The Light Dark Matter eXperiment, LDMX

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The constituents of dark matter (DM) are still unknown, and the viable possibilities span a very large mass range. Specific scenarios for the origin of DM sharpen the focus on a narrower range of masses: the natural scenario where DM originates from thermal contact with familiar matter in the early Universe requires the DM mass to lie within about an MeV to 100 TeV. Considerable experimental attention has been given to exploring Weakly Interacting Massive Particles (WIMPs) in the upper end of this range (a few GeV – TeV), while the region ∼ MeV to ∼ GeV is largely unexplored. Most of the stable constituents of known matter have masses in this lower range, tantalizing hints for physics beyond the Standard Model have been found here, and a thermal origin for DM works in a simple and predictive manner in this mass range as well. It is therefore a priority to explore. If there is an interaction between light DM and ordinary matter, as there must be in the case of a thermal origin, then there necessarily is 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. The Light Dark Matter eXperiment (LDMX) is a planned electron-beam fixed-target missing-momentum experiment that has unique sensitivity to light DM in the sub-GeV range. This contribution will give an overview of the theoretical motivation, the main experimental challenges and how they are addressed, as well as projected sensitivities in comparison to other experiments.

INTRODUCTION

The existence of dark matter (DM) in the Universe has been long-established through astrophysical observations including measurements of the rotational curves of spiral galaxies [1], studies of gravitational lensing [2], and measurements of the cosmic microwave background [3]. Despite this large amount of evidence, a viable DM candidate is yet to be discovered. Many possible theoretical frameworks have been proposed to explain the nature, mass-scale, and origin of dark matter. Amongst the simplest is one in which DM arose as a thermal relic from the hot early Universe, requiring only small non-gravitational interactions between dark sector and Standard Model (SM) particles. This is robustly viable from the MeV to TeV mass range.

This compelling scenario is largely model independent and only requires the DM - SM interaction rate exceed the Hubble expansion rate in the early Universe. This mechanism is generic, equilibrium is hard to avoid even for small DM - SM couplings; and predictive, since a minimum annihilation rate of $< \sigma_\nu >\sim 10^{-26} cm^3 s^{-1}$ is implied in order to avoid producing an overabundance of dark matter at "freeze-out." This minimum annihilation rate defines a minimum cross section which must be experimentally probed to rule out DM of thermal origin.

Most direct and indirect detection experiments have focused primarily on the hypothesis that DM originates from weak boson-mediated interactions with masses in a range from a few GeV to a TeV being well-explored. To date, these searches have provided only null results and have excluded the thermal relic hypothesis for a range of masses. However, the lower mass range of MeV to GeV has remained stubbornly difficult to explore.

The **Light Dark Matter eXperiment (LDMX)** [4] is a planned experiment, to be based at SLAC, which will utilise an electron beam to explore the sub-GeV thermal DM mass range. LDMX will provide high-luminosity measurements of missing momentum in fixed target collisions which could potentially result from direct dark matter and dark mediator particle production. The requirement that thermal freeze-out reactions gives rise to the relic abundance of DM casts a spotlight on DM interactions with electrons which is only a few orders of magnitude beyond current accelerator-based sensitivity.

There are many viable light dark matter models in the MeV - GeV mass range. The simplest of these models contain a vector mediator, A', boson and a neutral dark matter particle, χ, which may be either a scalar or fermion [5]. The A' can be assumed to mix kinetically with the photon, but there are a wide array of models where the vector coupling arises from a new interaction. For the purposes of DM detection, these different models have broadly similar predictions, so the kinetically-mixed A' is considered as the example in most discussions.

The production of DM particles in the collisions of an electron beam with a dense target is analogous to a bremsstrahlung process. The big difference being that, in the "dark-bremsstrahlung" scenario, an A' is produced which can produce a pair of $\chi\bar{\chi}$ DM particles (assuming $m_{A'} > 2m_\chi$), which will not be detected in any experiment. The kinematics of the "dark- bremsstrahlung" process are different from regular bremsstrahlung since the A' boson has a relative large mass. As a result, a large fraction of the momentum after the collision is carried by the A' boson, and the outgoing electron will have a moderate transverse momentum. The electron beam will see significant energy loss. The LDMX experiment will combine information from measurements of the electron's energy-loss in the target, its transverse momentum after the interaction, and the absence of any other SM final states in the detectors, to achieve definitive results on the thermal relic hypothesis for low-mass DM.

