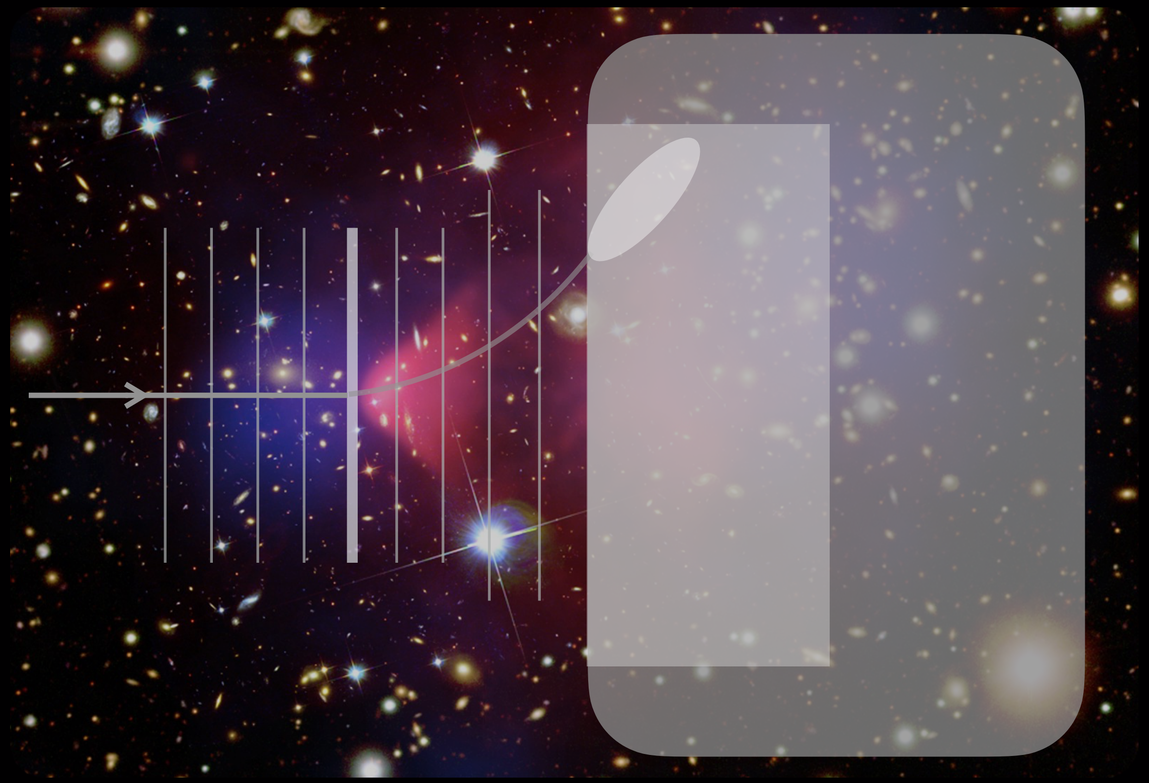
Search for light DM with primary electron beams: Prospects at SLAC

FIPs 2022, CERN

Ruth Pöttgen, Lund University
On behalf of the LDMX Collaboration

LDMX

The Light Dark Matter eXperiment



FIPs 2022, CERN

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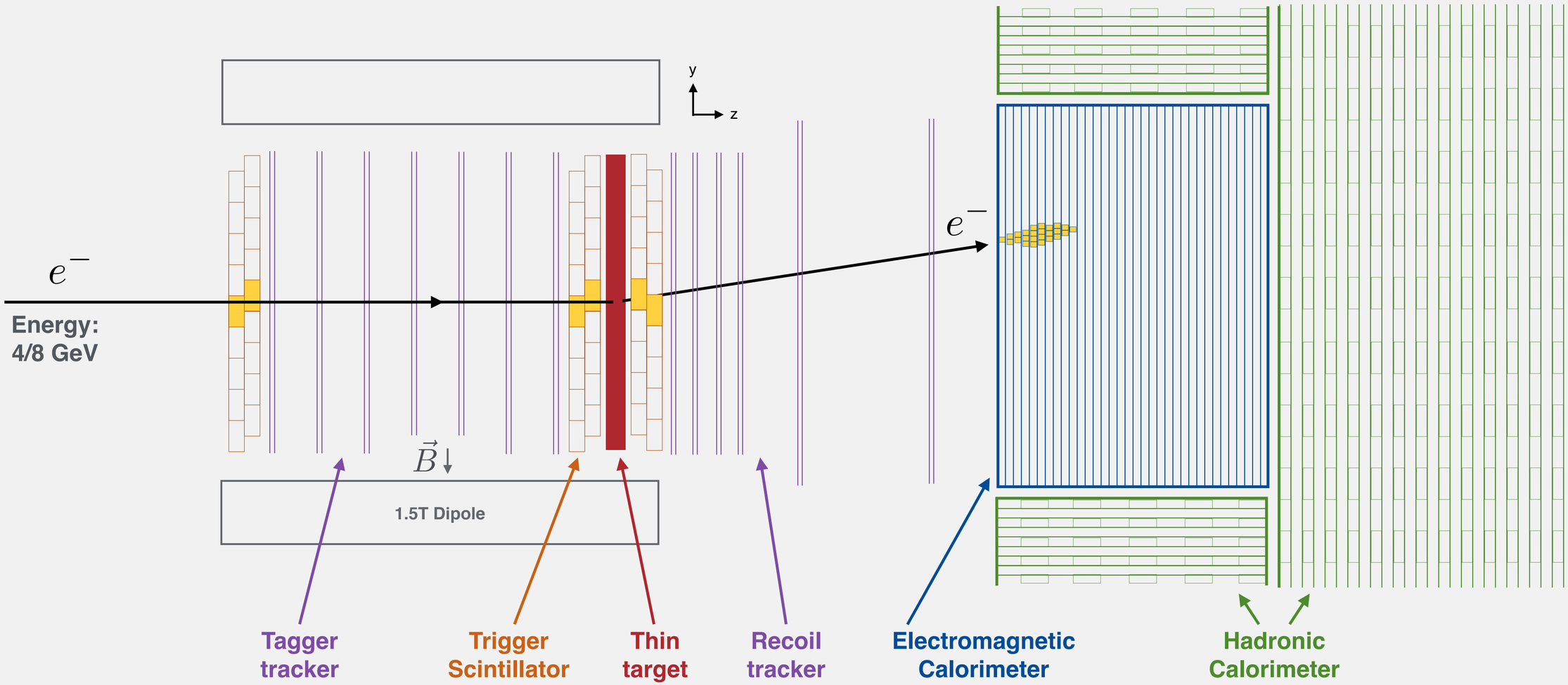
Concept

Individually measure (missing) energy/transverse momentum for up to 10^{16} e^- scattering off a (thin) target



Requires special beam properties

The Beam

Goal: *Individually* measure (missing) energy/transverse momentum
for up to 10^{16} electrons scattering off a (thin) target

Requires special **beam properties**:

Energy ideally 4 GeV < E_B < 20 GeV

High duty-cycle to gather sufficient statistics *despite*

Low intensity (≤10 e^- per bunch) to resolve individual e^-,
helped by **large beam spot**

Choices:

SLAC (*in progress*, first stage)
dedicated transfer line from LCLS-II

CERN (potentially later stage)
new Linac injecting electrons into SPS

LESA @ LCLS-II @ SLAC

https://confluence.slac.stanford.edu/display/MME/Publications+and+Presentations

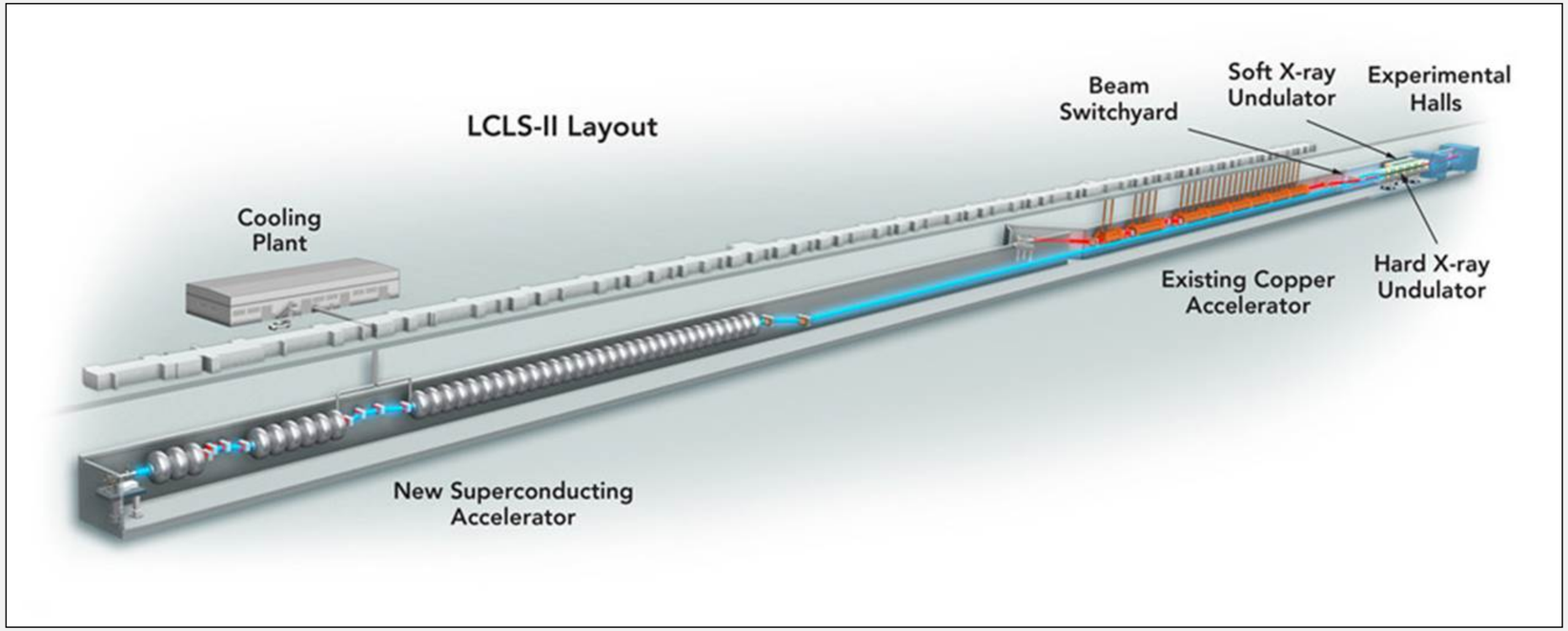
Linac to end station A

Energy: 4 (8) GeV

Bunch frequency: ~40 MHz (186 MHz)

$4x10^{14}$ EoT year 1

Parasitic



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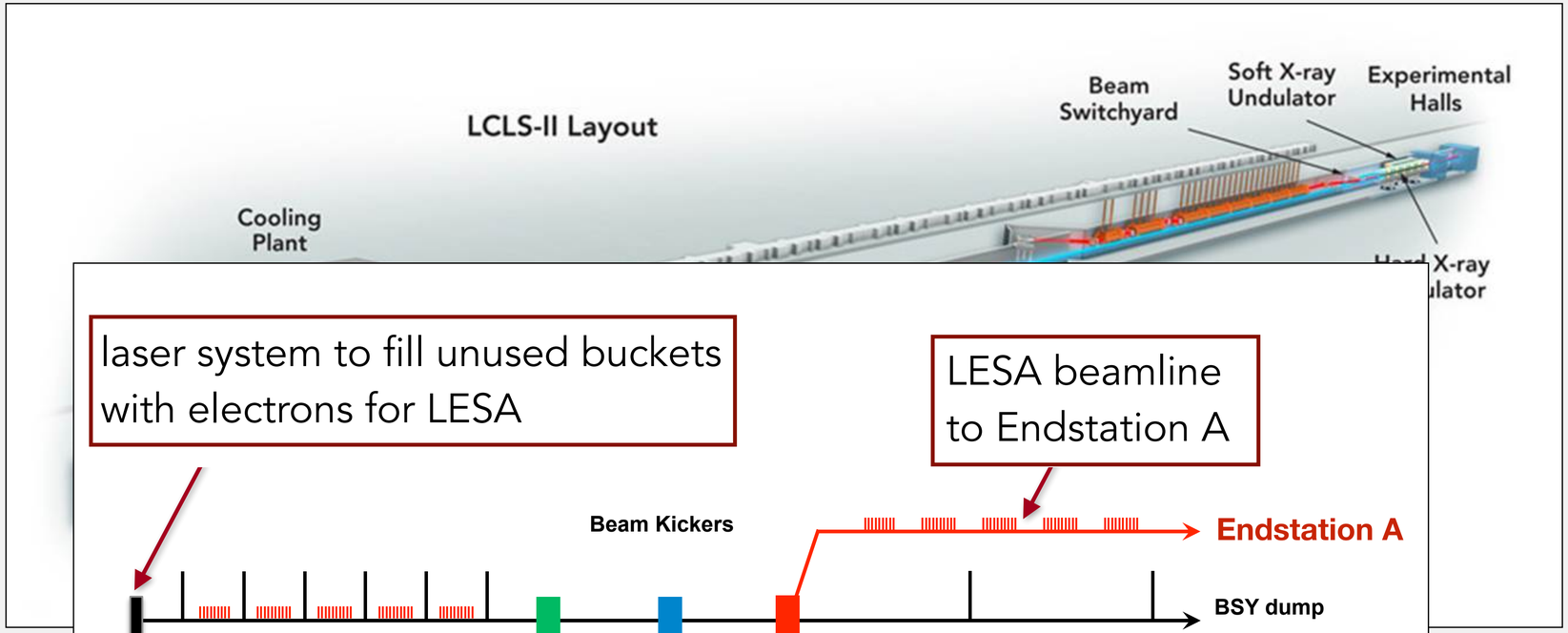

