Exploring light dark matter with the LDMX experiment

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Caltech

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Outline

Introduction

Light thermal dark matter
Direct detection and accelerators

Light dark matter at accelerators

Collider, fixed target and beam dump experiments
A few recent results

The LDMX proposal

Design and sensitivity
Physics program
Beamlines

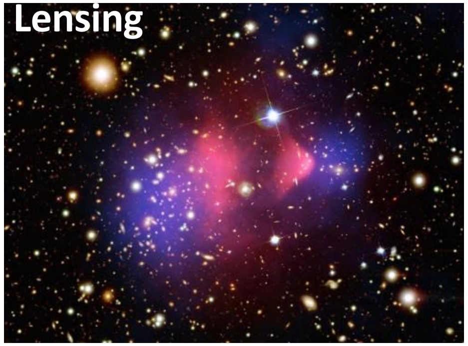
Summary

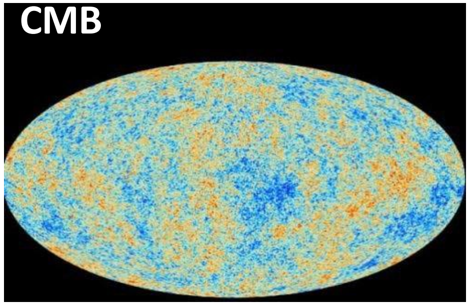
Dark matter: an old puzzle

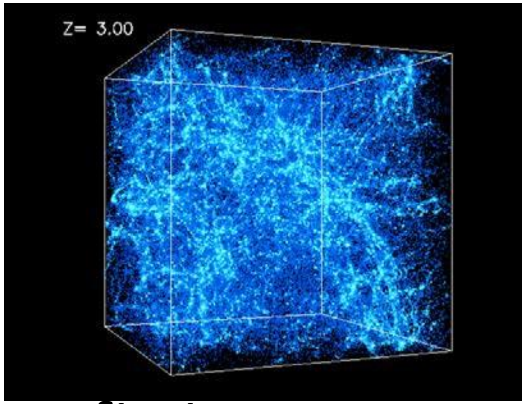
In 1933, Fritz Zwicky posited the existence of unseen “dark” matter after analyzing the velocity dispersion of galaxies in the coma cluster


Coma cluster SDSS

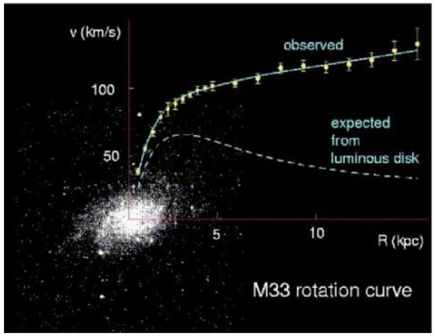
Since then, we have collected strong evidence for dark matter


Lensing


CMB



Structure



Rotation

But we still know very little about its nature

Dark Matter has been found in Victoria, BC

Our Family Of Beers

DARK MATTER
HOYNE PILSNER
ALPHA ACID IPA
HELIOS
VIENNA
APPLETON E.S.B.
DOWN EASY PALE ALE
SUMMER HAZE HONEY HEFE
ENTRE NOUS
WOLF VINE

DARK MATTER

Deep inside the Hadron Collider physicists hurtle sub-atomic particles with lightning speed on a collision course with each other. They do so in the pursuit of pure science, in the hope of one day being able to unlock the mystery of the elusive unseen fabric upon which our universe is embroidered: Dark Matter.

For A Dark Night **Elusive** **Smoooooth**

COLOUR
Light Dark

HOPS
Mild Hoppy

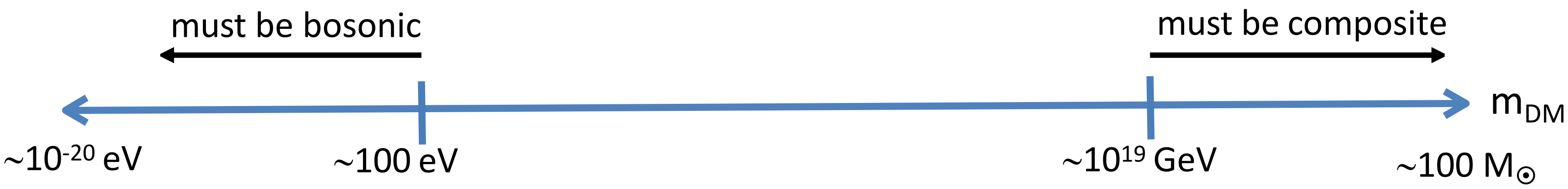
MALT
Pale Roasted

ABV 5.3 **650ml**

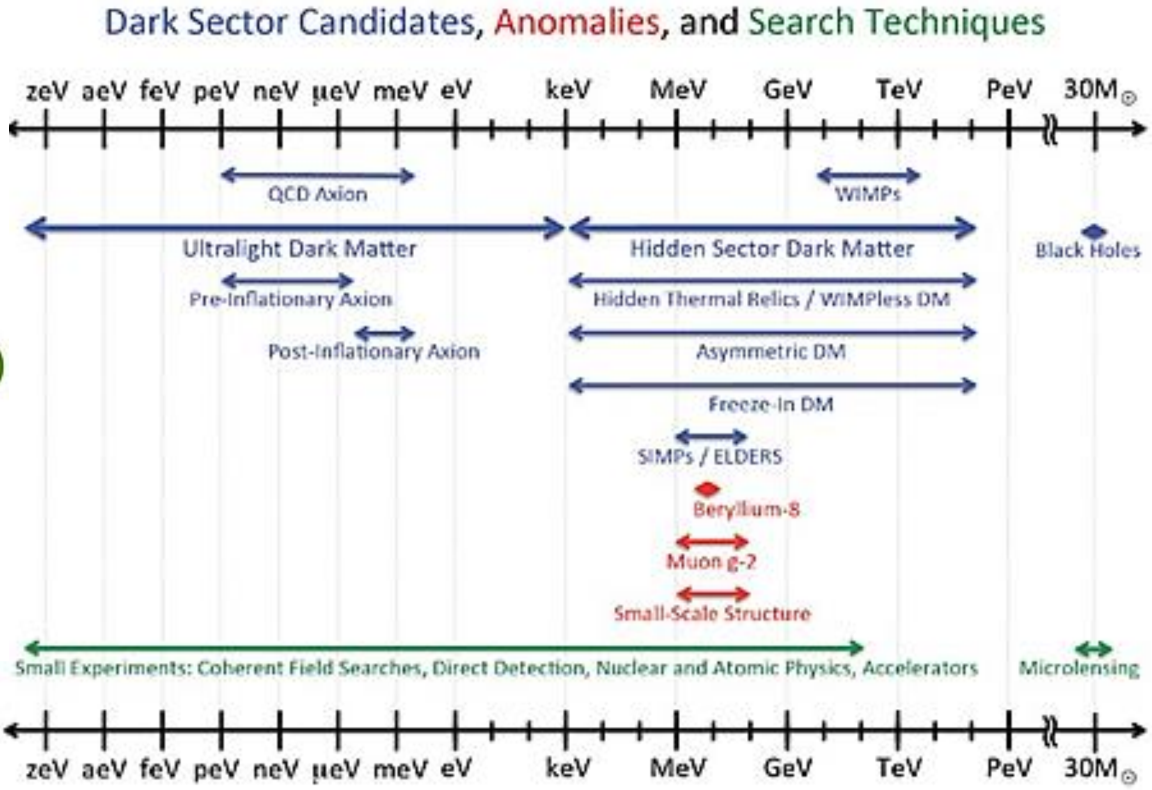
Hops: --
Malts: --
Yeast: --
Specific Gravity: Blackhole

One name, many possibilities

What we know: equation of state (ρ_{DM}), electrically neutral and interacts via gravity.



Bertone and Tait, arxiv:1810.01668



Need to make some assumptions to start addressing the problem!

Thermal dark matter

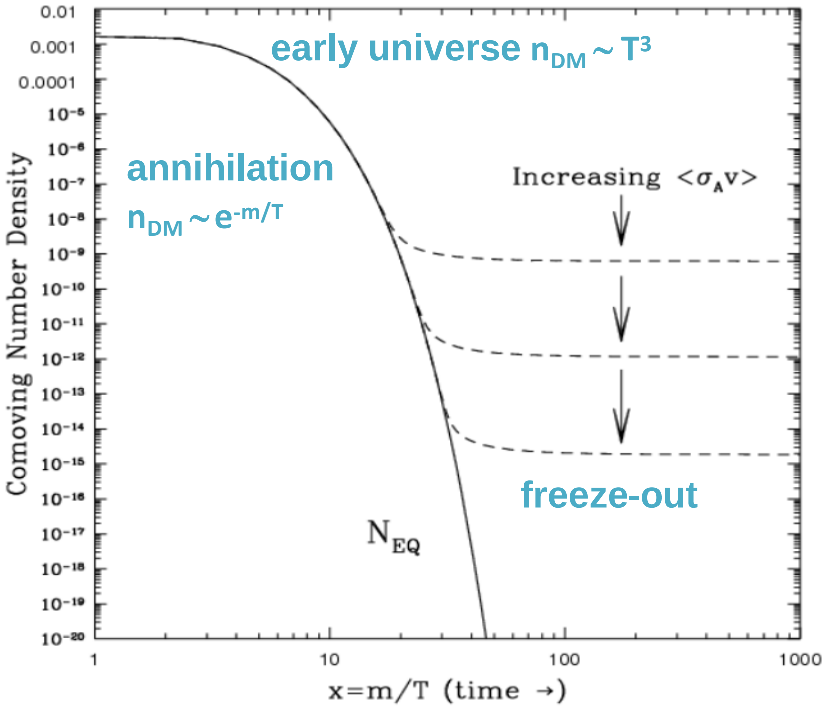
Thermal dark matter, originating as a relic in the early Universe, is arguably one of the most compelling paradigms

Simple: Requires only that the non-gravitational interaction rate between dark and ordinary matter exceed the Hubble expansion rate. Compatible with nearly all UV scenarios

Generic: Applies to nearly all models with coupling large enough to allow detection. The axion is a rare counter example.

Reasonable: There is evidence from the CMB and from BBN for a hot and dense thermal phase of the early Universe.

Predictive: The DM mass and coupling to the SM set the abundance → target



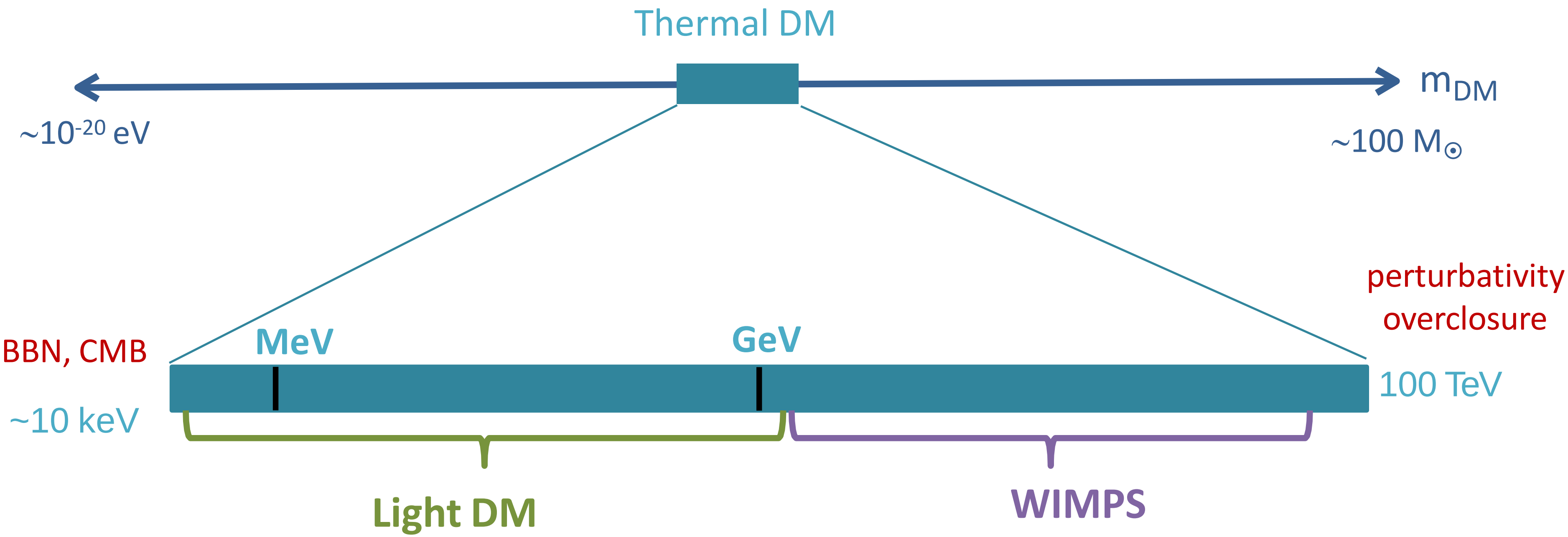
Thermal DM

$\sigma v_{sym} \sim 3\text{x}10^{-26}\ \text{cm}^3\text{s}^{-1}$ (symmetric)
$\sigma v_{asym} > 3\text{x}10^{-26}\ \text{cm}^3\text{s}^{-1}$ (asymmetric)

There is a target

Thermal dark matter

The thermal hypothesis also greatly restricts the range of allowed masses



Thermal DM

m_{DM}

~10^{-20} eV

~100 $M_\odot$

perturbativity
overclosure

BBN, CMB

MeV

GeV

~10 keV

100 TeV

Light DM

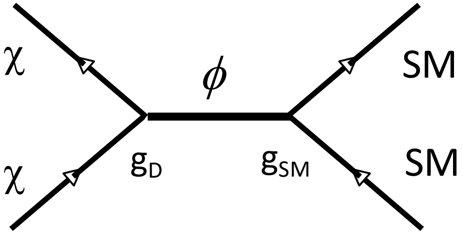
WIMPS

Thermal contact implies a new mediator
Hidden sector light DM model is well-motivated

Thermal freeze-out for weak scale masses
Has driven DM searches for last ~30 years

Light thermal dark matter

A freeze-out scenario with light dark matter (χ) requires a new light mediator to explain the relic density, or else dark matter would be overproduced



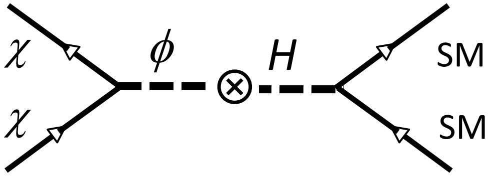
$$< \sigma v >_{relic} \sim \frac{g_D^2 \, g_{SM}^2 \, m_x^2}{m_\varphi^4} \qquad (m_\varphi \gg m_x)$$

$$m_f^4 \sim \frac{g_D^2 \, g_{SM}^2 \, m_x^2}{<\sigma v>} \leq \frac{m_x^2}{<\sigma v>} \qquad \text{since } g \leq O(1)$$

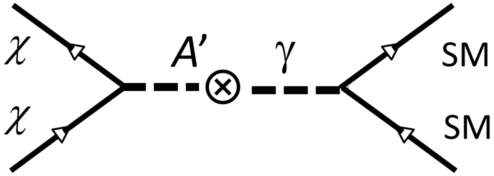
What kind of mediator?

Must be neutral under the SM and renormalizable. The simplest choices:

New scalar (ϕ) with Higgs coupling



New vector (A') with photon coupling



These are naturally realized in the context of hidden sectors.

The vector portal is much less constrained that the scalar, so focus on this possibility.

Dark sector and vector portal

Dark sectors (DS)

- New particles that don't couple directly to the Standard Model.
- Theoretically motivated: string theory and many other BSM scenarios (*e.g.* EW symmetry breaking) include dark sectors

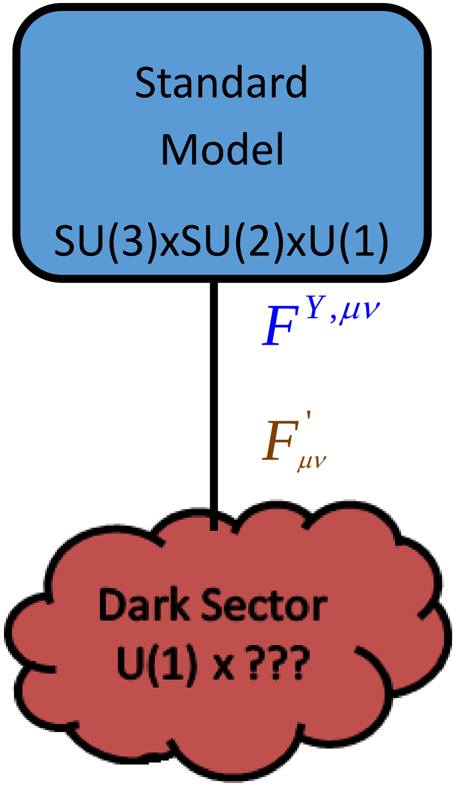
Vector portal

- Dark sector with a new gauge group U(1)' and a corresponding gauge boson, the dark photon *A'*
- There is a generic interaction of the following form with the SM (kinetic mixing)

$$\Delta\mathcal{L} = \frac{\varepsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

between the SM hypercharge and U(1)' fields with a mixing strength ε

- After EWSB, there is a coupling between the dark photon and the photon (as well as the *Z*)



Standard Model

SU(3)xSU(2)xU(1)