PHYSICS REACH

The particle physics community has identified the sub-GeV mass region as one of the primary targets for new experiments [7]. To comprehensively study all direct annihilation models on an equal footing a dimensionless interaction strength, y, is defined:

$$y = \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}^4}\right)^4, \qquad (1)$$

where m_χ and $m_{A'}$ are the DM particle and A' masses respectively. This is a convenient variable for quantifying sensitivity because for each choice of m_χ there is a unique value of y compatible with thermal freeze-out independently of the individual values of α_D, ϵ and $\frac{m_\chi}{m_{A'}^4}$. The right plot in Fig. 1 lists various "thermal targets" for direct annihilation models plotted in the (y, m_χ) plane. These are the same models shown on the left plot in this figure, switching to this parameterization reveals the underlying similarity of these models in the relativistic regime and their relative proximity to existing accelerator bounds.

For sub-GeV DM masses, LDMX will provide the sensitivity needed to explore most of the scalar and Majorana dark matter coupling range compatible with thermal freeze-out into SM final states, and to cover a significant part of the fermion DM parameter space in a first phase. LDMX will then probe the remaining fermion parameter space in its second phase. Fig. 2 shows the limits achieved by these two phases. Limits from colliders, direct-detection experiments, and other fixed-target experiments, are also presented and compared to the targets for either scalar or fermion relic dark matter particles. Collider detectors can produce limits over a wide range of masses, but are limited in cross-section sensitivity compared to the thermal-relic target low masses. Direct-detection experiments typically have a low-mass cut-off due to the small amplitude of the recoil compared with the noise. The strongest limits in the low mass region have been established using fixed-target techniques, which allow for very high luminosity to combat the very small predicted cross-section in the thermal relic hypothesis. The projections shown in Fig. 2 are given for two phases of detector operation. Phase 1 will utilize a 4 GeV electron beam and acquire at total of $(O)(10^{14})$ electrons-on-target. Phase 2 will utilize and 8 GeV beam and acquire a further $\mathcal{O}(10^{16})$ electrons-on-target.

Additional Physics

Alongside the described benchmark physics search for $A' \to \chi\bar{\chi}$, Ref. [9] discusses how LDMX is also sensitive to a wide range of new physics which can couple to electrons and produce missing momentum. This includes: quasi-thermal DM; long-lived resonances produced in the dark sector (SIMP); new force carriers coupling to electrons, decaying visibly or invisibly (i.e. ALPs) and milli-charged dark sector particles.

In addition, Ref. [10] describes how LDMX data can also benefit the long baseline neutrino program by providing measurements of electro-nuclear cross-sections at 4 GeV - a regime of interest for the upcoming DUNE experiment.

EXPERIMENTAL CONCEPT

The signature for DM production in LDMX would be substantial energy loss by the electron beam, an outgoing electron with a potentially large transverse momentum kick, and absence of any additional SM final-state particles that could account for the energy lost by the electron.

Fig. 3 shows the LDMX apparatus. The design is driven by the requirement to measure the kinematics of the interaction precisely and reject all possible background processes. The experiment consists of a tungsten target in a 1.5 T dipole magnetic field. The target is preceded by a low-mass "tagging tracker" and followed by a "recoil tracker." Both a high-granularity electro-magnetic calorimeter (ECAL) and a hadronic calorimeter (HCAL) follow the recoil tracker and help identify, and veto, backgrounds. It should be noted that the detector design is not final, and adjustments are on-going a simulation studies are made and as prototypes are tested.

