Search for Light Dark Matter with LDMX

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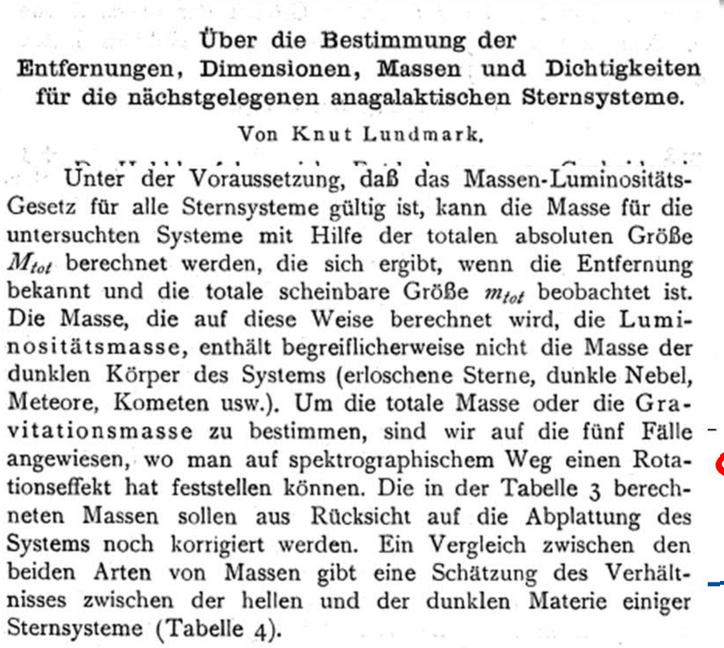
Oxford, 16 Feb 2021

91 years after observation of Dark Matter: Knut Lundmark – 1930

New: Lundmark also, 3 years before Zwicky, found evidence for dark matter!

Knut Lundmark, Lund Medd. No125 (1930) 1 – 10 (Thanks to D.Dravins and A. L'Huillier, Lund University for digging out the original paper, in German, my translation):

"Under the condition that the mass-luminosity relation is valid for all stellar systems, the mass for the investigated systems can be computed using the total absolute magnitude M_{tot} *which can be found when the distance is known and the total apparent* m_{tot} *is observed. The mass computed in this way, the luminous mass, does understandably not include the mass of the dark objects of the system (extinguished stars, dark clouds, meteors, comets, and so on). To determine the total mass or the gravitational mass, we need to rely on the five cases where one has detected an effect of rotation by spectrographical means. … A comparison between the two kinds of masses gives an estimate of the ratio of luminous and dark matter for some stellar systems (Table 4)."*



Über die Bestimmung der Entfernungen, Dimensionen, Massen und Dichtigkeiten für die nächstgelegenen anagalaktischen Sternsysteme.

Von Knut Lundmark.

Unter der Voraussetzung, daß das Massen-Luminositäts-Gesetz für alle Sternsysteme gültig ist, kann die Masse für die untersuchten Systeme mit Hilfe der totalen absoluten Größe M_{tot} berechnet werden, die sich ergibt, wenn die Entfernung bekannt und die totale scheinbare Größe m_{tot} beobachtet ist. Die Masse, die auf diese Weise berechnet wird, die Luminositätsmasse, enthält begreiflicherweise nicht die Masse der dunklen Körper des Systems (erloschene Sterne, dunkle Nebel, Meteore, Kometen usw.). Um die totale Masse oder die Gravitationsmasse zu bestimmen, sind wir auf die fünf Fälle angewiesen, wo man auf spektrographischem Weg einen Rotationseffekt hat feststellen können. Die in der Tabelle 3 berechneten Massen sollen aus Rücksicht auf die Abplattung des Systems noch korrigiert werden. Ein Vergleich zwischen den beiden Arten von Massen gibt eine Schätzung des Verhältnisses zwischen der hellen und der dunklen Materie einiger Sternsysteme (Tabelle 4).

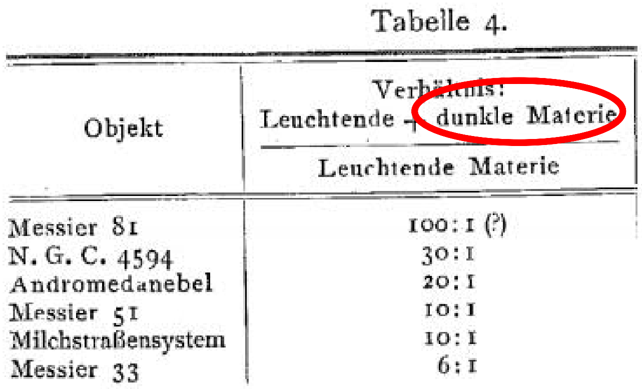


Tabelle 4.

Objekt	Verhältnis: $\frac{\text{Leuchtende + dunkle Materie}}{\text{Leuchtende Materie}}$
Messier 81	100:1 (?)
N. G. C. 4594	30:1
Andromedanebel	20:1
Messier 51	10:1
Milchstraßensystem	10:1
Messier 33	6:1

Slide by

Lars Bergström, OKC Stockholm

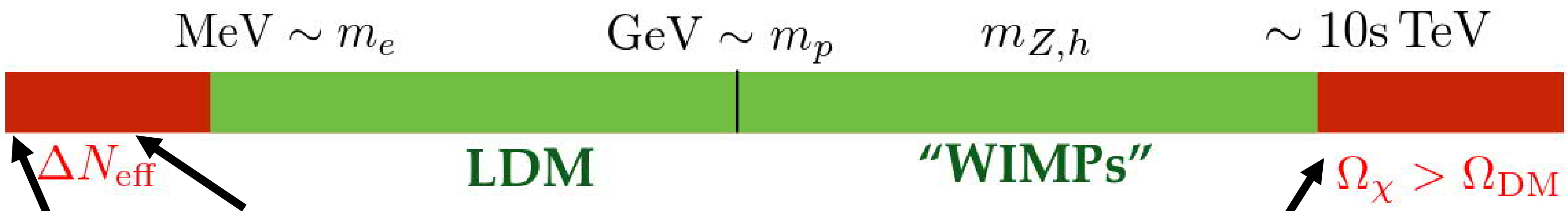
Dark matter; its nature and the thermal origin

Observations of gravitational effects give little information on dark matter’s composition

→ 10^{-22} eV – 100 $M_\odot$

Cosmological scenarios for the origin of dark matter give different mass ranges.

A thermal origin (*) gives an allowed mass range ~MeV to O(10) TeV



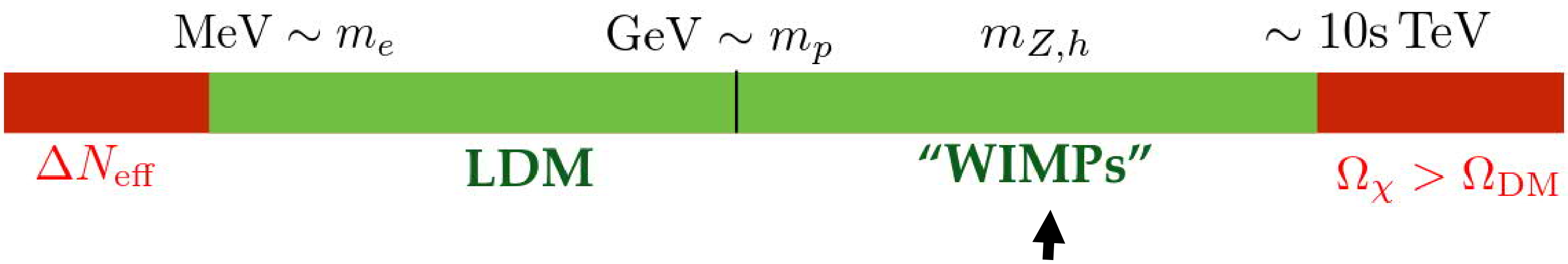
Requires Dark matter annihilation to ν, difficult with model of Hidden QED (see later); & problems with BBN

Incompatible with structure formation and the hydrogen distribution

Cannot annihilate to the correct relic abundance

(*) That dark matter and Standard Model matter were in thermal equilibrium, and dark matter annihilated into Standard Model particles until the annihilation rate < universe expansion rate

Thermal dark matter; WIMPs

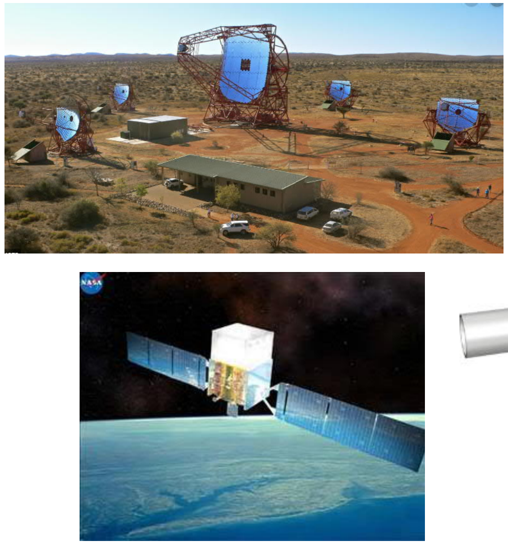


$\mathrm{MeV} \sim m_e$ $\mathrm{GeV} \sim m_p$ $m_{Z,h}$ $\sim 10\mathrm{s\ TeV}$

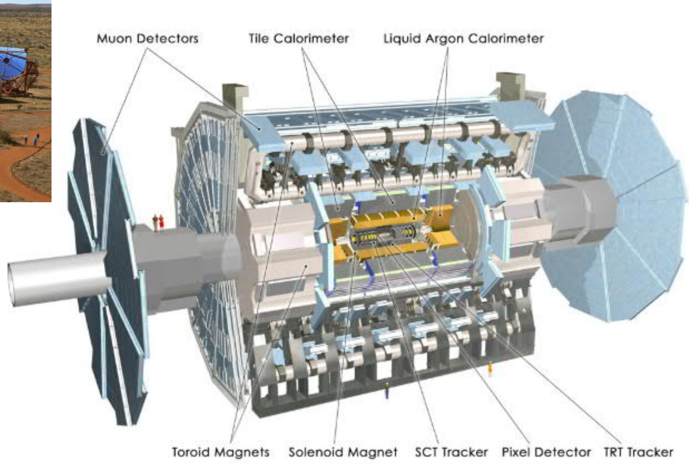
ΔN_{eff} **LDM** **"WIMPs"** $\Omega_\chi > \Omega_{\mathrm{DM}}$

The so-called WIMP miracle makes the range a few GeV – O(10) TeV attractive

This range is also motivated by Super Symmetry



Photons from dark matter annihilation in space

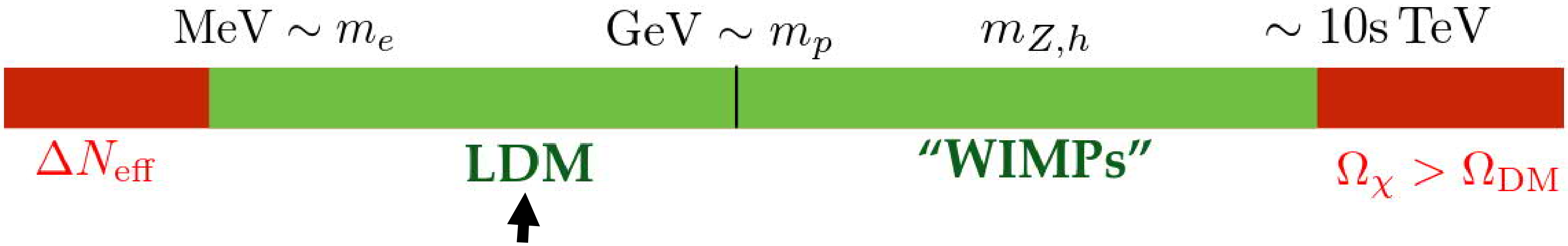


Production of dark matter

Dark matter colliding with matter in an underground detector

Up to now no sign in this range

Thermal dark matter; Light Dark Matter, LDM



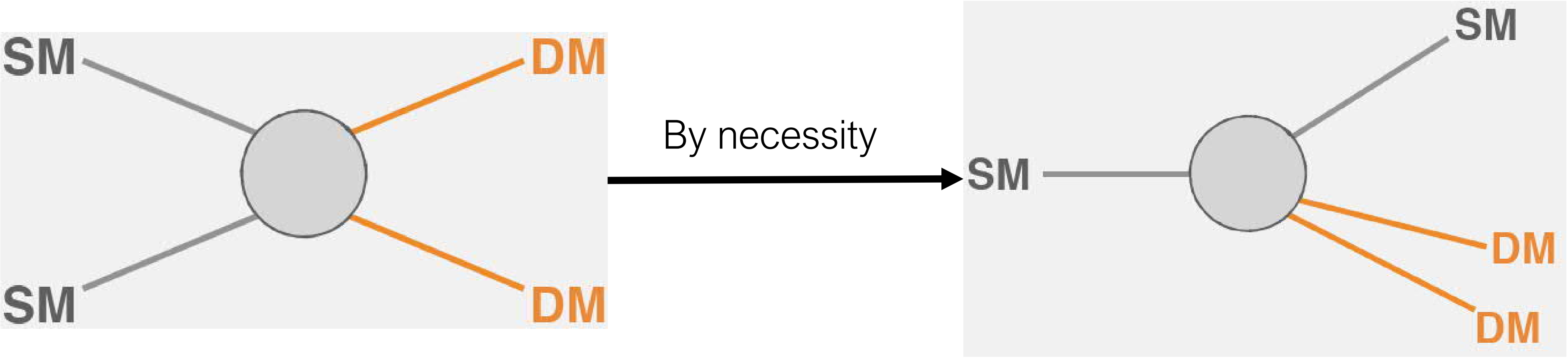
The lower part of this mass range is less explored

