The LDMX experiment:

search for light dark matter and new sub-GeV particles

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KITP – April 2018

LDMX in a nutshell

LDMX (Light Dark Matter eXperiment) is a new proposal aimed at exploring sub-GeV BSM physics with unprecedented sensitivity.

The experiment uses a missing momentum technique to search for new particles coupling to electrons and focuses on invisible or displaced decays (ultra-short baseline beam dump experiment).

This technique has sensitivity to a broad array of physics, including light dark matter, new force carriers, millicharged particles, axions, “long-lived” particles,…

In addition, LDMX could also perform useful measurement for future neutrino experiments.

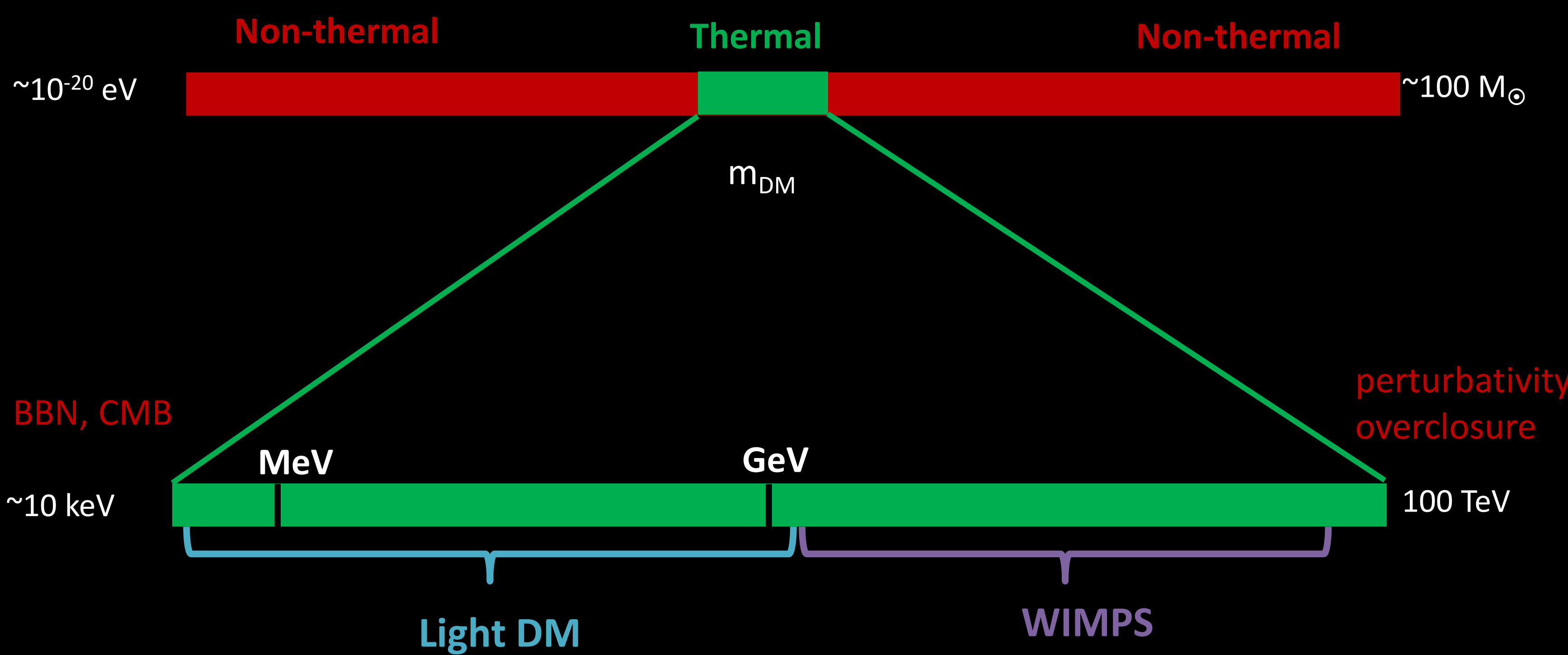
The experiment requires multi-GeV, low-current, high repetition rate beam with large beam spot. Potential candidates are DASEL or CEBAF.

On-going studies to optimize the detector technology / layout.

En route!

Thermal dark matter

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



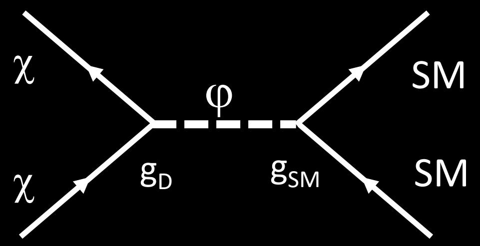
Thermal contact implies new mediator
Hidden sector light DM well-motivated model

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

Focus recently shifted to light DM as WIMP parameter space closes

Light thermal dark matter

Freeze-out scenario with light dark matter (χ) requires new light mediator to explain the relic density, or dark matter is overproduced



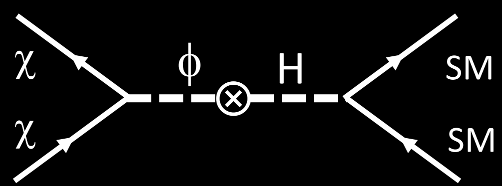
$$< \sigma v >_{relic} \sim \frac{g_D^2\, g_{SM}^2\, m_x^2}{m_\varphi^4} \qquad (m_\varphi \gg m_x)$$

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

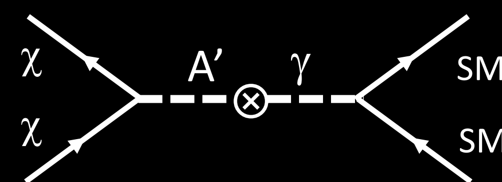
What kind of mediator?

Must be neutral under the SM and renormalizable. Simplest choices:

New scalar (ϕ) with Higgs coupling



New vector (A') with photon coupling



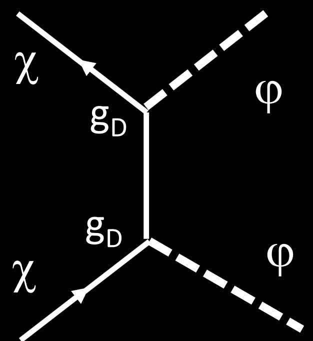
Naturally realized in the context of dark sectors

Light thermal dark matter

The DM / mediator mass ratio determines the type of annihilation and the mediator decay

Secluded decay

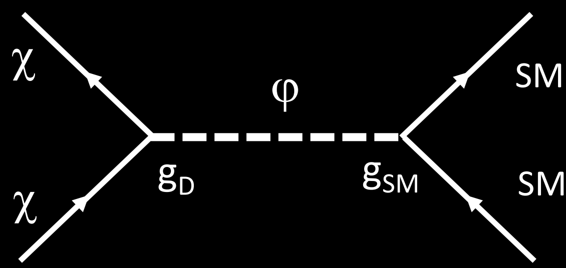
$m_\chi > m_\varphi$



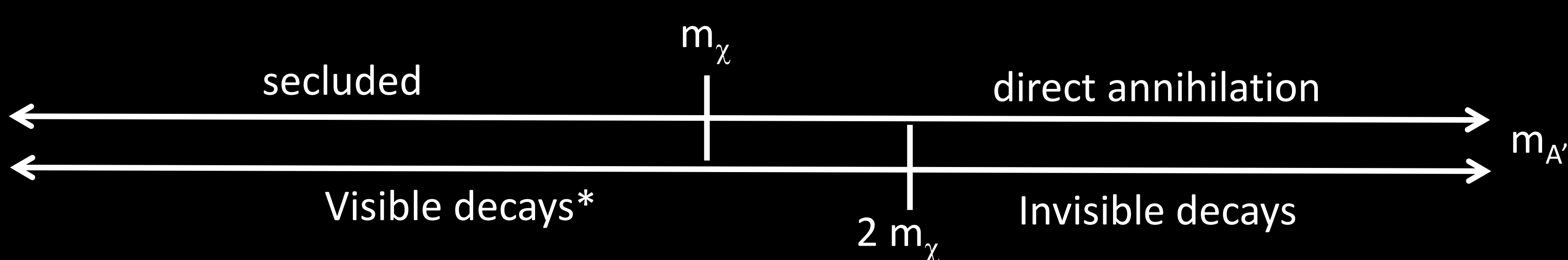
Wide parameter space / no specific targets
viable for scalar/vector mediator

Direct annihilation

$m_\chi < m_\varphi$



Define specific target
ruled out for scalar mediator**



*Look at extra material for visible decay constraints ** arXiv:1512.04119

Light thermal dark matter

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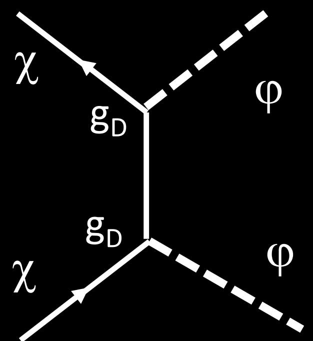

Direct annihilation

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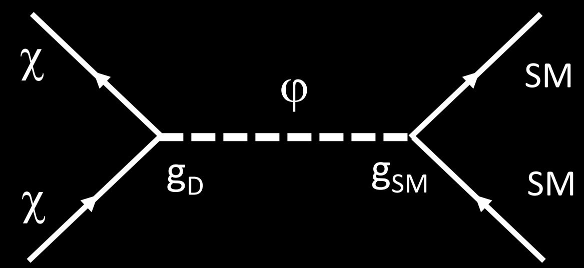

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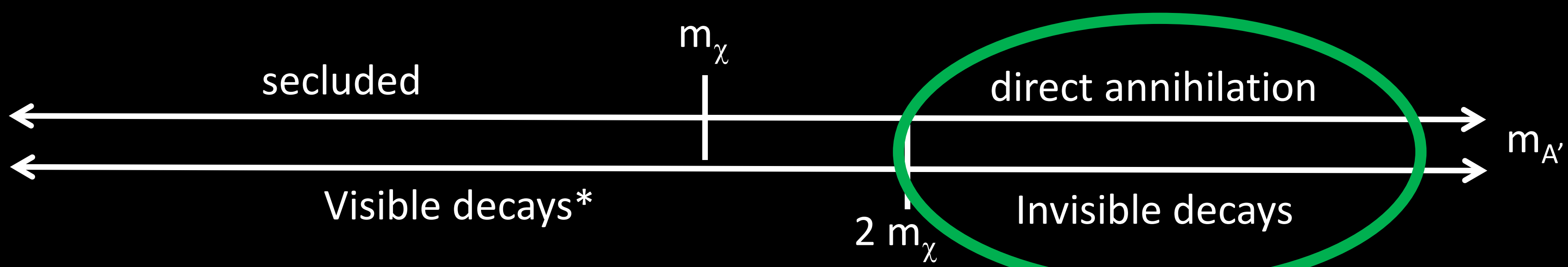

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Secluded decay – WIMP next door

Consider case in which the DM-SM coupling was large enough to keep the two sectors in thermal equilibrium at early times (+renormalizable interactions)

→ thermal equilibrium provides a minimal, UV-insensitive cosmological DM history that implies a minimum DM-SM coupling (with a few caveats….)

