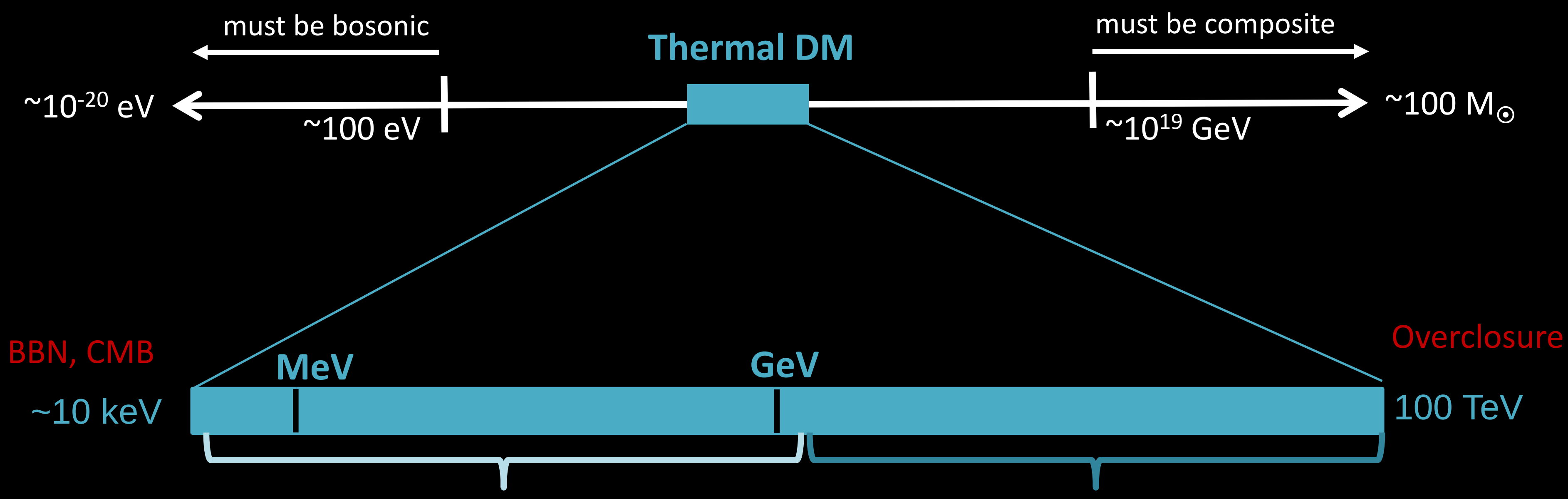
The Light Dark Matter eXperiment, LDMX

Bertrand Echenard
Caltech

TeVPA 2019 - Sydney – December 2019

Thermal dark matter

Thermal dark matter, originating as a relic in the early Universe, is arguably one of the most compelling paradigm. It is both generic – only requires a non-gravitational interaction between dark and familiar matter – and predictive.



Light DM

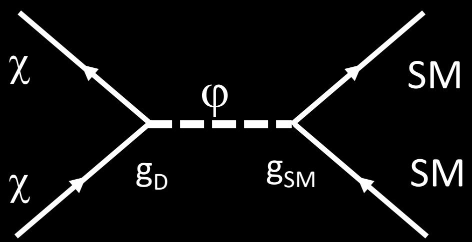
Thermal contact implies new mediator
Hidden sector light DM well-motivated model

WIMPS

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

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

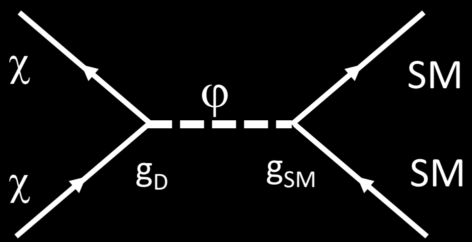


$$<\sigma v>_{relic} \sim \frac{g_D^2\, g_{SM}^2\, m_x^2}{m_\varphi^4} \qquad (m_\varphi \gg m_x)$$

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

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



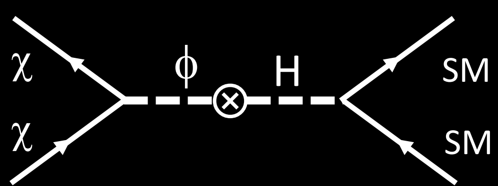
$$< \sigma v >_{relic} \sim \frac{g_D^2\, g_{SM}^2\, m_x^2}{m_\varphi^4} \qquad (m_\varphi \gg m_x)$$

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

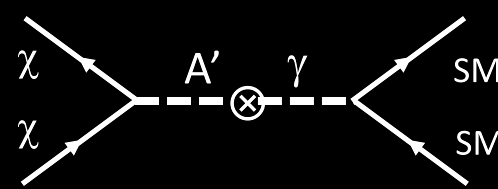
What kind of mediator?

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

New scalar (ϕ) with Higgs coupling



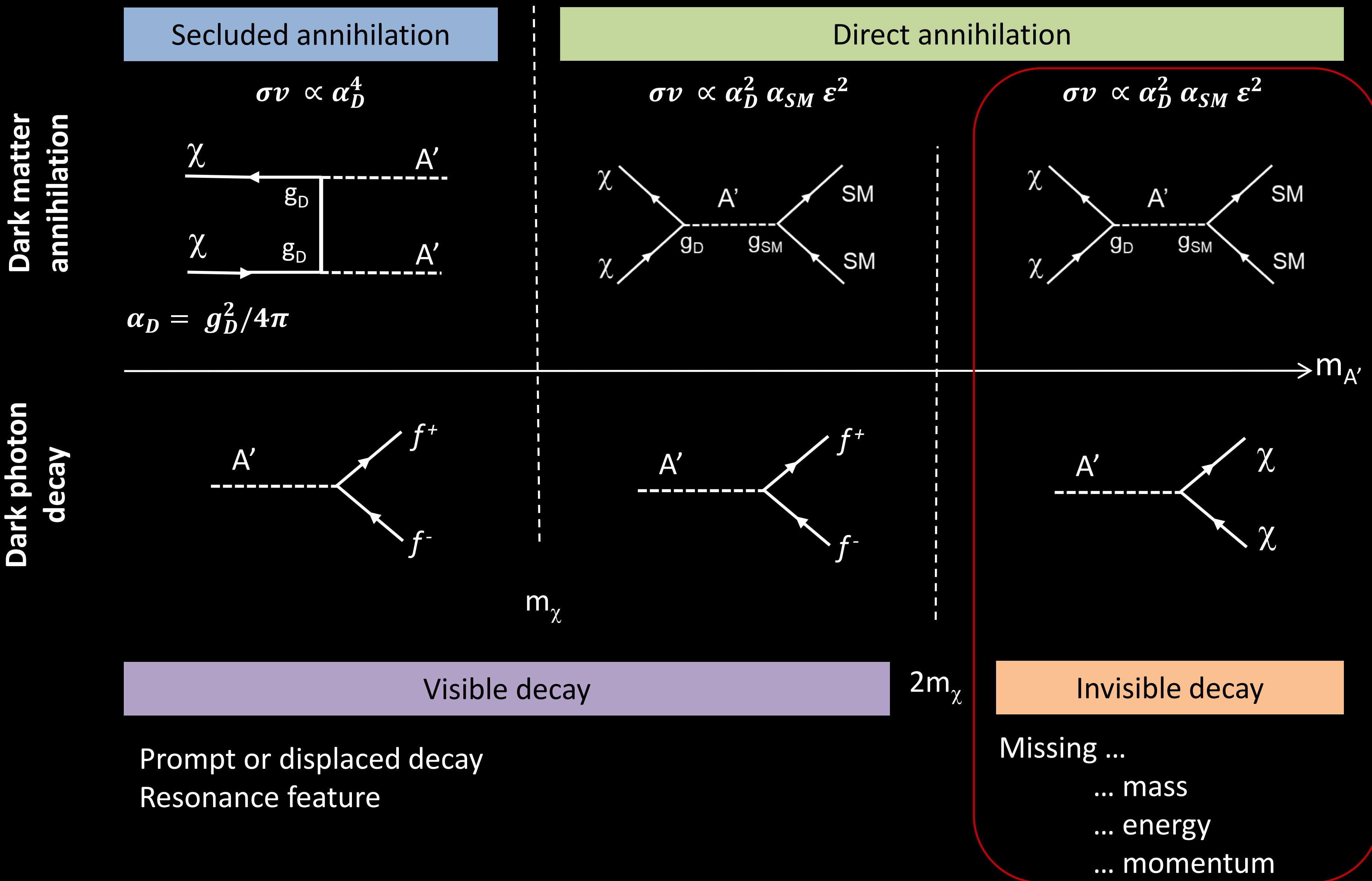
New vector (A') with photon coupling



Naturally realized in the context of hidden sectors.

Vector portal much less constrained that scalar one, so focus on this possibility.