This is the range where we have most known matter (e, μ, (τ), u, d, s, (c))

Dark matter as such, is a significant Beyond the Standard Model (BSM) phenomenon, and there are hints of BSM at low energy/low mass:

- Measured g-2 is not compatible with the Standard Model (Phys.Rev.D73:072003,2006)
- Signs of a 17 MeV resonance in the ^{8}Be and ^{4}He decays with no explanation in the Standard Model (Phys. Rev. Lett. 116, 042501 (2016) , 1910.10459)
- (A possible hint for a 3.5 keV emission and absorption line not fitting with atomic energy levels, observed by astronomers.) (1402.2301, 1402.4119, 1608.01684)

Light dark matter; production in a laboratory

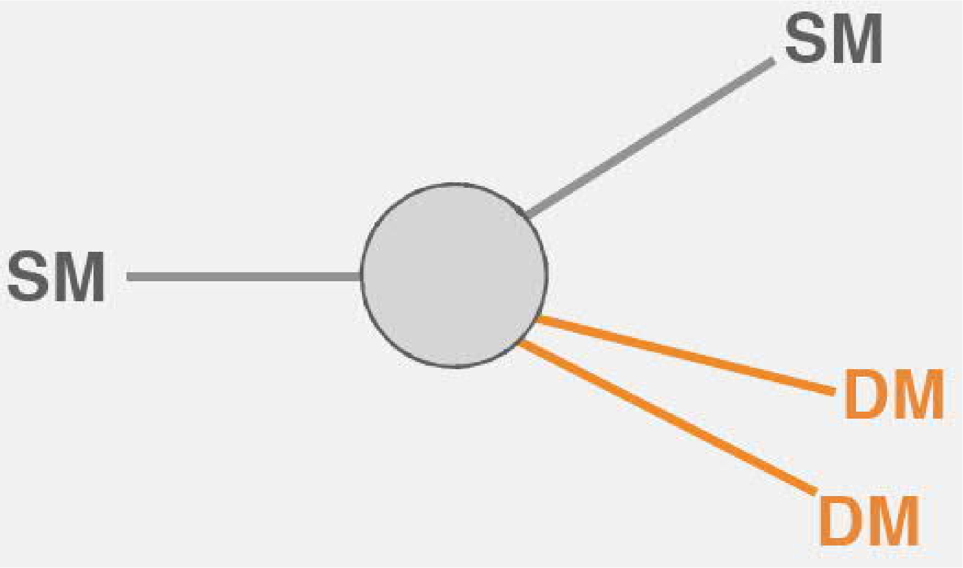


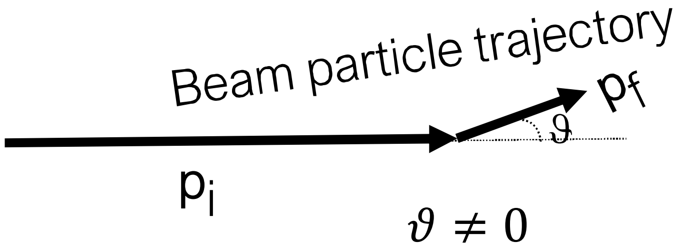
Thermal equilibrium between known and dark matter requires an <u>interaction</u> between them

Dark matter will be produced in an accelerator-based experiment, with a rate determined by the strength of that <u>interaction</u>

Weak interaction cannot give the observed dark matter abundance, if dark matter particles are light. Light dark matter therefore implies a new interaction. A <u>hidden sector of physics</u> with weak connection with the physics we know.

Light dark matter; kinematics in production in a laboratory





If mass is produced
(1) the trajectory must change, (2) beam particle energy lost into the created particle(s)

The lower mass the beam particle has, the bigger the effect → electron beam

The interaction is very weak → need many electrons to see an effect

Signal modelling

A LDM model must have the properties:

Light forces: Comparably light force carrier to mediate an efficient annihilation rate for thermal freeze-out

Neutrality: Both the DM and the mediator must be singlets under the full SM gauge group

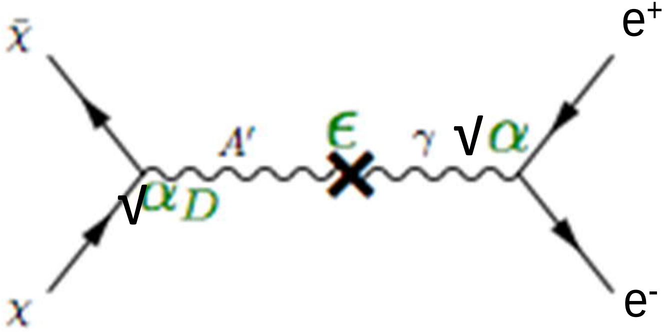
Simplest: A hidden sector QED

- Fine structure constant α_D
- Dark photon A’
- Dark matter particles χ

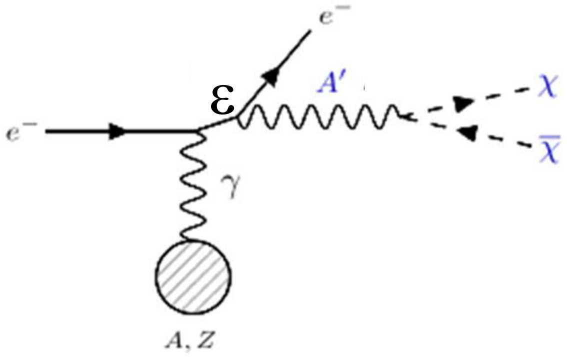
This hidden sector QED connects to the known physics by the A’ mixing with the photon (γ) with a small mixing strength ε

Conservative choice: $\alpha_D = 0.5$ and $m_{A'} = 3m_\chi$

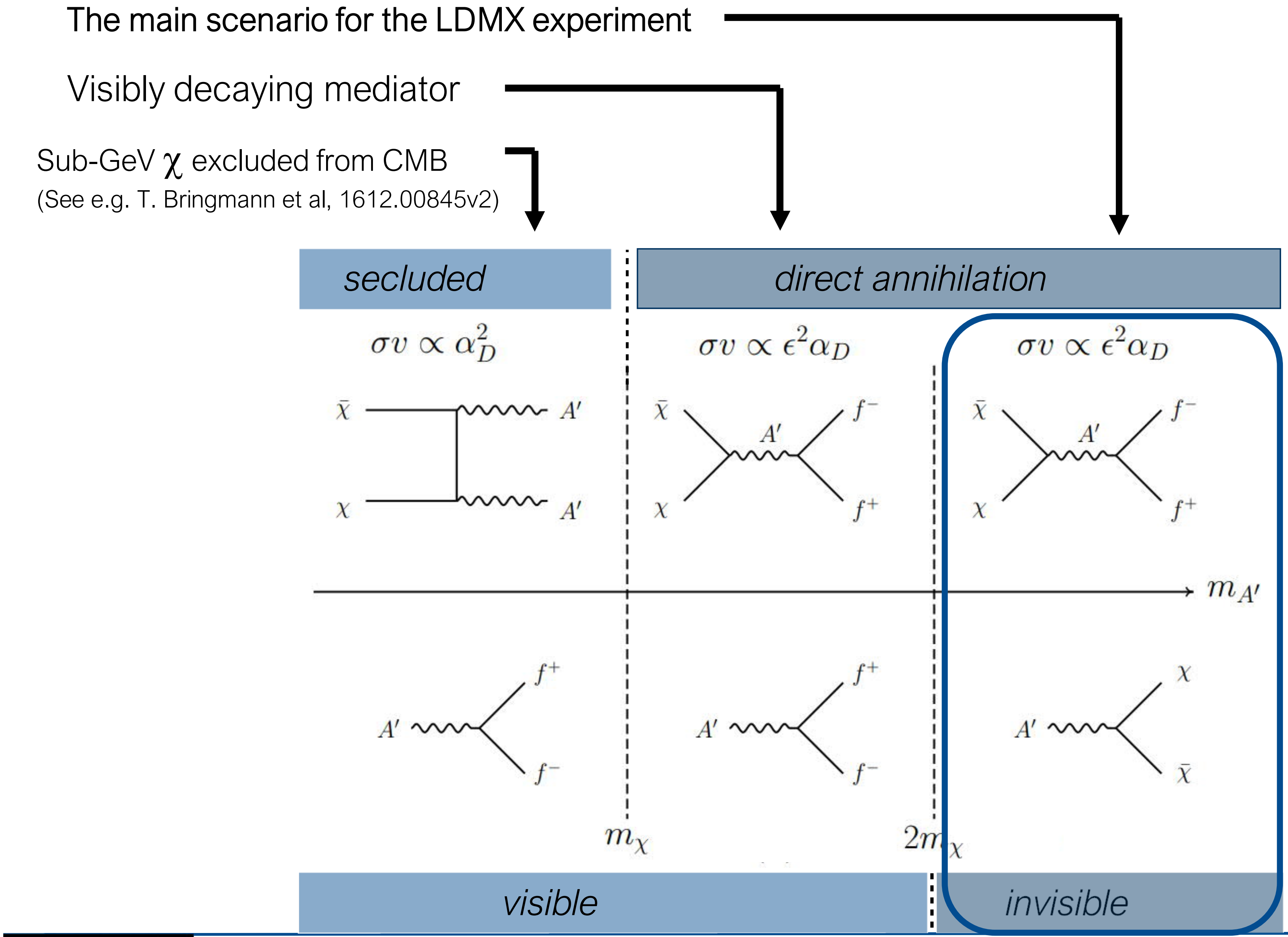
Thermal equilibrium in the early universe



Reaction in the laboratory



Mass of A’ and mass of χ



The main scenario for the LDMX experiment

Visibly decaying mediator

Sub-GeV χ excluded from CMB

(See e.g. T. Bringmann et al, 1612.00845v2)