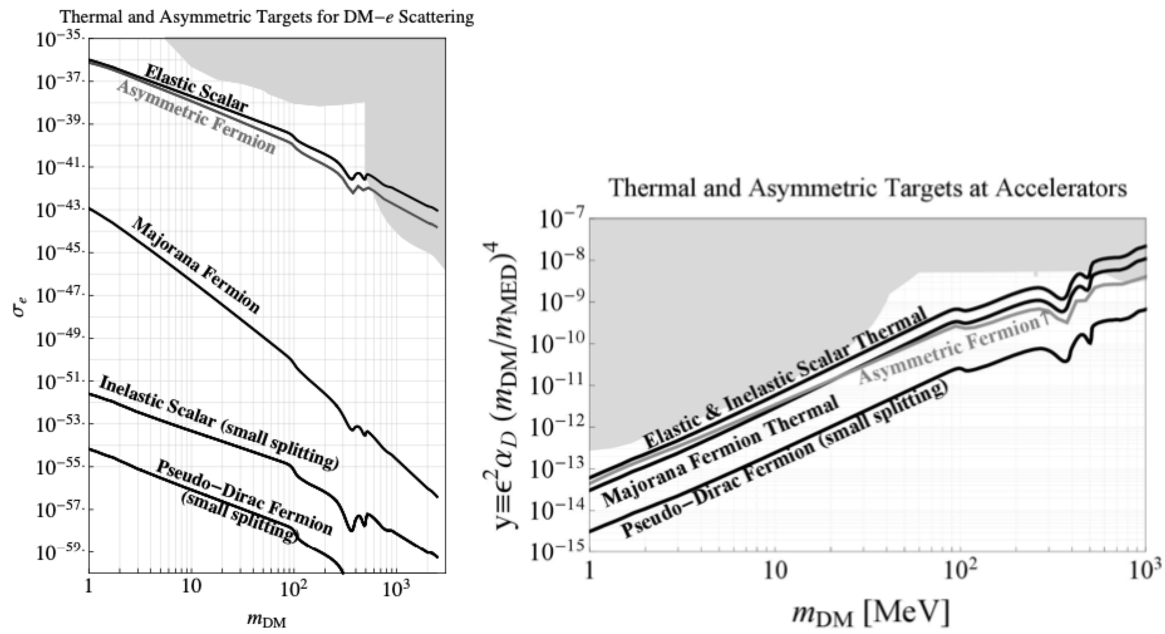

FIG. 1. Plots taken from Ref. [6]. "Freeze out" curves for several direct annihilation models are shown. In the direct detection plane (left) these curves sit up to $\mathcal{O}(10^{20})$ apart, this is due to features of the models themselves such as velocity suppression, spin suppression or loop level factors. This masks the similarity at the relativistic scale. The right plot shows the accelerator regime and reveals how similar these models are at the relativistic scale. Accelerator-based searches can be designed (such as LDMX) which can thus explore all these models over the sub-GeV range. The shaded region indicates exisiting bounds.

Backgrounds

In order to conclusively say that any missing momentum has gone to DM particles, it is crucial that all potential SM backgrounds are vetoed, this includes:

- **Incident low-energy particles, beam impurities and non-interacting electrons** - electrons with less than the full-momentum expected in the beam could impact the target, resulting naturally in a low energy observed in the detector. Suppressing this background requires good beam quality and a incoming beam "tagging tracker" to confirm that each incoming electron has the expected momentum. Electrons that don't interact will deposit energy equivalent to the beam energy in the ECAL.

- **Hard bremsstrahlung** - bremsstrahlung will be common, occurring at a rate of $\mathcal{O}(10^{-2})$. Ordinarily this is easy to veto, with two showers present in the ECAL with total energy of $\sim E_{beam}$. A more challenging case is when the outgoing photon undergoes a rare process such as a photo-nuclear (PN) reaction or conversion to a muon or pion pair. The ECAL and HCAL are necessary to account for all the outgoing particles in these final states. Ref. [11] details the efficiency of the rejection efficiency on bremstrahlung photons.

- **Neutrino Backgrounds** - neutrino production in electron fixed-target experiments is very low, particularly at energies below 20 GeV. For the luminosities required for LDMX, neutrino processes should be unobservable.

