Dark Sector Searches with LDMX

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Brookhaven Forum
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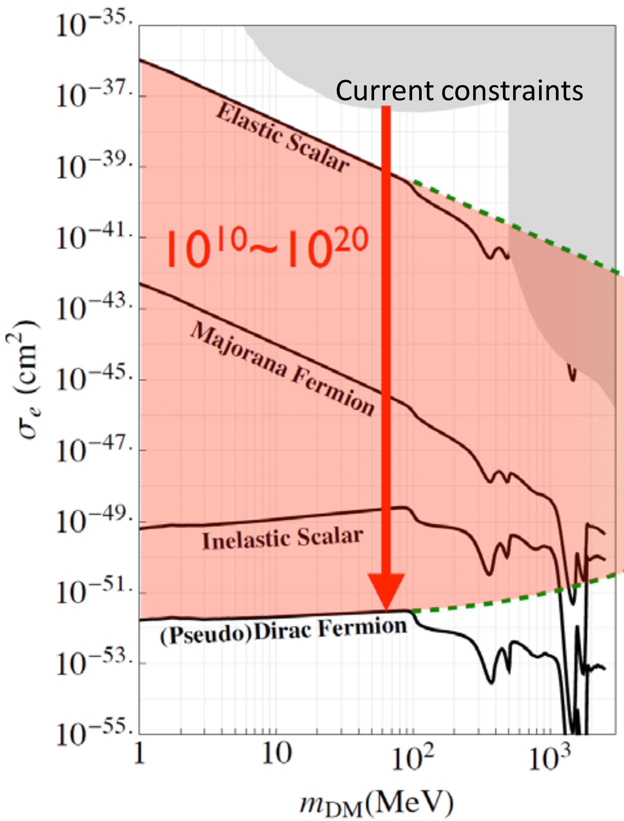
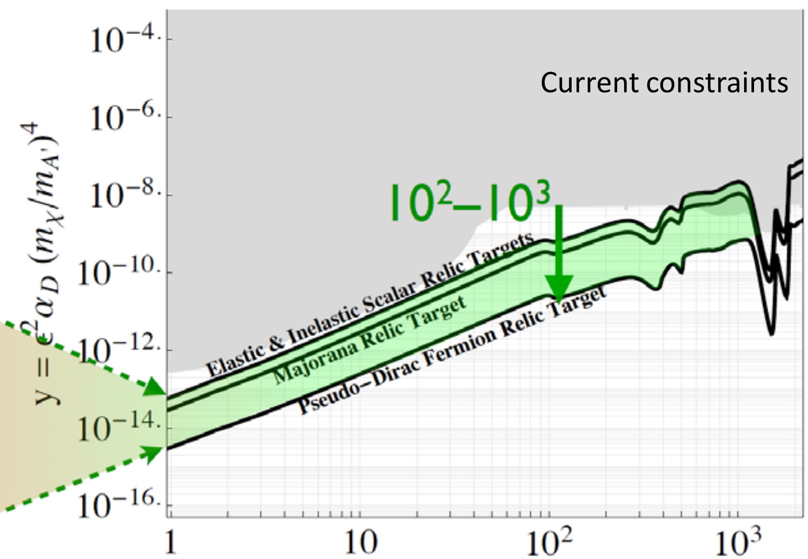
Direct detection and accelerators

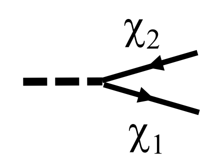
Direct detection targets



Accelerator targets



v≈1



Relativistic production at accelerators probes all spin choices over a wide mass range

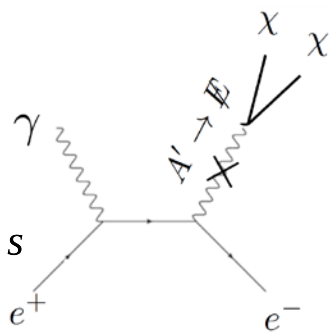
- Accelerators are well-positioned to directly probe annihilating thermal LDM
  - Lighter dark sector masses are more difficult to access – the coupling must be much lower, which makes it difficult to produce in a collider
  - Fixed-target configurations are likely the way to get large-enough luminosities

Accelerator approaches

Missing mass

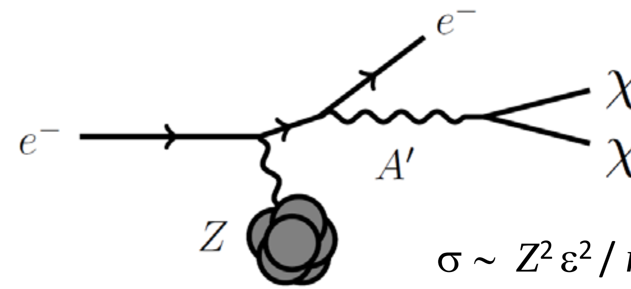
$\sigma \sim \varepsilon^2/s \quad m_A << s$

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



Resonant signal

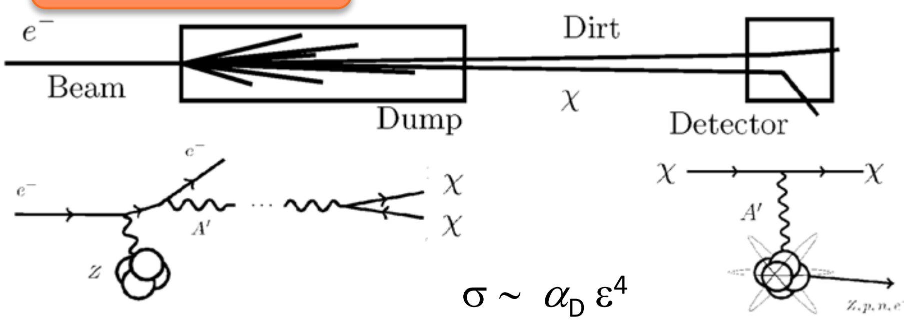
Missing energy / momentum



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

Large yield at low $m_{A'}$

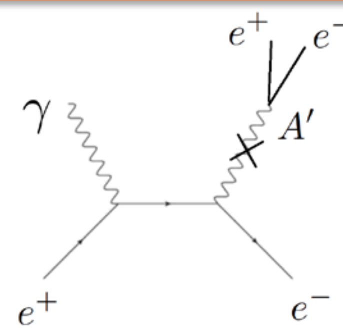
Beam dump



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

Probes DM interaction twice

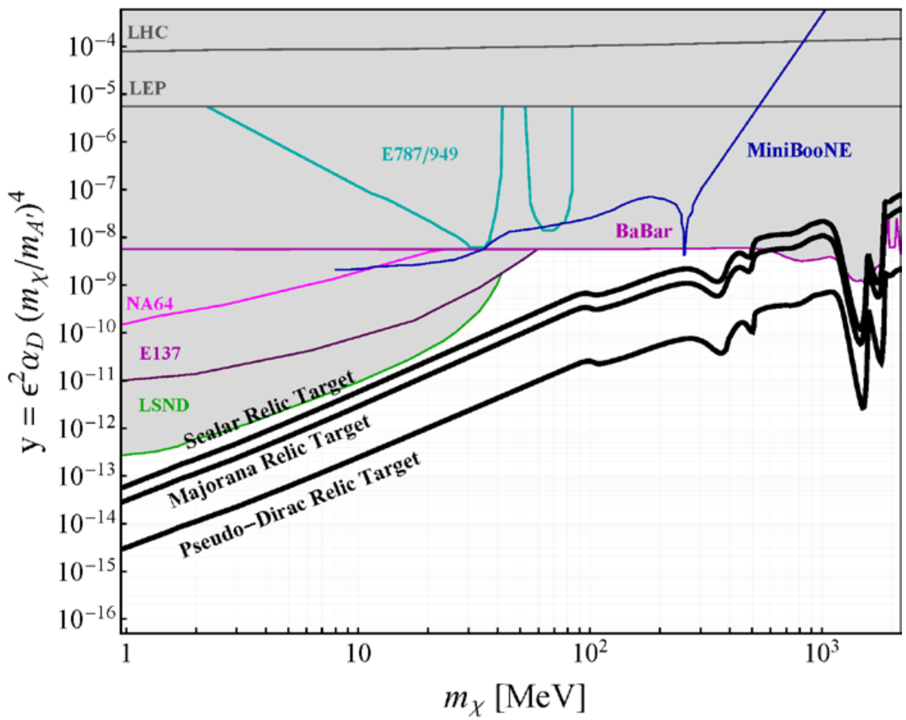
Direct mediator search

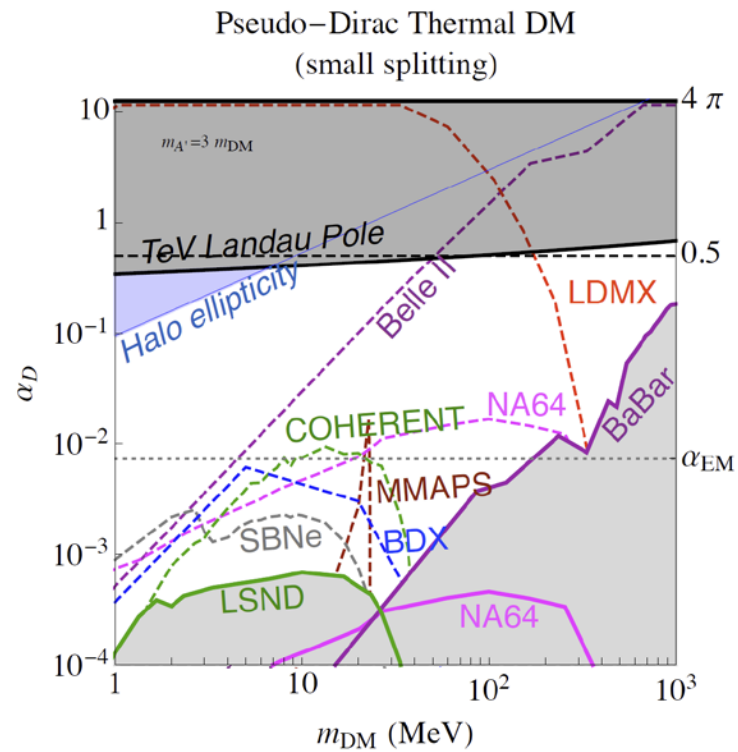


Visible decay $m_{A'} < 2m_\chi$

Accelerator experiments can explore the physics in detail ($\varepsilon, m_{A'}, m_\chi, \alpha_D$), while direct detection is needed to establish cosmological stability