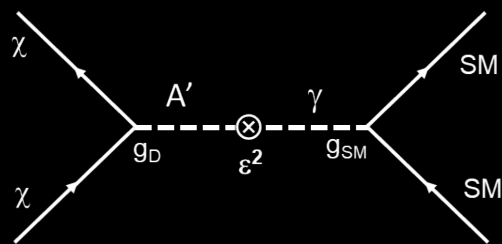
Production and decay



Representative benchmark scenario

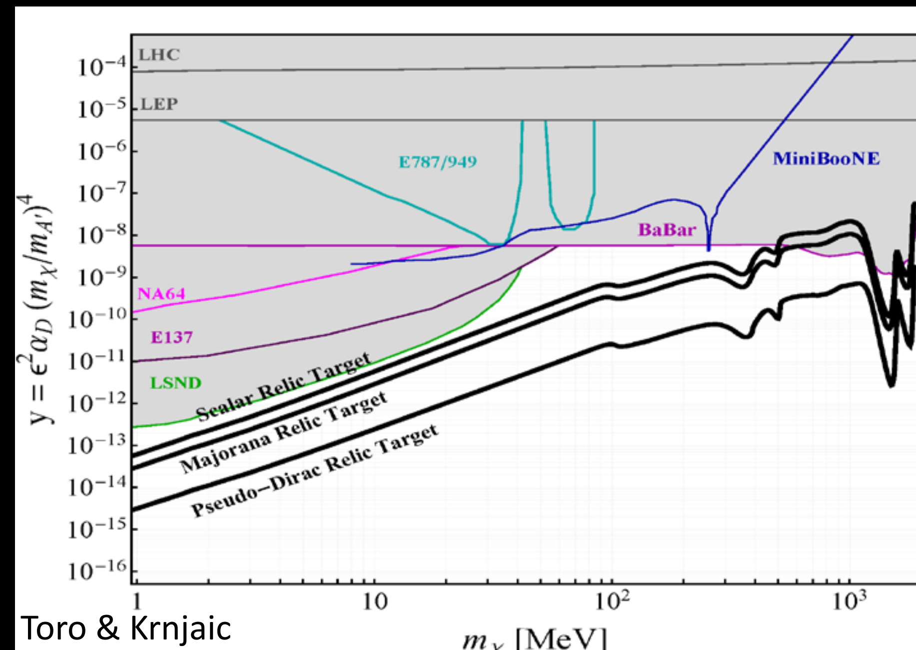
Hidden sector thermal LDM with vector portal.

Dark photon A' kinetically missing with strength ε



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

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



Toro & Krnjaic

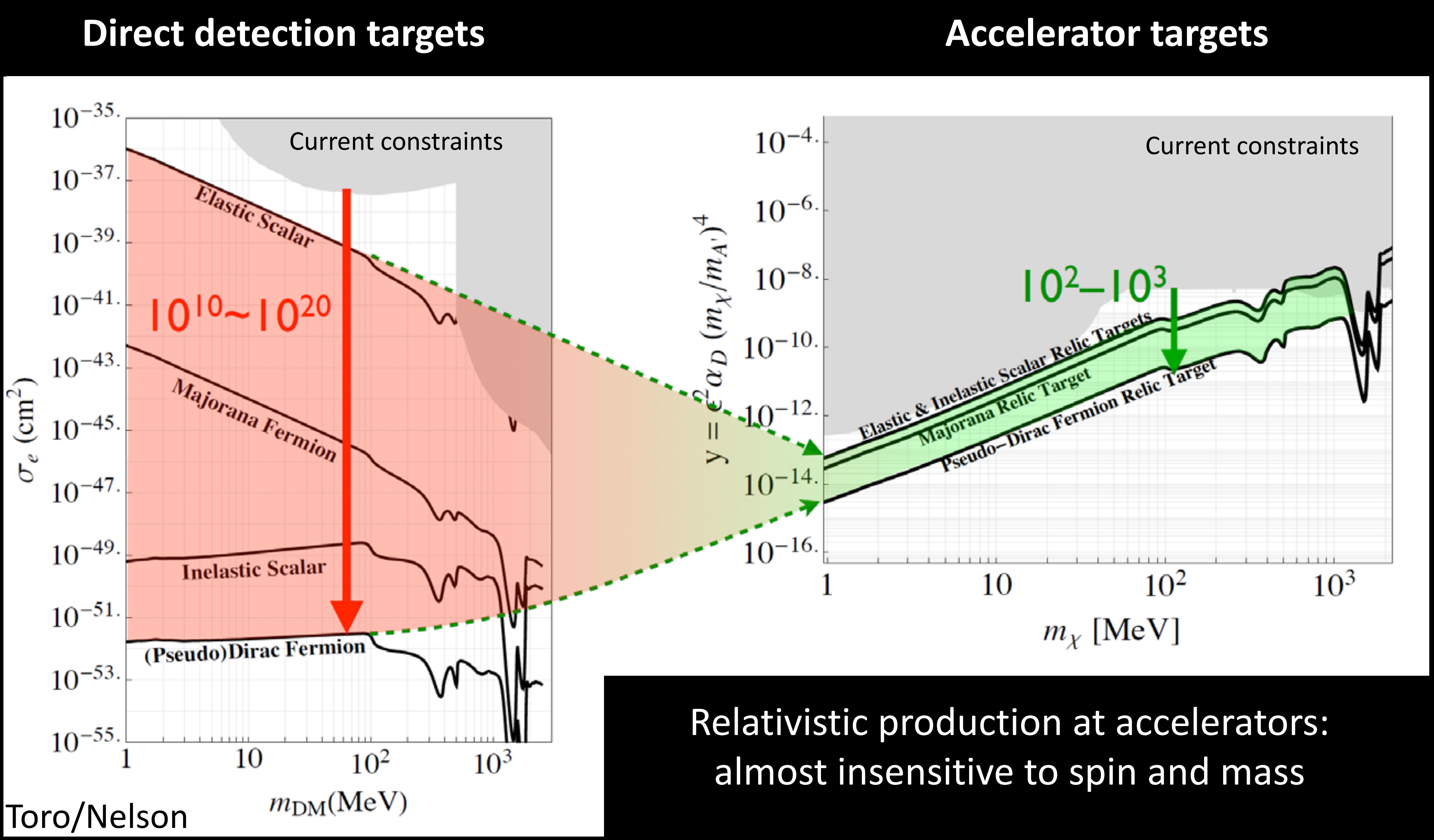
Conservative assumptions (α_D = 0.5 and m_A/m_χ = 3) made for plotting constraints from missing mass / momentum / energy experiments.

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

Accelerator / direct detection complementarity

MAJORANA
v^2 suppressed
$v \sim 10^{-3}$

INELASTIC
loop diagram
suppressed



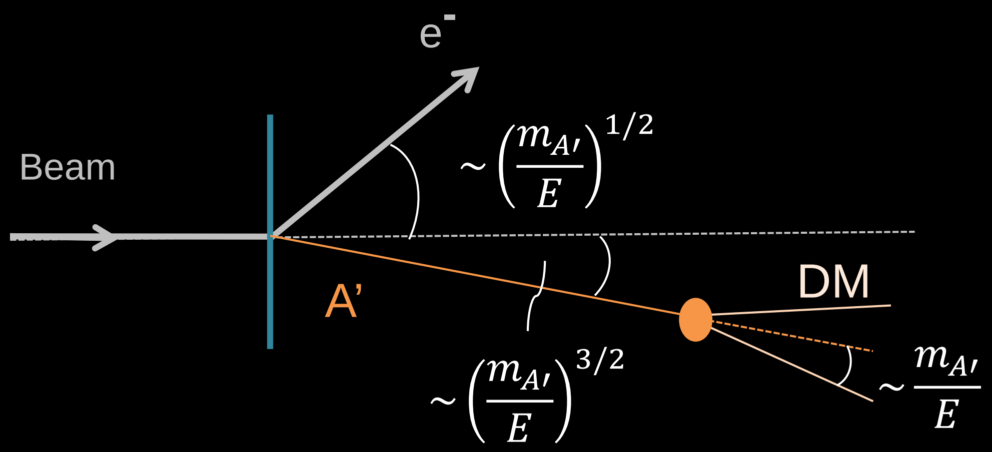
Relativistic production at accelerators: almost insensitive to spin and mass

Accelerators uniquely positioned to probe directly annihilating thermal LDM, but still need direct detection to establish cosmic stability

Missing momentum and LDMX

Missing momentum - kinematics

The kinematics is very different from bremsstrahlung emission.

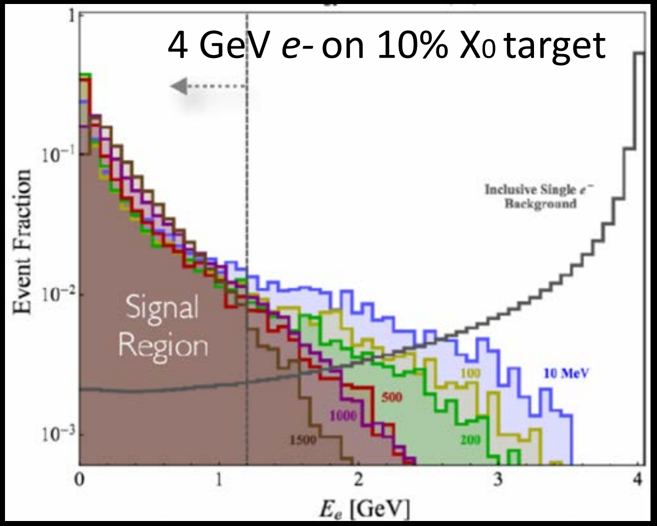


The A' is emitted at low angle and carries most of the energy:

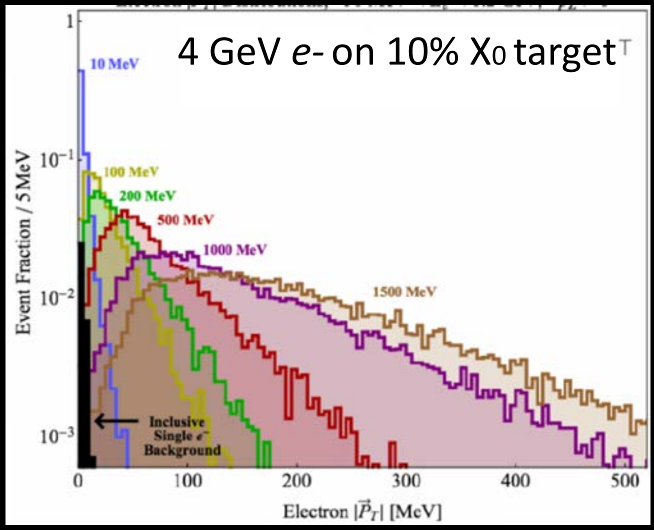
- large missing energy, soft recoil electron
- large missing p_T, large angle recoil electron

