electron beam to produce dark matter in fixed-target collisions, making use of missing energy and momentum to identify and measure dark matter reactions [17, 16]. The NA64 experiment at CERN has already carried out a first physics run for a fixed-target electron beam experiment using missing energy as the identifying signature [5, 6]. That experiment promises to reach a sub-GeV dark matter sensitivity surpassing all existing constraints by 2020 [4, 12], but will fall short of the required sensitivity primarily due to luminosity limitations. At masses above $\mathcal{O}(500)$ MeV, Belle II’s future missing mass measurements might provide the required sensitivity, but will certainly fall short at lower masses due to luminosity and background limitations.

The “Light Dark Matter eXperiment” (LDMX) is designed to meet the following science goals:

- Provide a high-luminosity measurement of missing momentum in multi-GeV electron fixed-target collisions, sensitive to **both** direct dark matter production and mediator particle production. This measurement would provide broad sensitivity to dark matter interactions over the entire sub-GeV mass range while circumventing limitations inherent to non-relativistic probes of dark matter. In contrast to other detection approaches, this would provide strong sensitivity to both scalar **and** fermion dark matter, for both spin-independent **and** spin-dependent interactions. LDMX would aim to extend sensitivity by three orders of magnitude beyond the expected reach of NA64 in the near future, providing the sensitivity needed to test most scenarios of dark matter freeze-out via annihilation into light Standard Model final states, a goal highlighted in [7] and [1]. This measurement will provide LDMX with excellent discovery potential, and is the primary science driver for the experiment.

- Using missing momentum measurements, explore broad and important new territory for secluded dark matter models, millicharge particles, invisibly decaying dark photons, axions, and dark higgs particles. By extension, explore significant new territory for SIMP [15, 14, 8], ELDER [19, 20], asymmetric [21, 22], and freeze-in [11, 13, 10] dark matter scenarios.
- Using LDMX as a short baseline beam dump, provide sensitivity to displaced visible decays of dark photons, axions, inelastic dark matter, dark higgs, and other long-lived dark sector particles. Variations of LDMX with a *muon* beam can also explore dark sectors whose particles couple preferentially to the second generation [18].

As a multi-purpose experiment, LDMX will be able to address an especially broad range of the dark sector science highlighted and prioritized by recent community planning efforts [7, 1], with special emphasis on the simplest thermal sub-GeV dark matter scenarios. We believe that LDMX would have extraordinary discovery potential and therefore provide the foundation for a successful light dark matter program in the US or abroad.

The Missing Momentum Measurement and Detector Concept To search for either dark matter or mediator production, LDMX reconstructs the kinematics of each beam electron both up- and down-stream of the target using low-mass tracking detectors. The up-stream tracker tags the incoming beam electrons while the down-stream tracker selects the low-energy, moderate transverse-momentum recoils of the beam electrons. Calorimetry is then used to veto events with an energetic forward photon or any additional forward-recoiling charged particles or neutral hadrons. Because each electron passes through the detector, the experiment must contend with high event rates in the tracker and electromagnetic calorimeter. Therefore, LDMX requires low-mass tracking that provides high-purity tagging for incoming electrons and clean, efficient reconstruction of recoils in a high-rate environment. The calorimetry for LDMX must simultaneously be fast enough to support this high rate of background events, most of which are "straightforward" to reject based on their high electromagnetic energy deposition, and sensitive enough to reject rare but subtle processes where a hard bremsstrahlung photon undergoes a photo-nuclear reaction in the target or in the calorimeter itself. These simultaneous requirements call for a high-speed, high-granularity calorimeter with minimum-ionizing particle (MIP) sensitivity to identify photo-nuclear products, used in conjunction with a hadron calorimeter that experiences much lower event rates. The primary physics trigger requires a positive signal in a scintillator pad overlaying the target, coincident with low (or no) energy deposition in the ECal relative to the number of full-energy electrons counted in the scintillator pad. As described in the whitepaper [2] and in [3], LDMX plans to meet these technical challenges by leveraging technology under development for the HL-LHC and Mu2e, as well as experience from the Heavy Photon Search (HPS) experiment. Figure 2 shows an overview of the LDMX detector concept (left) and a cutaway highlighting the trackers, target, ECal, and HCal (right).

