LDMX

The Light Dark Matter eXperiment

APS-DPF 2021

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

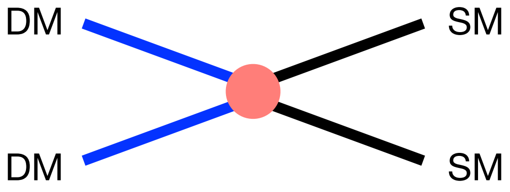
Caltech Fermilab Lund University SLAC Stanford University Texas Tech University UCSB University of Minnesota University of Virginia

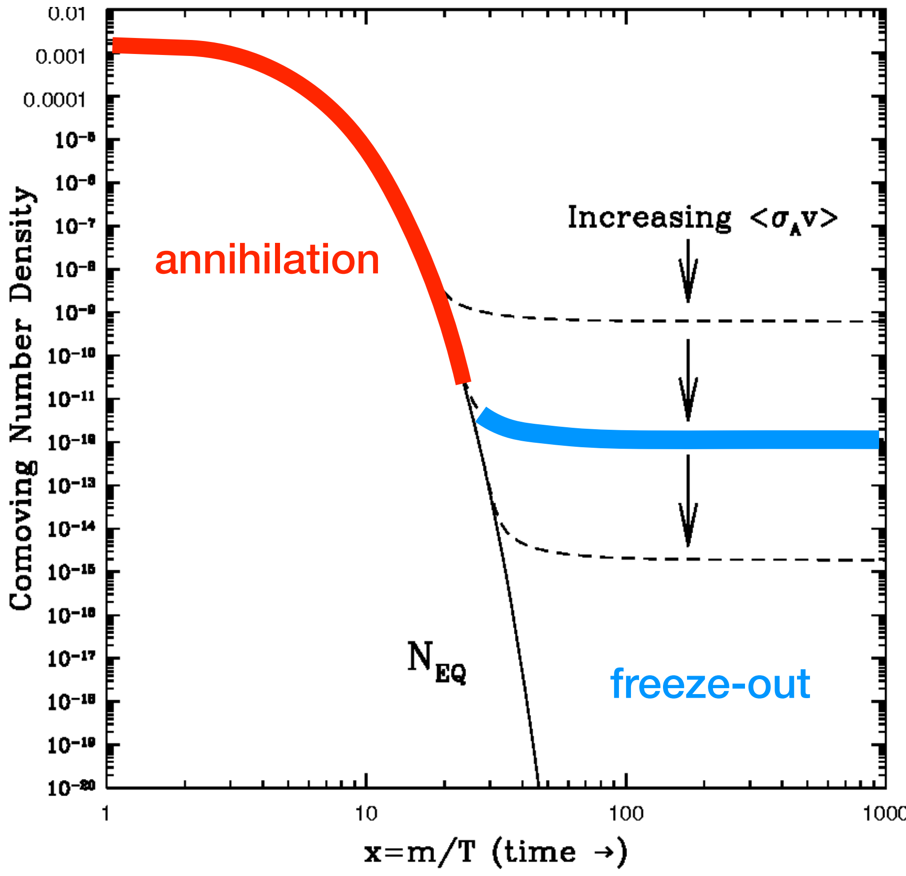
Thermal relic dark matter

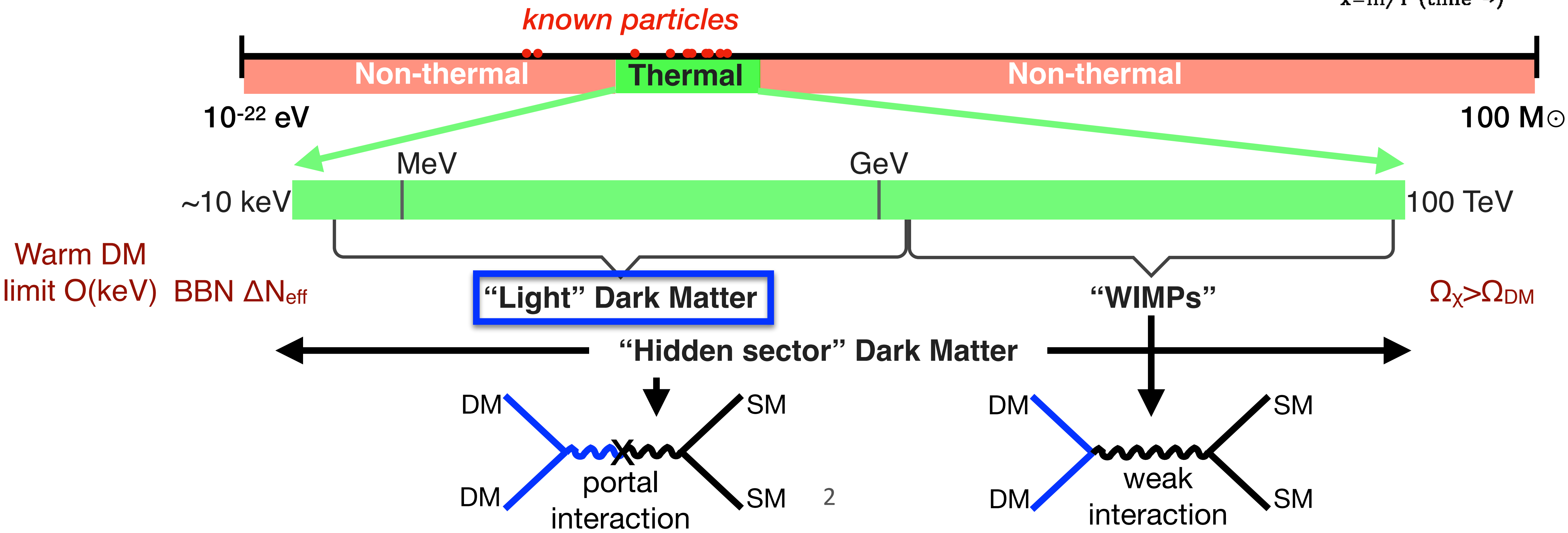
Simple and predictive explanation for origin of DM abundance

WIMPs have been a significant focus of experimental efforts so far

Active community effort to expand the program






known particles

Non-thermal **Thermal** **Non-thermal**

10^{-22} eV **100 M⊙**

MeV GeV

~10 keV 100 TeV

Warm DM limit O(keV) BBN ΔN_{eff}

“Light” Dark Matter

“WIMPs”

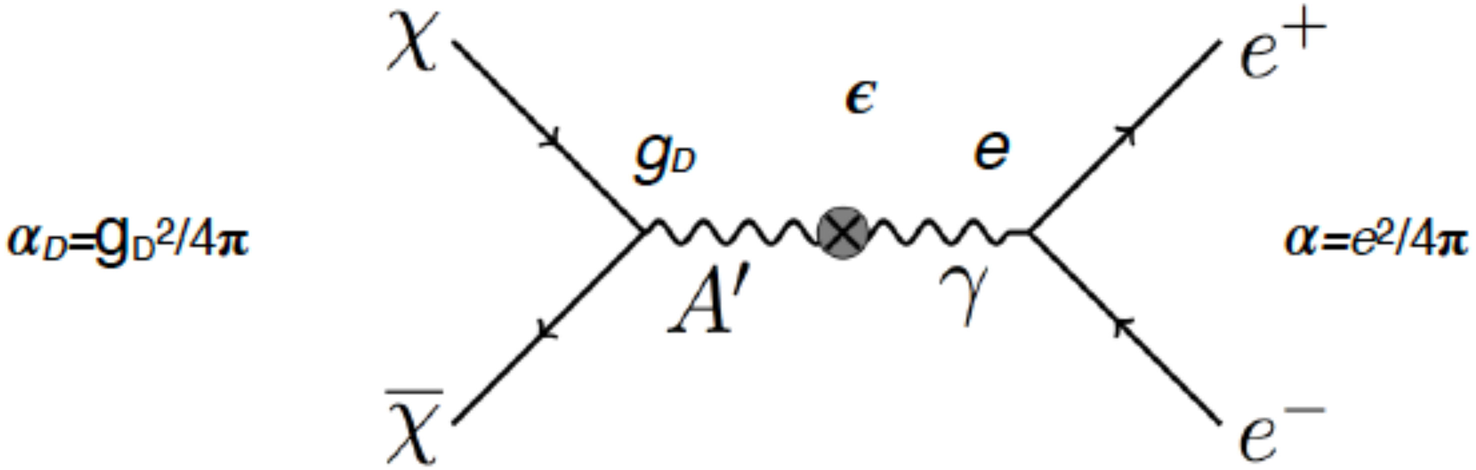
$\Omega_X > \Omega_{DM}$

“Hidden sector” Dark Matter

Light dark matter

“Hidden sector” dark matter: charged under new force, extends thermal DM mass range down to electron mass

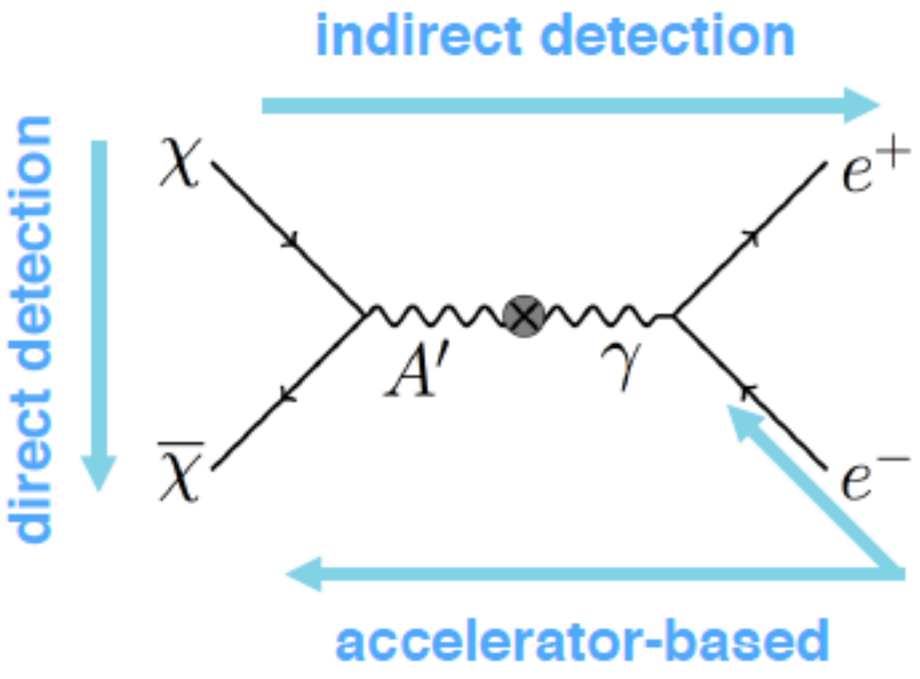
Simple dark sector extension: vector mediator that mixes with SM photon



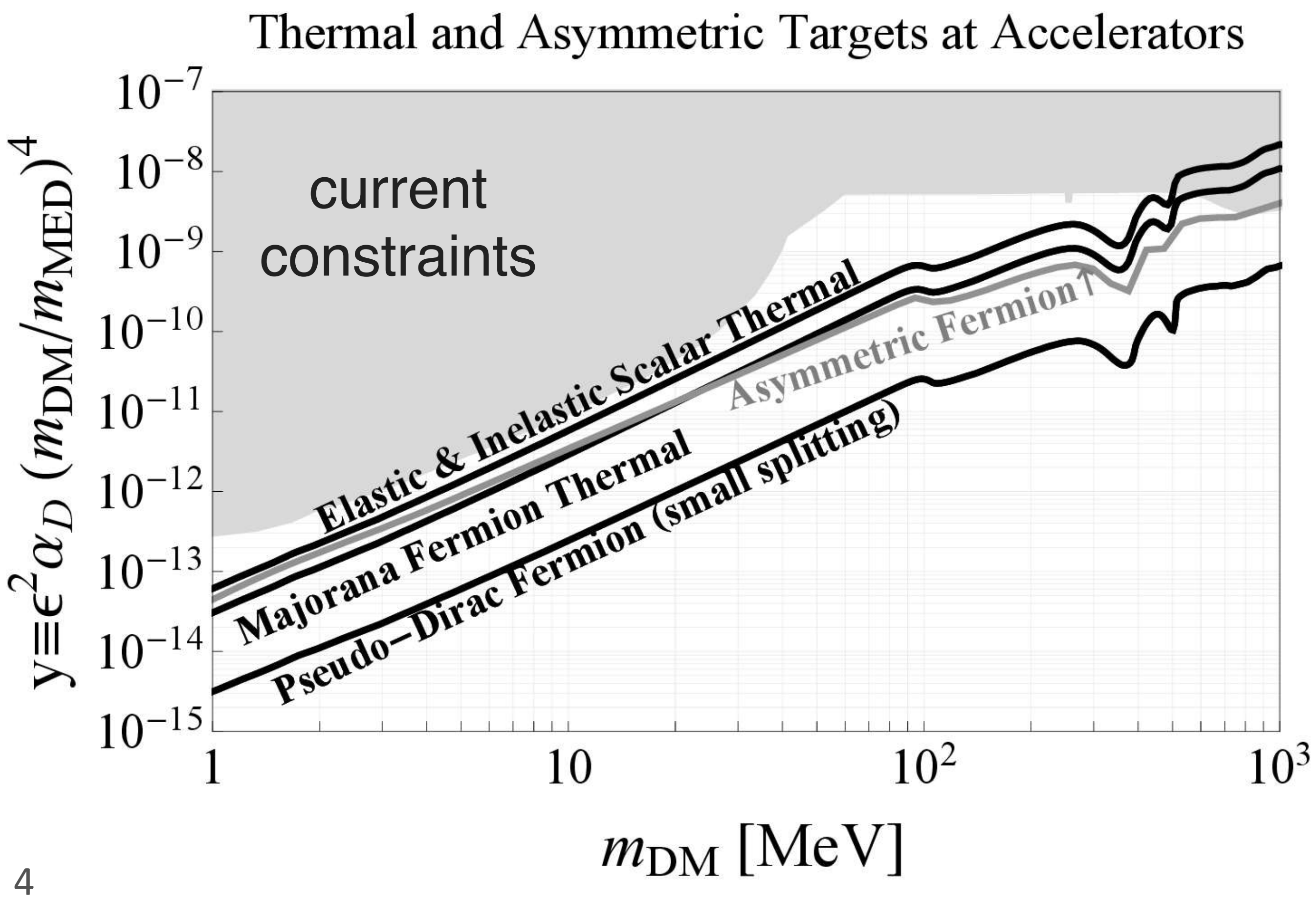
Light dark matter

“Hidden sector” dark matter: charged under new force, extends thermal DM mass range down to electron mass

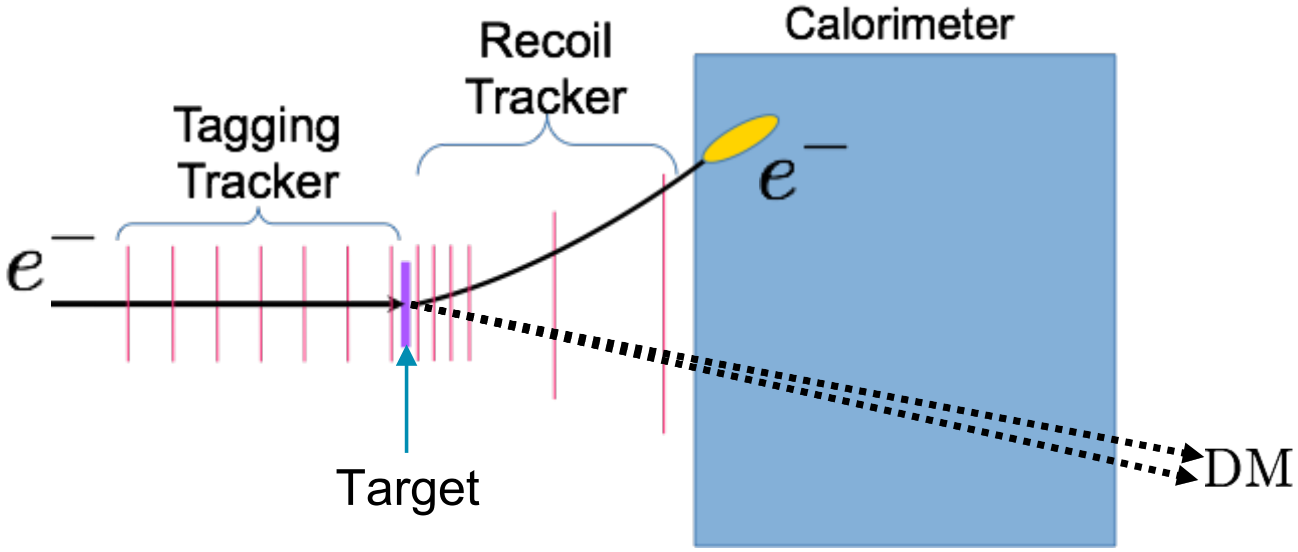
Simple dark sector extension: vector mediator that mixes with SM photon