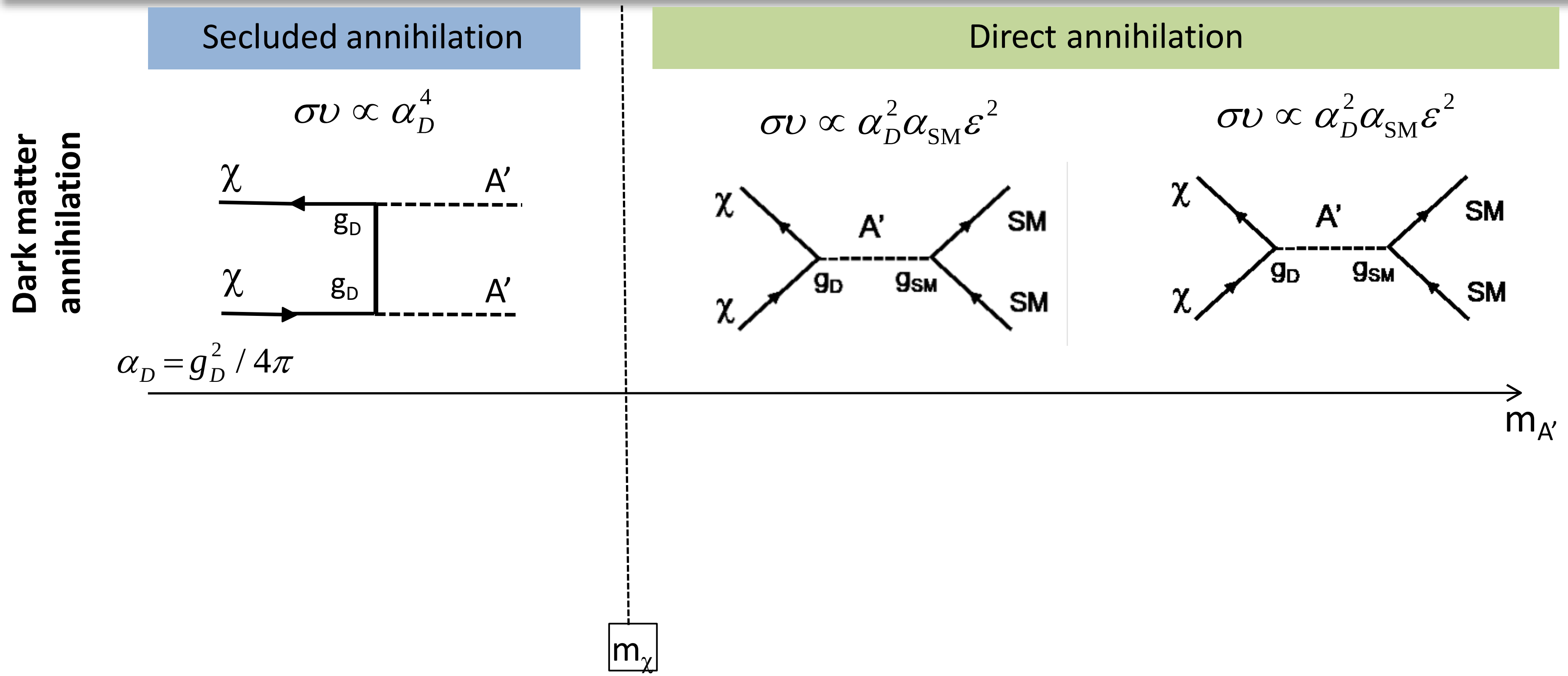
$F^{Y,\mu\nu}$

$F'_{\mu\nu}$

Dark Sector
U(1) x ???

dark photon – SM fermion coupling with strength $\alpha' = \varepsilon^2\alpha$

Light DM production and decay



Secluded annihilation

$\sigma\upsilon \propto \alpha_D^4$

$\alpha_D = g_D^2 / 4\pi$

Direct annihilation

$\sigma\upsilon \propto \alpha_D^2 \alpha_{\mathrm{SM}} \varepsilon^2$

$\sigma\upsilon \propto \alpha_D^2 \alpha_{\mathrm{SM}} \varepsilon^2$

Production and decay

Secluded annihilation

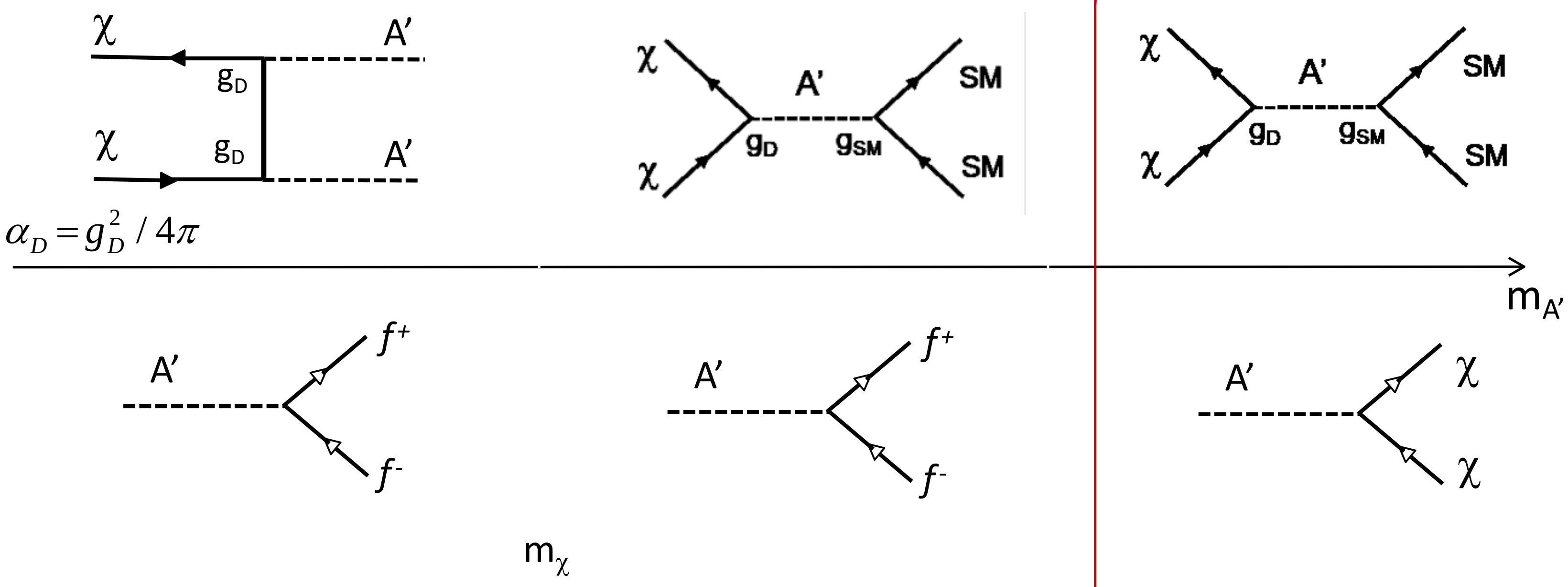
Direct annihilation

Dark matter annihilation

$\sigma v \propto \alpha_D^4$

$\sigma v \propto \alpha_D^2 \alpha_{\mathrm{SM}} \varepsilon^2$

$\sigma v \propto \alpha_D^2 \alpha_{\mathrm{SM}} \varepsilon^2$



$\alpha_D = g_D^2 / 4\pi$

Dark photon decay

Visible decay

$2m_\chi$

Invisible decay

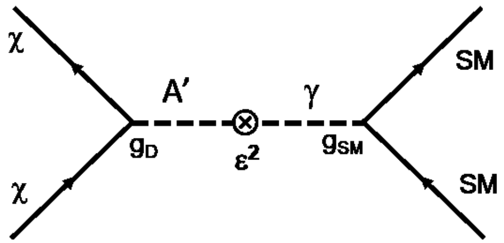
Prompt or displaced decay
Resonance feature

Missing …
… mass
… energy
… momentum

LDMX Representative benchmark scenarios

Hidden sector thermal LDM with a vector portal

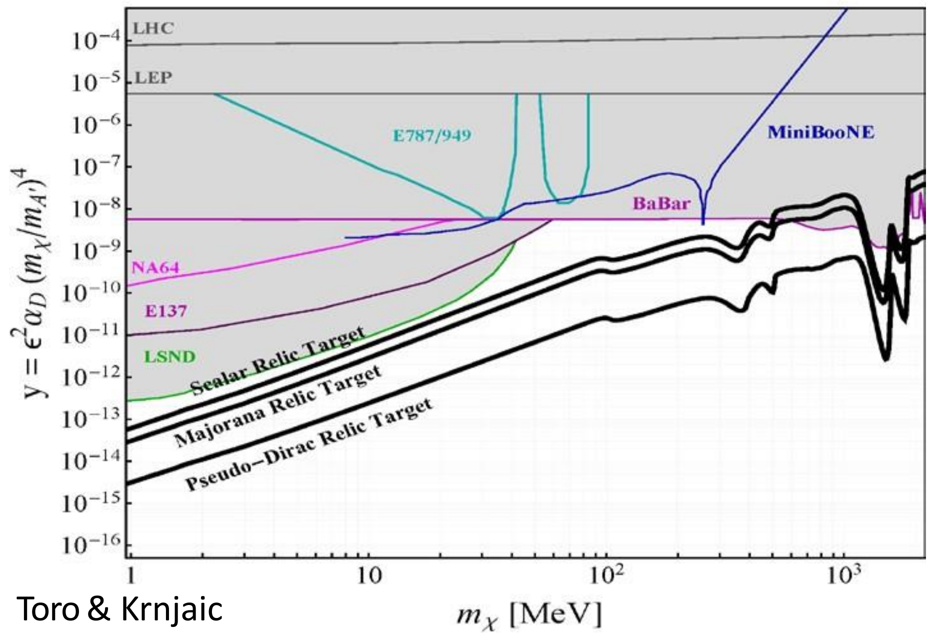
Dark photon *A'* kinetic mixing with strength ε



$$<\sigma\upsilon> \sim \alpha_D \varepsilon^2 \frac{m_x^2}{m_A^4} \sim y\frac{1}{m_x^2}$$

Dimensionless variable

$$y=\alpha_D\varepsilon^2\frac{m_x^4}{m_A^4}$$



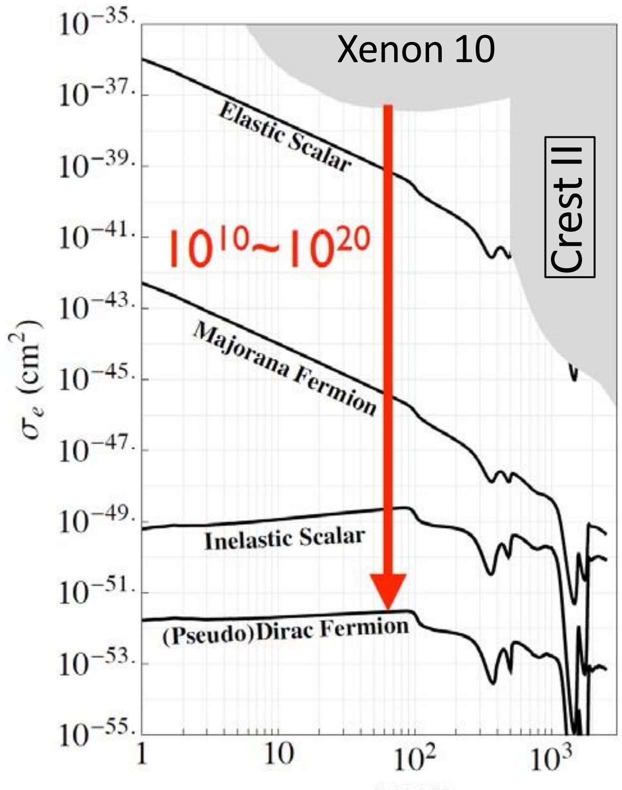
Toro & Krnjaic

Conservative assumptions (α_D = 0.5 and m_A/m_χ = 3) made for plotting constraints from missing mass / momentum / energy experiments.

Definitive predictions as a function of mass and particle type

Why not direct detection?

Direct detection targets



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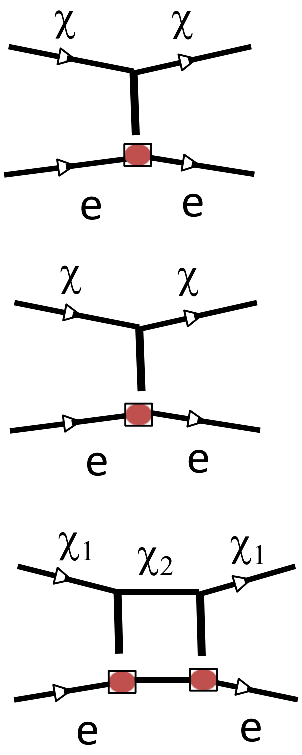


SCALAR

$\sigma_e \sim 10^{-39}$ cm^2

MAJORANA

$\sigma_e \sim 10^{-39} v^2$ cm^2 $\quad v \sim 10^{-3}$

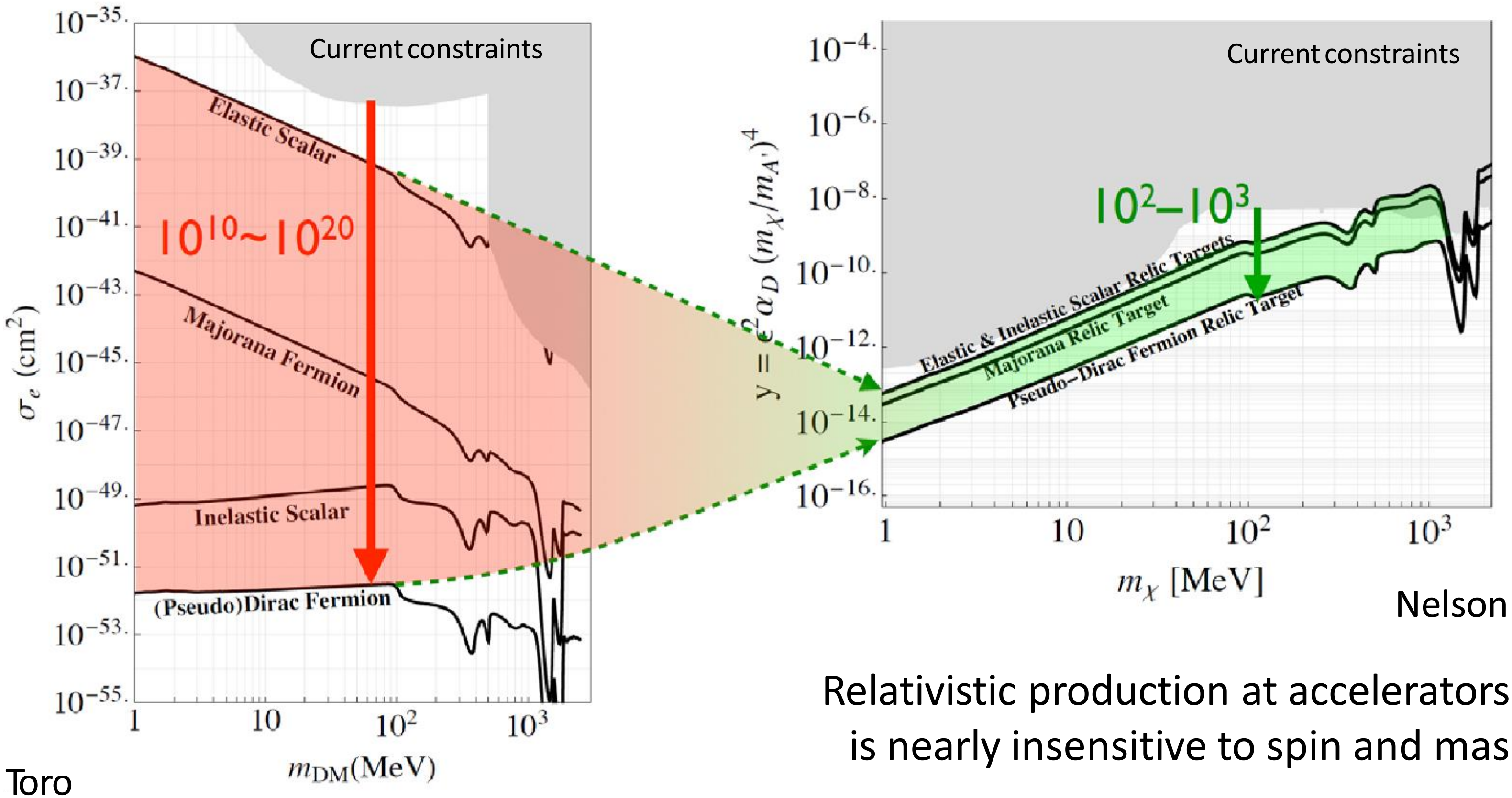
INELASTIC

$\sigma_e \sim 10^{-50}$ cm^2 loop diagram

Is there a way to put these on the same footing?

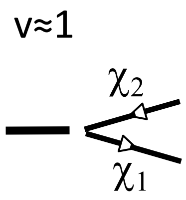
Why not direct detection?

Direct detection targets **Accelerator targets**



Toro

Nelson



Relativistic production at accelerators is nearly insensitive to spin and mass

Accelerators are uniquely positioned to probe directly annihilating thermal LDM

More generally…

The scope of accelerator-based experiments is much more extensive, and encompasses models such as

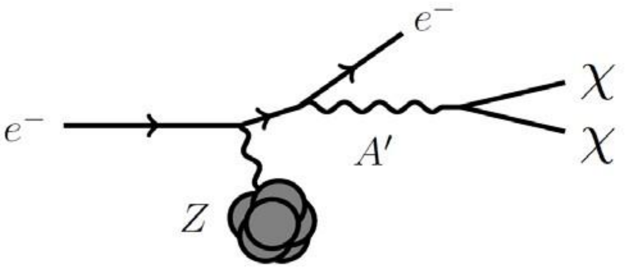
- Quasi-thermal DM, such as asymmetric DM and ELDER DM
- New long-lived resonances produced in the dark sector (SIMP)
- Freeze-in models with heavy mediators
- New force carriers coupling to electrons, decaying visibly or invisibly
- Milli-charged dark sector particles
- ….

In essence, exploring physics that couples to electrons in the sub-GeV mass range is well-motivated and important, and accelerator based experiments can generically probe a vast array of possibilities in addition to light thermal DM.

