

PREPARED FOR SUBMISSION TO JHEP

Light Dark Matter eXperiment (LDMX): Conceptual Design Report

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ABSTRACT: this is good stuf

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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 (Editors: Tim Nelson, Omar Moreno)

The LDMX beamline is relatively simple, consisting only of an analyzing magnet and a vacuum chamber into which the tagging and recoil trackers are installed. The analyzing magnet is a common 18D36 dipole magnet with a 12-inch vertical gap and operated at a central field of 1.5 T. A stainless-steel vacuum chamber with 1/2" walls fits just inside the magnet bore supporting the tracking detectors and their readout electronics. The upstream end of the vacuum chamber is closed by a plate with a 6" conflat flange for connection to the upstream beampipe and the downstream end is closed by a titanium vacuum window in front of the

ECal face which sits 20 cm downstream of the target at roughly the same z position as the outer face of the magnet coils. The magnet is rotated by approximately 100 mrad about the vertical axis with respect to the upstream beamline so that the incoming 4 GeV beam follows the desired trajectory to the target, with the incoming beam arriving at normal incidence to, and centered on, the target. Although the specific dimensions differ, this arrangement (aside from the vacuum window) is very similar to the magnet and vacuum chamber employed by the HPS experiment at JLab. As with HPS, additional vacuum boxes at the upstream and/or downstream ends will be appended to the vacuum chamber to accommodate feedthroughs for power, readout and cooling.

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](#)

Figure 2. Drawing of the trigger fiber hodoscope

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 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 electronics 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 $\mathcal{O}(1 \text{ kHz})$ 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 2 \$\mu\$ s](#).

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 periphery 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 be 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 Calorimetry Systems (Editors: Owen Colegrove, Joe Incandela)

A common simulation framework is utilized for the electromagnetic and hadronic calorimeter systems based solely on GEANT4. In addition to a full implementation of the sampling layers for both calorimeters, the target, recoil tracker and magnetic field are also included.

4.1.1 Digitization of Forward Electromagnetic Calorimeter

add stuff here, make it common with trigger description?

4.1.2 Digitization of the Hadronic Veto System (Editors: Nhan Tran, Andrew Whitbeck)

After full GEANT4 simulation, we simulate the digitization of the particle-level interactions in our detector to understand how well we can reconstruct events in the hadronic calorimeter. Given the particle-level energy deposition per layer, we can convert that into the number of minimum ionizing particles (MIP) that we expect in that layer. The translation comes by first estimating the typical energies deposited in a calorimeter model for a MIP. This can be seen in Fig. 3 where a distribution of energies deposited in a given layer is shown for a single MIP muon.

By translating the energy deposited into a single layer, we can compute how many MIPs we expect in a given layer in a given event. From CMS testbeam studies [], it is computed that 1 MIP corresponds to about 13.5 photo-electrons measured in the SiPM. We then set the threshold for a layer becoming vetoed in our detector simulation based on number of photo-electrons measured in the SiPM. That threshold is set at 9 photo-electrons which is $> 4\sigma$ above the typical noise in SiPMs which is typically 2 photo-electrons.

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)

The tagging tracker must identify incoming beam-energy electrons with extremely high purity, suppressing the mis-reconstruction of any incoming low-momentum charged particles as beam energy electrons. In particular, any incoming charged particle within the recoil acceptance for signal that is reconstructed as having the beam energy in the tagging tracker is an irreducible background. The design of the tagging tracker makes the likelihood of such errors vanishingly small, with good resolution for both beam energy and off-energy incoming tracks and an exceedingly low rate of mis-reconstruction for tracks within the recoil energy acceptance.

In order for an incoming low momentum particle to fake a beam energy electron in the tagger, a number of conditions must simultaneously be met:

1. The incoming particle must reach the first tagger layer or it will not intersect with any material until it hits the wall of the vacuum chamber.
2. The particle must either scatter in each layer in order to fake a 4 GeV track or create secondaries that generate occupancy which confuses the pattern recognition in the tracker resulting in reconstruction of a fake 4 GeV track.
3. The resulting track must have a trajectory consistent with that of a typical 4 GeV beam electron all the way through the tracker.
4. The resulting track must have an impact point at the target consistent with a reconstructed track within the signal acceptance in the recoil tracker.