$m(\chi) < m(A')$



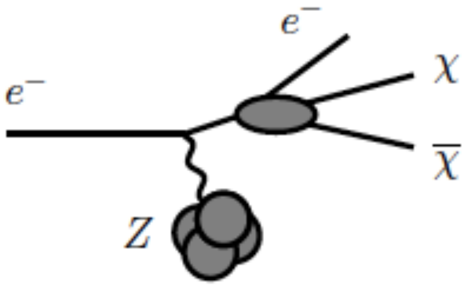
LDMX concept

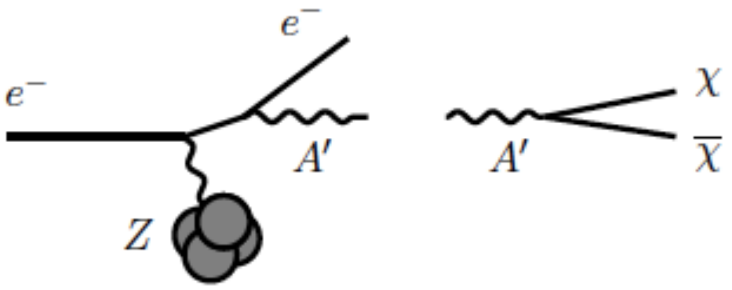


LDMX*: an electron-based fixed-target missing momentum search for light dark matter*

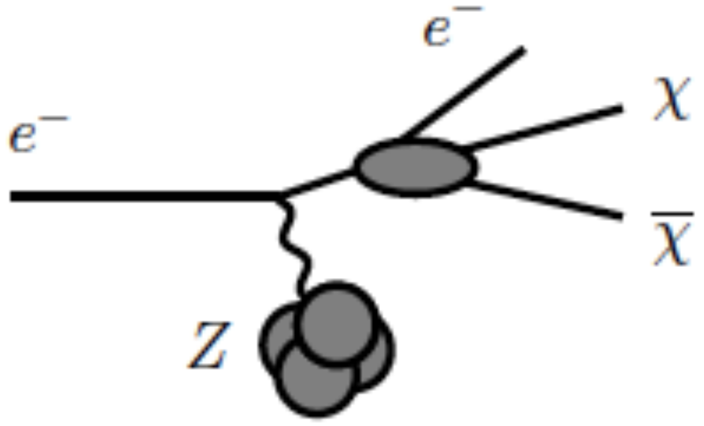
Missing momentum/energy approach:

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





DM production kinematics

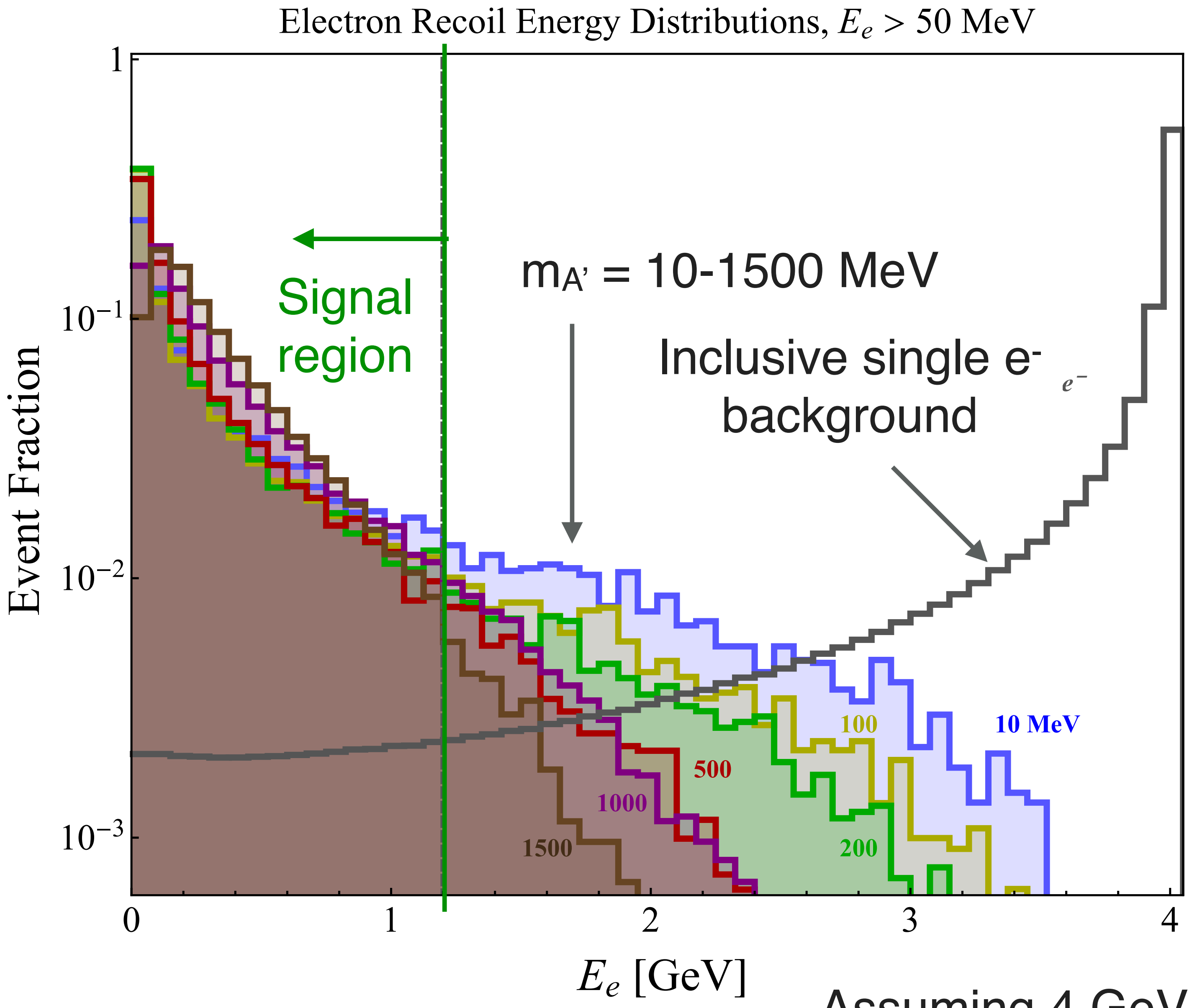


Signal characteristics

- A’ takes most of the beam energy
- No visible final state particles except low-energy recoil electron, possibly with large transverse momentum kick

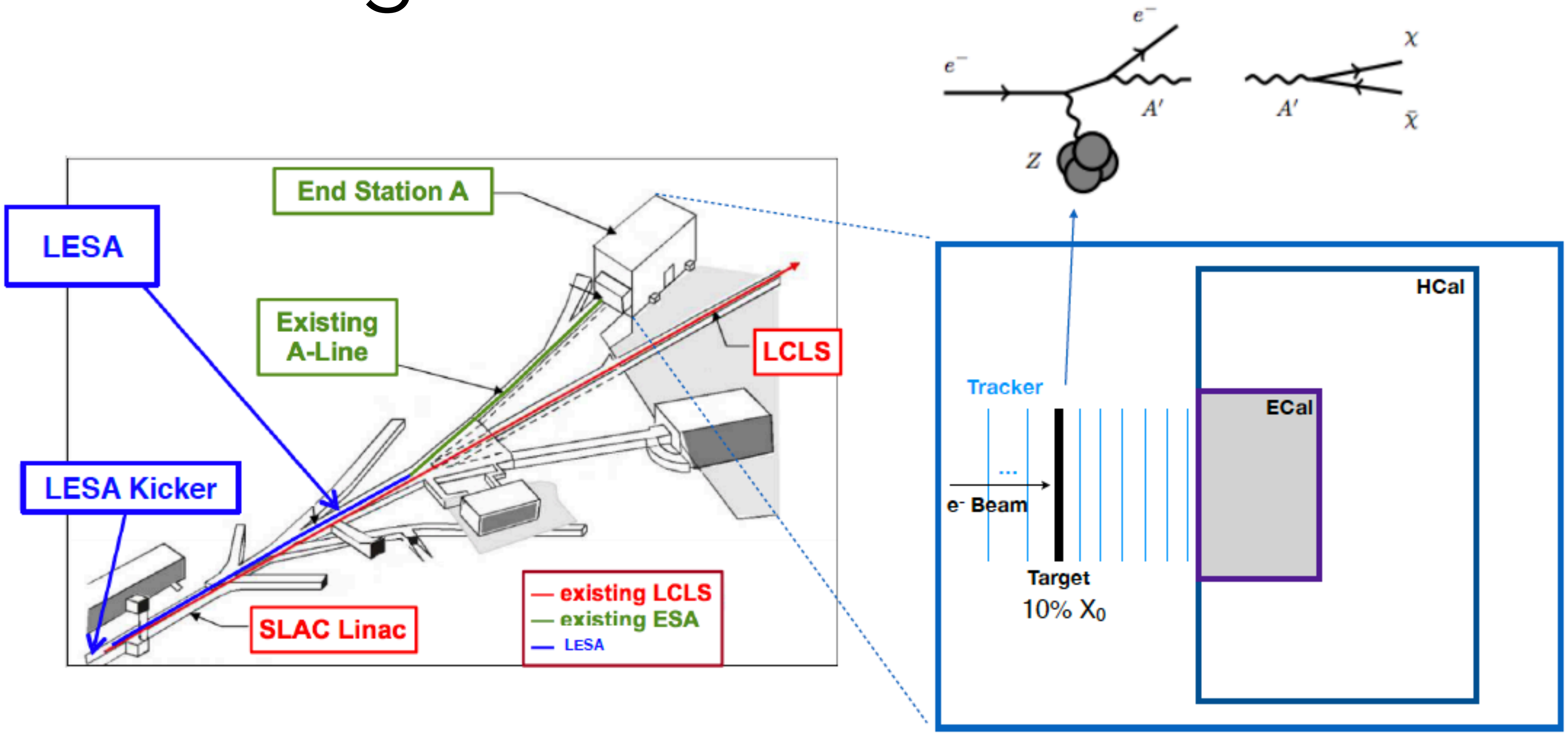
Signal: $E_{total} = E_{recoil} << E_{beam}$

Recoil e^- kinematics allow efficient background rejection and signal selection



Assuming 4 GeV e^- beam

LDMX design



Beam:

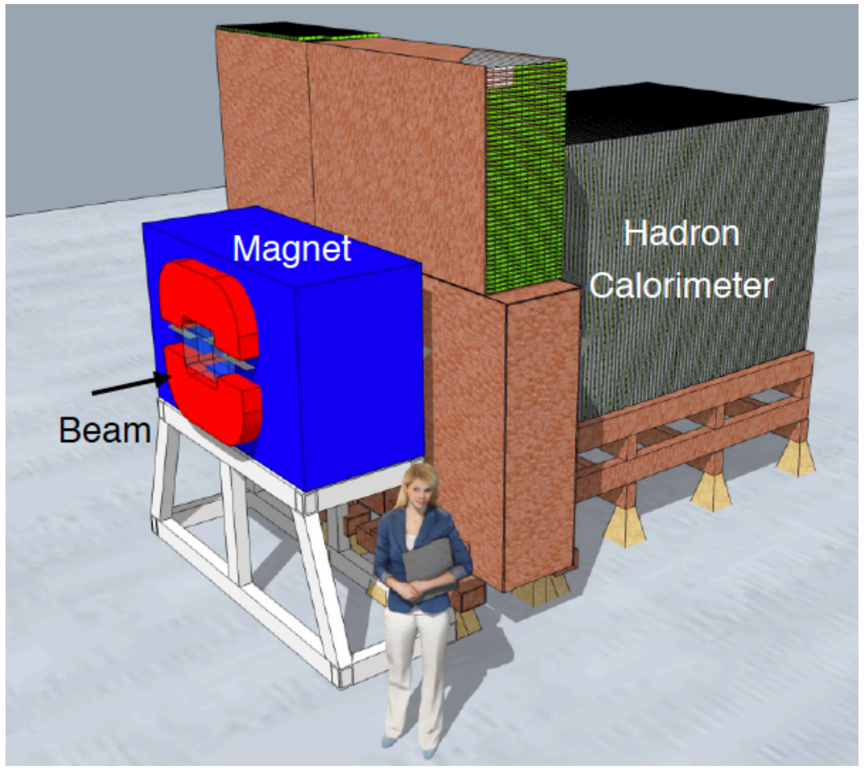
- Parasitic use of LCLS-II beam at SLAC via dedicated transfer line (LESA)
- Initial beam energy 4 GeV, later upgrade to 8 GeV
- Individual tagging & reconstruction of up to 10^{16} electrons on target (EoT) → low current, high repetition rate

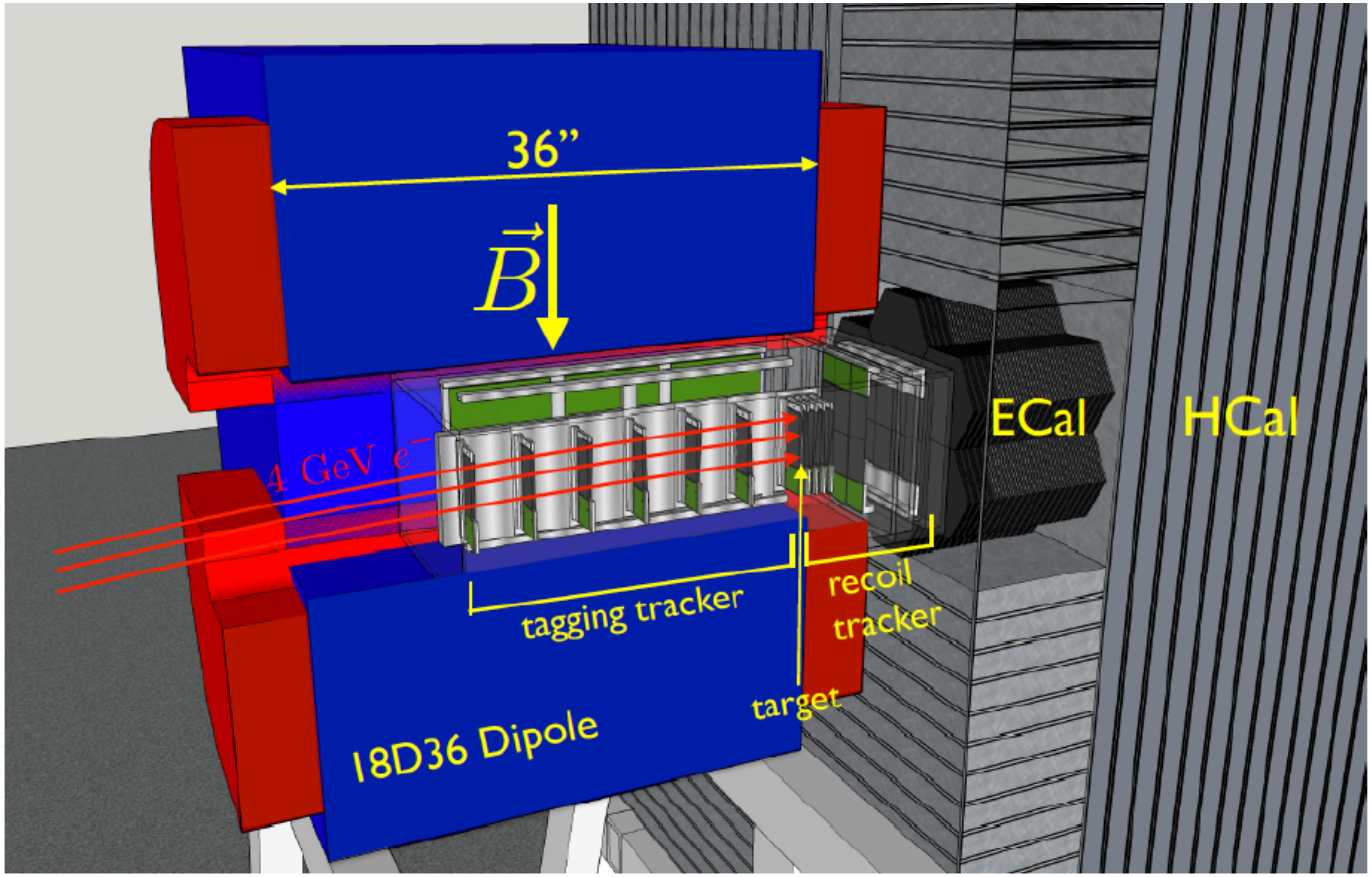
Detector technology suited for high rates, high radiation doses:

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

Design study on arXiv: arXiv:1808.05219

LDMX design


Magnet
Hadron Calorimeter
Beam


36”
$\vec{B}$
4 GeV e^-
ECal
HCal
tagging tracker
recoil tracker
target
18D36 Dipole

Trackers and trigger scintillator

Tagging tracker

- In central dipole field, measures incoming electron

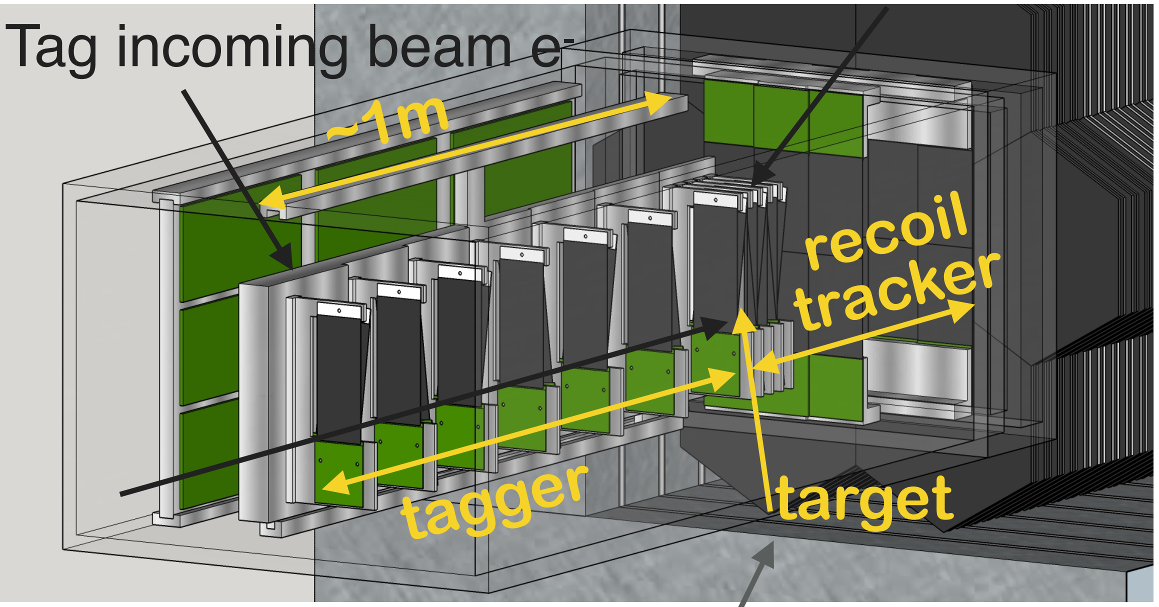
Recoil tracker

- In fringe field, measures recoil electron and vetoes extra particles
- Momentum resolution limited by multiple scattering in target

Trigger scintillator →

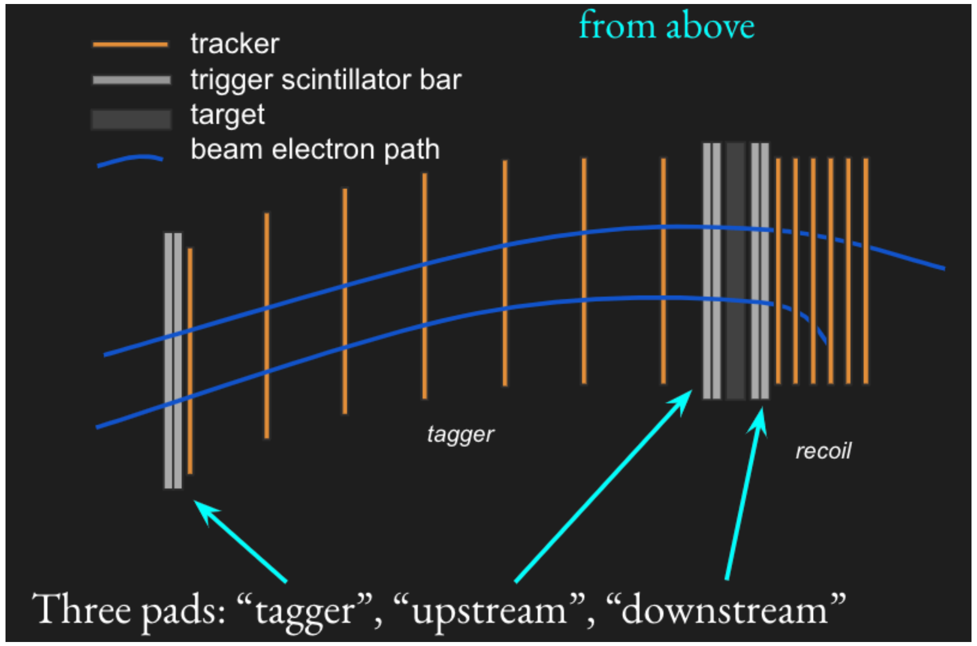
- Arrays of scintillator bars along incoming beam
- Provides fast count of incoming electrons as input to missing-energy trigger

Select recoil e^-

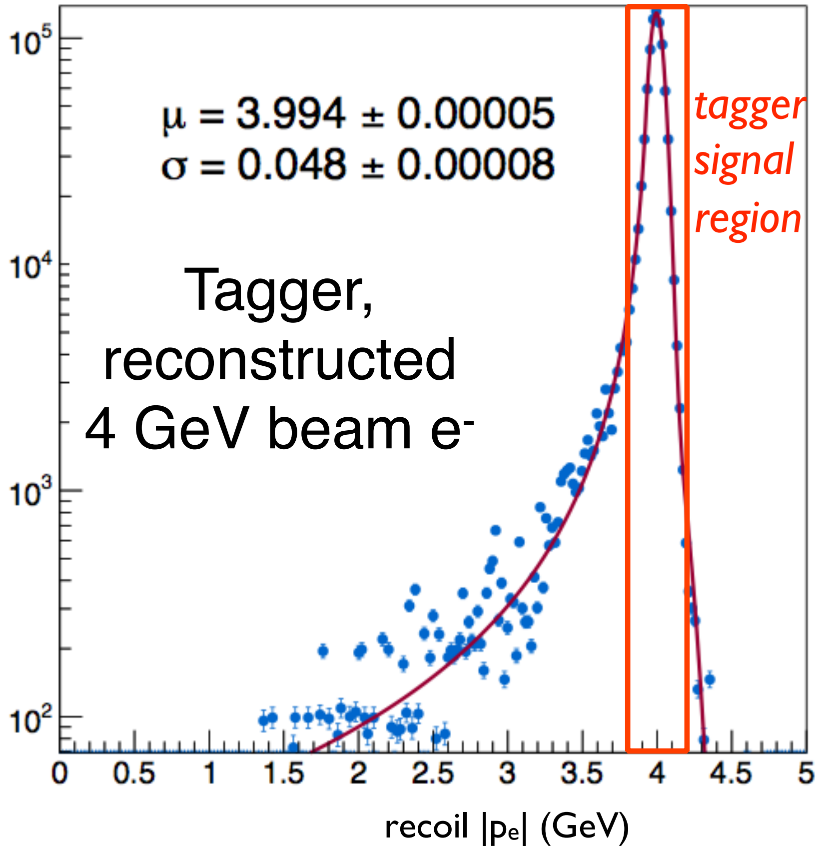


0.1 X_0, tungsten, balance signal rate vs momentum resolution

See Niramay's talk next!



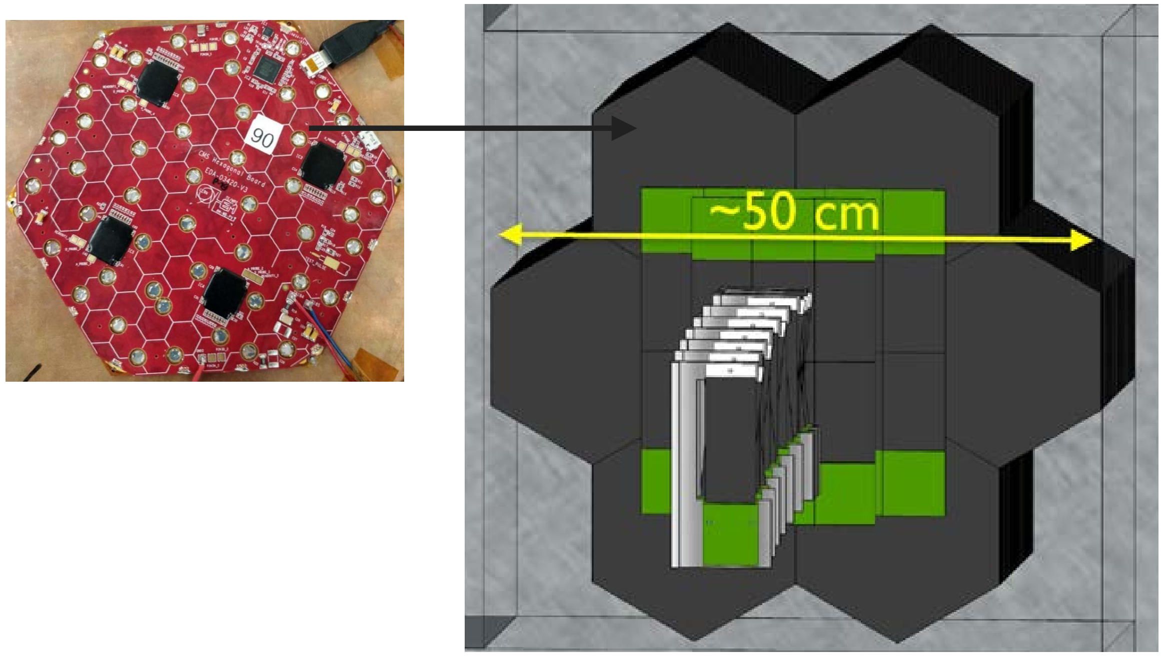
Three pads: "tagger", "upstream", "downstream"

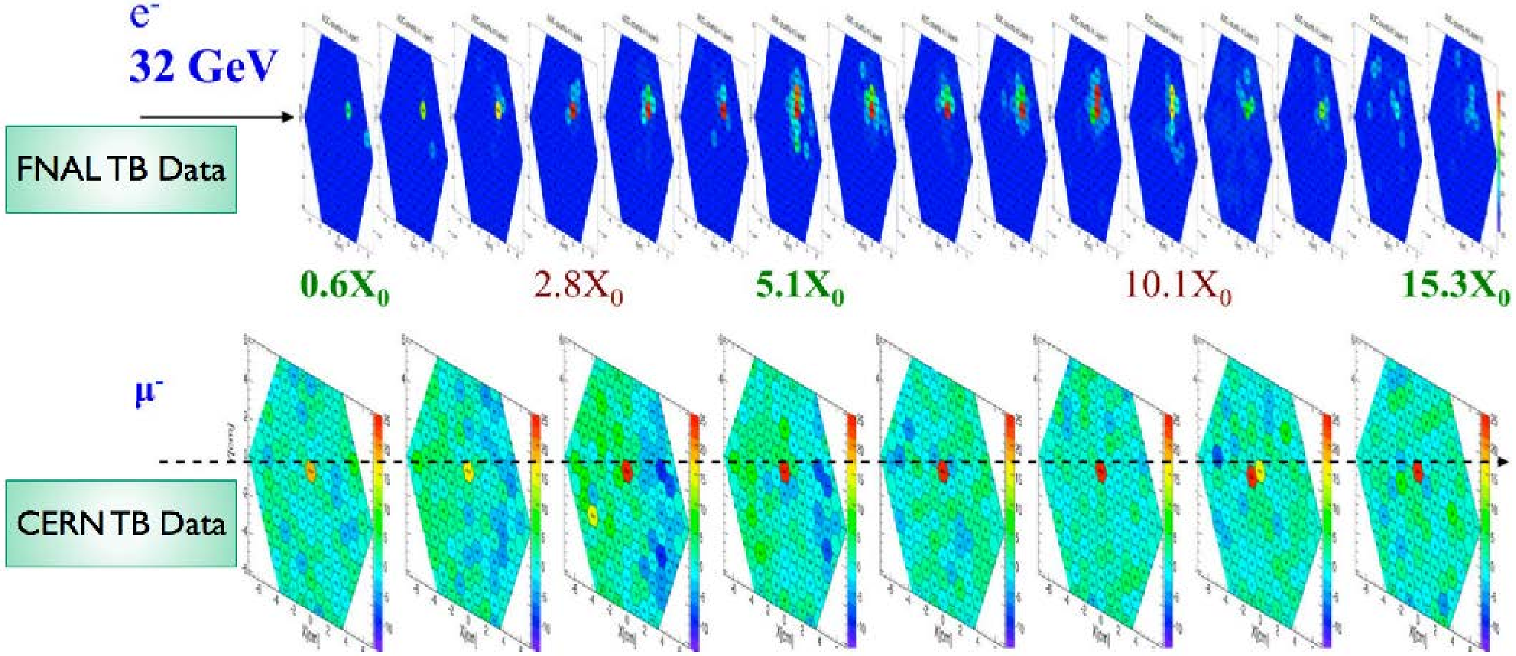


Electromagnetic calorimeter

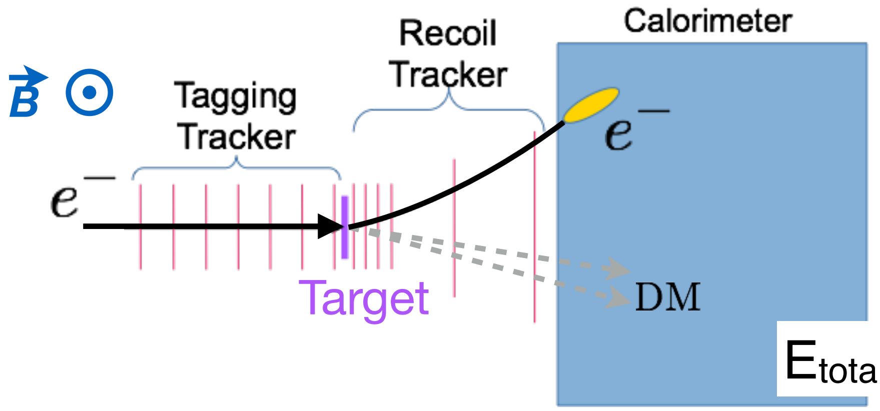
40 X_0 silicon-tungsten sampling calorimeter

- Fast, dense, radiation hard, full shower containment
- Provides fast trigger (missing energy)
- High granularity, can exploit both transverse and longitudinal shower shapes to reject background
- MIP tracking capabilities