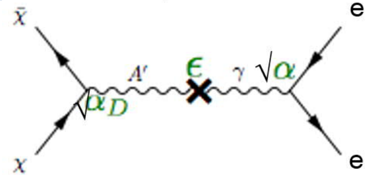
secluded

direct annihilation

visible

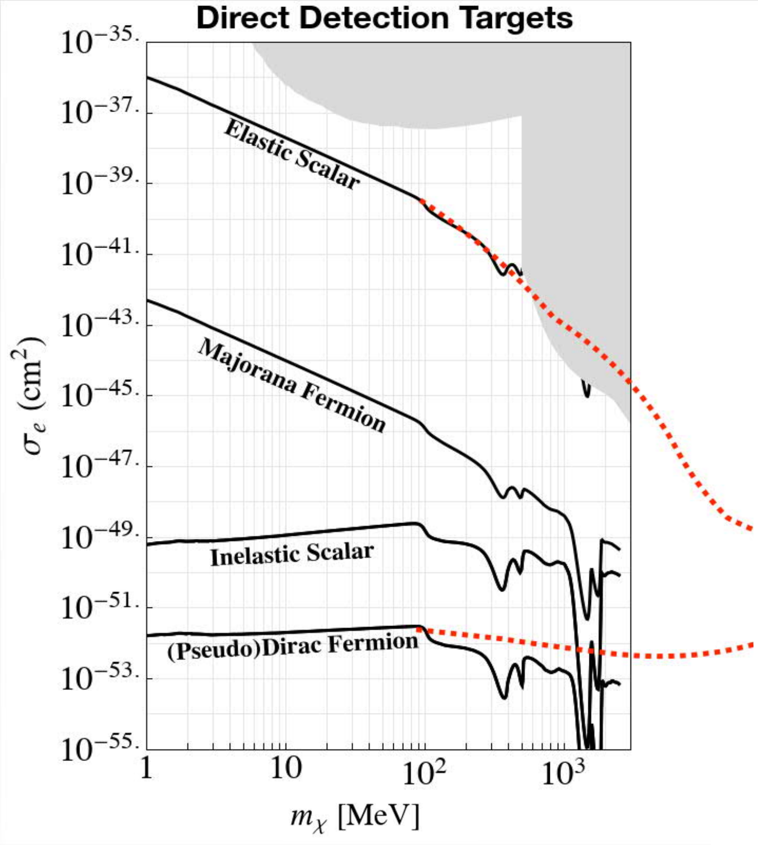
invisible

Direct Detection and Accelerator Based Production

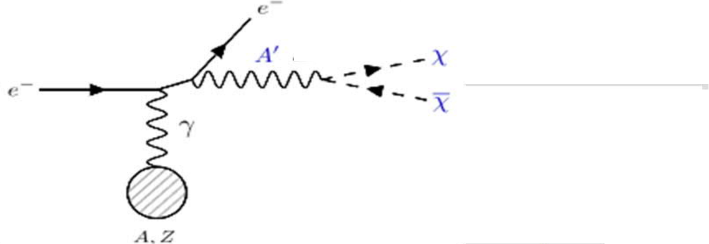


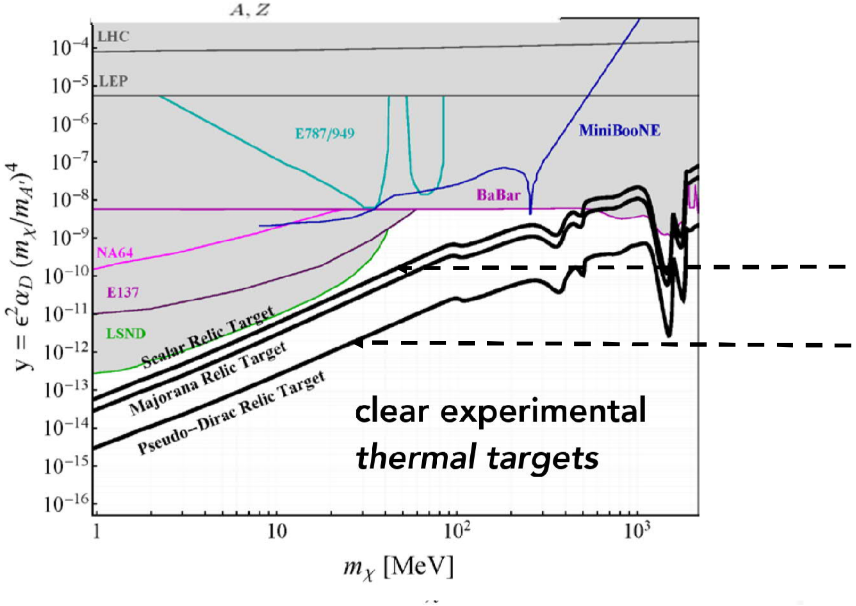
$$\sigma v \sim \varepsilon^2 \alpha_D \frac{m_\chi^2}{m_{A'}^4} = \frac{y}{m_\chi^2};\ y = \varepsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4$$

But, cross sections can be loop- or velocity- suppressed in the non-relativistic regime of direct detection:



$$\sigma \sim \left(\frac{m_{A'}}{m_\chi}\right)^2 \frac{yZ^2}{\alpha_D m_\chi^2} \Rightarrow \boxed{y \sim \left(\frac{m_\chi}{m_{A'}}\right)^2 \frac{m_\chi^2 \alpha_D}{Z^2} \sigma}$$



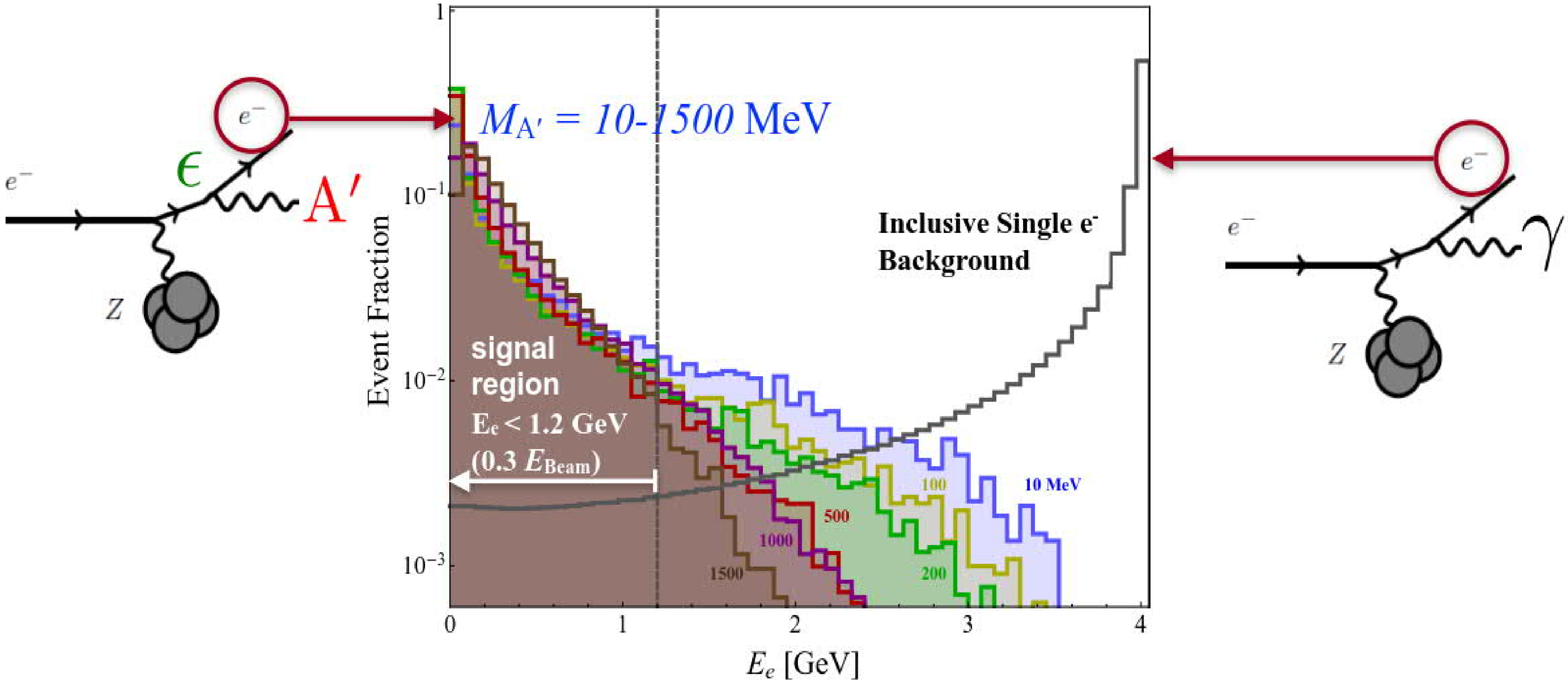


Need 10^{14} e$^-$

Need 10^{16} e$^-$

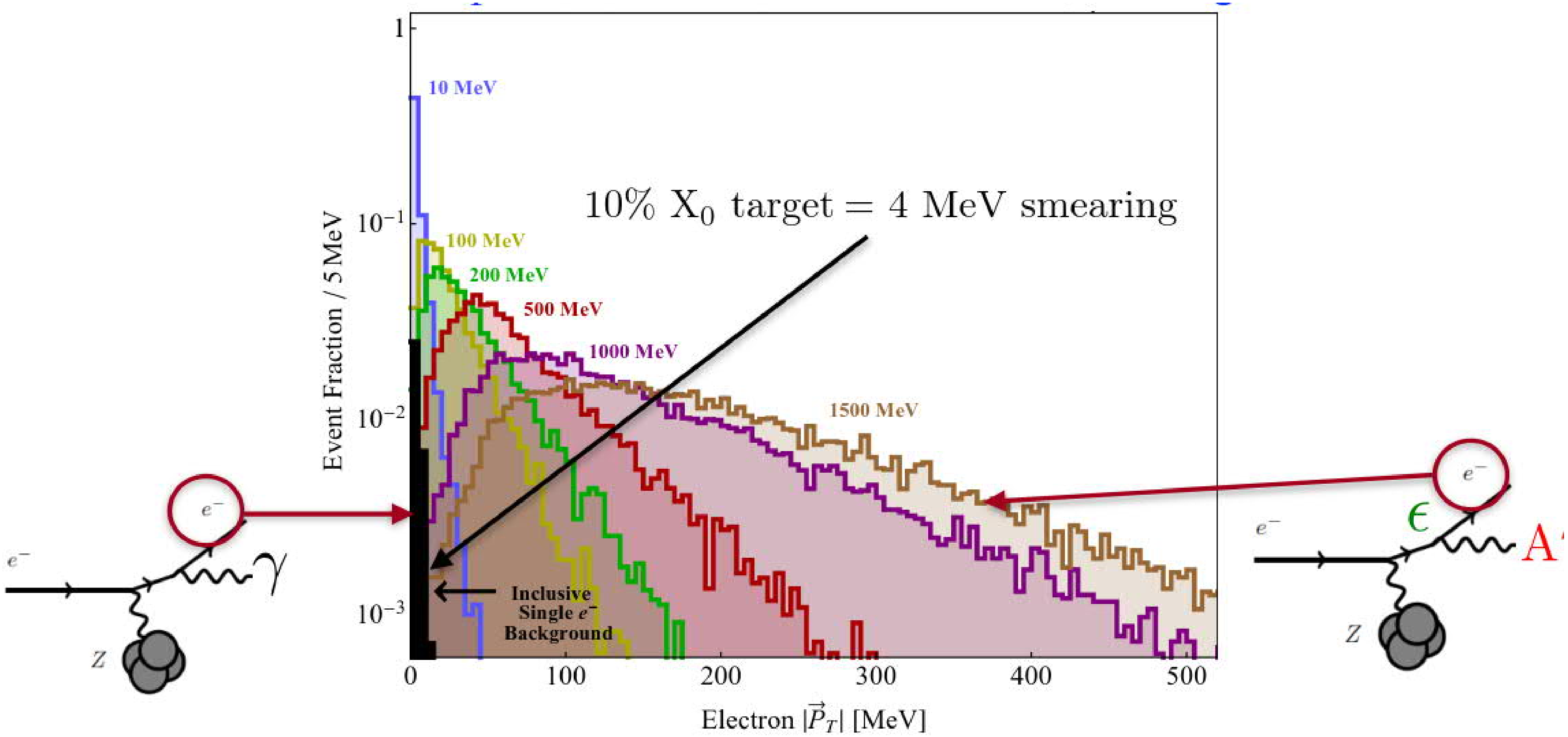
$\alpha_D = 0.5$ and $m_{A'} = 3m_\chi$

Kinematics: electron energy



A’ created close to threshold in the em-field around the target nucleus, since the A’s, heavier that the electrons, take most of the incoming electron energy —> soft recoil electron, large missing energy

Kinematics: electron p_T



p_T of the recoil electron very different from bremsstrahlung.

