Searching for Dark Matter with Electron Beams using the Missing Momentum and Energy Techniques

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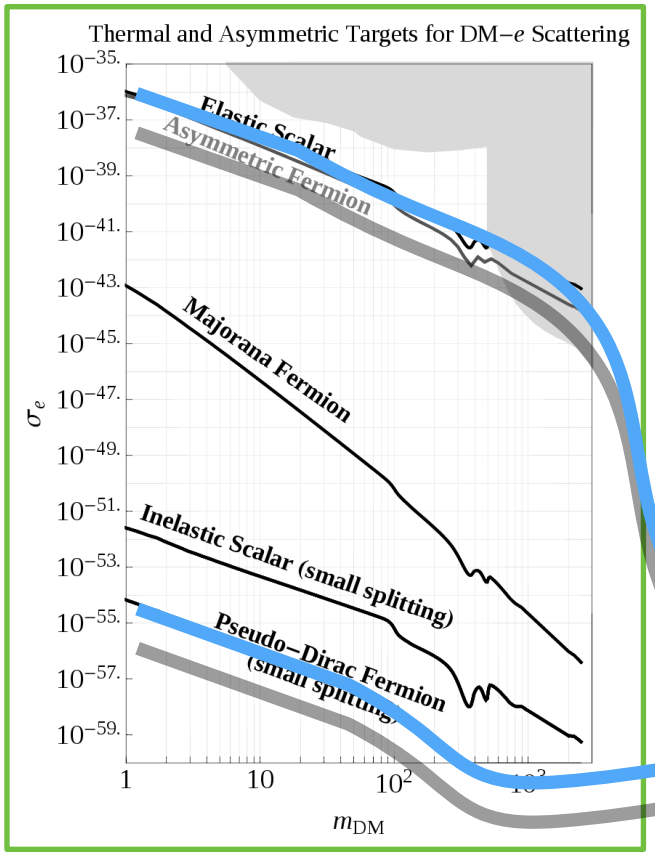
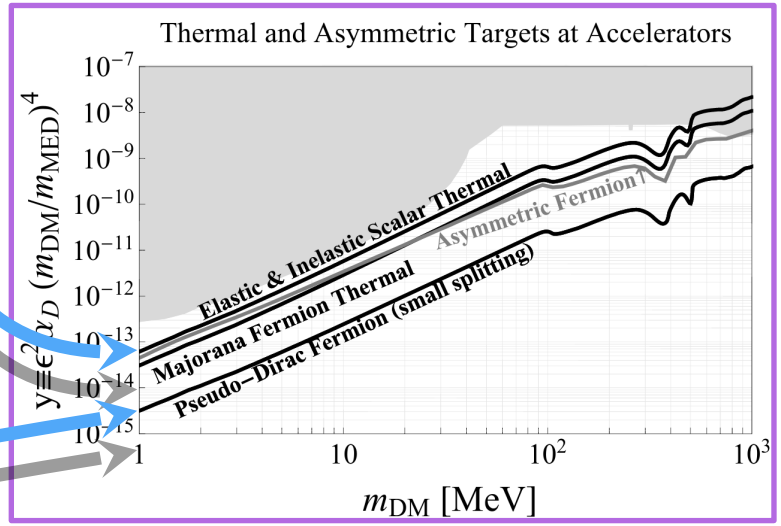
Light Dark World 2023

Jeremiah Mans, University of Minnesota
For the LDMX Collaboration

Thermal dark matter below ~1 GeV

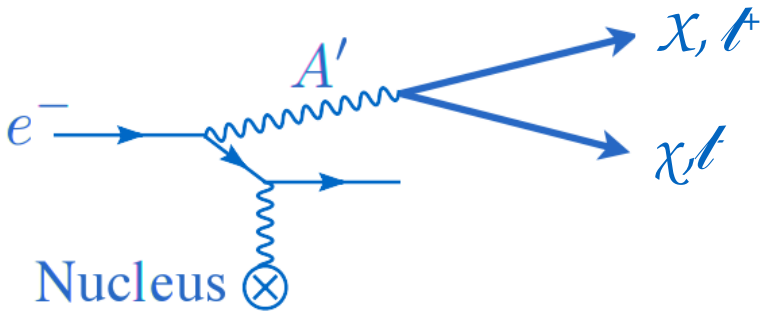


- The existence of dark matter is well-established by cosmological and astrophysics observations
- The freeze-out hypothesis has been a key motivating concept in the search for dark matter
  - Dark matter particle mass is a ~free parameter, but lighter masses require weaker couplings to the visible SM
- Light dark matter naturally implies a new force carrier mediating the "weaker-than-weak" connection between the SM and DM sectors

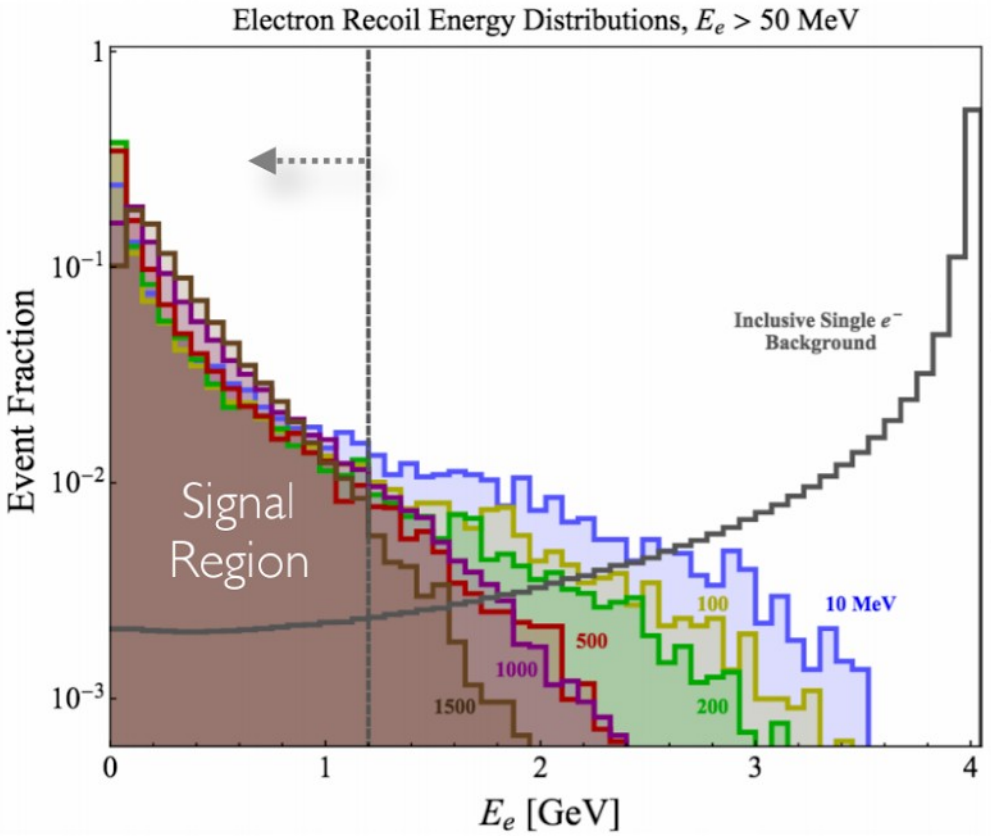


- Direct-detection requires experimental observation of non-relativistic dark matter
  - Sensitive to the details of the coupling, which can result in very large scattering rate suppression
- Accelerator-based production of dark matter moves the production to the relativistic regime, where the thermal target for freeze-in naturally collapses to a narrow band

