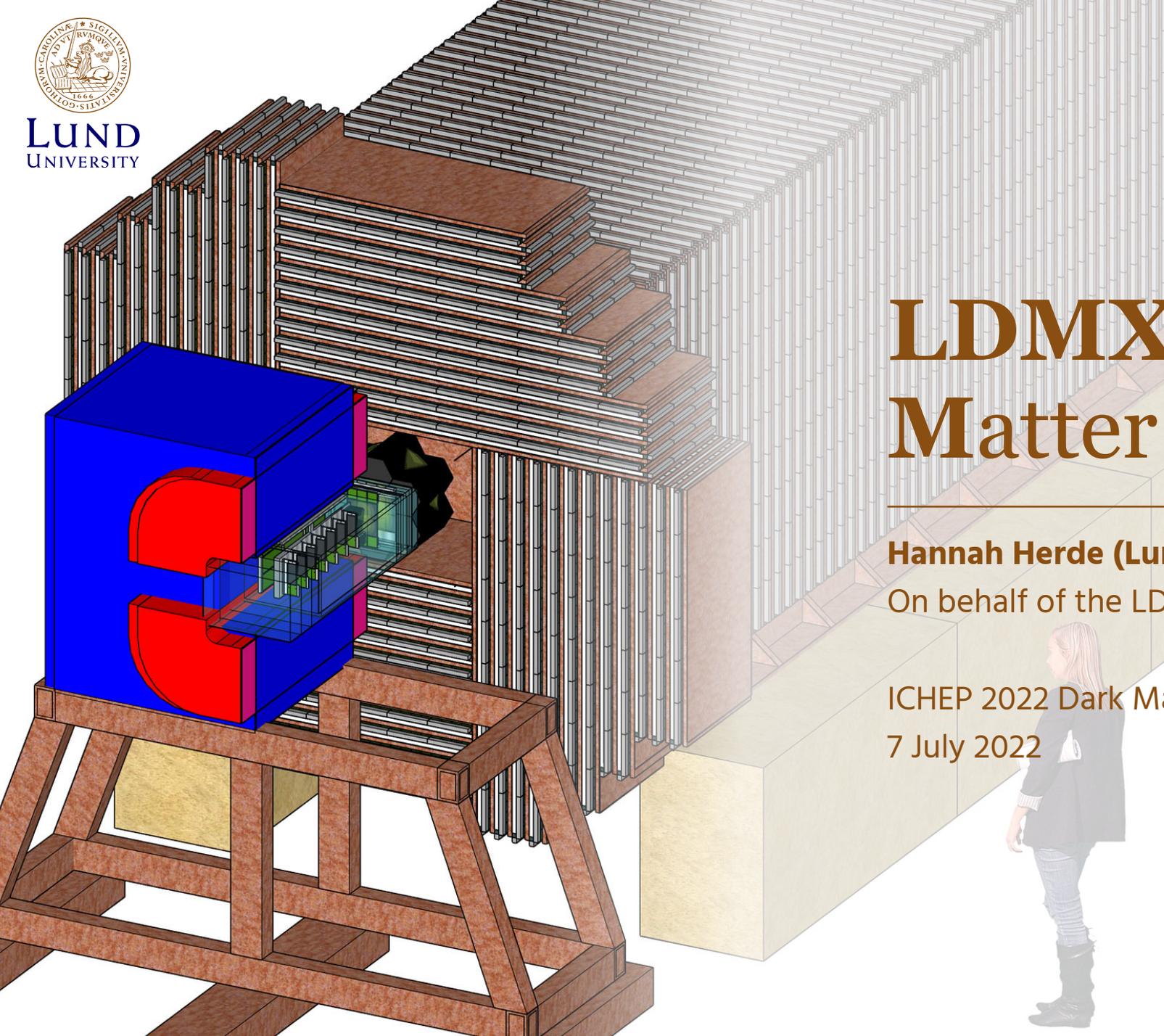




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LDMX: Light Dark Matter eXperiment

Hannah Herde (Lund University)

On behalf of the LDMX Collaboration

ICHEP 2022 Dark Matter Parallel

7 July 2022



Hubble Space Telescope: Galaxy cluster CI 0024+17

Mass distribution: Galaxy cluster CI 0024+17

THE CASE FOR LIGHT DARK MATTER

Theoretical motivation

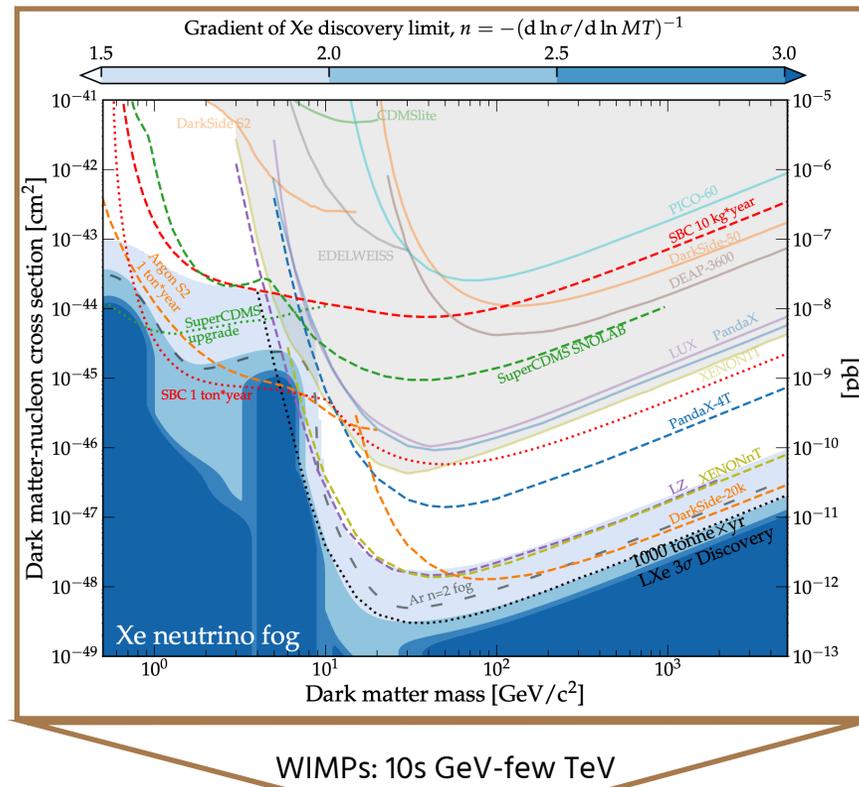


Dark matter candidates

Possible DM mass:
~80 orders of magnitude!

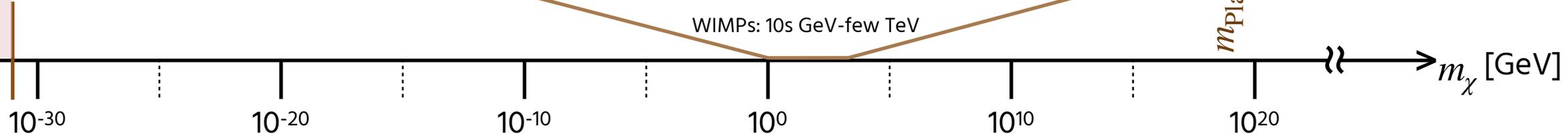
Forbidden: Constraint on λ_{DB}^{DM}

$m_\chi > 10^{-22}$ eV: λ_{DB}^χ
short enough \rightarrow
dwarf galaxies,
galactic halos form



$m_{\text{Planck}} \sim 1.2 \times 10^{19} \text{ GeV}$

$m_\chi \sim 10^s M_\odot$:
Observational limits
on massive compact
halo objects, CMB
anisotropies



Tight experimental limits on WIMPs inspire exploring other models

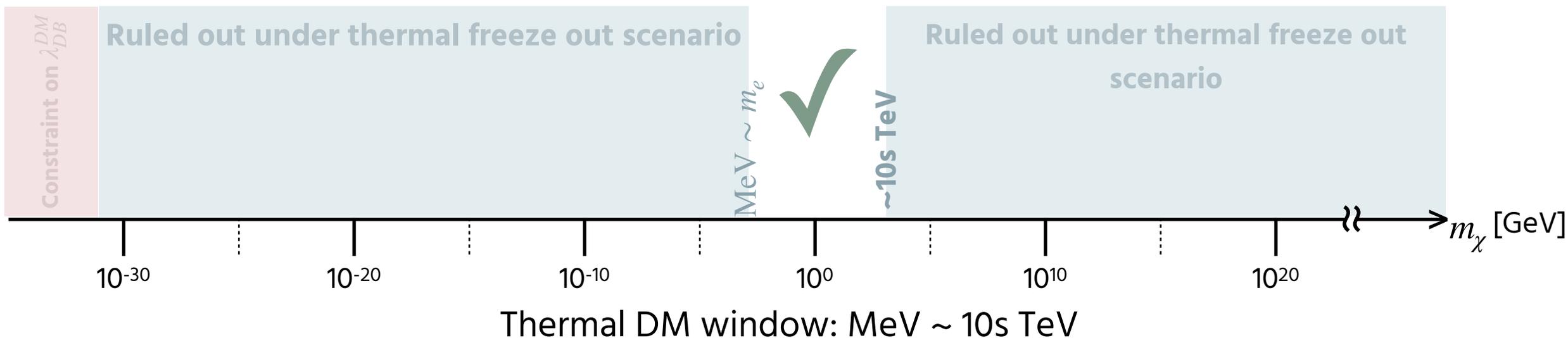
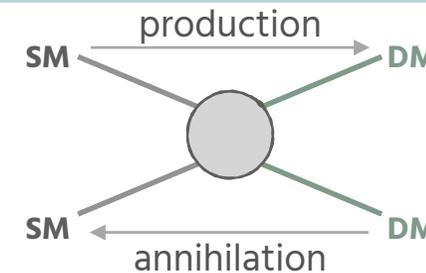
Plot: Snowmass 2021 Cosmic Frontier dark matter direct detection status and prospects, fig 1, <https://arxiv.org/abs/2203.08084>



Thermal relic density guides us

Guaranteed: $\frac{\rho_{DM}}{\rho_{baryonic}} \sim \mathcal{O}(1)$ now

Assumption: Thermal contact history between SM and DM

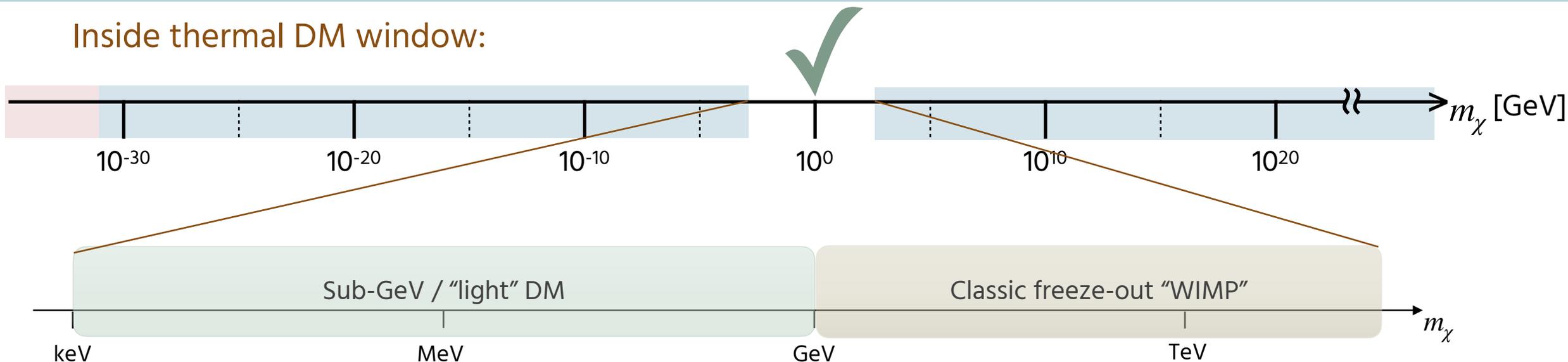


Based on LDMX design paper, fig 2, <https://arxiv.org/abs/1808.05219>



Thermal relic density guides us

Inside thermal DM window:



Well-motivated with hidden sector models & largely unexplored

Relic abundance \rightarrow minimum annihilation rate \rightarrow minimum cross section (otherwise too much DM produced)

\therefore scannable production cross sections. Accelerator-based searches possible!

Benchmark scenarios for light dark matter



MeV-GeV mass range

★ Light forces

- Low-mass force carriers mediate efficient annihilation rate for thermal freeze-out

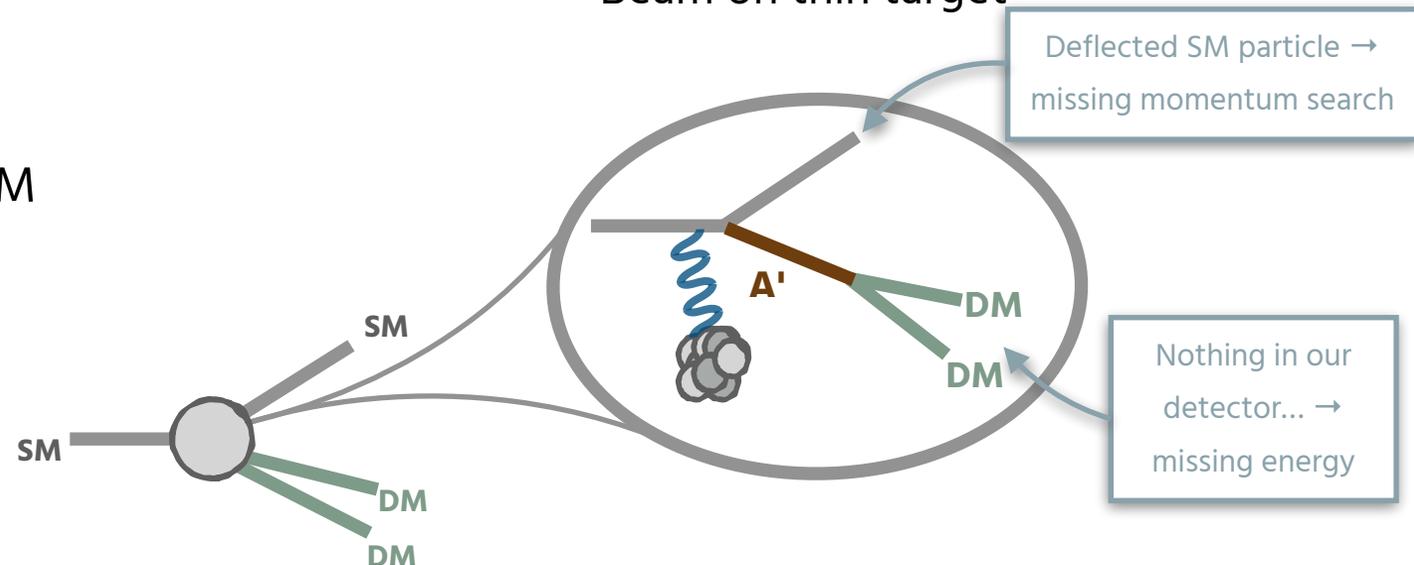
★ Neutrality

- DM & mediator singlets under full SM gauge group
 - Otherwise, we'd have seen them already!

