The Light Dark Matter eXperiment

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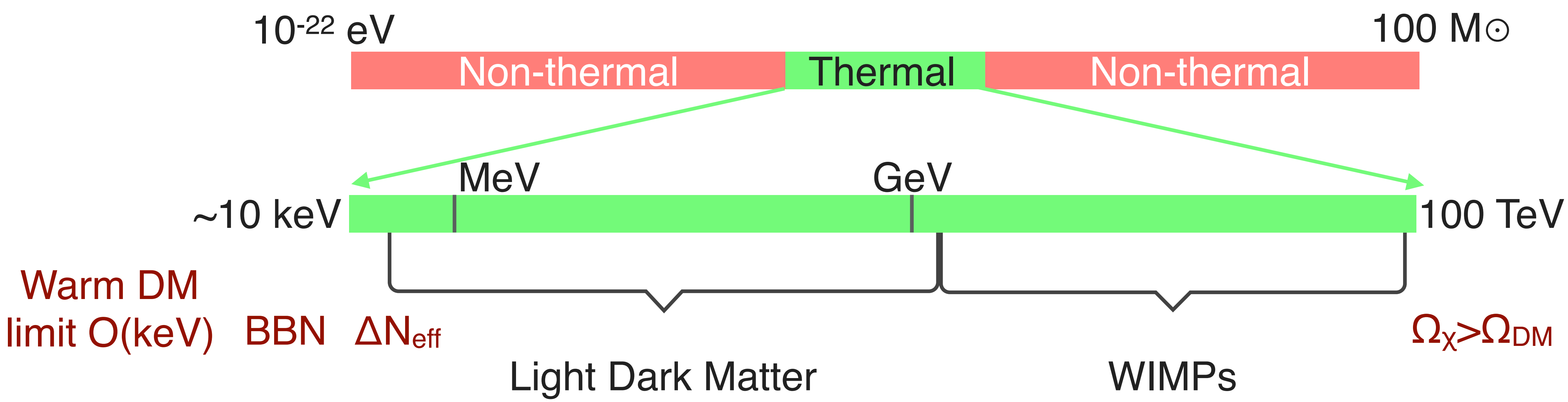
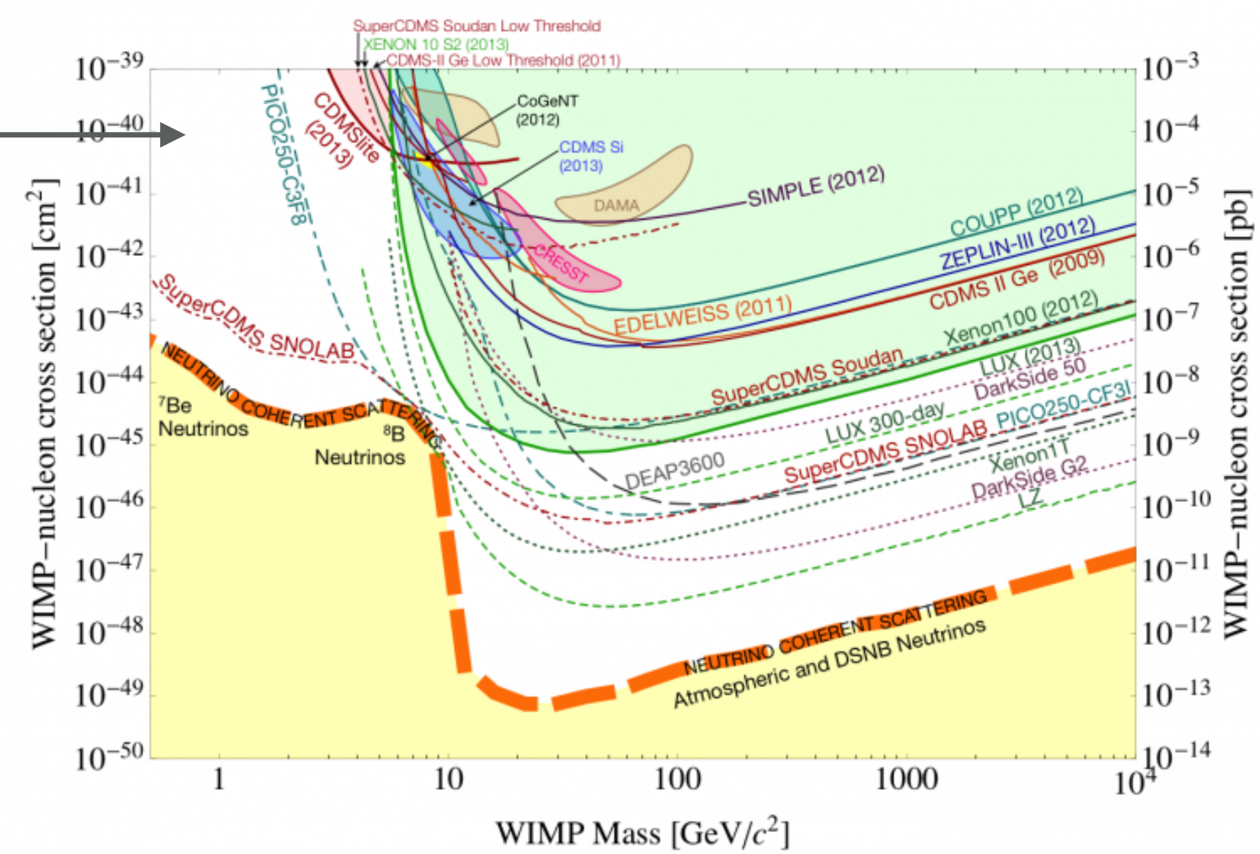
*on behalf of the **LDMX Collaboration***

Caltech Fermilab Lund University SLAC Texas Tech University UCSB University of Minnesota University of Virginia

Motivation



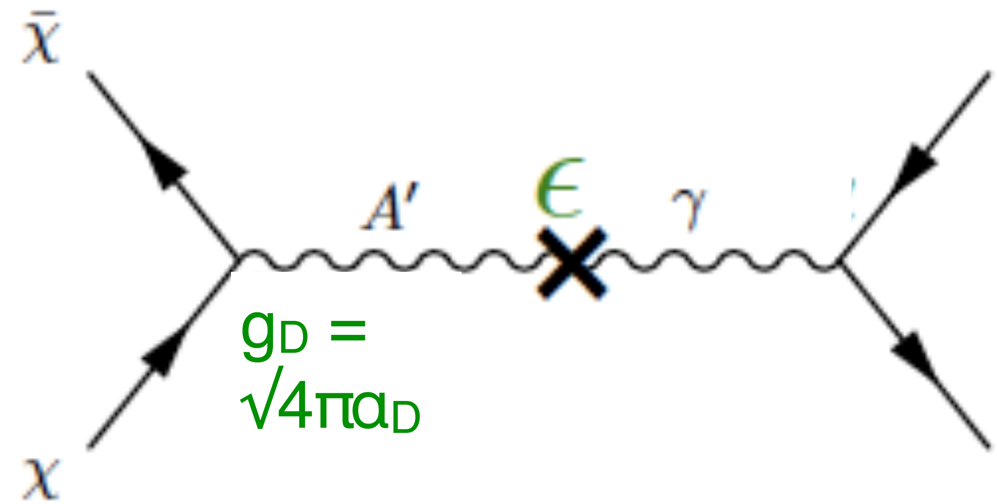
WIMPs extensively explored with past and upcoming experiments



Light dark matter:

- Well motivated by "hidden-sector" models
- Can be extensively probed with accelerator-based experiments

Introducing hidden-sector DM



m(χ) < m(A')

DM annihilation rate

$$\sigma v(\chi\chi \to A'^* \to f f) \propto \epsilon^2 \alpha_D \frac{m_\chi^2}{m_{A'}^4} = \frac{y}{m_\chi^2} \quad , \quad y \equiv \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4$$

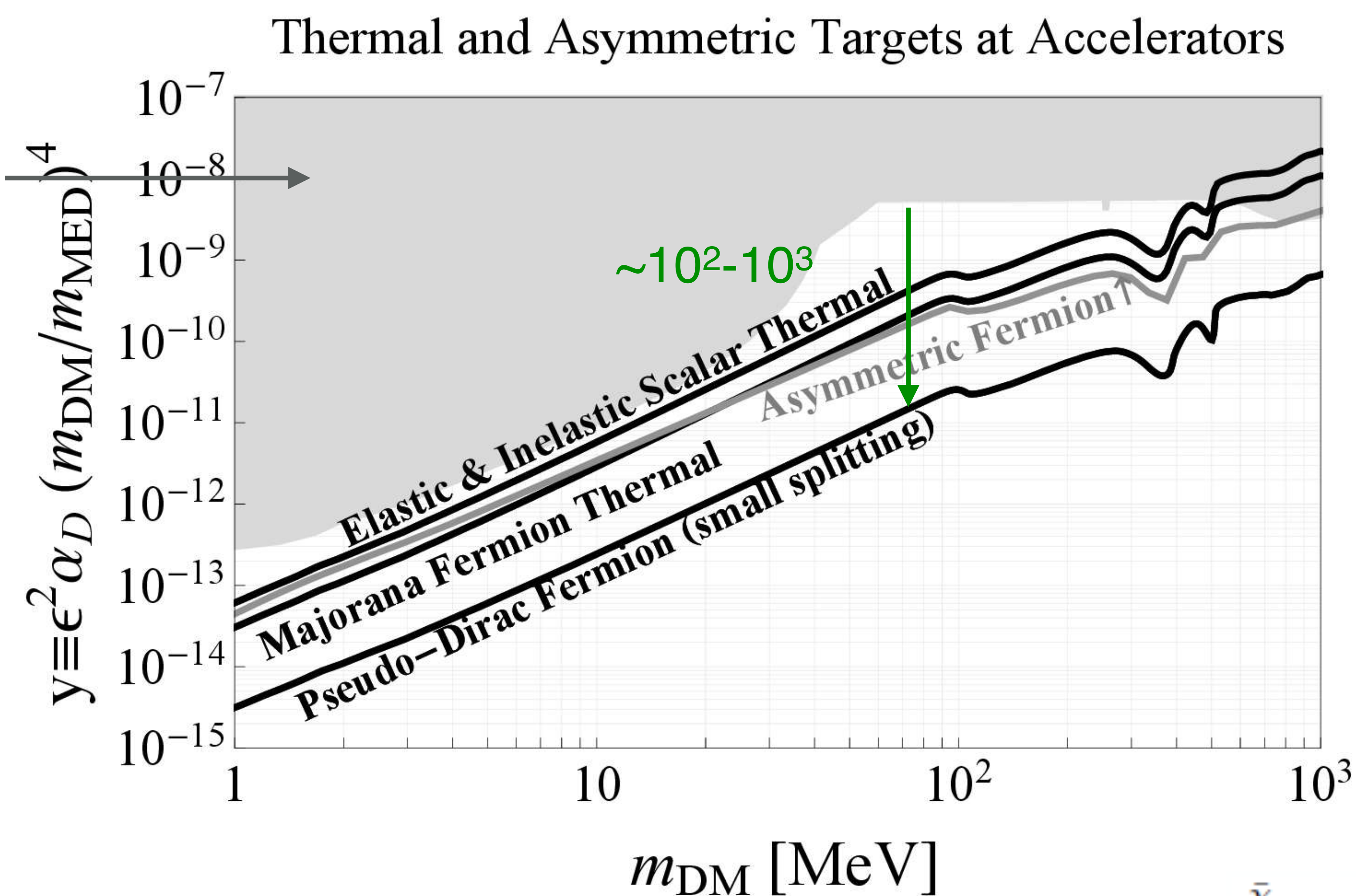
y: dimensionless interaction strength

Accelerator targets

US Cosmic Visions 2017 Community Report

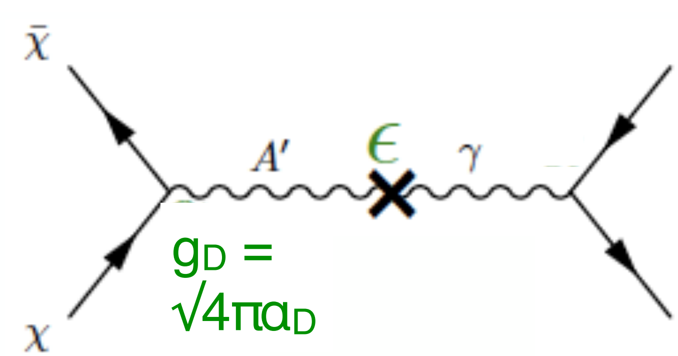
Accelerator targets

current constraints



Thermal targets: unique value of y compatible with thermal freeze-out for each DM mass

Using conservative values for α_D (=0.5), $m_\chi/m_{A'}$ (1/3) for experimental constraints

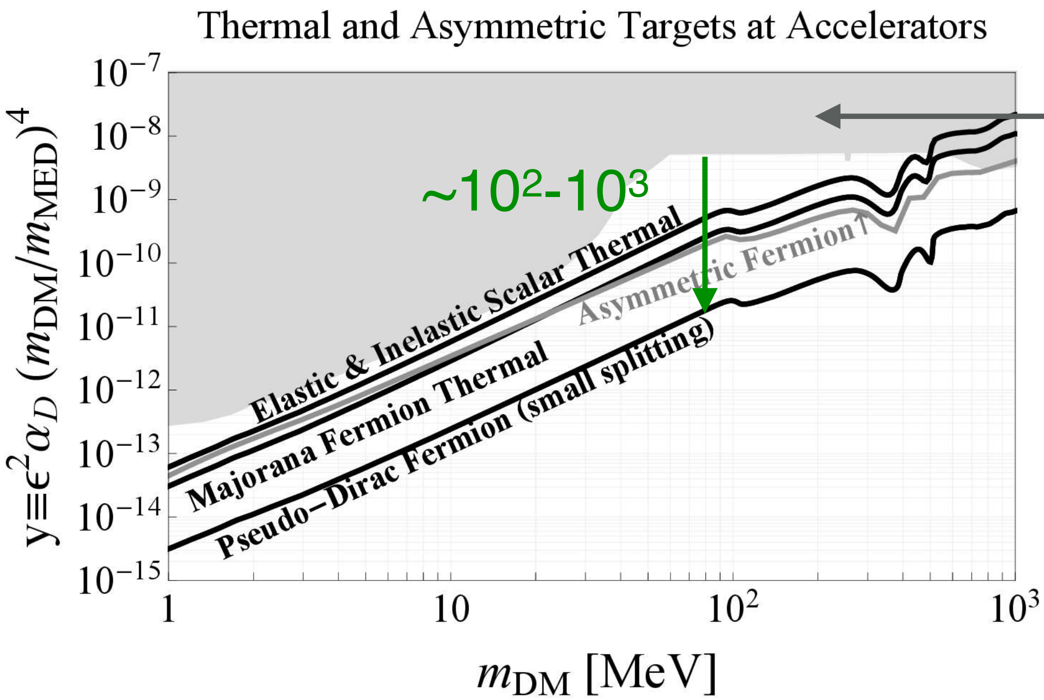


Relativistic production at accelerators nearly insensitive to DM spin and mass

Accelerator vs direct detection

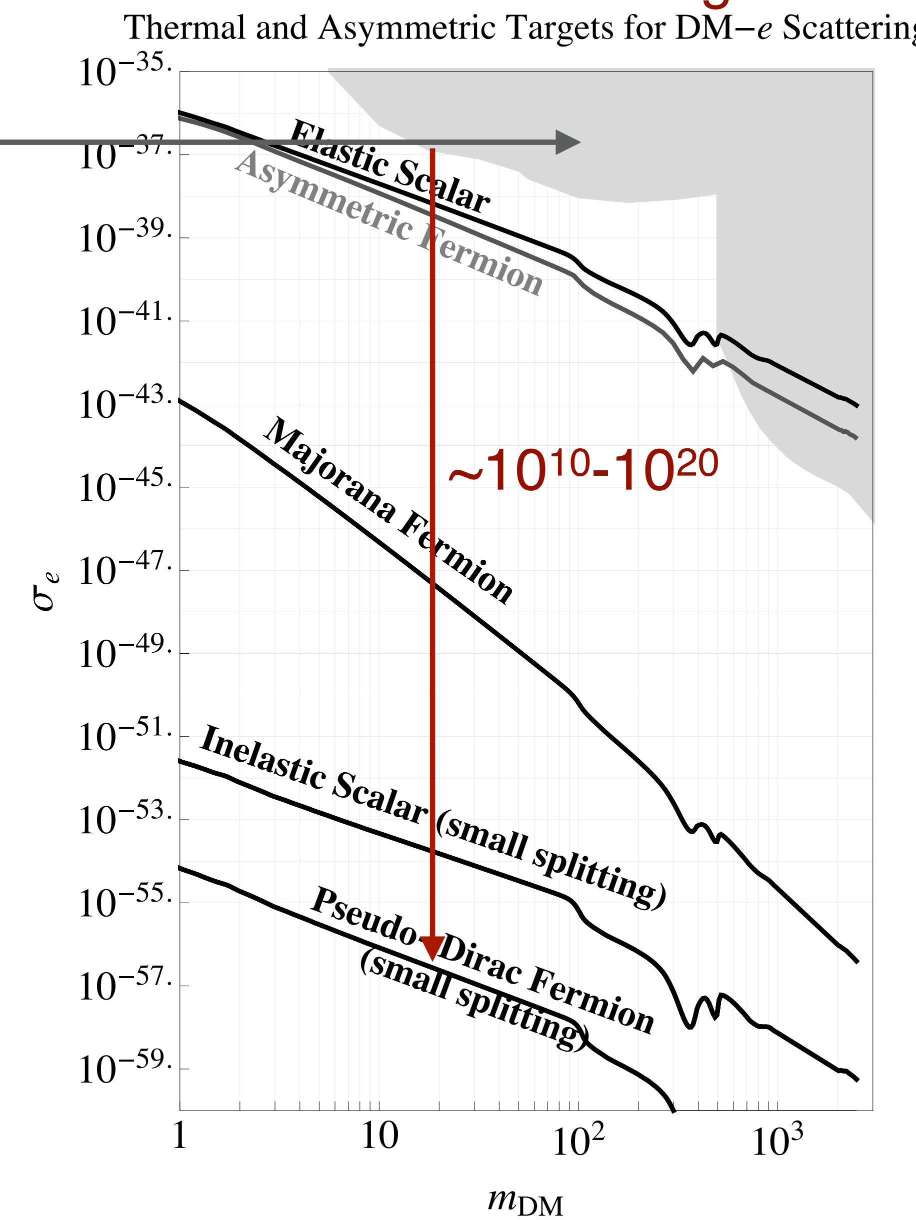
US Cosmic Visions 2017 Community Report

Accelerator targets



current constraints

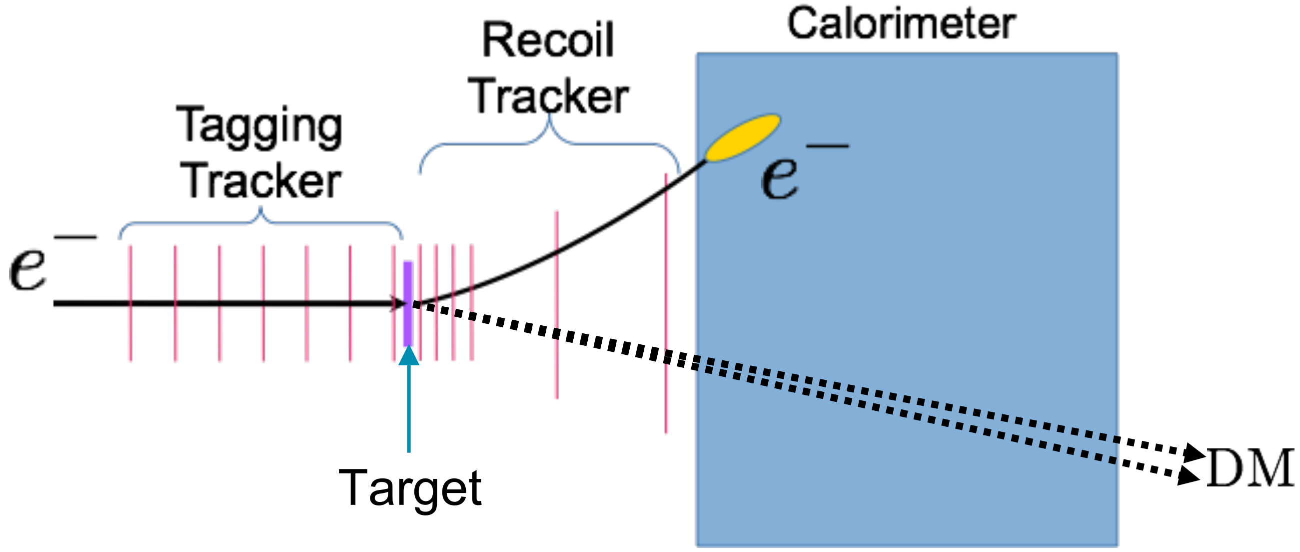
Direct detection targets



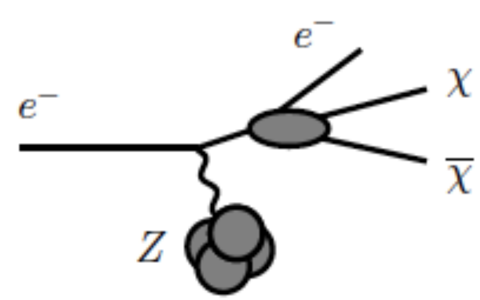
Using conservative values for α_D (=0.5), $m_\chi/m_{A'}$ (1/3) for experimental constraints

