Light Dark Matter eXperiment (LDMX)

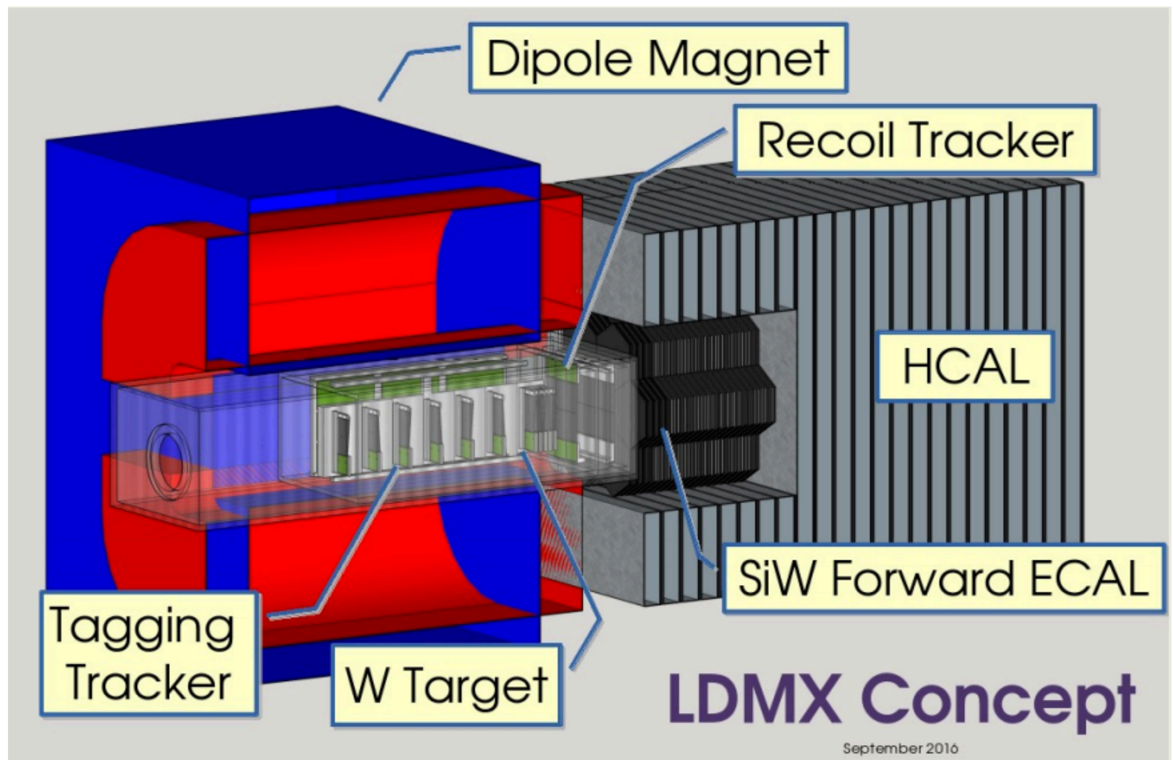
Scientific Goals and status of Design Studies

O. Colegrove (UCSB)

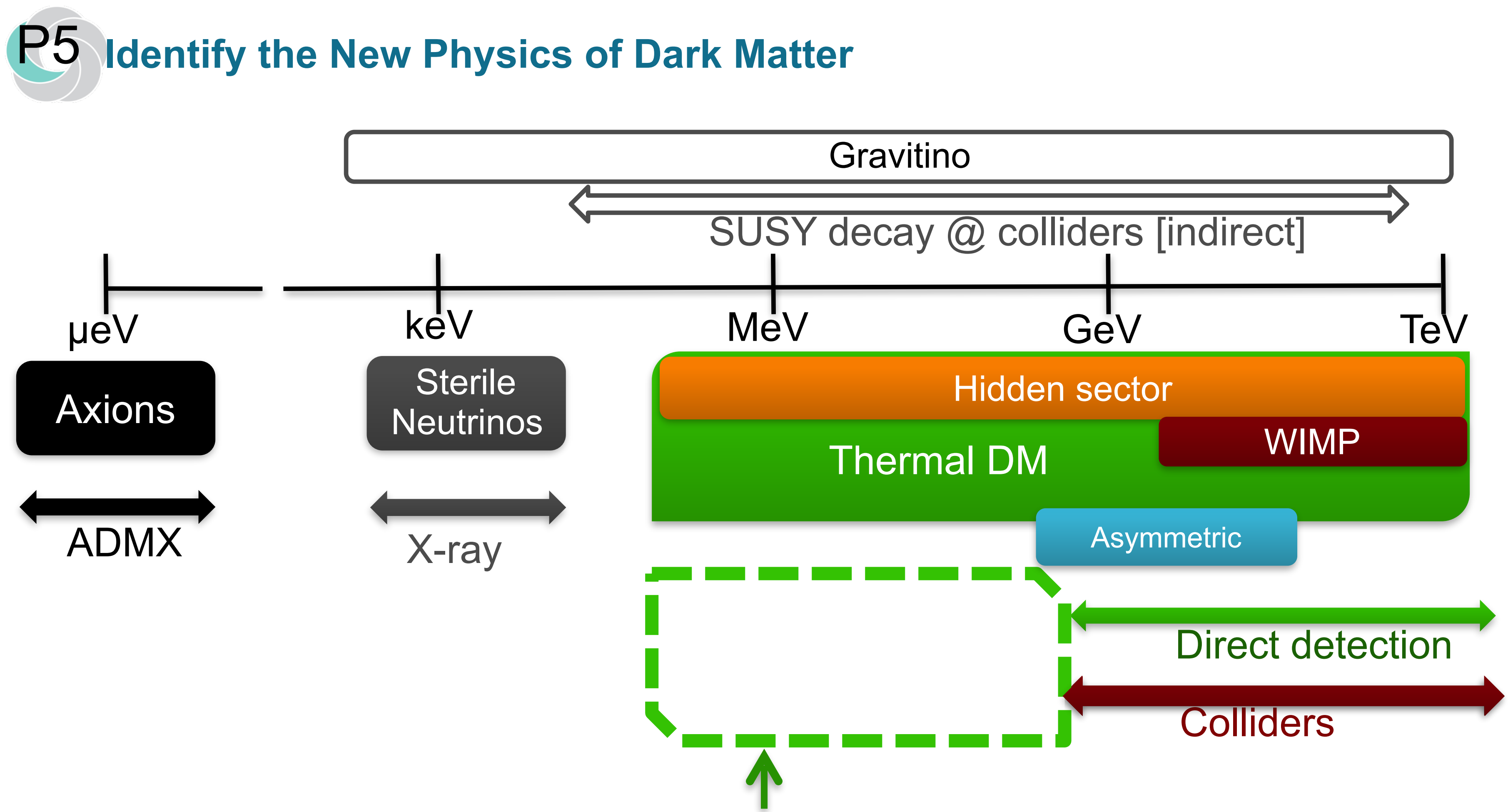
For the LDMX Collaboration:

SLAC, UCSB, UMN,

UCSC, Caltech, and FNAL



Motivation for Sub-GeV Dark Matter

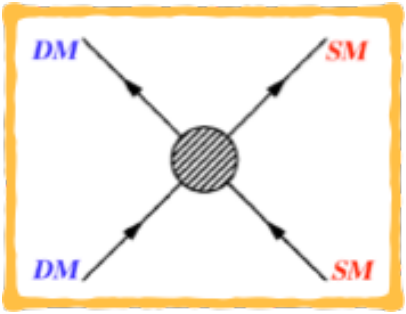


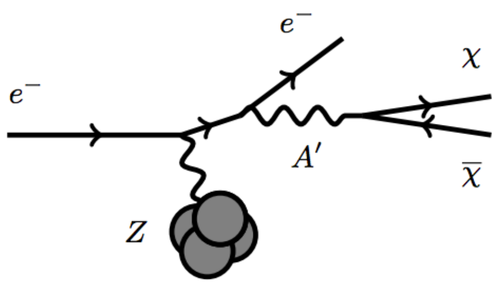
- Next frontier for Dark Matter science
  - Logical place to focus given LHC and Direct Detection null results
  - Unique opportunity for high impact from small experiment!

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



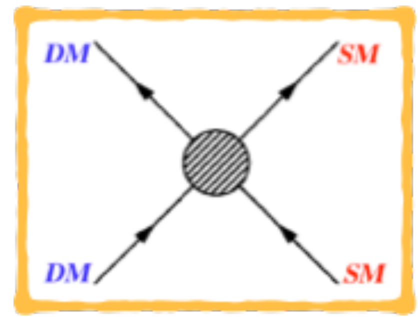


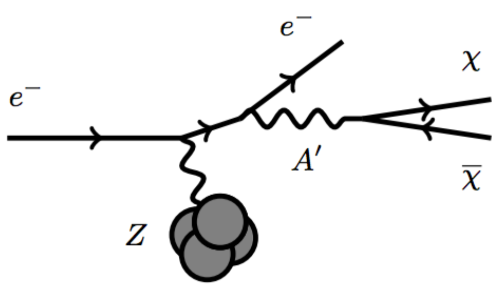
$e^- Z \to e^- Z A'; A' \to invisible$

Implications of Sub-GeV Dark Matter

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

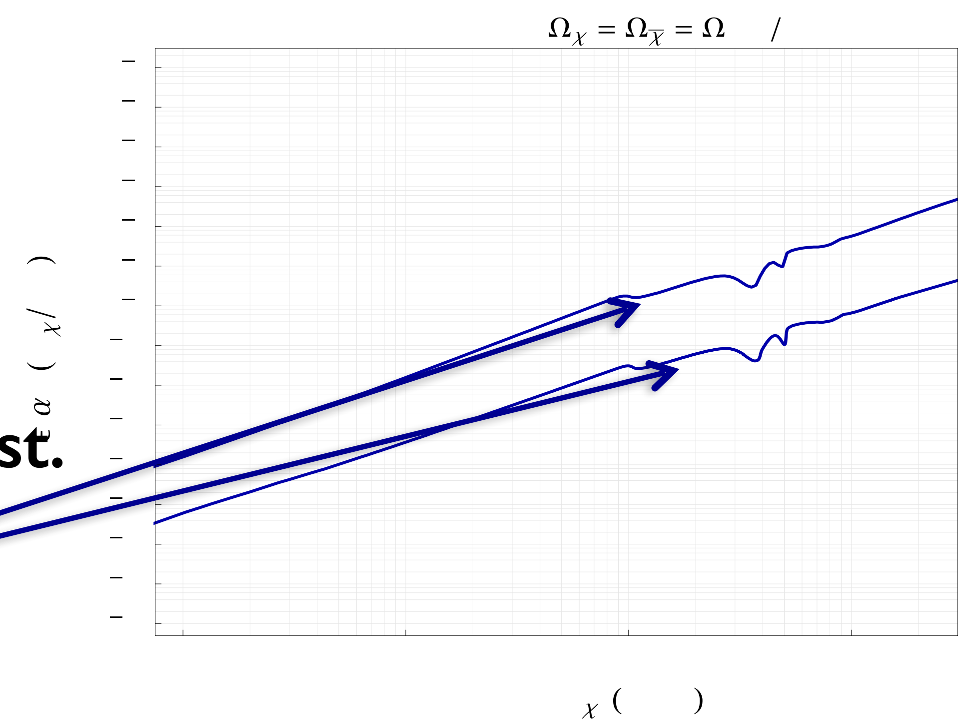
1. DM lighter than a few GeV must annihilate via new **light** force carrier
   → DM production at low-energy accelerators through new force





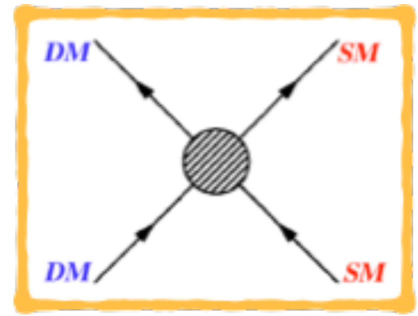
$e^- Z \to e^- Z A'; A' \to invisible$

2. **Implies a minimum coupling const.**
   → Minimum production cross-section **(thermal relic target)**

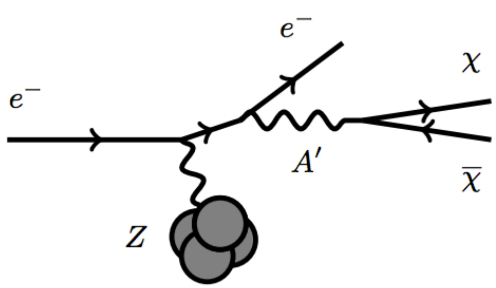


Implications of Sub-GeV Dark Matter

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

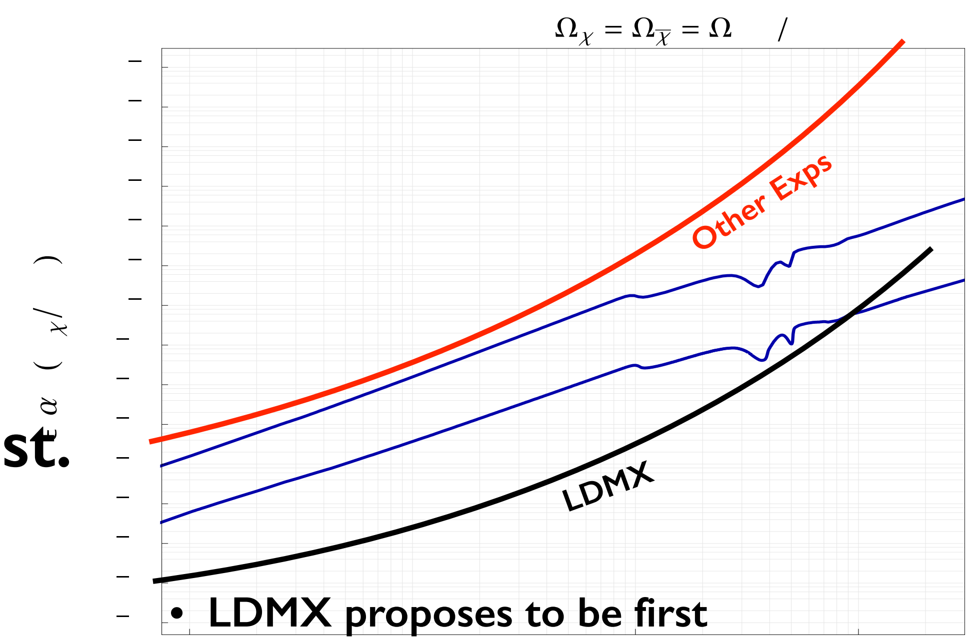


1. DM lighter than a few GeV must annihilate via new **light** force carrier
   → DM production at low-energy accelerators through new force