Electron fixed-target kinematics

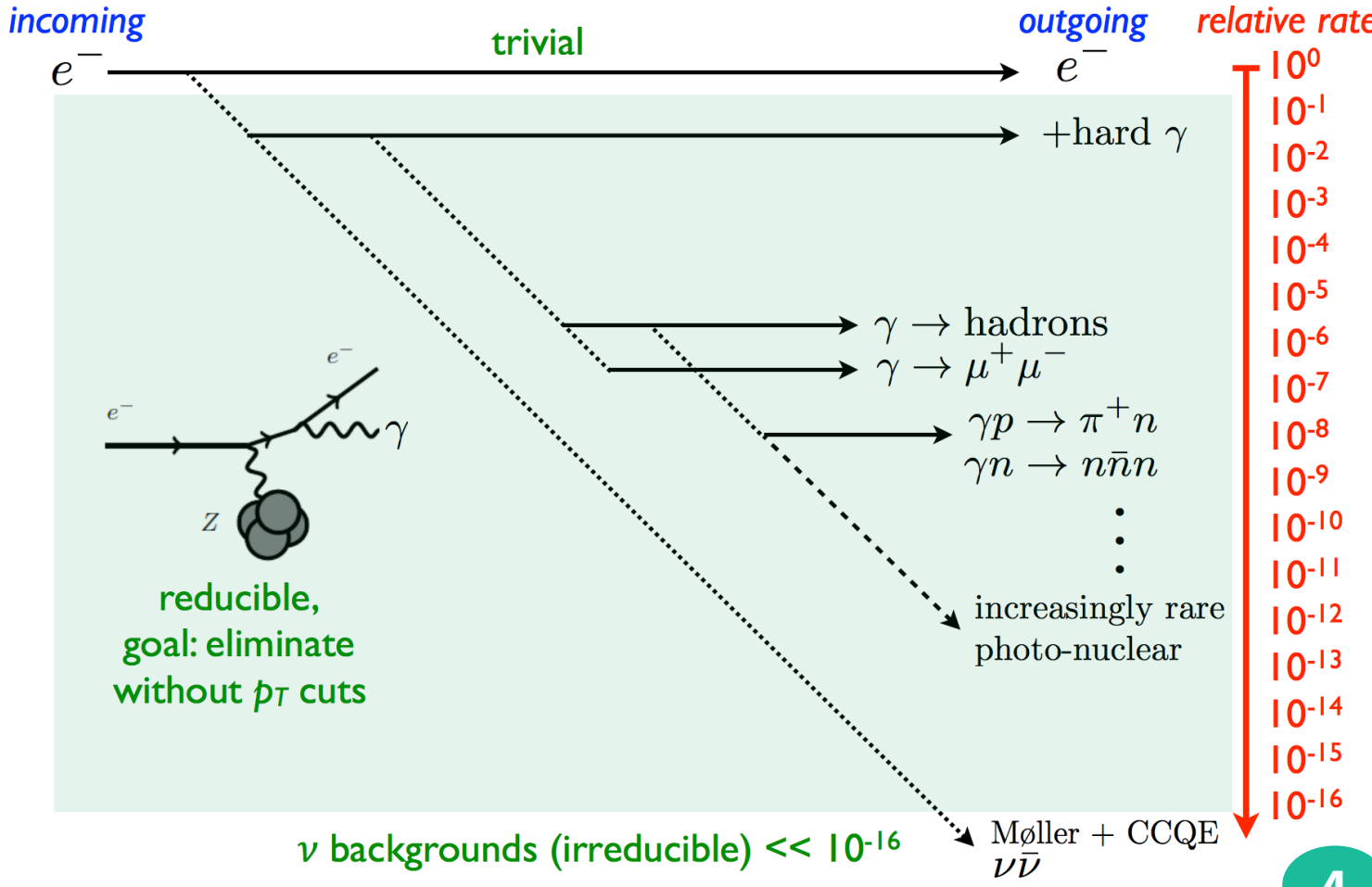


- For $m_{A'} > \sim 2m_e$, A' carries most of the momentum after the interaction
- Signal signature is a single low-momentum electron → large missing momentum/energy
- Recoil electron receives a transverse momentum kick ~ $\sqrt{m_{A'}}$

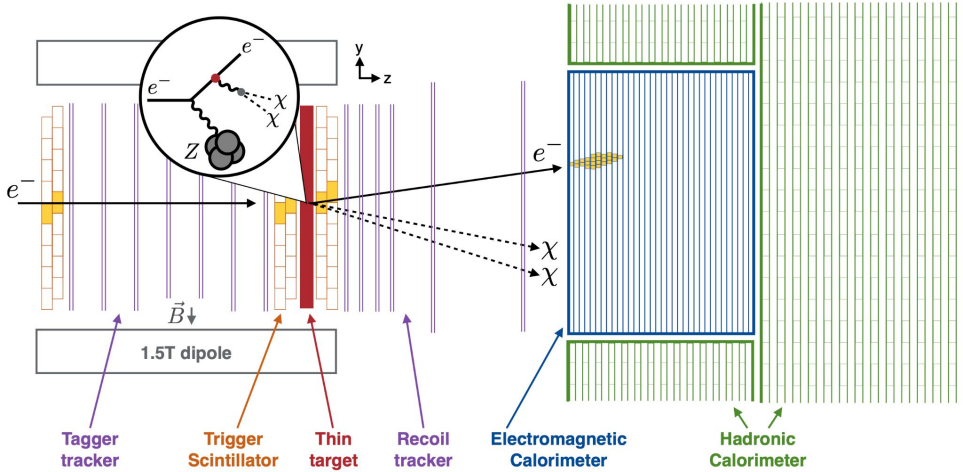


Hierarchy of backgrounds

- **Dominant backgrounds initiated by standard-model bremsstrahlung**
  - Observation of photon showers is critical
- **Irreducible backgrounds are at a very low level for beam energies < 20 GeV**
  - Increasing rate of neutrino background as beam energies increase



Experimental concept



Detector technology with fast readout and high radiation tolerance

high momentum resolution, low mass tagger/recoil tracker

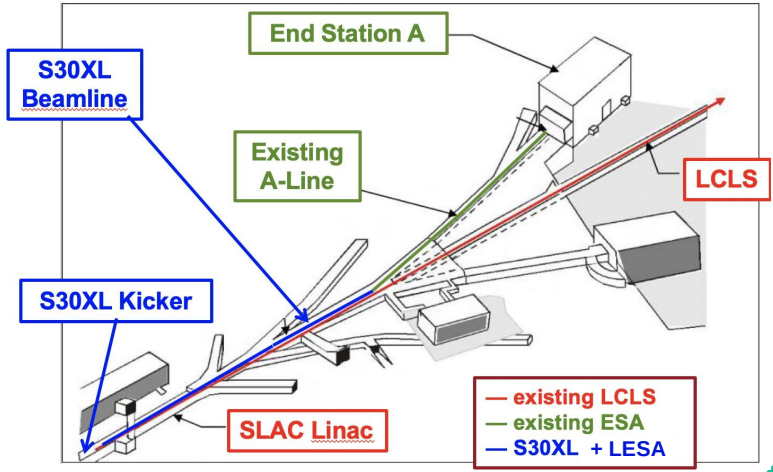
high energy resolution EM calorimeter (ECal)

deep hadron calorimeter (HCal) with good efficiency for O(1 GeV) neutrons

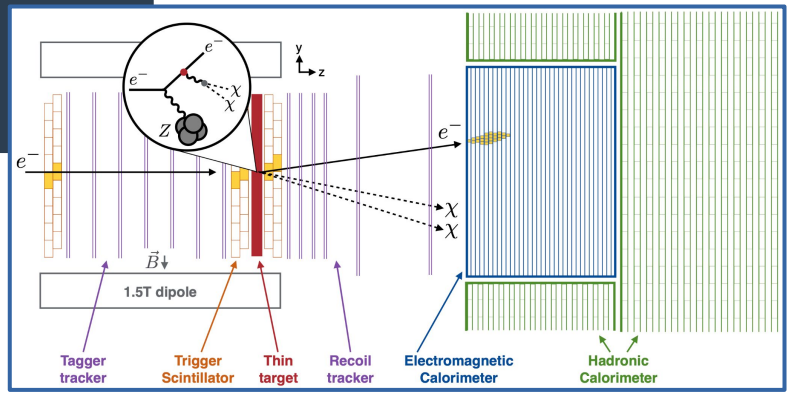
Beam which enables O(10^{16}) electrons to be individually identified & reconstructed

low-current, high repetition rate beam (10^{16}/year is ~ $1e^-$ / 3 ns)

S30XL+LESA using idle cycles of LCLS-II @ SLAC (4/8 GeV)