Current constraints





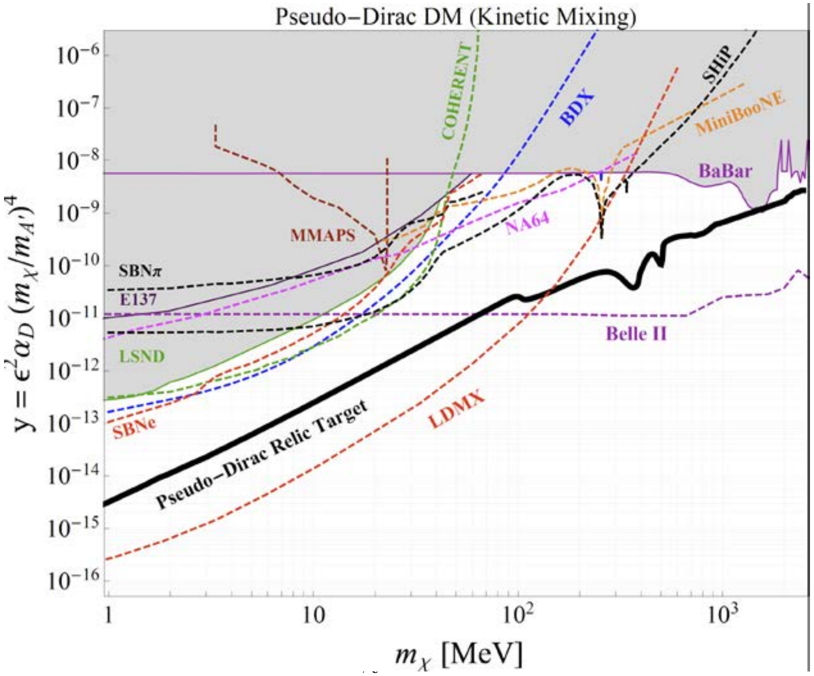
- Some assumptions are needed to plot constraints from missing mass/momentum/energy experiments
- We choose very conservative parameters: α_D = 0.5 and m_A/m_χ = 3.
- These parameters lead to the weak(est) constraints
  For smaller values of α_D or larger mass ratio, the constraints are stronger, while the targets are invariant

A simple LDM scenario

Invisible decays $m_{A'}/m_\chi = 3$, $\alpha_D = 0.5$

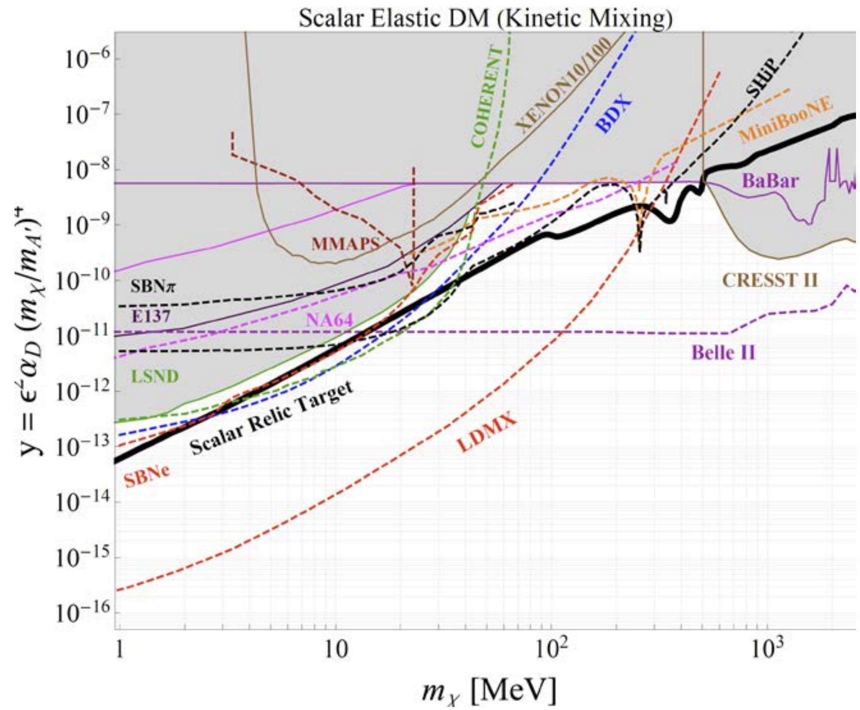
Izaguirre, Krnjaic, Schuster, Toro 1505.00011

Pseudo-Dirac



α

Scalar



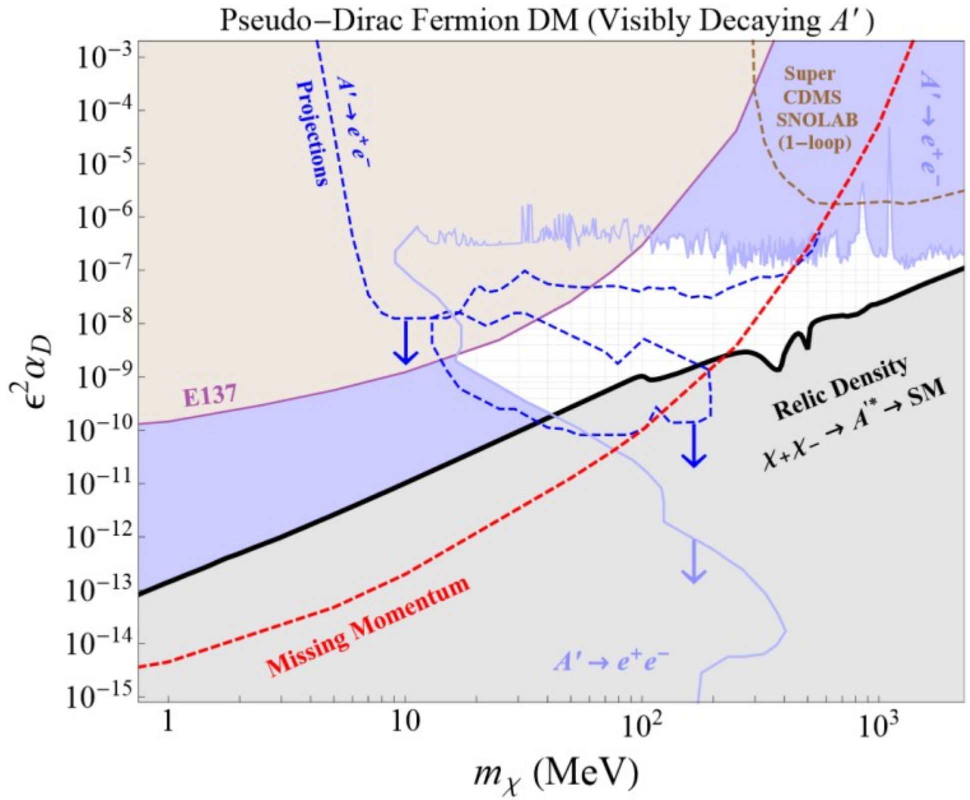
Constraints from various measurements vary with α_D and the $m_{A'}/m_\chi$ mass ratio

Some constraints vary significantly with the type of dark matter

The full thermal relic target coupling may not be covered by a single experiment

A simple LDM scenario

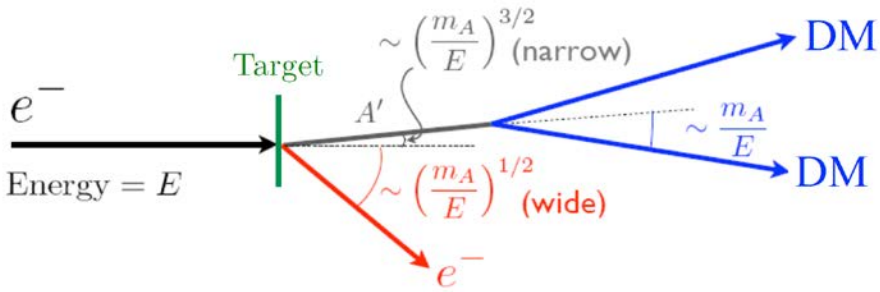
If $2m_\chi > m_{A'} > m_\chi$, A' decays visibly



The constraints from visible decays come into play

Future experiment will probe some of the remaining parameter space

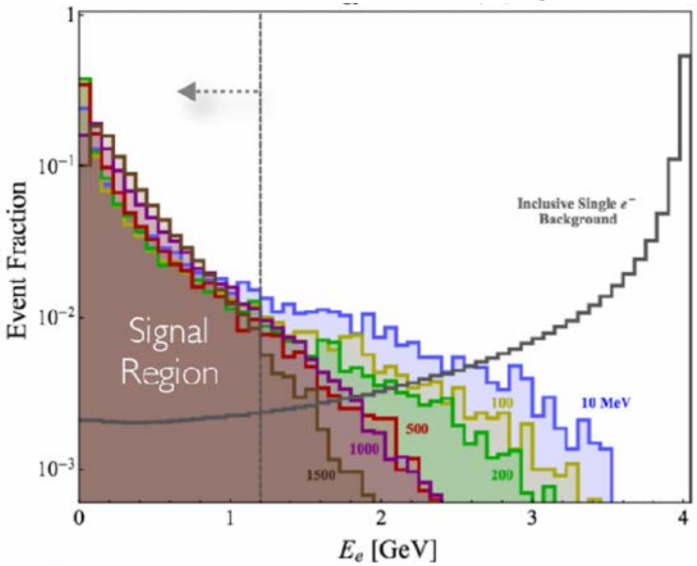
Missing energy/momentum kinematics



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

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

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



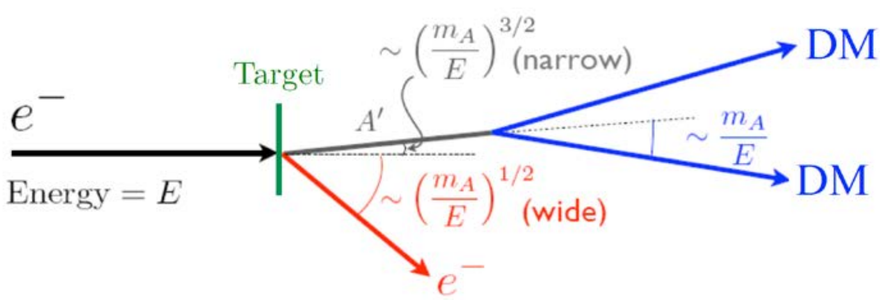
The kinematics are quite different from ordinary bremsstrahlung emission

