Instructions

Use this template to create your LDRD project proposal, and to provide an explanation of your budget, if necessary.

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Name your proposal file name following the convention: *Leadlastname_projectname_LDRD_FYYear*.

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Please submit your proposal as an MS Word file.

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The proposal must not exceed 5 pages (Sections II-V ONLY).

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NATIONAL ACCELERATOR LABORATORY

LABORATORY DIRECTED RESEARCH AND DEVELOPMENT PROPOSAL TITLE

DESIGN STUDIES FOR DARK SECTOR EXPERIMENTS AT LCLS-II

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Proposal Term:	**From:** October 1, 2016 **Through:** September 30, 2017

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I. Executive Summary

We propose accelerator design studies for a unique small-scale facility at SLAC hosting groundbreaking dark matter experiments. The new facility, **DA**rk **S**ector **E**xperiments at **L**CLS-II (DASEL), will divert electrons in unused buckets from the LCLS-II linac to a new beamline that enables electron fixed-target experiments with a wide range of beam currents and phase-space profiles. The experiments envisioned for this beamline will decisively test dark matter scenarios in the largely untested GeV-scale mass range, placing SLAC at the top of a highly competitive international effort to explore this physics. Extracting beam for DASEL downstream of the extraction points for the X-ray lines ensures that DASEL will not affect LCLS-II operations. This LDRD would fund design of a new kicker system, beamline, and spoiler/collimator system required for DASEL, leading to a proposal that will be presented to the DOE Office of High Energy Physics in tandem with experimental proposals using the new beamline.

II. Project Description

A. INTRODUCTION

The identity of Dark Matter is among the most pressing questions in fundamental physics today. Searching for dark matter is a core science driver for cosmology in the SLAC strategic plan, and is among the major areas prioritized by the particle physics community in the P5 report.

Among the best-motivated and unexplored possibilities is that Dark Matter is comprised of particles with mass similar to familiar matter, in the MeV-GeV range, and survives as a relic from an era of thermodynamic equilibrium in the early universe. This simple scenario is realized by a "dark sector" containing the Dark Matter particle, a new force carrier of comparable mass, and possibly other accompanying particles. Though these particles couple weakly to familiar matter, the observed Dark Matter abundance implies a lower bound on the coupling in simple models, which is accessible in high-sensitivity fixed-target experiments.

This possibility has spurred a broad international program of experiments searching for dark forces and light dark matter, including dedicated experiments at Jefferson Lab (APEX [1], HPS [2], DarkLight [3], BDX [4]), Mainz [5], INFN Frascati (PADME [6]), and CERN (P348 [7]). This program was one of five focal areas for the 2013 Snowmass process [8], has twice been the subject of APS mini-symposia [9], and was the subject of recent dedicated international meetings at Frascati [10], Brookhaven [11], and Genova [12]. Multi-GeV continuous electron beams are particularly well suited to these experiments, and the APEX and HPS experiments at Jefferson Lab (both of which have SLAC researchers in leadership roles) are flagship efforts involving over 100 scientists at 35 institutions in 7 countries. The next generation of experiments does not require CEBAF's beam polarization or precisely tunable energy, but will require sustained low beam currents for which CEBAF was not designed, as well as extensive run times and real physics priority, which are very unlikely at CEBAF given its 10 year backlog of experiments and the priority of Nuclear Physics at JLab.

Two experimental proposals are being developed in tandem with the accelerator design proposed here, and these serve as benchmarks to inform the beam requirements. A "missing momentum" experiment (MME) [13] searching for electroproduction of light dark matter calls for a diffuse beam at very low current (at the 30-300 pA scale) impinging on a target with tracking and a high-granularity calorimeter directly in the beamline so that the trajectories of individual beam electrons and their byproducts through the detector can be reconstructed in detail. This approach has unique potential to explore interaction strengths at the lower bound consistent with thermal dark matter (see Figure 1), and would decisively test the hypothesis that Dark Matter annihilates into familiar matter in much of the sub-GeV mass range [14]. A second concept (SuperHPS) [15] would extend HPS sensitivity by reconfiguring the detector to increase acceptance, improve mass resolution, and support higher beam currents in the μA range. A beamline capable of delivering beam to the very different specifications of these two benchmark experiments will also be capable of supporting a wide range of future experiments that call for a high repetition rate, multi-GeV electron beam.