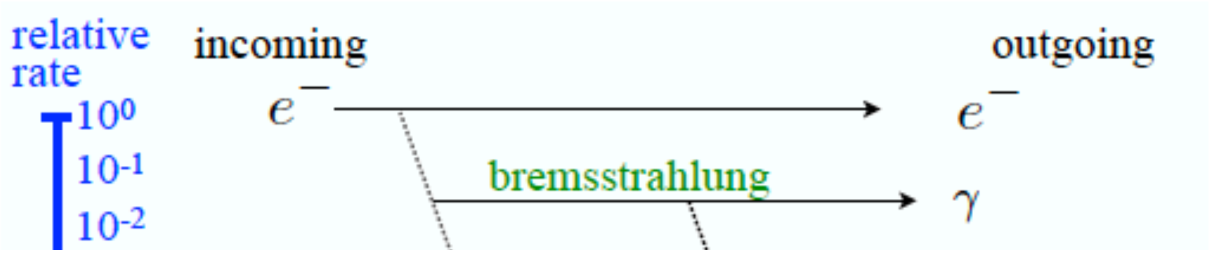


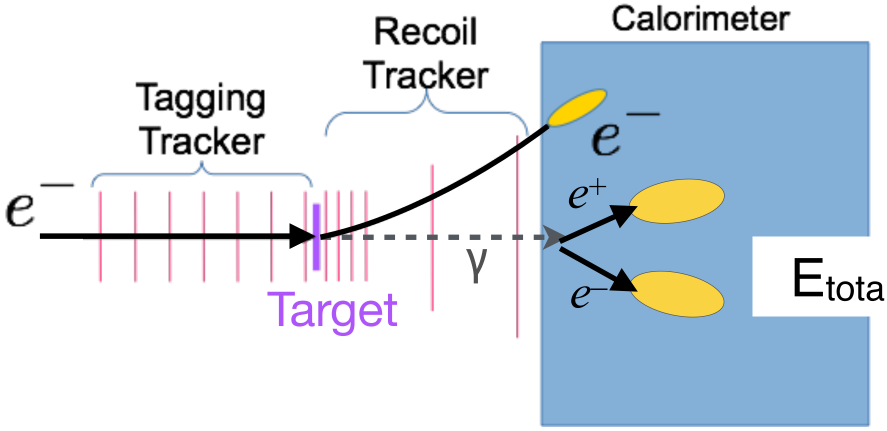
ECAL energy as veto handle



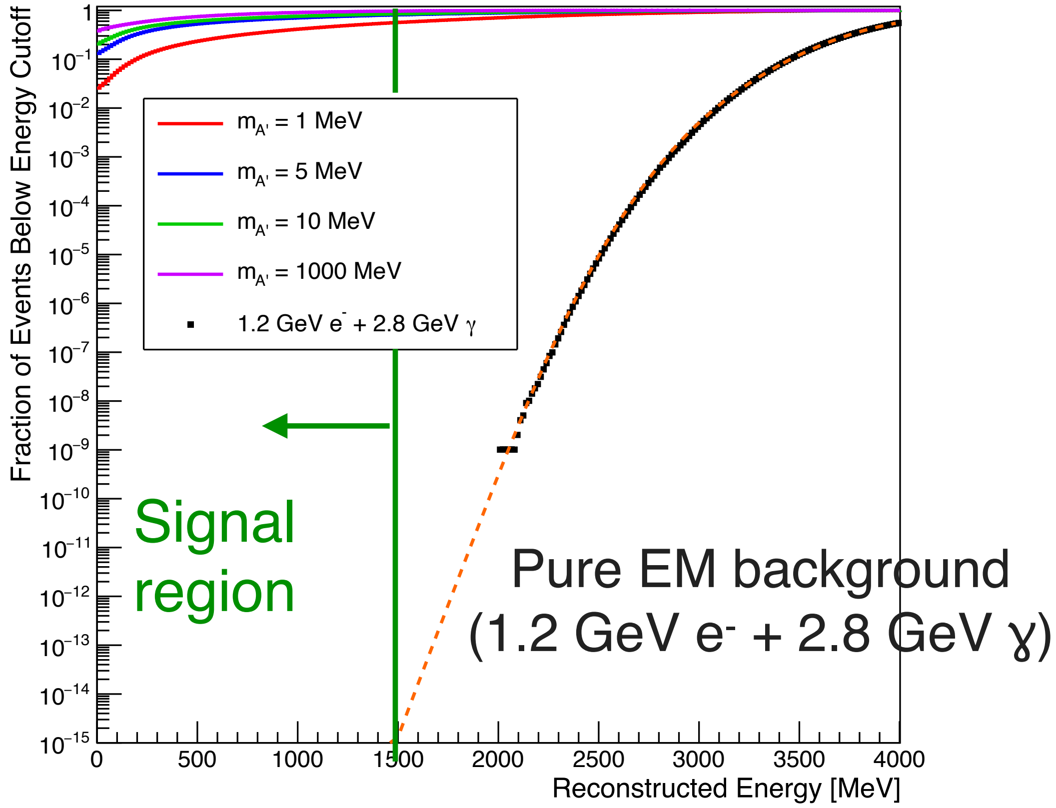
$E_{total} = E_{recoil} << E_{beam}$

vs





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

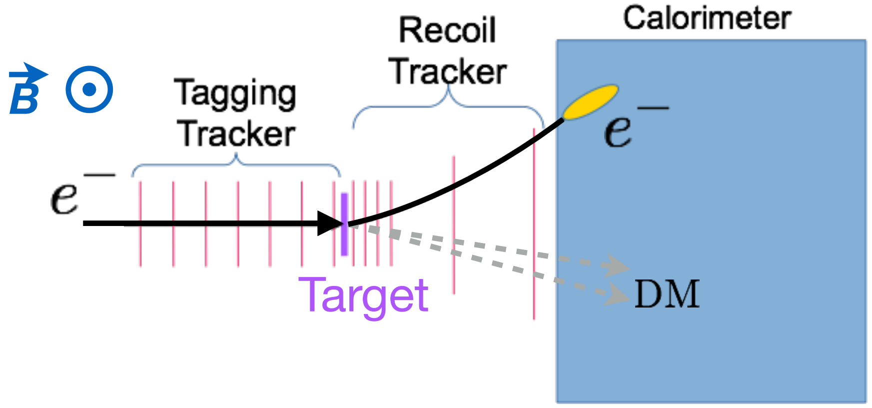


Signal region

Pure EM background
(1.2 GeV e^- + 2.8 GeV γ)

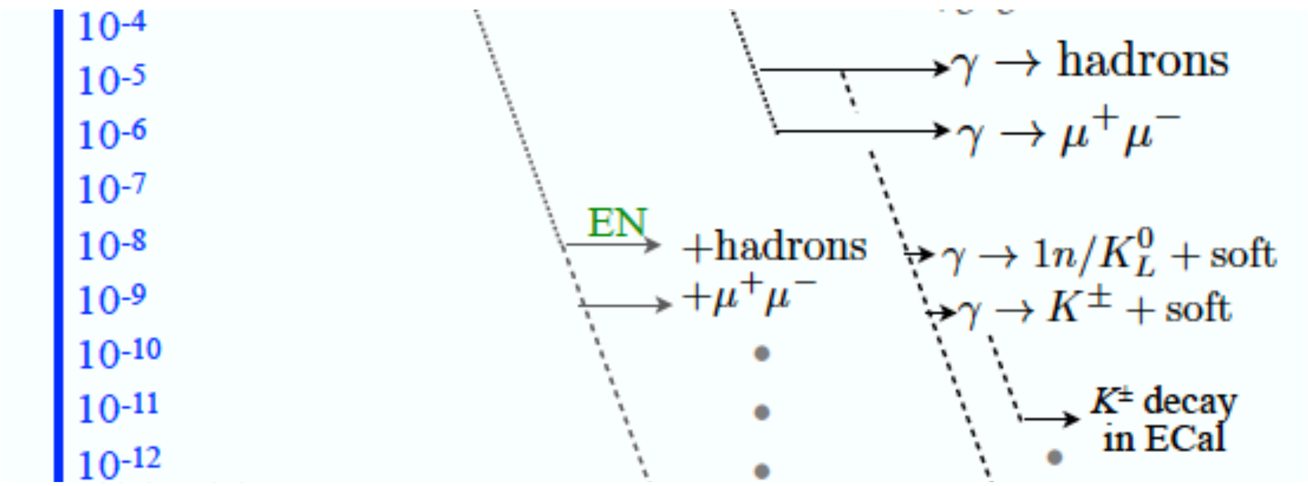
Only look at events with low energy deposition

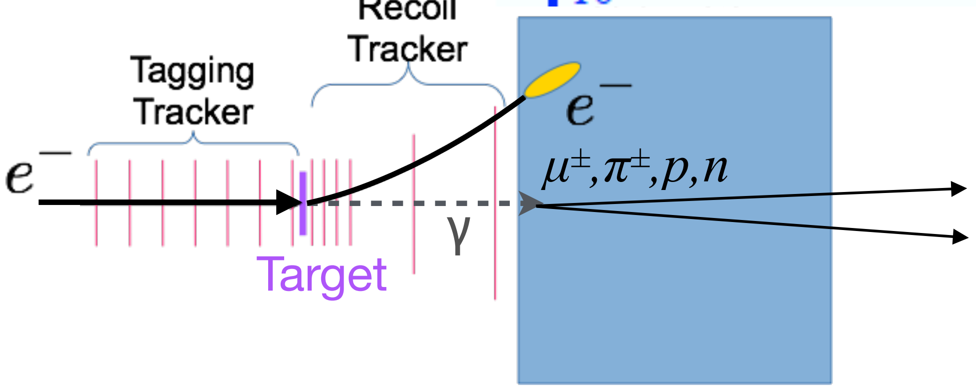
Rare backgrounds



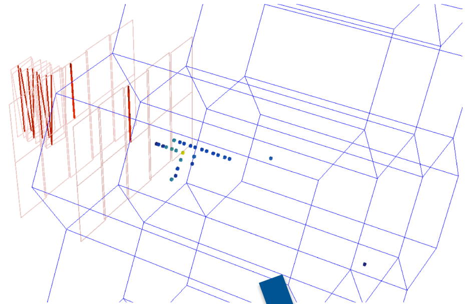
vs

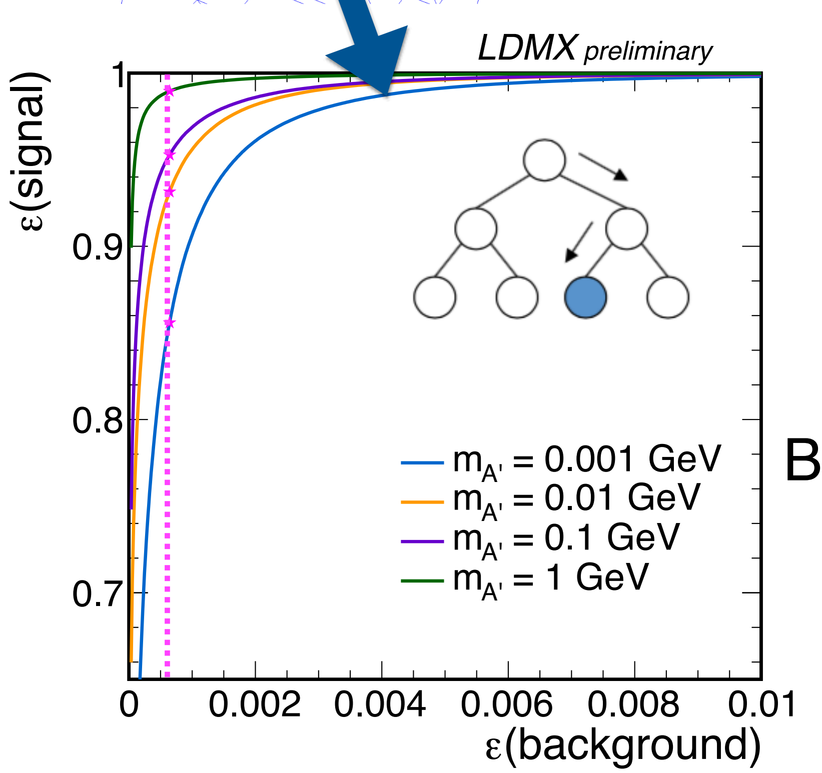
More challenging: photon has rare reaction leading to low total energy



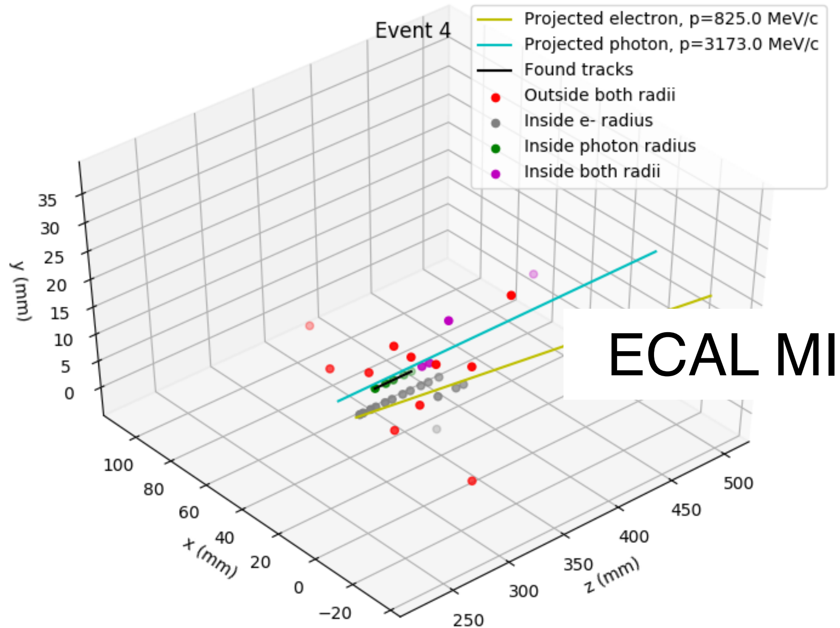


Pattern recognition with machine learning identifies “wide” or “long” showers, charged particle tracks



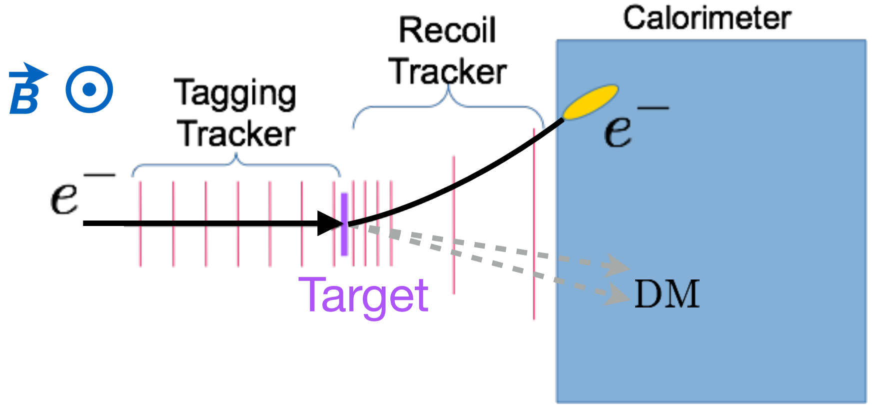


Boosted decision tree based on ECAL features

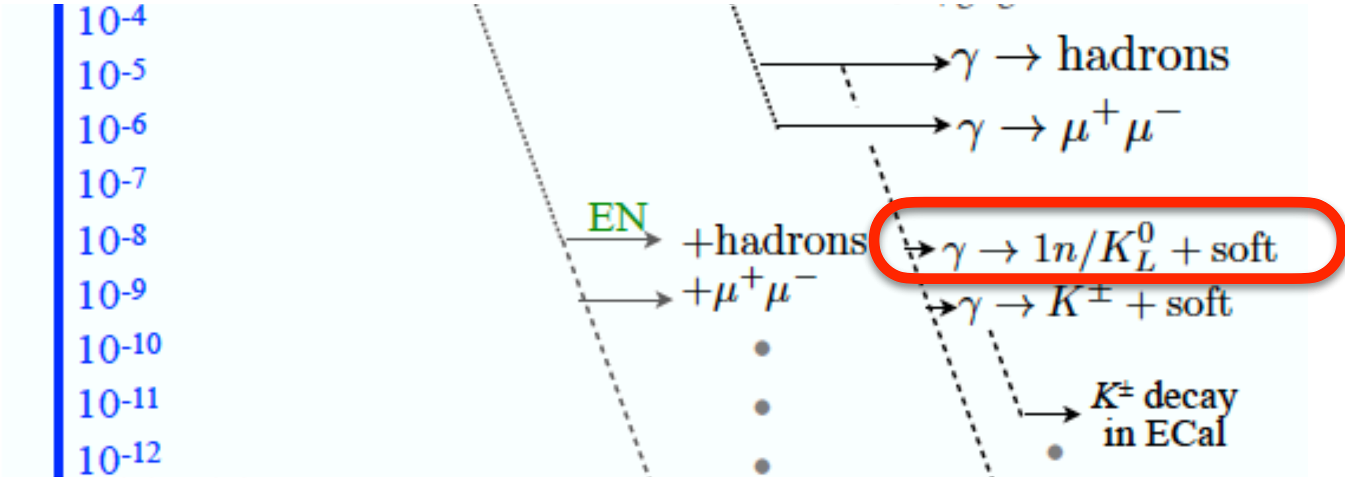


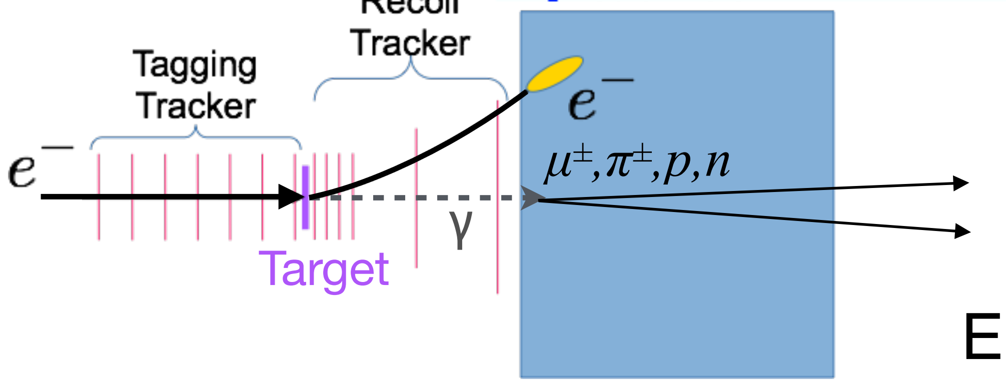
ECAL MIP tracking

What's left?



