Prepared for submission to JHEP

Light Dark Matter eXperiment (LDMX): Conceptual Design Report

---

an author[a]

[a] *an institution*

Abstract: this is good stuf

Contents

---

1 Overview and Executive Summary (Editors: Philip Schuster, Gordan Krnjaic)

2 Science Goals (Editors: Philip Schuster, Gordan Krnjaic)

2.1 Dark Matter

- sub-GeV dark matter - summary of production kinematics

2.2 Fundamental Forces

- hidden photons, scalars...etc - summary of production kinematics

2.3 Nuclear Physics

- rare photo-nuclear reactions

3 Detector Concept

Basic Considerations and Overview

- Signal characteristics
- Possible backgrounds
- Achieving high luminosity
- Explain why we want a tagger tracker, moderate 0.1 X0 target, recoil tracker, high granularity calorimeter, hadronic veto
- Summarize the overall layout of the experiment

3.1 Beamline, Magnet, and Vacuum Layout (Editors: Tim Nelson, Omar Moreno)

3.2 Tagging Tracker (Editors: Tim Nelson, Omar Moreno)

3.3 Target (Editors: Tim Nelson, Omar Moreno)

3.4 Recoil Tracker (Editors: Tim Nelson, Omar Moreno)

3.5 Forward Electromagnetic Calorimeter (Editors: Joe Incandela)

3.6 Hadronic Veto System (Editors: Jeremy Mans, Nhan Tran, Andrew Whitbeck)

It is also important to extend the calorimeter to veto neutral hadrons being produced in photo-nuclear reactions. As exclusive reactions of this type are rare, the rates and radiation doses will be much lower as the design for the HG calorimeter is designed to fully contain the electromagnetic showers. This removes the requirement for silicon in the hadronic calorimeter section. A scintillator-based sampling calorimeter is a natural solution in this situation. The goal of the hadronic veto system is to identify neutral hadrons in the energy range from above approximately 100 MeV to several GeV with high efficiency. This requires a hadronic calorimeter with at least 5 nuclear interactions of depth in order to fully contain the most energetic of neutrons with greater than 99% probability. Simultaneously, in order to detect lower energy neutrons, absorbing layers cannot be too thick such that neutrons of hundreds of MeV are captured in the absorbers. Therefore, a steel-scintillator (polystyrene) calorimeter of approximately 15 layers and totaling 5 nuclear interaction lengths is proposed. Each layer is structured as 50 mm of Steel, 2 mm air gap, 6 mm of scintillator, and 2 mm of air gap where the air gaps are left for detector services. The transverse size of each layer is 1 x 1 m to cover the solid angle of the signal acceptance. Transverse granularity of the system is not required due to the lower rates expected in the hadronic system and in order to maintain high efficiency for neutral hadron detection. An illustration of the hadronic veto system is given in Fig. 1.

Figure 1. Placeholder... Drawing of HCAL, is it needed? Could be integrated into a full detector rendering

Fast readout is also required of the hadronic calorimeter system in order to coincide with electromagnetic calorimeter information. Readout will be based on the CMS Phase 1 upgrade HCAL system which has fast readout capabilities intrinsically at frequencies of 40 MHz and would be sufficient for the DASEL beam structure. Scintillating light is read out by wavelength shifting fibers with silicon photomultipliers (SiPMs) as the photodetectors. SiPM technology is chosen due to high gain and low noise capabilities. Each layer is read out by N wavelength shifting fibers and the light is optically summed into M photodetectors In addition to the SiPMs, readout modules (48/64 channels per) and charge integration

Figure 2. Drawing of the trigger fiber hodoscope

electronics designed for the CMS detector can be re-purposed for the LDMX experiment with minimal changes and takes advantage of experience of CMS collaborators on LDMX. The timescale for commissioning of the readout electrons in CMS are 2017/2018 and thus are appropriate for the LDMX timeline.

3.7 Wide-Angle Calorimeter ??

3.8 Trigger System (Editors: Jeremy Mans, Nhan Tran, Andrew Whitbeck)

The LDMX trigger system is designed to reduce the typical beam particle arrival rate of ≈ 40 MHz to a rate of O(1 kHz) for storage and analysis. The selection is performed by a combination of dedicated hardware and software running on general-purpose computers.

The first stage trigger is implemented in hardware and allows the selection of both candidate events for dark matter production and important samples for calibration and detector performance monitoring. The overall trigger management is provided by a trigger manager board, which receives inputs from the various triggering subsystems including the silicon calorimeter and the scintillator calorimeter. The latency requirements on the trigger calculation latency are set by the tracker readout ASIC to 2us.

The primary physics trigger is based on the silicon calorimeter and is designed to select events with energy deposition significantly lower than the full beam energy. The silicon calorimeter ASIC calculates the total energy in 2x2 fundamental cells for every 40 MHz pseudo-bucket. The energy information is transferred by digital data link to the peripherary of the calorimeter, where sums can be made over larger regions and transferred by optical link to the trigger electronics. The total energy is then used to select the events.