“Dark QED”
DM particle charged under U(1) gauge field
Mediator = dark photon, A'

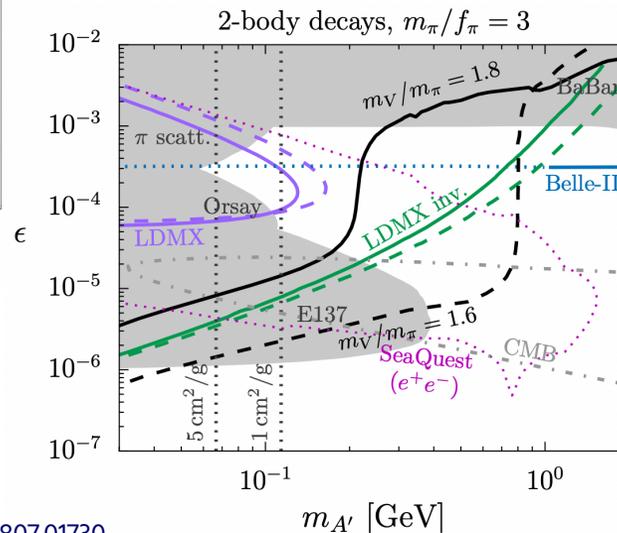
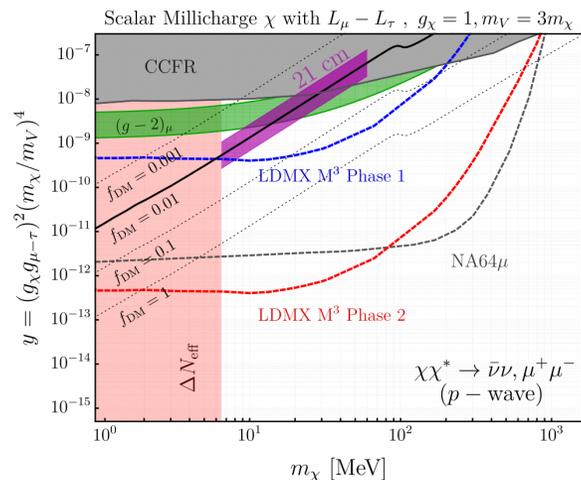
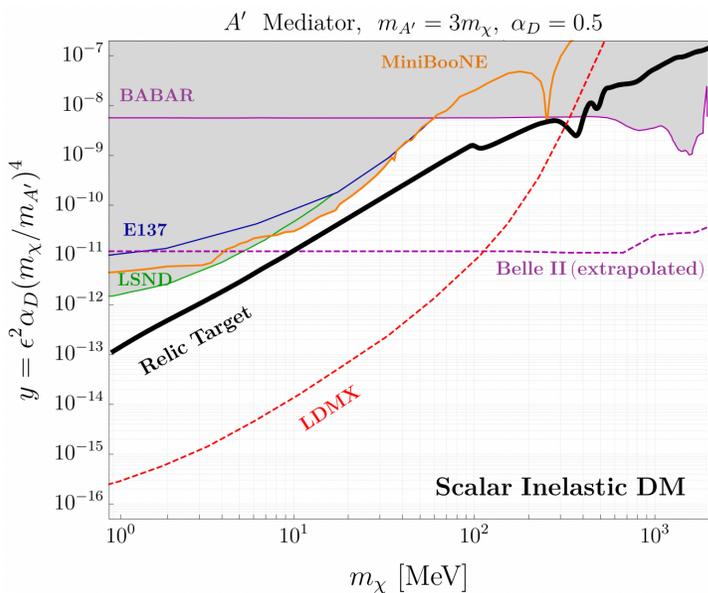
Signature with accelerator production

Beam on thin target





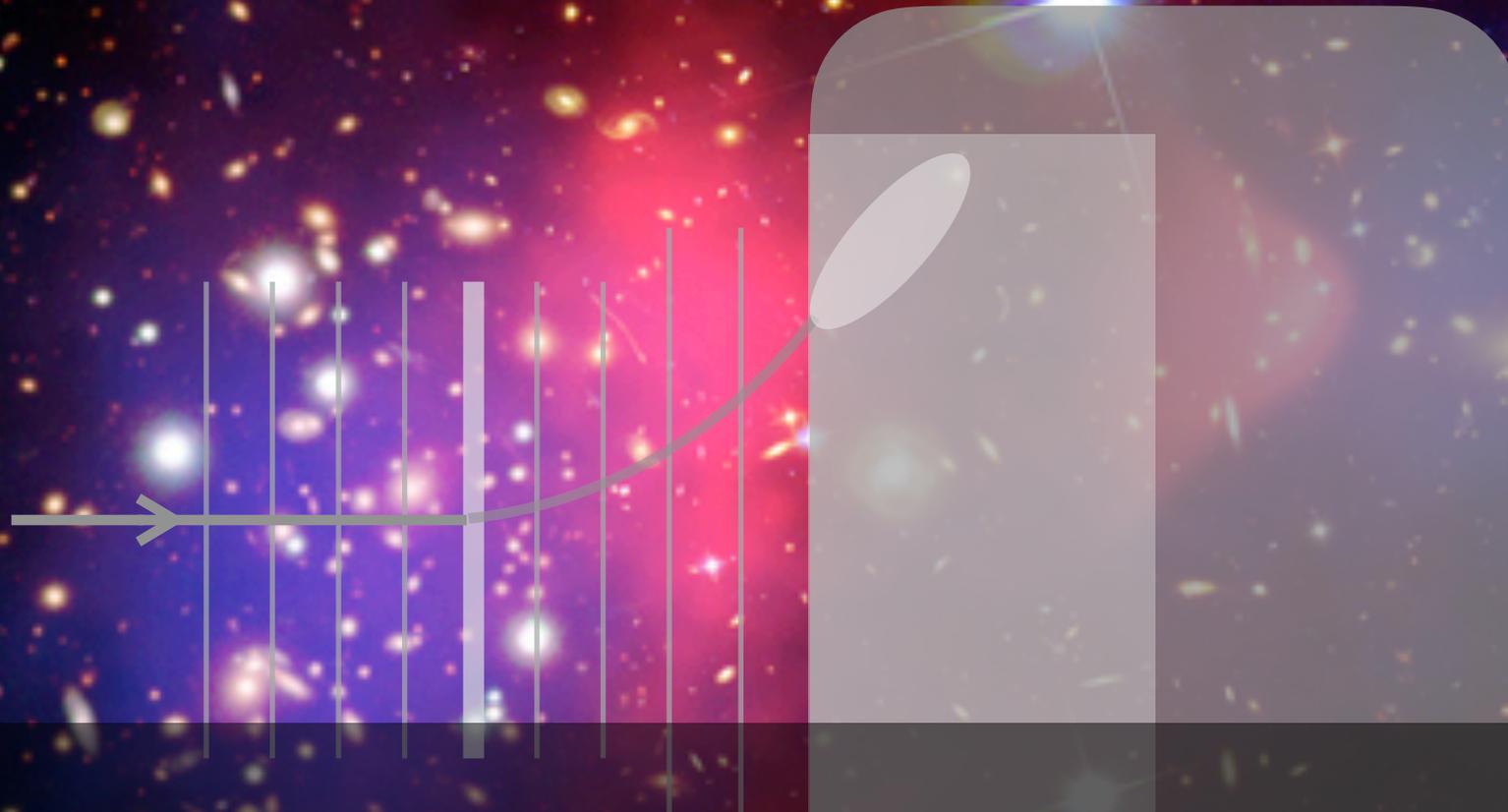
Broad physics potential for missing-momentum-style experiments



Dark photon models and...

- ★ Millicharged particles
- ★ Strongly interacting dark sectors
- ★ Minimal dark photons
- ★ Minimal U(1) gauge bosons
- ★ Axion-like particles
- ★ Light new leptophilic scalar particles...

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

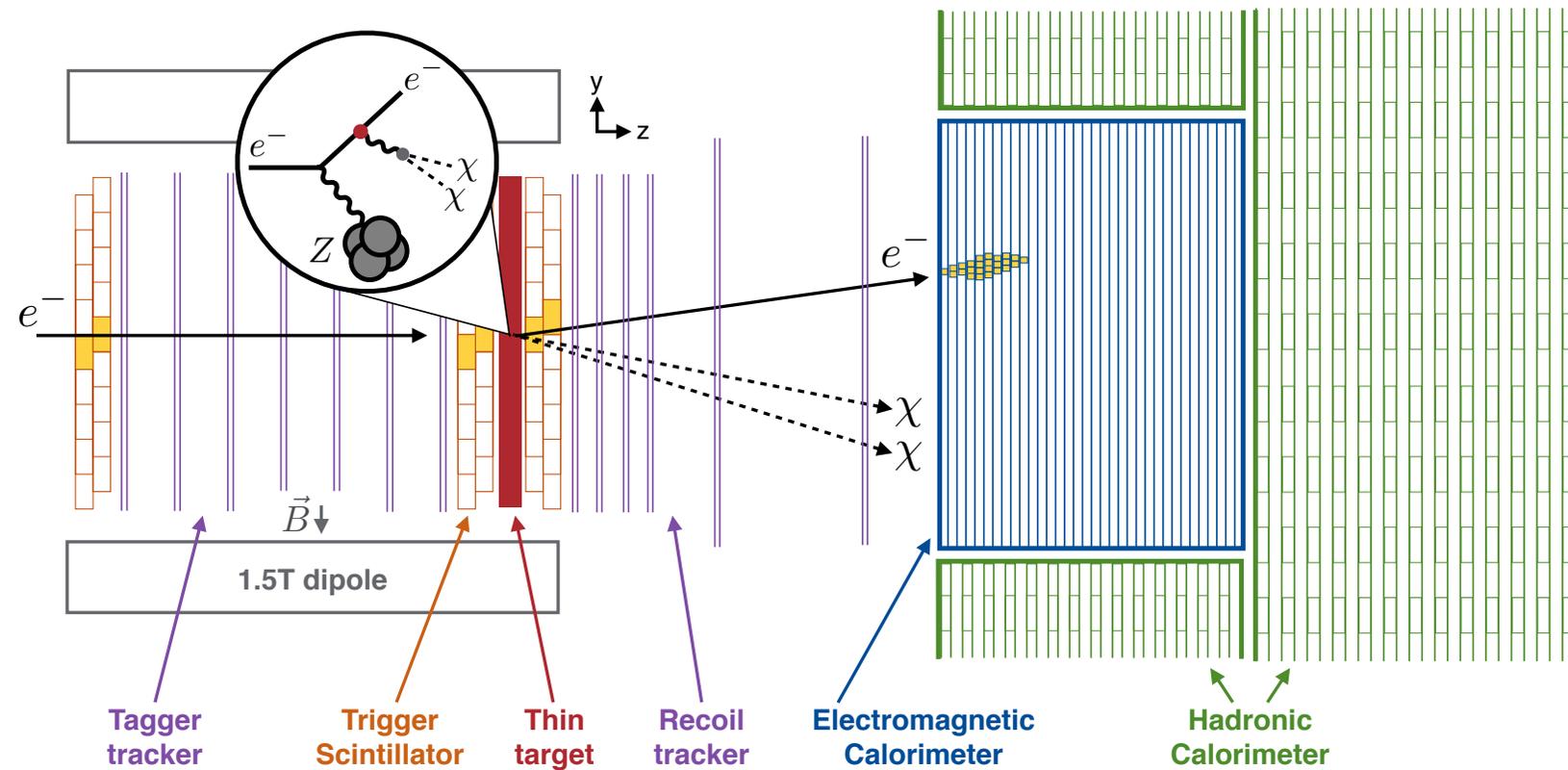


LDMX DESIGN

Detector design drivers

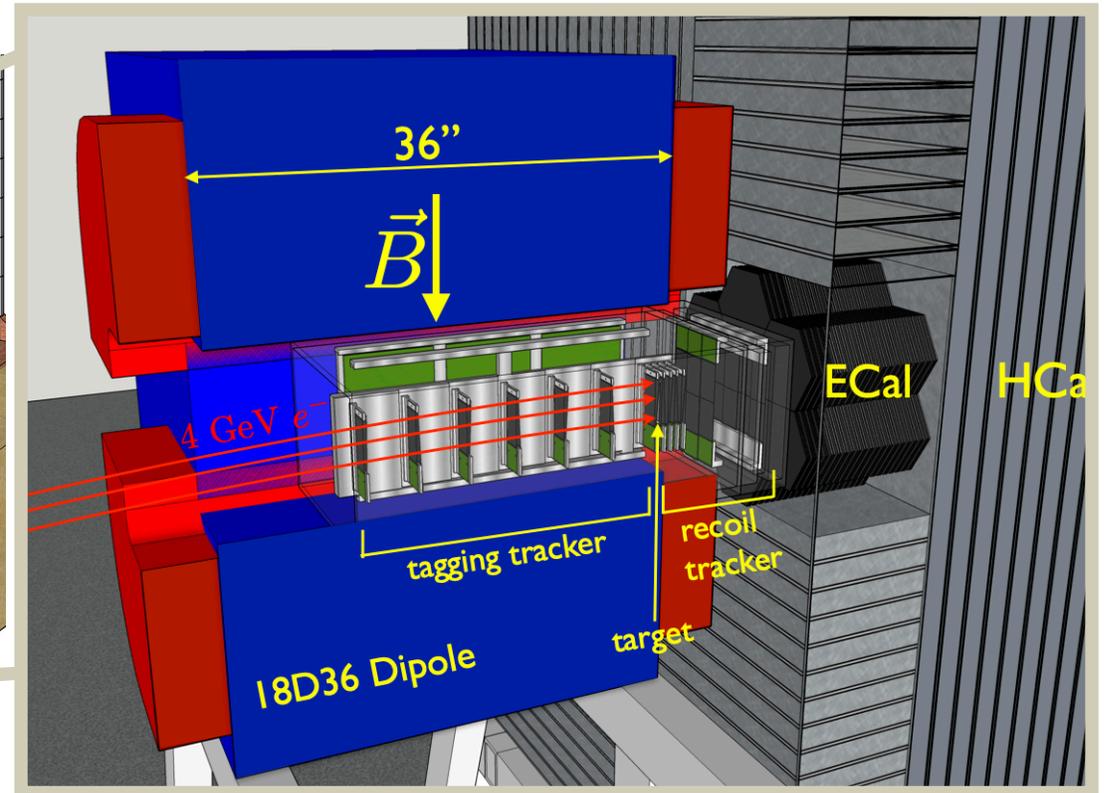
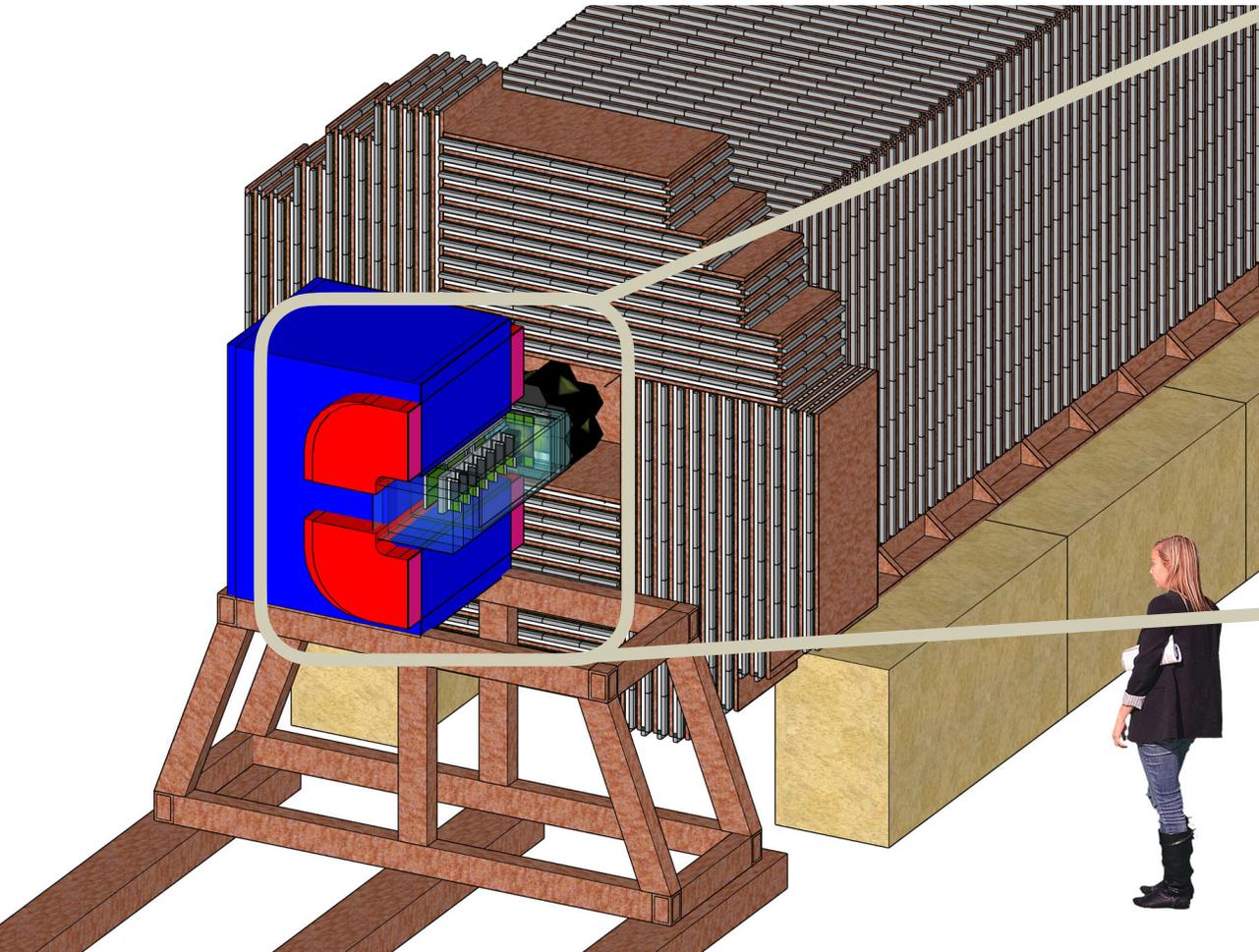