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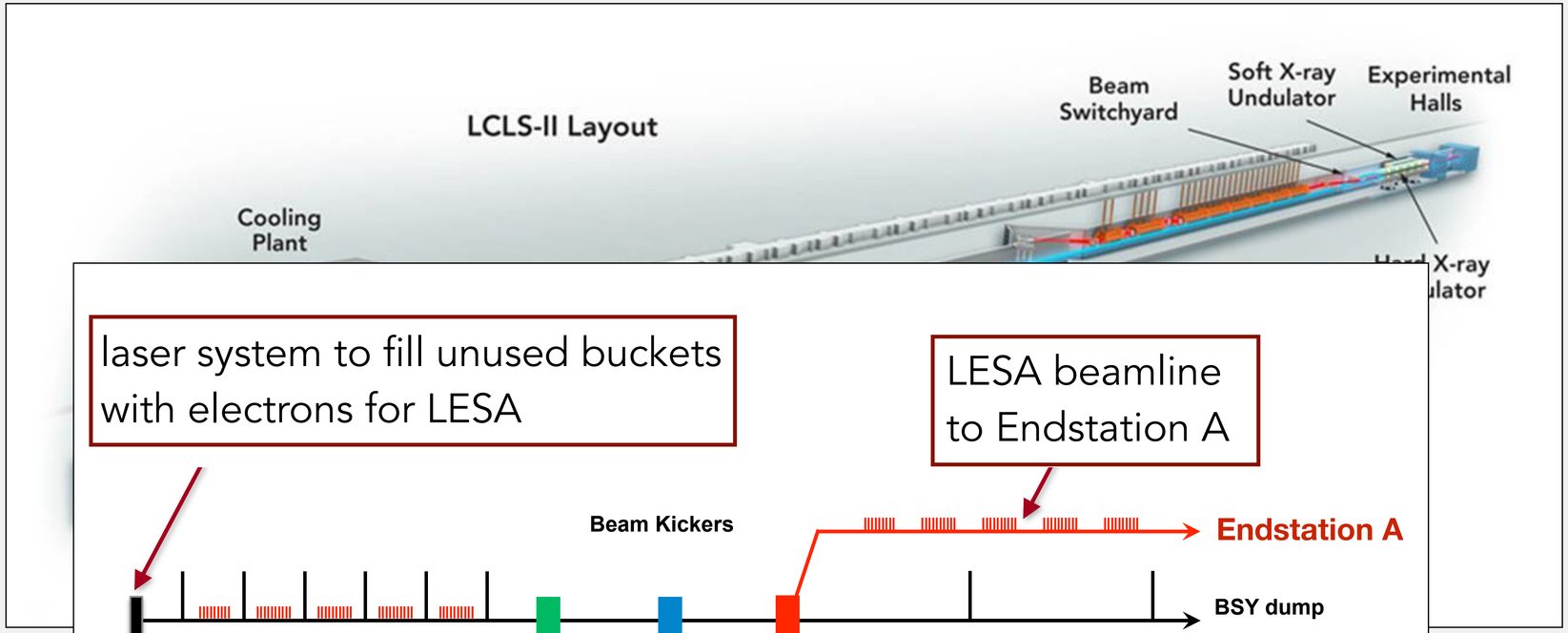
S30 Accelerator Improvement Project (kicker & ~100m beamline – ending in beam switchyard) currently under construction



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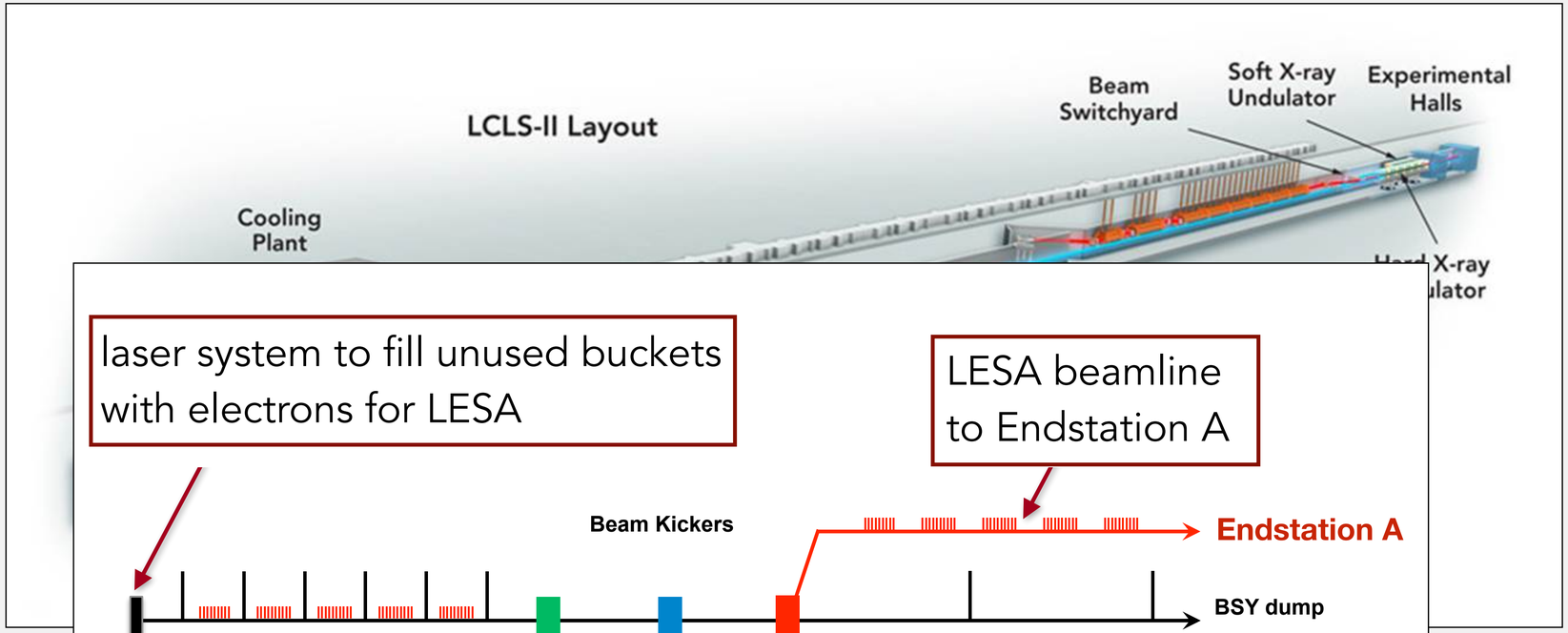
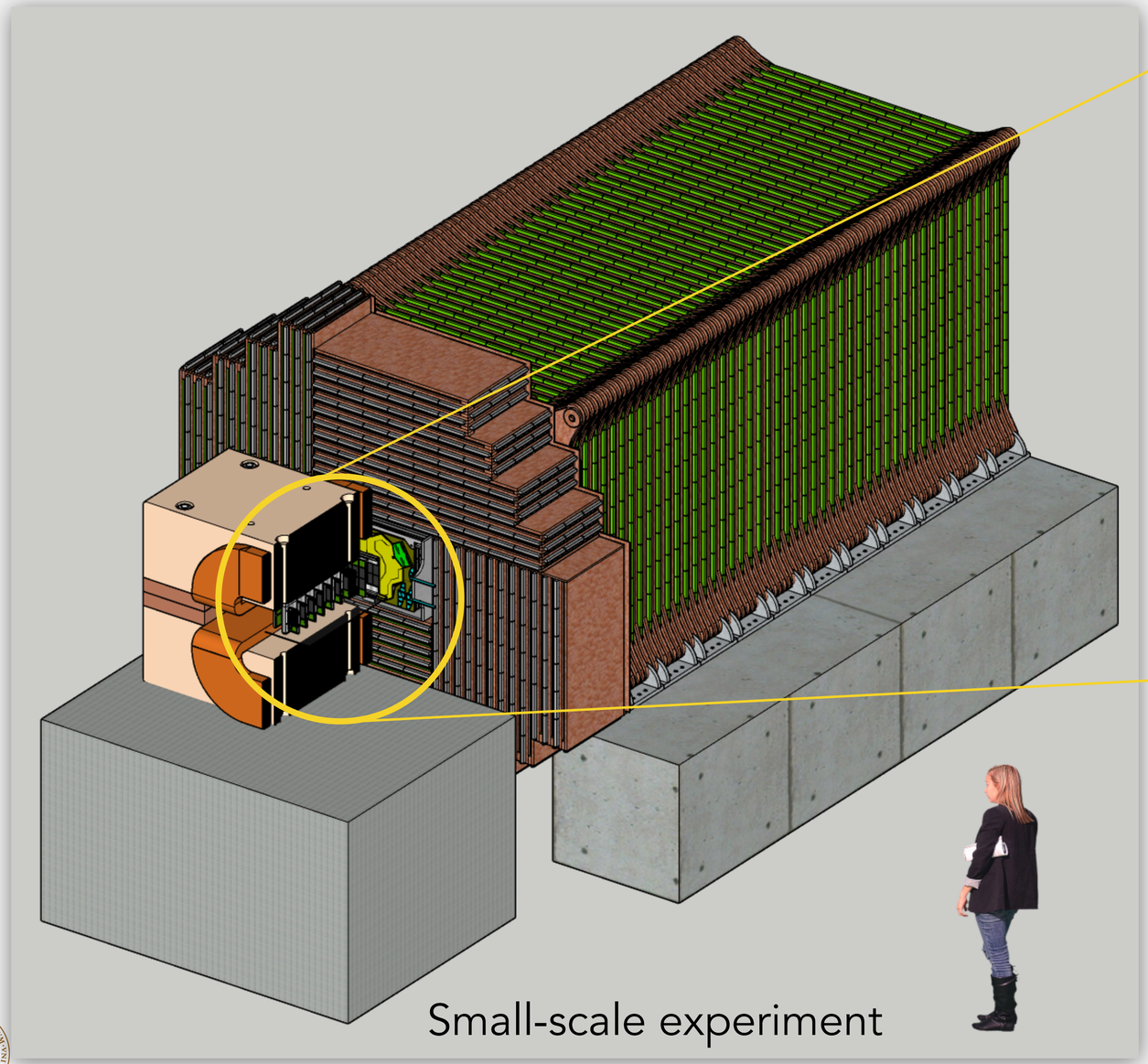
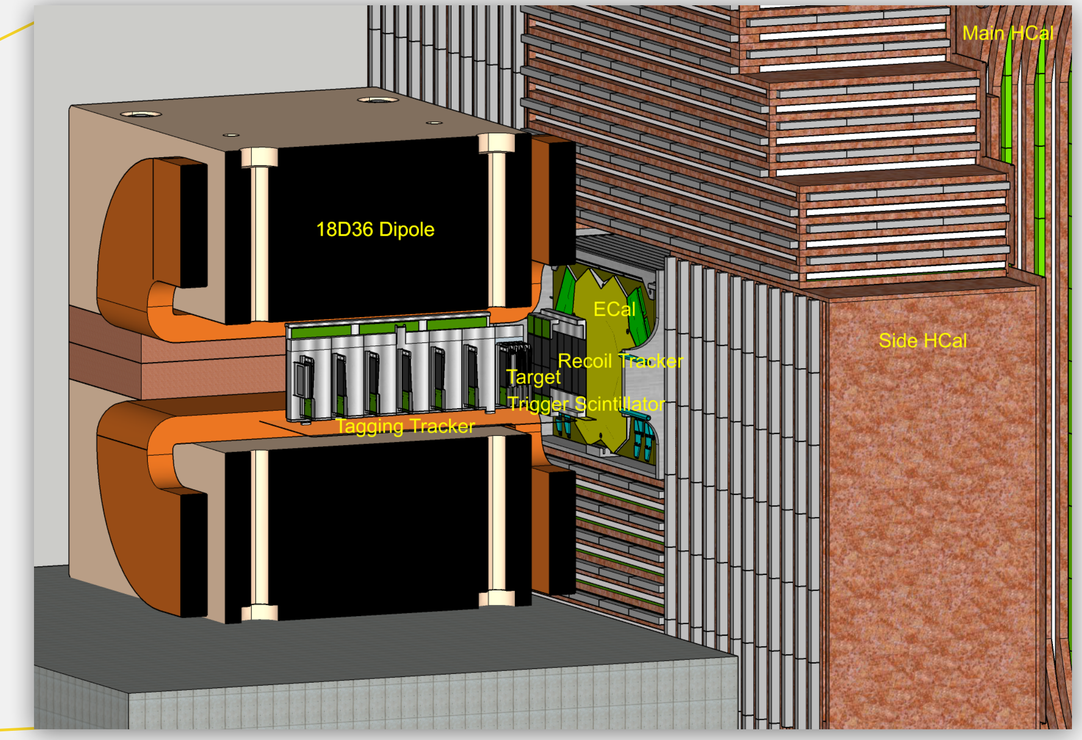
LESA expected to deliver beam to ESA in late FY23



Current Design





Draw on solutions developed for existing experiments:

- Tracking: HPS Silicon Vertex Tracker
- ECal: CMS HGCAL
- HCal: Minos/Mu2e

Design paper on arxiv
arxiv:1808.05219

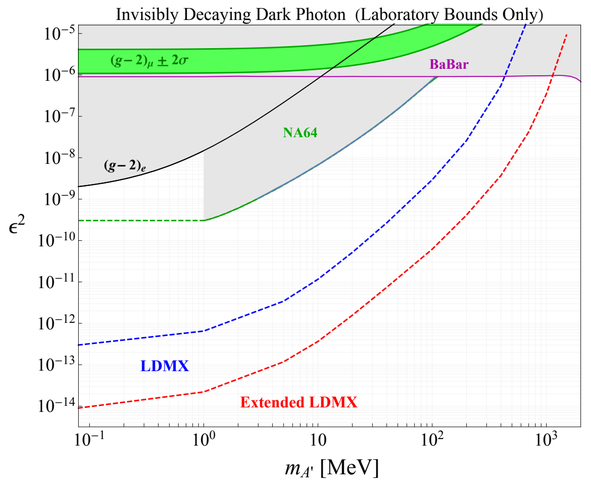
Science

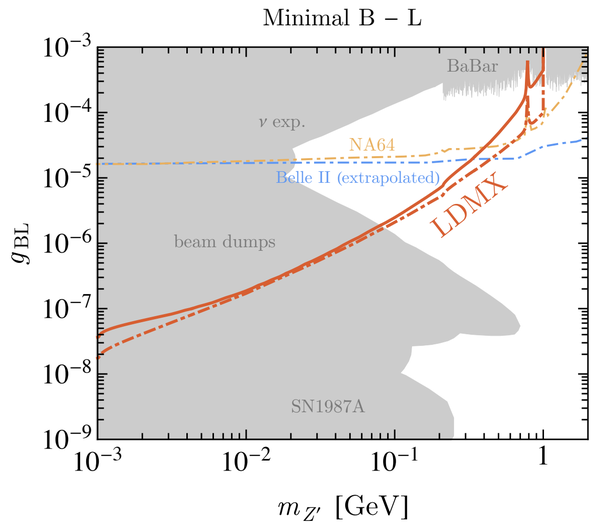
Sensitive to rich spectrum of invisible and visible signatures of new physics

