Light Dark Matter eXperiment (LDMX)

Scientific Goals and status of Design Studies

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LDMX Concept
September 2016
Motivation for Sub-GeV Dark Matter

Identify the New Physics of Dark Matter

- Next frontier for Dark Matter science
  - Logical place to focus given LHC and Direct Detection null results
  - Unique opportunity for high impact from small experiment!
Implications of Sub-GeV Dark Matter

Observed DM density fixes particle annihilation cross-section – this tells us a lot about its interactions!

1. DM lighter than a few GeV must annihilate via new **light** force carrier
   → DM production at low-energy accelerators through new force

\[ e^- Z \rightarrow e^- Z A'; A' \rightarrow \text{invisible} \]
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2. Implies a minimum coupling const.
   → Minimum production cross-section (thermal relic target)
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2. **Implies a minimum coupling const.**
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The Missing Momentum Approach

- Considered by many to be the most robust technique for discovering Sub-GeV thermal dark matter
- LDMX employs this technique via fixed target electron scattering
  - Dark photon radiated in 10% $X_0$ target decays to DM ($A' \rightarrow XX$)
The Missing Momentum Approach

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- LDMX employs this technique via fixed target electron scattering
  - Dark photon radiated in 10% $X_0$ target decays to DM ($A' \rightarrow \chi\chi$)
  - Distinctive signal kinematics ($M_e << M_{A'} << E_{\text{beam}}$) yields a final state with hard $A'$ (invisible) and a very soft recoil electron
    - Results in the measurement of significant missing momentum/energy

![Graph showing electron recoil energy distributions and electron $|P_T|$ distributions.](image)

- SM recoil electrons have low $p_T$ and an associated hard photon
- Phase I — $4 \times 10^{14}$ electrons delivered over 1-2 years of running
  - Requires multi-GeV electron beam that operates at MHz scale.
  - Possible w/ proposed DASEL beamline at SLAC’s LCLS-II or CEBAF at JLAB.
  - LDMX Phase I is sensitive to sub-GeV DM beyond the Scalar Relic Target

Projected Sensitivity

- **Projected Limits (dotted)**
- **Existing Limits (solid)**

- **Missing Mass/Momentum Experiments (Kinetic Mixing)**

- **Scalar Relic Target**
- **Fermion Relic Target**
- **LDMX Phase 1**
- **LDMX Phase 2 (4 & 8 GeV)**

*Limits w/ beam dump results in backup*
LDMX Detector Concept

- Magnet and Tracking
  - Collimated precision tagger tracker in full field → 10% $X_0$ target → compact and precision recoil tracker in fringe field
- Si-W sampling calorimeter (ECAL)
  - 40 $X_0$, 1.5 $\lambda$, 30 Layers, 7 modules per layer of high efficiency, high granularity calorimetry
- Scintillator-Steel sampling calorimeter (HCAL)
  - HCAL Forward — Up to 50 layers (15 $\lambda$), un-segmented for simplicity, veto boosted hadrons
  - HCAL Surround — Up to 20 Layers, 6 $\lambda$, veto wide-angled hadrons
Tagger and Recoil Tracker

- A beam’s eye view of the tagging and recoil trackers
Tagger and Recoil Tracker

- **Tagger tracker:** Tag incoming e-
  - Precise p and (x,y) position at target.
  - 7 Layers — Modules like HPS SVT
    - Veto straggling (off $E_{\text{Beam}}$) electrons

- **Recoil tracker:**
  - Associates recoil electron track w/ incoming tagged track.
    - Measure $\Delta p$ across target
  - 6 Layers — Modules like HPS SVT
  - Compact design, placed in fringe field
    - Accurate momentum measurement for e-'s with $E \geq 50$ MeV.
Electromagnetic Calorimeter

- A beam’s eye view of a typical 4 GeV e-’s shower in the ECAL
• 40 $X_0$ (30 layers) High Granularity Si-W Calorimeter
  • Small Molière radius, ability to track isolated min. ionizing particles (mips).
  • Sufficient resolution to fully veto E&M background
  • Leverage CMS technology — extensively validated radiation hard modules
    • Can withstand the effective fluence of $10^{13}$ n/cm$^2$ caused by $10^{14}$ e$^-$'s on target
Photonuclear Background

Energy Deposited in the ECAL Si ($E_{dep}$) Distribution:
- For a typical 4 GeV $e^{-}$, $E_{dep}$ follows a Gaussian with $\mu \sim 68$ [MeV], $\sigma \sim 6$ [MeV]
- Photonuclear (PN) reactions create a non-Gaussian (power-law) low energy tail

LDMX’s hardest background:
- Initial results show that neutron dominated final states are the most difficult
- ECAL geometry has been optimized to help with detection
- HCAL still required to successfully mitigate all PN events
Photonuclear Background

*γ[from target] (E ≥ 2.5 GeV) → PN reaction (~3B such events expected from 10^{14} EOT)

- LDMX's hardest background:
  - Initial results show that neutron dominated final states are the most difficult
  - ECAL geometry has been optimized to help with detection
    - HCAL still required to successfully mitigate all PN events
- Inclusive Geant4 background vetoed at O(10^{10}) e- on target
  - O(10^{12}) sample is under study

- Energy Deposited in the ECAL Si (E_{dep}) Distribution:
  - For a typical 4 GeV e- E_{dep} follows a Gaussian w/ \( \mu \sim 68 \) [MeV], \( \sigma \sim 6 \) [MeV]
  - Photonuclear (PN) reactions create a non-Gaussian (power-law) low energy tail

\[ E_{dep}[\text{MeV}] \]
Hadron Calorimeter

CMS/LHC upgrades and SLAC hardware
Hadron Calorimeter

- Mechanics
  - Steel absorber and plastic scintillator
  - Thin absorbers for high efficiency