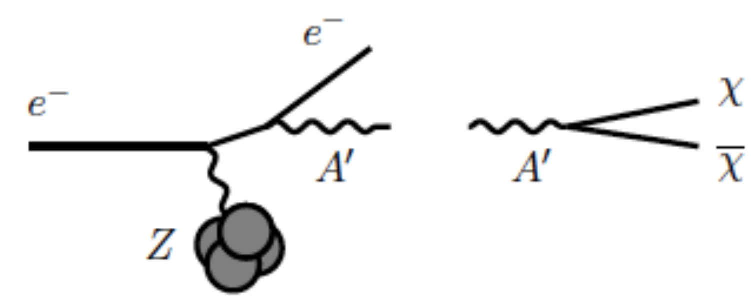
Direct detection: non-relativistic DM scattering highly sensitive to DM nature

LDMX concept



***LDMX**: an electron-based fixed-target missing momentum search for light dark matter*



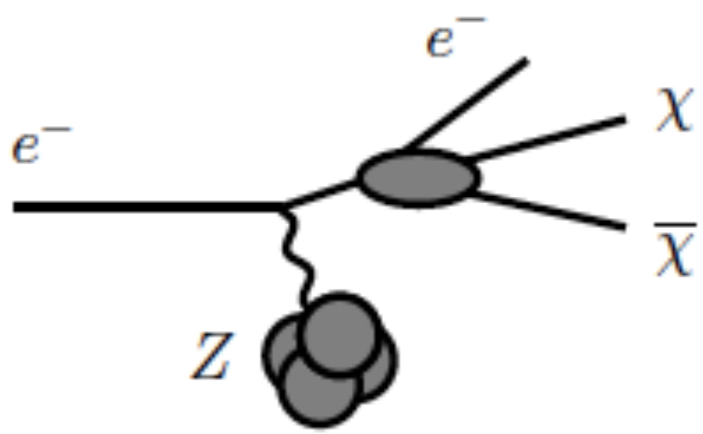


Missing momentum/energy approach:

- DM production identified by missing energy and momentum in detector
- Equipped for e/ɣ particle ID
- p_T can be used as a signal discriminator and identifier

Assuming DM produced via "dark bremsstrahlung", $\sigma \sim Z^2\epsilon^2/m_{A'}^2$

DM production kinematics

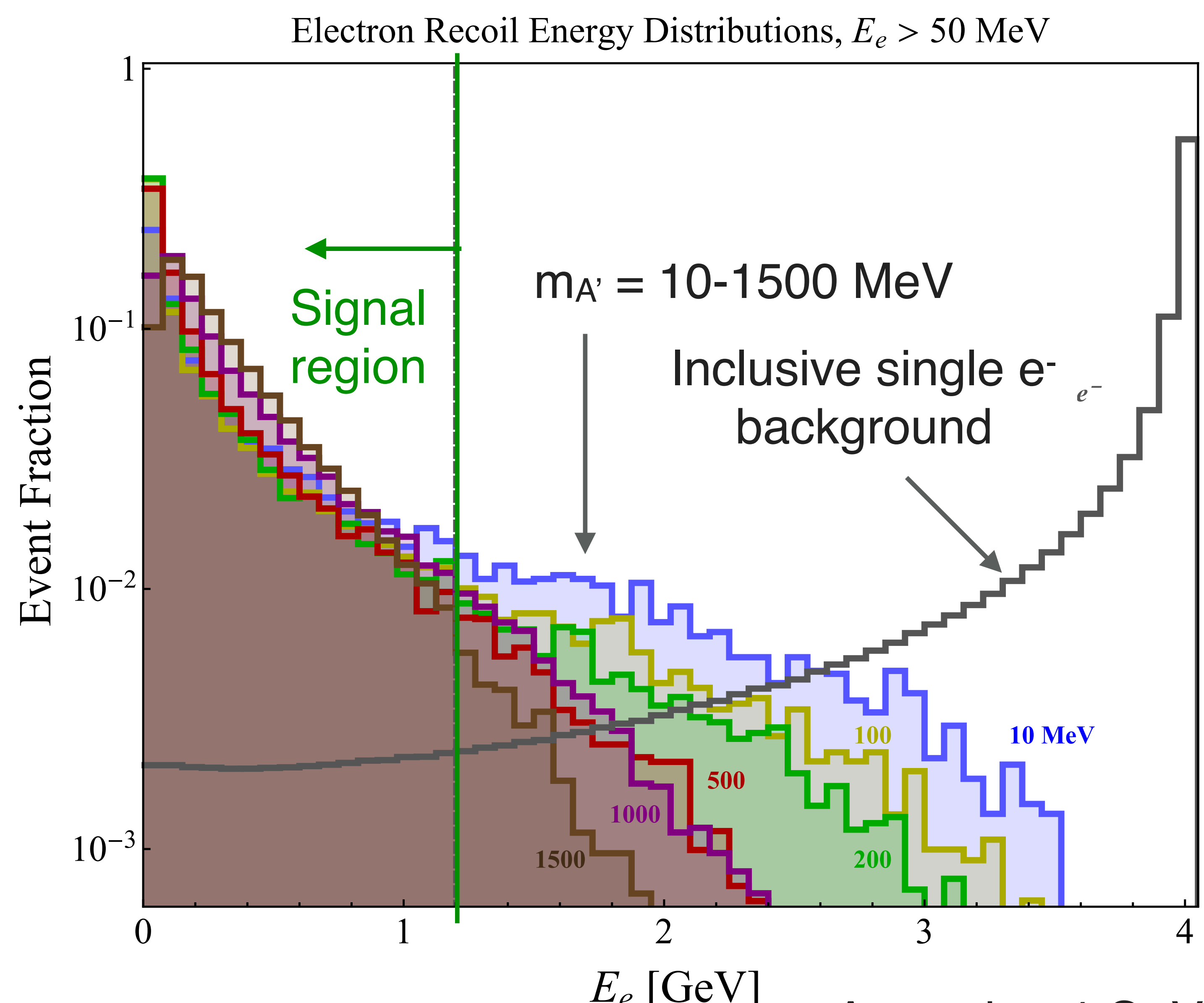


Signal characteristics

- A' takes most of the beam energy
- Recoil electron soft, at wide angles —> large missing momentum

Signal: $E_{total} = E_{recoil} << E_{beam}$

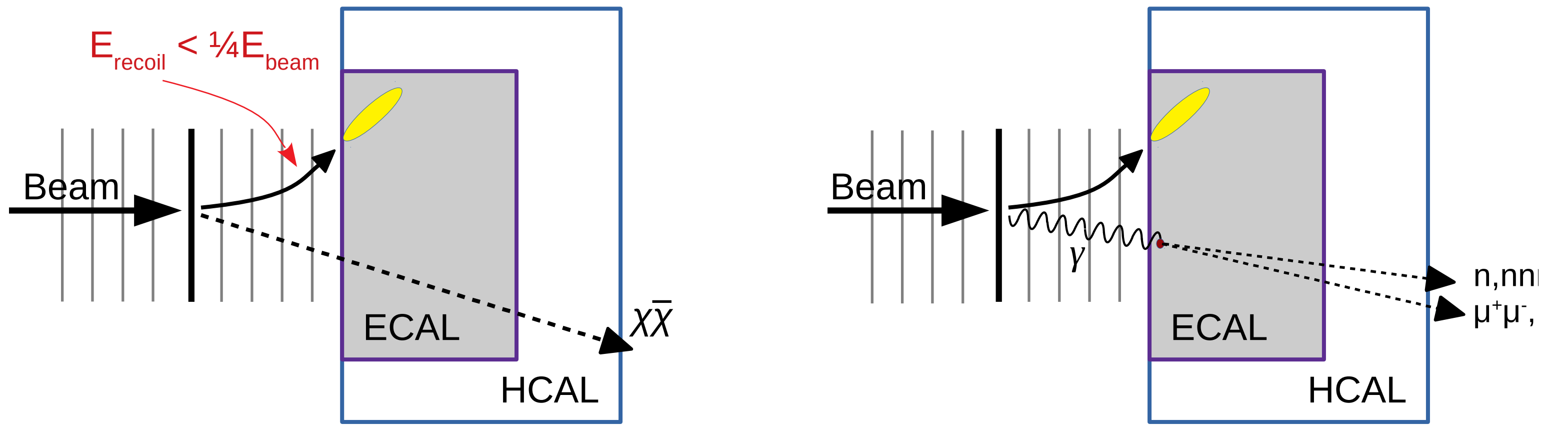
Recoil e⁻ kinematics allow efficient background rejection and signal selection



Assuming 4 GeV e⁻ beam

LDMX design considerations

Design study on arXiv: arXiv:1808.05219



Individual tagging and reconstruction of up to 10^{16} e^- on target (EoT)

- 4-20 GeV, low current beam with high repetition rate (10^{16} e^-/year ≈ 1e^-/3 ns)
- Large beam spot (~10 cm^2) to spread out occupancy and radiation doses
- Potential beamlines: S30XL @SLAC, eSPS @CERN, CEBAF @JLAB

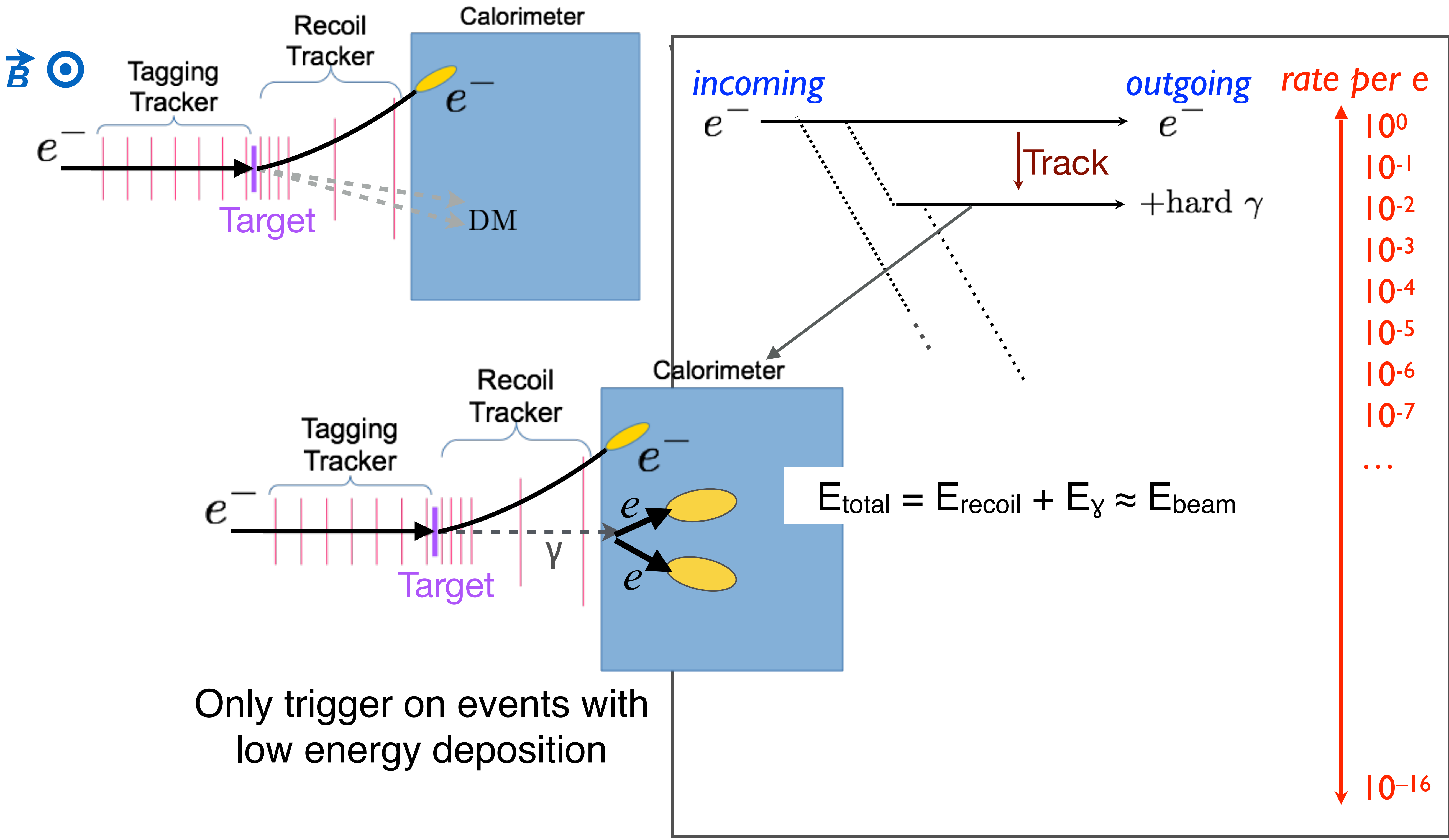
Detector technology suited for high rates, high radiation doses

- Fast, high momentum resolution, low mass trackers
- Fast, granular EM calorimeter with good energy resolution, hermetic HCAL veto

Two-stage approach: initial goal: $4x10^{14}$ EoT, extending to 10^{16} EoT, higher energy