Flagship objective: Missing momentum signatures • Phase 1: 4 GeV e beam • Phase 2: 8 GeV e beam



- ★ Resolve electrons' energy & momentum
 - Individually measure energy & momentum for up to 10^{16} e^- scattered off thin tungsten target
 - Beamline under construction at SLAC
- ★ Eliminate neutral backgrounds
 - SM γ bremsstrahlung
 - Photonuclear reactions \rightarrow neutral final states

Design overview



Leverage technologies developed for ongoing experiments

Tracking: HPS Silicon Vertex Tracker

Electromagnetic calorimeter, ECal: CMS high granularity calorimeter

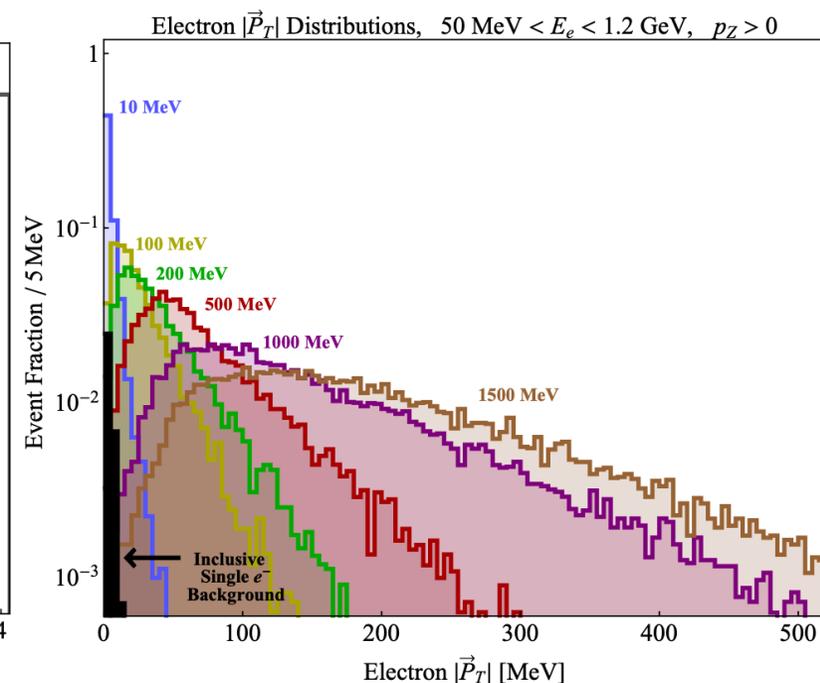
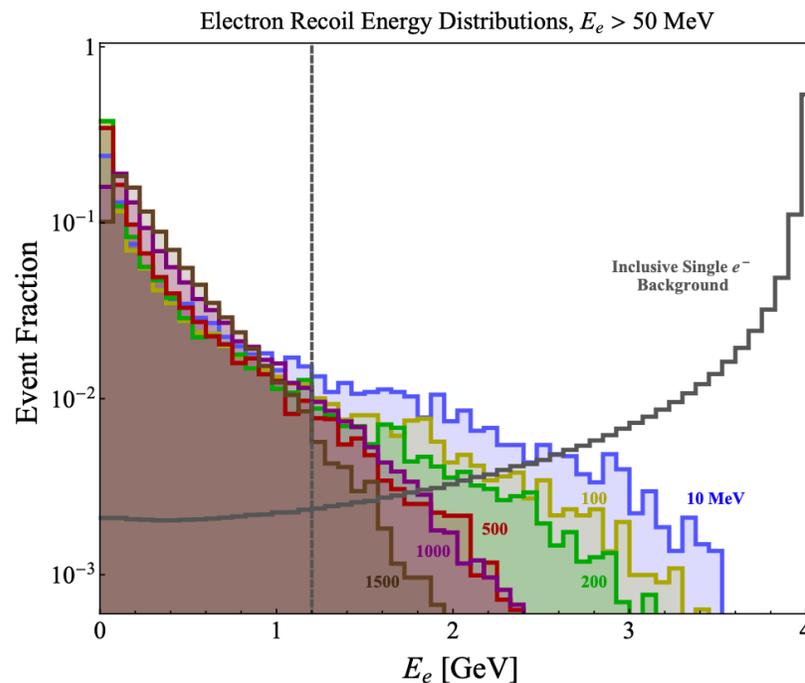
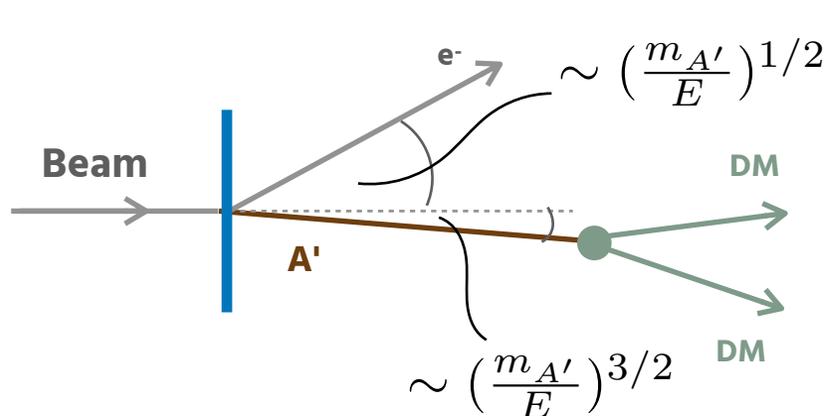
Hadronic calorimeter, HCal: MINOS/Mu2e

Snowmass 2021 LDMX status and prospects, fig 2a & 2b , <https://arxiv.org/abs/2203.08192>



Missing particle signature distinctive from SM bremsstrahlung

Kinematics



★ Mediator A' carries bulk of energy

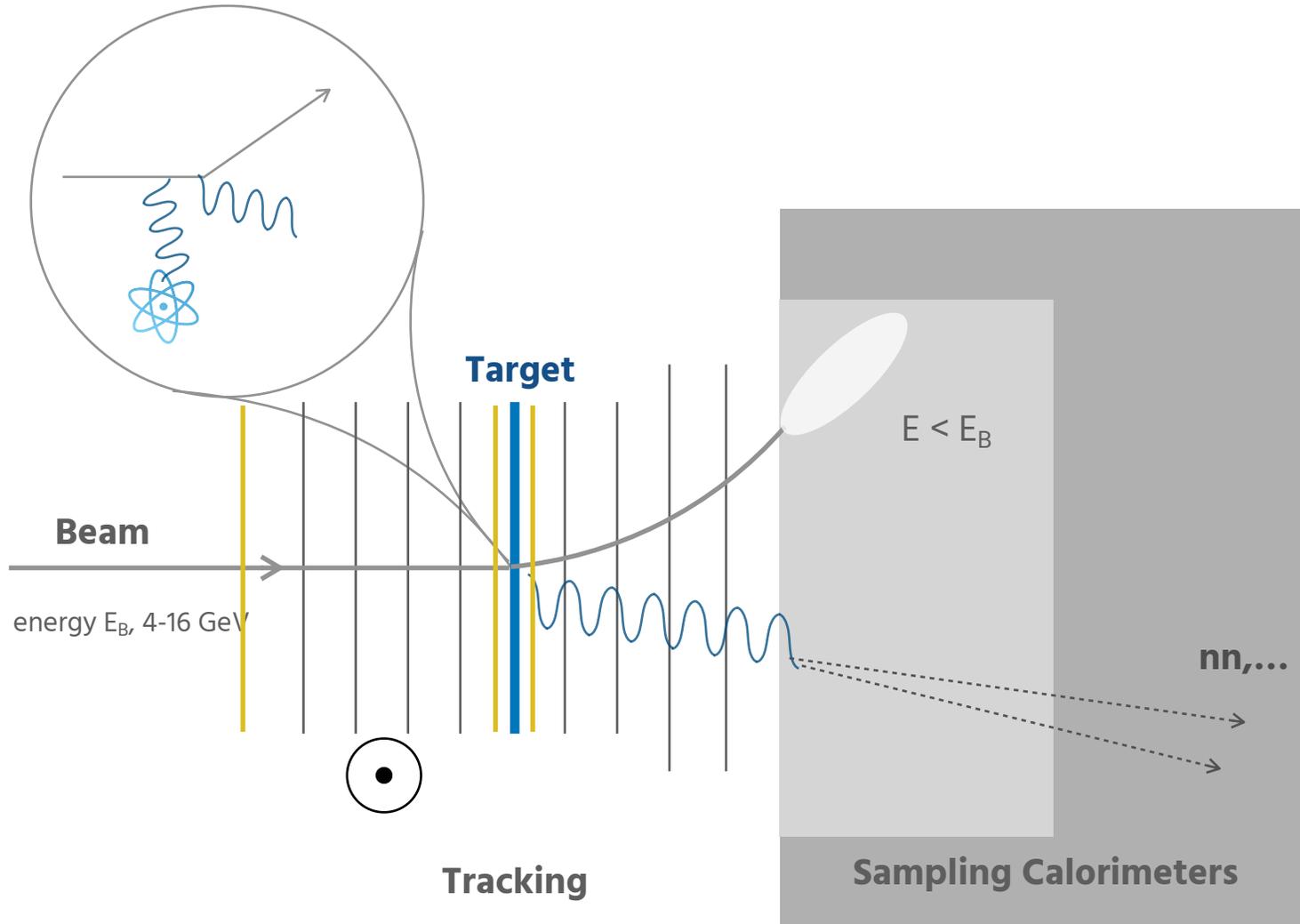
- Soft recoil electron
- Large missing energy

★ Recoil electron kicked in transverse momentum

- Large missing transverse momentum

LDMX measures energy
(calorimeters) AND momentum
(trackers either side of target)

Challenge: Neutral background processes



Main background: SM γ bremsstrahlung

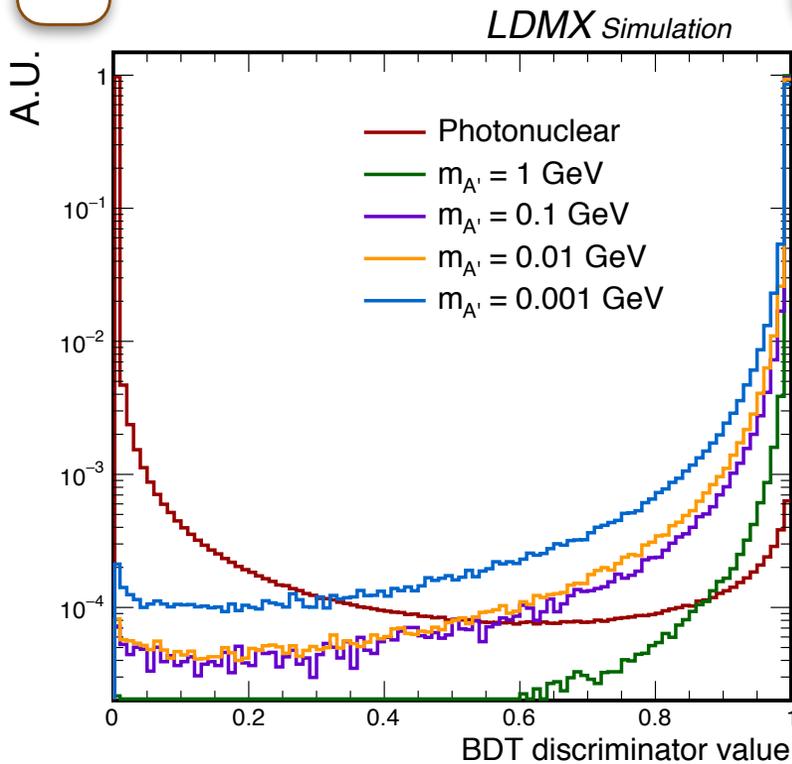
- ★ Photo-nuclear reactions producing neutral final states
 - Relative rate: $\sim 10^{-8}$
- ★ LDMX backgrounds = measurements of photo- and electro-nuclear processes for neutrino experiments
 - Phys. Rev. D 101, 053004, <https://arxiv.org/abs/1912.06140>

Analysis strategy

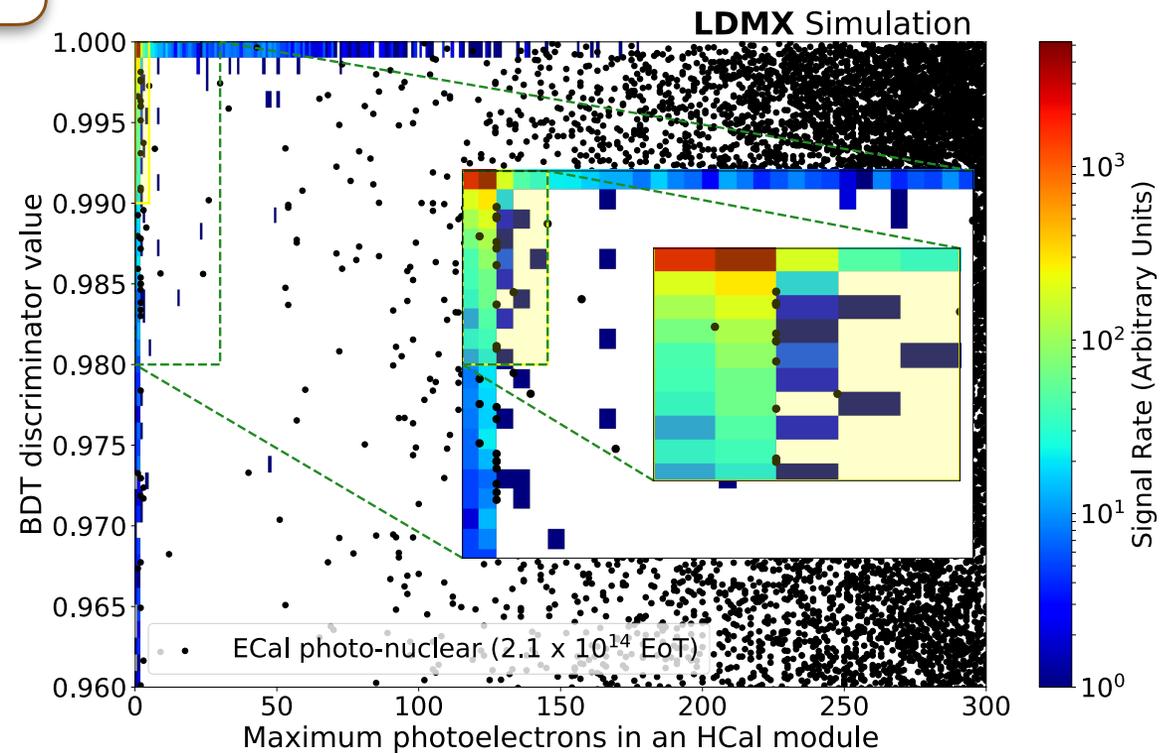


@ 4 GeV: close to **zero background** for 4×10^{14} electrons on target (simulation studies)