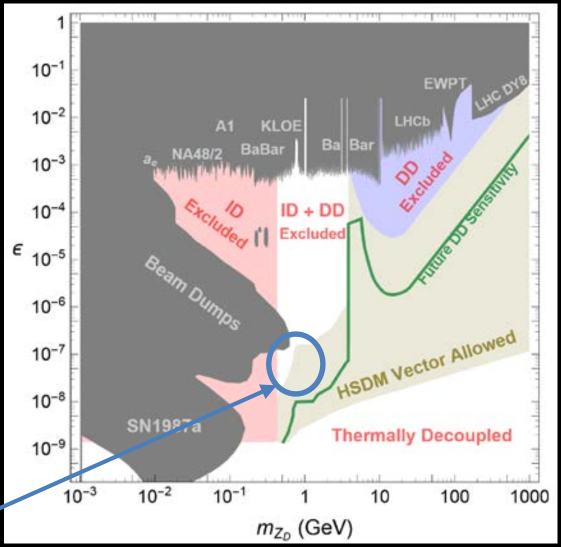
→ WIMP next door

LDMX only sensitive to a small fraction of allowed parameter space for vector mediator (at most a few GeV)

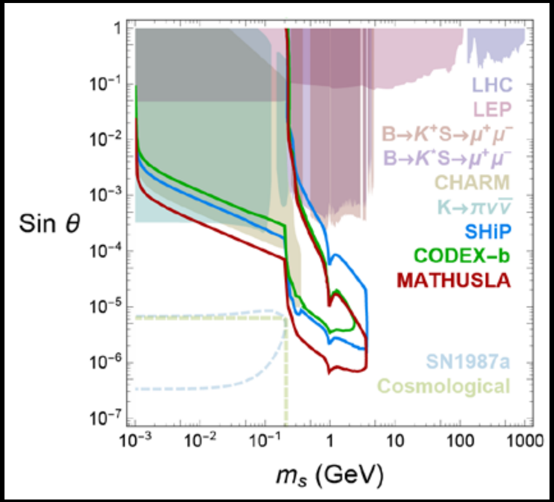
Coupling to electrons only significant in a small mass range ($2m_e < m_S < 2m_\mu$) for scalar mediator

NOT FURTHER DISCUSSED

Vector mediator

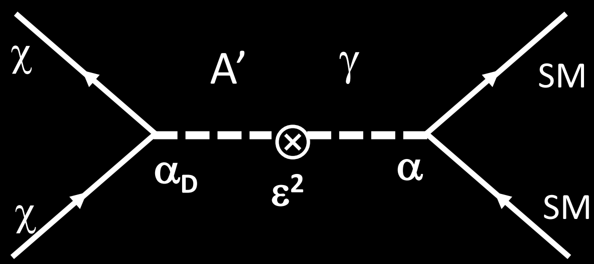


Scalar mediator



Evans, Gori & Shelton, arxiv:1712.03974

Direct annihilation – vector mediator

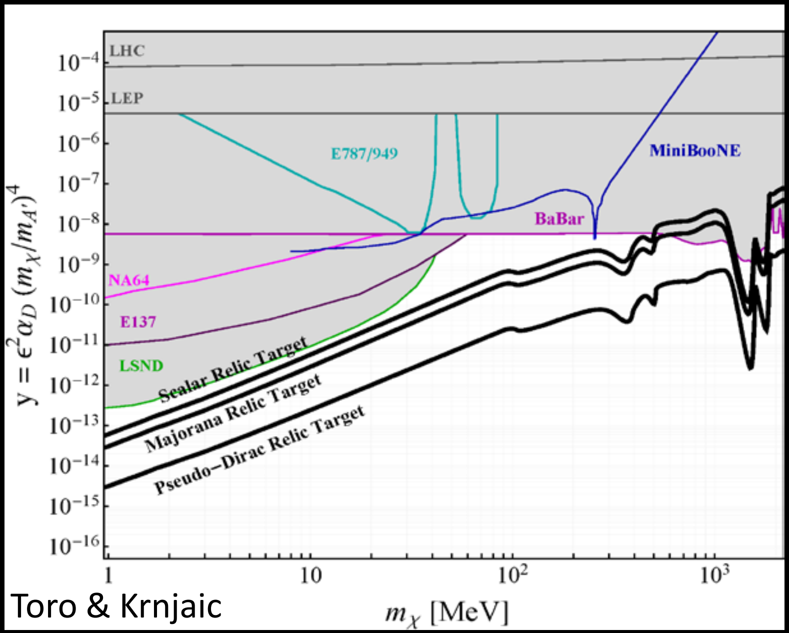


$$< \sigma v > \sim \alpha_D \varepsilon^2 \frac{m_x^2}{m_A^4} \sim \alpha_D \varepsilon^2 \frac{m_x^4}{m_A^4} \frac{1}{m_x^2} = y \frac{1}{m_x^2}$$

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

Dimensionless variable

Definitive predictions as a function of mass and particle type !!!

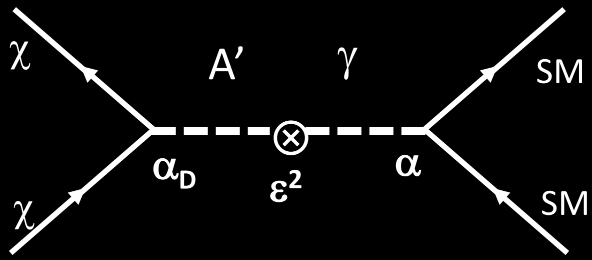


Assume very conservative parameters:
$\alpha_D = 0.5$ and $m_A/m_\chi = 3$
to plot missing energy/mass curves

These parameters lead to weak(est) constraints, i.e. constraints go down for smaller values of α_D or larger mass ratio but targets remains invariant.

pseudo-Dirac DM: Dirac fermion whose two Weyl states are split by a small Majorana term

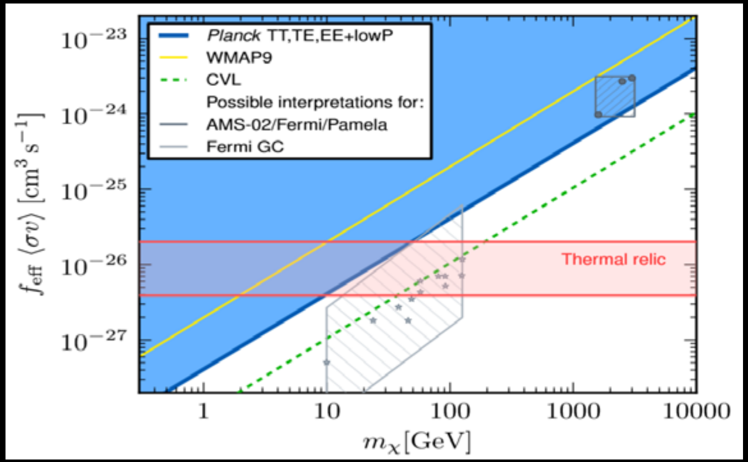
Direct annihilation – vector mediator



Cosmological constraints rule out Dirac fermion DM (s-wave annihilation).

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

Constraints on the self-annihilation cross-section at recombination x efficiency parameter



Planck collaboration, 1502.01589

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

Dimensionless variable

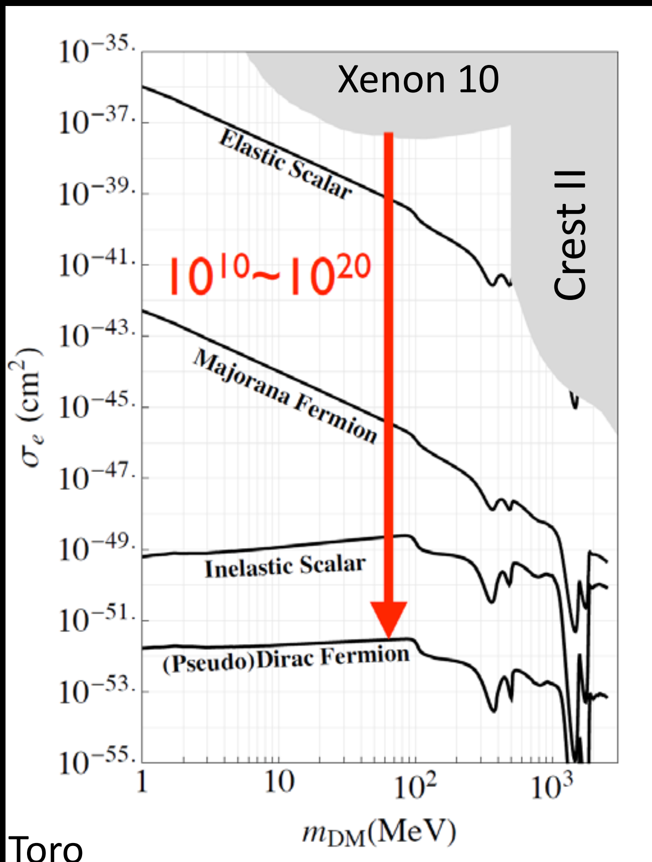
Definitive predictions as a function of mass and particle type !!!

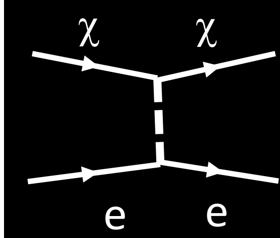
Scalar, Majorana and pseudo-Dirac (inelastic) DM are possible candidates

pseudo-Dirac DM: Dirac fermion whose two Weyl states are split by a small Majorana term

