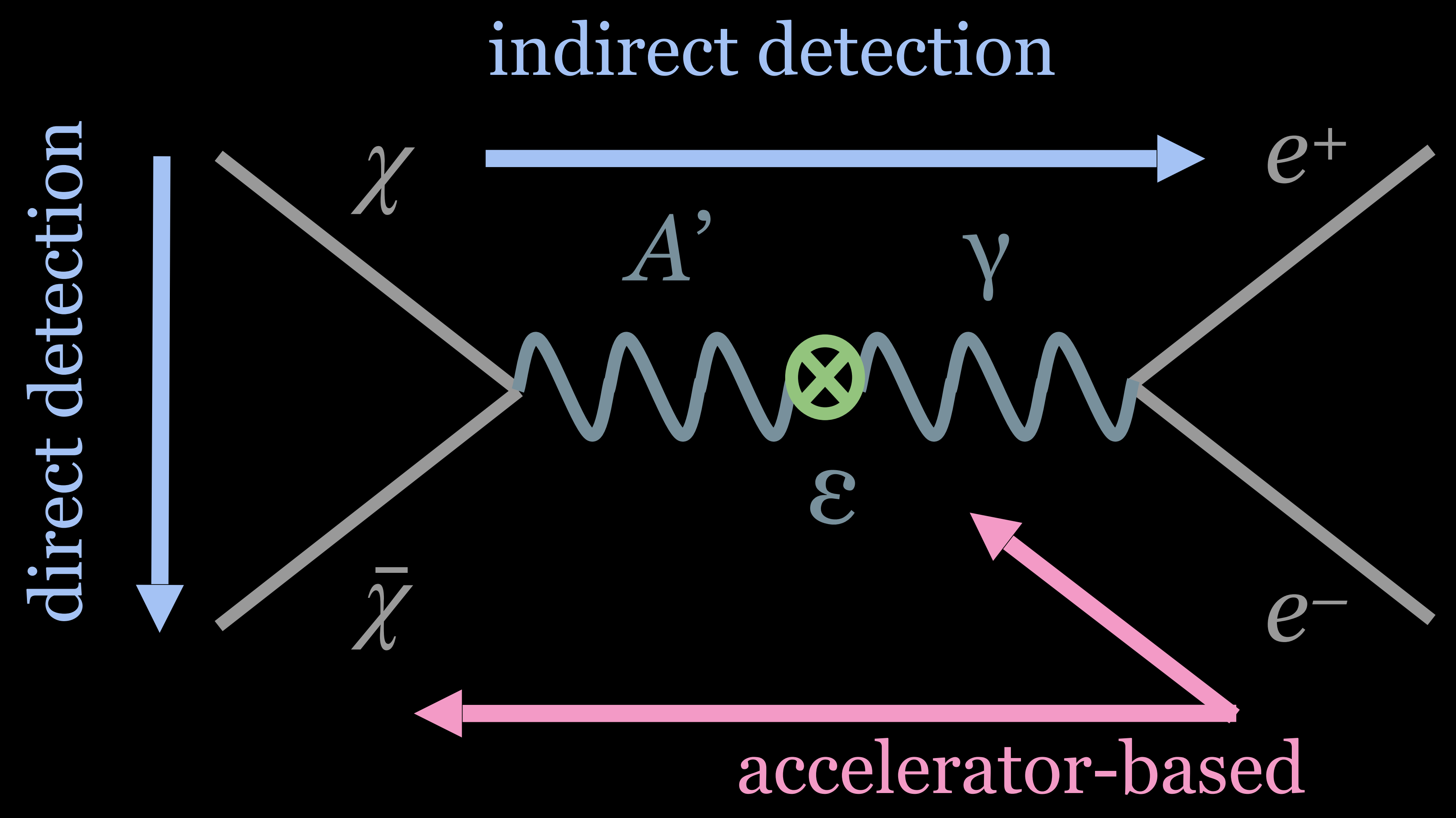
Status of the Light Dark Matter eXperiment

Lene Kristian Bryngemark, Lund University

TAUP, Vienna, August 28 - September 1 2023

Dark sector light mediator: dark photons

- “Simplest” possible dark sector extension
- dark QED + kinetic mixing (ε) = a feeble interaction with SM matter $\bar{\chi}$



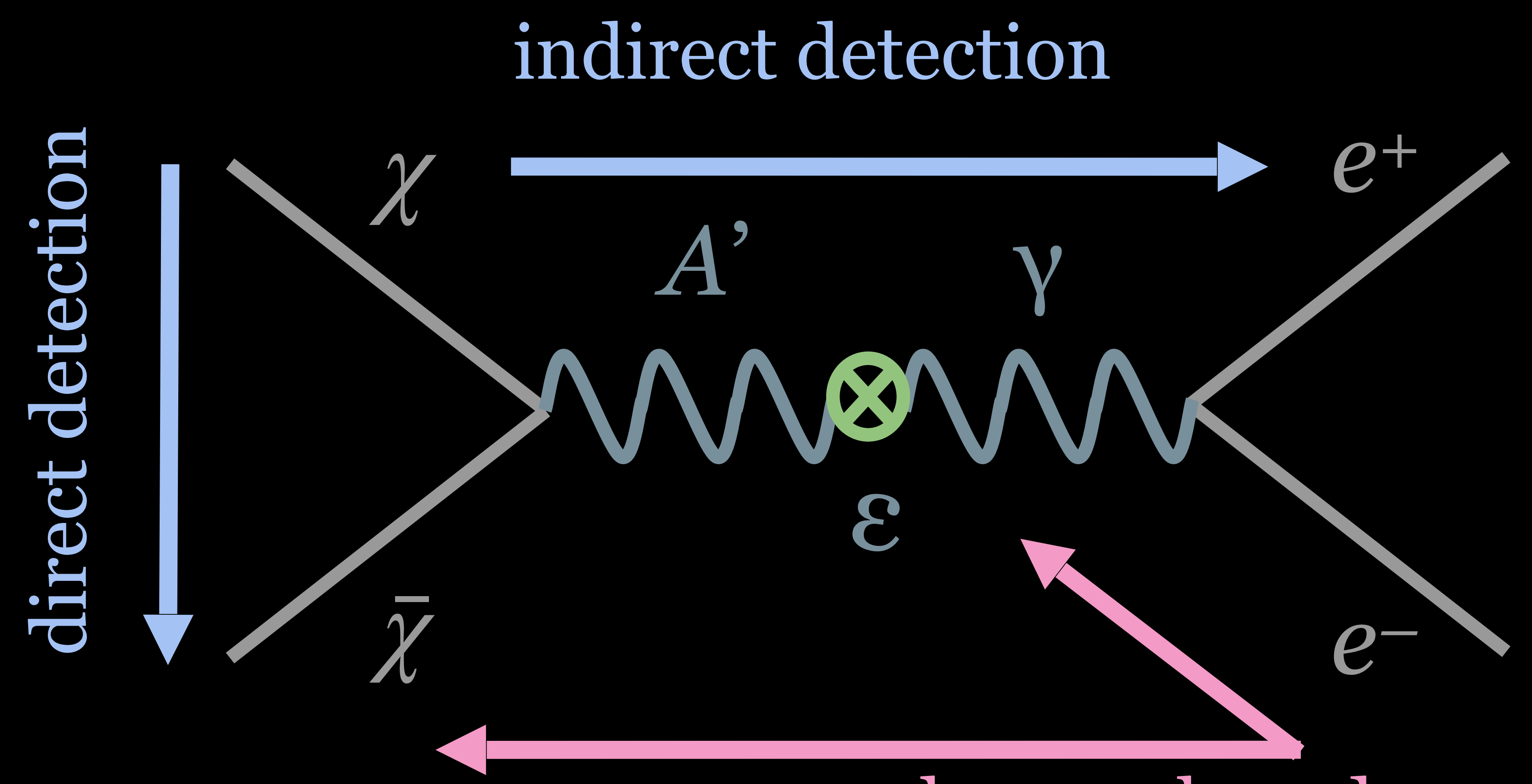
$$\langle \sigma v \rangle \propto \varepsilon^2 \alpha_D$$

TAUP 2023

LK Bryngemark

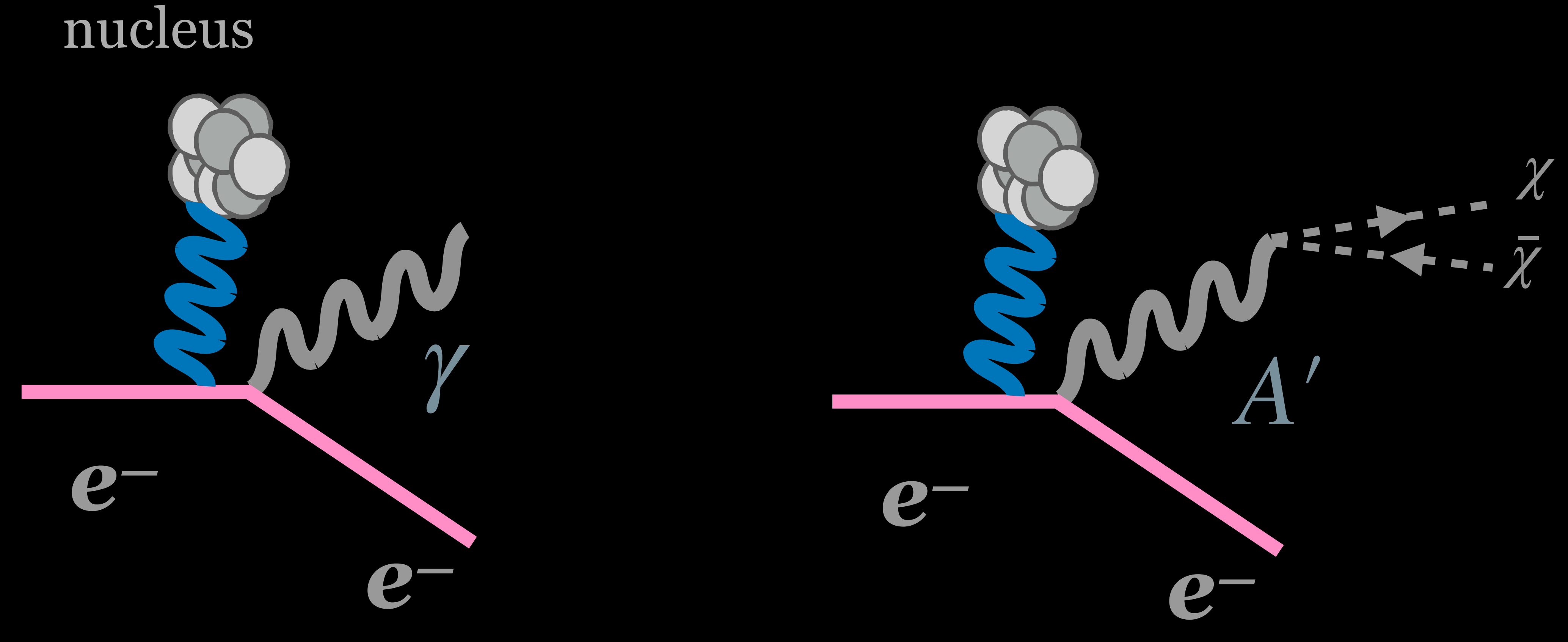
Dark sector light mediator: dark photons

- “Simplest” possible dark sector extension
- dark QED + kinetic mixing (ε) = a feeble interaction with SM matter $\bar{\chi}$



$$\langle \sigma v \rangle \propto \varepsilon^2 \alpha_D$$

With an electron beam



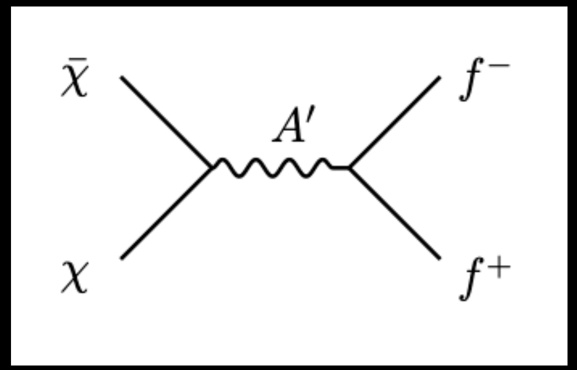
SM (QED) bremsstrahlung

Dark photon bremsstrahlung

A' production $\propto \varepsilon^2$; with subsequent DM-SM interactions $\propto \varepsilon^4$

Accelerator advantage: relativistic DM production

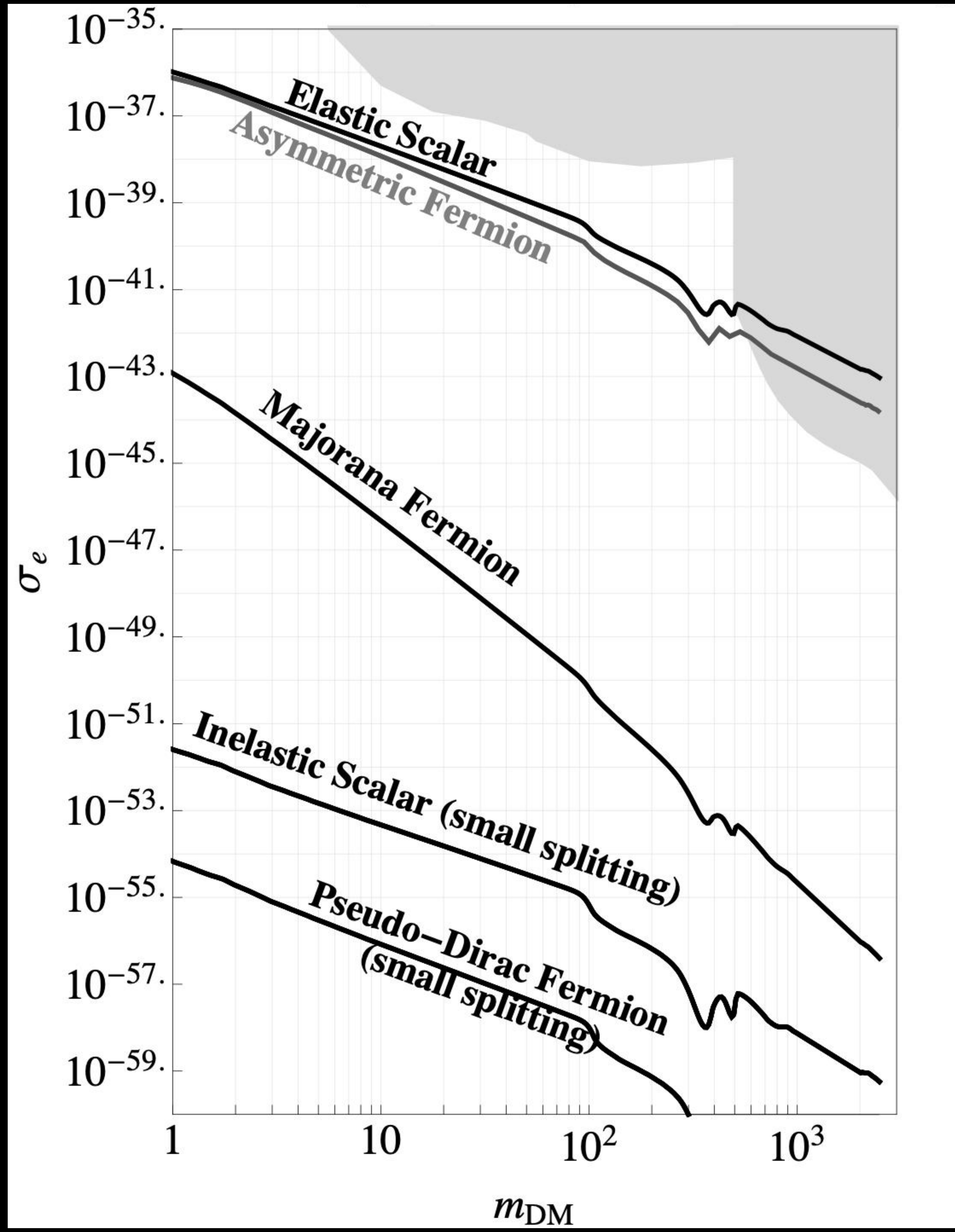
Reduces sensitivity to Lorentz structure of interactions

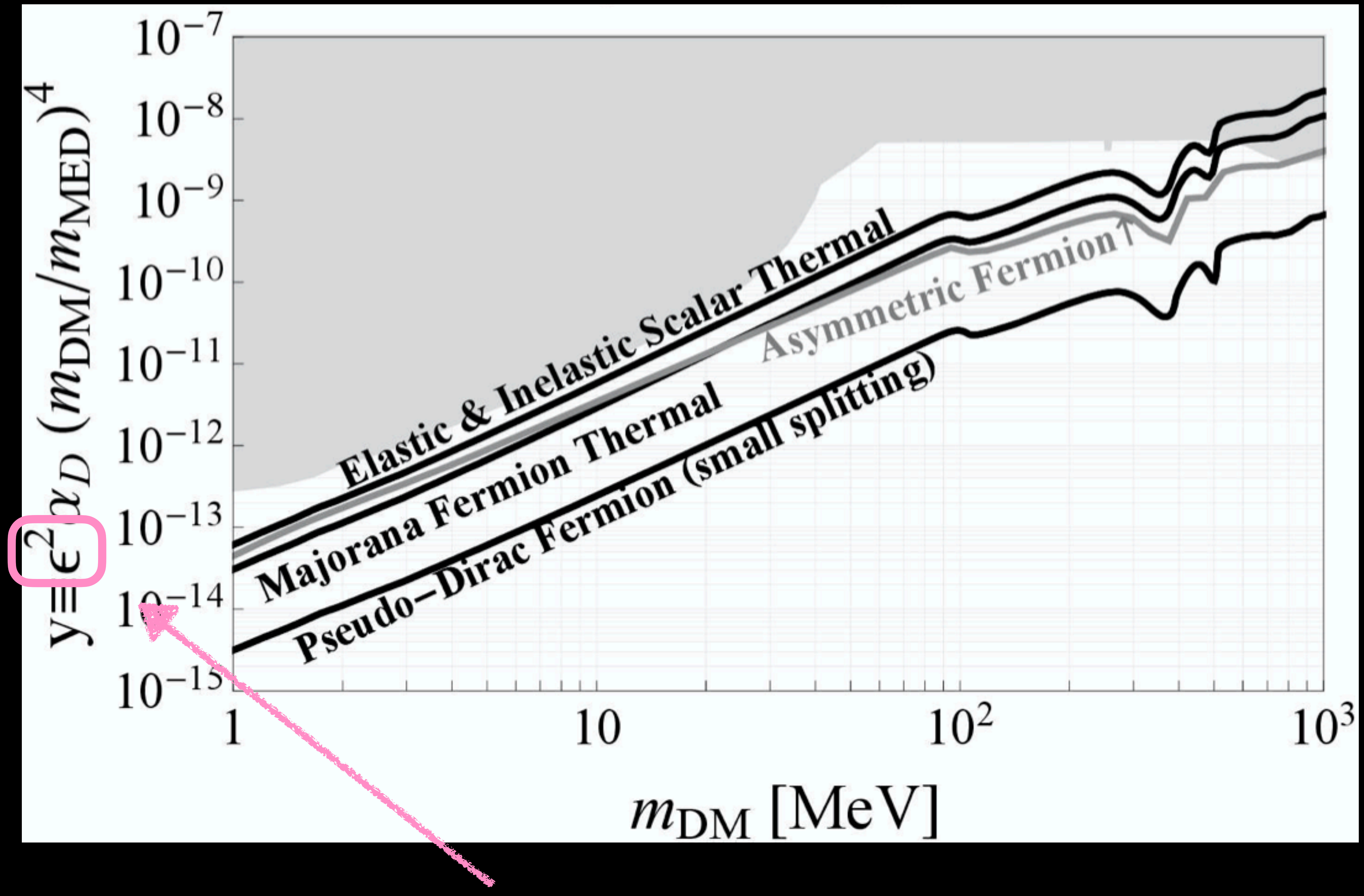


- sub-GeV thermal prediction targets line up within reach at accelerators

$$\sigma v(\chi\chi \to A' \to ff) \propto \varepsilon^2 \alpha_D \frac{m_\chi^2}{m_{A'}^4} = \frac{y}{m_\chi^2}$$

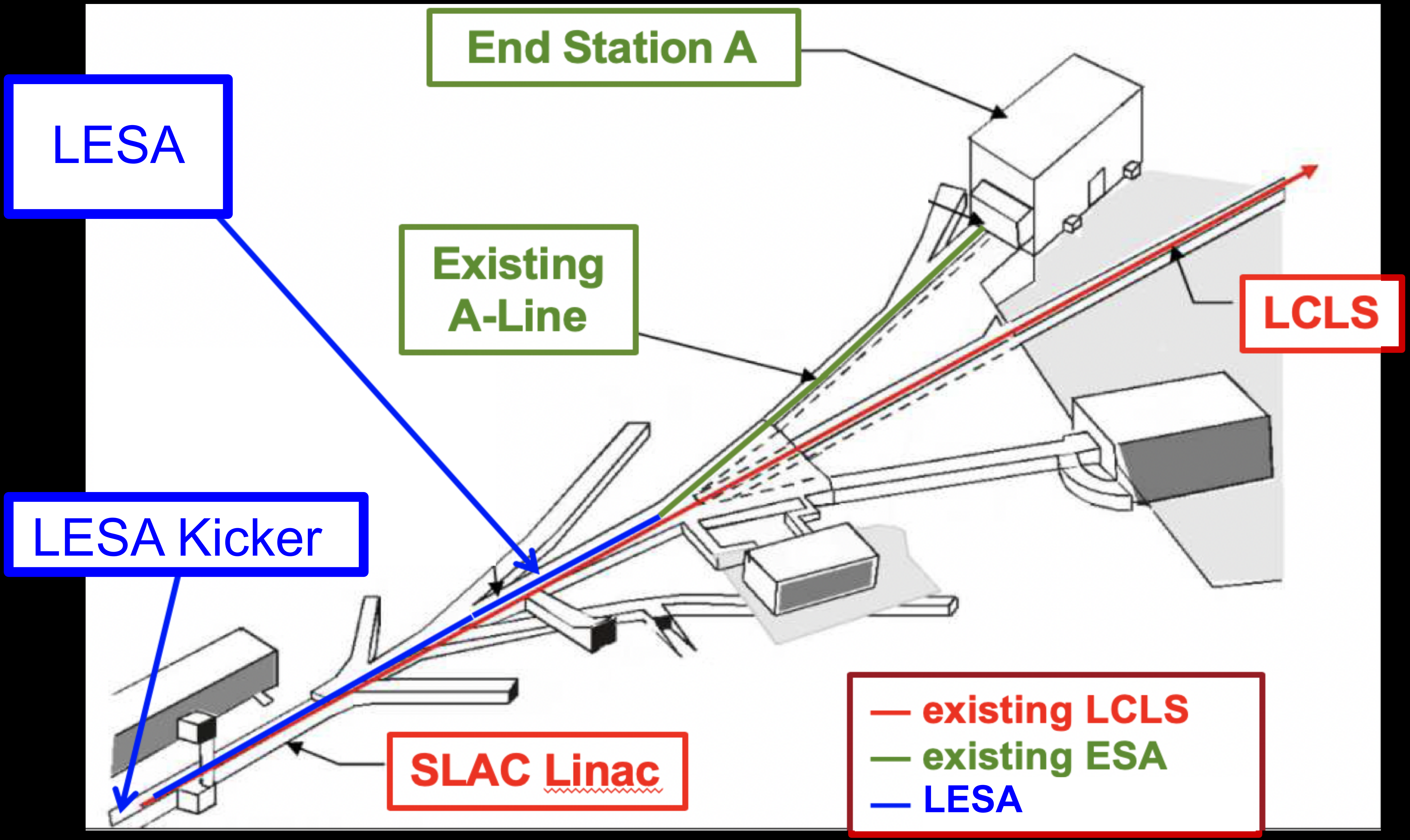
DM-electron scattering cross section





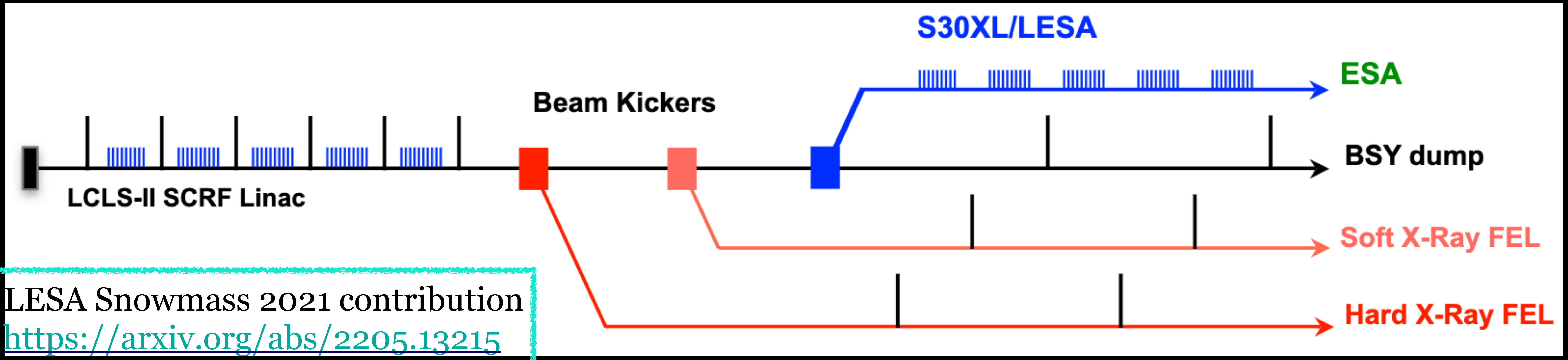
mixing parameter

GeV-scale electron beam at SLAC



LCLS-2 beam at SLAC:

- electron beam for photon science
  - divert unused low-multiplicity bunches via Linac to End Station A (LESA)
- upgrade: 4→8 GeV beam energy
- low current
  - measure each incoming and outgoing electron
- fast repetition rate
  - expect 37.1 MHz bunch frequency
  - and ~10^{14} electrons on target in 1-2 years



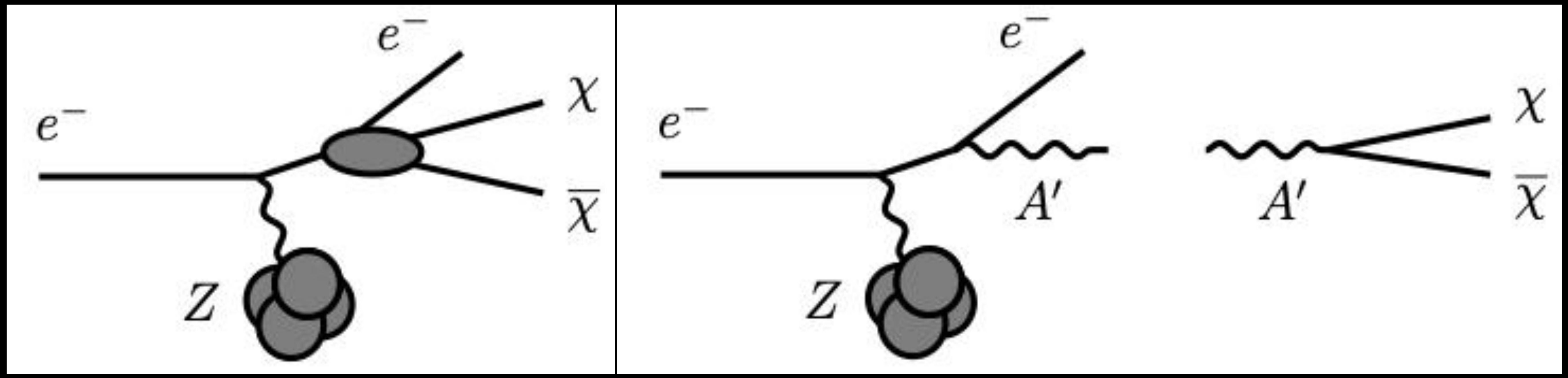
LESA Snowmass 2021 contribution
https://arxiv.org/abs/2205.13215

End Station A, upstream

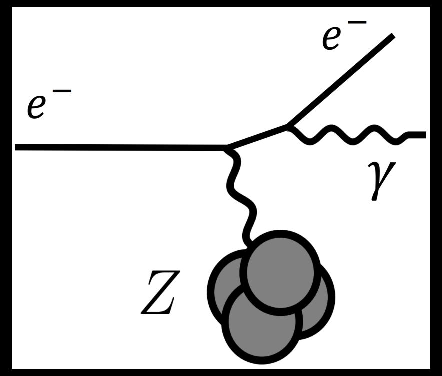
(TK Nelson)

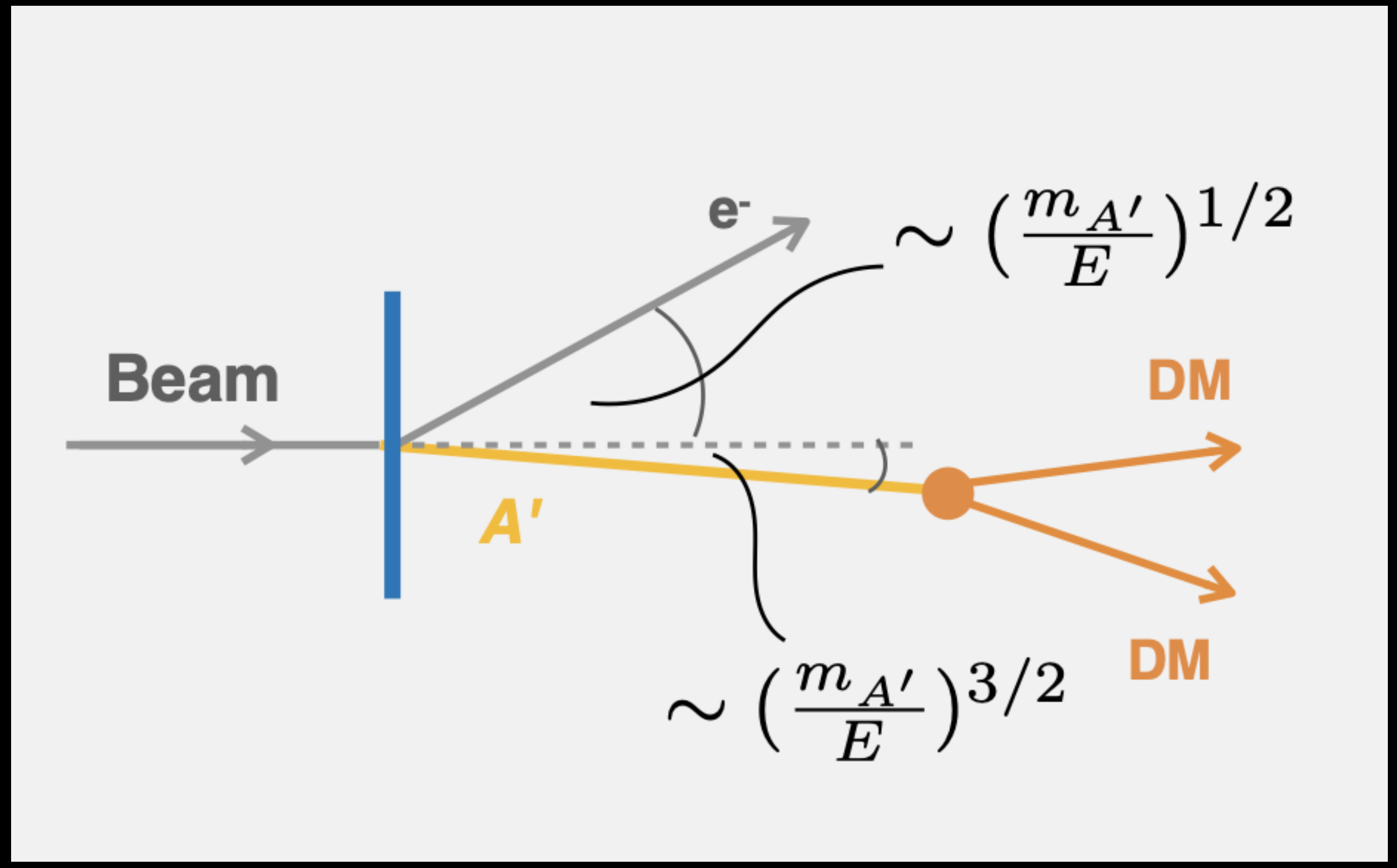
LDMX: a fixed-target missing momentum experiment

LDMX focuses on *escaping* dark matter:



c.f. SM process: photon bremsstrahlung





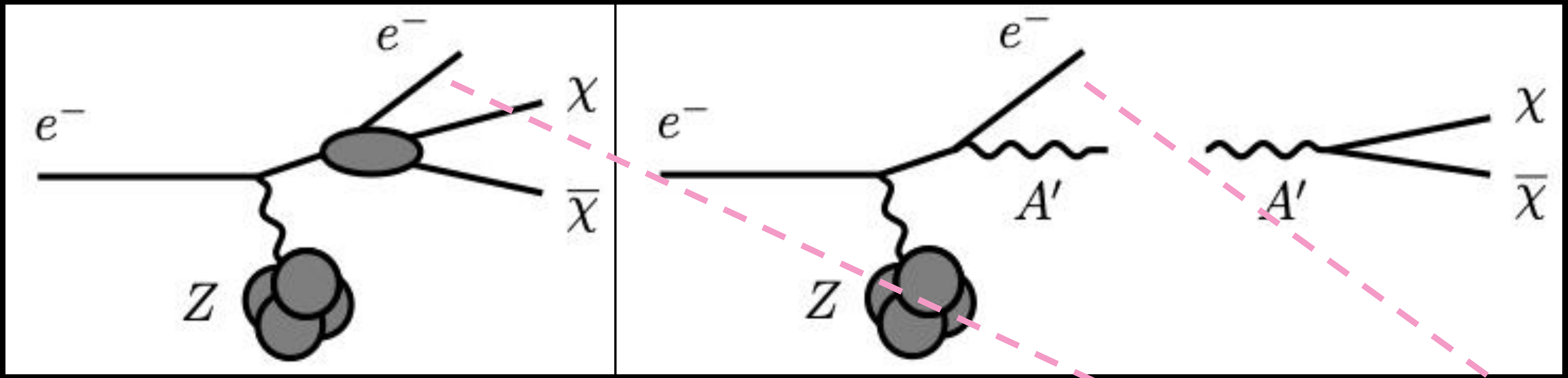
- massive dark photon (*A*') bremsstrahlung in thin target
- agnostic when it comes to (invisible) fate of the *A*'
  - notice that energy goes missing
- strategy: make "all" SM backgrounds appear in detector
  - veto everything but low-activity events

Massive photon → momentum kick; missing *momentum* experiment

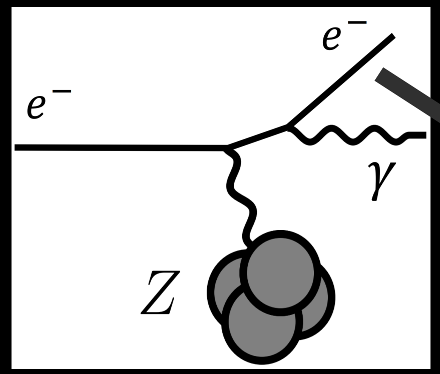
More detail: A high efficiency photon veto for the Light Dark Matter eXperiment, JHEP04 (2020) 003

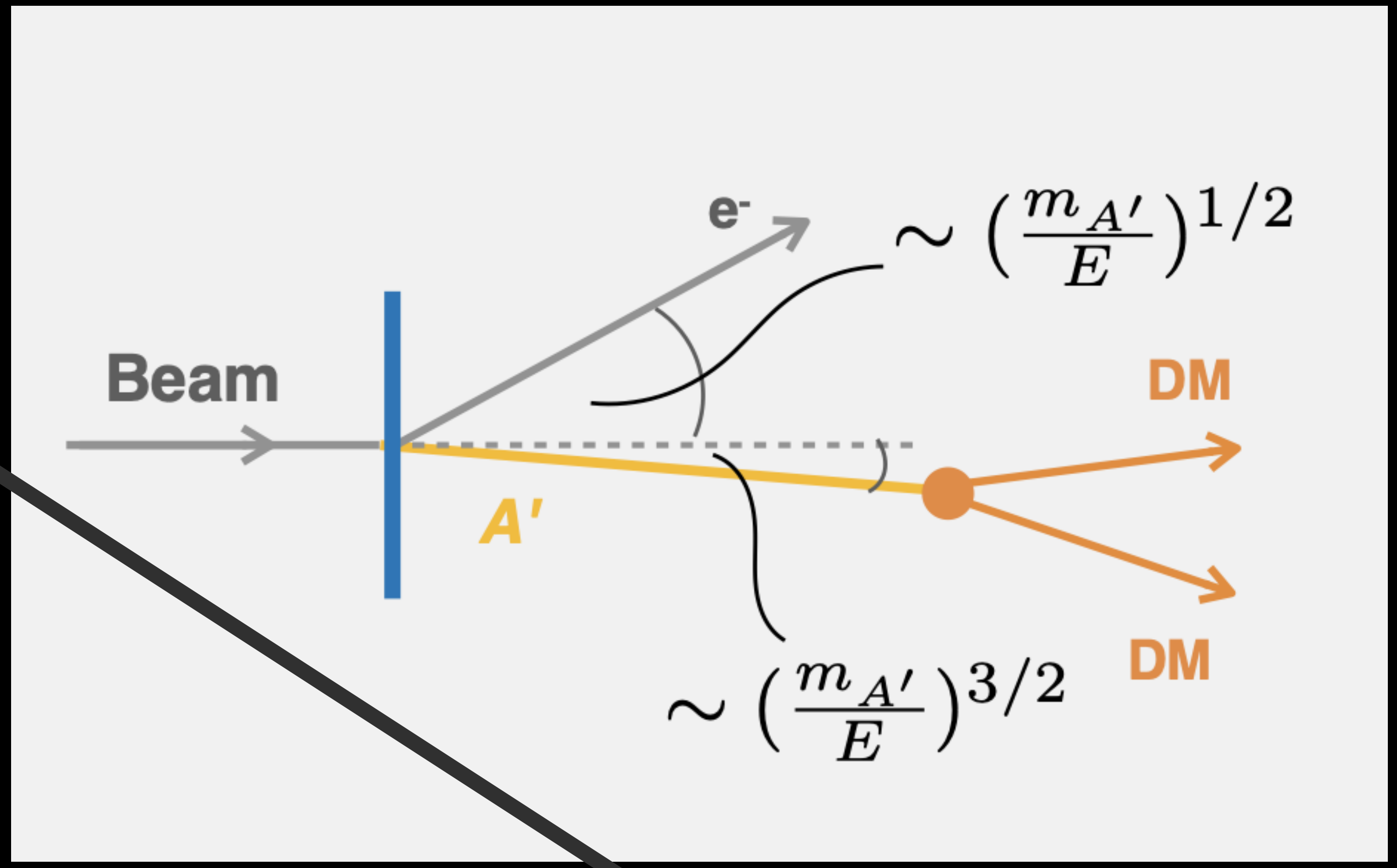
LDMX: a fixed-target missing momentum experiment

LDMX focuses on *escaping* dark matter:

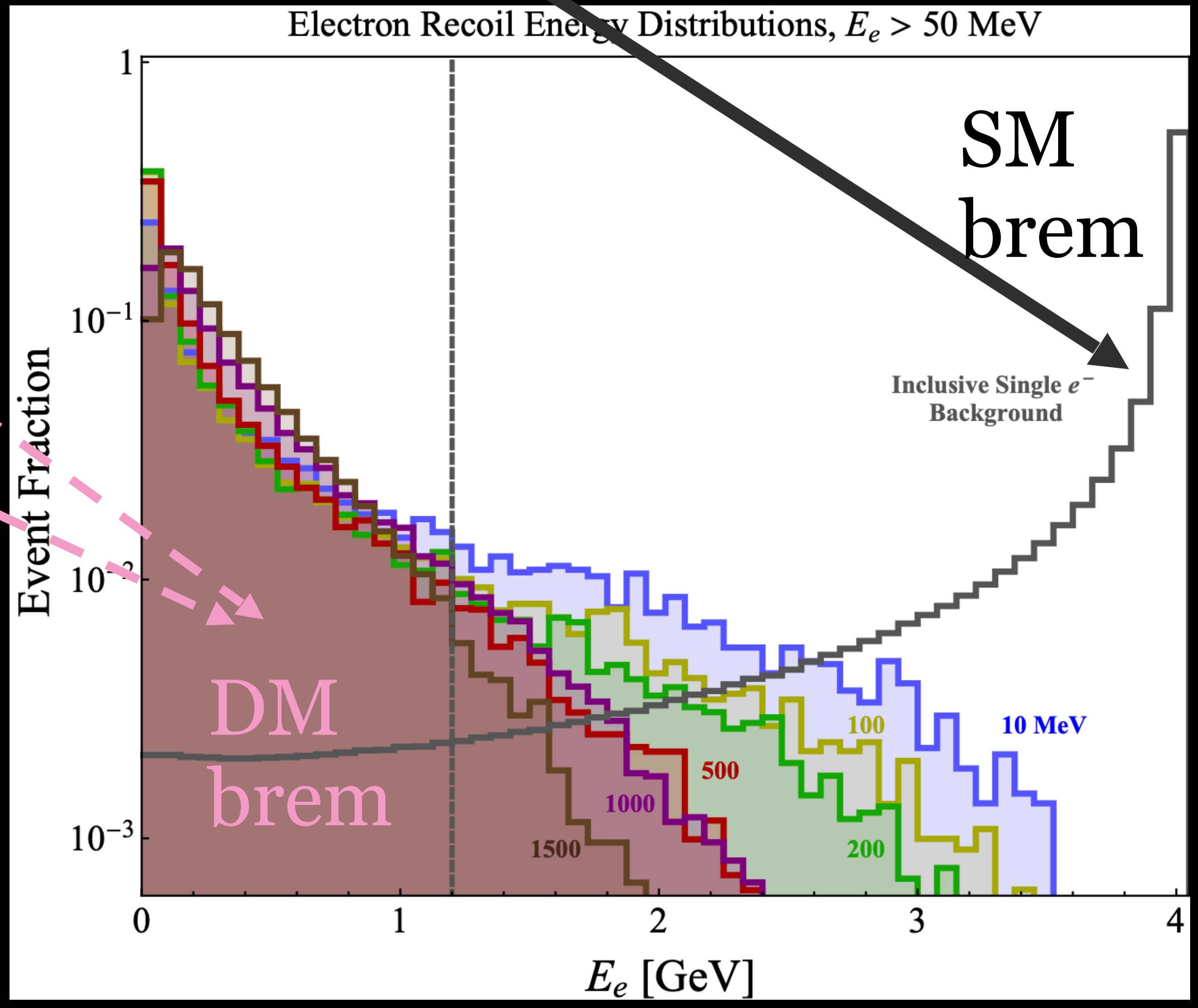


c.f. SM process: photon bremsstrahlung





- massive dark photon (*A*') bremsstrahlung in thin target
- agnostic when it comes to (invisible) fate of the *A*'
  - notice that energy goes missing
- strategy: make "all" SM backgrounds appear in detector
  - veto everything but low-activity events