Strong discrimination, recoil momentum distribution carries information about the mediator mass

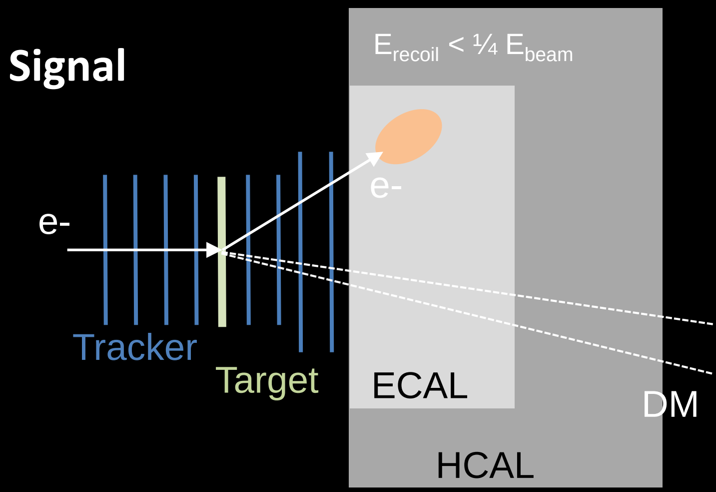
Recoil energy

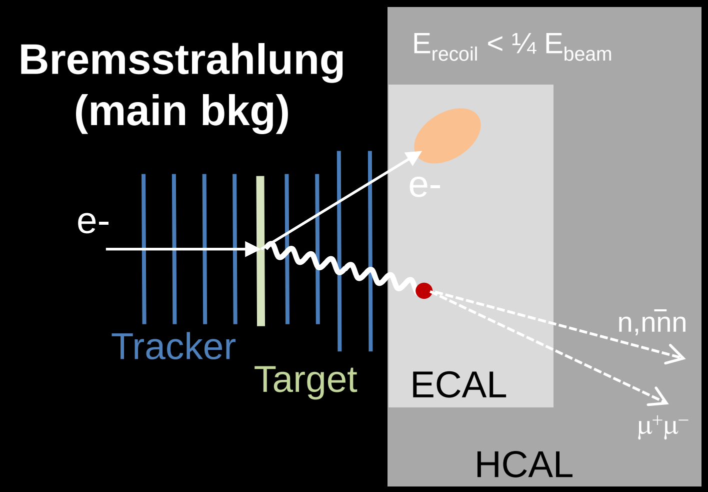


Recoil p_T,



Missing momentum - experimental approach





Particularly challenging: few body photo-nuclear reactions

The main ingredients

Beam allowing individual reconstruction of each incident electron

- A multi-GeV, low-current, high repetition rate beam with a large beam spot.
- Current option: S30XL @ SLAC - Potential future possibility at CERN: eSPS

Detector technology with high rate capabilities and high radiation tolerance

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

S30XL @ LCLS-II - SLAC

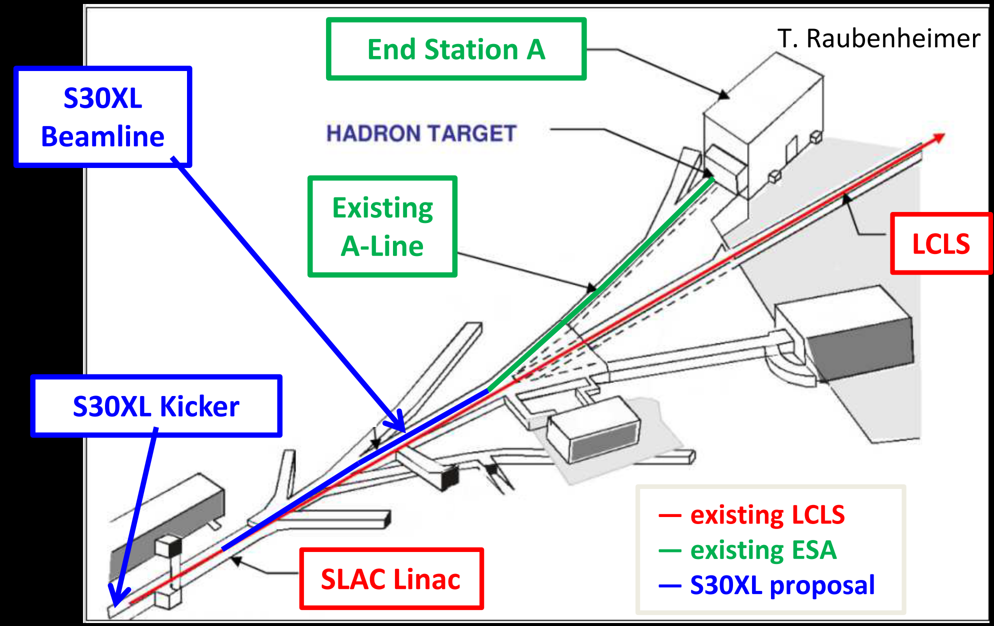
S30XL (Sector 30 transfer line)

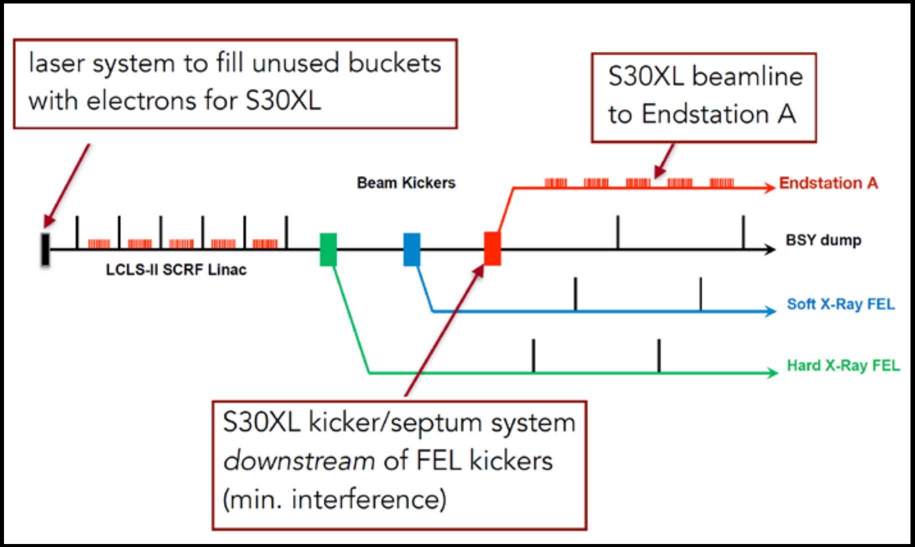
Parasitically extract low-current, high rate electron beam from LCLS-II linac at SLAC

Energy: 4 GeV, upgrade to 8 GeV

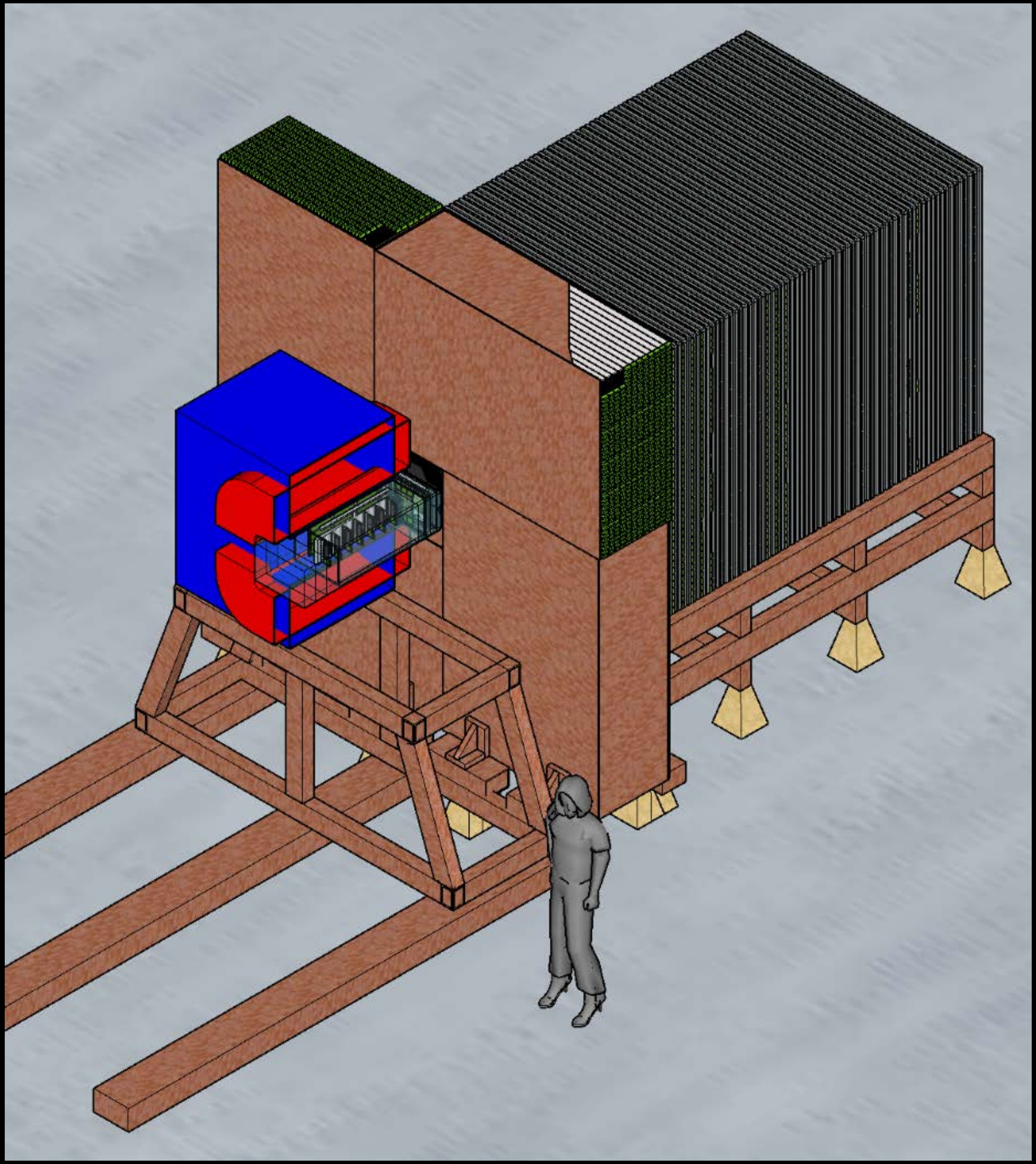
First stage:
- S30 Accelerator Improvement Project. Design underway and review scheduled for early January 2020.
- Technology demonstration, characterization of dark current, high-rate single electron test beam