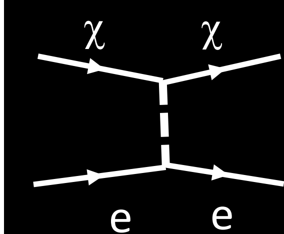
Direct detection and accelerators

Direct detection targets

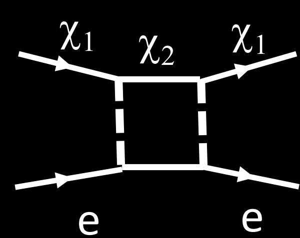




SCALAR
$\sigma_e \sim 10^{-39}$ cm^2



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

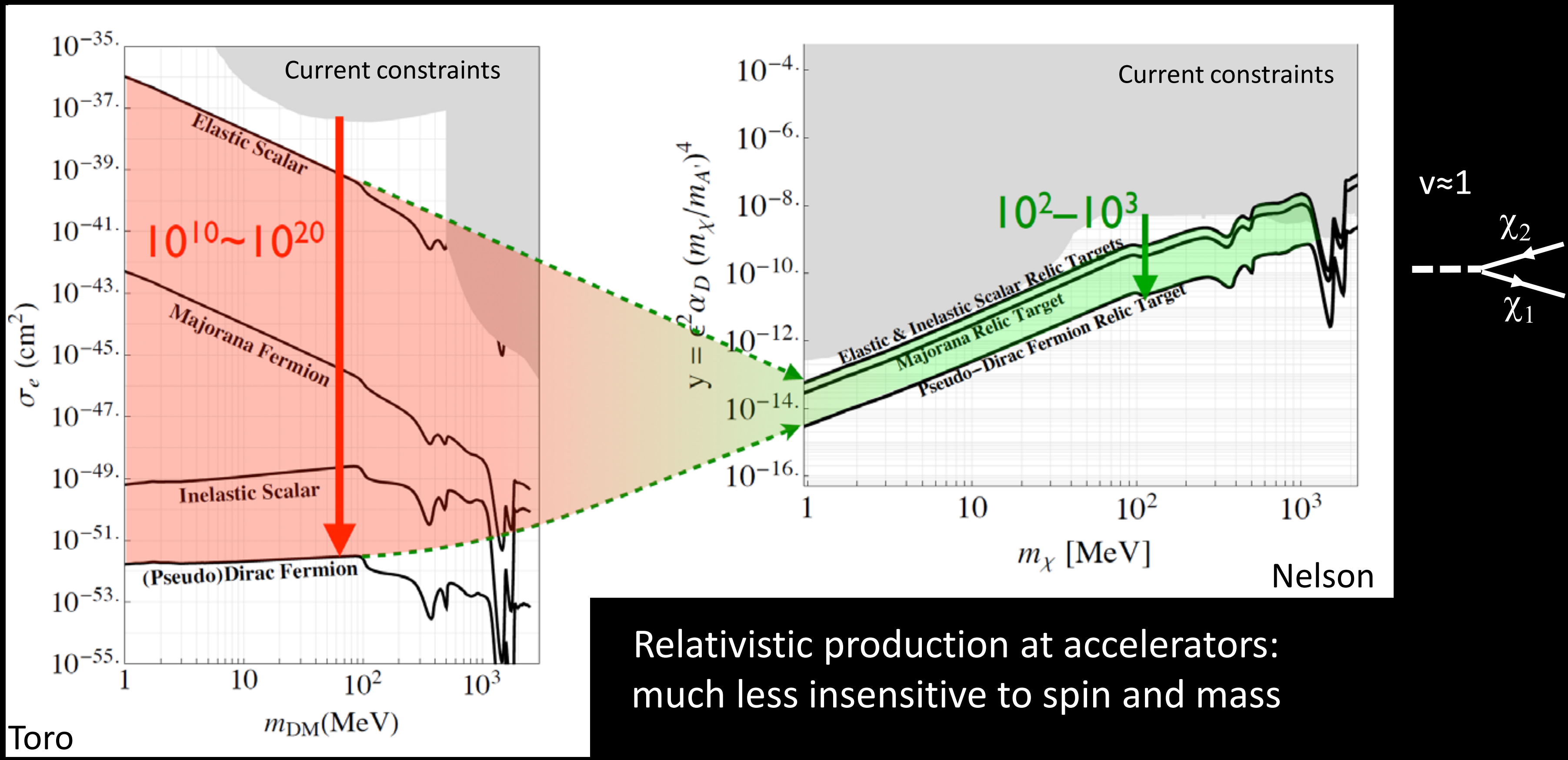


INELASTIC
$\sigma_e \sim 10^{-50}$ cm^2 loop diagram

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

Direct detection and accelerators

Direct detection targets | **Accelerator targets**



Relativistic production at accelerators:
much less insensitive to spin and mass

Accelerators uniquely positioned to robustly probe directly annihilating thermal LDM

More generally…

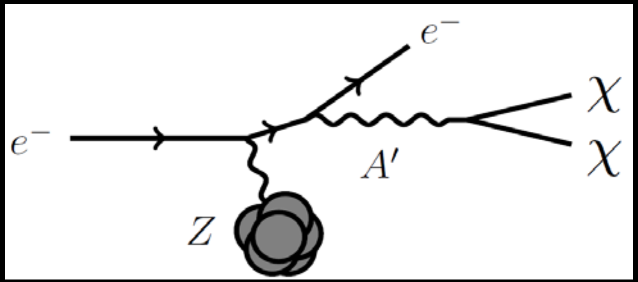
The scope of accelerator-based experiments is much more extensive, and encompass models such as

- 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 could generically probe a vast array of possibilities in addition to light thermal DM.

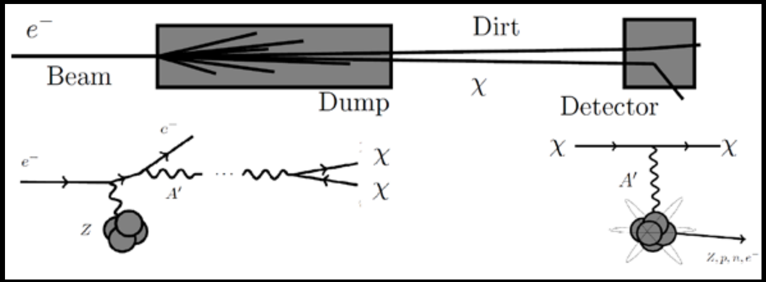
Maximizing dark photon detection

Missing energy / momentum



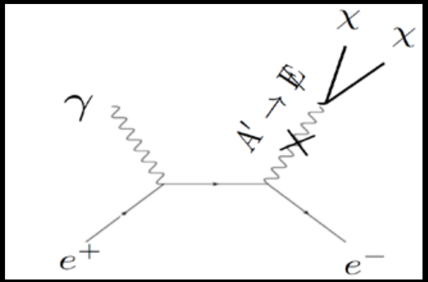
$\sigma \sim Z^2 \varepsilon^2 / m_A^2$

Beam dump



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

Missing mass



$\sigma \sim \varepsilon^2/s \quad m_A \ll s$

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

Fixed target

large dark photon yield production for low mediator masses

Missing energy/momentum:

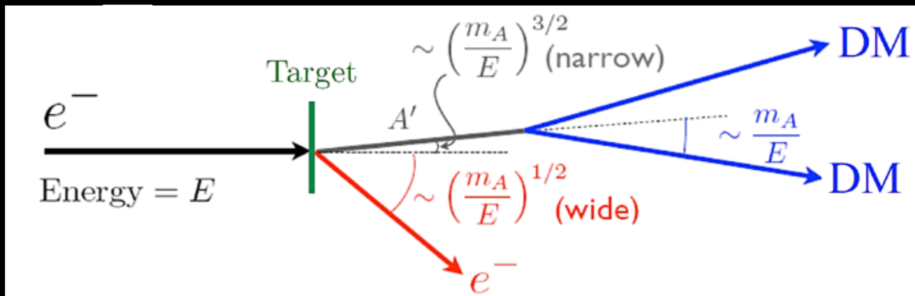
large "detection" yield

Missing energy / momentum maximizes low mass dark matter production and detection. Missing mass provides best yield for larger masses.

Accelerators can access explore the physics in detail ($\varepsilon, m_{A'}, m_{\chi}, \alpha_D$),
Complementarity: direct detection needed to establish cosmological stability

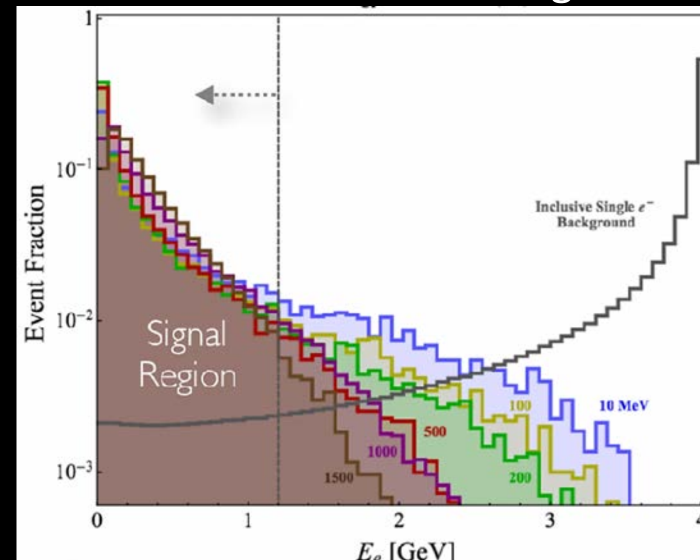
Missing momentum kinematics

Recoil energy,
4 GeV *e*- on 10% X_0 target



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

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



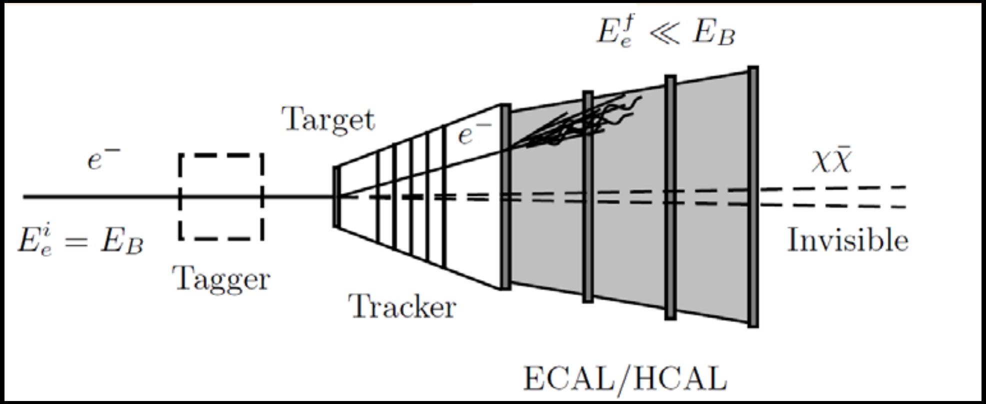
Bremsstrahlung suppressed by factor ~30 is signal region

The kinematics is very different from bremsstrahlung emission.

The A' is emitted at low angle and carries most of the energy, so

- large missing energy, the recoil electron is soft
- large missing p_T, the recoil electron is emitted at large angle

Missing energy / momentum



Missing energy:

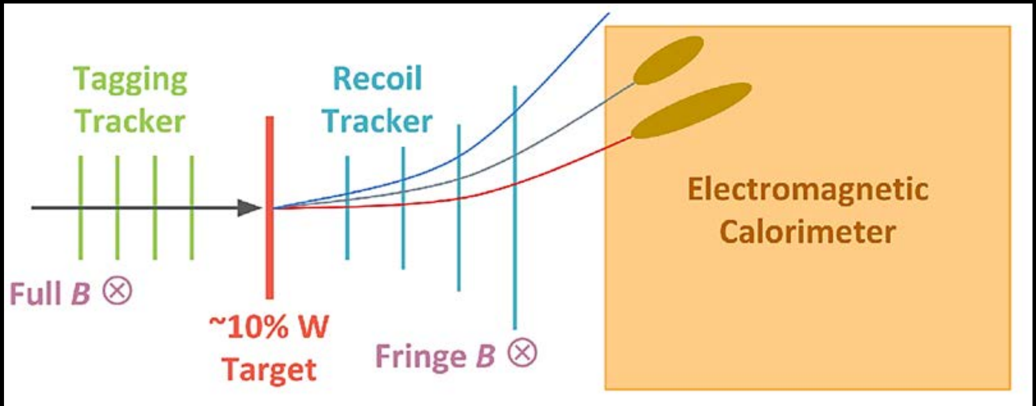
- Higher signal yields / EOT
- Greater acceptance
- Backgrounds beyond 10^{14} EOT might require e-γ identification

Missing momentum:

- Reconstruct outgoing electron, better bkg rejection
- p_T spectrum sensitive to $m_{A'}/m_\chi$
- Lower signal yield / ETO

A missing momentum experiment can also perform a missing energy measurement!