The experiment is planned to run the experiment in two phases. Phase I plans for a total luminosity of 0.8 pb^{-1}, corresponding to 4×10^{14} tagged electrons on target. This can be achieved by running S30XL at a mean charge of 1 e^{-} per bunch for one 150-day operating year. This first phase achieves groundbreaking sensitivity with only minor deviations from established detector technologies. The studies and results in [2] primarily focus on Phase I performance at a beam energy of 4 GeV and imply

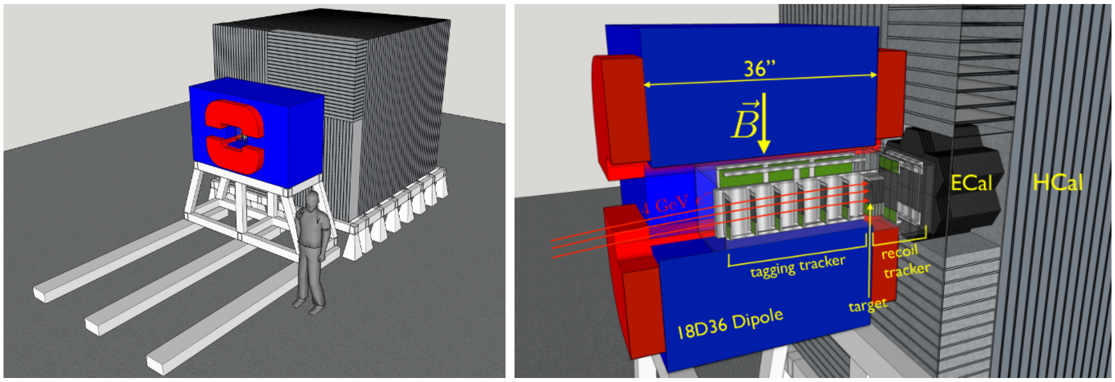

Figure 1: (From [2]) Left: An overview of the LDMX detector showing the full detector apparatus with a person for scale. Right: A cutaway overview of the LDMX detector showing, from left to right, the trackers and target inside the spectrometer dipole, the forward ECal, and the HCal.

a healthy margin of safety for contending with potential backgrounds. These results also suggest that higher (by factor of ~ 25) luminosity running at 8 GeV energies will be possible, with background rates falling steeply with incident beam energy. Therefore, Phase II will increase the integrated luminosity 30-fold (through a combination of modest increases in current, target thickness, and run duration) at 8 GeV energy. As discussed below, the timeline for running these two phases is compatible with the timeframe for S30XL construction and the LCLS-II HE upgrade.

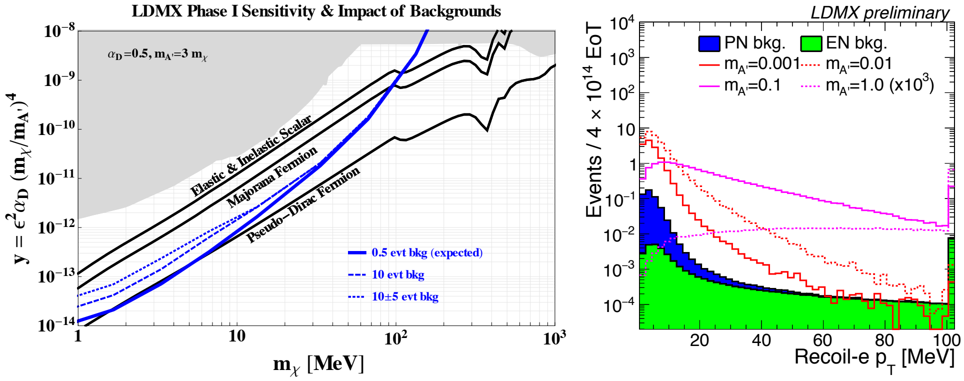

Figure 2: (From [2]) Left: Projected sensitivity of LDMX to a benchmark dark matter model in Phase I operation, with expected level of background rejection according to Monte Carlo studies (solid curve) or unexpectedly larger background rates (dashed/dotted lines illustrate well calibrated background or background with 50% normalization uncertainty). Right: Transverse momentum distribution of the recoiling electron, in signals at different mass scales (open histograms) and photonuclear and electronuclear backgrounds (filled histograms).

