Light Dark Matter eXperiment (LDMX)

IDM 2024

Einar Elén, on behalf of the LDMX collaboration

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Fermilab
Lund University
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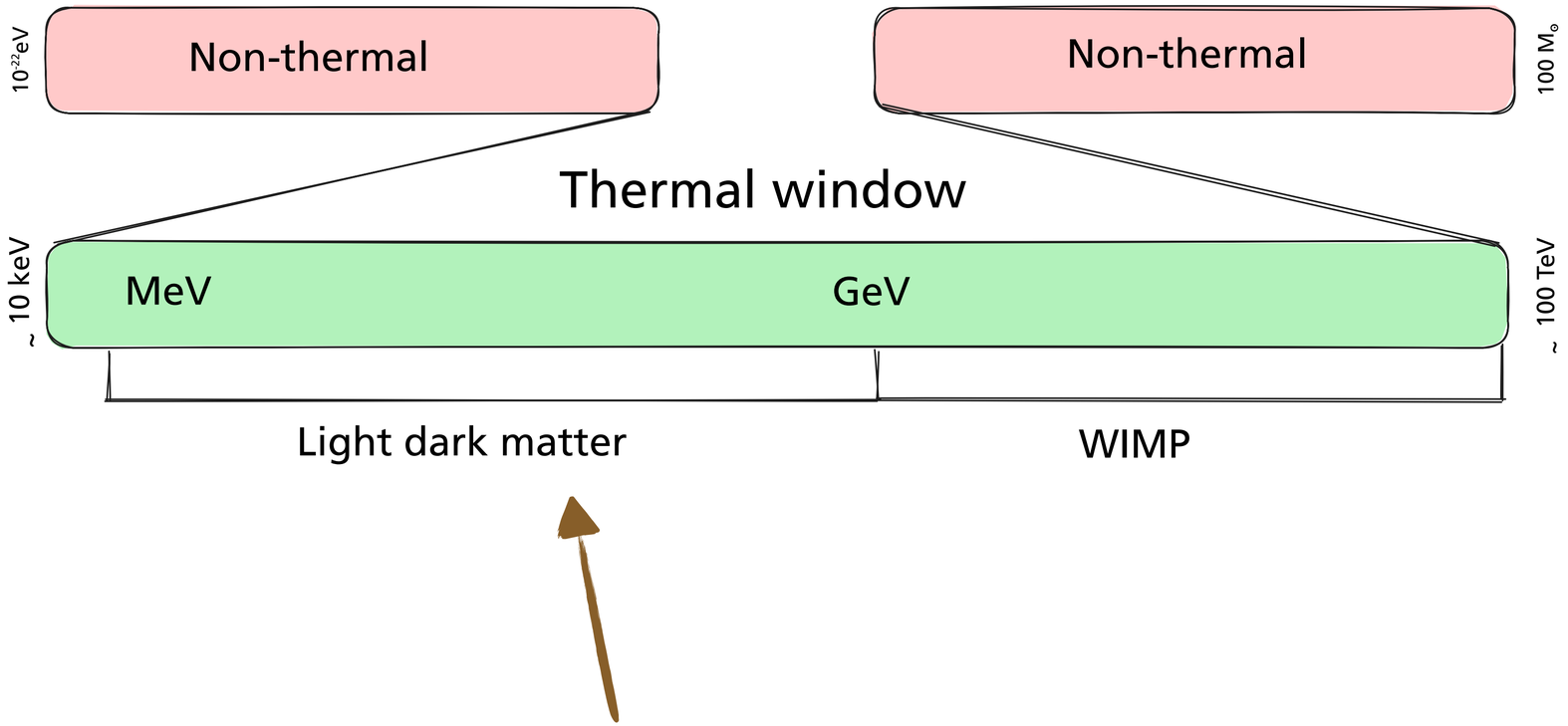
SLAC National Accelerator Laboratory
Stanford University
University of Virginia

A very brief motivation for accelerator based searches for light dark matter

How far can we get with generic assumptions?

Assuming very little



We will focus here

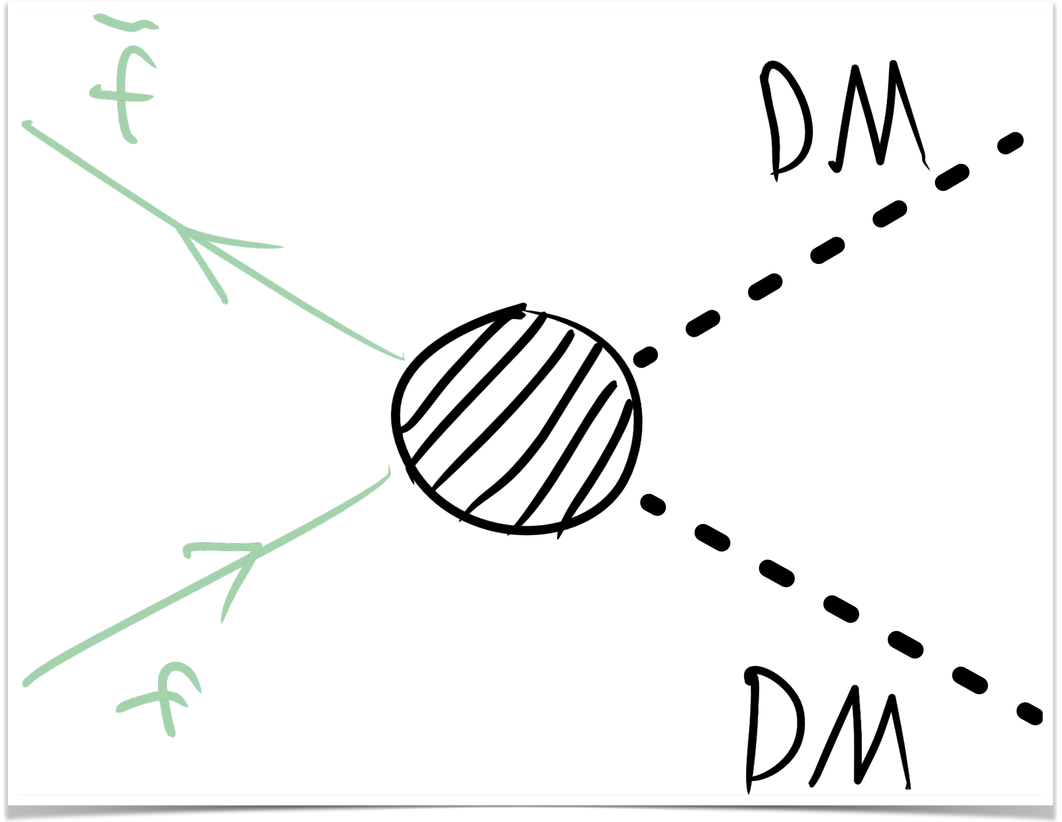
Assuming very little

Relic density determines cross section

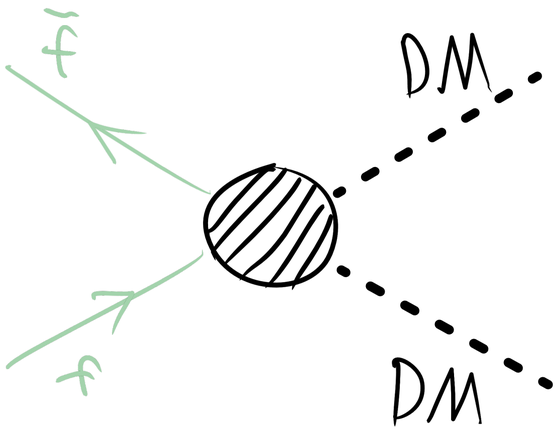
- For example: $f^+ f^- \to \chi\bar{\chi}$
  - Given $\langle \sigma v \rangle$ at freezeout (s_{freeze}) from relic density & m_χ

$$s_{freeze} \approx 4m_\chi^2$$

$$|\mathscr{M}(s_{freeze})|^2 \sim 10^{-6} \frac{m_\chi^2}{\mathrm{GeV}^2}$$

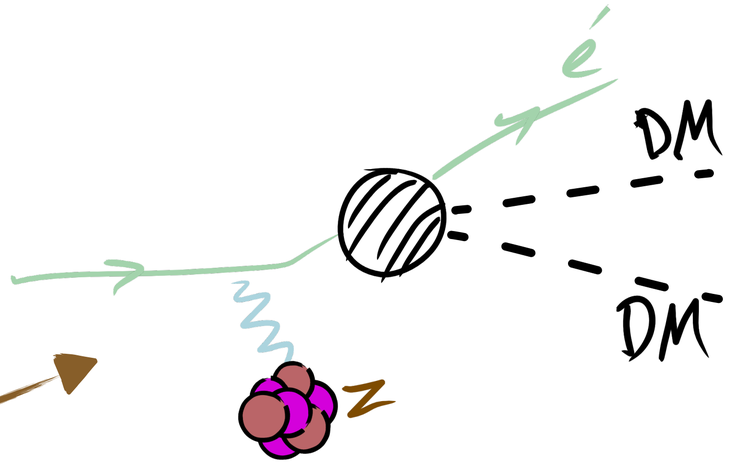


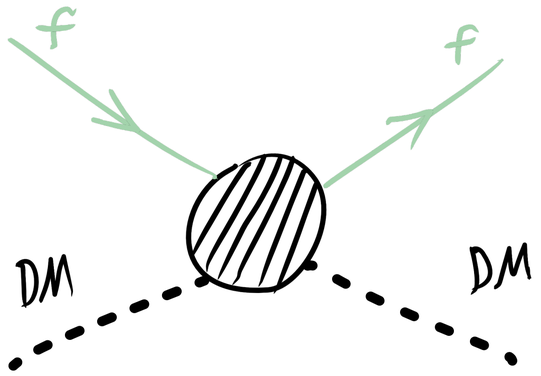
Assuming very little



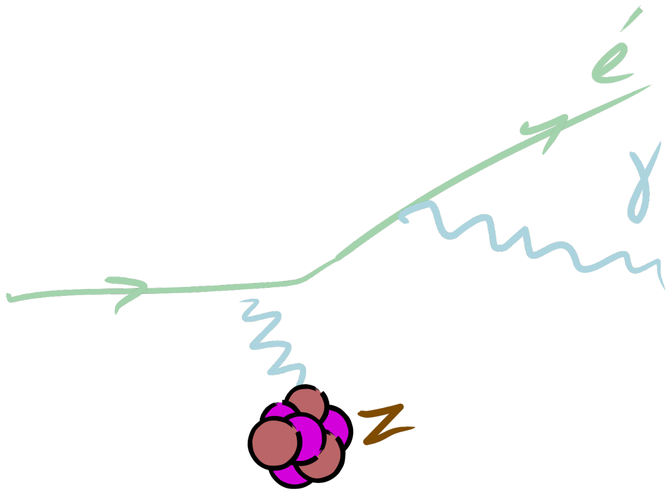
Gives us amplitude for direct detection & accelerator production