A successful missing momentum design



Beam allowing individual reconstruction of each incident electron

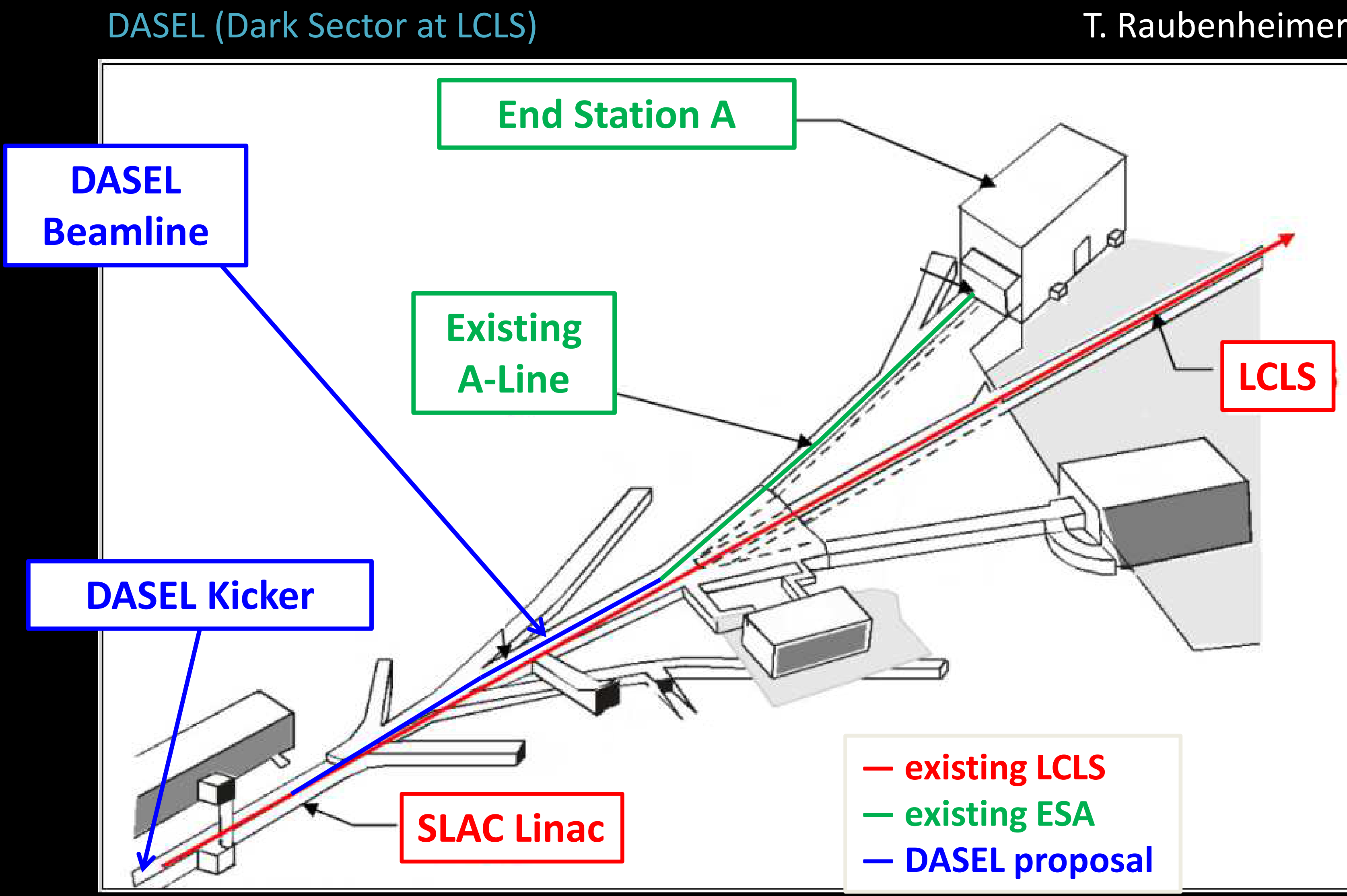
- A multi-GeV, low-current, high repetition rate (10^{16} EOT / year ≈ 1e / 3 ns) beam with a large beam spot to spread out the occupancy / radiation dose.
- DASEL @ SLAC (4/8 GeV) or CEBAF @ JLab (up to 12 GeV) are candidates

Detector technology with high rate capabilities and high radiation tolerance

- Fast, low mass tagger / recoil tracker to tag each electron with good momentum resolution
- Fast, granular, radiation-hard EM calorimeter

The LDMX experiment has been proposed to realize these design requirements in two phases: Phase-I with 10^{14} EOT (1e- / 25 ns) , and Phase-II with 10^{16} EOT (1e- / 3 ns)

DASEL proposal



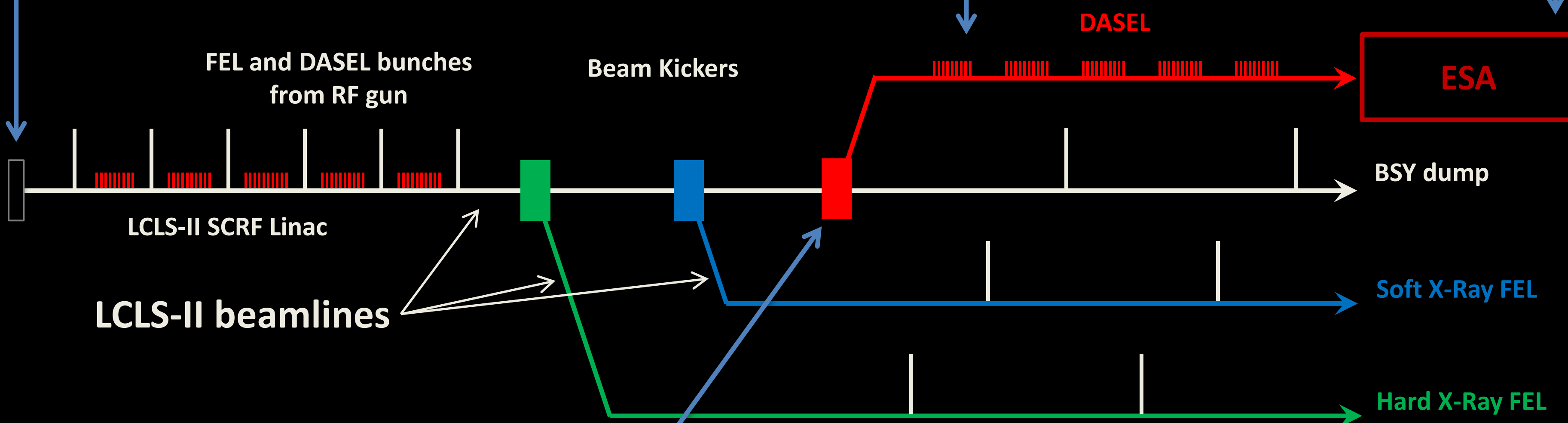
DASEL proposal

T. Raubenheimer

Experimental Facilities
- Small upgrades to ESA systems

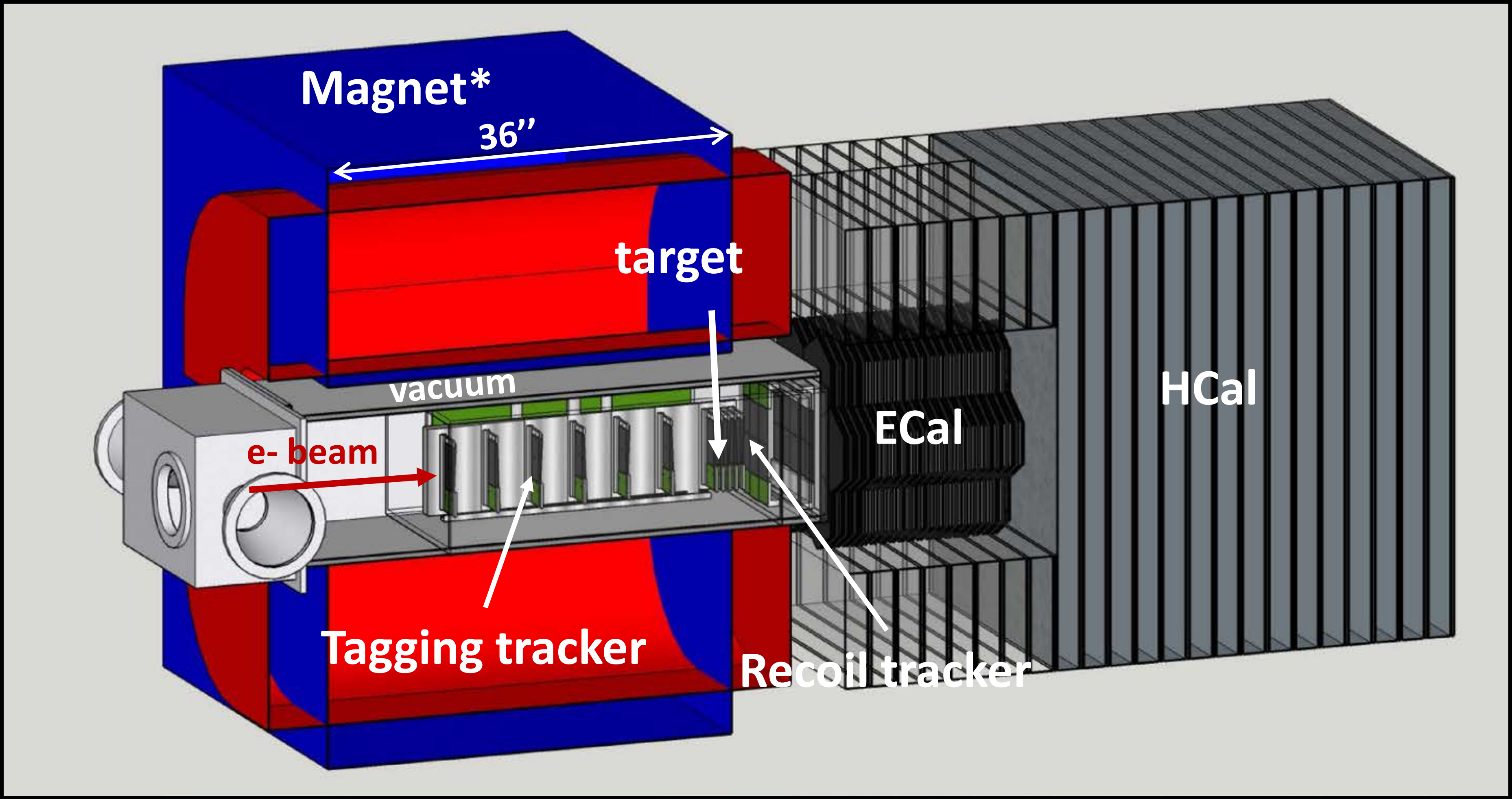
Laser system to fill “unused” buckets with electrons for DASEL