Second stage:
- New beamline (~100m) to connect LCLS beam line to existing A-line





The LDMX experiment



LDMX concept

- Magnet: 18D36 at SLAC
- Tracking: Silicon Vertex Tracker similar to HPS
- ECal: CMS high-granularity calorimeter
- HCal: scintillator/steel sampling calorimeter a la Mu2e

LDMX Whitepaper arxiv:1808.05219

Caltech Fermilab SLAC NATIONAL ACCELERATOR LABORATORY LUNDS UNIVERSITET UNIVERSITY OF MINNESOTA UCSB UNIVERSITY of VIRGINIA

Tracking system

Two tracking systems:

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

Single dipole magnet, two field regions

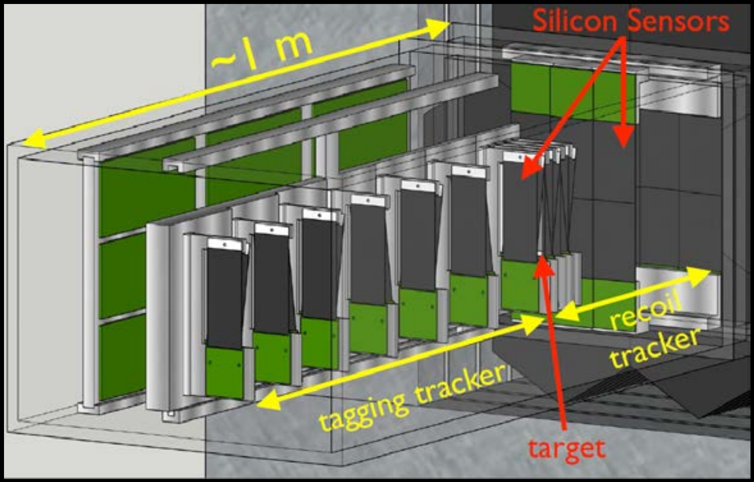
- Tagging tracker placed in the central region for p_e = 4 GeV,
- Recoil tracker in the fringe field for p_e ~50 – 1200 MeV

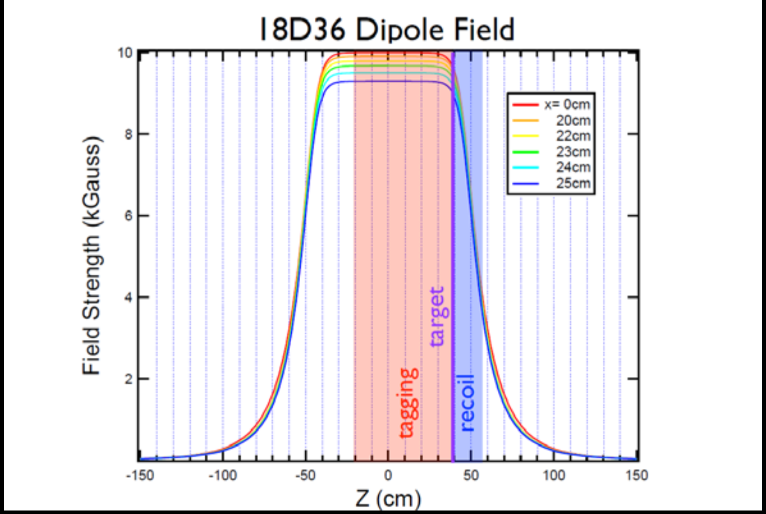
Silicon tracker similar to HPS SVT

- Fast (2ns hit time) and radiation hard

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



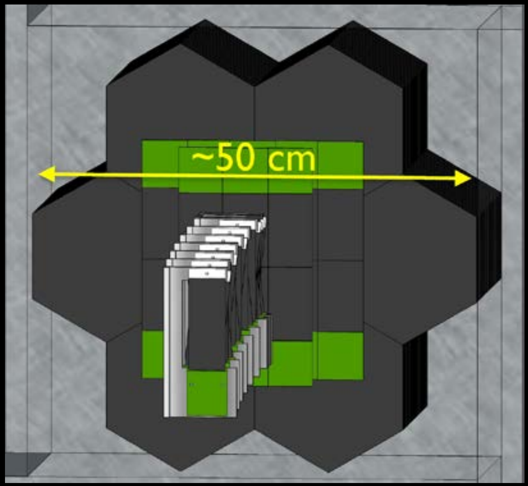


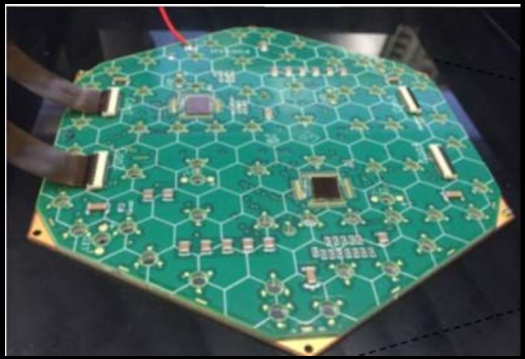
EM calorimeter

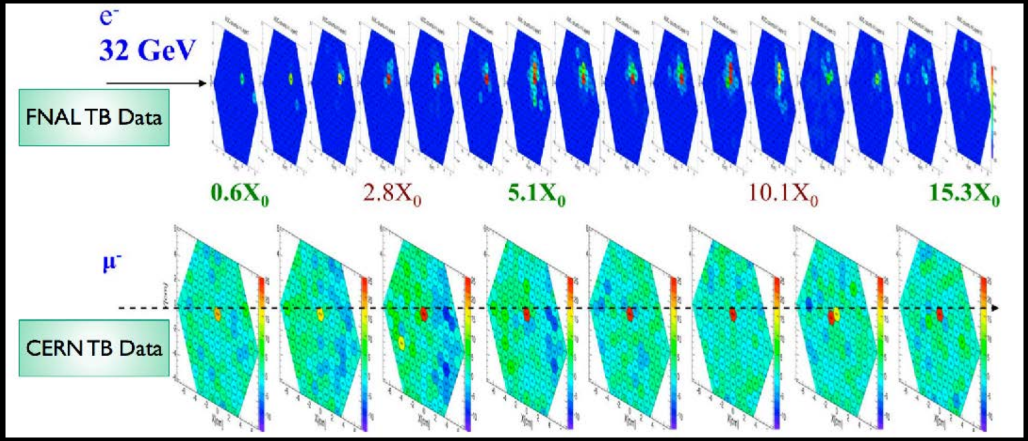
Si-W sampling calorimeter

- Fast, dense and radiation hard
- ~$40X_0$ deep for extraordinary containment
- High granularity, exploit transverse & longitudinal shower shapes to reject background events
- Provide fast trigger – accept event with ECal < 1.2 GeV

Currently developed for CMS HCal upgrade, adaptable to LDMX







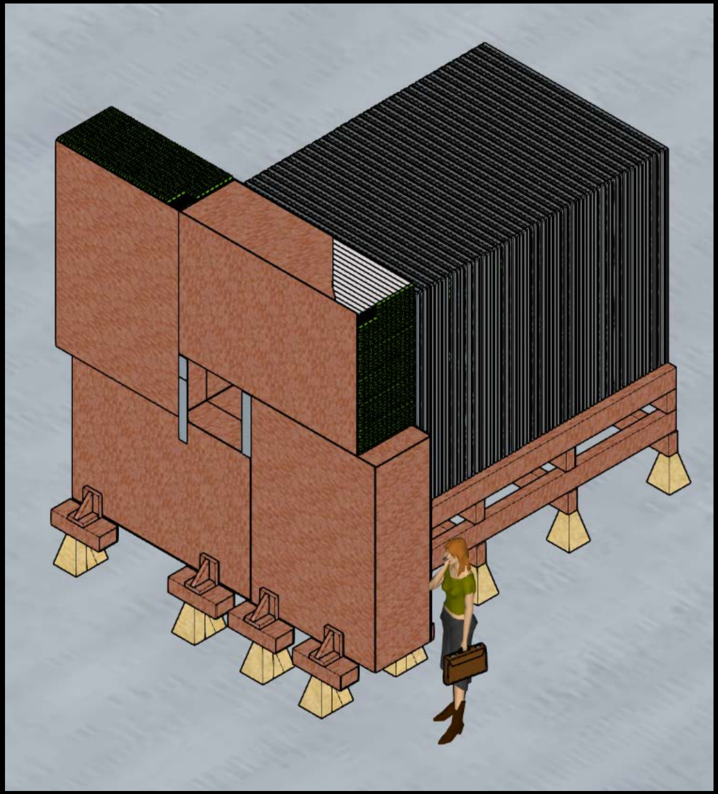
High granularity critical to reject photon-induced background (e.g. PN reactions or $\gamma \rightarrow \mu\mu$)