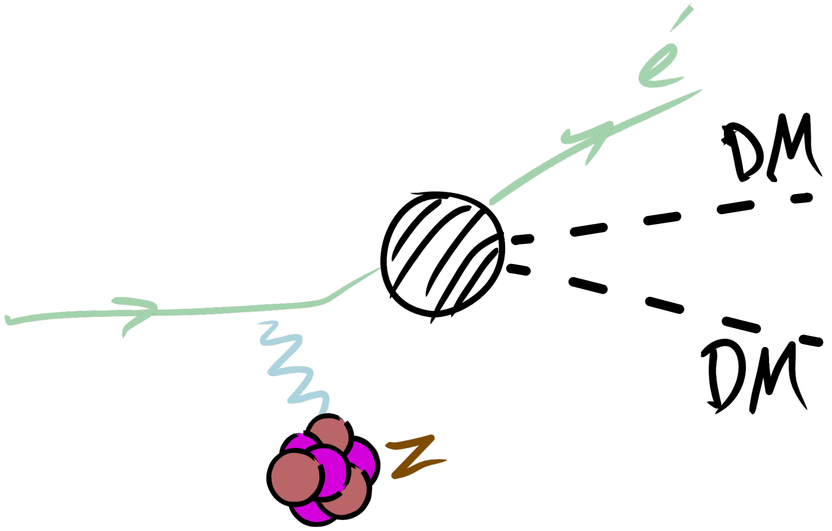
$$|\mathscr{M}(s_{freeze})|^2$$





Assuming very little



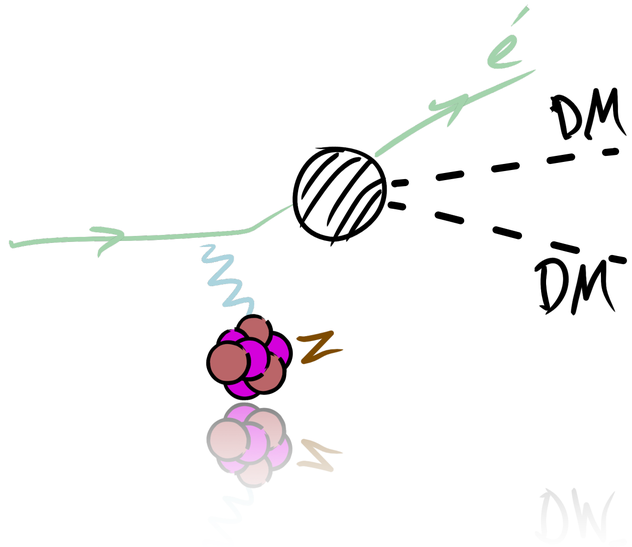


Assuming very little

$$\left(\frac{\sigma_{eZ\to\chi\bar{\chi}}}{\sigma_{eZ\to\gamma}}\right)_{brem} \approx \left(\frac{|\mathcal{M}|^2}{e^2}\right)\left(\frac{1}{48\pi^2}\right)\left(\frac{m_\chi^{-2}}{m_e^{-2}}\right) f_{coherence}$$

- How often would we see this?

  At $s \sim s_{freeze}$ we know the amplitude from before*



Relative suppression w.r.t. SM bremsstrahlung

$$\left(\frac{\sigma_{eZ\to\chi\bar{\chi}}}{\sigma_{eZ\to\gamma}}\right)_{brem} \sim 2\cdot 10^{-15} f_{coherence}$$

Need to measure $\sim 10^{14} - 10^{16}$ electrons

*Conservative assumptions

Key takeaway

Without relying on any model-specific assumptions:

An accelerator experiment measuring 1e16 electrons on target can discover thermal relic light dark matter

Benchmark model

- Benchmark model: Standard dark photon
  - See T. Gray's talk on Spin-1 DM for examples of extended scenarios

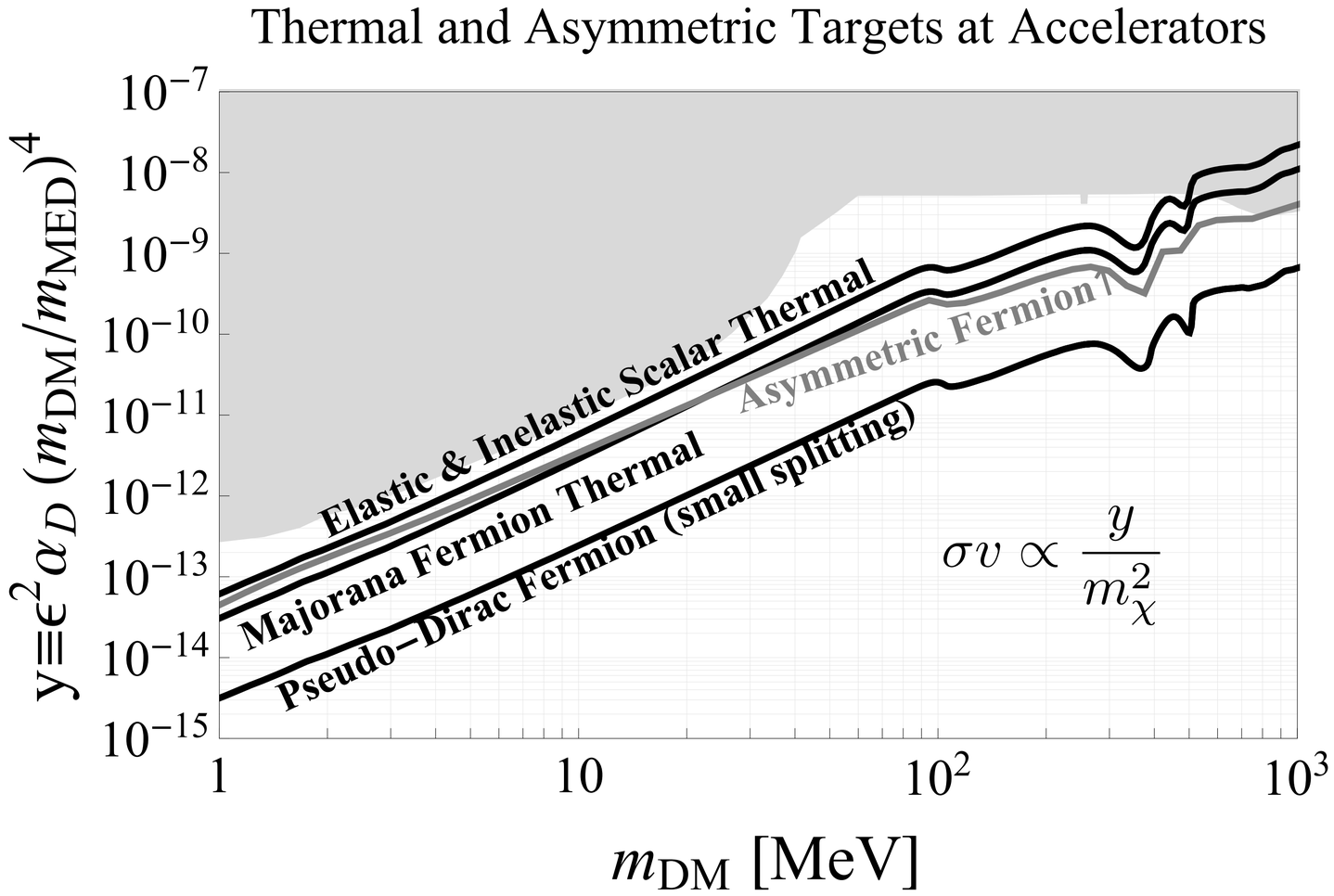
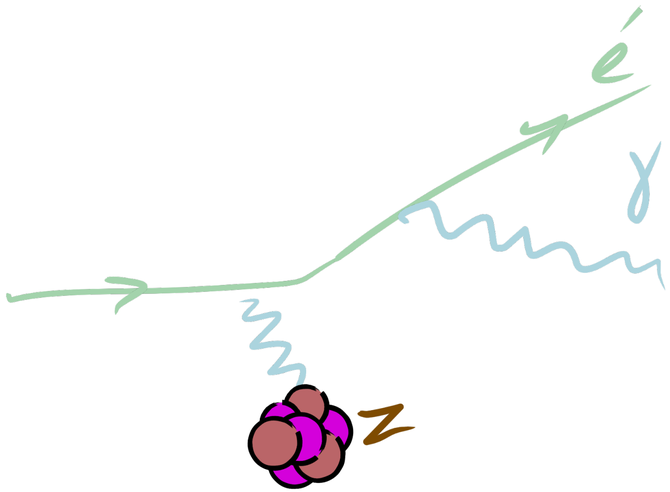
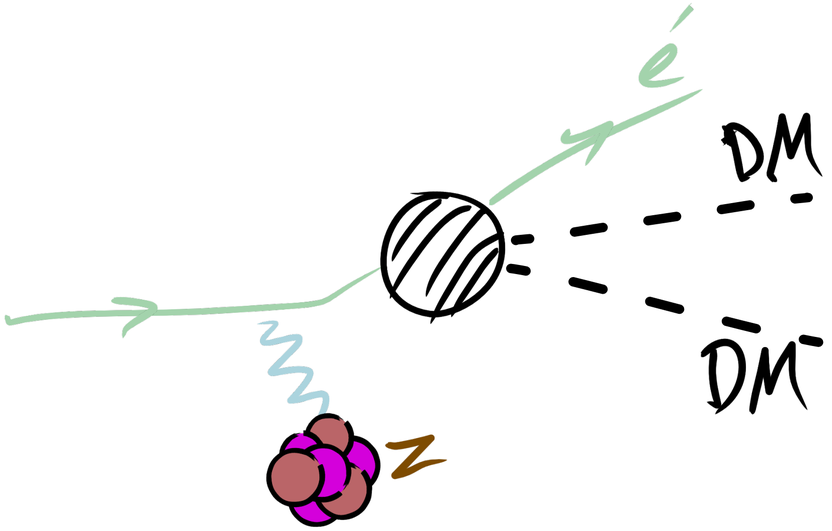


Figure: US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report [arxiv:1707.04591]
Details on vector meson decays, see Schuster, Toro, and Zhou, "Probing Invisible Vector Meson Decays with the NA64 and LDMX Experiments." (Phys. Rev. D 105, 035036) [arxiv:2112.02104]

How to produce and see your signal process

Signal identification





Signal identification

- How does $eA \rightarrow eA + \gamma$ differ from $eA \rightarrow eA + \chi\bar{\chi}$
- Key difference:
  - Dark object has mass
  - Fundamentally different kinematics, regardless of model

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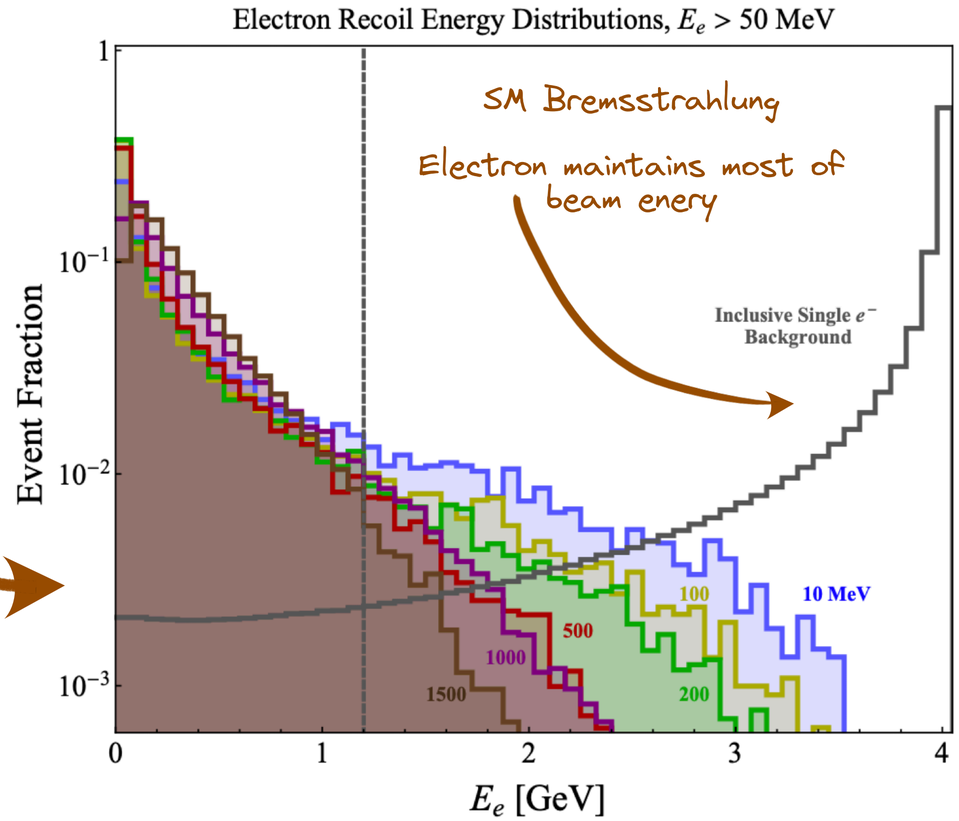
DM Bremsstrahlung