2



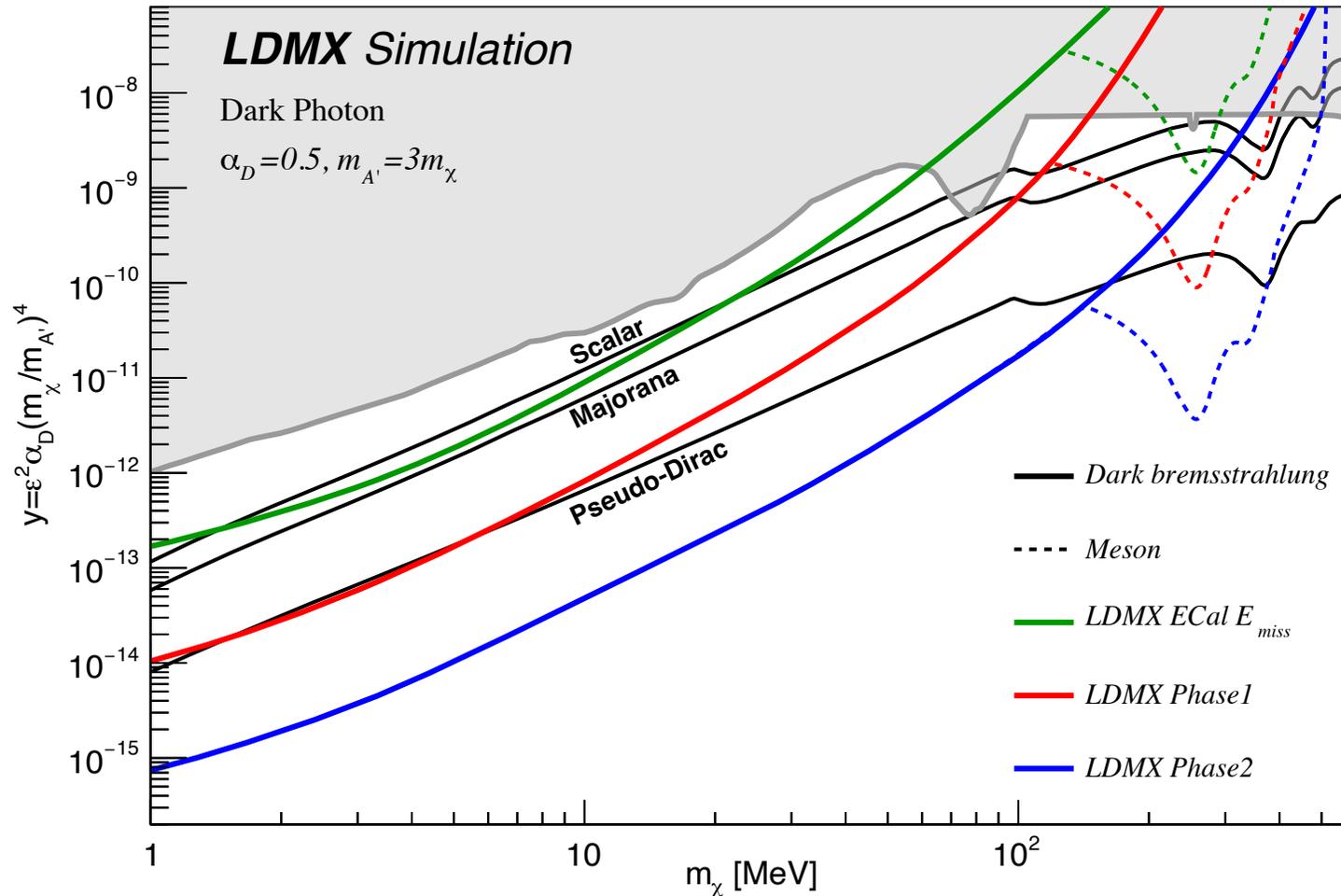
3



No requirements on electron transverse momentum...yet

1. Trigger on 2.5 GeV missing energy
2. Combine ECal features with BDT
3. Veto activity in HCal
4. Require MIP tracking in ECal

Projected sensitivities



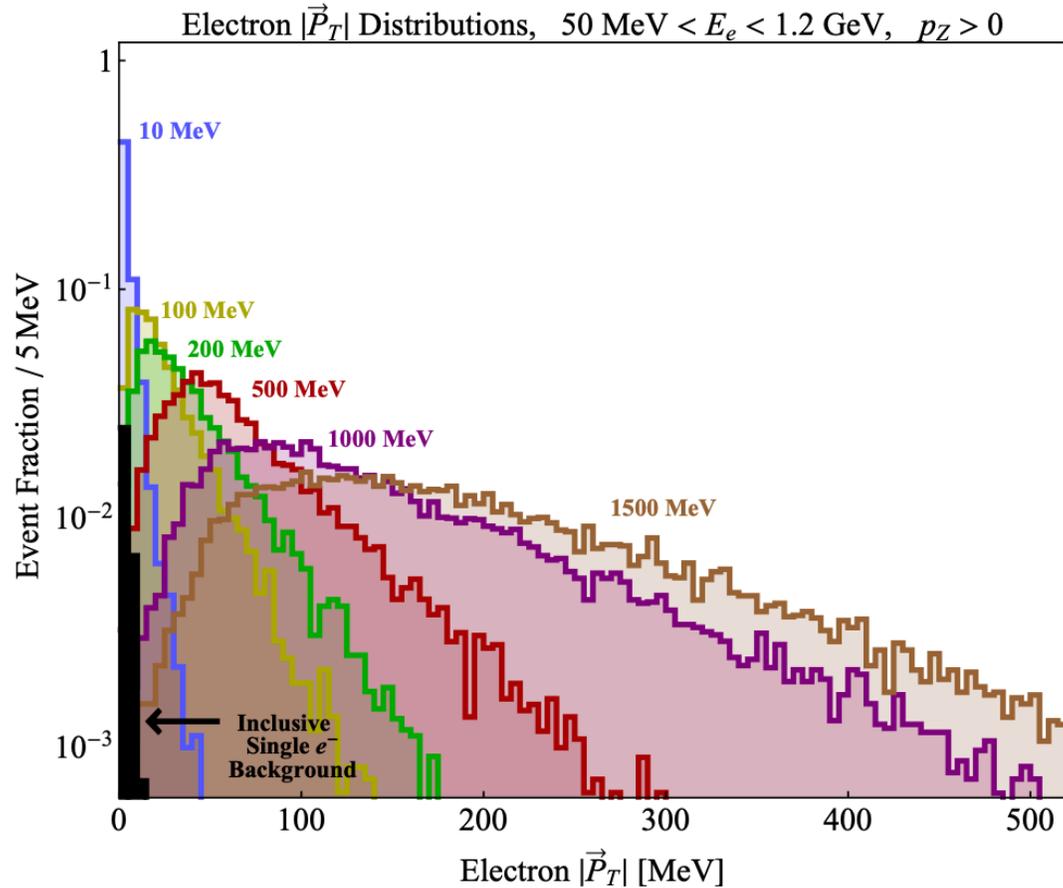
Dark photon benchmark model

- ★ Phase-1 LDMX run (baseline)
 - 4×10^{14} electrons on target
 - 4 GeV beam energy
- ★ Phase-2 LDMX run
 - $\sim 10^{16}$ electrons on target (+ x100)
 - 8 GeV beam energy
- ★ Limits calculated with < 1 background event
 - Achievable based on detailed simulation studies at 4 GeV (see J. High Energy Phys. 2020, 3 (2020) <https://arxiv.org/abs/1912.05535>)
- ★ Limits calculated without electron transverse momentum selection criteria

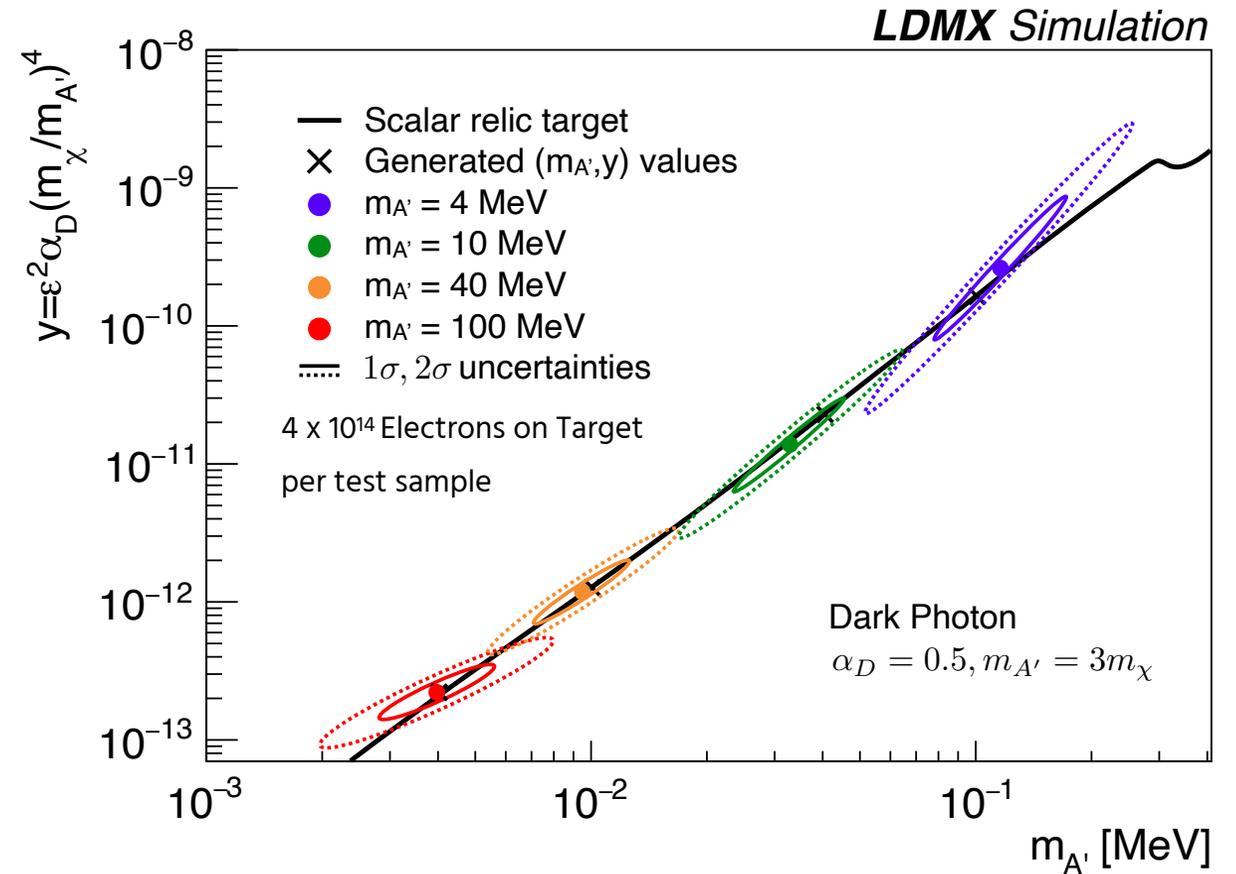
Strength: Transverse momentum *in addition to energy*

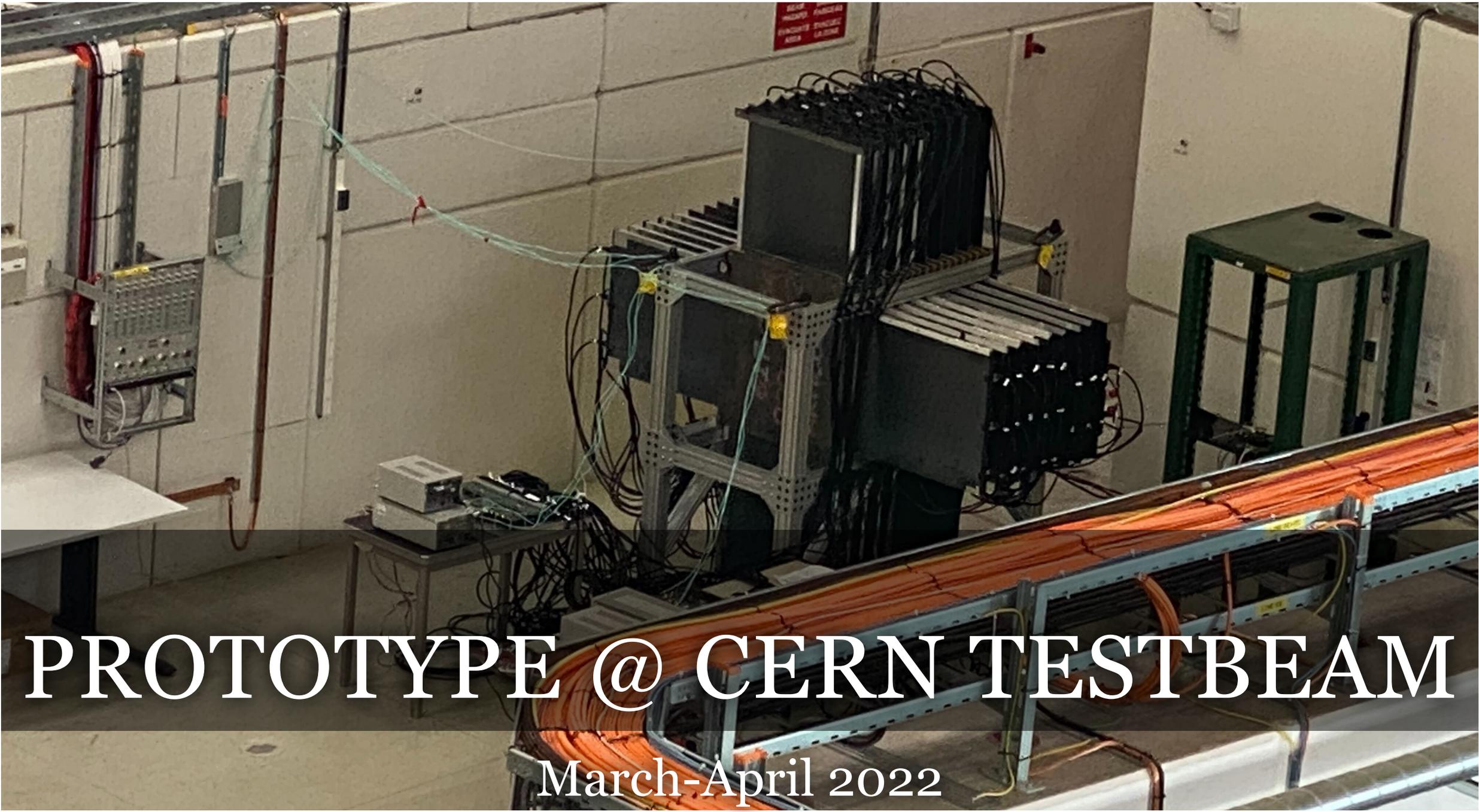


Excellent signal-background discriminant to **confirm observation**



Combine p_T & $E \rightarrow$ **reconstruct mediator mass**





PROTOTYPE @ CERN TESTBEAM

March-April 2022



CERN East Area: T9 beamline



T9 beamline

LDMX prototype

Experimental hutch

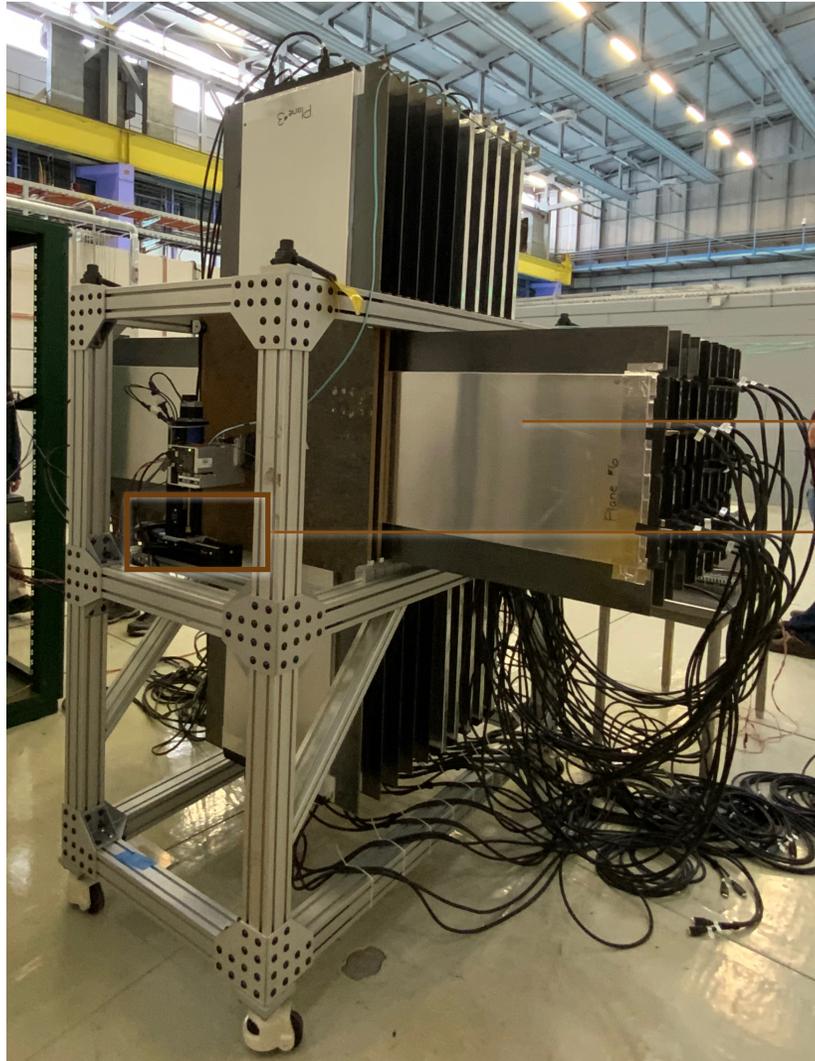
Mixed beam • $E_{\max} = 15 \text{ GeV}$