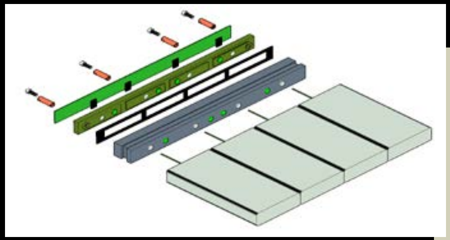
Hadronic calorimeter

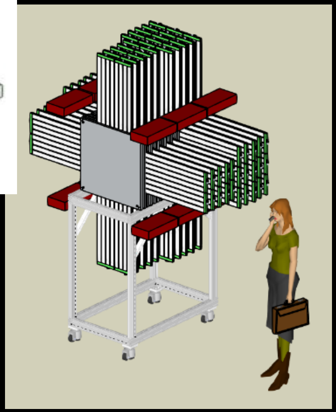
Steel / plastic scintillator sampling calorimeter

- Main role: veto hadronic PN events, in particular PN events emitting hard/soft neutrons or K_L
- Secondary role: physics with displaced signatures, electro-nuclear measurements, trigger
- Plastic scintillator bars with WLS fibers read out by SiPM (a la Mu2e CRV) and steel absorber.
- Current design has 25mm absorber plates with ~13λ for the back HCal, 2m transverse size.
- Additional side HCal (~ 5λ) surrounding the ECal with thinner absorber
- HCal prototype test planned for fall 2020

Design parameters still being finalized







Sensitivity estimate – phase I

Analysis strategy

Trigger on missing energy
+ Track quality criteria
+ Combine ECal feature into BDT
+ Veto HCal activity

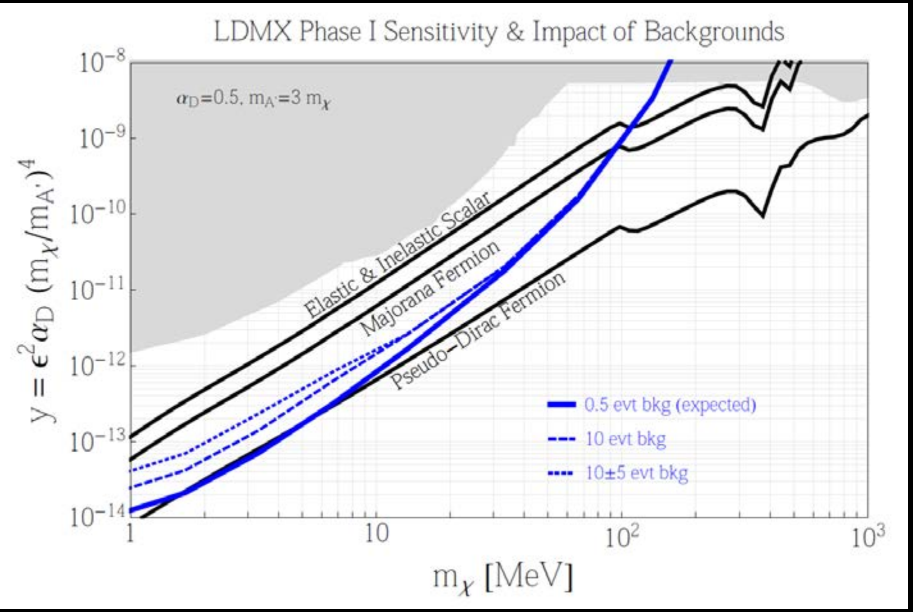
= Close to zero event for 4e14 EOT at 4 GeV based on current simulations

Not used so far

Recoil electron p_T (additional rejection)
HCal veto still unoptimized
Further ECal BDT improvements

Several control samples in data can be collected to verify rejection power

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



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

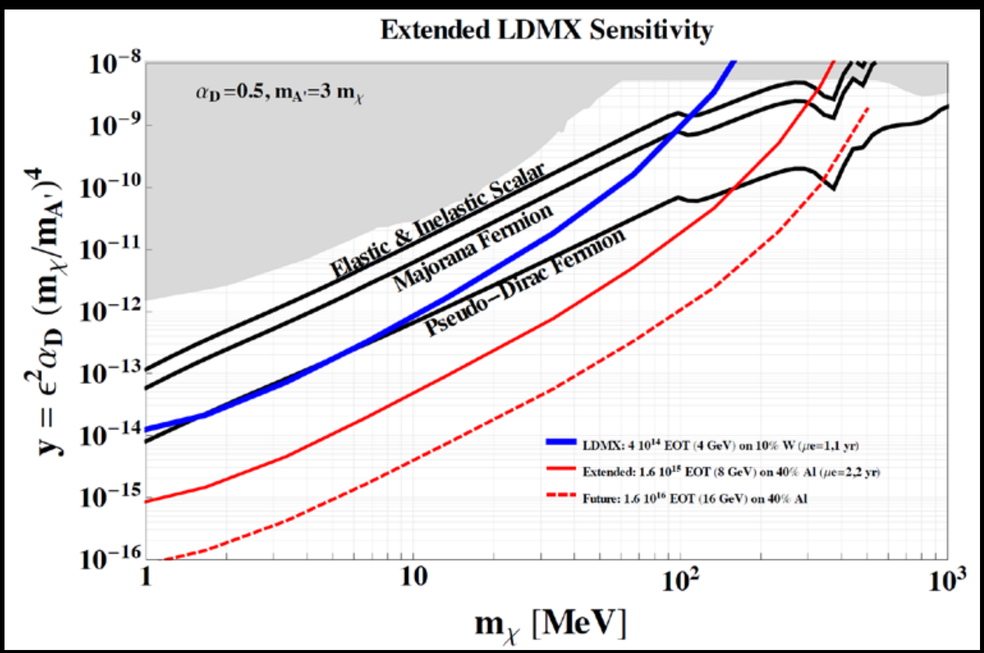
Similar results for a few bkg events, and further improvements in the pipeline.

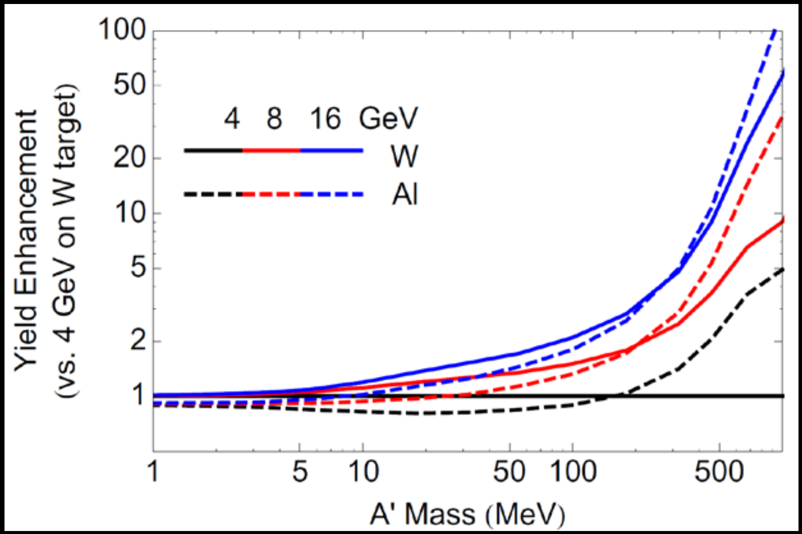
All details in whitepaper - arxiv:1808.05219.

Phase II upgrade

Several strategies are available for improving Phase I reach: increasing the beam energy, changing the target density or thickness.

Phase II could probe pseudo-Dirac target up to O(100) MeV.



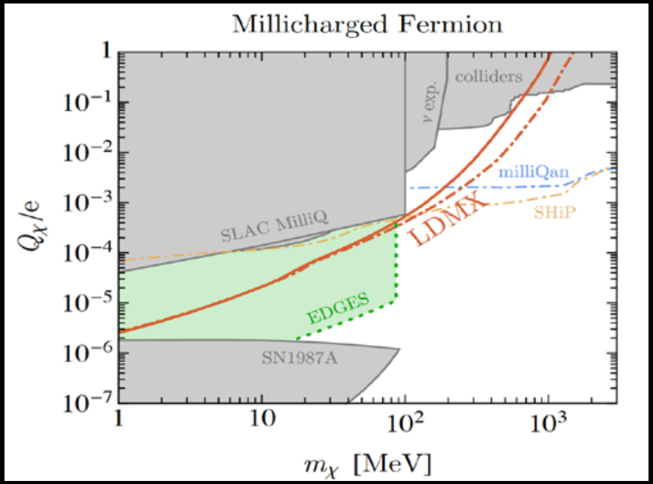


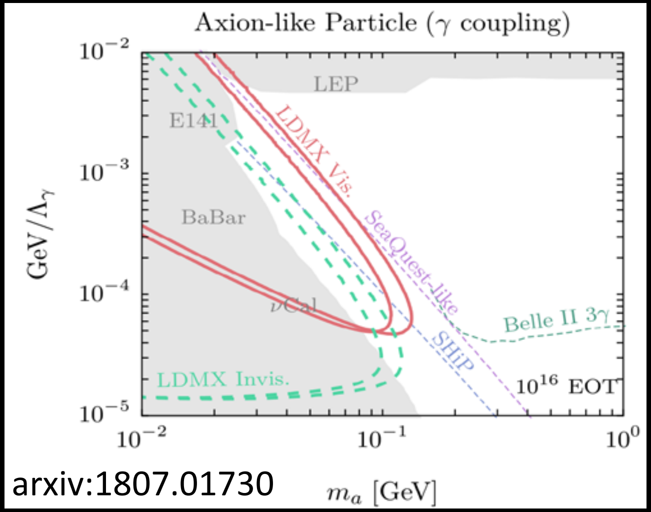
Mass Range [MeV]	Factor needed		E_e [GeV]	E_e Factor	Target $[X_0]$	Target Factor	μ_e	Years running	Factor achieved
$0.01 \le M_\chi < 20$	2		4	1	0.15 W	1.5	1.5	1	~2
			4	1	0.1 W	1	1.5	1.5	
			4	1	0.15 W	1.5	1	1.5	
$20 \le M_\chi < 75$	6		8	2	0.1 W	1	2	1.5	~6
			8	2	0.15 W	1.5	1	2	
			4	1	0.15 W	1.5	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	$\sim 7 \times 10^3$

More generally…

LDMX would also be sensitive to many other BSM physics scenarios, 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
- And could provide useful information for future neutrino experiments





In essence, LDMX could explore a vast array of sub-GeV BSM physics.