B. OBJECTIVES

We propose to design a beamline, parasitic to LCLS-II, delivering multi-GeV electrons at a 186 MHz repetition rate with currents ranging from 1 pA to 1 μA. This would furnish SLAC with the unique opportunity to host the next generation of cutting edge dark matter and dark force experiments. We refer to the new beamline and facility collectively as **DA**rk **S**ector **E**xperiments at **L**CLS-II (DASEL).

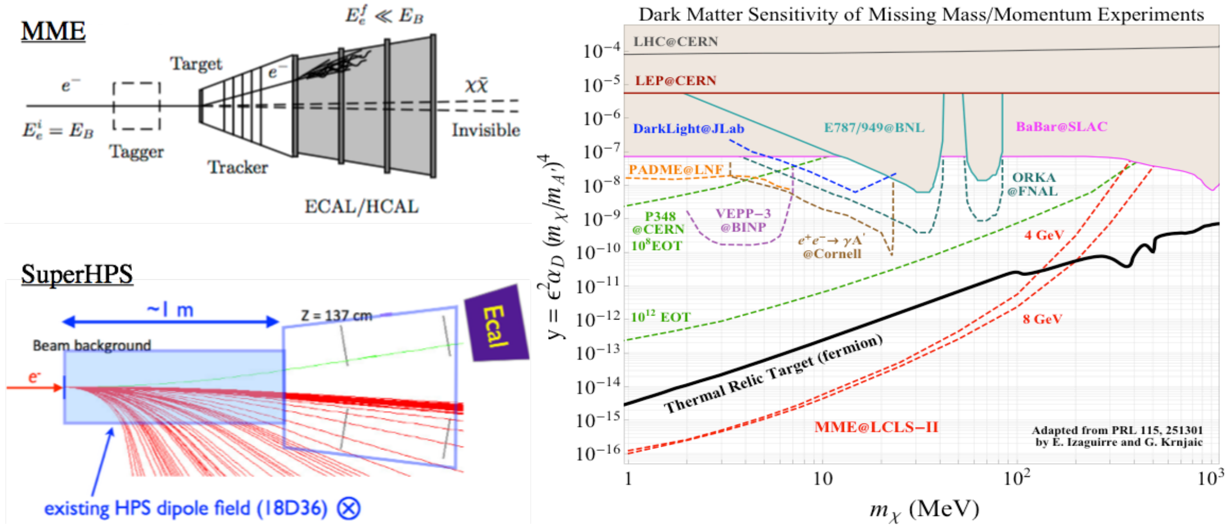

Figure 1: Left: Sketches of the MME and SuperHPS experimental concepts. **Right:** Yield-Limited Dark Matter sensitivity of missing momentum experiment vs. other current and proposed limits on dark matter production at accelerators. The y-axis is a dimensionless interaction strength, while the black line is the minimum interaction strength consistent with thermal relic Dark Matter. Assumptions for missing momentum yields are as in Scenario III of [13] but shown for a 4 GeV and 8 GeV beam.

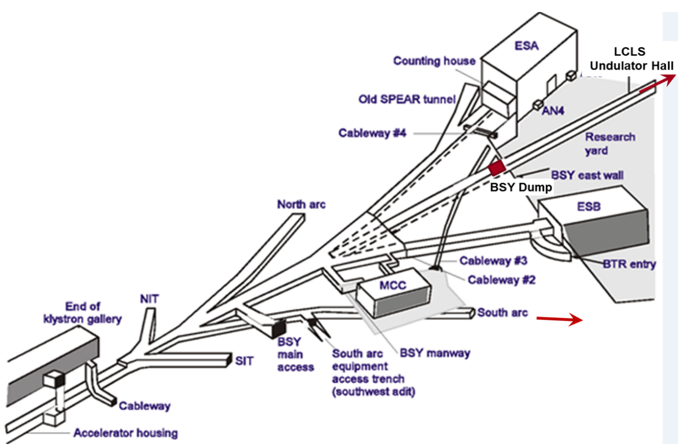

Figure 2: We propose to evaluate the feasibility of three possible locations for DASEL: South Arc or End Station A or B, as illustrated in Figure 2, which would use beam from the LCLS-II superconducting linac in a parasitic mode of operation. If it is found to be feasible, these studies will pave the way for DOE-HEP proposals for the beamline and first-generation experiments. Completing the studies in a timely manner is key to identify design elements that must start early for an efficient installation during the planned accelerator down times in 2018.