Data collected at 500 MeV-8 GeV

- ★ 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

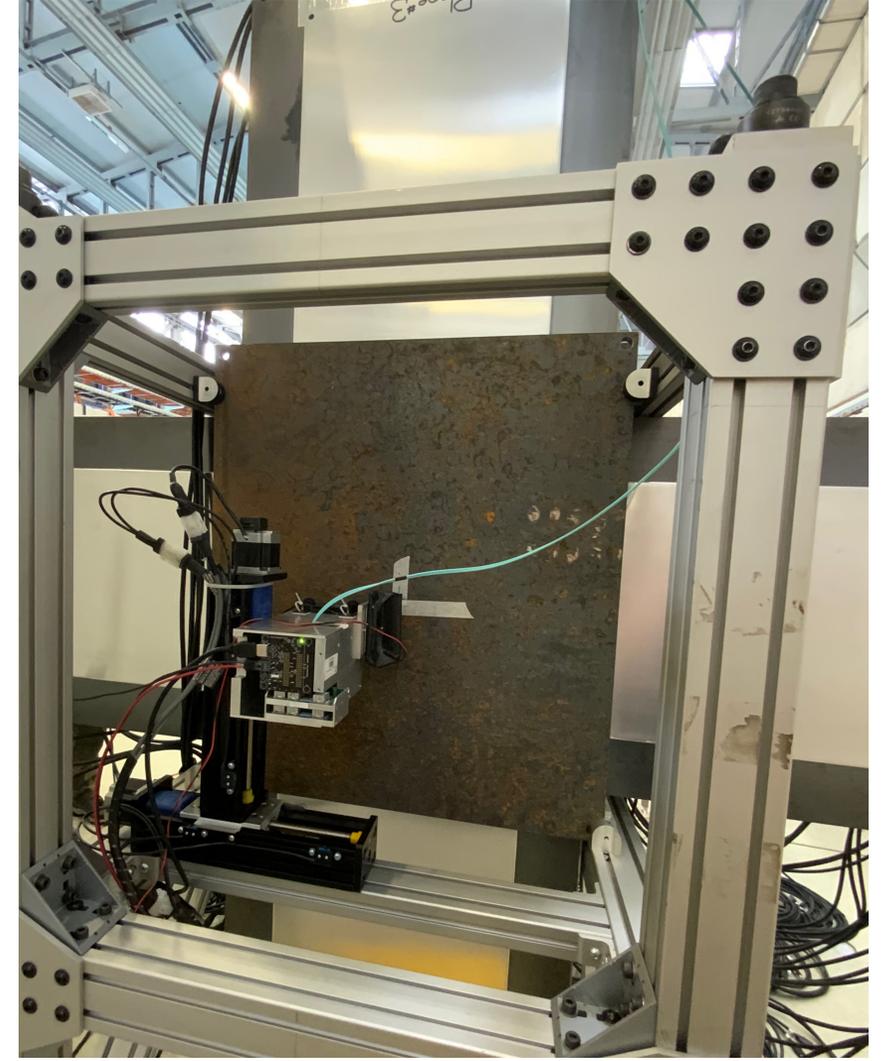


Prototype in the beam area



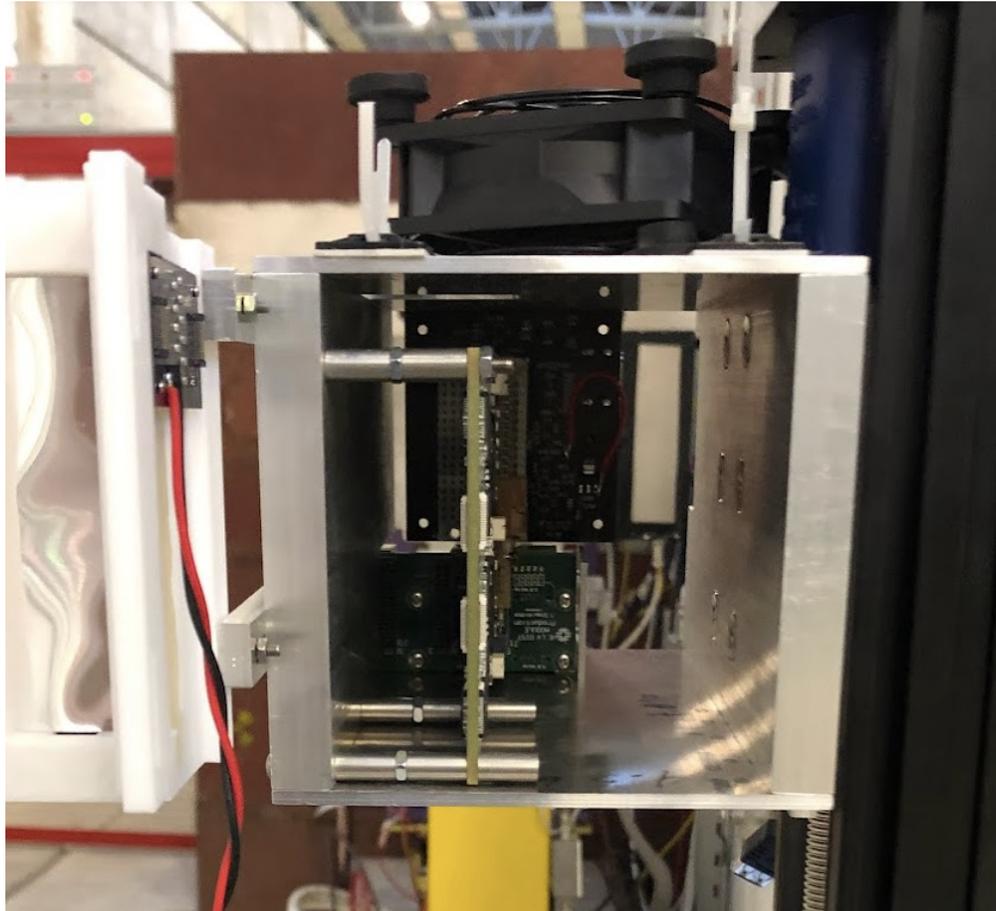
Hadronic Calorimeter (HCal)

Trigger scintillator (TS)





Prototype subdetectors



Trigger scintillator prototype



Hadronic calorimeter scintillator bars layer

Inset: Fibre optic cable pokes through bare scintillator bar



Trigger scintillator (TS) prototype

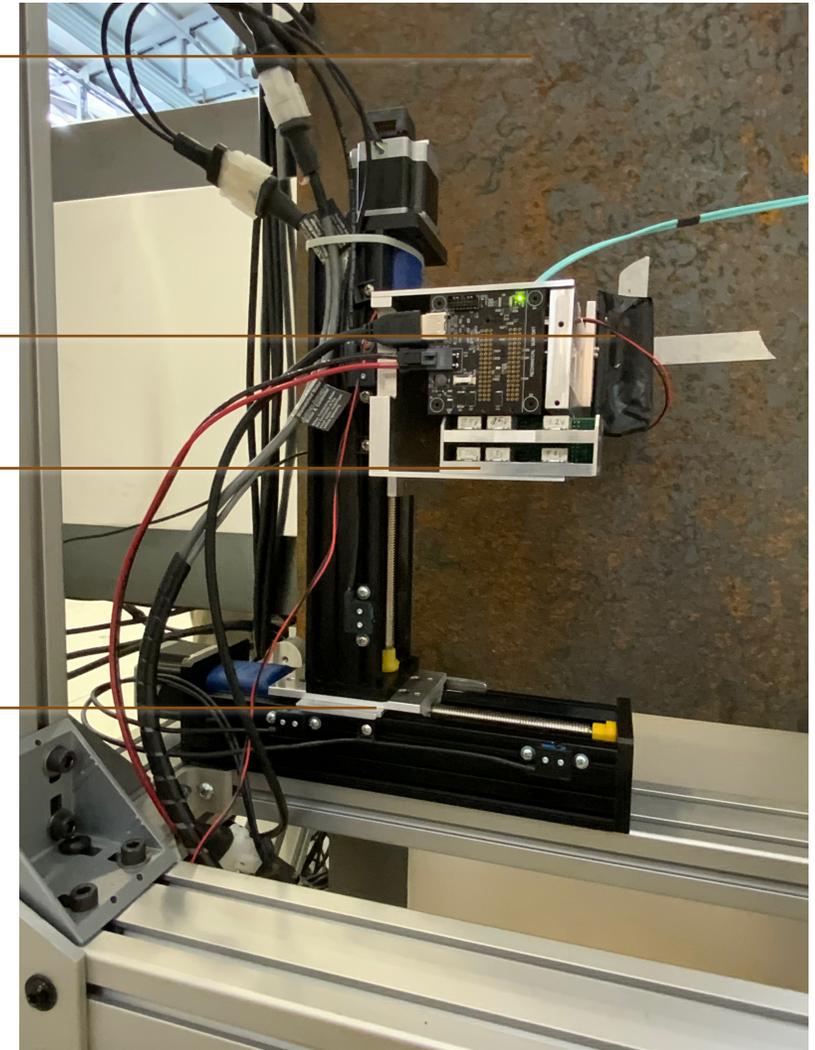


First steel absorber layer
of the hadronic calorimeter

TS plastic scintillator
encased in black tape
for light tightness

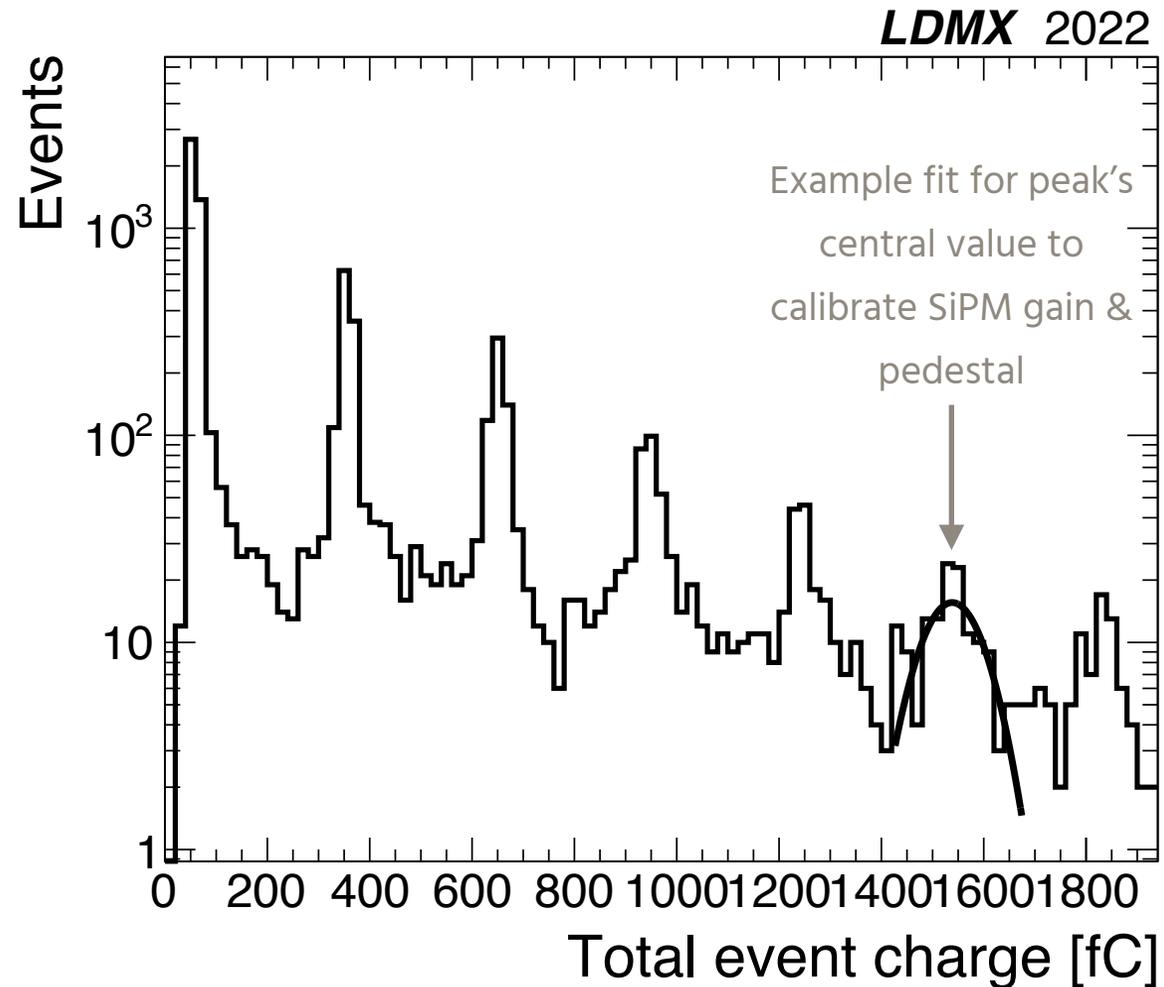
TS readout electronics

Gantry to adjust
position of TS in beamspot





TS: Single photoelectron spectrum

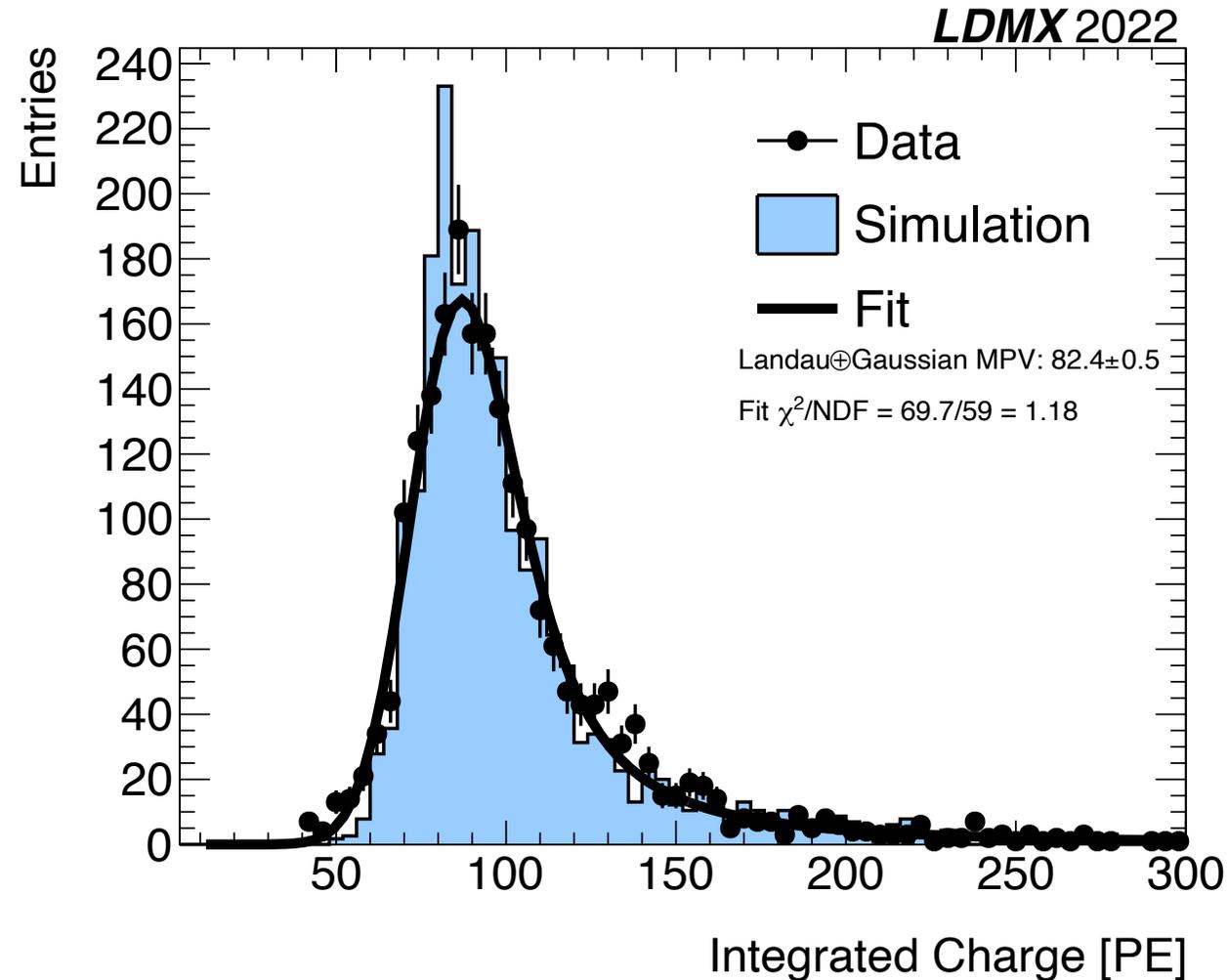


Gain calibration

- ★ 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
 - Normalised to 1 photoelectron equivalent
- ★ Most probable value of cell's response to MIP = 82 photoelectrons
 - Model: Landau + Gaussian convolution