- HCAL Surround
  - Help w/ high PN multiplicity

- Electronics
  - Planes read out w/ wavelength-shifting fibers into SiPM-based electronics
Summary and Conclusions

- Made possible by leveraging latest detector tech.
  - CALICE & CMS inspired high granularity/rad. hard Si-W ECAL
  - HPS based High resolution SVT
  - Low noise SiPM HCAL readout

- Steps are being made to meet an aggressive timeline
  - Experiment is focused on operation in early 2020s

LDMX will comprehensively explore the sub-GeV DM phase space.
- Largely unexplored, simplest and well motivated thermal relic scenarios
- LDMX is the only proposed experiment capable of meeting the thermal relic target
The end

- Please refer to Dark Sectors 2016: Community Report for more on LDMX
- We will be participating in: U.S. Dark Matter Workshop (March 23-25 at University of Maryland)
DArk Sector Experiments at LCLS-II (DASEL): Concept

DASEL is a proposal to deliver low-current CW beam for Dark Matter searches parasitically from LCLSII linac.

The LCLS-II bunch rate of 0.929 MHz (1.1 us spacing) << RF frequency of the gun (186 MHz) and linac (1,300 MHz).

The SCRF linac can accelerate modest current in these “unused” buckets with minor modifications and no interference.

Resulting low-current CW beam can support unique & high-impact dark matter experiments.
Tagging Tracker Performance

- Momentum resolution of \( \sim 1\% \) found in simulation matches analytic calculations
  - \( \sim \)Vanishing likelihood for 1.2 GeV e- to be reco. as 4 GeV e-
- Momentum Resolution \((\sigma_{p_x}, \sigma_{p_y})\) at target is (1.0, 1.4) MeV
  - Small compared to 4 MeV smearing from multiple scattering in 10% X0 target.
- Excellent impact parameter resolution
  - Defines small “beam-spot” to match tagger and recoil tracks
Good acceptance efficiency over a wide range of $A'$ masses (10 to 1500 MeV shown).

Compact recoil tracker can reliably distinguish non-interacting 4 GeV electrons from low-momentum signal recoils.

Tests are underway to determine the possibility including an active target to reject hard brem. photons which promptly undergo a photonuclear reaction.
ECAL Performance

E&M Response and Resolution

More than 7σ fluctuation is required for a 4 GeV E&M shower to be measured as a 1.2 GeV e⁻.

Granularity also allows one to track reasonably well-isolated charged hadrons.

Resolution

Fluka studies show that $10^{14}$ e⁻’s on target results in an effective fluence of $10^{13}$ n/cm².

500 um Si is preferred for best resolution.

It appears liquid cooling will be sufficient for this environment.

Other Considerations
Hadron Veto Performance

- **Primary role**
  - Identification of energetic (1-2.5 GeV KE) neutral hadrons produced in photonuclear interactions in the target or early layers of the ECAL
  - Extension surrounding ECAL will also be useful for wide-angle bremsstrahlung from target and recoil tracker

- **Initial optimization**
  - Studied benefit of additional layers to improve the efficiency for tagging energetic neutrons
  - Further work is ongoing to tune detector layout, but cost is not likely to change
Off-detector electronics and DAQ

- Common off-detector electronics system based on the RCE/RPM ATCA electronics developed at SLAC
  - System is powerful enough to implement the trigger, DAQ, and controls in one ATCA crate

**DAQ**

- Est. event size 2.5 kB
- The DAQ is capable of readout at 50 kHz, providing a factor of 10 safety on the trigger rate
- DAQ bandwidth is additionally sufficient for a factor of five expansion in data volume, should the estimates be low
LDMX Physics Trigger

- ECAL based trigger
  - Energy sums performed using the first 16 layers of calorimeter
  - DAQ needs a reduction of $\sim 10^{-4}$
  - Simulation indicates reduction factor of $2 \times 10^{-5}$ possible with no inefficiency for signal
Two tracking systems, separated by a target in separate vacuum, one magnet

- **Tagging tracker**: Tag incoming e-
  - Precise p and (x,y) position at target.
  - 7 stereo Layers: Modules like HPS SVT (L1-L3)
- **Recoil tracker**: Associate tag to recoil
  - Matches recoil electron track to incoming tagger track.
    - Momentum measurement for e-'s with E > 50 MeV.
  - 4 Stereo Layers: Modules like HPS SVT (L1-L3)
  - 2 Axial Layers: Modules like HPS SVT (L4-L6)

- **Screen out straggling (off E_{Beam}) electrons**
- **Measure Δp across target**
  - Recoil tracker placed in fringe field
ECAL Modules

• Specifications
  • Modules to be mounted on thin C/Al cooling planes
  • 256-512 channel 8 in. hexagon sensors
  • Radiation hard design
  • Support 25 ns readout rate

• Leverage CMS HGCal technology
  • CMS HGROCs front end readout chip
  • Module validation provided by CMS’s extensive test beam campaign
  • 210 modules required — Production can be achieved within 2 wks at one of five CMS production facilities

Successful test beams carried out at FNAL & CERN in 2016
Steps are being made to meet an aggressive timeline
- DASEL beamline design is at an advanced stage
- Project is being discussed with DOE to install beamline during LCLS-II construction stop in 2019
- Construction schedule is focused on operation in 2020/21

Studies are underway to understand photonuclear background.
- Inclusive Geant4 background vetoed at $O(10^{10})$ e- on target
- Analysis is ongoing for $O(10^{12})$ & exclusive processes

**Summary and Conclusions**

- LDMX would comprehensively expand current exclusion limits of sub-GeV DM.
  - Detector design leverages US expertise

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