Detailed Phase I performance studies in [2] indicate an expected Phase I background of < 1 event after a combination of vetoes using tracking, ECal energy deposition and shower profile, and HCal energy deposition requirements. The performance of this analysis chain has been studied on both pure electromagnetic showers and dedicated high-statistics Monte Carlo samples for photonuclear and muon-conversion reactions of a hard bremsstrahlung photon, as well as electronuclear reactions of the primary electron in the target. The latter reaction classes can be challenging to reject, and few-particle event topologies are design drivers for specific sub-systems. For example, the rate of events with a single energetic neutron or K_0^L drives the needed HCal depth, while the rate of di-neutron events with sizable opening angle largely determines the required transverse size. The rates and kinematics for these exclusive final states have been derived directly from exclusive cross-section measurements, in addition to the more inclusive Monte Carlo studies. The expected sensitivity of a Phase I search to dark matter particle production, in a commonly quoted benchmark parameter space, is illustrated by the blue curve in Figure 1(left). The sensitivity of LDMX to a range of other dark matter models and other physics signals is presented in [2, 9]. The dashed (dotted) curves correspond to sensitivies achievable with 20x larger than expected backgrounds, with subdominant, or 50%, systematic uncertainty in background rate, respectively. In these cases, the sensitivity to low-mass signals is world-class but visibly degraded. At higher masses, background-free sensitivity is maintained by using the transverse momentum p_T of the recoiling electron as an additional discriminating variable. This distribution is well understood theoretically, quite uncorrelated with the instrumental vetoes, and, as illustrated in Figure 1(right), strikingly different between background reactions (filled histograms) and dark matter signals (open histograms).

The greater luminosity of Phase II will enable sensitivity at the level of the red curve in Figure 3. Achieving this sensitivity requires improved background rejection beyond Phase I, but this is greatly facilitated by the higher beam energy, because (i) the rate of few-body reactions that are limiting backgrounds falls as a high power of beam energy ($1/E^3$ in most cases), and (ii) the larger boost of the CM frame leads to more forward kinematics for the products of these reactions, facilitating the detection of both high- and low-energy products. For these reasons, the overall quality of background rejection is actually expected to improve from a 4 GeV Phase I to an 8 GeV Phase II. Rather, the greatest challenges anticipated for Phase II will be managing the side effects of higher luminosity, such as increased pile-up and initial/final state interactions in a thicker target.

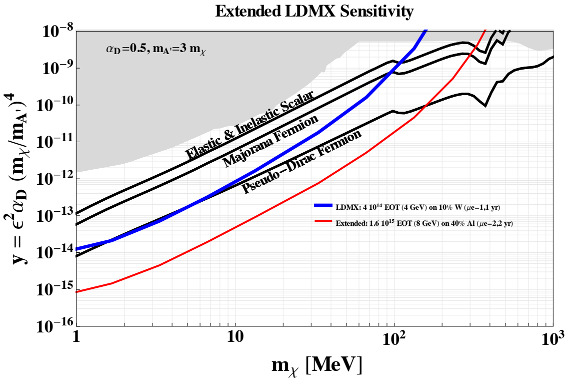

Figure 3: (From [2]) Left: Projected sensitivity of LDMX Phase I and an example configuration for Phase II. Each "year" in the legend refers to 150 days of beam with the S30XL 60% duty-cycle macropulse structure.

Required Space and Infrastructure As shown in Figure 2, the detector's space requirement is dominated by the HCAL, which in simulation studies has been conservatively modeled as filling a 3m × 3m × 3m volume, so that the entire detector fits in a 3m × 3m × 4.5m volume. Current performance studies suggest that a 2m transverse dimension for the HCAL may achieve sufficient background rejection. In either case, the detector can be readily accommodated in the rear of End Station A.

Basic infrastructure in End Station A is suitable for construction and operation of LDMX. There is coverage with a 50 ton crane, as well as low conductivity water (LCW), air and power, as well as communications to a counting house. The personnel protection systems have been recently updated and allow access within minutes. There are large power supplies capable of operating the 18D36 magnet for the experiment, and the LCW supply is more than adequate to provide the 55 gpm expected to cool the magnet, which is expected to consume approximately 450 kW at the operating point of 1.5 T.

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Test Beam Applications of S30XL-LESA

Section editor: Timothy K. Nelson

This section presents some illustrative examples of test beam applications for the S30XL-LESA facility.

As a test beam, S30XL-LESA offers three principal distinctive features:

- a high repetition rate of up to one pulse every 21 ns, directly applicable to high-rate performance and pile-up studies, and advantageous more generally for rapid accumulation of data,
- a ps or sub-ps scale pulse length, advantageous for calibrating precision timing detectors, and
- beam delivery parasitic to normal LCLS-II operations, the core activity at SLAC, resulting in ~250 day/year availability (to be shared between test beam and other HEP applications).