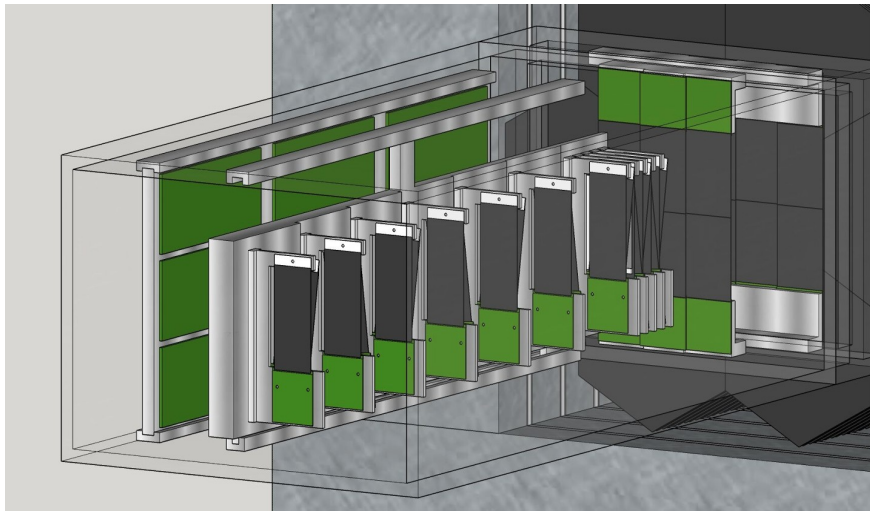
Tracker

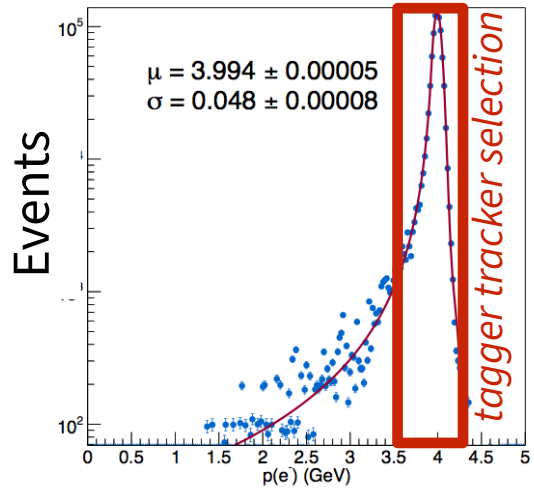


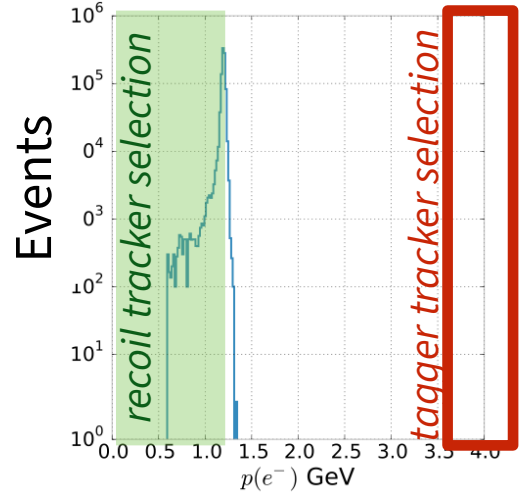
Tracker based on successful HPS design

Tagger Tracker in 1.5T dipole field to reject off-momentum incoming particles

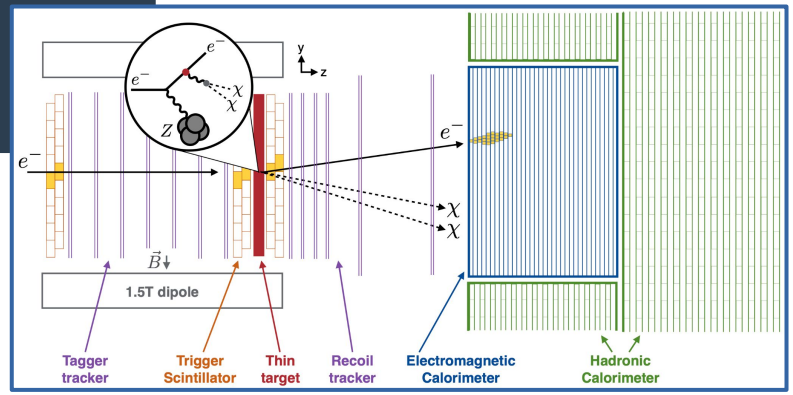
Recoil Tracker in fringe field to measure momentum of recoil electron (including p_T), reject tridents and other events with multiple charged particles emerging from the target







Electromagnetic Calorimeter

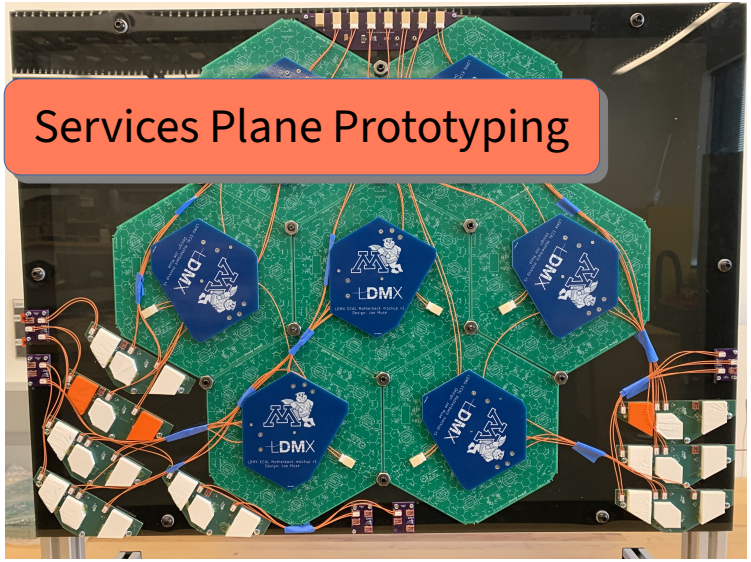


Electromagnetic calorimeter based on CMS HL-LHC Endcap Calorimeter (HGCAL)

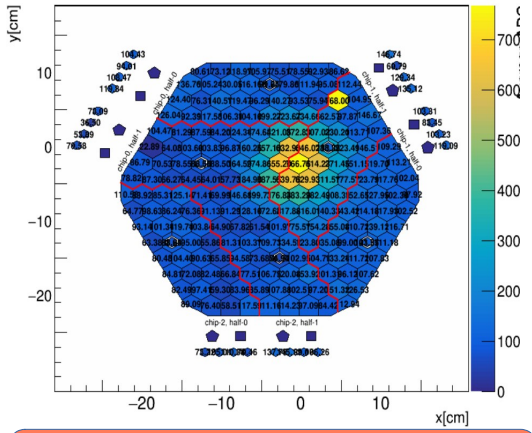
40 X0 tungsten-silicon imaging calorimeter with fast shaping and readout, radiation tolerant

MIP sensitivity (S/N=10-15), precision shower timing (50 ps)

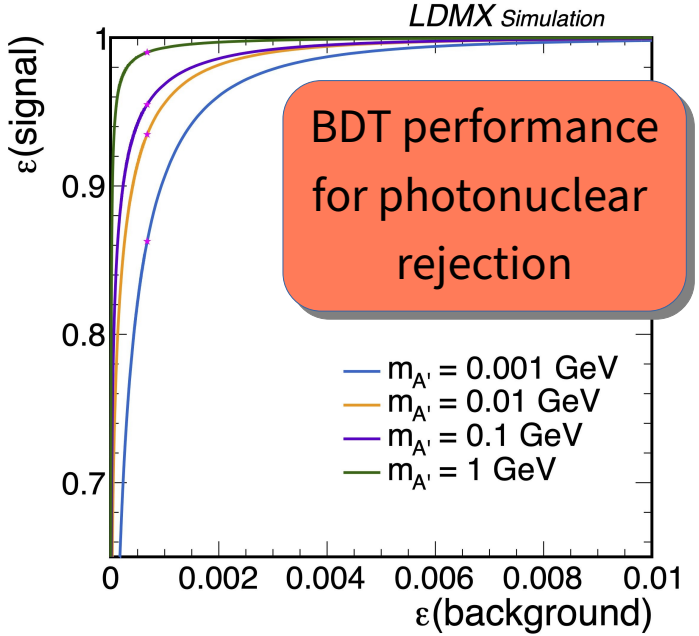
High granularity (100k channels): can exploit both transverse & longitudinal shower shapes to reject PN events using ML algorithms and handle multiple incoming electrons in a single integration period