$e^- Z \to e^- Z A'; A' \to invisible$

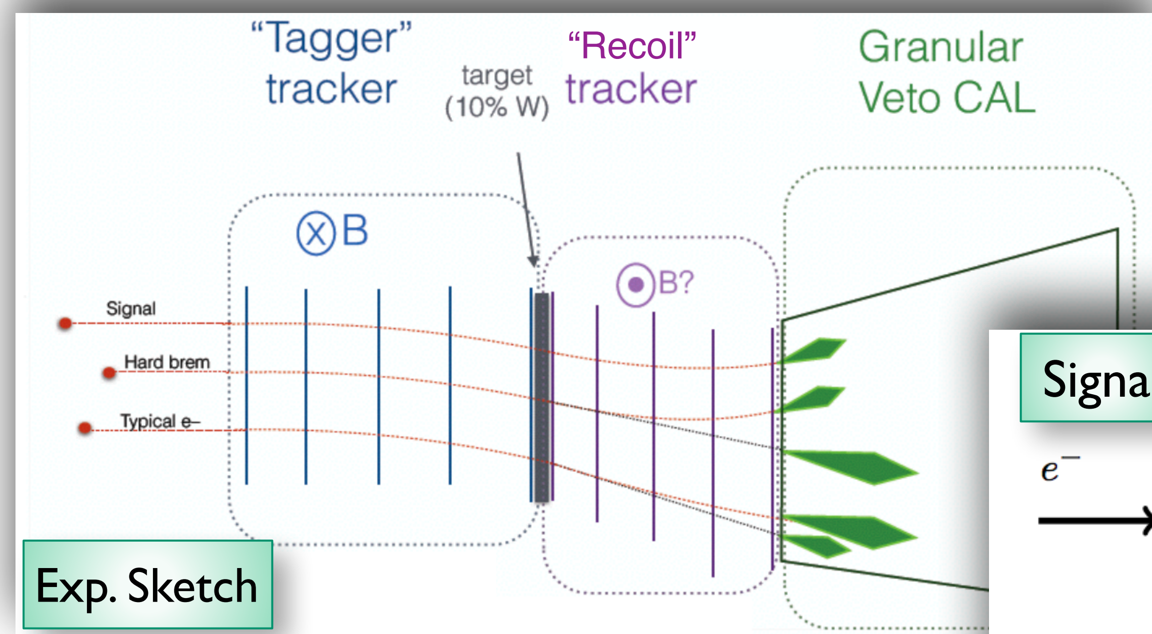
2. **Implies a minimum coupling const.**
   → Minimum production cross-section **(thermal relic target)**

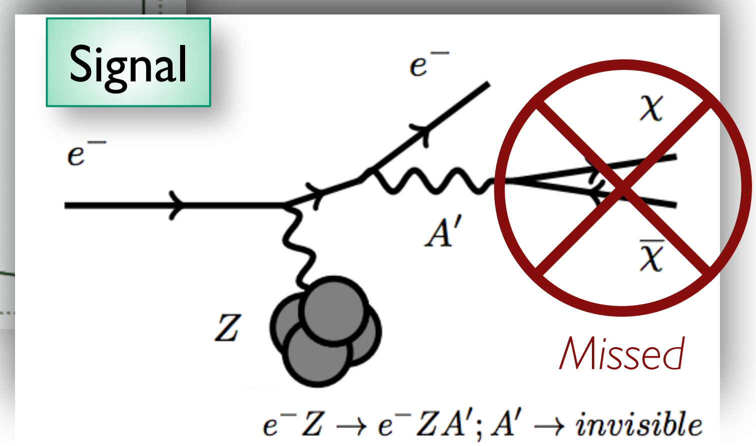


- **LDMX proposes to be first experiment sensitive to sub-GeV DM at/beyond the thermal relic target**

The Missing Momentum Approach

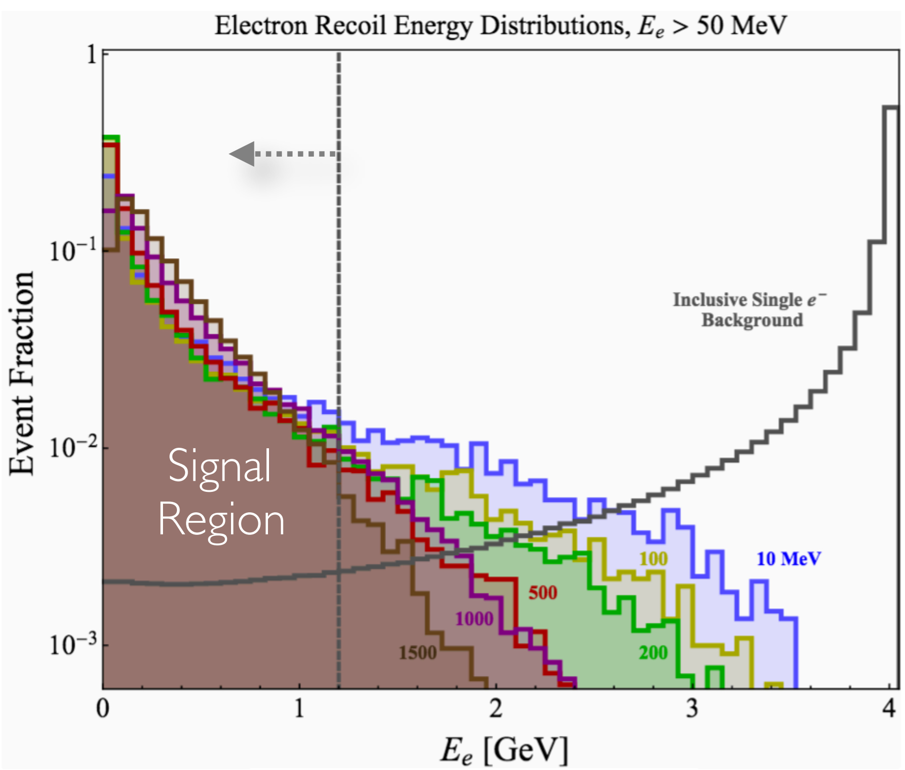
- Considered by many to be the most robust technique for discovering Sub-GeV thermal dark matter
- LDMX employs this technique via fixed target electron scattering
  - Dark photon radiated in 10% X_0 target decays to DM (A' → χχ)

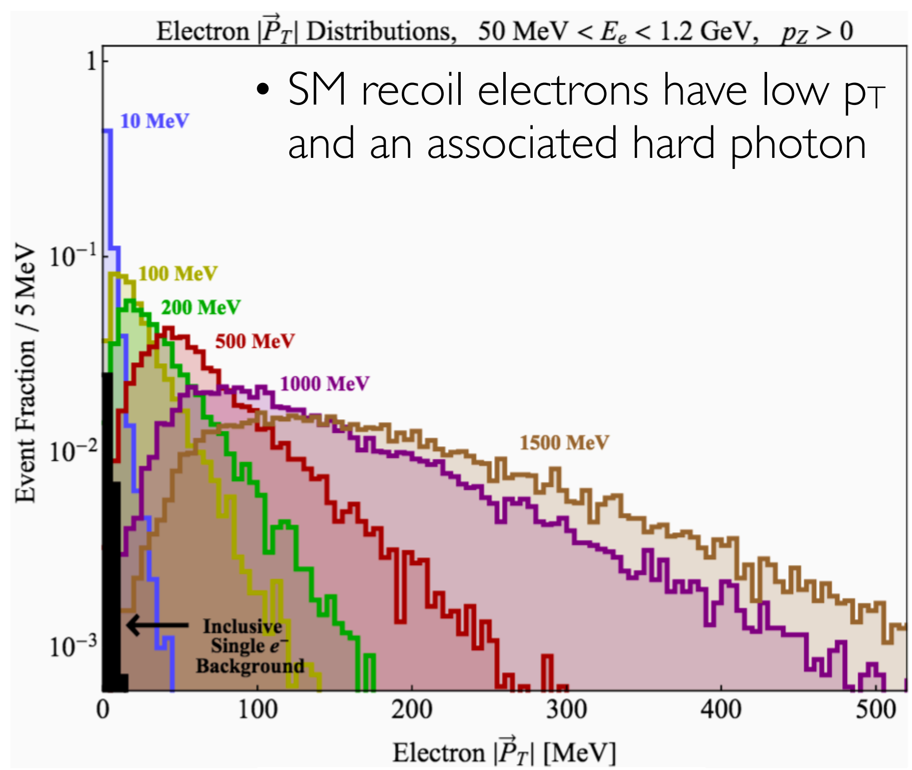




The Missing Momentum Approach

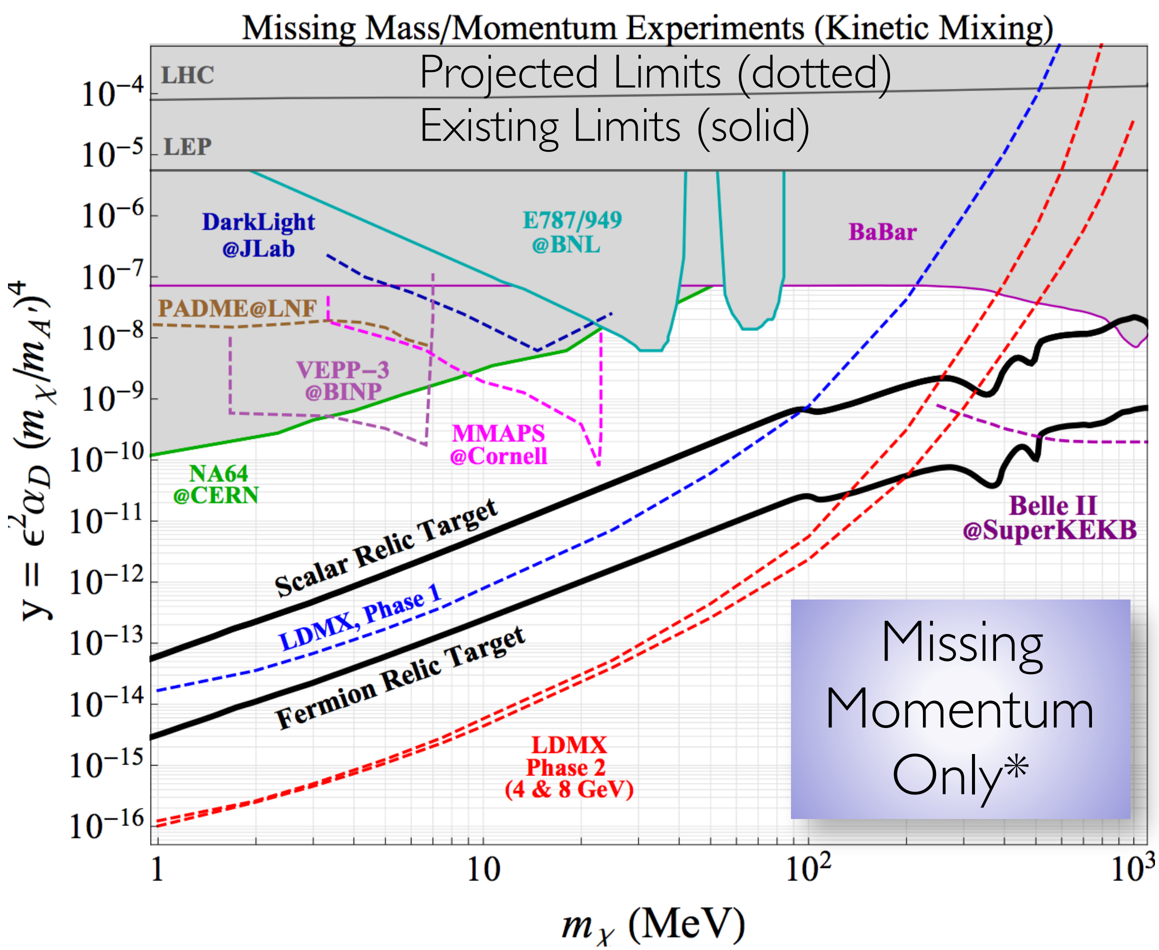
- Considered by many to be the most robust technique for discovering Sub-GeV thermal dark matter
- LDMX employs this technique via fixed target electron scattering
  - Dark photon radiated in 10% X_0 target decays to DM (A' →χχ)
  - **Distinctive signal kinematics (M_e << $M_{A'}$ << E_{beam}) yields a final state with hard A' (invisible) and a very soft recoil electron**
    - **Results in the measurement of significant missing momentum/energy**