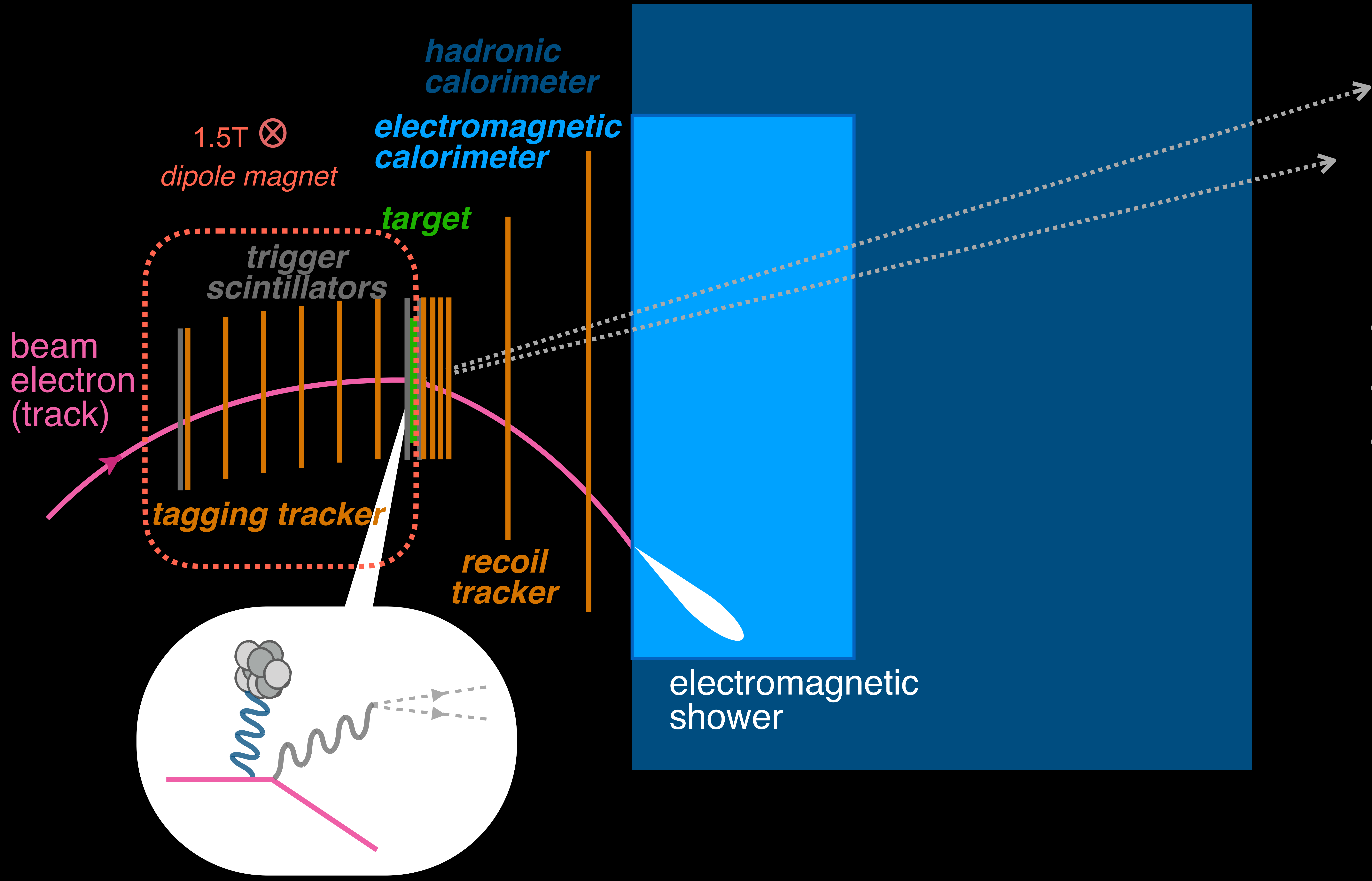


Massive photon → momentum kick; missing *momentum* experiment

More detail: A high efficiency photon veto for the Light Dark Matter eXperiment, JHEP04 (2020) 003

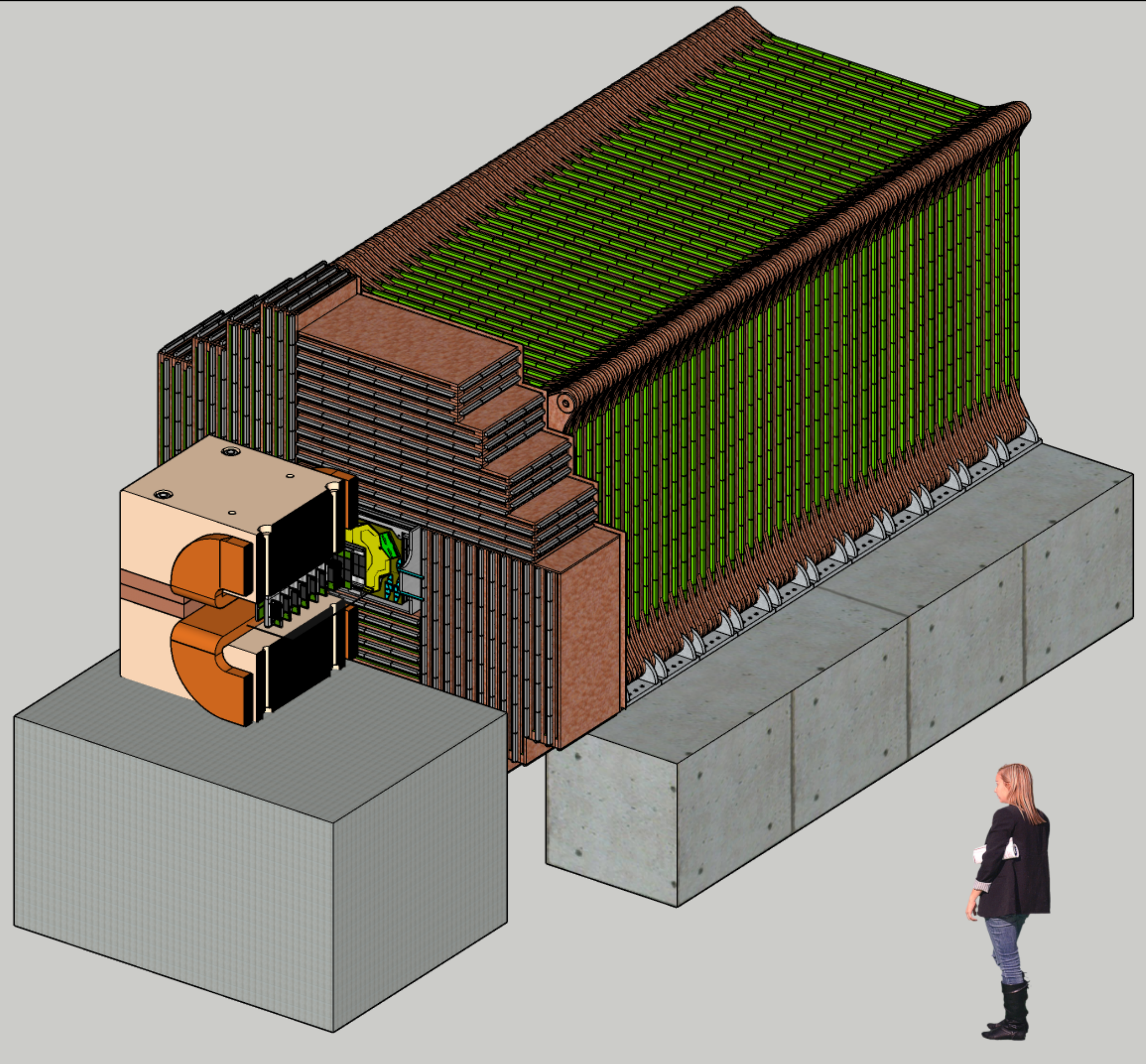
LDMX detector concept

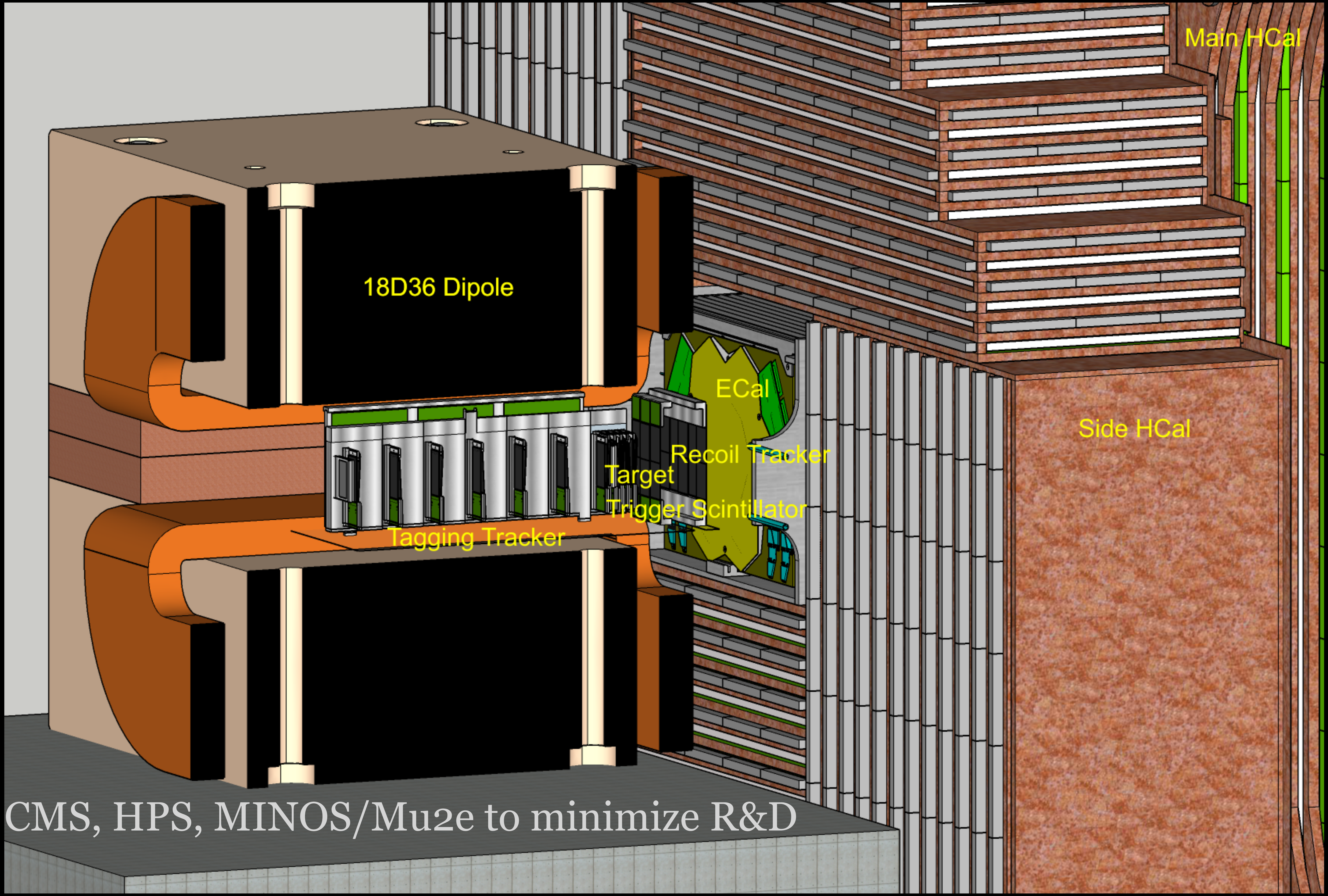
Signal cartoon



- $0.1\ X_0$ W target
- $40\ X_0$ ECal, $17\ \lambda_i$ HCal
- Measure (missing) energy in calorimeters, momentum in trackers

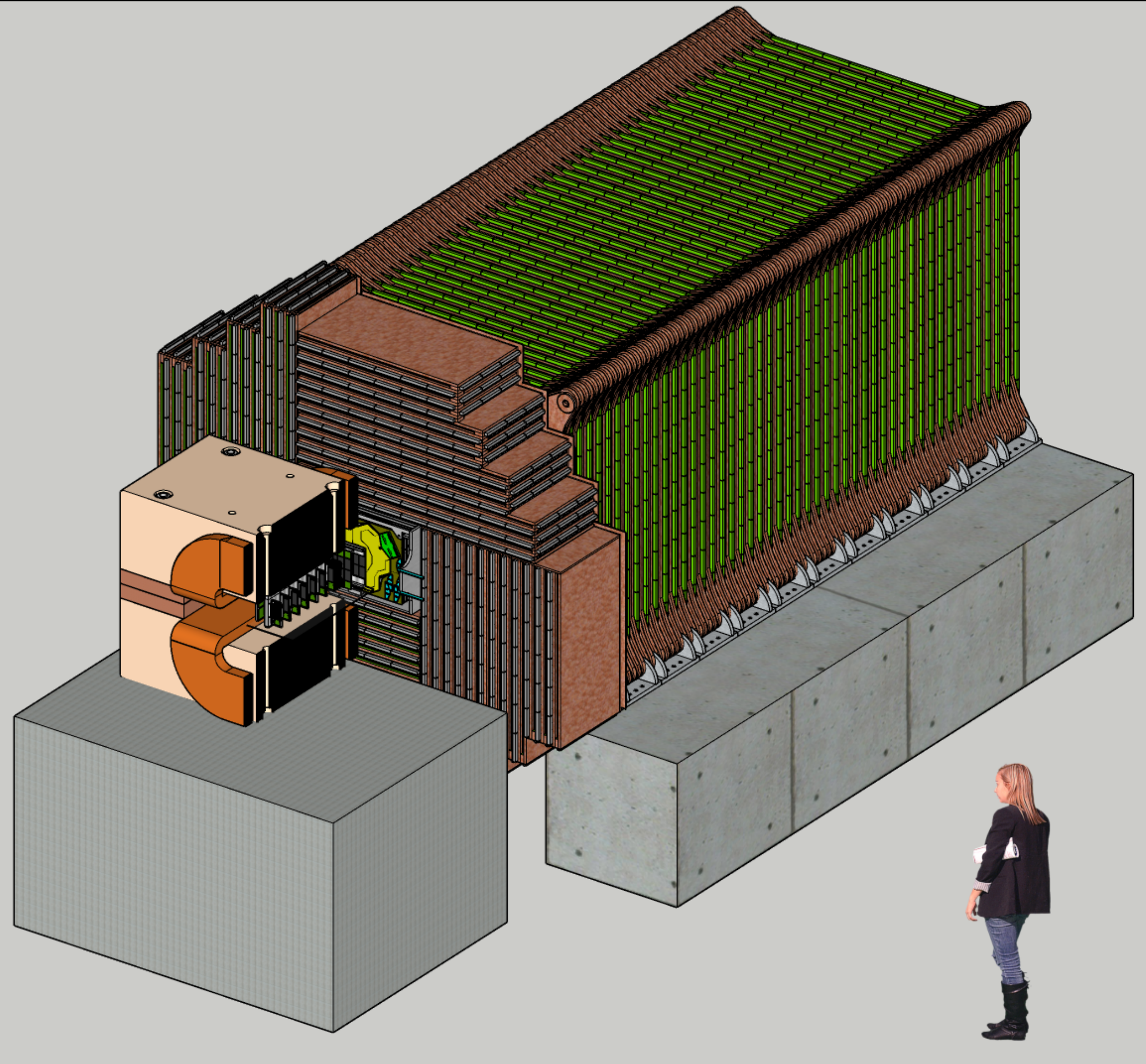
or, in more detail

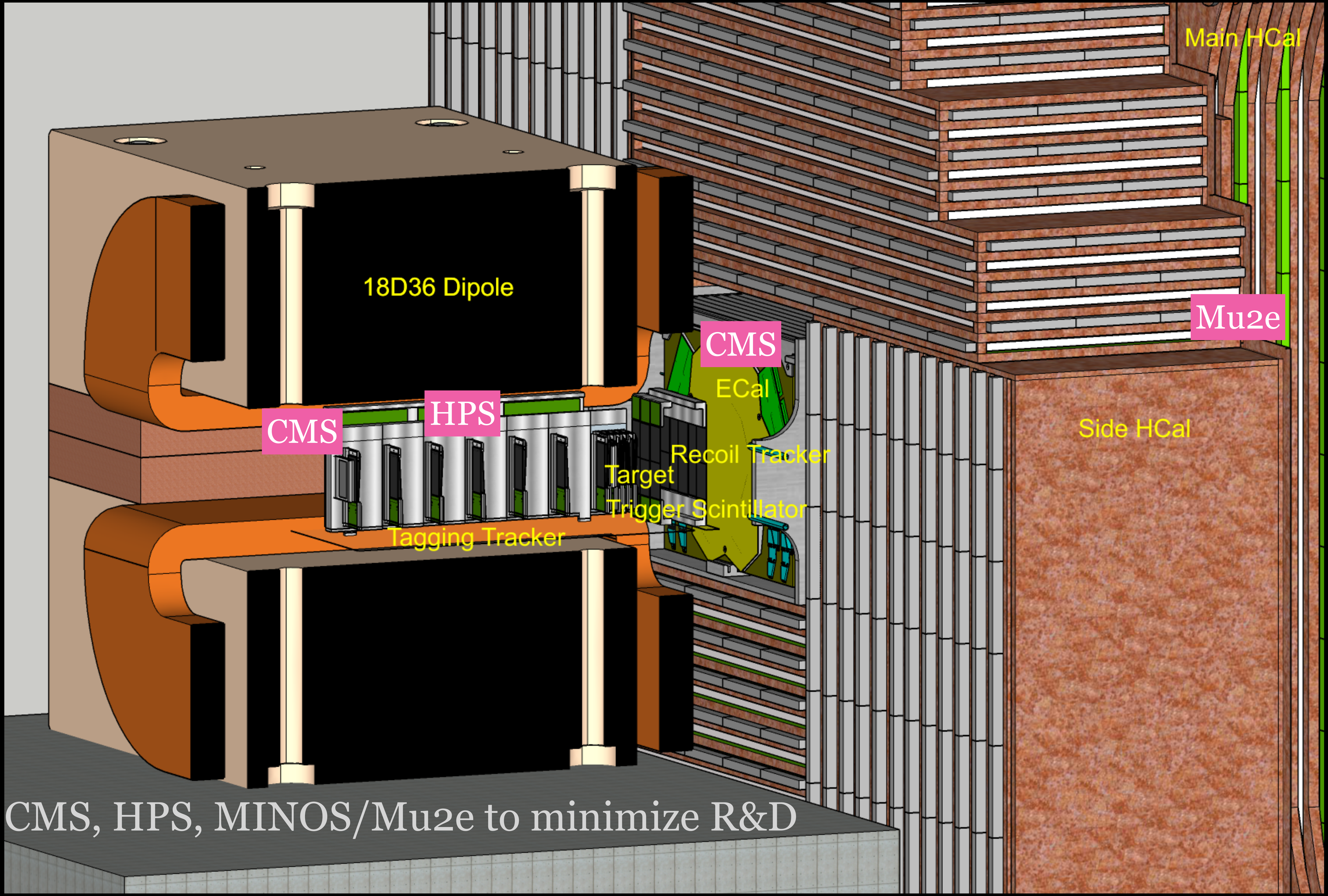




Leverage technologies from CMS, HPS, MINOS/Mu2e to minimize R&D

or, in more detail





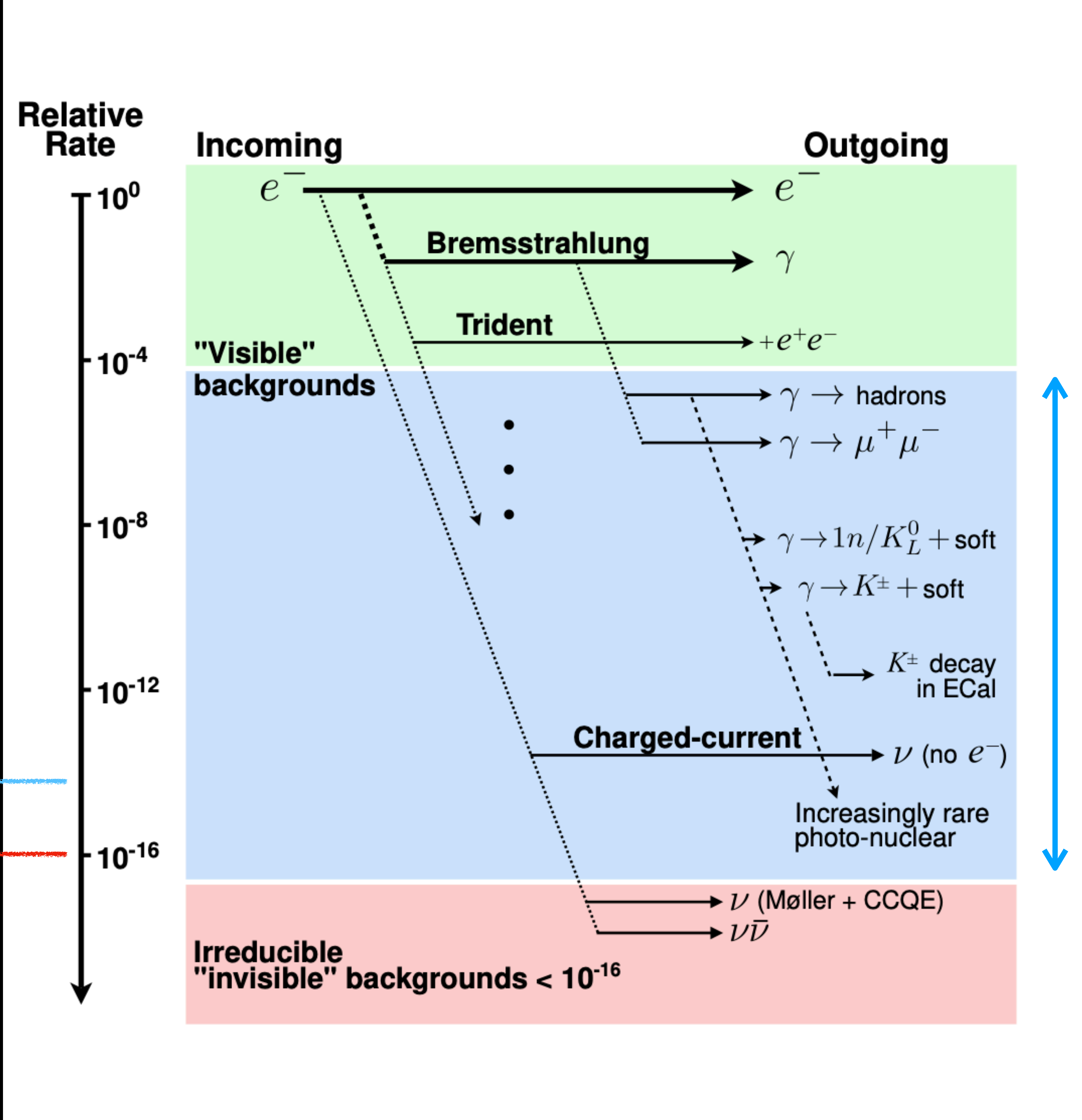
Leverage technologies from CMS, HPS, MINOS/Mu2e to minimize R&D

Backgrounds

shaping the requirements on the detector

expected reach Phase 1

expected ultimate dataset

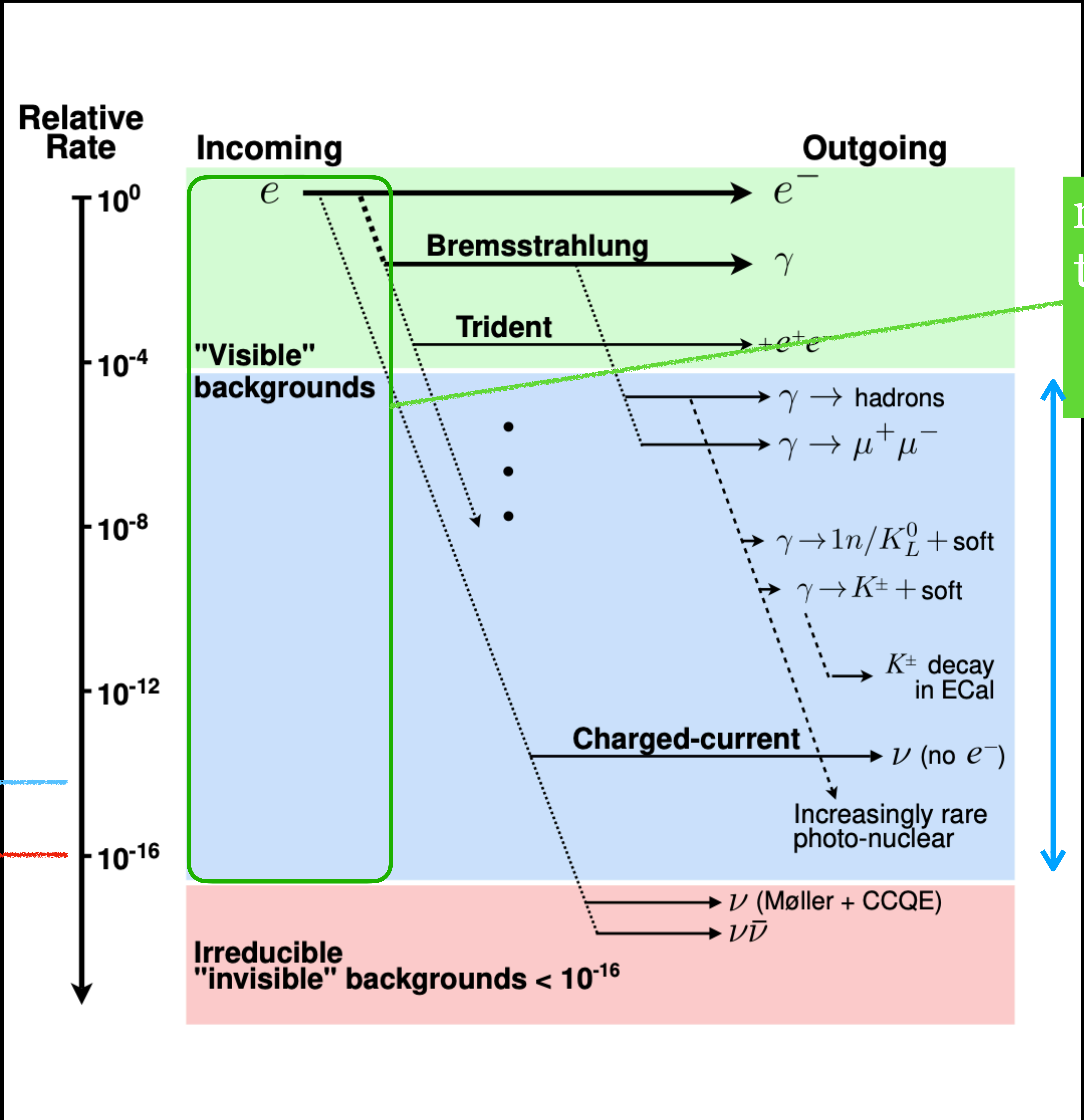


fate of bremsstrahlung photon

invisible backgrounds not within reach

Backgrounds

shaping the requirements on the detector



expected reach Phase 1

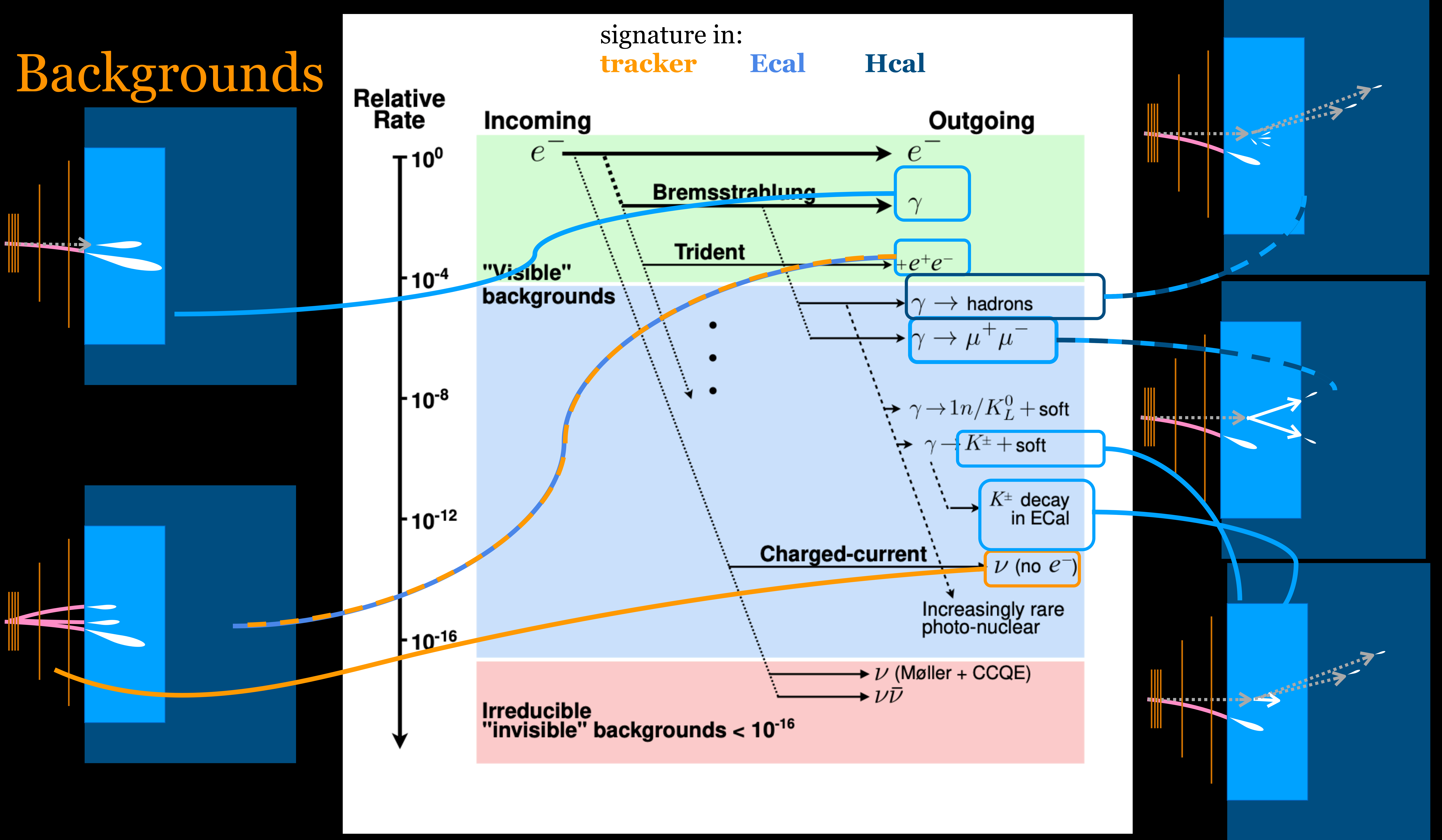
expected ultimate dataset

make visible with tracker and high-granularity calorimetry

fate of bremsstrahlung photon

invisible backgrounds not within reach

Backgrounds

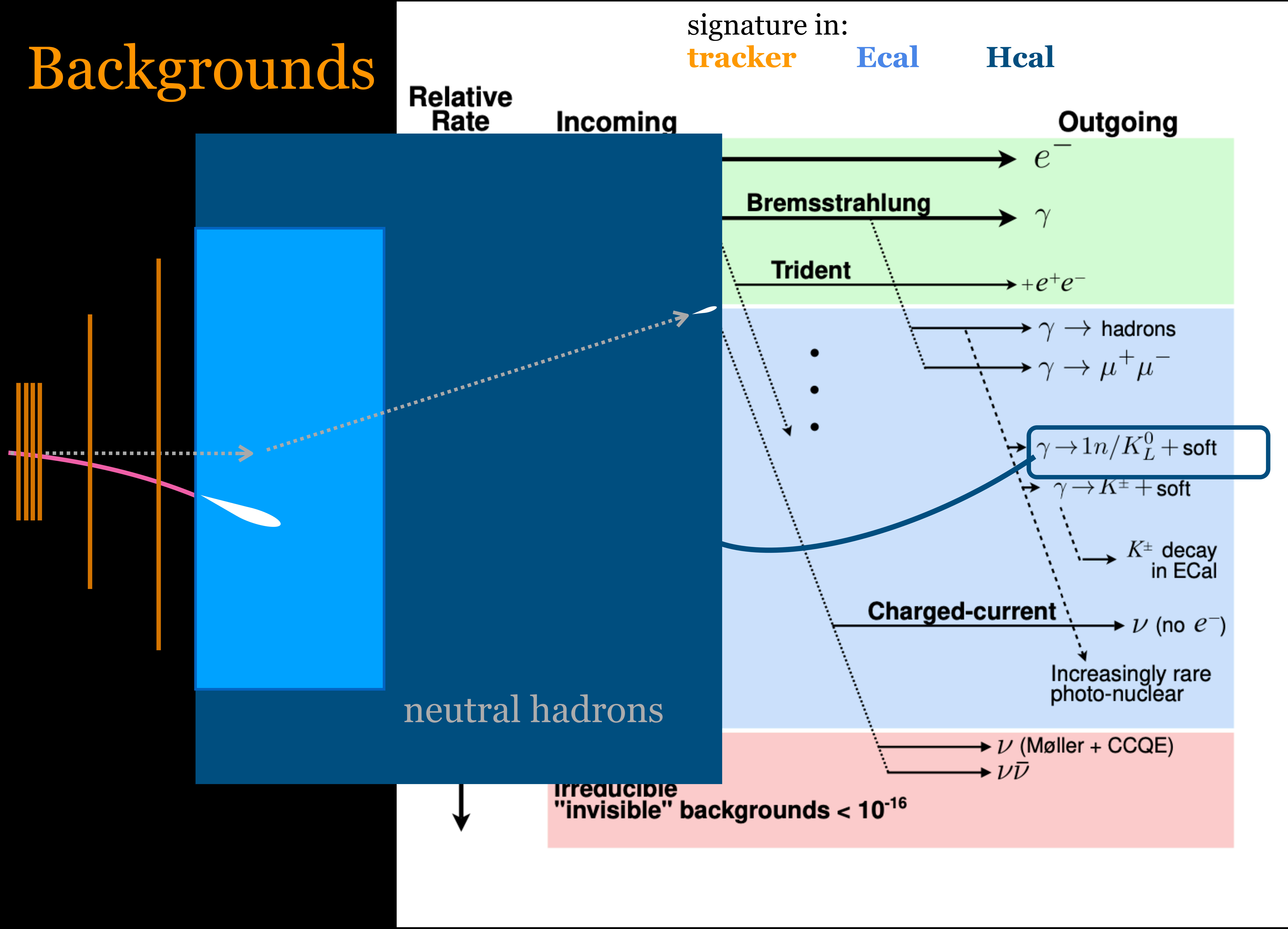


TAUP 2023

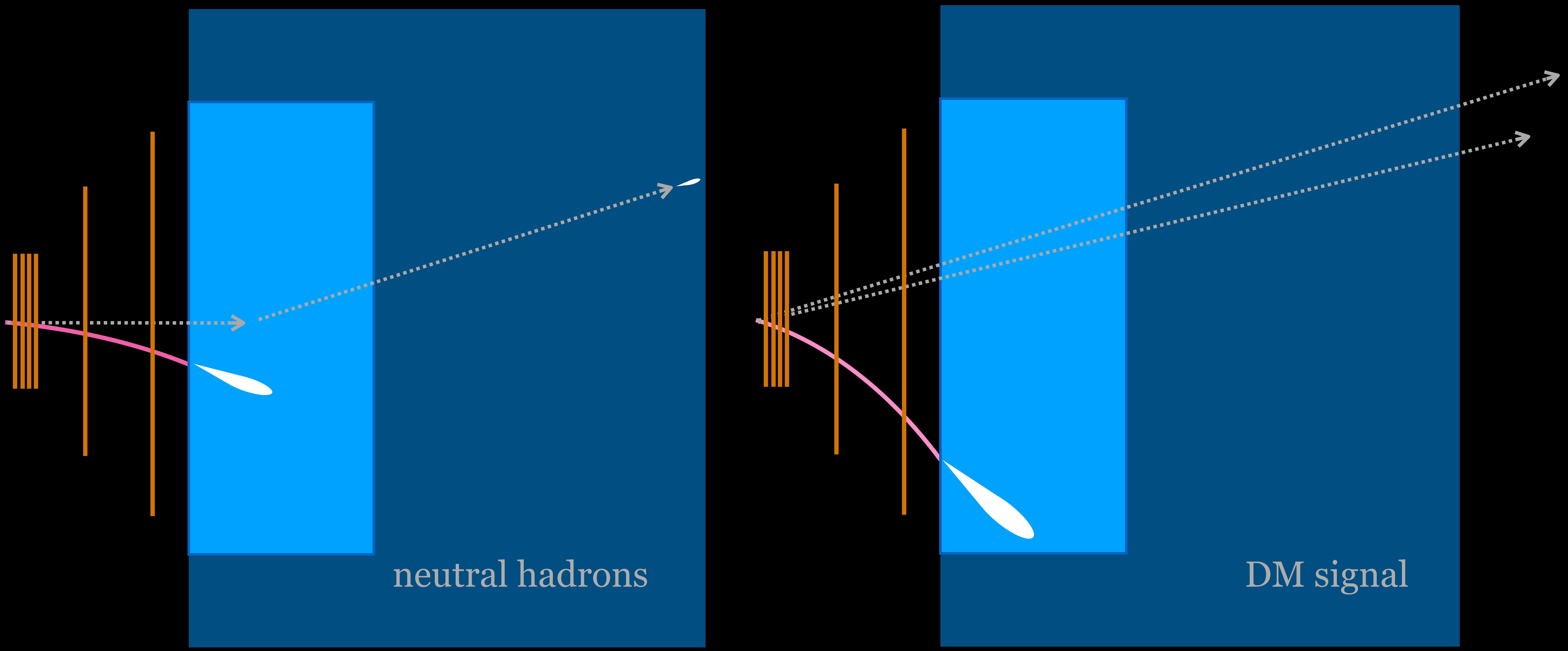
LK Bryngemark

LDMX

Backgrounds

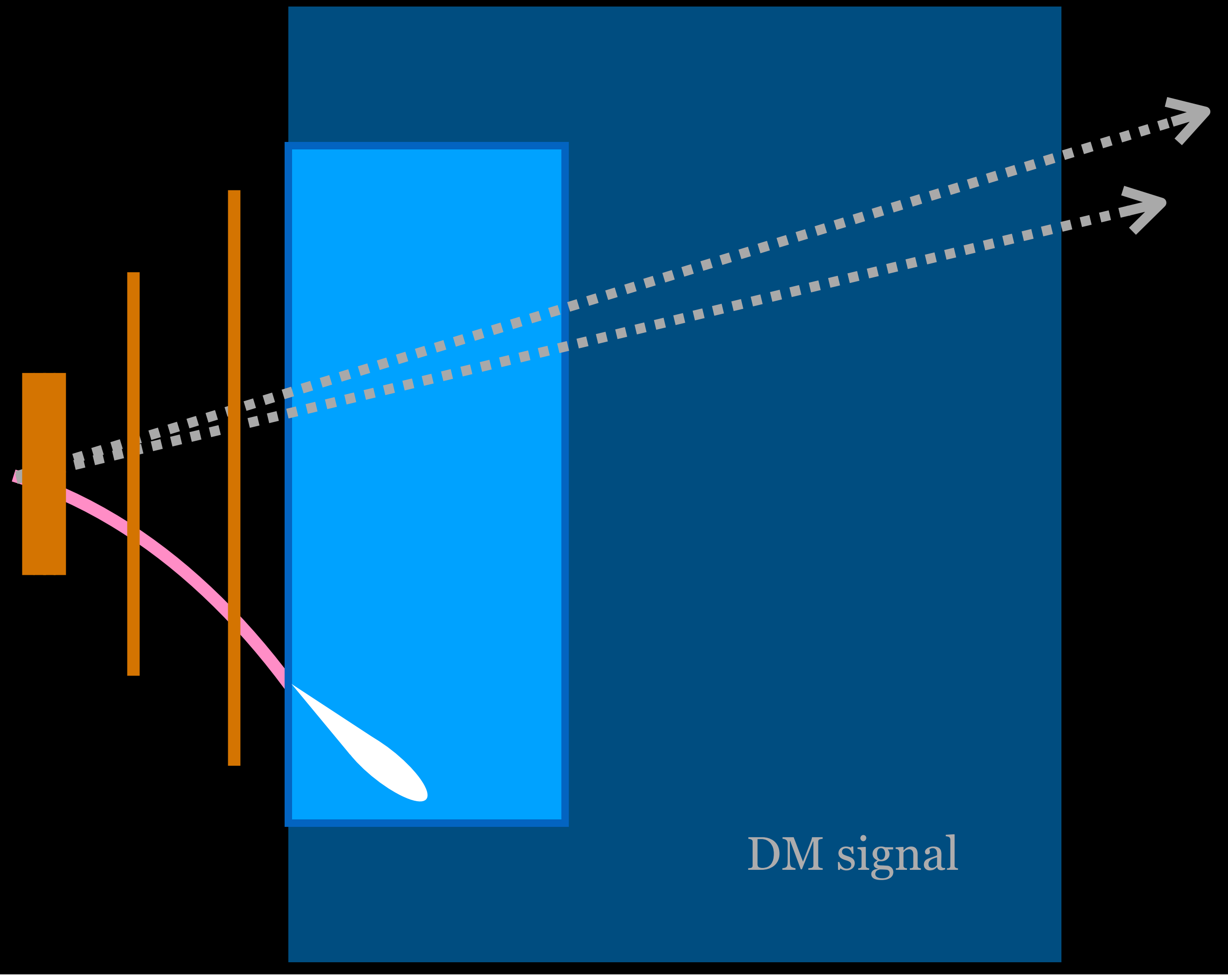


Backgrounds



Event selection/vetoes for invisible DM

Goal: no background from ~10^{14} electrons on target

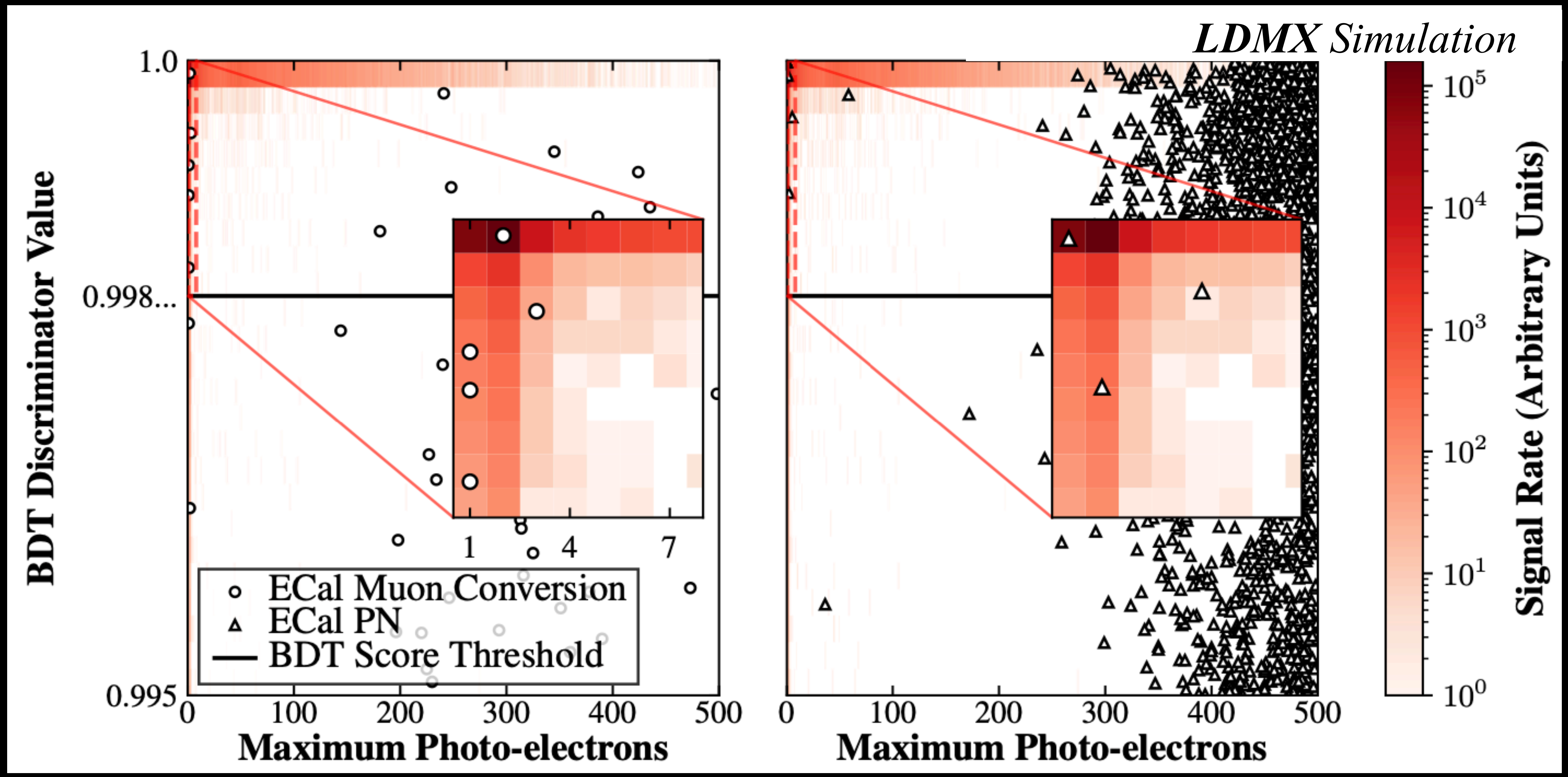


First handle: recoiling electron

- Count incoming electrons, measure in Ecal, calculate missing energy
  - trigger if consistent with one electron losing significant energy
- veto if number of outgoing tracks > incoming tracks
- veto if no soft recoil electron track