C. APPROACH/METHOD

LCLS-II [16] fills a GHz accelerator with pulses at a MHz, so the approach is to fill the unused buckets with a low current that can readily supply DASEL. The LCLS-II superconducting linac will accelerate up to 250 kW of electrons to the beam switch-yard (BSY). The baseline LCLS-II design has a maximum bunch rate of 929 kHz but the linac RF operates at 1.3 GHz and the RF gun operates at 186 MHz [17]. 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 BSY.

DASEL will use RF gun dark current and/or a secondary gun laser operating at 186 MHz to produce a lower-current beam with 5.4 ns bunch spacing. These "dark" bunches will be diverted to the DASEL beamline headed to ESA, ESB, or SARC by a third (new) kicker. The secondary gun laser and a spoiler/collimation system will control the charge delivered to DASEL. This concept should be completely parasitic to LCLS-II operation, since the DASEL beam is low-current (<1 μA compared to 62 μA nominal LCLS-II current) and is deflected downstream of the kickers to the undulators. In the following we outline requirements for the secondary source laser, DASEL beamline, kicker, and spoiler/collimation system.

Dark current originating in the RF gun is expected to be accelerated to the full 4 GeV energy, while all other sources will be collimated away. This dark current is expected to uniformly fill the buckets with a 5.4 ns (1/186 MHz) spacing, but its absolute level is unknown. Injector specification requires dark current below 400 nA [18], while dark current measurements of the RF gun prototype are less than 1 nA. To achieve higher currents for DASEL (as for SuperHPS), a separate gun laser may be used to intentionally populate 'dark current' bunches at the gun frequency. These bunches would be well separated from the primary beam bunches so they could be extracted downstream. The new gun laser could be similar to the baseline gun laser but operating at lower power and higher repetition rate [19]. This system will need specification.

Figure 3 illustrates the configuration of the beamline in the BSY region, the location of the extractions to the HXR and SXR undulators, and possible locations for extraction to ESA, ESB, or SARC for DASEL. The BSY is a complicated region with 4 beamlines running through a 0.65-m x 0.65-m cross-section, so the new beamline will need a detailed design to understand feasibility and cost.

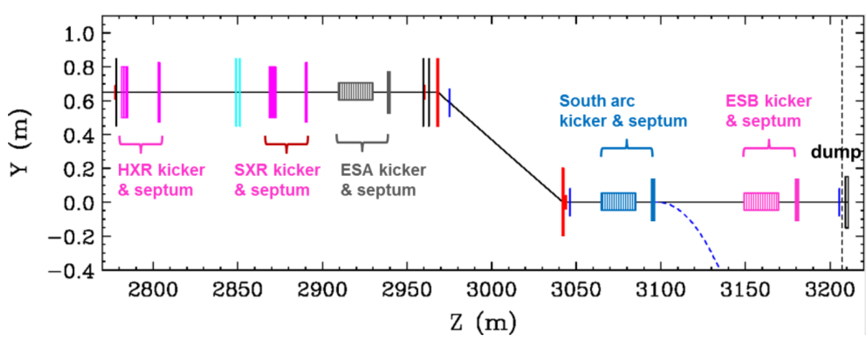

Figure 3. LCLS-II beam from SCRF linac to BSY dump showing locations of the HXR and SXR undulator extraction beamlines and possible locations for beamlines to ESA, ESB or SARC.