EXPERIMENTAL COMPONENTS

Beamline and Magnet

LDMX requires a high-charge, low-current electron beam of 4-10 GeV. This beam would ideally deliver between $10^7 - 10^8$ electrons per second. The LCLS-II at SLAC can provide this beam. A beamline will be constructed to transport the electrons to SLAC's End Station A Hall where LDMX is to be located. The beam-line consists of a large-diameter beam-pipe terminating upstream of an analyzing magnet which contains the target and two trackers. The analyzing magnet is a common 18D36 dipole magnet with a 14-inch vertical gap and operated at a central field of 1.5 T.

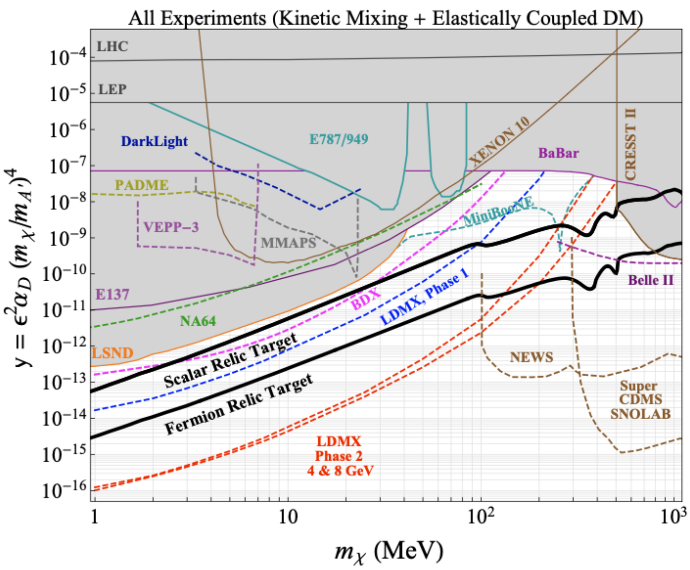

FIG. 2. The parameter space for current results (solid areas) and future experimental projections (dashed lines) in the $y - m_\chi$ plane plotted against the thermal relic targets for scalar and fermion dark matter. The results assume the mediator couples to either scalar or fermion dark matter which scatters elastically off standard model particles. Results are evaluated for $\frac{m_\chi}{m_{A'}} = 1$ and $\alpha_D = 0.5$ which is a conservative assumption [8].

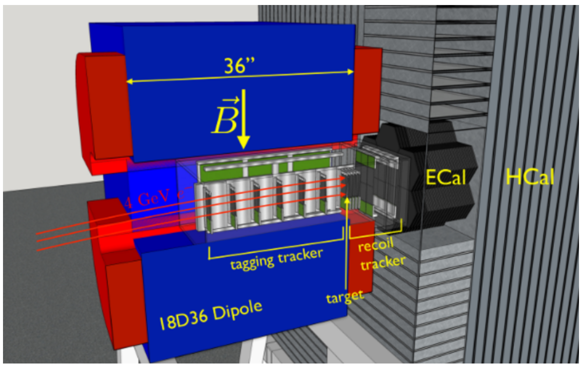

FIG. 3. Conceptual layout of the LDMX Experiment

The magnet is rotated by approximately 100 mrad about the vertical axis with respect to the upstream beam-line so that as the incoming 4 GeV beam is deflected by the field and follows the desired trajectory to the target.

Tagging Tracker

The tagging tracker sits upstream of the target and measures each incoming electron and ensures each has full beam momentum and is delivered to the target at normal incidence. It must also measure the impact position of the incoming beam electron, for comparison with tracks in the recoil tracker and clusters in the calorimeters. The tagging tracker is based on the HPS tracker [12]. It consists of seven double-sided modules of silicon micro-strips arranged at 10 cm intervals. The modules contain a pair of 4 cm $\times$ 10 cm sensors, with one sensor oriented vertically and the other at $\pm$ 100 mrad stereo angle, allowing improved pattern recognition and three-dimensional tracking, providing excellent spatial resolution. The readout provides reconstruction of hit times with a resolution of $\sim$ 2 ns. At the low hit occupancies anticipated in LDMX, three-sample readout may suffice, enabling a maximum trigger rate approaching 100 kHz. This design is expected to provide 1% resolution for 4 GeV incoming electrons. Full simulation of the detector design indicates transverse momentum resolution less than 1.5 MeV. The impact parameter resolution is expected to be approximately 7 μm (48 μ m) in horizontal (vertical) direction. Finally, simulated 1.2 GeV electrons which are injected such that they can contact all seven layers of the tagging tracker are misidentified as full-energy electrons at a rate of less then 10^{-6}.