Backgrounds

vs

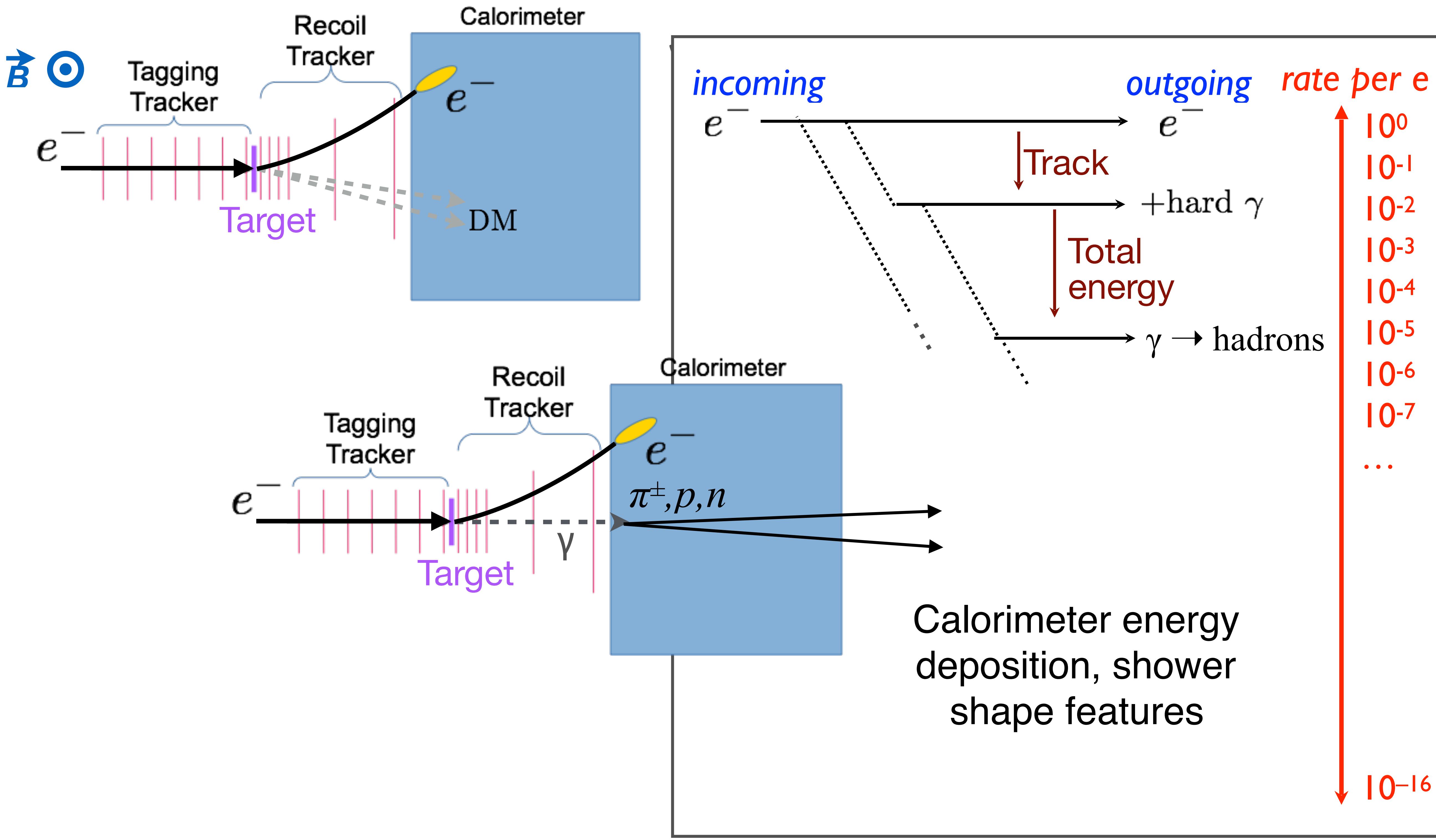


$E_{total} = E_{recoil} + E_{\gamma} \approx E_{beam}$

Only trigger on events with low energy deposition

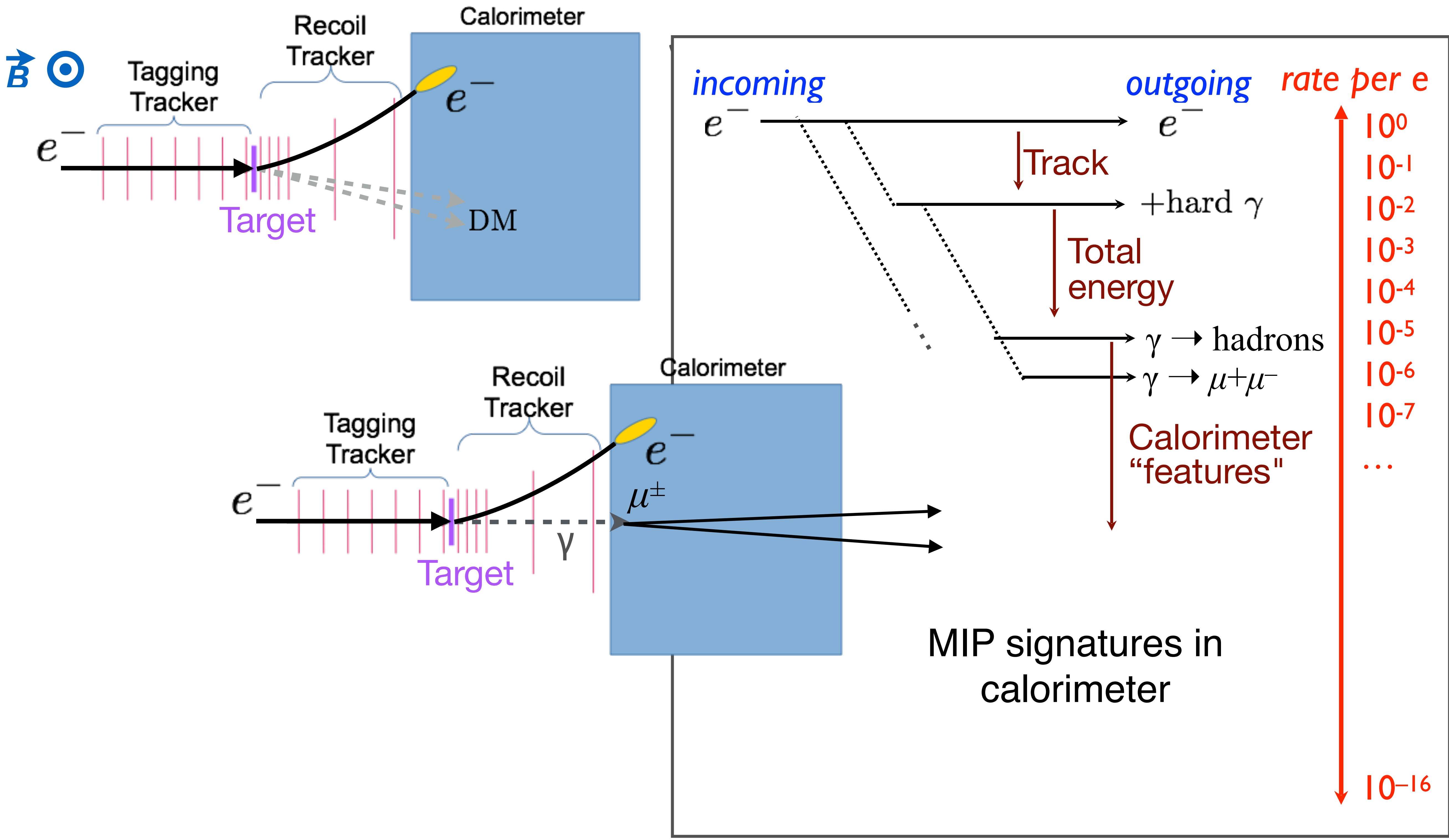
Backgrounds

vs



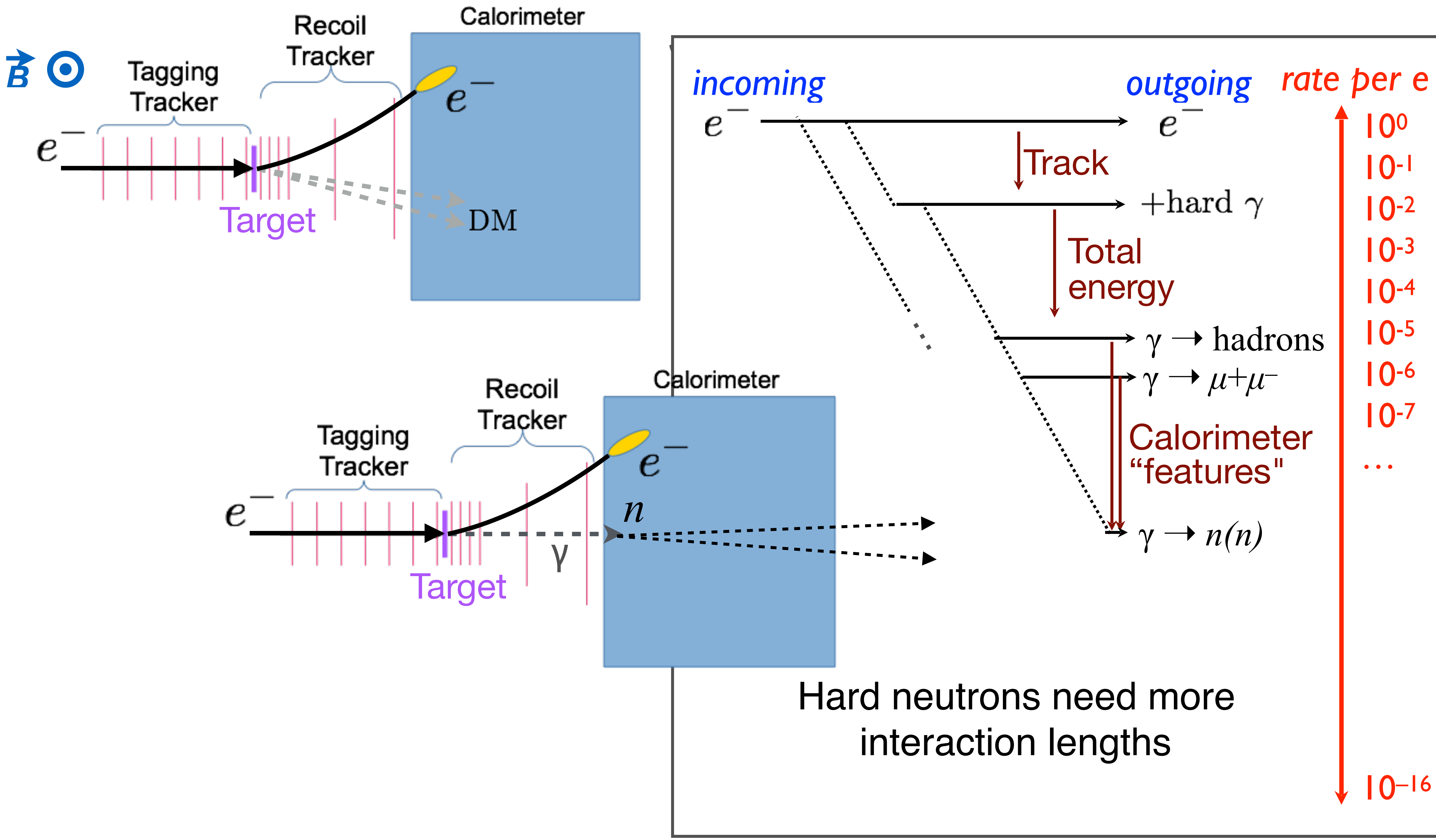
Backgrounds

vs

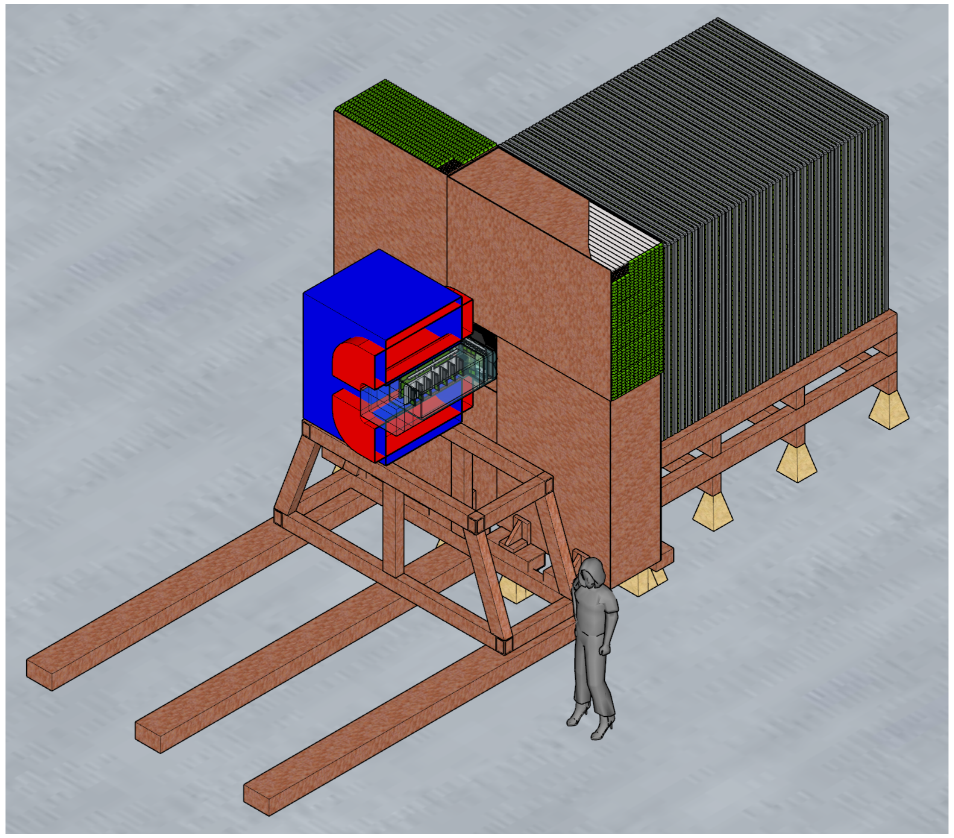


Backgrounds

vs



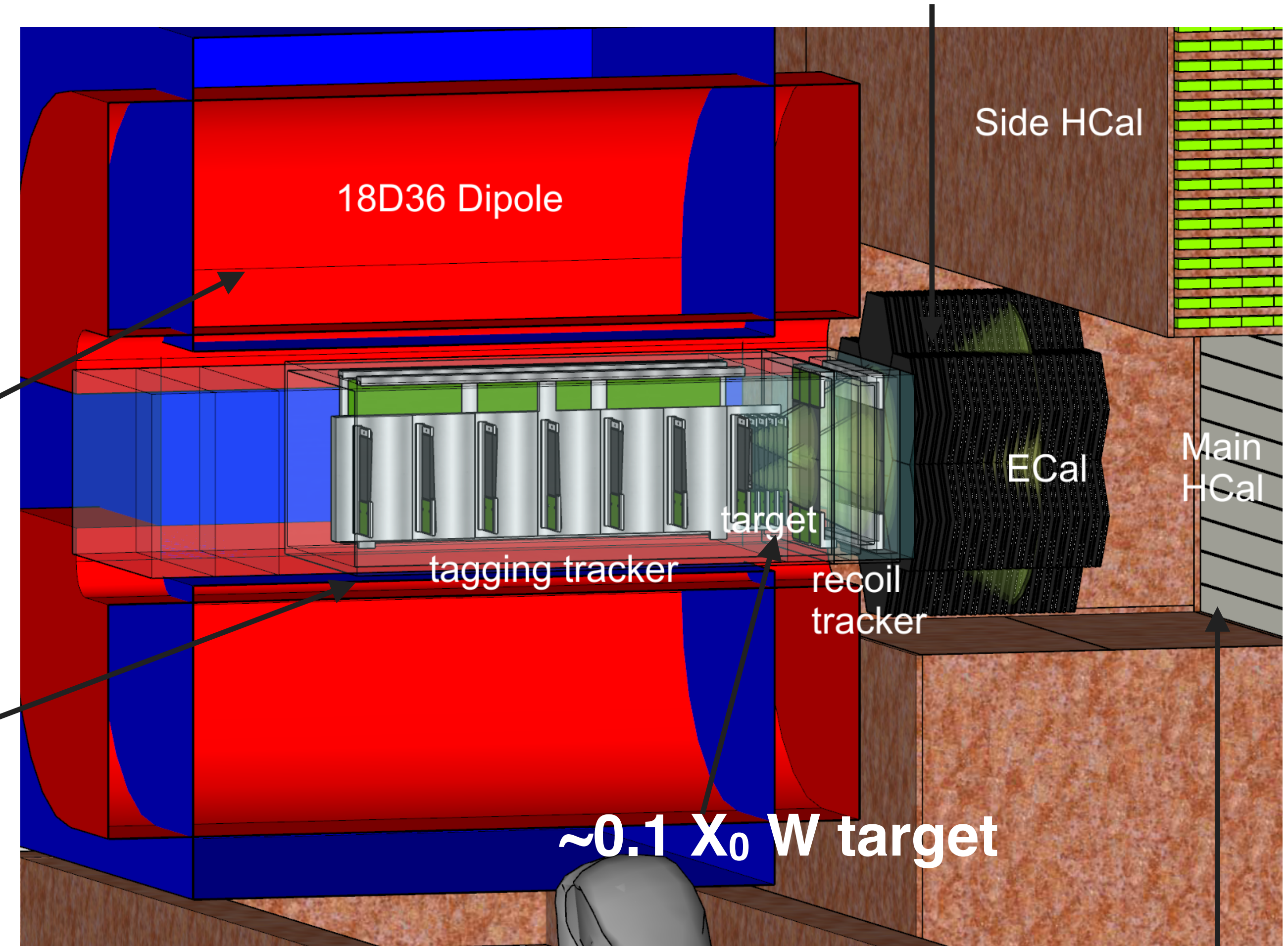
LDMX design



Small scale experiment

Leverage detector techniques from existing/planned experiments

ECAL: draw on Si/W technology of High Granularity Calorimeter upgrade for CMS



Magnet: existing 18D36 dipole at SLAC

Tracker: adapted from Silicon Vertex Tracker of HPS at JLab

HCAL: scintillator/steel sampling calorimeter similar to Mu2e Cosmic Ray Veto system

Tracking system

Adapted from Silicon Vertex Tracker of HPS at JLab

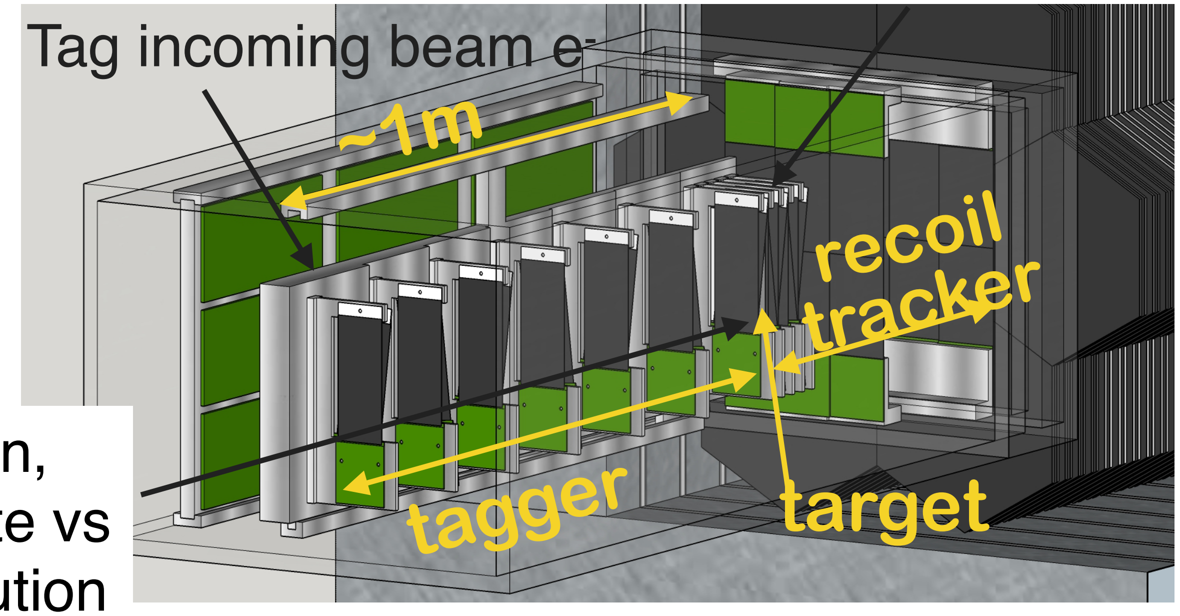
- Fast (2ns hit time resolution), radiation hard

Tagging tracker

- In central dipole field, measure incoming electron

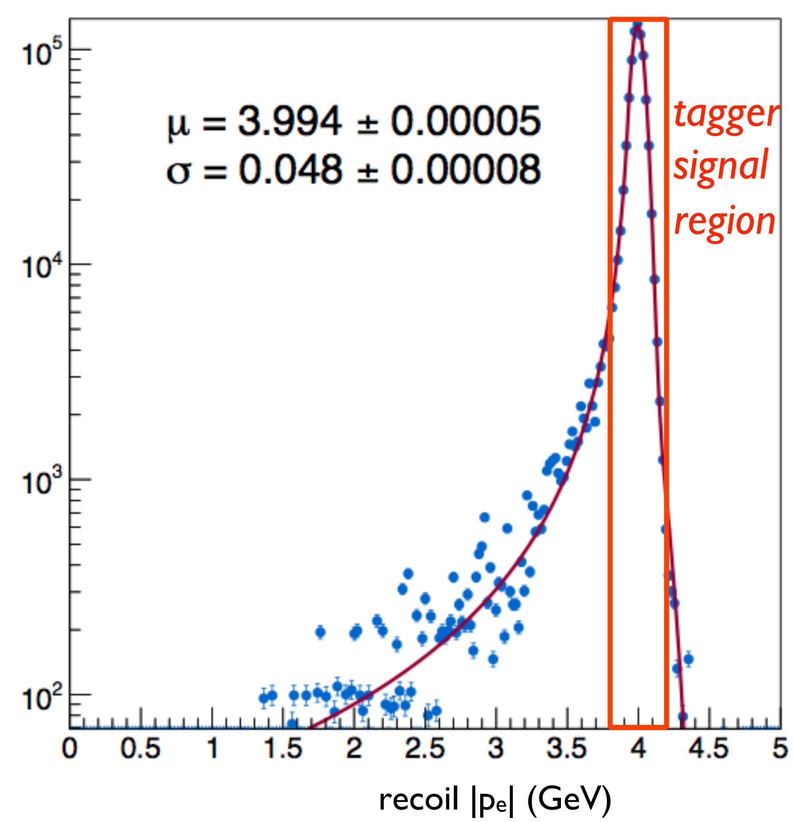
Recoil tracker

- In fringe field, measure recoil electron and veto extra particles
- Momentum resolution limited by multiple scattering in target (~4 MeV smearing)