DASEL Beamline connecting to ESA line
- 3 dipoles & 14 quads (all refurbished)



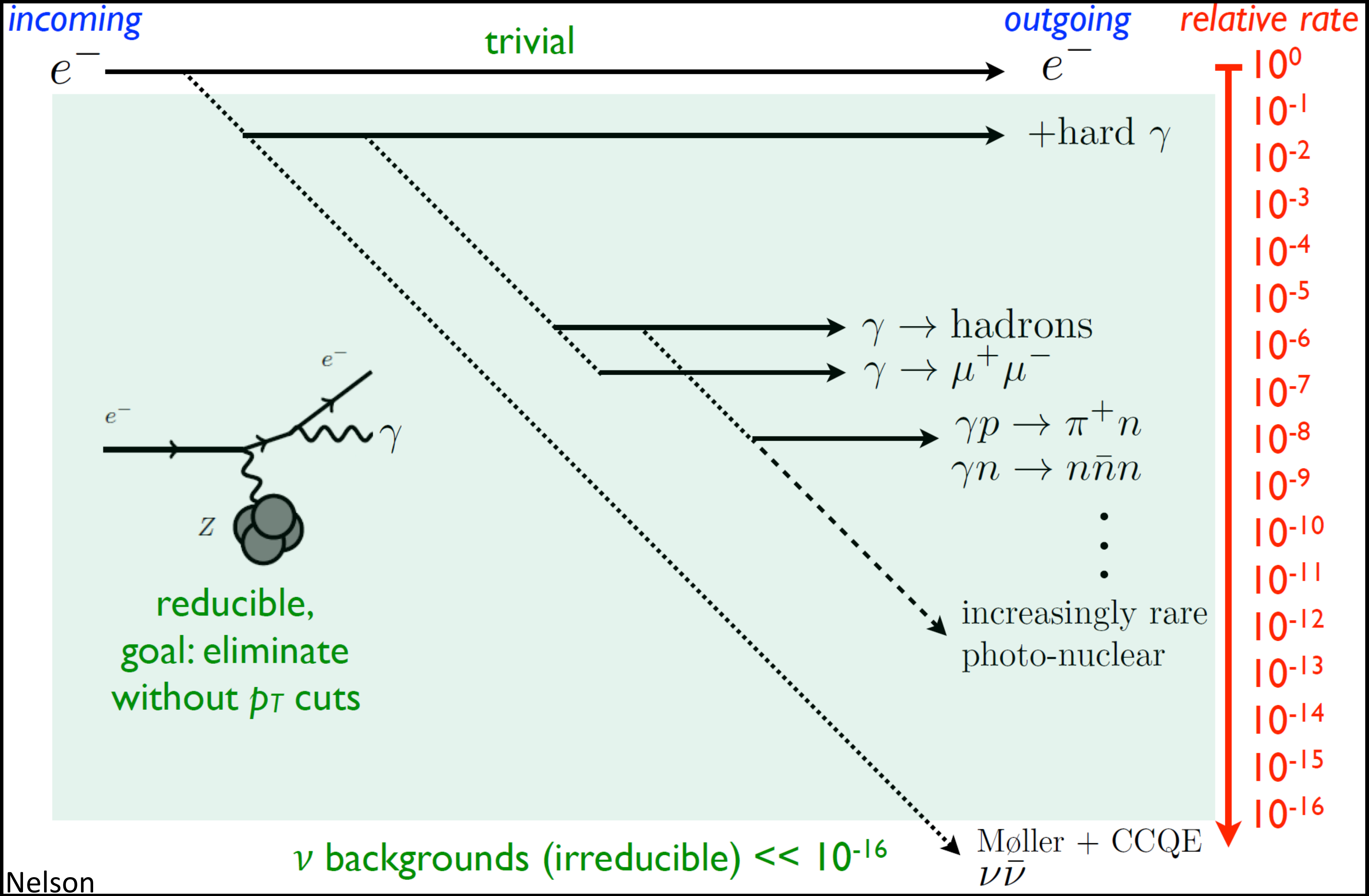
DASEL kicker/septum system downstream of FEL kickers to eliminate interference
- Based on LCLS-II design

LDMX detector concept – Phase I



* 36’’ magnet readily available at SLAC

Fighting the backgrounds



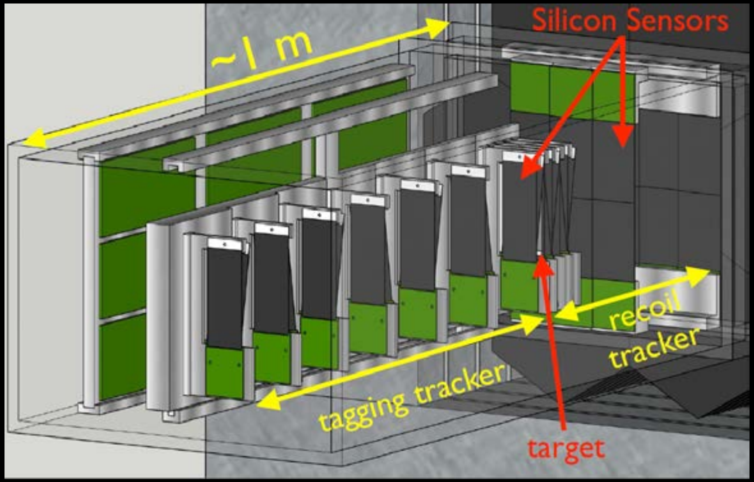
Tracking system

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 ~ 50 – 1200 MeV



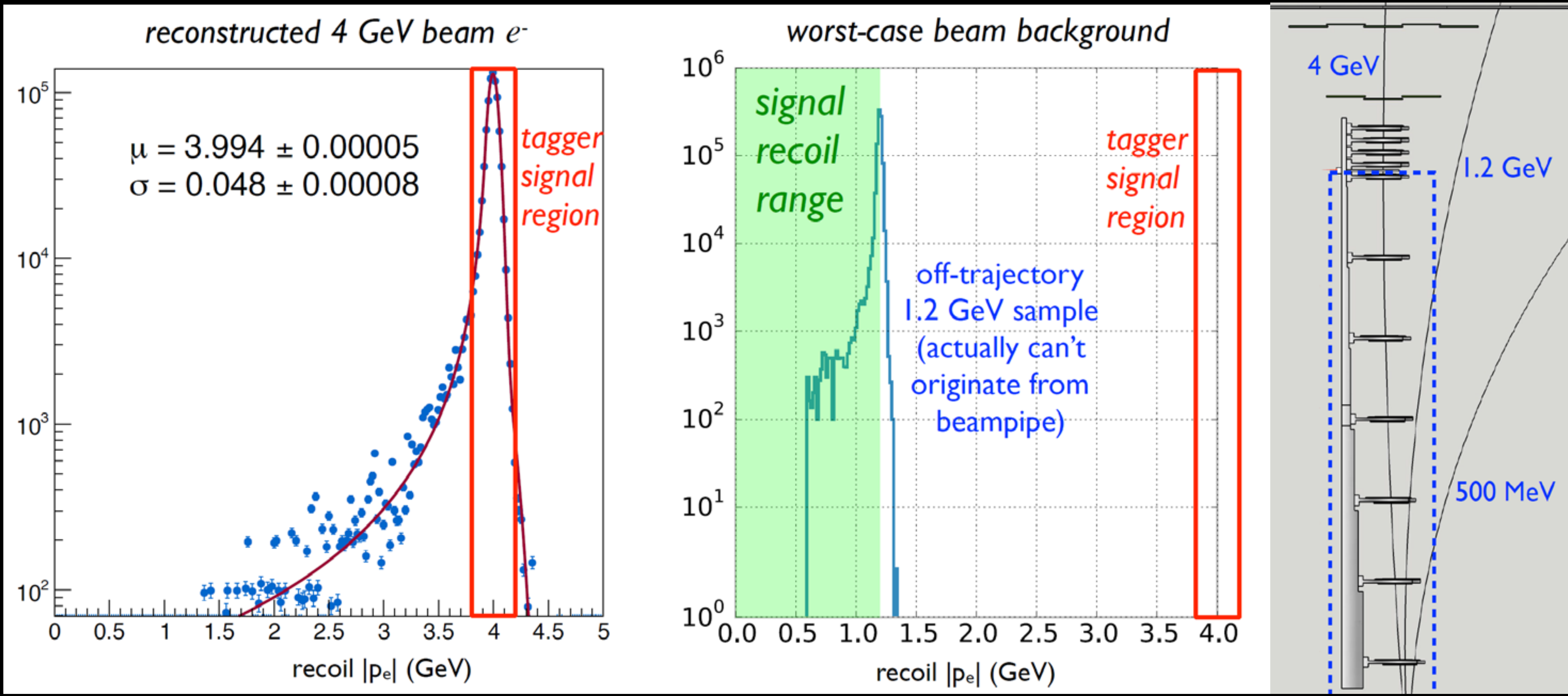
Silicon tracker similar to HPS SVT

- Fast (2ns hit time) and radiation hard, technology well understood

Tungsten target between the two trackers

- 0.1-0.3 X_0 thickness to balance between signal rate and momentum resolution
- Scintillator pads at the back of target to veto empty events

Tracking system



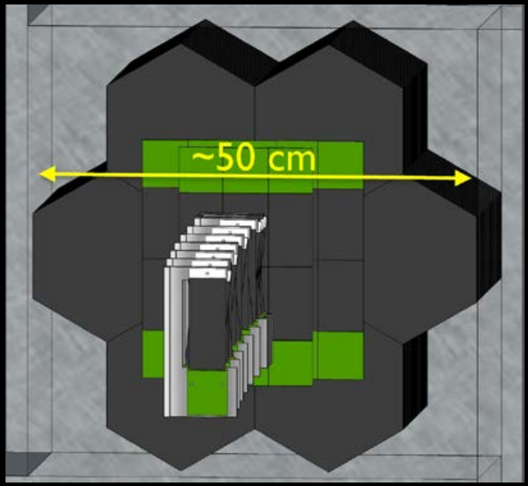
Tagging tracker efficiently rejects beam-induced background