Below are nine statements of interest that illustrate the breadth of test beam applications for S30XL-LESA. These have been organized into three broad areas:

- Detector studies for LHC upgrade detectors and related experiments, such as
    - Characterizing position and timing resolution of ATLAS silicon detector prototypes
    - Studying EM shower response and pileup effects in the CMS HGCAL
    - Tests of Silicon Pixel Tracking and Fast Timing Detectors for ATLAS upgrades and future colliders
- Basic detector R&D efforts, including
    - Testing the Timing Vertex Detector technology
    - Characterization of low-gain avalanche detectors under development for 4D tracking
    - R&D towards using the fast scintillation component of BaF2 for high resolution and high rate crystal calorimeter
    - Studies of EM-induced radiation damage for high-luminosity electron colliders and EIC
- Detector development for other experimental programs in HEP and NP
    - Detector tests for projects in the CERN Physics Beyond Colliders umbrella, such as a FASER upgrade and MATHUSLA
    - Measuring the detector response of fused silica integrating detectors for the MOLLER experiment, in both single-electron and integrating regimes

Statement Of Interest: Characterization of Silicon Tracking Devices

M. Garcia-Sciveres

March 31, 2019

Abstract

The ATLAS group at LBNL has a long standing interest in test beam measurements of silicon detector protototypes. These are needd to characterize the response, such as position and timing resolution. High statistics are helpful and S30XL will provide a very important improvement over the present SLAC test beam rep rate of 5Hz.

The LBNL ATLAS experiment group has carried out electron beam tests at ESA on several occasions over the past few years with excellent results. We typically measure the performance of precision tracking detector prototypes. This benefits from high statistics and up to now the 5Hz rate at SLAC has been a limitation. While he beam is capable of a large number of particles per shot, most measurements require few particles per shot and high rep rate. S30XL would provide a major improvement in this direction.

Detector R&D into silicon tracking devices at LBNL will continue into the next decade to support further upgraded at the HL-LHC as well as R&D for future colliders. We will have a need for test beams and will propose experiments to measure silicon tracking detector performance at S30XL. While other facilities exist (FNAL and CERN), they are in high demand and not sufficient to accommodate all users. Also no facility is available year-round.

A unique feature at SLAC that other facilities do not have is very sharp timing of beam pulses with a provided trigger. The importance of this feature will grow in importance over the coming years as the incorporation of sub 100ps timing is incorporated into silicon tracking devices.

Typical test beam campaigns require between 3 and 7 days of beam time. Shorter times are usually not productice due to significant setup. A beam telescope as already present at ESA is mandatory for many measurements.

Possible collaborating institutions: SLAC, ANL, UCSC, U. Washington, U of Oregon, KEK.

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COMPACT MUON SOLENOID COLLABORATION
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To whom it concerns

Geneva, 25 March 2019

Notre référence / Our reference : `CMS-20190325/SLACTB`

Letter of support for the planned Test Beam Facility at SLAC

CMS strongly supports the realization of the proposed electron test beam facility at SLAC featuring a highly programmable laser gun with a fundamental 4 ns RF spacing. The possibility to produce controlled pulse sequences would open up the possibility to study dedicatedly out-of-time pile-up. This will be very useful for CMS and in particular important for the new High Granularity Calorimeter HGCAL with an intrinsic need to study showers arising from electrons. The energy range (4-8 GeV) is sufficient to instigate these electromagnetic showers (with suitable absorber materials) and the repetition rate will facilitate realistic pileup studies. These investigations would take place over the course of the coming 2-3 years as our final electronics become available. Therefore, there is significant interest from the HGCAL community to exploit the electron beam line at SLAC, as these dedicated studies are not possible at CERN nor at DESY. This effort would complement studies at DESY and CERN. We are also evaluating the interest of the Precise Timing Detectors.

CMS strongly supports the realization of this facility and we are looking forward to using it.

Sincerely Yours,

Frank Hartmann – CMS Upgrade Coordinator

*Adresse postale pour le courrier posté en France : CERN : Site de Prévessin, F-01631 CERN Cedex

Statement Of Interest:
Silicon Pixel Tracking and Fast Timing Detector Test Beam at S30XL

D. Su

April 1, 2019

Abstract

The local ATLAS community at the Bay Area has benefited significantly from the existing SLAC End Station A Test Beam (ESTB) for ATLAS HL-LHC upgrade related sessions. S30XL is of strong interest to this community with various development on silicon pixel tracking and fast timing detectors for HL-LHC mid-term inner pixel replacement and future hadron and e^+e^- colliders.