Bremsstrahlung is suppressed by factor ~30 in the signal region

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

- Signature: large missing energy; soft recoil electron

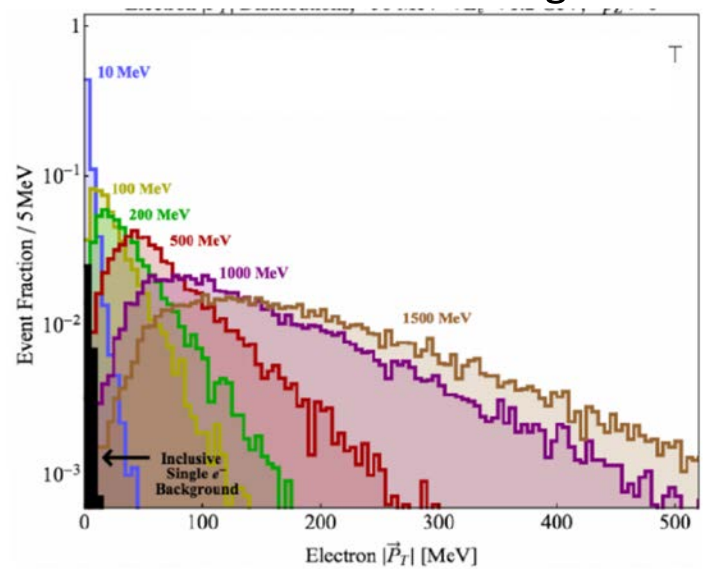
Missing energy/momentum kinematics



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

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

Recoil p_T,
4 GeV e- on 10% X_0 target



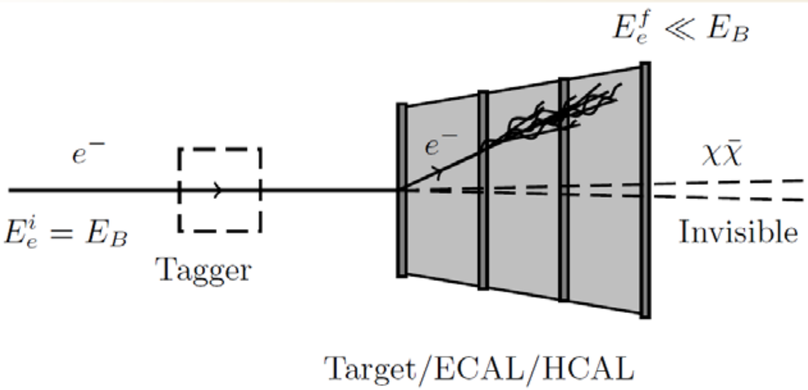
The kinematics are quite different from ordinary bremsstrahlung emission

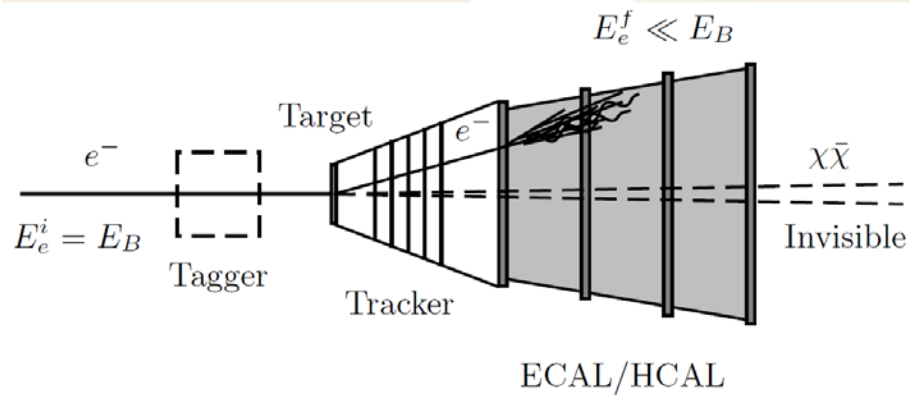
Clear separation from bremsstrahlung background

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

- Signature: large missing energy; soft recoil electron
- large missing p_T: recoil electron is emitted at a large angle

Missing energy / momentum





Missing energy:

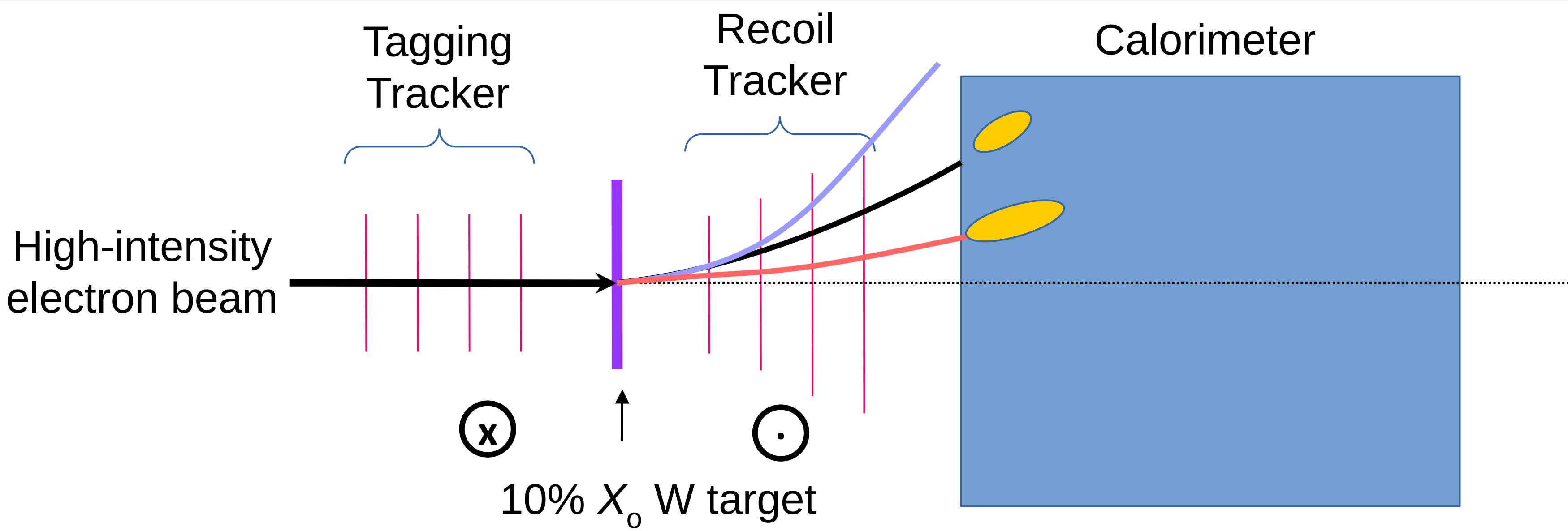
- Higher signal yields / EOT
- Greater acceptance
- Backgrounds beyond 10^{14} EOT might require e-γ identification

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 make a missing energy measurement

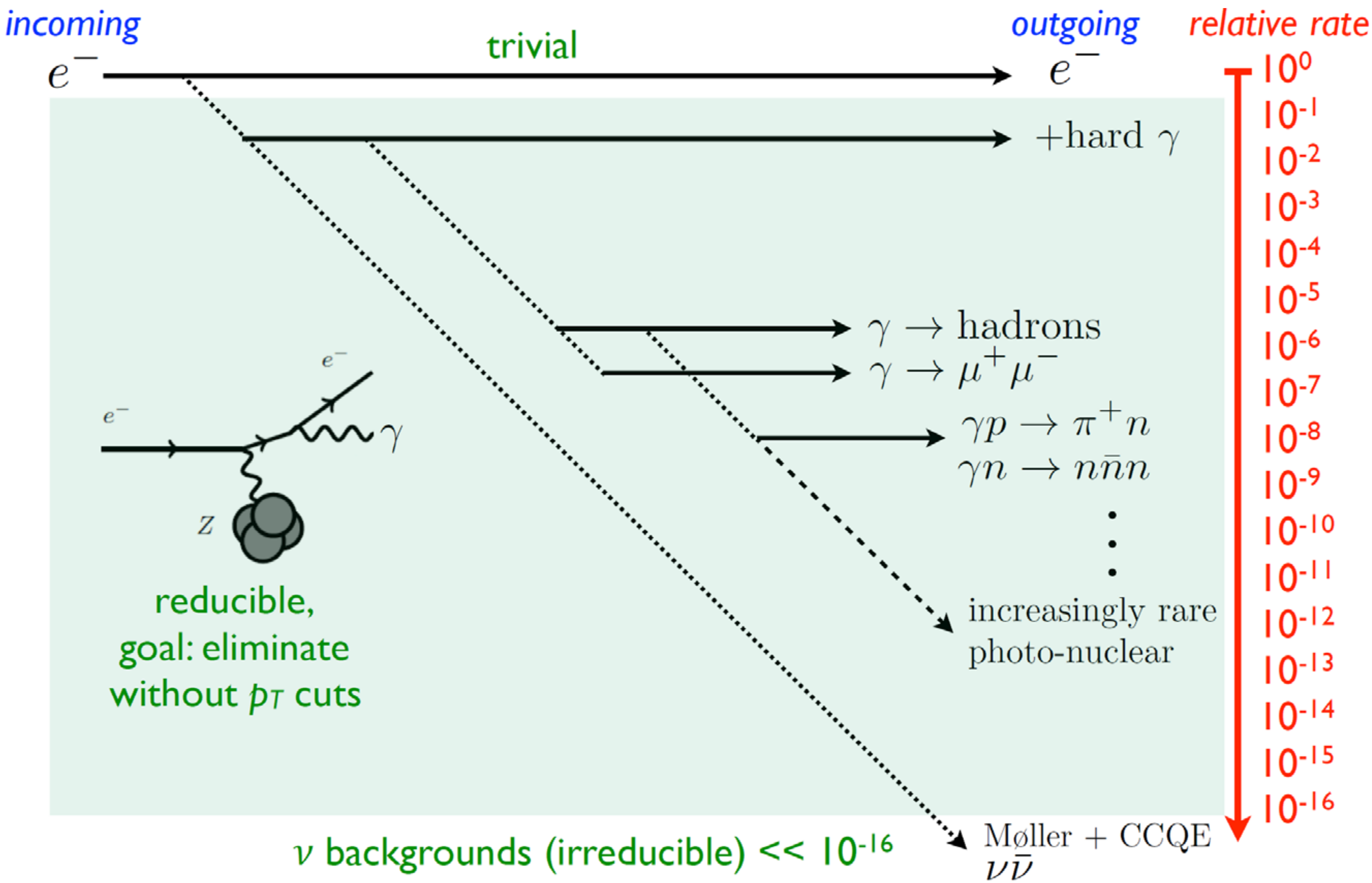
The LDMX concept



- Signal is a low energy, moderate p_T electron and an otherwise empty calorimeter in an event initiated by a full-energy beam electron
  - Recoil p_T between ~80 MeV and 800 MeV
- Backgrounds come from hard interactions in the target (*e.g.*, bremsstrahlung)
  - Challenging backgrounds arise from forward photons having a photonuclear interaction

$$\gamma + n \rightarrow n\bar{n}n \qquad \gamma + p \rightarrow \pi^+ n \qquad \gamma + N \rightarrow N\,\pi^+\pi^-$$