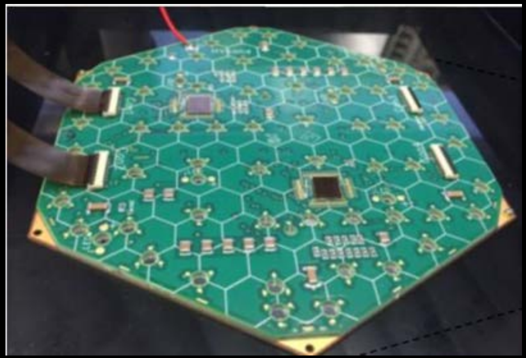
EM calorimeter

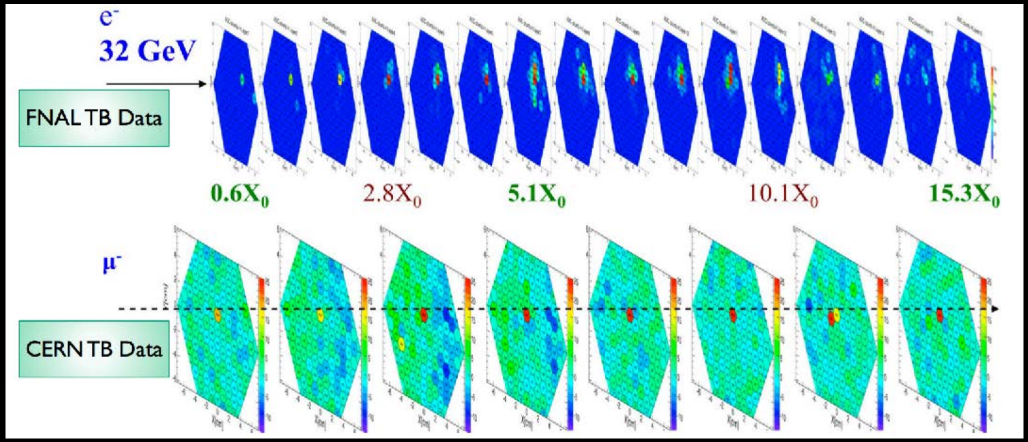
Si-W sampling calorimeter

- Fast, dense and radiation hard
- 40 X_0 deep for extraordinary containment
- High granularity, exploit transverse & longitudinal shower shapes to reject background events
- Can provide fast trigger

Currently developed for CMS upgrade, adaptable to LDMX

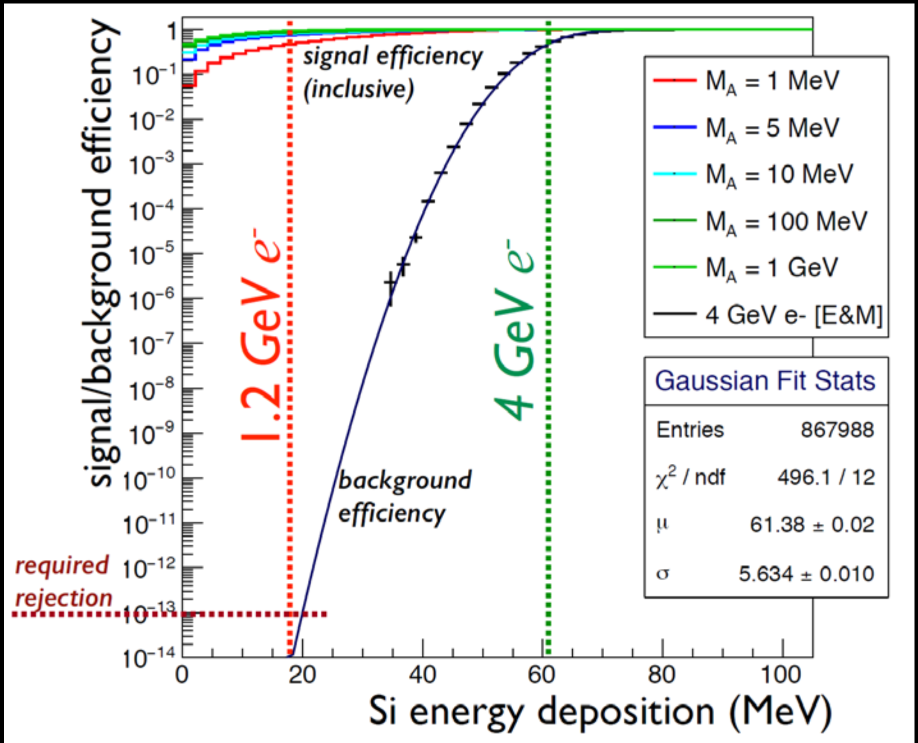






High granularity enables muon vs. electron discrimination, important to reject $\gamma \to \mu\mu$ bkg

EM calorimeter



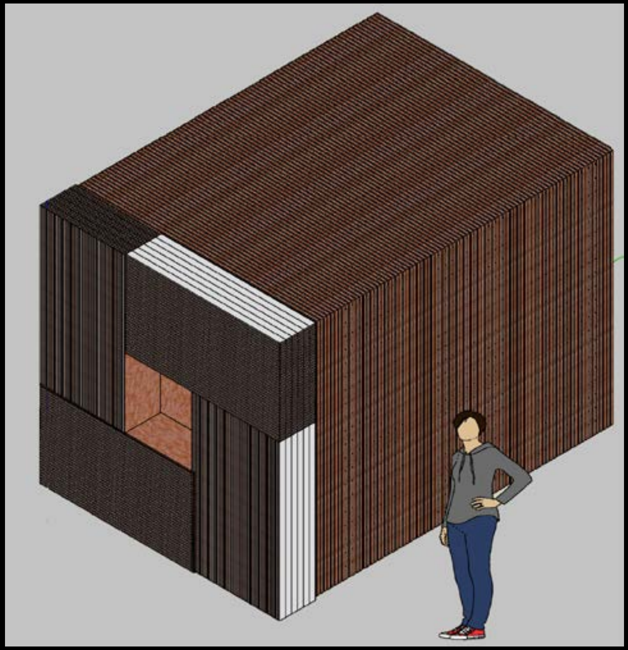
Preliminary studies show that even without using shower shape, the ECAL can reject EM background (4 GeV e- + γ) from signal (E_e < 1.2 GeV) at the level required for Phase I.

On-going work to include shape information and substantially improve the ECAL performance

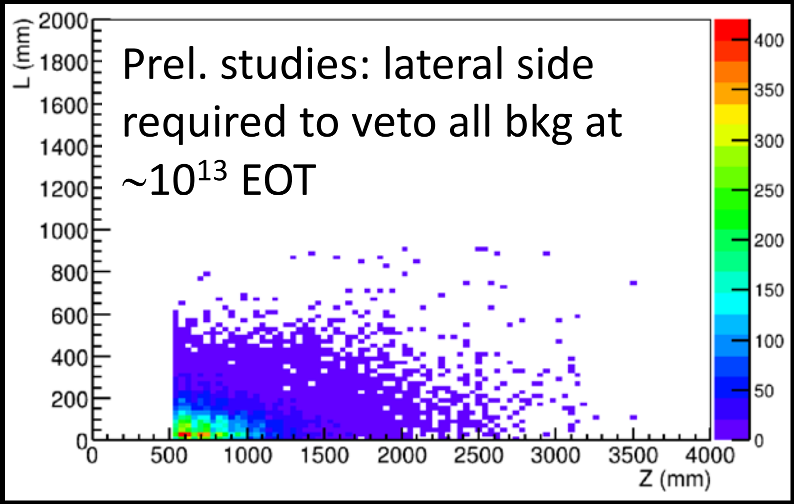
Hadronic calorimeter

Steel / plastic scintillator sampling calorimeter

- Surround ECAL as much as possible
- Catch hadrons from PN events, in particular PN events emitting several hard neutrons (e.g. $\gamma n \to n\bar{n}n$) or many softer neutrons
- Catches wide angle bremsstrahlung, and generally helps with overall veto



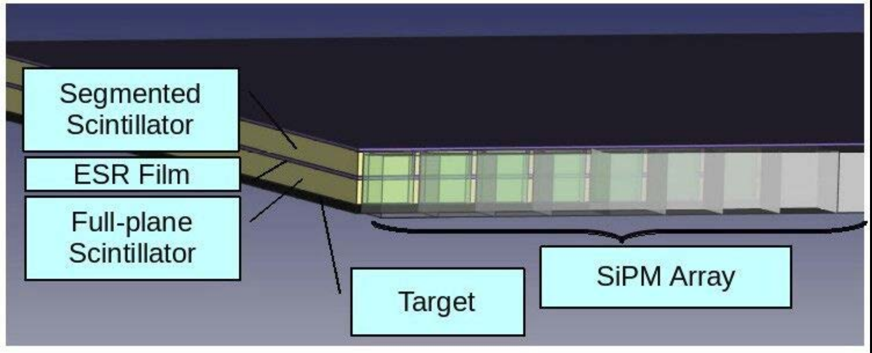
On-going studies to determine the best design parameters and general layout. Scintillator read out by SiPM and WLS fibers.



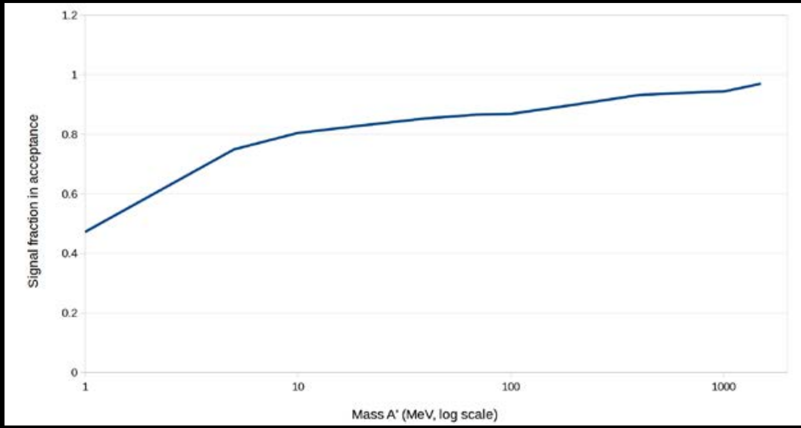
Trigger

Trigger systems

- Reject beam-energy backgrounds (non-interacting e-, bremsstrahlung,...)
- Sum energies of the first 20 layers of Ecal
- Scintillator behind target to suppress empty events



Signal acceptance



Signal efficiency 50-100% with 10^{-4} bkg rejection (prel. studies)

Photonuclear background

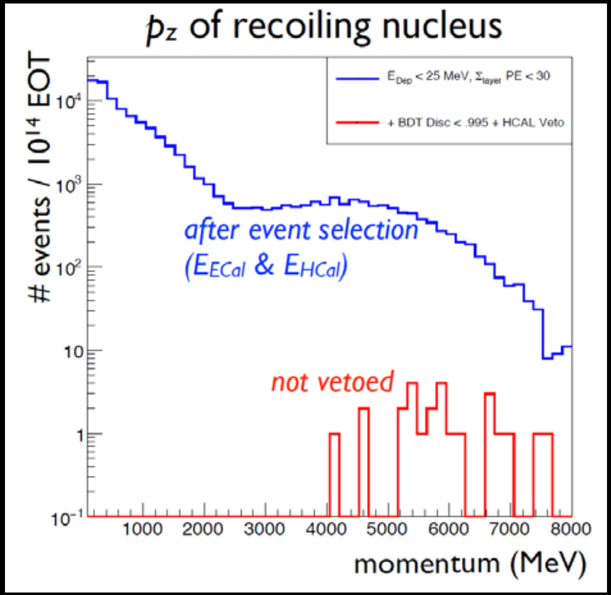
A photon can induce PN reactions in the target, recoil tracker or ECAL. These must be efficiently vetoed.