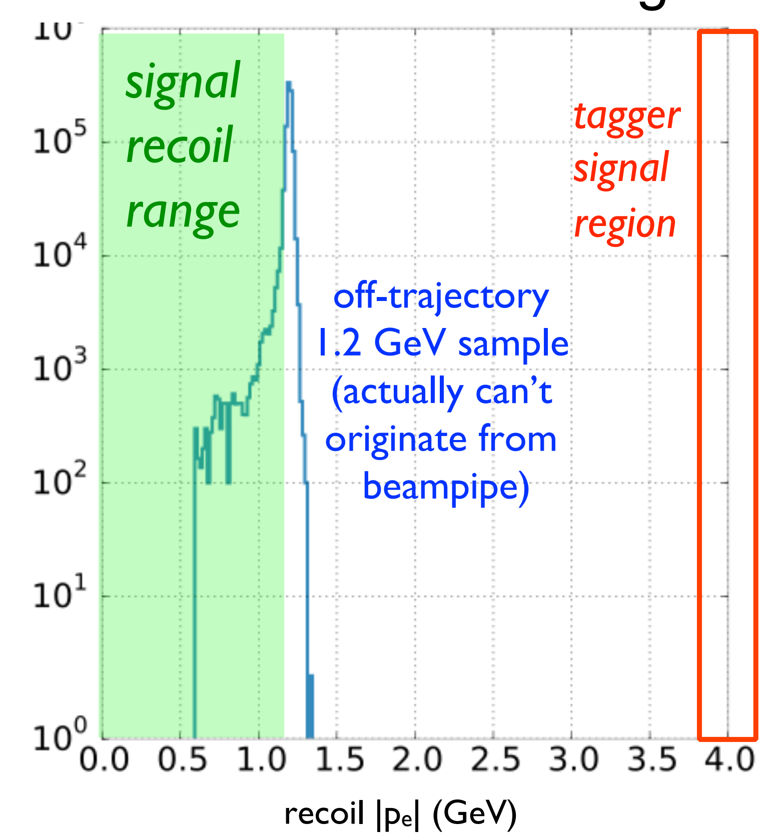


0.1 X0, tungsten, balance signal rate vs momentum resolution

Reconstructed 4 GeV beam e-



Worst-case beam bkg

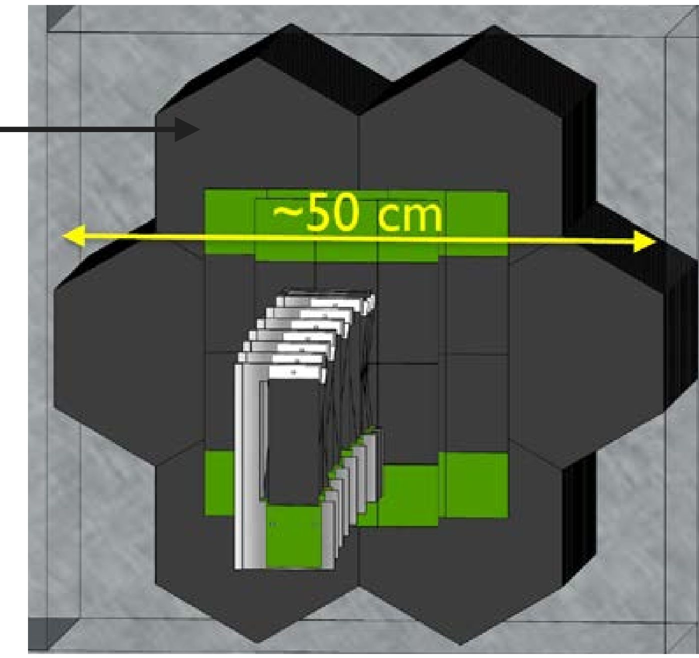


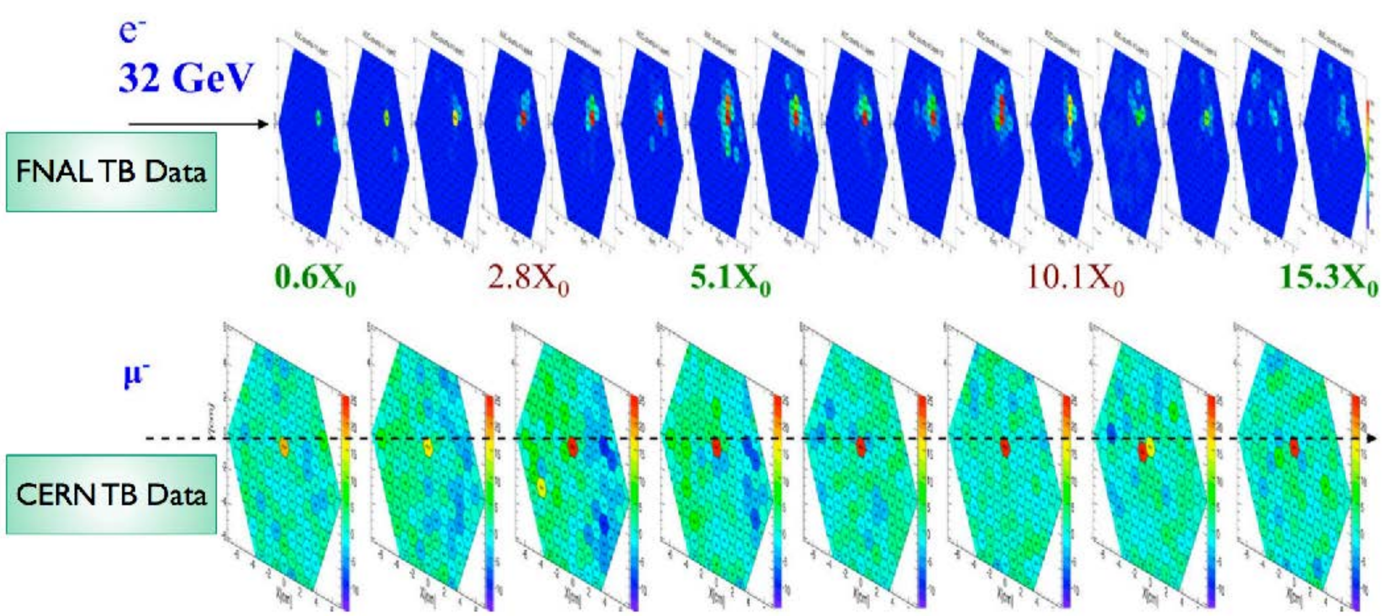
Tagging tracker efficiently rejects beam backgrounds

Electromagnetic calorimeter

Draws on design of CMS high granularity endcap calorimeter upgrade

- Si/W sampling calorimeter
- Fast, dense, radiation hard
- 34 layers, each with 7 silicon modules, up to 432 pads/module
- ~40 X_0 deep for full shower containment

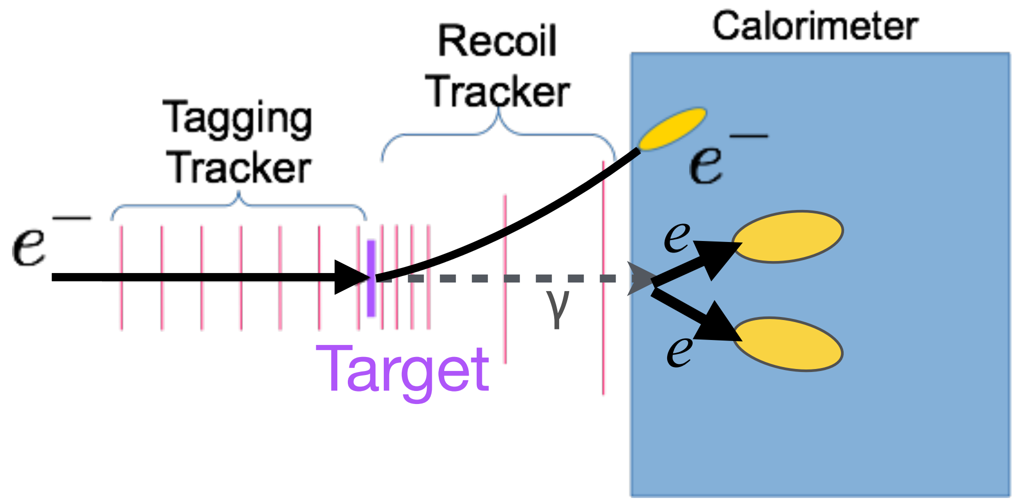


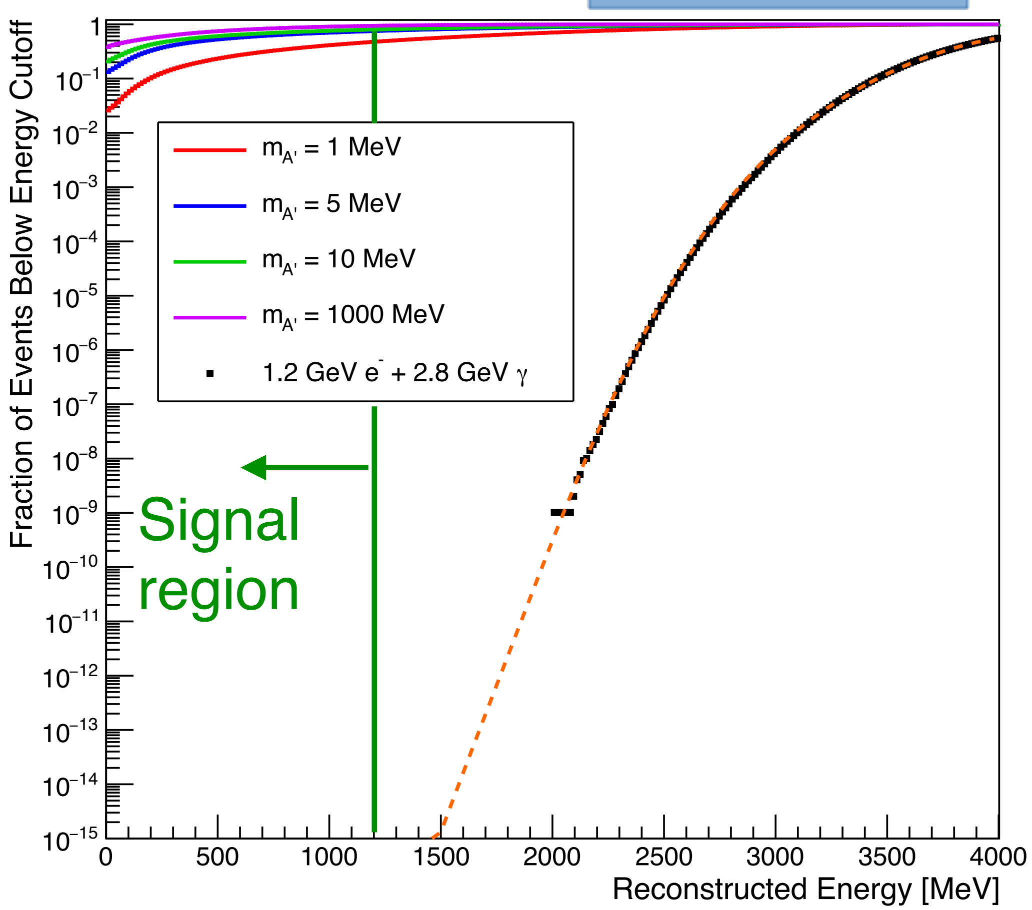


Capabilities

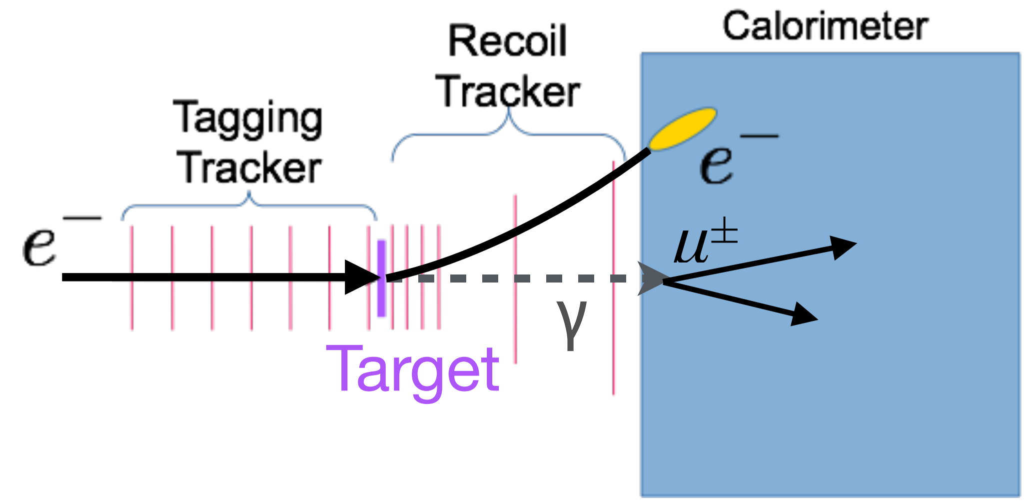
- Provides fast trigger: energy sum in first 20 layers, 3×10^3 bkg rejection for ~50-100% signal efficiency
- High granularity, both transverse and longitudinal shower shapes can be exploited to reject background
- Capable of MIP tracking to further improve background rejection

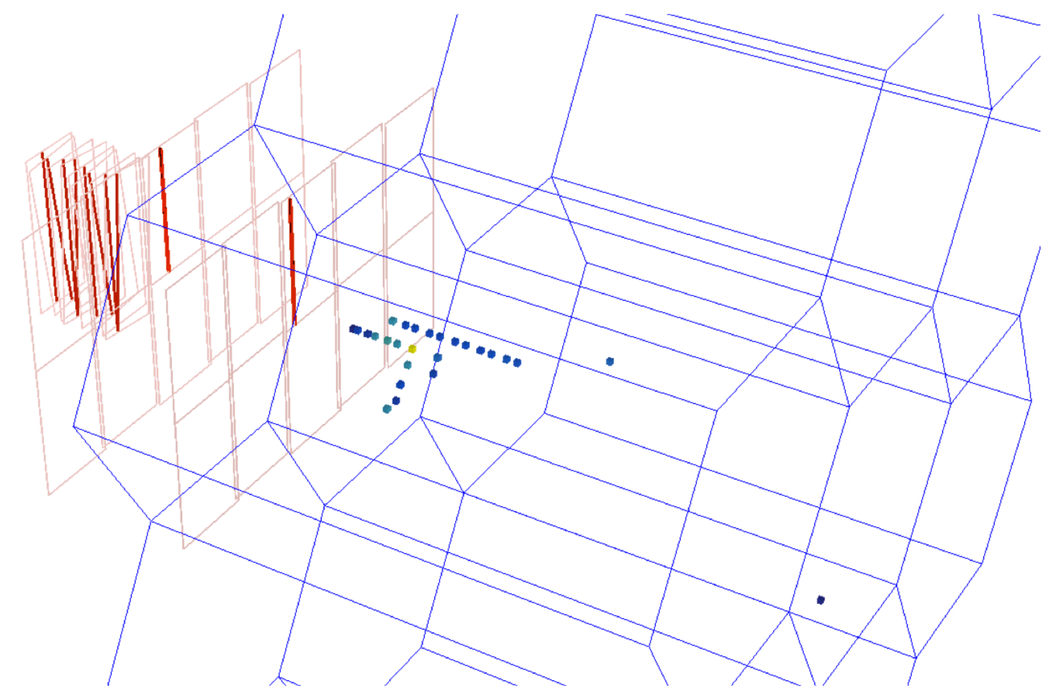
Electromagnetic calorimeter





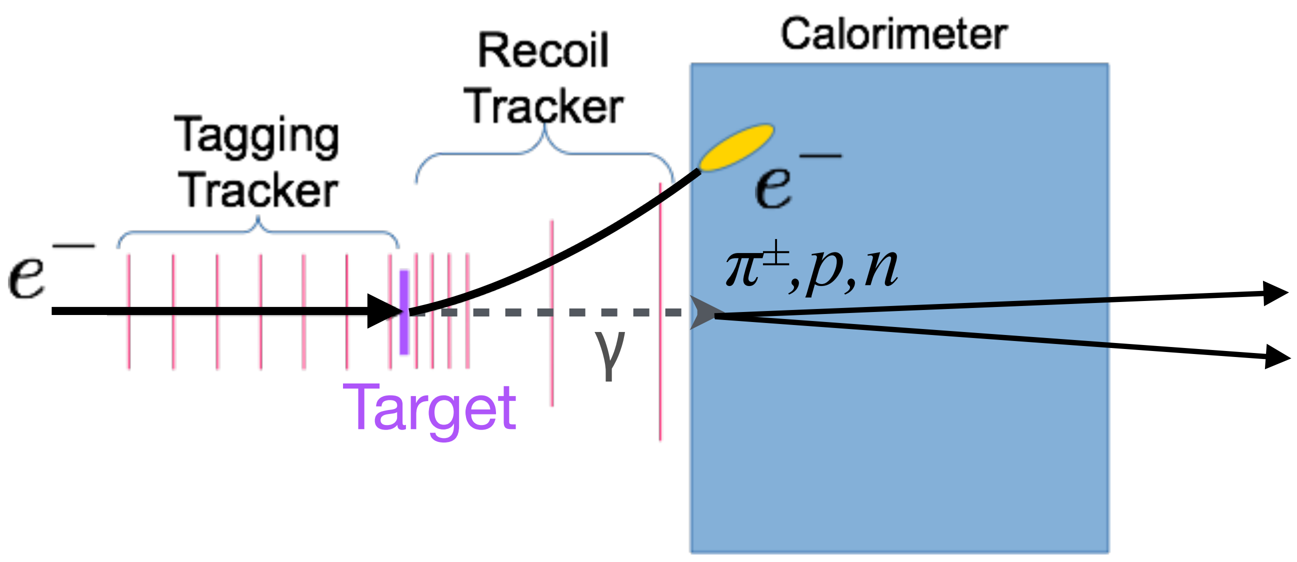
Bremsstrahlung background
(1.2 GeV e^- + 2.8 GeV γ)

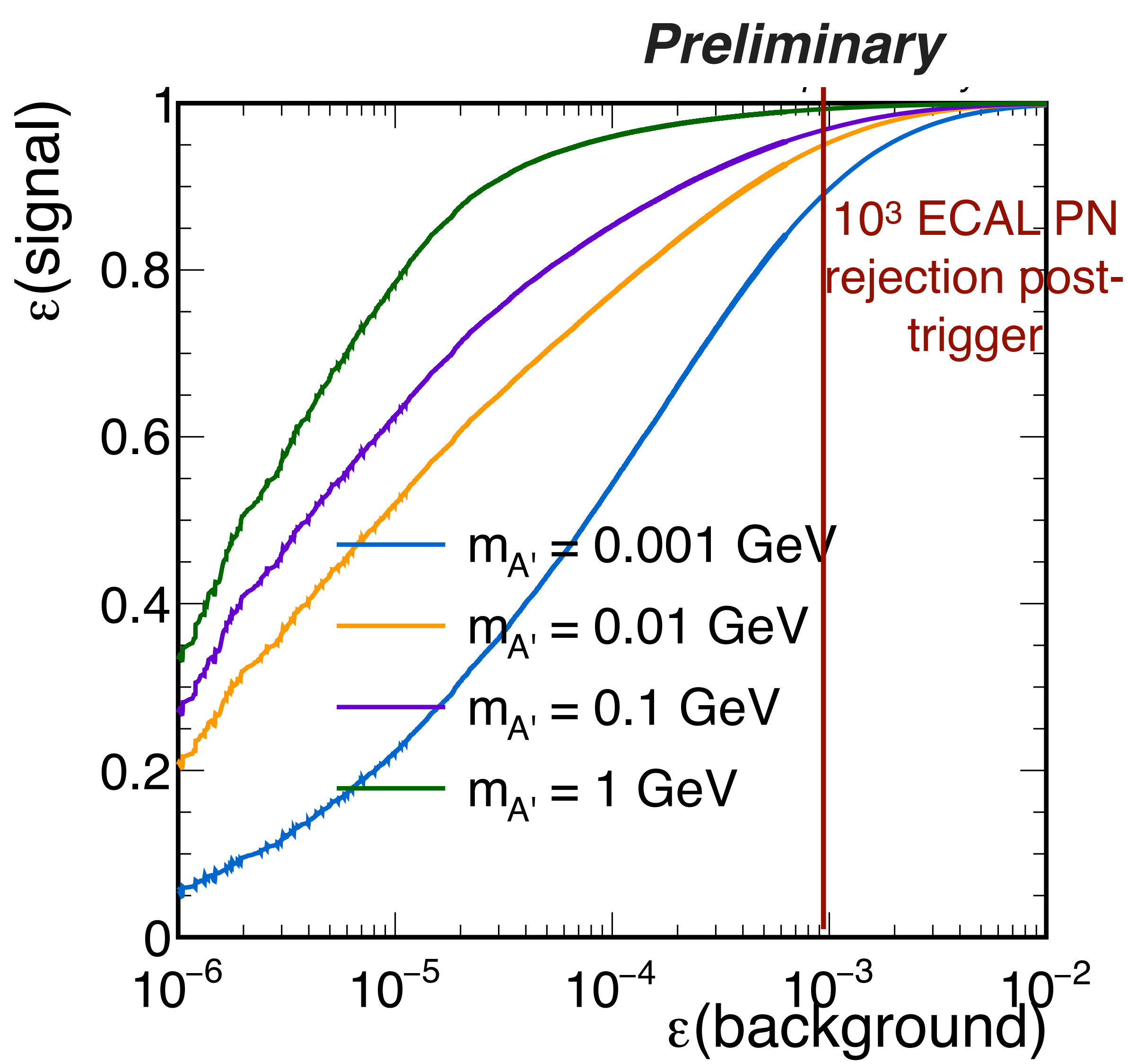




$\gamma^* \to \mu^+\mu^-$ event contained in ECAL
(soft μ^+, μ^- decay-in-flight)