Backgrounds



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

LDMX: a missing momentum design

Beam time structure must allow reconstruction of each individual incident electron event

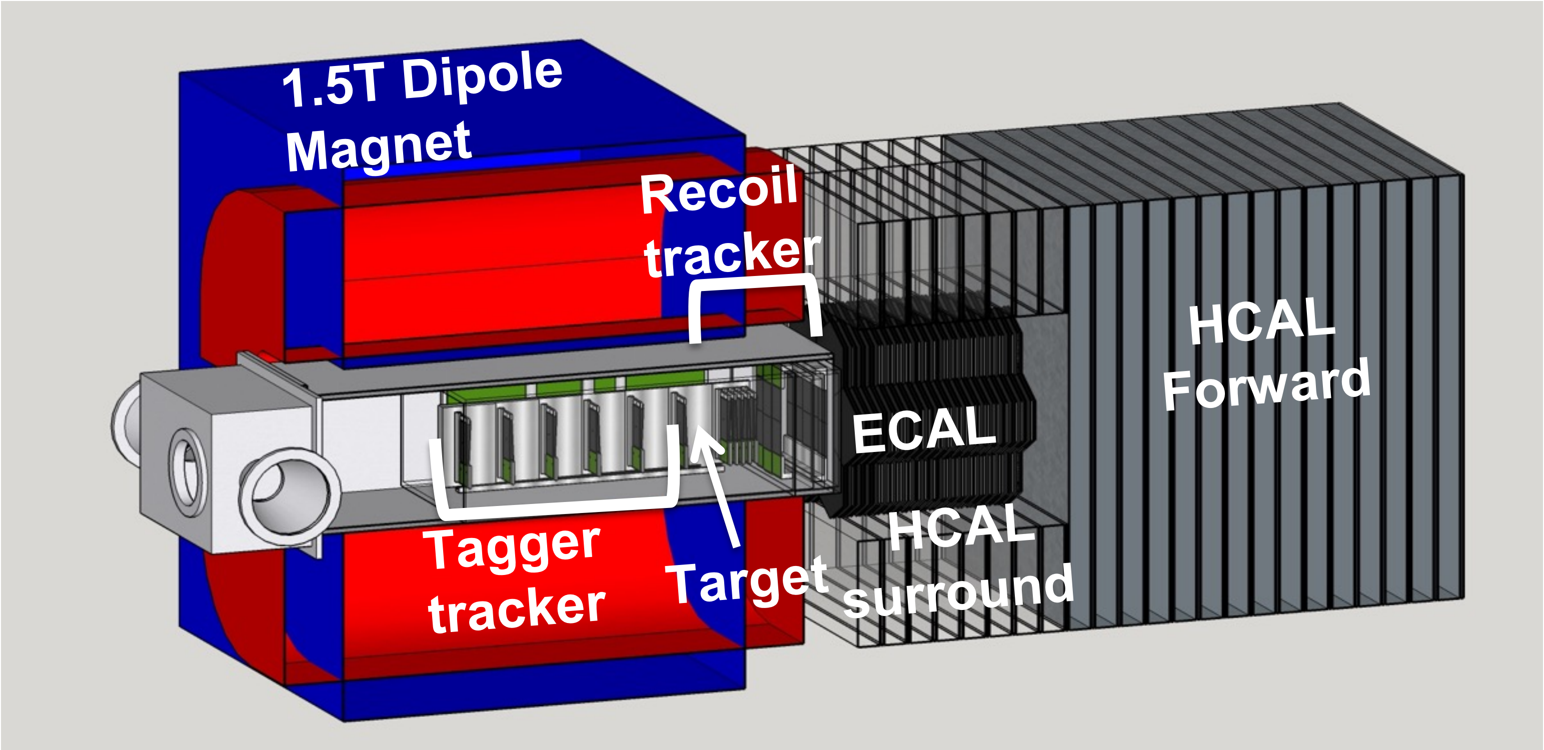
- A multi-GeV, low-current, high repetition rate (CW) (10^{16} EOT/year ≈ 1e^- / 3 ns) beam with a large beam spot to spread the occupancy/radiation dose
- Candidate beams: DASEL @ SLAC (4/8 GeV) and CEBAF @ JLab (up to 12 GeV)

Detector technology with high rate capabilities and high radiation tolerance

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

LDMX has will 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)

LDMX conceptual design



- Dual purpose Magnet and Tracking System
  - Collimated precision tagger tracker in full field → 10% X_O target → compact precision recoil tracker in the fringe field
- Si-W sampling calorimeter (ECAL)
  - *40 X_O, 30 Layers, 7 modules per layer of high efficiency, high granularity calorimetry*
- Scintillator-High Z sampling calorimeter (HCAL) behind and around ECAL
  - *Veto any event with hadronic activity*

LDMX tracker systems

There are two **tracking systems**:

- A tagging tracker to measure the incoming e^-
- A recoil tracker to measure the scattered e^-

Conventional **dipole magnet** w/ two field regions

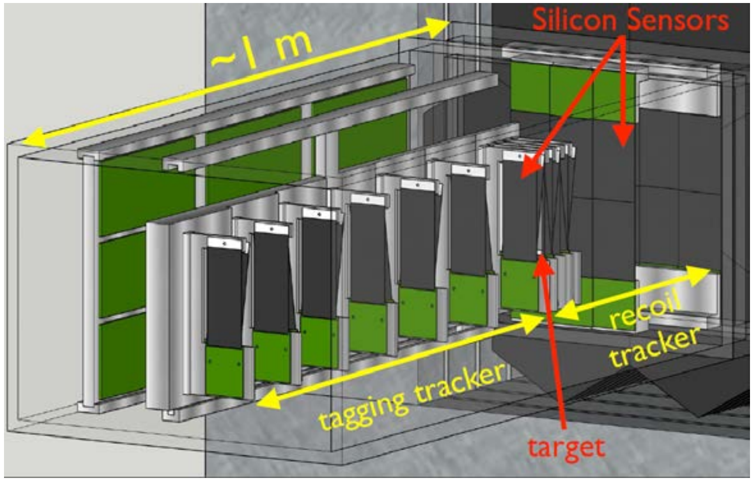
- The tagging tracker is placed in the central region for p_e = 4 GeV,
- The recoil tracker in the fringe field for p_e ~ 50 – 1200 MeV

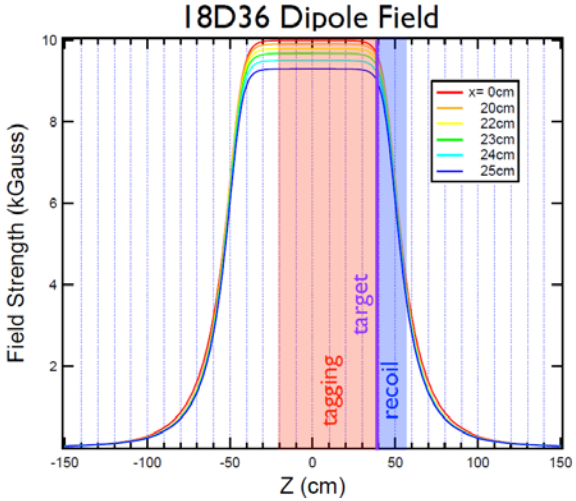
The silicon tracker design is similar to the HPS SVT

- Fast (2ns hit time) and radiation hard

There is a tungsten target between the two trackers

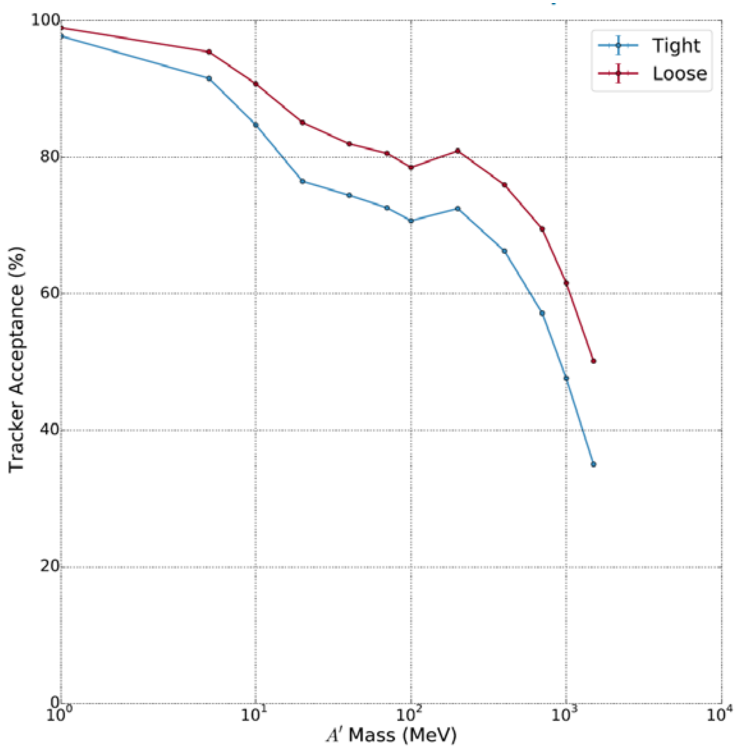
- 0.1-0.3 X_0 thickness to optimize signal rate *vs.* momentum resolution
- There are scintillator pads at the back of the target to veto empty events
- An active radiator target is also being investigated