The LCLS-II pulse structure and profiles of the FEL kickers and proposed DASEL kicker are illustrated in Figure 4. The DASEL kicker will operate at the same rate but a lower amplitude and looser tolerance than the FEL kickers. The FEL kickers have a 90% rise/fall time less than 300 ns [19], so that roughly 800 ns of dark current between successive primary bunches would be available for DASEL experiments. The DASEL kicker would only deflect dark current and would need to avoid the high current primary beam bunches that may be headed to the BSY dump (which could be used, in a parallel effort, for a complementary beam-dump search for light dark matter as in [4]). The DASEL kicker system will need specification and initial prototyping to ensure the viability of the concept.

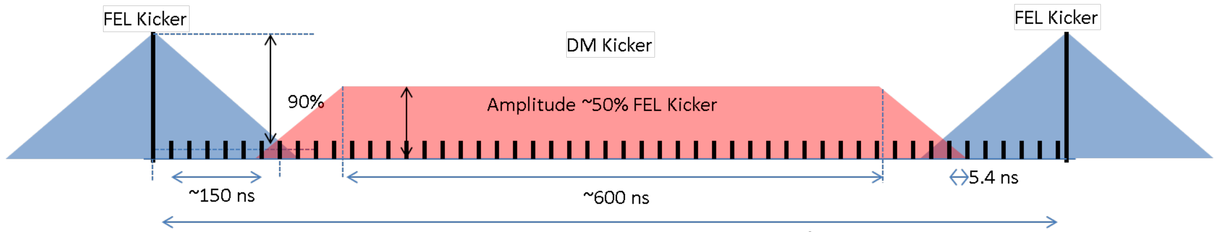

Figure 4. LCLS-II pulse structure showing primary pulses with 4×10^8 e- and dark current bunches from the gun with ~30 e- per bunch. The DASEL beam would require control of the dark current population with an additional seed laser and a spoiler/collimation system to deliver final current in the pA (for MME) to μA (for SuperHPS) range.

The MME benchmark would require limiting the average beam current to 5-30 pA for its first engineering run, increasing to about 300 pA for an ultimate physics run. Spoilers and collimators along the DASEL beamline can be used together with the secondary laser to carefully control the number of particles and the phase space of the e- arriving at the detector. MME will require a high suppression of off-energy electrons. It is expected that graphite spoilers and LCLS-II-style collimators will be sufficient for this task but the spoiler/collimator system needs to be designed.

D. ANTICIPATED RESULTS/ DELIVERABLES

The timeline is set by the LCLS-II construction and installation schedule. Areas in the BSY are optimally accessed during this period so as not to interfere with LCLS-II commissioning and operation. We anticipate a LDRD project duration of 12 months. Progress will be monitored by weekly meetings and two semi-annual reviews. By the time of the first review we will

- Evaluate and decide on the location for DASEL (SARC, ESA, ESB). Each choice has advantages and disadvantages arising from existing beamlines (ESA) and infrastructure (ESA,ESB), the need to deal with dispersion induced by the LCLS-II vertical bend (SARC, ESB) and long term alternative plans for the areas (ESA, ESB).
- Have a beamline design to the preferred location and a good understanding of how the location and design will impact the experimental infrastructure, machine protection and personnel protection systems. Conceptual designs for the kicker, the spoiler/collimation system and the source laser system will be available.

By the time of the second review, we will have

- A detailed beamline design based when possible on pre-existing magnets together with lists of vacuum, instrumentation, and power supply components. Additionally, we will perform an engineering study of how to interface to the SLAC infrastructure without adversely impacting LCLS-II as well as an installation plan. Engineering specifications of the kicker, the spoiler/collimation system and the source laser system, based on prototype studies when required, will be available.
- A cost estimate suitable for seeking DOE-HEP construction funding for DASEL in tandem with experimental proposals.

III. Strategic Alignment

This proposal will fund the crucial design work needed to seek FY18 DOE-HEP funding for engineering and construction of a new small-scale facility for accelerator-based searches for dark matter and related interactions. Scientific proposals for the first experiments on the beamline will be developed in parallel by collaborating institutions and SLAC. This timeline allows much of the installation to proceed during LCLS-II installation, and for a first experimental run to start in 2020. It is foreseen that the first-generation MME and SuperHPS would remain on the floor at DASEL for about 5-6 years, and that the facility would support other user experiments thereafter.