The right beam is fundamental for the experiment

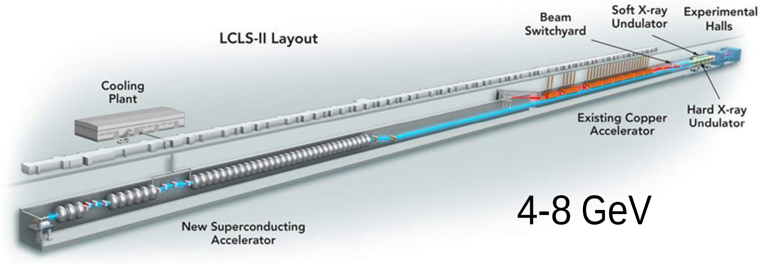
Need 10^{14} - 10^{16} electrons on target

To measure the p_T of the recoil electron requires modest beam energy and to measure the electron both before and after the target

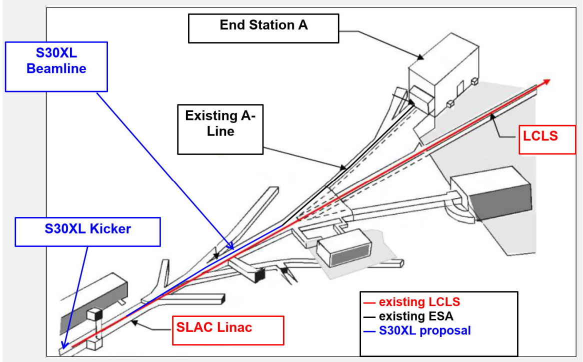
→Low current – high duty cycle – 4-20 GeV – primary electron beam

→A primary electron beam dedicated to the experiment

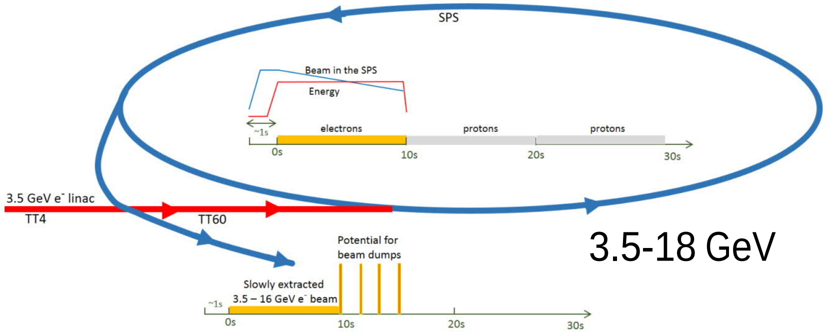
Baseline – SLAC



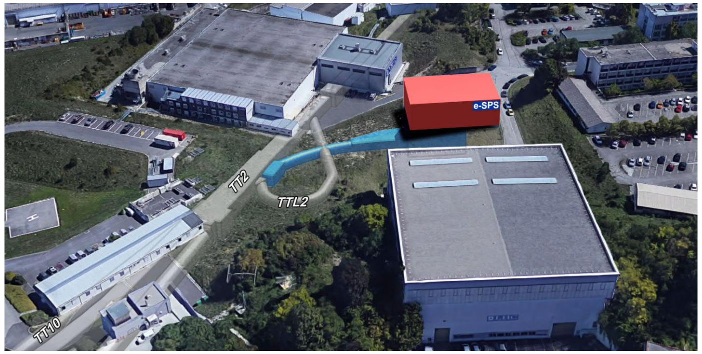
4-8 GeV



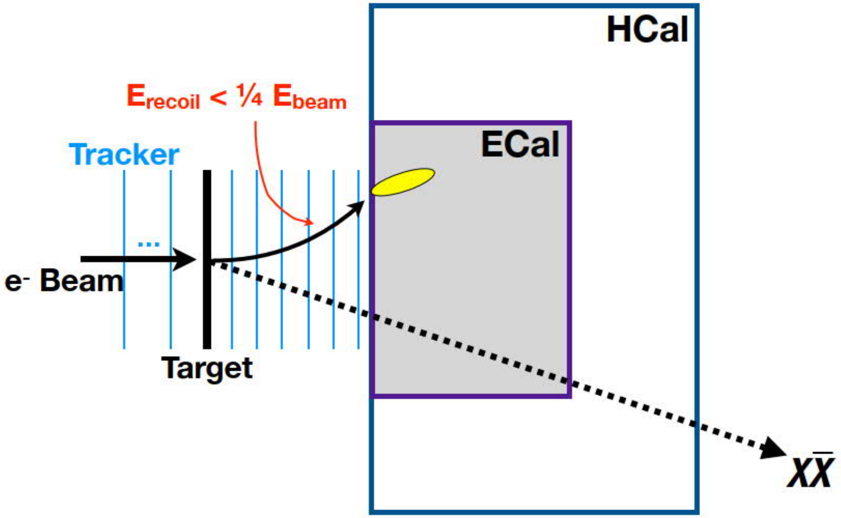
CERN



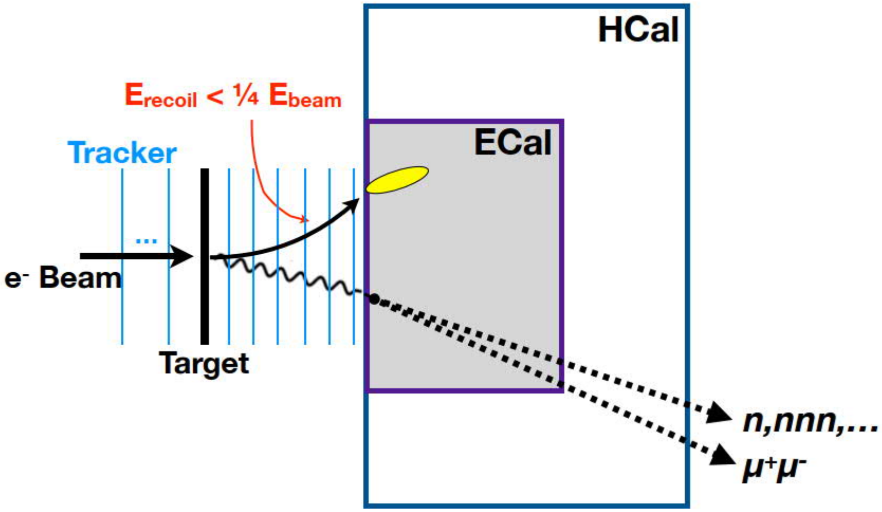
3.5-18 GeV



Basic task for the experiment



Select these



Reject these

The experiment
is to a big degree
a question of
rejecting these

The Light Dark Matter eXperiment – LDMX arXiv: 1808:05219

[Craig Group & Son]

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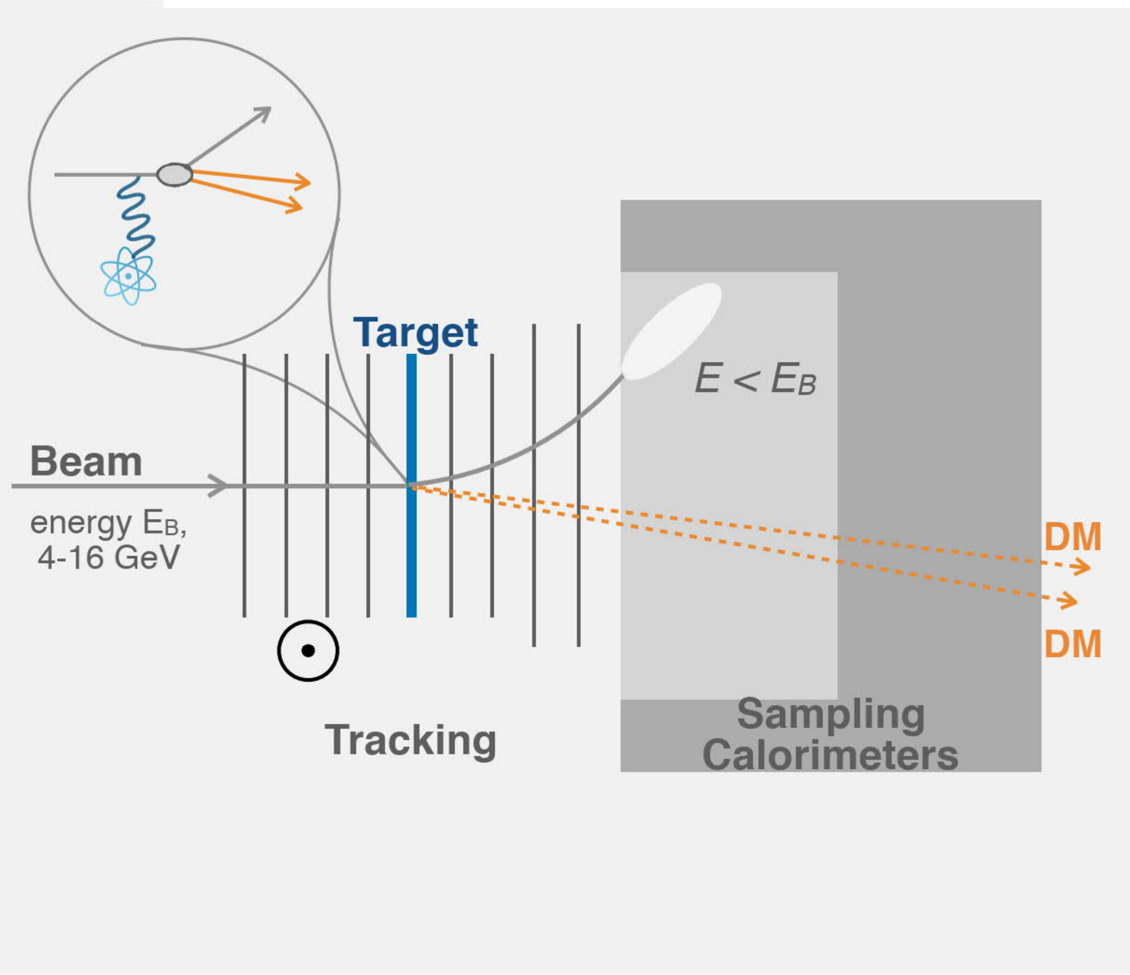
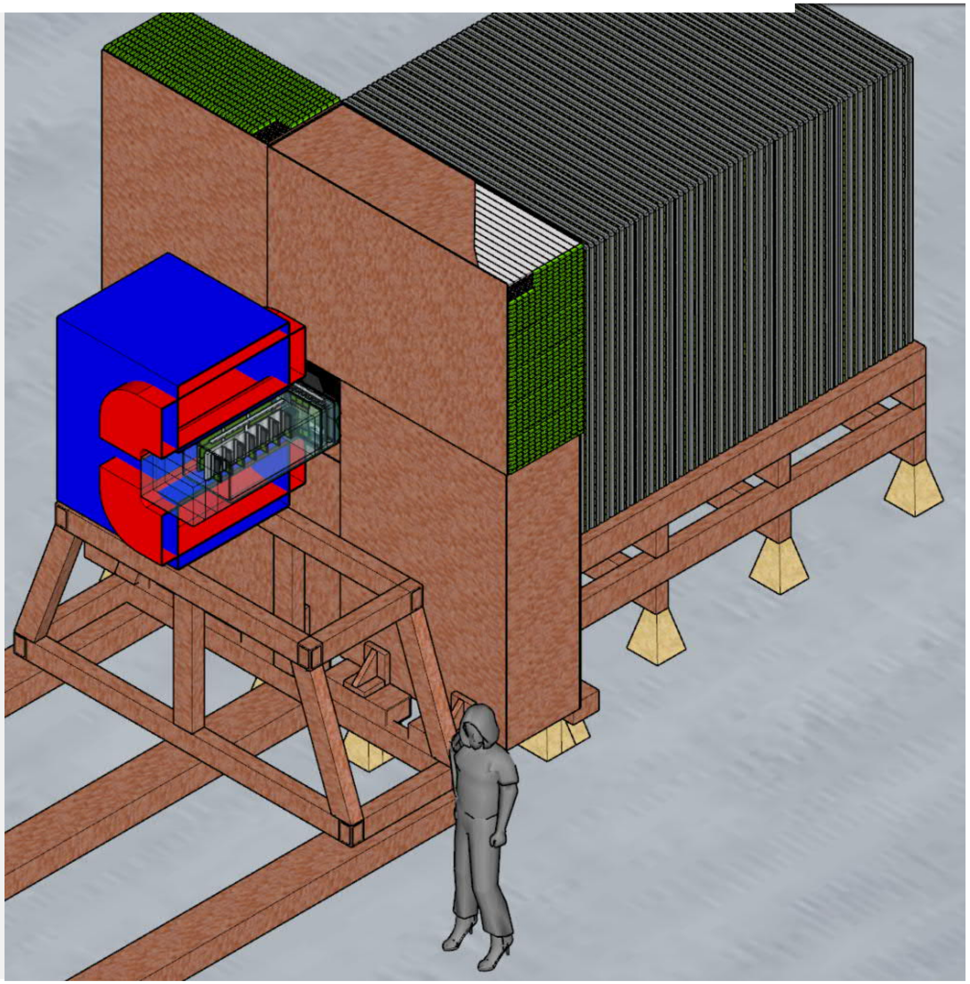
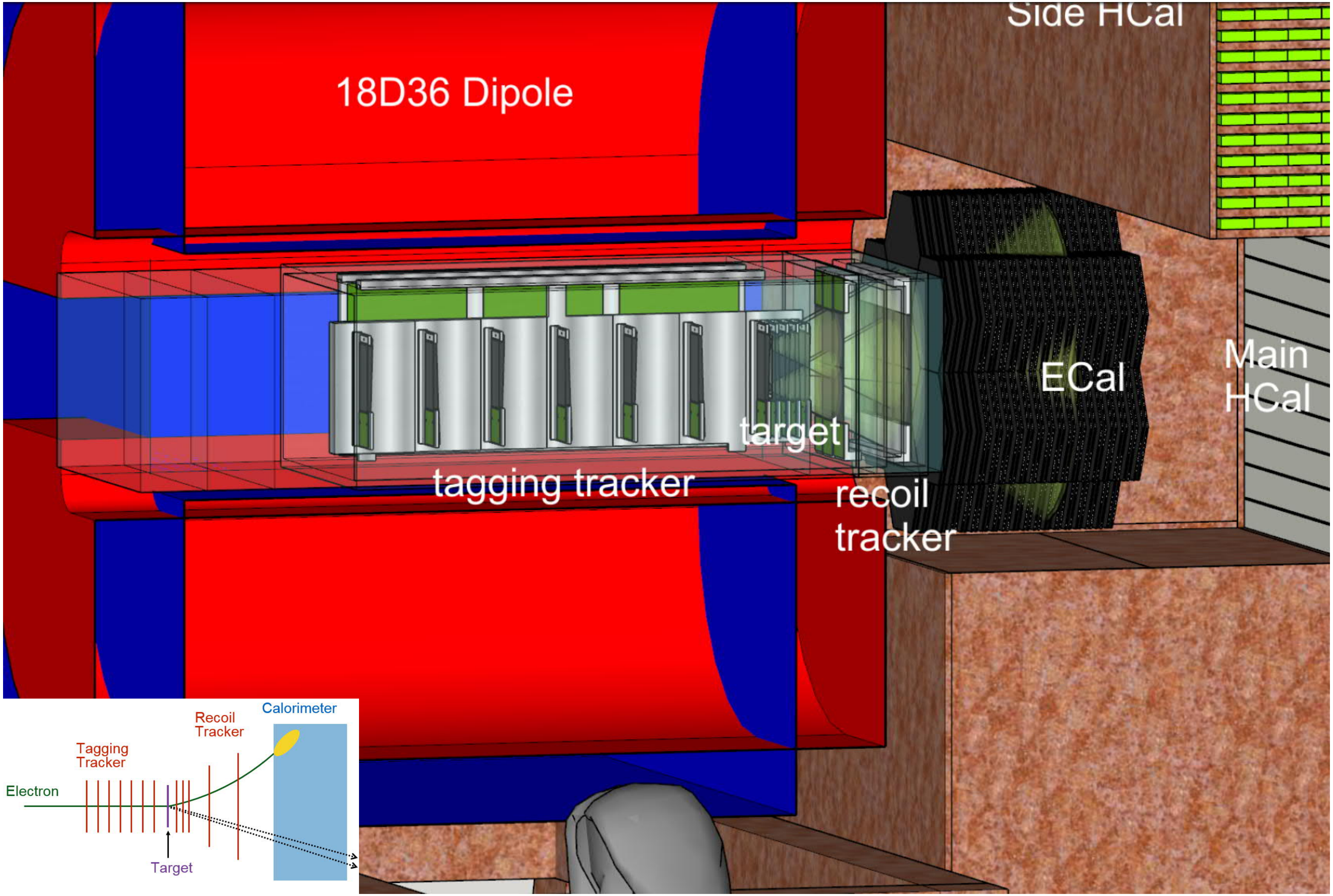
Caltech
Fermilab
LUND UNIVERSITY
UNIVERSITY OF MINNESOTA
SLAC NATIONAL ACCELERATOR LABORATORY
Stanford University
TEXAS TECH UNIVERSITY SYSTEM
UNIVERSITY of VIRGINIA