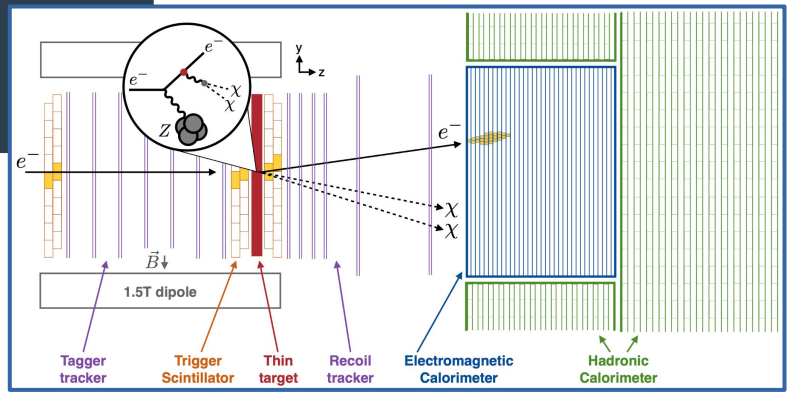
Services Plane Prototyping



CMS Electron Testbeam

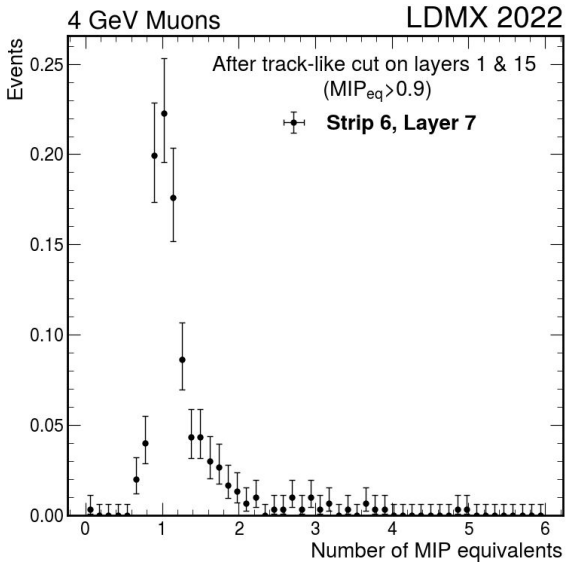


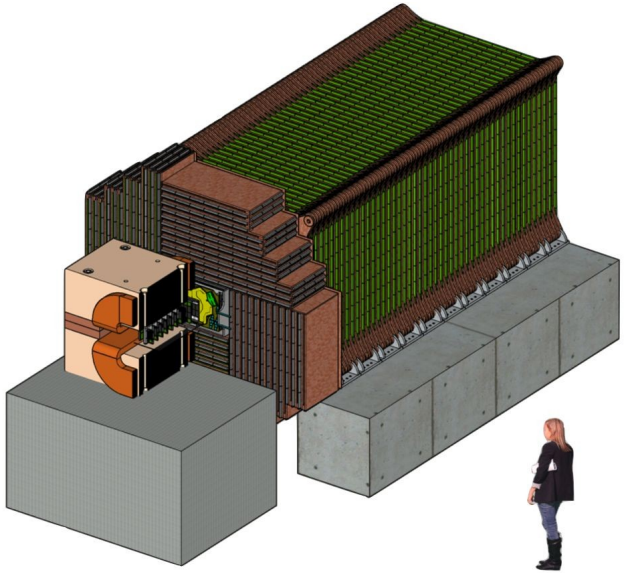
Hadron Calorimeter



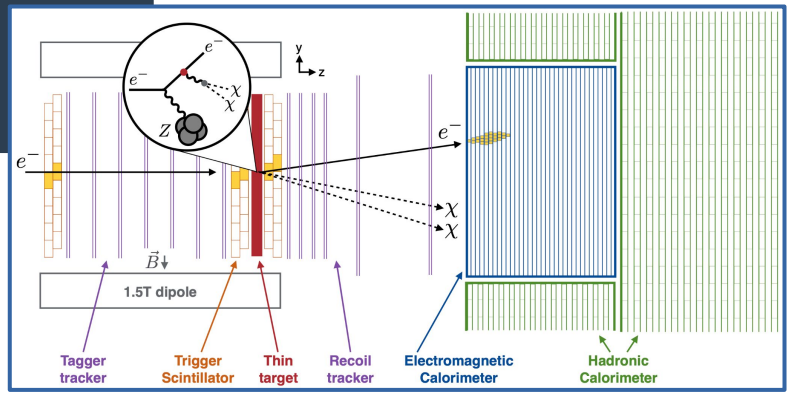
Steel/scintillator calorimeter with WLS fiber/SiPM readout

- Highly efficient veto (10^{-6}) for photonuclear processes that produce neutral hadrons
- Side HCal rejects wide angle bremsstrahlung and γ→μ+μ-
- Enables synergistic measurements in visible signatures and nuclear processes relevant for DUNE program
- Performance demonstrated in CERN testbeam





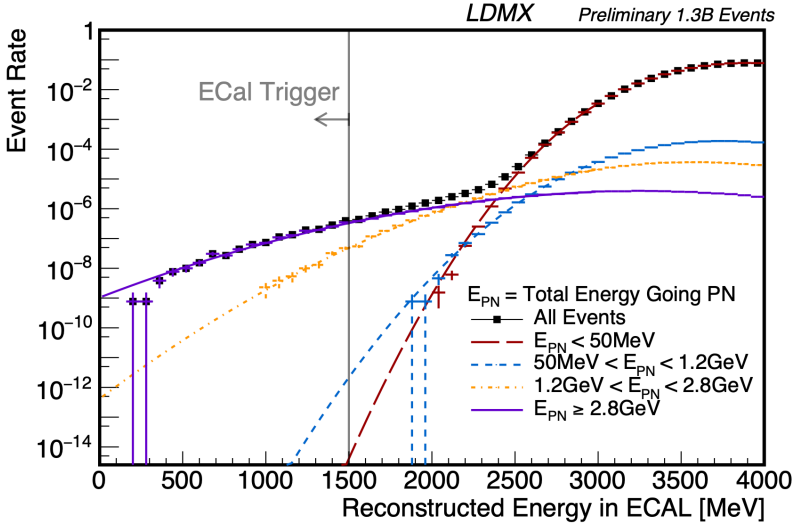
Missing energy trigger

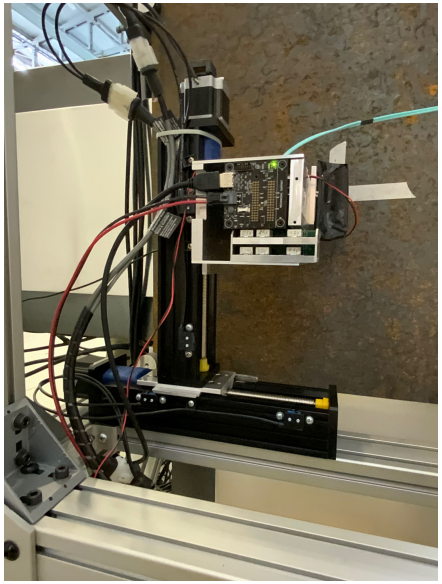


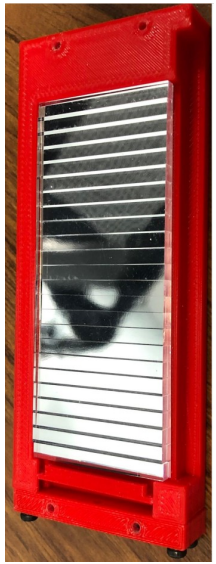
Trigger based on missing energy as measured in ECal

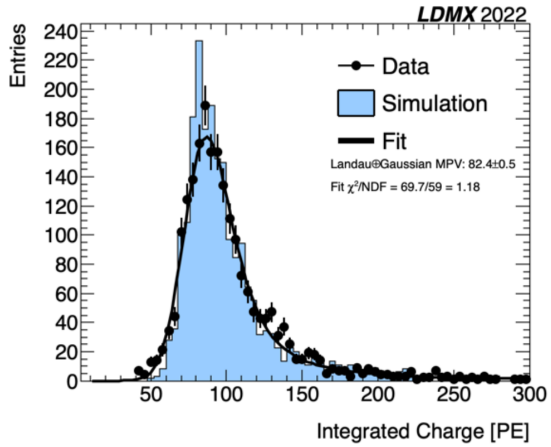
ECal triggering with a missing energy of 2.5 GeV reduces rate from 37 MHz to O(1 kHz)

Trigger scintillator hodoscope determines number of incoming electrons in an event, which is needed to determine appropriate total energy expectation for a given bunch.