ECAL BDT





ECAL veto based on boosted decision tree optimized to reject ECAL photo-nuclear (PN) background

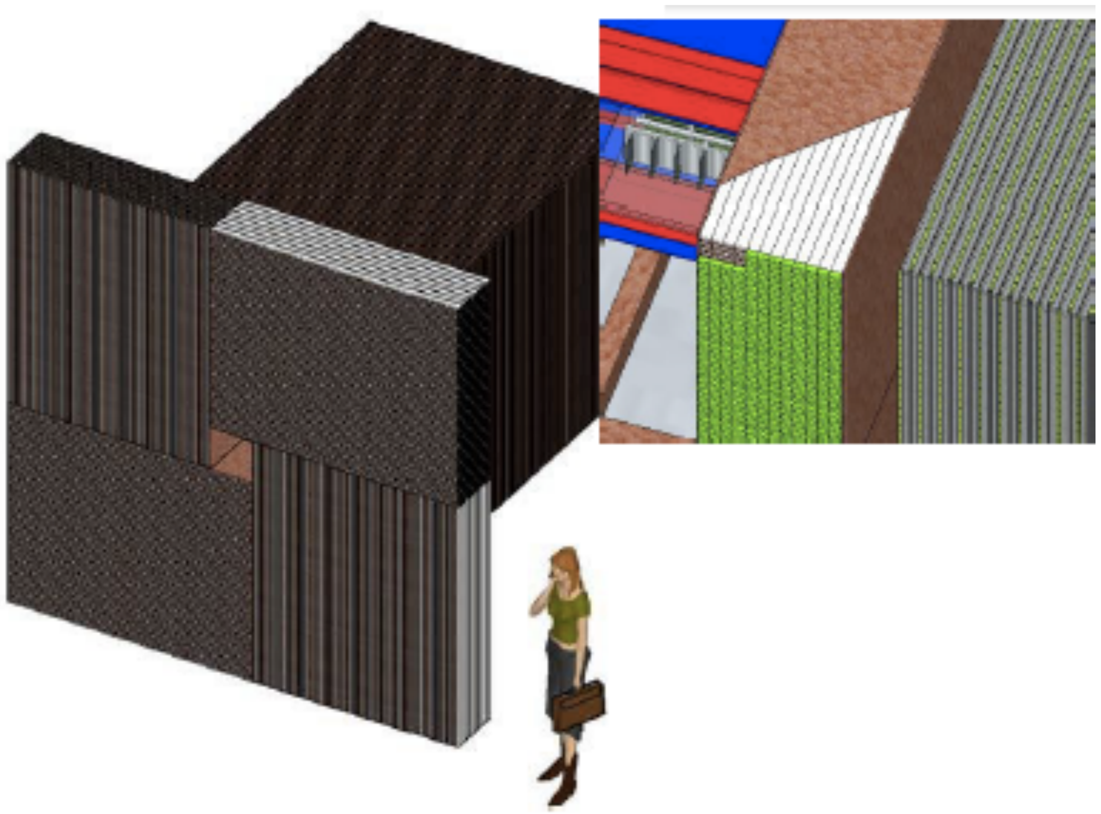
- Information related to energy deposition, transverse and longitudinal shower shapes, shower containment regions
- Provides additional 10^3 rejection for ECAL PN events passing trigger for ~90-99% signal efficiency

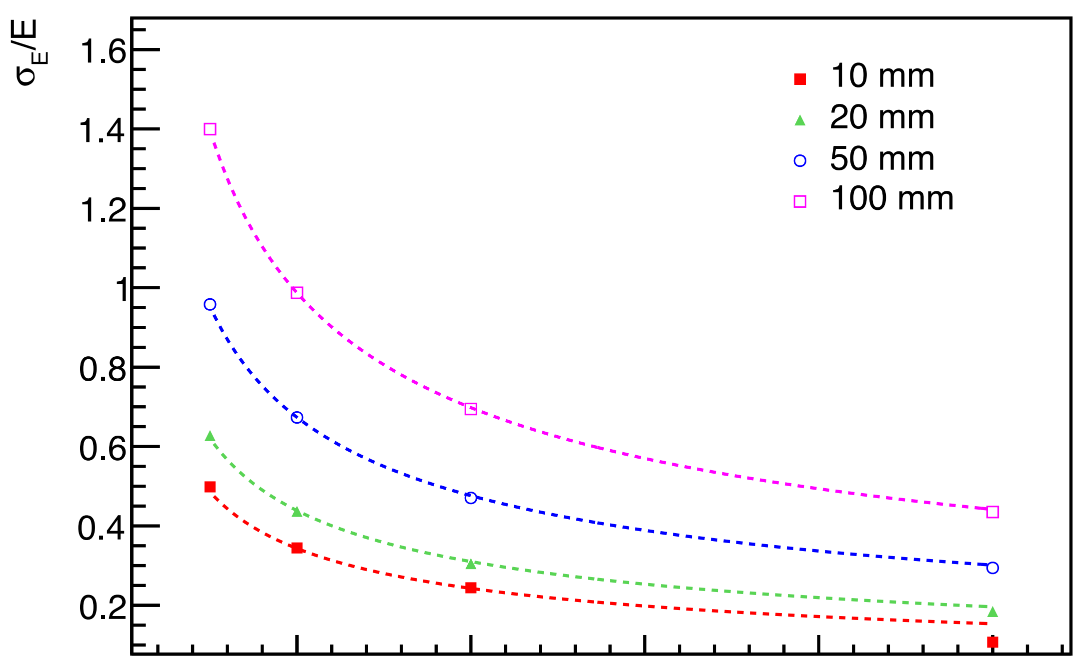
Hard-to-veto events: very little energy deposition from PN products in ECAL e.g. containing high-energy forward-going neutrons, need HCAL to veto

Hadronic calorimeter

Based on Mu2e Cosmic Ray Veto technology

- Steel/plastic scintillator sampling calorimeter
- Plastic scintillator bars with WLS fibers read out by SiPM, steel absorber
- Surrounds ECAL as much as possible





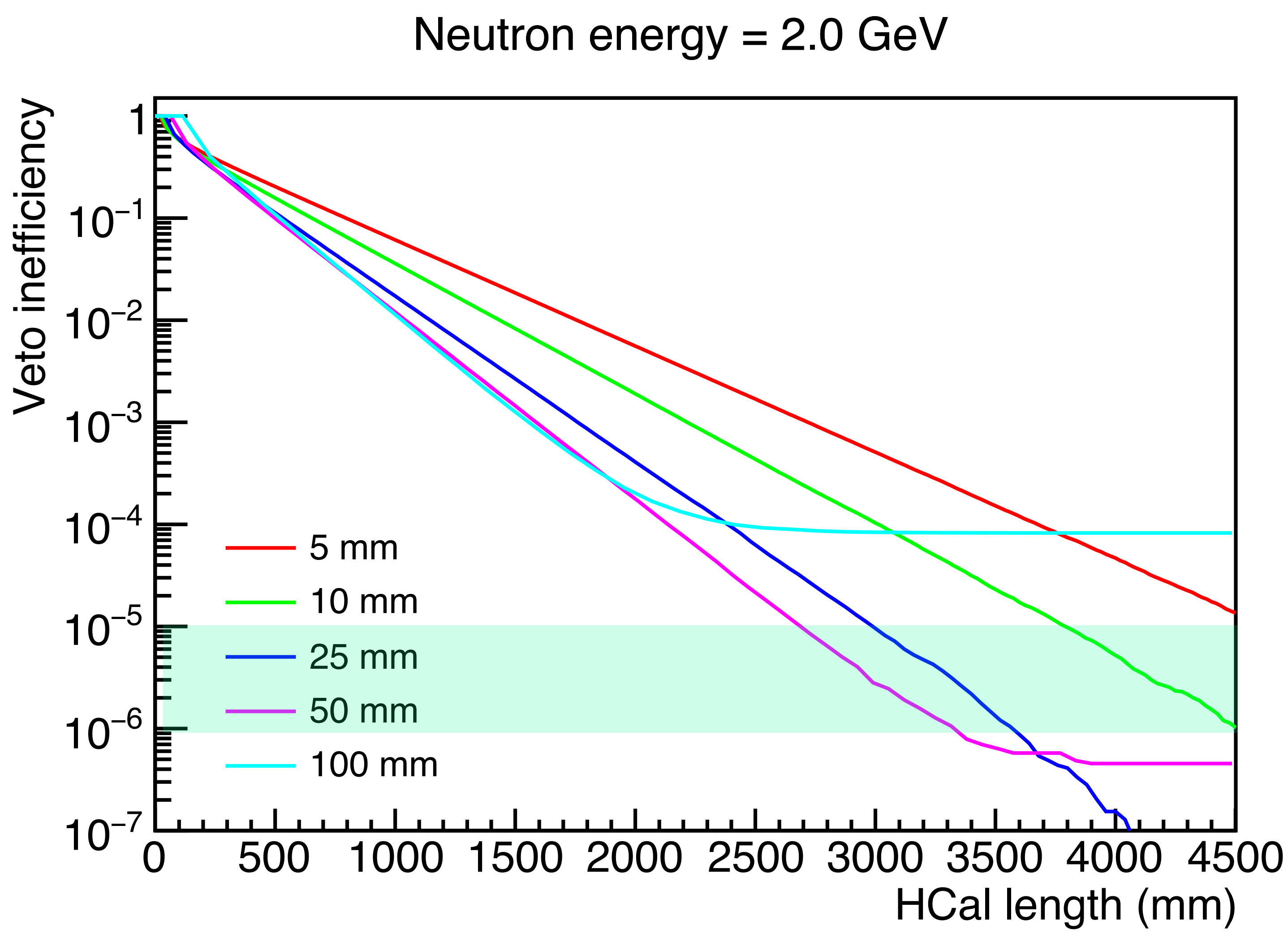
Preliminary studies indicate good energy resolution

Capabilities

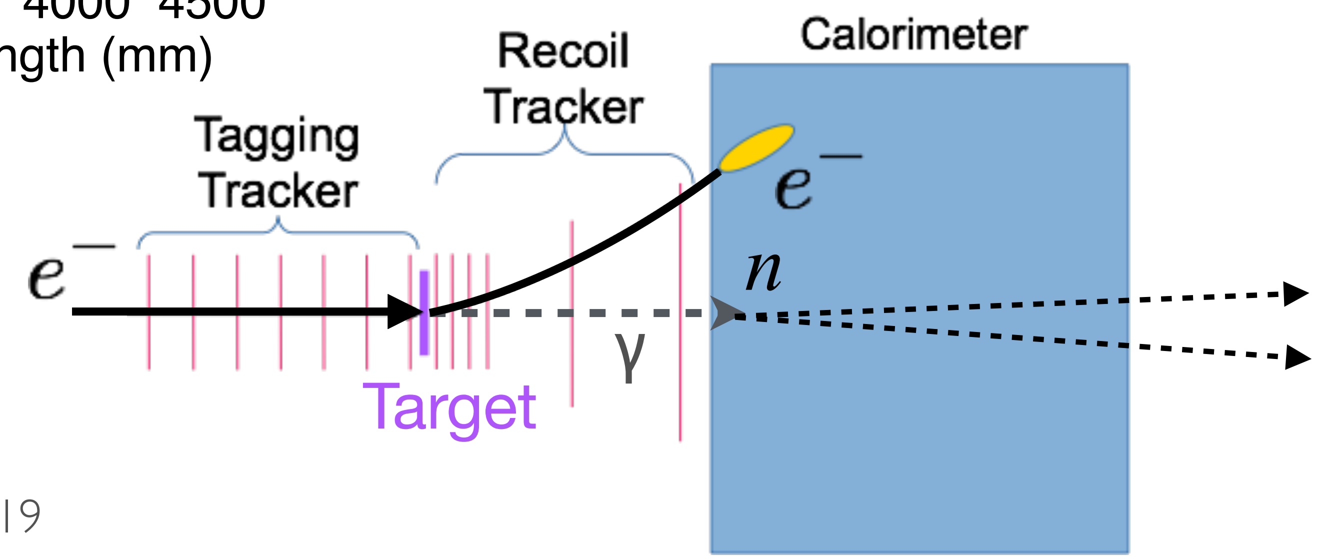
- Highly efficient veto for photonuclear events producing low- or high-energy hadrons
- Also catches wide-angle bremsstrahlung
- Strong rejection for $\gamma \rightarrow \mu^+\mu^-$

Hadronic calorimeter

Single neutron veto inefficiency vs HCAL depth
for different sampling fractions

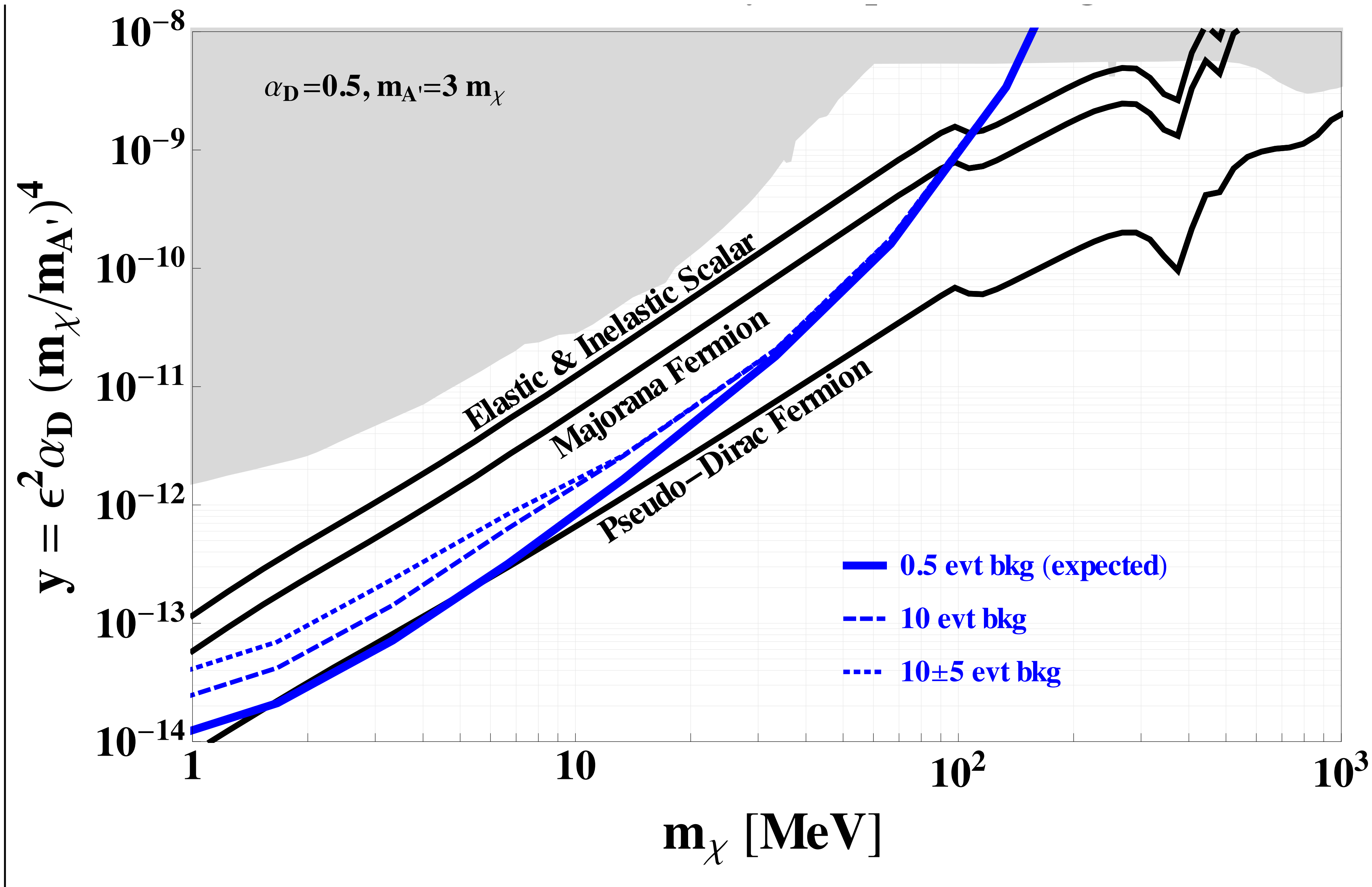


Veto on HCAL activity used to reject background events that survive tracker, ECAL vetoes



LDMX sensitivity with 4x10^{14} EoT

Sensitivity with 4x10^{14} electrons on target @ 4 GeV

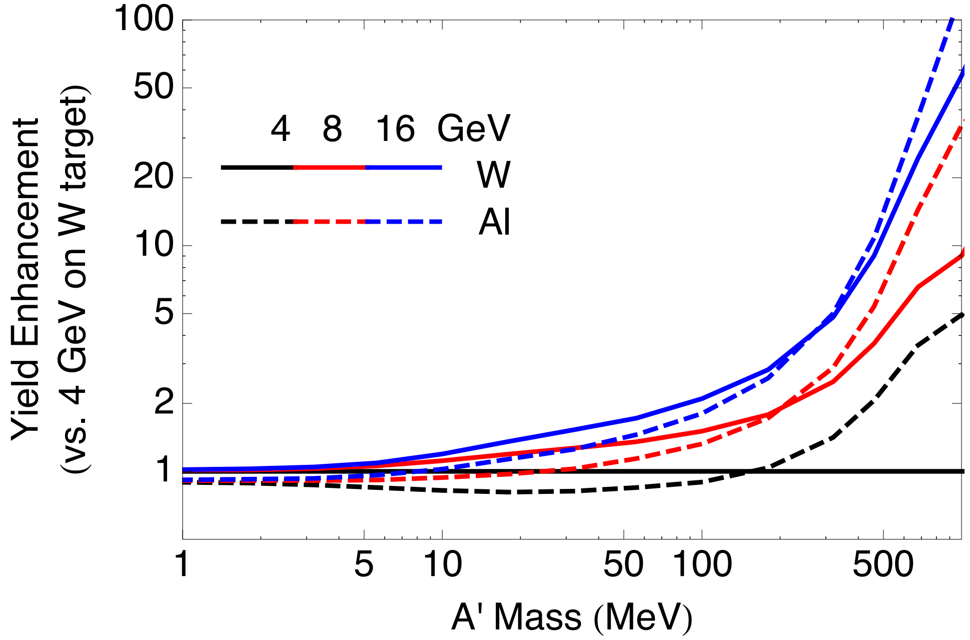


Sensitivity extends past scalar and majorana fermion targets below 100 MeV

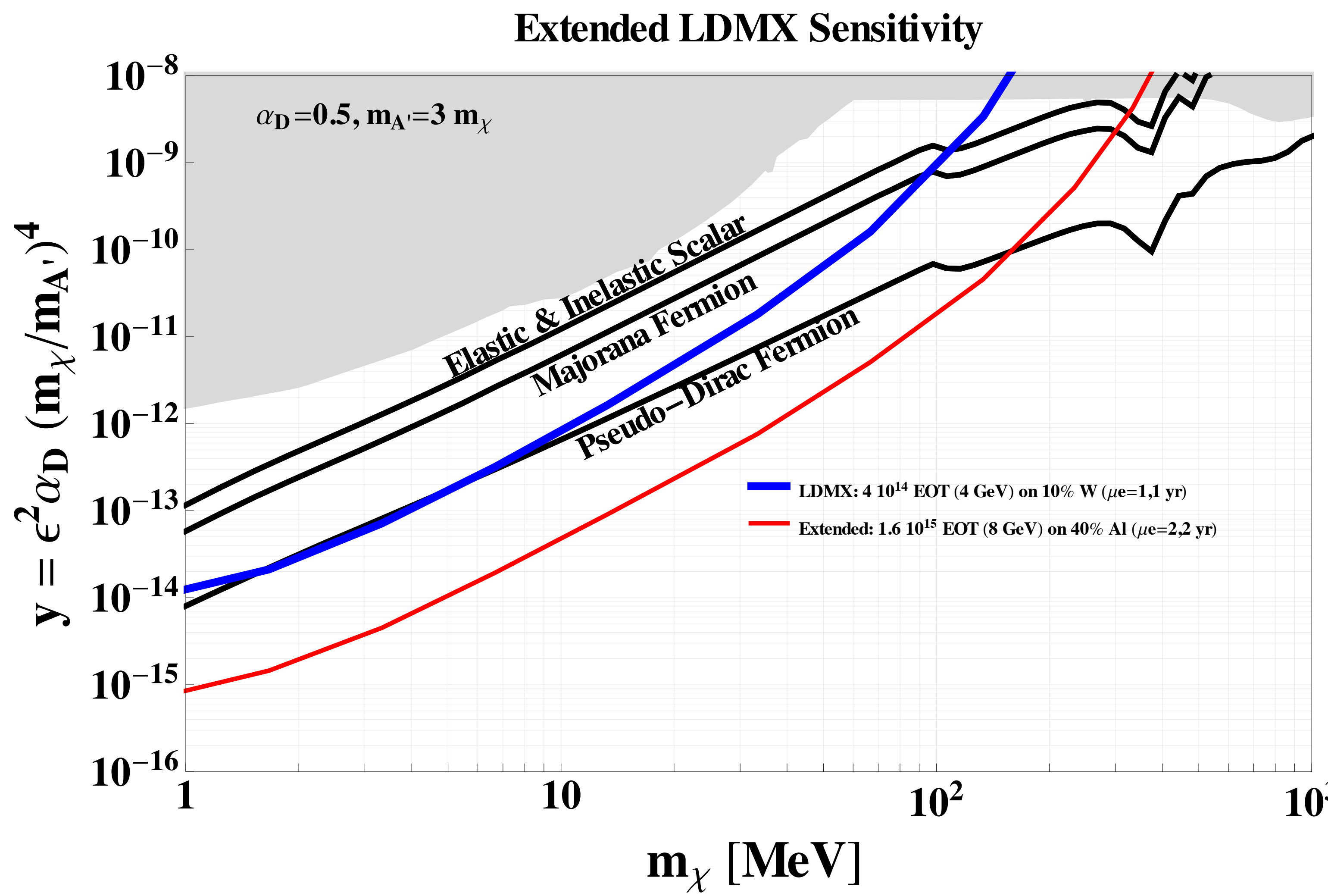
Detailed analysis in arXiv:1808.05219

Full LDMX sensitivity

Strategies to improve initial reach: higher beam energies, change target density/thickness