vs



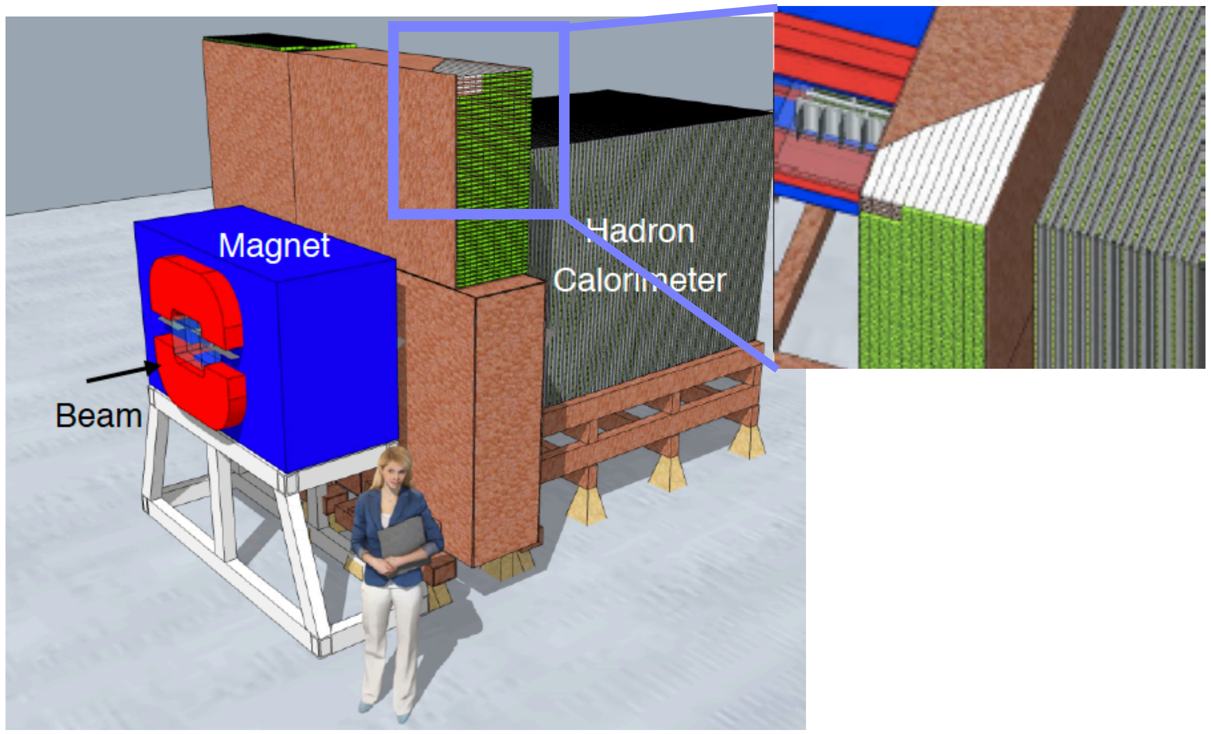


Energetic neutrons need more material

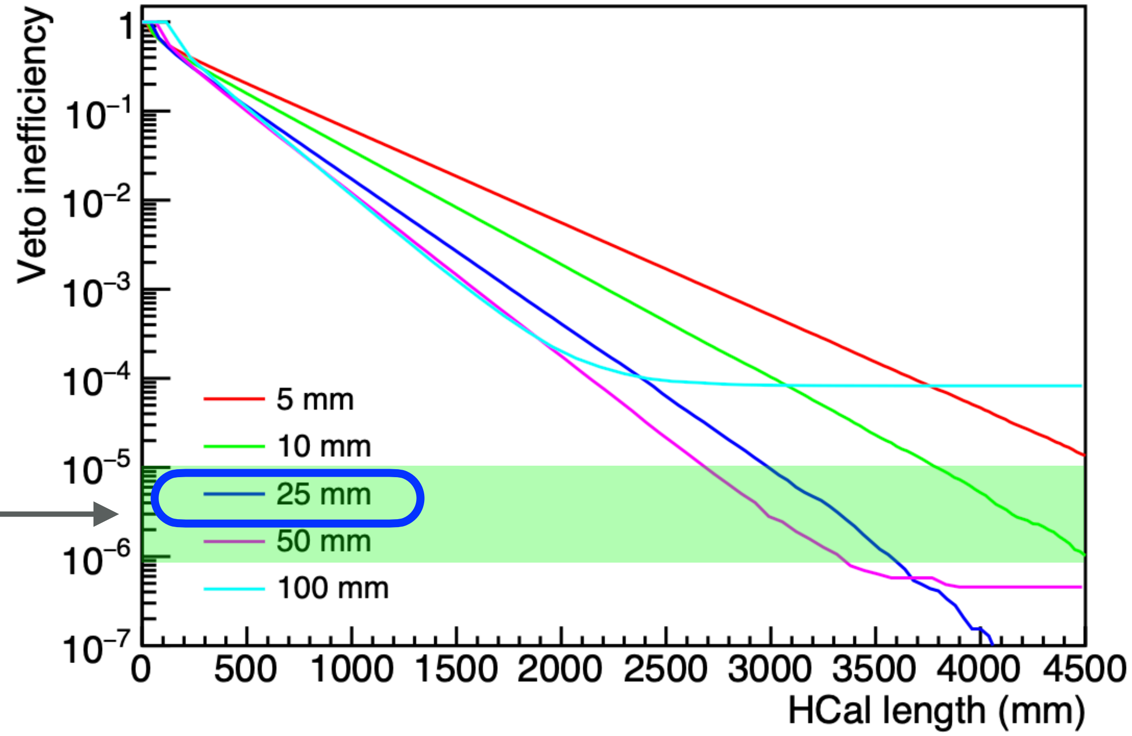
Hadron calorimeter

Steel/plastic scintillator sampling calorimeter

- Plastic scintillator bars with wavelength-shifting fibers read out by SiPM, steel absorber
- Surrounds ECAL as much as possible
- Highly efficient veto for photo nuclear events producing hadrons
- Also catches wide-angle bremsstrahlung and $\gamma \rightarrow \mu^+\mu^-$

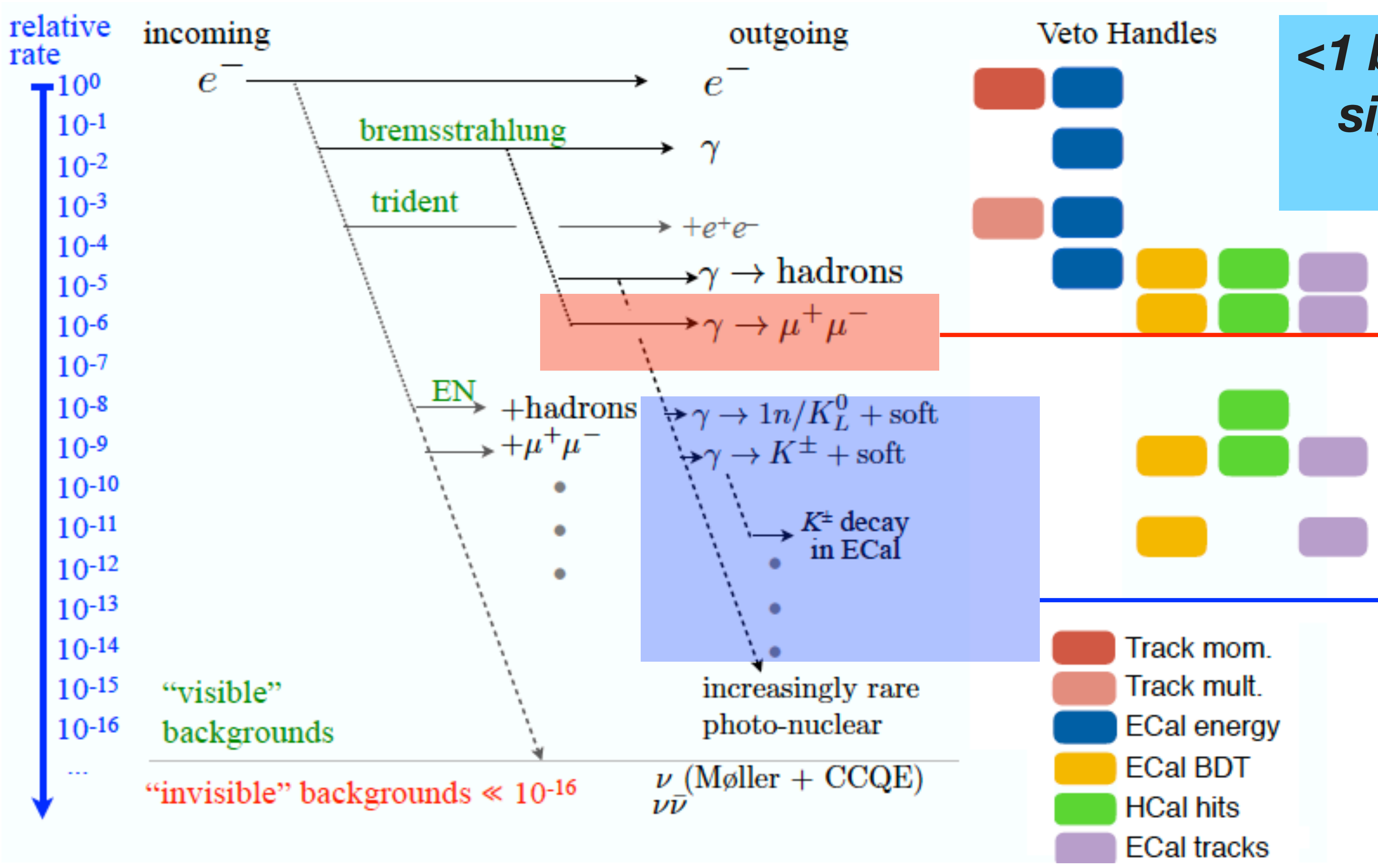


Single neutron veto inefficiency vs HCAL depth, energy = 2 GeV



Desired rejection power: ~10^{-5} - 10^{-6}

Putting it all together

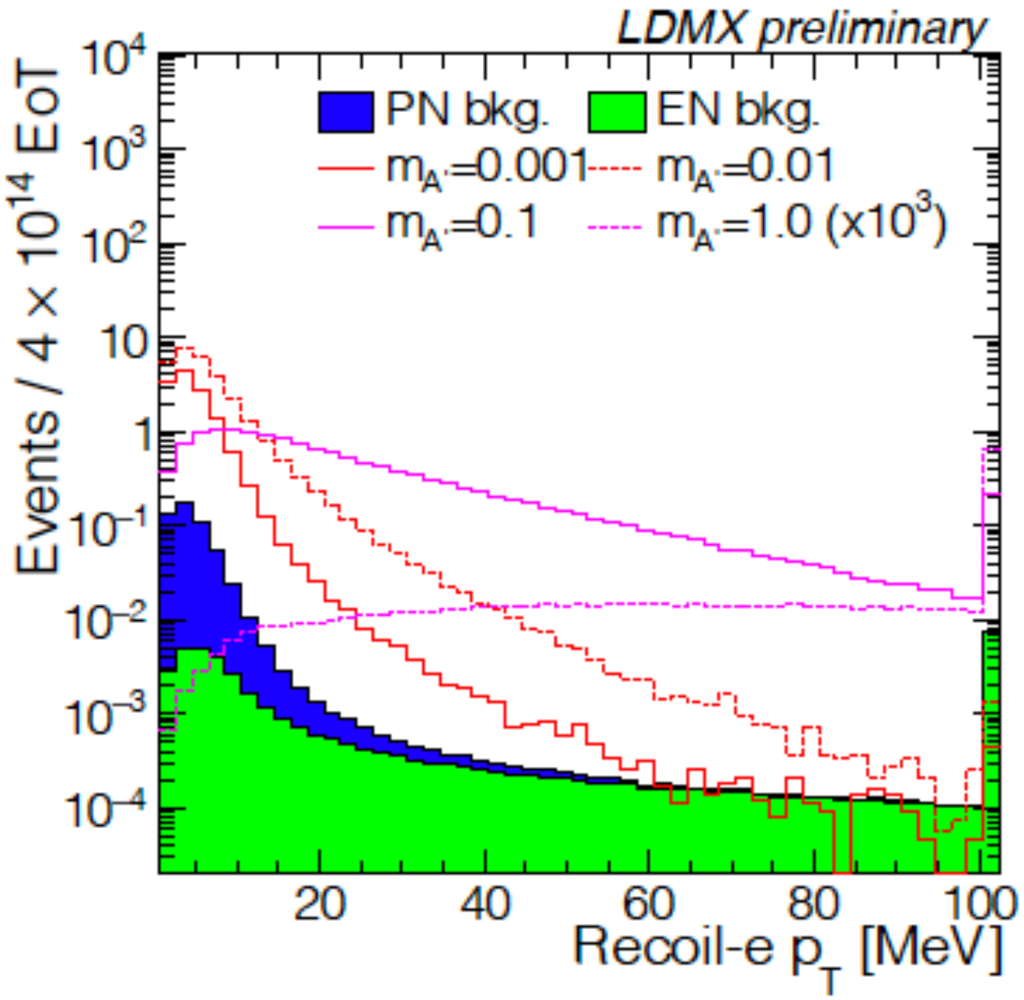


<1 background event for 35-50% signal efficiency *combining all systems for O(1e14) EoT*

	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

From paper studying background veto performance with high-statistics simulation samples: arXiv:1912.05535

Characterizing signal

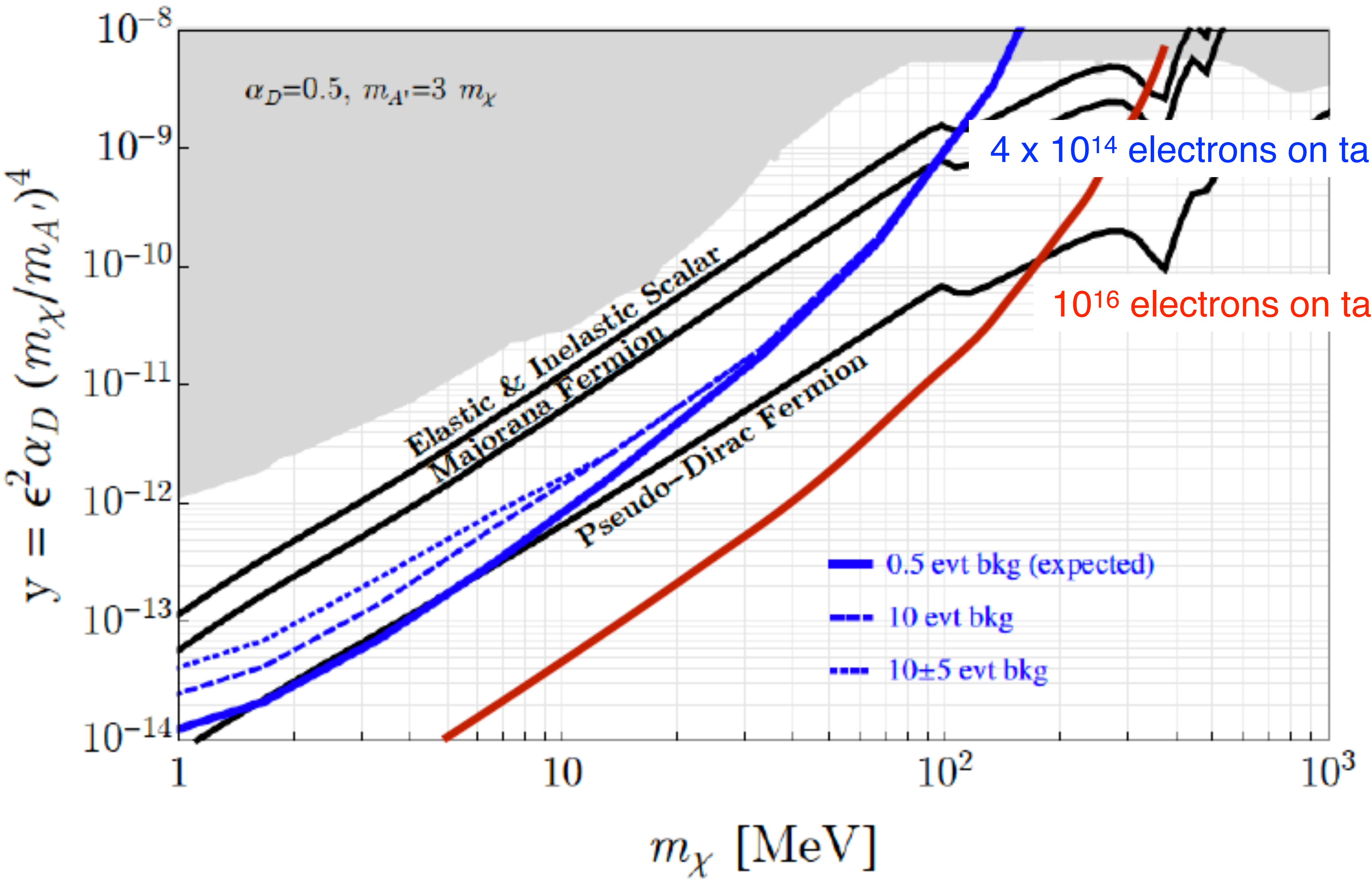


A final handle

Recoil electron transverse momentum key final measurement, not touched in veto handles

Gives confidence in signal + estimate of dark matter mass scale!