Dark object carries most of beam enery



Figures: Åkesson et al., "Light Dark Matter eXperiment (LDMX)." [arXiv:1808.05219]

For details using a dark photon benchmark model, see Bjorken et al., "New Fixed-Target Experiments to Search for Dark Gauge Forces." (Phys.Rev.D80:075018,2009) [arxiv:0906.0508]

Signal identification

- How does $eA \rightarrow eA + \gamma$ differ from $eA \rightarrow eA + \chi\bar{\chi}$
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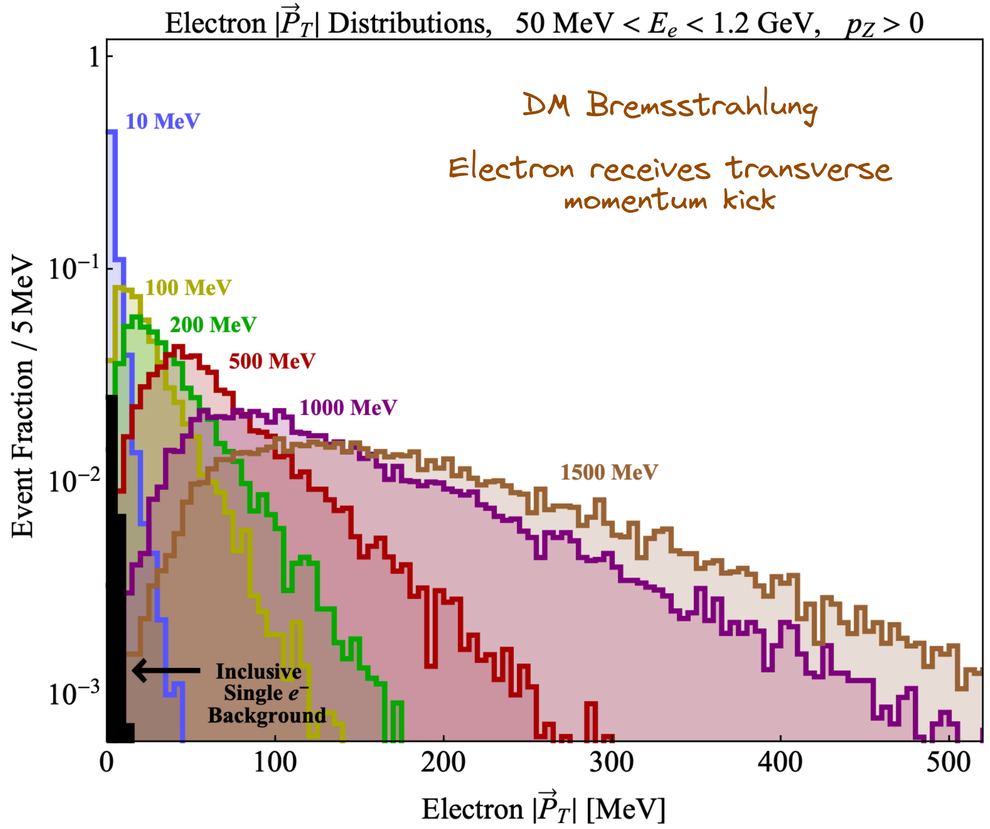
SM Bremsstrahlung

Electron continues with small scattering angle



Figures: Åkesson et al., "Light Dark Matter eXperiment (LDMX)." [arXiv:1808.05219]

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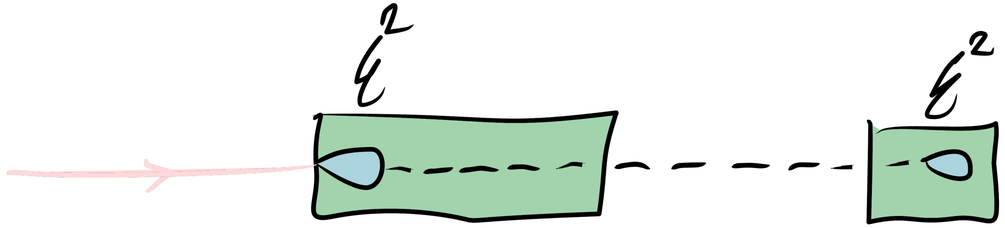
Key takeaway

The missing energy and momentum signatures
are primarily features of massive
bremsstrahlung in general

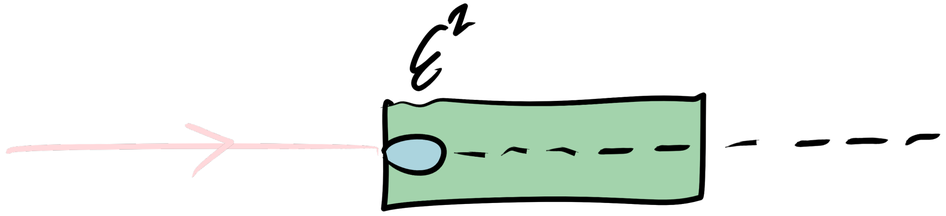
If you can exploit these features, you will be
sensitive to light dark matter production

Measurement strategies

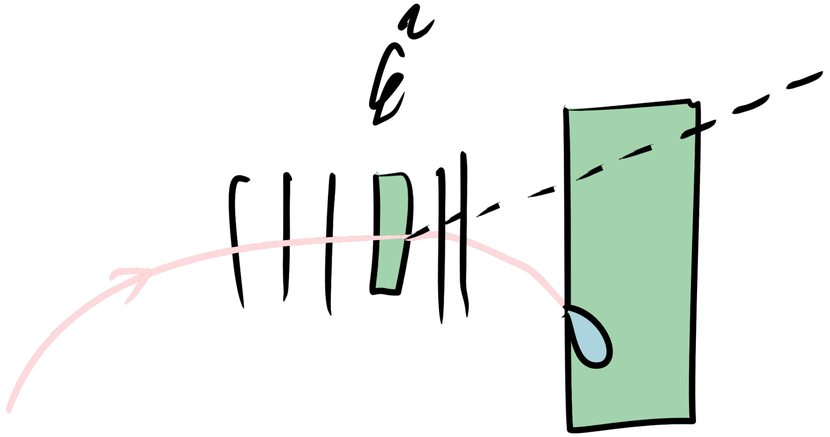
Traditional beam dump



Active beam dump/Missing energy



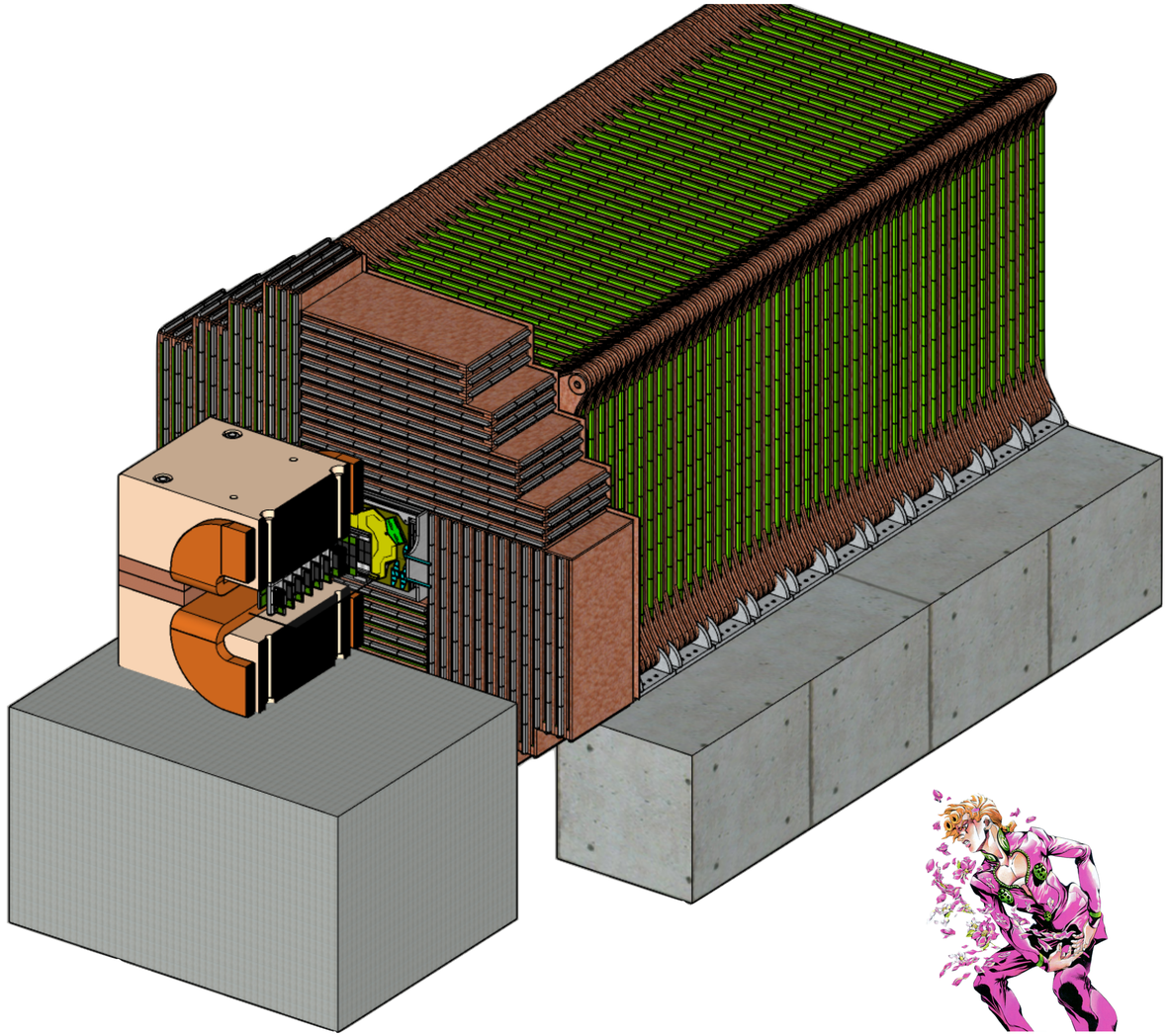
Missing momentum



The LDMX experiment

Let's build an experiment for that

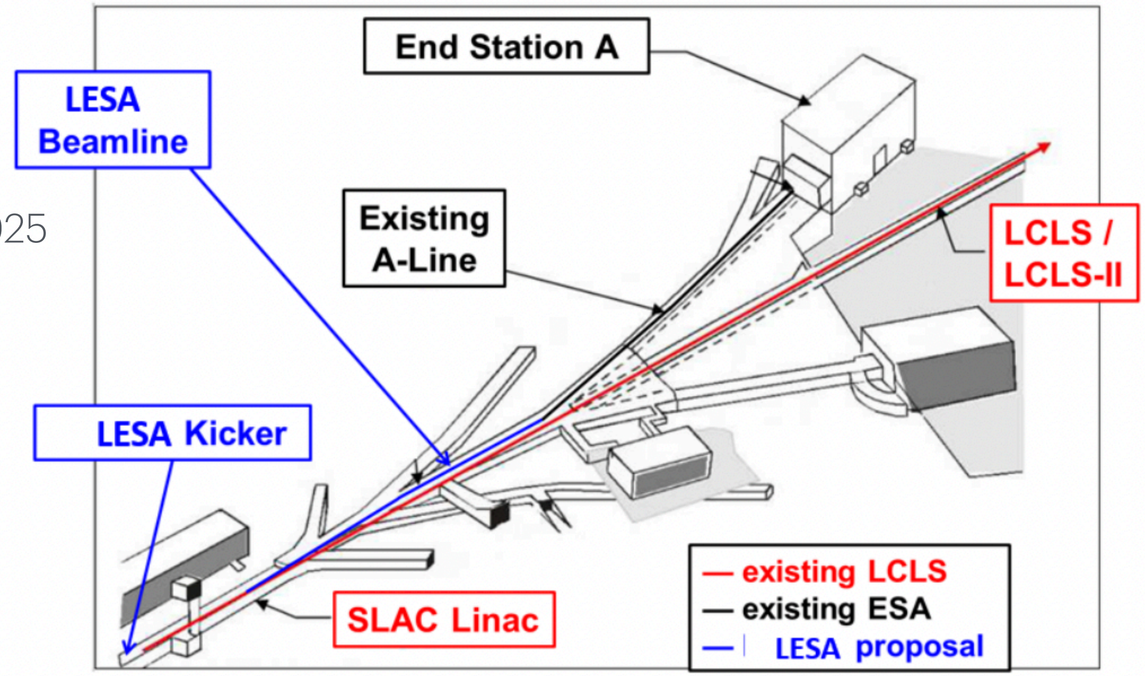
- Light Dark Matter eXperiment (LDMX)
  - Fixed target
  - Missing momentum
- Measure individual electrons and their products for $10^{16}\, e^-$
  - Veto all SM background events