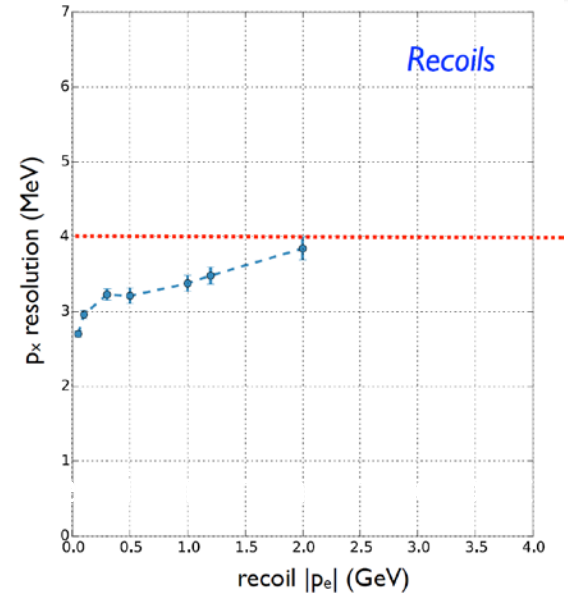


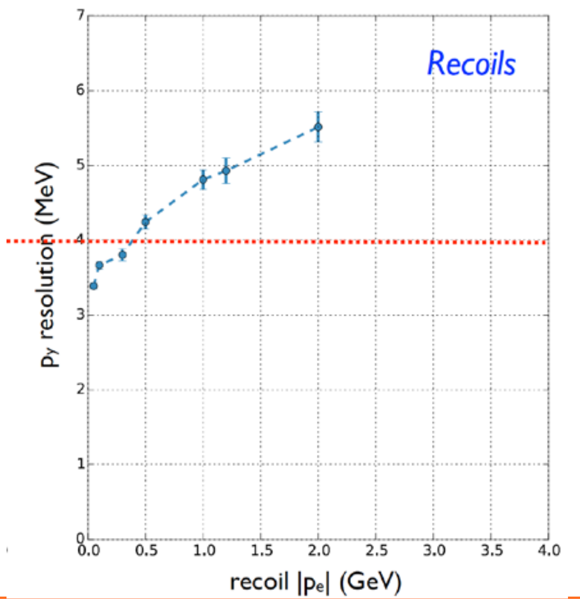


Tracker performance

Acceptance for recoil electrons







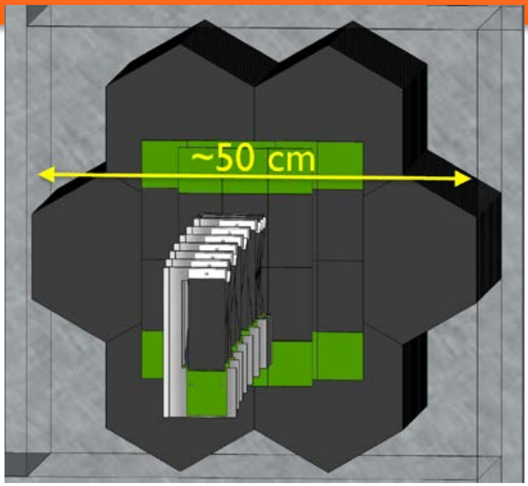
The tracker has good acceptance,
limited at high masses by kinematics,
Recoil momentum resolution is limited
by multiple Coulomb scattering in the target

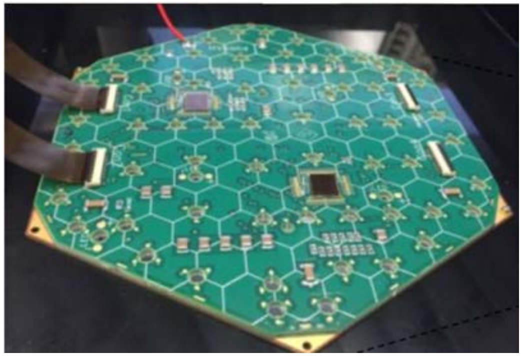
Electromagnetic calorimeter

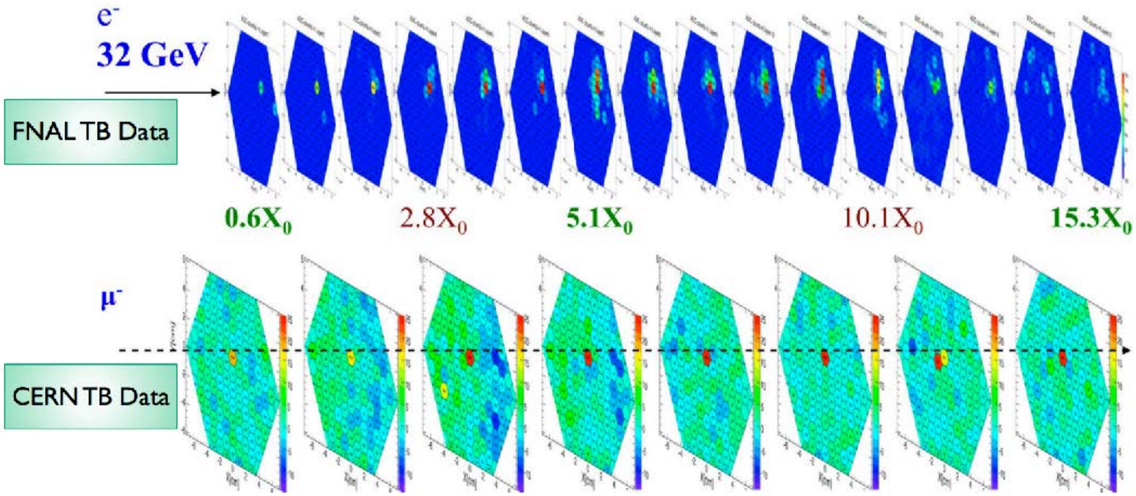
The electromagnetic calorimeter is a Si-W sampling device

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

The ECAL is based on technology currently being developed for the CMS upgrade, which is readiliy adaptable to LDMX

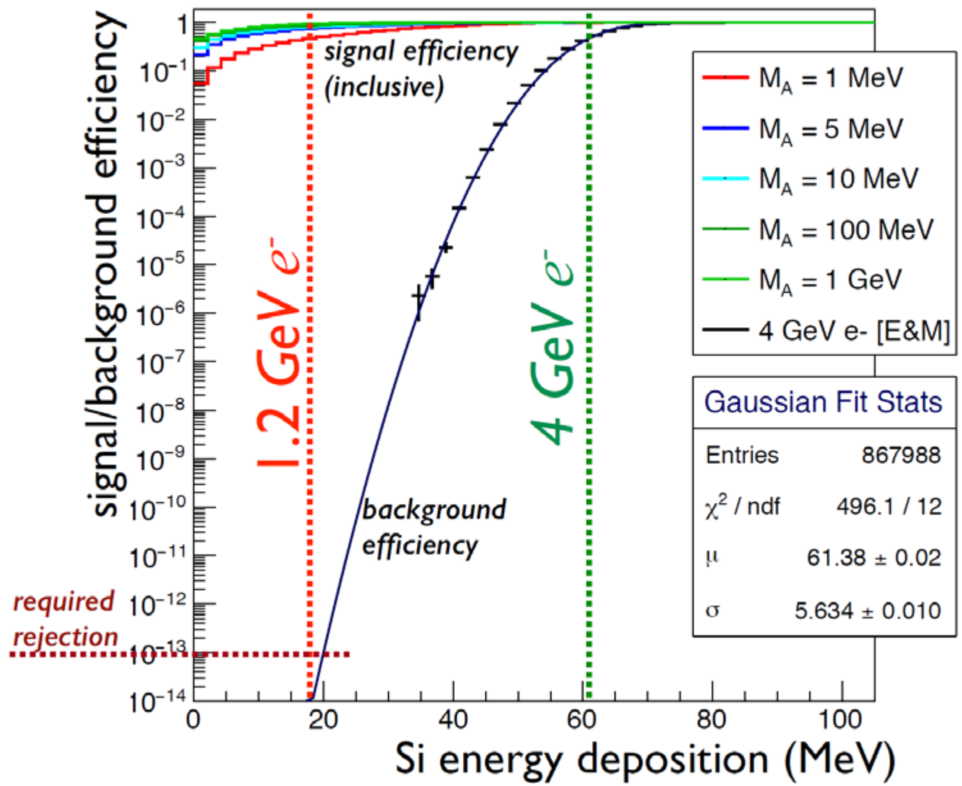






High granularity enables muon/electron discrimination, which is important to reject $\gamma \rightarrow \mu\mu$ background

Electromagnetic calorimeter



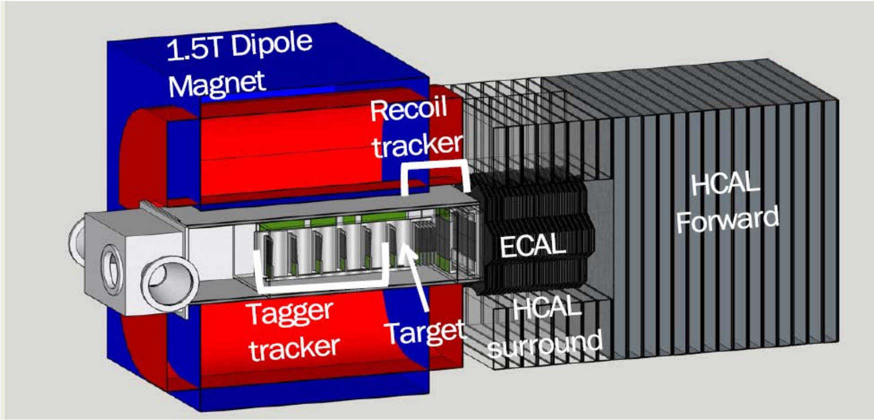
Preliminary studies show that even without using shower shape, the ECAL can distinguish EM background (4 GeV $e^{-}+\gamma$) from signal ($E_e < 1.2$ GeV) at the level required for Phase I

ECAL performance can be further improve the by the use of shower shape information