Conclusion

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

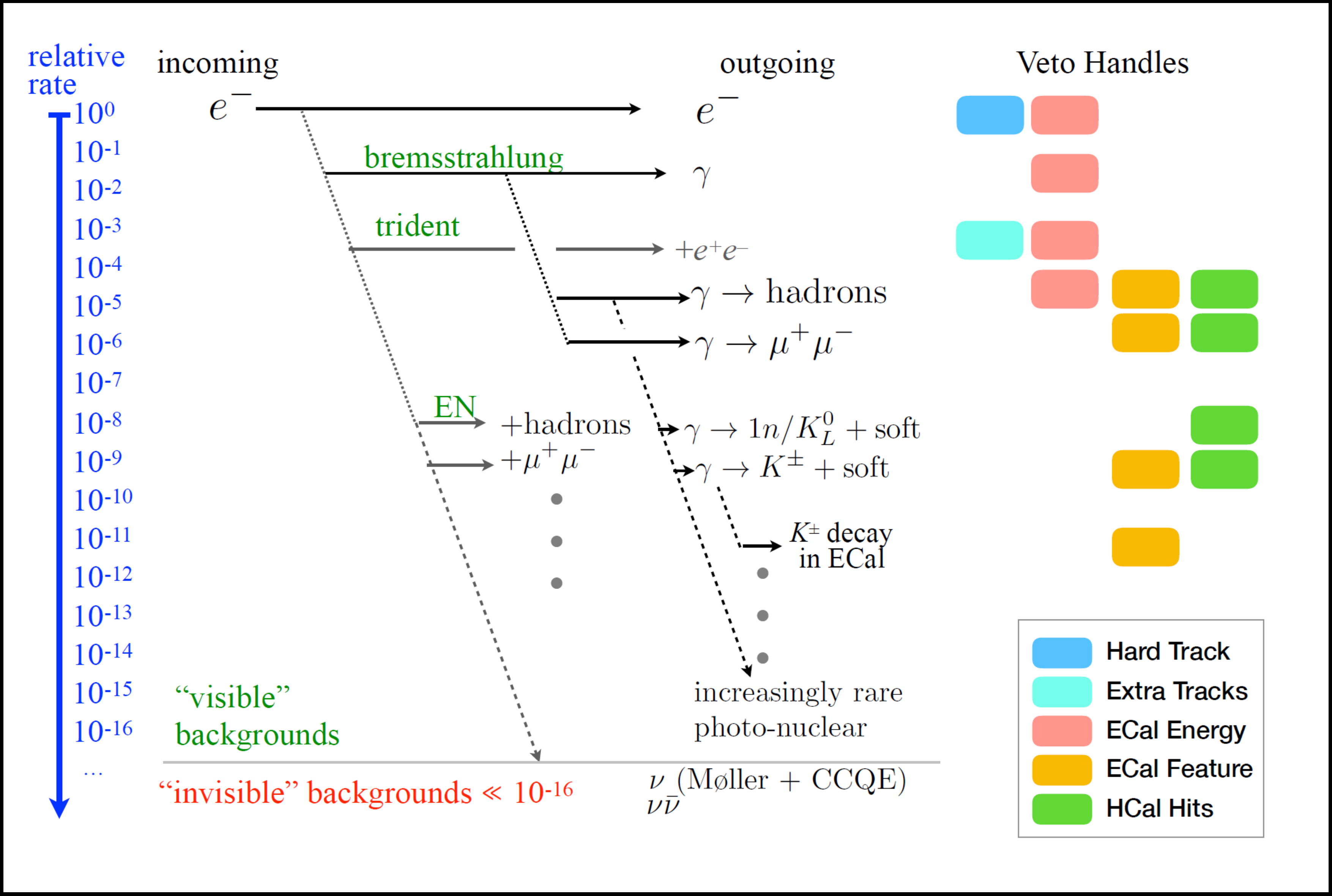
Among potential approaches, missing energy / momentum provide the best luminosity per sensitivity.

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. The experiment could also probe many sub-GeV new physics models, and provide measurements useful for planned neutrino experiments.

LDMX can complete this program within the next decade, and potentially result in a groundbreaking discovery.

Extra material

Background rejection



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)

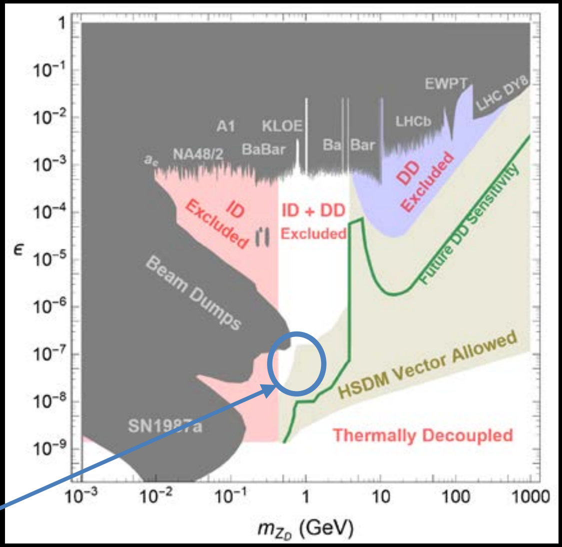
$\rightarrow$ thermal equilibrium provides a minimal, UV-insensitive cosmological DM history that implies a minimum DM-SM coupling (with a few caveats….)

$\rightarrow$ WIMP next door

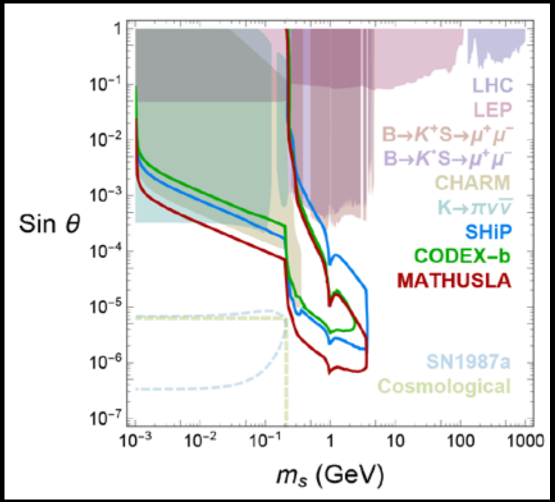
LDMX only sensitive to a small fraction of allowed parameter space for vector mediator (at most a few GeV)