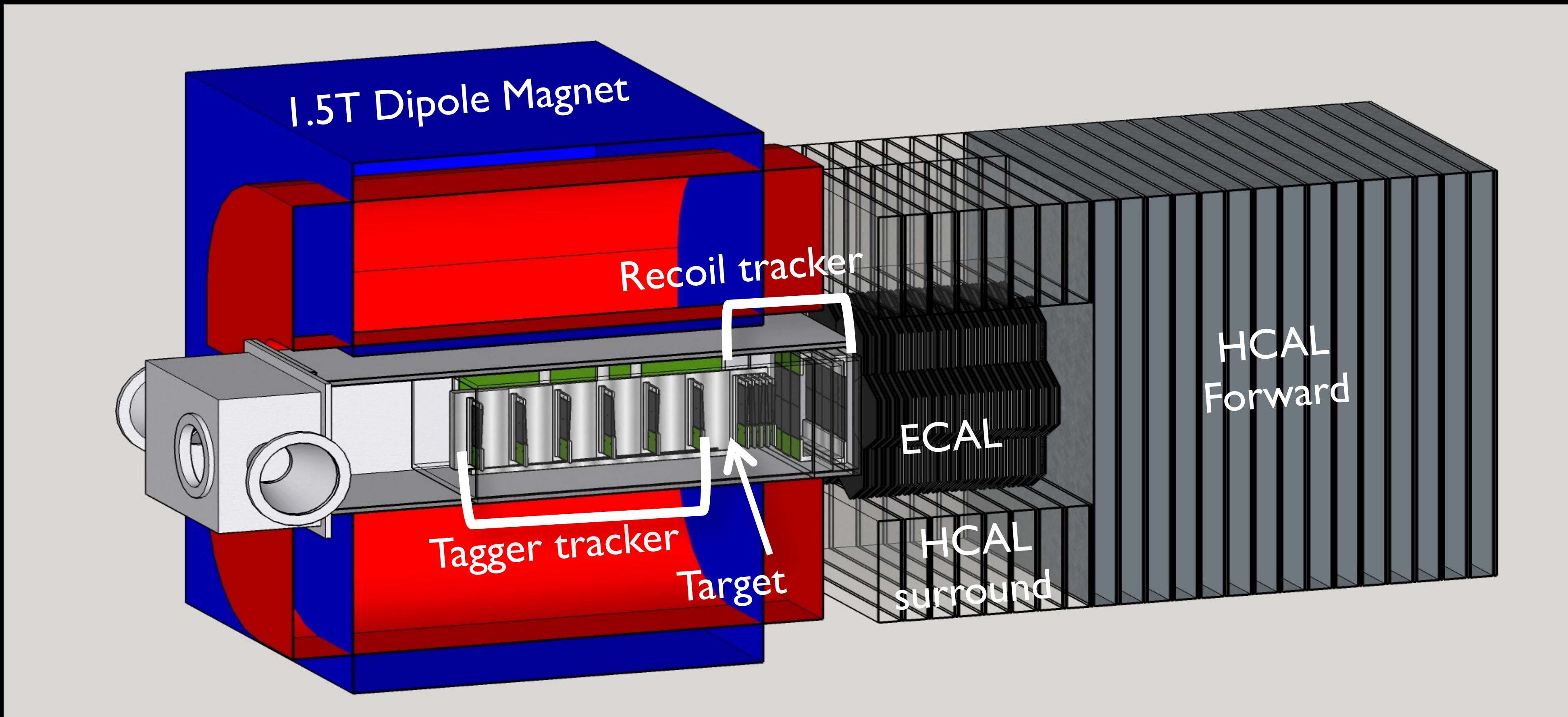
Projected Sensitivity

- Phase I — $4 \bullet 10^{14}$ 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 1 is sensitive to sub-GeV DM beyond the Scalar Relic Target



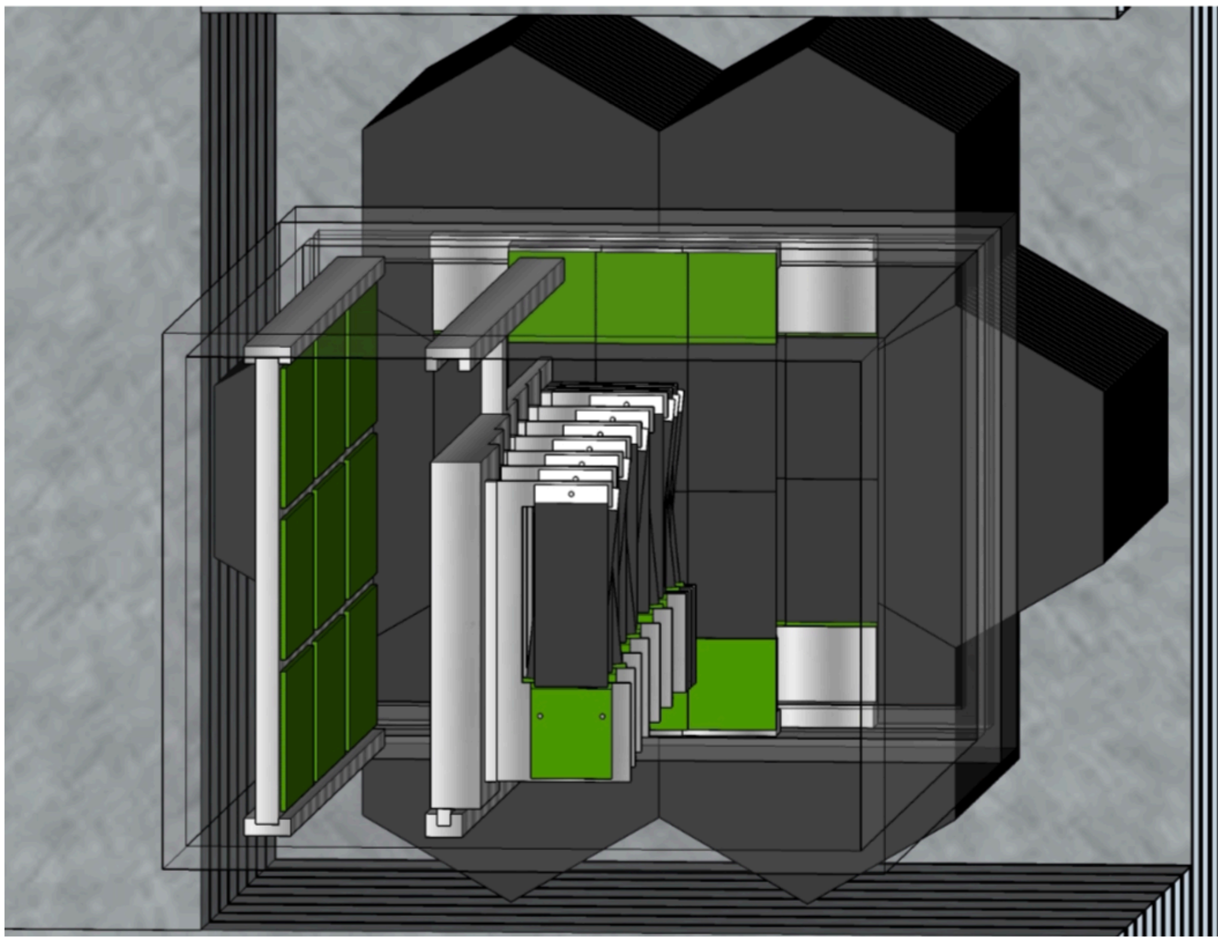
*Limits w/ beam dump results in backup

LDMX Detector Concept



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

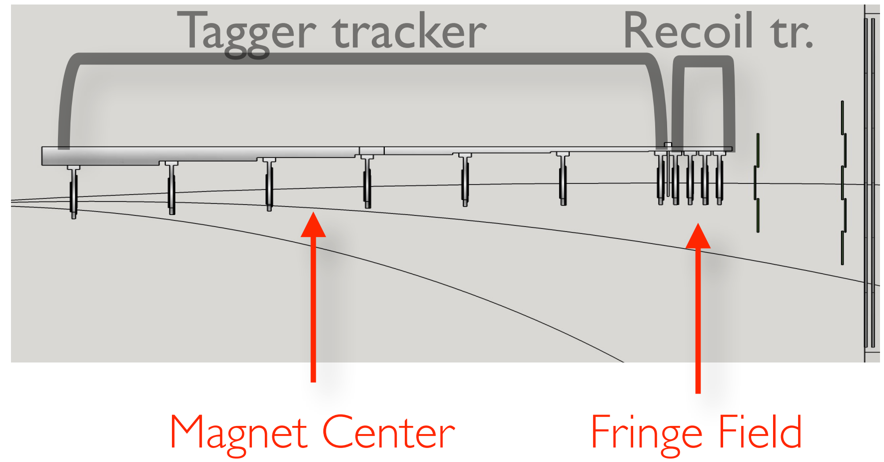
Tagger and Recoil Tracker

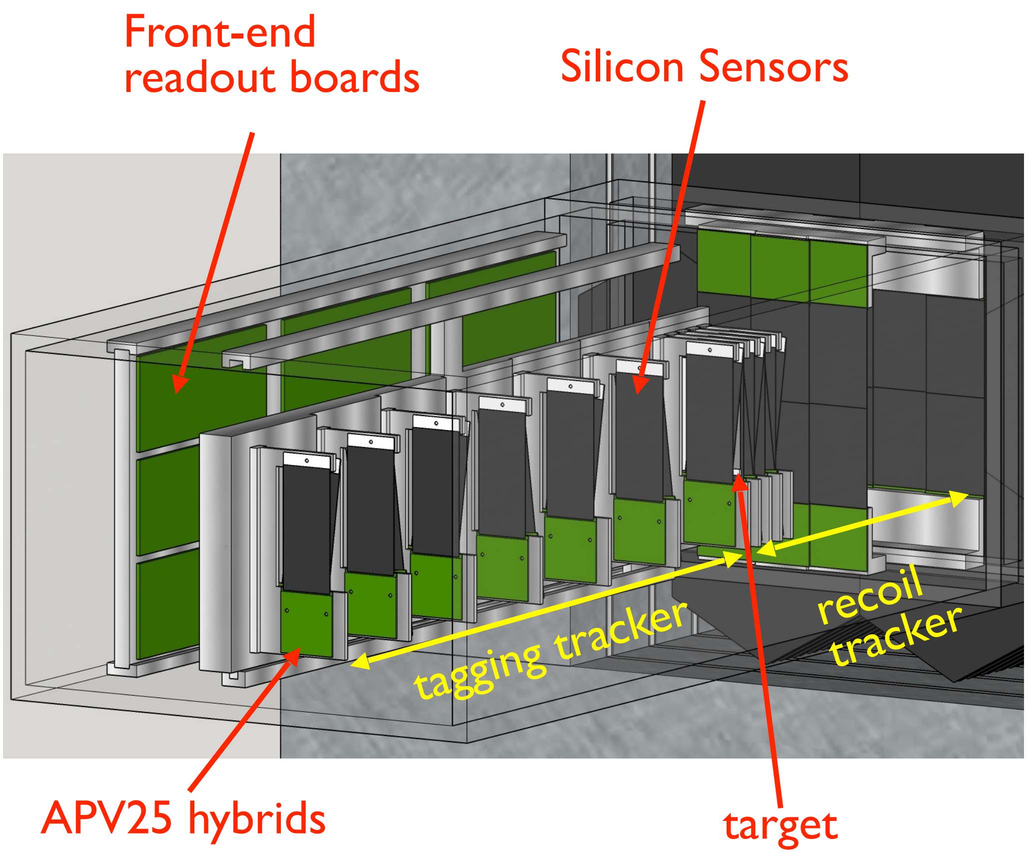


- A beam's eye view of the tagging and recoil trackers

Tagger and Recoil Tracker

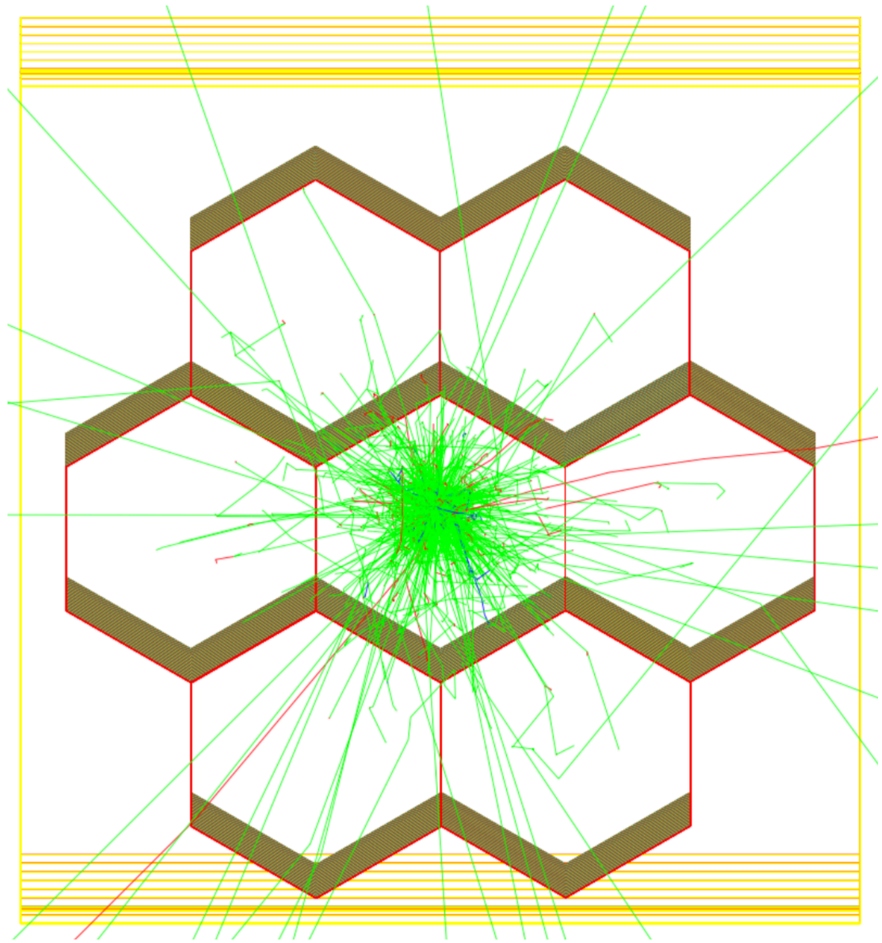
- Tagger tracker: Tag incoming e-
  - Precise p and (x,y) position at target.
  - 7 Layers — Modules like HPS SVT
    - Veto straggling (off E_{Beam}) electrons





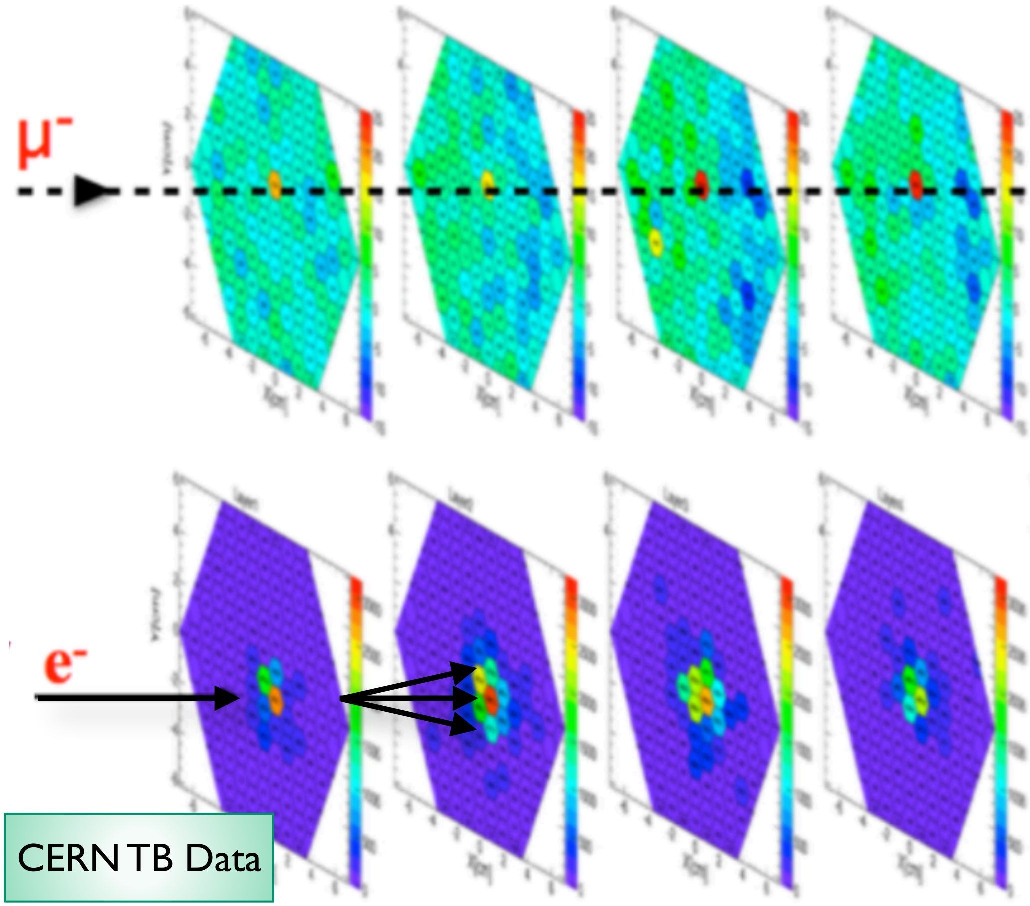
- Recoil tracker:
  - Associates recoil electron track w/ incoming tagged track.
    - Measure Δp across target
  - 6 Layers — Modules like HPS SVT
  - Compact design, placed in fringe field
    - Accurate momentum measurement for e-'s with E ≳ 50 MeV.