The close vicinity of the SLAC ESTB has enabled convenient and effective test beam sessions for the sizable local Bay Area ATLAS community for various HL-LHC upgrade projects. Two main areas of ESTB sessions for this community were ATLAS ITk pixel detector prototypes and the High Granularity Timing Detector (HGTD) prototypes. The interests from this community in silicon pixel detector and fast timing detector development for future collider could be well served by the availability of S30XL. The ATLAS Inner Pixel system for HL-LHC we are currently building is expected to last for 2000 fb^{-1} which could be as early as 4 years since the start of HL-LHC, so that the planning and active R&D may need to start before the end of the construction of the initial HL-LHC upgrade. This line of development in the near term would evolve towards future hadron colliders. The less stringent demands on radiation hardness and rate capability, but more stringent material and power budget at future e^+e^- colliders will motivate synergistic variants of these development. Possible detector R&D directions may include, but not limited to, e.g.:

- More granular pixel and fast timing detectors with readout chips at finer feature size
- Radiation hard monolithic CMOS pixel sensors
- Combined 4D tracking device with balance spatial resolution and timing resolution to facilitate e.g. long lived particle searches and providing moderate particle ID through time of flight.

We believe the successful development these devices will be crucial for accomplishing the key scientific goals at the most challenging environment of future colliders, while the various novel approaches will further benefit a much wider range of application across HEP and beyond.

The functionalities to be tested from these R&D devices can include e.g.:

- Device efficiencies mapped in a fine grid within each pixel to validate the sensor design details
- Spatial resolution of pixel sensors
- Device performance after heavy irradiation

- Fast timing resolution
- Fast timing device uniformity

The required test sessions are similar to ESTB with 1-2 week long sessions and a few sessions each year. The much higher repetition rate of the S30XL beam vs ESTB is already a major improvement to allow more rapid individual tests to fit into each session. Our beam usage are typically low rate secondaries at 1-100 particles per bunch. We can tolerate fairly large energy spread of the beam and secondaries debris. Although we prefer higher energy beams at >8 GeV for tests on spatial resolution, majority of the tests can still be conducted at lower energy of ~4 GeV. The distinctive characteristic of the very short bunches of the SLAC beam can be particularly beneficial for fast timing detector test beams. The spray of particles in the same short bunch over a large array of fast timing detector may be one the best ways to calibrate and examine the relative timing spread between pixels in the same array. Previous ESTB session benefited significantly from the EUDET telescope Caladium on loan from Univ. of Carleton. Continued availability of such on loan telescope and support TestFac would be very beneficial. We can mostly provide readout electronics and local support assemblies for test devices ourselves while the remote controlled movable stages provided by TestFac to mount these test device assemblies will continue to be very useful.

Possible collaborating institutions: LBNL, UC Santa Cruz, California State University (various campuses) as the core participants while likely to also involve ATLAS collaborators worldwide.

Statement Of Interest: Timing Vertex Detector

Kurtis N. Nishimura, Gary S. Varner

March 27, 2019

Abstract

The Timing Vertex Detector is a novel silicon pixel tracking detector that exchanges time for one of the spatial dimensions. Evaluation of initial prototypes and full-scale modules are needed, to optimize the design and verify spatial and timing resolution of this technology.

Finely pixelated silicon sensors are generally required to precisely determine the decay vertex location in a collider detector, which leads to an enormous number of readout channels. At high luminosity, this leads to many challenges in power, cooling and data throughput. One concept to reduce the channel count by roughly 3 orders of magnitude is that of a Timing Vertex Detector (TVD) [1,2]. This is shown conceptually in this figure.

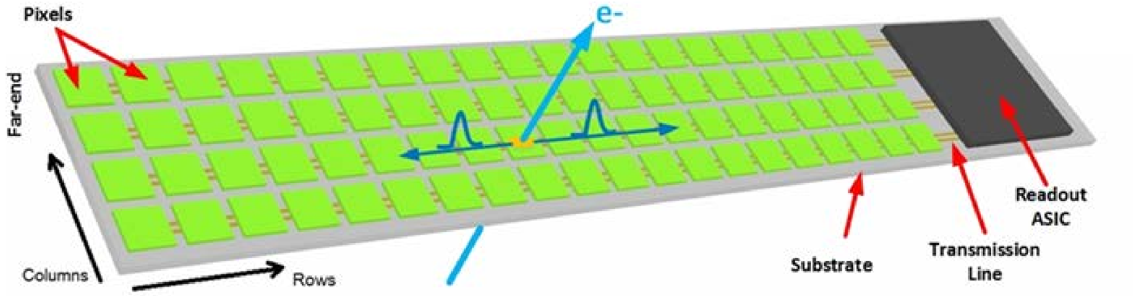

Figure 1: Cartoon of the TVD geometry. See published references for details.