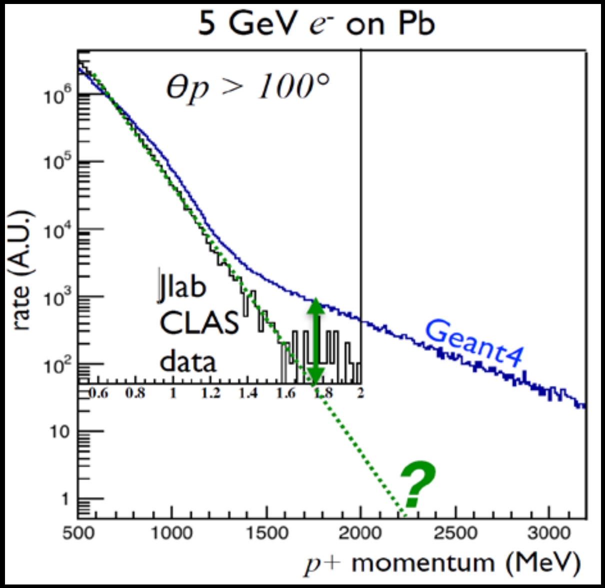
An initial veto that using information from each sub-detector eliminates all but a few events with extremely large momentum transfer to the nucleus at $\sim 10^{13}$ EOT.

Geant4 produces a large number of this type of events:

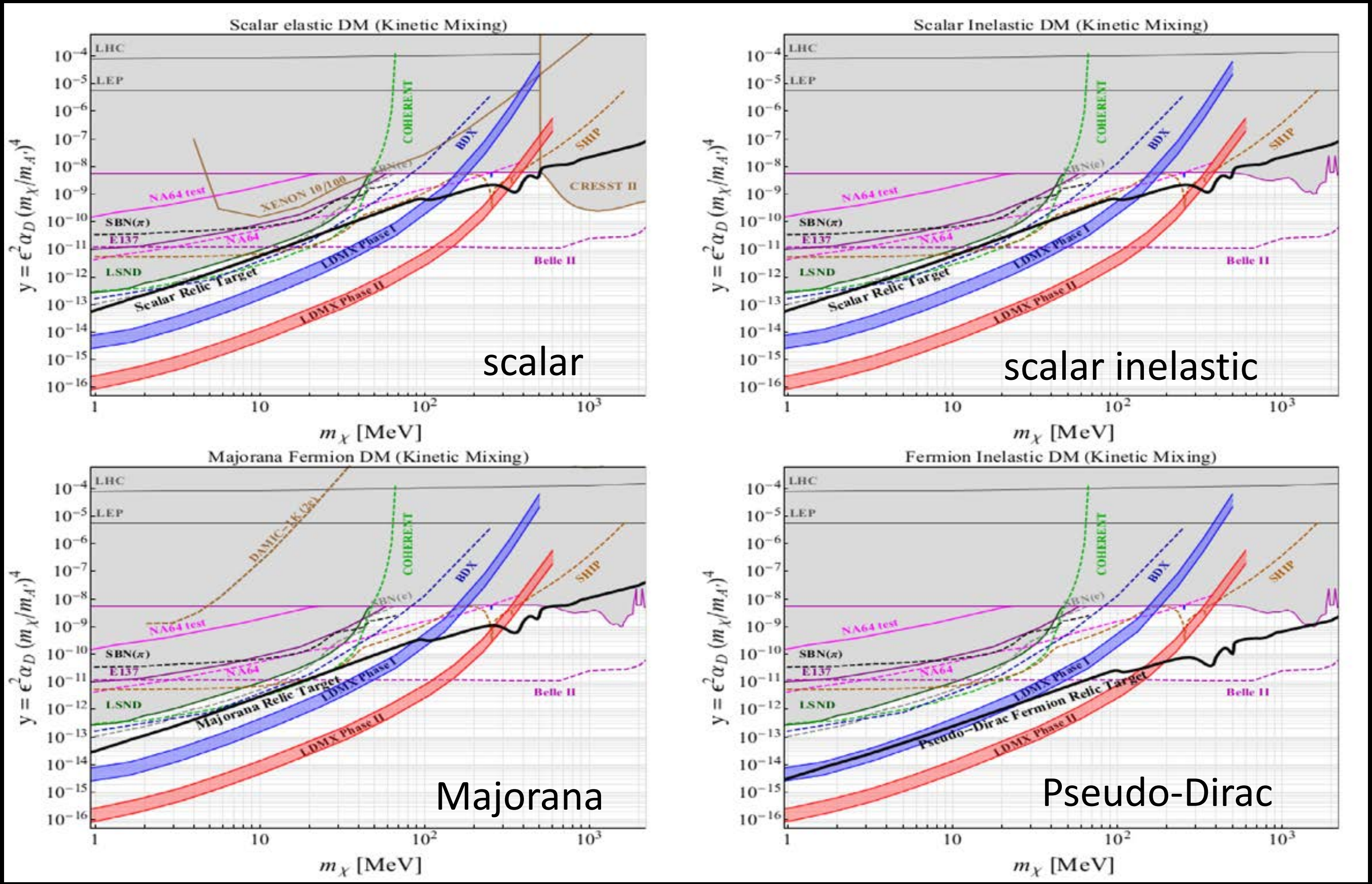
- Not tuned to data in this regime (sparse data available)
- Energy/angle spectra from data suggests that these rates might be overestimated by orders of magnitude.

Working on improving our understanding of these type of events and validating the simulation





Sensitivity estimates



No bkg
$\alpha_D = 0.5$
$m_A/m_\chi = 3$

Phase I 10^{14} EOT @ 4 GeV probes scalar, Majorana and scalar inelastic DM

Phase II 10^{16} EOT @ 8 GeV probes Pseudo-Dirac DM

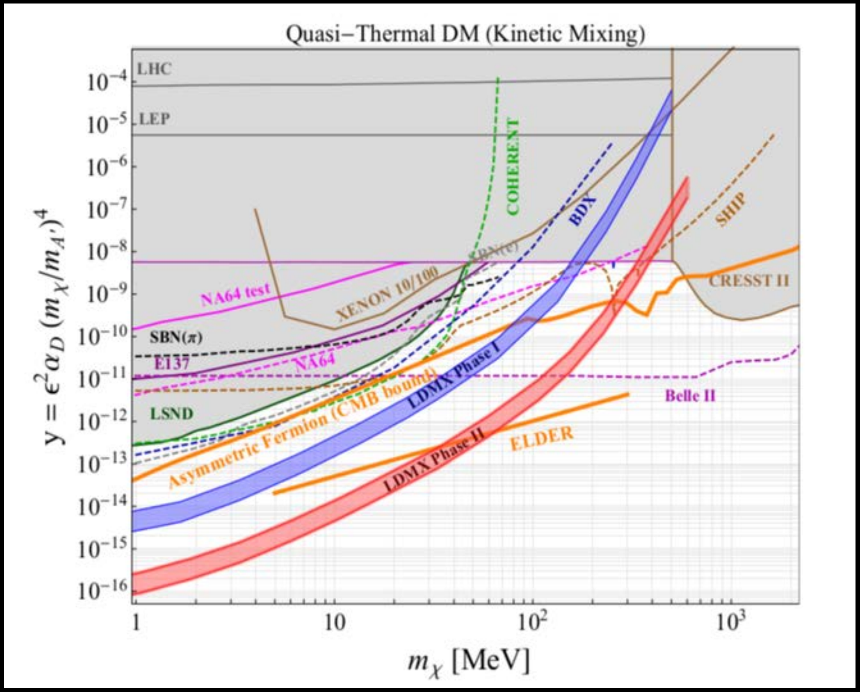
Unprecedented sensitivity surpassing all existing and projected constraints by orders of magnitude for DM masses below a few hundred MeV.

Sub-GeV BSM physics

Sample of BSM scenarios LDMX would be sensitive to:

- Asymmetric DM / ELDER

US cosmic vision report arXiv: 1707.04591

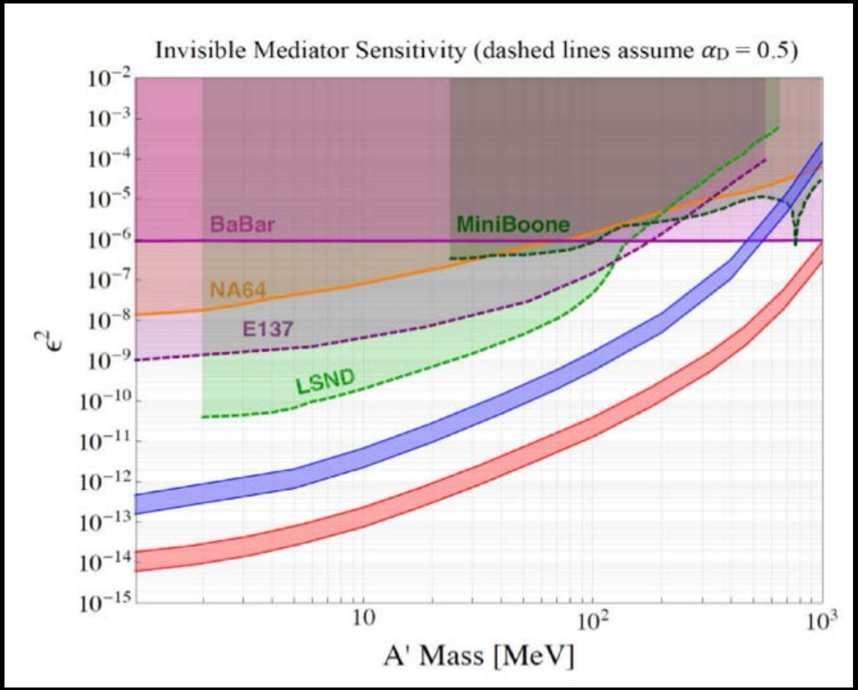


Sub-GeV BSM physics

Sample of BSM scenarios LDMX would be sensitive to:

- Asymmetric DM / ELDER
- Invisible mediator decays, see e.g. Ilten et al. (1801.04847) for B-L, leptophobic or protophobic models

US cosmic vision report arXiv: 1707.04591

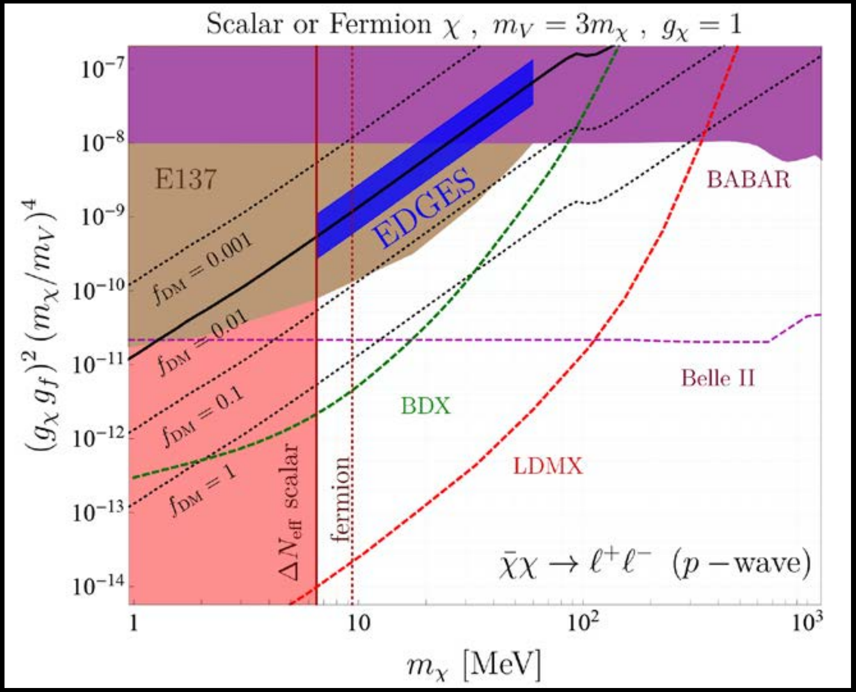


Sub-GeV BSM physics

Sample of BSM scenarios LDMX would be sensitive to:

- Asymmetric DM / ELDER
- Invisible mediator decays, see e.g. Ilten et al. (1801.04847) for B-L, leptophobic or protophobic models
- Milli-Charged particles

Milli-charged DM annihilation to SM via vector portal



Krnjaic, Berlin, Hooper, McDermott, 1803.02804

Model based on EDGES hint excluded, but LDMX sill greatly improves sensitivity

Sub-GeV BSM physics

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- Asymmetric DM / ELDER
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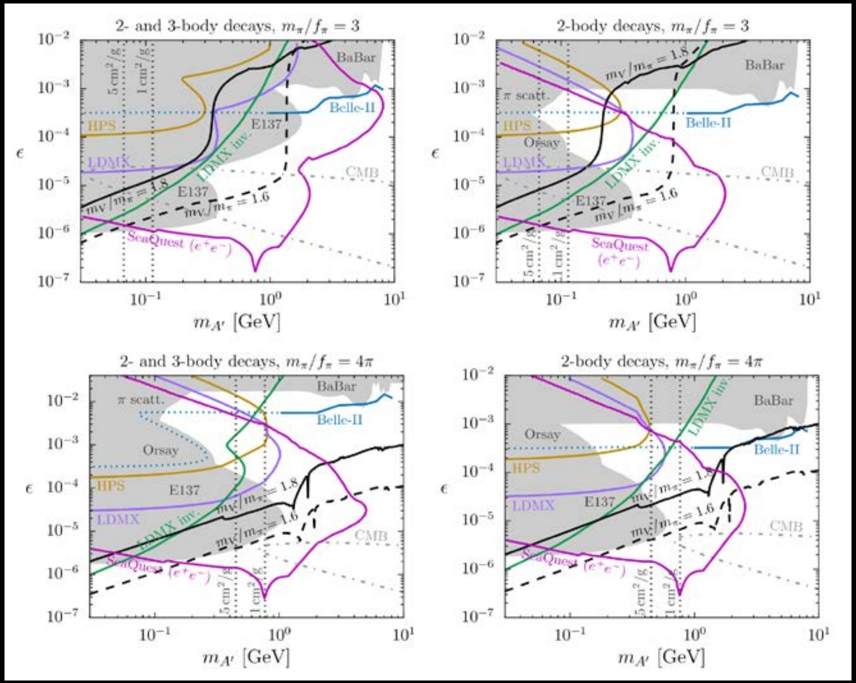
- Milli-Charged particles
- Strongly Interactive Massive Particle and displaced vertices

Hidden sector vector meson decay



Berlin, Blinov, Gori, Schuster, Toro, 1801.05805

See Asher's talk

Sub-GeV BSM physics

Sample of BSM scenarios LDMX would be sensitive to:

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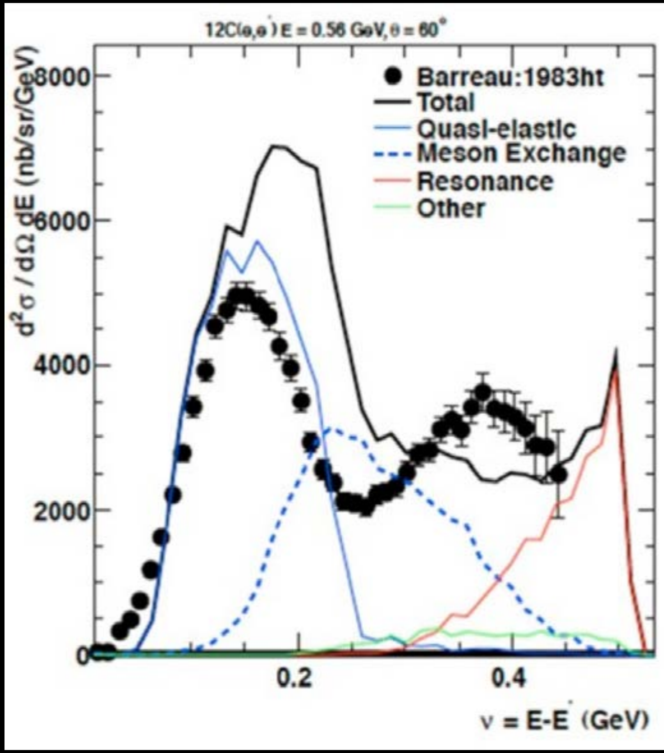
And can also provide useful electro-nuclear and photo-nuclear measurement for future neutrino experiments.

Electron scattering data needed to tune MC



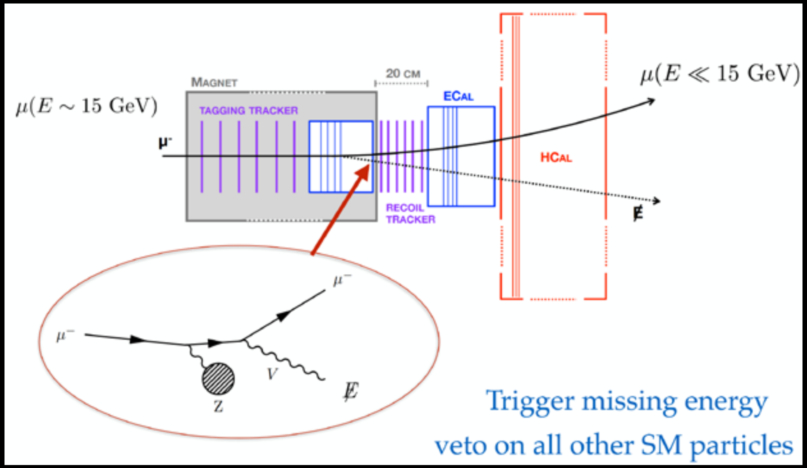
T. Katori, 1304.6014

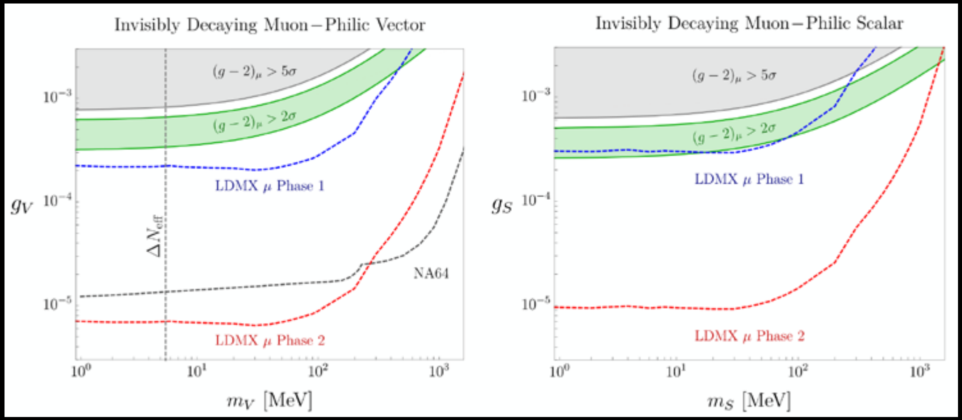
LDMX-mu

LDMX-like detector with a muon beam at FNAL (Krnjaic, Tran, Whitbeck, Kahn)

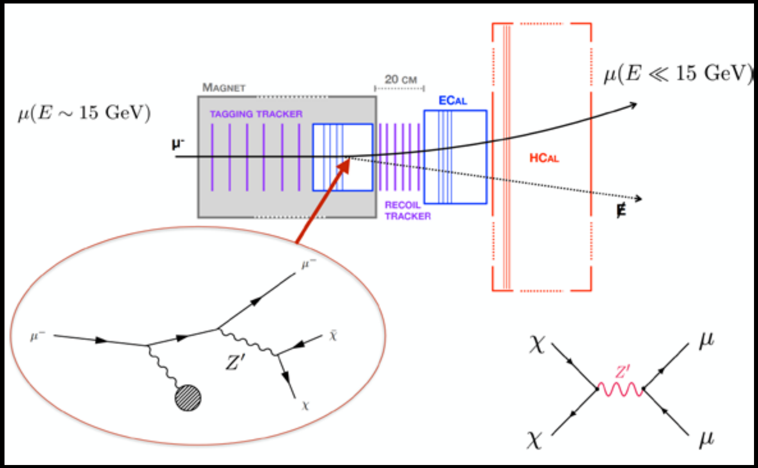
See also Natalia's talk

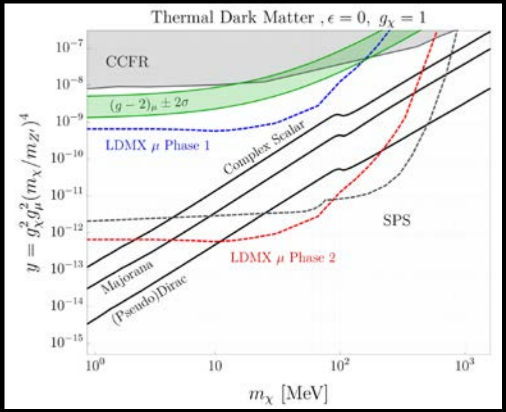
New light muon-philic particles





Muon-philic dark mediator





LDMX collaboration

SLAC NATIONAL ACCELERATOR LABORATORY

Norman Graf, Jeremy McCormick, Takashi Maruyama, Omar Moreno, Tim Nelson, Philip Schuster, Natalia Toro

UCSB

Owen Colegrove, Joe Incandela, Gavin Niendorf, Alex Patterson, Melissa Quinnan

UNIVERSITY OF MINNESOTA

Josh Hiltbrand, Jeremy Mans, Reese Petersen, Michael Revering

Fermilab

Gordan Krnjaic, Nhan Tran, Andrew Whitbeck

Caltech

Bertrand Echenard, David Hitlin

UC SANTA CRUZ

Robert Johnson

LUND UNIVERSITY

Torsten Åkesson, Ruth Pottgen

Take away message

The thermal paradigm is arguably one of the most compelling DM candidate, and the broad vicinity of the weak scale is a good place to be looking – logical extension of WIMP

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

LDMX would offer unprecedented sensitivity to light DM, surpassing all existing and projected constraints by orders of magnitude for DM masses below a few hundred MeV.

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

We are currently writing a comprehensive whitepaper and we hope to be ready for publication in the coming months. Stay tuned…