DASEL is highly cost-effective because it runs parasitically to LCLS-II. It is unique and well-motivated, shedding light on one of the foremost questions in cosmology by offering the beam needed to decisively test dark matter and dark force scenarios in the MeV-to-GeV-mass range. And, it will become a world center for dark sector experiments with excellent discovery potential, resonating with three of SLAC's four Strategic Initiatives – "Innovate and Operate Premier Accelerator-based Facilities", "Identify and Pursue New Science Enabled by Our Facilities", and "Pursue a Frontier Program in Cosmology".

IV. Management Plan

The personnel covered under the LDRD plan are 1) Tony Beukers, who will design and specify the kicker, demonstrating proof of concept via a test system if deemed advisable, 2) Thomas Markiewicz, who will produce a conceptual design of the spoiler/collimation system and integrate facility features resulting from experimental or safety requirements, and 3) Yuri Nosochkov, who will design the optical systems that integrate a kicker and septum to the LCLS-II beam and the magnetic elements to match the extracted beam and transport it to the experimental facility.

Other personnel centrally involved include: Natalia Toro and Philip Schuster, who will coordinate the efforts by SLAC and external collaborators on the design of the experiments and Tor Raubenheimer, who will ensure the interface to LCLS-II. They will regularly meet with Beukers, Nosochkov, and Markiewicz to assess progress and status. When a location is decided upon, the relevant SLAC safety departments will be consulted as to the requirements that would be imposed. Throughout, Joe Incandela (UCSB), John Jaros (SLAC), and Tim Nelson (SLAC) will also be regularly consulted on the experimental interface with the beamline.

After the LDRD funding period, we expect the DOE-OHEP to fund the construction of the beamline, facility, and initial experiments.

V. Budget Explanation

A total budget of $240,000 has been developed according to the guidance given that is comprised of 20% effort from each of two scientific staff (Nosochkov and Markiewicz) and 20% of ICDAPSE engineering (Beukers) along with $30k M&S for kicker development.

VI. References

Please note references 17-19 are internal LCLS-II project documents but these can be made available to interested parties.

1. R. Essig, P. Schuster, N. Toro and B. Wojtsekhowski, "An Electron Fixed Target Experiment to Search for a New Vector Boson A0 Decaying to e+e," JHEP 1102, 009 (2011) [arXiv:1001.2557 [hep-ph]]; S. Abrahamyan *et al.* [APEX Collaboration], "Search for a New Gauge Boson in Electron-Nucleus Fixed-Target Scattering by the APEX Experiment," Phys. Rev. Lett. 107, 191804 (2011) [arXiv:1108.2750 [hep-ex]].
2. https://confluence.slac.stanford.edu/display/hpsg/Project+Overview; M. Battaglieri, S. Boyarinov, S. Bueltmann, et al., "The Heavy Photon Search Test Detector," Nucl. Instrum. Meth. A 777 91 (2014), arXiv:1406.6115 [physics.ins-det]
3. J. Balewski et al., "DarkLight: A Search for Dark Forces at the Jefferson Laboratory Free-Electron Laser Facility," arXiv:1307.4432.
4. M. Battaglieri et al. [BDX Collaboration], "Dark matter search in a Beam-Dump eXperiment (BDX) at Jefferson Lab," arXiv:1406.3028 [physics.ins-det]
5. H. Merkel et al. [A1 Collaboration] "Search for Light Gauge Bosons of the Dark Sector at the Mainz Microtron," Phys. Rev. Lett. 106, 251802 (2011); H. Merkel et al., "Search at the Mainz Microtron for Light Massive Gauge Bosons Relevant for the Muon g-2 Anomaly," Phys. Rev. Lett. 112 22, 221802 (2014) [arXiv:1404.5502 [hep-ex]]; M. Molitor, "Detectors for dark photon search with MESA," http://web.mit.edu/lns/PEB_Workshop/talks/Molitor_MESA_Study.pdf
6. M. Raggi and V. Kozhuharov, "Proposal to Search for a Dark Photon in Positron on Target Collisions at DAΦNE Linac," Adv. High Energy Phys, 2014, 959802 (2014) [arXiv:1403.3041 [physics.ins-det]].
7. S. Andreas et al., "Proposal for an Experiment to Search for Light Dark Matter at the SPS," arXiv:1312.3309 [hep-ex]; S. Gninenko "Search for dark sector physics in missing-energy events," https://p-348.web.cern.ch/sites/p-348.web.cern.ch/files/p348-gninenko-red.pdf
8. R. Essig, J. A. Jaros, W. Wester, et al., "Working Group Report: Dark Sectors and New, Light, Weakly-Coupled Particles" arXiv:1311.0029 [hep-ph]
9. "Dark Forces Below the Proton Mass Scale", APS April Meeting 2012; "New Forces at the GeV Scale and Dark Matter I-III", APS April Meeting 2015
10. http://www.lnf.infn.it/conference/dark/
11. "Dark Interactions: Perspectives from Theory and Experiment" June 11-13, 2014 https://www.bnl.gov/di2014/ and October 4-7, 2016 https://www.bnl.gov/di2016/
12. "Light Dark Matter at Accelerators," June 24-26 2015 https://www.ge.infn.it/~ldma2015/LDMA2015/Welcome.html