Target and Trigger Scintillator

The target is a 350 micron tungsten sheet, comprising of 10% of a radiation length (0.1 X_0). This thickness provides a balance between signal rate and transverse momentum transfer due to multiple scattering. The tungsten sheet is glued to a stack of two 2 mm planes of PVT scintillator - known as the "trigger scintillator." This enables a fast count of the incoming electrons in each bunch as required to select the appropriate threshold employed by the ECAL trigger.

Recoil Tracker

The recoil tracker is designed to identify low-momentum recoil electron in the range 50-1.2 GeV and precisely measure their momentum, direction, and impact position at the target. It must also work with the calorimeters to distinguish low-momentum signal recoils from scattered beam electrons and backgrounds. The recoil tracker is placed at the beginning of the magnet's fringe field to optimize tracking for low momentum electrons. The detector is short and wide for good acceptance in angle and momentum and to minimize the distance from the target to the calorimeters to improve their angular coverage. The recoil tracker provides 3D tracking for both direction and impact parameter resolution and consists of four stereo layers located immediately downstream of the target and two axial layers at larger intervals in front of the ECAL. The area of the axial layers is larger than that of the stereo layers to maintain angular acceptance. This design provides transverse momentum measurements at the 4 GeV resolution limit from multiple-scattering in the target. It maintains ¿ 99% track reconstruction efficiency for recoil tracks with momentum greater than 1 GeV and falls below 80% at $\sim$ 100 MeV.

Electromagnetic Calorimeter

The ECAL is a high-granularity, Si-W, sampling calorimeter, based on the High Granularity Calorimeter (HGC) for the forward calorimeter upgrade of the CMS experiment for the HL-LHC [13]. The hexagonal sensors, front-end readout electronics and front-end trigger architecture will be the same since the sampling time for the CMS HGC (40MHz) is comparable to that planned for LDMX (46 MHz).

With this design the ECAL design can cope with high rates, is highly-granular in order to separate the showers of multiple beam electrons in a single integration interval, and is able to withstand the effective fluence of 10^{13} n/cm^2 from 10^{14} EOT. 30 layers of 300 μm thick silicon sensors with absorber layers of tungsten and copper will be required. Each layer will contain seven hexagonal modules and will $\sim$ 51 cm wide. The absorbers will be thinner in the first layers and thicker further in because PN backgrounds are most dangerous when the interactions occur as the first or second interaction of

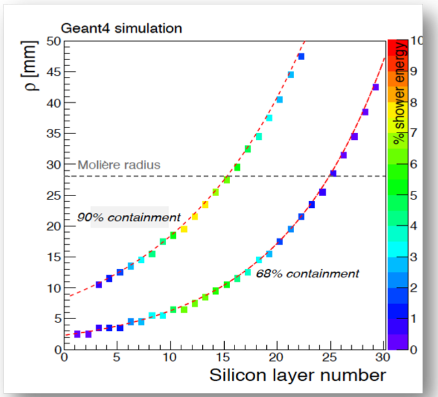

FIG. 4. Shower size as measured by 68% or 90% containment is small for the first 20 or 10 layers respectively.

an electromagnetic shower. This will increase the probability that highly-ionizing fragments from an early PN interaction are measured by the silicon rather than being lost in the absorber. The full depth of the ECAL would be $40X_0$ and $\sim$ 30 cm.