Projected sensitivity



4 x 10^{14} electrons on target @ 4 GeV

10^{16} electrons on target @ 8 GeV

Detailed analysis in arXiv:1808.05219

Summary

LDMX exploits missing momentum/energy technique towards powerfully probing the sub-GeV range for thermal relic dark matter

Unique potential to reach all thermal DM milestones at masses below O(100 MeV)!

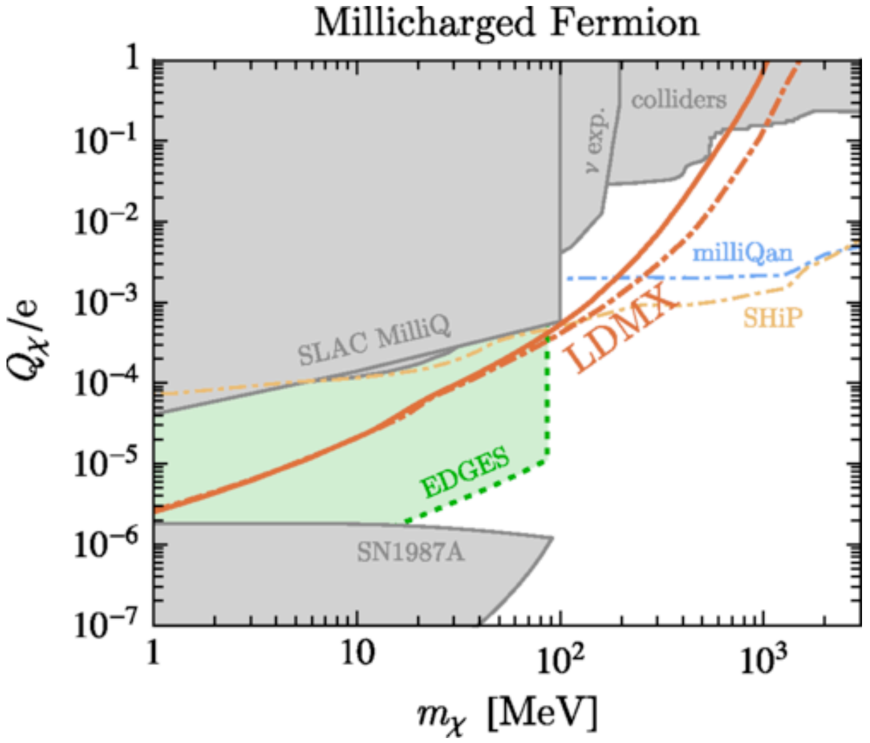
+Broad range of sensitivity to dark sector physics, also sensitive to visible displaced decays

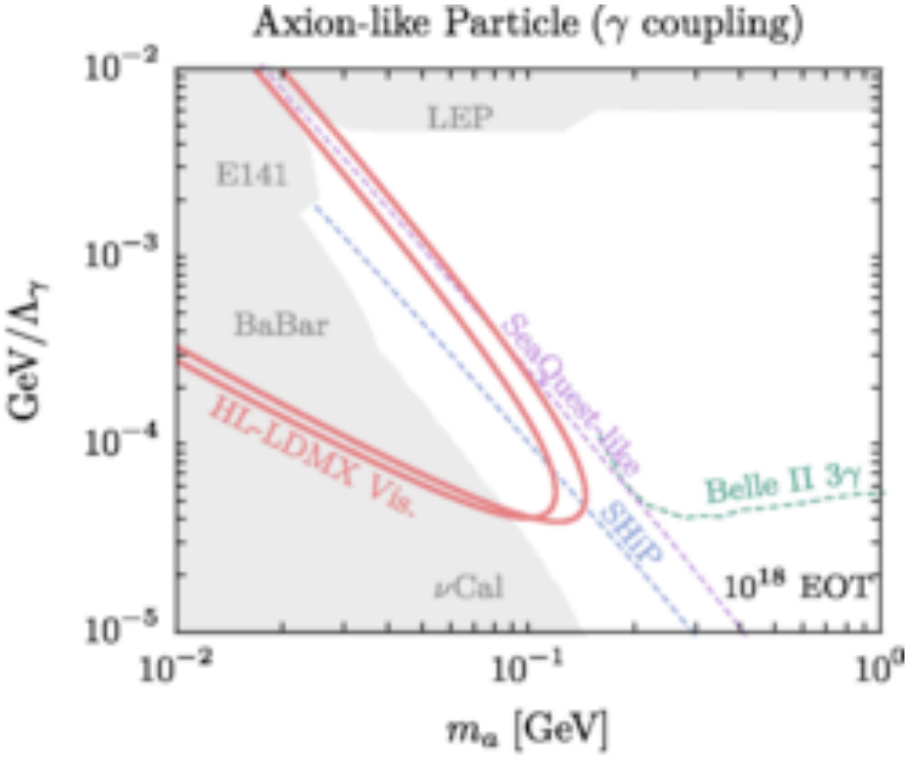
+Electronuclear measurements to support neutrino program

Exciting times ahead as we move forward towards construction phase!

Sensitivity to many new physics scenarios explored in arXiv:1807.01730

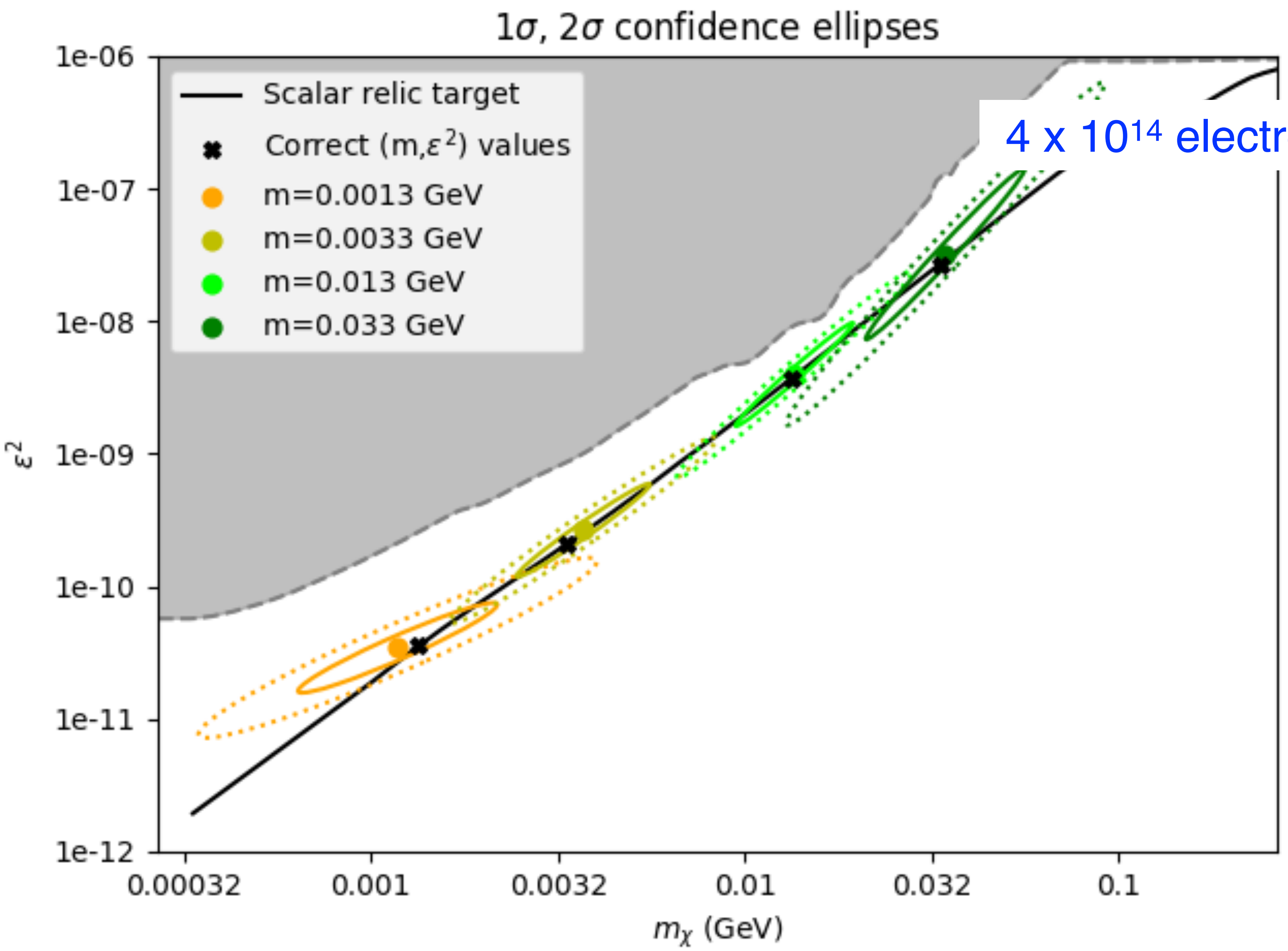
(A. Berlin, N. Blinov, G. Krnjaic, P. Schuster, N. Toro)