Exploit high-granularity Ecal features

- BDT trained to reject photonuclear events in Ecal
- MIP tracking powerful on sparse events

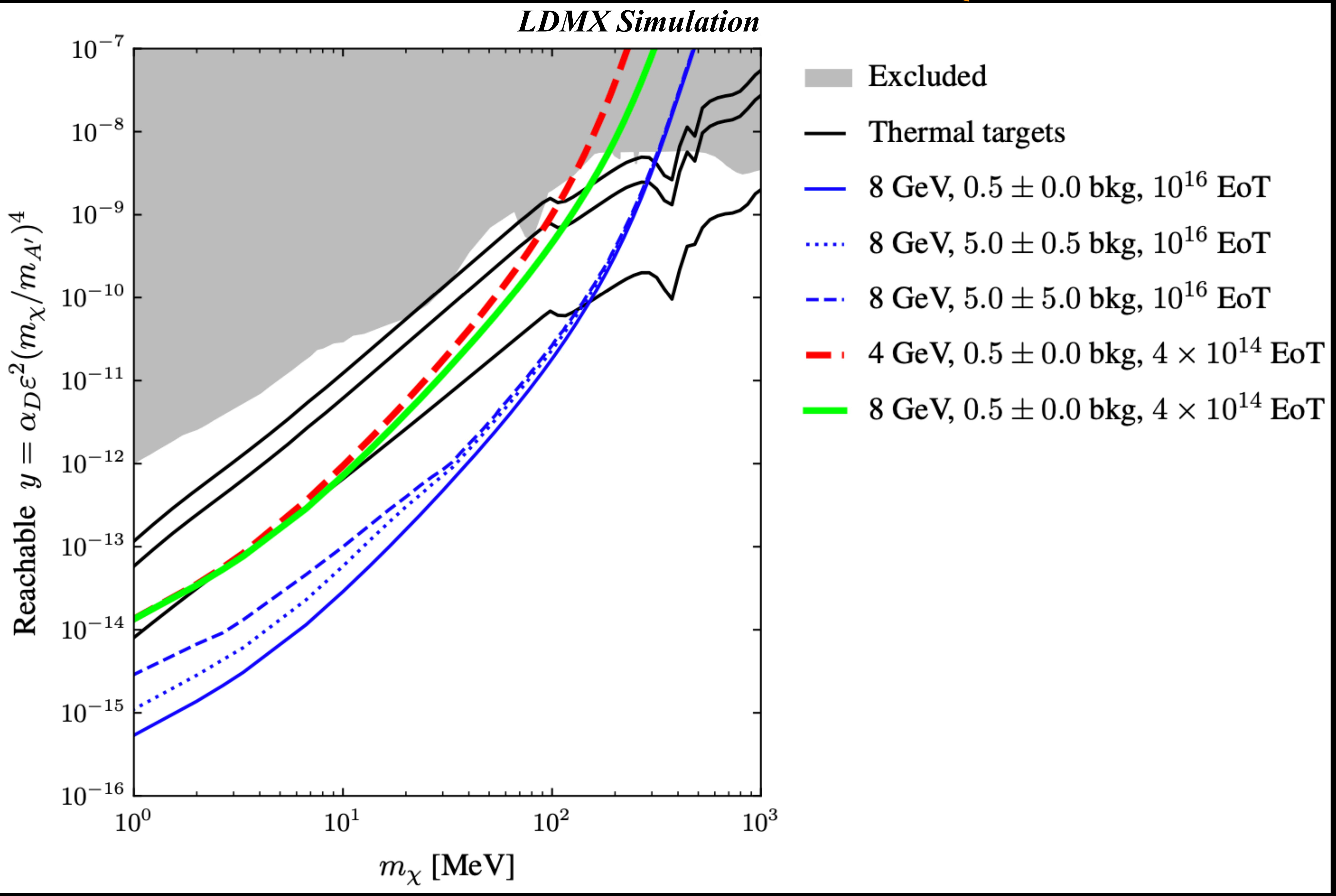


Veto on Hcal activity

- allow no activity above detector noise
- deep enough to tease out even single neutrons

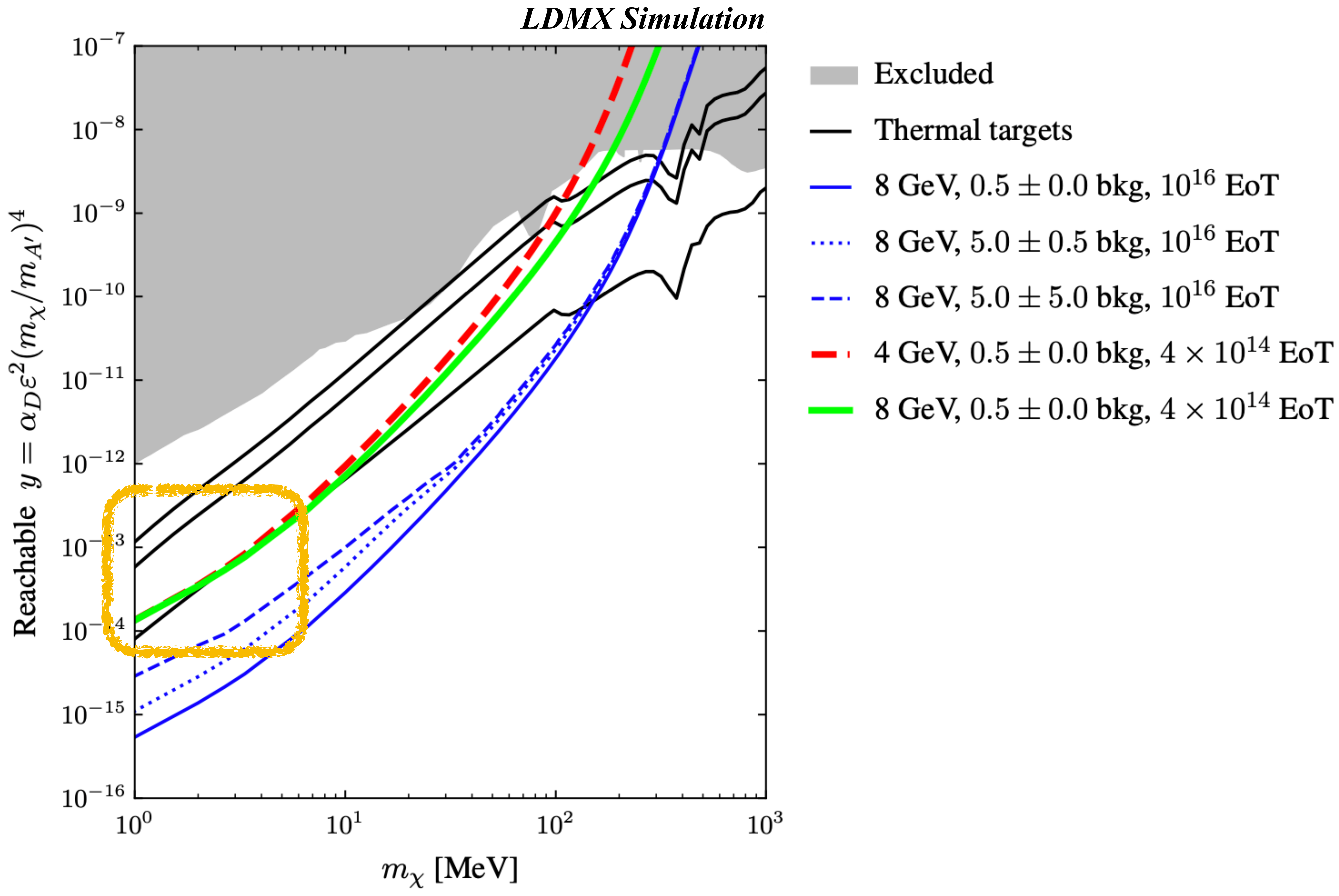
extensively studied for 4 GeV beam in A high efficiency photon veto for the Light Dark Matter eXperiment, JHEP04 (2020) 003

New result! Impact on sensitivity going from 4 to 8 GeV beam (and final dataset size)



SLAC-PUB-17550
FERMILAB-PUB-23-433-PPD-T
https://arxiv.org/abs/2308.15173

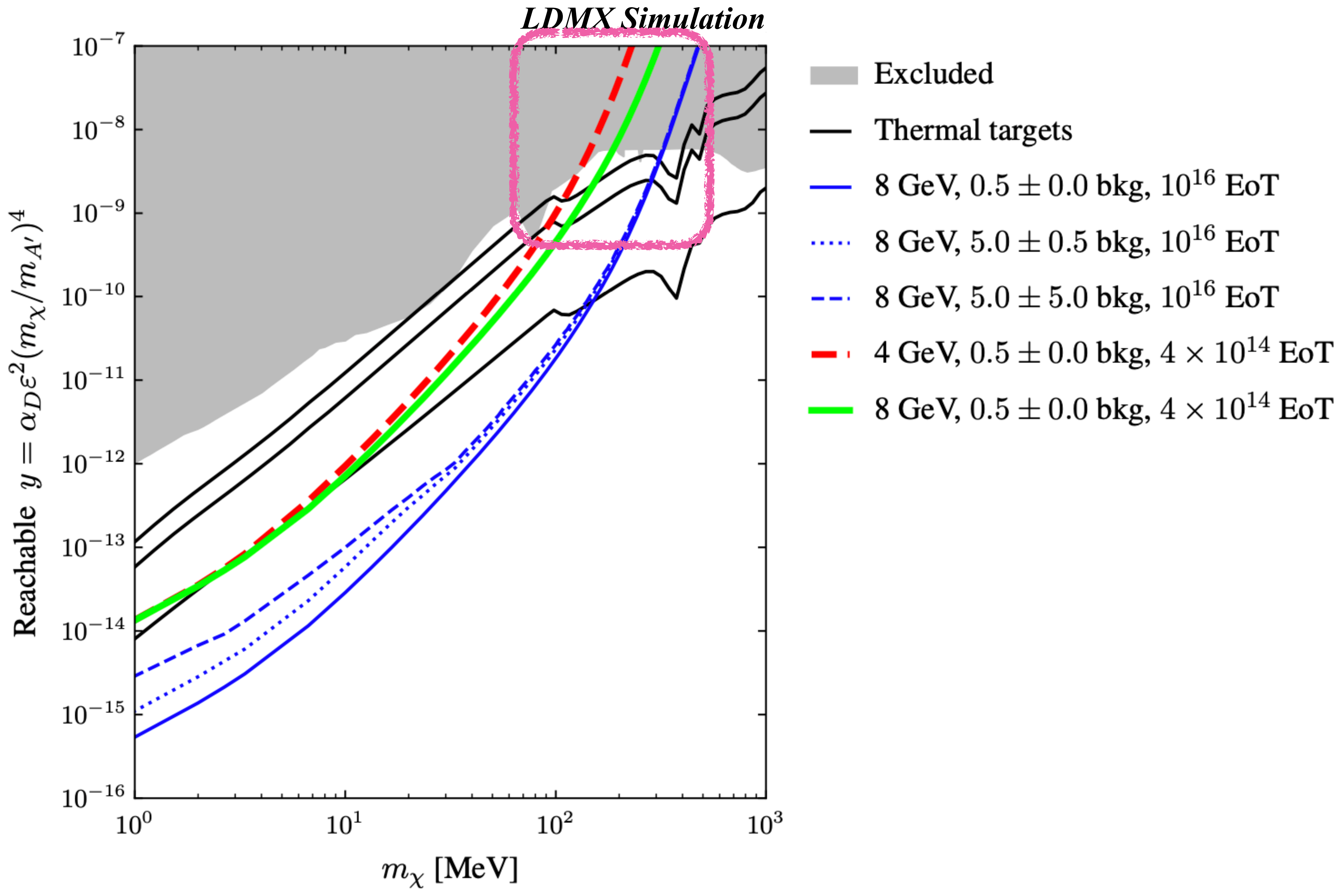
New result! Impact on sensitivity going from 4 to 8 GeV beam (and final dataset size)



- Same sensitivity as 4 GeV at low masses

SLAC-PUB-17550
FERMILAB-PUB-23-433-PPD-T
https://arxiv.org/abs/2308.15173

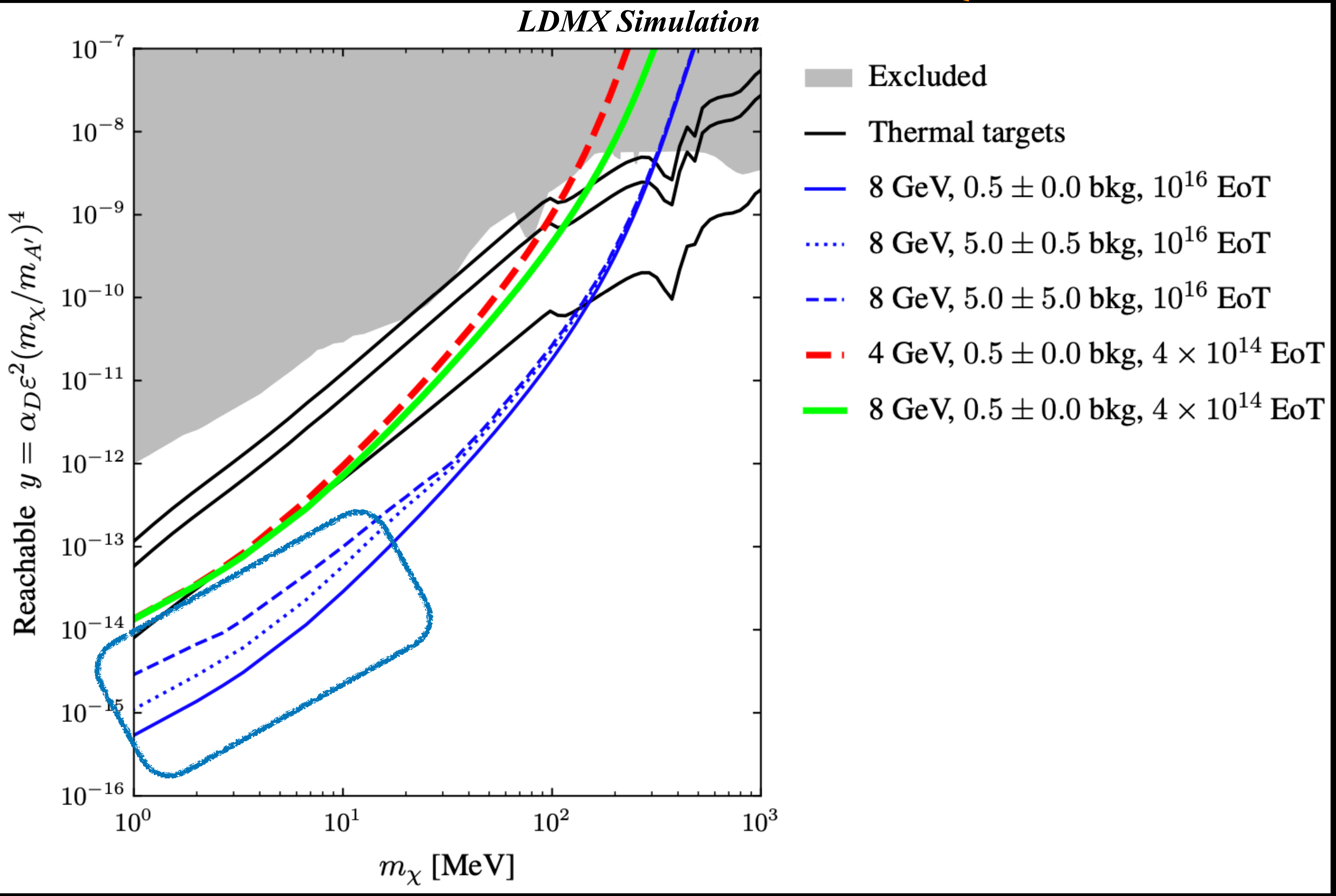
New result! Impact on sensitivity going from 4 to 8 GeV beam (and final dataset size)



- Same sensitivity as 4 GeV at low masses
- Increased reach at higher masses

SLAC-PUB-17550
FERMILAB-PUB-23-433-PPD-T
https://arxiv.org/abs/2308.15173

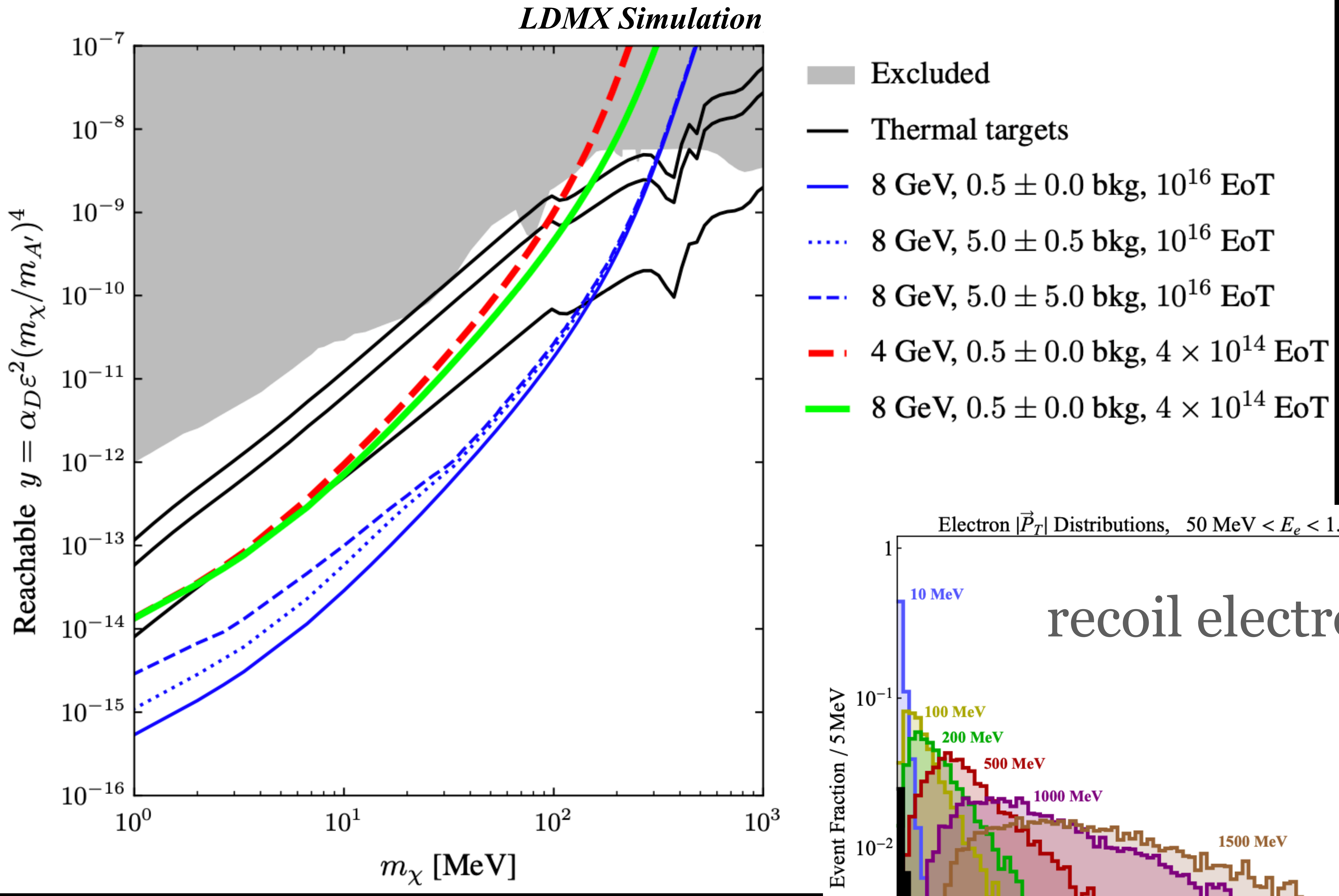
New result! Impact on sensitivity going from 4 to 8 GeV beam (and final dataset size)



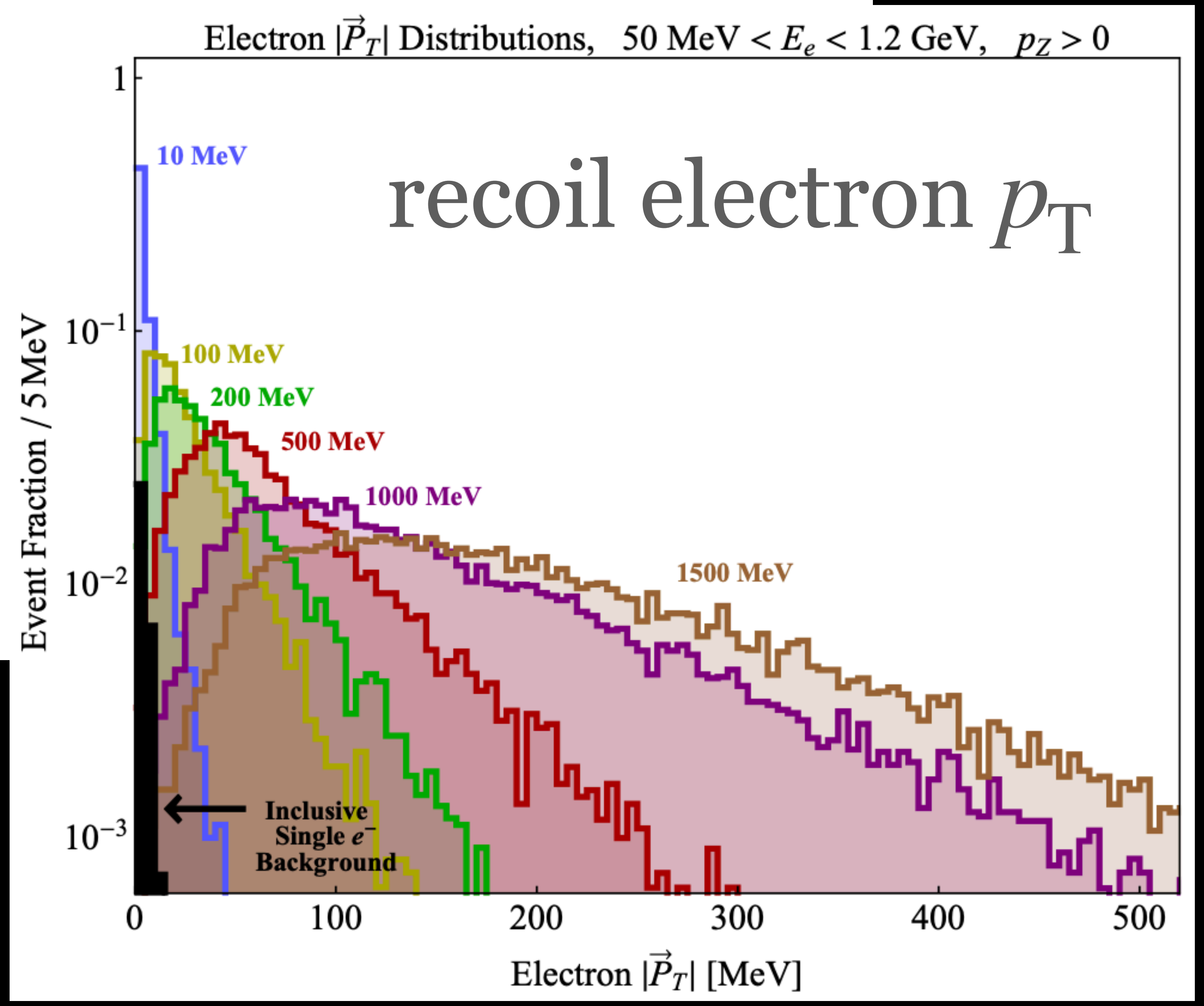
- Same sensitivity as 4 GeV at low masses
- Increased reach at higher masses
- Background uncertainty reduced at higher mass using p_T information — great advantage of missing momentum experiment!

SLAC-PUB-17550
FERMILAB-PUB-23-433-PPD-T
https://arxiv.org/abs/2308.15173

New result! Impact on sensitivity going from 4 to 8 GeV beam (and final dataset size)



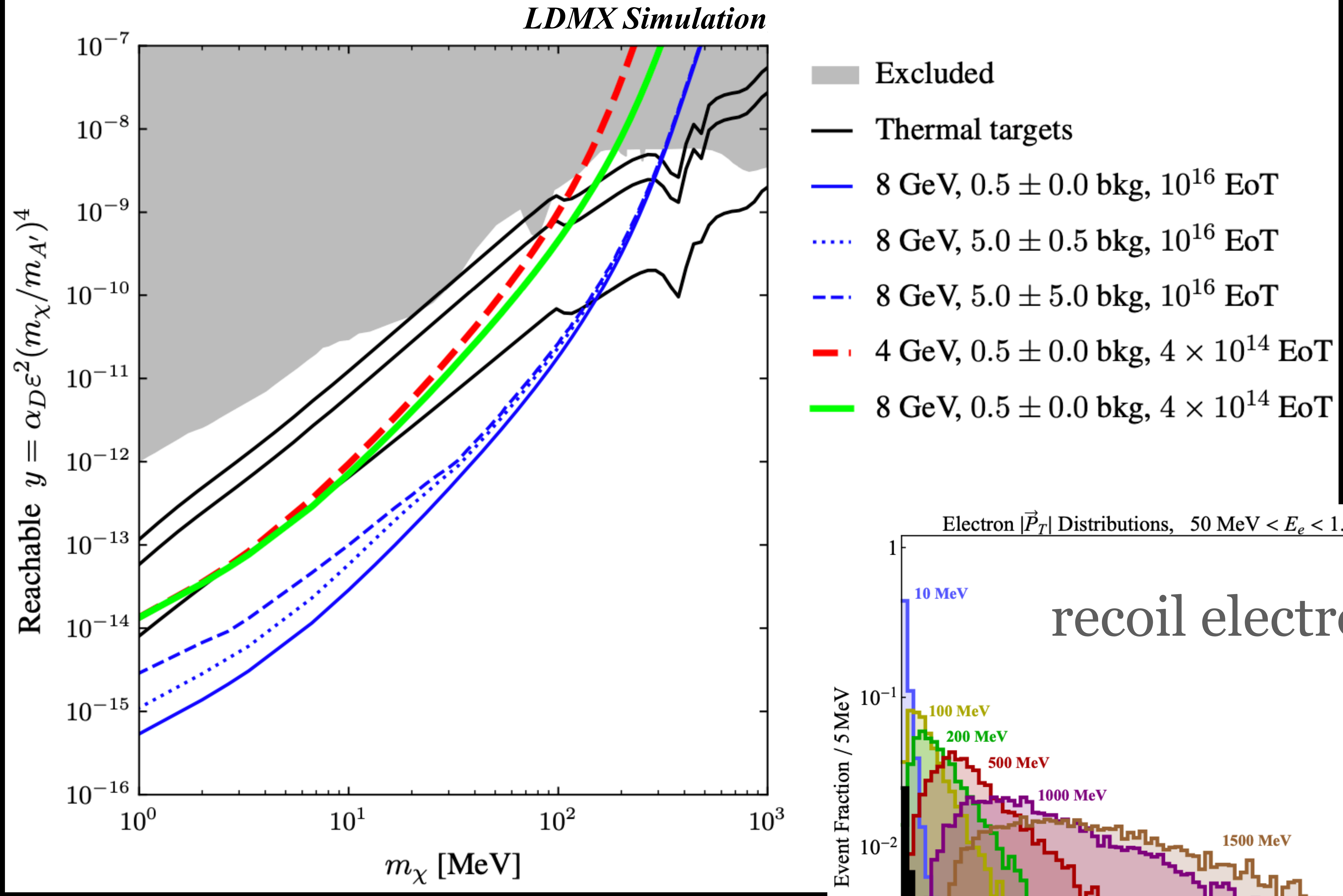
- Same sensitivity as 4 GeV at low masses
- Increased reach at higher masses
- Background uncertainty reduced at higher mass using p_T information — great advantage of missing momentum experiment!



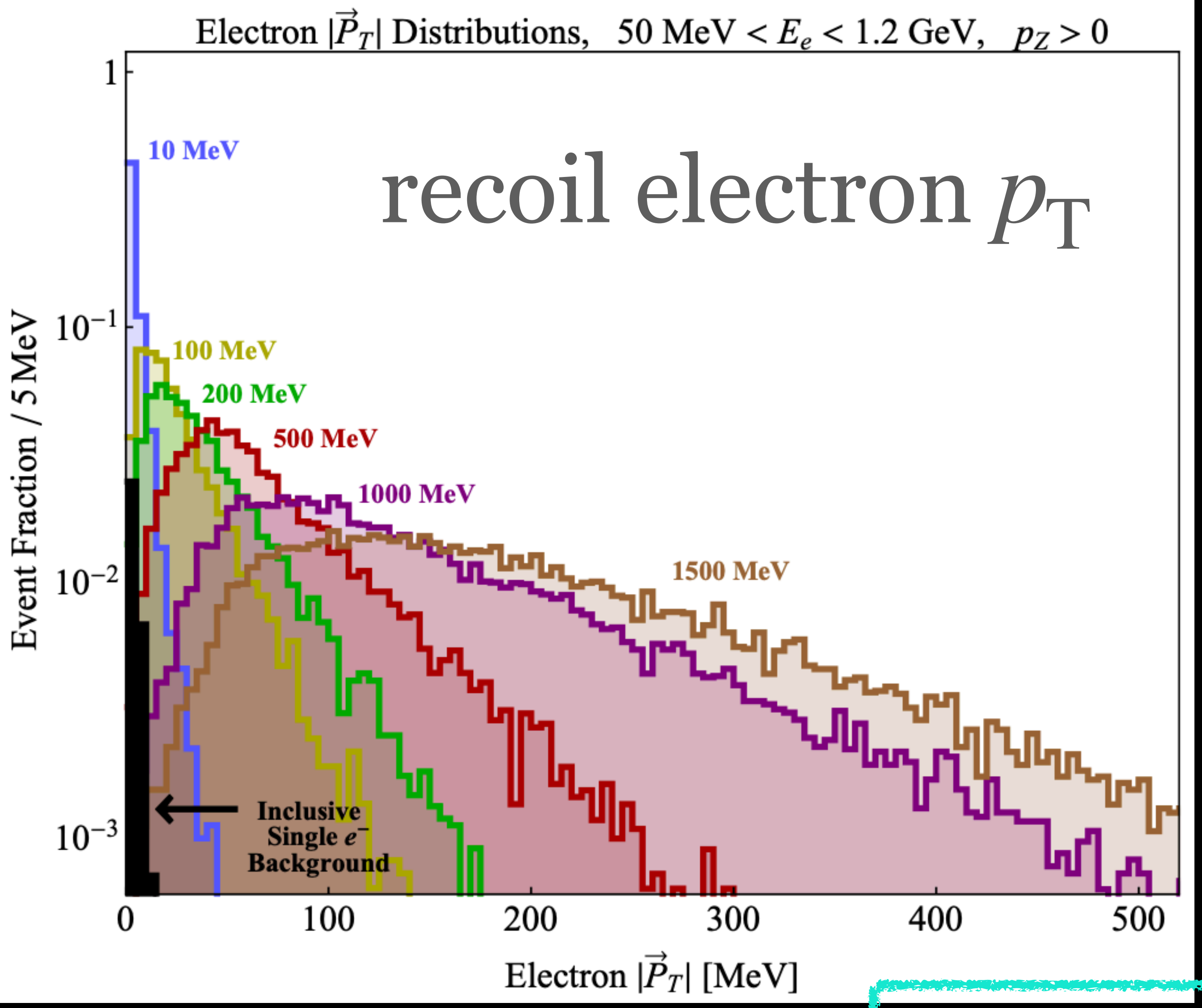
SLAC-PUB-17550
FERMILAB-PUB-23-433-PPD-T
https://arxiv.org/abs/2308.15173

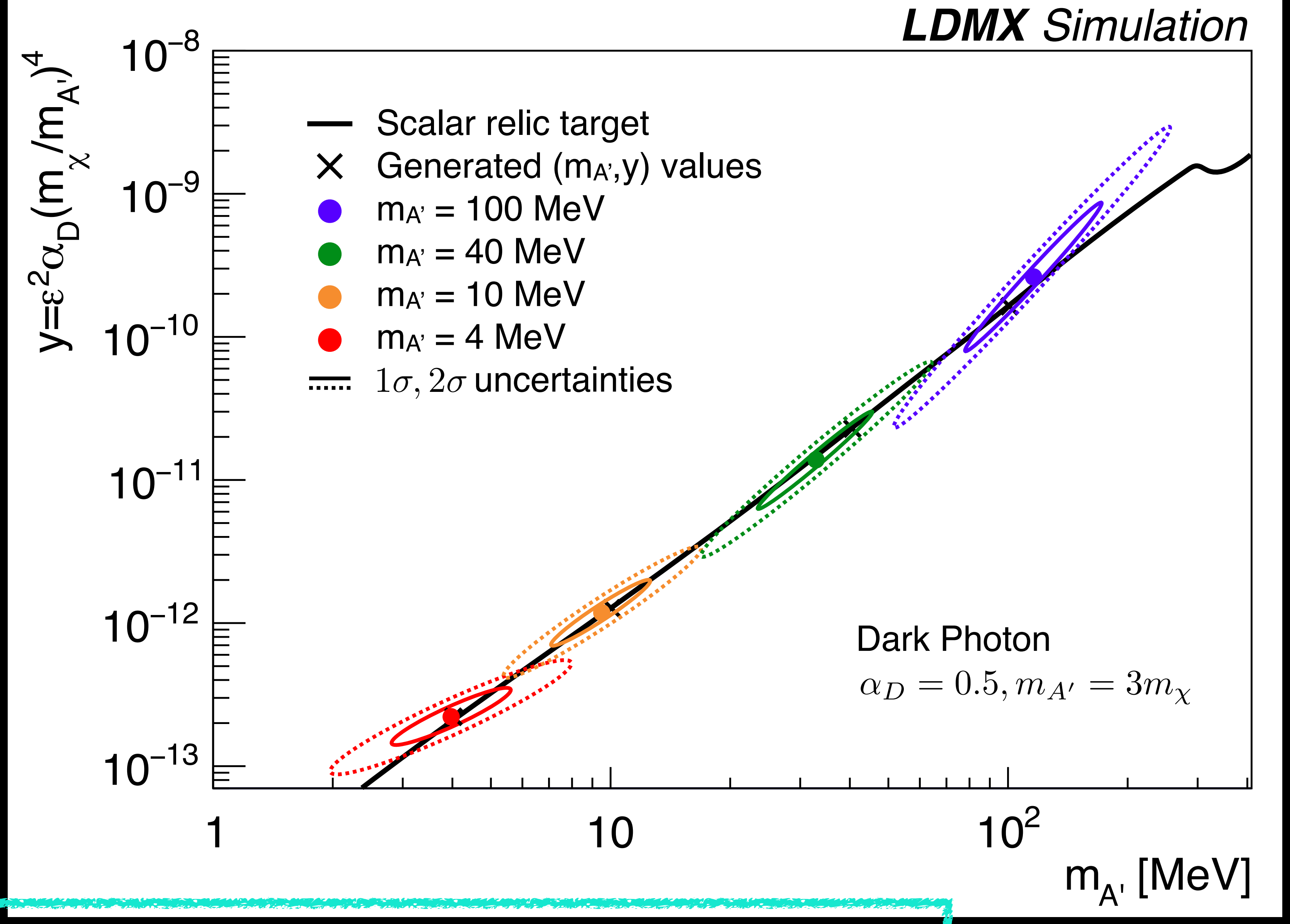
TAUP 2023
LK Bryngemark
LDMX

New result! Impact on sensitivity going from 4 to 8 GeV beam (and final dataset size)



- Same sensitivity as 4 GeV at low masses
- Increased reach at higher masses
- Background uncertainty reduced at higher mass using p_T information — great advantage of missing momentum experiment!