Whitepaper: [arxiv:1808.05219]

The beamline @ SLAC

- LCLS-II e- accelerator @ SLAC:
  - Ordinarily for photon science
  - LDMX will operate parasitically
  - LESA beamline under construction, testbeam operations ~2025
- 8 GeV beam
  - Low current
    - Allows for measurements of individual electrons
  - High repetition rate
    - Reaching sufficient statistics



Beam layout, from The SLAC Linac to ESA (LESA) Beamline for Dark Sector Searches and Test Beams [arxiv:2205.13215]

The LDMX design

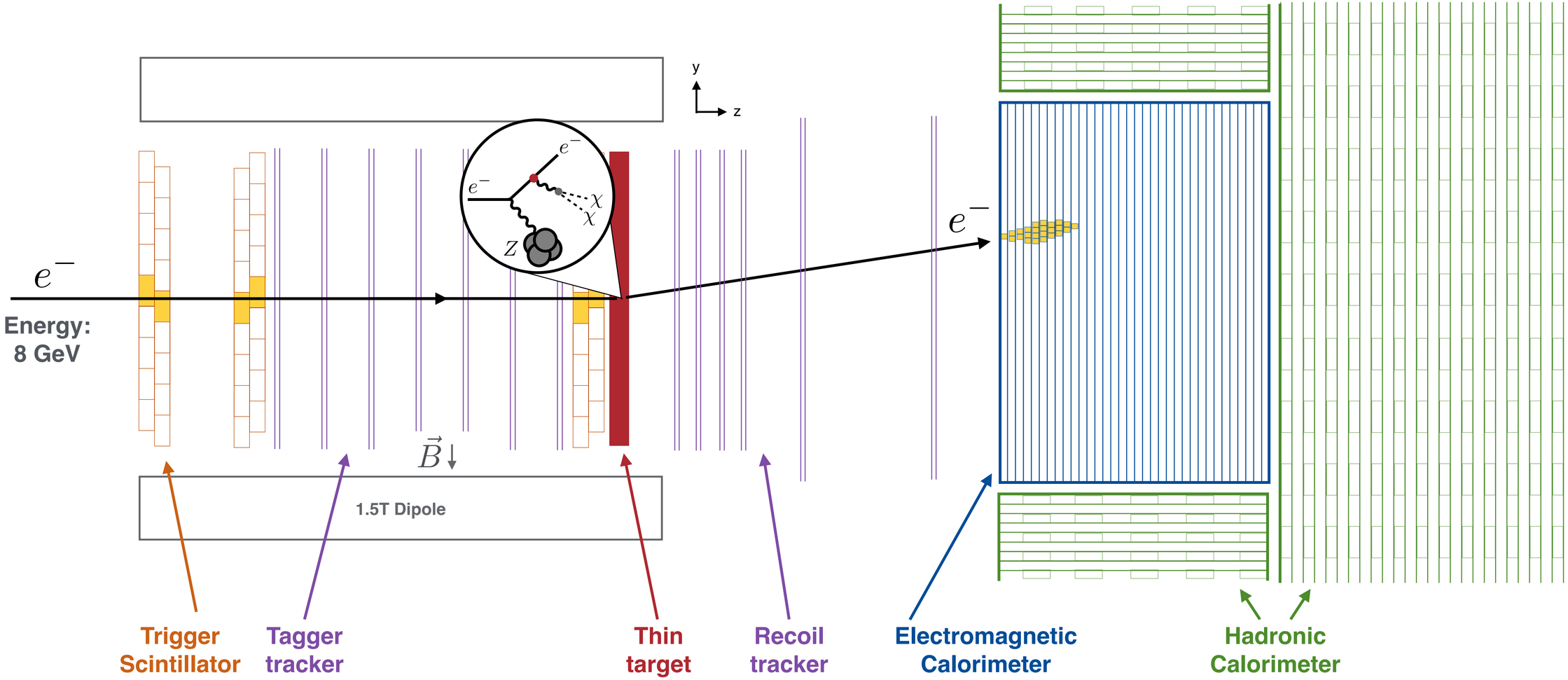
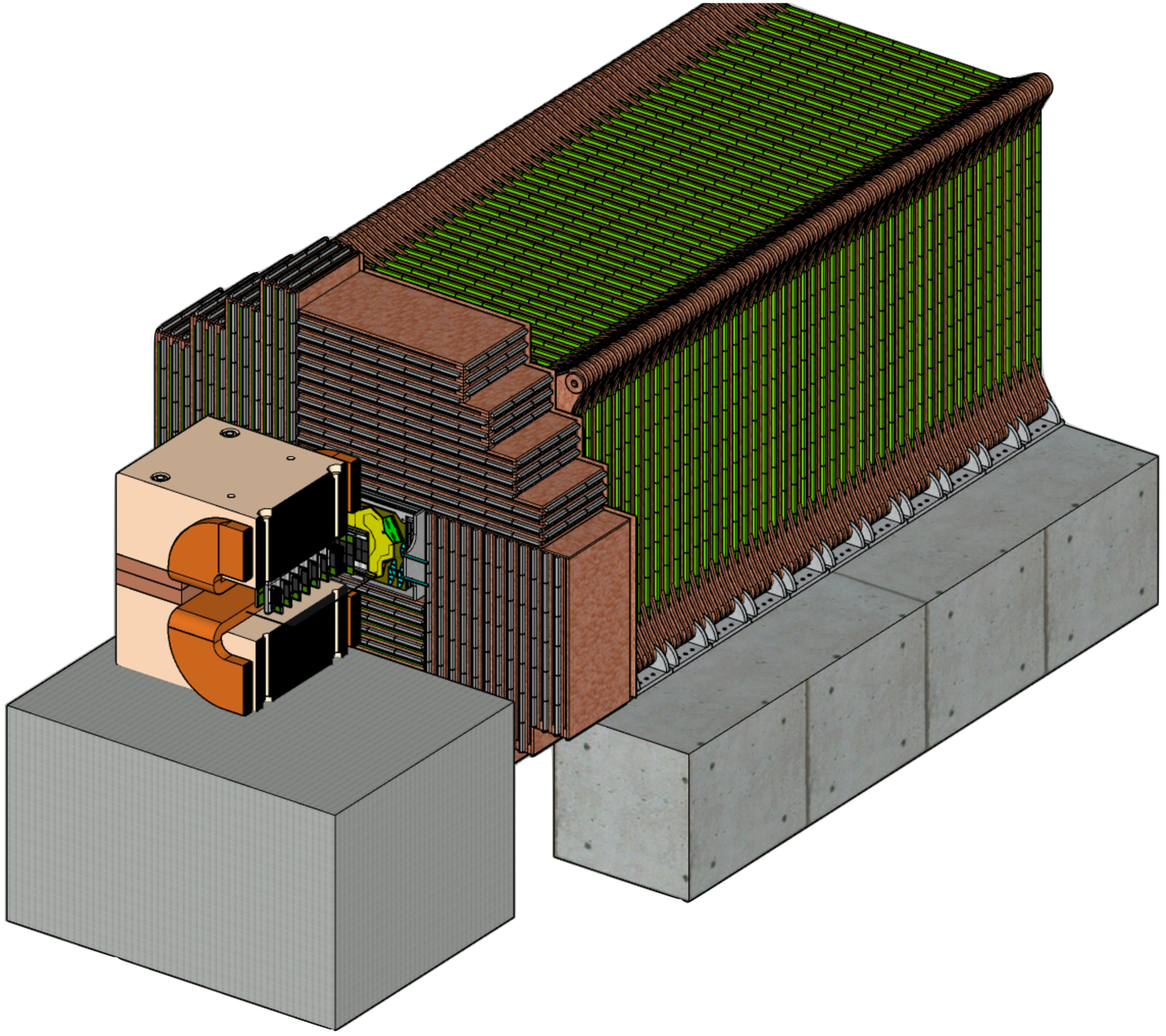
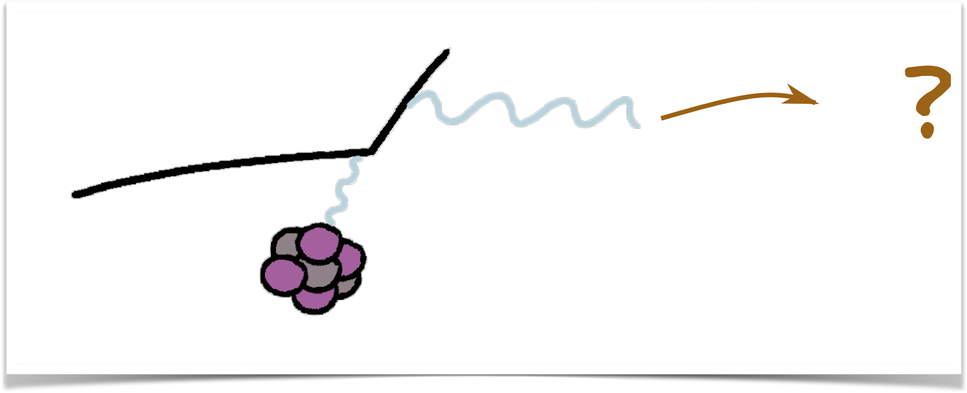


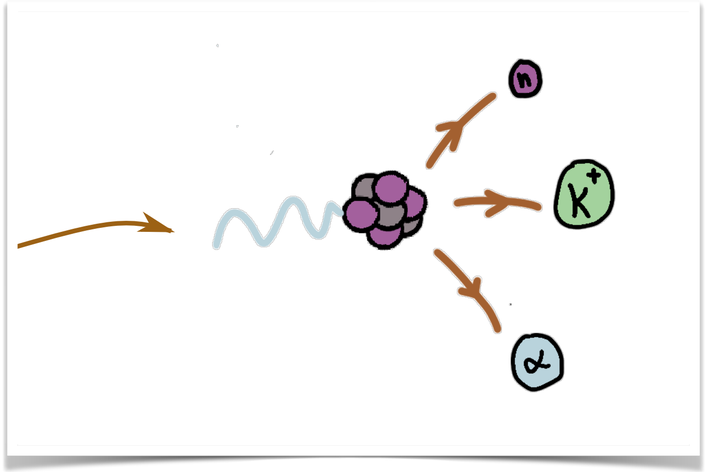
Figure adapted from: Current Status and Future Prospects of the Light Dark Matter Experiment [arxiv[2203.08192]]