At higher energy, reduced fraction of hard-to-reject events (e.g. hard single neutron) → potential for lower background



Extend sensitivity past pseudo-Dirac target up to 100 MeV

Detailed analysis in arXiv:1808.05219

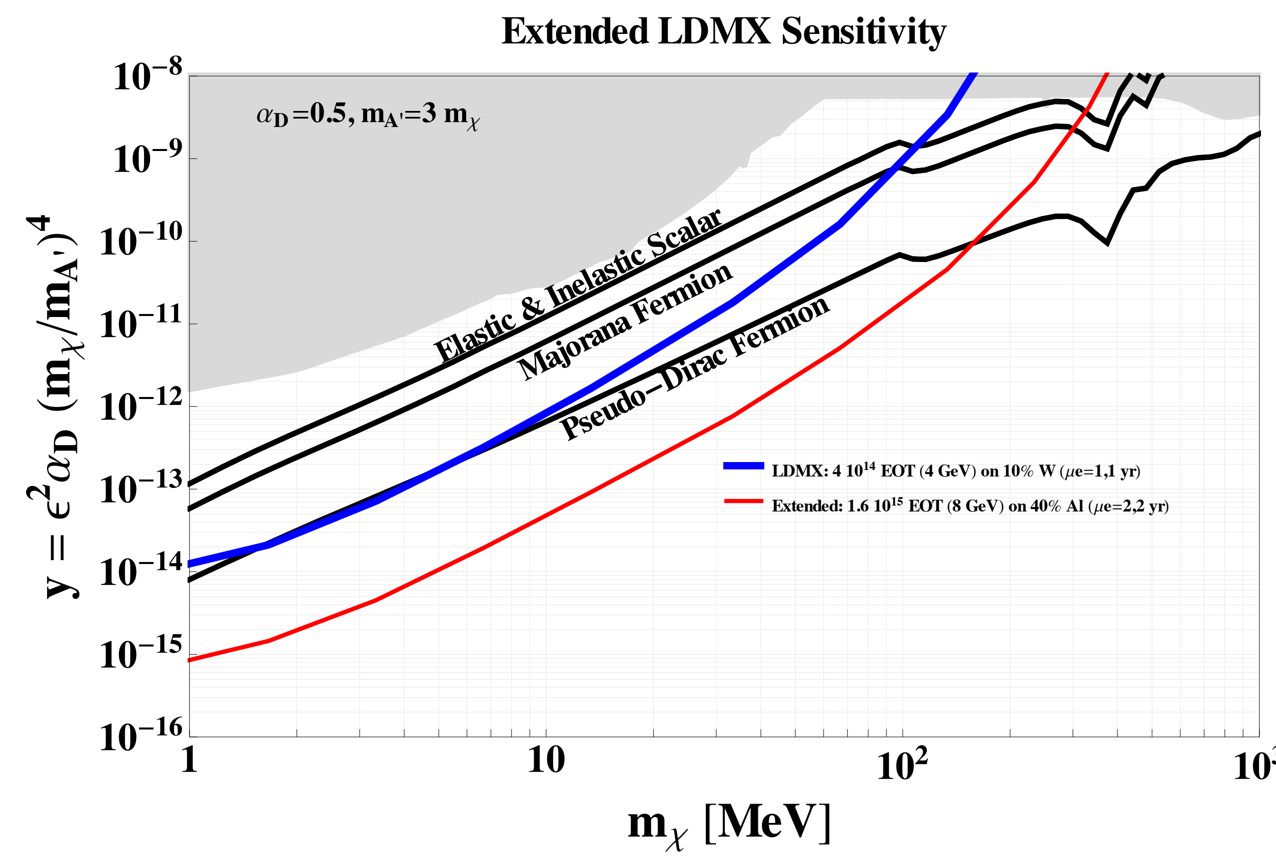
Summary

Accelerator-based experiments have unique capabilities in the search for light dark matter

- Missing energy/momentum experiments provide best sensitivity per luminosity

LDMX can probe all thermal targets over most of the MeV-GeV mass range

- Broad physics potential[1]
- Can also be used for photonuclear and electonuclear measurements
- Can be realized within the next decade!

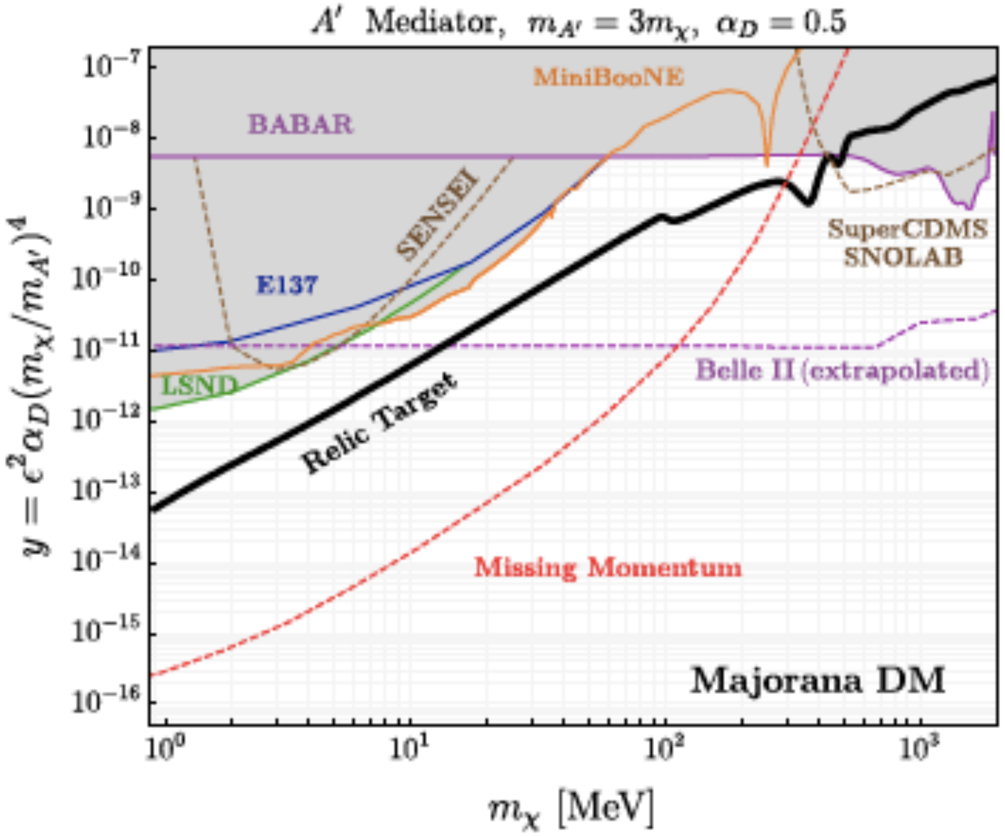


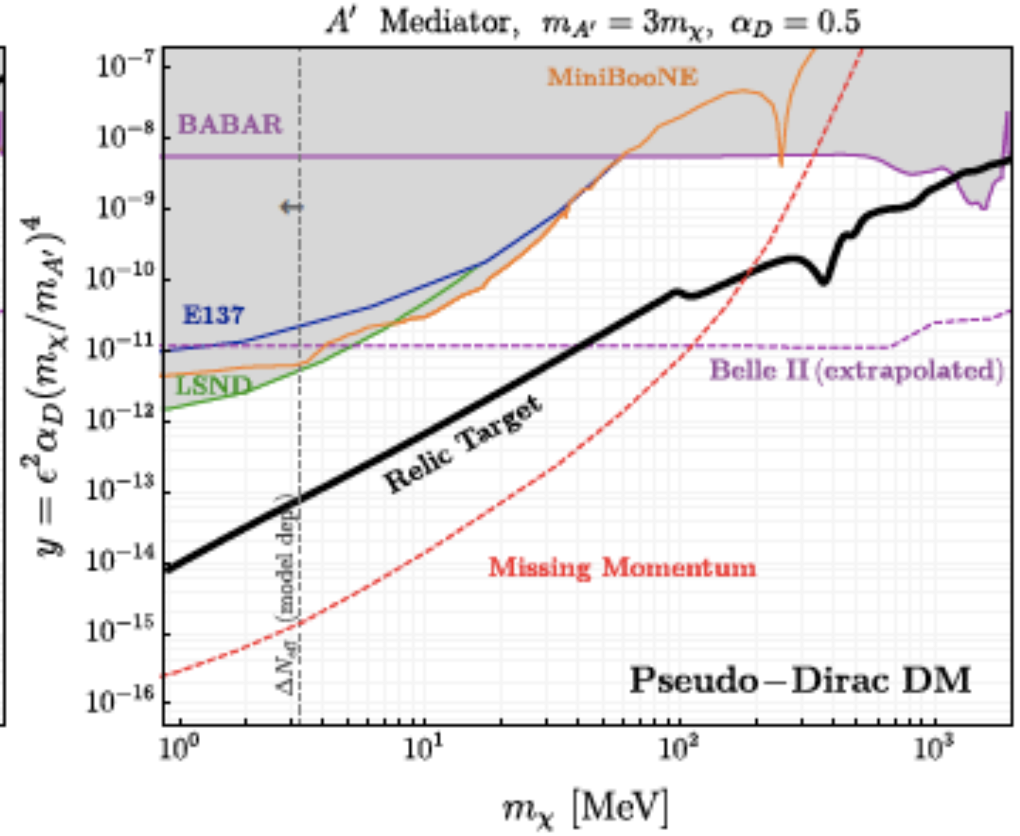
[1]Also sensitive to

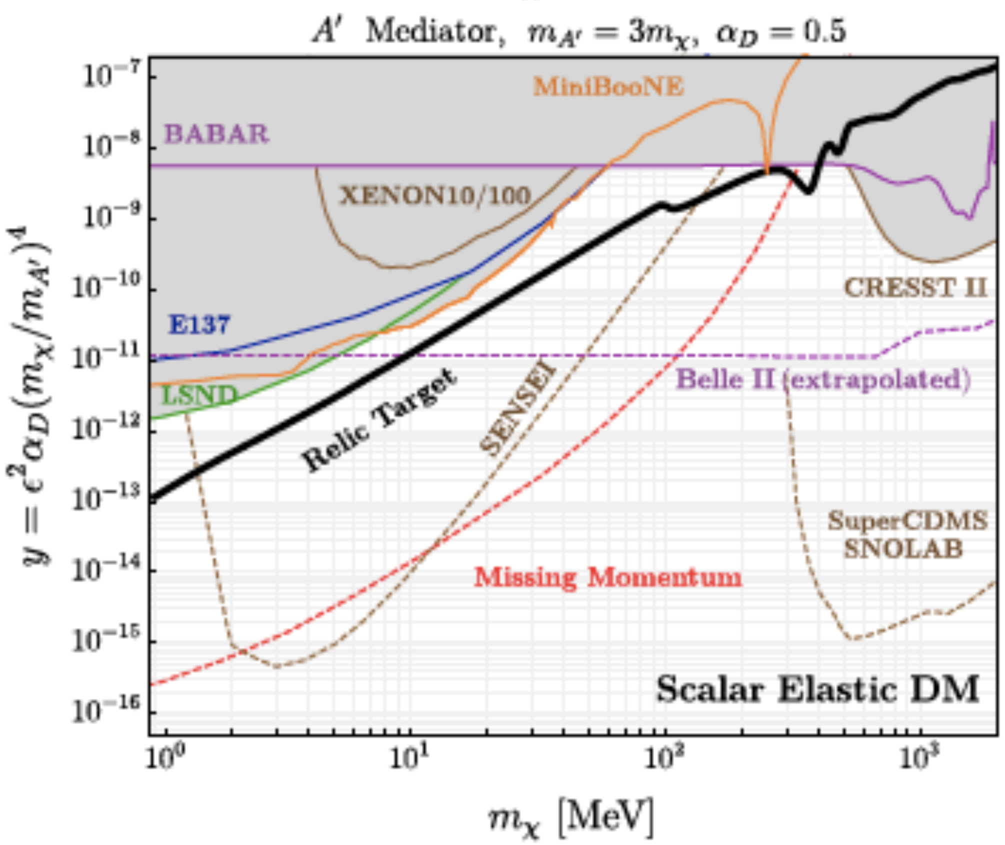
- DM with quasi-thermal origin (asymmetric DM, SIMP/ELDER scenarios)
- new invisibly decaying mediators in general
- displaced vertex signatures from DM co-annihilation or SIMP model
- axion-like particles
- milli-charged particles