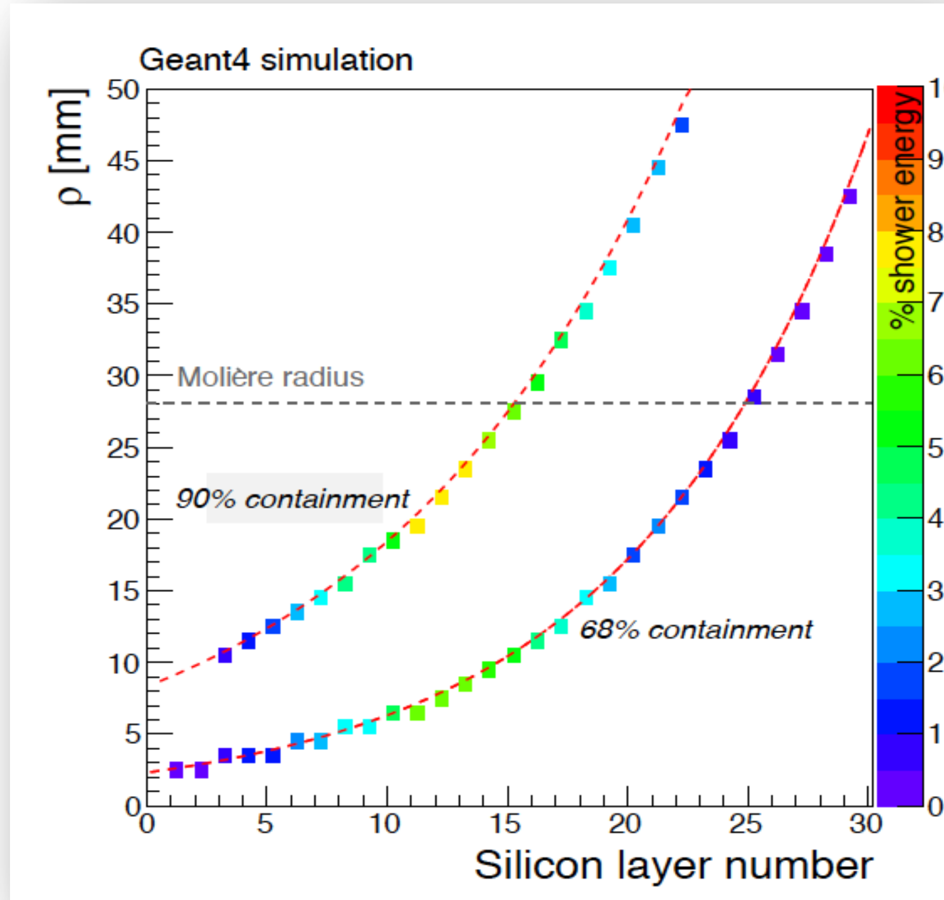
Electromagnetic Calorimeter



- A beam's eye view of a typical 4 GeV e-'s shower in the ECAL

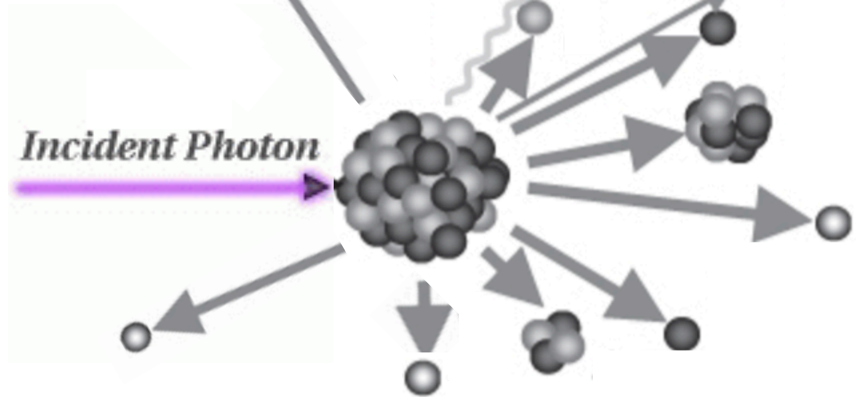
Electromagnetic Calorimeter

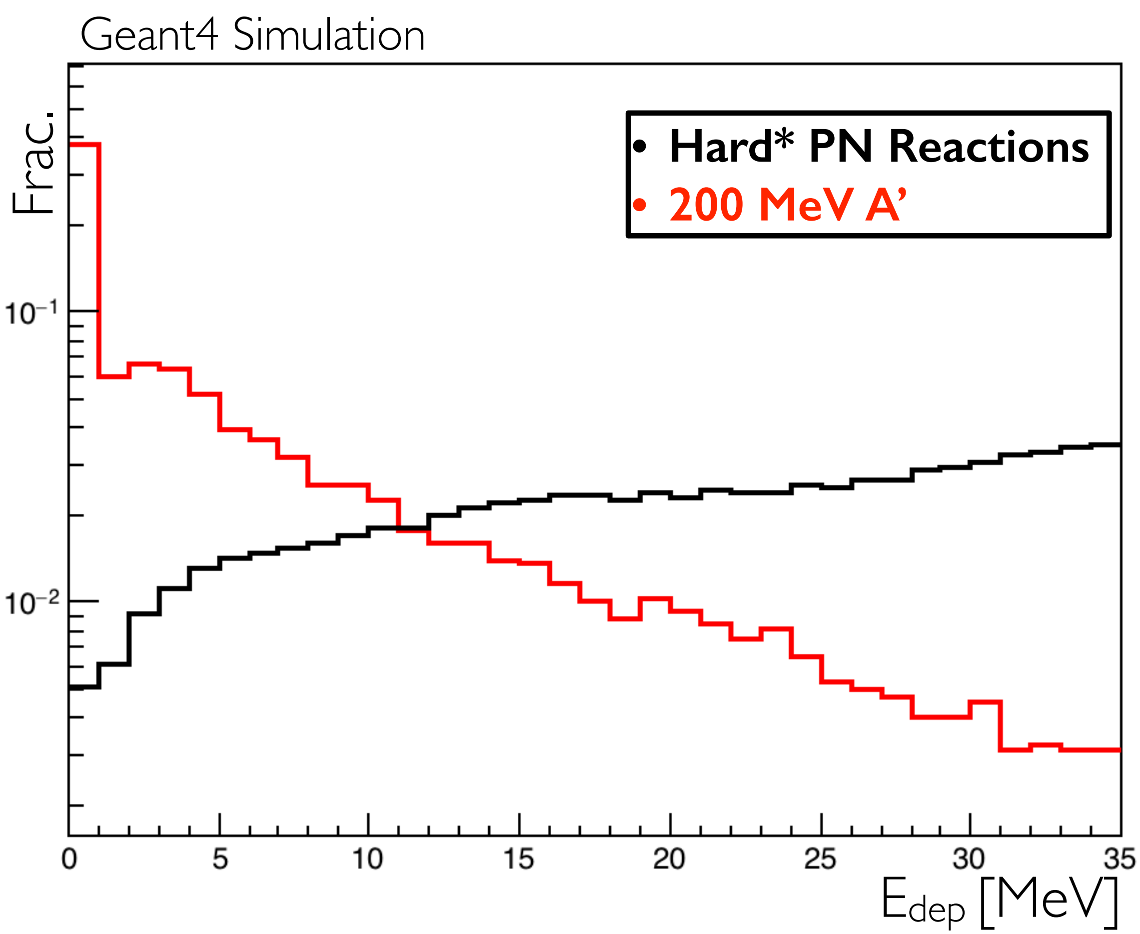




- 40 X_O (30 layers) High Granularity Si-W Calorimeter
  - Small Molière radius, ability to track isolated min. ionizing particles (mips).
  - Sufficient resolution to fully veto E&M background
  - Leverage CMS technology — extensively validated radiation hard modules
    - Can withstand the effective fluence of 10^{13} n/cm^2 caused by 10^{14} e-'s on target

Photonuclear Background

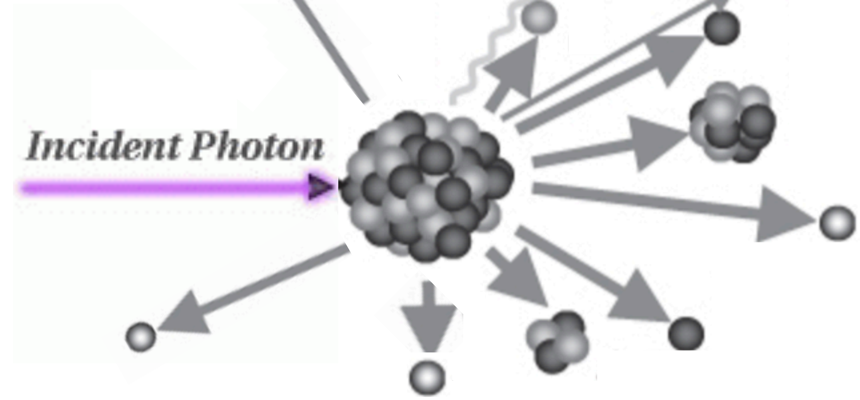




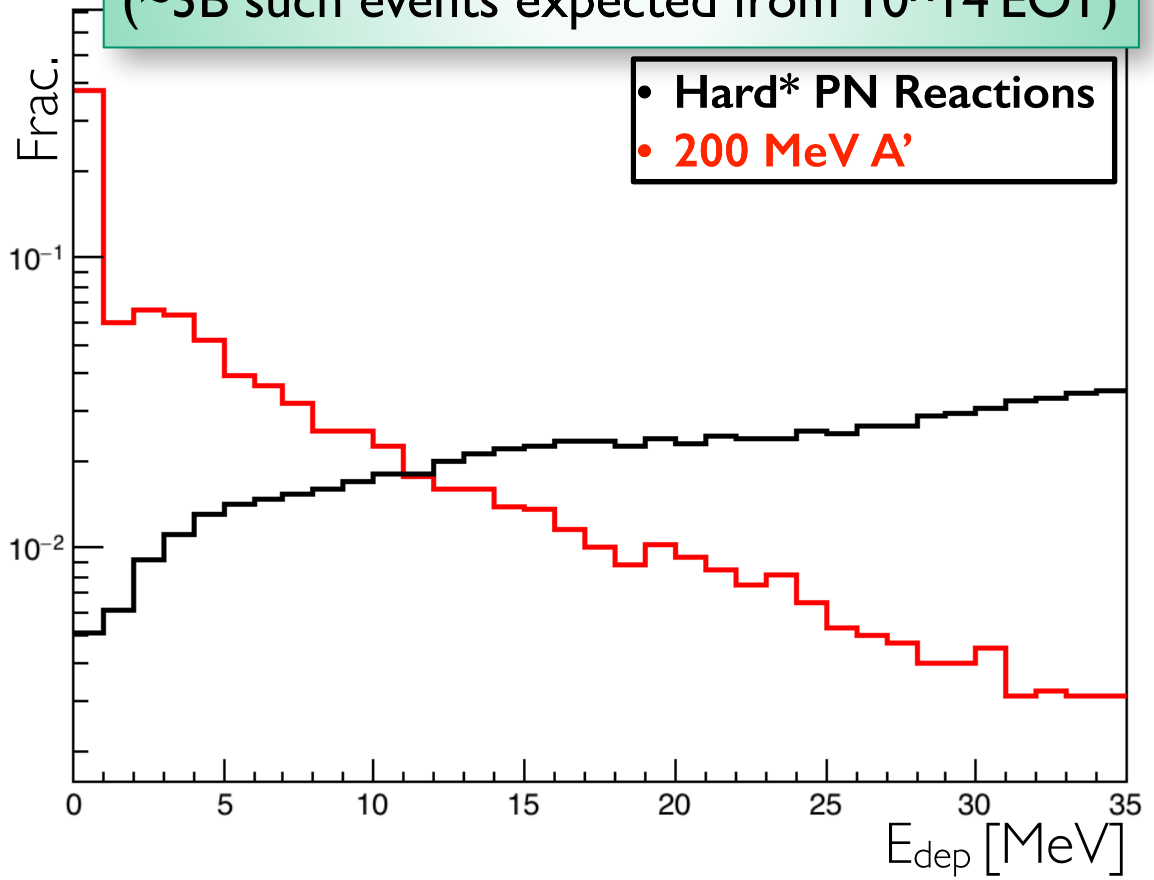
- LDMX's hardest background :
  - Initial results show that neutron dominated final states are the most difficult
- ECAL geometry has been optimized to help with detection
  - HCAL still required to successfully mitigate all PN events

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

Photonuclear Background



*$\gamma_{[\text{from target}]}$ (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**