The Light Dark Matter eXperiment – LDMX

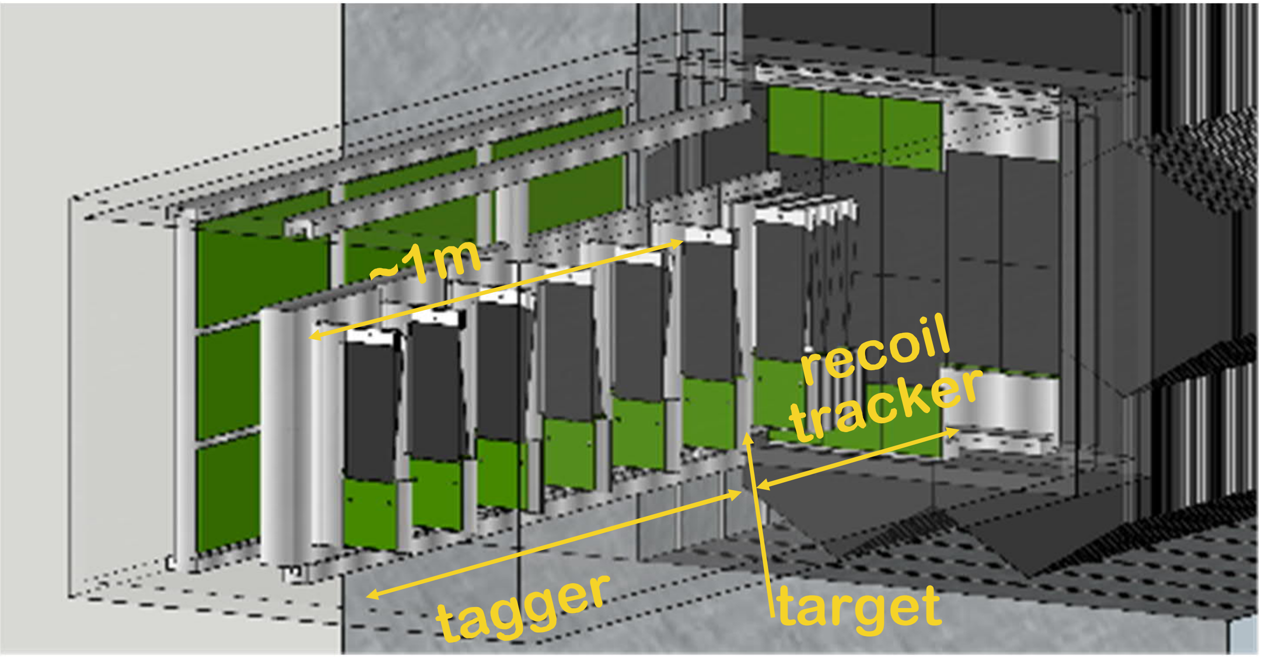




The Light Dark Matter eXperiment – LDMX

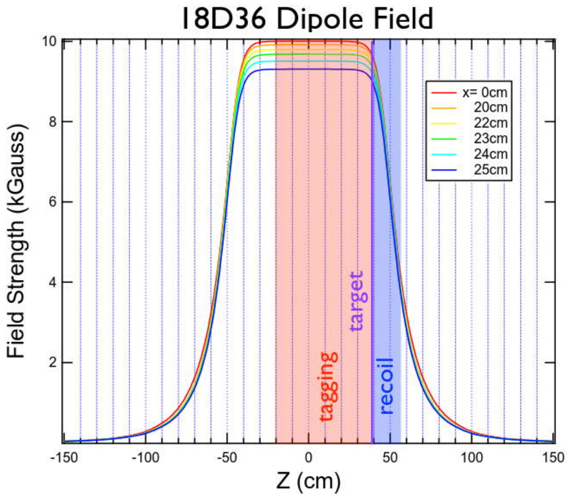


Tracking System



- simplified version of the Silicon Vertex Tracker (SVT) of HPS experiment

- fast (2ns hit time resolution)
- 6 μm resolution in bending plane
- 100 mrad stereo layers in double sided Si
- radiation hard
- technology well understood



tagging tracker

- *60 cm length in 1.5T field*
- *6 stereo layers*
- momentum filter
- impact point on target

recoil tracker

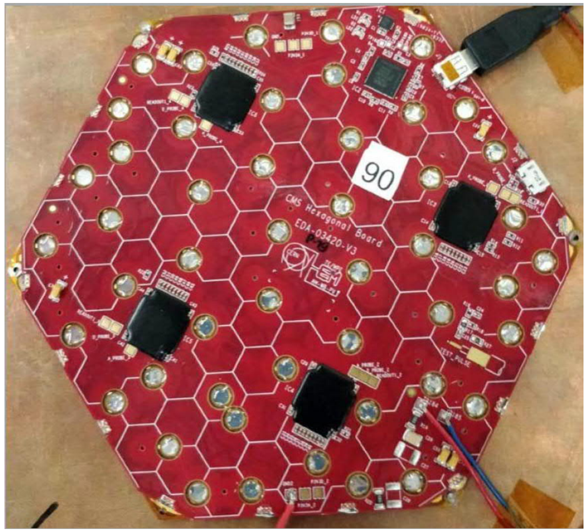
- 18 cm length in fringe field
- 4 stereo layers + 2 axial layers
  - Momentum (50 MeV – 1.2 GeV)
  - Measure p, direction and impact

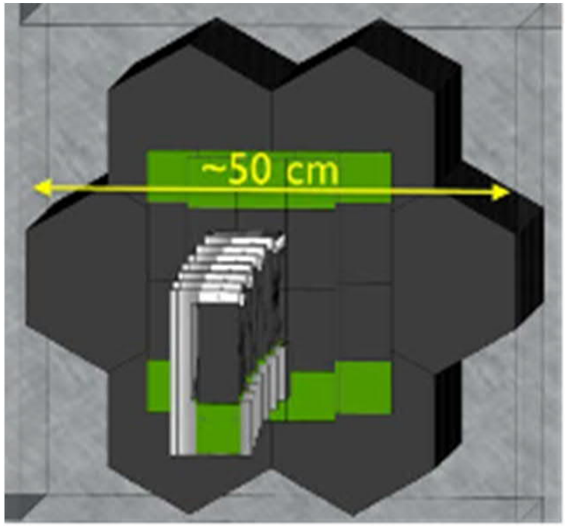
target

- ~0.1 - 0.3 X_0 W/Al
- balance signal rate and momentum smearing

Electromagnetic Calorimeter - ECal

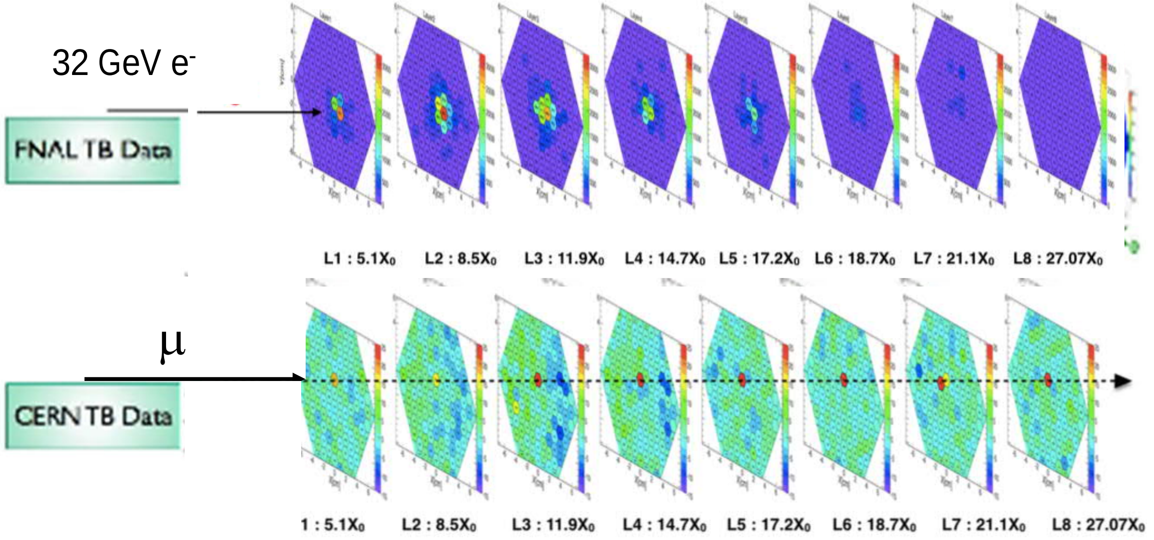
A variant of the forward SiW sampling calorimeter for CMS@HL-LHC