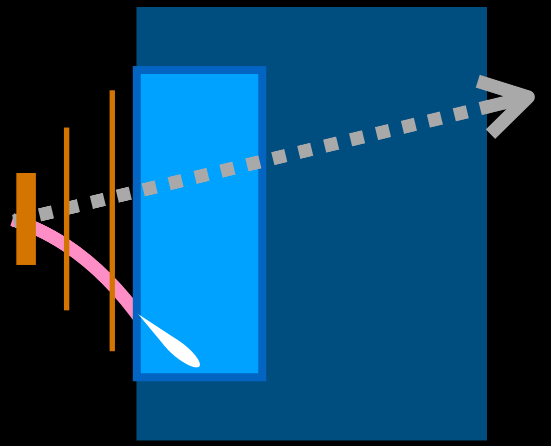




SLAC-PUB-17550
FERMILAB-PUB-23-433-PPD-T
https://arxiv.org/abs/2308.15173

4 GeV, e.g. https://arxiv.org/abs/2203.08192

A rich physics potential

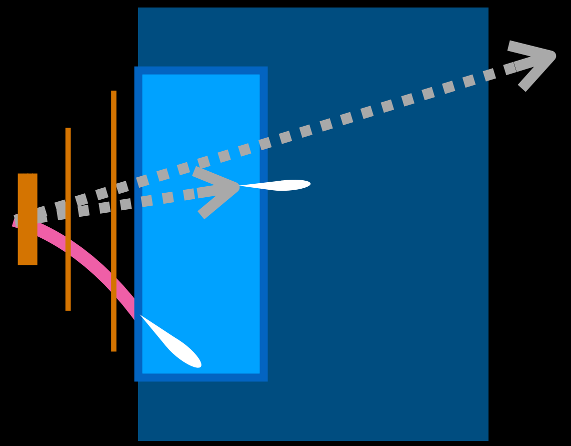


Interpret missing momentum measurements

Secluded dark matter models, millicharge particles, invisibly decaying dark photons, axion-like particles, …

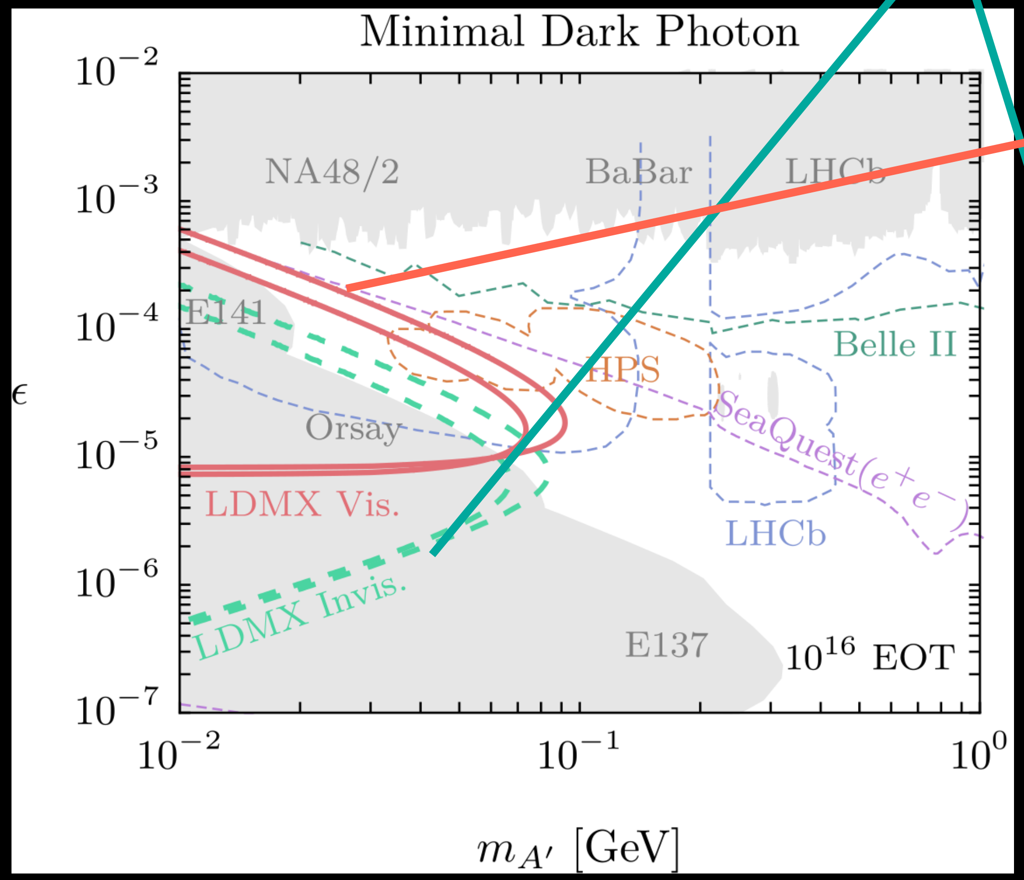
Interpret as a short-baseline beam dump

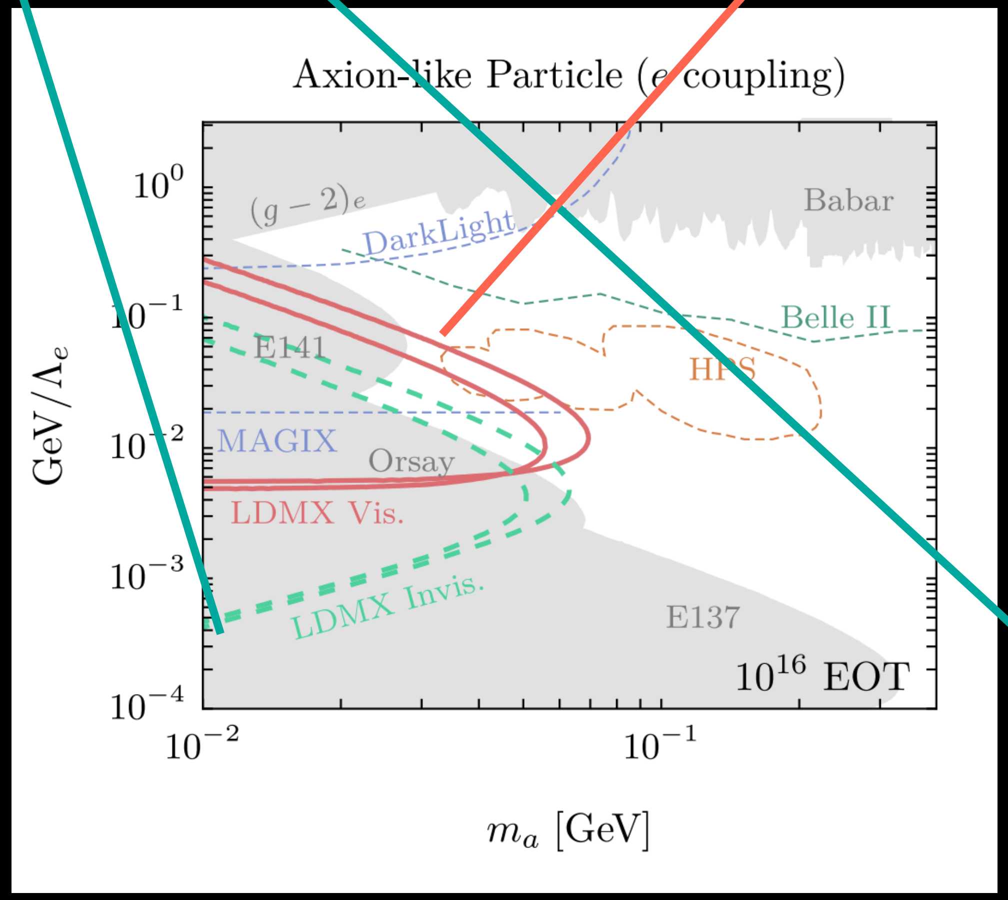
Displaced visibly decaying dark photons, axion-like or long-lived particles, inelastic dark matter, …



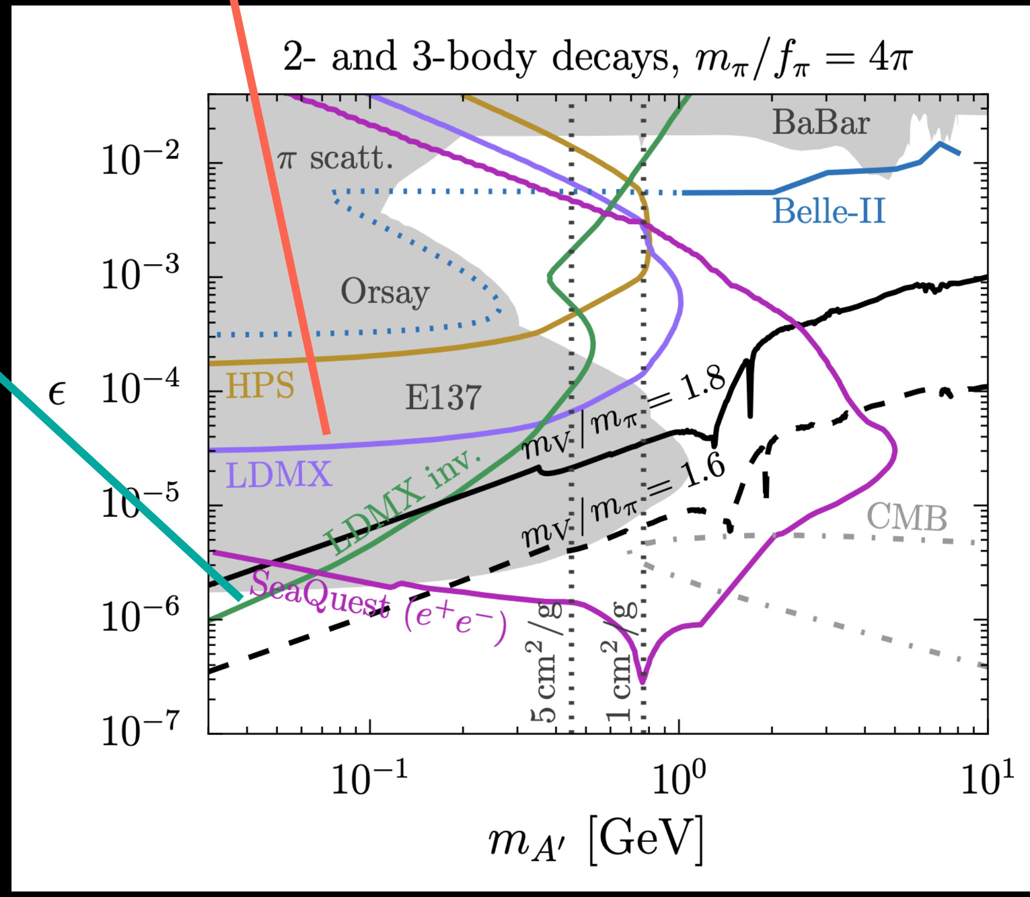
and Spin-1 DM — previous talk by Taylor Gray

Phys. Rev. D 101, 053004, https://arxiv.org/abs/1912.06140



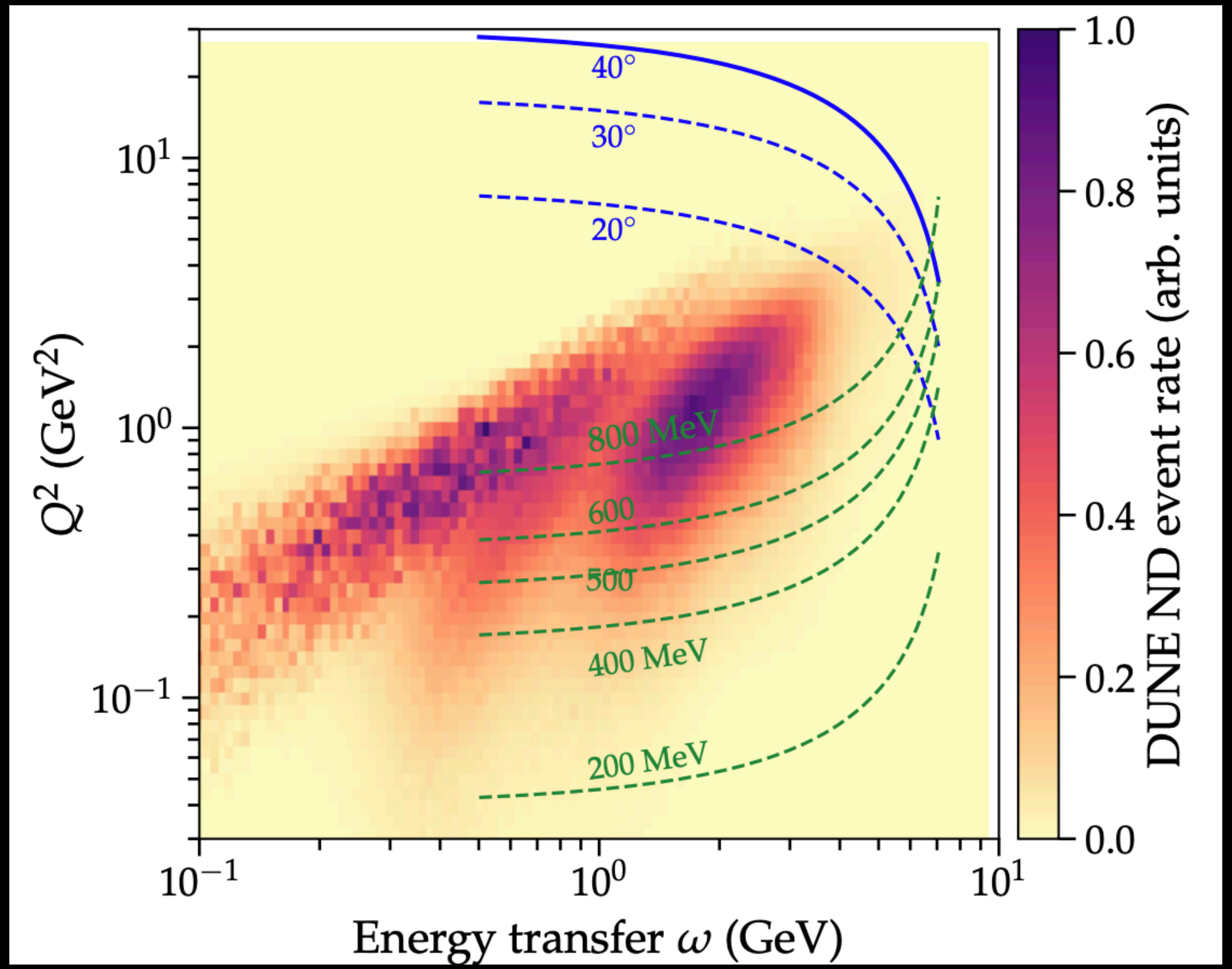


Phys. Rev. D 99, 075001 (2019), https://arxiv.org/abs/1807.01730



SIMPs

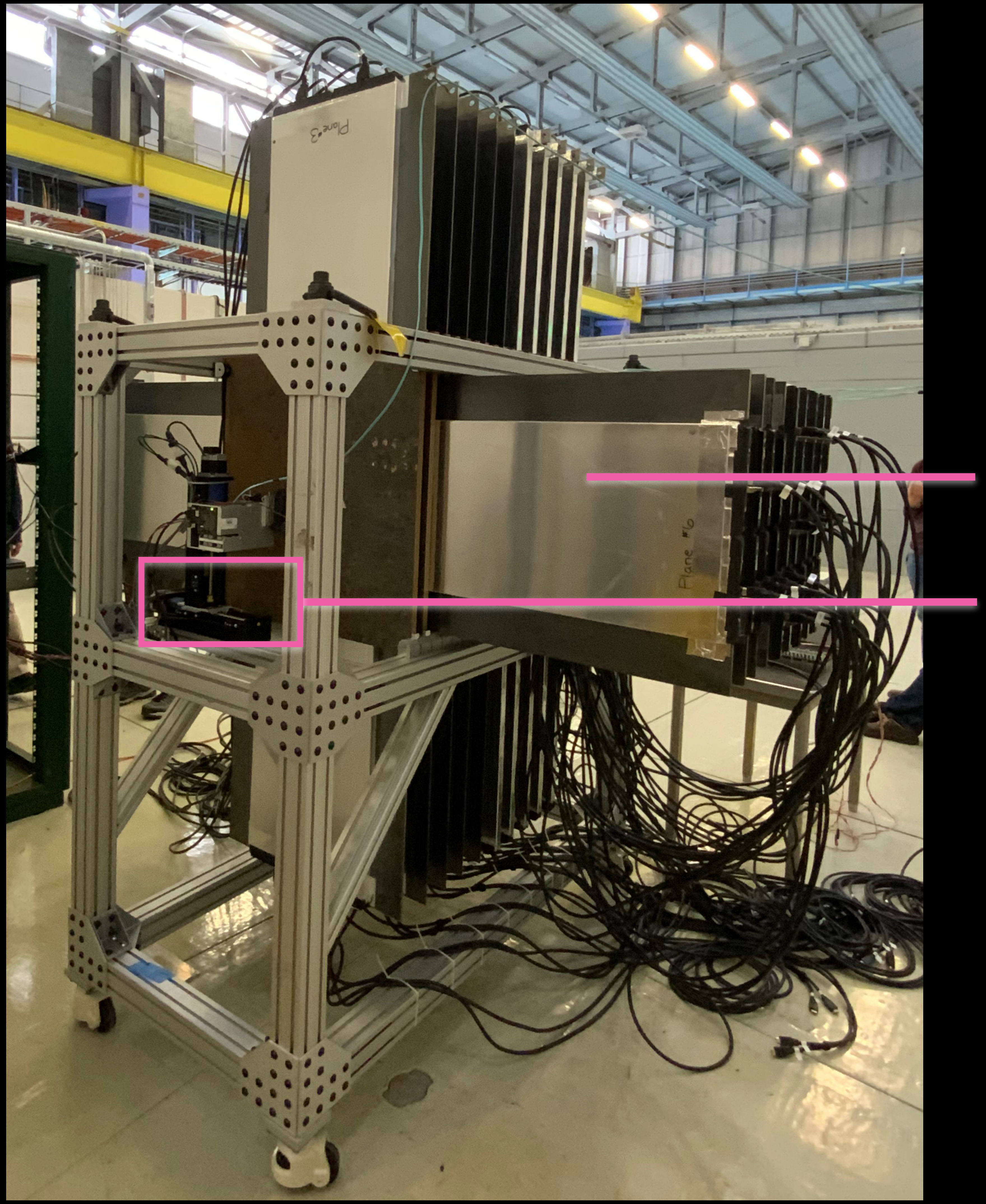
Electro-nuclear scattering particle spectra constrain theoretical uncertainties in neutrino experiments



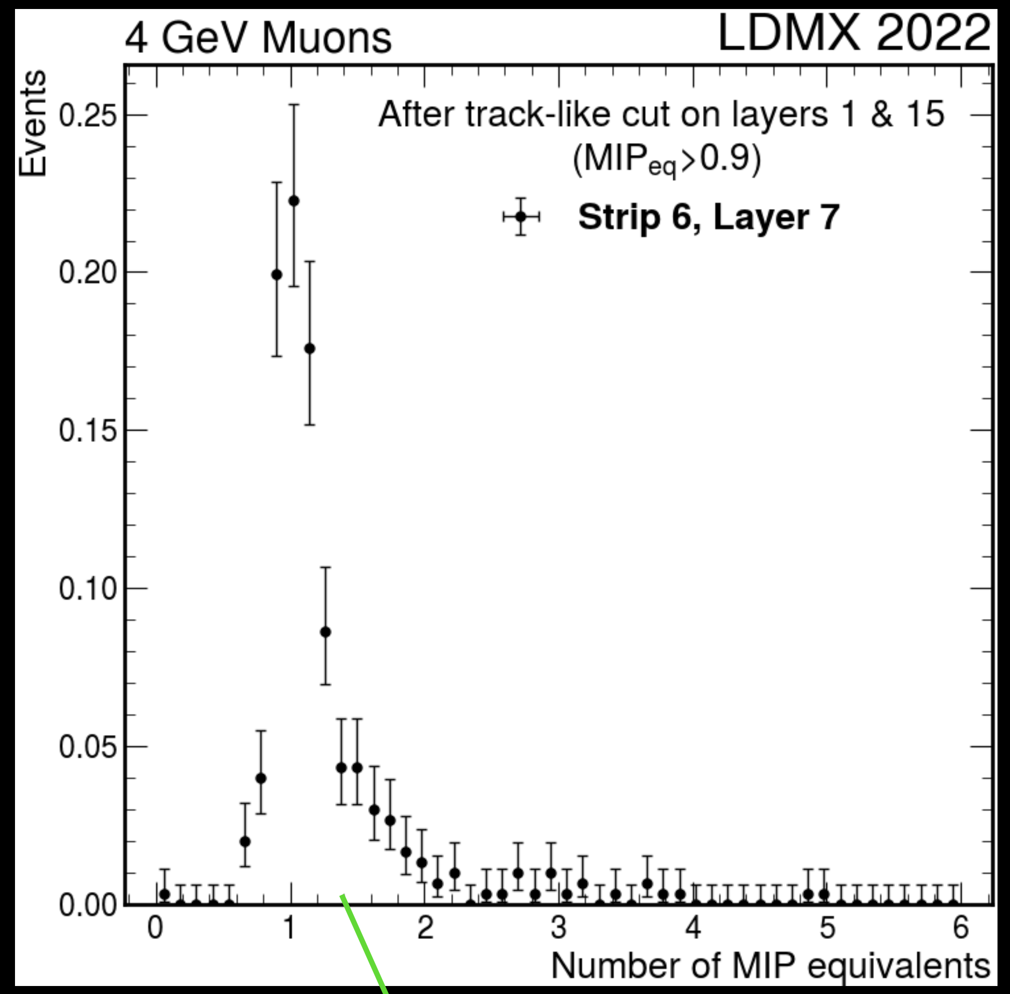
Overlap of LDMX acceptance (curves) and DUNE DIS phase space (color)

LDMX Snowmass 2021 contribution https://arxiv.org/abs/2203.08192

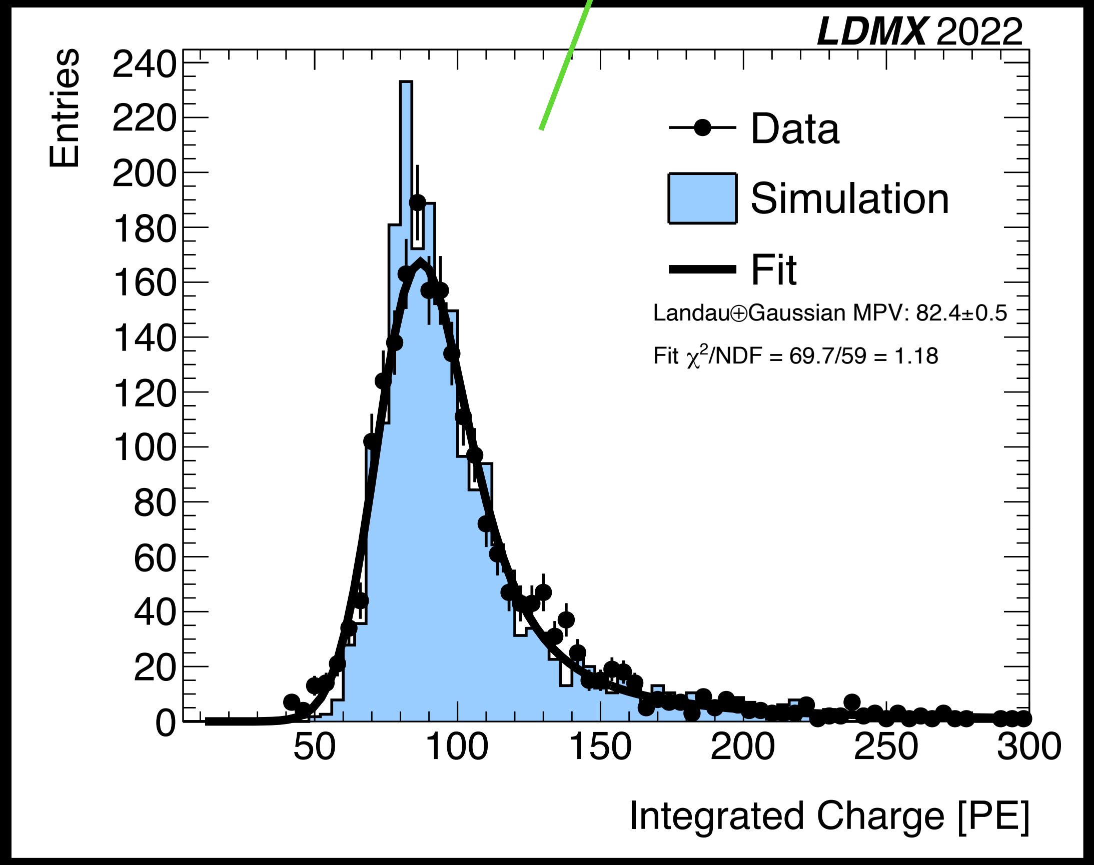
Current status: prototype beam tests



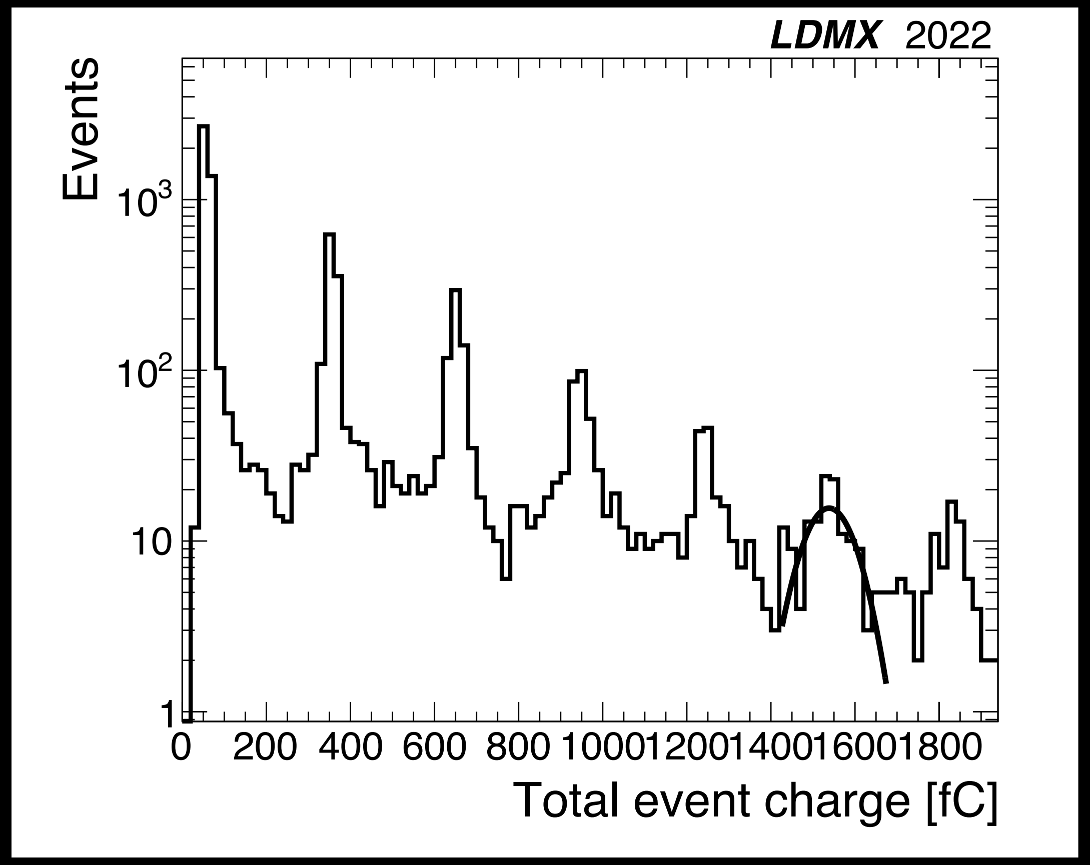
CERN test beam, March-April 2022



MIP response



TS single-photoelectron gain calibration



Searching for DM with an electron beam at the GeV scale is a well-motivated and worthwhile effort.

- LDMX can conclusively probe the stable matter mass range for DM of thermal origin, and has a broad physics potential beyond this goal
- Simulation and hardware understanding rapidly maturing → design is being finalized
  - can reach required background rejection — new 8 GeV sensitivity study submitted to arXiv!
  - prototype beam tests performed at CERN, paper in preparation

U.S. DEPARTMENT OF ENERGY
Knut and Alice Wallenberg Foundation
Kungl. Fysiografiska Sällskapet i Lund
Crafoord foundation
Caltech
Carnegie Mellon University
Fermilab
Lund University
University of Minnesota Driven to Discover®
UC Santa Barbara
SLAC National Accelerator Laboratory
Stanford University
Texas Tech University
University of Virginia

backup

references

Measurements of photo- and electro-nuclear processes for neutrino experiments:
Lepton-Nucleus Cross Section Measurements for DUNE with the LDMX Detector ,Phys. Rev. D 101, 053004,
https://arxiv.org/abs/1912.06140

Background rejection to < 1 event
at 4 GeV: A High Efficiency Photon Veto for the Light Dark Matter eXperiment, J. High Energ. Phys. 2020, 3 (2020)
https://arxiv.org/abs/1912.05535,
8 GeV submitted to arXiv: (SLAC-PUB-17550, FERMILAB-PUB-23-433-PPD-T)
https://arxiv.org/abs/2308.15173

Current Status and Future Prospects for the Light Dark Matter eXperiment, LDMX Snowmass 2021 contribution,
https://arxiv.org/abs/2203.08192

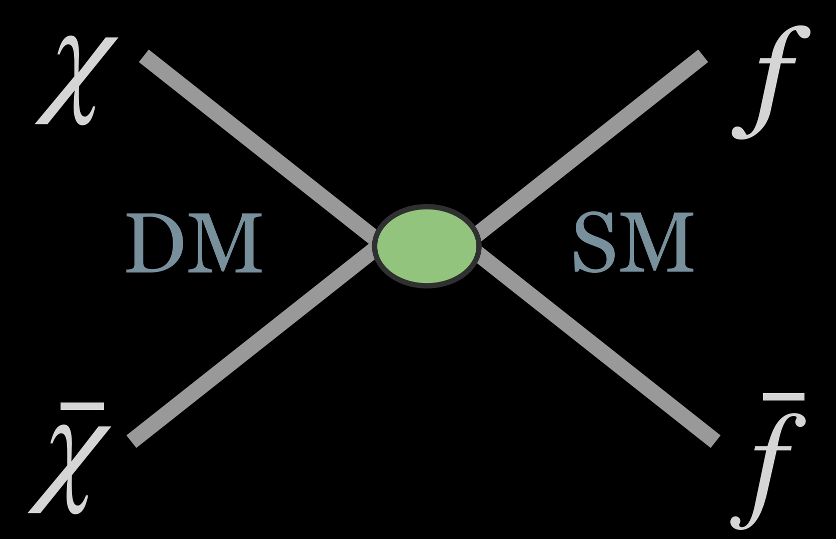
The SLAC Linac to ESA (LESA) Beamline for Dark Sector Searches and Test Beams, Snowmass 2021 contribution,
https://arxiv.org/abs/2205.13215

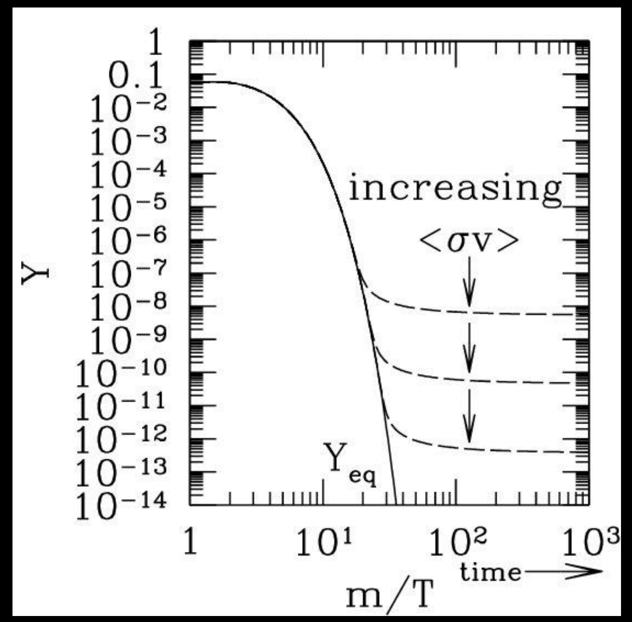
Schuster, Toro, Zhou, Probing Invisible Vector Meson Decays with NA64 and LDMX, Phys. Rev. D 105, 035036 (2022)
https://arxiv.org/abs/2112.02104

Building a Distributed Computing System for LDMX: Challenges of creating and operating a lightweight e-infrastructure for small-to-medium size accelerator experiments, vCHEP2021 proceedings,
https://arxiv.org/abs/2105.02977

Light Dark Matter eXperiment (LDMX),
https://arxiv.org/abs/1808.05219

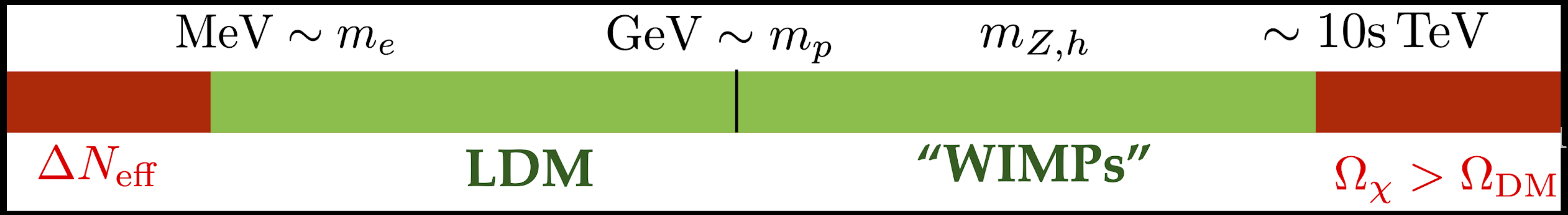
Thermal-relic dark matter: a predictive model





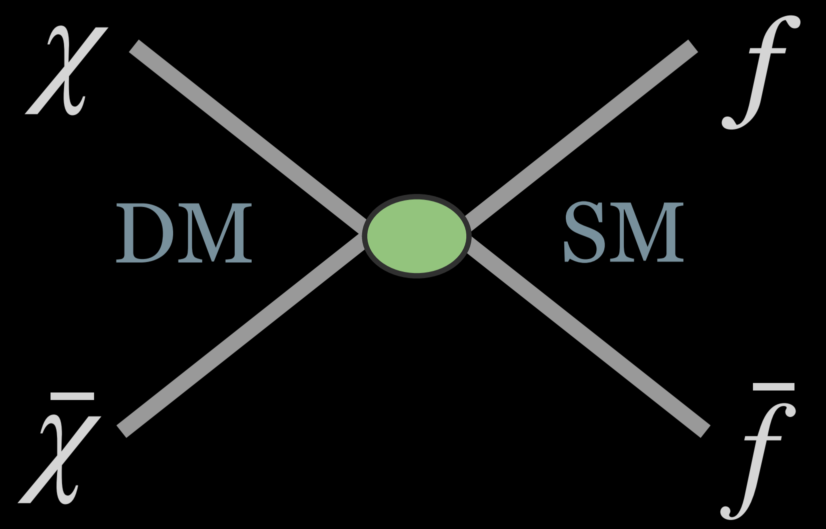
Is present-day dark matter a freeze-out relic from the hot early Universe?

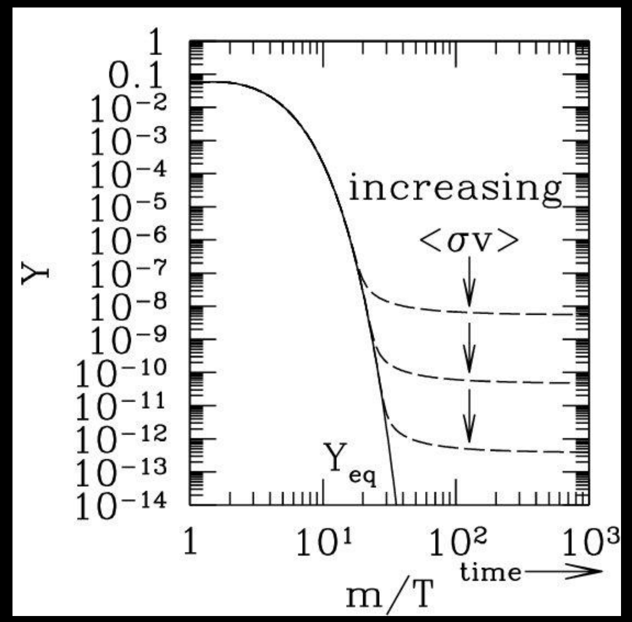
- viable with ***minimal*** assumptions
  - some minimum non-gravitational interaction → reaches thermal equilibrium at some point in history
- predicts a minimum interaction strength
  - experimental sensitivity target
- constrains the ~90 orders of mag. DM mass range
  - light mediator: non-SM force/dark sector



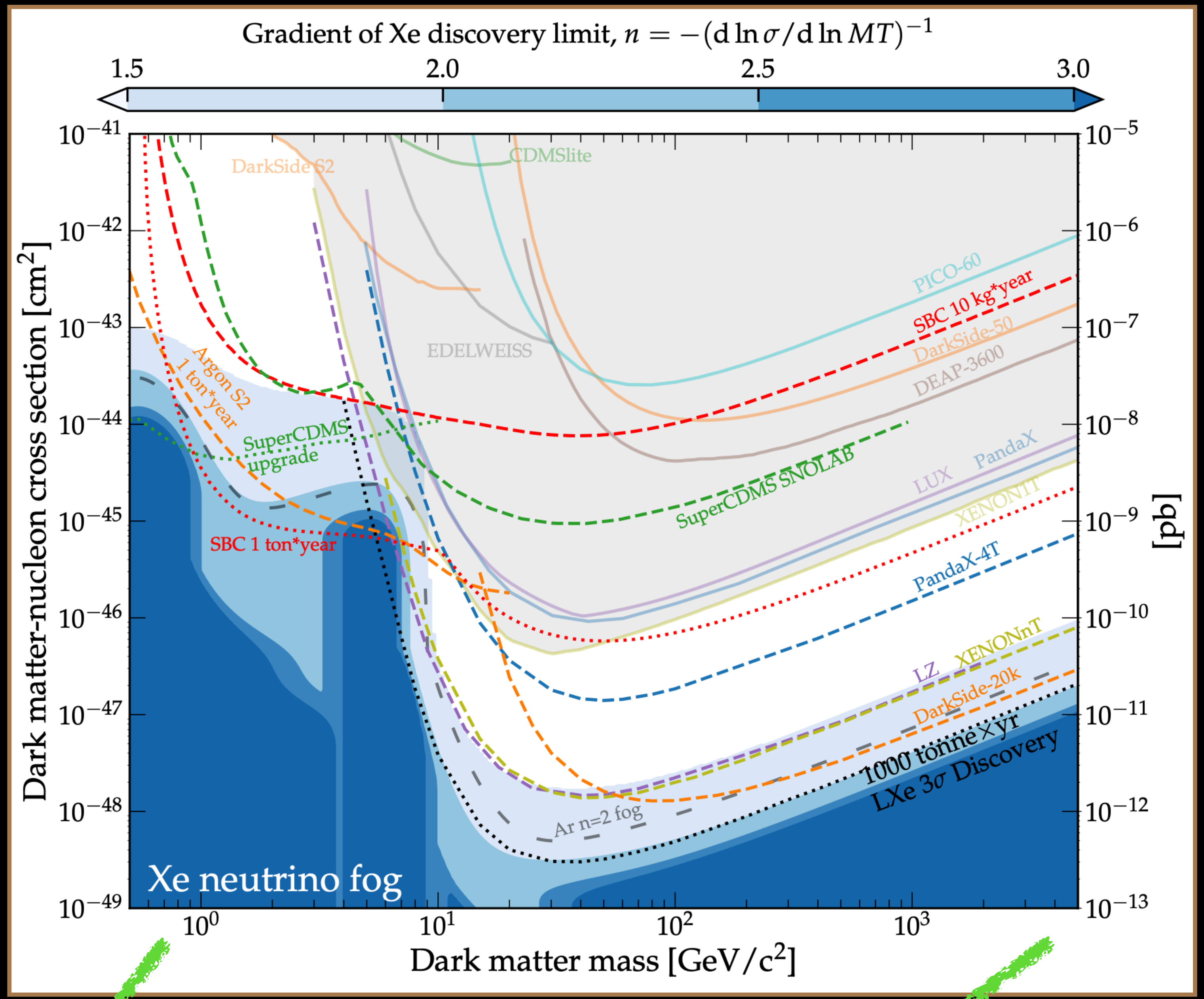
Thermal-relic dark matter: a predictive model

Is present-day dark matter a freeze-out relic from the hot early Universe?