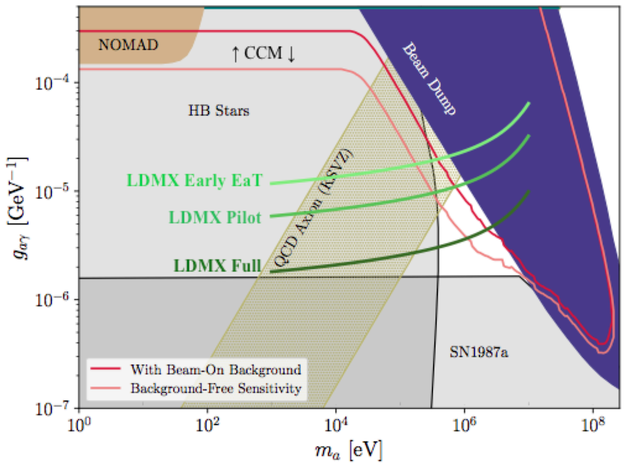
- ***Light (sub-GeV) thermal relic dark matter***
- Dark matter with quasi-thermal origin (asymmetric, SIMP/ELDER scenarios)
- New invisibly decaying mediators in general (A' one example)
- Displaced vertex signatures (e.g. co-annihilation, SIMP)
- Milli-charged particles
- ALPs…

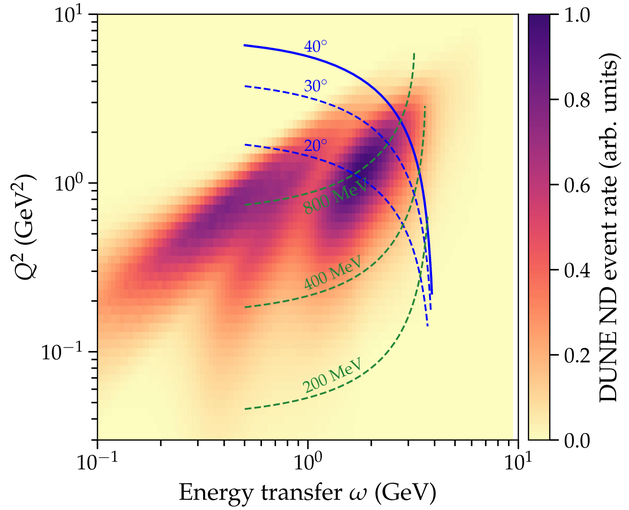
arxiv:1807.01730 arxiv:2203.08192

In addition: ***Measurement*** of photo- and electro-nuclear processes (for neutrino experiments), e.g. Phys. Rev. D 101, 053004

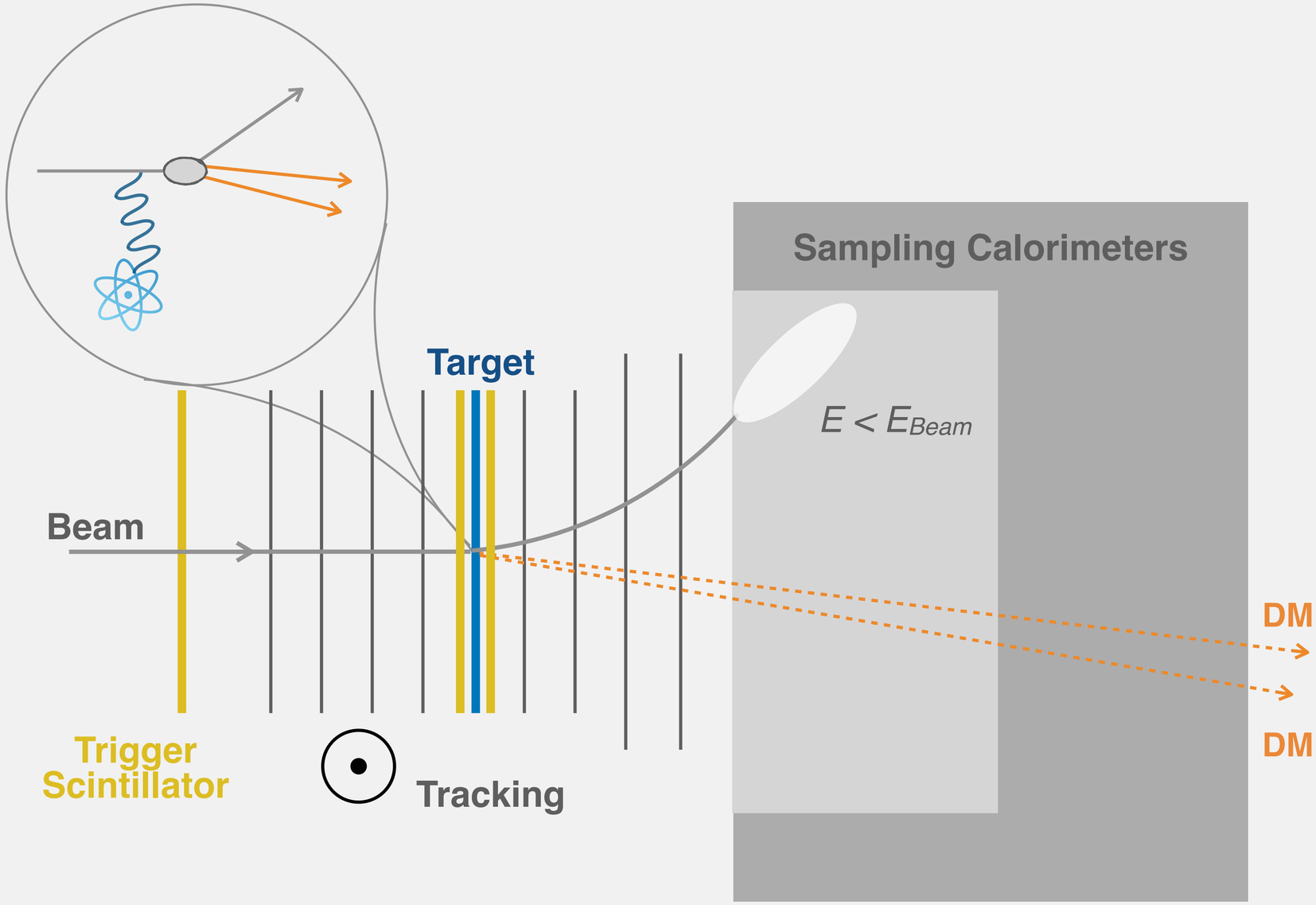






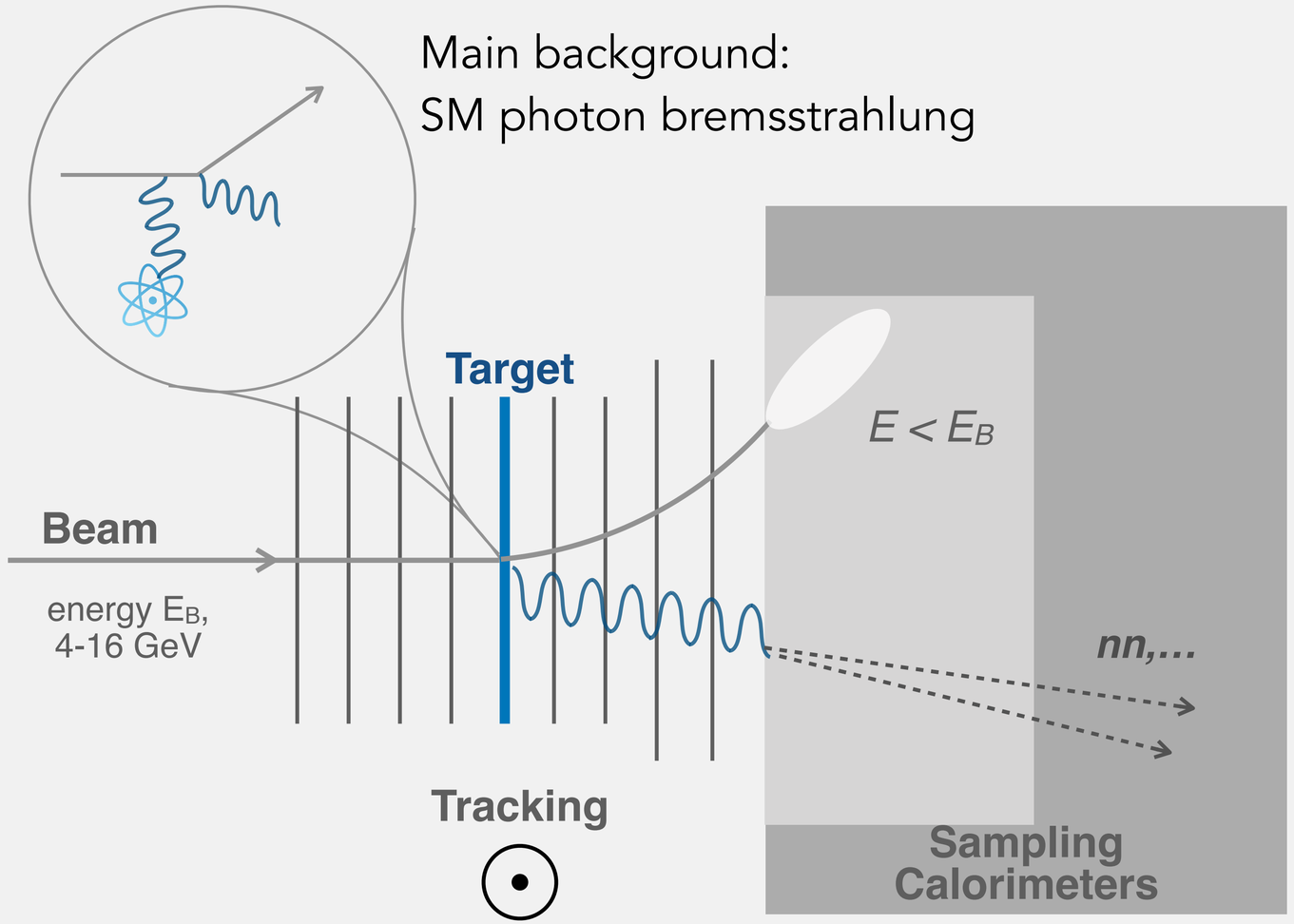


Signal Signature



Challenge

Detect SM particles produced in background reactions, with inefficiencies as low as 10^{-6}
(No irreducible physics backgrounds, only instrumental)



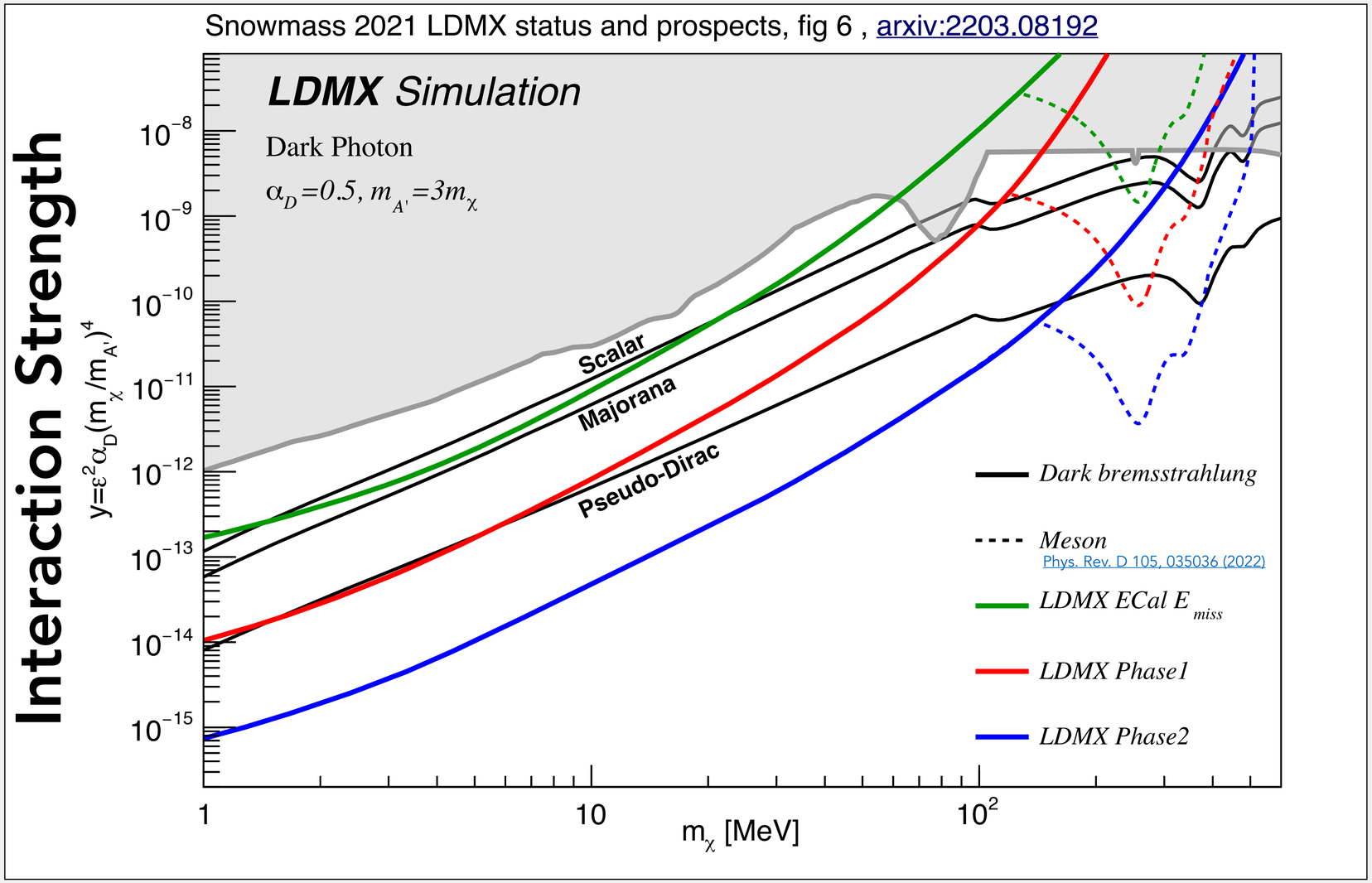
Particularly challenging:

Photo-nuclear reactions producing *neutral final states* (relative rate: ~10^{-9})

Design drivers, especially for HCal!