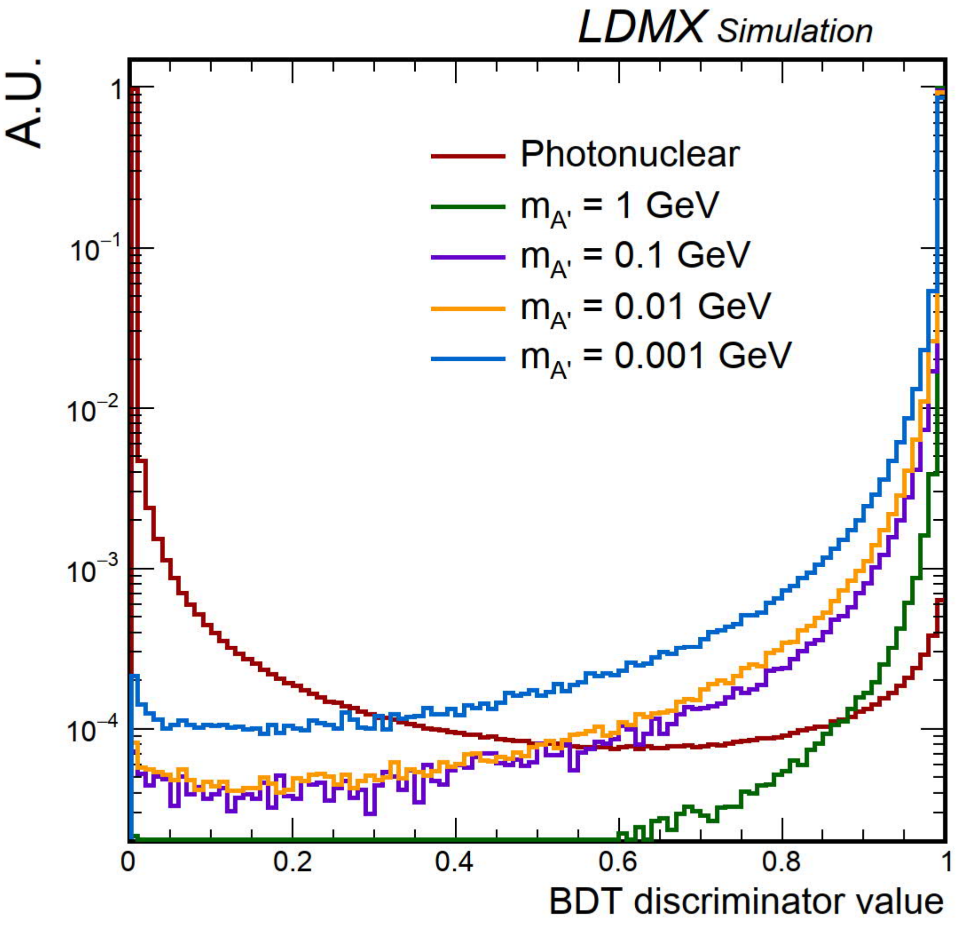


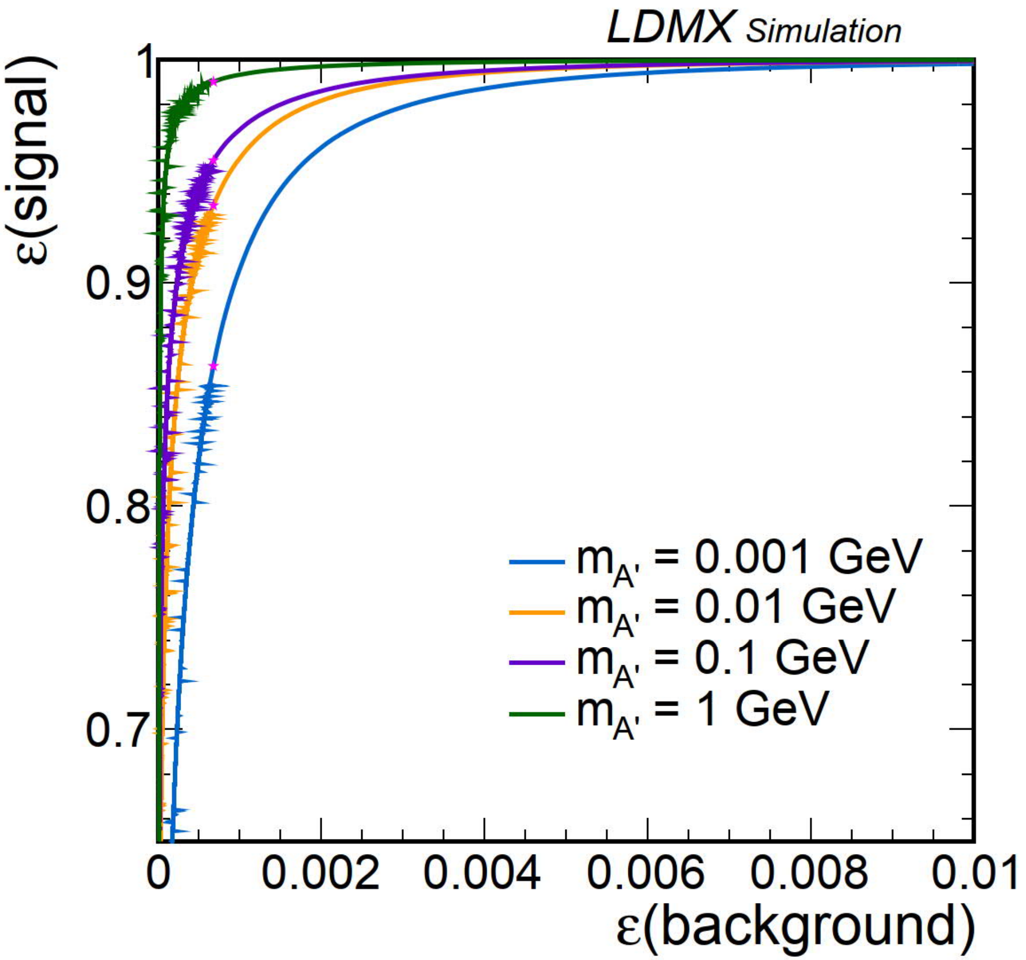
- in LDMX:
  - 40 radiation lengths deep
  - 30 layers, 7 modules each
  - central modules with higher granularity (up to 1000 channels)

  ECal can track minimum ionizing particles, for rejection of $\gamma\rightarrow\mu^+\mu^-$ and $\gamma\rightarrow$photonuclear events



ECal : Background rejection using a Boosted Decision Tree

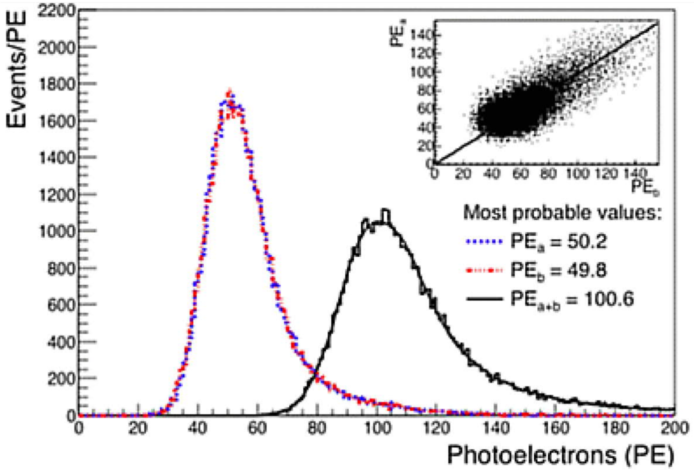


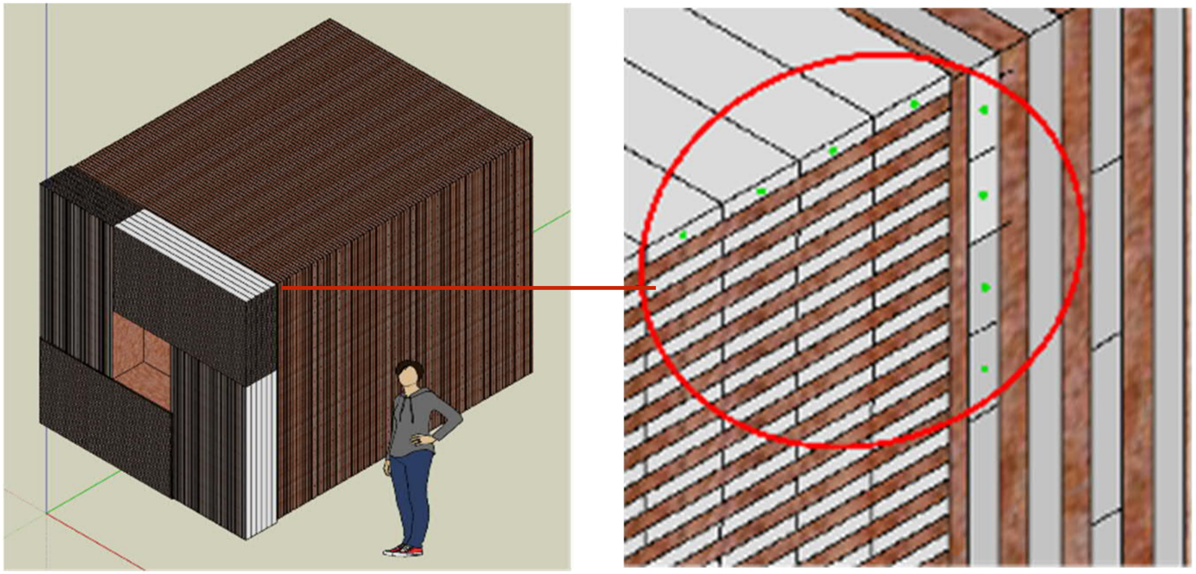


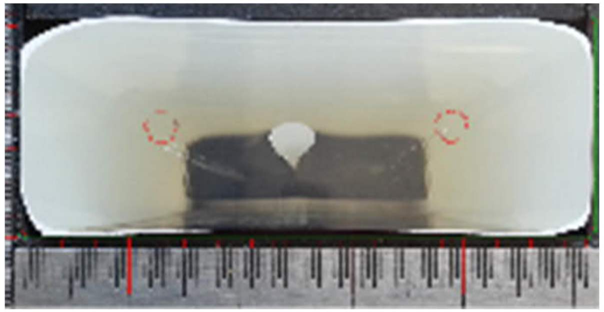
Hadronic Calorimeter - HCal

- Main task: **Veto background**
  - In particular: photo-nuclear reactions that produce only neutral particles
    - Should detect neutral hadrons (mainly n and K^0_L) in the range 100 MeV – a few GeV with an inefficiency not exceeding 10^{-6}
    - Sampling calorimeter with plastic scintillator (extruded polystyrene with WLS fibre) + absorber (steel)
    - Read by SiPM with a modified version from mu2e