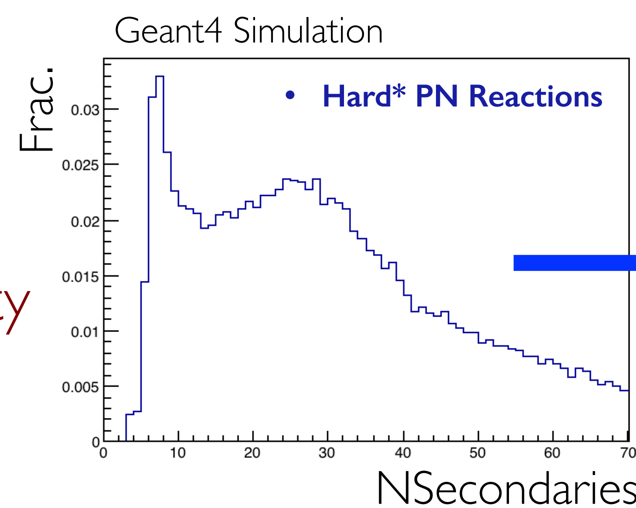
- Energy Deposited in the ECAL Si (E_{dep}) Distribution :
  - For a typical 4 GeV e- E_{dep} follows a Gaussian w/ **μ** ~ 68 [MeV], **σ** ~ 6 [MeV]
  - Photonuclear (PN) reactions create a non-Gaussian (power-law) low energy tail

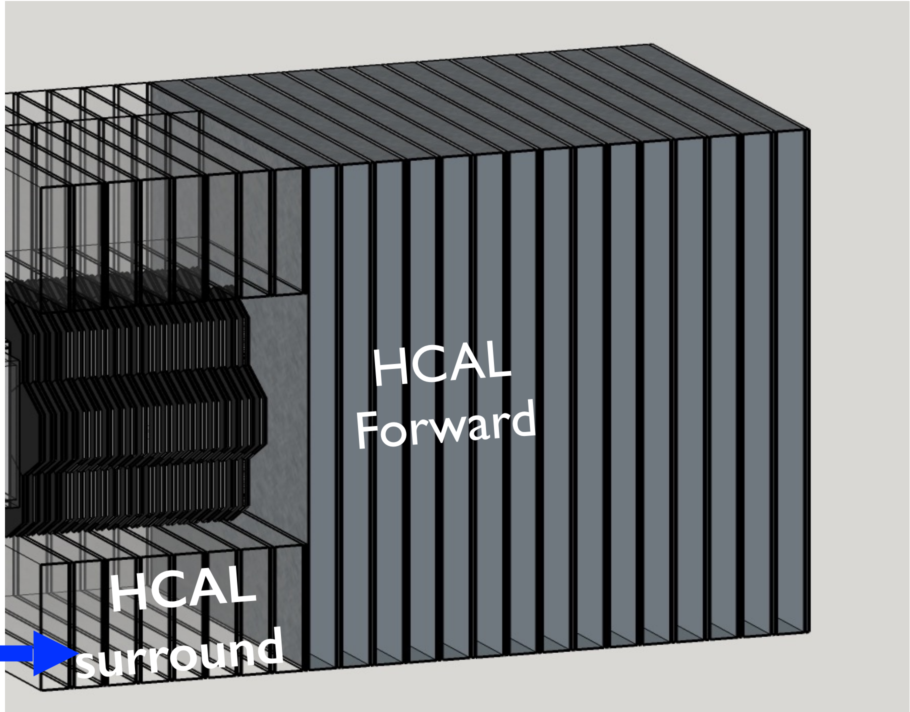
Hadron Calorimeter

CMS/LHC upgrades and SLAC hardware

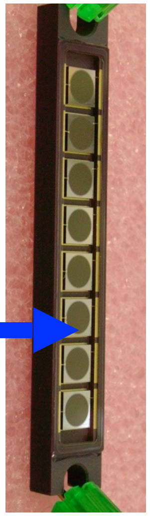
Hadron Calorimeter

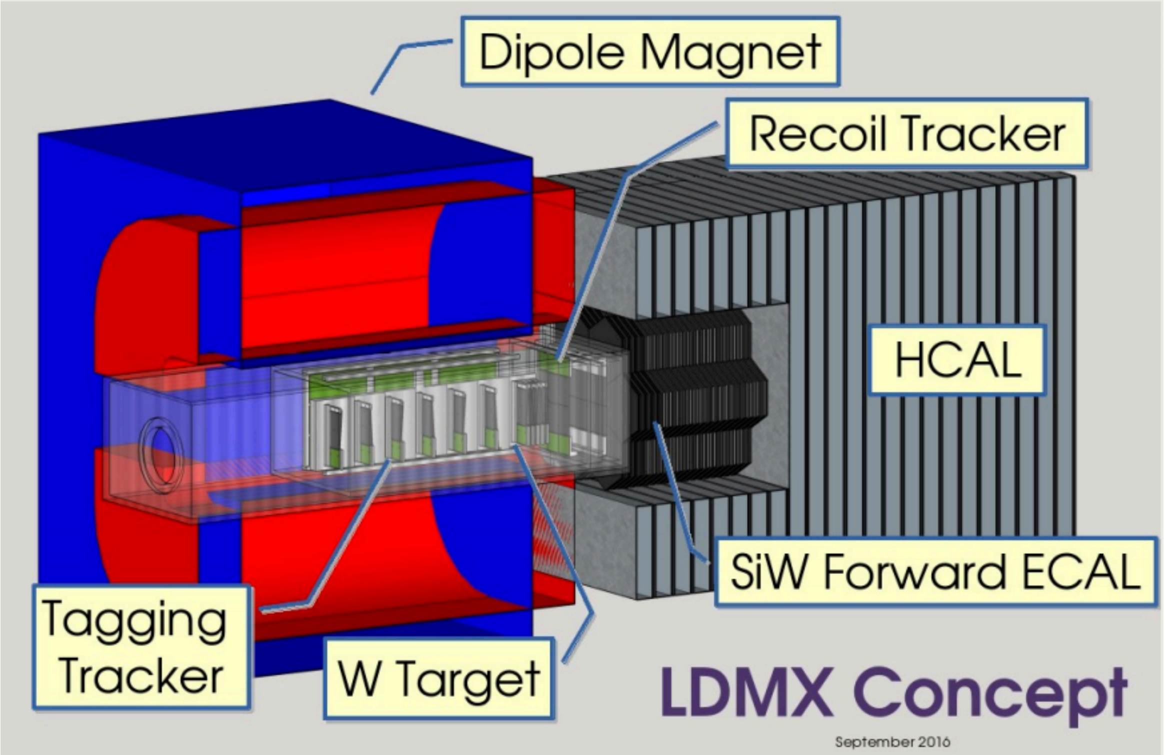
- Mechanics
  - Steel absorber and plastic scintillator
  - Thin absorbers for high efficiency
- HCAL Surround
  - Help w/ high PN multiplicity





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





Summary and Conclusions

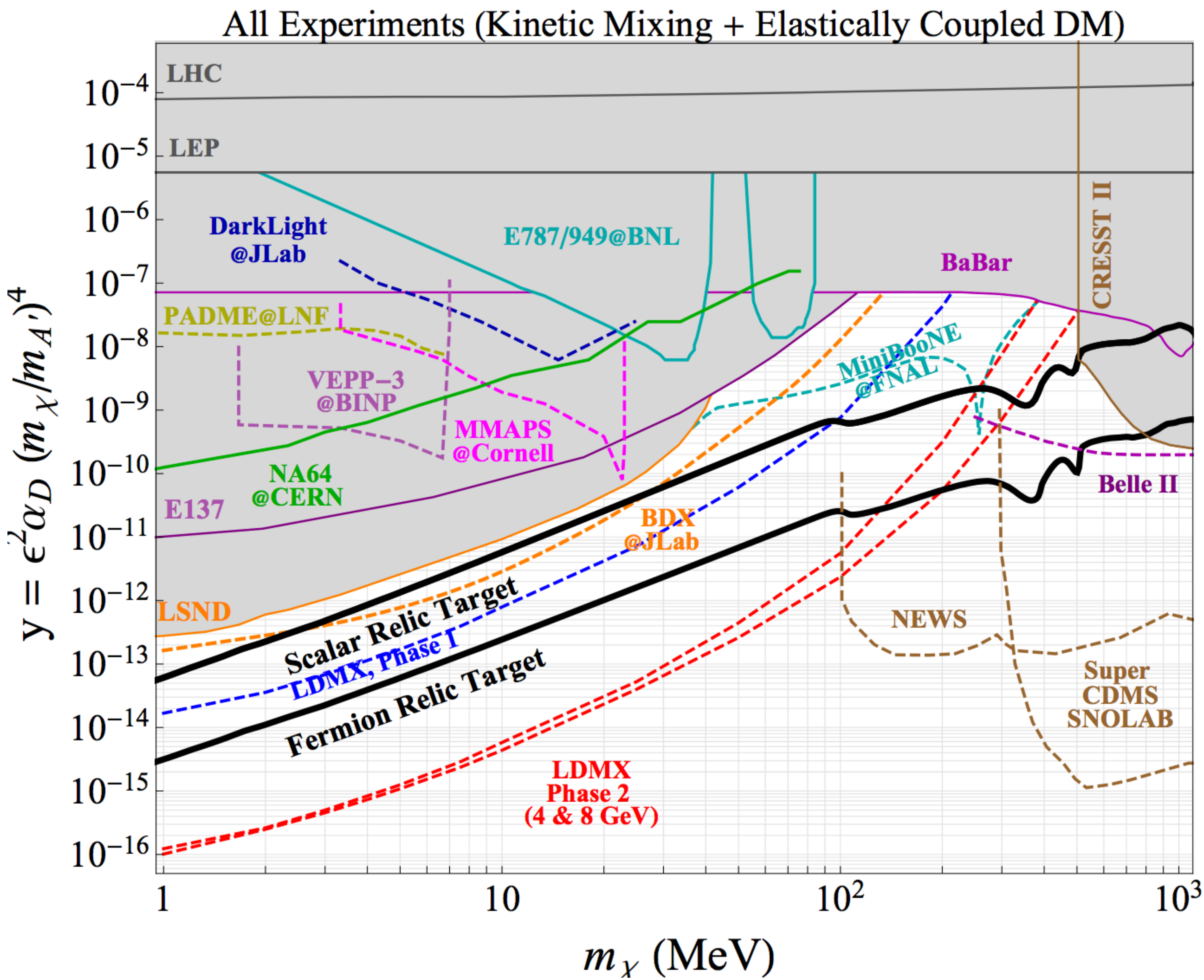
- LDMX will comprehensively explore the sub-GeV DM phase space.
  - Largely unexplored, simplest and well motivated thermal relic scenarios
  - LDMX is the only proposed experiment capable of meeting the thermal relic target
- Made possible by leveraging latest detector tech.
  - CALICE & CMS inspired 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

The end

Dark Sectors 2016 Workshop: Community Report

Jim Alexander (VDP Convener),[1] Marco Battaglieri (DMA Convener),[2] Bertrand Echenard (RDS Convener),[3] Rouven Essig (Organizer),[4,*] Matthew Graham (Organizer),[5,†] Eder Izaguirre (DMA Convener),[6] John Jaros (Organizer),[5,‡] Gordan Krnjaic (DMA Convener),[7] Jeremy Mardon (DD Convener),[8] David Morrissey (RDS Convener),[9] Tim Nelson (Organizer),[5,§] Maxim Perelstein (VDP Convener),[1] Matt Pyle (DD Convener),[10] Adam Ritz (DMA Convener),[11] Philip Schuster (Organizer),[5,6,¶] Brian Shuve (RDS Convener),[5] Natalia Toro (Organizer),[5,6,**] Richard G Van De Water (DMA Convener),[12] Daniel Akerib,[5,13] Haipeng An,[3] Konrad Aniol,[14] Isaac J. Arnquist,[15] David M. Asner,[15] Henning O. Back,[15] Keith Baker,[16] Nathan Baltzell,[17] Dipanwita Banerjee,[18] Brian Batell,[19] Daniel Bauer,[7] James Beacham,[20] Jay Benesch,[17] James Bjorken,[5] Nikita Blinov,[5] Celine Boehm,[21] Mariangela Bondí,[22] Walter Bonivento,[23] Fabio Bossi,[24] Stanley J. Brodsky,[5] Ran Budnik,[25] Stephen Bueltmann,[26] Masroor H. Bukhari,[27] Raymond Bunker,[15] Massimo Carpinelli,[28,29] Concetta Cartaro,[5] David Cassel,[1,5] Gianluca Cavoto,[30] Andrea Celentano,[2] Animesh Chaterjee,[31] Saptarshi Chaudhuri,[8] Gabriele Chiodini,[24] Hsiao-Mei Sherry Cho,[5] Eric D. Church,[15] D. A. Cooke,[18] Jodi Cooley,[32] Robert Cooper,[33] Ross Corliss,[34] Paolo Crivelli,[18] Francesca Curciarello,[35] Annalisa D'Angelo,[36,37] Hooman Davoudiasl,[38] Marzio De Napoli,[22] Raffaella De Vita,[2] Achim Denig,[39] Patrick deNiverville,[11] Abhay Deshpande,[40] Ranjan Dharmapalan,[41] Bogdan Dobrescu,[7] Sergey Donskov,[42] Raphael Dupre,[43] Juan Estrada,[7] Stuart Fegan,[39] Torben Ferber,[44] Clive Field,[5] Enectali Figueroa-Feliciano,[45] Alessandra Filippi,[46] Bartosz Fornal,[47] Arne Freyberger,[17] Alexander Friedland,[5] Iftach Galon,[47] Susan Gardner,[48,47] Francois-Xavier Girod,[17] Sergei Gninenko,[49] Andrey Golutvin,[50] Stefania Gori,[51] Christoph Grab,[18] Enrico Graziani,[52] Keith Griffioen,[53] Andrew Haas,[54] Keisuke Harigaya,[10,55] Christopher Hearty,[44] Scott Hertel,[10,55] JoAnne Hewett,[5] Andrew Hime,[15] David Hitlin,[3] Yonit Hochberg,[10,55,1] Roy J. Holt,[41] Maurik Holtrop,[56] Eric W. Hoppe,[15] Todd W. Hossbach,[15] Lauren Hsu,[7] Phil Ilten,[34] Joe Incandela,[57] Gianluca Inguglia,[58] Kent Irwin,[5] Igal Jaegle,[59] Robert P. Johnson,[60] Yonatan Kahn,[61] Grzegorz Kalicy,[62] Zhong-Bo Kang,[12] Vardan Khachatryan,[4] Venelin Kozhuharov,[63] N. V. Krasnikov,[49] Valery Kubarovsky,[17] Eric Kuflik,[1] Noah Kurinsky,[5,8] Ranjan Laha,[13,8] Gaia Lanfranchi,[35] Dale Li,[5] Tongyan Lin,[10,55] Mariangela Lisanti,[61] Kun Liu,[12] Ming Liu,[12] Ben Loer,[15] Dinesh Loomba,[64] Valery E. Lyubovitskij,[65,66,67] Aaron Manalaysay,[68] Giuseppe Mandaglio,[69] Jeremiah Mans,[70] W. J. Marciano,[38] Thomas Markiewicz,[5] Luca Marsicano,[2] Takashi Maruyama,[5] Victor A. Matveev,[49] David McKeen,[71] Bryan McKinnon,[72] Dan McKinsey,[10] Harald Merkel,[39] Jeremy Mock,[68] Maria Elena Monzani,[5] Omar Moreno,[5] Corina Nantais,[73] Sebouh Paul,[53] Michael Peskin,[5] Vladimir Poliakov,[74] Antonio D Polosa,[75,76] Maxim Pospelov,[6,11] Igor Rachek,[77] Balint Radics,[18] Mauro Raggi,[30] Nunzio Randazzo,[22] Blair Ratcliff,[5] Alessandro Rizzo,[36,37] Thomas Rizzo,[5] Alan Robinson,[7] Andre Rubbia,[18] David Rubin,[1] Dylan Rueter,[8] Tarek Saab,[78] Elena Santopinto,[2] Richard Schnee,[79] Jessie Shelton,[80] Gabriele Simi,[81,82] Ani Simonyan,[43] Valeria Sipala,[28,29] Oren Slone,[83] Elton Smith,[17] Daniel Snowden-Ifft,[84] Matthew Solt,[5] Peter Sorensen,[10,55] Yotam Soreq,[34] Stefania Spagnolo,[24,85] James Spencer,[5] Stepan Stepanyan,[17] Jan Strube,[15] Michael Sullivan,[5] Arun S. Tadepalli,[86] Tim Tait,[47] Mauro Taiuti,[2,87] Philip Tanedo,[88] Rex