Light dark matter at accelerators

Maximizing dark matter sensitivity

Missing energy / momentum



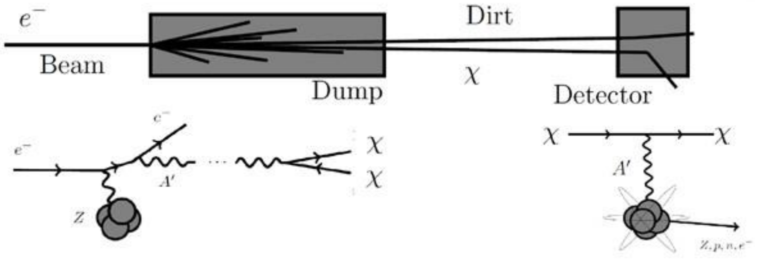
$\sigma \sim Z^2 \varepsilon^2 / m_A^2$

Large production yield for low mediator masses

Large “detection yield”

NA64
LDMX

Beam dump



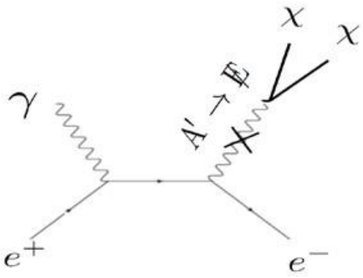
$\sigma \sim \alpha_D \varepsilon^4$

Probe dark sector coupling

Process suppressed by ε^4

E137
BDX
MiniBooNE
SHiP

Colliders



$\sigma \sim \varepsilon^2/s$ $m_A \ll s$
$\sigma \sim \varepsilon^2/(s-m_A^2)$ $m_A \sim s$

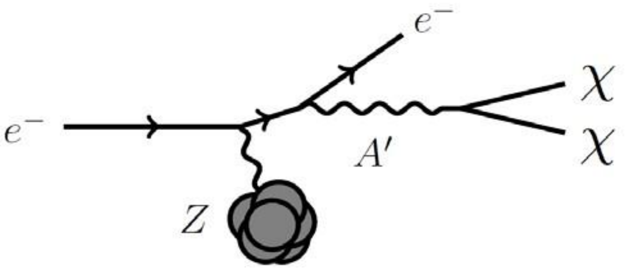
Large production yield on resonance

Best yield at high masses

BABAR
Belle II
PADME
LHCb (prompt)

Maximizing dark matter sensitivity

Missing energy / momentum



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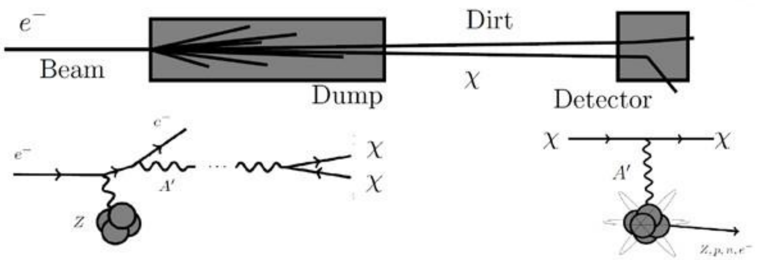

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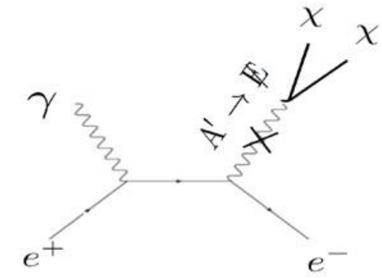
Probe dark sector coupling

Process suppressed by ε^4

Colliders



$\sigma \sim \varepsilon^2/s \qquad m_A << s$

$\sigma \sim \varepsilon^2/(s-m_A^2) \quad m_A \sim s$

Large production yield on resonance

Best yield at high masses

Accelerators can explore the physics in detail (ε, $m_{A'}$, m_χ, α_D),

direct detection needed to establish cosmological stability

Colliders

BABAR @ PEP II

Search for $e^+e^- \rightarrow \gamma A', A' \rightarrow$ invisible by tagging the recoil photon in "single photon" events.

Requires single photon trigger, only with a small fraction of the data (53 fb^{-1})

Exclude dark photon as explanation of $(g\text{-}2)_\mu$ anomaly

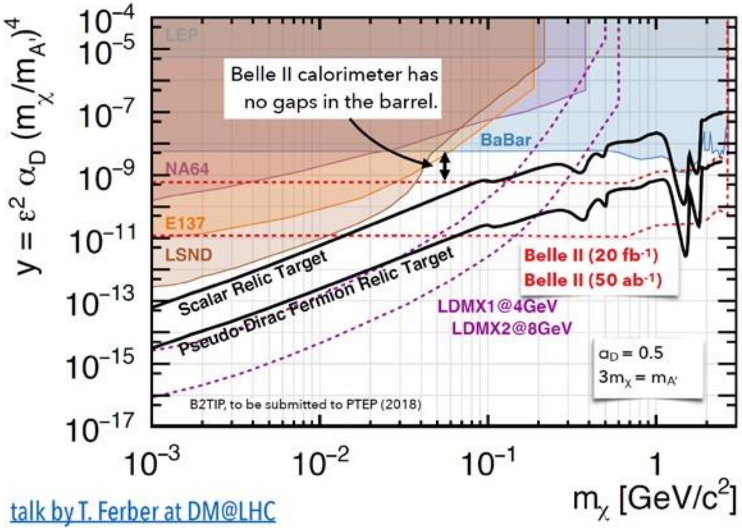
BABAR @ PEP II

BELLE II @ SuperKEKB

Search for same final state

Much larger data set (50 fb^{-1}) by 2027
Phase II (partial detector) ended last summer.
Phase III with complete detector will start next summer.

Belle II projected sensitivity



talk by T. Ferber at DM@LHC

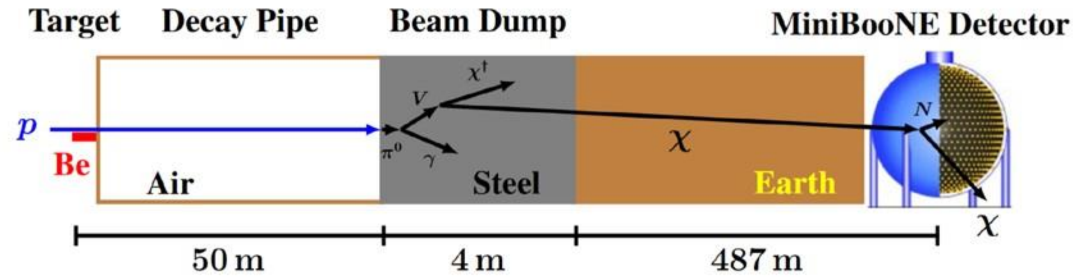
Proton beam dump

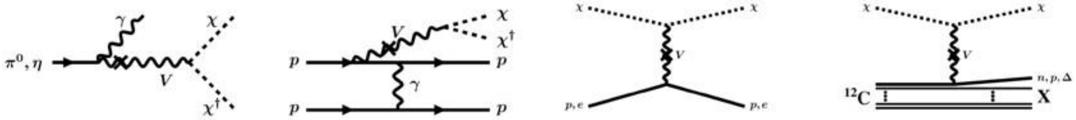
MiniBooNE

Probes quark coupling to dark matter

First dedicated dark matter search in proton beam dump experiments in 2013-2014 with 1.86 x 10^{20} POT

Bypass target to minimize neutrino production and use timing to further reject background





(a) Meson Decay

(b) Proton Bremsstrahlung + Vector-Mixing

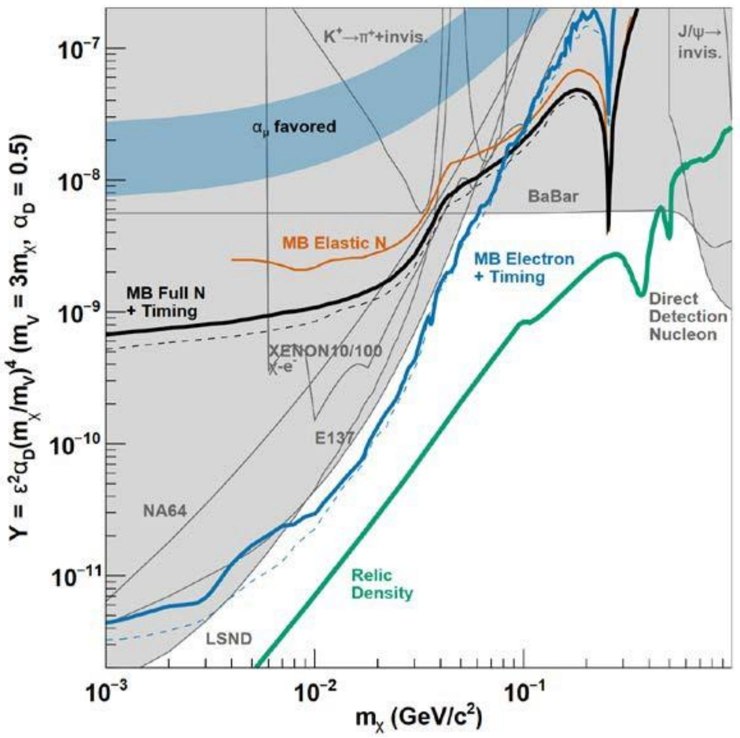
(a) Free Protons or Electrons

(b) Bound Nucleons

Production scales as ε^2

Detection scales as $\alpha_D \varepsilon^2$

Phys. Rev. D 98, 112004 (2018)

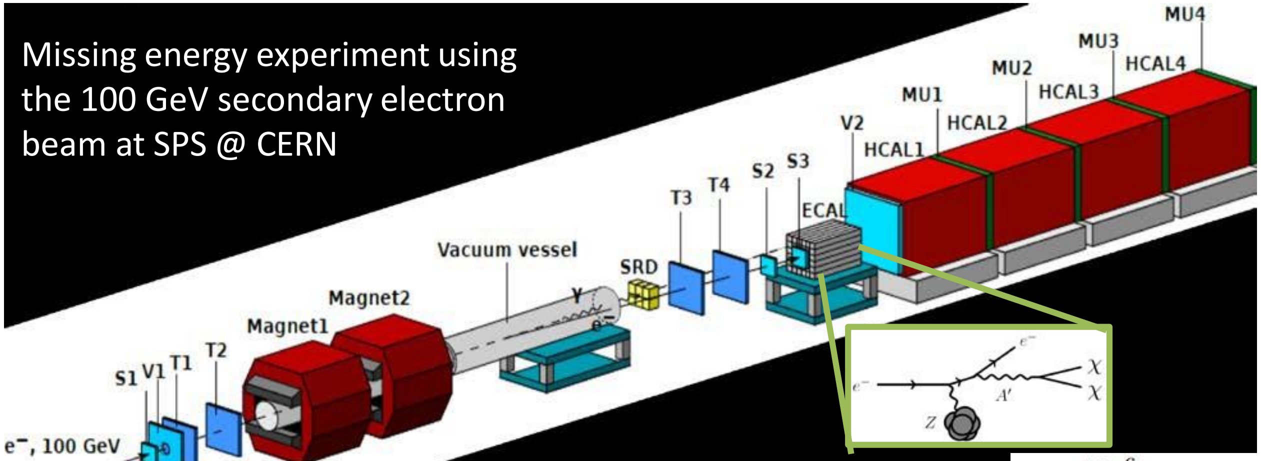


Proposal to continue DM searches with SBN program to improve by ~ an order of magnitude

SHiP, T2K, DUNE,… will also probe the vector and baryonic portals.

Missing energy

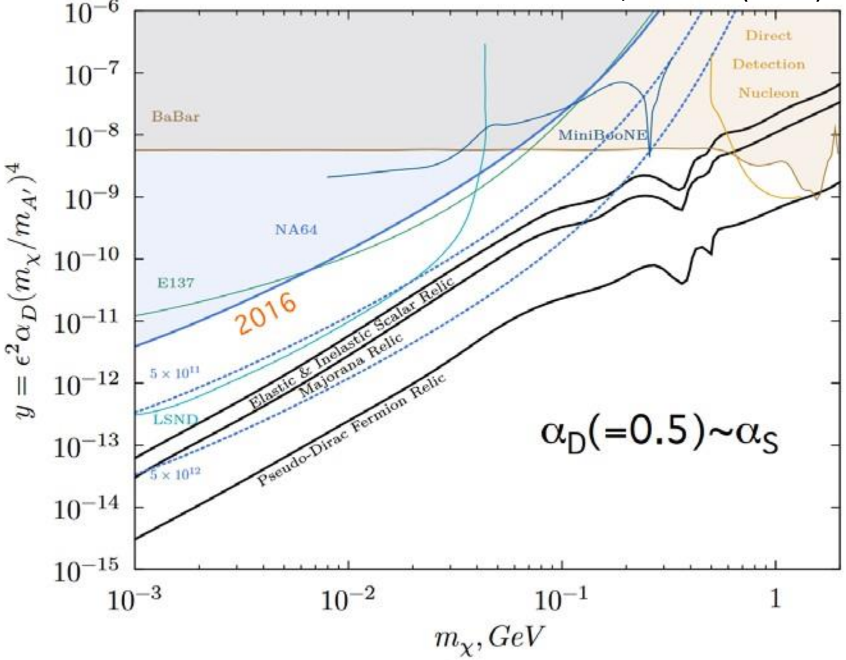
NA64 at CERN



Missing energy experiment using the 100 GeV secondary electron beam at SPS @ CERN

- Tracking system to identify 100 GeV e^-
- ECAL as active target
- HCAL and muon detector to veto hadronic reactions

PRD 97, 072002 (2018)



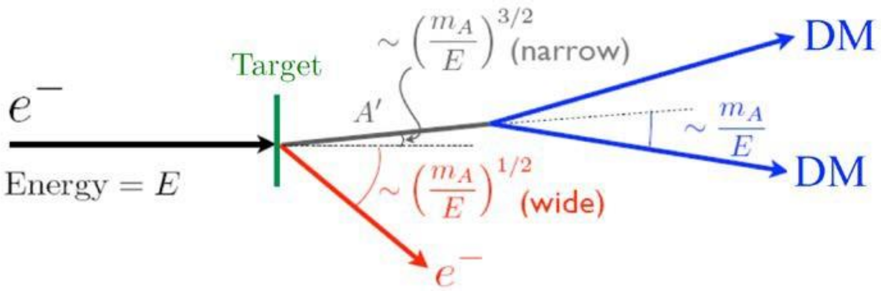
Results and future runs

2016 - 4.3×10^{10} EoT
2017 - 5.0×10^{10} EoT
2018 - $\sim 2 \times 10^{11}$ EoT

Approved run in 2021, goal 3×10^{11} EoT

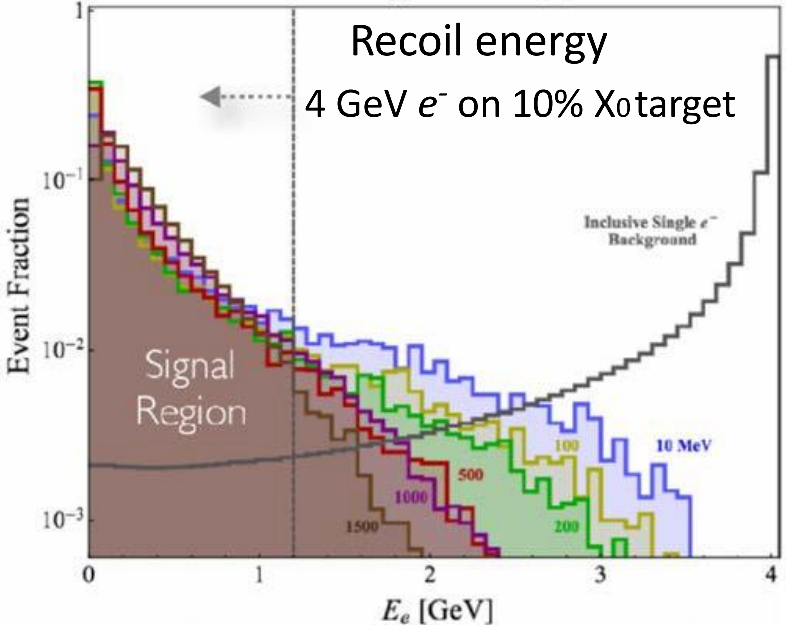
The missing momentum approach: The LDMX experiment

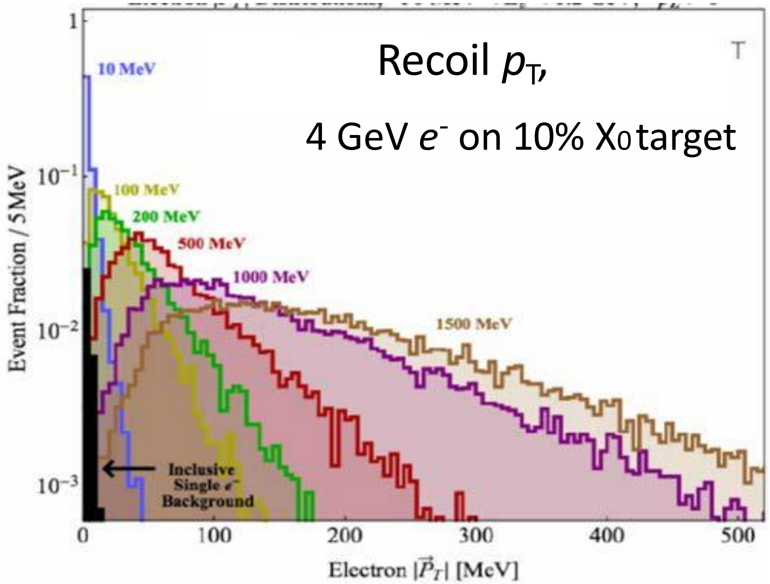
Missing momentum kinematics



$$\frac{d\sigma}{dx} \propto \frac{\alpha^3}{\pi} \frac{\epsilon^2}{m_e^2 \cdot x + \boxed{m_A^2(1-x)/x}}$$

$$x = \frac{E_A}{E}$$



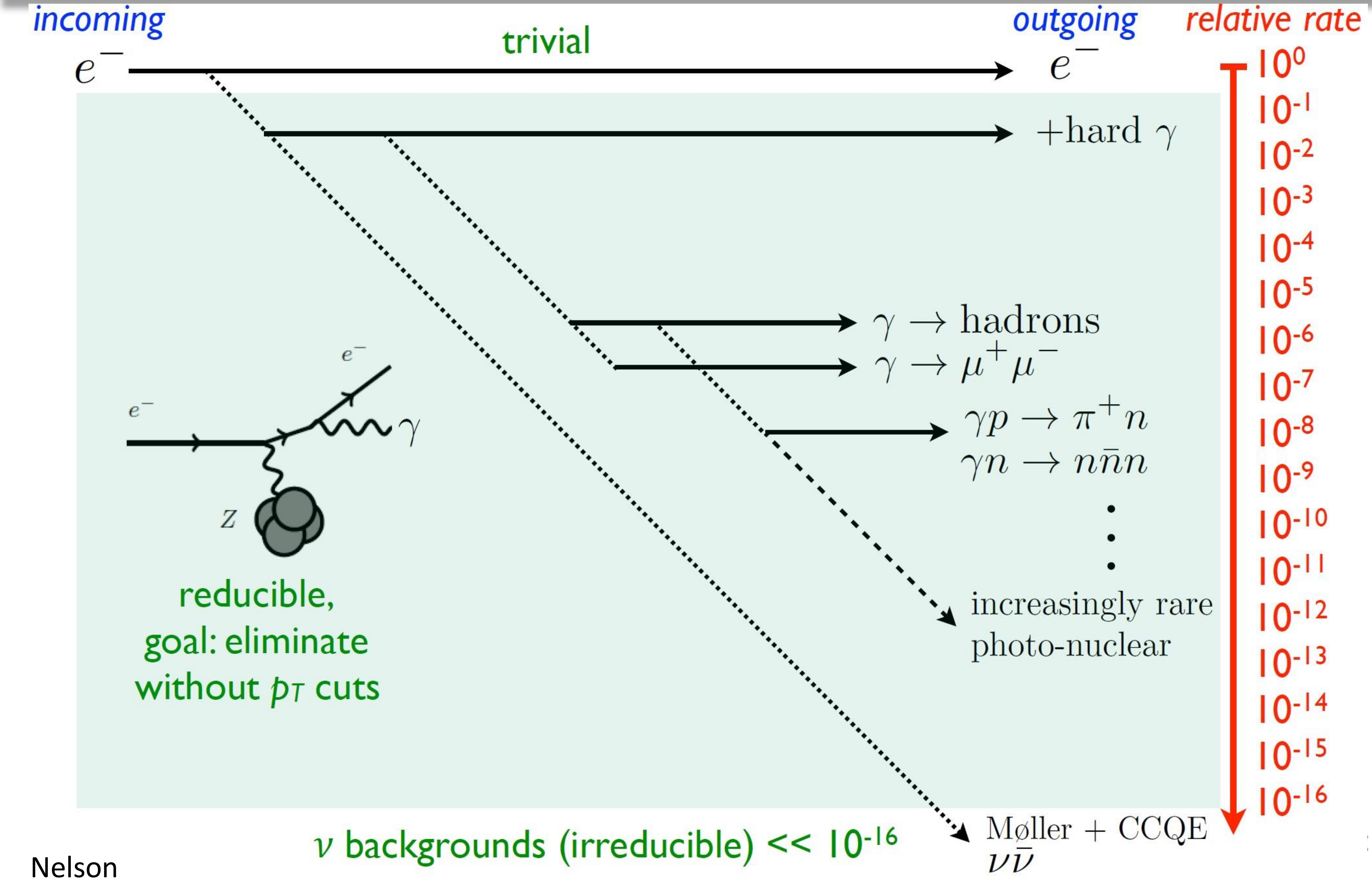


The kinematics is very different from bremsstrahlung

The *A'* is emitted at low angle and carries most of the energy:

- large missing energy, soft recoil electron
- large missing p_T, large angle recoil electron

Backgrounds



+hard γ

$\gamma \to$ hadrons

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

$\gamma p \to \pi^+ n$

$\gamma n \to n\bar{n}n$

⋮

increasingly rare photo-nuclear

Møller + CCQE

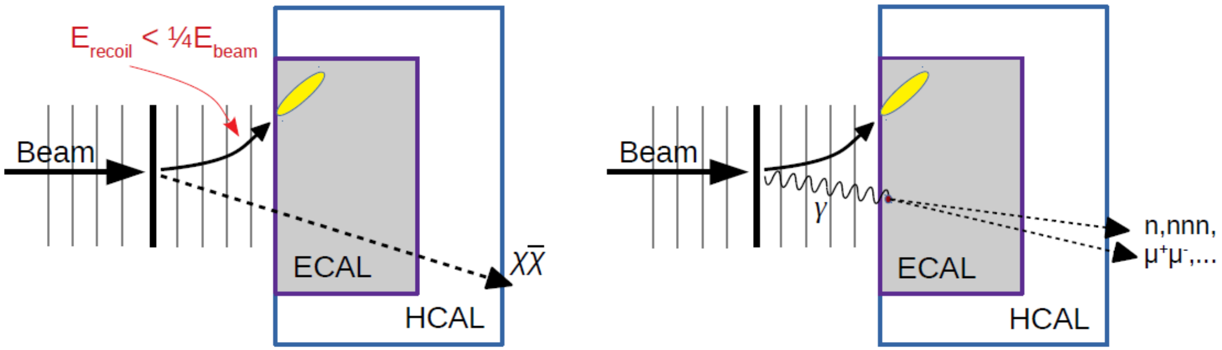
$\nu\bar{\nu}$

reducible,
goal: eliminate
without p_T cuts

ν backgrounds (irreducible) << 10^{-16}

Nelson

A missing momentum design



Beam must allow individual reconstruction of each incident electron

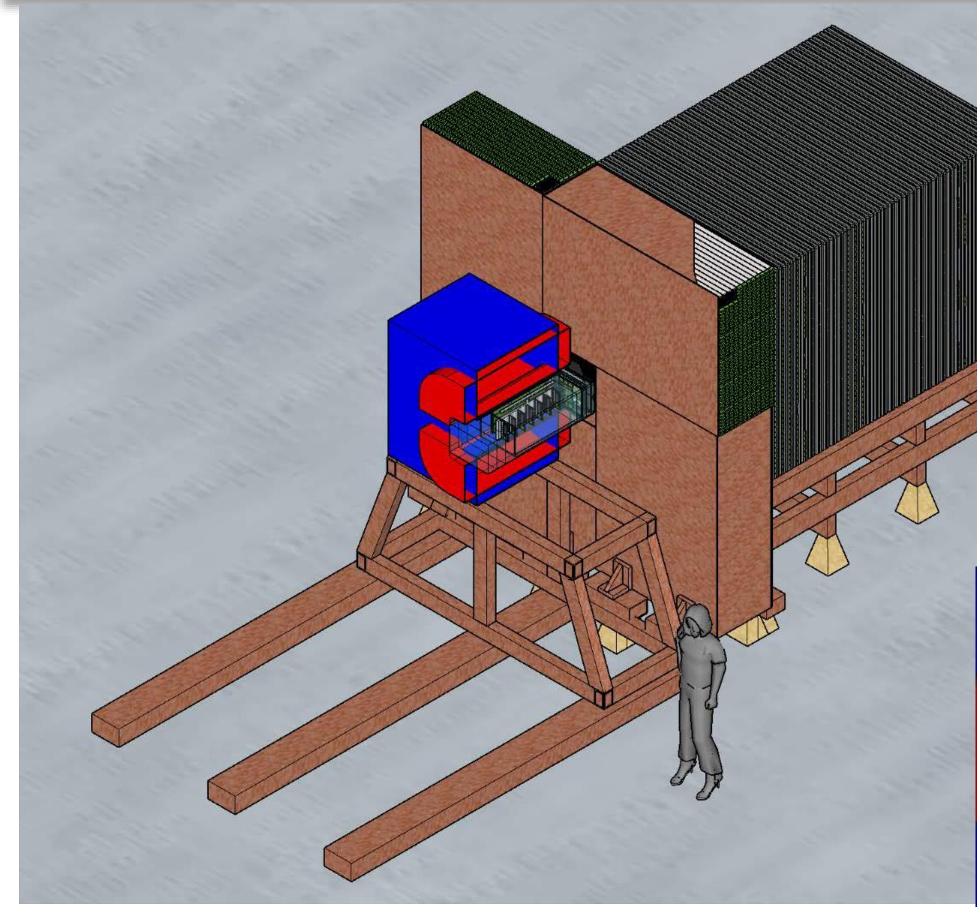
- A multi-GeV, low-current, high repetition rate (10^{16} EOT / year ≈ 1 *e* / 3 ns) beam with a large beam spot to spread out the occupancy / radiation dose.
- Potential beamlines: S30XL @ SLAC, e-SPS @ CERN or CEBAF @ JLab.

Detector technology with high rate capabilities and high radiation tolerance

- Fast, low mass tracker with good momentum resolution to tag each electron
- Fast, granular, radiation-hard EM calorimeter, and hermetic HCAL veto

The LDMX experiment is designed to realize these requirements in two phases: Phase-I with 10^{14} EOT, and Phase-II with 10^{16} EOT

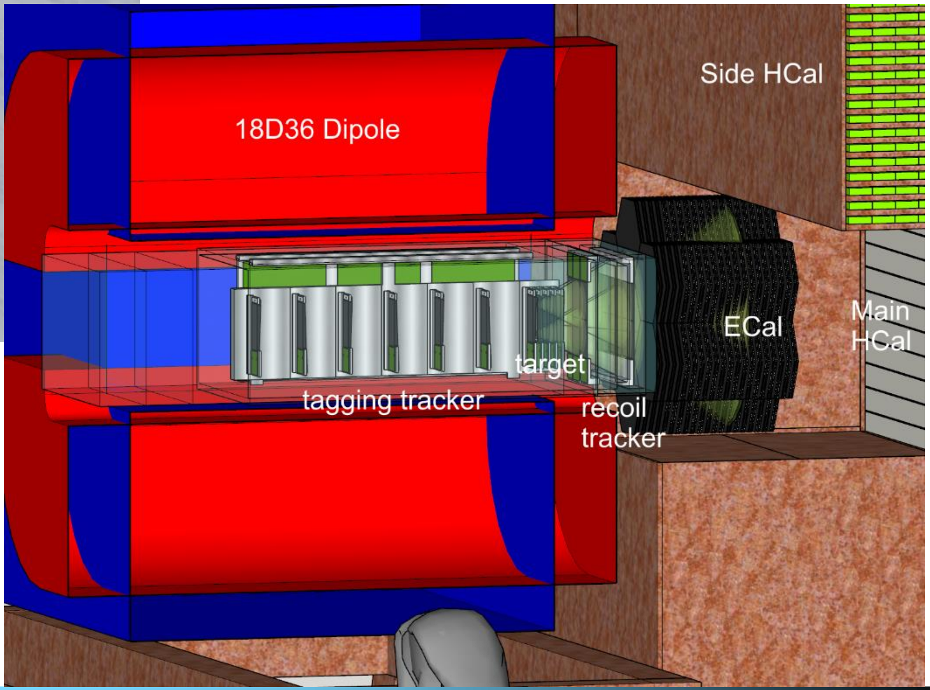
LDMX detector concept – Phase I



The LDMX detector

- Magnet: existing 18D36 dipole at SLAC
- Tracking: Silicon Vertex Tracker of HPS
- ECal: CMS high-granularity calorimeter
- HCal: scintillator/steel sampling calorimeter based on Mu2e CRV

LDMX Whitepaper arxiv:1808.05219



Tracking system

Two tracking systems:

- Tagging tracker to measure incoming e^-
- Recoil tracker to measure scattered e^-

Single dipole magnet, two field regions

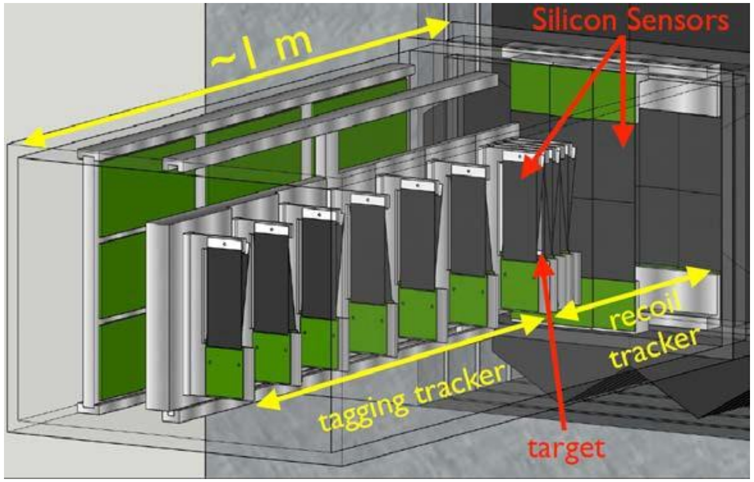
- Tagging tracker is placed in the central region for $p_e = 4$ GeV,
- Recoil tracker is in the fringe field for $p_e \sim 50 - 1200$ MeV

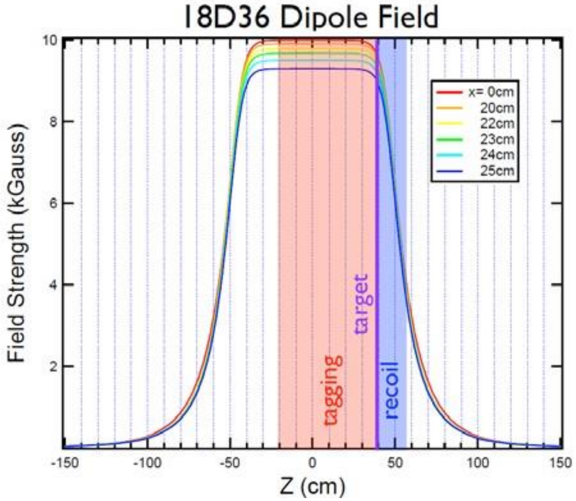
Silicon tracker is similar to the HPS SVT

- Fast (2ns hit time) and radiation hard

Tungsten target is between the two trackers

- $\sim 0.1 X_0$ thickness to balance between signal rate and good momentum resolution
- Scintillator pads at the back of target to veto empty events





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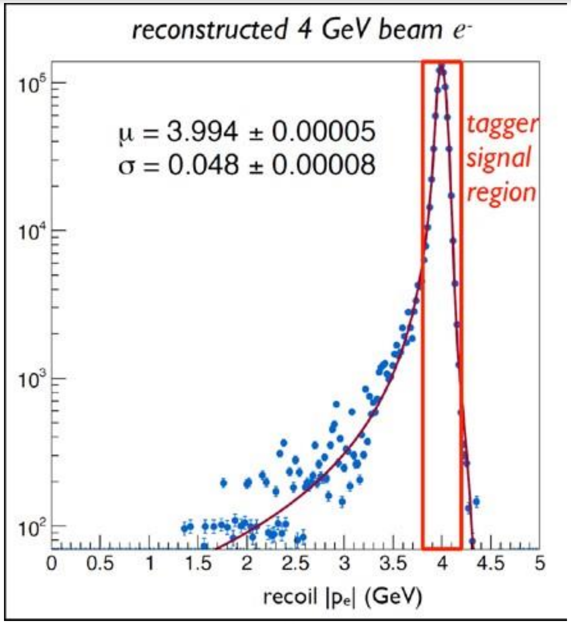
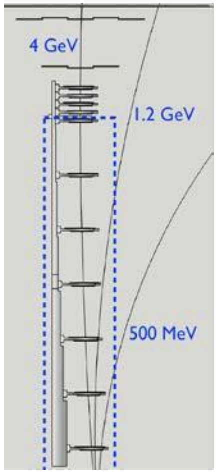
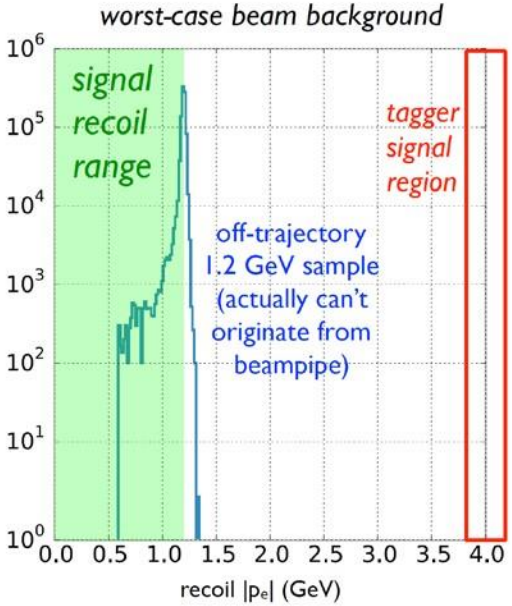
- Scintillator pads at the back of target to veto empty events







Tagging tracker efficiently rejects beam-induced background

Tracking system

Two tracking systems:

- Tagging tracker to measure incoming e^-
- Recoil tracker to measure scattered e^-

Single dipole magnet, two field regions

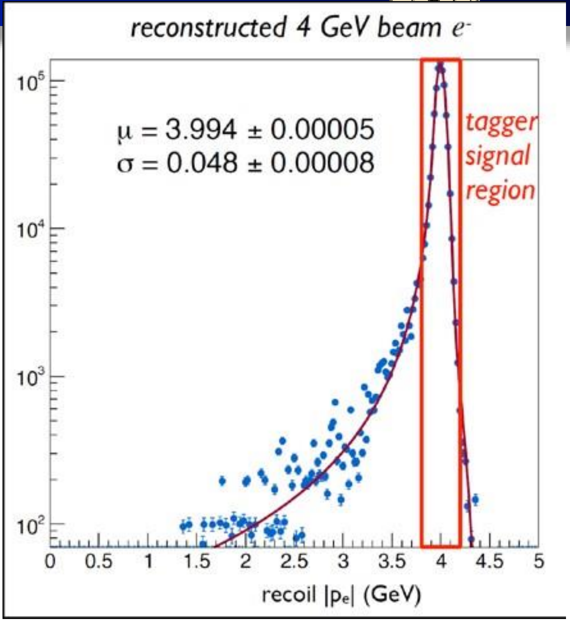
- Tagging tracker placed in the central region for $p_e = 4$ GeV,
- Recoil tracker in the fringe field for $p_e \sim 50 - 1200$ MeV

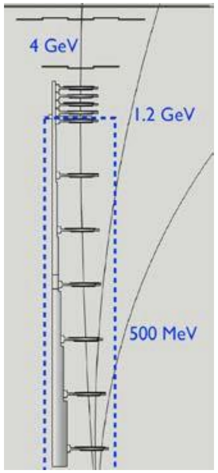
Silicon tracker similar to HPS SVT

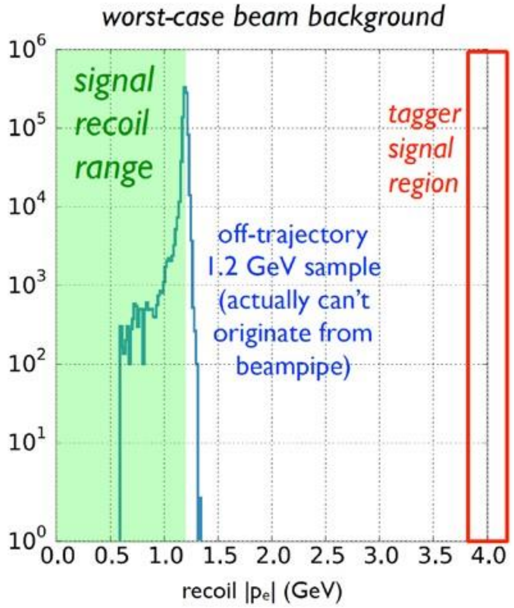
- Fast (2ns hit time) and radiation hard

Tungsten target between the two trackers

- ~0.1X_0 thickness to balance between signal rate and momentum resolution
- Scintillator pads at the back of target to veto empty events