Additional Material

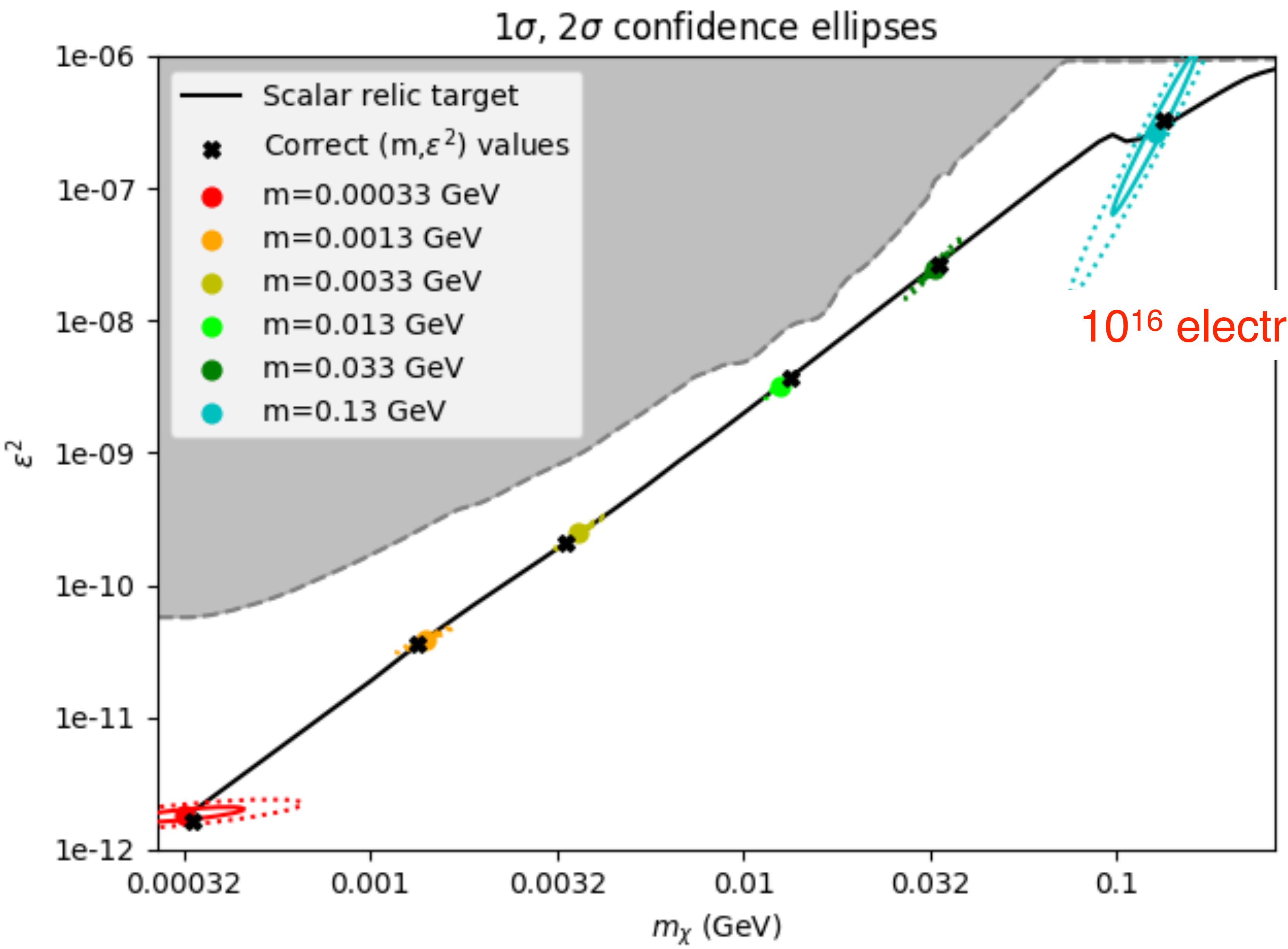
Mass determination



4 x 10^{14} electrons on target @ 4 GeV

Assuming 0 background

Mass determination

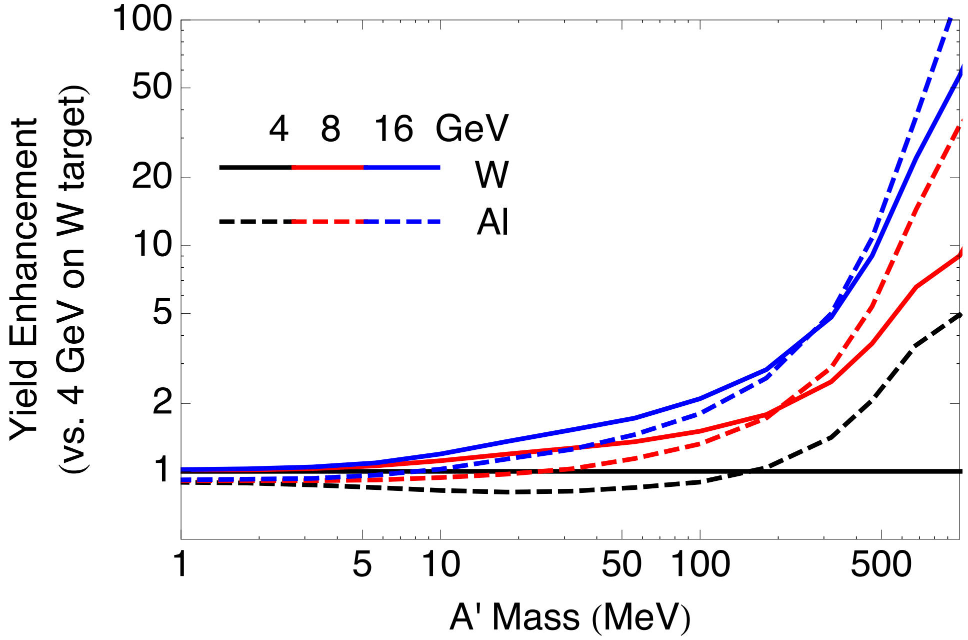


10^{16} electrons on target @ 8 GeV

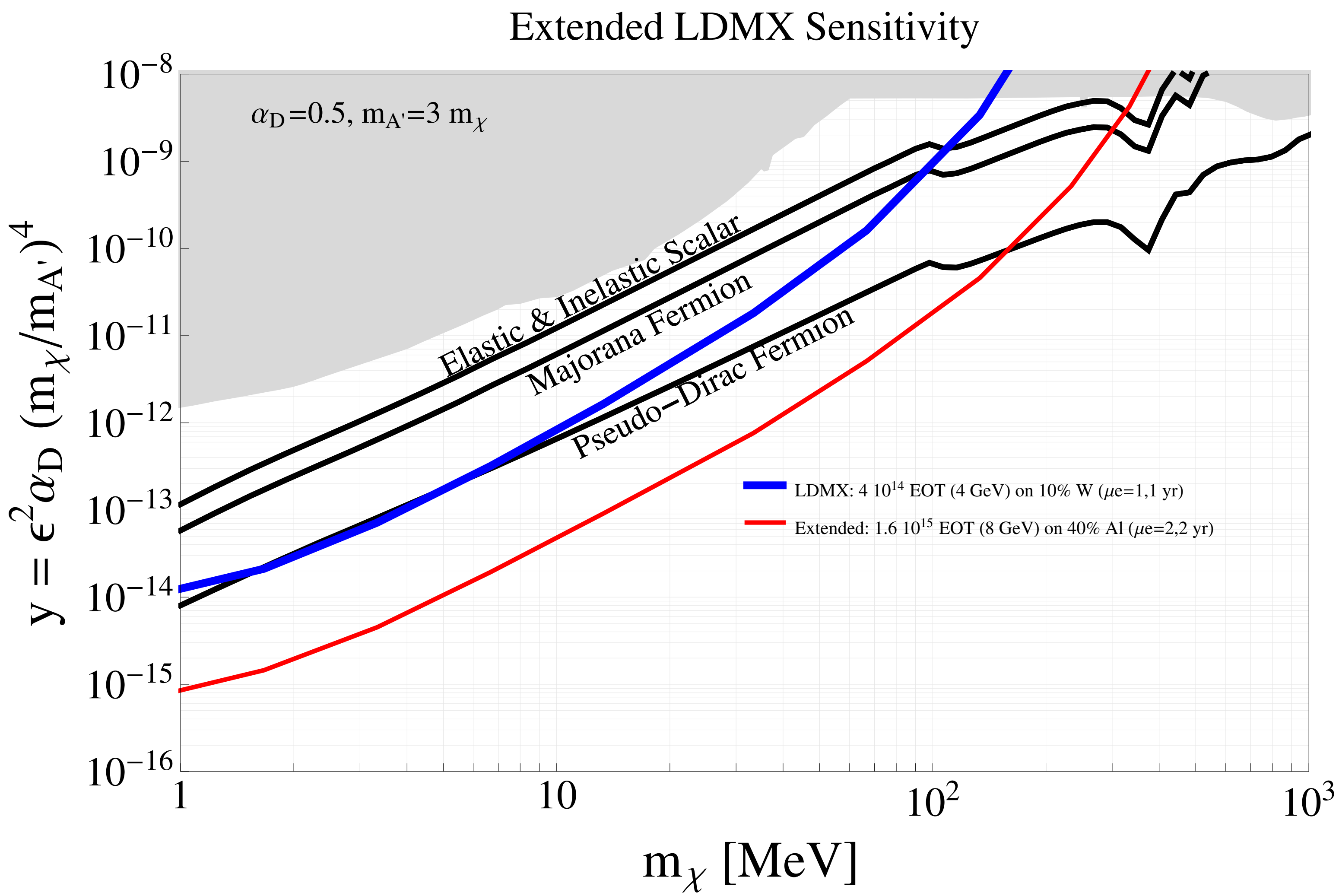
Assuming 0 background

Full LDMX sensitivity

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



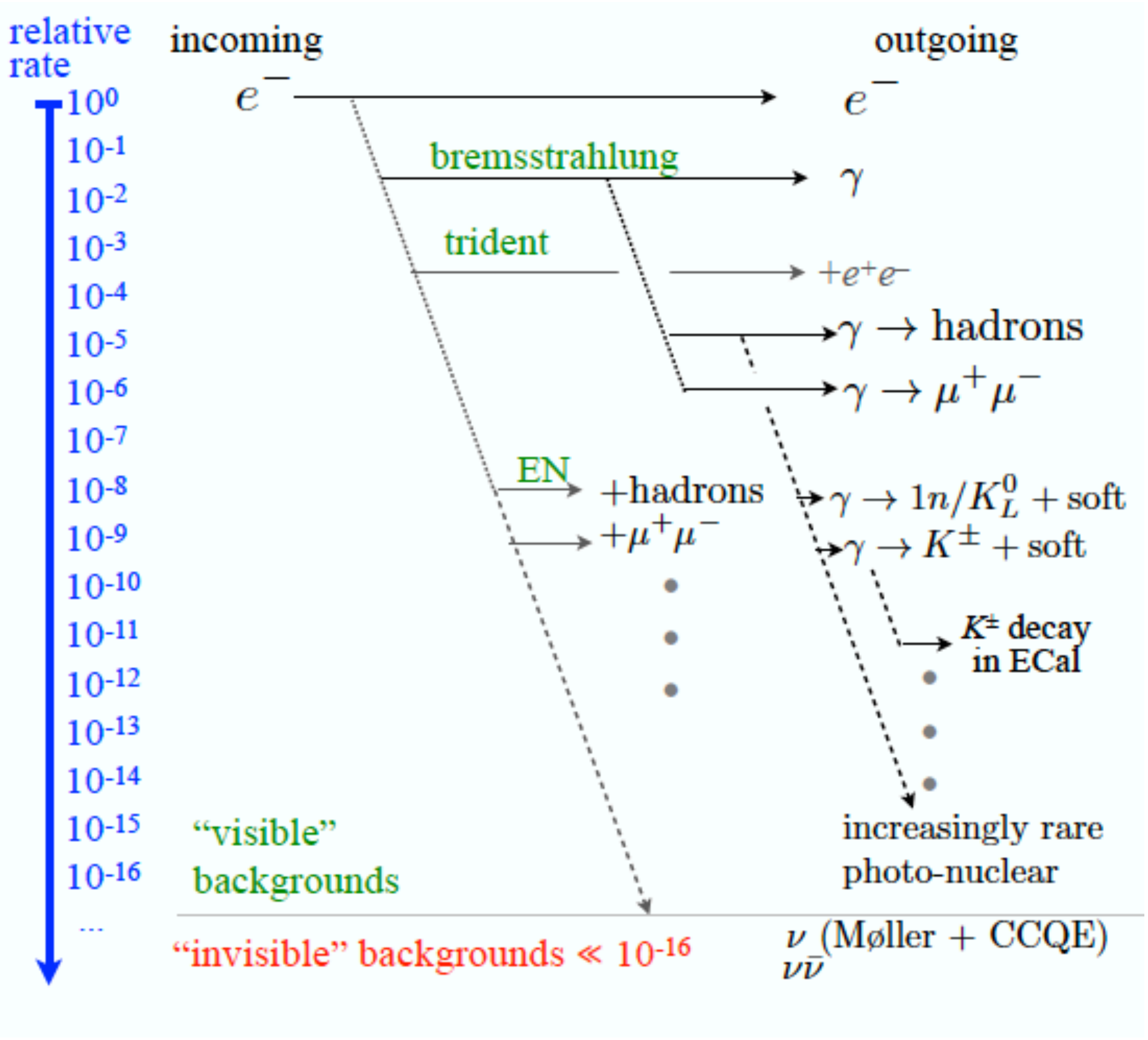
At higher energy, reduced fraction of hard-to-reject events (e.g. hard single neutron) → potential for lower background


Extended LDMX Sensitivity

Extend sensitivity past pseudo-Dirac target up to 100 MeV

Detailed analysis in arXiv:1808.05219

Rates per incoming electron



relative rate

10^0 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12} 10^{-13} 10^{-14} 10^{-15} 10^{-16} …

incoming

e^-

outgoing

e^-

bremsstrahlung

γ

trident

$+e^+e^-$

$\gamma \to$ hadrons

$\gamma \to \mu^+\mu^-$

EN

+hadrons

$+\mu^+\mu^-$

$\gamma \to 1n/K_L^0 + \text{soft}$

$\gamma \to K^\pm + \text{soft}$

$K^\pm$ decay in ECal

increasingly rare photo-nuclear

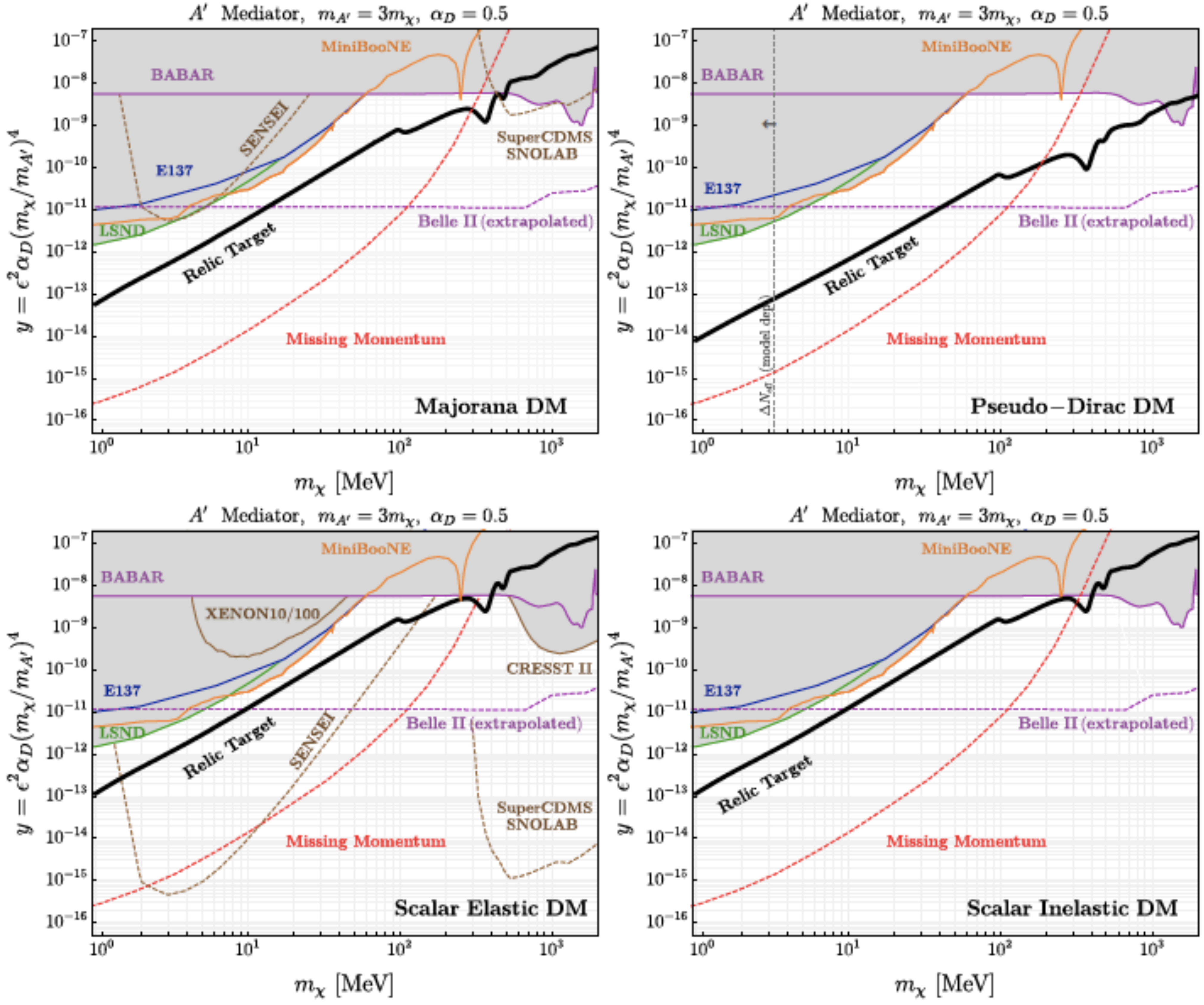
"visible" backgrounds

"invisible" backgrounds ≪ 10^{-16}

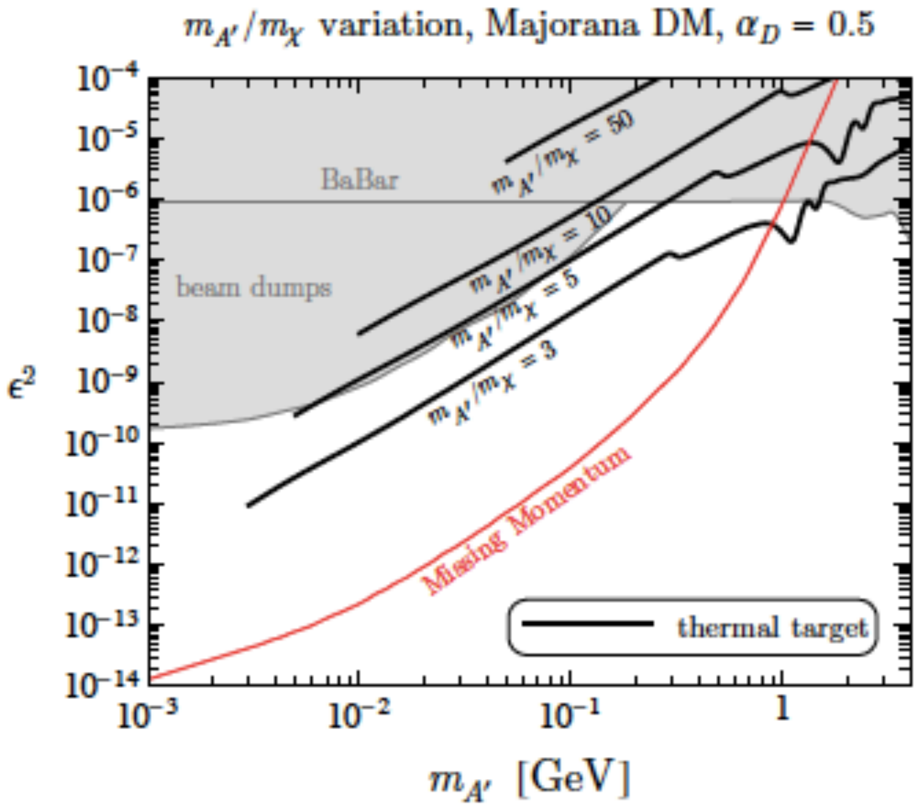
ν (Møller + CCQE)