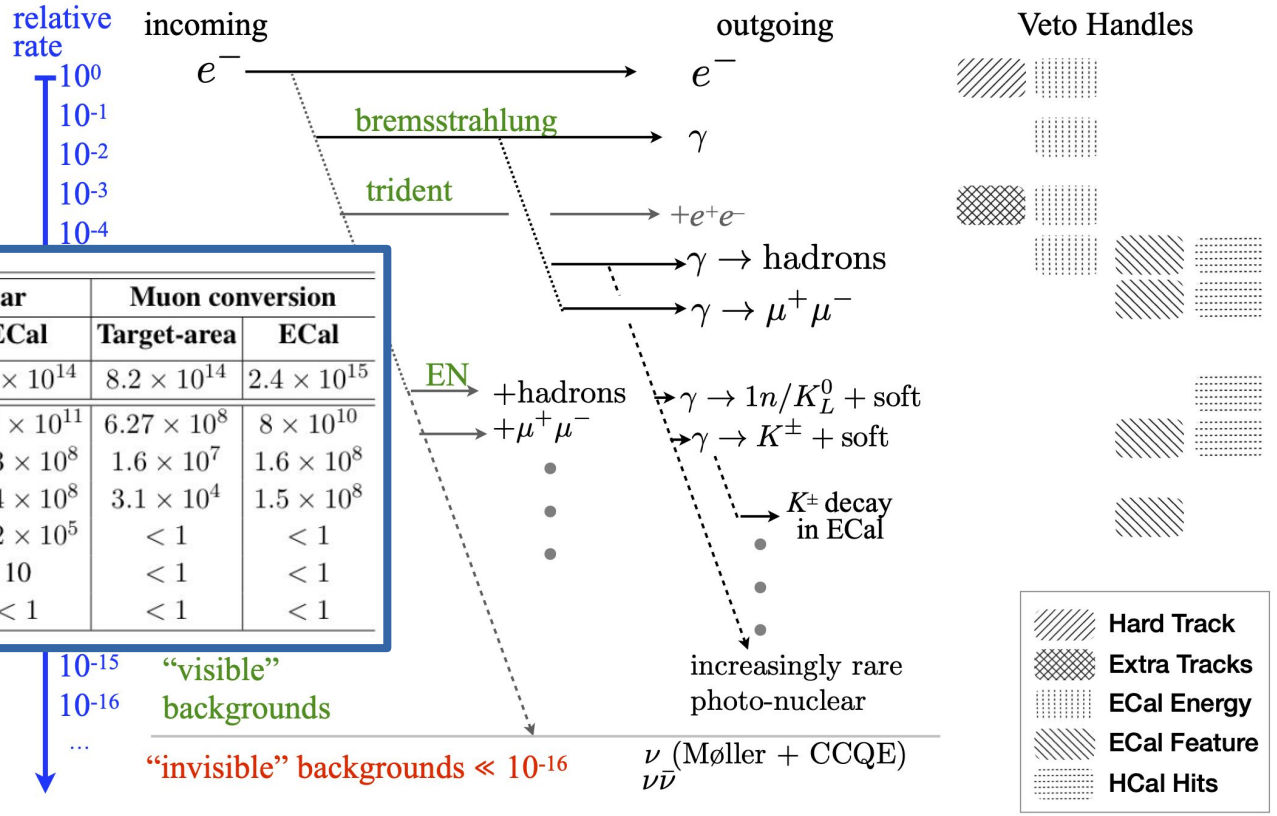






Missing Momentum Search (4 GeV)

	Photo-nuclear		Muon conversion	
	Target-area	ECal	Target-area	ECal
EoT equivalent	4×10^{14}	2.1×10^{14}	8.2×10^{14}	2.4×10^{15}
Total events simulated	8.8×10^{11}	4.65×10^{11}	6.27×10^{8}	8×10^{10}
Trigger, ECal total energy < 1.5 GeV	1×10^{8}	2.63×10^{8}	1.6×10^{7}	1.6×10^{8}
Single track with $p < 1.2$ GeV	2×10^{7}	2.34×10^{8}	3.1×10^{4}	1.5×10^{8}
ECal BDT (> 0.99)	9.4×10^{5}	1.32×10^{5}	< 1	< 1
HCal max PE < 5	< 1	10	< 1	< 1
ECal MIP tracks = 0	< 1	< 1	< 1	< 1

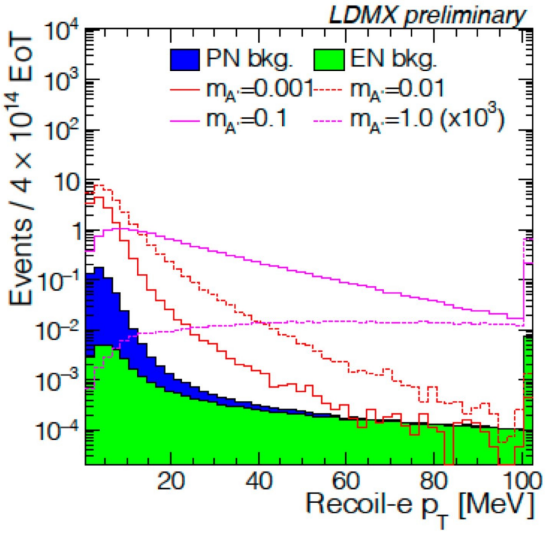


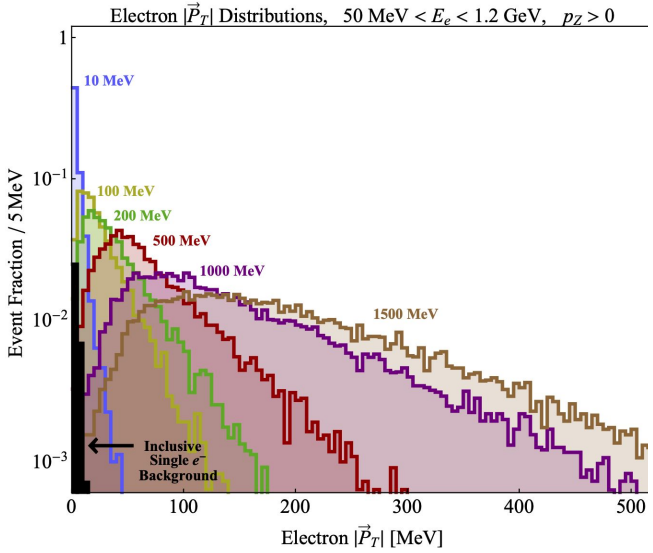
10.1007/JHEP04(2020)003

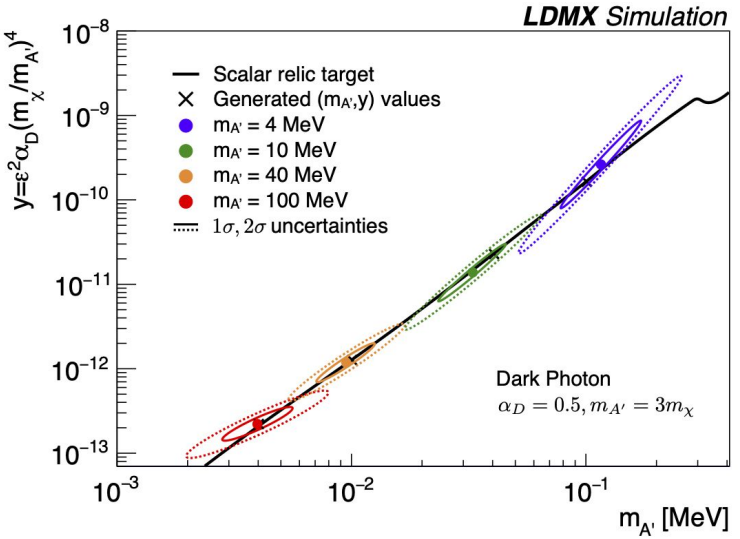
Using signal kinematics in missing momentum