Backgrounds

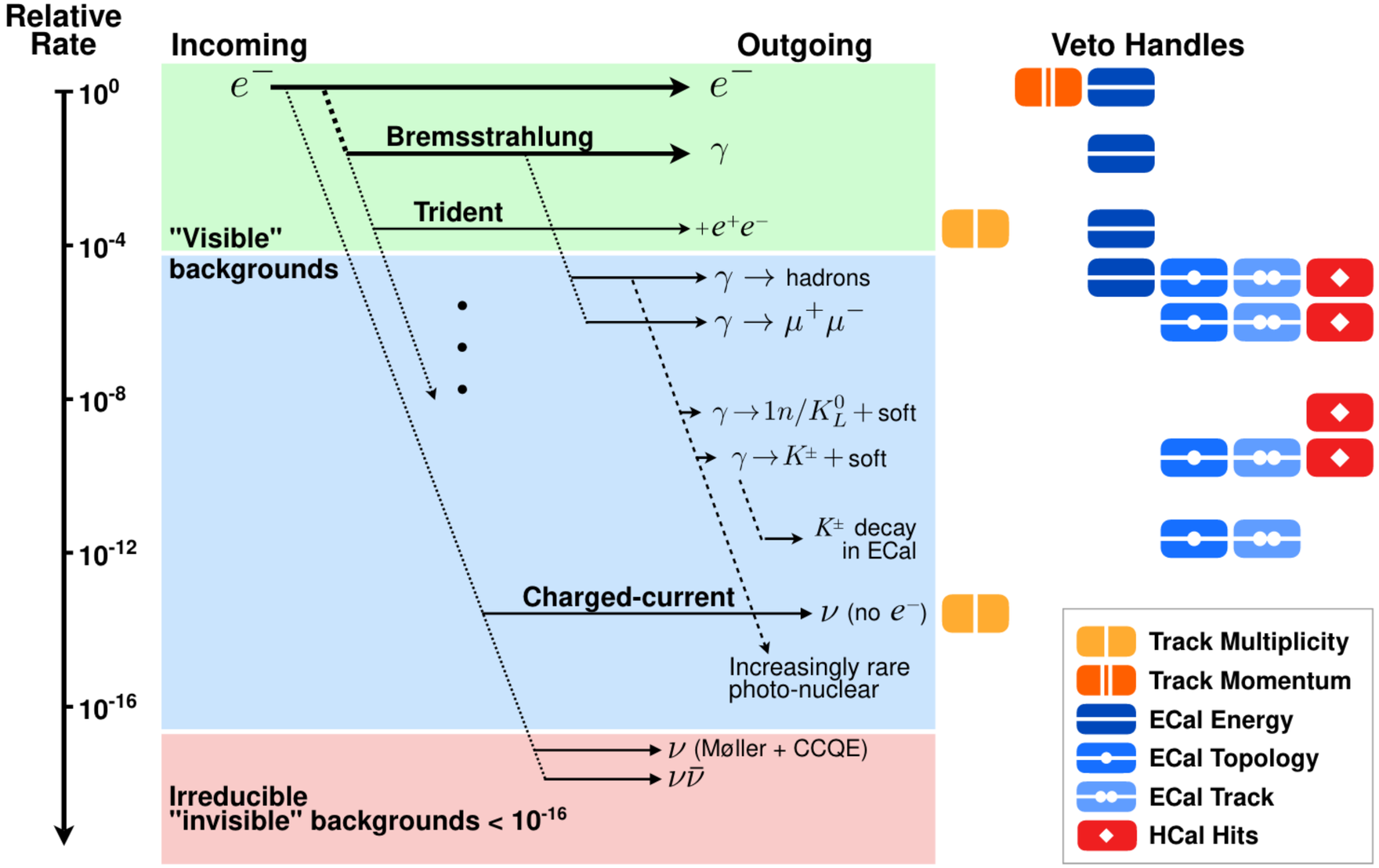
Photon-induced





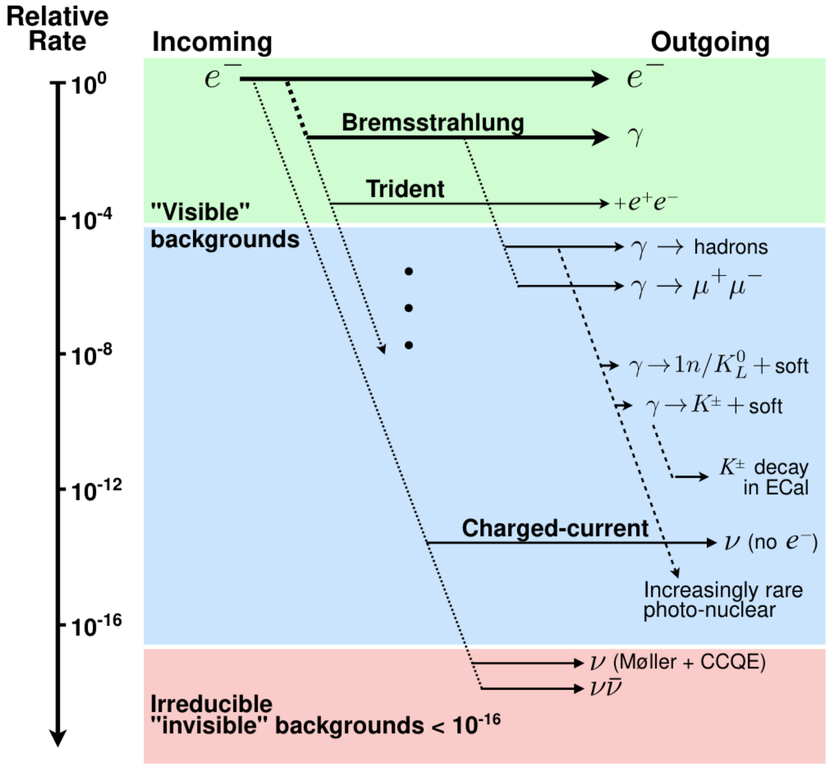
Backgrounds

Figure from Åkesson et al., "Photon-Rejection Power of the Light Dark Matter eXperiment in an 8 GeV Beam." JHEP12(2023)092 [arxiv:2308.15173]



Analysis & Veto strategy

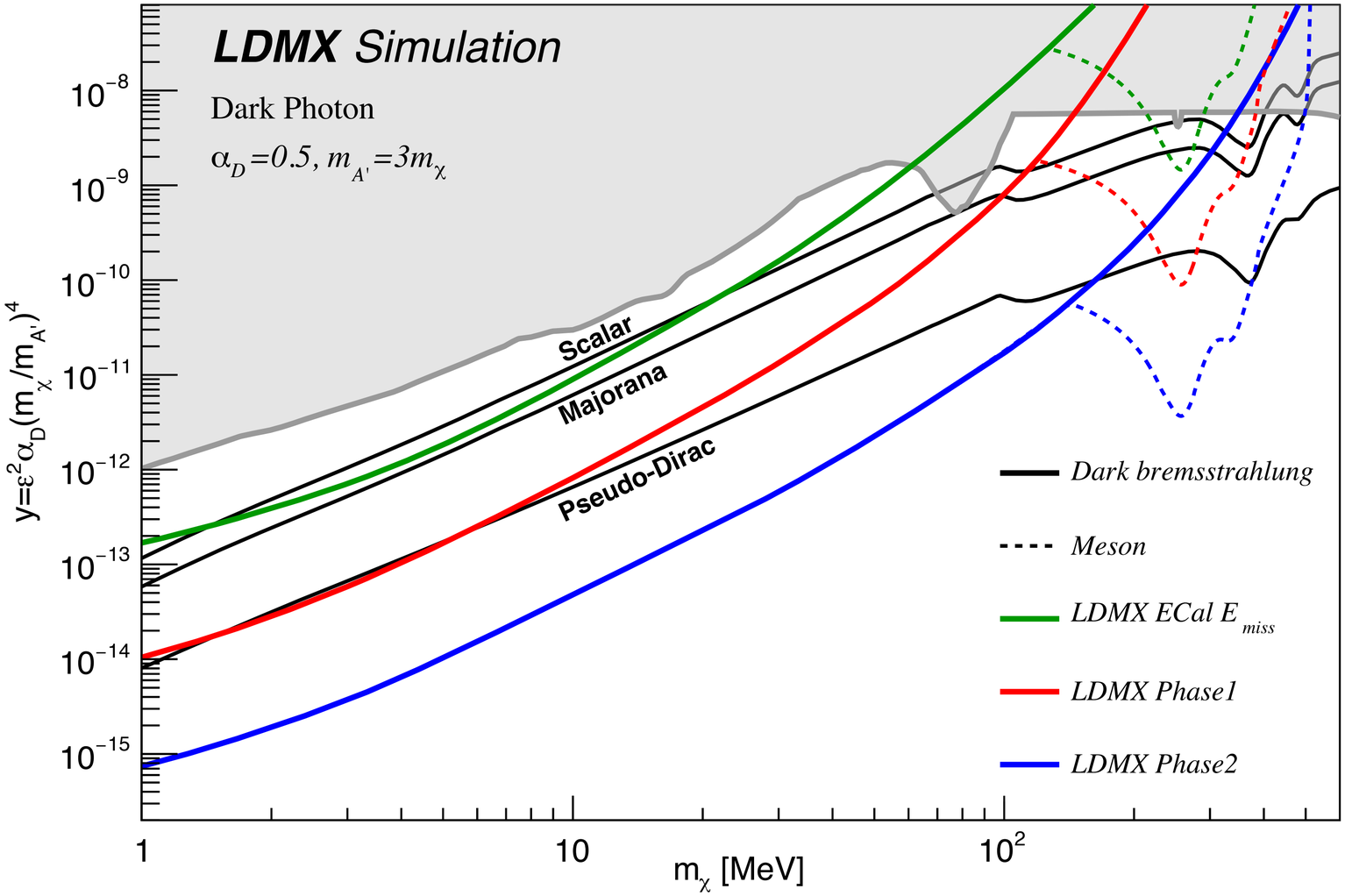
Recoil electron p_T is not used in the analysis

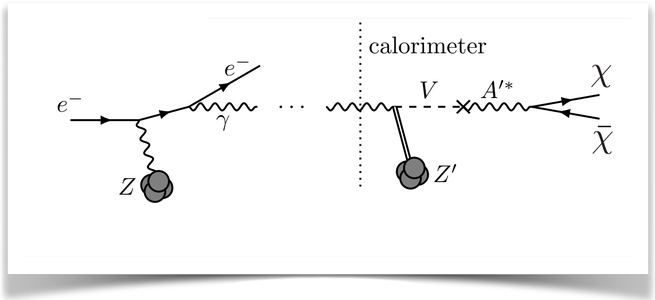


1. Count electrons and trigger on missing energy
2. Identify & require electron track with missing momentum
3. Exploit ECAL's high granularity & imaging capabilities to veto SM processes
   - BDT + MIP Tracking
4. Require no activity in HCAL

Figure & results from Åkesson et al., "Photon-Rejection Power of the Light Dark Matter eXperiment in an 8 GeV Beam." JHEP12(2023)092 [arxiv:2308.15173]
Original analysis with 4 GeV beam: Åkesson et al., "A High Efficiency Photon Veto for the Light Dark Matter Experiment." JHEP04(2020)003 [arxiv:1912.05535]