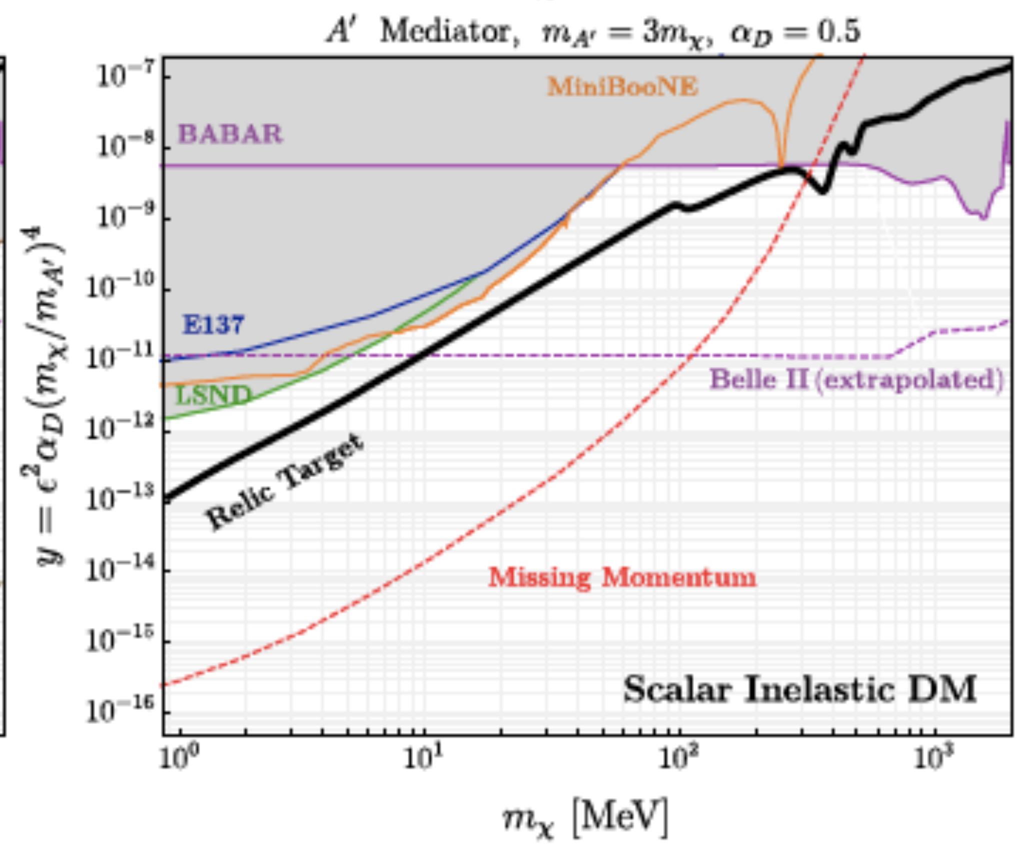
Additional Material

Missing momentum reach

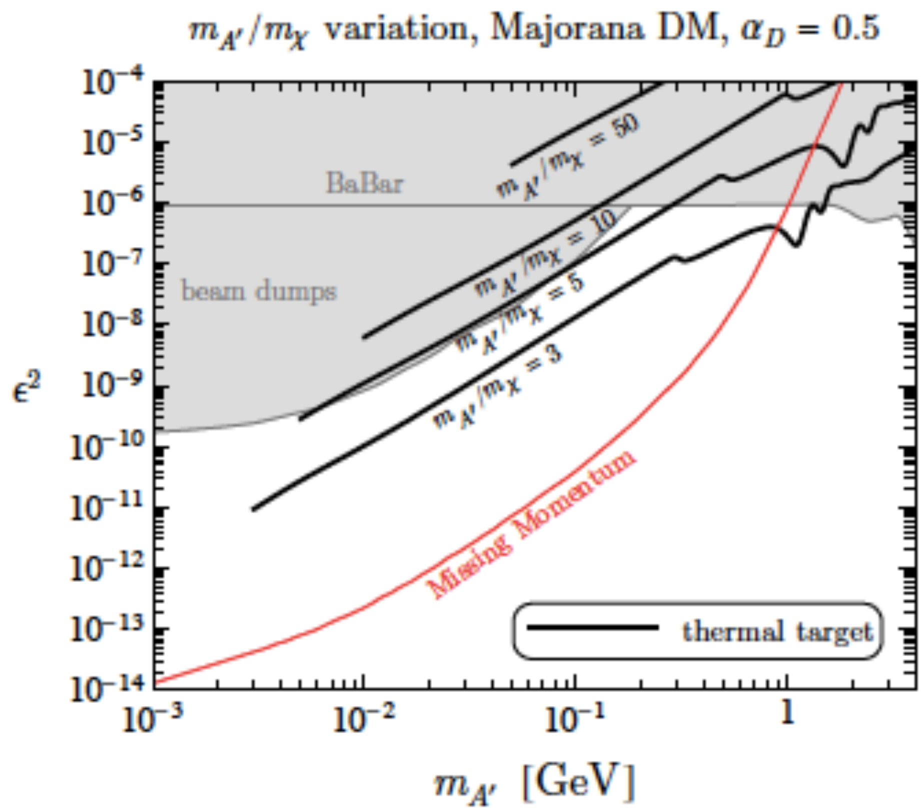


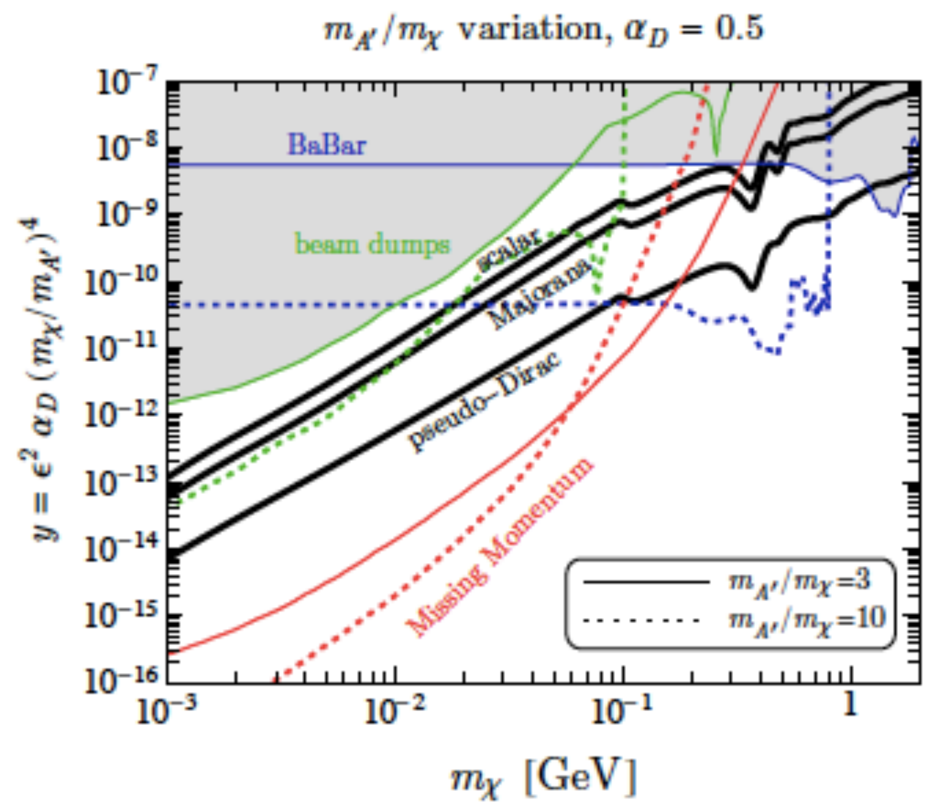


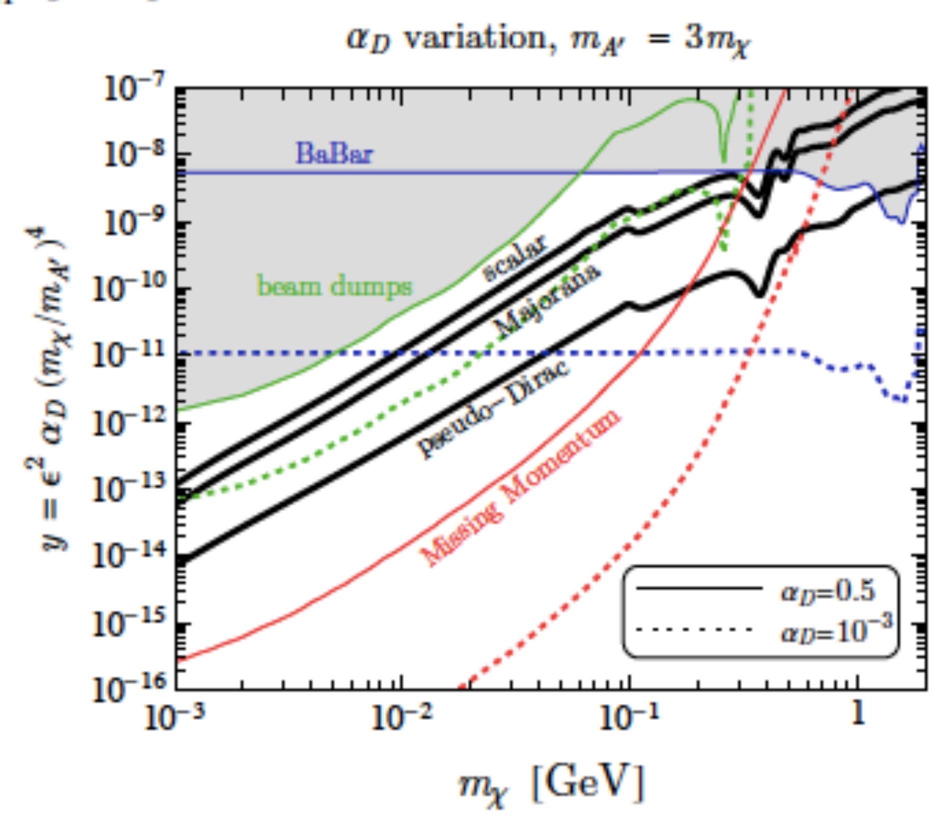




Parameter dependence

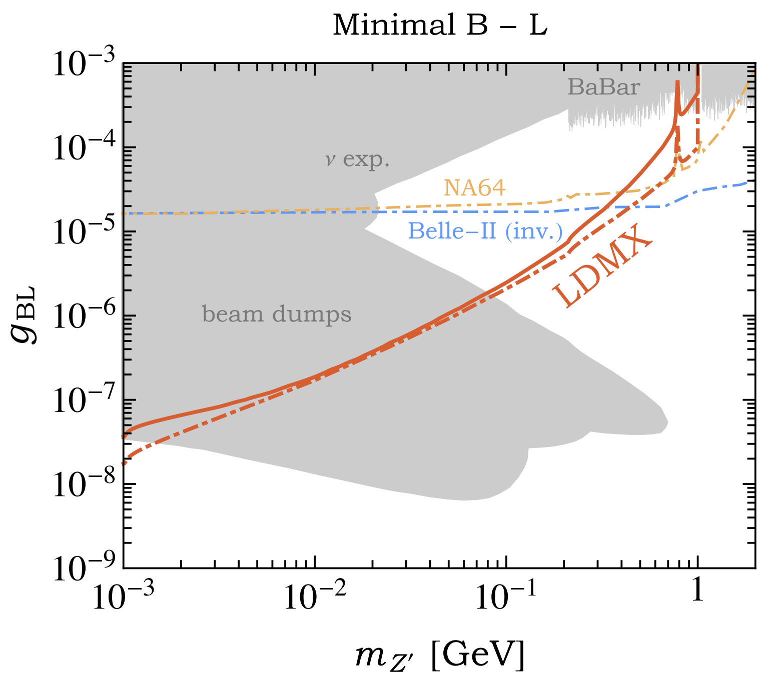


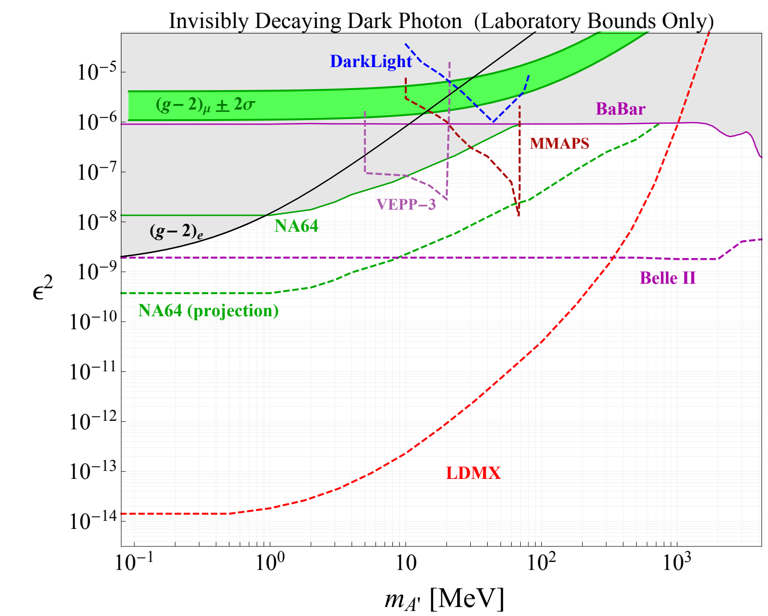


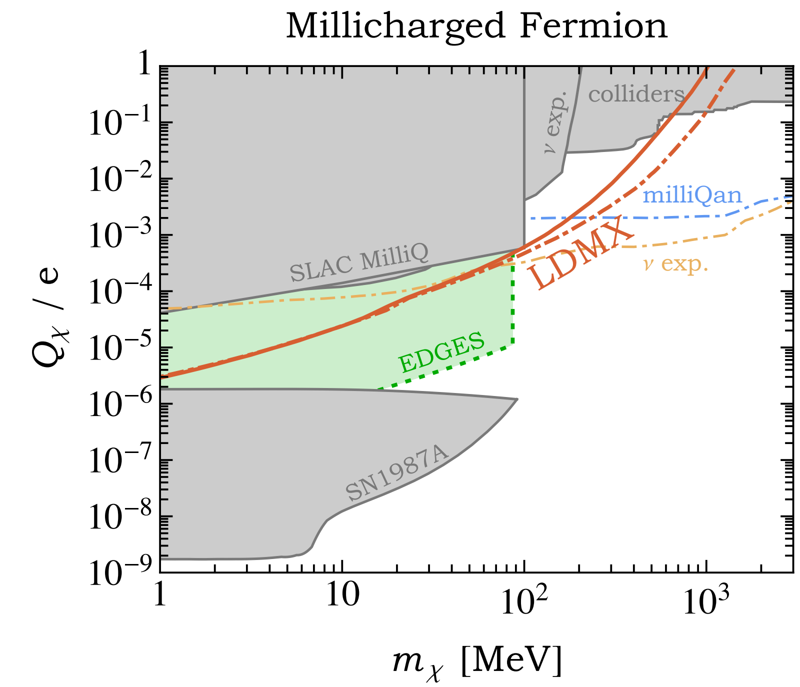


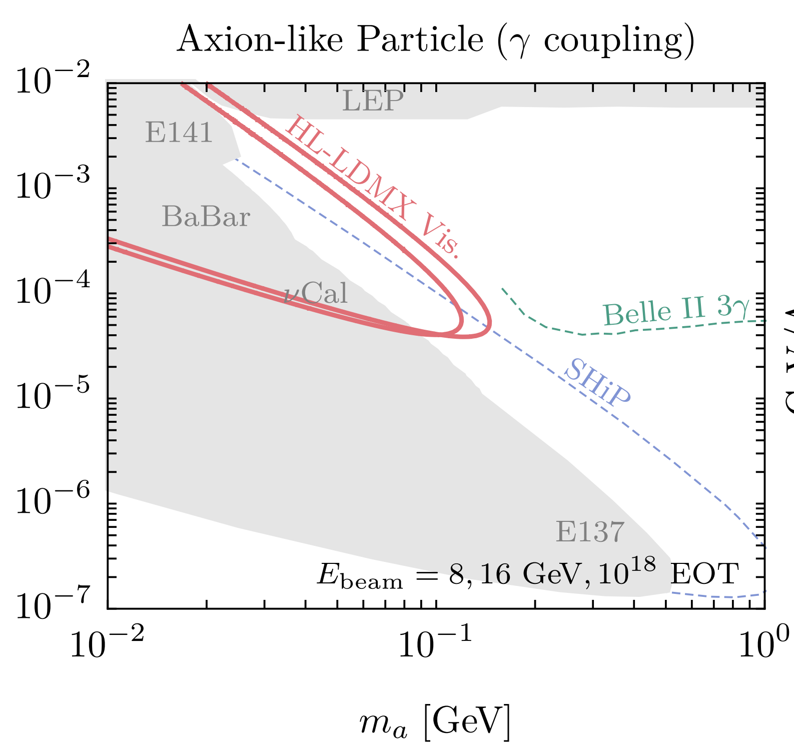
LDMX potential

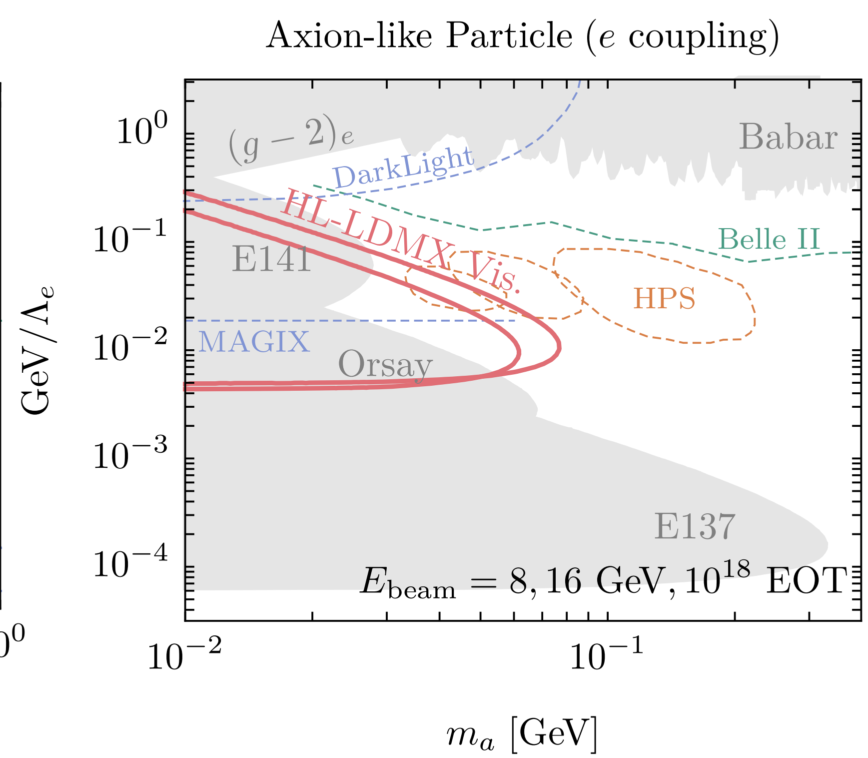
arXiv:1807.01730

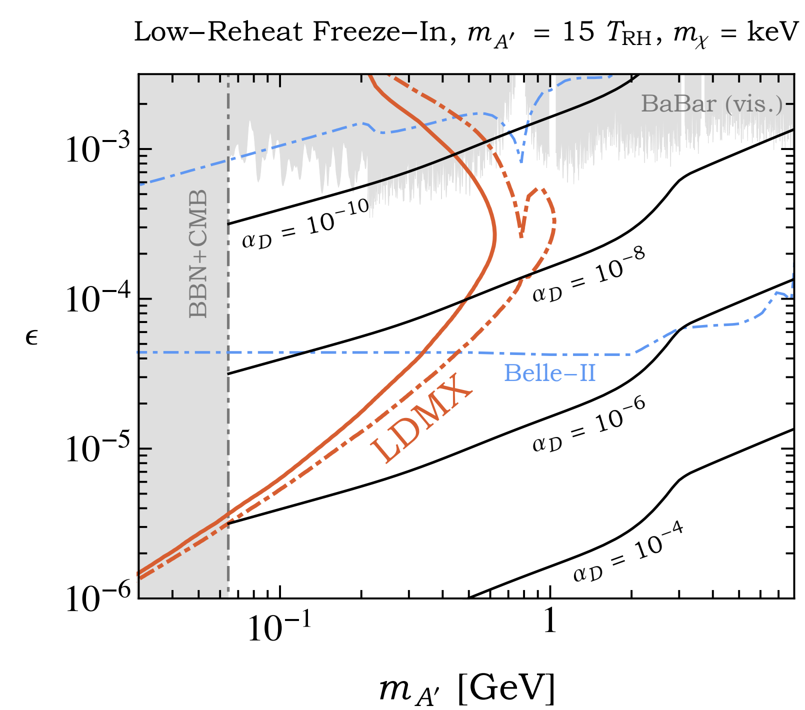




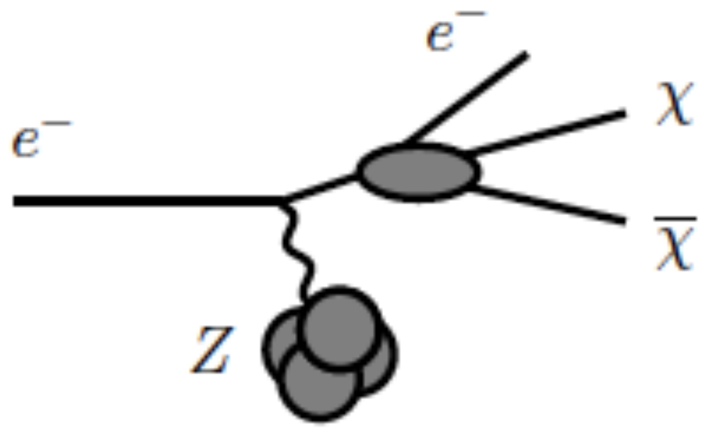




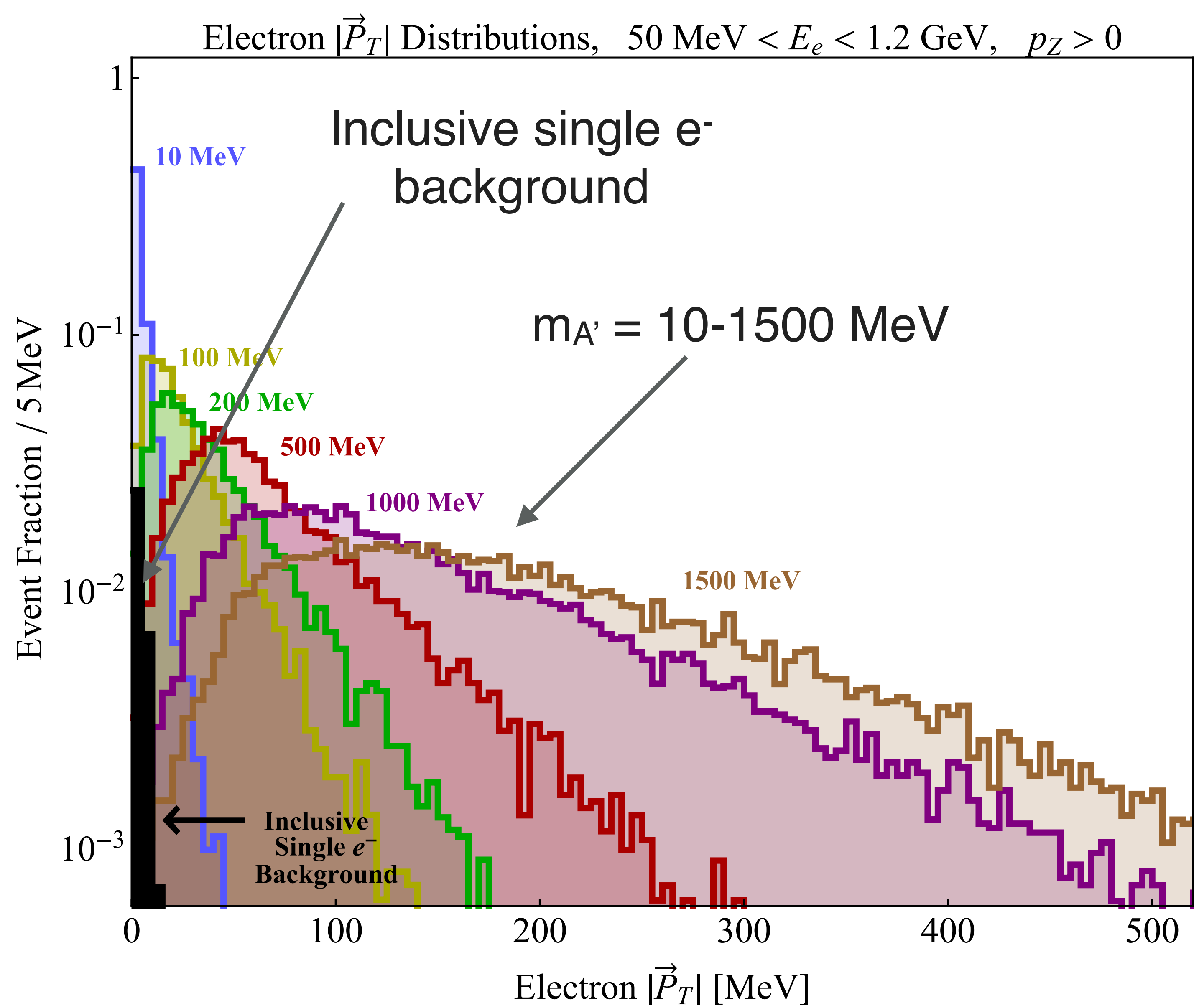




DM production kinematics



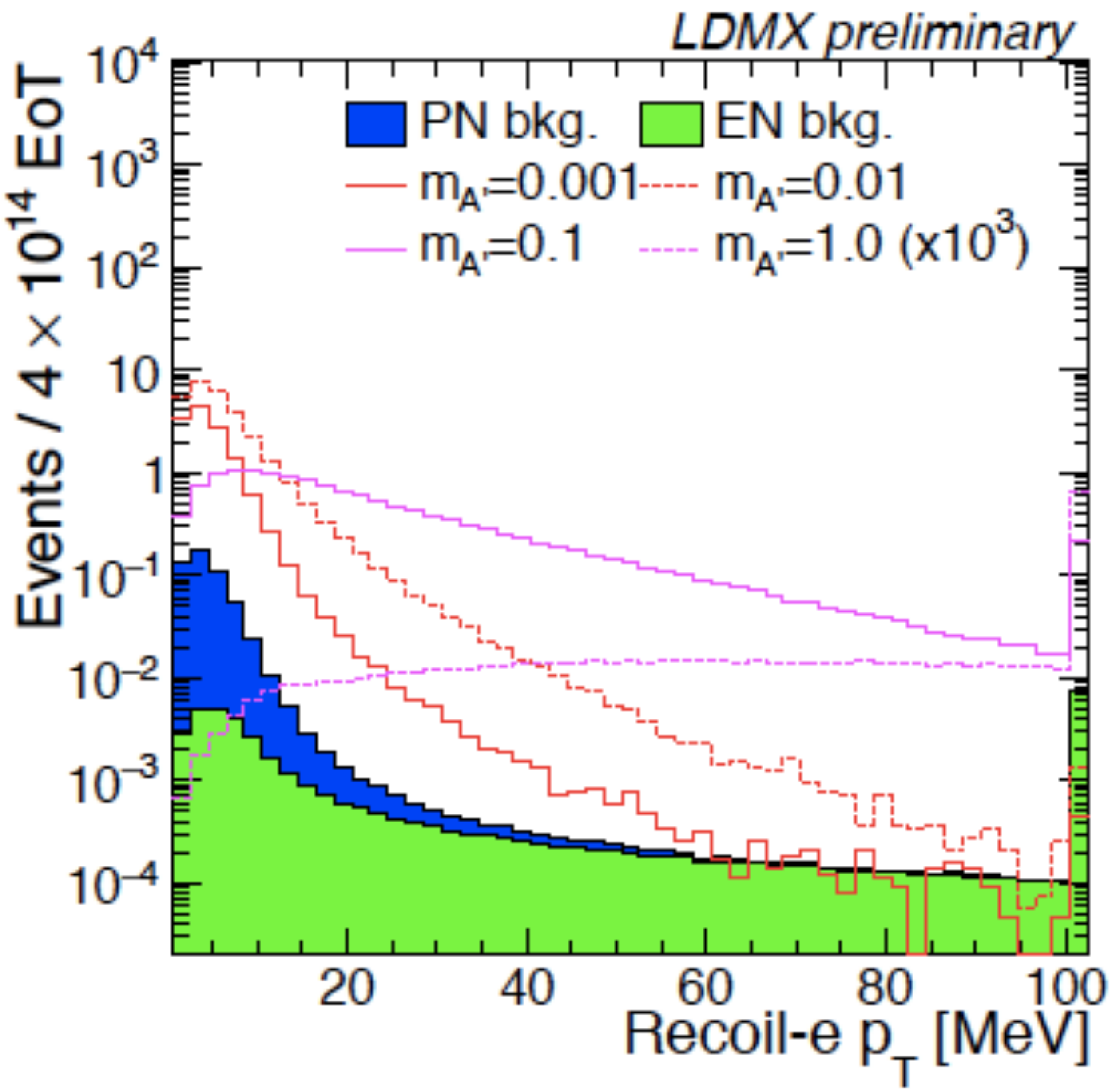
Recoil e⁻ p_T also a strong signal discriminator, depends on A' mass



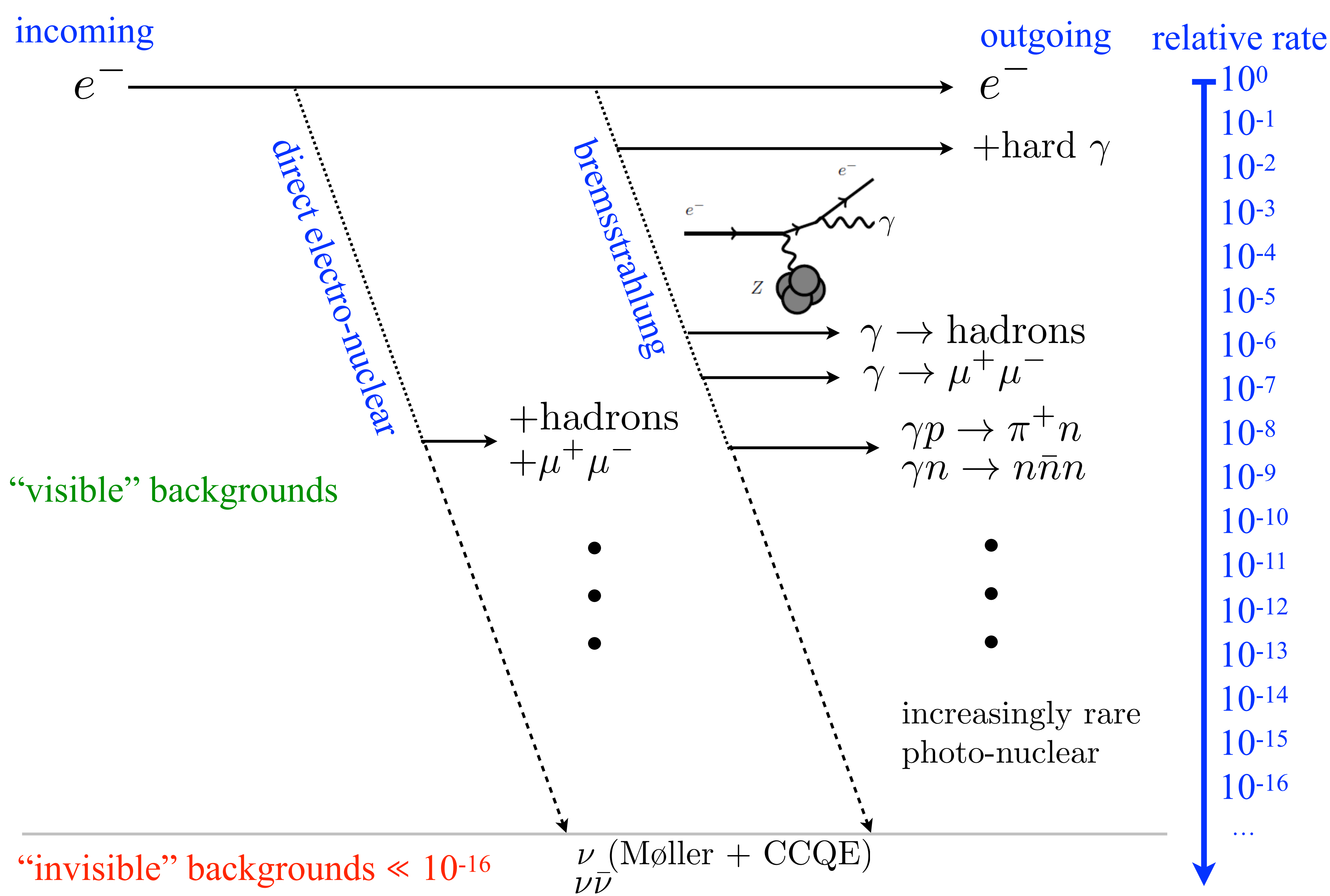
Signal characteristics

- A' takes most of the beam energy
- Recoil electron soft, at wide angles —> large missing momentum

Signal and background p_T



Backgrounds



Background rejection summary

Hard bremsstrahlung (E_e < 1.2 GeV) followed by photonuclear (PN) reaction in target or ECAL

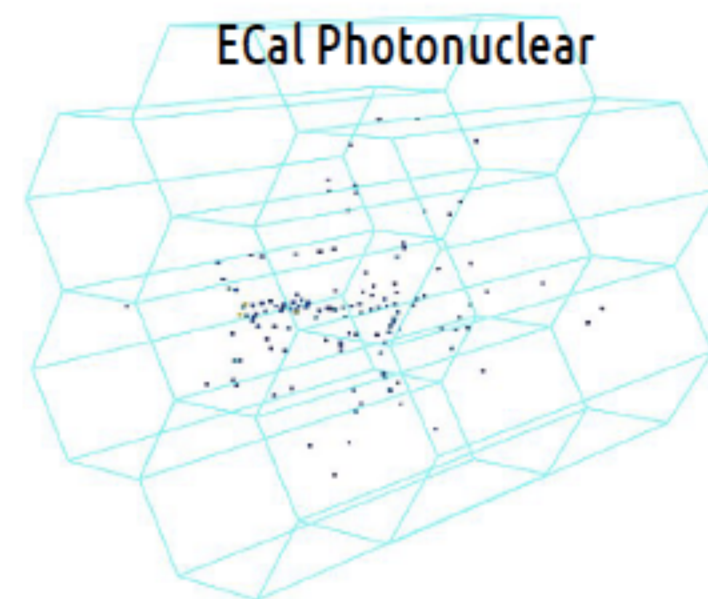