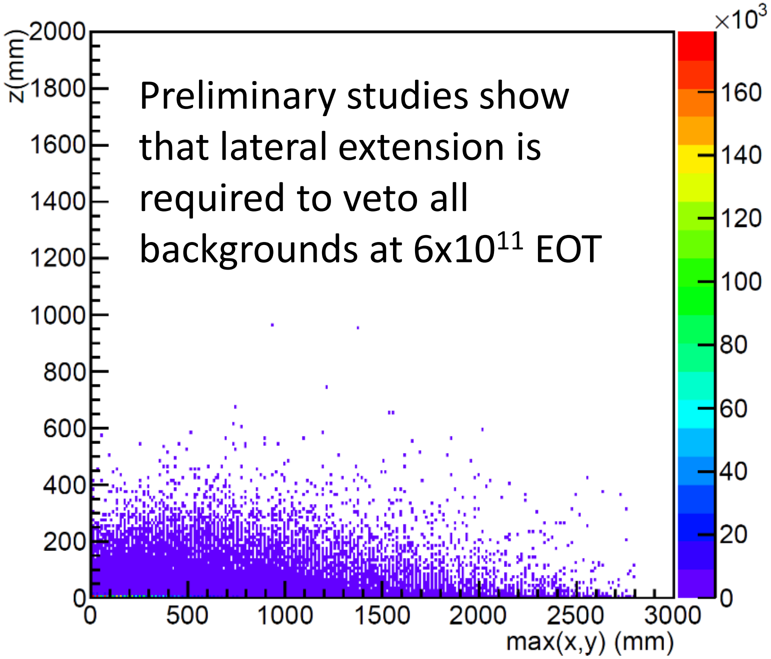
Hadronic veto calorimeter

High Z/plastic scintillator sampling calorimeter

- The HCAL veto surrounds the ECAL, in order to intercept wide angle bremsstrahlung and other EM energy that escapes the ECAL
- Must be efficient for hadrons from photonuclear events, in particular events having several hard neutrons ($e.g\ \gamma n \rightarrow n n \bar{n}$) or many soft neutrons



- Studies are on-going to optimize the absorber material (steel, uranium), scintillator thickness and general layout
- Scintillator read out: WLS fibers and SiPMs
- Detailed studies will also determine the HCAL transverse and longitudinal dimensions
  - We currently simulate a very large volume that will be reduced to a practical size when the ECAL veto has been optimized



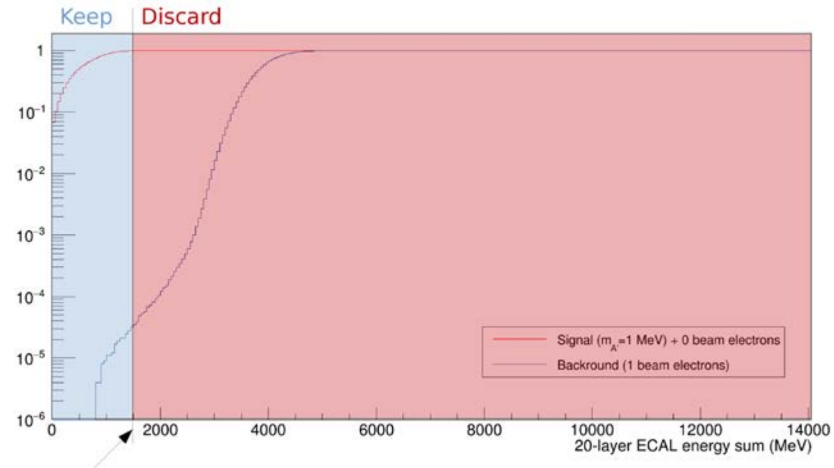
Preliminary studies show that lateral extension is required to veto all backgrounds at 6x10^{11} EOT

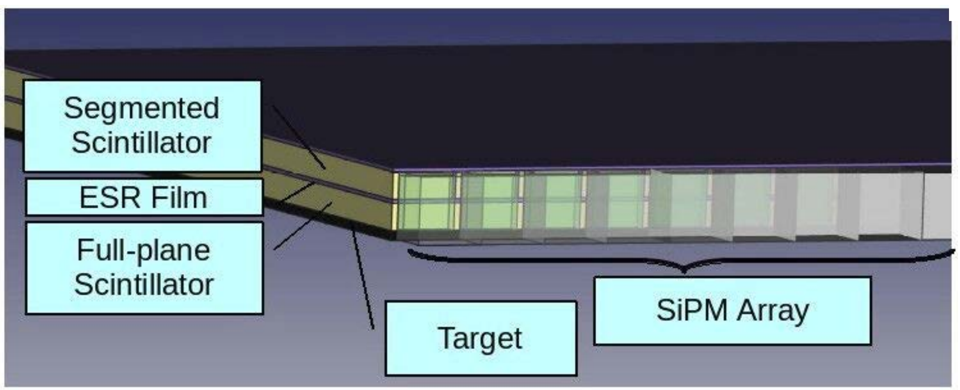
Trigger

Trigger system requirements

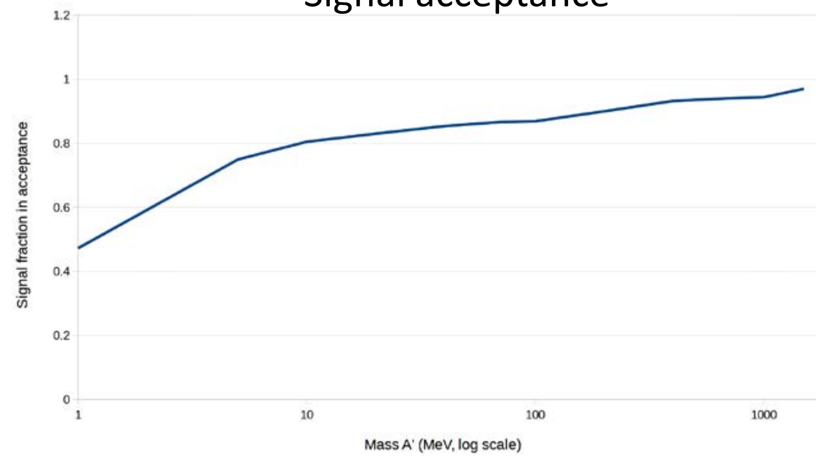
- Reject beam-energy backgrounds (non-interacting e^-, bremsstrahlung,…)
- Sum energies of the first 20 layers of the ECAL
- Suppress empty events (w/ scintillator behind the target)
- Have a signal efficiency 50-100% with 10^{-4} background rejection

Sum of the energies of the first 20 layers of ECAL with recoil electron E < 1.2 GeV





Signal acceptance

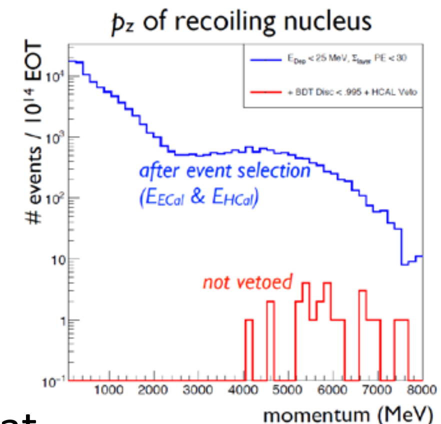


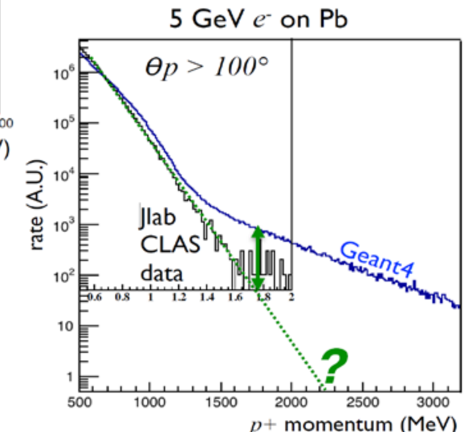
Photonuclear background and muon pairs

- Two example backgrounds originating in the target, recoil tracker or ECAL
  - Photonuclear reactions
  - Muon pair production
- These must be **efficiently vetoed**

Geant4 is not well-tuned to the (sparse) existing data for these reactions

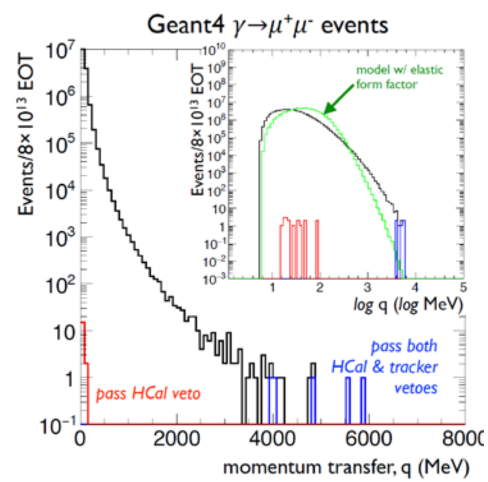
- Energy/angle spectra from data suggests that photonuclear rates may be overestimated by orders of magnitude.
- The rate of $\gamma \rightarrow \mu^+\mu^-$ events with very large momentum transfer q^2 is also overestimated