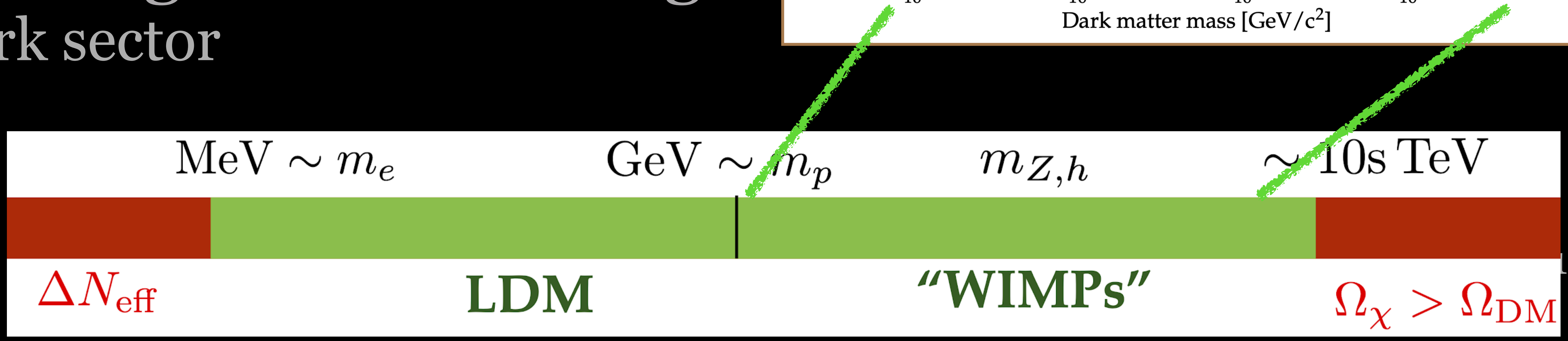


- viable with ***minimal*** assumptions
  - some minimum non-gravitational interaction → reaches thermal equilibrium at some point in history

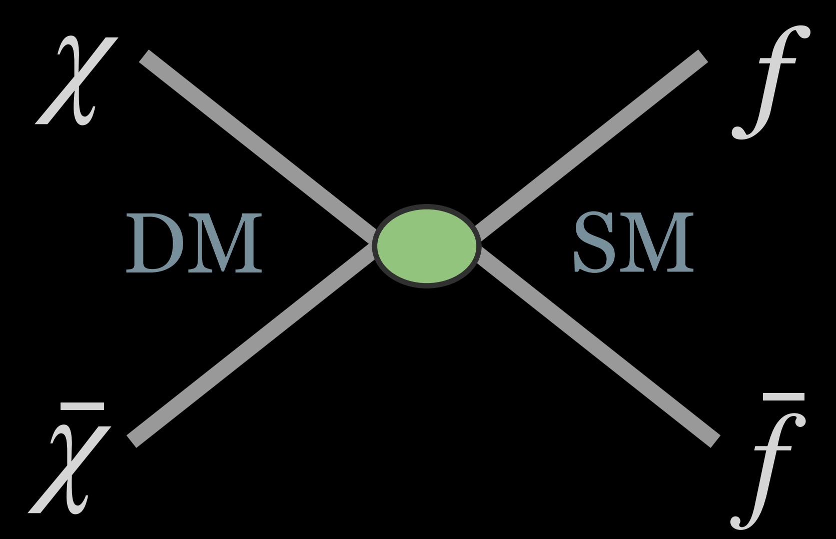


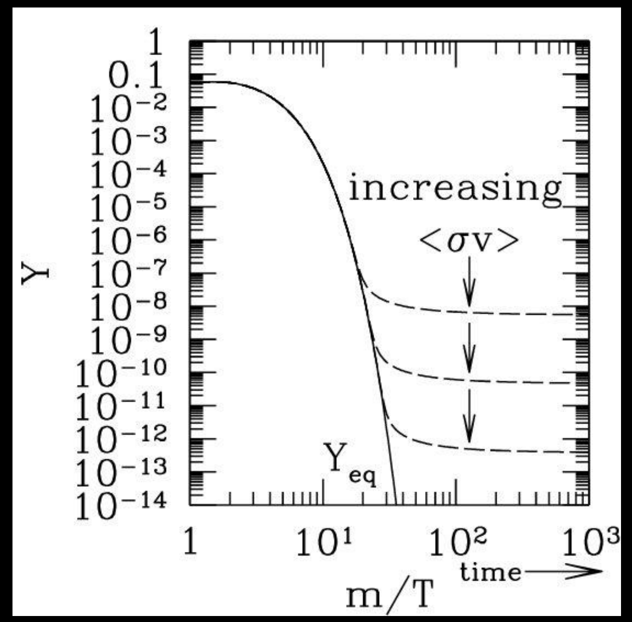
- predicts a minimum interaction strength
  - experimental sensitivity target

- constrains the ~90 orders of mag. DM mass range
  - light mediator: non-SM force/dark sector



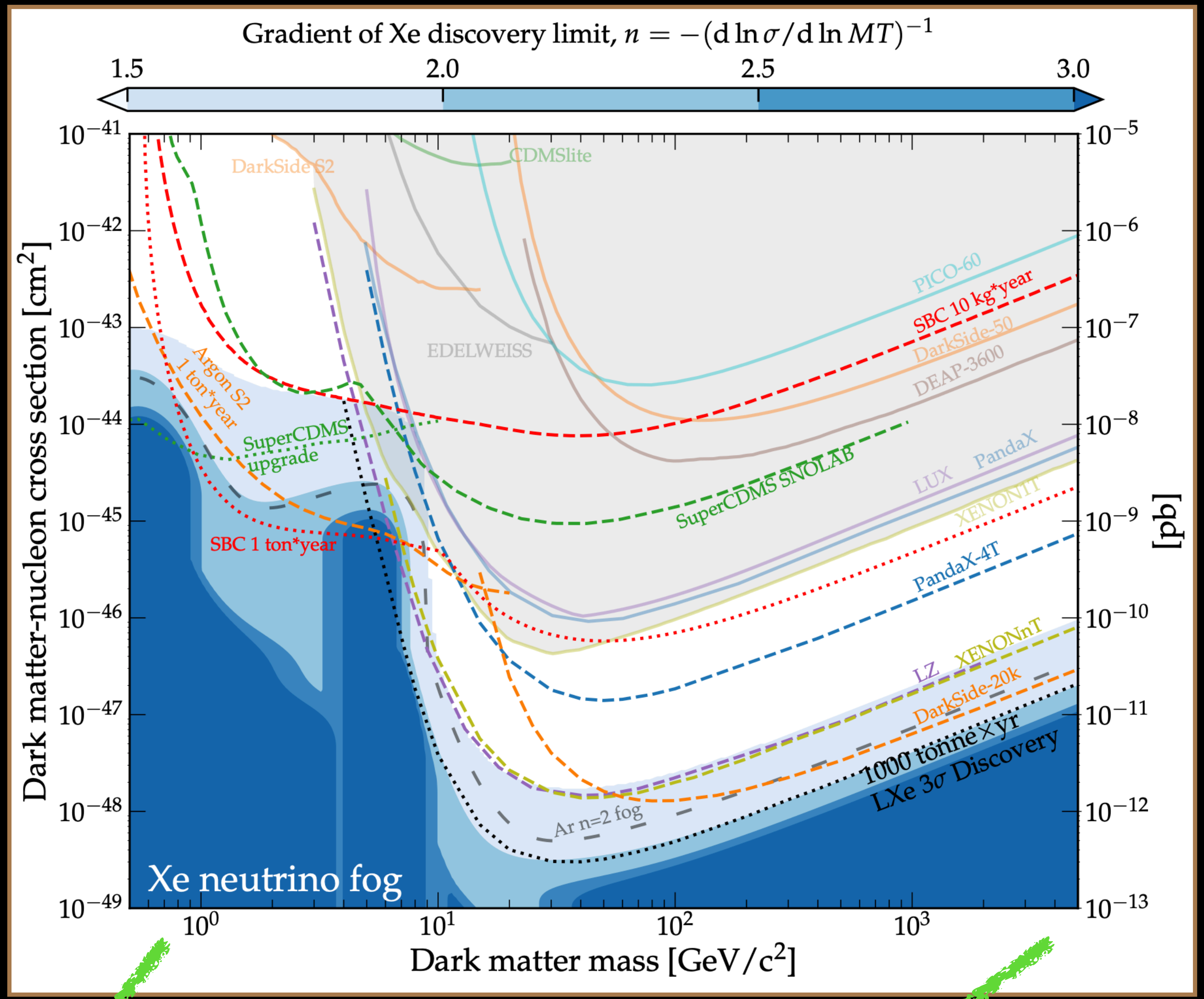
Thermal-relic dark matter: a predictive model

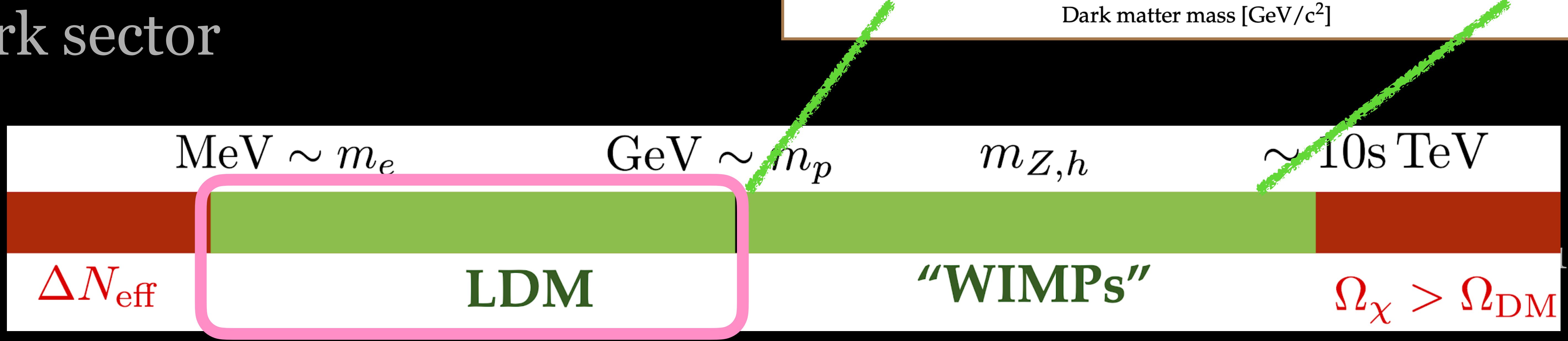




Is present-day dark matter a freeze-out relic from the hot early Universe?

- viable with ***minimal*** assumptions
  - some minimum non-gravitational interaction → reaches thermal equilibrium at some point in history
- predicts a minimum interaction strength
  - experimental sensitivity target
- constrains the ~90 orders of mag. DM mass range
  - light mediator: non-SM force/dark sector





What do we need from Dark Matter to produce it with a ~GeV electron beam?

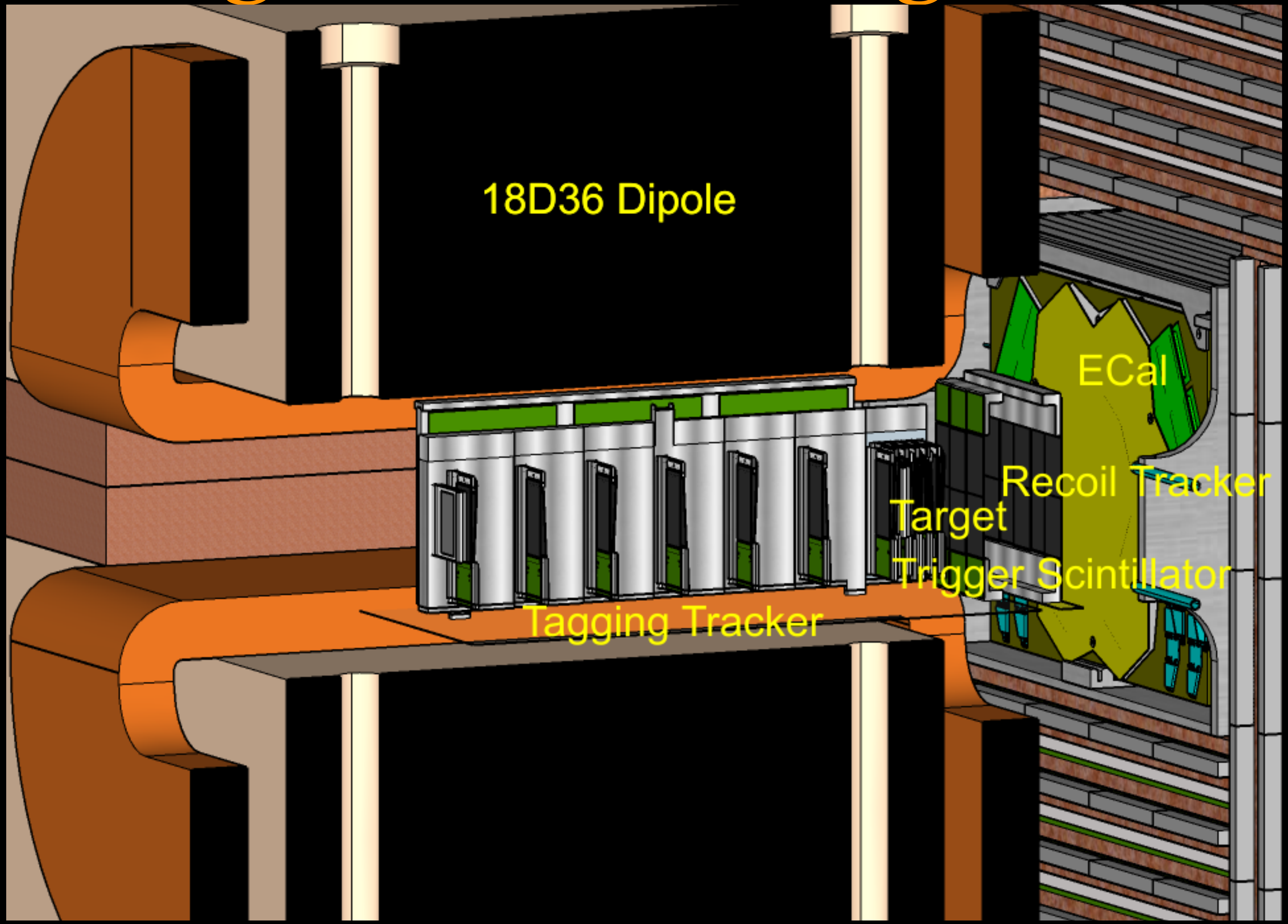
- Has to be light
  - In the mass range of known stable particles — can't be a WIMP
    - Has to interact through some other mediator
- Not too feeble to ever happen
  - Rate should respect present DM relic abundance, unitarity, …

And from us: a suitable beam and detection strategy

Detectors pre-target: knowing what's coming in

Trigger scintillators:

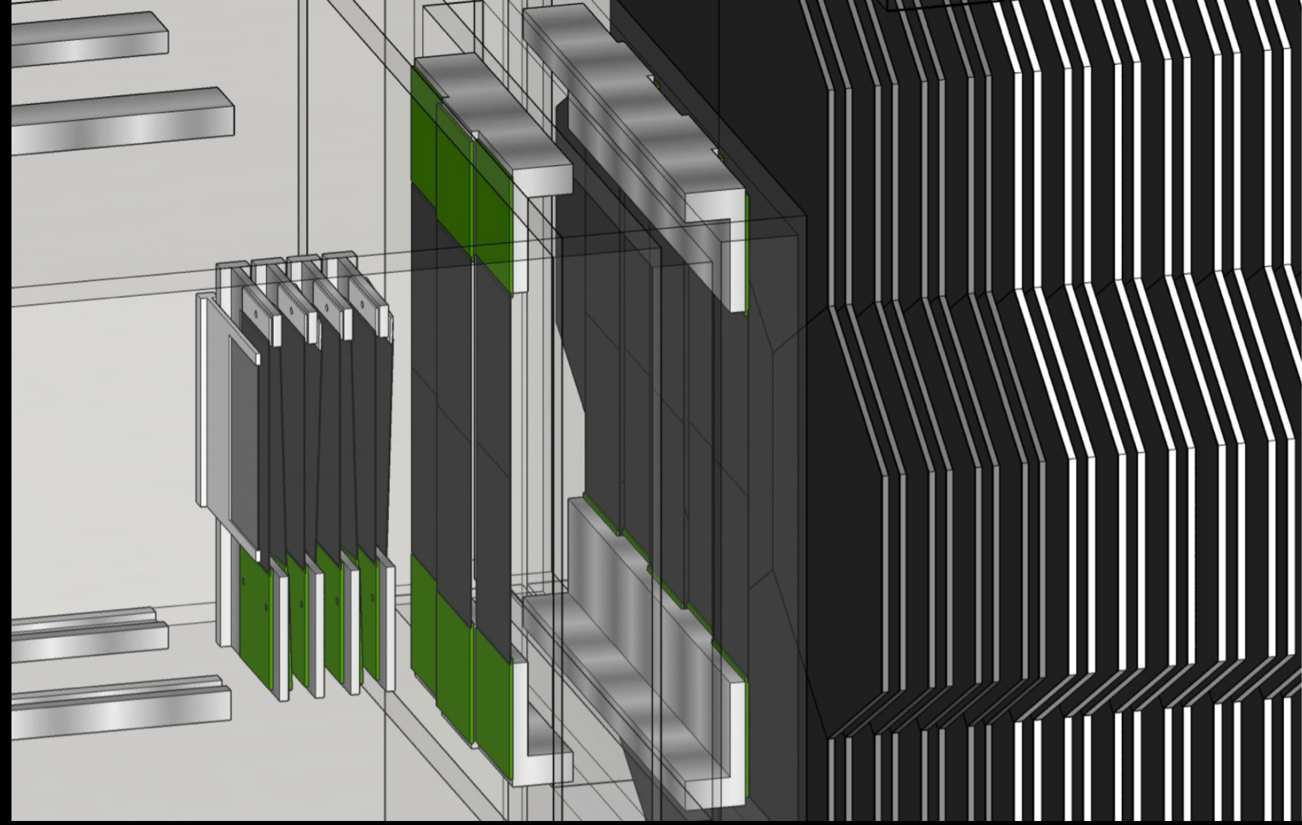
- Trigger-level electron counting, input to missing-energy trigger
- 3 arrays of horizontal scintillating bars, positioned along incoming beam



Tagging tracker (based on HPS tracker design):

- Tag beam electrons (momentum and impact parameter), offline
- 7 double-sided silicon strip modules, 100 mrad stereo angle
  - 10 cm apart, along incoming beam trajectory
  - vertically oriented strips for optimal momentum resolution

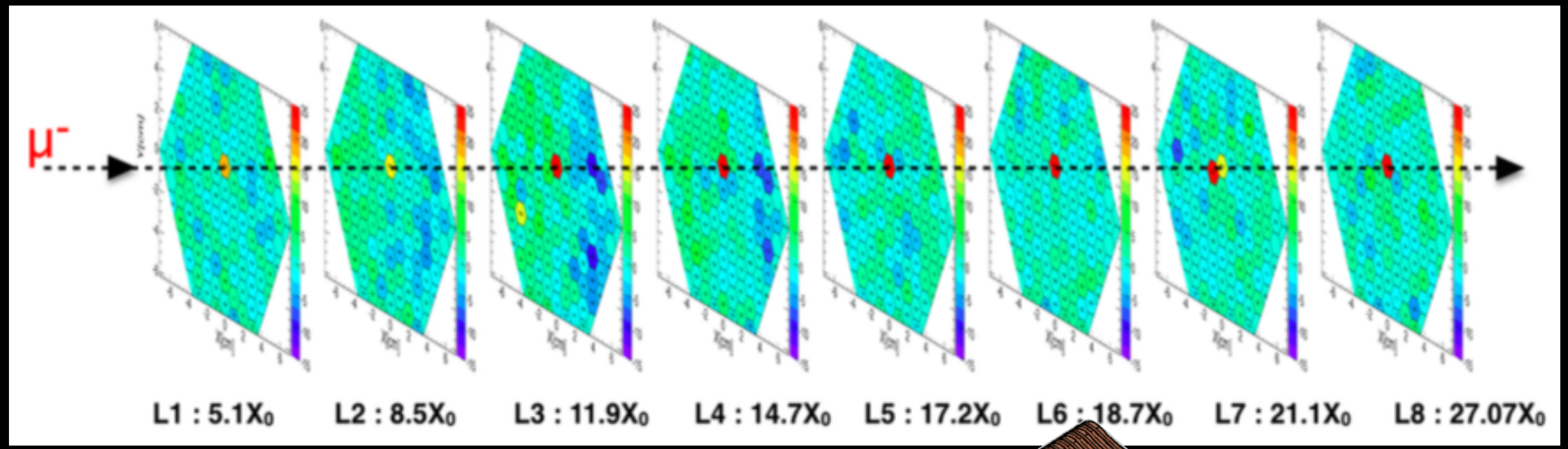
After target: recoil tracker, Ecal and Hcal



A.Martelli on behalf of CMS, [arXiv:1708.08234]

Recoil tracker:

- optimized for momentum resolution and acceptance at 1-2 GeV

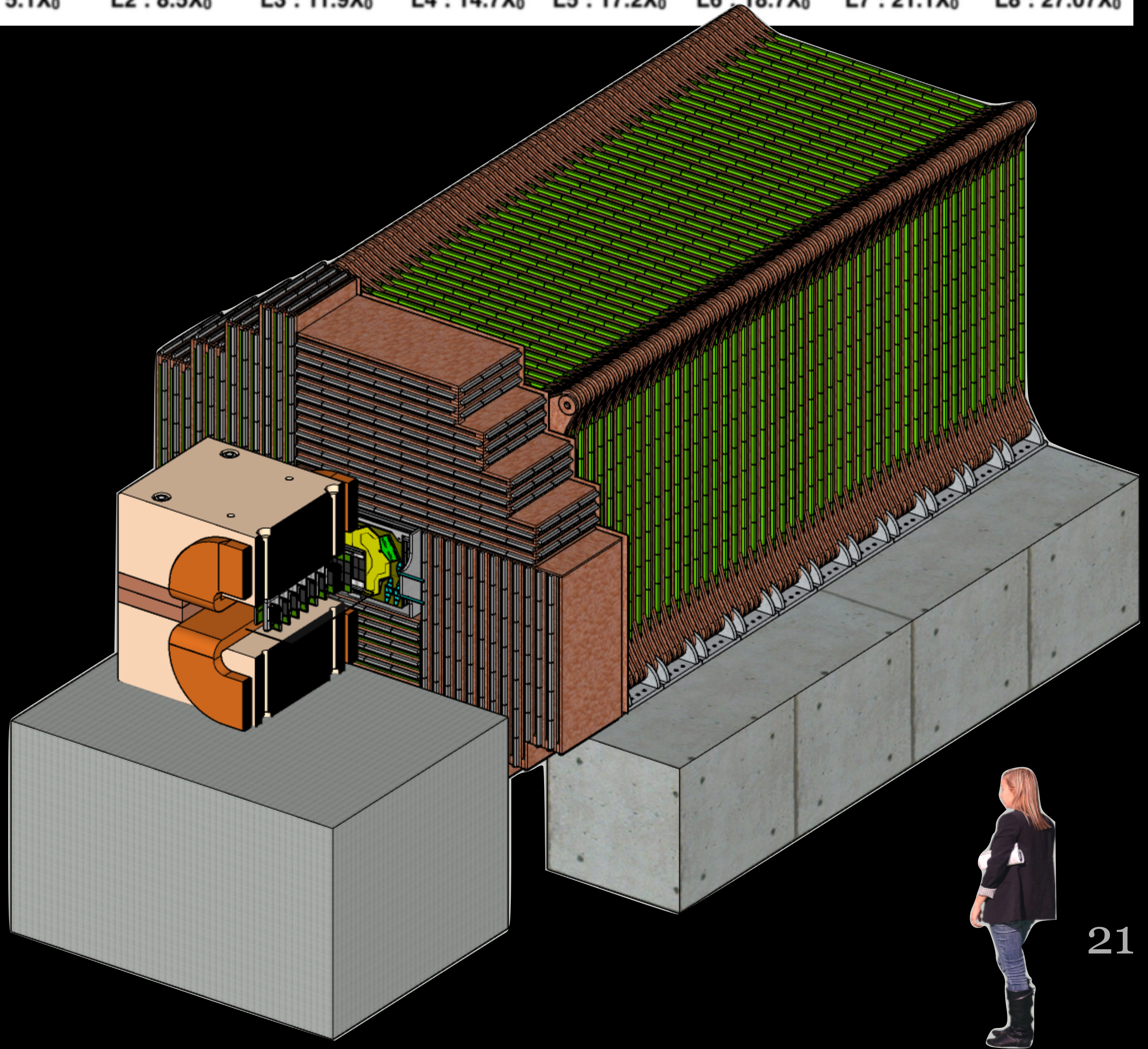


Electromagnetic calorimeter (based on CMS HGCal upgrade):

- high-granularity, capable of MIP tracking
- 40 X_0 Si-W calorimeter, radiation hard

Hadronic calorimeter (adapted from Mu2e cosmic ray veto):

- on all sides and behind Ecal for wide and deep coverage
- sampling calorimeter, steel absorber, 17λ deep
- readout in scintillator bars of alternating x/y orientation



Event selection/vetoes

Goal: no background from ~10^{14} electrons on target

First handle: recoiling electron

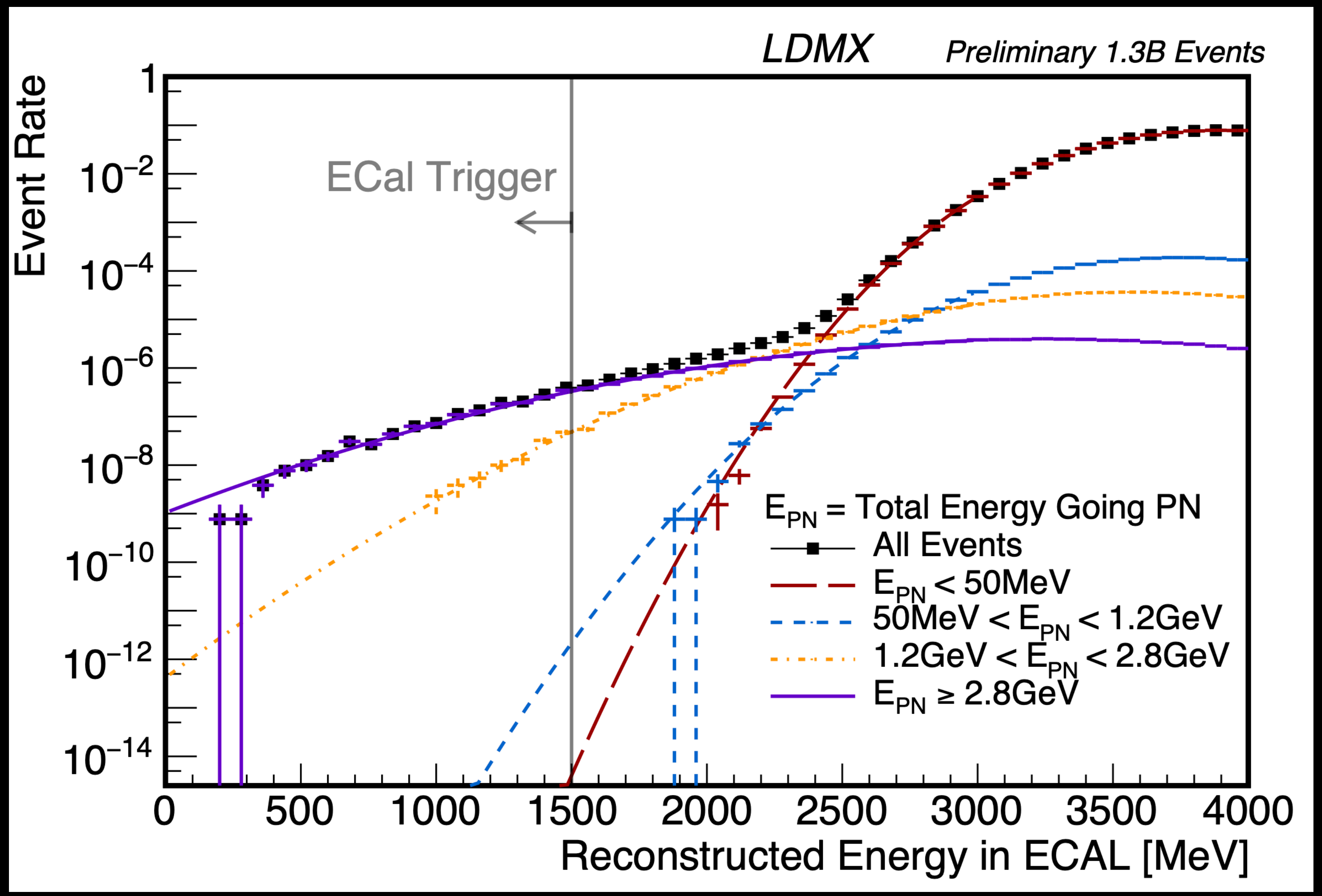
- trigger on Ecal $E < 1.5$ GeV (1e);
- select recoil electron momentum < 1.2 GeV
- veto if number of outgoing tracks > incoming tracks

Exploit high-granularity Ecal features

- BDT trained to reject photonuclear events in Ecal
- MIP tracking powerful on sparse events

Veto on Hcal activity

- allow only a few photoelectrons
- deep enough to tease out even single neutrons



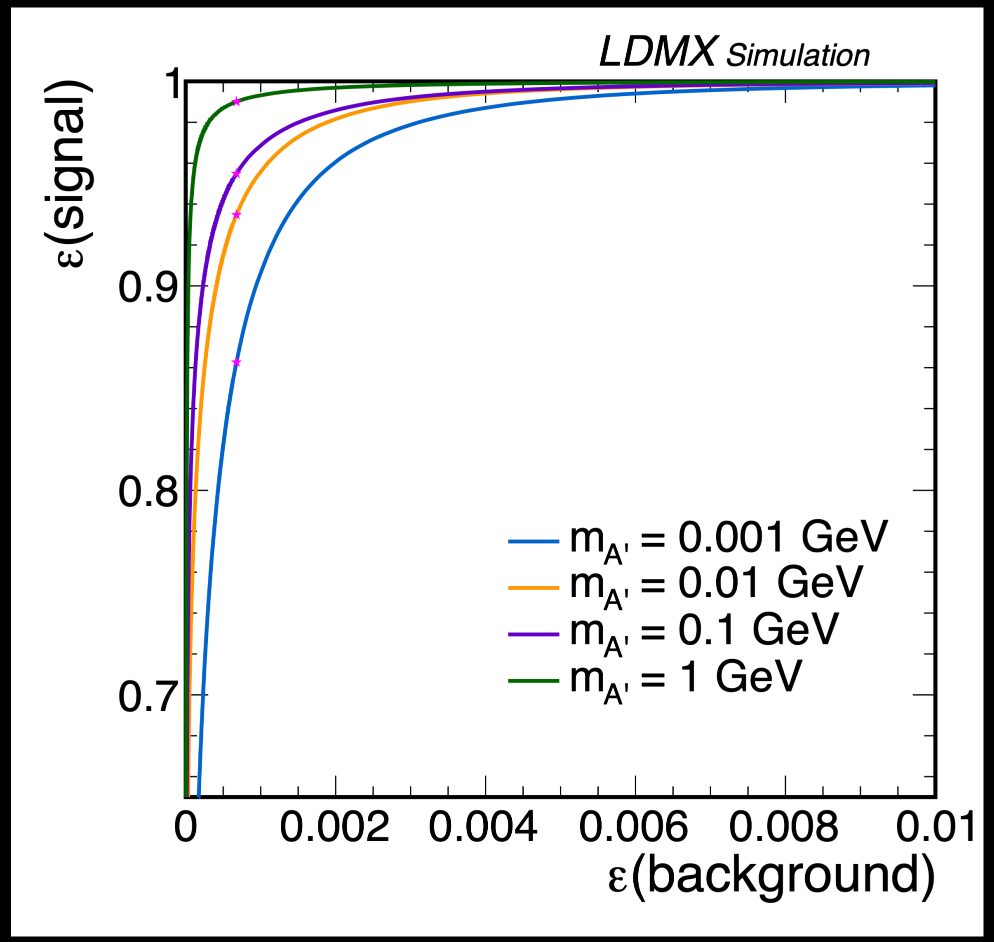
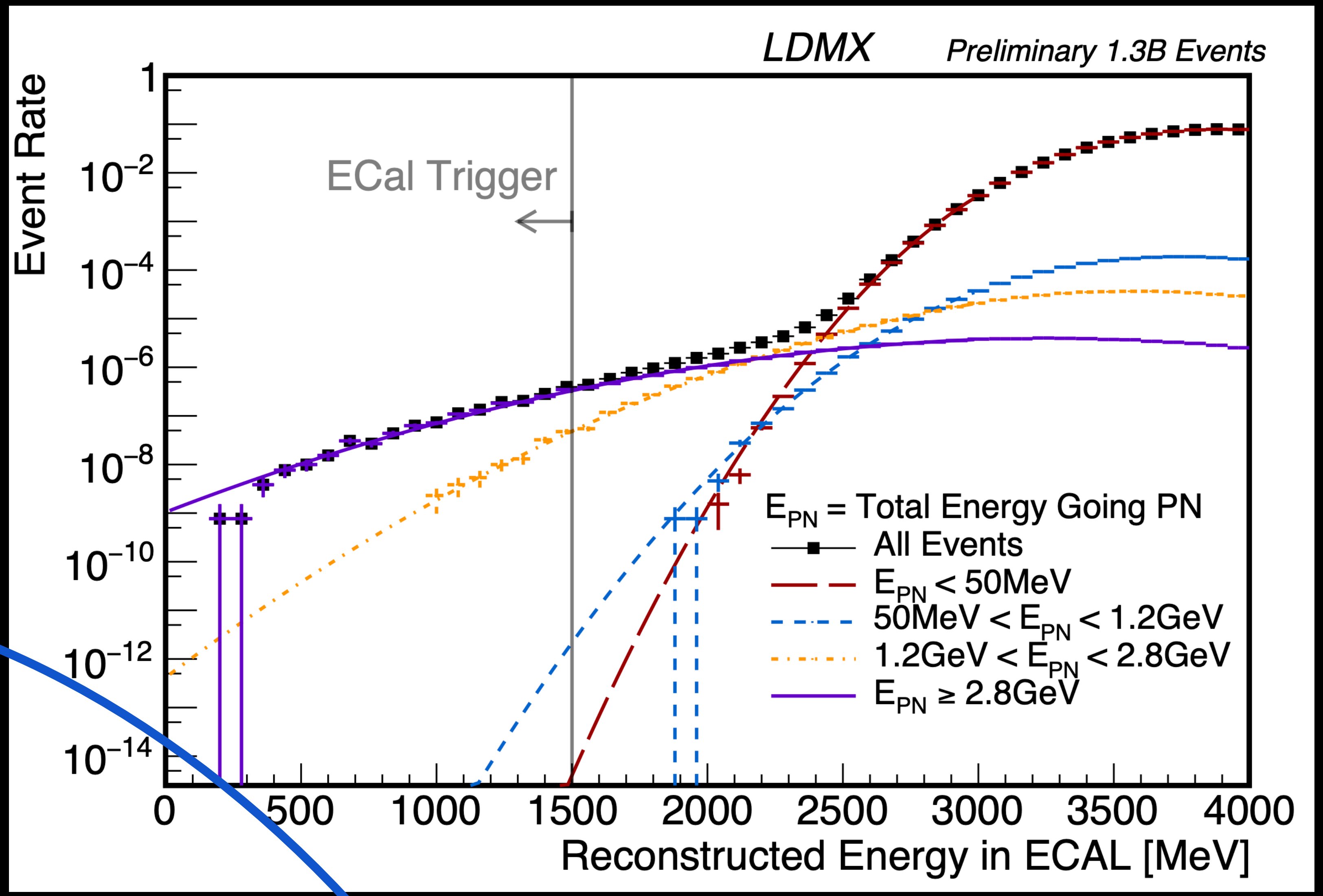


	Photo-nuclear		Muon conversion	
	Target-area	ECal	Target-area	ECal
EoT equivalent	4×10^{14}	2.1×10^{14}	8.2×10^{14}	2.4×10^{15}
Total events simulated	8.8×10^{11}	4.65×10^{11}	6.27×10^{8}	8×10^{10}
Trigger, ECal total energy < 1.5 GeV	1×10^{8}	2.63×10^{8}	1.6×10^{7}	1.6×10^{8}
Single track with $p < 1.2$ GeV	2×10^{7}	2.34×10^{8}	3.1×10^{4}	1.5×10^{8}
ECal BDT (> 0.99)	9.4×10^{5}	1.32×10^{5}	< 1	< 1
HCal max PE < 5	< 1	10	< 1	< 1
ECal MIP tracks = 0	< 1	< 1	< 1	< 1

Event selection/vetoes

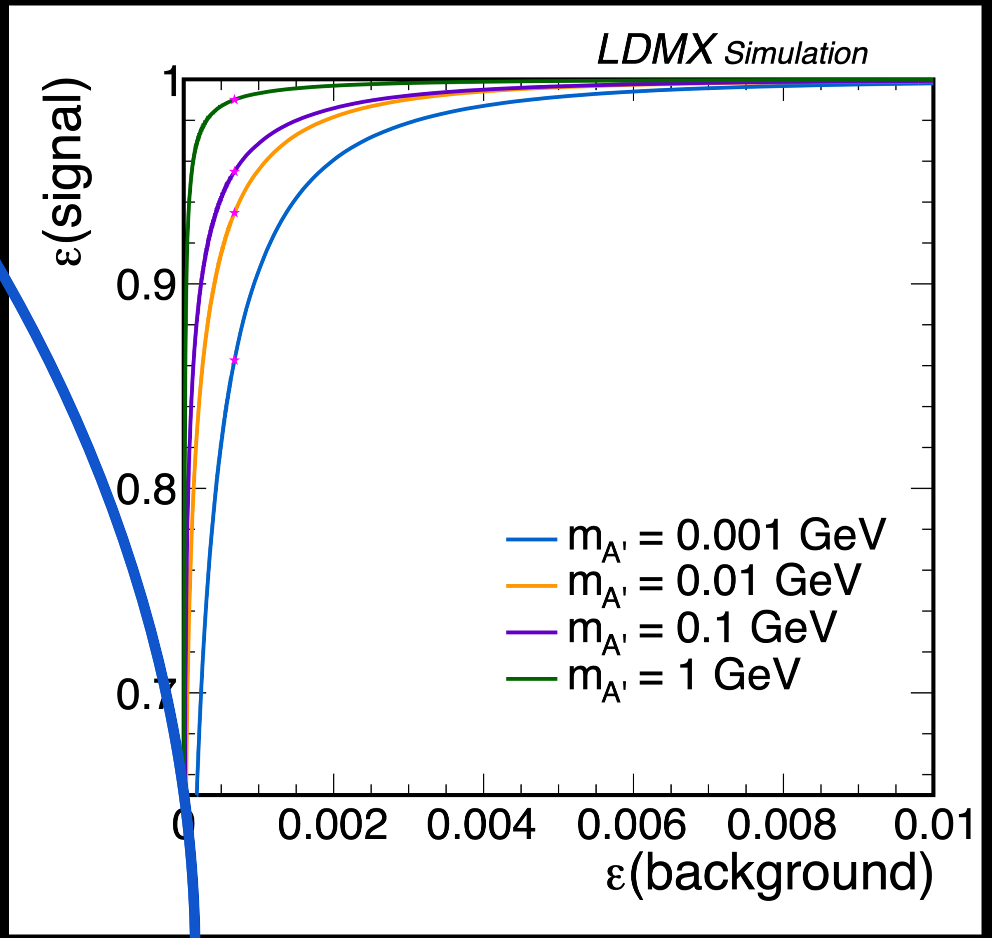
Goal: no background from ~10^{14} electrons on target

most challenging background:



First handle: recoiling electron

- trigger on Ecal $E < 1.5$ GeV (1e);
- select recoil electron momentum < 1.2 GeV
- veto if number of outgoing tracks > incoming tracks



Exploit high-granularity Ecal features

- BDT trained to reject photonuclear events in Ecal
- MIP tracking powerful on sparse events

Veto on Hcal activity

- allow only a few photoelectrons
- deep enough to tease out even single neutrons

	Photo-nuclear		Muon conversion	
	Target-area	ECal	Target-area	ECal
EoT equivalent	4×10^{14}	2.1×10^{14}	8.2×10^{14}	2.4×10^{15}
Total events simulated	8.8×10^{11}	4.65×10^{11}	6.27×10^{8}	8×10^{10}
Trigger, ECal total energy < 1.5 GeV	1×10^{8}	2.63×10^{8}	1.6×10^{7}	1.6×10^{8}
Single track with $p < 1.2$ GeV	2×10^{7}	2.34×10^{8}	3.1×10^{4}	1.5×10^{8}
ECal BDT (> 0.99)	9.4×10^{5}	1.32×10^{5}	< 1	< 1
HCal max PE < 5	< 1	10	< 1	< 1
ECal MIP tracks = 0	< 1	< 1	< 1	< 1

Event selection/vetoes

Goal: no background from ~10^{14} electrons on target

First handle: recoiling electron

- trigger on Ecal E < 1.5 GeV (1e);
- select recoil electron momentum < 1.2 GeV
- veto if number of outgoing tracks > incoming tracks

Exploit high-granularity Ecal features

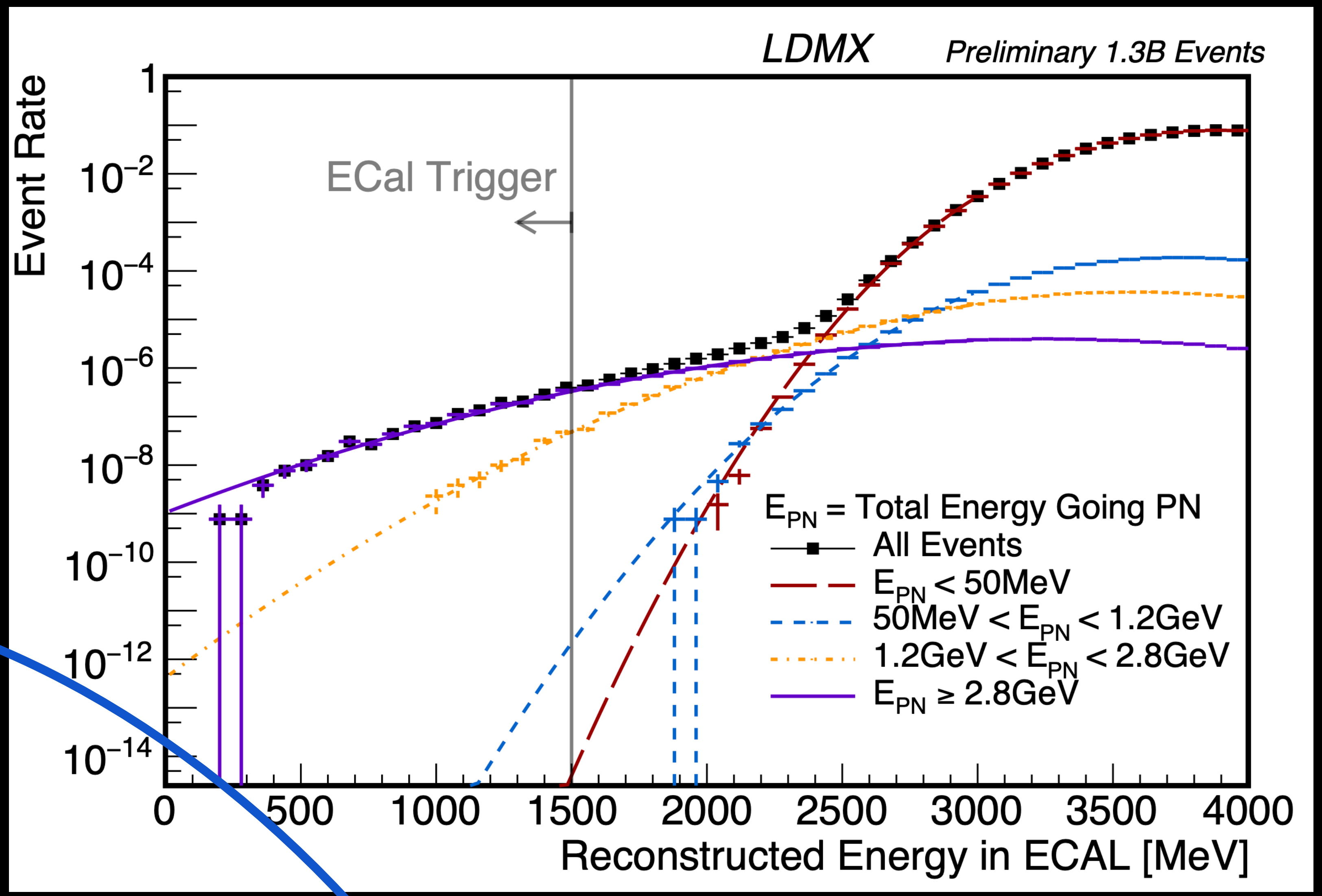
- BDT trained to reject photonuclear events in Ecal
- MIP tracking powerful on sparse events