Using an analytic model of the tagging tracker that includes the effect of intrinsic resolutions and multiple scattering in the tracker planes, it is evident that each of these requirements places a very heavy penalty on any off-energy component in the beam. First, incoming particles with less than approximately 500 MeV momentum will not hit the first layer of the tagger unless they are significantly off-trajectory as well. Furthermore, even at 500 MeV, a first scatter of more than 10° is needed in order for the incoming particle to appear to be on the correct trajectory. It is clear then that the most challenging scenario is large contamination with incoming charged particles at the top of the momentum range for signal recoils, nominally 1.2 GeV. Such particles have the highest likelihood of reaching the first layer of the tagger tracker without being bent away by the magnetic field and require much smaller scatters and/or track reconstruction errors to result in fake tags. In order for a 1.2 GeV particle to make a trajectory through the tracker consistent with a 4 GeV track, six successive scatters of approximately ten milliradians must occur, each equivalent to approximately 15σ on the multiple scattering distribution. From the tails of the Moliere scattering distribution, the likelihood of each of these scatters is smaller than one per million. Therefore, the much more likely scenario is the generation of secondaries in the material of the tagger tracker followed by misreconstruction of a fake 4 GeV track. Since the resulting 4 GeV track must arrive at the target on the correct trajectory and beam energy electrons arrive normal to the target with a one-sigma error of 250 microradians, there is very little phase space for randomly

reconstructed 4 GeV fakes to have the correct trajectory. Finally, any falsely reconstructed 4 GeV track must have a common impact point in the target with a real track of matching momentum in the recoil tracker, which is unlikely for a falsely reconstructed tracks.

In order to more fully test these scenarios, two samples of incident electrons were simulated and reconstructed in the tagger tracker. The first is a sample of XXX 4 GeV electrons on the nominal beam trajectory. The second is a sample of XXX 1.2 GeV electrons on a trajectory that allows them to pass through all seven layers of the tagging tracker. The 4 GeV sample confirms the expected resolutions, as shown in Figures ??.

These indicate that tight requirements can be made in both the energy and trajectory at the target that rejects off-momentum particles that could be present in the incoming beam and that the tagging tracker identifies a precise impact position that can be used for tracking recoil candidates. The 1.2 GeV sample confirms at the level of 1 part in 10^7 that these tracks cannot be mistaken for 4 GeV tracks, as shown in Figure 6. In order to probe the likelihood of reconstructing fake 4 GeV tracks at higher statistics we further introduce random noise hits on all planes of the tracker at rates of 10^{-3} , 10^{-2} and 10^{-1} in all planes of the tracker, where typical noise occupancies in similar HPS modules are roughly 10^{-4} . Figure 7 shows the resulting distribution of reconstructed tracks in energy and p_T at the target. Obviously, such extreme occupancies in the tracker are atypical, and would easily be selected against with negligible impact on signal efficiency. Furthermore, these fake tracks, not being due to an individual low-momentum track, will typically not align with a low-momentum track in the recoil tracker. Although further study will be required to find the beam intensity limits for this tagging tracker design, we can safely conclude that it is more than capable of providing the tagging purity required for the first stage of the LDMX experiment.

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:

- $\gamma N \rightarrow (\rho, \omega, \phi) N \rightarrow \pi^+ \pi^- N$ ($\lesssim 10^8$ of this event type).
- $\gamma N \rightarrow \mu^+ \mu^- N$ ($\lesssim 2 \times 10^7$ of this event type).
- $\gamma p \rightarrow \pi^+ n$ ($\lesssim 4 \times 10^5$ with $\sim 4 \times 10^3$ of these having a backscattered π^+).
- $\gamma n \rightarrow n \bar{n} n$ ($\lesssim 4 \times 10^5$ of this type).
- $\gamma(p, n) \rightarrow K_L K_L + X$ (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](#)

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 8 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

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

Allocations are extremely rough at the moment!

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

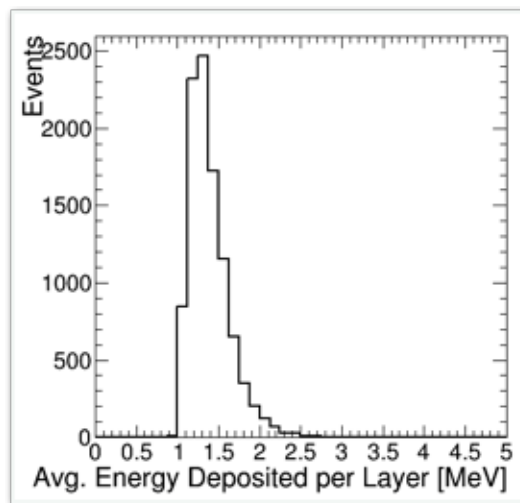


Figure 3. Placeholder... [Distribution of energies deposited in scintillator from muon](#)