- 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)

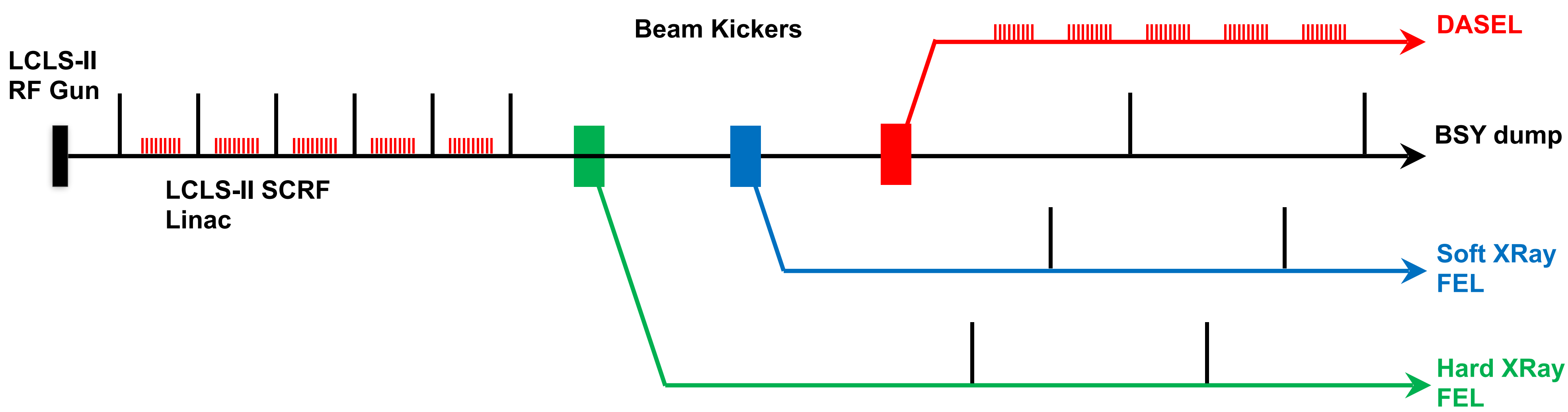

All Experiments (Kinetic Mixing + Elastically Coupled DM)
LHC
LEP
DarkLight @JLab
E787/949@BNL
BaBar
CRESST II
PADME@LNF
VEPP−3 @BINP
MMAPS @Cornell
NA64 @CERN
E137
MiniBooNE @FNAL
Belle II
BDX @JLab
LSND
NEWS
Scalar Relic Target
LDMX, Phase I
Fermion Relic Target
Super CDMS SNOLAB
LDMX Phase 2 (4 & 8 GeV)
$y = \epsilon^2 \alpha_D (m_\chi/m_{A'})^4$
m_χ (MeV)

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).

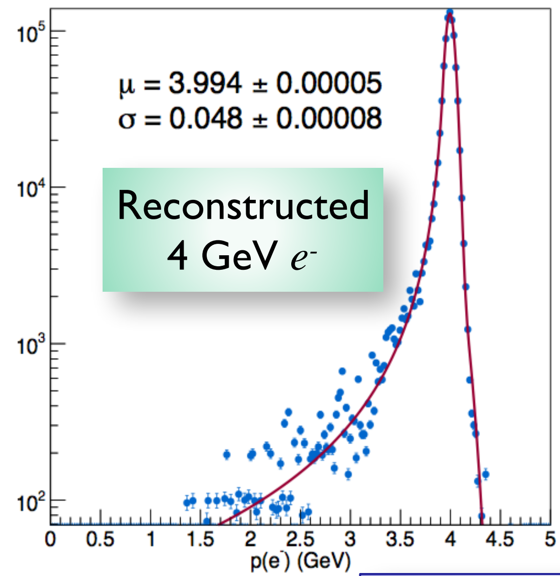
The SCRF linac can accelerate modest current in these “unused” buckets with minor modifications and no interference

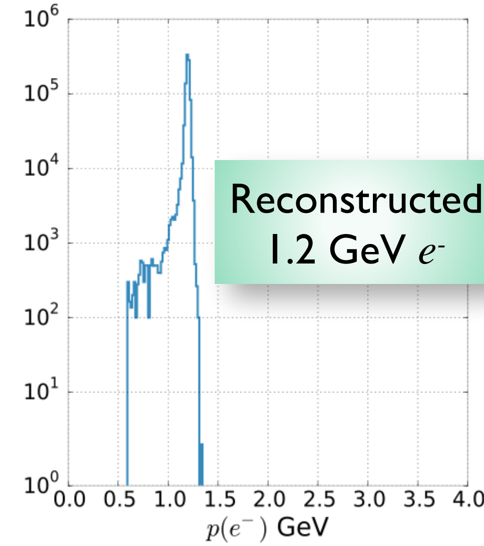


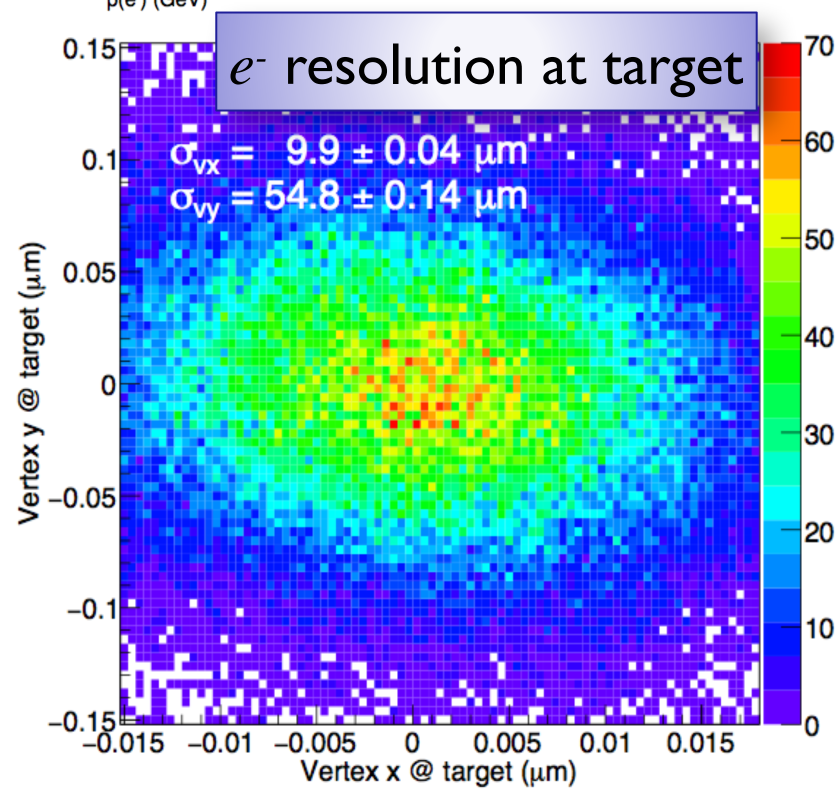
Resulting low-current CW beam can support unique & high-impact dark matter experiments

Tagging Tracker Performance

- Momentum resolution of ~1% found in simulation matches analytic calculations
    - ~Vanishing likelihood for 1.2 GeV e- to be reco. as 4 GeV e-
- Momentum Resolution (σ_{px}, σ_{py}) 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

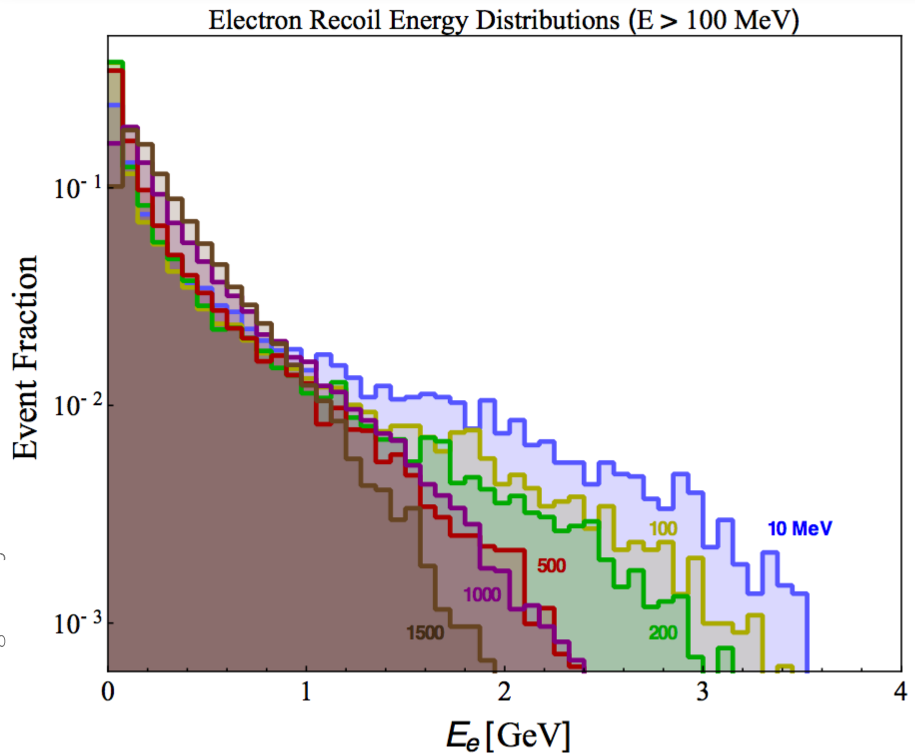


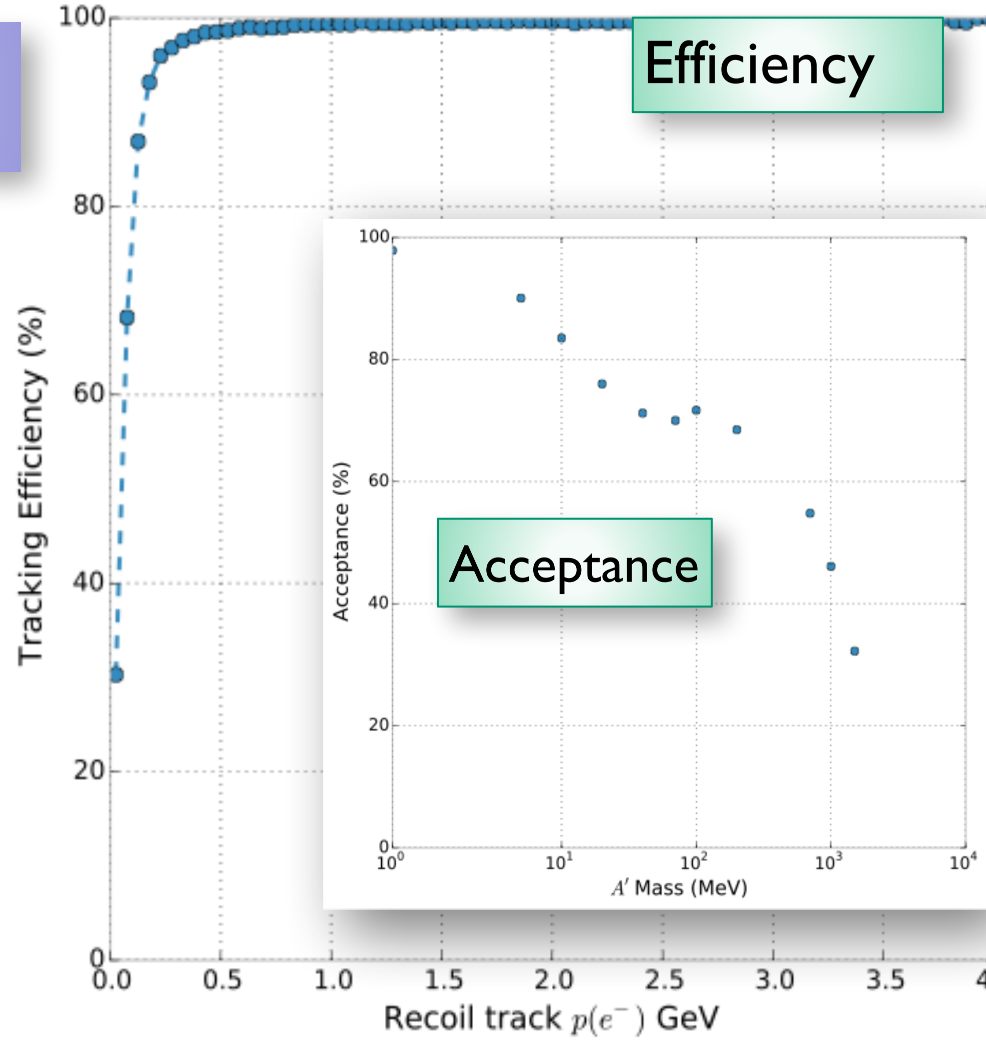




Recoil Tracker Performance

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.