Simulation studies indicate
<1 background event for
4×10^{14} EoT [JHEP04(2020)003]

Projected Sensitivity (*Before* using p_T information!)



LDMX can explore a lot of new parameter space

Sensitive to several thermal targets already with **pilot runs** at 4 GeV

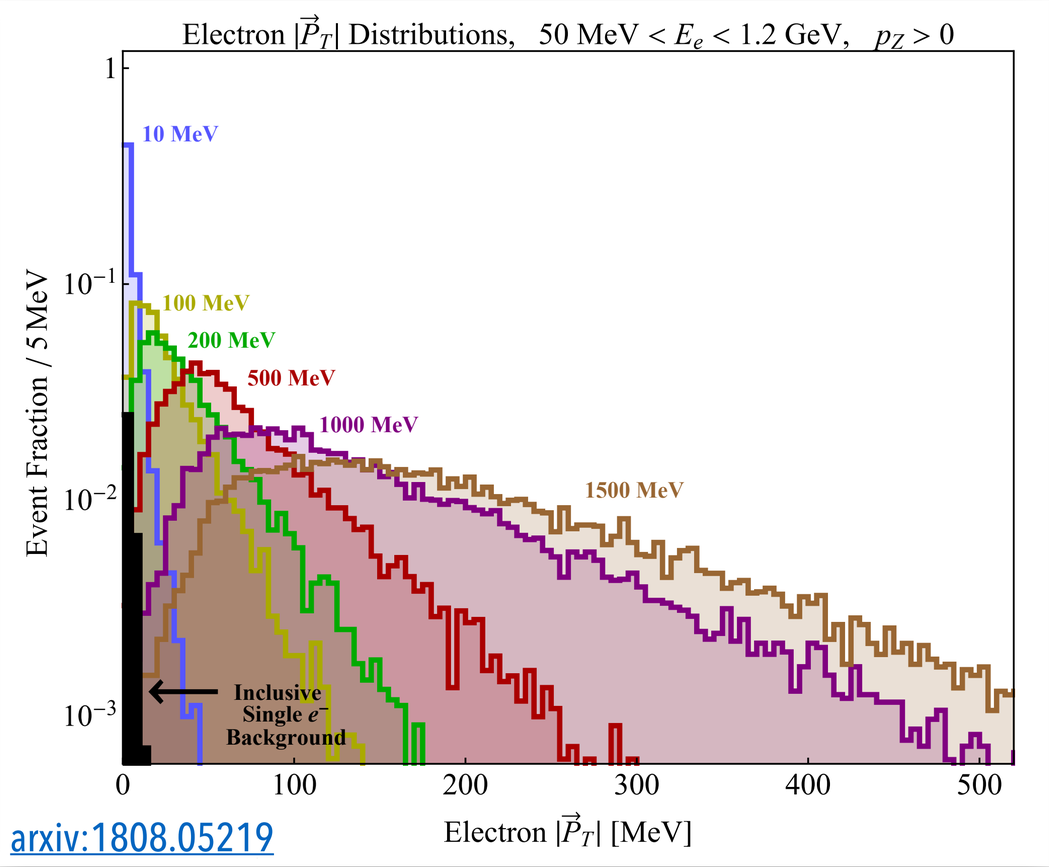
Higher energy (8 GeV) & higher intensity allows exploration beyond thermal targets

Timescale: few years

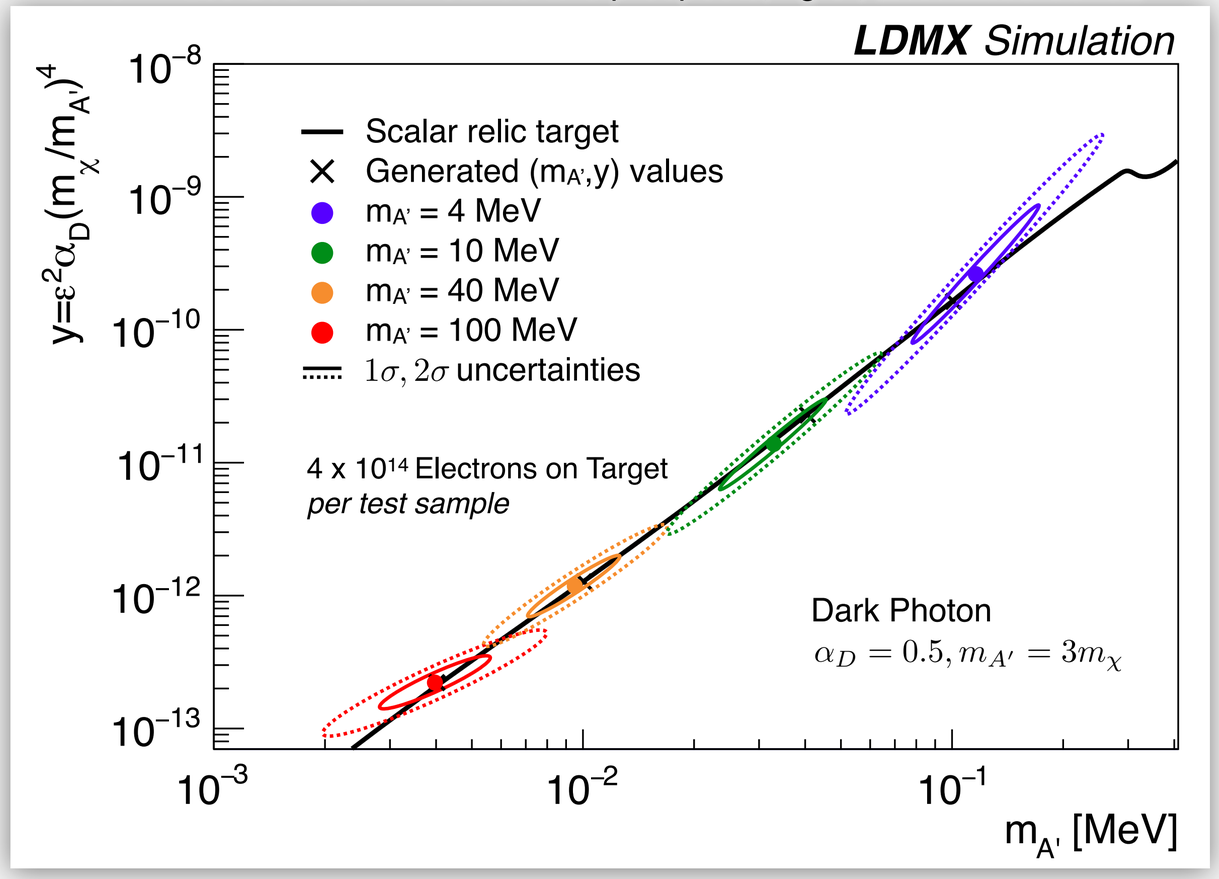
Ultimately potential to probe all thermal targets up to O(100) MeV

For details on background rejection strategy see JHEP04(2020)003

Special Strength: p_T measurement



Snowmass 2021 LDMX status and prospects, fig 8 , arxiv:2203.08192



Measurement of p_T: strong discriminator AND information about (missing) mass!

Recent Milestone: Test Beam at CERN

Prototypes

HCal

19 layers:

Steel absorber + scintillator bars

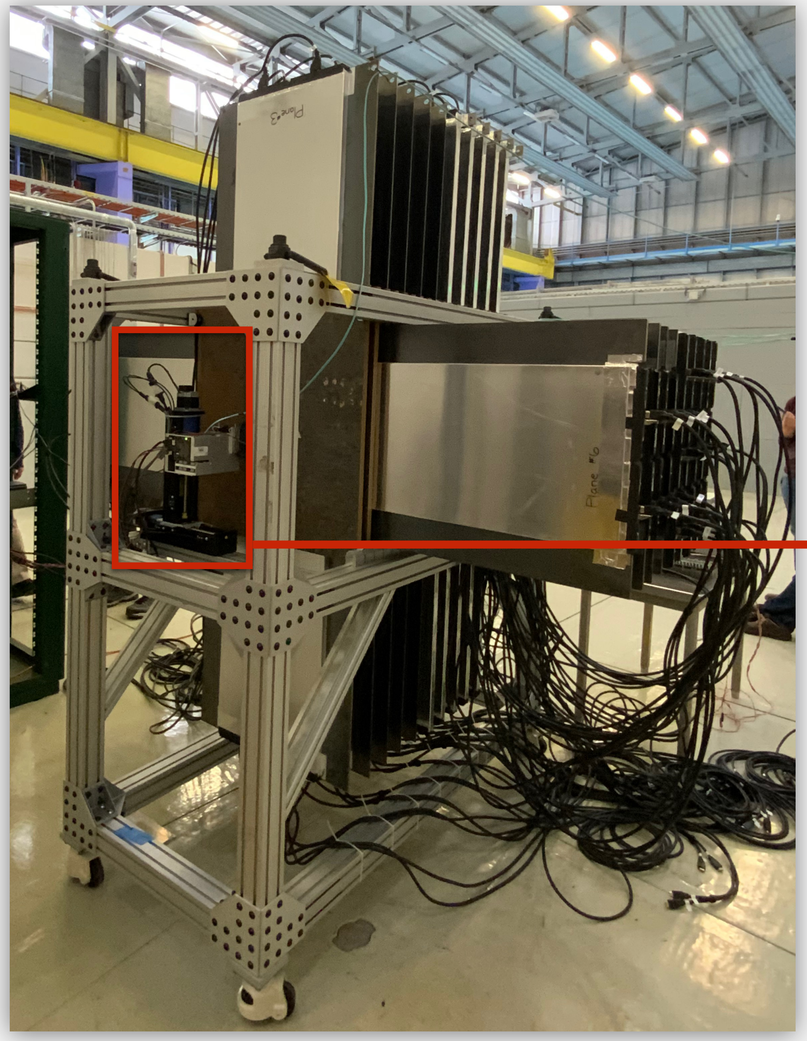
Read out via SiPMs

Trigger Scintillator

Arrays of plastic scintillator or LYSO bars, read out via SiPMs

Movable within beam by means of a gantry

HCal



Trigger Scintillator

Test Beam

2 weeks beam time at T9 beam line at CERN in April 2022

Collected data at 0.1 - 8 GeV (E_{max} = 15 GeV)

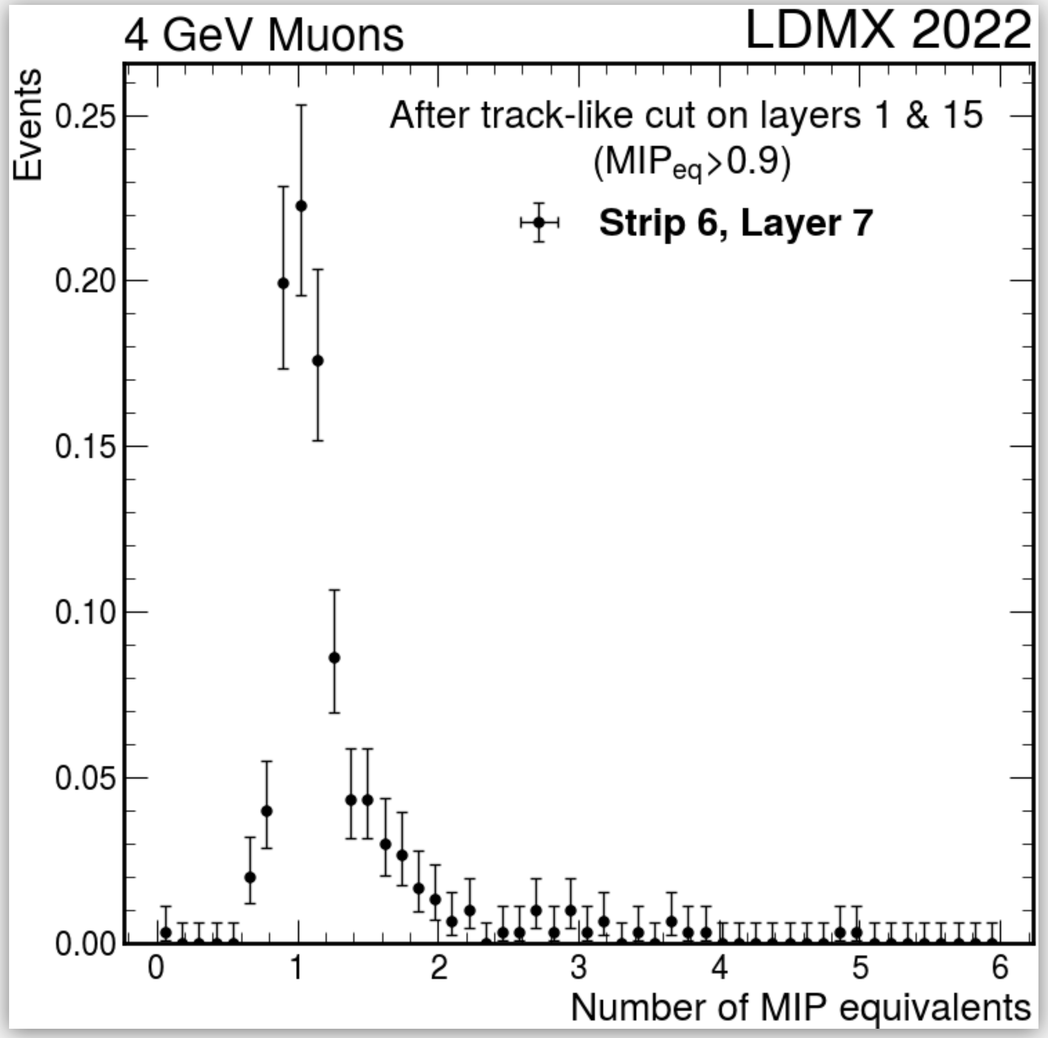
Electrons, muons and hadrons
(Cherenkov detectors for particle ID)