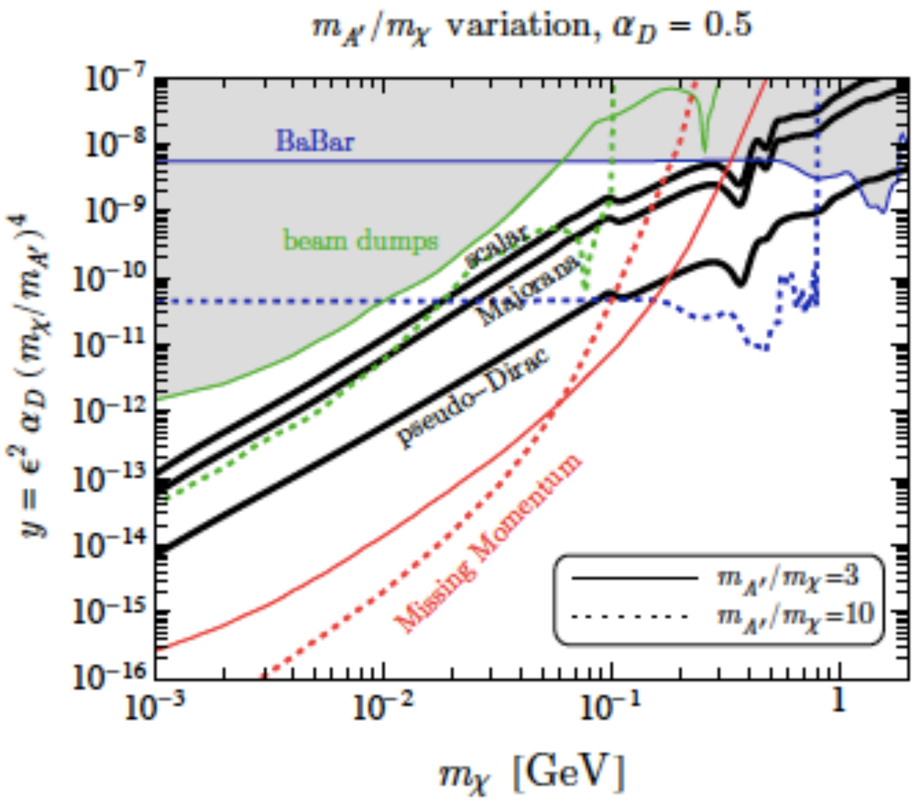
$\nu\bar{\nu}$

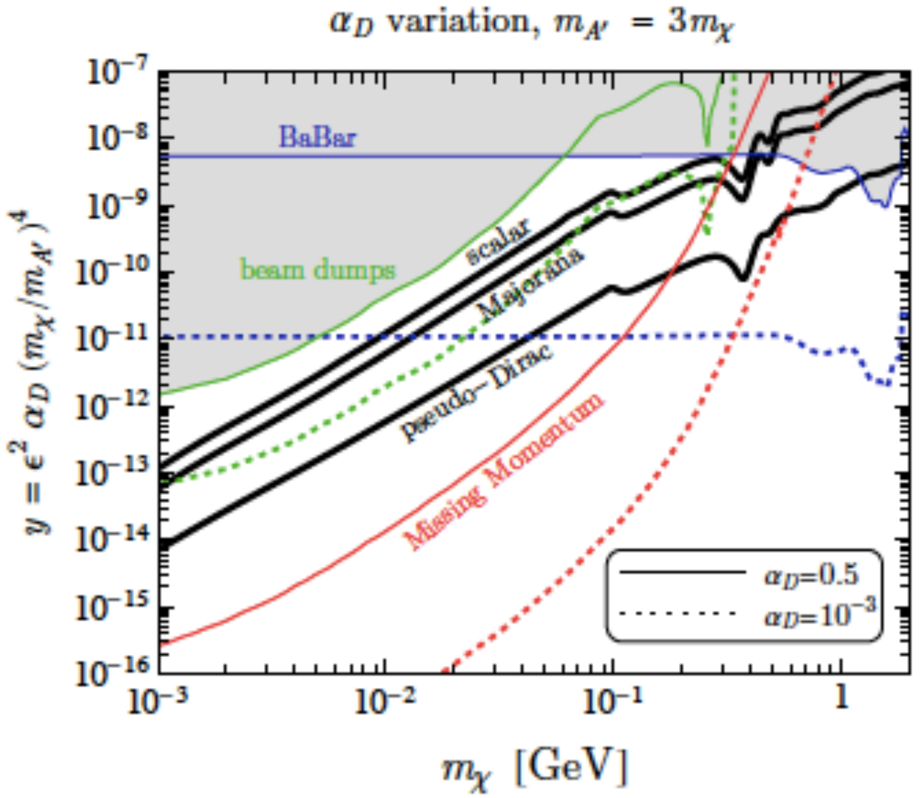
Missing momentum reach



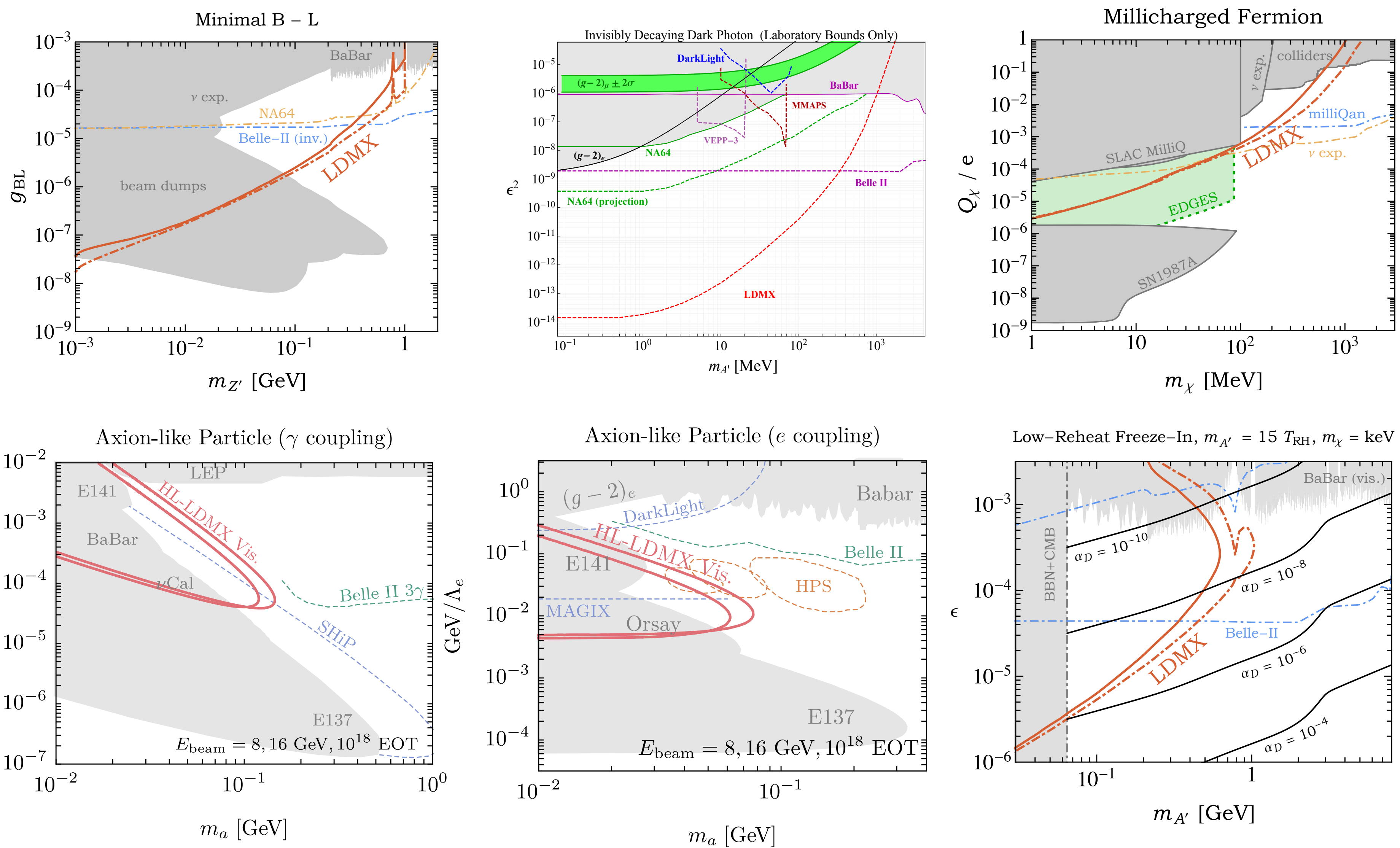
Parameter dependence







LDMX potential

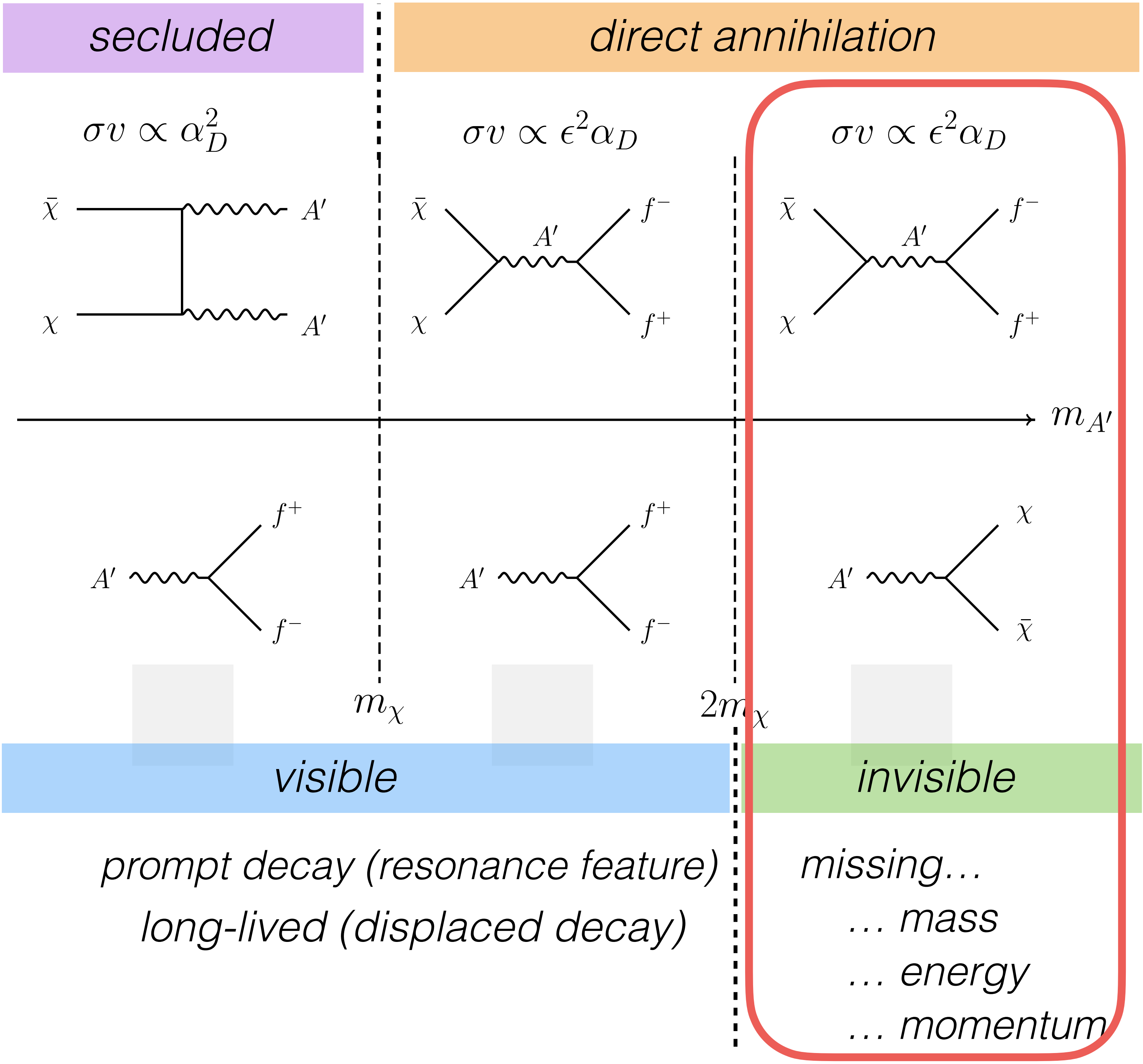


arXiv:1807.01730

LDMX 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

Signatures



secluded

direct annihilation

$\sigma v \propto \alpha_D^2$

$\sigma v \propto \epsilon^2 \alpha_D$

$\sigma v \propto \epsilon^2 \alpha_D$

visible

invisible

prompt decay (resonance feature)

long-lived (displaced decay)

missing…

… mass

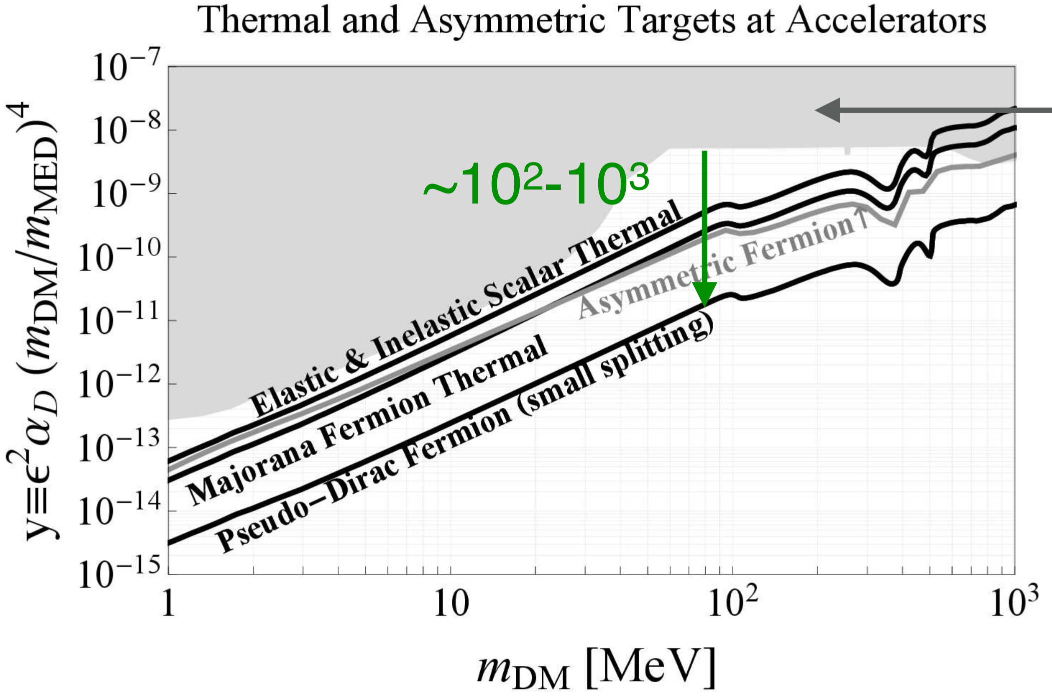
… energy

… momentum

Accelerator vs direct detection

US Cosmic Visions 2017 Community Report

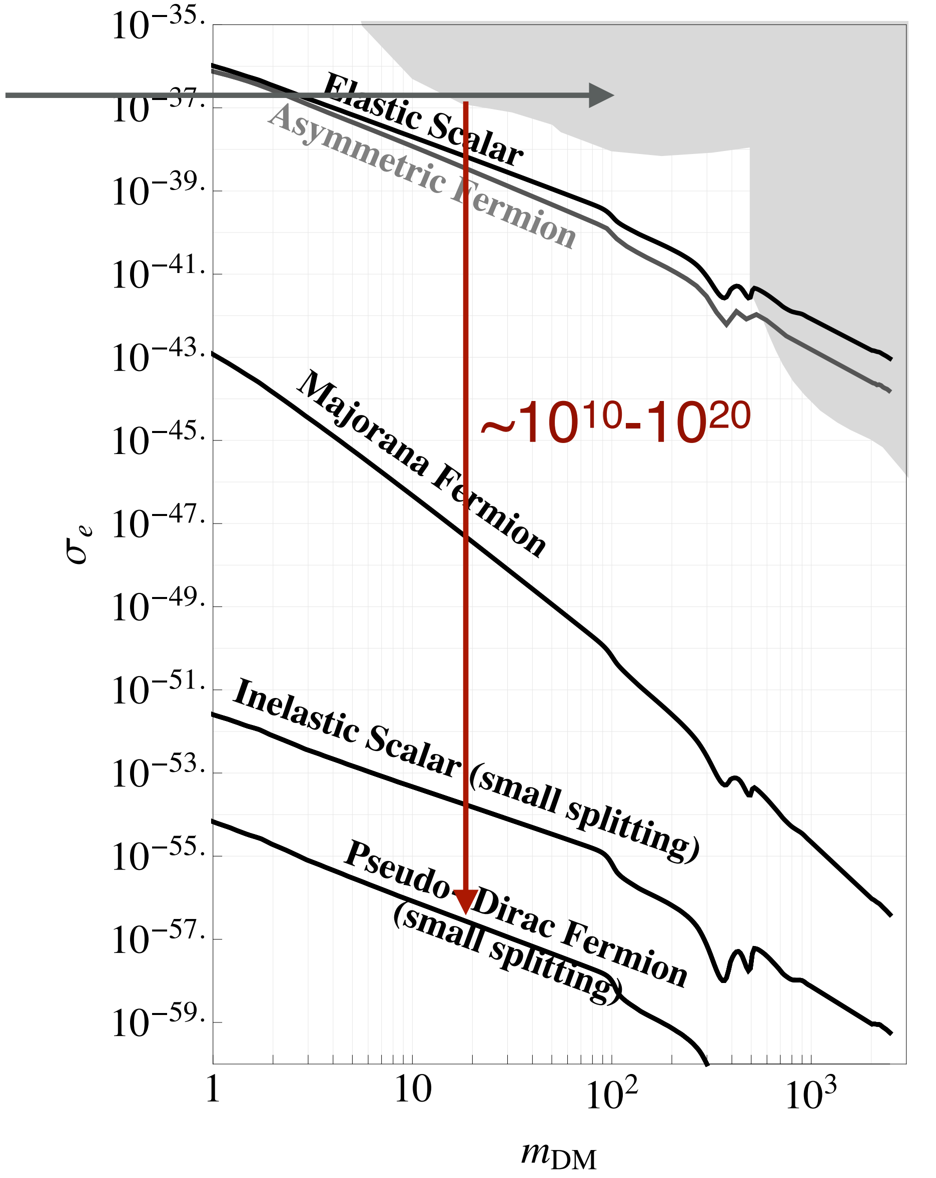
Accelerator targets



Thermal and Asymmetric Targets at Accelerators

current constraints

Direct detection targets



Thermal and Asymmetric Targets for DM−e Scattering

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