13. E. Izaguirre, G. Krnjaic, P. Schuster and N. Toro, "Testing GeV-Scale Dark Matter with Fixed-Target Missing Momentum Experiments, PRD91 (2015) 9, 094026, arXiv:1411.1404 [hep-ph].
14. E. Izaguirre, G. Krnjaic, P. Schuster, N. Toro "Analyzing the Discovery Potential for Light Dark Matter," PRL 115 (2015) 25, 251301, arXiv:1505.00011 [hep-ph].
15. https://indico.fnal.gov/contributionDisplay.py?contribId=422&confId=6890; https://indico.fnal.gov/contributionDisplay.py?contribId=423&confId=6890; https://confluence.slac.stanford.edu/download/attachments/192193555/SuperHPS_NEXT.pdf?version=1&modificationDate=1452628699000&api=v2
16. T. O. Raubenheimer, "LCLS-II Status of the CW X-ray FEL Upgrade to the LCLS Facility," FEL 2015, Daejeon, Korea WEP014 (2015); "LCLS-II Final Design Report," LCLSII-1.1-DR-0251 (2015).
17. See table 1 of "LCLS-II Timing System Physics Requirements Document", LCLSII-2.7-PR-0345 (2015).
18. "LCLS-LL SCRF Injector System Physics Requirements Document," LCLSII-2.2-PR-0084 (2014).
19. "LCLS-II Spreader Kicker Engineering Specifications Document," LCLSII-2.4-ES-0494 (2015).

VII. Biographical Sketch

Natalia Toro

Education

Massachusetts Institute of Technology – Physics – S.B.2003

Massachusetts Institute of Technology – Mathematics – S.B. 2003

Harvard University – Physics – Ph.D. 2007

Professional Appointments

2007-2010	Postdoctoral Researcher, Stanford University
2010-	Faculty, Perimeter Institute for Theoretical Physics
2011	Member, School of Natural Sciences, Institute for Advanced Study
2015-	Associate Professor of Particle Physics & Astrophysics, SLAC

Awards and Honors

2015 New Horizons in Physics Prize (Breakthrough Prize Foundation)

2014 Ontario Early Researcher Award

2006 Maurice and Gertrude Goldhaber Prize for Graduate Research, Harvard University

2003-2007 National Science Foundation Graduate Research Fellowship

2003-2006 National Defense Science and Engineering Fellowship

1999 First Prize in Intel Science Talent Search

Relevant Publications

E. Izaguirre, G. Krnjaic, P. Schuster, N. Toro "Analyzing the Discovery Potential for Light Dark Matter," PRL 115 (2015) 25, 251301, arXiv:1505.00011 [hep-ph].

E. Izaguirre, G. Krnjaic, P. Schuster and N. Toro, "Testing GeV-Scale Dark Matter with Fixed-Target Missing Momentum Experiments, PRD91 (2015) 9, 094026, arXiv:1411.1404 [hep-ph].