Veto on Hcal activity

- allow only a few photoelectrons
- deep enough to tease out even single neutrons

most challenging background:

down to 10^8



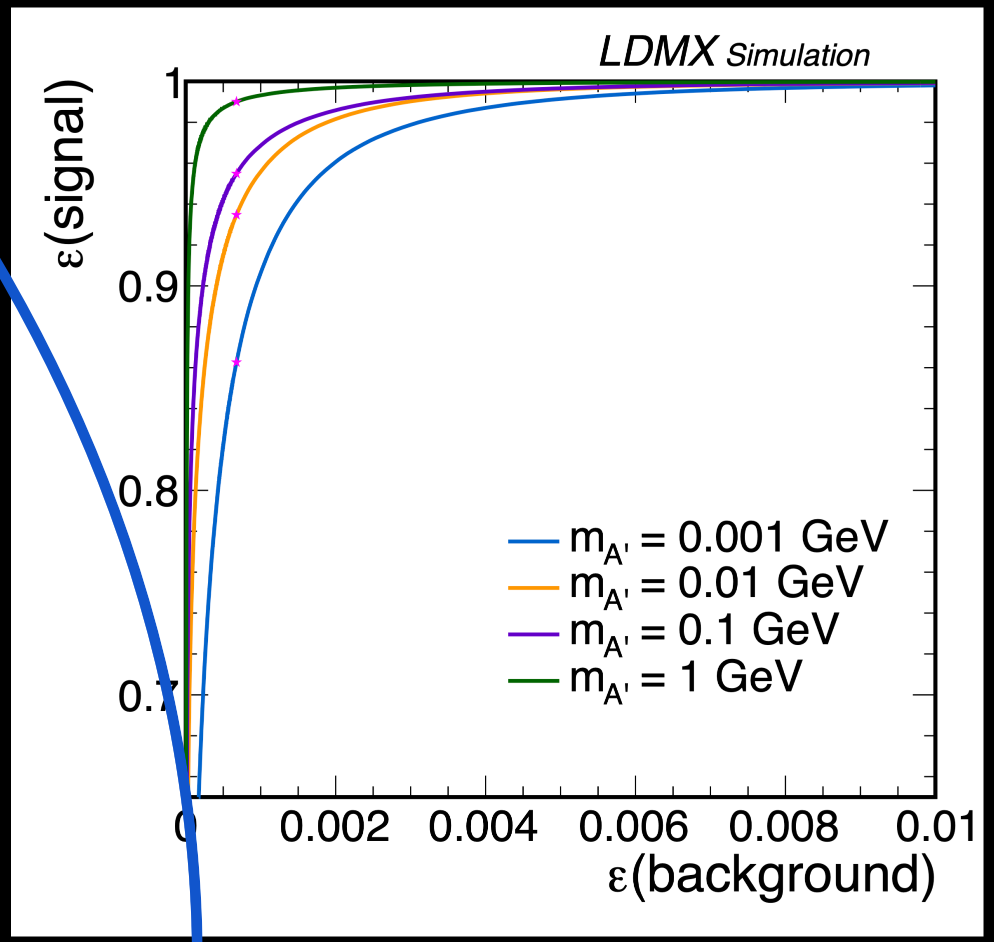


	Photo-nuclear		Muon conversion	
	Target-area	ECal	Target-area	ECal
EoT equivalent	4×10^{14}	2.1×10^{14}	8.2×10^{14}	2.4×10^{15}
Total events simulated	8.8×10^{11}	4.65×10^{11}	6.27×10^{8}	8×10^{10}
Trigger, ECal total energy < 1.5 GeV	1×10^{8}	2.63×10^{8}	1.6×10^{7}	1.6×10^{8}
Single track with p < 1.2 GeV	2×10^{7}	2.34×10^{8}	3.1×10^{4}	1.5×10^{8}
ECal BDT (> 0.99)	9.4×10^{5}	1.32×10^{5}	< 1	< 1
HCal max PE < 5	< 1	10	< 1	< 1
ECal MIP tracks = 0	< 1	< 1	< 1	< 1

Event selection/vetoes

Goal: no background from ~10^{14} electrons on target

most challenging background:

First handle: recoiling electron

down to 10^8

- trigger on Ecal E < 1.5 GeV (1e);
- select recoil electron momentum < 1.2 GeV
- veto if number of outgoing tracks > incoming tracks

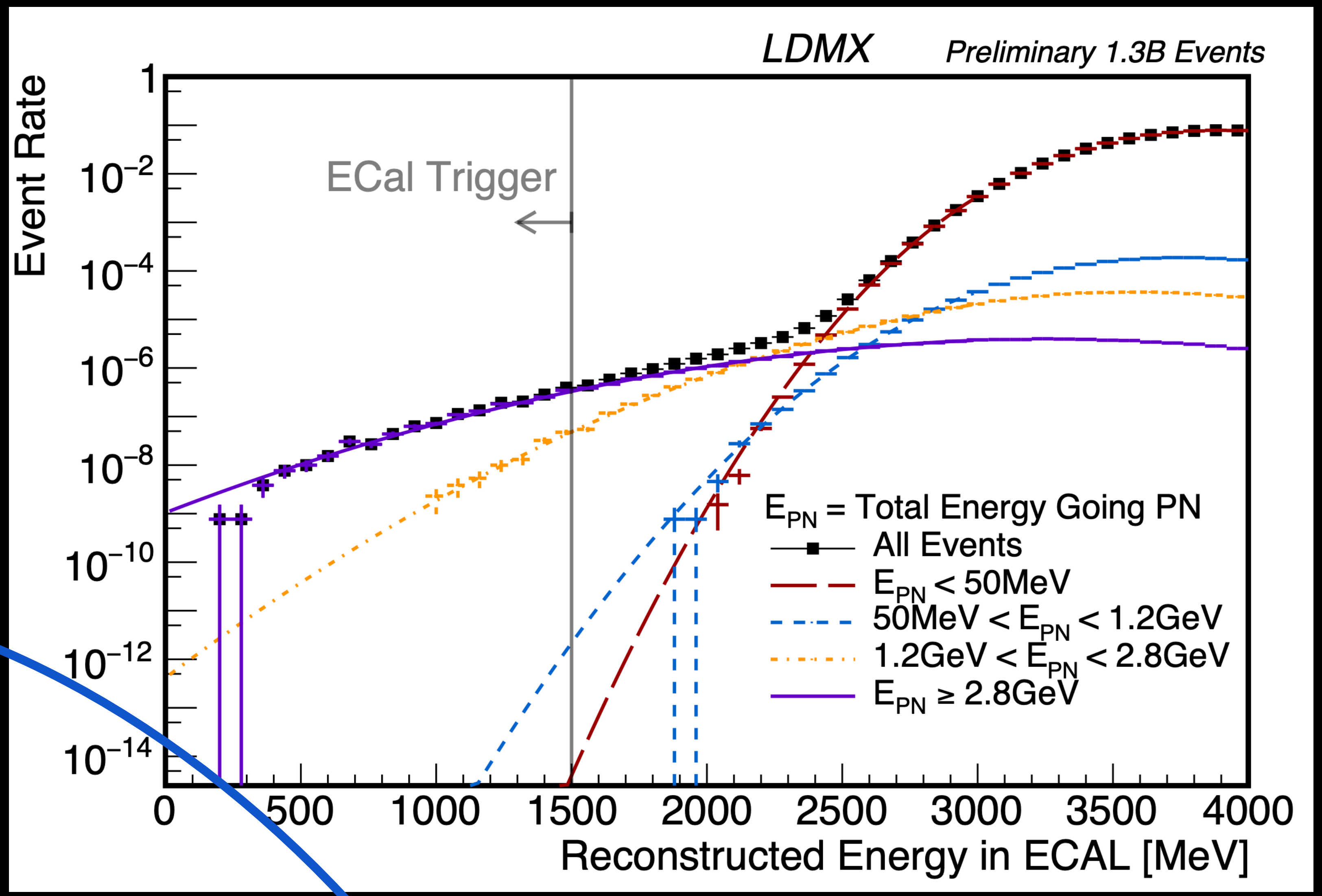
Exploit high-granularity Ecal features

down to 10^5

- BDT trained to reject photonuclear events in Ecal
- MIP tracking powerful on sparse events

Veto on Hcal activity

- allow only a few photoelectrons
- deep enough to tease out even single neutrons



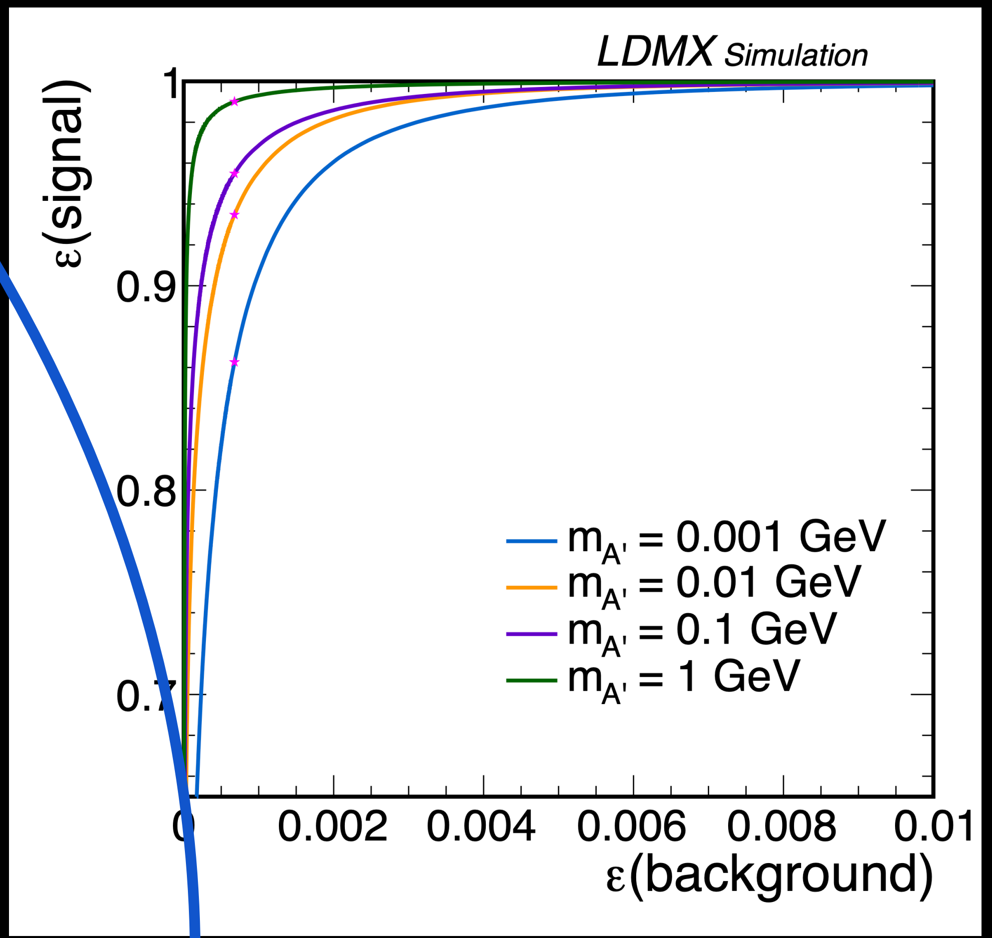


	Photo-nuclear		Muon conversion	
	Target-area	ECal	Target-area	ECal
EoT equivalent	4×10^{14}	2.1×10^{14}	8.2×10^{14}	2.4×10^{15}
Total events simulated	8.8×10^{11}	4.65×10^{11}	6.27×10^{8}	8×10^{10}
Trigger, ECal total energy < 1.5 GeV	1×10^{8}	2.63×10^{8}	1.6×10^{7}	1.6×10^{8}
Single track with $p < 1.2$ GeV	2×10^{7}	2.34×10^{8}	3.1×10^{4}	1.5×10^{8}
ECal BDT (> 0.99)	9.4×10^{5}	1.32×10^{5}	< 1	< 1
HCal max PE < 5	< 1	10	< 1	< 1
ECal MIP tracks = 0	< 1	< 1	< 1	< 1

Event selection/vetoes

Goal: no background from ~10^{14} electrons on target

most challenging background:

First handle: recoiling electron

down to 10^8

- trigger on Ecal E < 1.5 GeV (1e);
- select recoil electron momentum < 1.2 GeV
- veto if number of outgoing tracks > incoming tracks

Exploit high-granularity Ecal features

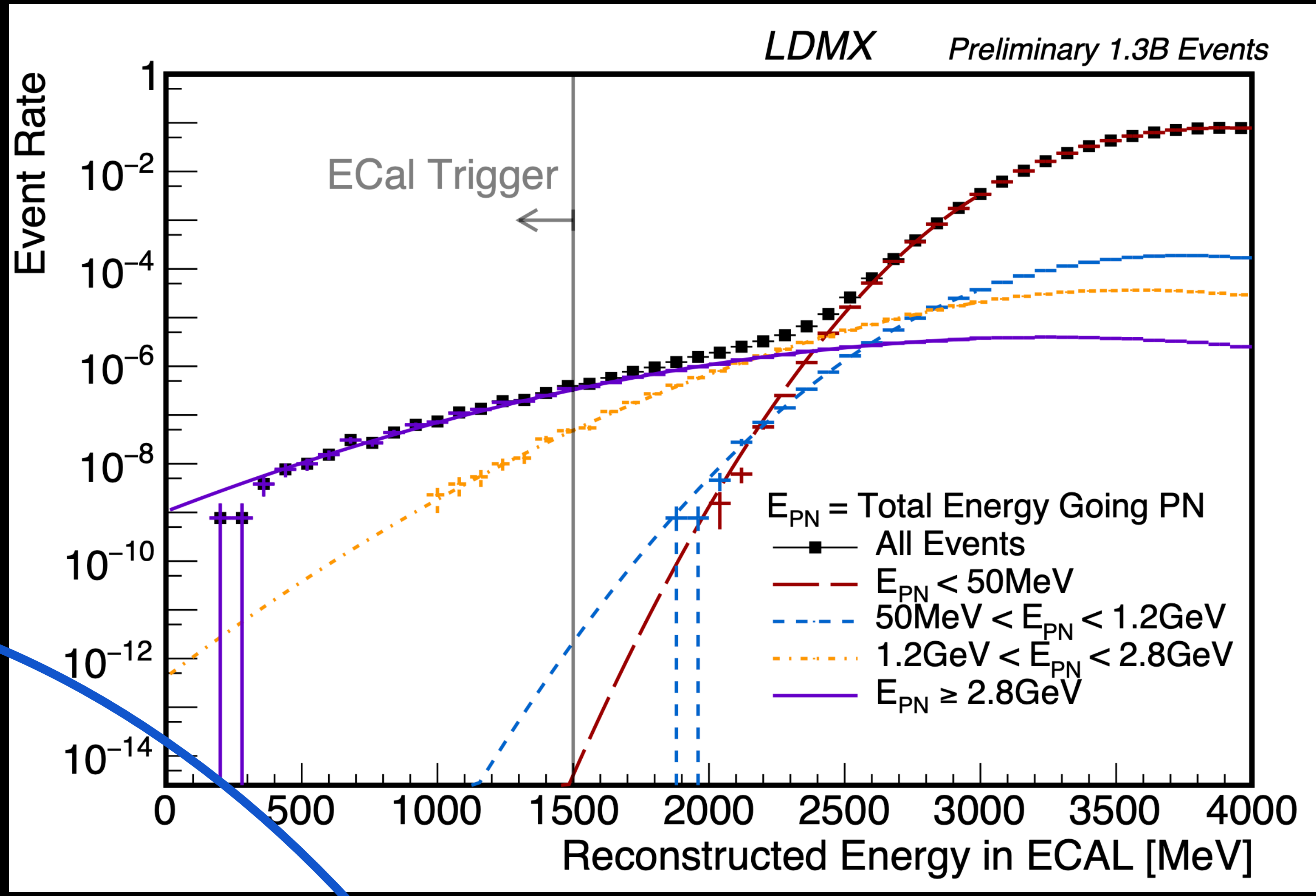
down to 10^5

- BDT trained to reject photonuclear events in Ecal
- MIP tracking powerful on sparse events

Veto on Hcal activity

down to 10

- allow only a few photoelectrons
- deep enough to tease out even single neutrons



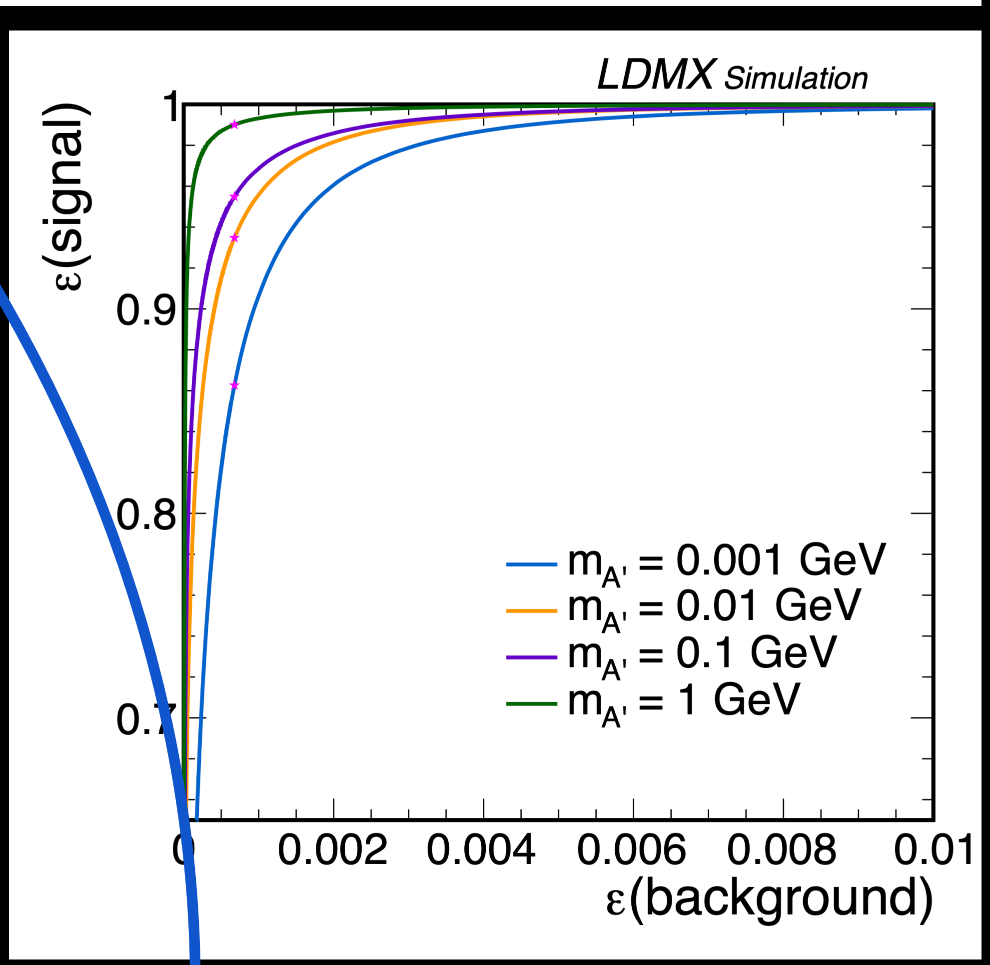


	Photo-nuclear		Muon conversion	
	Target-area	ECal	Target-area	ECal
EoT equivalent	4×10^{14}	2.1×10^{14}	8.2×10^{14}	2.4×10^{15}
Total events simulated	8.8×10^{11}	4.65×10^{11}	6.27×10^{8}	8×10^{10}
Trigger, ECal total energy < 1.5 GeV	1×10^{8}	2.63×10^{8}	1.6×10^{7}	1.6×10^{8}
Single track with p < 1.2 GeV	2×10^{7}	2.34×10^{8}	3.1×10^{4}	1.5×10^{8}
ECal BDT (> 0.99)	9.4×10^{5}	1.32×10^{5}	< 1	< 1
HCal max PE < 5	< 1	10	< 1	< 1
ECal MIP tracks = 0	< 1	< 1	< 1	< 1

TAUP 2023

LK Bryngemark

LDMX

Event selection/vetoes

Goal: no background from ~10^{14} electrons on target

most challenging background:

First handle: recoiling electron

down to 10^8

- trigger on Ecal E < 1.5 GeV (1e);
- select recoil electron momentum < 1.2 GeV
- veto if number of outgoing tracks > incoming tracks

Exploit high-granularity Ecal features

down to 10^5

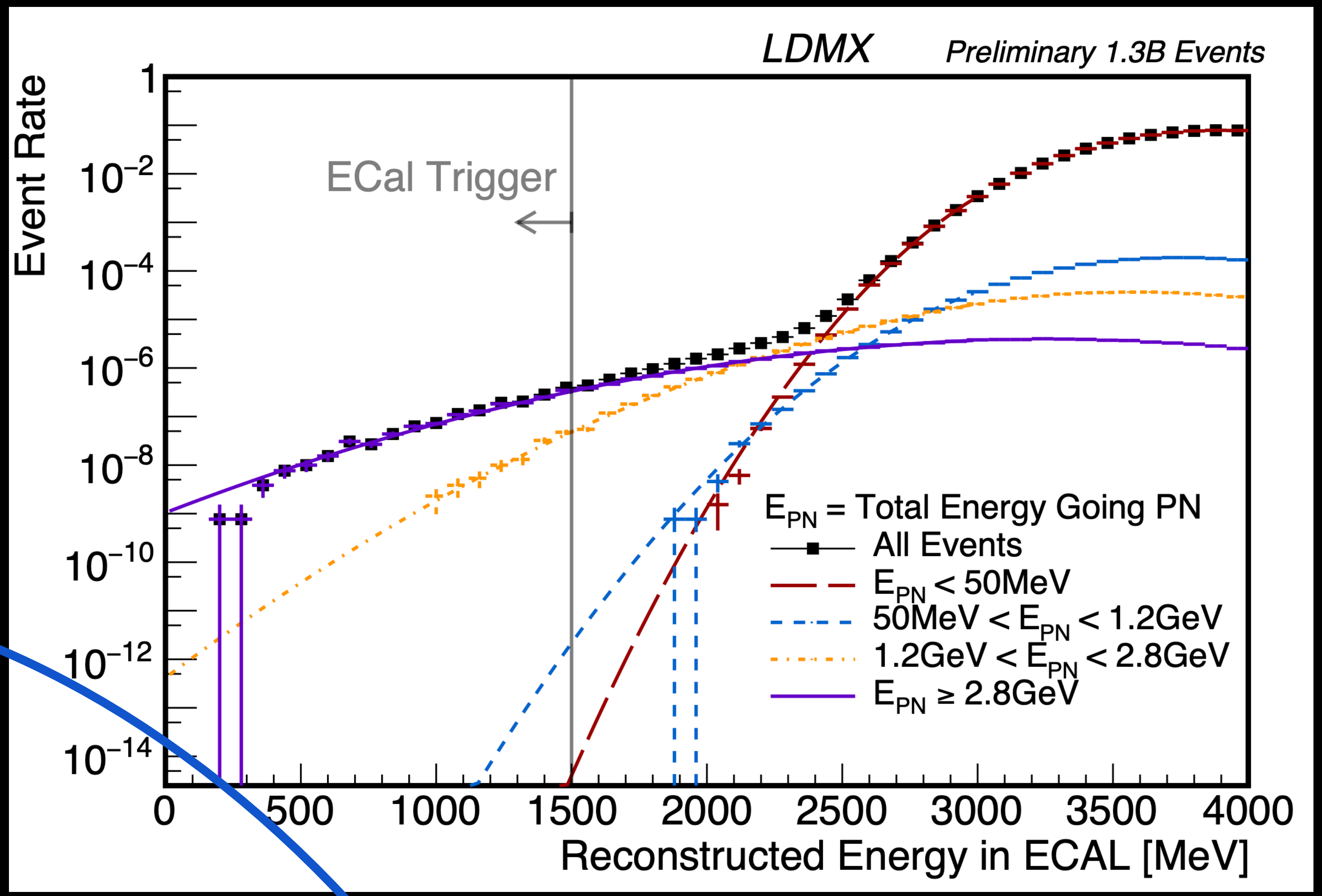
- BDT trained to reject photonuclear events in Ecal
- MIP tracking powerful on sparse events

down to <1!

Veto on Hcal activity

down to 10

- allow only a few photoelectrons
- deep enough to tease out even single neutrons



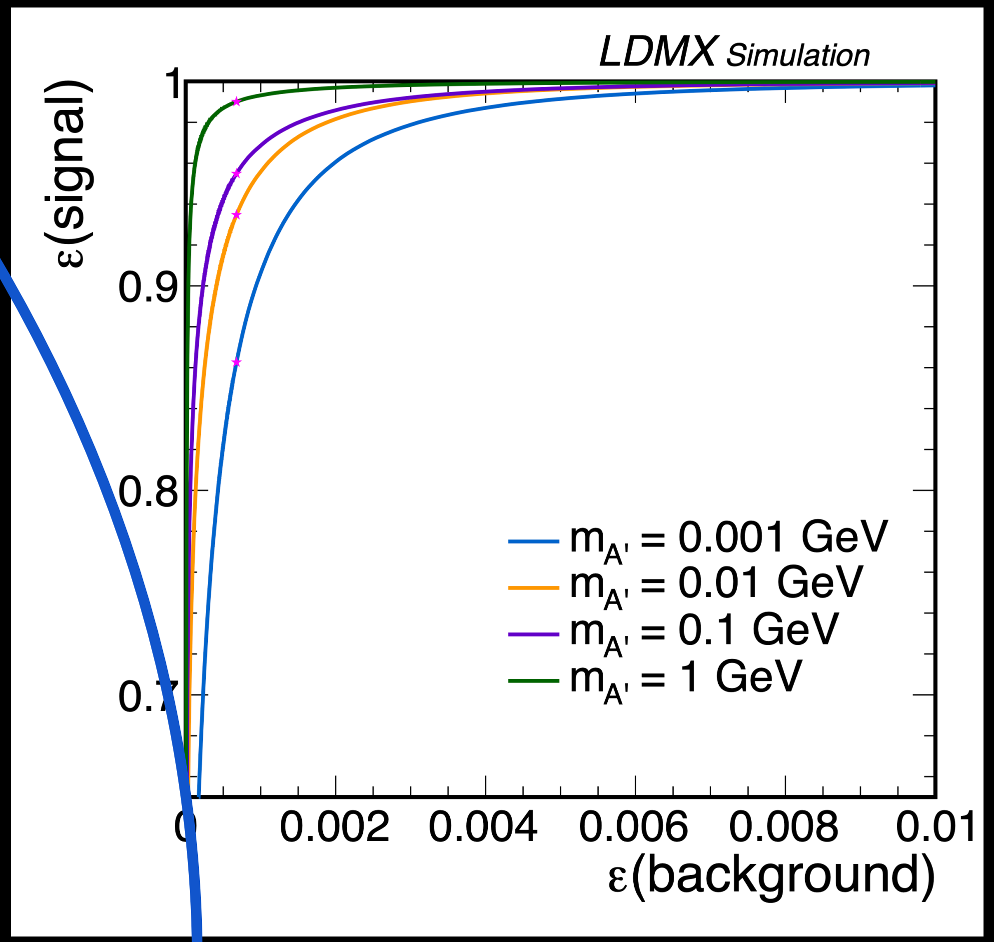
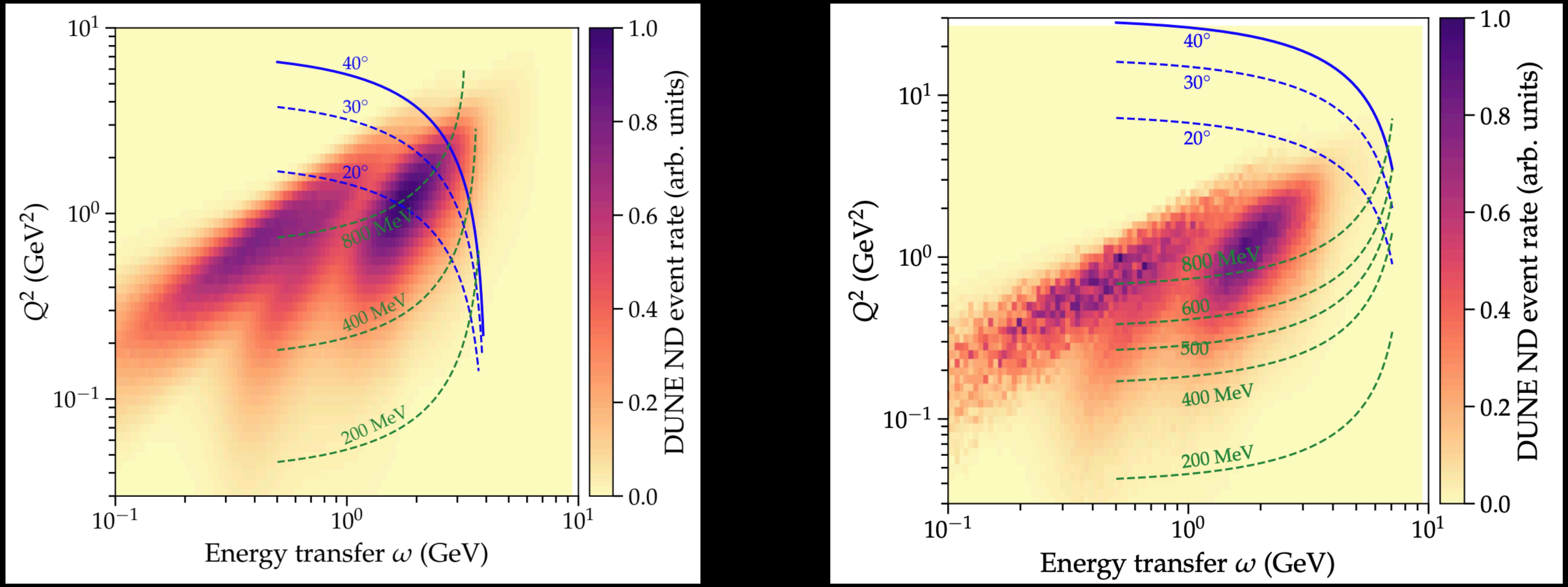


	Photo-nuclear		Muon conversion	
	Target-area	ECal	Target-area	ECal
EoT equivalent	4×10^{14}	2.1×10^{14}	8.2×10^{14}	2.4×10^{15}
Total events simulated	8.8×10^{11}	4.65×10^{11}	6.27×10^{8}	8×10^{10}
Trigger, ECal total energy < 1.5 GeV	1×10^{8}	2.63×10^{8}	1.6×10^{7}	1.6×10^{8}
Single track with p < 1.2 GeV	2×10^{7}	2.34×10^{8}	3.1×10^{4}	1.5×10^{8}
ECal BDT (> 0.99)	9.4×10^{5}	1.32×10^{5}	< 1	< 1
HCal max PE < 5	< 1	10	< 1	< 1
ECal MIP tracks = 0	< 1	< 1	< 1	< 1

Electronuclear measurements at 4 and 8 GeV

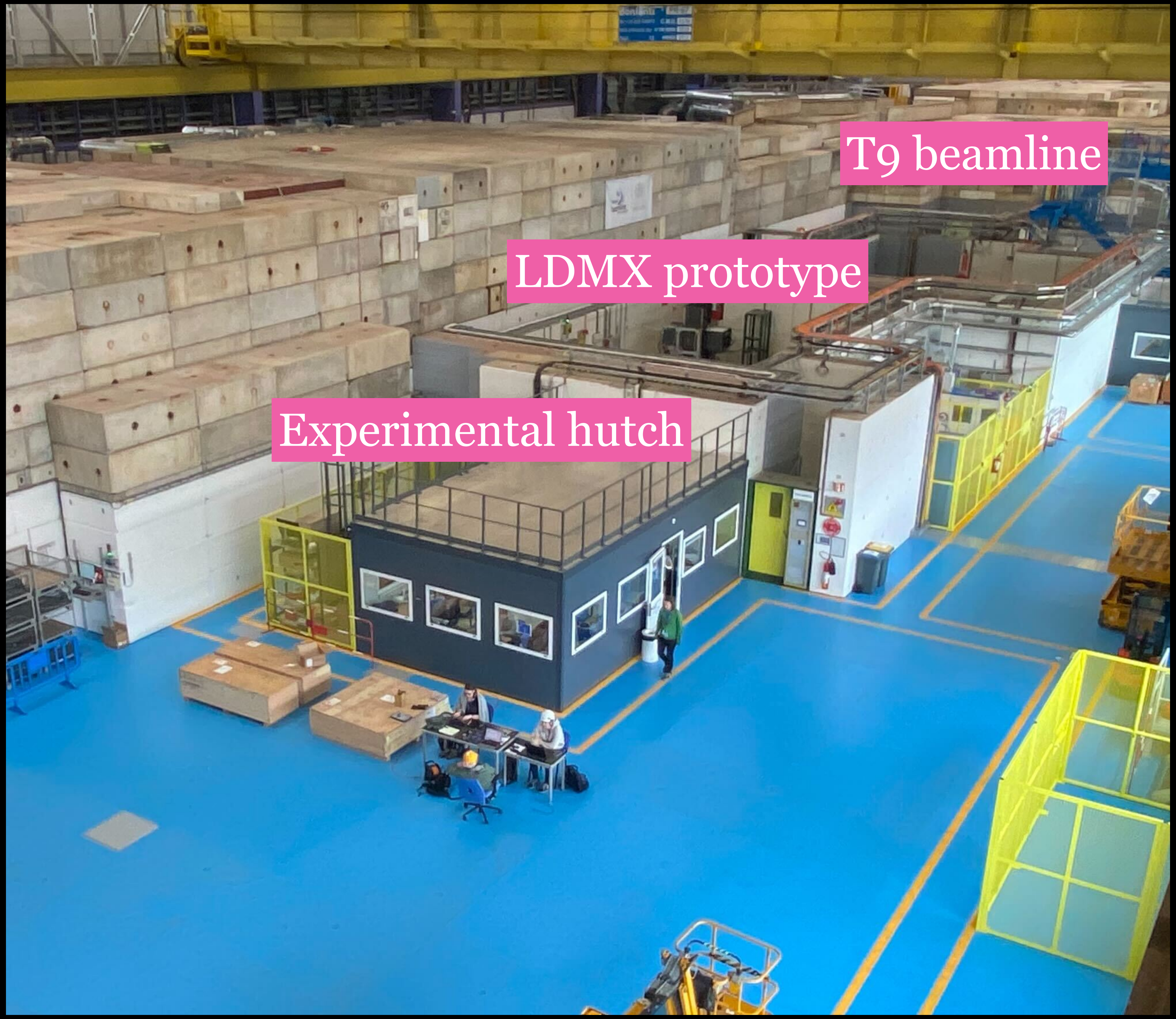


Curves show LDMX acceptance, color scale represents event rate for DIS events in DUNE, indicating the relevant phase space

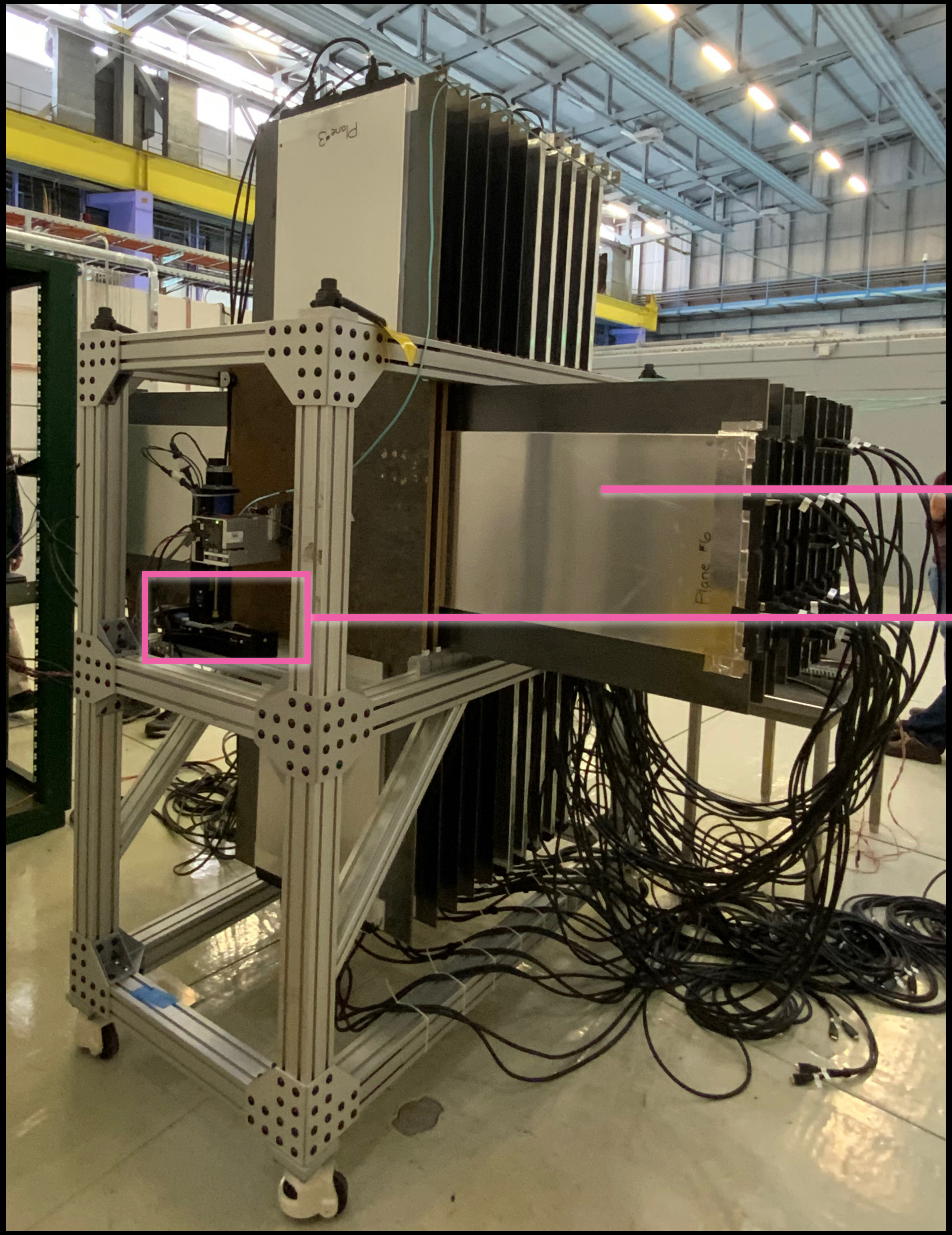
Prototype at CERN Testbeam

CERN East Area: T9 beamline

- PS protons → East Area
- Beam via North Target to T9: e, μ, π
  - Beamline's configuration isolates final particle species from secondary beam
    - ~1k particles/spill
    - Particle ID: Cherenkov detectors
- Maximum intensity: Few million particles/spill