Hadronic calorimeter (HCal) prototype

19 alternating layers, usually¹ Al cover • scintillator bars • steel absorber plate

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



9 layers with 2 quad bars

10 layers with 3 quad bars

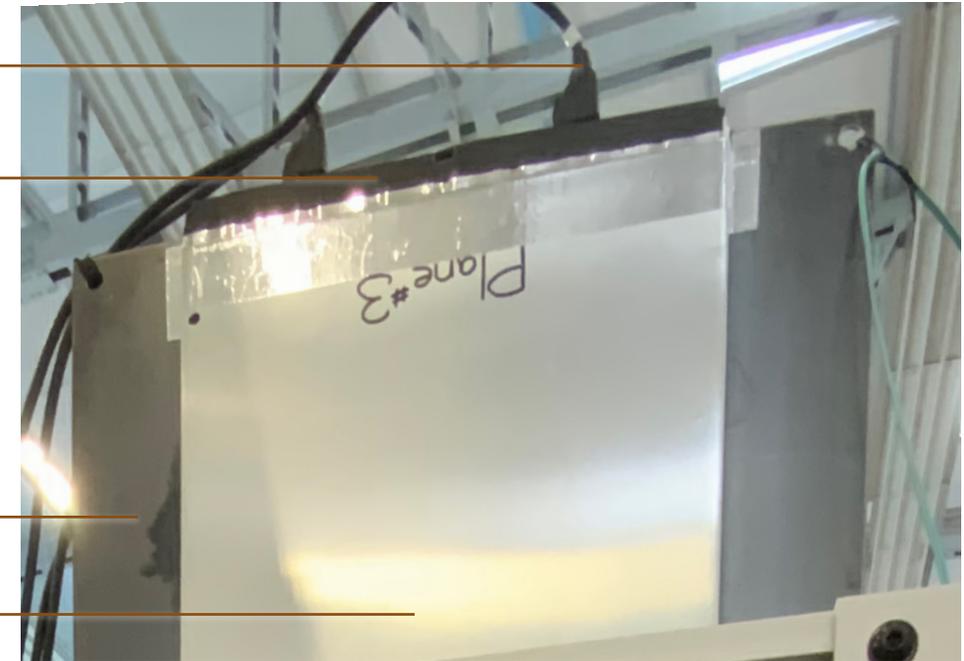
HDMI cable

Readout manifold

Scintillator bars with readout

Steel absorber

Aluminium cover

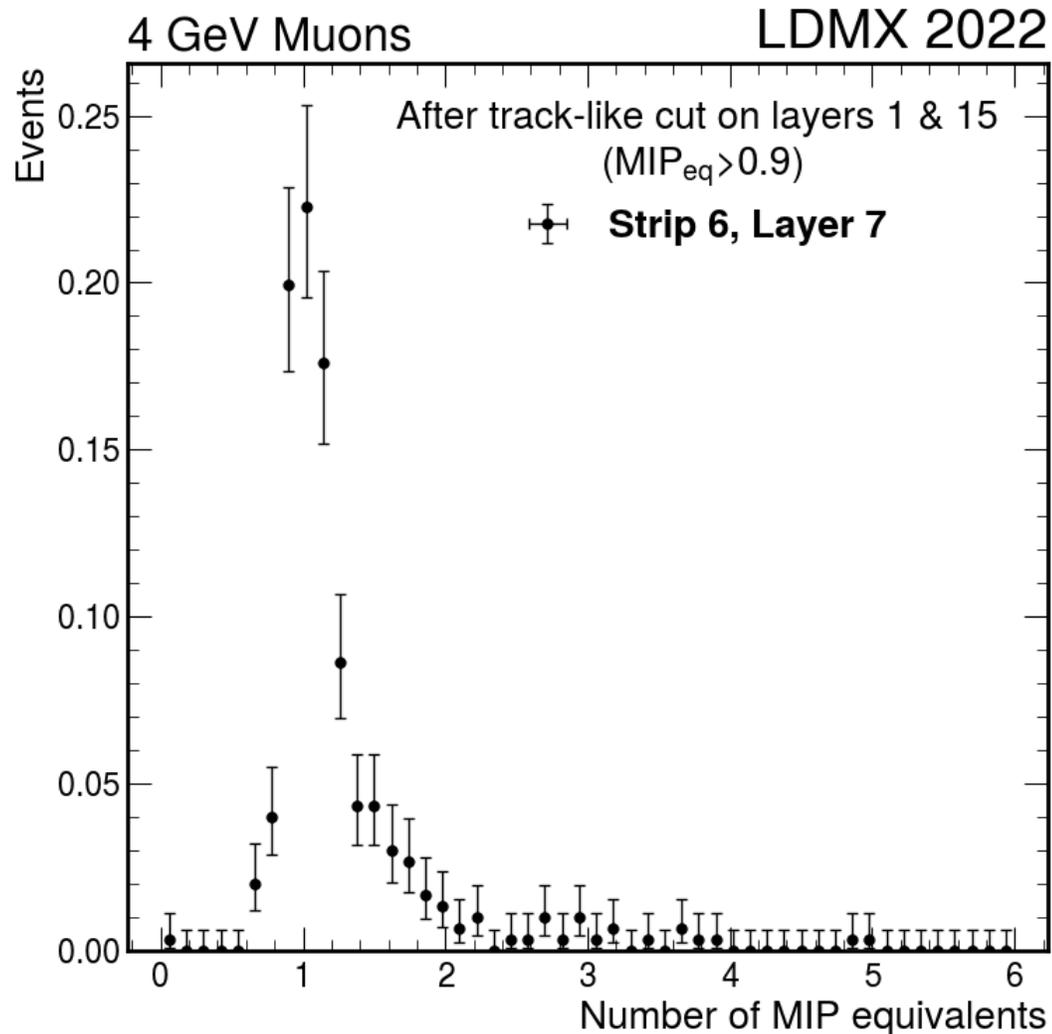


Example: Section of a vertical layer of the HCal

¹ First HCal layer is steel absorber, then scintillator bars



HCal: MIP response



4 GeV muon beam

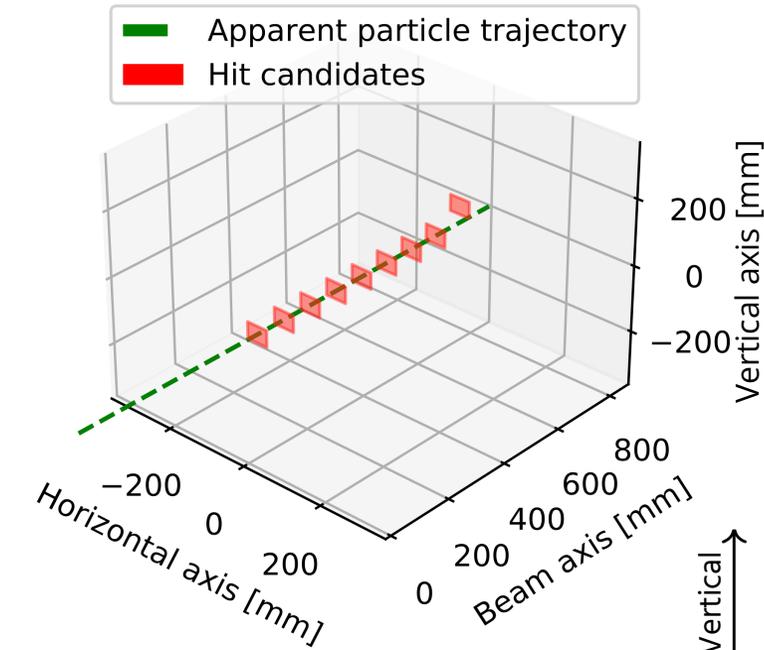
- ★ Sum of ADC counts in a single layer and strip of HCal prototype

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

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



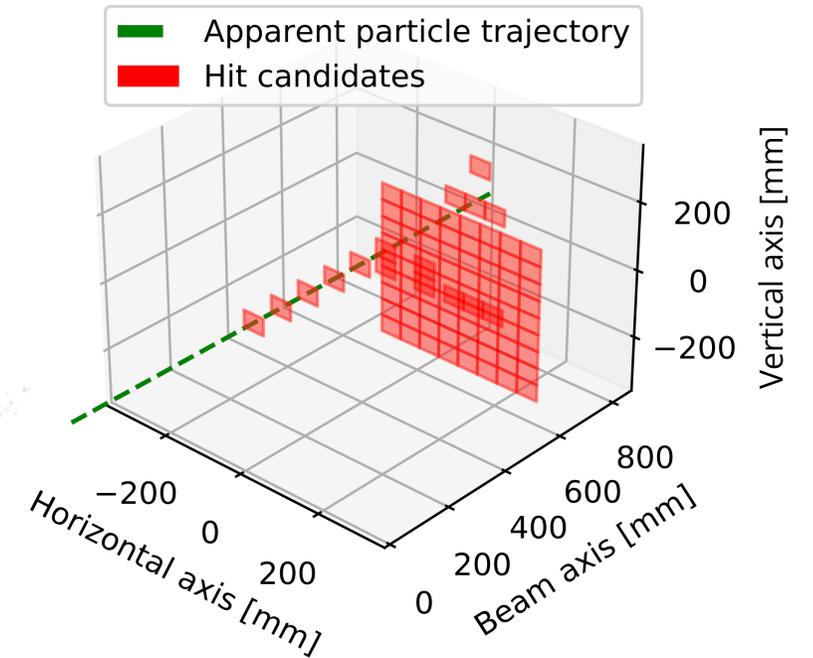
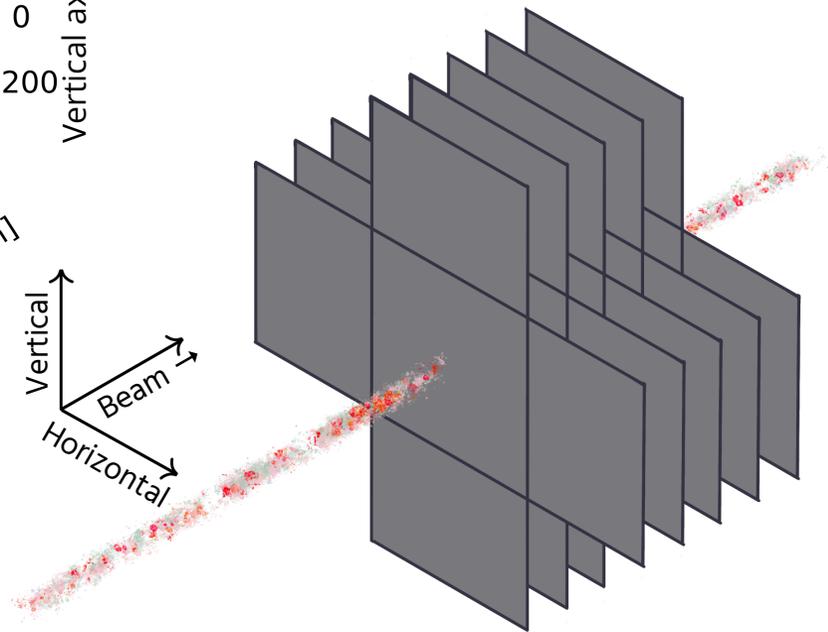
HCal: Event displays



MIP candidate

Sequential, crisp signature in
HCal

Beam & HCal orientation



Pion candidate

MIP-like deposits followed by
cloud in HCal



PROJECT OUTLOOK

CERN test beam, March-April 2022 - A crane lifts HCal prototype into beam area

Key messages



LDMX improves search sensitivity for sub-GeV dark matter by up to 3 orders of magnitude



C. Group & son

- ★ LDMX scientific potential
 - Interpret missing momentum measurements → secluded dark matter models, millicharge particles, invisibly decaying dark photons, axions, dark Higgs particles,...
 - Interpret as short baseline beam dump → displaced visibly decaying dark photons, axions, inelastic dark matter, dark Higgs, long-lived particles...
- ★ First results shown for test beam data collected at CERN in March-April 2022
- ★ Recent DOE review finds project and technical development on track to start construction in FY23
- ★ Earliest funding availability for construction in FY24
- ★ Electron beam will be available in experimental area before construction can be completed



CERN test beam, March-April 2022

UC SANTA BARBARA

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Fermilab

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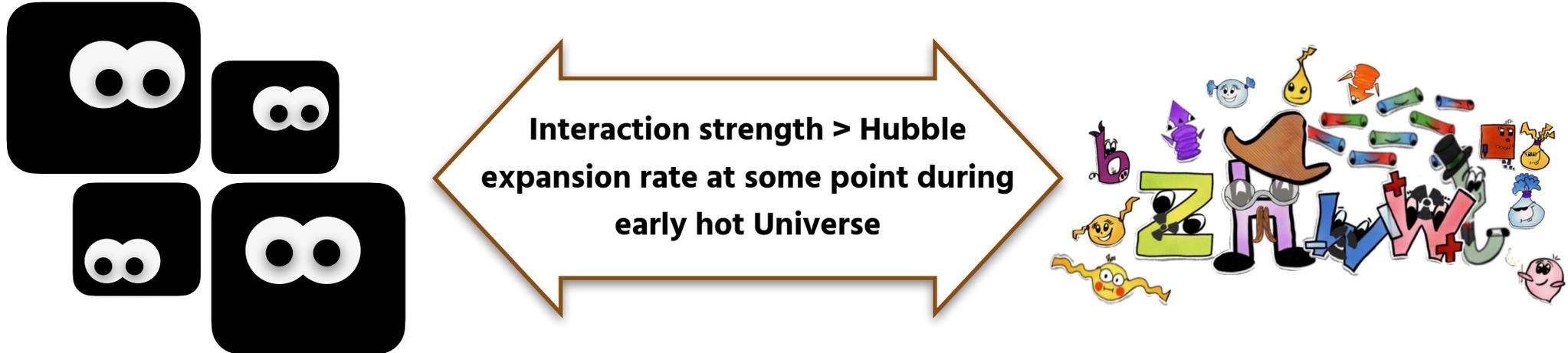
Knut and Alice Wallenberg Foundation
Crafoord foundation

 U.S. DEPARTMENT OF ENERGY
ENERGY

 LUND-FYSIOGRAFISKA SÄLLSKAPET I LUND

Thermal freeze-out scenario

Using present-day relic abundance & thermal freeze-out hypothesis \rightarrow scannable production cross sections