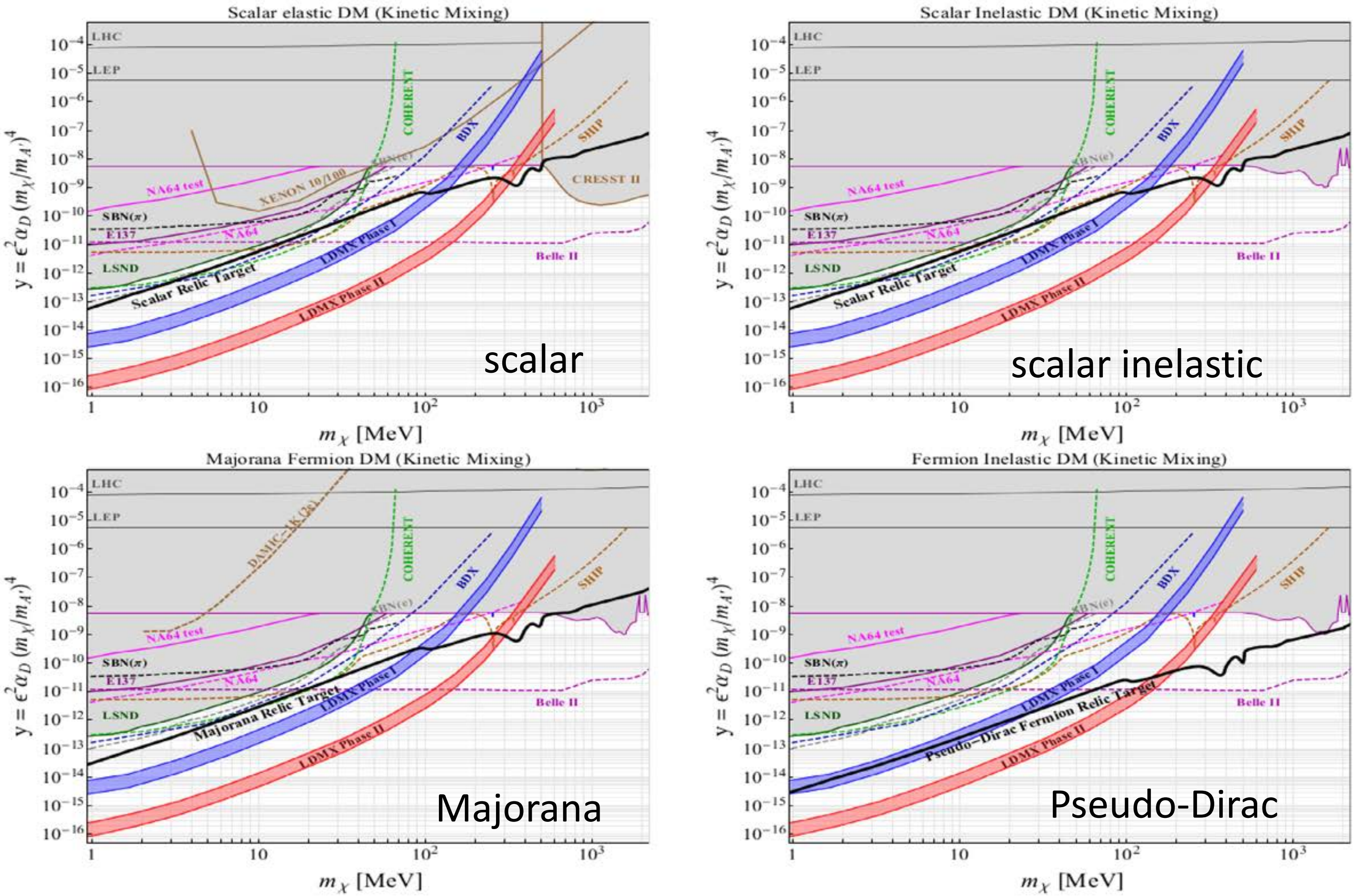


We are working on improving our understanding of these type of events and validating the simulation

An initial veto using information from each sub-detector eliminates all but a few photonuclear events with extremely large momentum transfer to the nucleus at ~10^{13} EOT and $\mu\mu$ events with ~10^{14} EOT



Sensitivity estimates

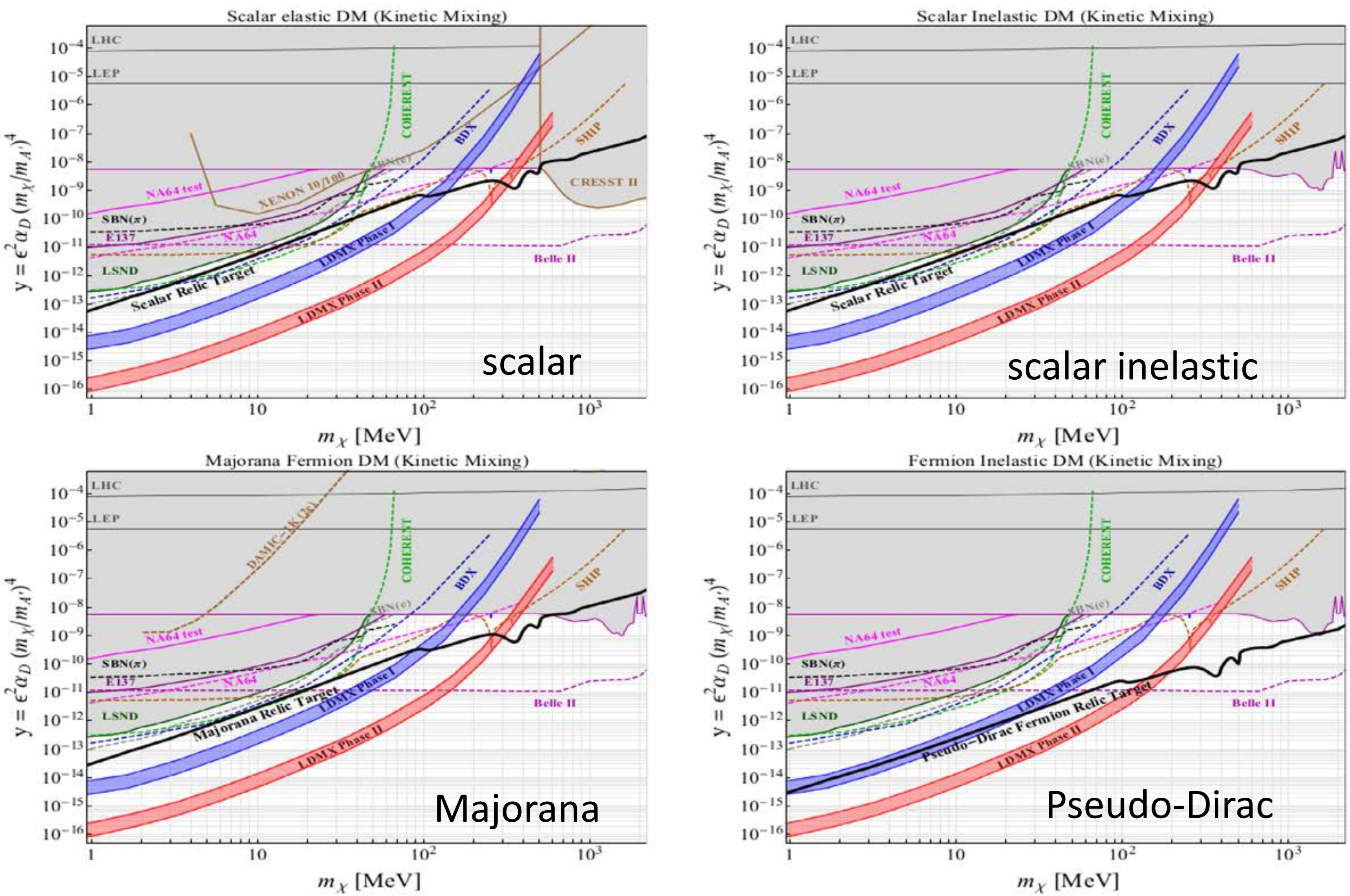


No bkg
$\alpha_D = 0.5$
$m_A/m_\chi = 3$

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

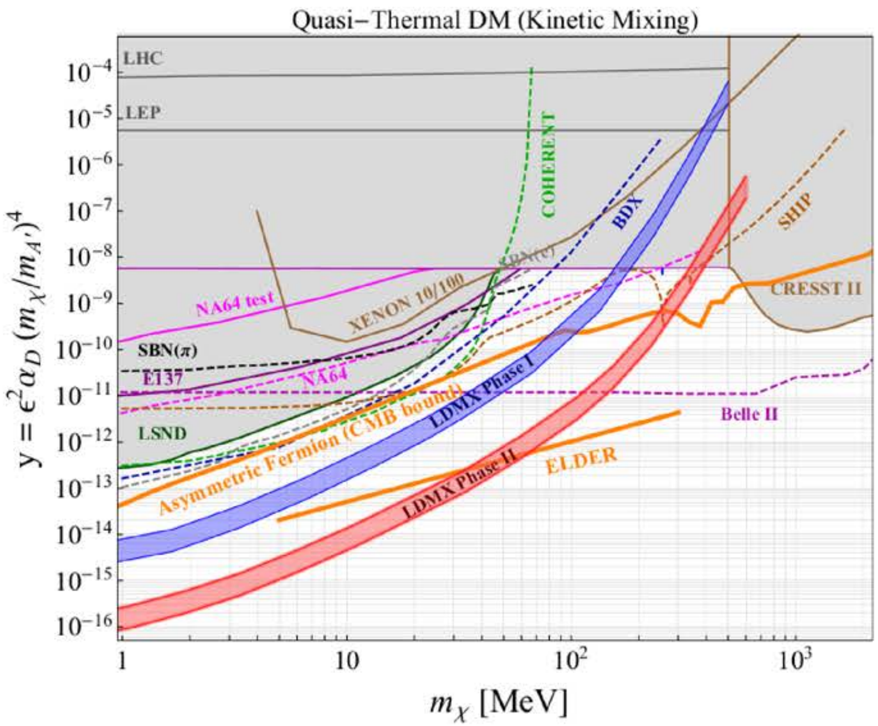
Sensitivity estimates

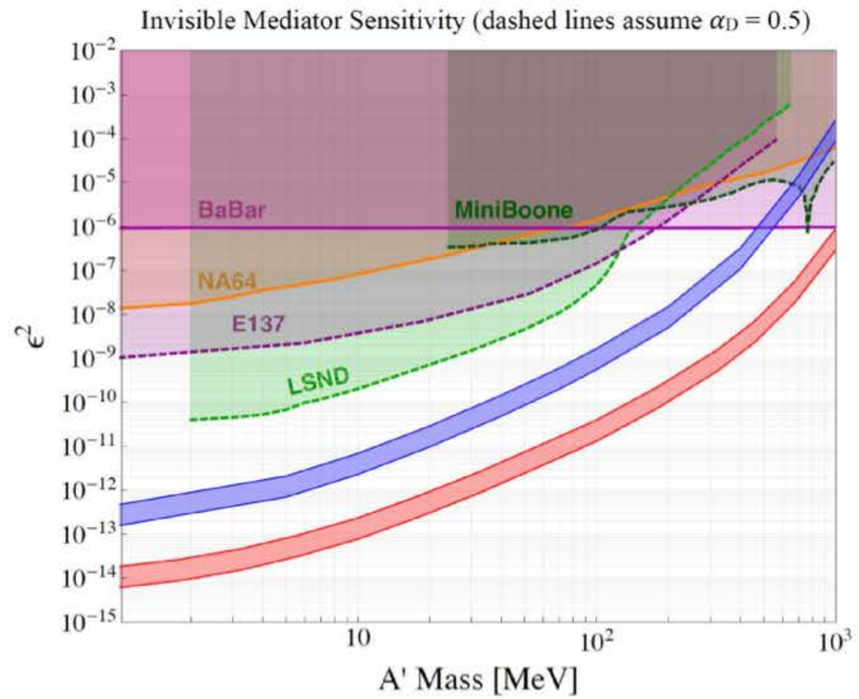


No bkg
$\alpha_D = 0.5$
$m_A/m_\chi = 3$

LDMX has unprecedented sensitivity, surpassing existing and projected constraints for DM masses below a few hundred MeV.