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

Vector mediator

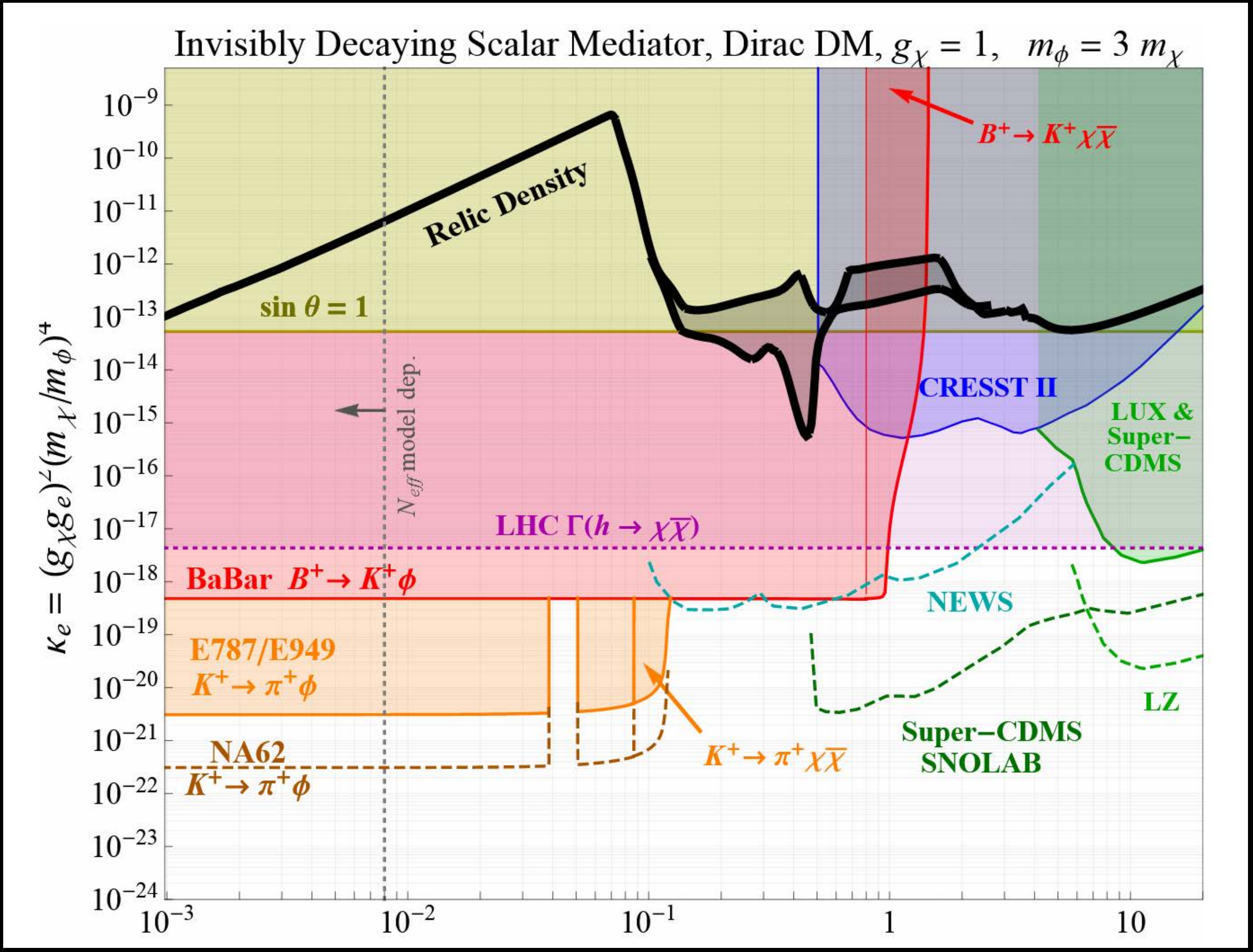


Scalar mediator



Evans, Gori & Shelton, arxiv:1712.03974

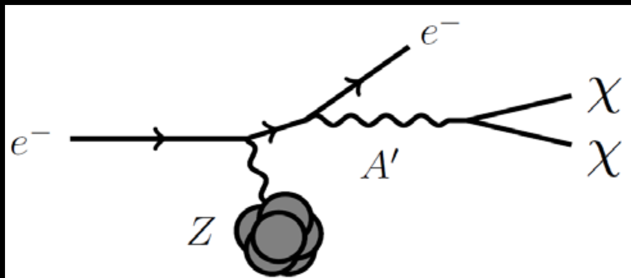
Scalar mediator



Krnjaic, arXiv:1512.04119

Maximizing dark matter sensitivity

Missing energy / momentum

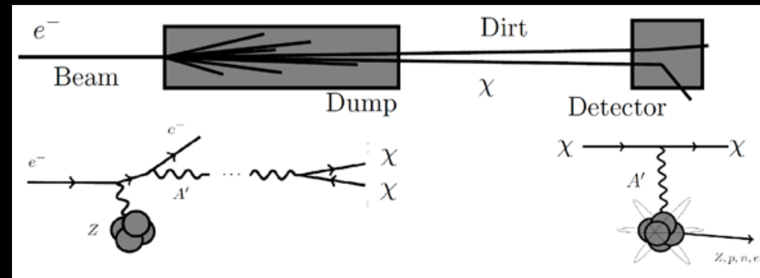


$\sigma \sim Z^2 \varepsilon^2 / m_A^2$

Large production yield for low mediator masses

Large "detection yield"

Beam dump

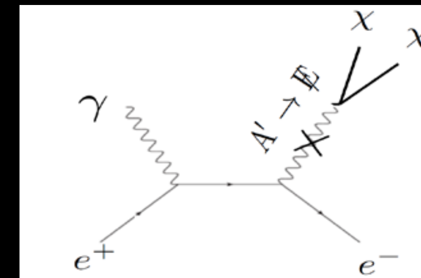


$\sigma \sim \alpha_D \varepsilon^4$

Probe dark sector coupling

Process suppressed by ε^4

Colliders



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

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

Large production yield on resonance

Best yield at high masses

Accelerators can access explore the physics in detail ($\varepsilon, m_{A'}, m_\chi, \alpha_D$),

direct detection needed to establish cosmological stability

Tracking system

Two tracking systems:

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

Single dipole magnet, two field regions

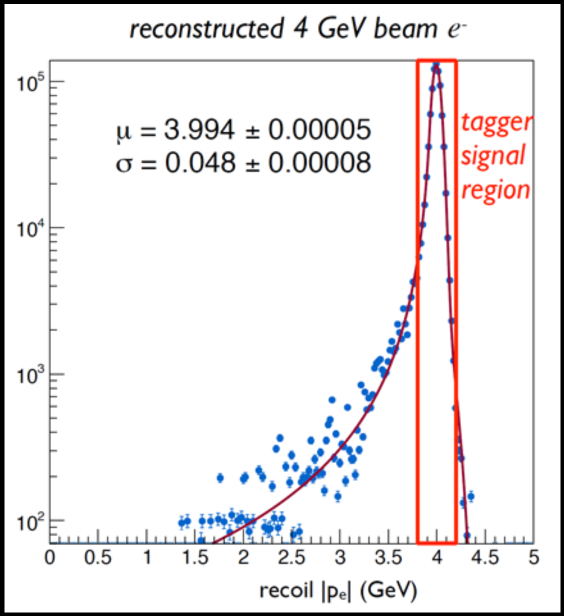
- Tagging tracker placed in the central region for p_e = 4 GeV,
- Recoil tracker in the fringe field for p_e ~50 – 1200 MeV

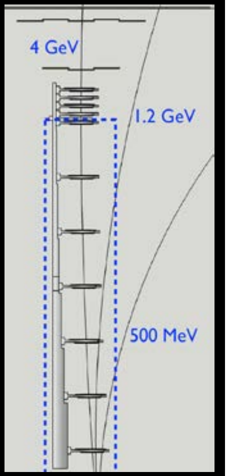
Silicon tracker similar to HPS SVT

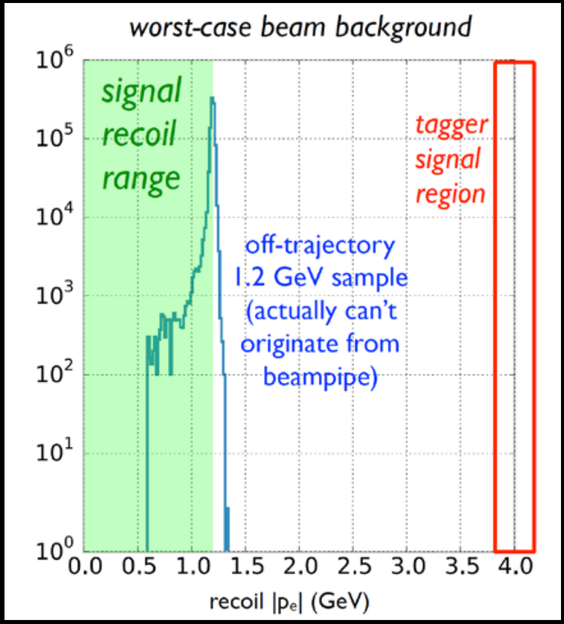
- Fast (2ns hit time) and radiation hard