- Wide range of hadronic final states, challenging cases with very little ECAL energy deposition
- Boosted decision tree (BDT) using ECAL observables used in combination with veto on HCAL activity
- Tracking provides further handles to reject target PN

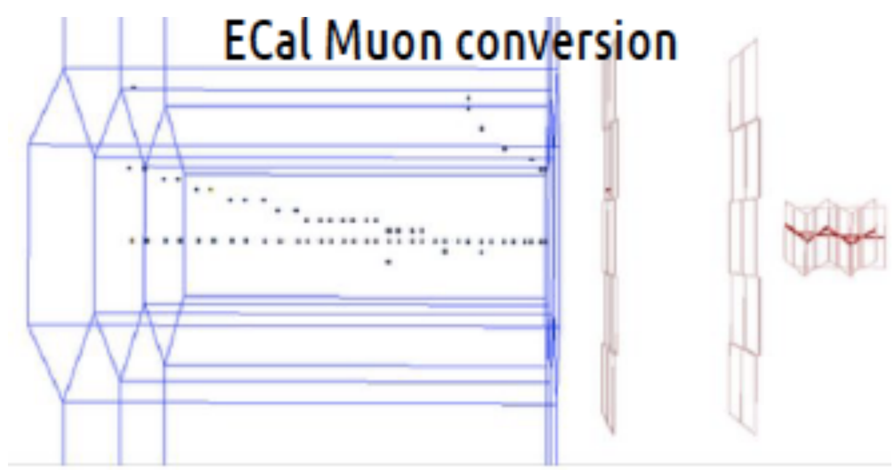
Electronuclear (EN) interactions in target

- Similar composition to PN, similar rejection strategy as target PN

Photon conversions to muons

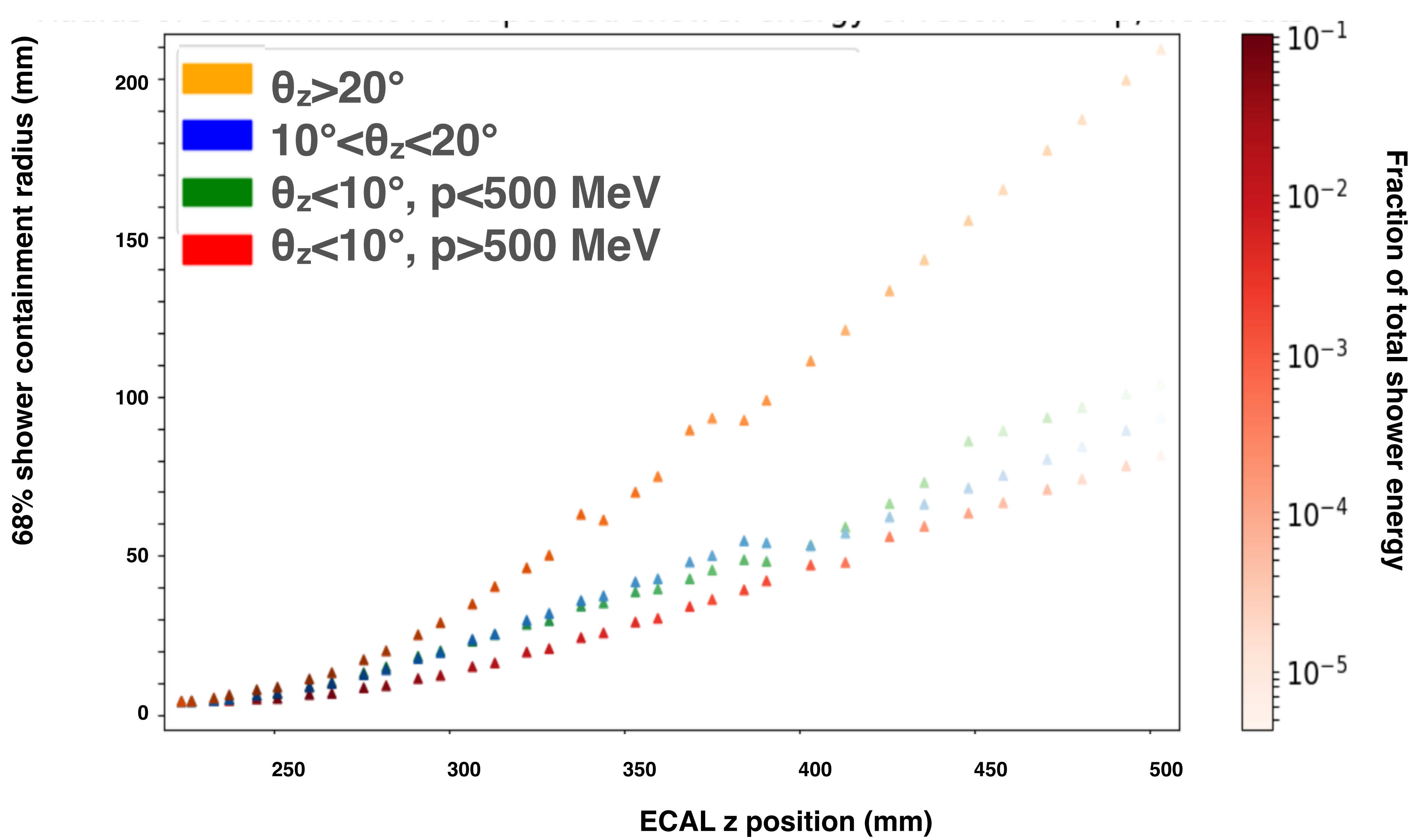
- Often leave MIP tracks in HCAL, can be vetoed based on HCAL activity
- ECAL MIP tracking and energy deposition can help to reject muons that decay or range out in ECAL



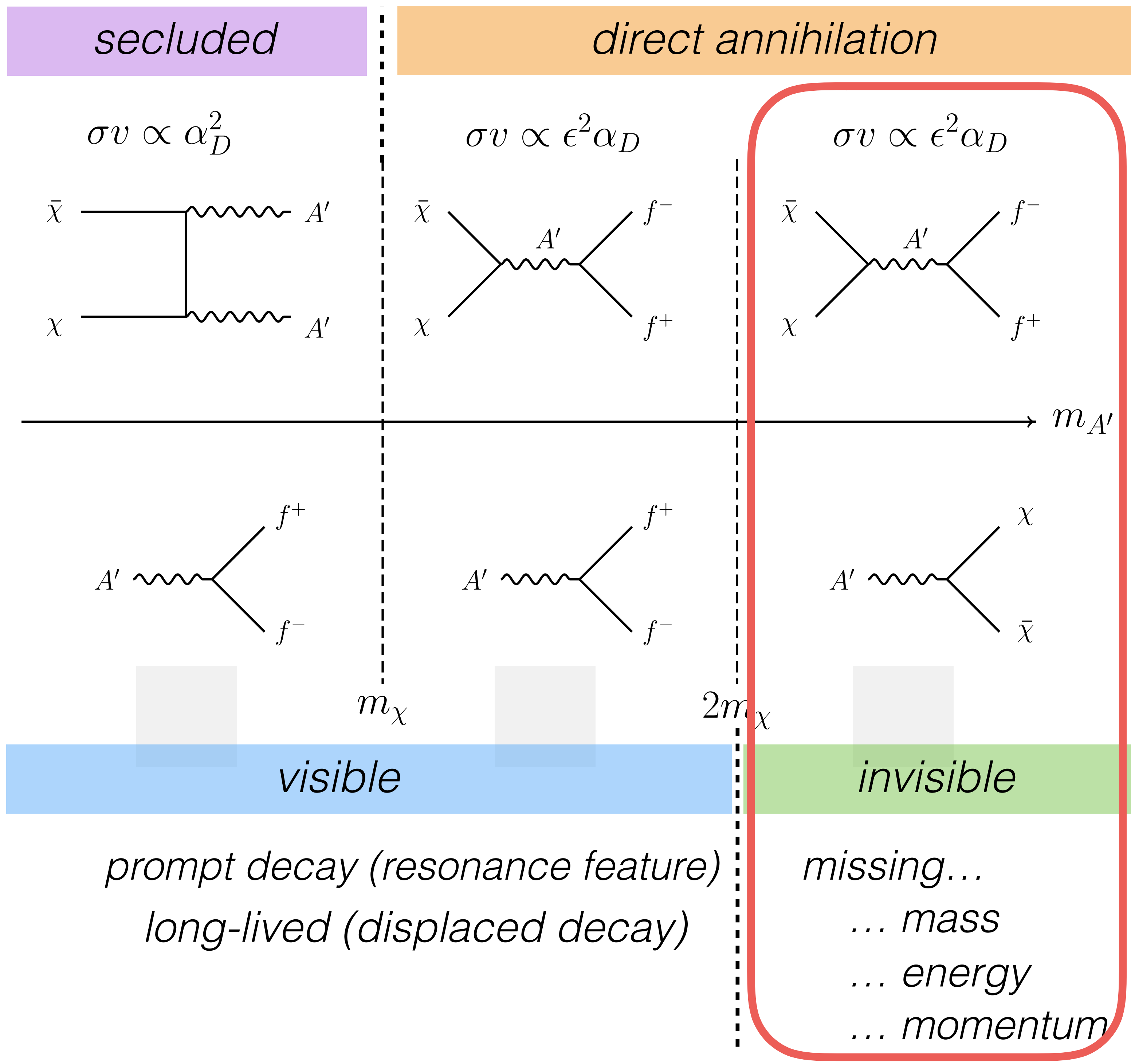


ECAL BDT

Improved discrimination by identifying expected shower containment regions using tracking and expected shower size vs depth



Signatures



secluded
direct annihilation
$\sigma v \propto \alpha_D^2$
$\sigma v \propto \epsilon^2 \alpha_D$
$\sigma v \propto \epsilon^2 \alpha_D$
$\bar{\chi}$
χ
A'
f^-
f^+
$m_{A'}$
m_χ
$2m_\chi$
visible
invisible
prompt decay (resonance feature)
long-lived (displaced decay)
missing…
… mass
… energy
… momentum