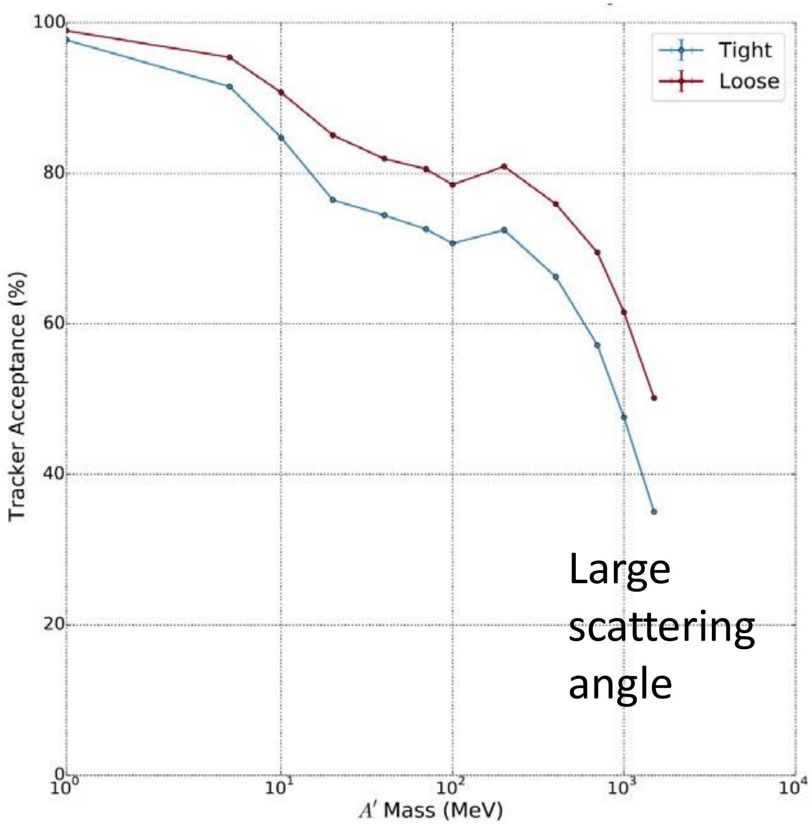




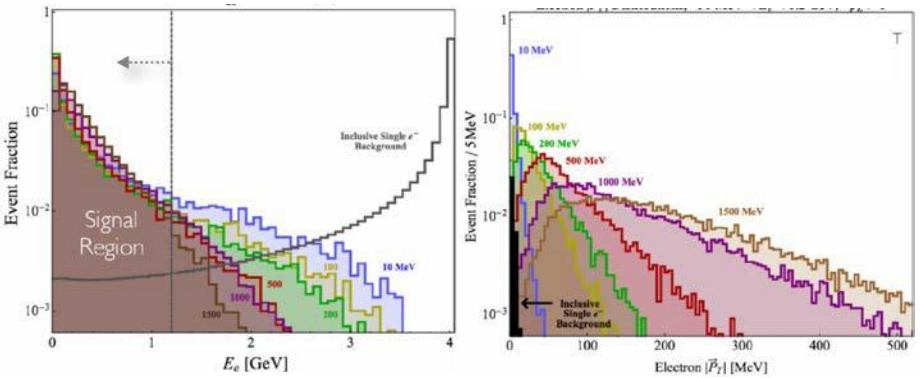
Tagging tracker efficiently rejects beam-induced background

Tracking system performance

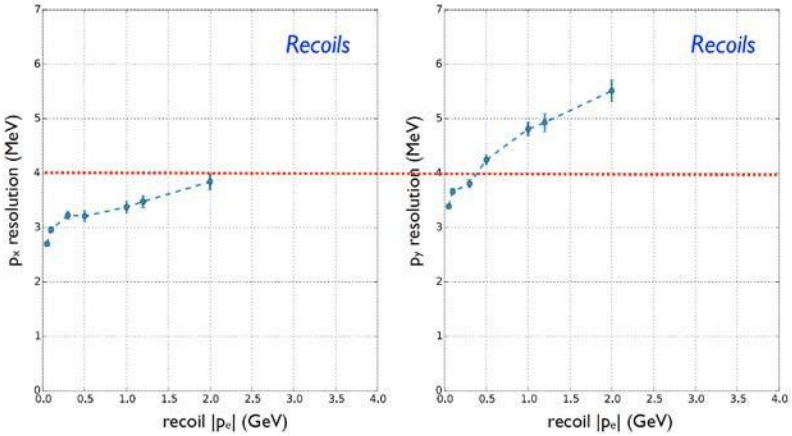
Acceptance for recoil electrons



Large scattering angle

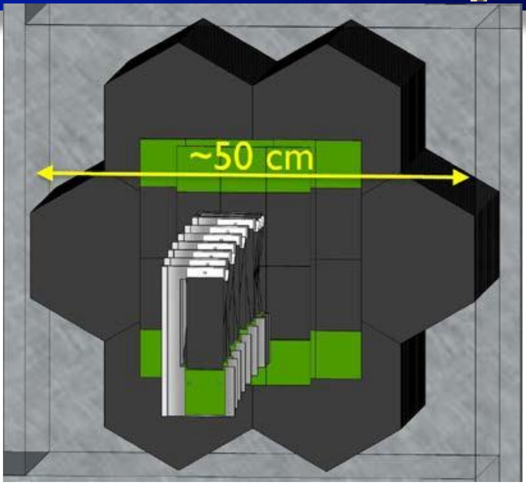


Recoil momentum resolution (p_x, p_y)



Good acceptance, limited at high masses by kinematics (large angle scattering),
Recoil momentum resolution is limited by multiple scattering in target

EM calorimeter



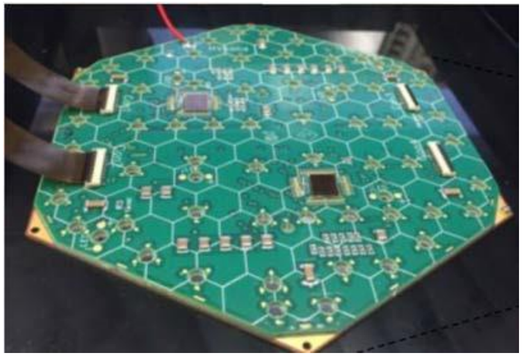
The electromagnetic calorimeter is a Si-W sampling design

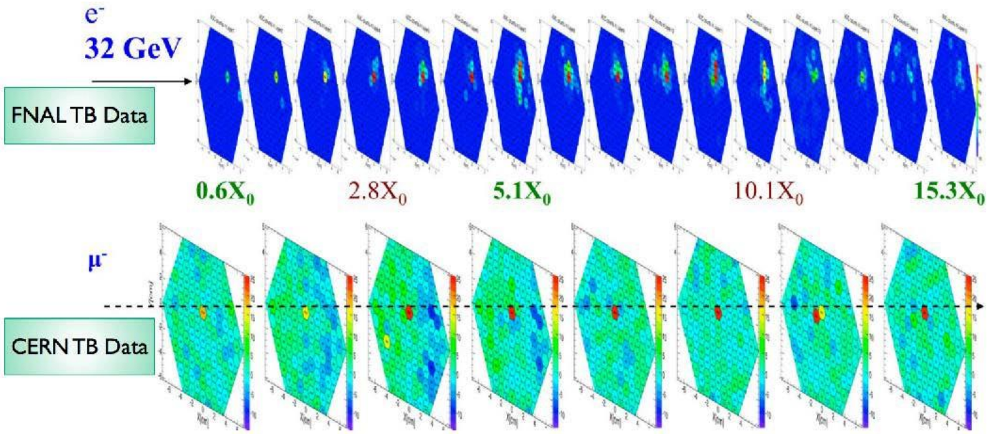
Based on the CMS ECal upgrade, adapted to LDMX

- Fast, dense and radiation hard
- ~40X_0 deep for fu;; shpwer containment
- High granularity, allows us toexploit transverse & longitudinal shower shapes to reject background

  Provides a fast trigger

  – accept events with ECal < 1.2 GeV

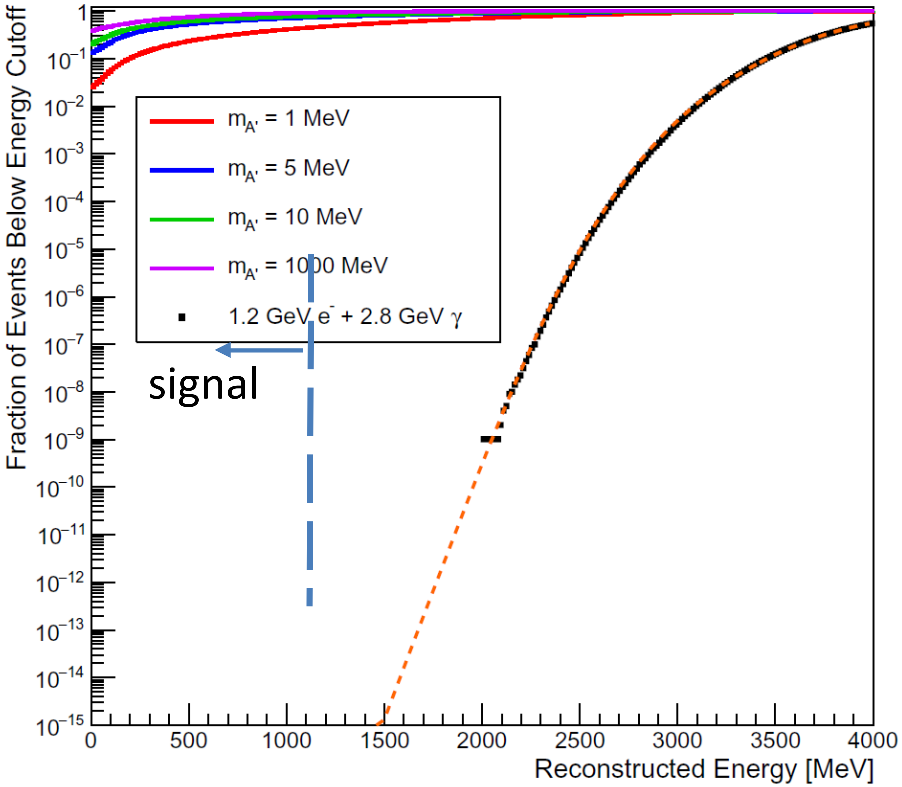




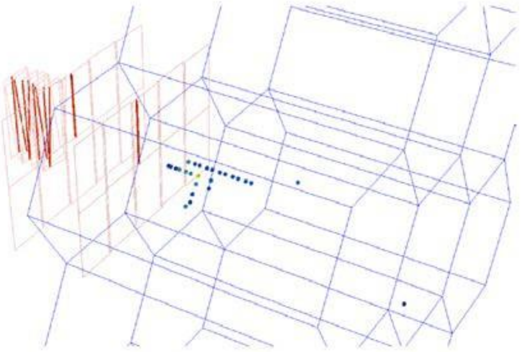
High granularity enables muon/electron discrimination, important to reject $\gamma \to \mu\mu$ background

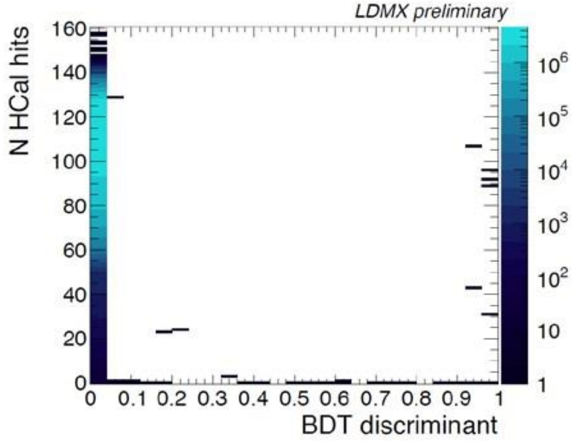
EM calorimeter

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



Dimuon background ($\gamma^* \to \mu\mu$)



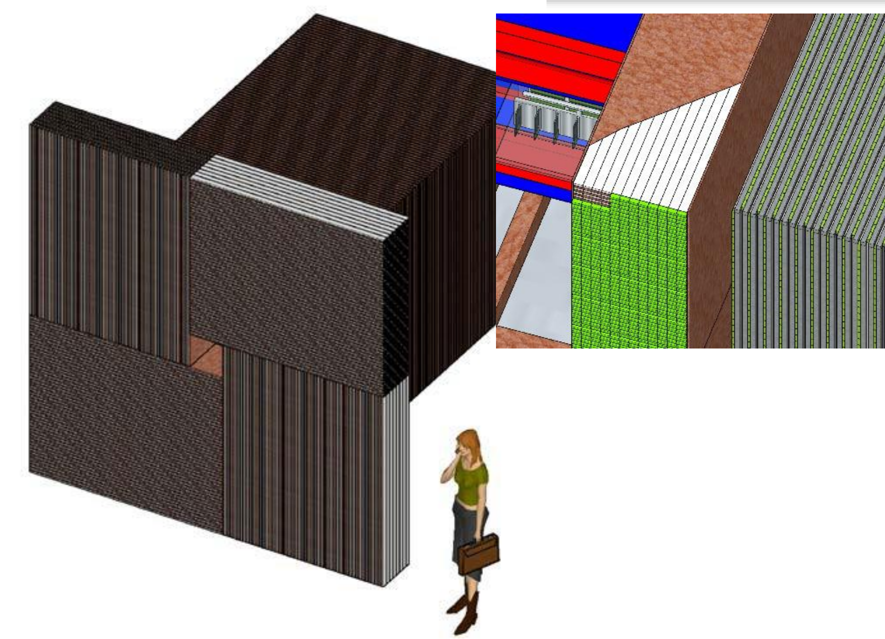


The ECal can efficiently reject background (*e.g.* 1.2 GeV *e*$^-$ + 2.8 GeV γ or dimuon production) from signal at the level required for Phase I

Hadronic calorimeter

Steel / plastic scintillator sampling calorimeter

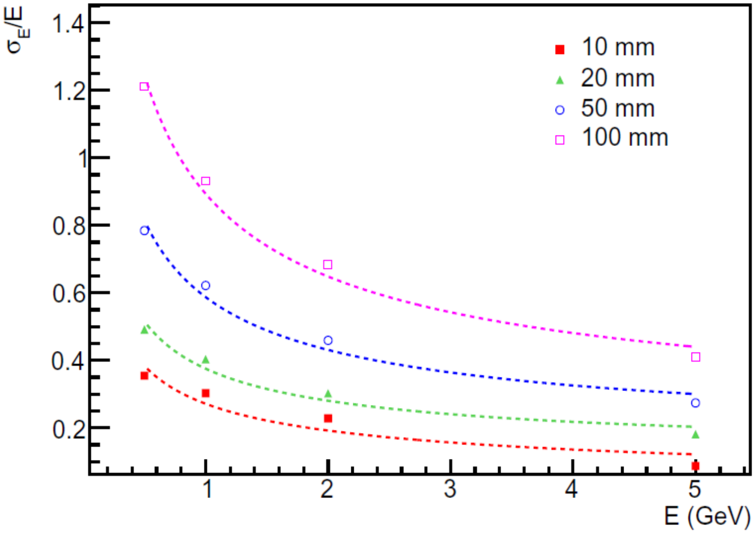
Based on Mu2e Cosmic Ray Veto technology



- Main function is to veto hadronic pn events, in particular pn events emitting several hard neutrons (*e.g.* $\gamma n \rightarrow n\bar{n}n$) or many soft neutrons
- Secondary role: physics with displaced signatures, electro-nuclear measurements and trigger, help with overall veto
- Plastic scintillator bars 5cm wide (x,y) with WLS fibers read out by SiPM and steel absorber
- Rear HCal (~13λ) and side HCal (~ 5λ), 2-3 m transverse size
  Final design parameters still under study

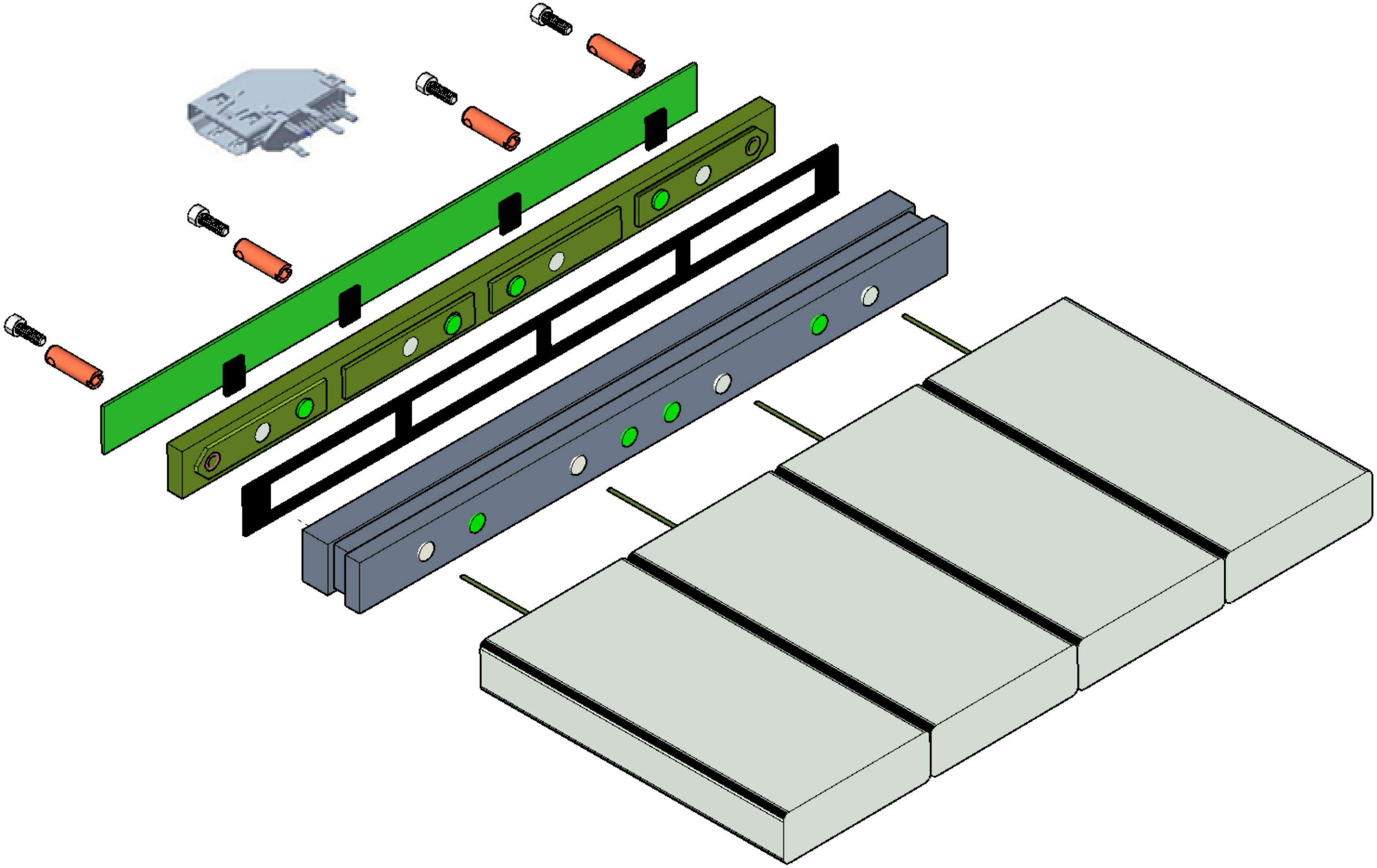
Current studies show that the HCal can achieve the required veto efficiency and decent energy resolution.