The ECAL is expected to have a resolution of approximately $17/\sqrt{E}\% \otimes 1.4\%$, allowing for good separation of 4 GeV beam particles from re-coil electrons, which are expected to have less than 1.2 GeV of energy. The ECAL must have the ability to identify low-activity PN events. The excellent MIP-tracking of the ECAL is important for this effort, as PN interactions may result in the production of a small number of charged pions or muons, which can be difficult to identify in some types of calorimeters.

The ECal is also an imaging calorimeter and has fine granularity which can see shower development and separate photon and electron showers well. Fig. 4 is taken from CMS the shower size as measured by 68% or 90% containment is small for the first 20 or 10 layers respectively. In the second picture below you see a simulation event display from CMS showing how clearly separated showers form individual particles are.

Hadronic Calorimeter

The hadronic calorimeter (HCAL) is responsible for identifying, and vetoing, penetrating hadronic backgrounds from PN reactions in the target or ECAL. The HCAL must identify neutral hadrons in the energy range of $\sim$100 MeV to several GeV with high efficiency. The most problematic events typically contain either a single high energy neutral hadron, or multiple lower energy neutral hadrons. The required efficiency for lower energy neutrons can be achieved with absorber plate sampling thicknesses in the range of 10% to 30% of a strong interaction length (λ). In order to reduce the probability of a single high energy forward-going neutron to escape without interacting to the required negligible level, a total HCAL depth of approximately 16 λ of the primary steel absorber is required. The ECAL is surrounded with a Side HCAL in order to intercept neutral hadrons produced at large polar angles.

A bar based geometry has been chosen. The design of the HCAL detector is based on that of the Mu2e Cosmic Ray Veto System [14]. The active material of the calorimeter is plastic scintillator with a steel absorber. These are read out with wavelength-shifter fibers coupled to SiPMs. The overall design of the HCAL is still being optimized and a proto-type will soon be tested at the CERN Test Beam later this year.

Trigger and Data Aquisition

LDMX uses the ECAL for a primary trigger. The CMS-developed front-end ASIC produces energy measurements for every 46 MHz accelerator bunch which are summed over a set of the front layers of the calorimeter. The trigger will require that the observed energy be significantly lower than that expected for a 4 GeV electron. This trigger can provide a rejection factor of 2×10^{-5}, with no loss of efficiency for signal. This is sufficient to allow a total trigger budget of 5 kHz, including multiple background-measurement triggers and detector monitoring triggers. The DAQ is designed based on the Reconfigurable Cluster Element (RCE) developed at SLAC [15], and is scaled to be capable of a readout bandwidth of 25 kHz. The design provides a substantial safety factor in trigger rate and event size.

CONCLUSION

The idea that dark matter arose as a thermal relic from the hot early Universe is a compelling one and is robustly viable from the MeV to TeV mass range. The lack of evidence at direct detection experiments searching for GeV - TeV scale WIMP DM motivates exploring the lighter, sub-GeV, region. The Light Dark Matter eXperiment (LDMX) aims to explore sub-GeV DM through high-luminosity measurements of missing momentum in fixed target collisions involving an electron beam. LDMX offers excellent sensitivity to a range of thermal DM models, or "targets," across the sub-GeV range.

LDMX will take place in two phases. Phase 1 will utilize a 4 GeV electron beam and acquire at total of 10^{14} EOT. Phase 2 will utilize and 8 GeV beam and acquire a further 10^{16} EOT. The experiment will utilize SLAC's LCLS-II beam and will be located at SLAC's End Station A. LDMX employs two high precision trackers: the tagging tracker measures the incoming beam and the recoil tracker measures the outgoing electrons, the designs of both are inspired by the HPS trackers. A highly-granular and radiation-tolerant Si-W ECAL, based on that designed for the CMS Upgrade, and a plastic scintillator HCAL, based on technology developed for the Mu2e experiment, are also required to help veto all SM final state backgrounds which could potentially fake a signal.

This design has sensitivity to the thermal-relic hypothesis over a wide range of masses below 1 GeV. The conceptual design is currently in an advanced state, with design optimization ongoing and performance studies underway using simulated data samples.

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