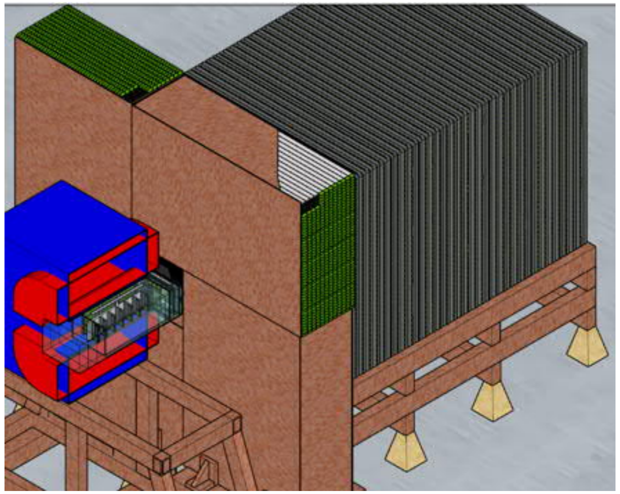
MIP through a 2cm thick, 2m long bar read by one 1.4mm WLS fibre







HCal – Optimisation of sampling and depth



Optimisation of the sampling structure and depth

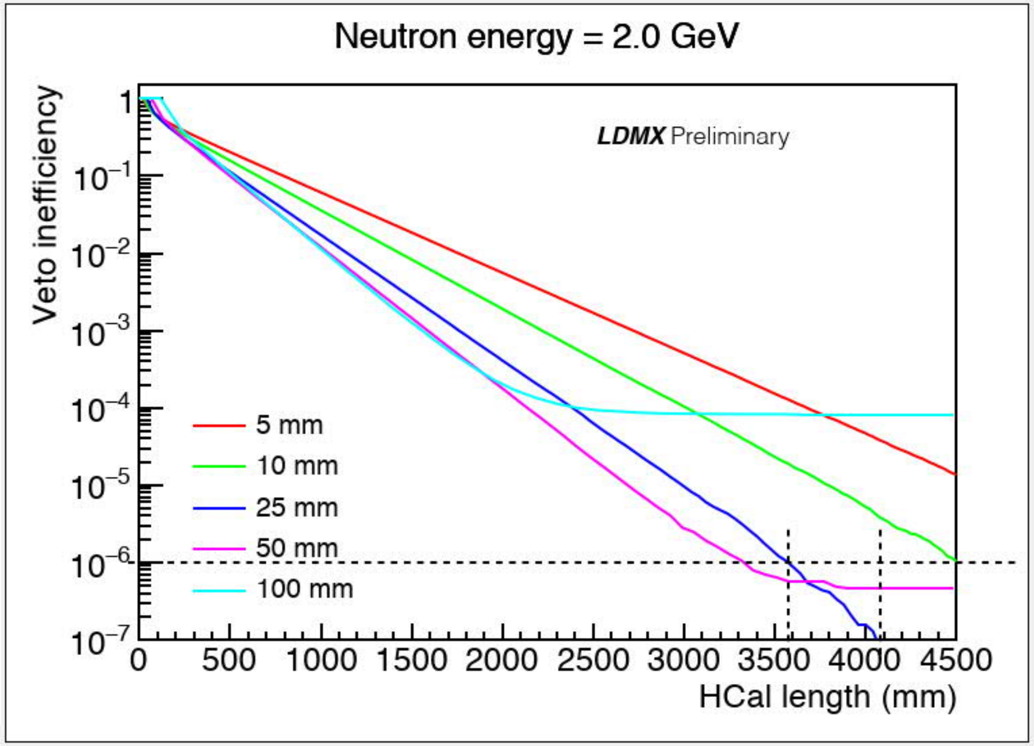
Benchmark example:
veto inefficiency of at most 10^{-6} for single neutrons (~15λ)

Absorber thickness?

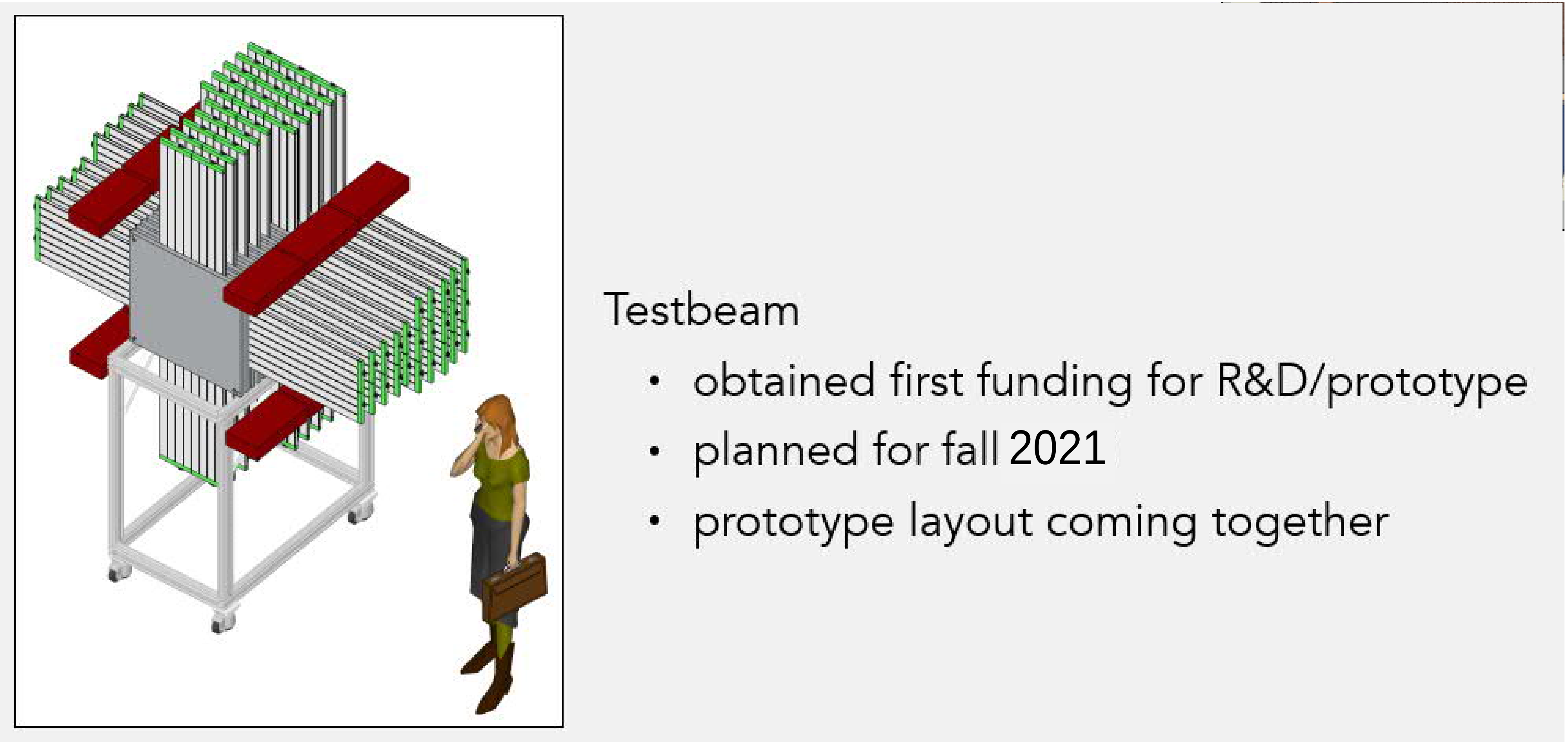
- too thick: neutrons 'get stuck'
  —> no signal in scintillator
- too thin: detector needs to be very large

Currently assuming 25mm, 4m deep, transverse size 2-3m

"Side HCal" around the ECal: Similar configuration, few λ deep



Hcal: Prototype for beamtest 2021 certify simulation



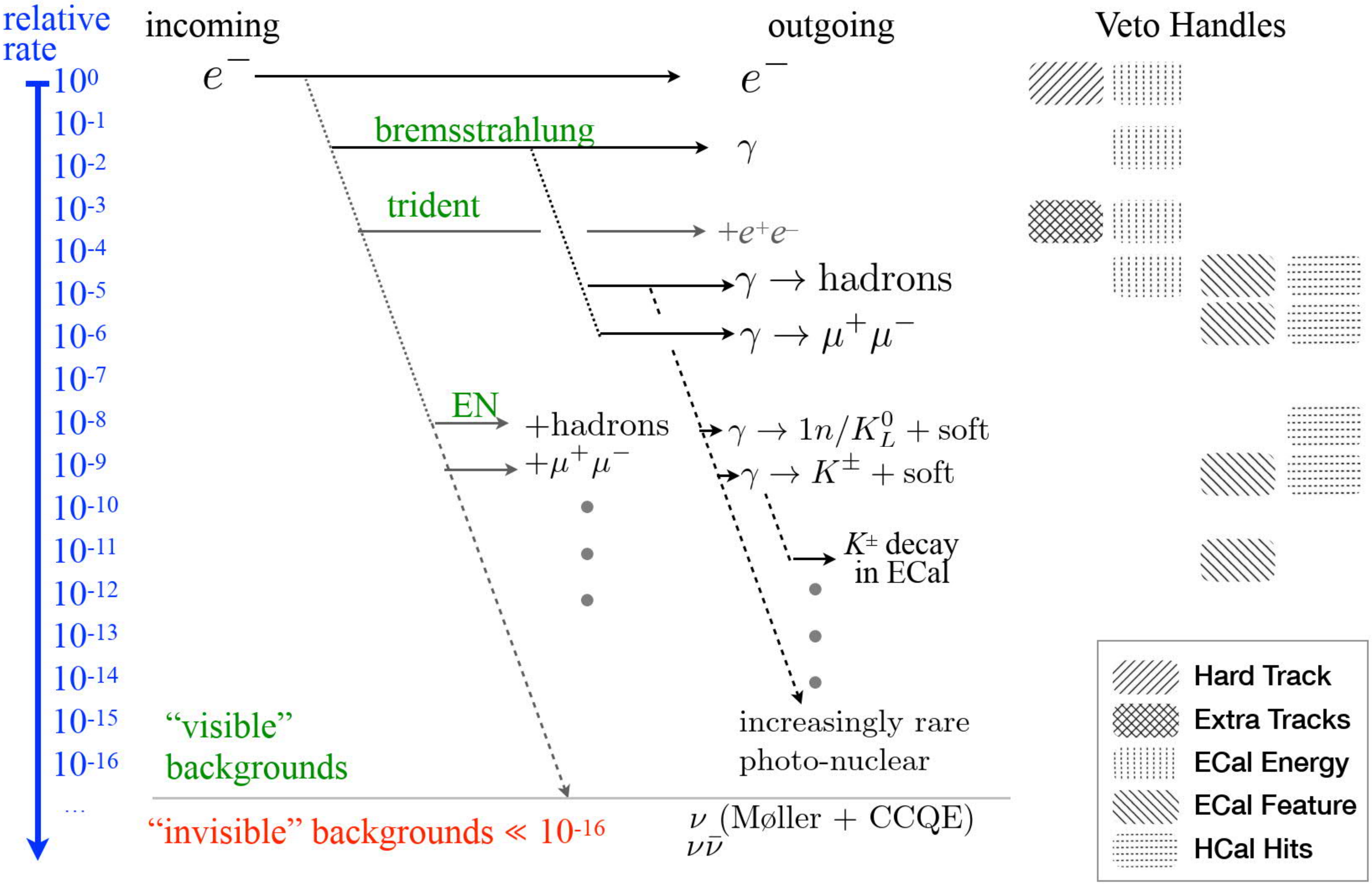
Testbeam

- obtained first funding for R&D/prototype
- planned for fall 2021
- prototype layout coming together