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A key enabling elements underlying this concept is using transient waveform sampling to record transmission-line initiated signals with sufficient temporal resolution (~100fs), to permit reconstruction with pixel-scale spatial resolution. This reduces a Super B-factory pixel vertex detector from 10's of millions of channels, to 10's of thousands. Moreover, one can record only hits from the bunch crossing of interest. Compared with the Belle II DEPFETs, for instance, this represents many orders of magnitude reduction in event size. Since the DEPFET dominates the overall Belle II event size, this conservatively represents a savings of many M$ in storage of the 10's of PetaByte storage requirements.

While this detector concept looks promising, work is needed on the sensors themselves, and a campaign to verify each component, and then small prototypes, and then finally full-scale half-ladders will be needed.

The S30XL facility will provide a very nice way of supporting this development and verification cycle. The requirements of facility are that very precise timing of single particles can be provided. A rather wide range of energies is acceptable, and desirable, during measurement campaigns. Each beam-time cycle is of the order of a week, based upon previous experience. No special beam parameters are required.

In order to evaluate the spatial resolution, a tracking telescope will be needed. If this is provided as a common infrastructure, it will be used. Alternatively, it will be provided, though will represent additional set-up and commissioning time.

The space requirements are a simple moving table, to permit scans, and a rack with power and networking, to support TVD prototype readout.

As a truly new type of detector concept, successful demonstration of the concept is likely to have applications in many cases where a streak-camera is desirable, but precluded due to limited repetition rate, form-factor, power or cost.

Possible collaborating institutions: we envision that a number of Belle II institutions that have been involved in precision vertexing may join as collaborators, though none are in a position to do so at the moment, as Belle II commissioning with the vertex detectors has just started, and the groups need to focus on getting that working first, before thinking about upgrades.

Statement Of Interest: Low-Gain Avalanche Detector Characterization

B. A. Schumm

March 26, 2019

Abstract

The recent development of Low-Gain Avalanche Detectors (LGADs) has opened up a significant need for high-rate, few-electron test beams to map out the response across the sensor and understand how various electrode-structure strategies affect the detector response, as a function of environmental parameters such as bias voltage and temperature. A number of future applications in both nuclear and particle physics and photon science motivate R&D towards significantly higher granularity devices than are currently available, making these sorts of test-beam studies even more important in the future. Recent test-beam studies conducted at the ESTB facility were several rate-limited.

Statement of support

The recent development of Low-Gain Avalanche Detectors (LGADs) has opened up a significant need for high-rate, few-electron test beams to map out the response across the sensor and understand how various electrode-structure strategies affect the detector response, as a function of environmental parameters such as bias voltage and temperature. The scale of interest of relevant feature sizes is on the order of microns, for a device of overall dimension of several square millimeters. Such a precision is possible with the MIMOSA-based Caladium beam telescope that is currently available in the SLAC ESTB. The system surrounds the Device Under Test (DUT) with three precise layers each before and after the DUT, providing a precision of several microns for the point of traversal of primary electrons though the DUT.

In order to map out LGAD prototype devices of this scale, between 10^4 and 10^5 primary electrons are needed per run, delivered in small numbers (preferable one) per beam crossing. Such a use would probably be limited more by readout rate than by the S30XL beam delivery capabilities, but even a conservative readout rate of 10^3 Hz would allow a full mapping to be done roughly every minute, providing a powerful tool for the quick and comprehensive characterization of LGAD prototypes that would rival that of the best facilities in the world. In a day or two of running, a number of prototypes could be fully characterized at a facility such as S30XL.

A broad program of LGAD detector R&D is underway, with many years of characterization work likely to be called for. Applications in particle physics (4-dimensional tracking) and nuclear physics (4D tracking as well as solid-state time-of-flight systems) and in photon science (ultra-fast Xray imaging) require significant improvements in both temporal resolution and granularity that will require a significant over a multi-year period. Some concerns, such as Brookhaven National Laboratory, are just now bringing up LGAD-oriented fabrication capabilities in anticipation of this program. There is no doubt that the S30XL facility, if built, would be an essential tool in this R&D program.

Possible collaborating institutions

The number of institutions that would be likely to make use of this facility is large, as there is a significant world-wide community engaged in LGAD development. The Santa Cruz Institute for Particle Physics is a leader in this effort, and collaborates regularly with groups at FNAL and ANL. Developing interest in photon science and nuclear physics applications is also inspiring LGAD-related links to groups at LANL and ANL. Several US universities are also becoming involved in LGAD development. SCIPP also has close collaborations with a number of European institutions doing LGAD development that would benefit greatly from the facility, likely brokered by SCIPP. These include groups at the University of Torino and at CERN.