M. Battaglieri, S. Boyarinov, S. Bueltmann, et al., "The Heavy Photon Search Test Detector," Nucl. Instrum. Meth. A 777 91 (2014), arXiv:1406.6115 [physics.ins-det]

M. Battaglieri et al. [BDX Collaboration], "Dark matter search in a Beam-Dump eXperiment (BDX) at Jefferson Lab", arXiv:1406.3028 [physics.ins-det]

E. Izaguirre, G. Krnjaic, P. Schuster and N. Toro, "Physics Motivation for a Pilot Dark Matter Search at Jefferson Laboratory," Phys. Rev. D 90, 014052 (2014), arXiv:1403.6826 [hep-ph]

J. M. Byrd, J. W. Flanagan, G. S. Varner, et al., "Working Group Report: High Intensity Electron and Photon Beams," http://inspirehep.net/record/ 1297179

R. Essig, J. A. Jaros, W. Wester, et al., “Working Group Report: Dark Sectors and New, Light, Weakly-Coupled Particles” arXiv:1311.0029 [hep-ph]

I. Izaguirre, G. Krnjaic, P. Schuster and N. Toro, “New Electron Beam-Dump Experiments to Search for MeV to few-GeV Dark Matter,” Phys. Rev. D 88, 114015 (2013), arXiv:1307.6554 [hep-ph]

J. L. Hewett, H. Weerts, et al., “Fundamental Physics at the Intensity Frontier”, arXiv:1205.2671 [hep-ex]

S. Abrahamyan et al. [APEX Collaboration], “Search for a New Gauge Boson in Electron-Nucleus Fixed-Target Scattering by the APEX Experiment,” Phys. Rev. Lett. 107, 191804 (2011) arXiv:1108.2750 [hep-ex]

T. R. Slatyer, N. Toro and N. Weiner, “Sommerfeld-Enhanced Annihilation in Dark Matter Substructure: Consequences for Constraints on Cosmic-Ray Excesses,” Phys. Rev. D 86, 083534 (2012) arXiv:1107.3546 [hep-ph]

R. Essig, R. Harnik, J. Kaplan and N. Toro, “Discovering New Light States at Neutrino Experiments,” Phys. Rev. D 82, 113008 (2010) [arXiv:1008.0636 [hep-ph]]

R. Essig, J. Kaplan, P. Schuster and N. Toro, “On the Origin of Light Dark Matter Species,” arXiv:1004.0691 [hep-ph]

G. Amelino-Camelia et al., “Physics with the KLOE-2 experiment at the up- graded DAφNE,” Eur. Phys. J. C 68, 619 (2010). arXiv:1003.3868 [hep-ex] (186 citations).

R. Essig, P. Schuster, N. Toro and B. Wojtsekhowski, “An Electron Fixed Target Experiment to Search for a New Vector Boson A′ Decaying to e+e−,” JHEP 1102, 009 (2011) arXiv:1001.2557 [hep-ph]

P. Schuster, N. Toro, N. Weiner and I. Yavin, “High Energy Electron Signals from Dark Matter Annihilation in the Sun,” Phys. Rev. D 82, 115012 (2010) arXiv:0910.1839

P. Schuster, N. Toro and I. Yavin, “Terrestrial and Solar Limits on Long-Lived Particles in a Dark Sector,” Phys. Rev. D 81, 016002 (2010) arXiv:0910.1602 [hep-ph]

J. D. Bjorken, R. Essig, P. Schuster and N. Toro, “New Fixed-Target Experiments to Search for Dark Gauge Forces,” Phys. Rev. D 80, 075018 (2009) arXiv:0906.0580 [hep-ph]

R. Essig, P. Schuster and N. Toro, “Probing Dark Forces and Light Hidden Sectors at Low-Energy e+e− Colliders,” Phys. Rev. D 80, 015003 (2009) arXiv:0903.3941 [hep-ph]

APPROVALS

Signing indicates you have reviewed the contents of this proposal, and support its submission to the LDRD process. Signatures are **required**.

X

Business Planner

X

Department Chair/Division Manager

X

Associate Laboratory Director