The use of a calorimeter trigger requirement of energy below a threshold also requires a beam-presence measurement to avoid very high trigger rates during crossings where there is no beam electron present. The trigger fiber hodoscope is designed to serve this purpose. The hodoscope is constructed of an array of 1 mm-diameter scintillating fibers, which are mounted immediately upstream of the tungsten target. [more details on the mechanics, including orientation of the fibers]

The fibers from the hodoscope are brought to an optical vacuum feedthrough and a clear fiber ribbon is connected on the outside of feedthrough to carry the light signals to the readout electronics. Based on studies by the LHCb collaboration[**?**], scaled to the diameter of fibers in use for the hodoscope, we expect a typical signal of [] photons to be produced in the hodoscope by a beam electron after a total absorbed radiation dose of XXX Gray. We expect to able to bring at least [50%] of these photons to the readout SiPMs.

The same electronics design is used for readout of the hodoscope and the scintillator calorimeter. This readout is based on SiPMs and the housing is designed to allow operation of the SiPMs at reduced temperatures (below 5°C) to reduce the thermally-induced single-photon noise. The typical photodetector efficiency of these SiPMs is [30%][**?**], providing a typical signal of [] PEs in the electronics. The readout electronics will continuously digitize the SiPM signal, providing an integrated charge as well as time-of-arrival measurement for the pulse with an LSB of 500 ps. Both amplitude and timing information can be provided to the trigger, allowing the correction of the calorimeter amplitude for timewalk effects already at trigger level.

3.9 DAQ (Editors: Jeremy Mans, Nhan Tran, Andrew Whitbeck)

4 Physics and Detector Simulation

Simulations Overview (Editors: Natalia Toro, Jeremy McCormick)

I don't think this should be a numbered section, but am keeping This section describes the methods used to simulate signal and background physics reactions and the responses of various detectors to these reactions. For historical reasons, two separate simulation frameworks have been used: the "tracker simulation" implemented in SLIC comprises a full simulation of the tagger tracker and recoil tracker, with ECAL material included but not its detector response. Likewise, the "calorimeter simulation" implemented directly in Geant4 comprises a full simulation of the ECAL and HCAL, with recoil tracker material included upstream. In both cases, the target material and magnetic field map are also included. Please check for accuracy These two simulations are described in more detail in §**??**–**??**.

While the primary simulation engine is Geant4 [**?**], the signal reaction (Dark Matter pair production) is modelled using an external generator based on MadGraph4 [**?**]. This generator, its validation, and the interface with Geant4 are described in §**??**. All background processes are modelled directly in Geant4, with modifications and biasing for photonuclear processes as discussed in §**??**.

4.1 Simulation of the Tagger and Recoil Trackers (Editors: Omar Moreno, Jeremy McCormick)

4.2 Simulation of the Forward Electromagnetic Calorimeter (Editors: Owen Colegrove, Joe Incandela)

4.3 Simulation of the Hadronic Veto System (Editors: Nhan Tran, Andrew Whitbeck)

This section should be similar to ECAL on the GEANT4 side. Then we will talk specifically about the digitization, how it is done, and what assumptions are made

4.4 External Physics Generator for Signal Reaction (Dark Matter Production) (Editor: Natalia Toro)

- signal reactions

4.5 Photonuclear Model and Biasing (Editors: Natalia Toro, Omar Moreno)

5 Performance Studies

Baseline luminosity: We want to handle 4×10^{14} electrons on target (EOT) with incoming energy of 4 GeV.

5.1 Signal Characteristics

Please note that we need to optimize the energy selection used below. Starting definition:

Tracking:

- One incoming beam electron with E_{beam} close to 4 GeV and a well measured trajectory.
- Quality cuts (as needed) to reduce any dangerous brem (or photo-nuclear) reactions in the tagger tracker material
- One recoiling electron with $E \lesssim 1.2$ GeV that points back to the incoming beam electron track.
- An activity cut in the recoil tracker to reject photo-nuclear reactions in the target
- An inferred "missing momentum" trajectory and magnitude

Calorimetry:

- One soft recoil shower with $E \lesssim 1.2$ GeV that is consistent with recoil tracker trajectory
- An activity cut in the "missing momentum" region for the ECal
- An explicit veto on energetic (energy range needs to be specified) hadrons in both the ECal and hadron veto system

5.2 Tagging Tracker Performance (Editors: Tim Nelson, Omar Moreno)

Needs to be spelled out in more detail...

- Acceptance
- Efficiency
- Purity (THIS ONE IS CRITICAL)

5.3 Recoil Tracker Performance, (Editors: Tim Nelson, Omar Moreno)

Needs to be spelled out in more detail...

- Acceptance
- Efficiency
- What kind of activity cuts do we want to apply? Background rejection power? Signal efficiency?