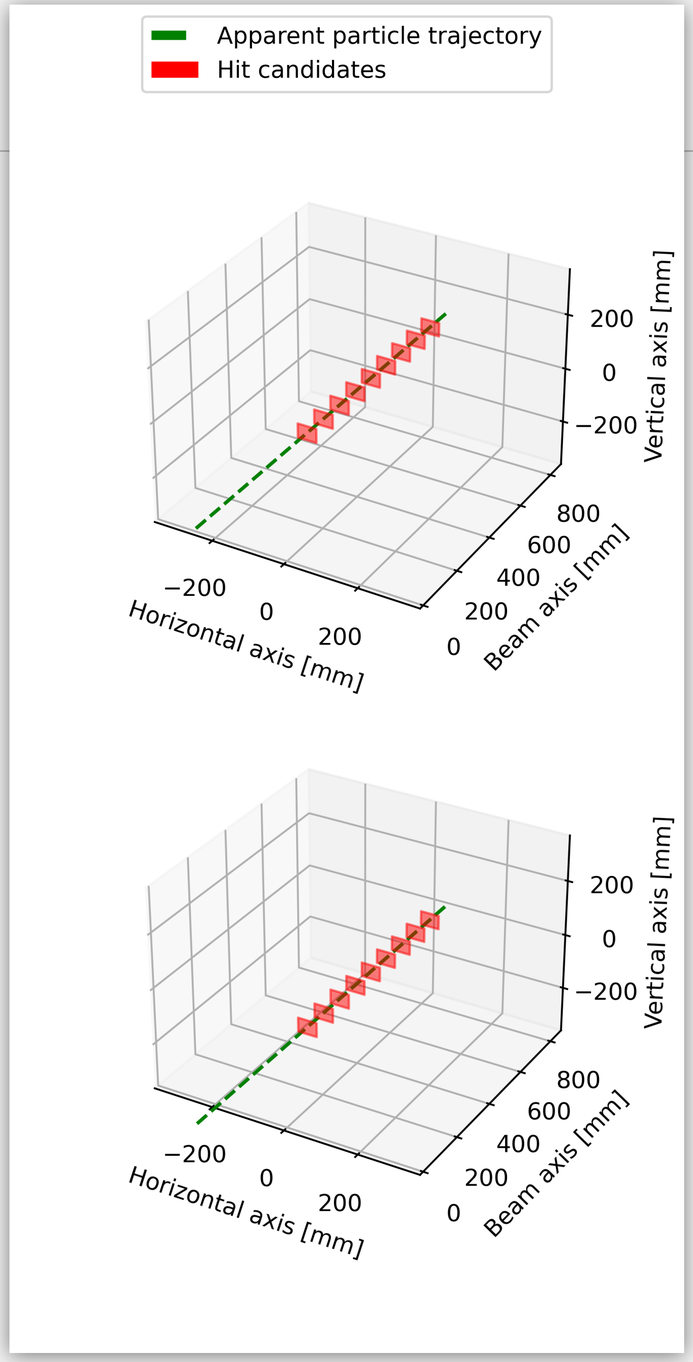
Goals:

- Validate simulations against data
- Test mechanical and electronic designs
- Practice readout chain & data acquisition

Some data: HCal

Response to muons (MIP)





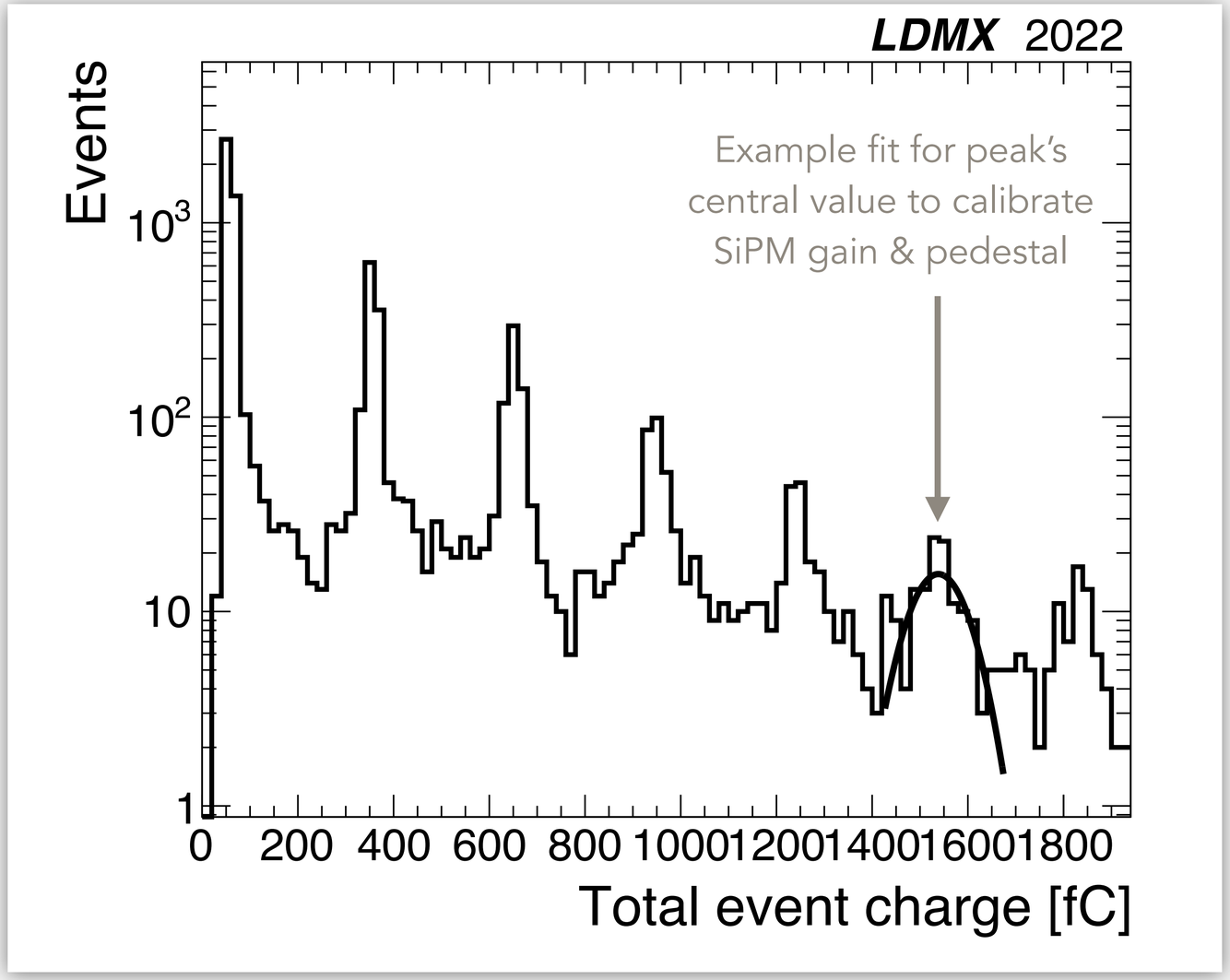
Some data: Trigger Scintillator

Gain calibration

Total charge in each event
for a single channel

1st peak: pedestal

Other: 1-6 SiPM pixels firing



Summary & Outlook

- LDMX powerful tool to search for new physics in forward electron scattering
- Can achieve outstanding sensitivity to sub-GeV dark matter (in O(years))
- Recent milestones in terms of detector development and physics studies
- DOE review June 2022: Project and technical development on track to start construction in FY23, earliest funding availability in FY24
  - Electron beam will be available in experimental area well before construction will be completed

The next few years will be exciting!

More information:

LDMX Confluence Webpage (with links to talks etc.)

Arxiv:1808.05219 (White Paper)

J. High Energ. Phys. 2020, 3 (2020) (Photon Veto Paper)

Arxiv:2203.08192 (Snowmass contributed White Paper)

[Craig Group & Son]

Thank you!

Knut and Alice Wallenberg Foundation

Crafoord foundation

U.S. DEPARTMENT OF ENERGY

KUNGL. FYSIOGRAFISKA SÄLLSKAPET I LUND

Additional Material

Potential LDMX Timeline

Conditional on funding situation

Beam

4 GeV beam
(~1 year)

Shutdown,
Upgrade to 8 GeV

8 GeV beam
(2-4 years)

2022 2023 2024 2025 2026 2027 2028

LDMX

Very positive DOE Review

Beam tests of prototypes at CERN

Construction, installation, commissioning

Data taking

Phase-1

Improvements based on 4 GeV experience

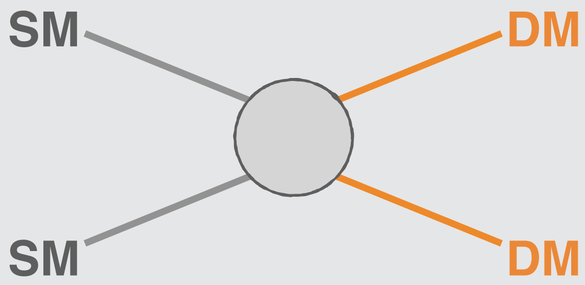
Data taking

Phase-2

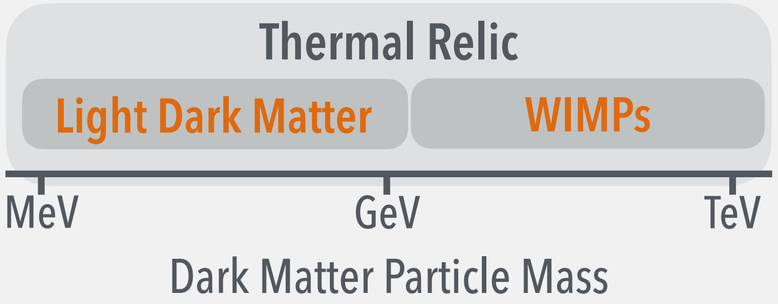
Bulk of data set will be at 8 GeV!

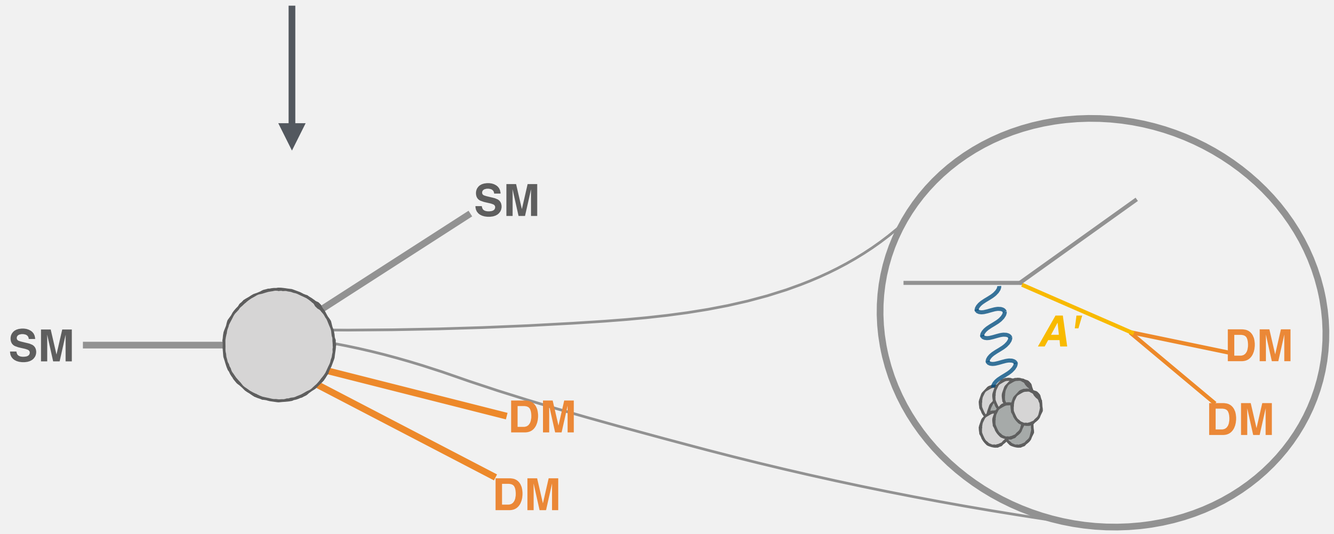
Why sub-GeV dark matter?

Thermal origin of Dark Matter



Allowed mass range: MeV - TeV





Production mechanism at accelerators

Benchmark model:

Dark photon (A') as new light mediator

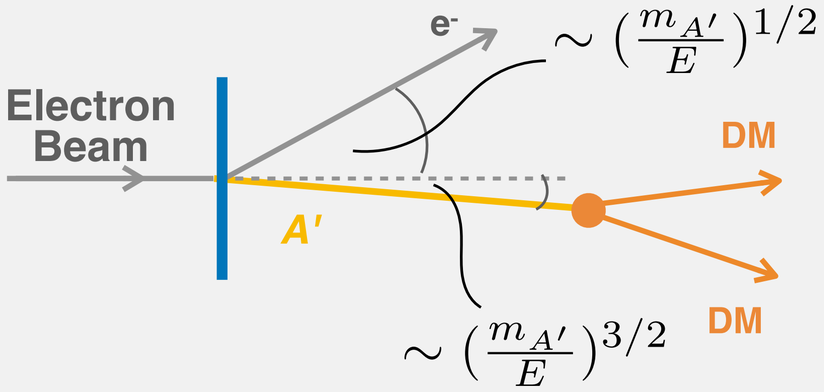
$m_{A'} > 2m_{\chi}$ —> invisible decay

Production e.g. via dark bremsstrahlung or invisible meson decays

Phys. Rev. D 105, 035036 (2022)