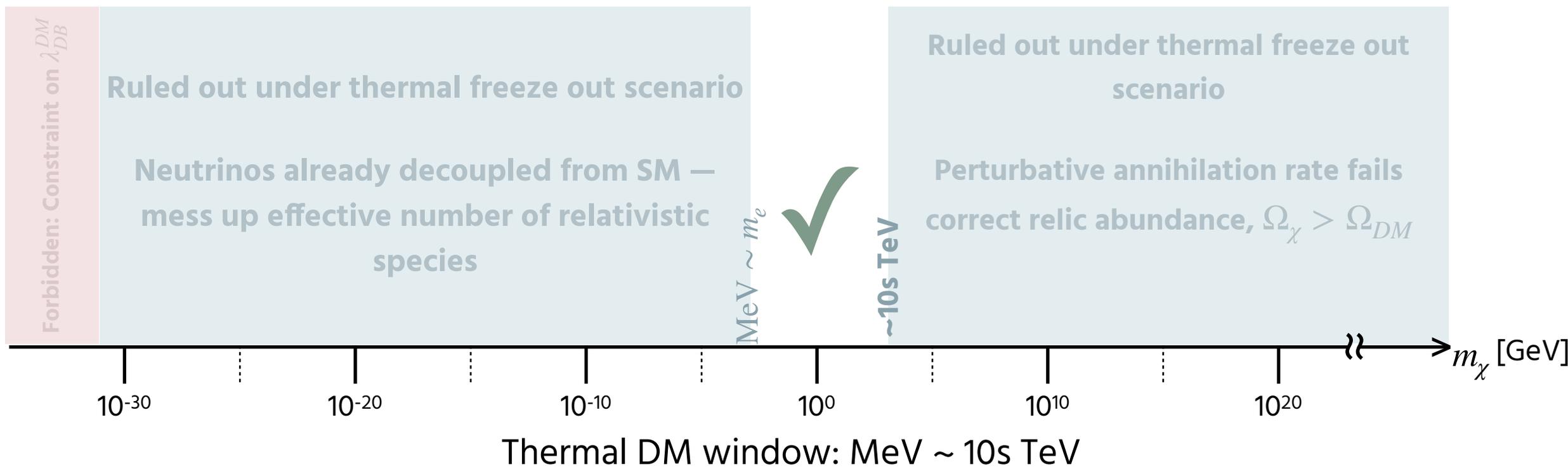
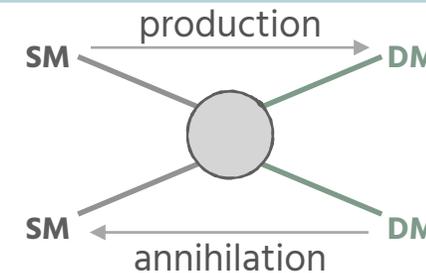
<p>If:</p>	 <p>The diagram illustrates the thermal freeze-out scenario. On the left, four black squares, each containing a white infinity symbol (∞), represent dark matter particles in thermal equilibrium. A large, hollow, double-headed arrow points from these particles towards the right. Inside the arrow, the text reads: "Interaction strength > Hubble expansion rate at some point during early hot Universe". To the right of the arrow is a colorful, cartoonish illustration of various particles and interactions, including a large 'Z' boson, a 'W' boson, and several smaller particles, representing the visible matter and radiation in the early hot universe.</p>
<p>Then:</p>	<p>Dark matter & visible matter \rightarrow thermal equilibrium \therefore relic abundance achieved</p> <p>Relic abundance \rightarrow minimum annihilation rate \rightarrow minimum cross section</p> <p>We can scan production cross sections.</p>



Thermal relic density guides us

Guaranteed: $\frac{\rho_{DM}}{\rho_{baryonic}} \sim \mathcal{O}(1)$ now

Assumption: Thermal contact history between SM and DM



Based on LDMX design paper, fig 2, <https://arxiv.org/abs/1808.05219>

Dark QED



General Lagrangian • A' : U(1) gauge boson & χ : light dark matter particle

$m_{A'}$: dark photon mass

ϵ : kinetic mixing parameter

$$\mathcal{L} \supset -\frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} + \frac{m_{A'}^2}{2} A'_\mu A'^\mu - A'_\mu (\epsilon e J_{EM}^\mu + g_D J_D^\mu)$$

SM electromagnetic current

g_D : U(1)_D coupling constant

Dark matter current

★ Relic density same dependence on model parameters $\{\epsilon, g_D, m_\chi, m_{A'}\}$

- We're OK even if each value of χ technically different J_D

LDMX goals



Flagship objective: High-luminosity missing momentum measurement via fixed-target collisions

“Dark bremsstrahlung” process
E-beam incident on thin target makes DM, carrying away most of incident e’s energy (energy appears to disappear)

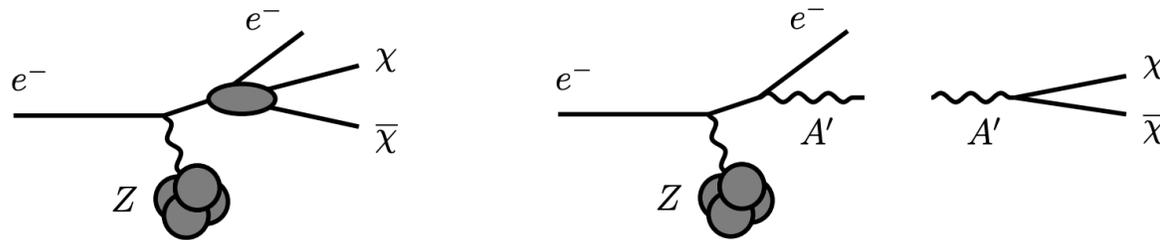


FIG. 1: Left panel: Feynman diagram for direct dark matter particle-antiparticle production. Right panel: Feynman diagram for radiation of a mediator particle off a beam electron, followed by its decay into dark matter particles. Measuring both of these (and similar) reactions is the primary science goal of LDMX, and will provide broad and powerful sensitivity to light dark matter and many other types of dark sector physics.

- ★ Interpret missing momentum measurements → secluded dark matter models, millicharge particles, invisibly decaying dark photons, axions, dark Higgs particles,...
- ★ LDMX as short baseline beam dump → displaced visibly decaying dark photons, axions, inelastic dark matter, dark Higgs, long-lived particles...

LDMX operations strategy



2 experimental phases

	Phase I	Phase II
Total luminosity	0.8 pb ⁻¹	
Tagged e on target	4 x 10 ¹⁴	~10 ¹⁶
Beam energy	4 GeV	8+ GeV
	Established detector technologies (eg, from HL-LHC developments, Mu2e, HPS)	

Beamline considerations



Goal: Individually measure energy & momentum for up to 10^{16} e⁻ scattered off thin tungsten target

★ Motivation: Generate high statistics! 10^{14} - 10^{16} electrons on target within few years

★ Requirements

- Beam energy: 4-16 GeV range
 - >16 GeV: Churn out neutrinos (= irreducible background)
- Low-current (~pA), high-bunch repetition (~40 MHz) e beam
- 10^8 electrons/second on target
- Resolve individual particles
 - Low number of electrons per bunch
 - Large beam spot

★ Intended beam line: dedicated 4-8 GeV beam transfer line [@ SLAC on LCLS](#) (under construction)

★ Possibility to exceed 8 GeV with third run of LDMX:

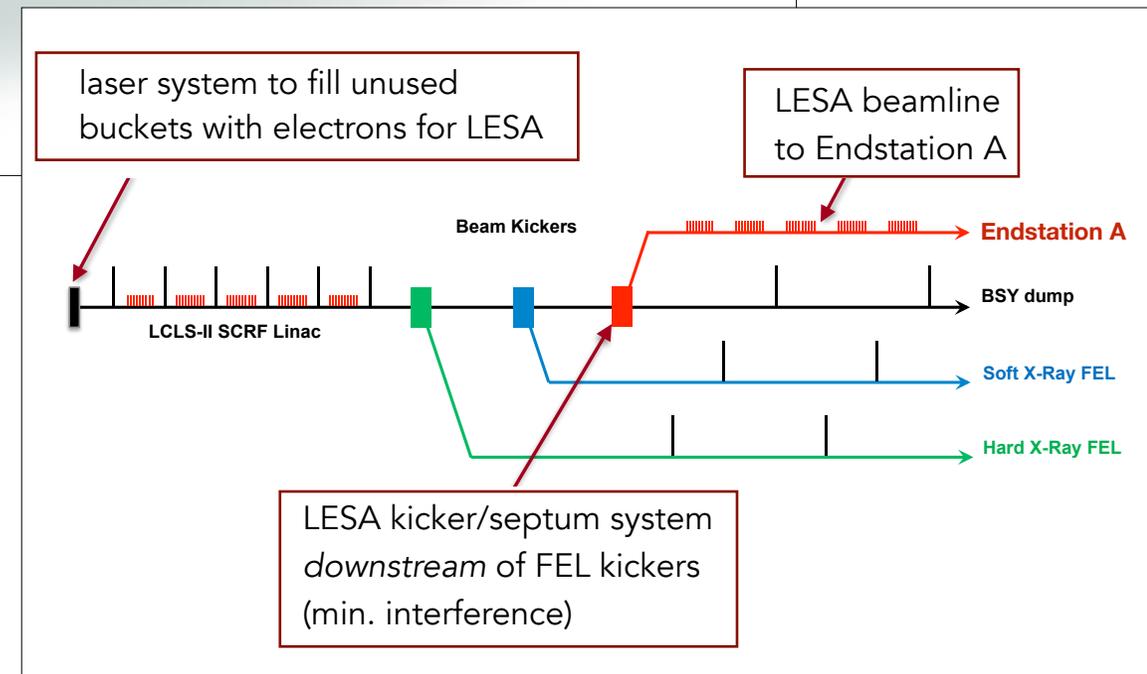
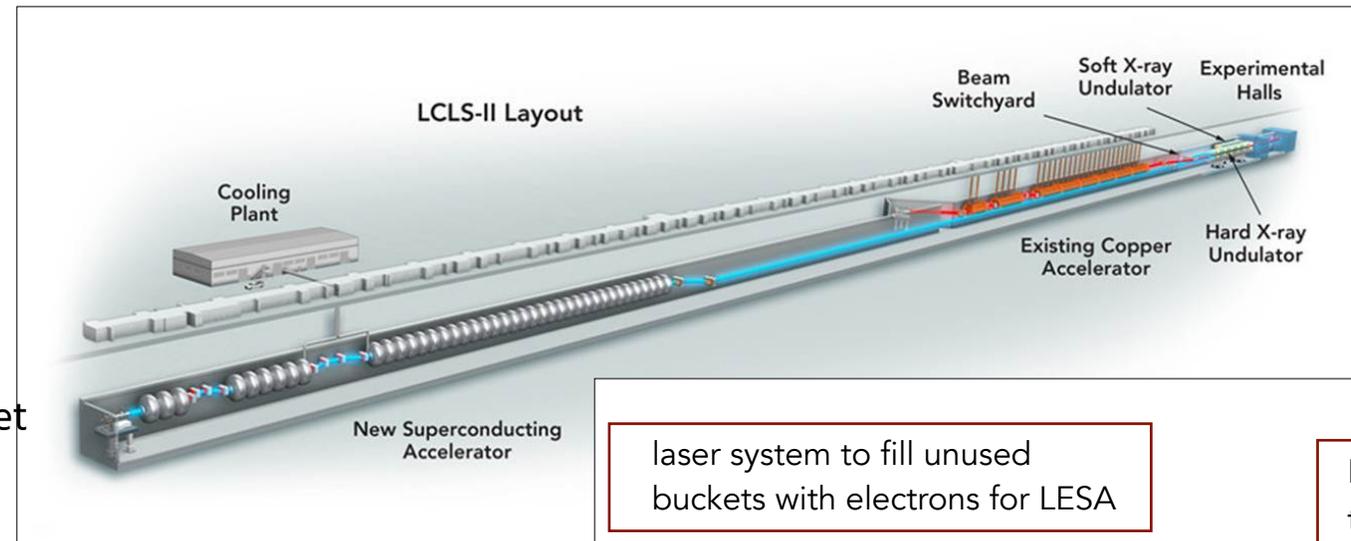
- 3.5-16 GeV beam from slow SPS extraction at CERN

LESA @ LCLS-II @ SLAC



Linac to end station A

- ★ Energy: 4 (8) GeV
- ★ Bunch frequency: ~40 MHz (186 MHz)
- ★ 1st year: 4×10^{14} Electrons on Target
- ★ Parasitic
- ★ S30 Accelerator Improvement Project (kicker & ~100m beamline – ending in beam switchyard) currently under construction
- ★ LESA expected to deliver beam to ESA before LDMX construction completed
 - Laser must also be installed at the injector for bunch frequency





Veto power in LDMX

Study in simulation at 4 GeV beam energy

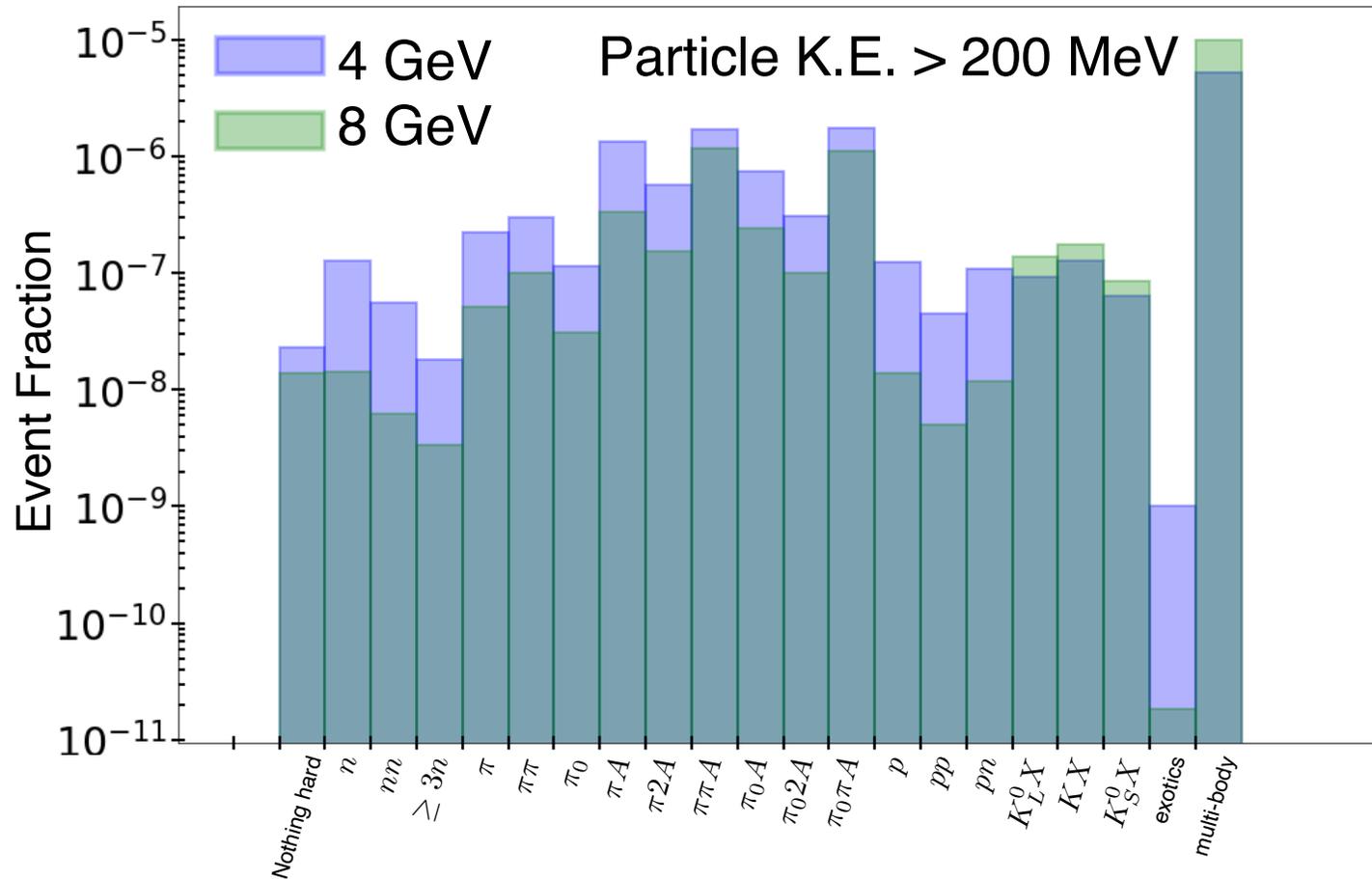
	Photo-nuclear		Muon conversion	
	Target-area	ECal	Target-area	ECal
EoT equivalent	4×10^{14}	2.1×10^{14}	8.2×10^{14}	2.4×10^{15}
Total events simulated	8.8×10^{11}	4.65×10^{11}	6.27×10^8	8×10^{10}
Trigger, ECal total energy < 1.5 GeV	1×10^8	2.63×10^8	1.6×10^7	1.6×10^8
Single track with $p < 1.2$ GeV	2×10^7	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

TABLE II: The estimated levels of photo-nuclear and muon conversion backgrounds after applying the successive background rejection cuts outlined in this paper. Here, the total events simulated corresponds to the total electrons fired on target in the simulation. The biasing factor passed to the GEANT4 occurrence biasing toolkit is used to scale the total events simulated to the electron on target (EoT) equivalent.