Energy resolution for pions



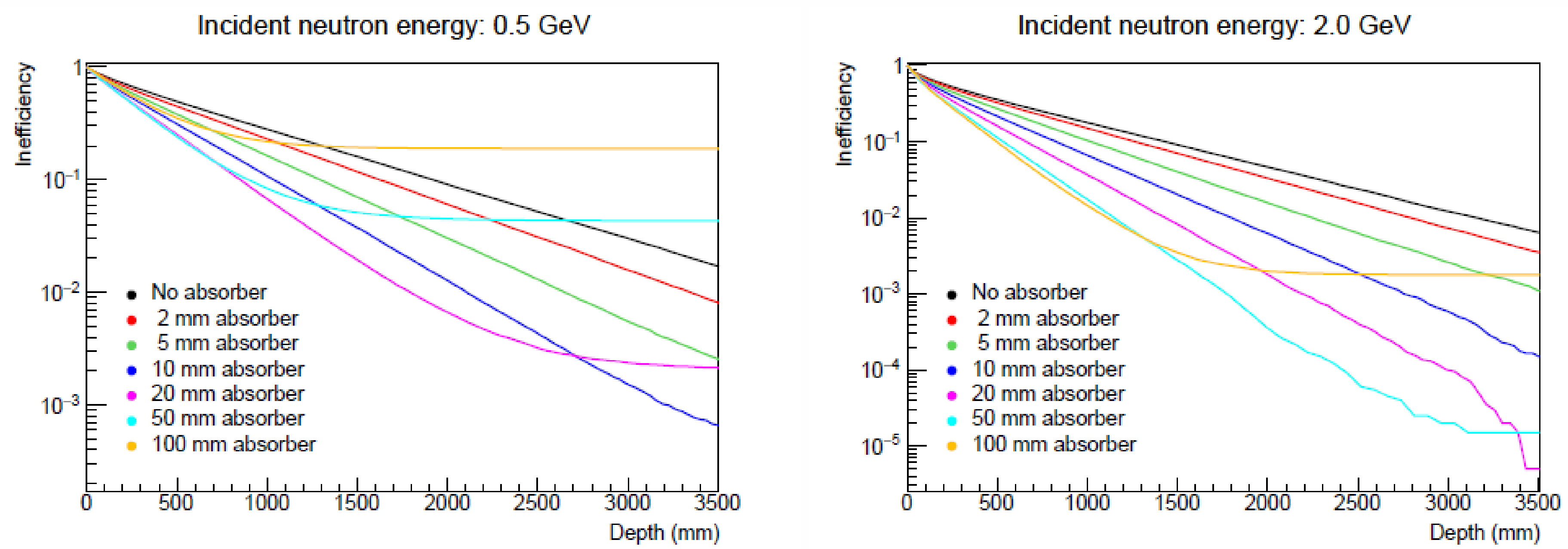
HCal fiber/SiPM readout

A modification of the Counter Motherboard developed for the Mu2e Cosmic Ray Veto



Optimizing the HCal sampling fraction

Single neutron veto inefficiency as a function of HCal sampling fraction



Incident neutron energy: 0.5 GeV

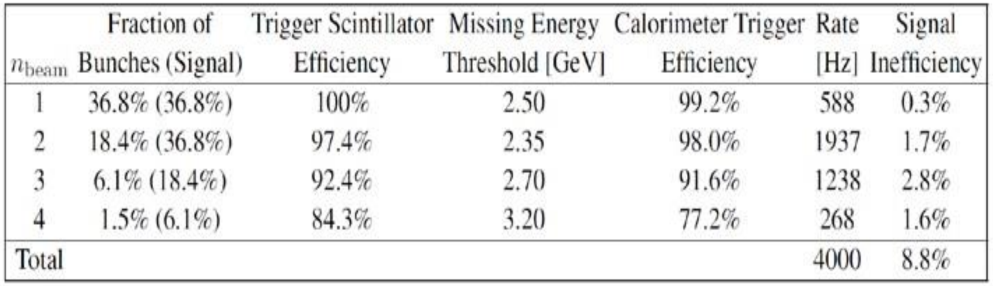
Incident neutron energy: 2.0 GeV

Trigger and DAQ

Trigger

- Reject beam-energy backgrounds (non-interacting *e*$^-$, bremsstrahlung,…)
- Sum energies of the first 20 layers of the ECal
- Scintillator behind target to suppress empty events

Signal efficiency 50-100% with 10^4 bkg rejection

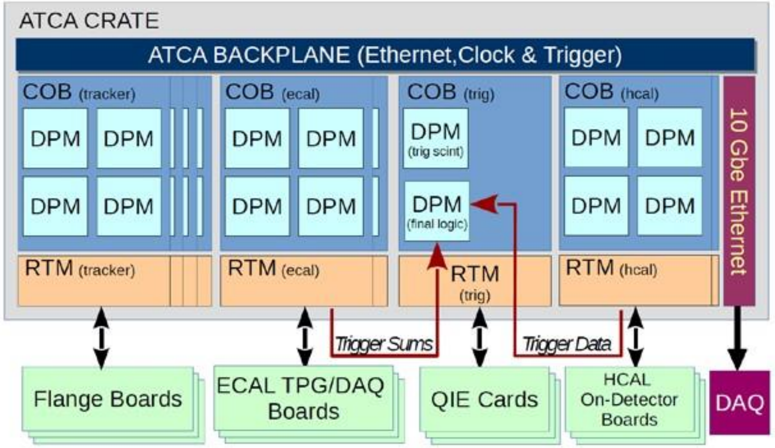


n_{beam}	Fraction of Bunches (Signal)	Trigger Scintillator Efficiency	Missing Energy Threshold [GeV]	Calorimeter Trigger Efficiency	Rate [Hz]	Signal Inefficiency
1	36.8% (36.8%)	100%	2.50	99.2%	588	0.3%
2	18.4% (36.8%)	97.4%	2.35	98.0%	1937	1.7%
3	6.1% (18.4%)	92.4%	2.70	91.6%	1238	2.8%
4	1.5% (6.1%)	84.3%	3.20	77.2%	268	1.6%
Total					4000	8.8%

DAQ systems

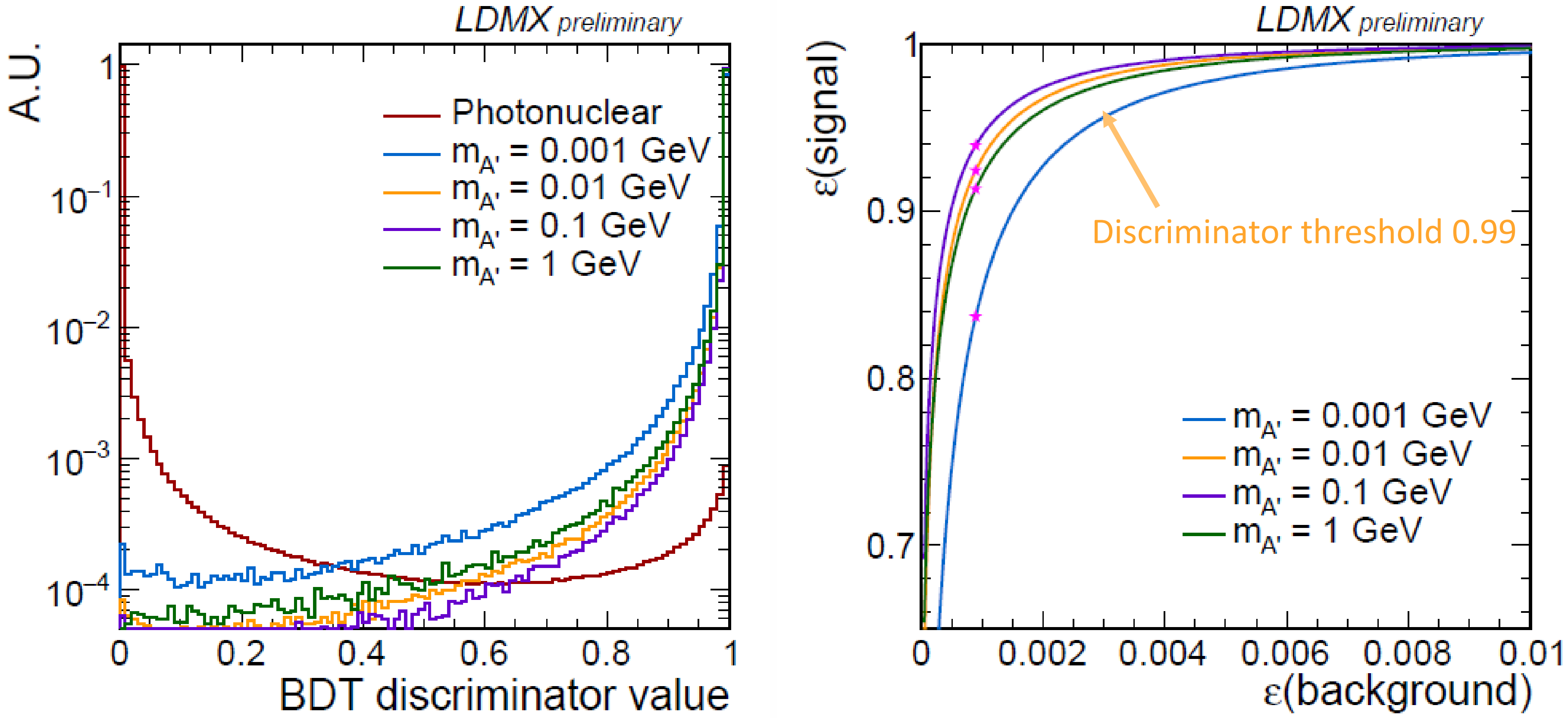
- ACTA crate using the Reconfigurable Cluster Element (RCE) generic computational building block developed by SLAC. Re-use components and algorithms already developed for other experiments.

- DAQ rate of 25 kHz.



Ecal BDT discriminator

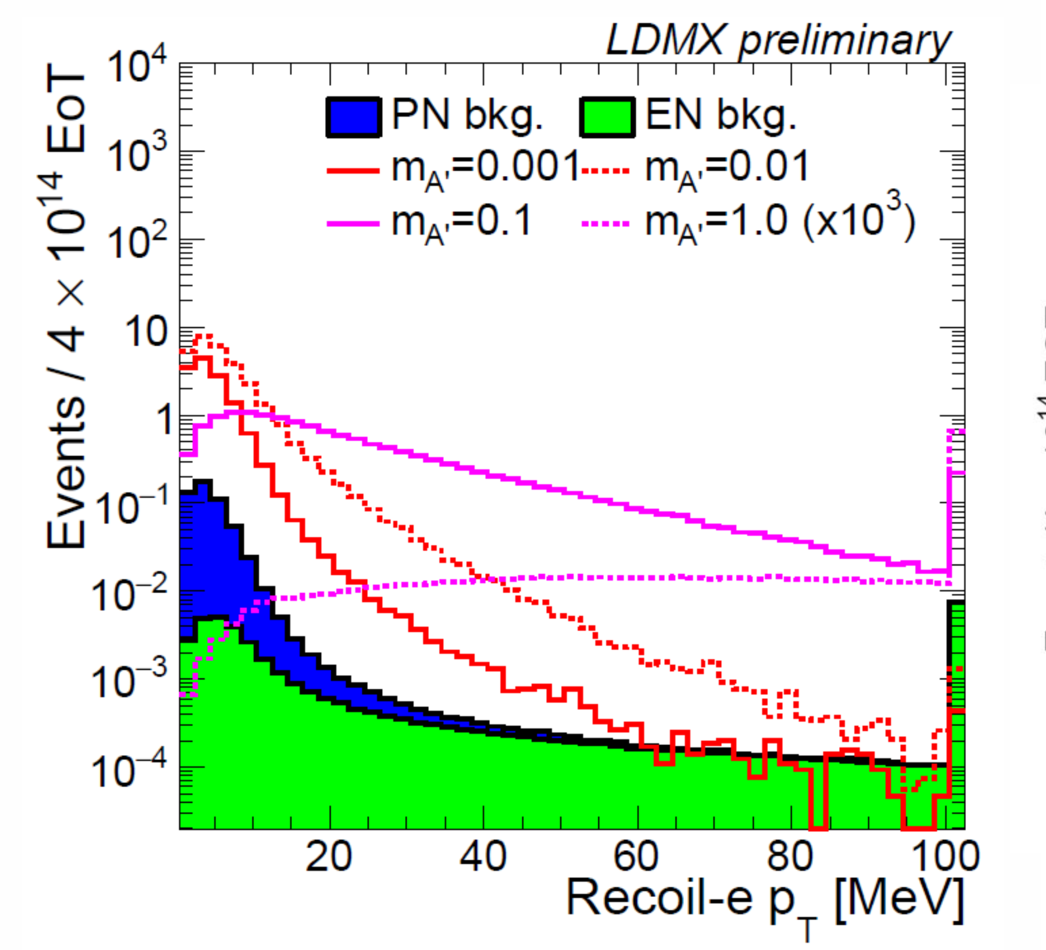
Preliminary BDT constructed for signal and photonuclear events

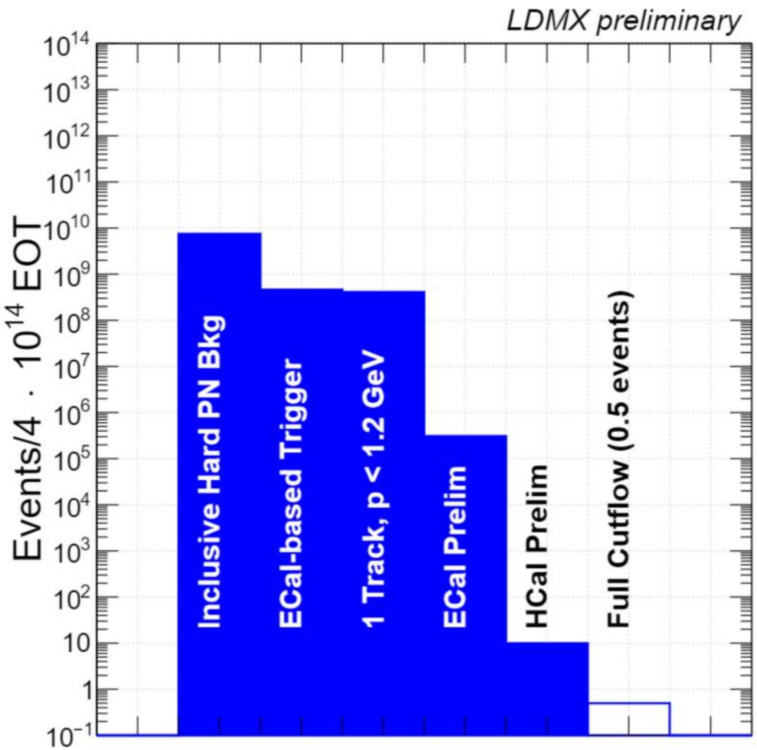


Discriminator threshold 0.99

p_T distribution of signal and background

Thermal freeze-out
elastic scalar dark matter
α_D=0.5, $m_\chi/m_{A'}$= 1/3





Don’t believe everything you read on the Internet (or in GEANT4)

Improving GEANT4 simulations

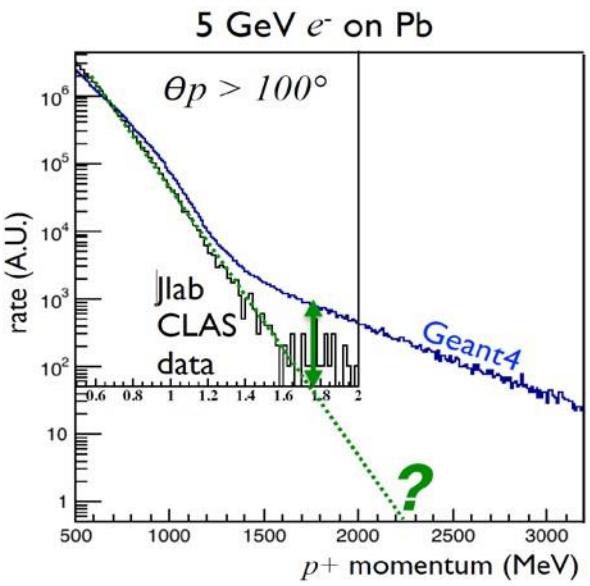
GEANT4 generated several unphysical backgrounds, such as photo-nuclear events with hard, large angle hadrons

This was traced to details of the Bertini cascade,

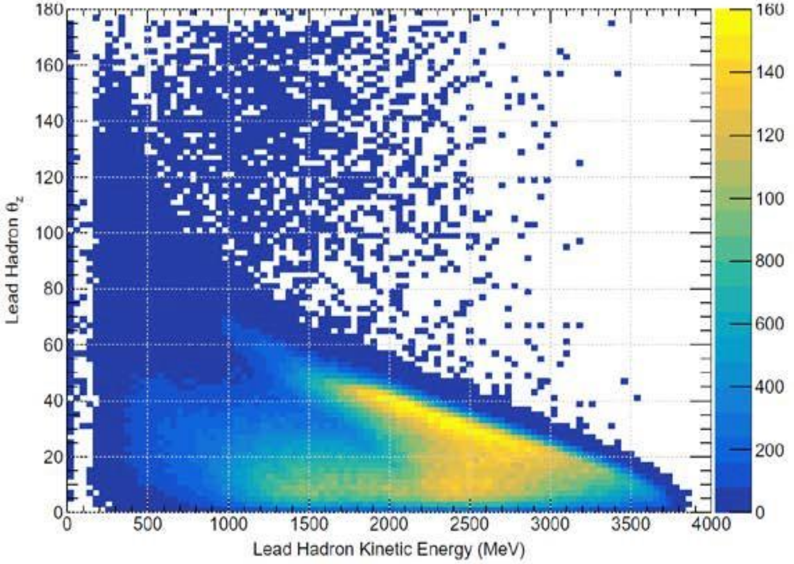
Work is on-going to improve the physics model

For our whitepaper studies, we reweighted events to improver agreement with experiment

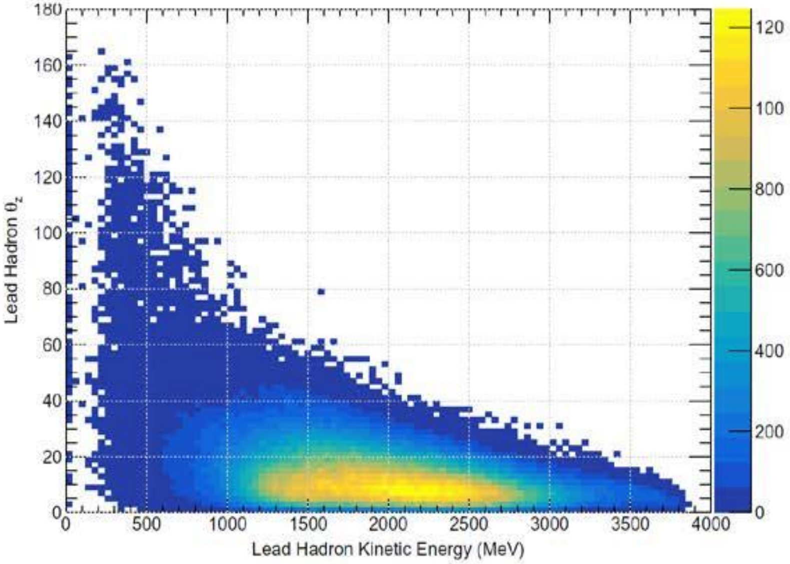
New background samples with an improved model have been generated for updated studies