Results and reach





A′ results from Åkesson et al., "Photon-Rejection Power of the Light Dark Matter eXperiment in an 8 GeV Beam." JHEP12(2023)092 [arxiv:2308.15173]
Invisible meson decays from Schuster, Toro, and Zhou, "Probing Invisible Vector Meson Decays with the NA64 and LDMX Experiments." (Phys. Rev. D 105, 035036) [arxiv:2112.02104]

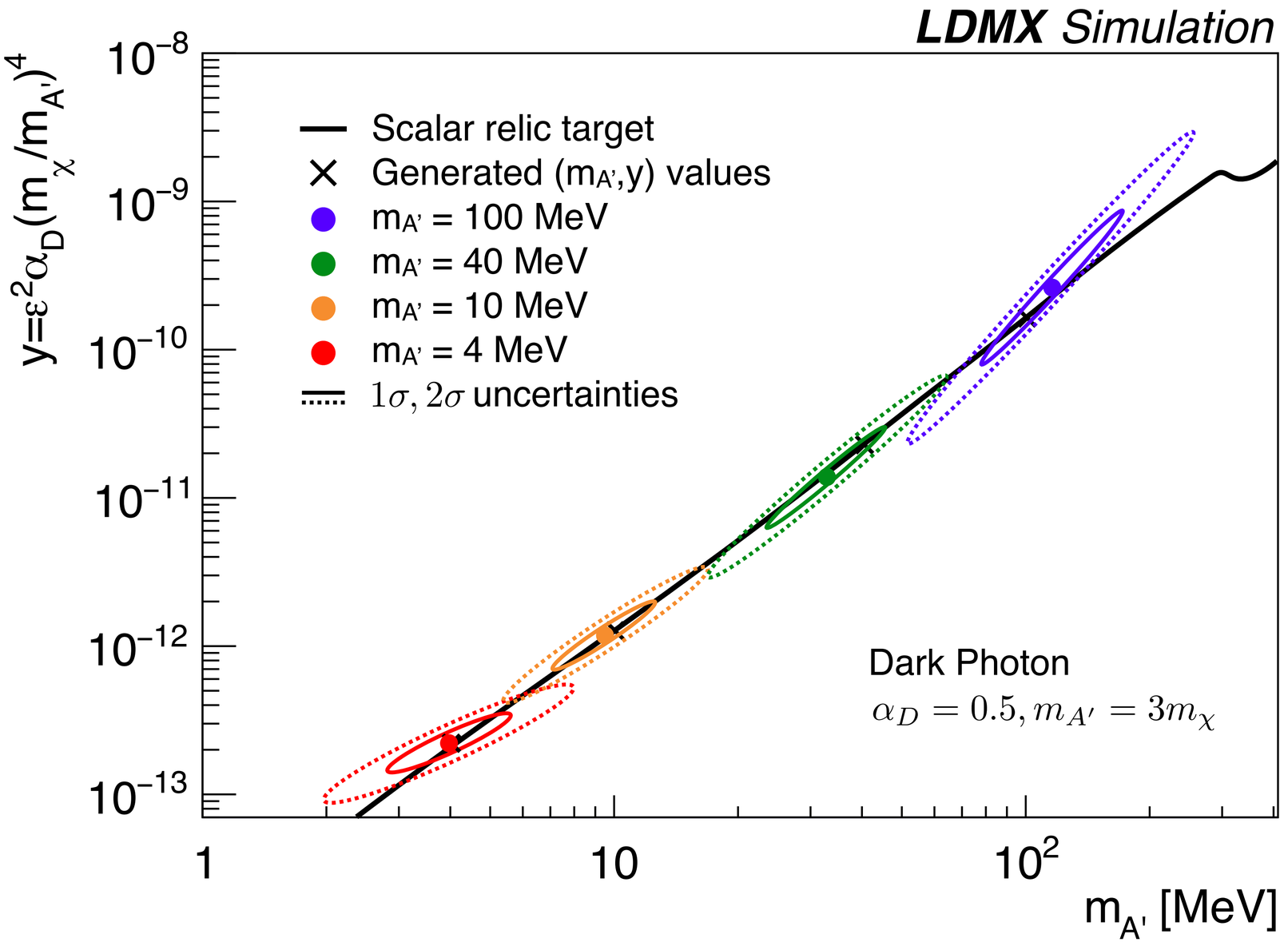


Figure from: Current Status and Future Prospects of the Light Dark Matter Experiment [arxiv[2203.08192]]

Resources

- A *brief* introduction to accelerator based searches for light dark matter
  - Bjorken et al., “New Fixed-Target Experiments to Search for Dark Gauge Forces.” (PhysRevD.80.075018) [arxiv:0906.0580]
  - Berlin et al., “Dark Matter, Millicharges, Axion and Scalar Particles, Gauge Bosons, and Other New Physics with LDMX.” (Phys. Rev. D 99, 075001 (2019)) [arXiv:1807.01730]
  - Schuster, et al., “Probing Invisible Vector Meson Decays with the NA64 and LDMX Experiments.” (Phys. Rev. D 105, 035036) [arxiv:2112.02104]
- The LDMX experiment
  - Whitepaper: [arxiv:1808.05219]
  - Current Status and Future Prospects of the Light Dark Matter Experiment [arxiv[2203.08192]]
- Fantastical background processes and where to veto them
  - Åkesson et al., “Photon-Rejection Power of the Light Dark Matter eXperiment in an 8 GeV Beam.” JHEP12(2023)092 [arxiv:2308.15173]
  - Åkesson et al., “A High Efficiency Photon Veto for the Light Dark Matter Experiment.” JHEP04(2020)003 [arxiv:1912.05535]
- Reach and prospects

DMX

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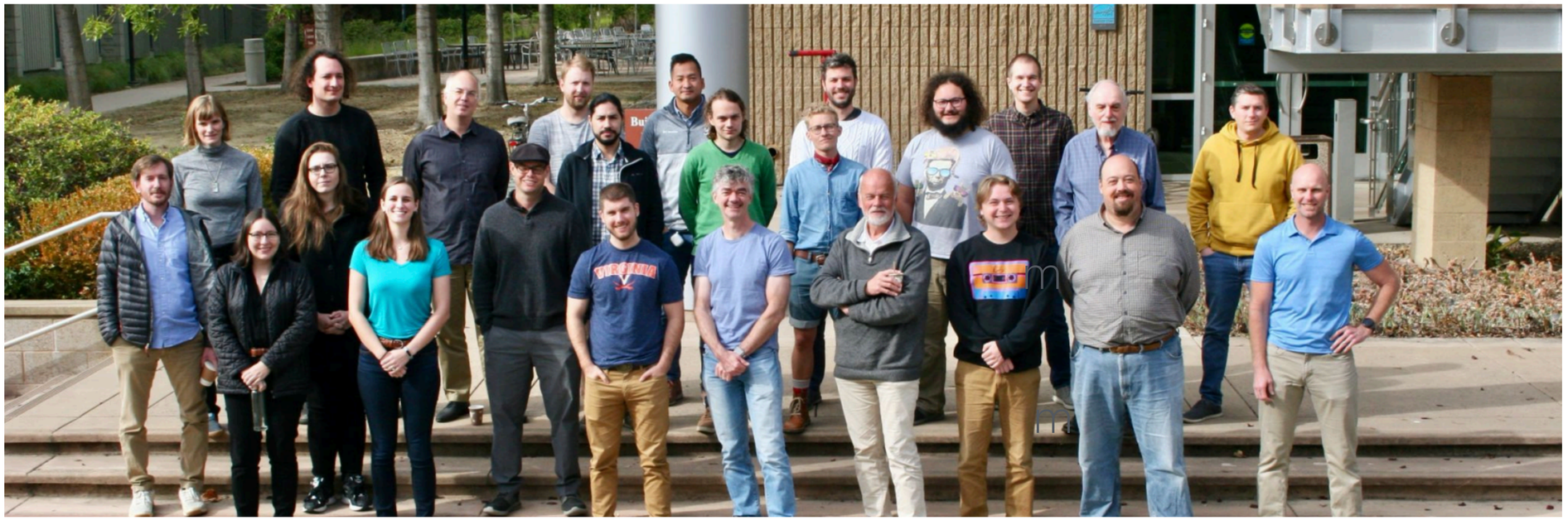

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U.S. DEPARTMENT OF ENERGY

Vetenskapsrådet

	Photo-nuclear		**Muon conversion**	
	Target-area	**ECal**	**Target-area**	**ECal**
EoT Equivalent	2.00×10^{14}	2.00×10^{14}	2.00×10^{14}	2.00×10^{14}
Trigger (front ECal energy < 3160 MeV)	7.57×10^{7}	4.43×10^{8}	2.37×10^{7}	8.12×10^{7}
Total ECal energy < 3160 MeV	2.73×10^{7}	7.27×10^{7}	1.76×10^{7}	6.06×10^{7}
Single track with p < 2400 MeV/c	3.03×10^{6}	6.64×10^{7}	5.32×10^{4}	5.69×10^{7}
ECal BDT (85% eff. $m_{A'} = 1$ MeV)	1.50×10^{5}	1.04×10^{5}	< 1	< 1
HCal max PE < 8	< 1	2.02	< 1	< 1
ECal MIP tracks = 0	< 1	< 1	< 1	< 1

Assuming very little

Depletion & Targets

- Relic density gives a *target cross section* for a given mass:
  - Thermal target in reach figures

$$\langle \sigma v \rangle$$

With

$$s_{freeze} \approx 4m_{\chi}^2$$

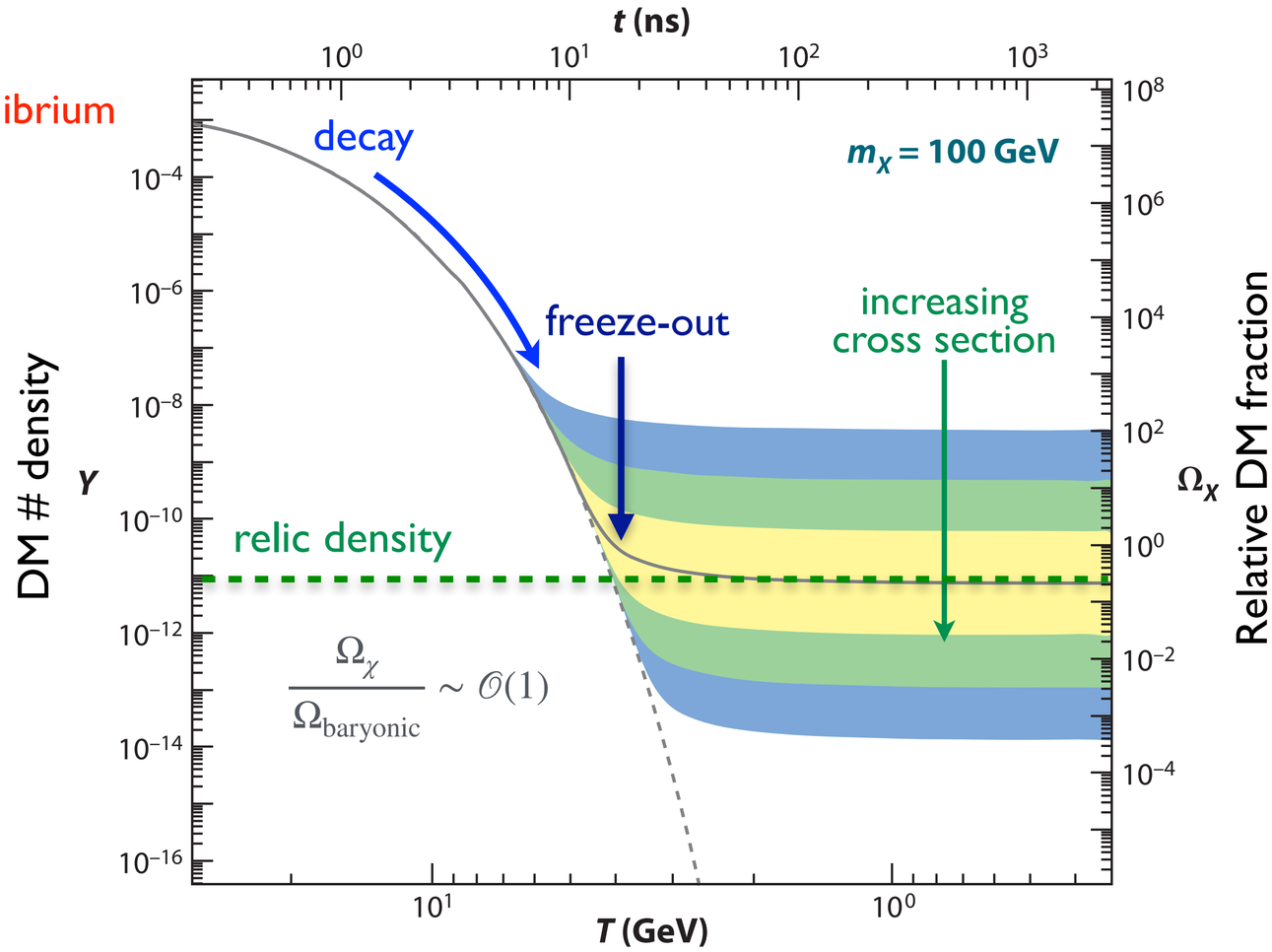


Figure adapted from J.L. Feng Dark Matter Candidates from Particle Physics and Methods of Detection (Ann. Rev. Astrophys. 48: 495, 2010) [arxiv:1003.0904] from T.K. Nelson