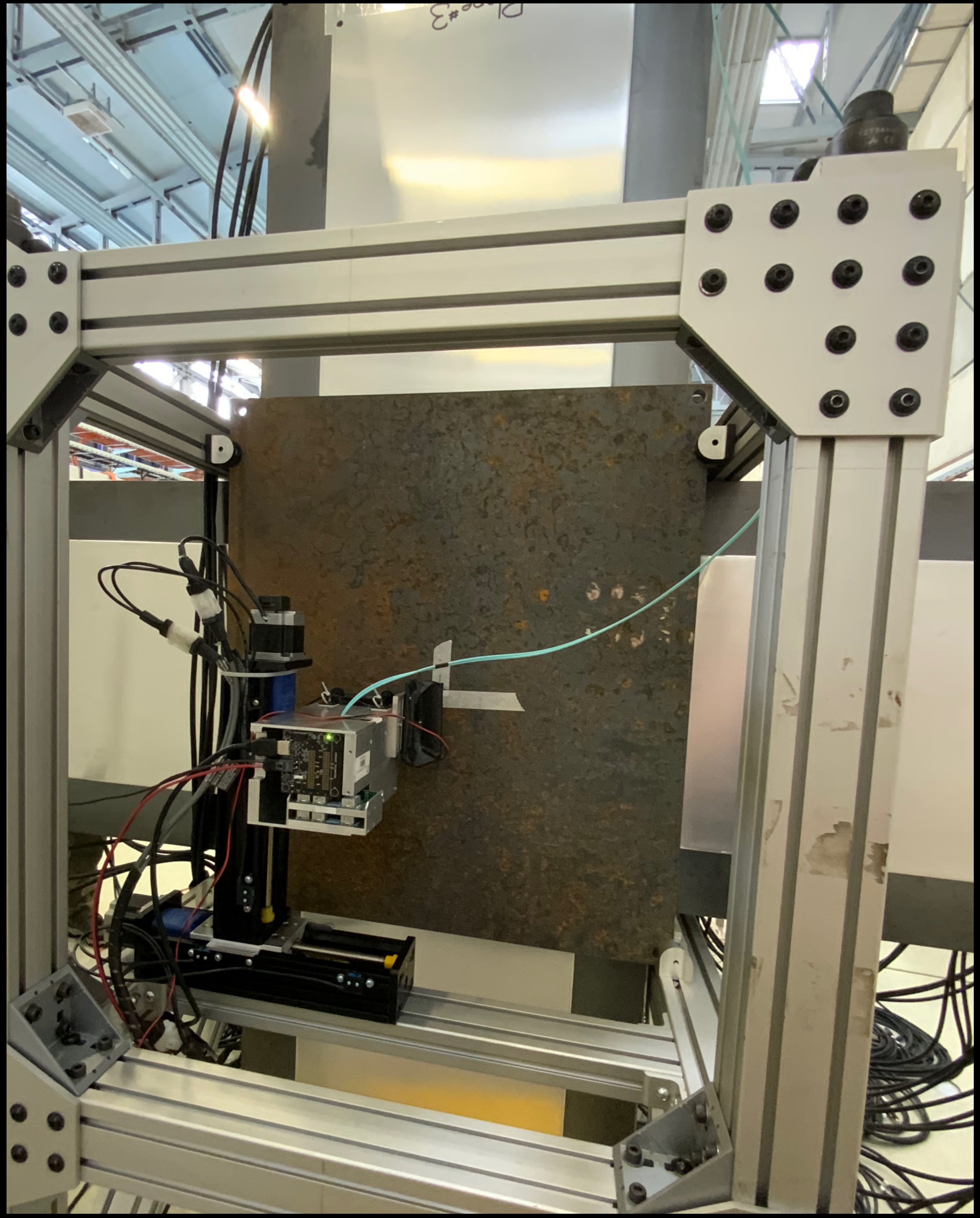


Prototype in the beam area

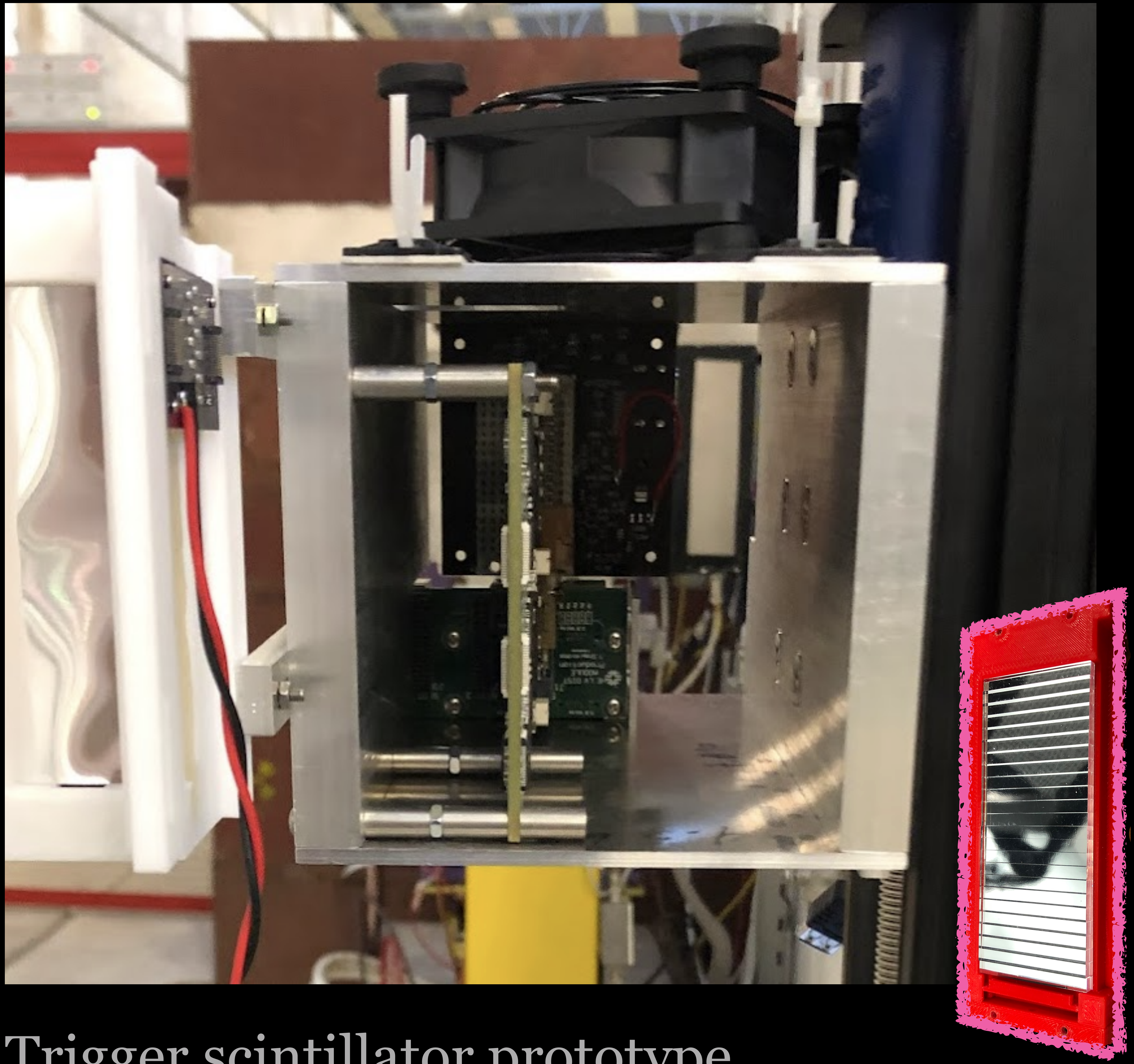


Hadronic Calorimeter
(HCal)

Trigger scintillator
(TS)



Prototype subdetectors



Trigger scintillator prototype

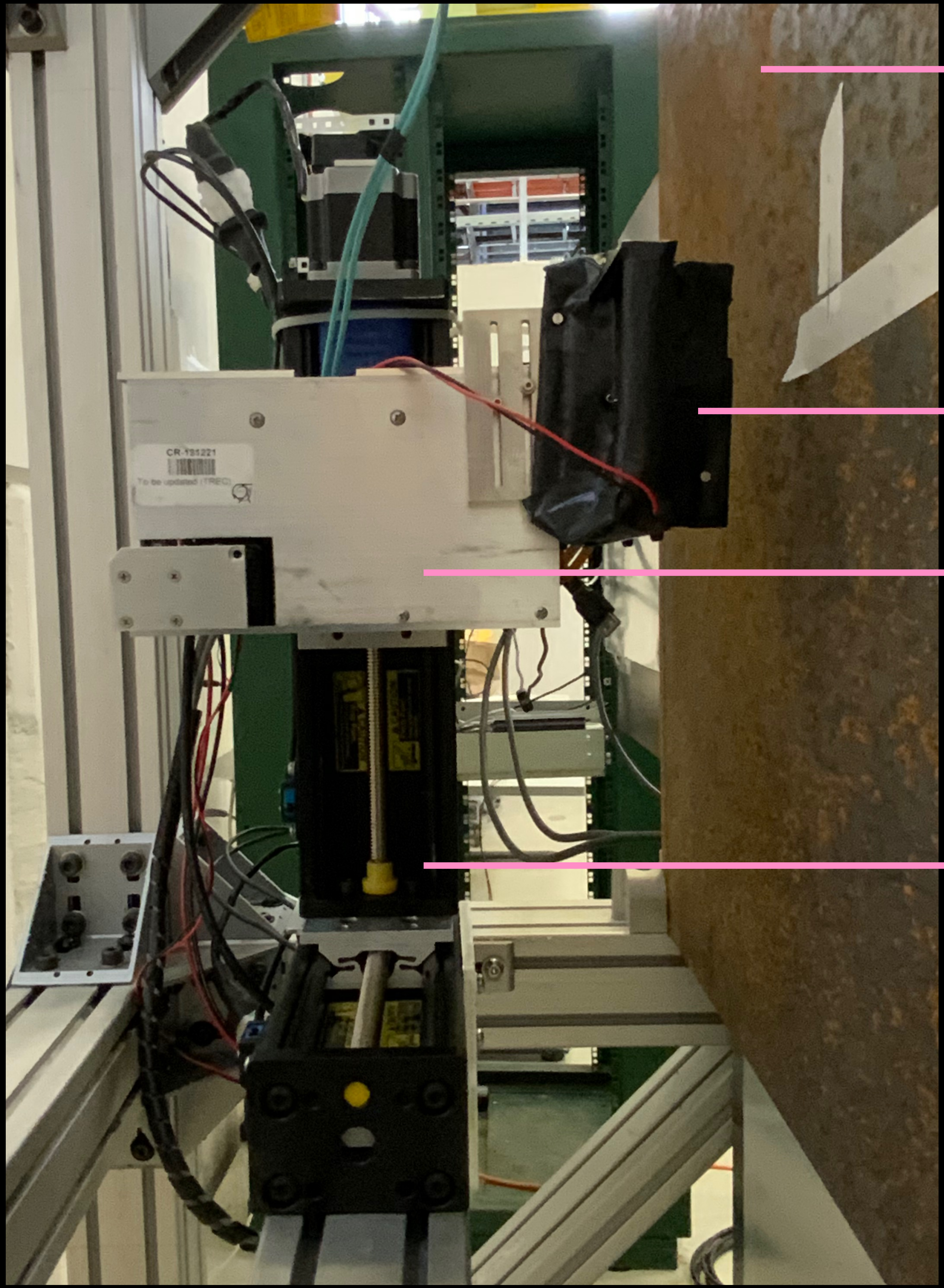
Inset: Aluminium-coated bare scintillator bar array in its 3D-printed holder

Hadronic calorimeter scintillator bars layer

Inset: Fibre optic cable pokes through bare scintillator bar

CERN test beam, March-April 2022

Trigger scintillator (TS) prototype

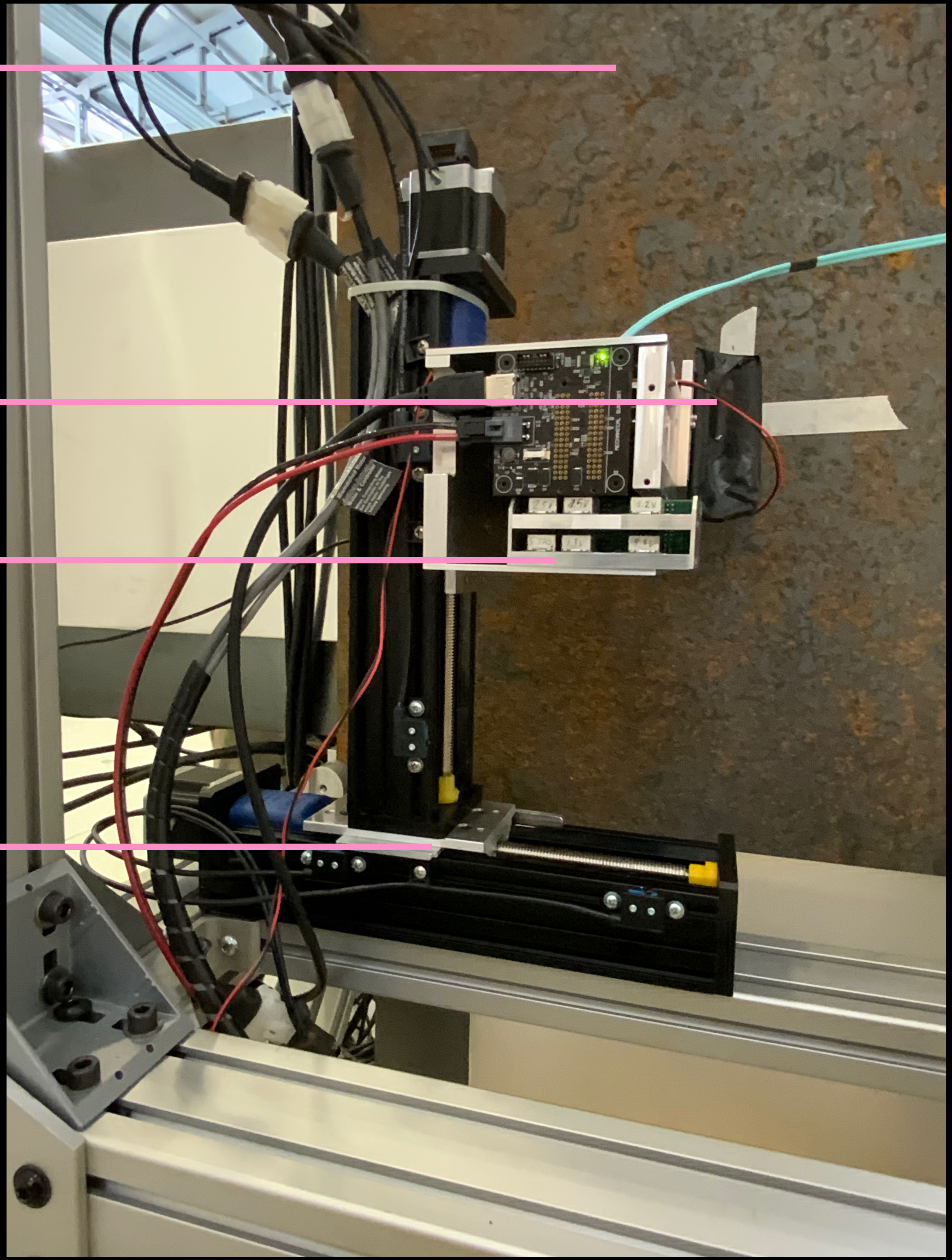


First steel absorber layer
of the hadronic calorimeter

TS plastic scintillator
encased in black tape
for light tightness

TS readout electronics

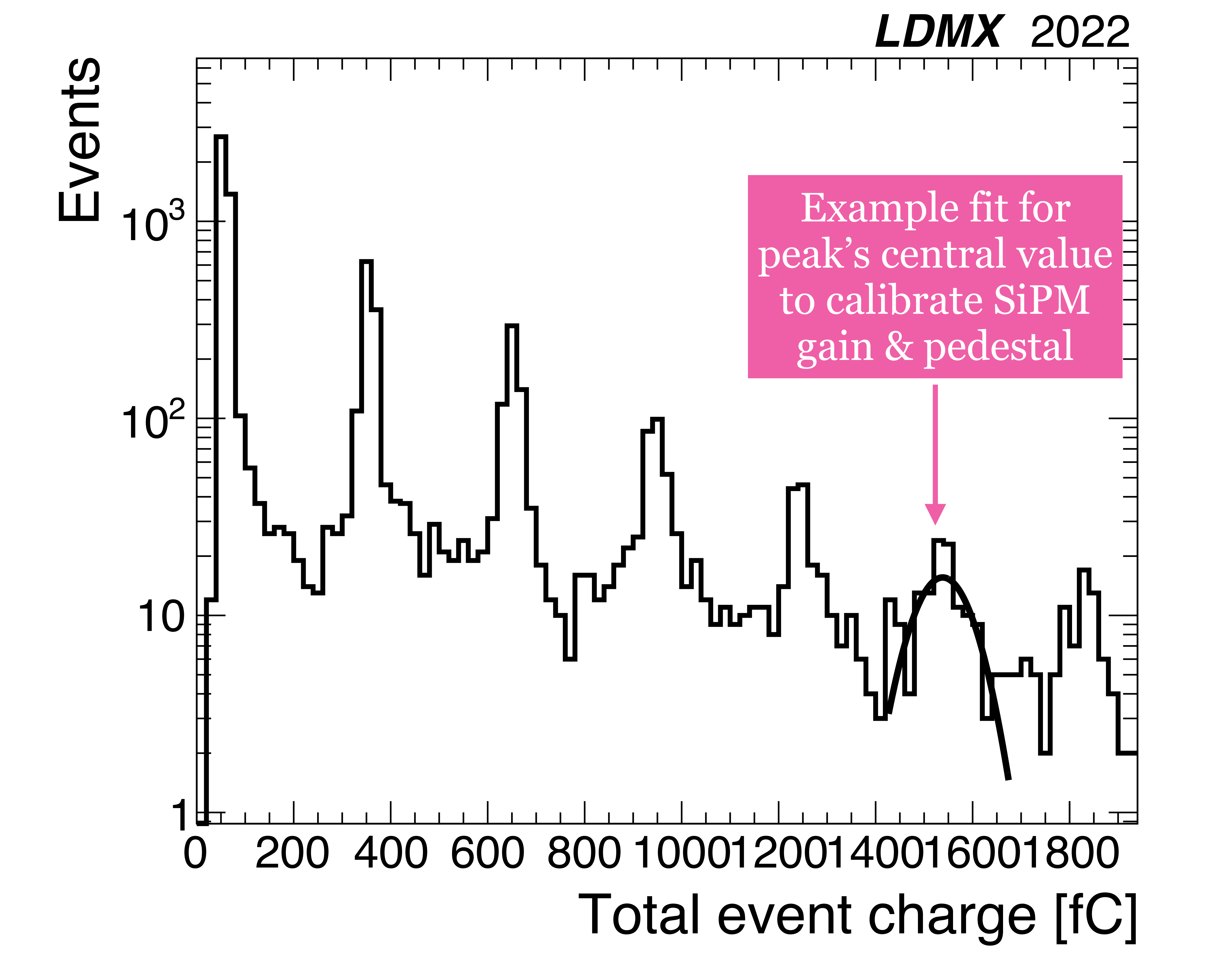
Gantry to adjust
position of TS in beamspot



TS: Single photoelectron spectrum

Gain calibration

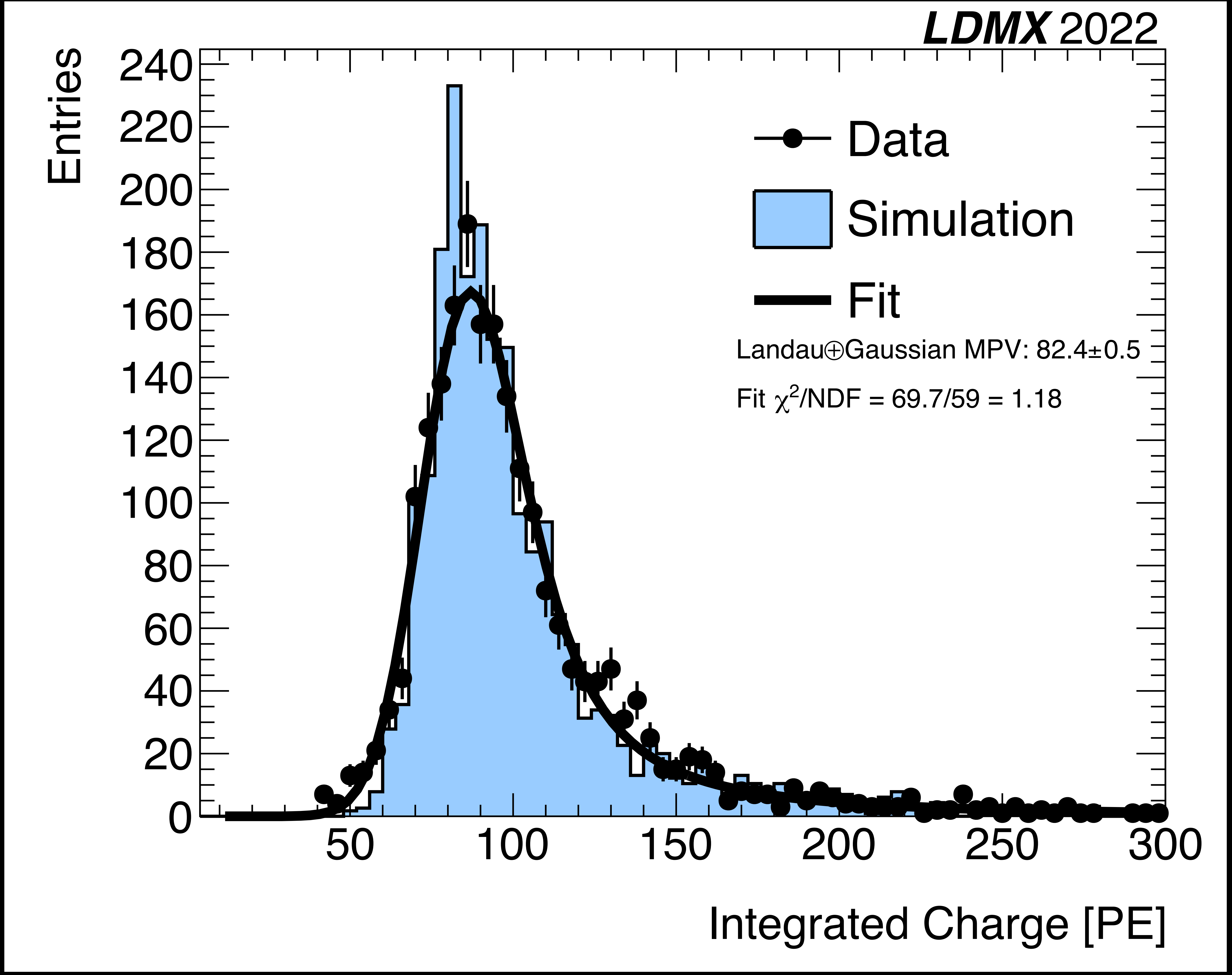
- Integrated charge/event for each TS channel
- Peaks
  - 1st: System pedestal
  - Additional: integer numbers of Si photomultiplier pixels firing



TS: Plastic MIP response

4 GeV electron beam

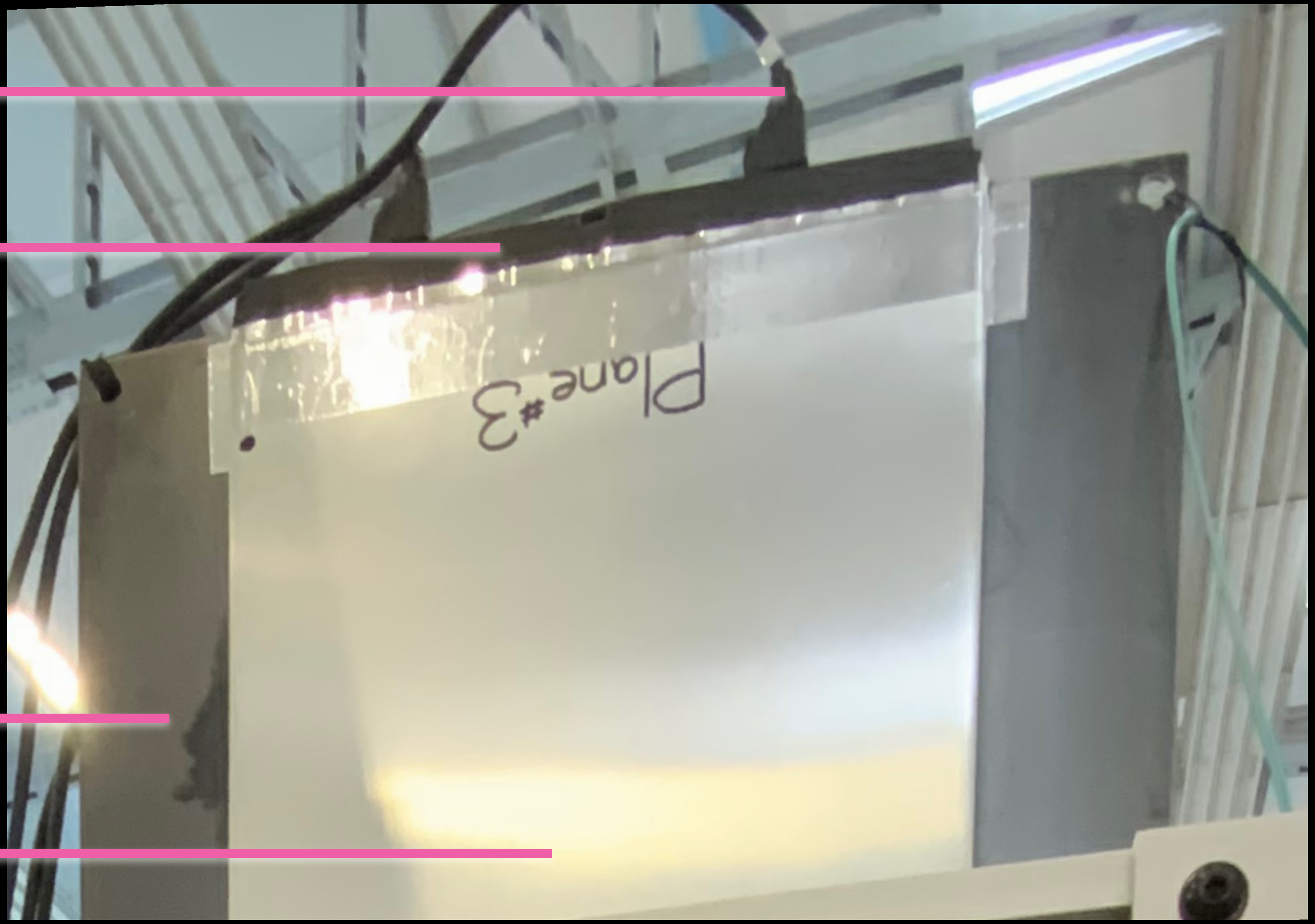
- Amplitude: Sum of charge measured for several time samples
    - Normalized to 1 photoelectron equivalent
- Most probable value of channel's response to MIP = 82 photoelectrons
    - Model: Landau + Gaussian convolution



Hadronic calorimeter (HCal) prototype

19 alternating layers, usually[1] Al cover • scintillator bars • steel absorber plate

6 HGCRoc boards (384 total channels; 64 per board) required for readout



Example: Section of a vertical layer of the HCal

[1] First HCal layer is steel absorber, then scintillator bars

CERN test beam, March-April 2022

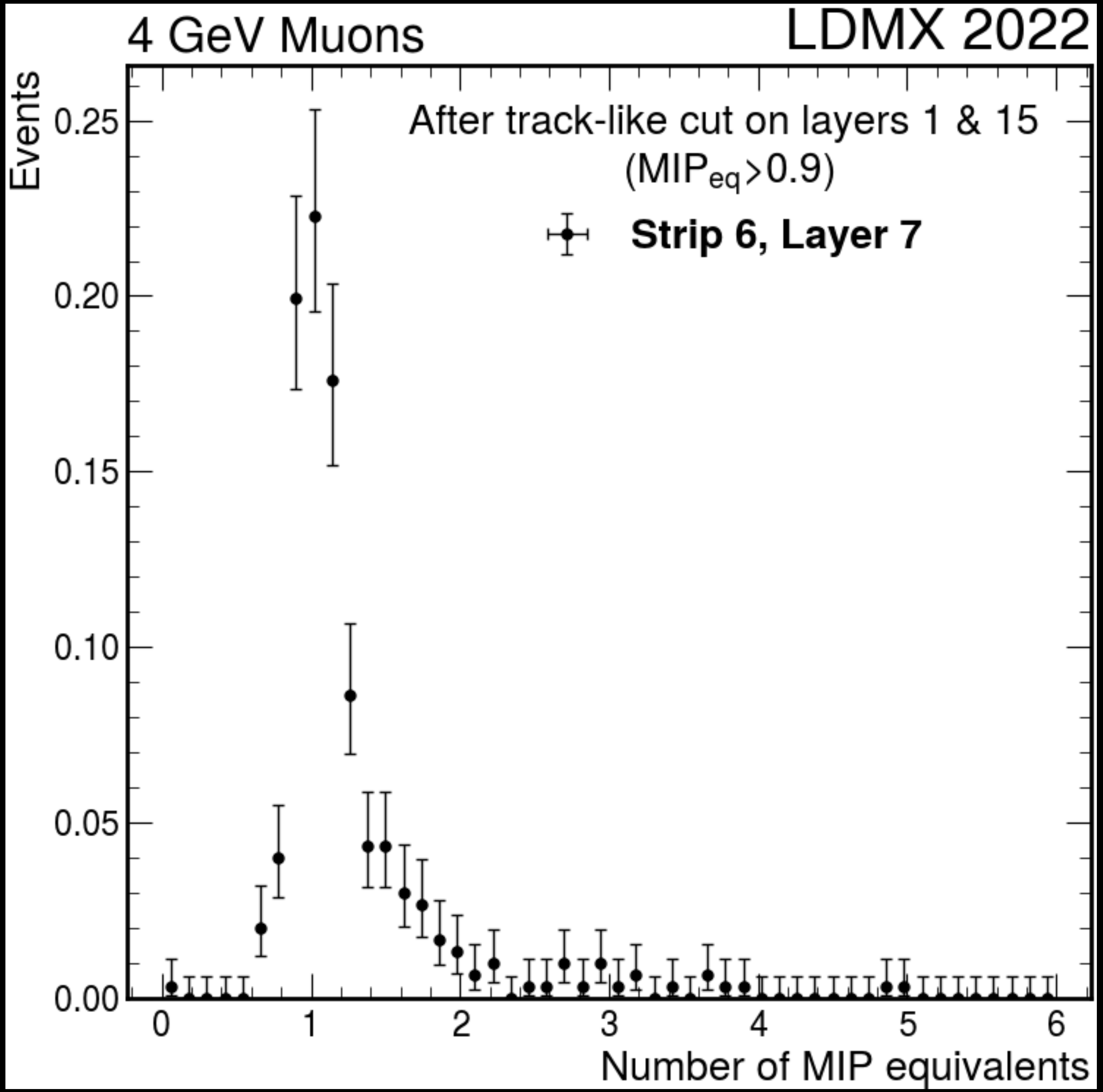
HCal: MIP response

4 GeV muon beam

- Sum of ADC counts in a single layer and strip of HCal prototype

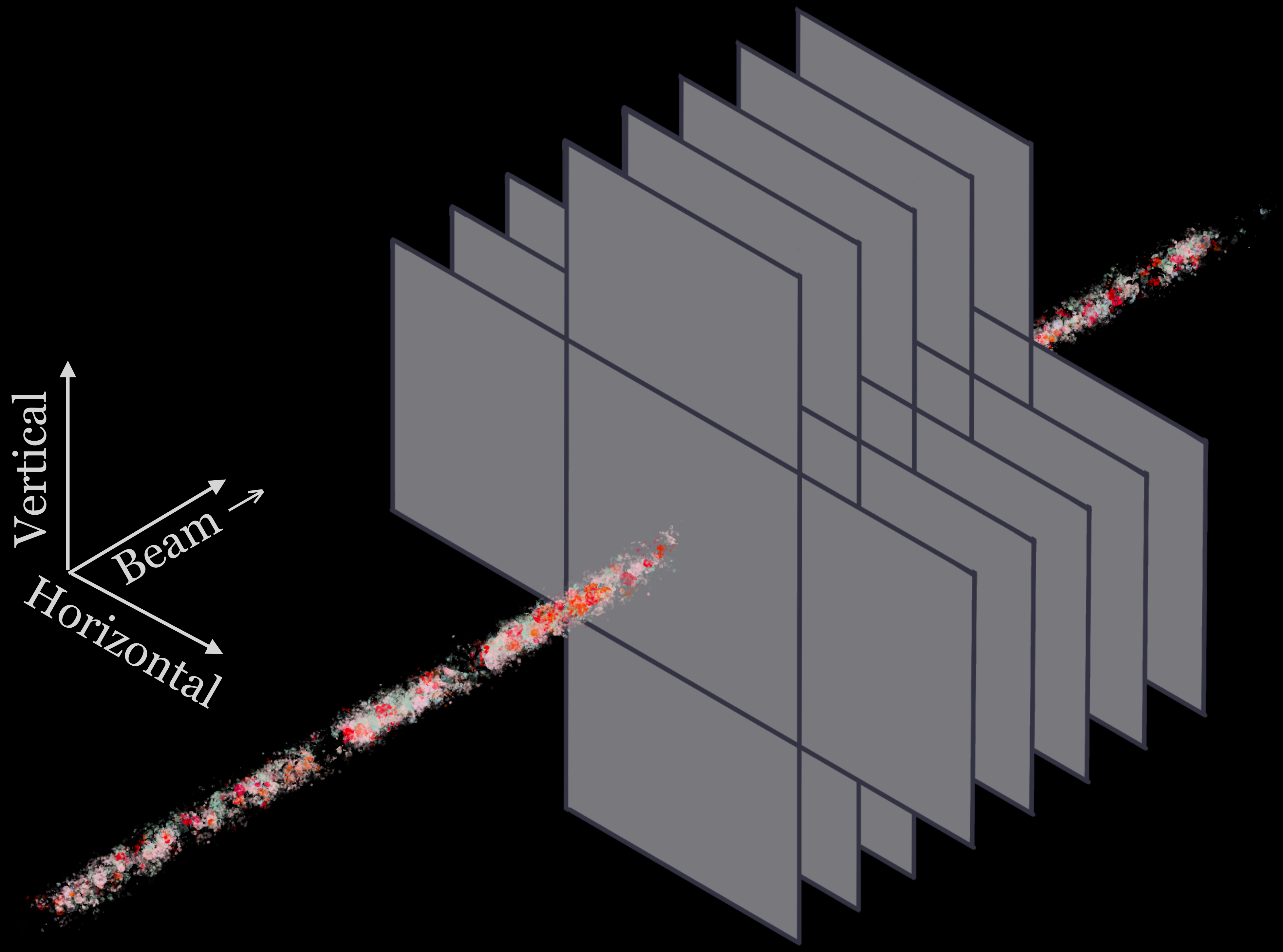
$$N_{MIPeq} = \frac{\sum \text{ADC counts}}{\text{Measured value for 1 MIP}}$$