Sensitivity estimates





LDMX can also explore DM with quasi-thermal origins, *e.g.* asymmetric DM or SIMP/ELDER scenarios, and improve the sensitivity on invisible A' decays

Other interesting possibilities

LDMX would also be sensitive to:

- New mediators decaying invisibly
- Displaced vertex signature from 'DM co-annihilation' models
- Displaced vertex signature from SIMP models
- Milli-charge particles

And could perform photonuclear & electronuclear measurements useful for future neutrino experiments.

LDMX Schedule

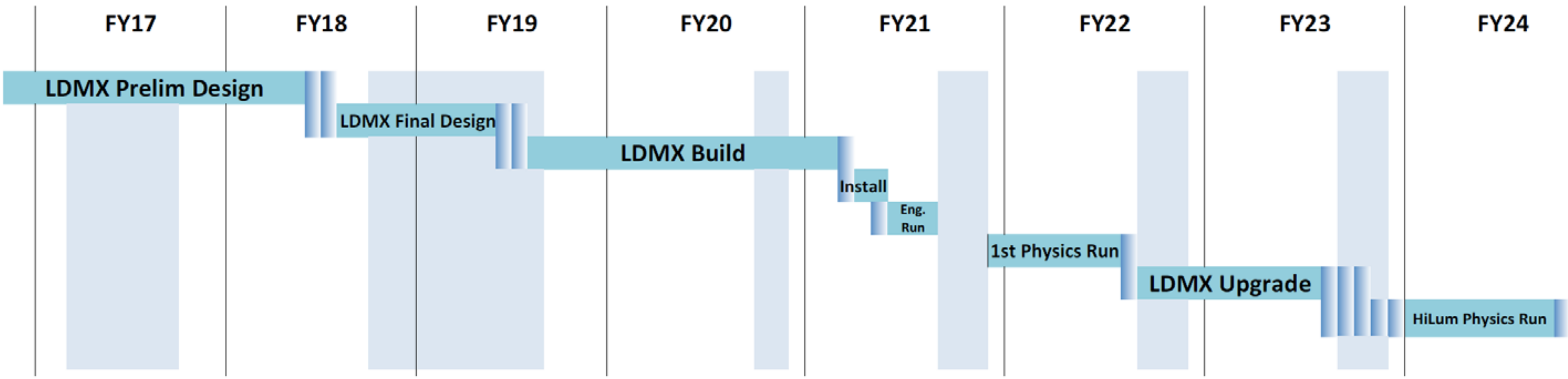
Schedule and Budget

LDMX

Anticipate 2 years to complete design + 2 years for construction

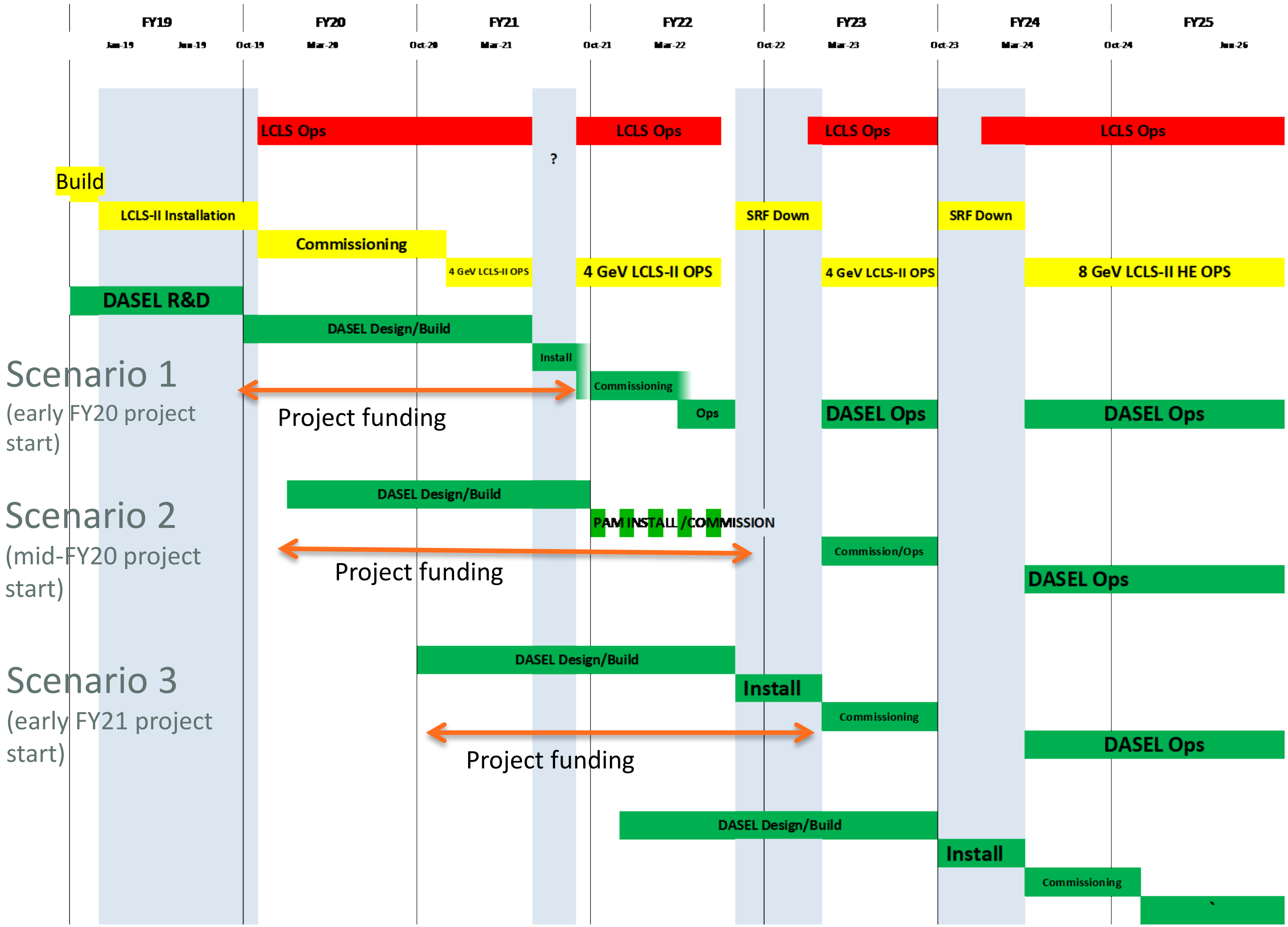
Phase I Run beginning in late 2021. Phase 2 two years later.

Details depend upon accelerator schedules.

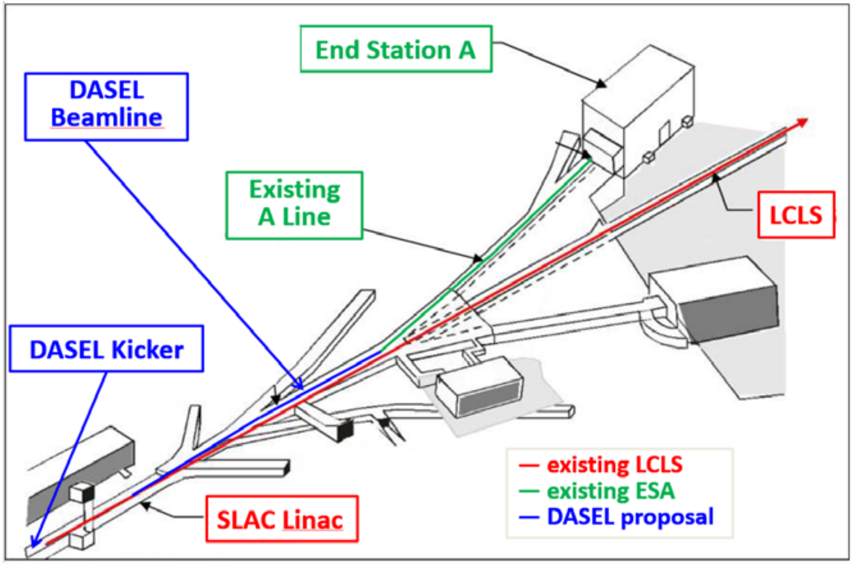


Tim Nelson at US cosmic visions workshop

DASEL Schedule



DASEL

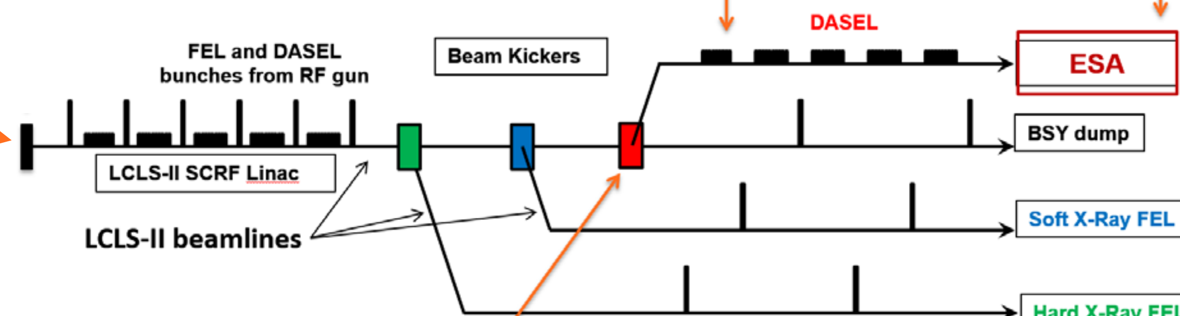


- DASEL is a proposed new beamline at LCLS-II at SLAC
- Makes use of RF buckets that are not used by the FEL – completely parasitic
- Built largely of existing beamline components
- Can provide the intensity and time structure required by LDMX
- Also provides a useful general purpose test beam, providing a high rate of single electrons

Experimental Facilities
- Small upgrades to ESA systems

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

Laser system to fill "unused" buckets with electrons for DASEL



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

Tor Raubenheimer

Conclusion

The thermal relic paradigm is arguably one of the most compelling DM candidates and the regime below the weak scale is the place to search – this is logical extension of the now highly-constrained WIMP idea

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

Among potential approaches, missing energy/momentum experiments provide the best sensitivity for a given luminosity

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

LDMX can also provide photonuclear & electronuclear measurements useful for planned neutrino experiments