Using the S30XL beamline for development of high resolution/high rate crystal calorimetry

B. Echenard, D.G. Hitlin

March 5, 2019

Abstract

There is much interest in improving the time resolution of inorganic scintillator crystal-based electromagnetic calorimetry using crystals such as yttrium-doped barium fluoride. S30XL, particularly in its LDMX configuration, would be well-matched as a test beam for such development

Barium fluoride has the fastest scintillation component (~600 ps) of any inorganic scintillator. It is tempting to try to utilize this component for high-resolution timing in a high rate environment. This has been difficult, because the BaF_2 fast component is at a wavelength of 220nm, and is accompanied by a much larger slow component (650ns decay time) at 300nm. Recent progress in doping barium fluoride with yttrium has shown that the slow component can be strongly suppressed, with little effect on the fast component.

This development has stimulated renewed interest in barium fluoride for use in several areas: high energy physics experiments such as Mu2e-II, in the analysis of high temperature, high density plasmas, and PET scanning. These uses also involve several distinct efforts in the development of fast photodetectors with good UV efficiency and either solar-blind or filtered response to eliminate the residual slow scintillation component response. Thus one can contemplate a series of beam tests scheduled over a period of years.

S30XL, particularly in the LDMX configuration would provide an excellent beam structure to both measure the ultimate time resolution of particular BaF_2/photodetector combinations and to cleanly characterize the rate capability of these systems. The initial energy of 4 GeV provides robust signals that facilitate optimization of parameters relevant to time resolution that can then be extrapolated to the lower energies involved in several of the applications.

Possible collaborating institutions: Caltech, INFN Frascati, INFN Pisa, Yale

Statement Of Interest: Studies of Electromagnetically-Induced Radiation Damage

B. A. Schumm

March 26, 2019

Abstract

While R&D for ever-intensifying LHC collisions has motivated extensive studies of hadronically-induced radiation damage, the nature of electromagnetically-induced radiation damage is much more poorly constrained. However, abiding interest in the development of high-luminosity electron colliders (ILC, CLIC, CEPC) and electron-ion colliders (EIC) increases the priority of developing an understanding of electromagnetically-induced radiation damage. The S30XL facility would be an ideal facility for its study and characterization.

Statement of support

The T506 campaign, carried out over the years 2013-2016 in the ESTB facility, provided empirical characterizations of electromagnetically-induced radiation damage, over a range of solid-state sensor technologies (Si diode, GaAs, SiC, industrial sapphire), to total ionizing doses of up to 600 Mrad. This body of work represents much of what is currently known about the behavior (leakage-current development and charge-collection loss) of solid-state sensors exposed to lifetime-level doses at the highest-radiation regions of future lepton colliders. The well-calibrated T506 target was also used to test the radiation hardness of various solutions proposed for the development of mechanical components for the LCLS-II upgrade.

While a picture has begun to emerge, much remains to be learned both conceptually and operationally about electromagnetically-induced radiation damage. For example, there is a suggestion from this work that, counter to expectations, leakage current is dominated by absorption of the electromagnetic component of the shower and not by dominated by neutron-induced damage [1]. The picture is far from complete, and a significant amount of further study is warranted, and will be encouraged by the availability of the S30XL facility.

T506 operated with the maximum energy and current provided to the ESTB, typically about 0.75 nA of 13 GeV primaries. Approximately 36 hours of beam time were required to accumulate a lifetime-scale dose in these running conditions. The availability of 25 nA beams, although at the lower primary energy of 4 GeV, would allow the rate of dose accumulation to be boosted by roughly a factor of eight, allowing a lifetime dose to be accumulated in less than five hours. Upgrading to 8 GeV primaries at 25 nA would reduce the needed exposure time to approximately two hours, roughly the time it takes for the target area to cool and then to prepare the target for the next run. Then increasing the beam current to 2 μA would result in an experimental duration dominated by target access and preparation.

Clearly, S30XL would be a very inviting place to perform radiation damage studies. In addition, the isolation of the ESA experimental hall from other activities eliminates the interference in other experiments from the target neutron field, which was the justification for rejecting a proposal to run a T506-like experiment at CEBAF. The T506 target could be made use of again; if the absorption of 25 μA of 4 GeV primaries created a greater heating load than could be accommodated by the T506 target, upgrading the target's cooling system would probably cost less than $10,000.