Veto features

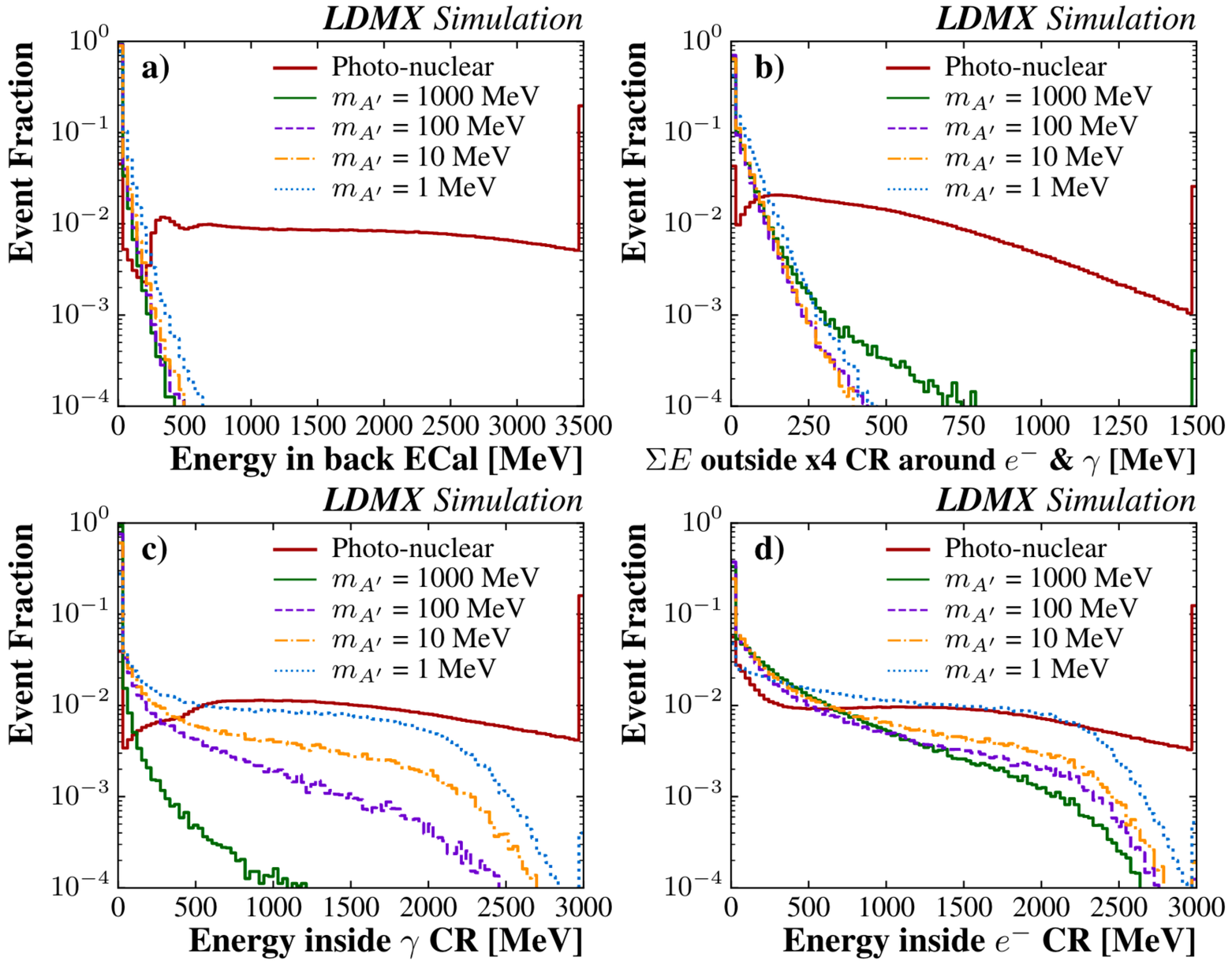
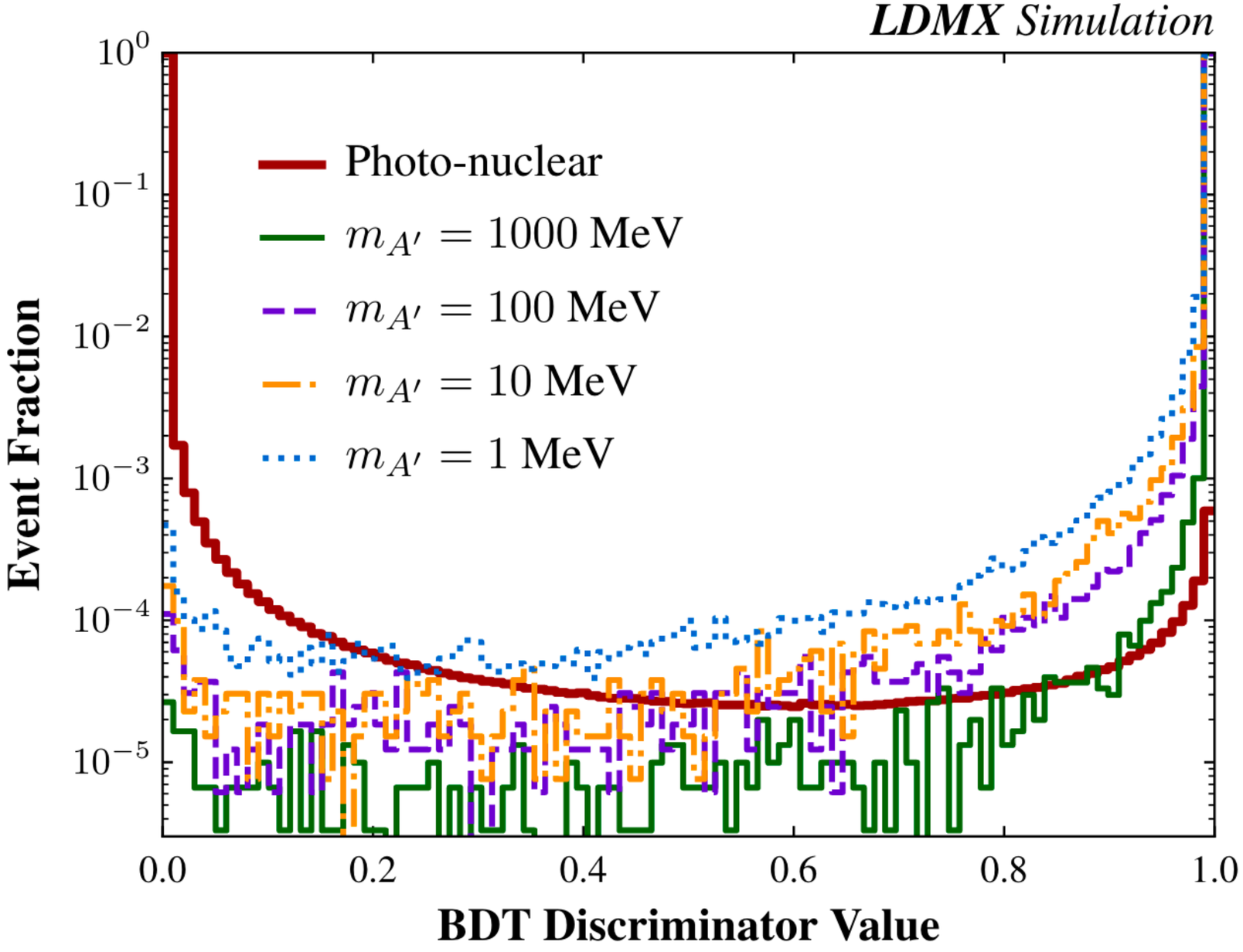


Figure: Åkesson et al., "Photon-Rejection Power of the Light Dark Matter eXperiment in an 8 GeV Beam." JHEP12(2023)092 [arxiv:2308.15173]



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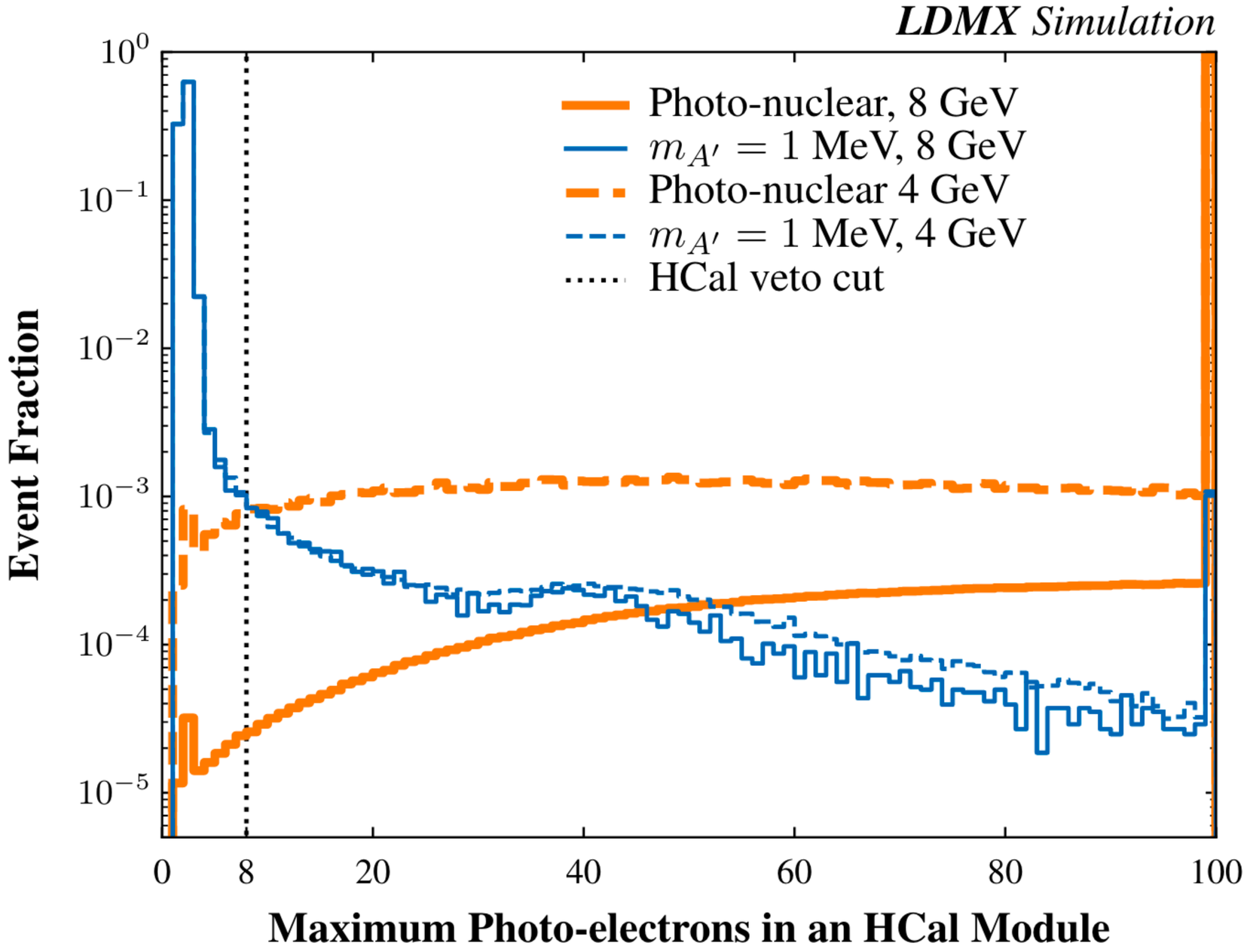