Simulation: Final state particle species



LDMX Simulation

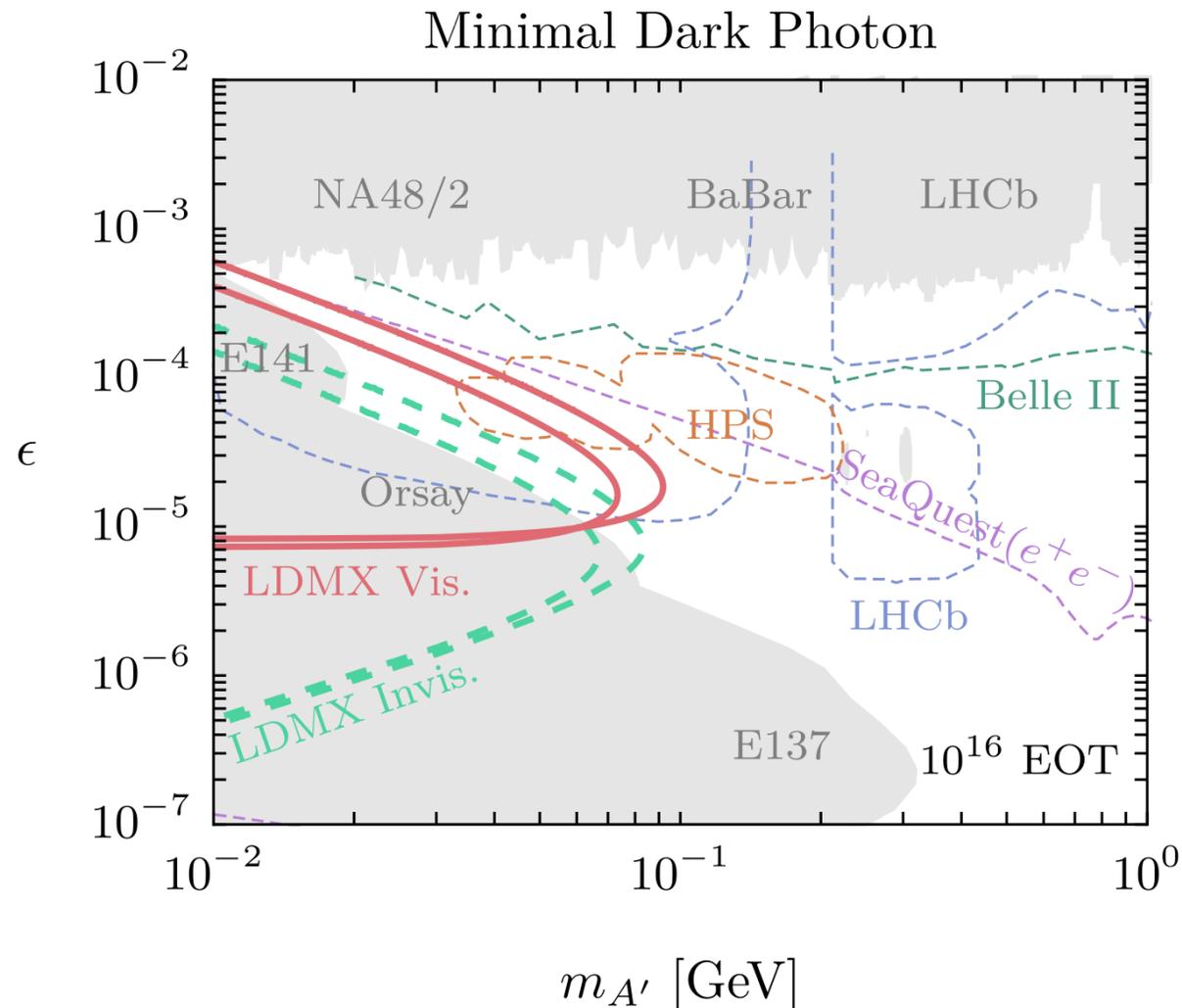


Photonuclear events

★ Blue: 4 GeV e beam

★ Green: 8 GeV e beam

Projected sensitivities: Minimal dark photon

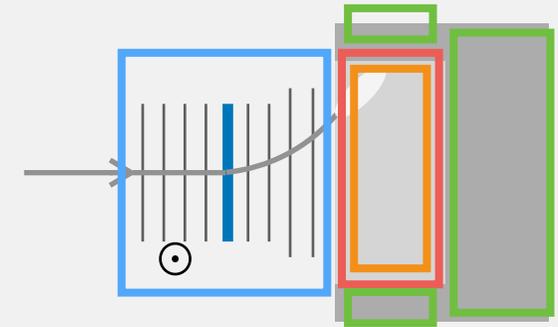
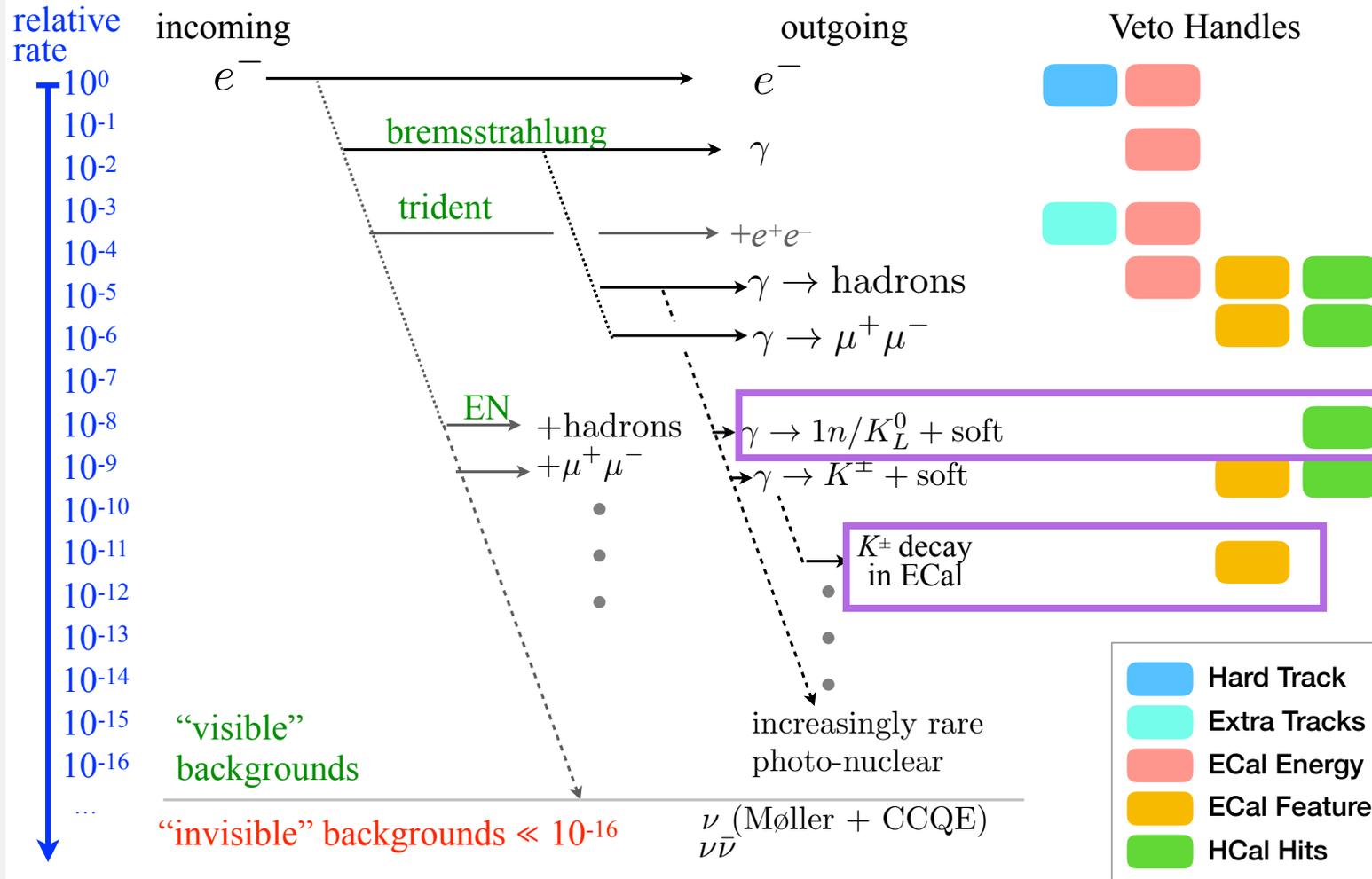


8 GeV beam energy

★ Invisible signatures

★ Visible signatures

Background processes



Essentially only instrumental backgrounds



Testbeam dataset

CERN East Area, T9 beamline • March-April 2022

★ Electrons

- >100k at 500 MeV, 1 GeV, 2 GeV, 4 GeV, 8 GeV

★ Pions

- >100k at 500 MeV, 1 GeV, 2 GeV, 4 GeV, 8 GeV
- >100k samples at 4 different positions along HCal bar for position reconstruction studies
- Samples at 100 MeV, 200 MeV, 300 MeV, 400 MeV

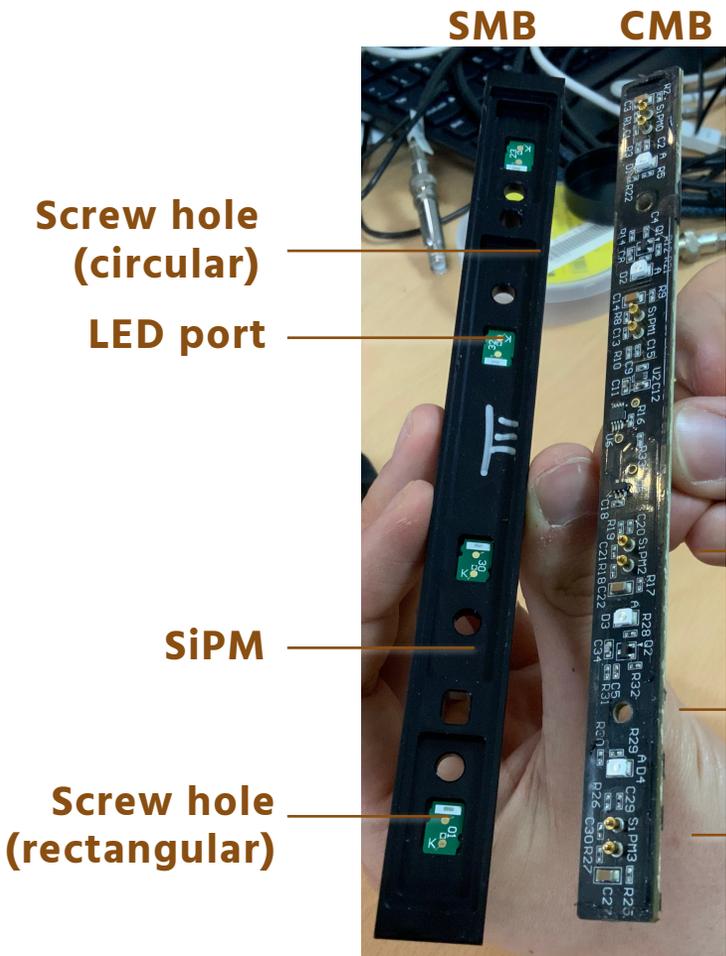
★ Muons

- >1M at 4GeV



HCal readout manifold

SiPM Mounting Block (SMB) and Counter Motherboard (CMB)



Screw hole (circular) Front panel with SiPMs visible

Screw hole (rectangular)

SiPM contacts (probe points)

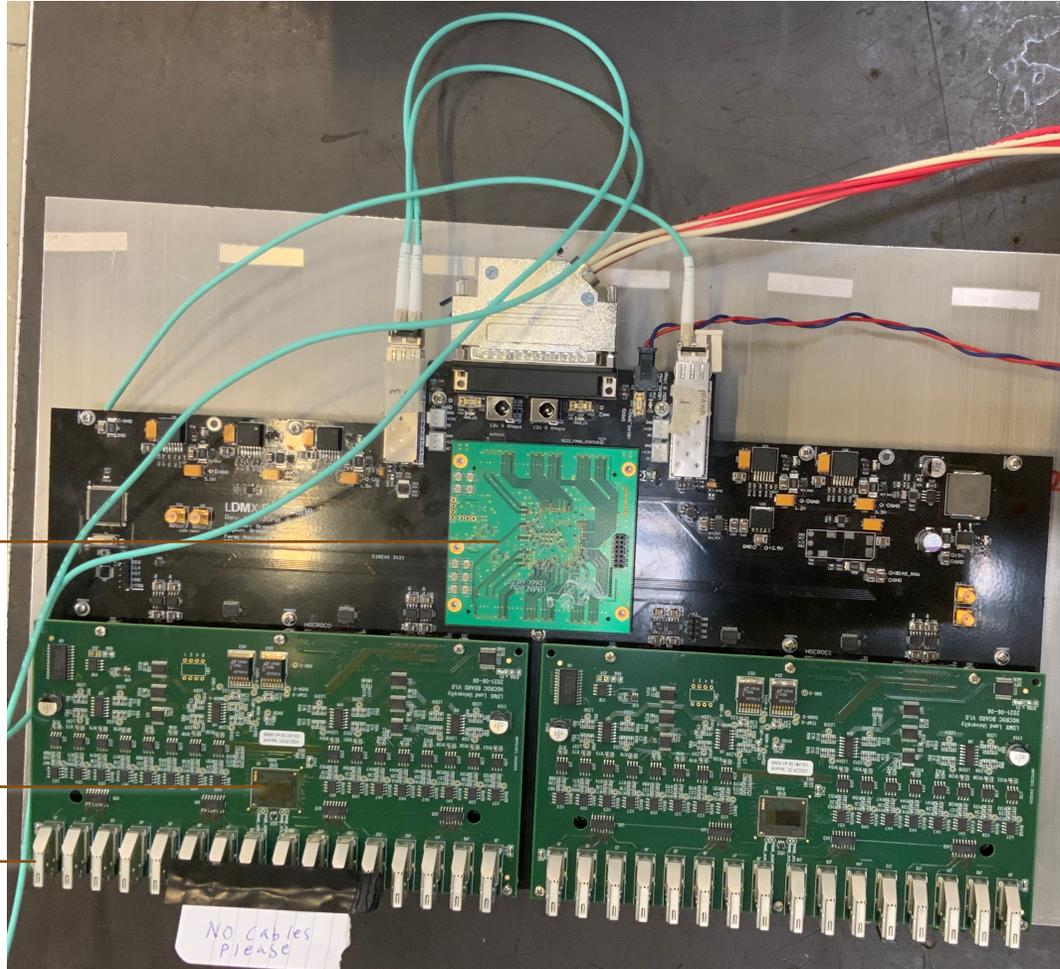


Backside of control board, showing HDMI port & SiPM probe points



Backplane

HGCROC and FPGA



Mezzanine card
Contains the FPGA

HGCROC

HDMI port

Backplane

Mezzanine
card

HGCROC board

HGCROC board

- ★ 4 HGCROC boards per backplane
- ★ Each HGCROC chip has 2 ~independent halves
 - Each HDMI connection = 4 readout channels
- ★ 2 halves/board x 4 boards → 8 ROC
“true/false” during readout configuration



H. Herde 2018-2022

Happy searching!