Transverse momentum kick in dark brehmsstrahlung, which is a powerful discriminant from photonuclear and electronuclear backgrounds, is kept **in reserve** for analysis to this point as a final handle in the case of higher-than-expected backgrounds

Transverse momentum distribution can be used to constrain the mediator mass in the case of an observation







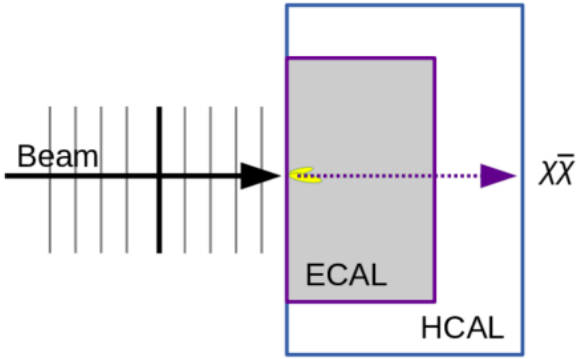
Missing Energy

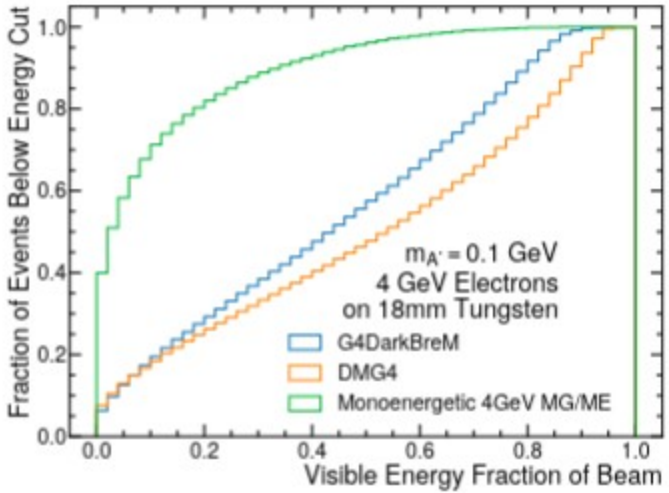
Electrons which do not interact in the target will impact the calorimeter. These electrons could also experience dark brehmsstrahlung, resulting in a missing energy signature

Negatives: Recoil electron transverse momentum cannot be measured, recoil shower overlaps location where photonuclear backgrounds are likely to occur, fewer handles for controlling backgrounds than missing momentum signature

Advantages: More effective luminosity than missing-momentum channel, particularly interesting early in the run of the experiment

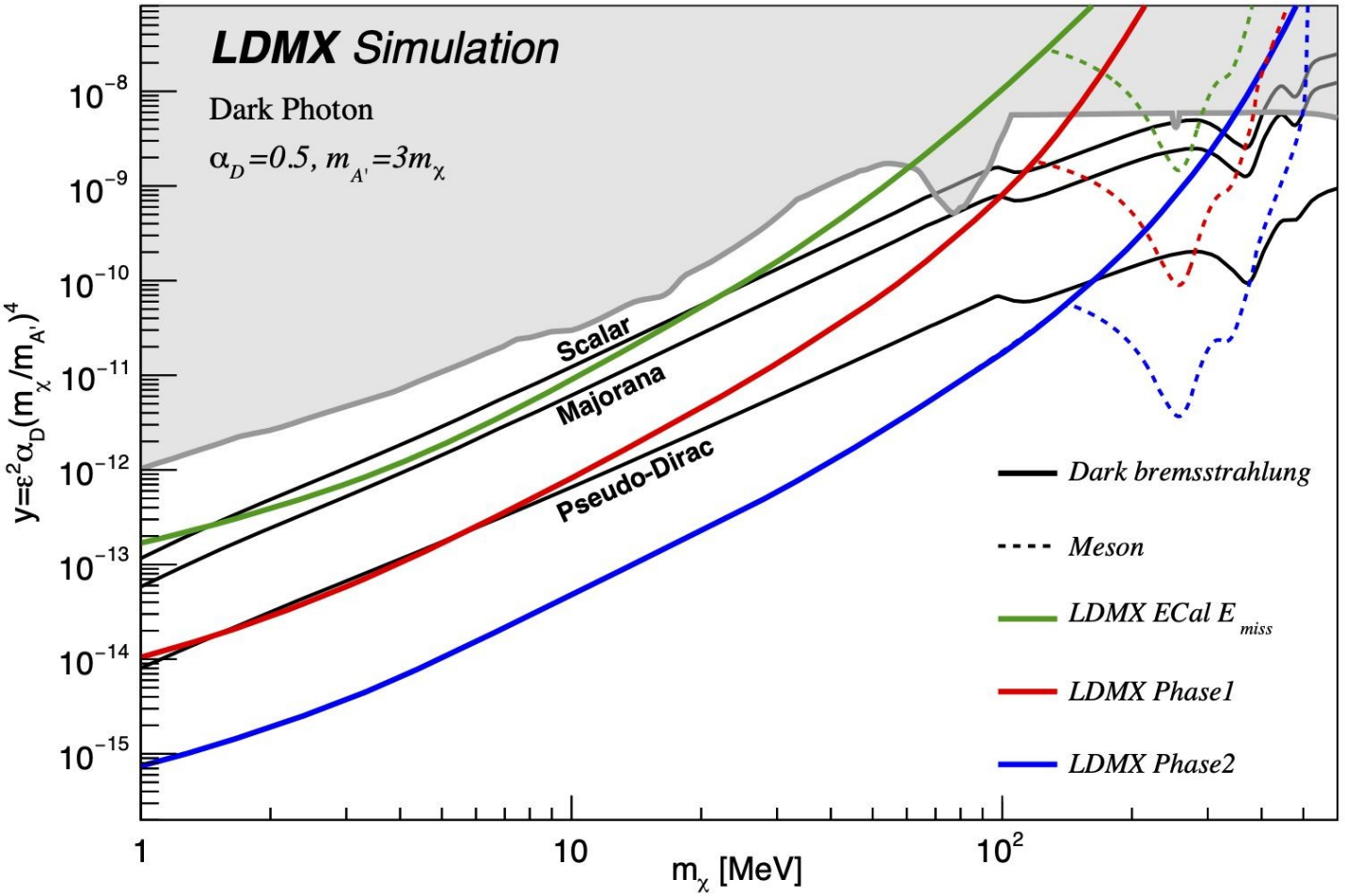
Developed technique for dark brehmsstrahlung physics process for Geant4 using key kinematic variables from a Madgraph/MadEvent library, allows proper handling of soft EM deposits before dark brehmsstrahlung





10.1016/j.cpc.2023.108690

LDMX Sensitivity (4 GeV)