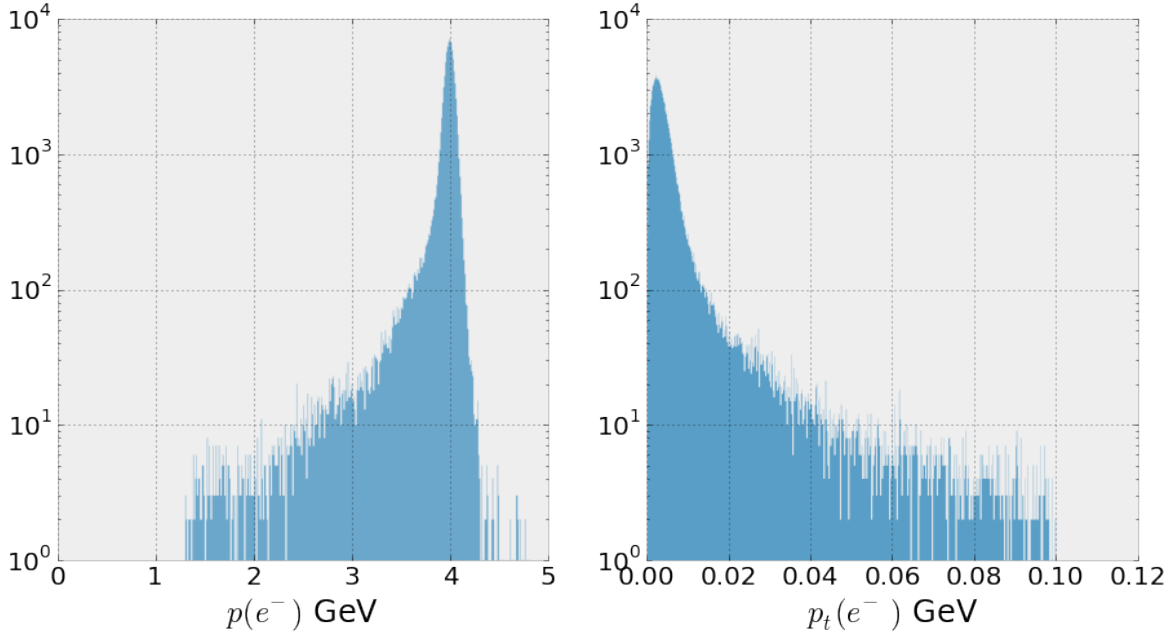


Figure 4. Reconstructed total momentum and momentum transverse to target for a sample of 4 GeV beam electrons.

Figure 5. Reconstructed Tagger track x - y position at the target for a sample of 4 GeV beam electrons.

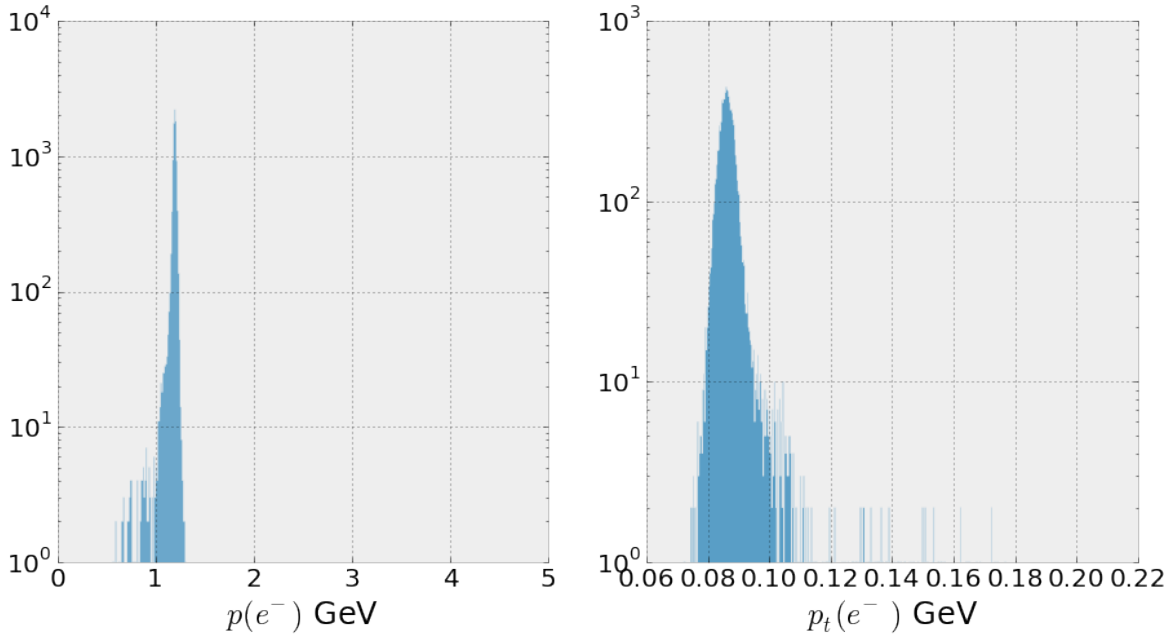


Figure 6. Reconstructed total momentum for a sample of 1.2 GeV beam electrons.

Figure 7. Reconstructed momentum vs. momentum transverse to the target for a sample of 1.2 GeV electrons in the presence of 10^{-3} , 10^{-2} and 10^{-1} random occupancy in all sensors.

Figure 8. Performance of the primary physics trigger for LDMX. The efficiency 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.