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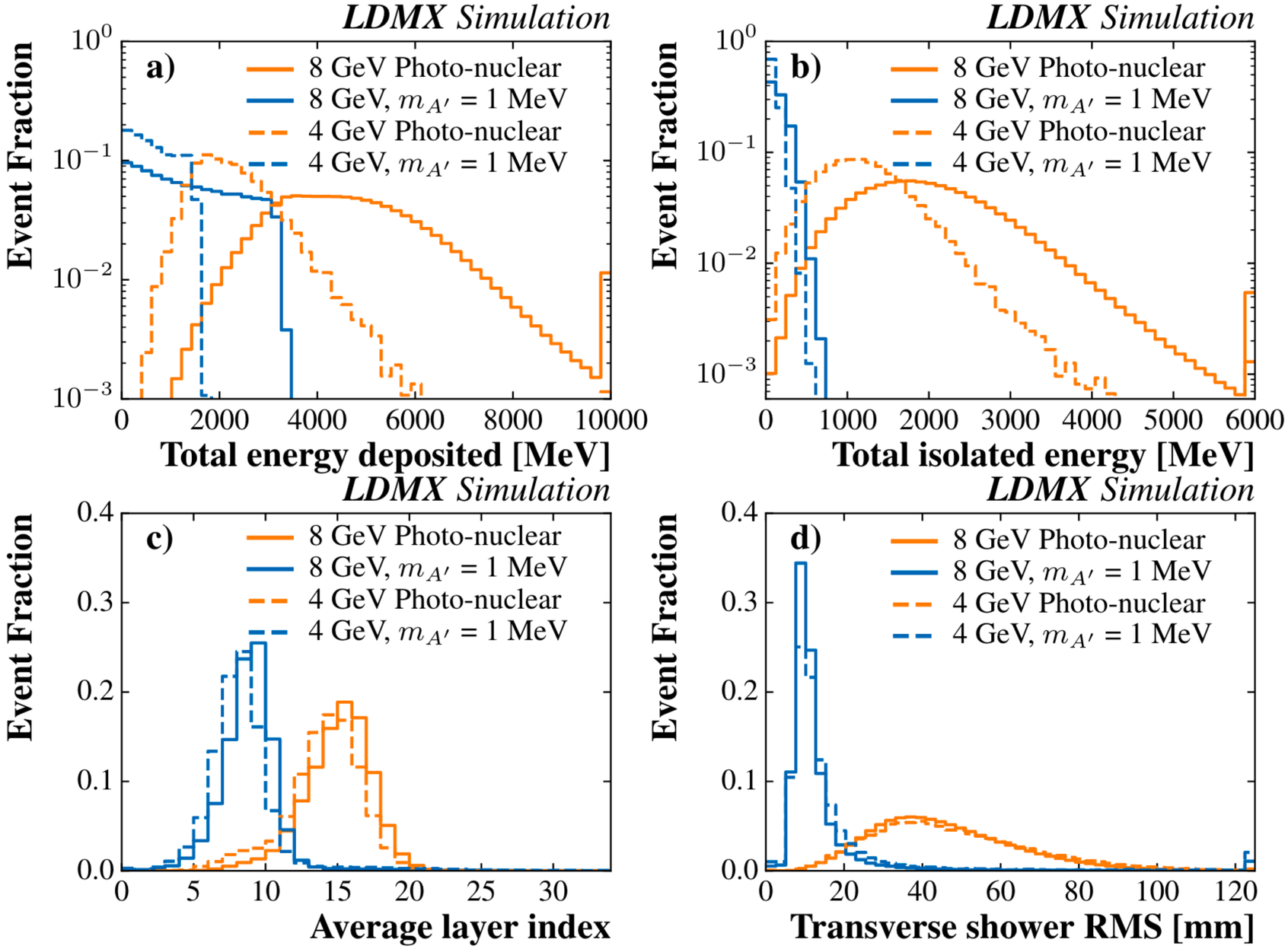
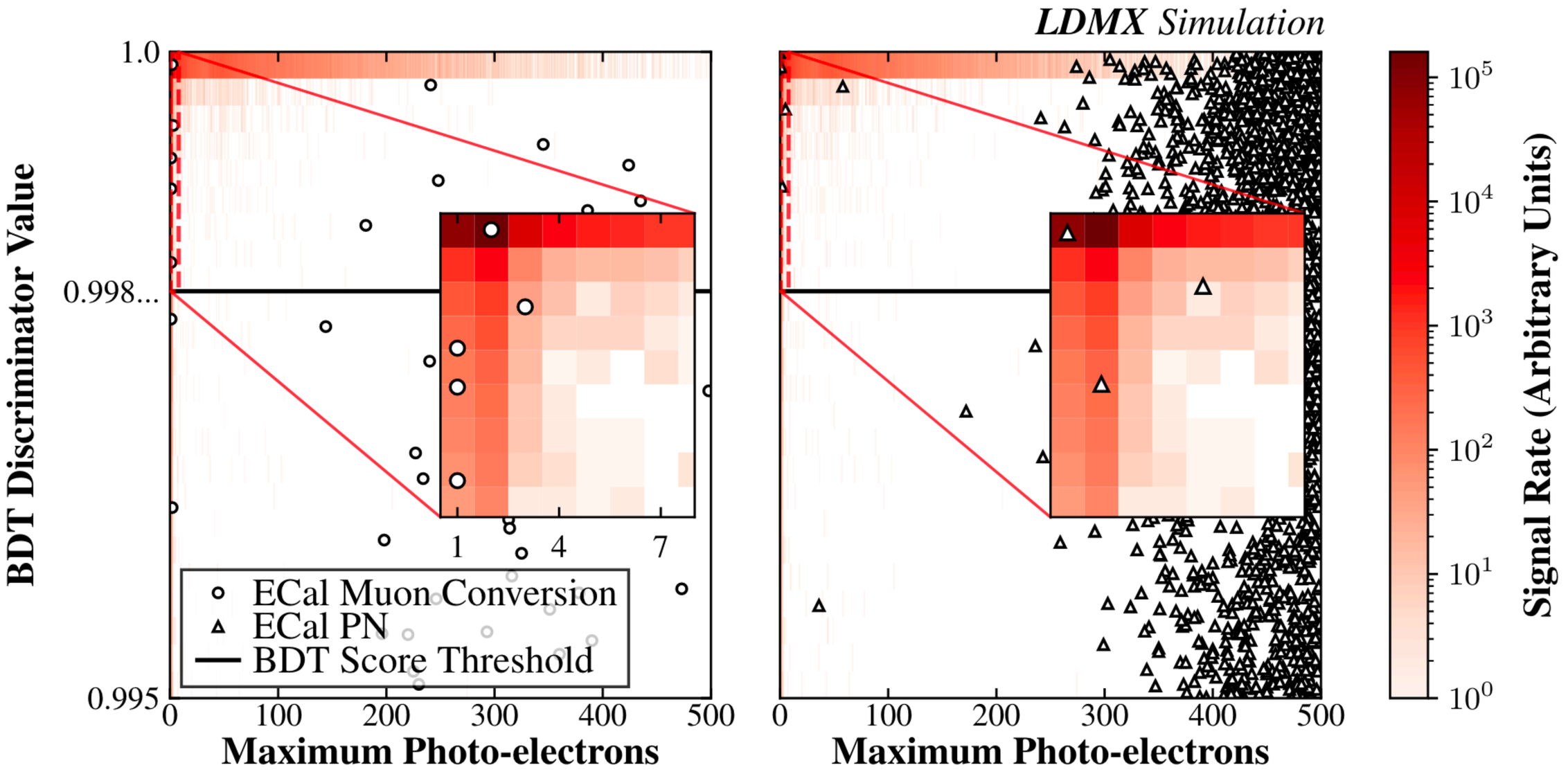

LDMX Simulation
a)
8 GeV Photo-nuclear
8 GeV, $m_{A'}$ = 1 MeV
4 GeV Photo-nuclear
4 GeV, $m_{A'}$ = 1 MeV
Event Fraction
Total energy deposited [MeV]
LDMX Simulation
b)
8 GeV Photo-nuclear
8 GeV, $m_{A'}$ = 1 MeV
4 GeV Photo-nuclear
4 GeV, $m_{A'}$ = 1 MeV
Event Fraction
Total isolated energy [MeV]
LDMX Simulation
c)
8 GeV Photo-nuclear
8 GeV, $m_{A'}$ = 1 MeV
4 GeV Photo-nuclear
4 GeV, $m_{A'}$ = 1 MeV
Event Fraction
Average layer index
LDMX Simulation
d)
8 GeV Photo-nuclear
8 GeV, $m_{A'}$ = 1 MeV
4 GeV Photo-nuclear
4 GeV, $m_{A'}$ = 1 MeV
Event Fraction
Transverse shower RMS [mm]



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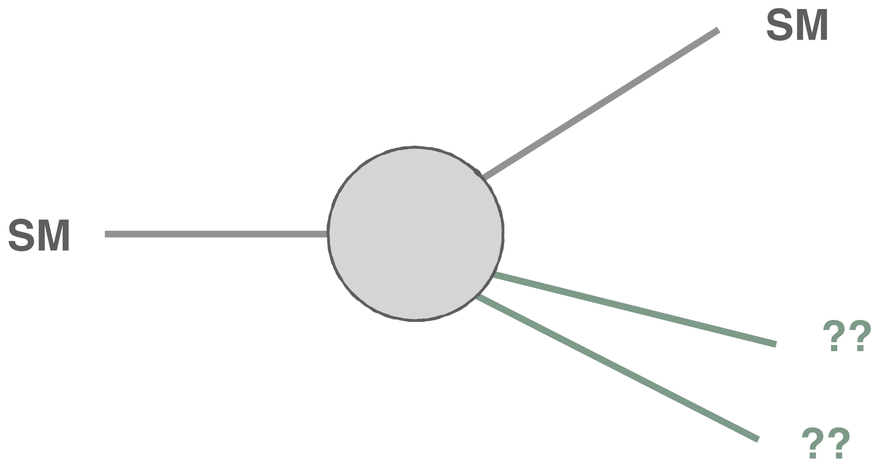

Direct detection of mass creation
Deflected SM particle → missing momentum search

No QCD or QED charge in escaped mass
Nothing in our detector… → missing energy