Original GEANT4

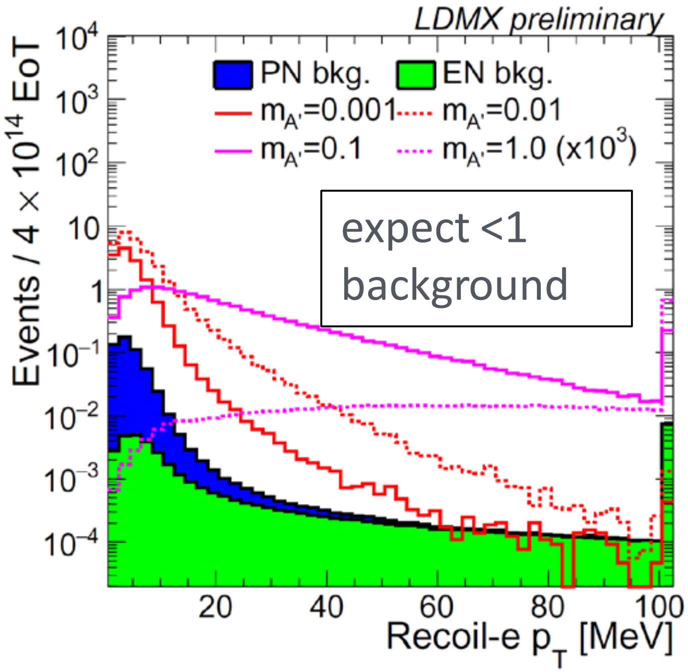


Improved Bertini cascade model



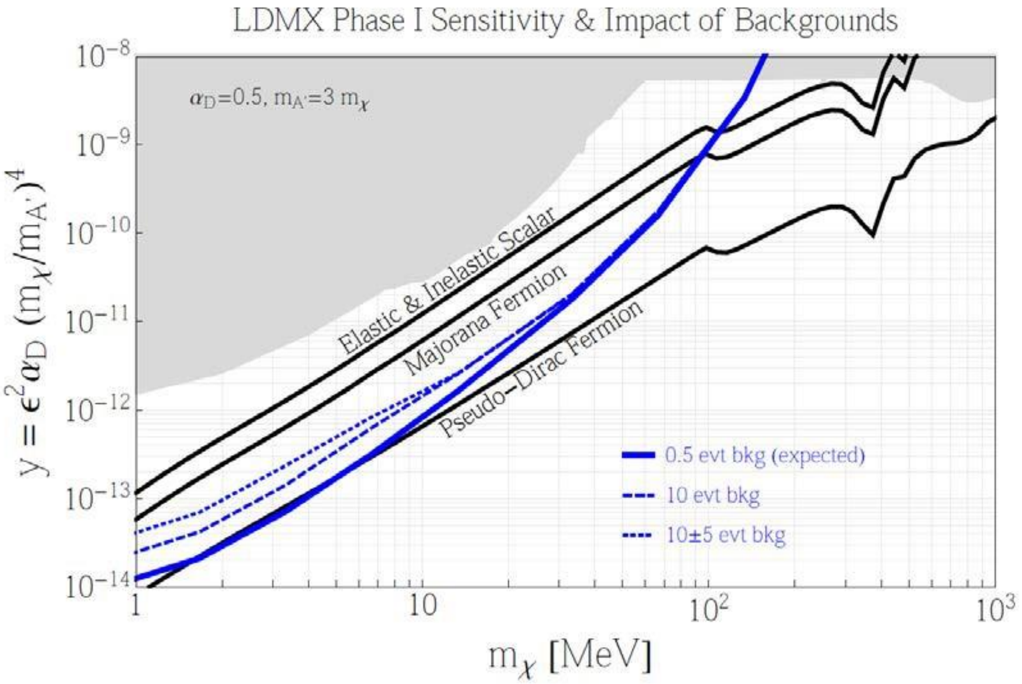
Phase I sensitivity

Recoil e^- p_T spectrum after all cuts

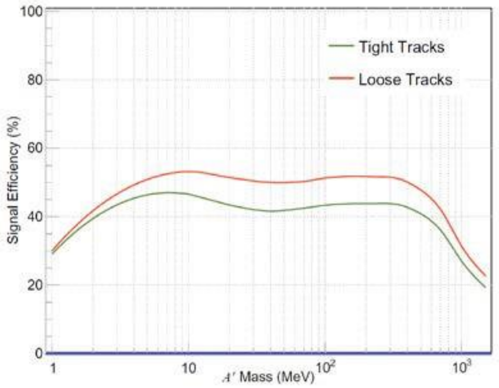


expect <1 background

LDMX Phase I sensitivity (4x10^{14} EOT @ 4 GeV)



Signal efficiency



Phase I probes scalar and Majorana targets below 100 MeV, grazes pseudo-Dirac target

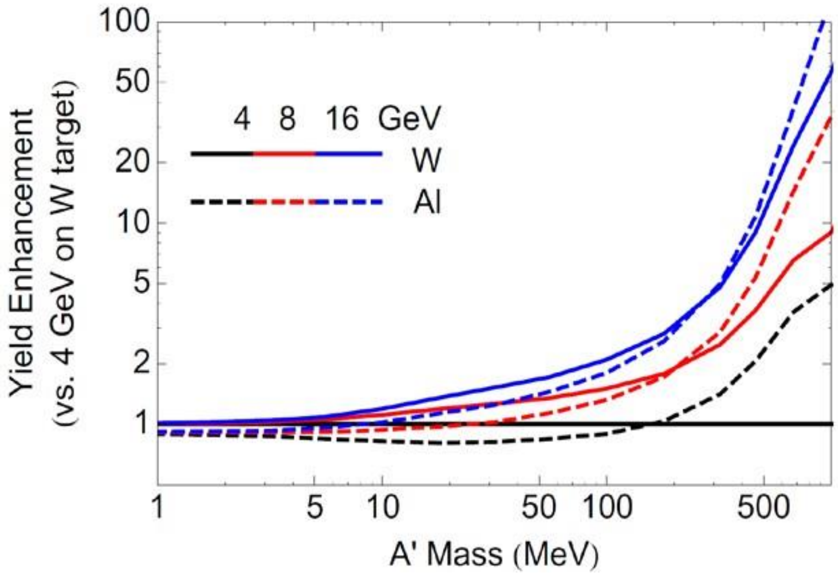
Additional improvements under study

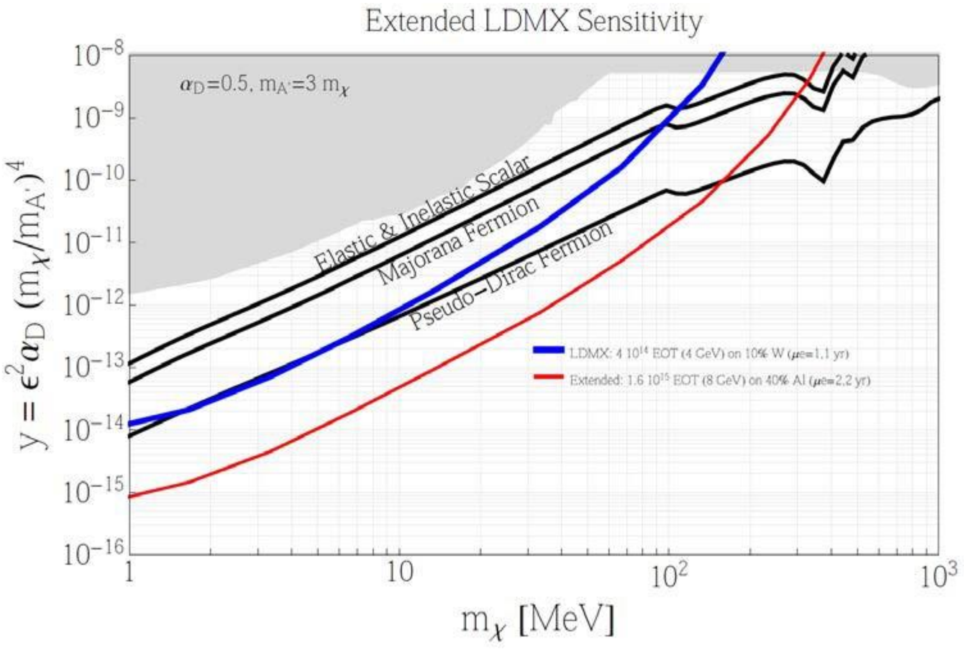
Details in whitepaper - arxiv:1808.05219.

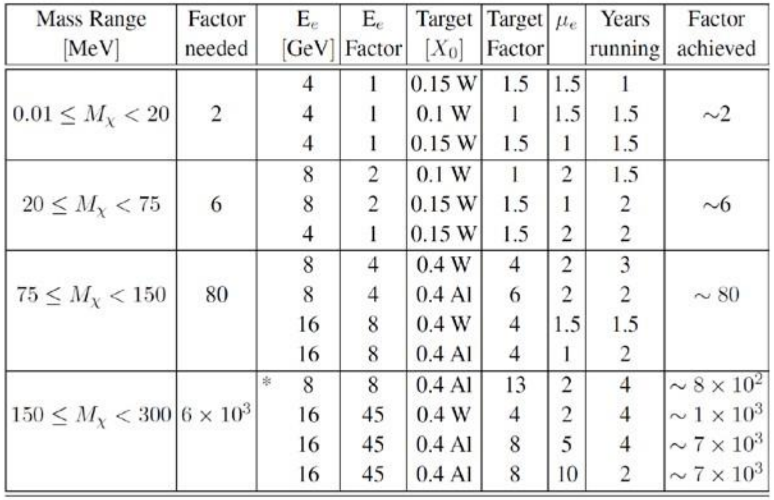
Phase II upgrade

There are several strategies to improve the Phase I reach:
increasing the beam energy,
changing the target density or thickness.

Phase II could probe pseudo-Dirac target up to $\mathcal{O}(100)$ MeV.



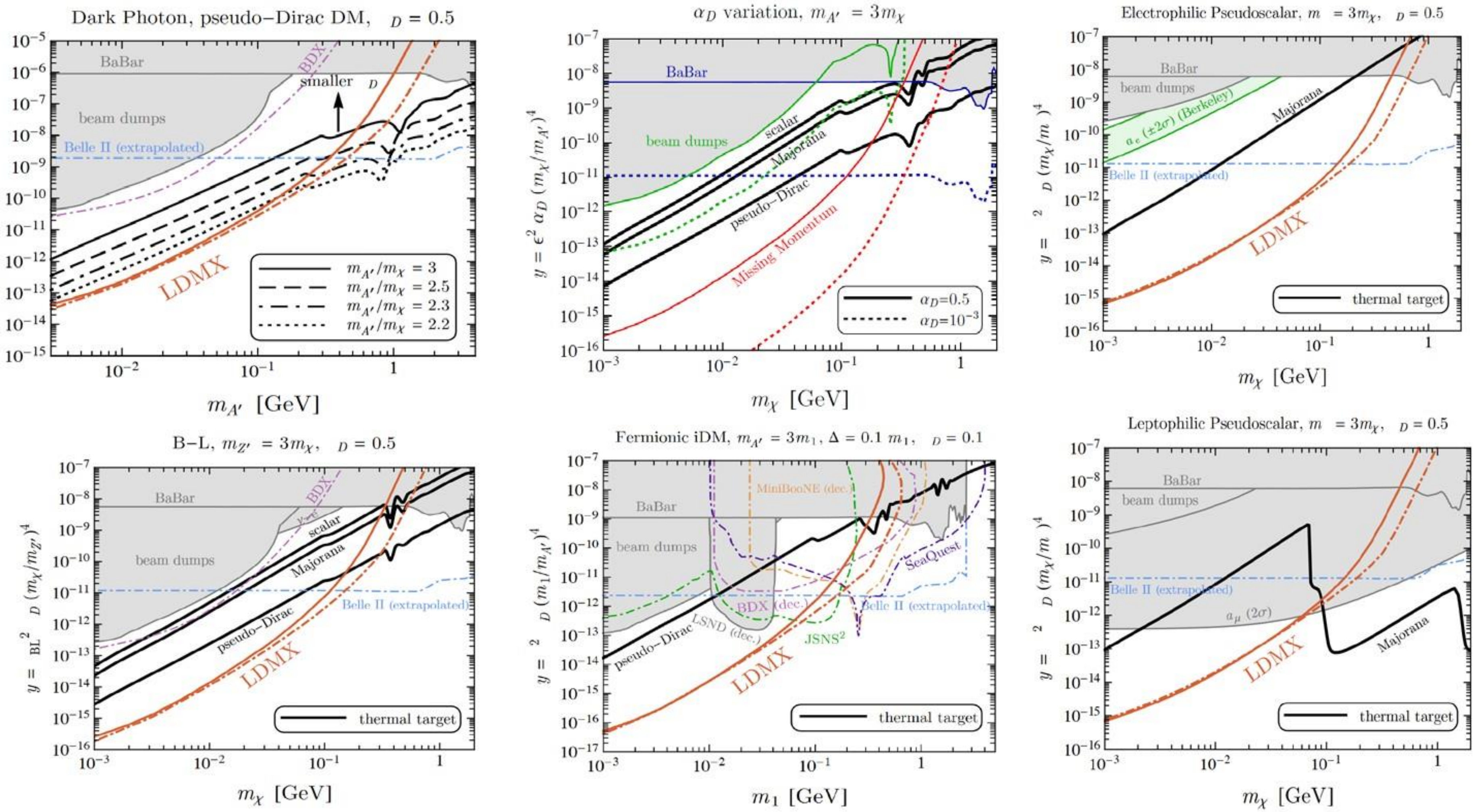




Mass Range [MeV]	Factor needed	E_e [GeV]	E_e Factor	Target $[X_0]$	Target Factor	μ_e	Years running	Factor achieved
$0.01 \le M_\chi < 20$	2	4	1	0.15 W	1.5	1.5	1	~2
		4	1	0.1 W	1	1.5	1.5	
		4	1	0.15 W	1.5	1	1.5	
$20 \le M_\chi < 75$	6	8	2	0.1 W	1	2	1.5	~6
		8	2	0.15 W	1.5	1	2	
		4	1	0.15 W	1.5	2	2	
$75 \le M_\chi < 150$	80	8	4	0.4 W	4	2	3	~ 80
		8	4	0.4 Al	6	2	2	
		16	8	0.4 W	4	1.5	1.5	
		16	8	0.4 Al	4	1	2	
$150 \le M_\chi < 300$	6×10^3	* 8	8	0.4 Al	13	2	4	$\sim 8 \times 10^2$
		16	45	0.4 W	4	2	4	$\sim 1 \times 10^3$
		16	45	0.4 Al	8	5	4	$\sim 7 \times 10^3$
		16	45	0.4 Al	8	10	2	$\sim 7 \times 10^3$

Variations on a theme

arxiv:1807.0173

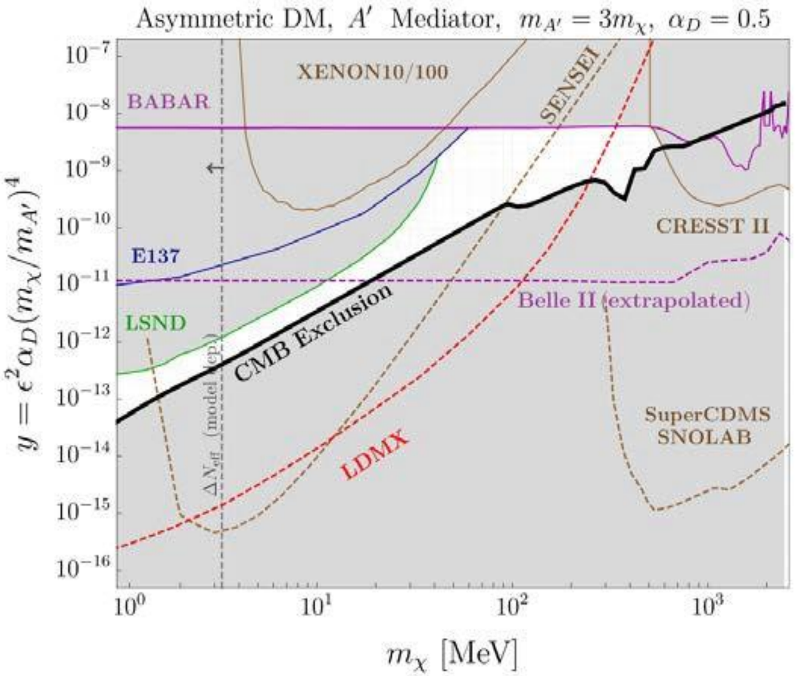


Sensitivity to a broad range of models and mild sensitivity to variation of parameters

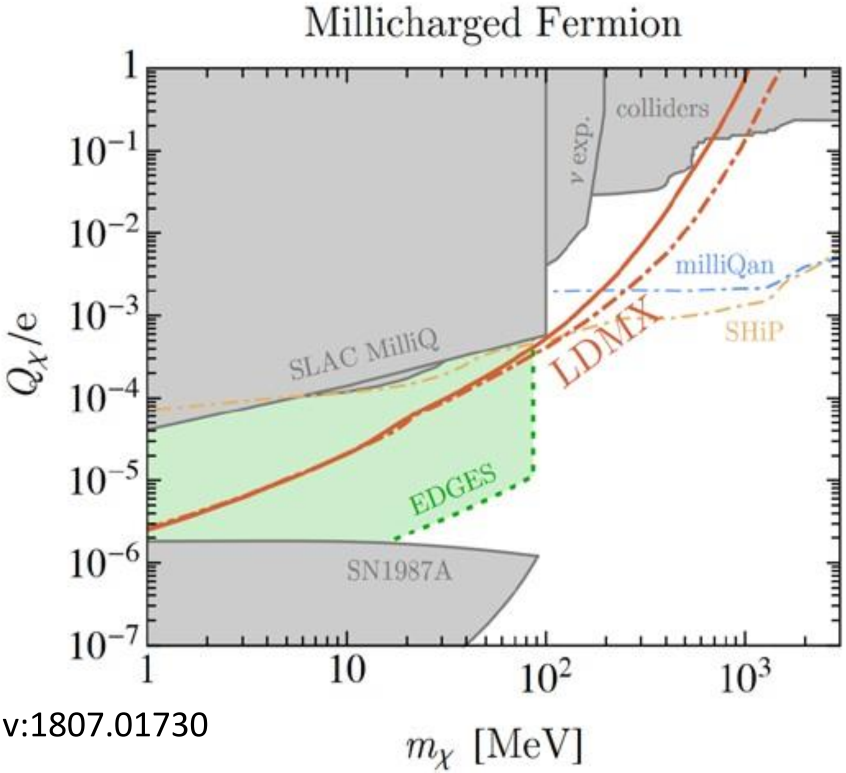
Sub-GeV BSM physics

Sample of BSM scenarios LDMX would be sensitive to:

- Asymmetric DM / ELDER
- Milli-charged fermions



arXiv:1807.0173



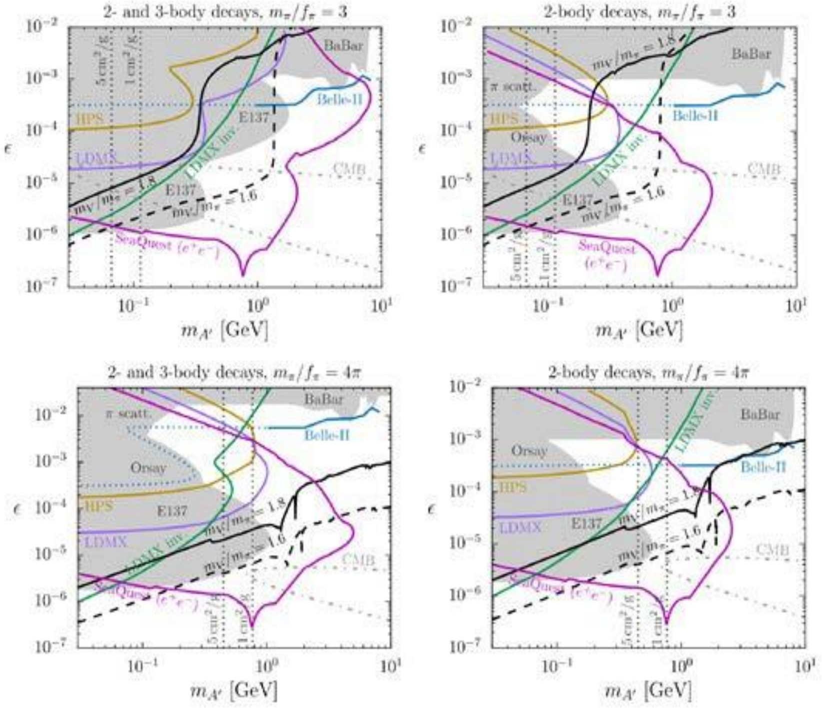
arXiv:1807.01730

Sub-GeV BSM physics

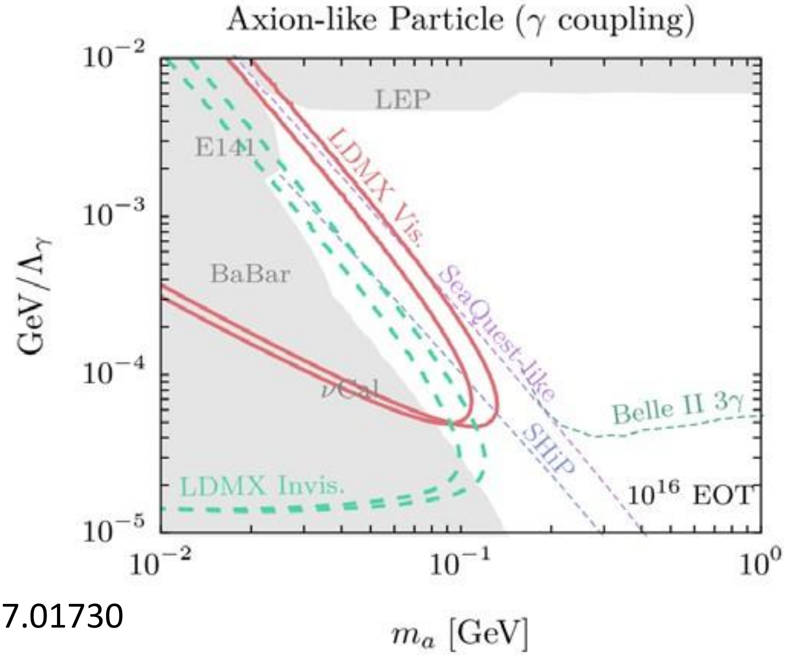
Sample of BSM scenarios LDMX would be sensitive to:

- Asymmetric DM / ELDER
- Milli-charged fermions
- Strongly interacting massive particles (SIMP) and displaced vertices
- Axion-like particles
- Generic visible and invisible mediator decays

Hidden sector vector meson decay



Berlin, Blinov, Gori, Schuster, Toro, arXiv 1801.05805



arXiv:1807.01730

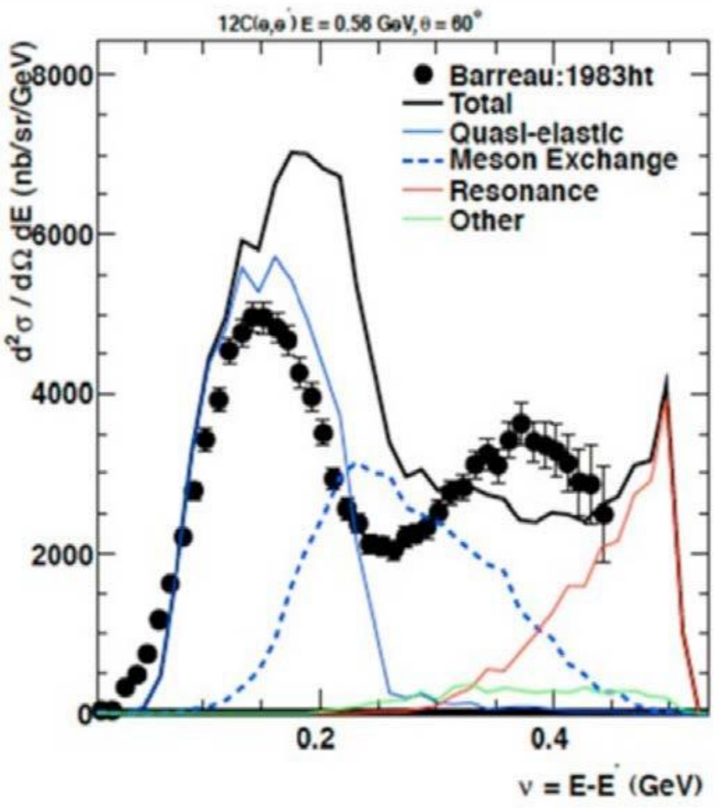
Sub-GeV BSM physics

Sample of BSM scenarios LDMX would be sensitive to:

- Asymmetric DM / ELDER
- Milli-charged fermions
- Strongly interacting massive particles (SIMP) and displaced vertices
- Axion-like particles
- Generic visible and invisible mediator decays

LDMX can also provide useful electro-nuclear and photo-nuclear measurement for future neutrino experiments.

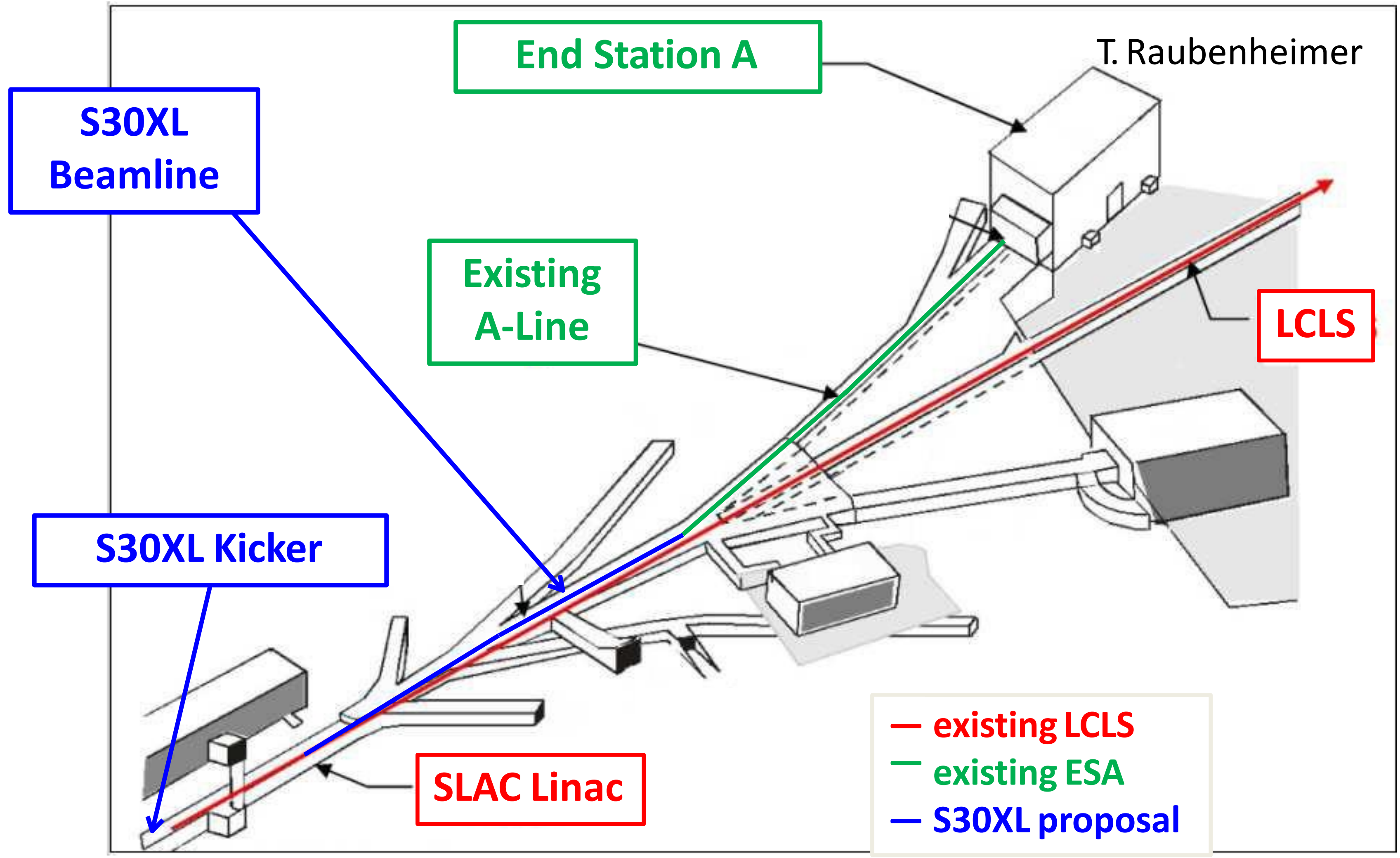
Electron scattering data is needed to tune MC



T. Katori, arXiv 1304.6014

S30XL @ SLAC proposal

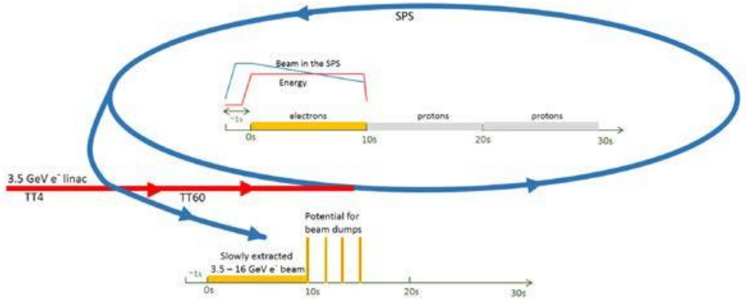
High rate, low-intensity (~1 e^-/bucket) beam extracted from LCLS-II



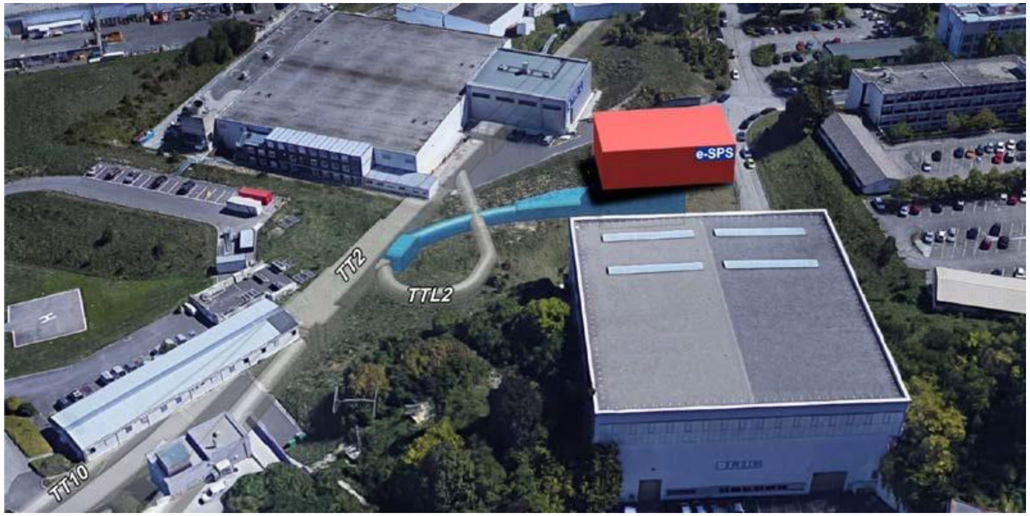
Proposal: *e*-SPS @ CERN

There is a proposal for a new multi-GeV Linac into SPS with high repetition rate and low current (arXiv:1805.12379)

Expression of interest to SPSC in October 2018 (https://cds.cern.ch/record/2640784) – see talks at PBC workshop.



Machine parameters:
- Energy: 3.5 – 16 GeV
- Bunch spacing: multiple of 5 ns
- Spill length: 10s in 30s super cycle
- Particles per bunch : 1 – 40

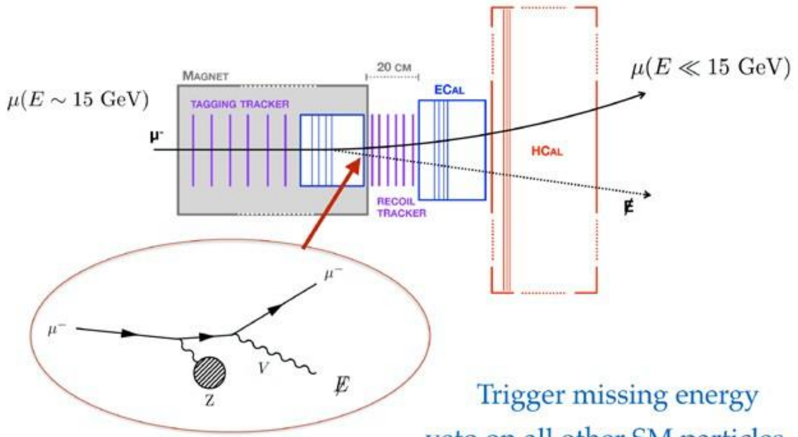


LDMX-mu

JHEP 1809 (2018) 153
arxiv:1804.03144

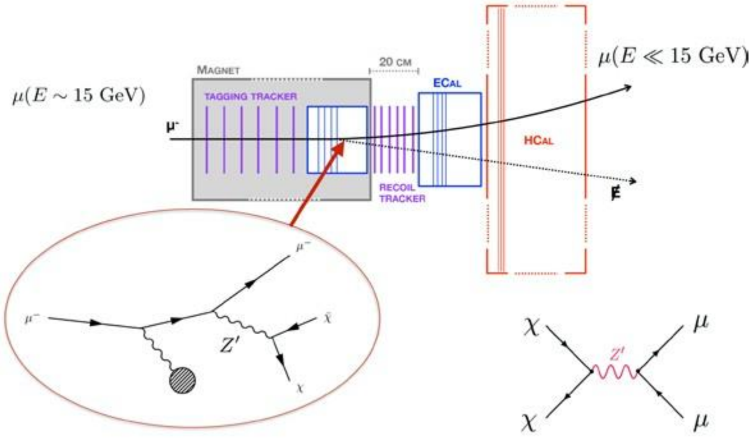
LDMX-like detector with a muon beam at FNAL

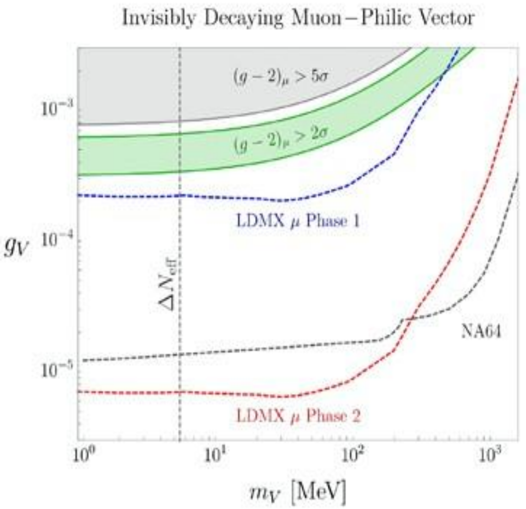
New light muon-philic particles

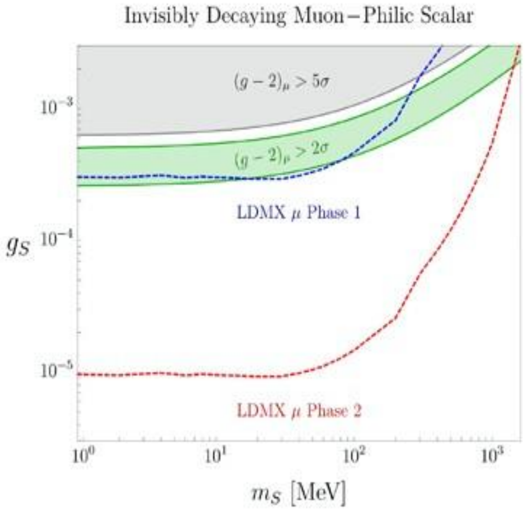


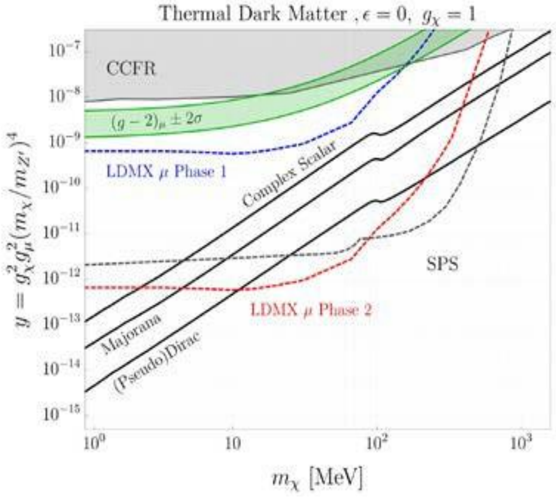
Trigger missing energy
veto on all other SM particles

Muon-philic dark mediator









Conclusions

The thermal paradigm is arguably one of the most compelling DM candidates - the broad vicinity of the weak scale is a good region to explore

Accelerator-based experiments are in the best position to decisively test most of the simplest scenarios of light dark matter and could reveal much of the underlying dark sector physics together with direct detection experiments

Among potential approaches, the missing energy/momentum technique provides the best sensitivity per luminosity

LDMX offers unprecedented sensitivity to light DM, improving constraints by orders of magnitude for DM masses below a few hundred MeV. The experiment can also perform photonuclear & electronuclear measurements useful for planned neutrino experiments.

LDMX can run parasitically at SLAC or at other facilities with a comparable electron beam time structure, completing the program within the next decade at reasonable cost, and potentially producing a groundbreaking discovery