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



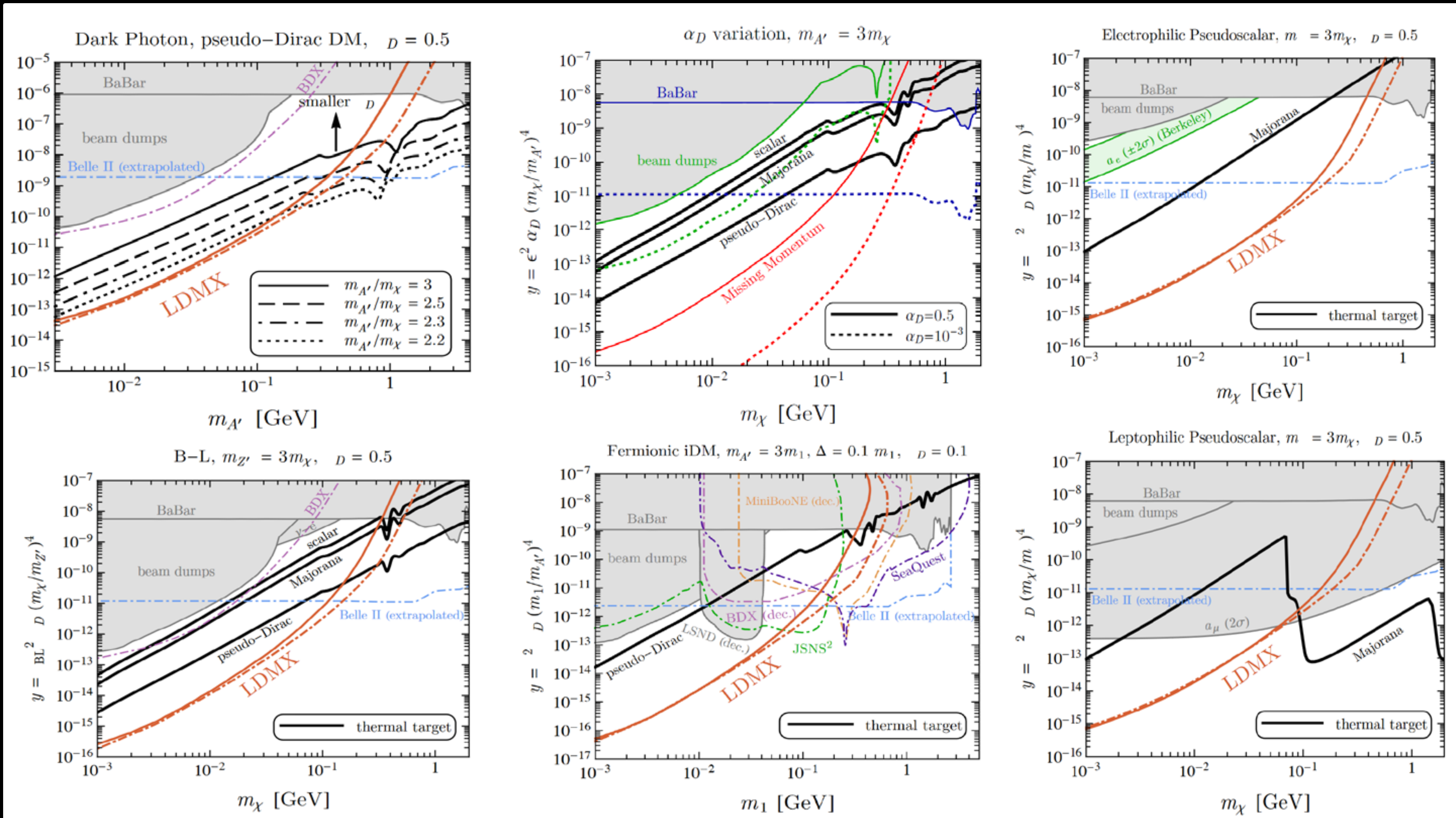




Tagging tracker efficiently rejects beam-induced background

Variations on a theme

arxiv:1807.01730



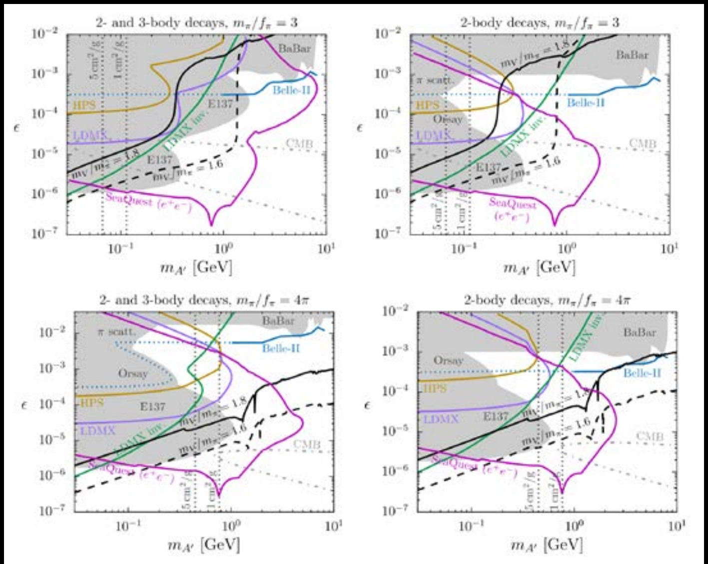
Sensitivity to a broad range of models and mild sensitivity to variation of parameters

Sub-GeV BSM physics

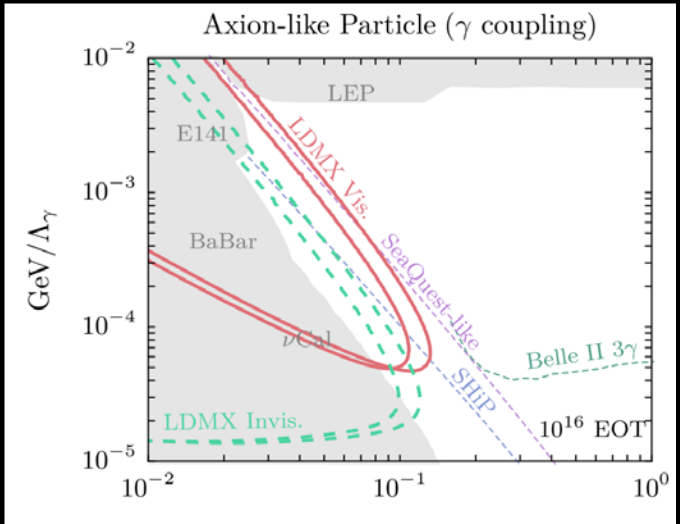
Sample of BSM scenarios LDMX would be sensitive to:

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

Hidden sector vector meson decay



Berlin, Blinov, Gori, Schuster, Toro, 1801.05805



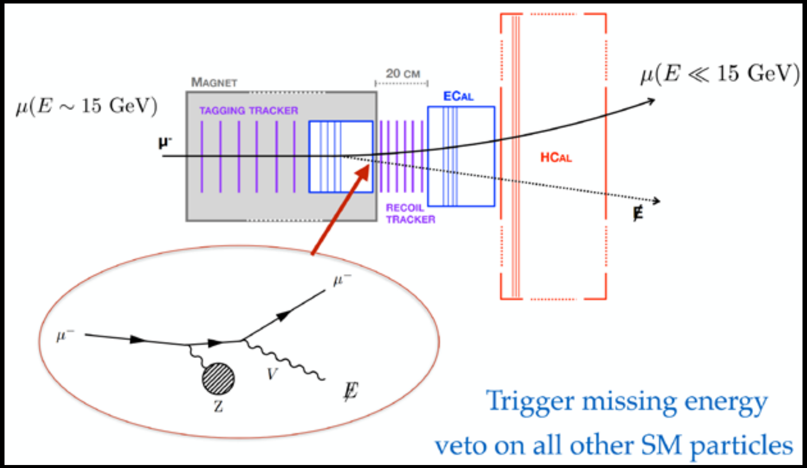
arxiv:1807.01730

LDMX-mu

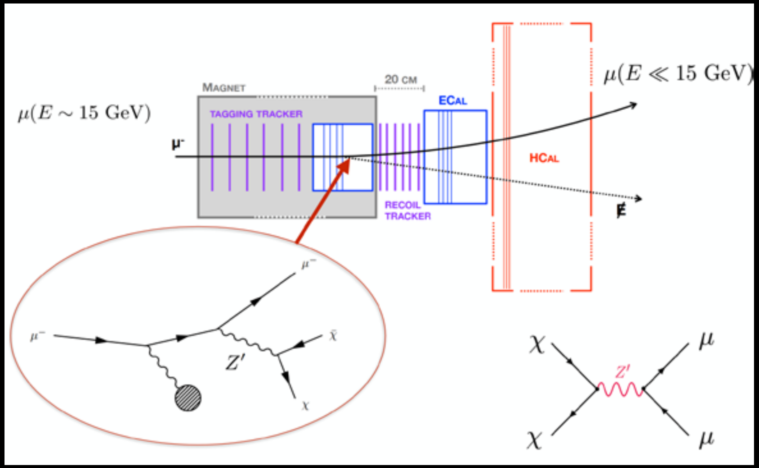
JHEP 1809 (2018) 153
arxiv:1804.03144

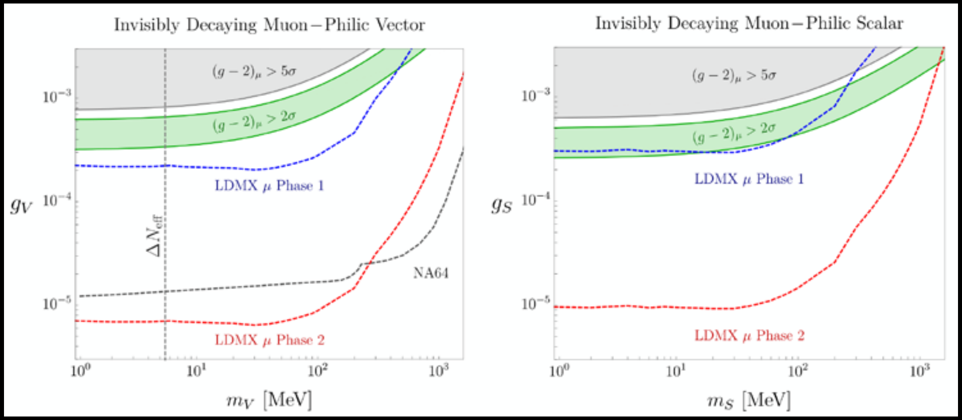
LDMX-like detector with a muon beam at FNAL

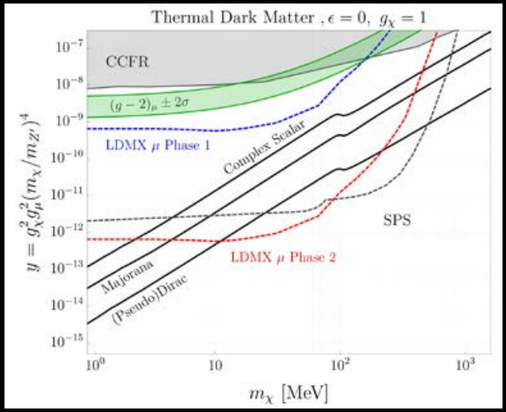
New light muon-philic particles



Muon-philic dark mediator



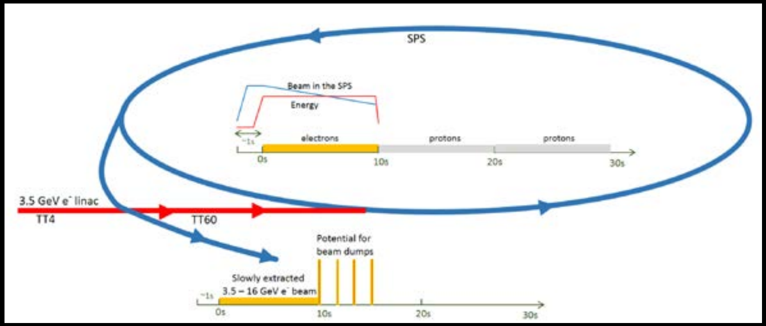




e-SPS @ CERN proposal

Possibility of 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).



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