- Require MIP-like signature in entrance & exit of HCal



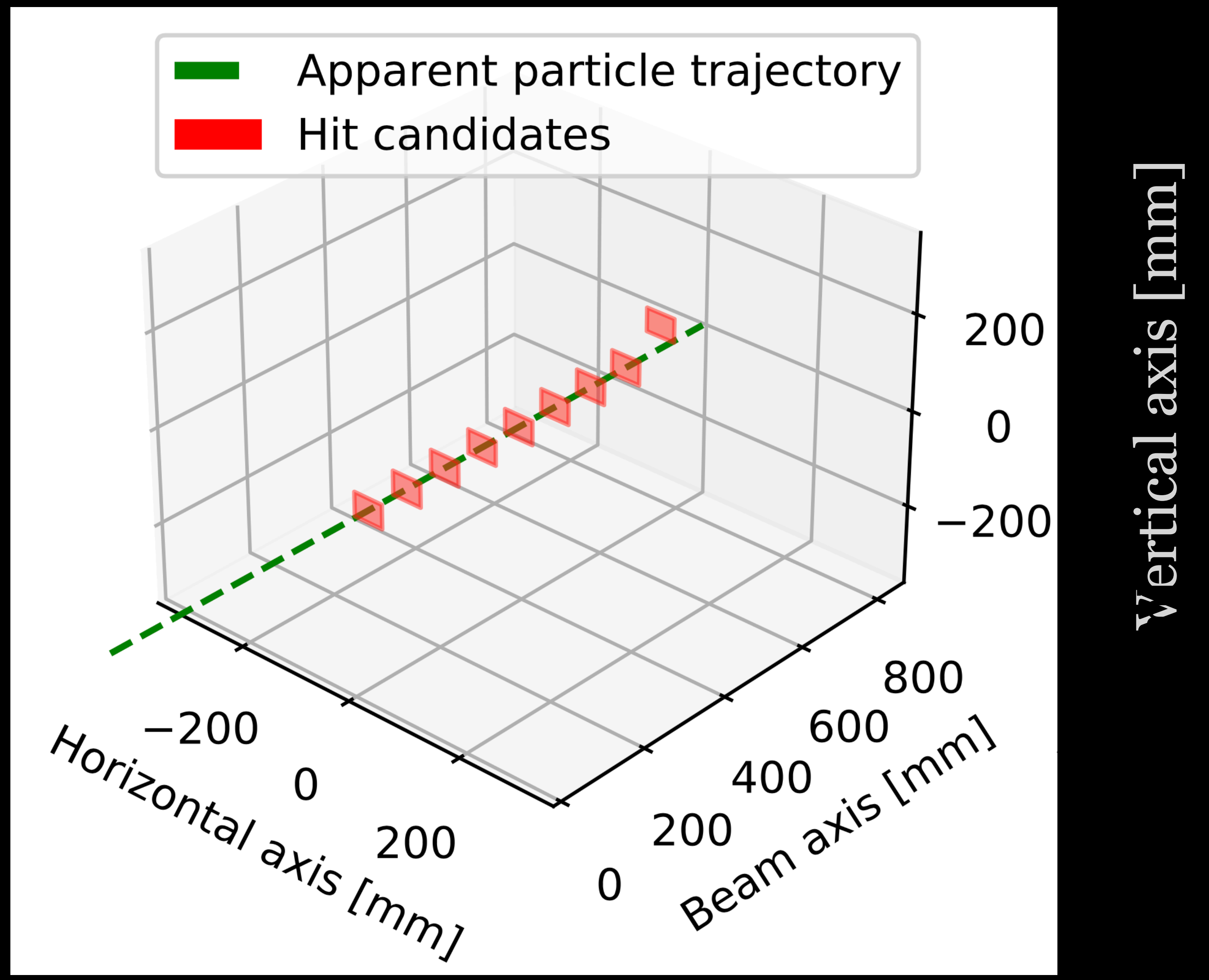
CERN test beam, March-April 2022

Beam & HCal orientation



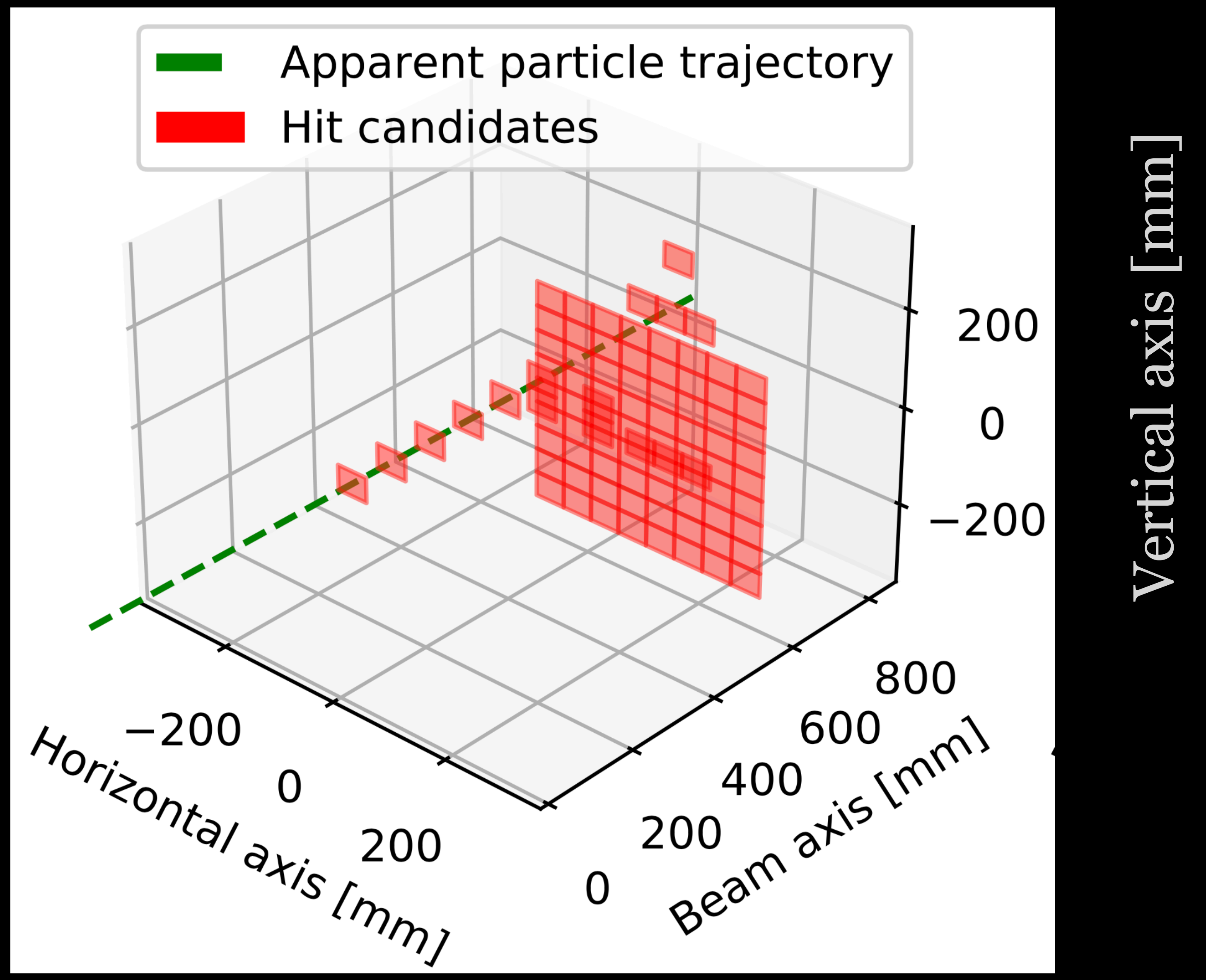
MIP candidate

Sequential, crisp signature in HCal

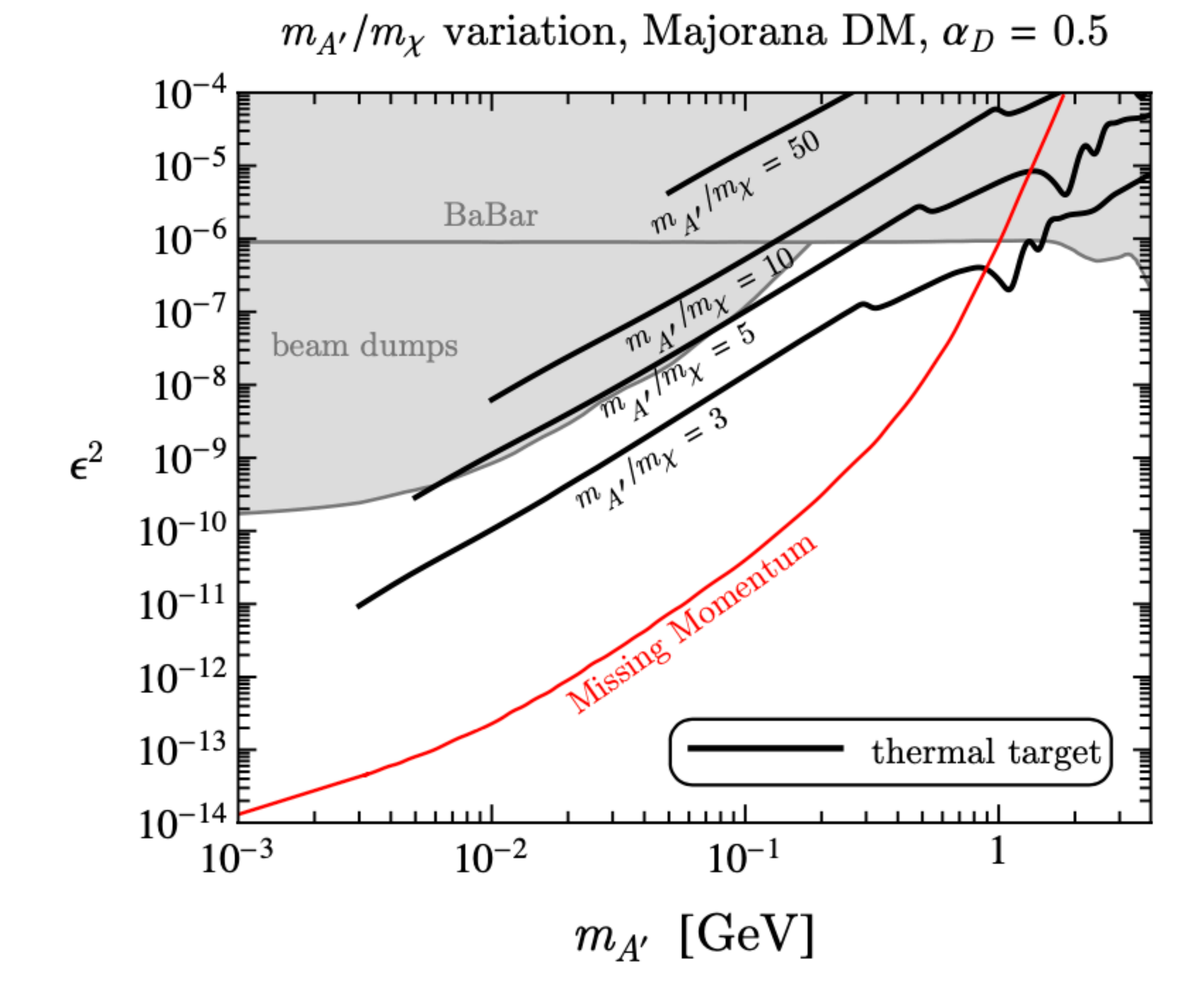


Pion candidate

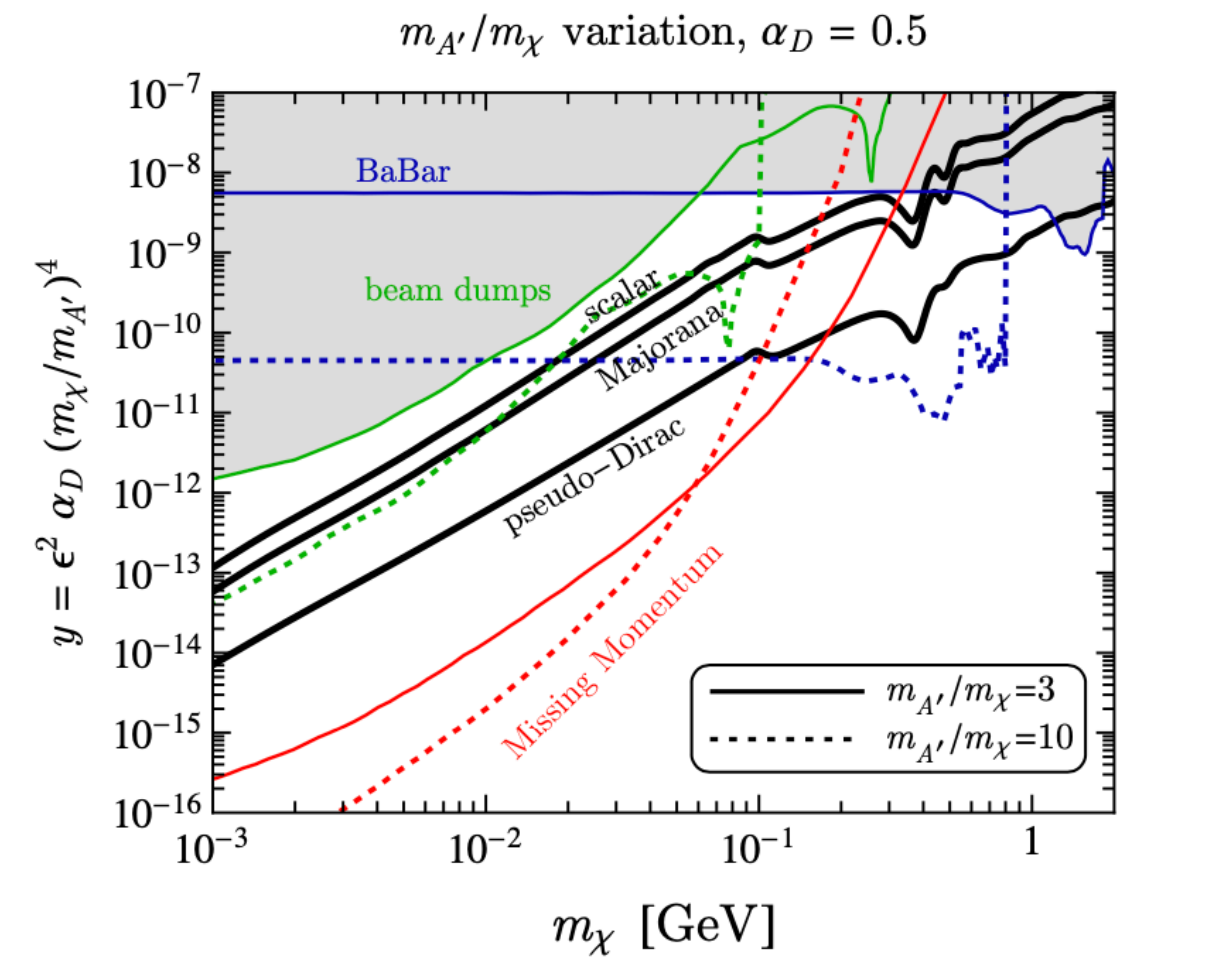
MIP-like deposits followed by cloud in HCal



Varying mass ratio

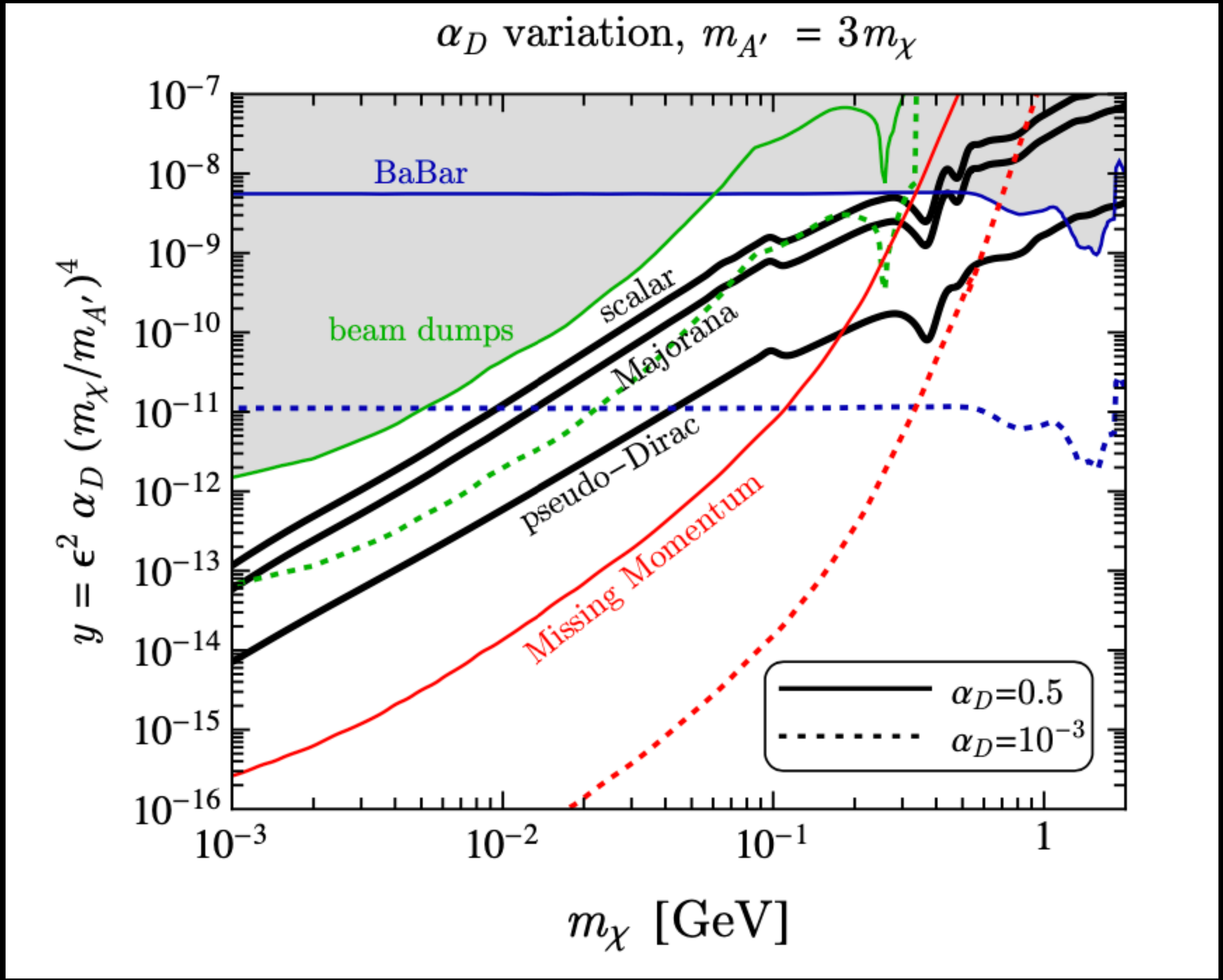


Expressed in ϵ^2, thermal curves move, accelerator line stays



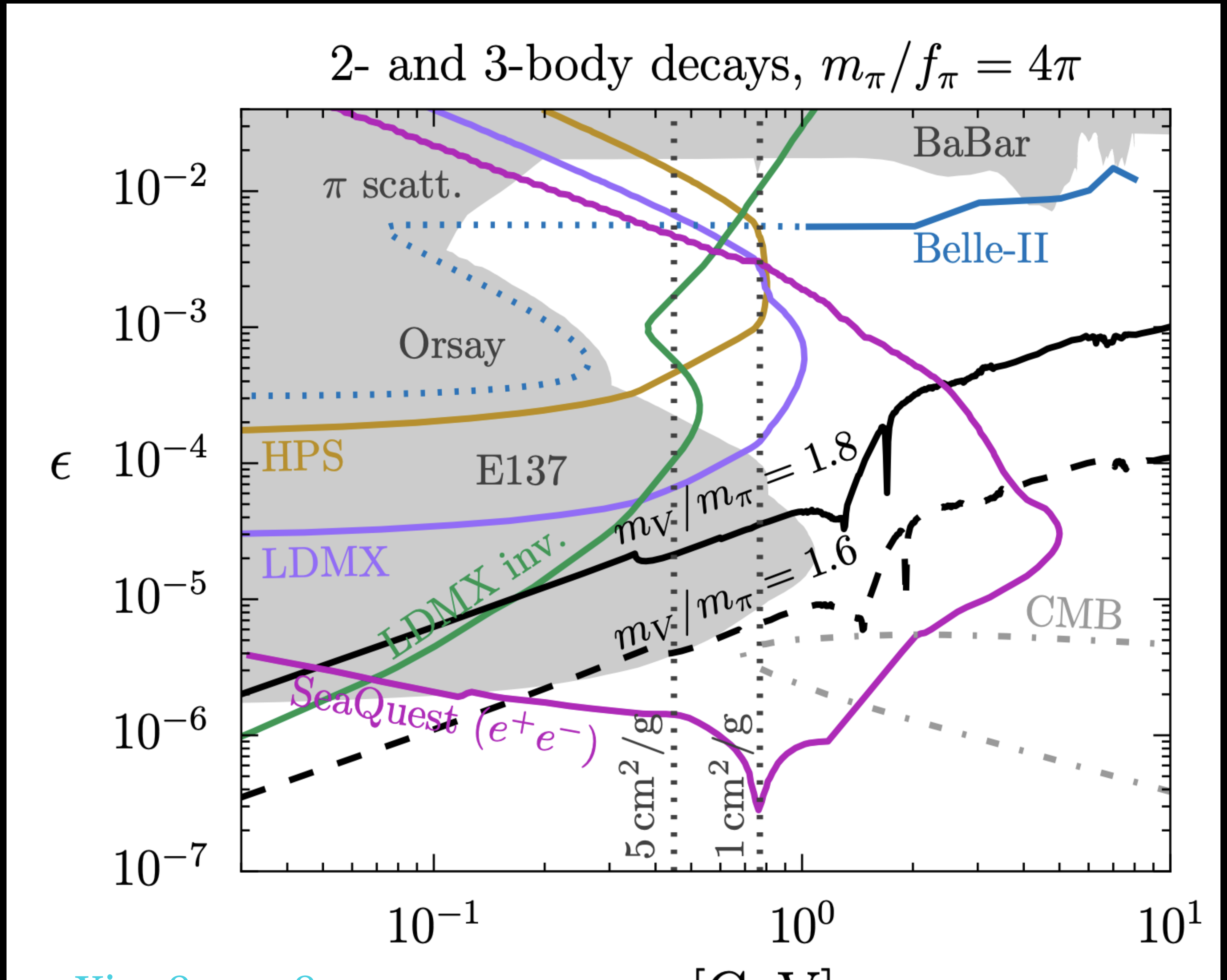
Expressed in y, thermal curves stay, accelerator lines tilt

Varying coupling

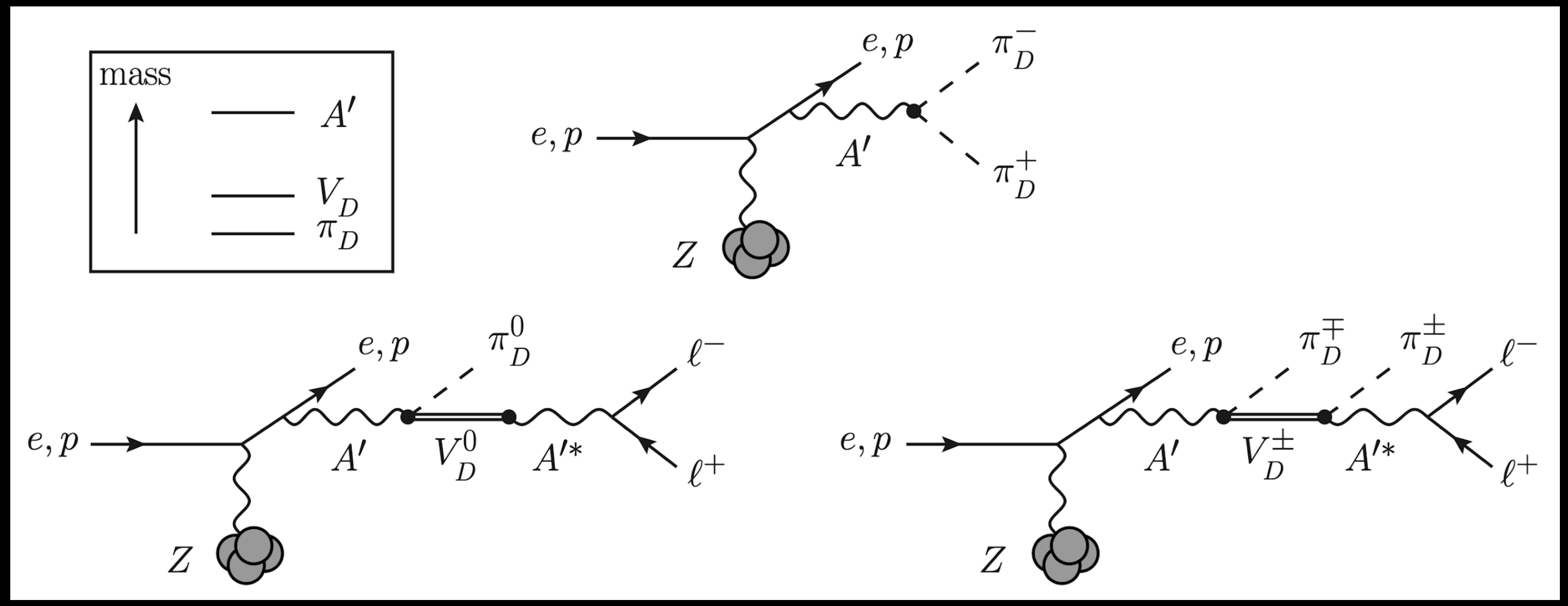


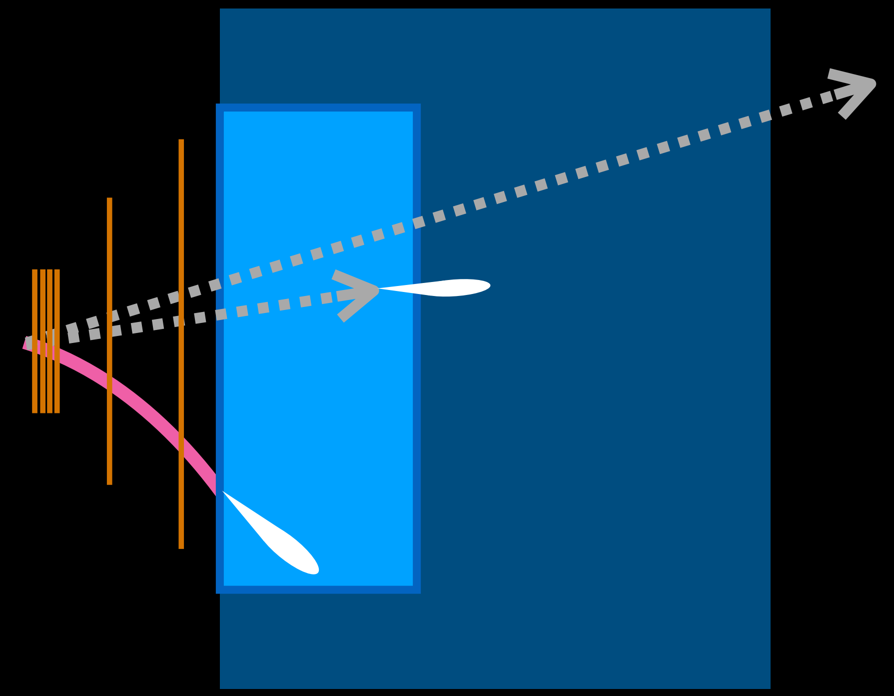
Bottom: parameter space in the y vs. m_χ plane where the solid curves are identical to those shown in Fig. 5 (with $\alpha_D = 0.5$), but the dotted curves show how the constraints and projections vary for the choice $\alpha_D = 10^{-3}$. For fixed values of y, a smaller α_D requires a larger ϵ^2 (i.e. larger mediator coupling), which makes that parameter point *easier* to constrain. Hence, accelerator sensitivity generally improves in the y vs. m_χ plane for smaller α_D. Note that the thermal freeze-out curves in this plane are identical for both values of α_D shown here because the thermal abundance scales with y.

Expected sensitivity: visible signatures (example)



arXiv:1801.05805

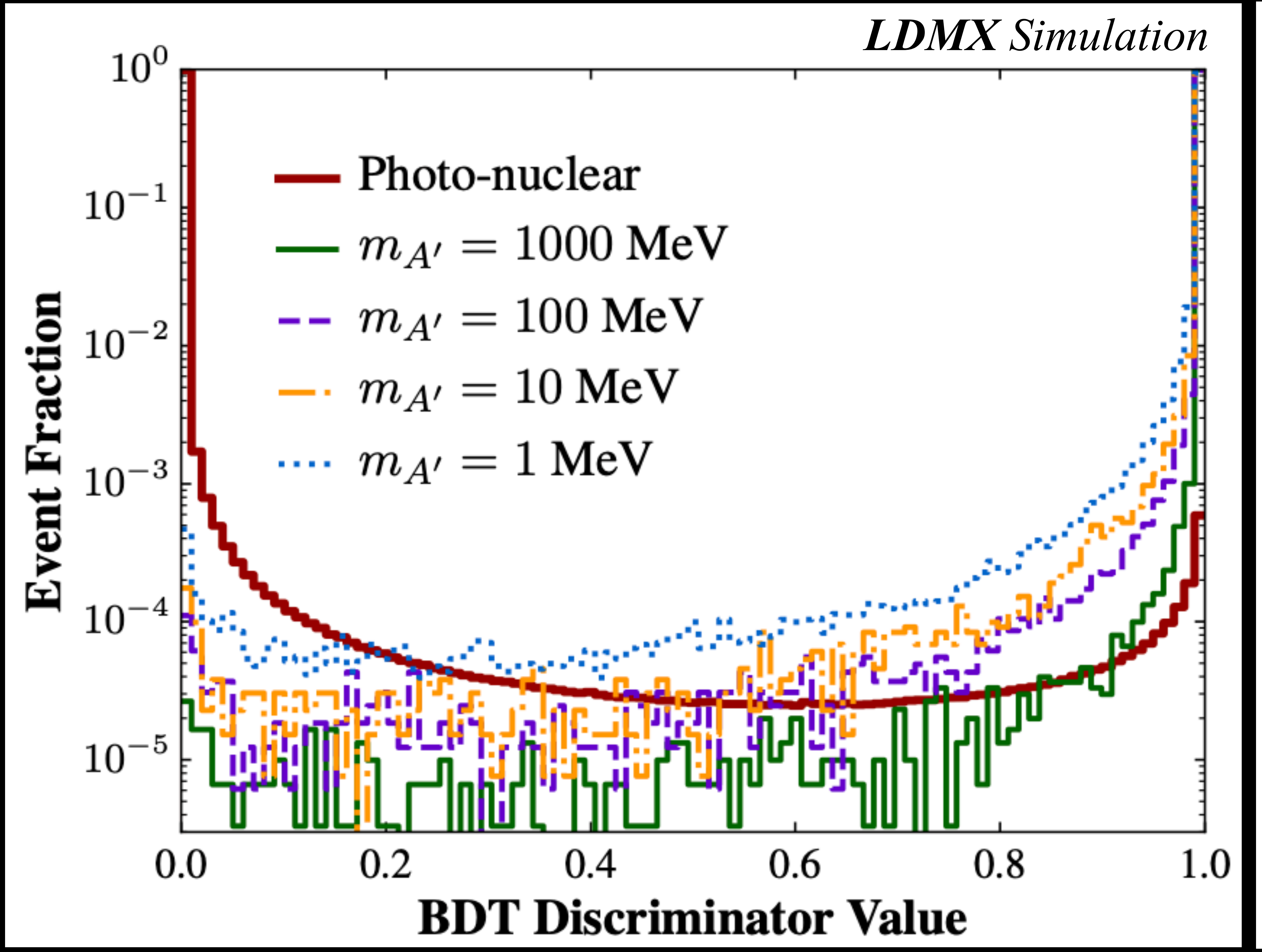


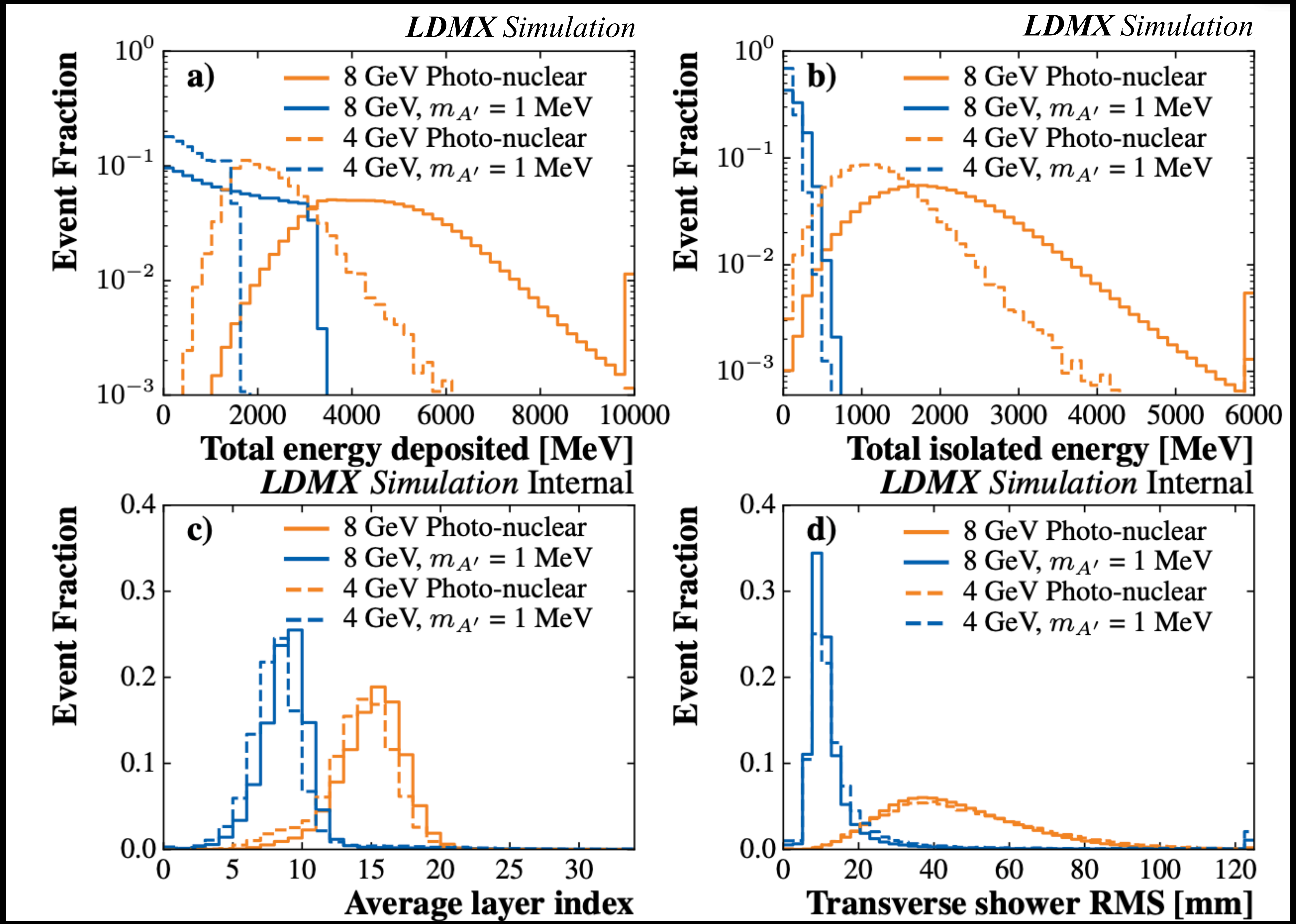


Example displaced decay model:
Strongly Interacting Massive Particles (SIMPs)

- slightly more complicated (indirect) DM depletion mechanism
- *A*' decays to hidden sector pions
- delayed lepton pair production
- → missing momentum or with displaced decay activity

BDT output, and input distributions for key ECal variables at 4 and 8 GeV





Photonuclear interactions

Signal process

Simulation cutflow at 4 and 8 GeV

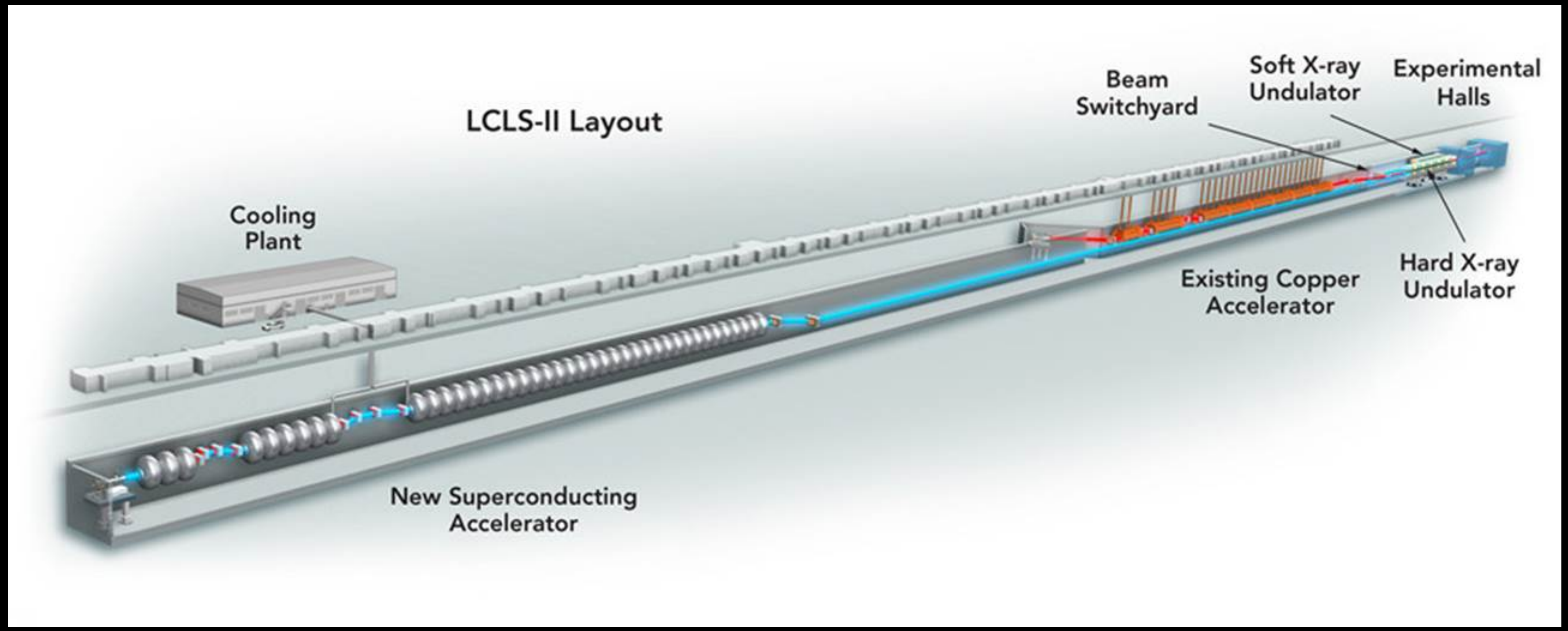
	Photo-nuclear		Muon conversion	
	Target-area	**ECal**	**Target-area**	**ECal**
EoT equivalent	4×10^{14}	2.1×10^{14}	8.2×10^{14}	2.4×10^{15}
Total events simulated	8.8×10^{11}	4.65×10^{11}	6.27×10^{8}	8×10^{10}
Trigger, ECal total energy < 1.5 GeV	1×10^{8}	2.63×10^{8}	1.6×10^{7}	1.6×10^{8}
Single track with $p < 1.2\,\text{GeV}$	2×10^{7}	2.34×10^{8}	3.1×10^{4}	1.5×10^{8}
ECal BDT (> 0.99)	9.4×10^{5}	1.32×10^{5}	< 1	< 1
HCal max PE < 5	< 1	10	< 1	< 1
ECal MIP tracks = 0	< 1	< 1	< 1	< 1

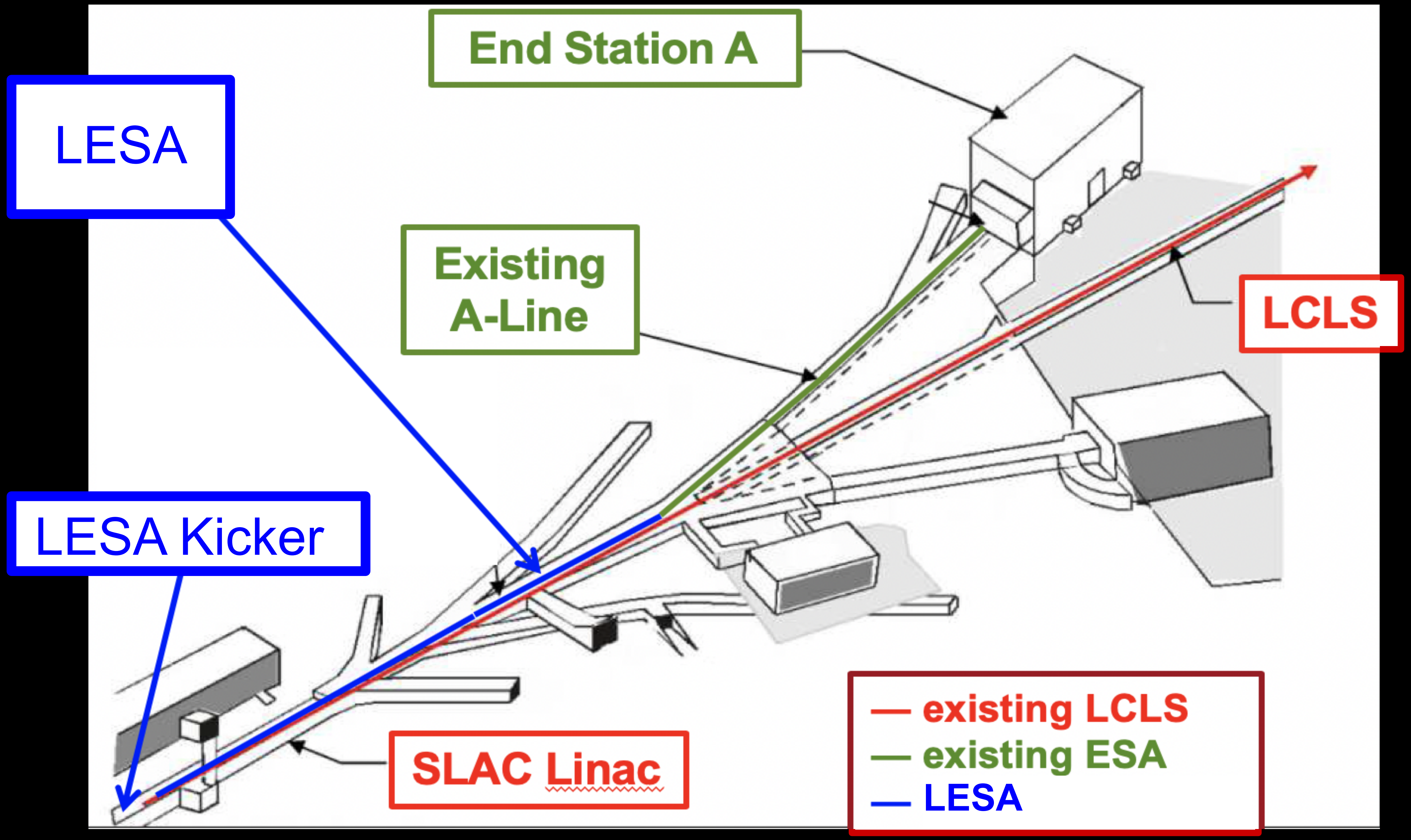
4-GeV beam energy

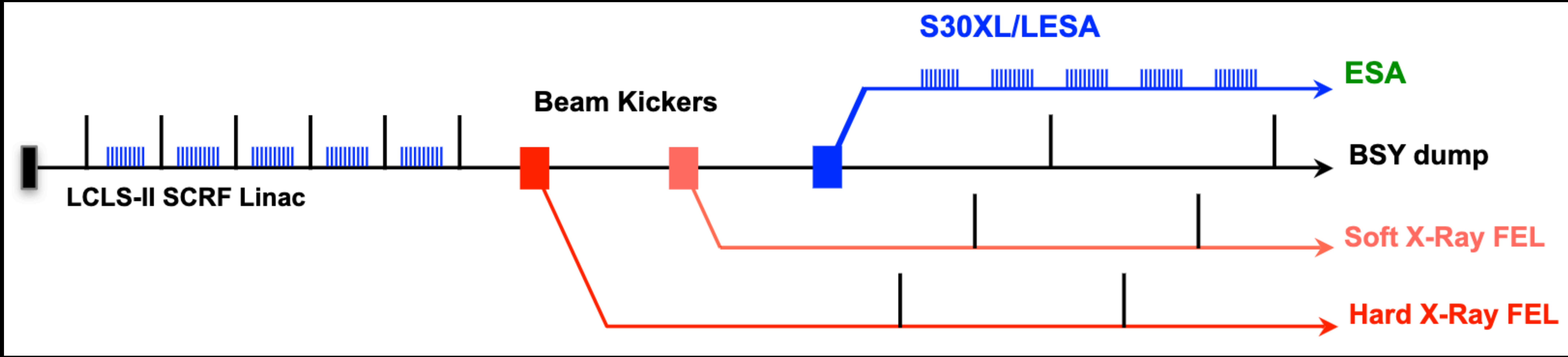
	Photo-nuclear		Muon conversion	
	Target-area	**ECal**	**Target-area**	**ECal**
EoT Equivalent	2.00×10^{14}	2.00×10^{14}	2.00×10^{14}	2.00×10^{14}
Trigger (front ECal energy < 3160 MeV)	7.57×10^{7}	4.43×10^{8}	2.37×10^{7}	8.12×10^{7}
Total ECal energy < 3160 MeV	2.73×10^{7}	7.27×10^{7}	1.76×10^{7}	6.06×10^{7}
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

8-GeV beam energy

GeV-scale electron beam at SLAC







Freeze-in

Phys. Rev. D 99, 075001 (2019), https://arxiv.org/abs/1807.01730

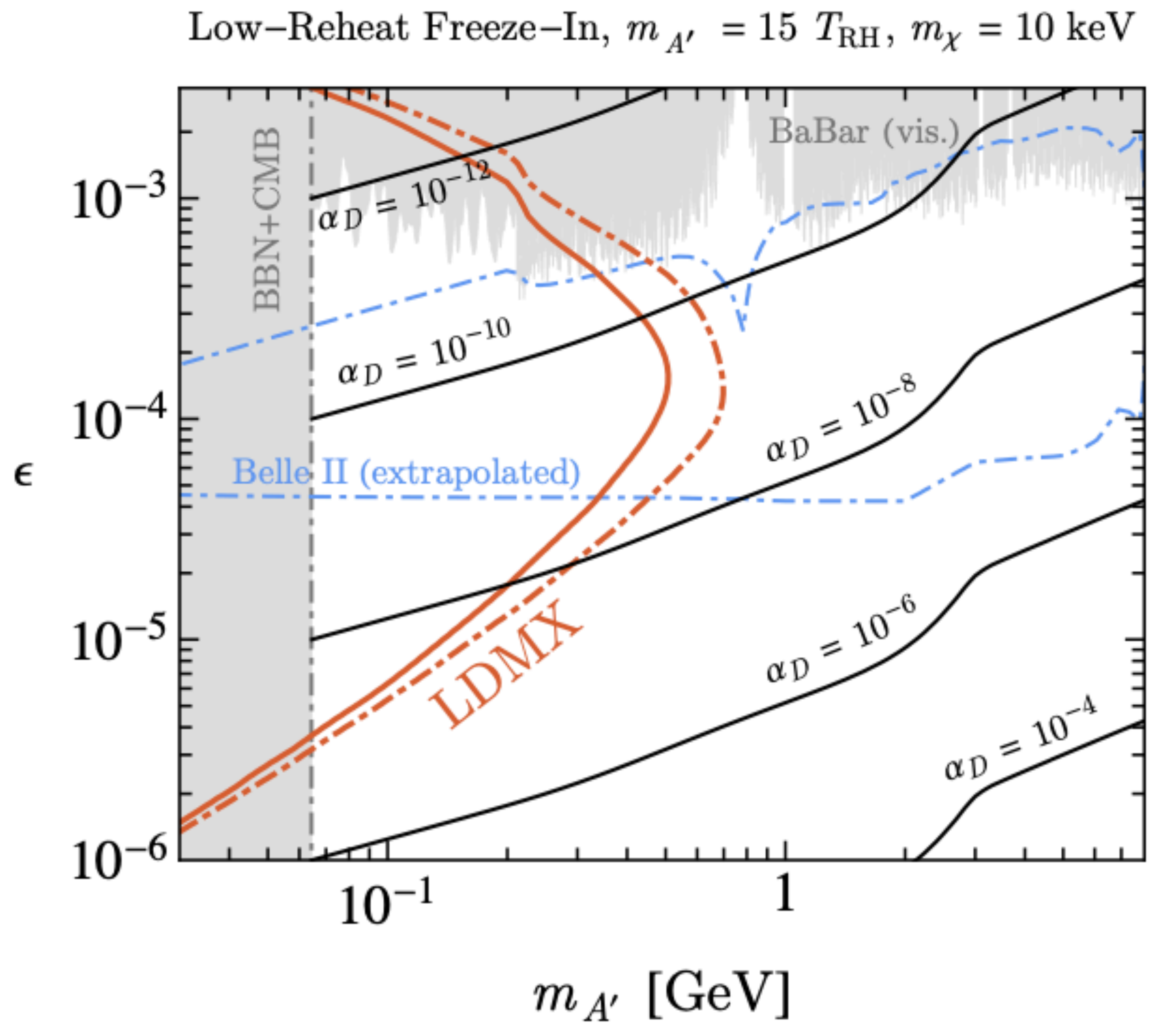


FIG. 14: LDMX sensitivity to the freeze-in scenario with a heavy dark photon and low-reheat temperature. The projected reach of LDMX is shown as the solid red (dashed-dotted red) line for a tungsten (aluminum) target and a 8 (16) GeV beam. The correct relic abundance is obtained along the black contours for different choices of α_D. The gray shaded regions are excluded by the BaBar resonance search [19] and by cosmological constraints on low reheating temperatures [139]. We also show the projected sensitivity of the Belle II monophoton search (blue dot-dashed) as computed by rescaling the 20 fb^{-1} background study up to 50 ab^{-1} assuming statistics limitation only [1, 87].