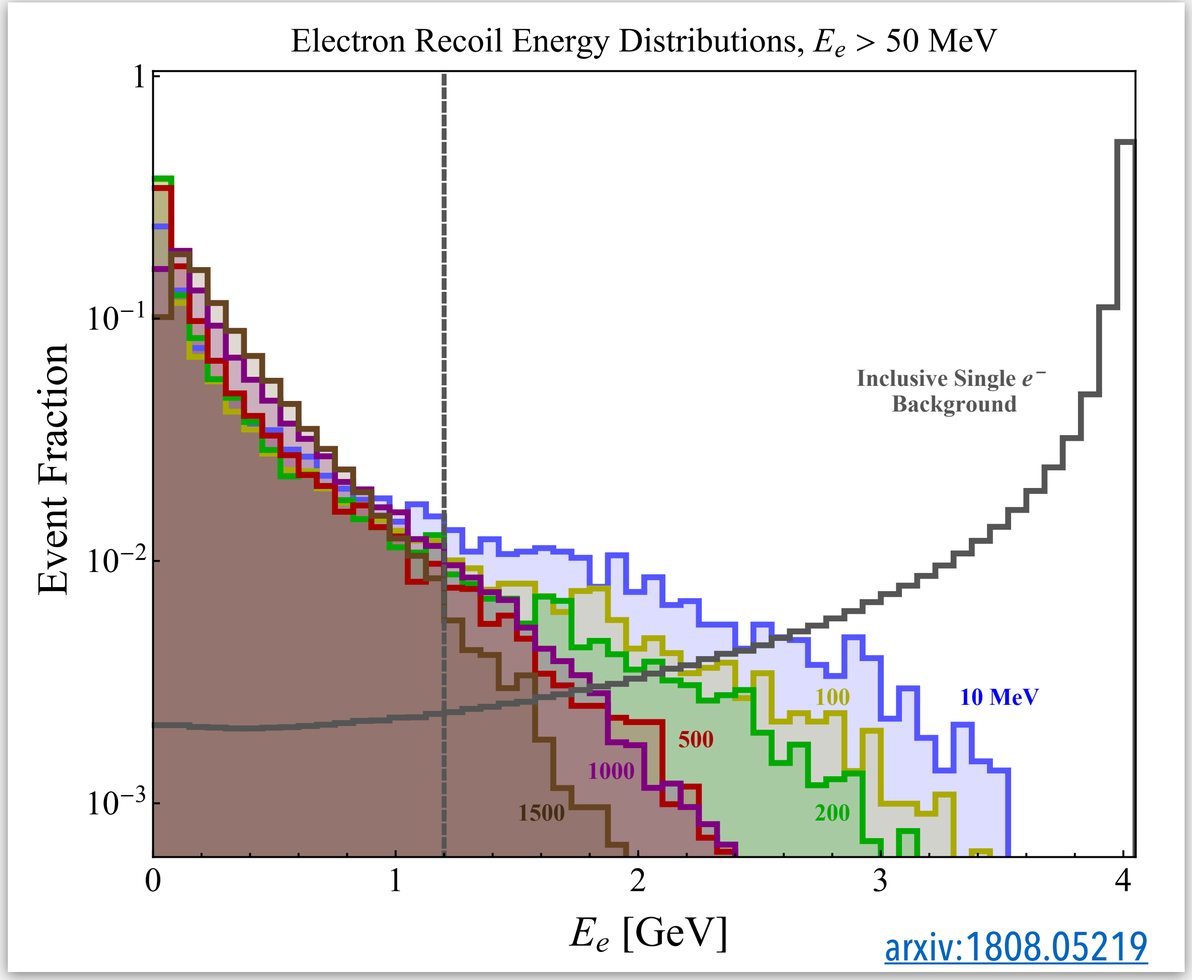
Kinematics

Very different from SM bremsstrahlung, the main background



Mediator carries most of the energy

—> soft recoil electron, large missing energy



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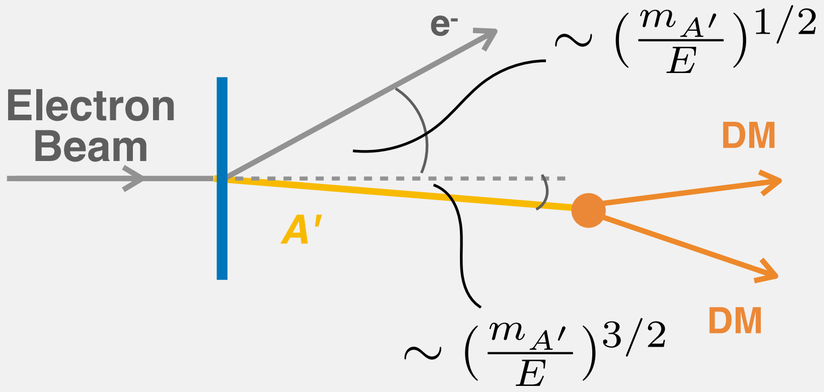
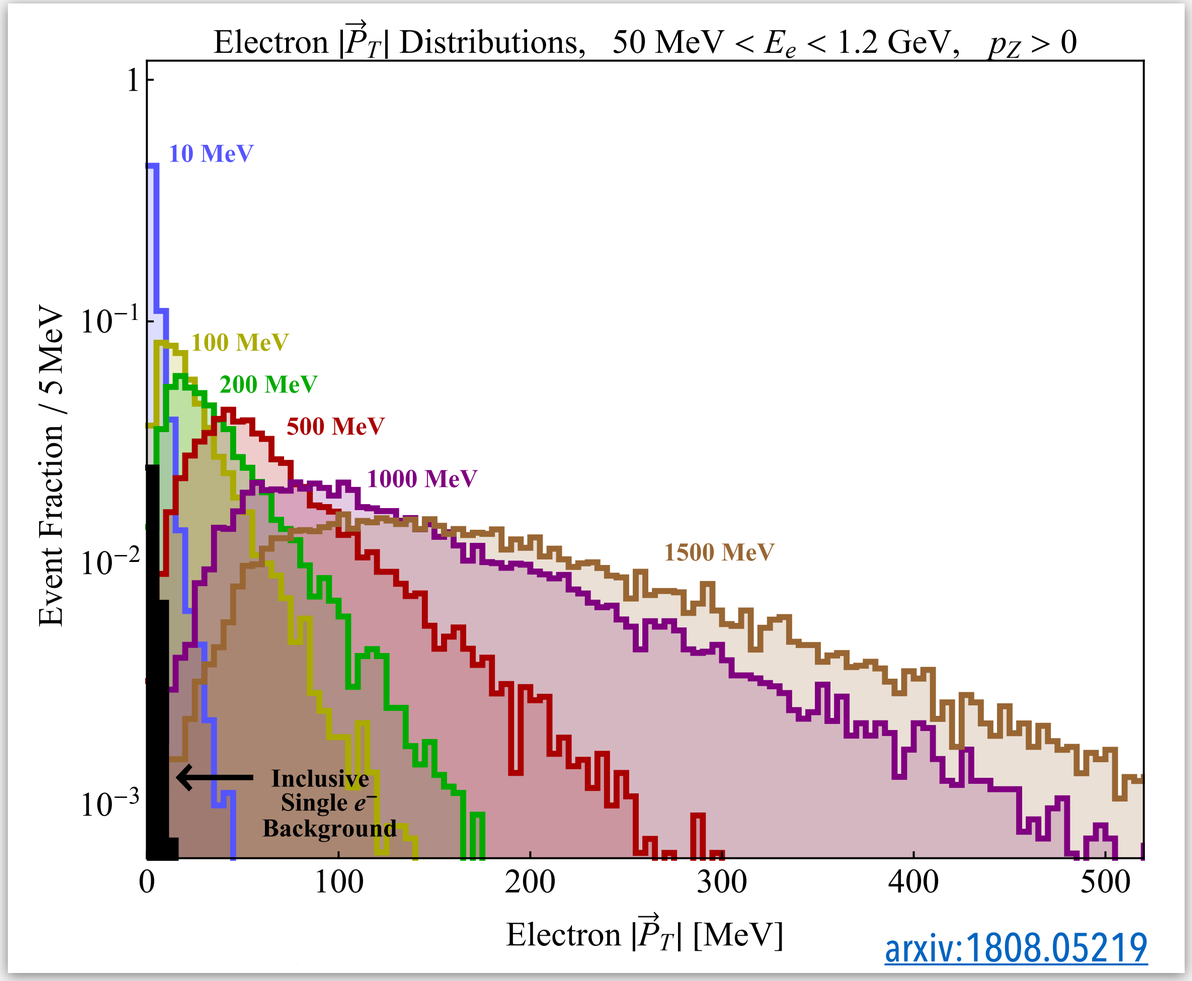
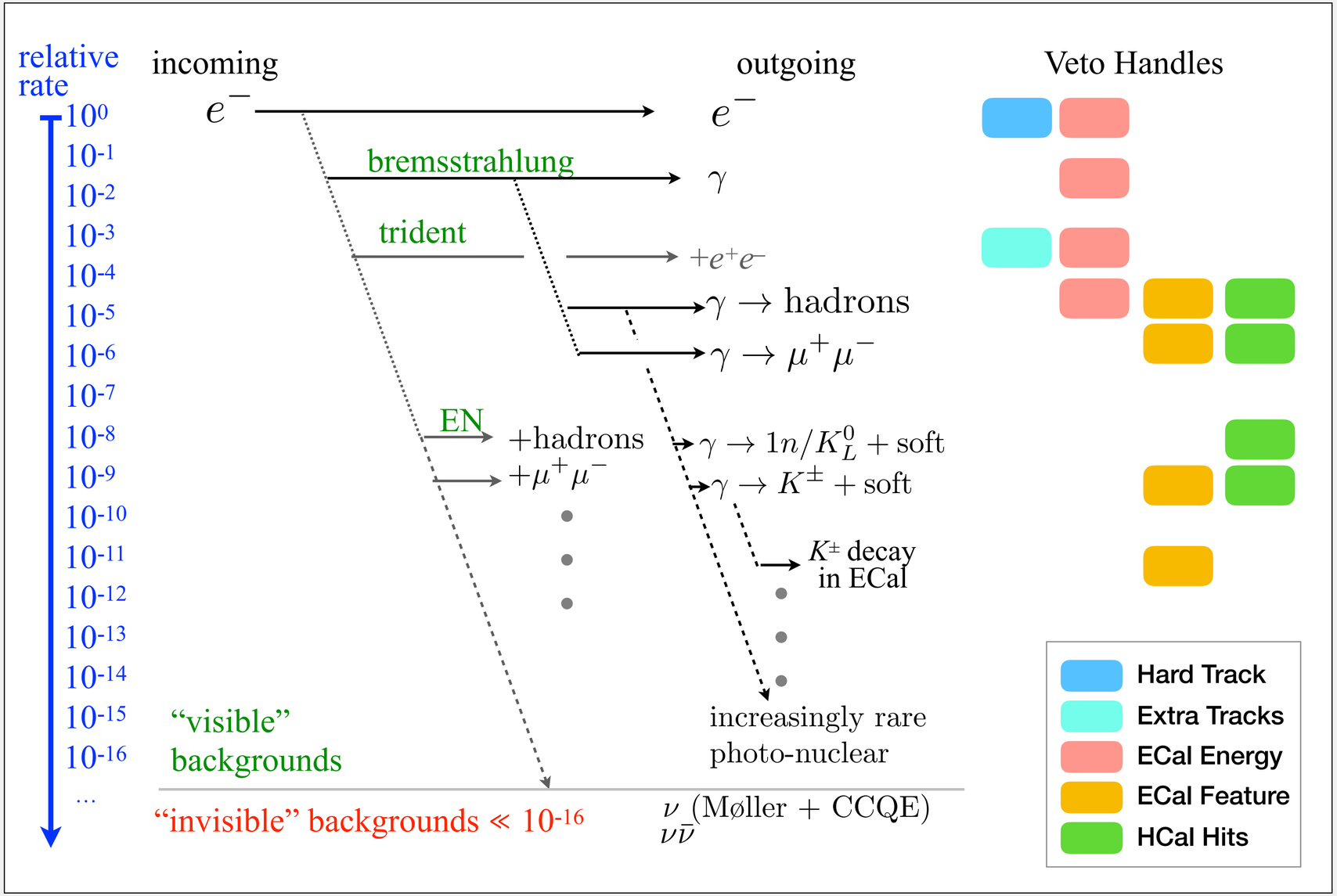


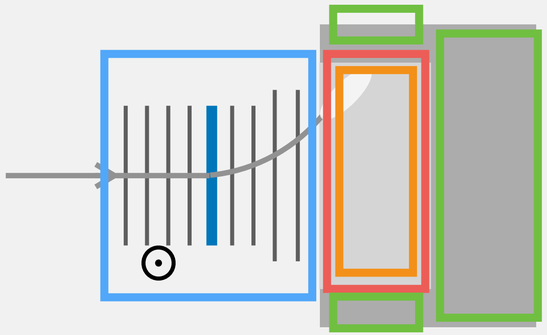
Mediator carries most of the energy
—> soft recoil electron, large missing energy

Recoil electron gets transverse 'kick'
—> large missing transverse momentum



Backgrounds



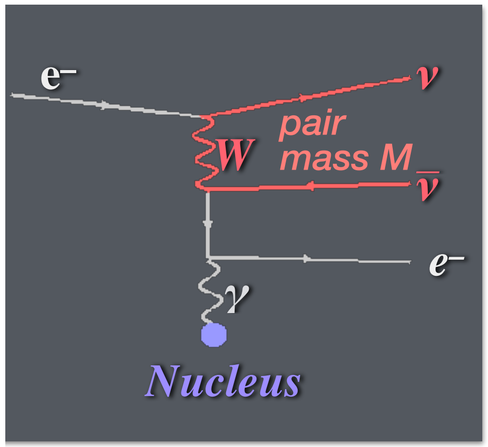


essentially only instrumental backgrounds

Neutrino Backgrounds

Prompt Neutrino Reactions

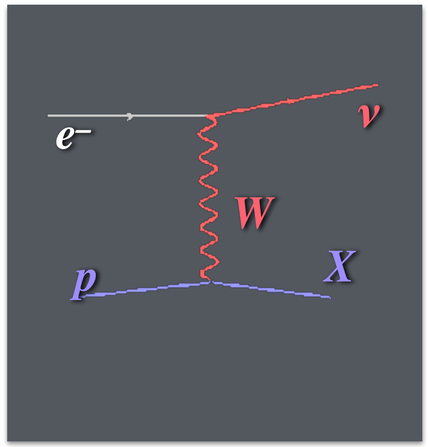
Neutrino Tridents



$N_{\nu\nu}/N_e$
$\sim 10^{-19}$ (E/4GeV)

irreducible

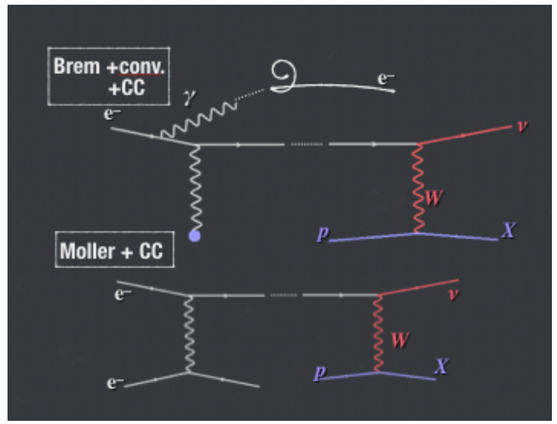
Charged Current



$N_{\nu\nu}/N_e$
$\sim 10^{-14}$ (E/4GeV)

no recoil electron
(bkg missing energy search, not for us)