5.4 Forward Electromagnetic Calorimeter (Editors: Joe Incandela)

Owen and Joe will discuss this at the July 8 meeting. But Philip's notes include:

- Hermiticity: make sure to include a study of cracks or dead material in the detector simulation. Do we need to worry about this? Why?

Large scale "top down" monte carlo study to demonstrate baseline performance of ECal and to justify more detailed study of specific reactions that dominate the tail of low energy deposition events. We need to quantify everything I'm about the say more carefully. Starting from 4×10^{14} EOT, the baseline tracker selections bring the event sample down to $\sim 4 \times 10^{12}$. So we're dealing with $\sim 4 \times 10^{12}$ events with a soft recoiling electron and a hard, ~ 3 GeV, photon. ECal events that are hadron rich occur about $\sim 10^{-3}$ of the time. So now we're down to $\sim 4 \times 10^{9}$ hadron rich events in the ECal.

- most importantly, we want to understand what dominates the low energy deposition events

- we want to characterize the hadron rich events (because we know they are a potential issue)

- explain veto strategy

- at what point is the energy deposition so low that it's not possible to veto effectively? what are these events types?

Specific "bottom up" studies of photo-nuclear reactions: We know that certain event types could pose a challenge, so let's study them. The numbers shown below are with very loose kinematic selections, so they are upper bounds. They are also for 9 GeV photons, so Philip and Natalia will need to correct them. This is a good starting point for study however:

- $\gamma N \to (\rho, \omega, \phi) N \to \pi^+ \pi^- N$ ($\lesssim 10^8$ of this event type).
- $\gamma N \to \mu^+ \mu^- N$ ($\lesssim 2 \times 10^7$ of this event type).
- $\gamma p \to \pi^+ n$ ($\lesssim 4 \times 10^5$ with $\sim 4 \times 10^3$ of these having a backscattered π^+).
- $\gamma n \to n \bar{n} n$ ($\lesssim 4 \times 10^5$ of this type).
- $\gamma(p, n) \to K_L K_L + X$ (expect this at the $\sim 10^3$ level, but we need to check this!)

The current plan is to use a particle gun and weight the depth of origination and angle/energy distribution using data. Let Philip and Natalia know when you're ready to do this. *We need to be especially careful to include the regions of phase space where the MIPs are soft or wide/back scattering by recoiling off the nucleons or atoms. This needs a dedicated study, starting with the physics simulations group, P,N,E,G.*

5.5 Hadronic Veto System (Editors: Jeremy Mans, Nhan Tran, Andrew Whitbeck)

A good starting point would be to focus on the event types that the ECal will certainly have a tough time with. These are the few-body photo-nuclear reactions for sure. So it might make sense to start with the "bottom up" study outlined above.

Document per particle performance studies

Figure 3. Performance of the primary physics trigger for LDMX. The effiency for signal electrons of differing energy and the trigger rate for all backgrounds induced by beam electrons are shown as a function of the trigger threshold in MIP units.

Table 1. Draft trigger menu for LDMX, showing the primary contributions to the trigger budget for a 40 MHz beam rate

Trigger	Prescale factor	Rate (Hz)
Physics Trigger	1	
E(ECAL) $<$ 1.2 GeV		850
Background-Measurement Triggers		*100*
E(ECAL) $>$ 3 GeV		25
E(ECAL) $>$ 2 GeV		50
HCAL single MIP trigger		25
Detector-Monitoring Triggers		*50*
Beam-arrival (hodoscope)	4000000	10
Empty-detector (hodoscope veto)		10

Allocations are extremely rough at the moment!

5.6 Trigger Performance

As described above, the primary physics trigger is based on the total energy observed in the calorimeter, combined with a requirement of a single incoming electron observed in the trigger fiber hodoscope. Figure 3 shows the simulated performance of the primary physics trigger for signal and background.

Besides the primary physics trigger, the LDMX trigger system will also allow the selection of events for calibration, alignment, and background studies. The trigger will include input from the scintillator calorimeter to allow selection of events with hadrons or muons. Each event will be marked with the set of triggers which fired. An initial draft trigger menu is shown in Table 1.

1. What is the rate of muon production? We would expect to trigger these, yes?
2. What is the impact of cosmics on the HCAL trigger?

6 Budget and Schedule

6.1 DASEL (Editors: Philip Schuster, Gordan Krnjaic)

6.2 Tracking (Editors: Tim Nelson, Omar Moreno)

6.3 Forward ECal (Editors: Joe Incandela, Jeremy Mans)

6.4 Hadronic Veto (Editors: Jeremy Mans, Nhan Tran, Andrew Whitbeck)

6.5 Trigger (Editors: Jeremy Mans, Nhan Tran, Andrew Whitbeck)

6.6 DAQ (Editors: Jeremy Mans, Nhan Tran, Andrew Whitbeck)

6.7 Operations