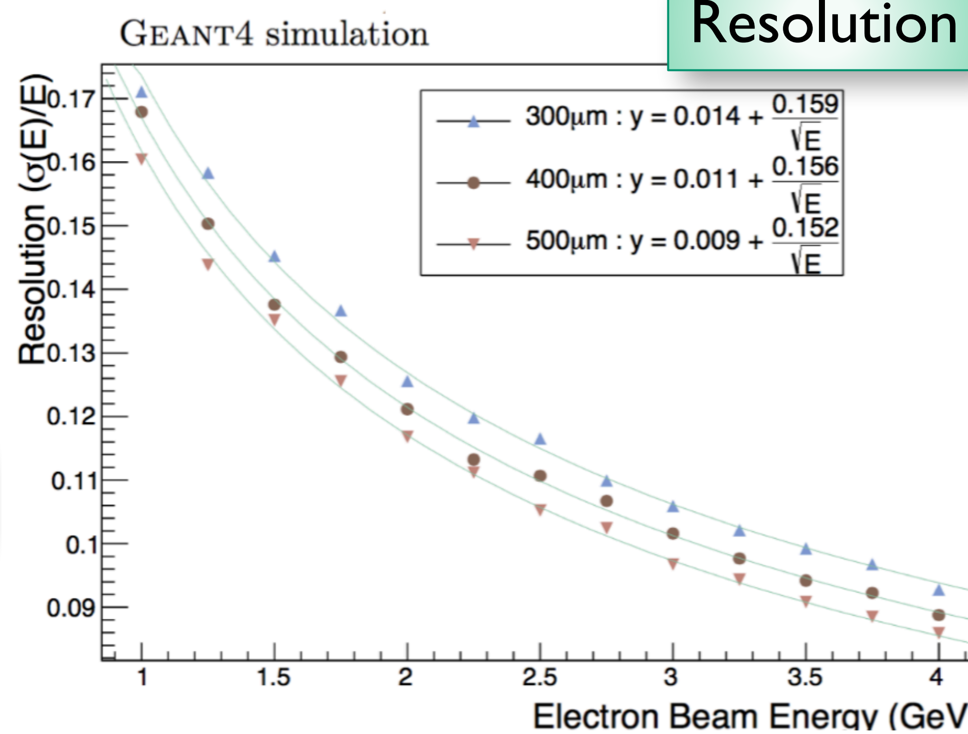
ECAL Performance

E&M Response and Resolution

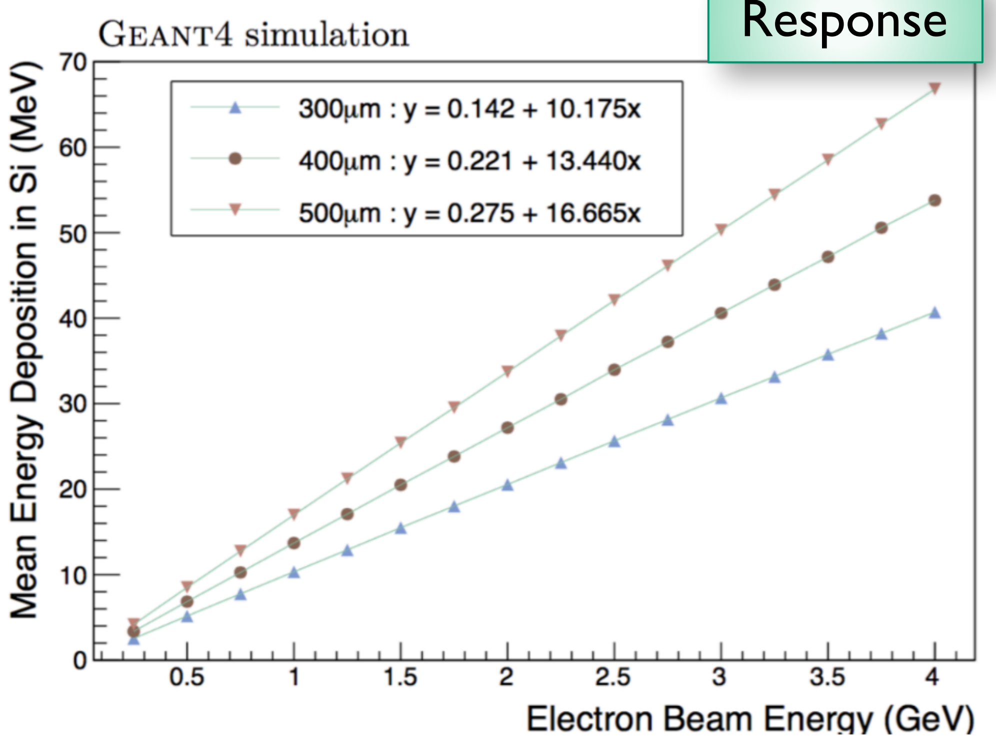
More than 7σ fluctuation is required for a 4 GeV E&M shower to be measured as a 1.2 GeV e-.

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

Resolution



Response



Other Considerations

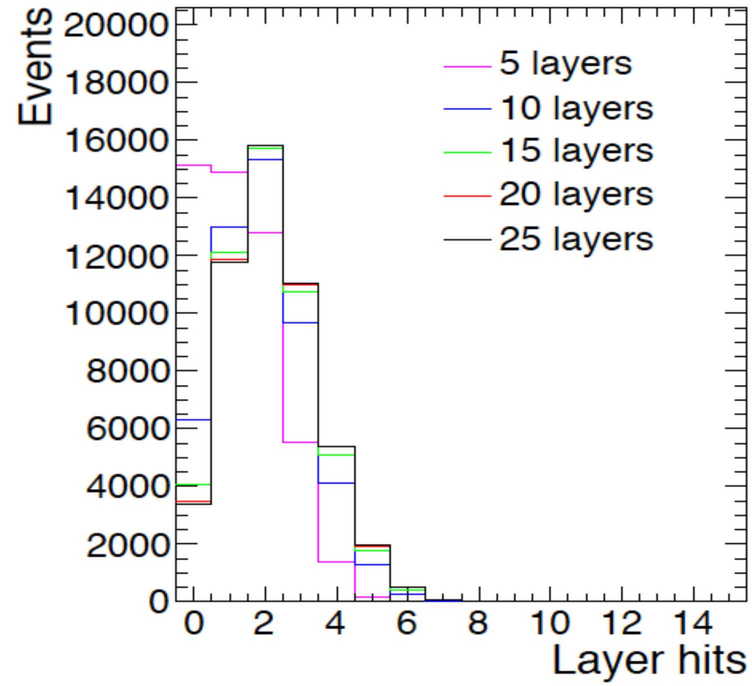
Fluka studies show that 10^{14} e-'s on target results in an effective fluence of 10^{13} n/cm^2

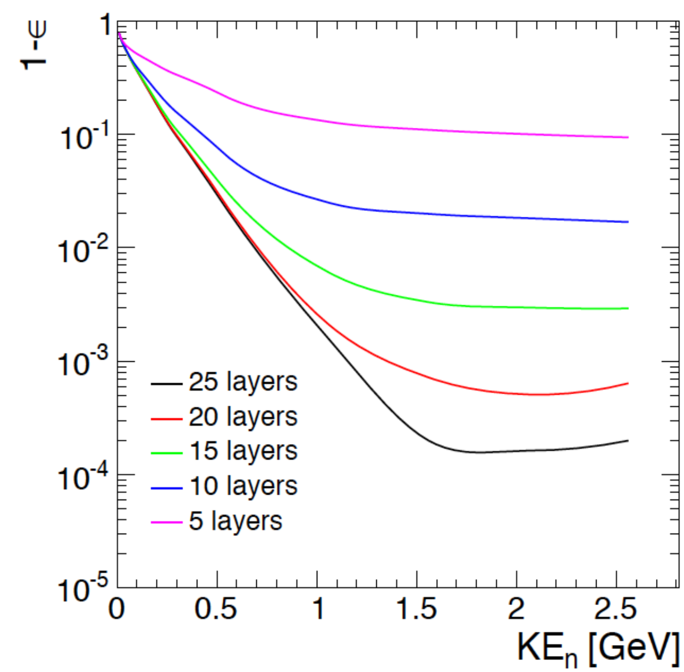
500 um Si is preferred for best resolution

It appears liquid cooling will be sufficient for this environment

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

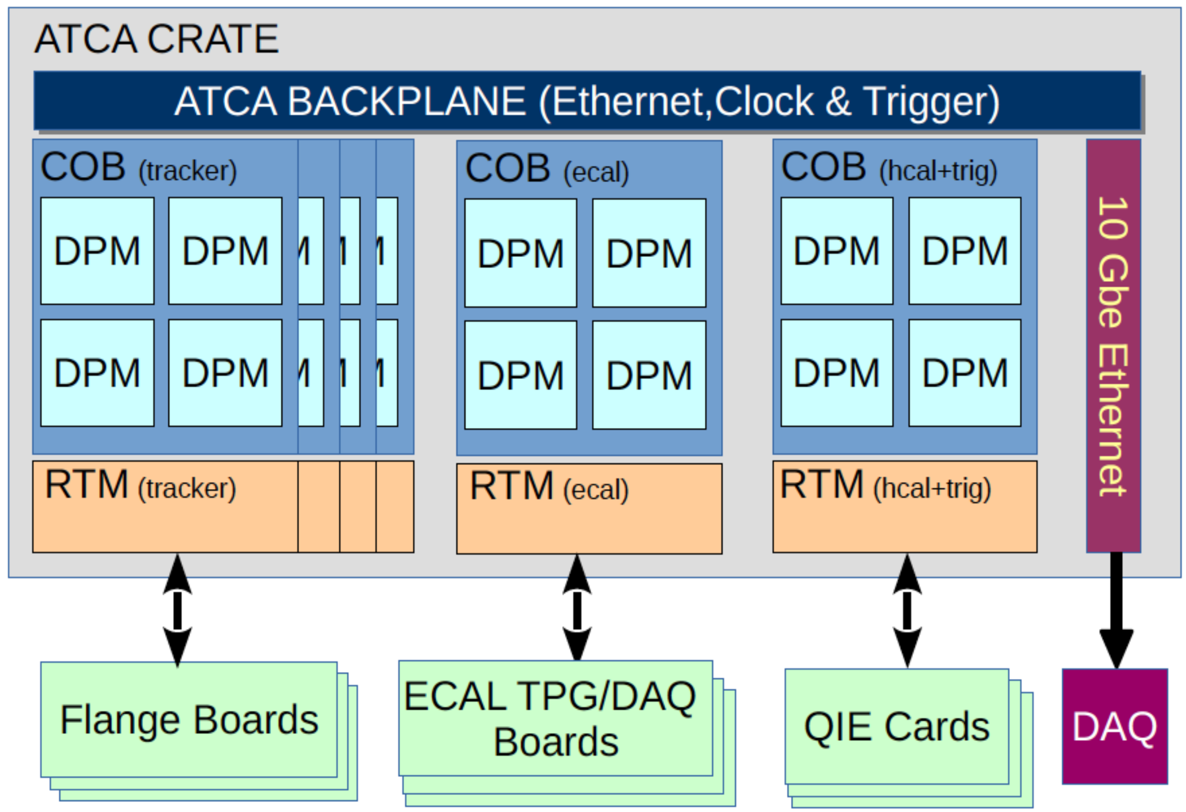




Off-detector electronics and DAQ

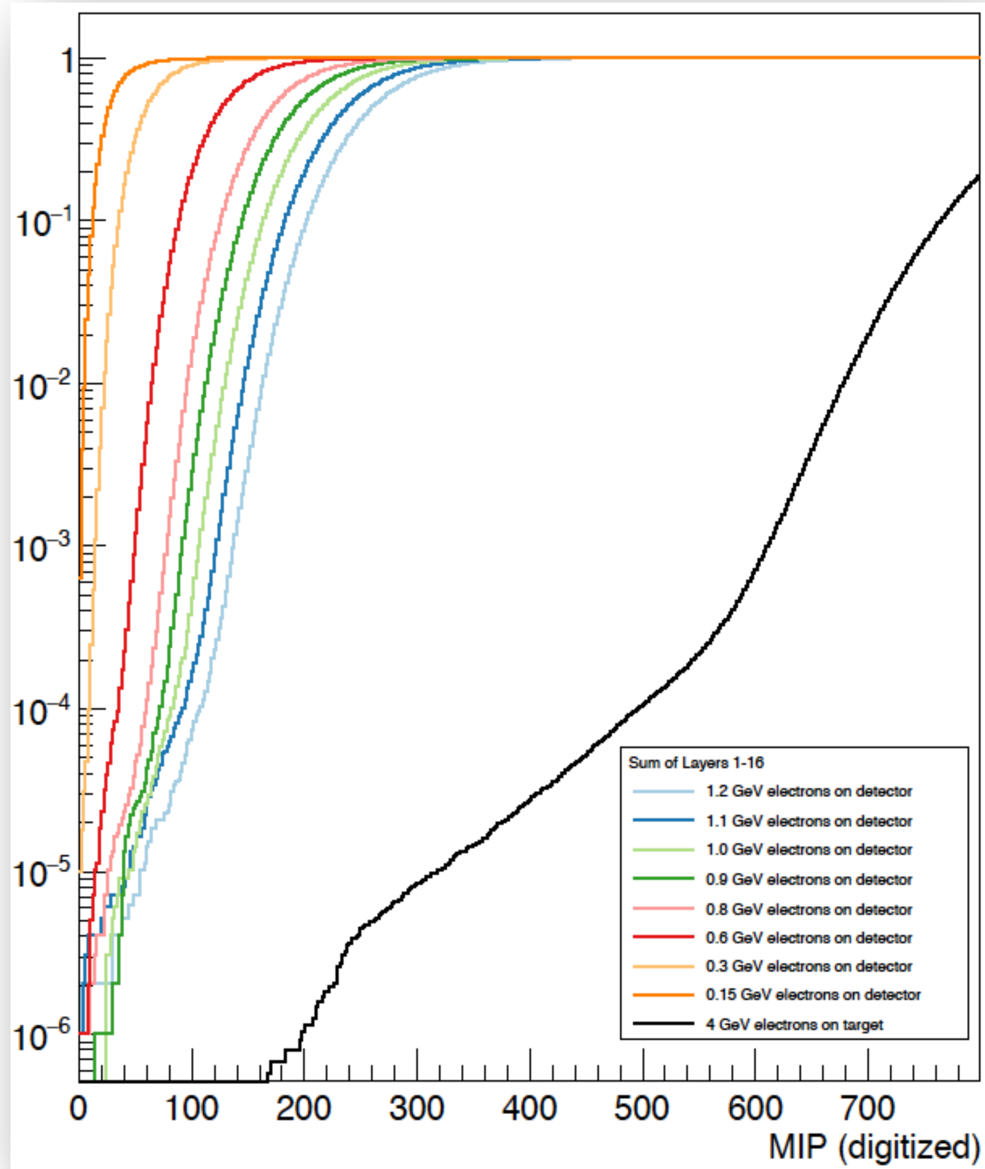
- Common off-detector electronics system based on the RCE/RPM ATCA electronics developed at SLAC
  - System is powerful enough to implement the trigger, DAQ, and controls in one ATCA crate