CCQE+…



$N_{\nu+Brem+conv.}/N_e$
$\sim 10^{-16}$ (E/4GeV)
x $(T_{target}/0.1\ X_0)^3$
a bit reducible
curler track veto, cut out Moller kinematics

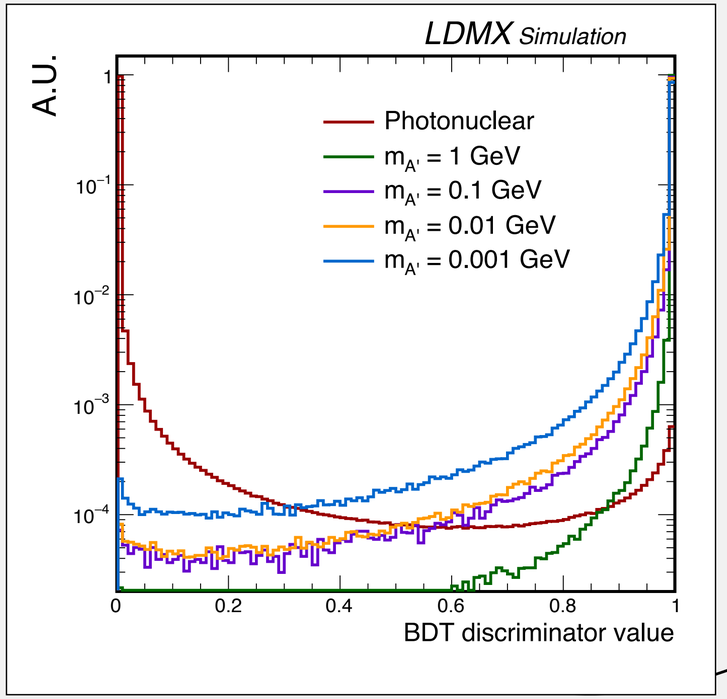
slide by Natalia Toro

Analysis Strategy

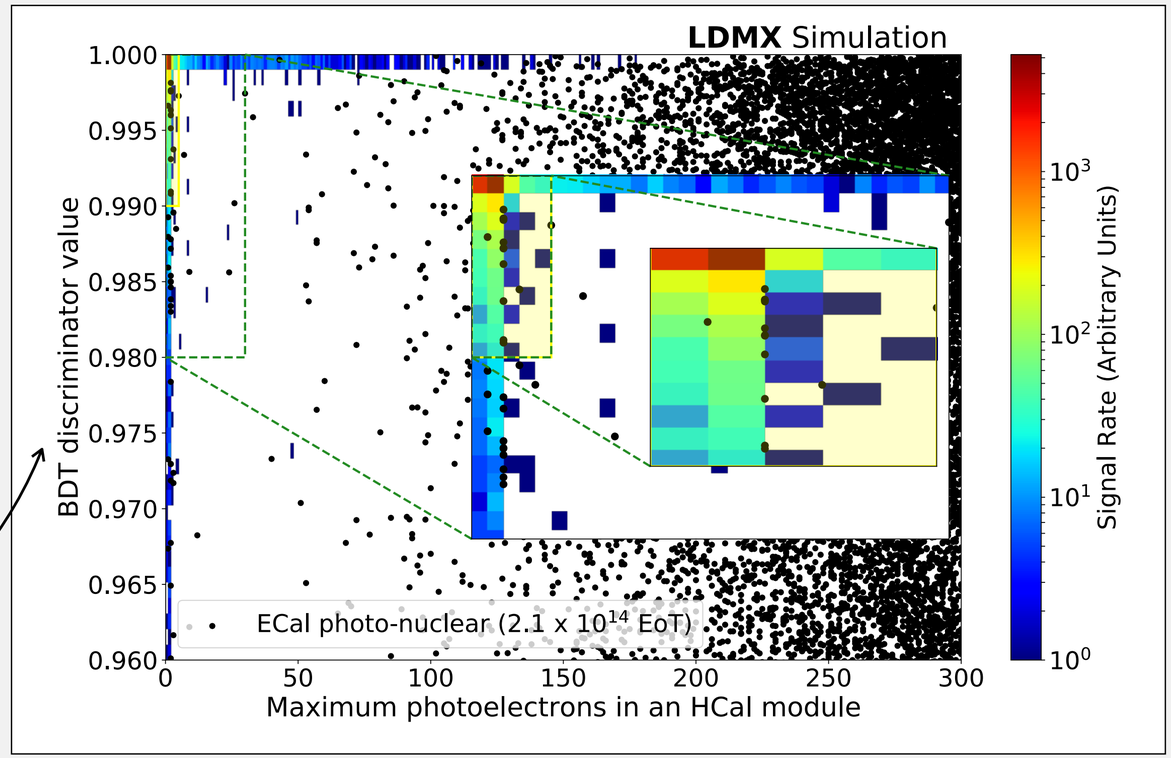
JHEP04(2020)003

trigger on *missing energy* (2.5 GeV)

+ combine ECal features into a BDT



+ veto on activity in *HCal*



+ MIP tracking in ECal

at 4 GeV: **close to 0-background** for 4e14 EoT based on simulation studies

Detector Design

design paper on arxiv
arxiv:1808.05219

extremely rare signal
—> need large statistics
goal: 10^{14} - 10^{16} EoT in few years

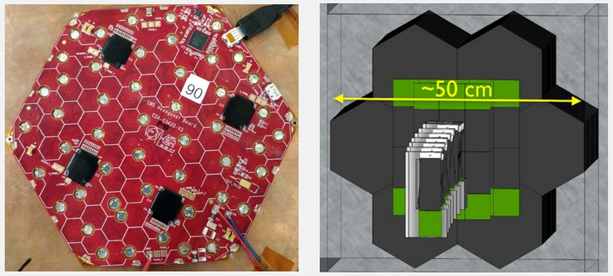
beam requirements:
- low current, high duty-cycle

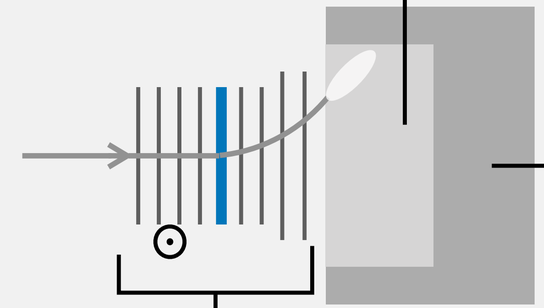
primary, multi-GeV e-beam

detector requirements:
- high-rate capabilities
- radiation hard
- high-granularity

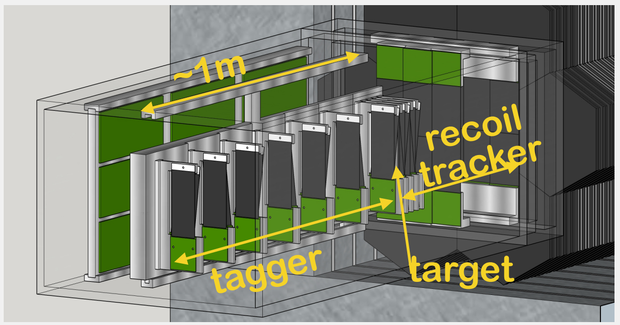
leverage techniques from existing/planned experiments

ECal: draw on design of *CMS* SiW HGCal
- 32 layers with 7 modules each, 40 X_0
- fast, radiation hard, dense
- high granularity (MIP 'tracking')

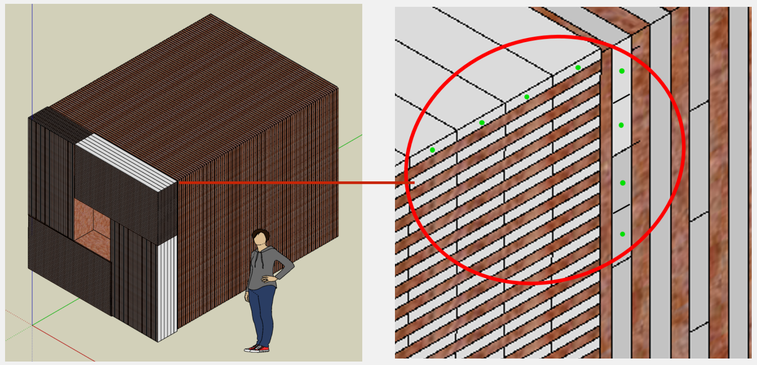




simplified copy of Silicon Vertex **Tracker** of *HPS*@JLab (visible Dark Photon search)



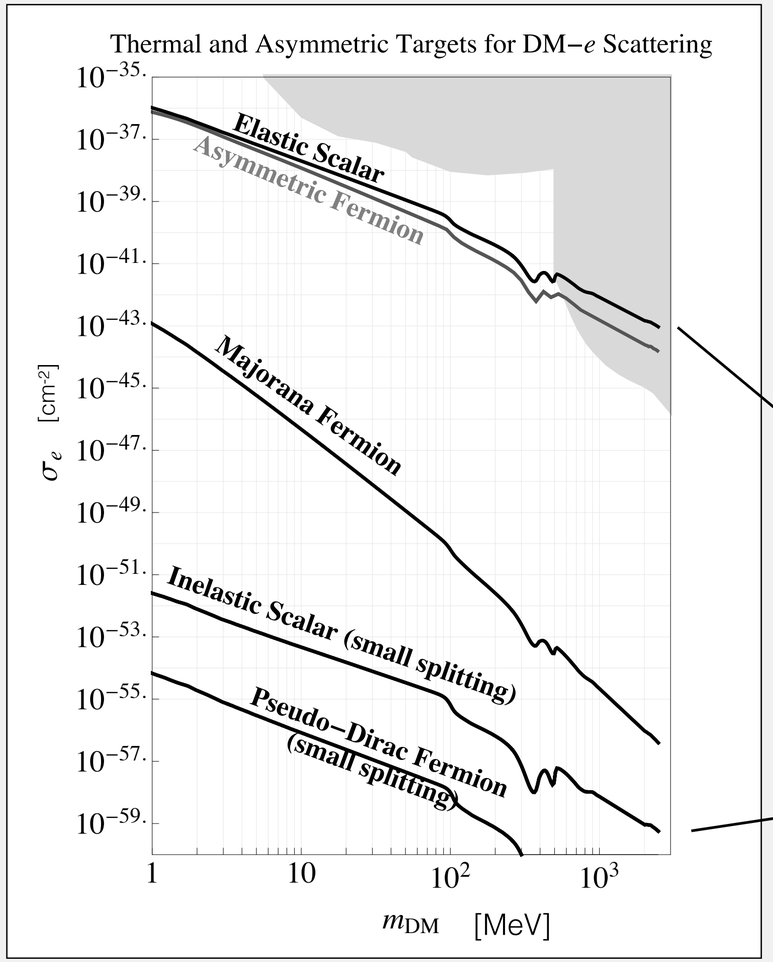
HCal inspired by *Minos/Mu2e*
- plastic scintillator with steel absorber
- readout via WLS fibres
- **optimise for neutral hadron rejection**



Why not only direct detection?

direct detection:

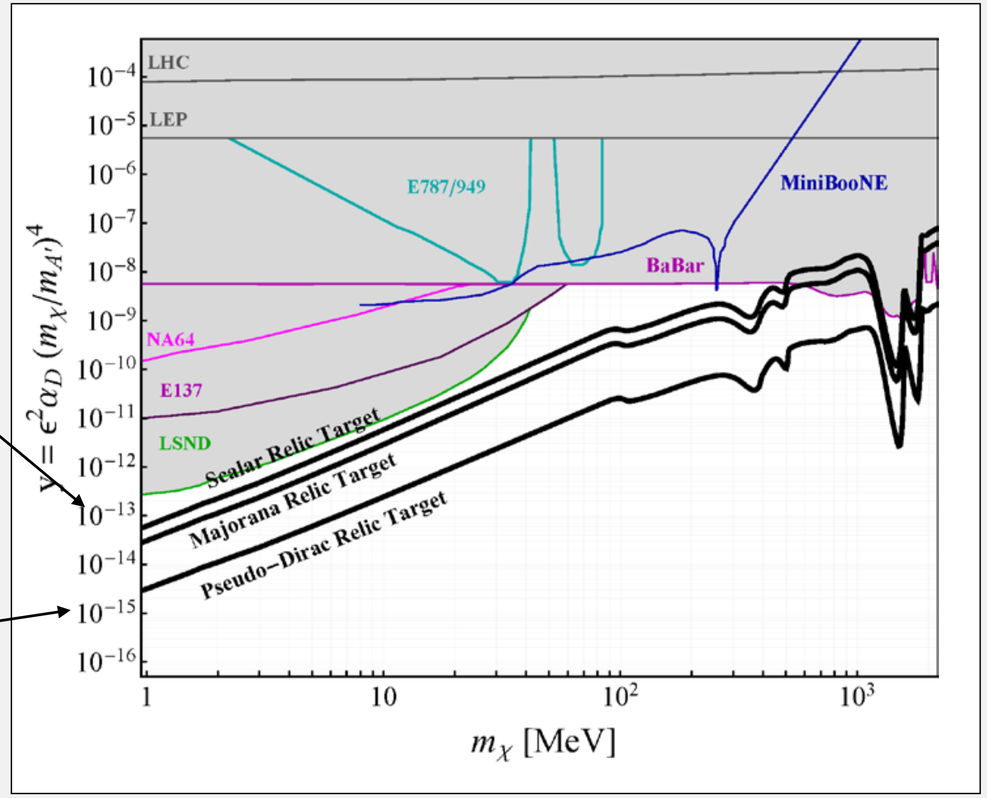
strong spin/velocity dependency



at accelerators: relativistic production

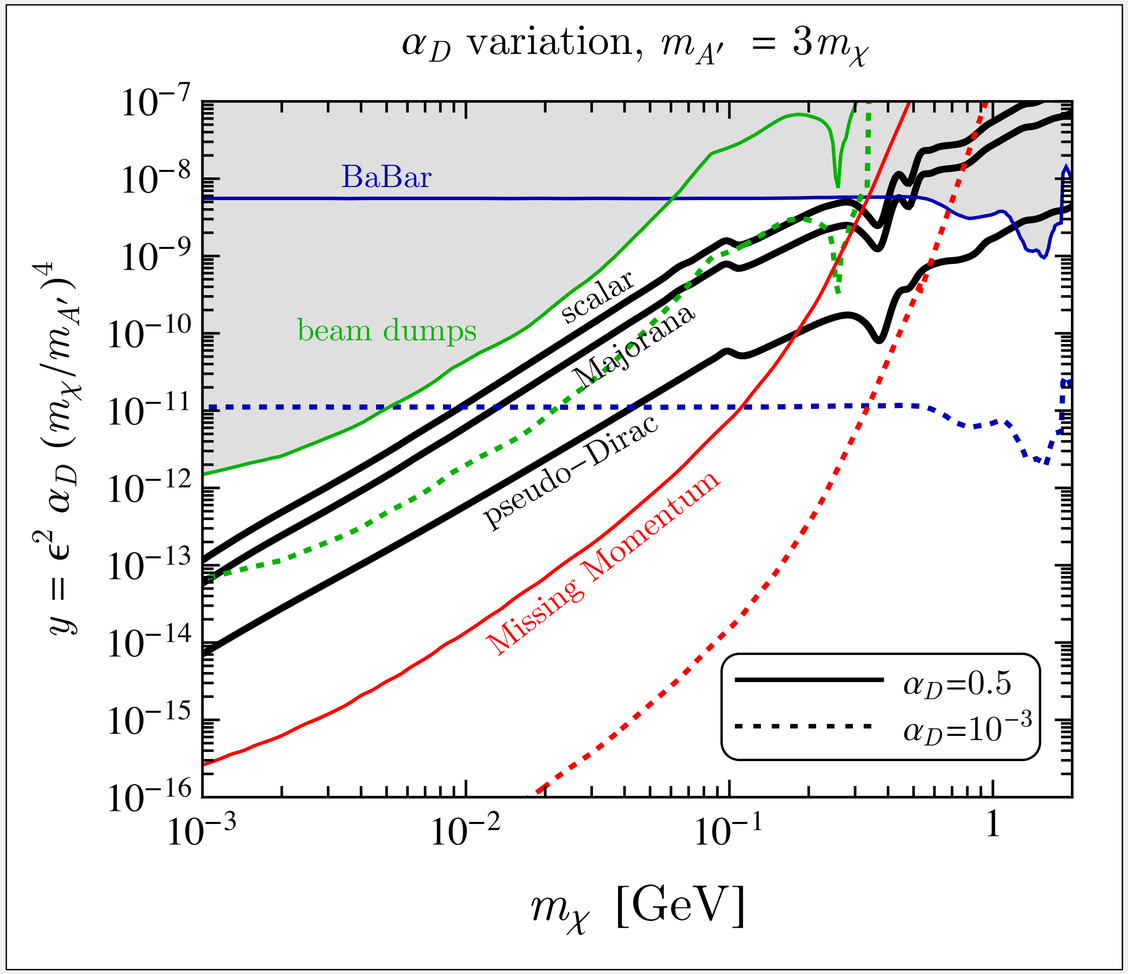
—> spin/velocity dependency reduced

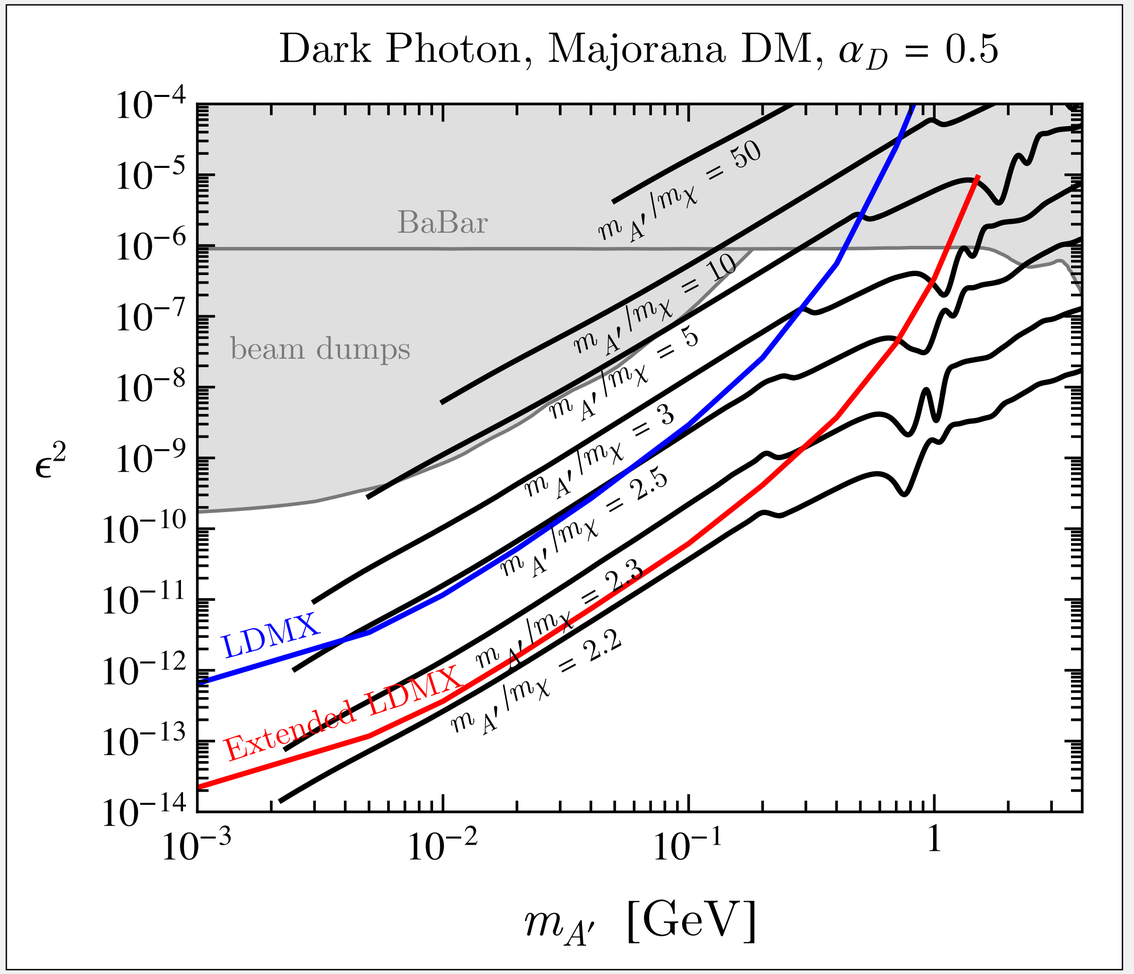
all thermal targets in reach!



arxiv:1808.05219

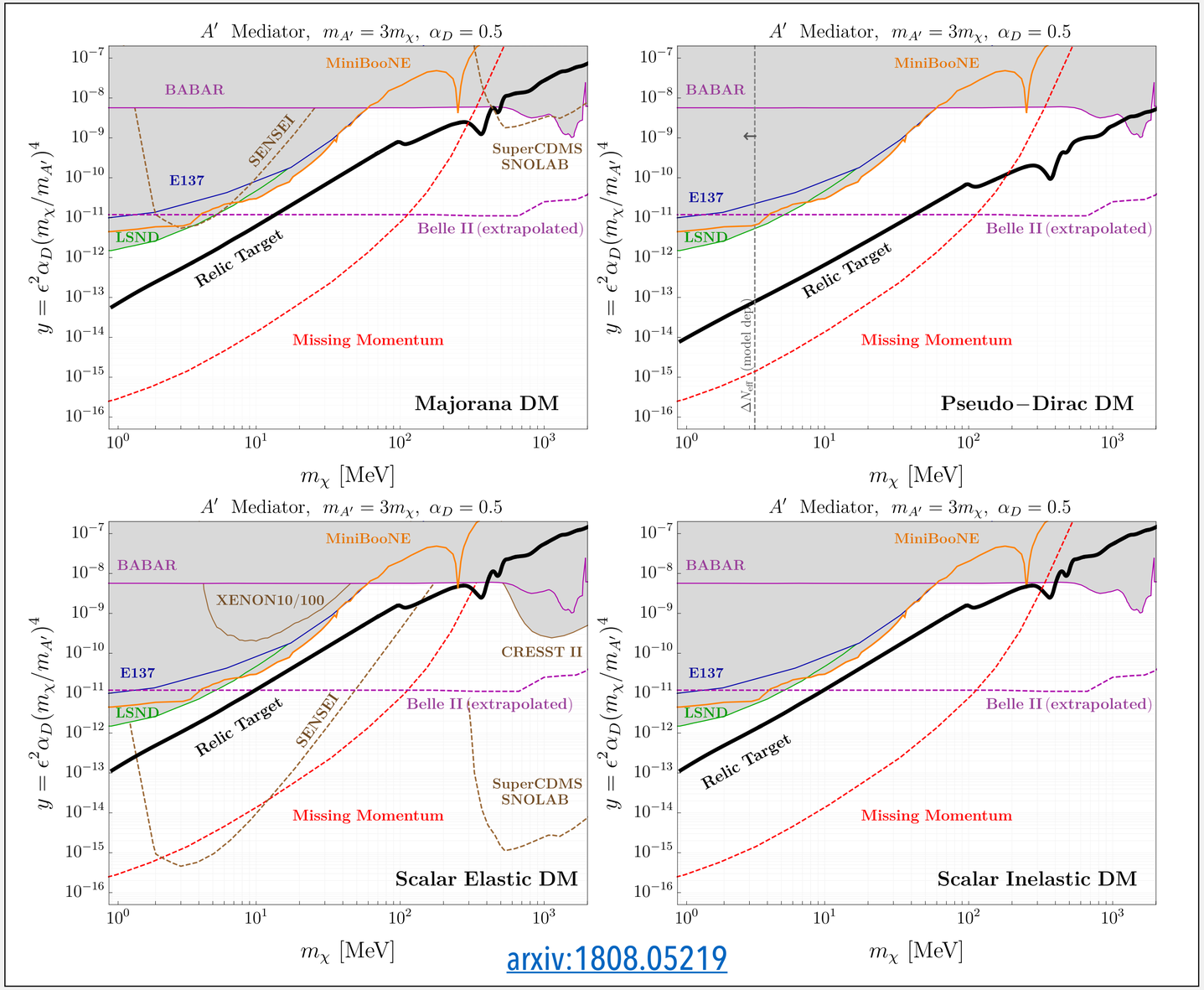
Parameter Dependence





arxiv:1808.05219

Various Future Projections



eSPS at CERN

Get e- back in CERN accelerators, next step for X-band linac developed for CLIC, accelerator R&D

Idea in fall 2017, arxiv:1805.12379 arxiv:1905.07657

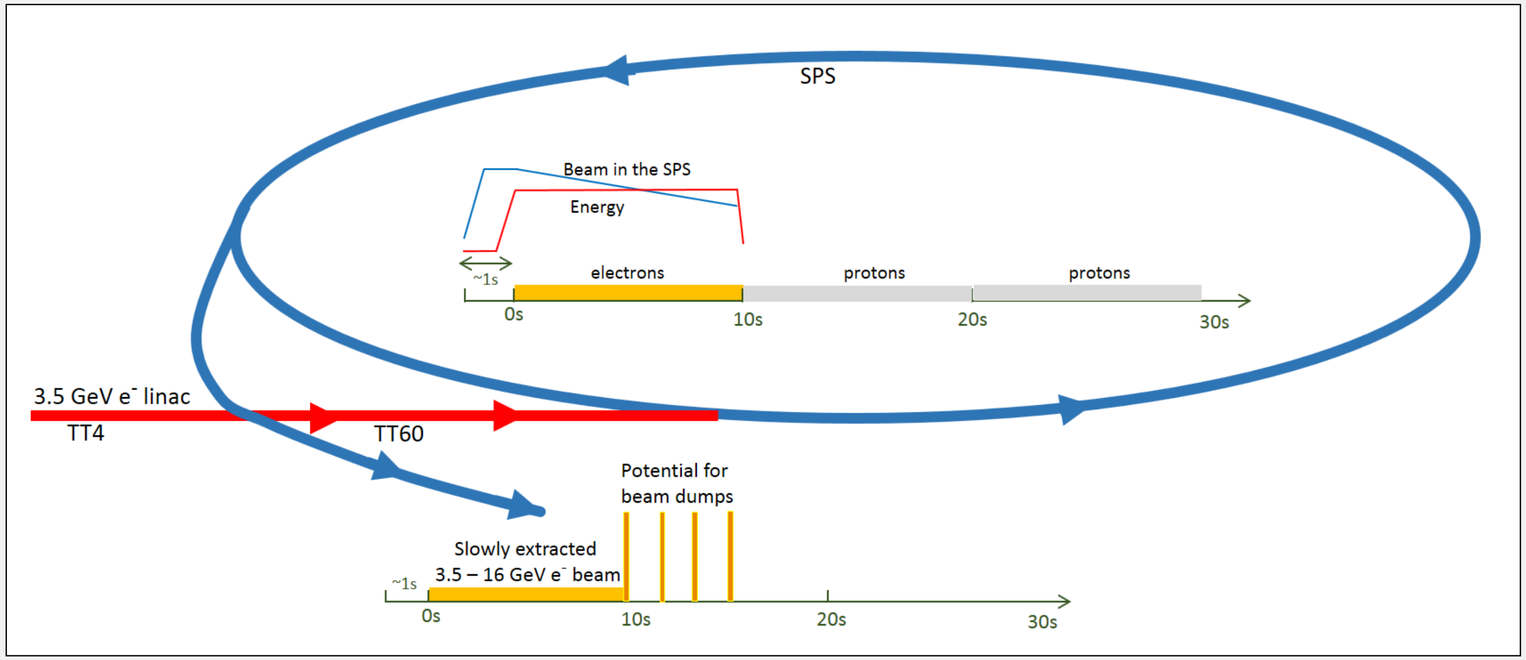
expression of interest to SPSC in October 2018, https://cds.cern.ch/record/2640784

Conceptual Design Report 2020 arxiv:2009.06938

- 3.5 GeV Linac as injector to SPS
- large number of electrons can be filled within 2s
- slow extraction over 10s
- can run in parallel with other SPS programme

flexible parameters:

- energy: 3.5 - 16 GeV
- electrons per bunch: 1 - 40
- bunch spacing: multiples of 5 ns
- adjustable beam size



optimal catering for LDMX-like experiment