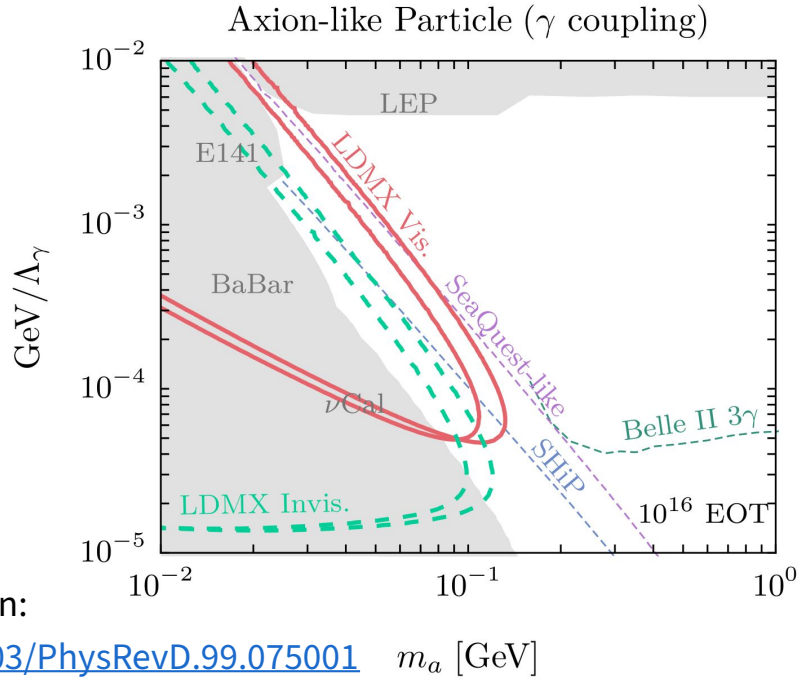
10^{13} EOT

$4x10^{14}$ EOT

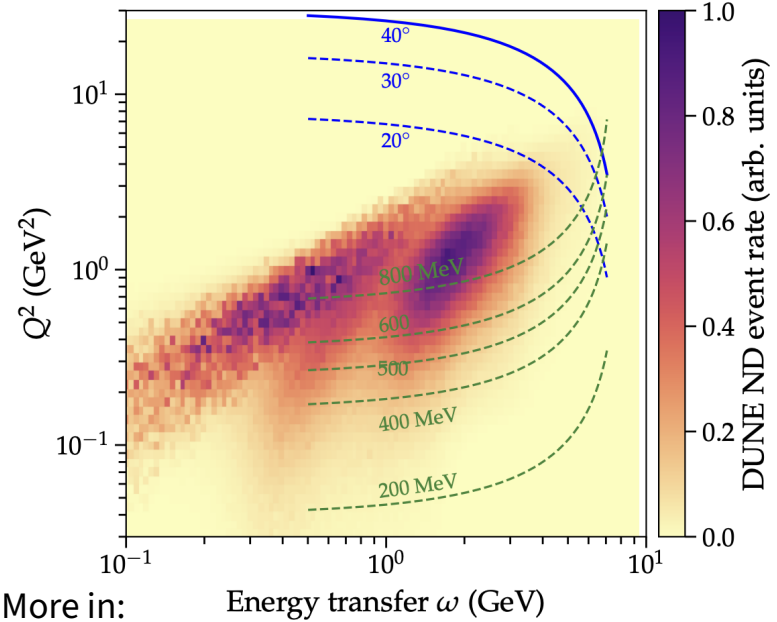
10^{16} EOT

Broader Physics Program

The broader LDMX physics program includes sensitivity to a range of other dark matter models in the invisible mode, searches for visible dark matter decays, as well as measurements of electron-nuclear scattering which are valuable for the DUNE program



More in:
10.1103/PhysRevD.99.075001



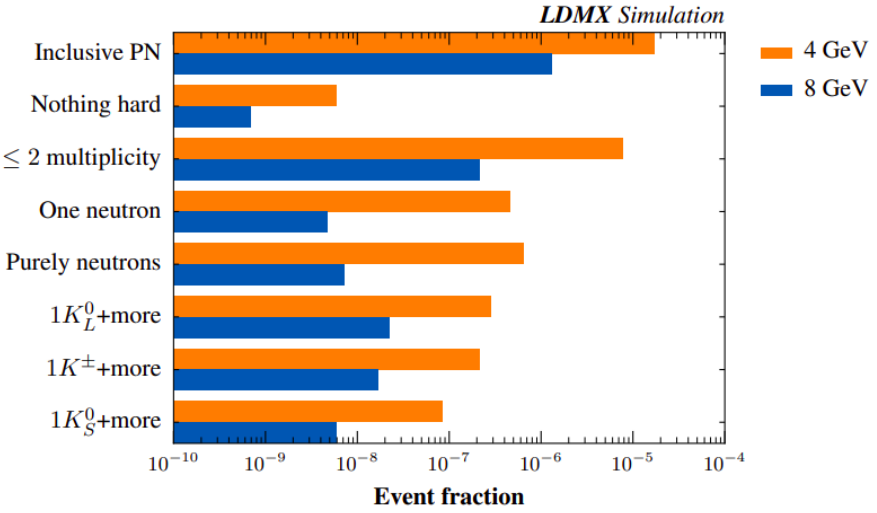
More in:
10.1103/PhysRevD.101.053004

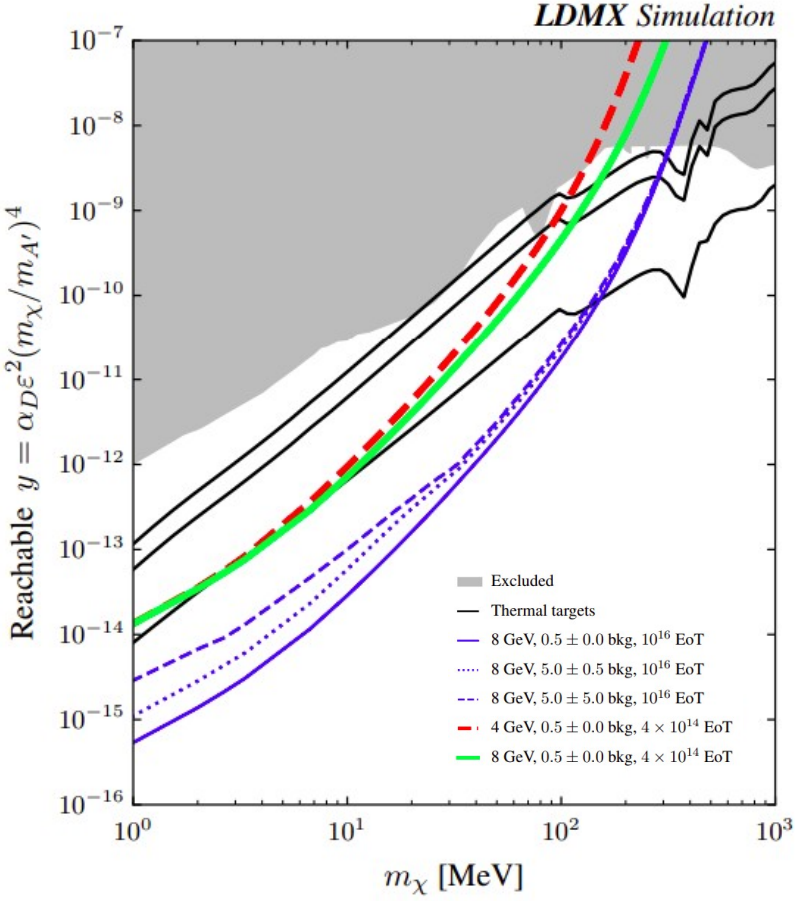
8 GeV Beam

LCLS-II is preparing an upgrade which will likely result in LDMX receiving much of its beam at 8 GeV rather than 4 GeV

Increase in beam energy results in reduced predicted relative rate of many photonuclear backgrounds, particularly for challenging cases like a single neutron

Change to 8 GeV improves reach somewhat at higher mass, retains performance at low mass





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LDMX Collaboration

Caltech
Fermilab
Lunds Universitet
University of Minnesota
UCSB University of California Santa Barbara
Carnegie Mellon University
SLAC National Accelerator Laboratory
Stanford University
Texas Tech University
University of Virginia

Prospects and Summary

The thermal-relic hypothesis is one of the most compelling DM scenarios, and the broad vicinity of the “normal matter” scale is a good place to be looking – that why there’s an LDW conference!