- 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

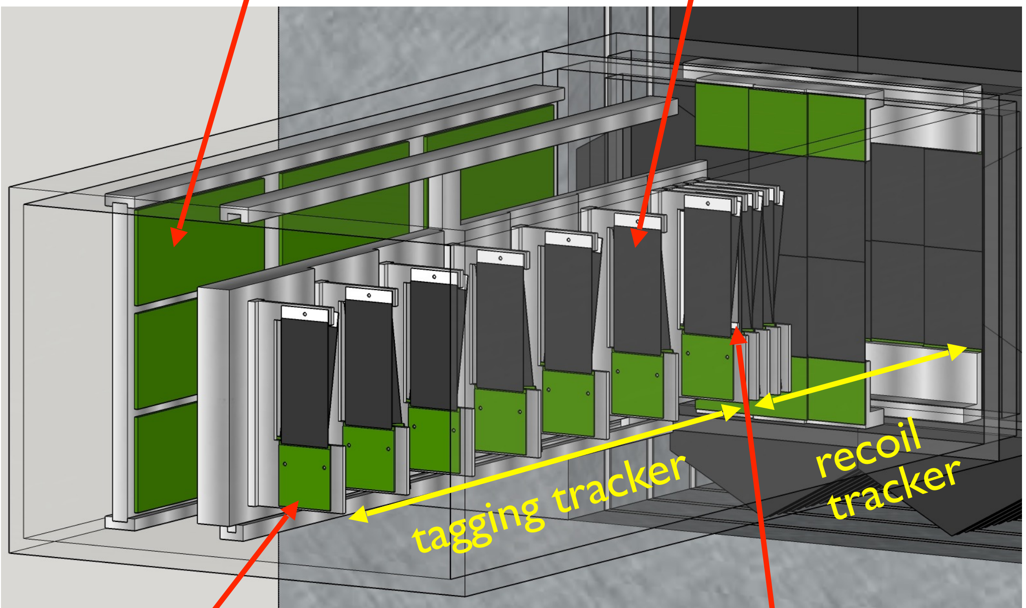


LDMX Physics Trigger

- ECAL based trigger
  - Energy sums performed using the first 16 layers of calorimeter
  - DAQ needs a reduction of ~10^{-4}
  - Simulation indicates reduction factor of 2×10^{-5} possible with no inefficiency for signal

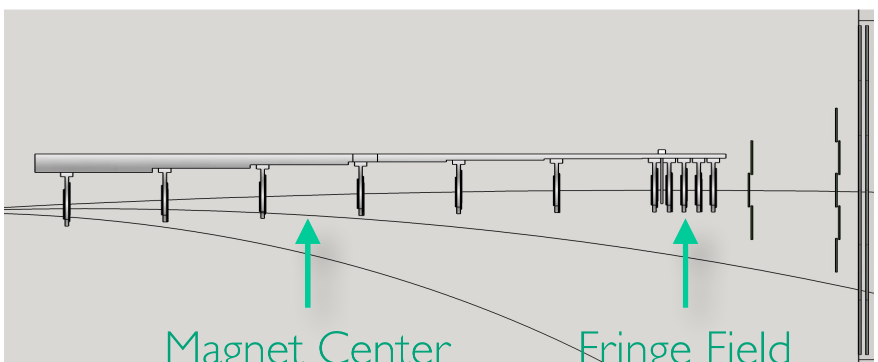


Tracker and Magnet

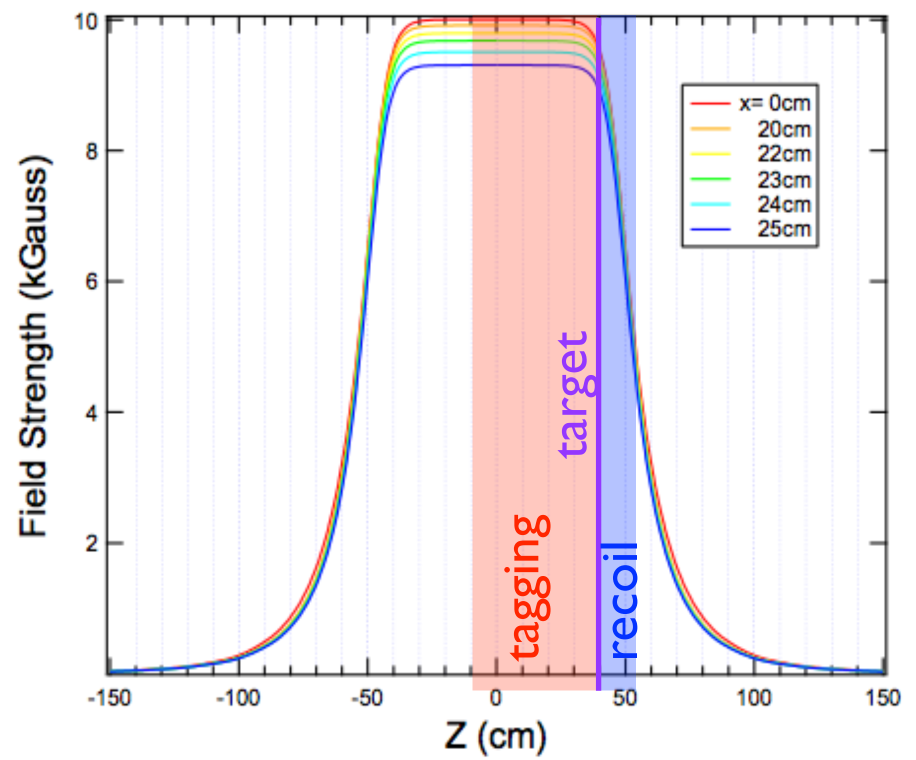


Two tracking systems, separated by a target in separate vacuum, one magnet

- 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)



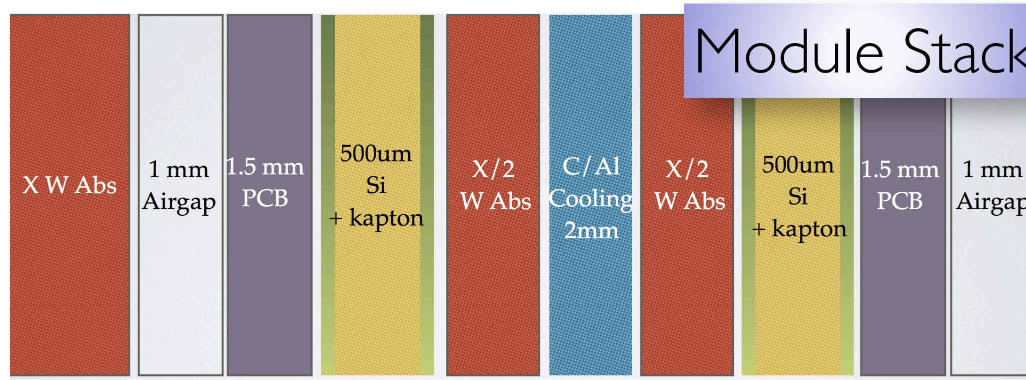
- Screen out straggling (off E_{Beam}) electrons
- Measure Δp across target
  - Recoil tracker placed in fringe field



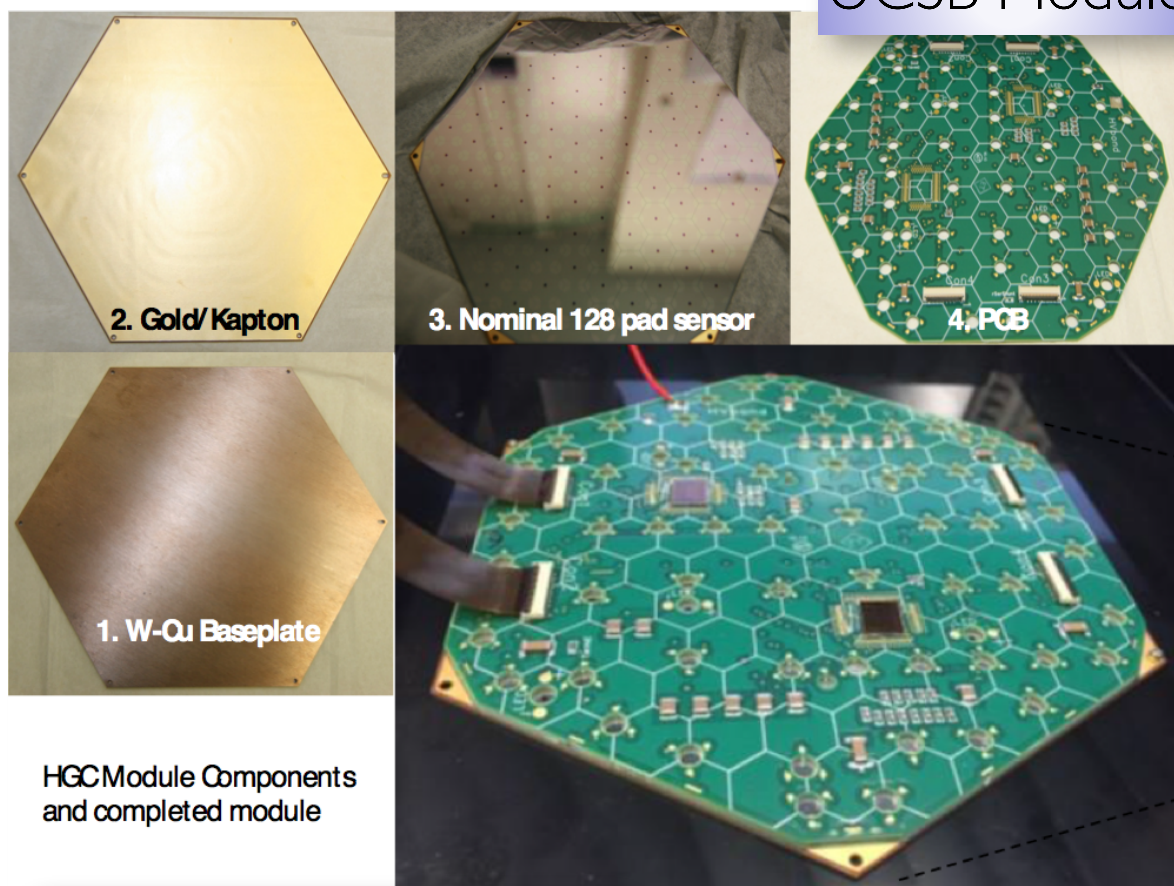
ECAL Modules

- 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 HGROC 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

Module Stack

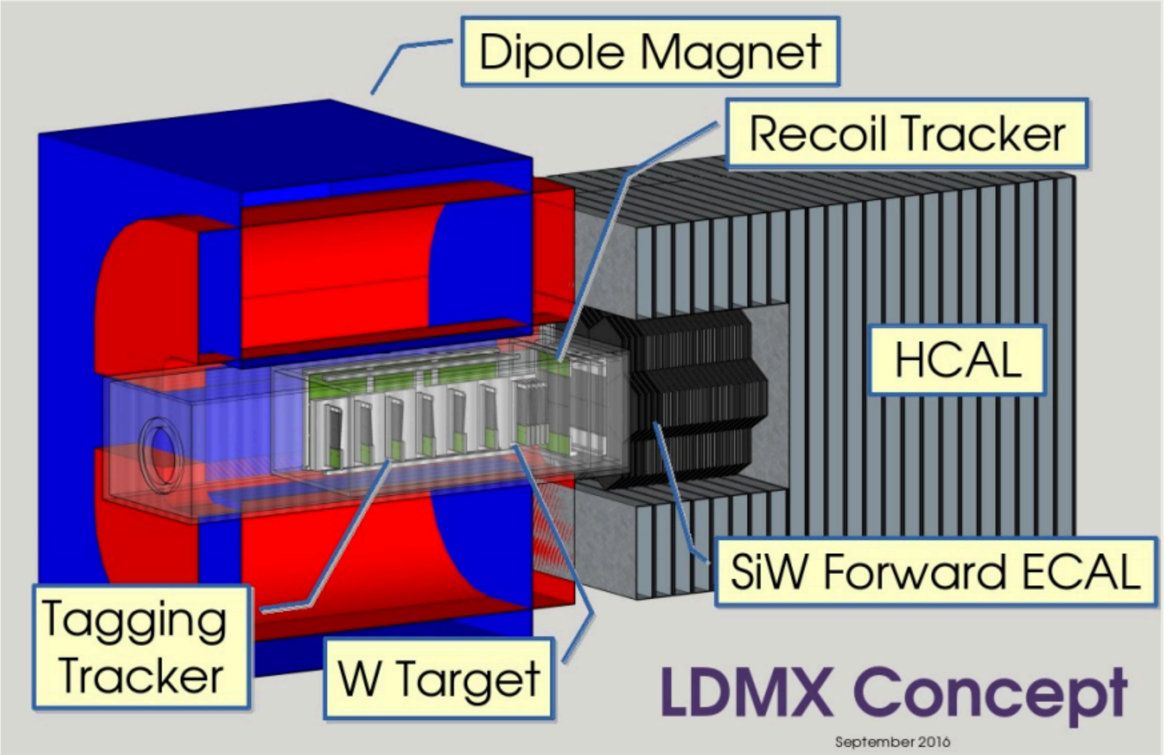


UCSB Module



HGC Module Components and completed module

Successful test beams carried out at FNAL & CERN in 2016



Summary and Conclusions

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