Possible collaborating institutions

The T506 campaign was a sole effort of SCIPP, with the generous support of the SLAC ESTB staff. However, a significantly upgraded dose rate is likely to attract collaborators from a broad range of institutions, as detector designs for lepton-collider detectors become more mature.

References

[1] Bruce A. Schumm and Benjamin Smithers, Operation of the prospective beamline calorimeter in the high-radiation forward environment of the international linear collider, Nucl. Instr. & Meth. A908 (2018), 198-205.

Statement Of Interest: Test Beam for LHC and PBC Experiments

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Upgrades of the experiments at the Large Hadron Collider (LHC), projects under the umbrella of the Physics Beyond Collider (PBC) study group at CERN and future colliders motivated by the physics results from the LHC can all benefit tremendously from a S30XL test beam.

The high luminosity upgrade of the LHC (HL-LHC) will increase the instantaneous rate by more than a factor of five over the design value and will deliver an overall data sample that is ten times that originally envisioned. Detectors are therefore being upgraded to handle the increased rate as well as the higher level of total irradiation. For example, US ATLAS is responsible for delivering the innermost precision silicon pixel tracking detector. The S30XL test beam can be used to characterize its tracking performance under different operating conditions. There is also interest in the high-granularity timing detector (HGTD) proposed to mitigate the effects of higher instantaneous rate. The S30XL test beam can be used to check its timing performance. US CMS has similar upgrade programs for HL-LHC.

Projects in the Physics Beyond Colliders study group report span a large range, and many of them can benefit from S30XL. I will mention just two of them here. FASER is an experiment to search for light, weakly interacting particles produced at the LHC. It is being installed and will start taking data in 2021 when the LHC resumes running after the currently on-going Long Shutdown 2 (LS2). For its upgrade to be installed during LHC Long Shutdown 3 (LS3) starting circa 2024, FASER can utilize a facility like S30XL to test its new detectors. MATHUSLA is a proposal for a large surface detector to search for Beyond Standard Model (BSM) long-lived particles produced in LHC collisions. It is anticipated to be taking data after LS3, i.e. starting 2026. This project is in the design stage where the focus is to develop detectors suitable for its large size. The test beam of S30XL would be well suited to test these detectors.

Possible projects on a longer-term time scale include the Compact Linear Collider (CLIC) and the Future Circular Collider (FCC) at CERN as well as the Circular Electron Positron Collider (CEPC) and the Super Proton-Proton Collider (SPPC) in China. Their physics goals include order-of-magnitude improvements over LHC in the study of the Higgs boson, several orders of magnitude greater precision than LEP in the study of the Z boson, and exploration of the energy regime beyond the

LHC. These experiments will require detectors with new capabilities. Test beams such as that at S30XL will be crucial for their realization.

These test beam campaigns vary in duration. With infrastructure already in place, an 8-hour shift can already provide enough data to characterize a new device. It will take significantly longer, on the scale of days to weeks, to map out in detail the response of a detector package.

The required beam parameters are easily achieved. For example, detector characterization is often done with beam intensity of one particle per spill to avoid confusion due to multiple incident particles. There is no strong constraint on the repetition rate although higher rates are often preferred to accumulate data faster.

It would be helpful if the test beam particle trajectory is well measured so the user can focus time and effort on his/her own detector.

A S30XL test beam will be an asset to the worldwide community of experimental particle physicists no matter where their projects are situated. I anticipate collaborators to come from universities and laboratories in the United States, Europe and Asia if such a facility is available.

Fused Silica Integrating Detector Investigations for the MOLLER Experiment

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1. Introduction

MOLLER proposes to make an ultra-precise measurement of the weak mixing angle using Moller scattering, improving on the SLAC E158 measurement by a factor of 5. The project has received CD-0 status at the Department of Energy Office of Science. New detector concepts have been developed to measure the scattered electron flux of about 150 GHz using fused-silica (quartz) Cherenkov radiators as the primary detector medium. Such radiation hard configurations, especially in calorimeter mode, have never before been used for such a measurement. The potential for having both single electrons per bunch as well as 1 microampere beam currents in the multi-GeV energy range would be tremendously useful for such investigations. It would be a unique facility with such capabilities in the US.

2. Description of possible test beams

The primary tests would use single electrons per bunch to measure detector response from 1 cm thick quartz bars with a cross-sectional area of roughly 10 x 20 cm to determine how well Cherenkov light propagates through quartz bars. Once this is accomplished, it is critical to direct nanoamperes of beam current on the quartz and measure the integrating response. Being able to carry this out in the same facility would allow complete characterization of such detectors in a manner that would validate the MOLLER application comprehensively.