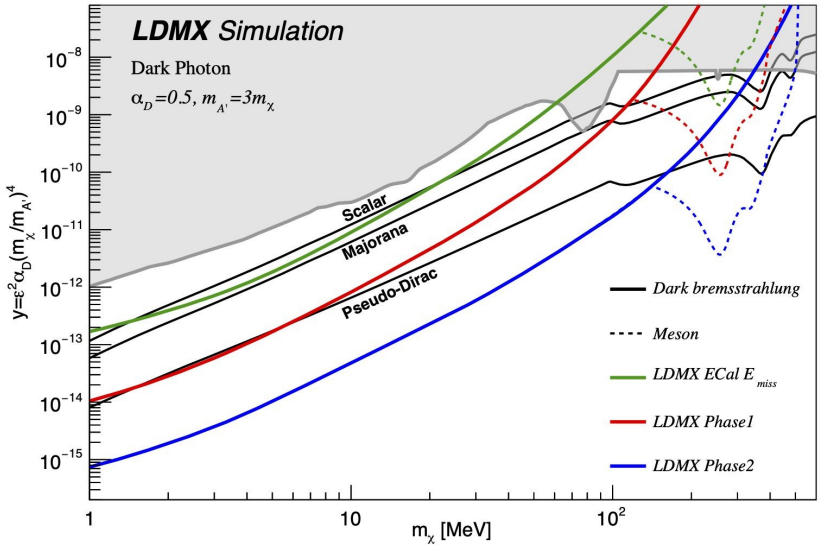
Accelerator based experiments are in a great position to test a wide range of scenarios for light dark matter - and could reveal much of the underlying dark sector physics together with direct detection experiments

LDMX offers unprecedented sensitivity to light DM over a wide range of dark matter and mediator masses.

More generally, the experiment will be able to explore a broad array of sub-GeV physics, and could also perform photonuclear & electronuclear measurements useful for planned neutrino experiments.

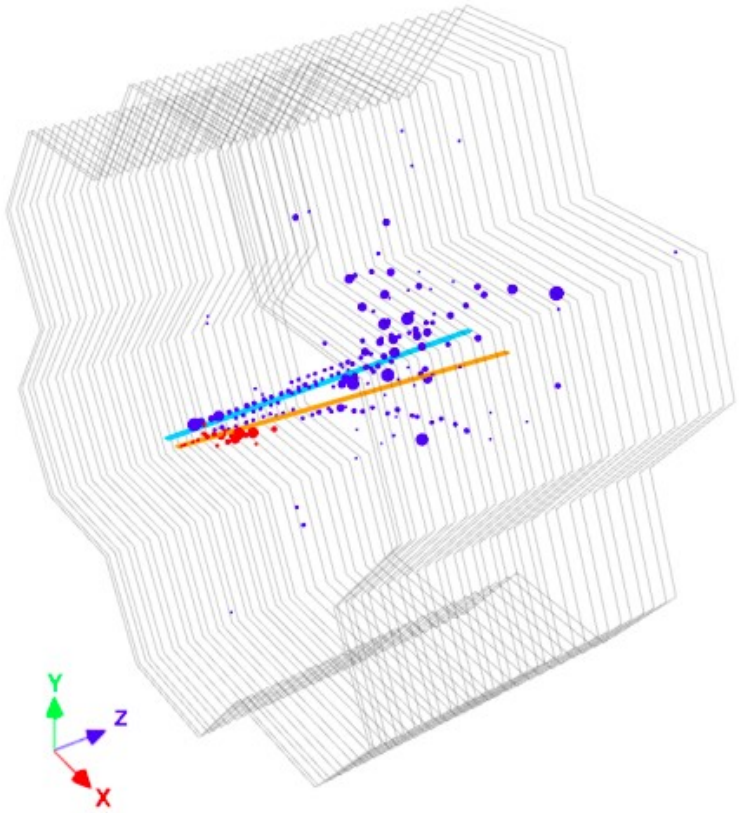
A beamline appropriate for LDMX is under construction at SLAC, and several systems have been demonstrated in recent testbeam studies

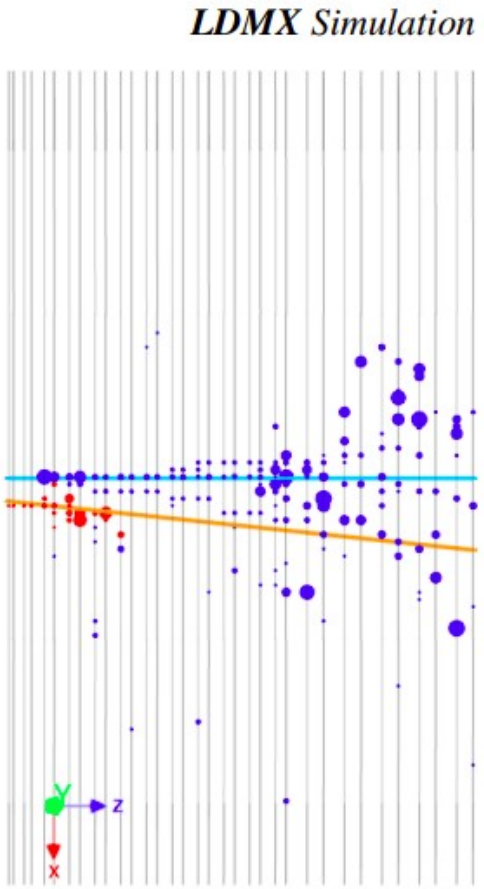
Construction start has been slowed by funding challenges from very large current projects, but active work is underway for a comprehensive design report



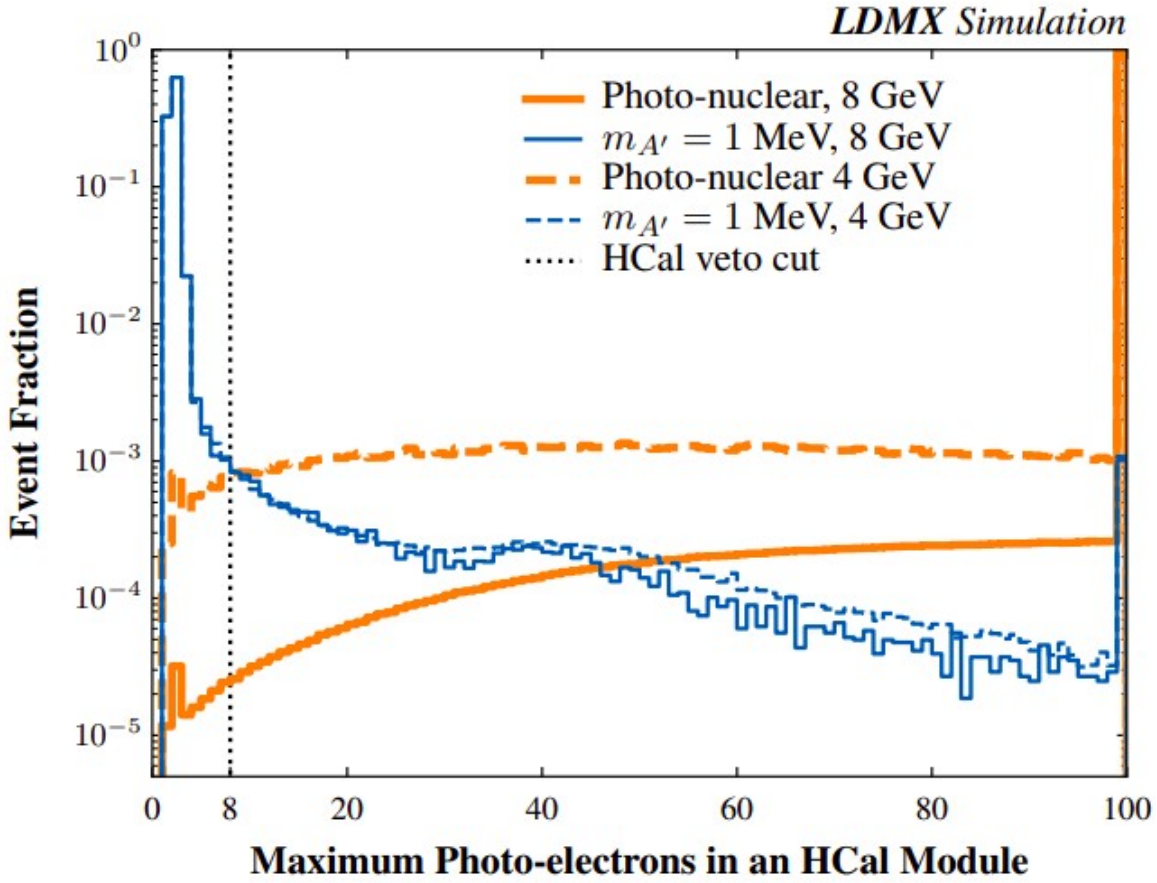
Additional Material

Event Display (Background)





Hadron Calorimeter 4 GeV vs 8 GeV



- Considering all events which pass the trigger requirement for significant missing energy in ECAL