The Royal Physiographic Society in Lund

PI: Ruth Pöttgen

Background Challenges



relative rate

10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
…

incoming

e^-

outgoing

e^-

bremsstrahlung

γ

trident

$+e^+e^-$

$\gamma \to$ hadrons

$\gamma \to \mu^+\mu^-$

EN

+hadrons

$+\mu^+\mu^-$

$\gamma \to 1n/K_L^0$ + soft

$\gamma \to K^\pm$ + soft

$K^\pm$ decay in ECal

increasingly rare photo-nuclear

"visible" backgrounds

"invisible" backgrounds ≪ 10^{-16}

ν (Møller + CCQE)
$\nu\bar{\nu}$

Veto Handles

▨ Hard Track
▩ Extra Tracks
▥ ECal Energy
▧ ECal Feature
▤ HCal Hits

Simulation for the design and to estimate performance

Signal

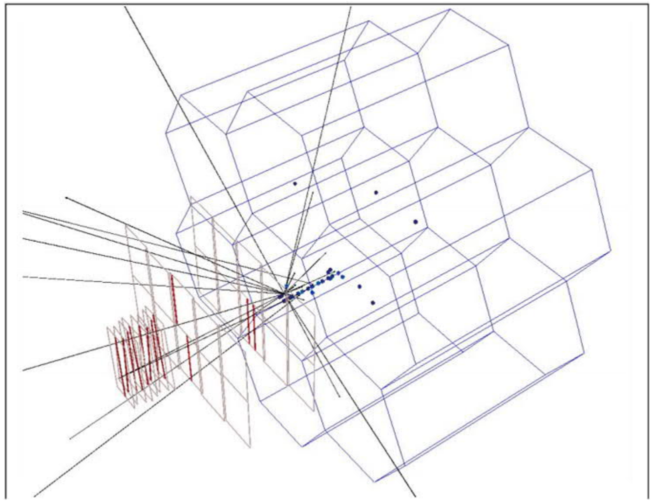
- $e^-W \rightarrow e^-WA'$ $(A' \rightarrow \chi\bar{\chi})$ simulated with MadGraph/MadEvent
- W assumed to be at rest initially
- The events are passed to GEANT4 to simulate the detector response.
- $1.5 - 3 \times 10^6$ events for $m_{A'} = 1, 10, 100$, and 1000 MeV

Background

- Generated directly in GEANT4
- Many fixes and modifications were done in GEANT4 to correctly model low energy reactions

Detector modelling

- Full geometry, B-field, material and detector response implemented in GEANT4



Torsten Åkesson[a] Nikita Blinov[b] Lene Bryngemark[c] Owen Colegrove[d] Giulia Collura[d] Craig Dukes[f] Valentina Dutta[d] Bertrand Echenard[i] Thomas Eichlersmith[j] Craig Group[f] Joshua Hiltbrand[j] David G. Hitlin[i] Joseph Incandela[d] Gordan Krnjaic[b] Juan Lazaro[d] Amina Li[d] Jeremiah Mans[j] Phillip Masterson[d] Jeremy McCormick[k] Omar Moreno[k] Geoffrey Mullier[a] Akshay Nagar[d] Timothy Nelson[k] Gavin Niendorf[d] James Oyang[i] Reese Petersen[j] Ruth Pöttgen[a] Philip Schuster[k] Harrison Siegel[d] Natalia Toro[k] Nhan Tran[b] Andrew Whitbeck[l]

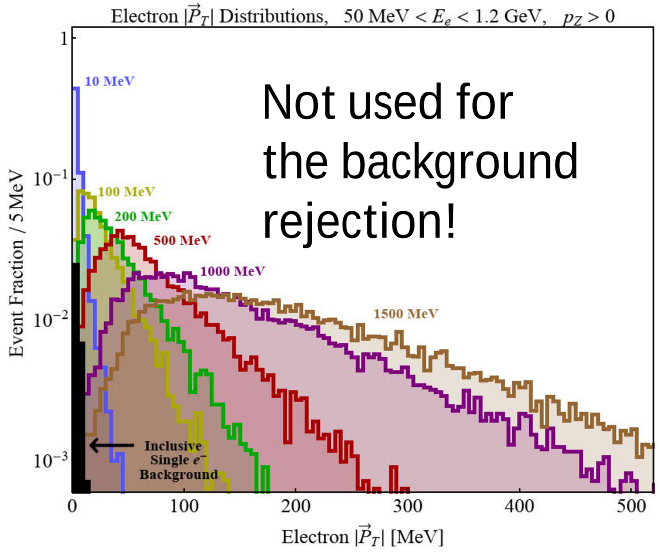
arXiv:1912.05535 and published in JHEP

Estimated performance on background rejection

Analysis strategy

1. Trigger on missing energy
2. Require single track in tracker
3. Combine ECal features in the BDT
4. Veto on signals in the HCal
5. MIP tracking in the Ecal

6. e^- p_T is not used for event selection. Its purpose is to certify potential signal events and to estimate the created mass



Not used for the background rejection!

Signal efficiency: 30% - 50%

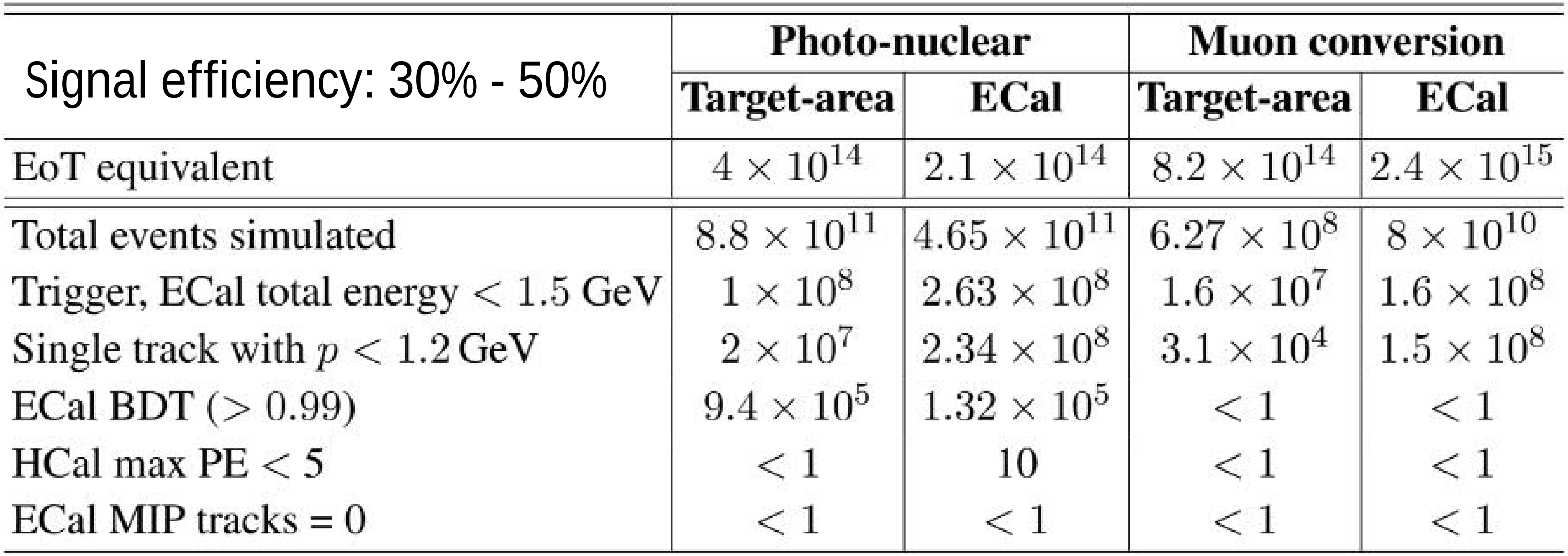
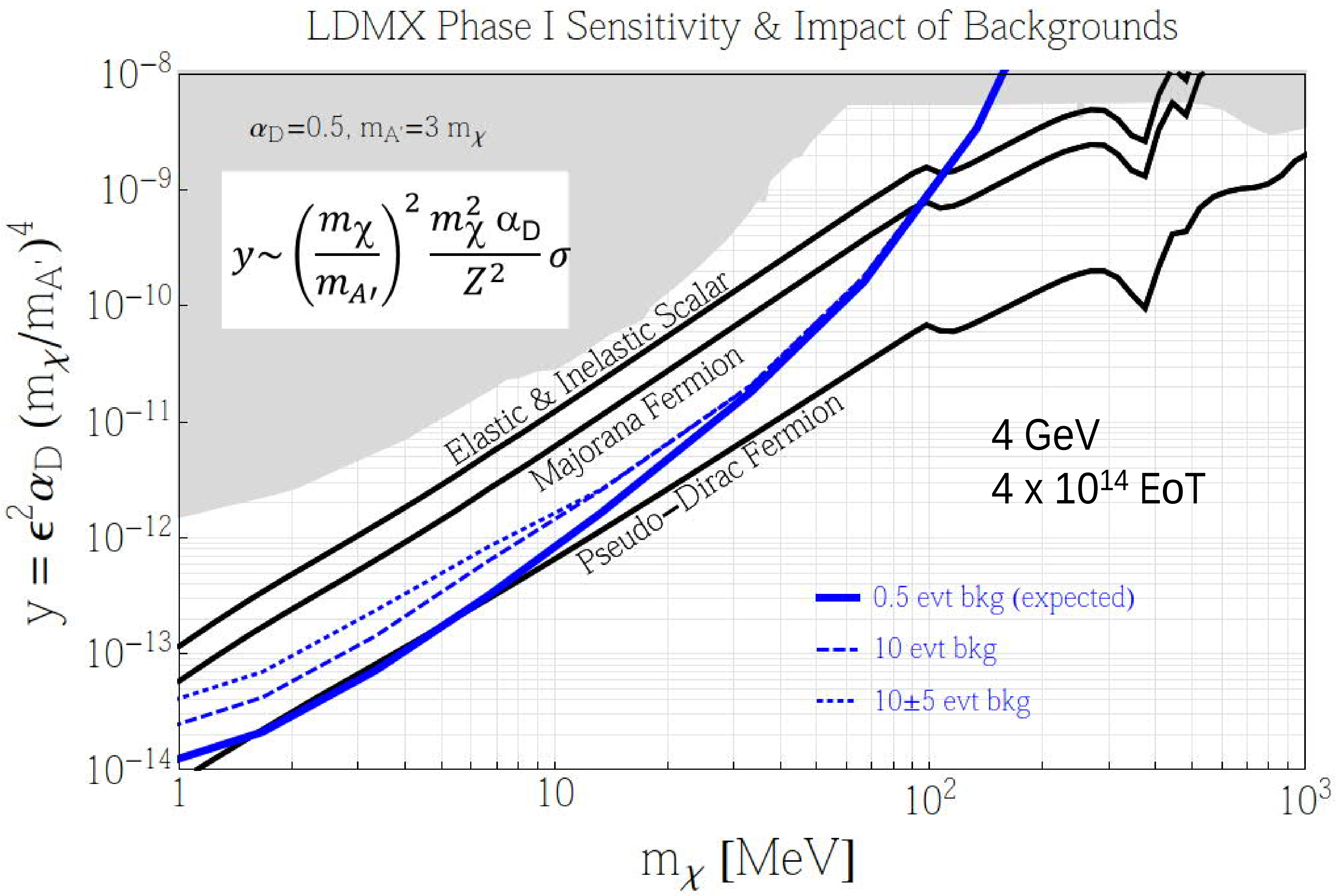


	Photo-nuclear		Muon conversion	
	Target-area	ECal	Target-area	ECal
EoT equivalent	4×10^{14}	2.1×10^{14}	8.2×10^{14}	2.4×10^{15}
Total events simulated	8.8×10^{11}	4.65×10^{11}	6.27×10^{8}	8×10^{10}
Trigger, ECal total energy < 1.5 GeV	1×10^{8}	2.63×10^{8}	1.6×10^{7}	1.6×10^{8}
Single track with $p <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

arXiv:1912.05535 and published in JHEP

Reach at 4 GeV beam energy; LMDX initial run



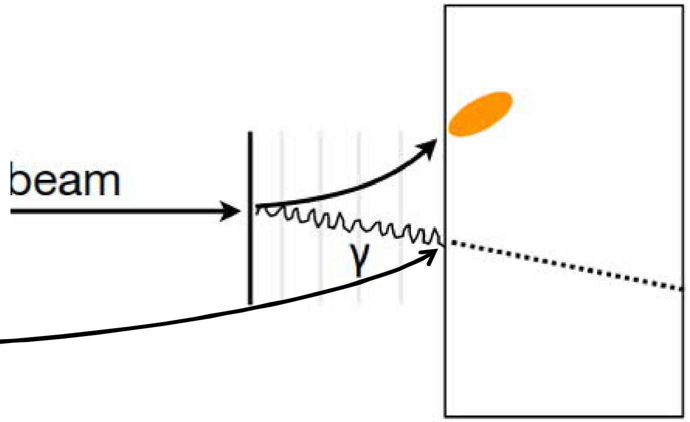
4 GeV

4 x 10^{14} EoT

arXiv: 1808.05219

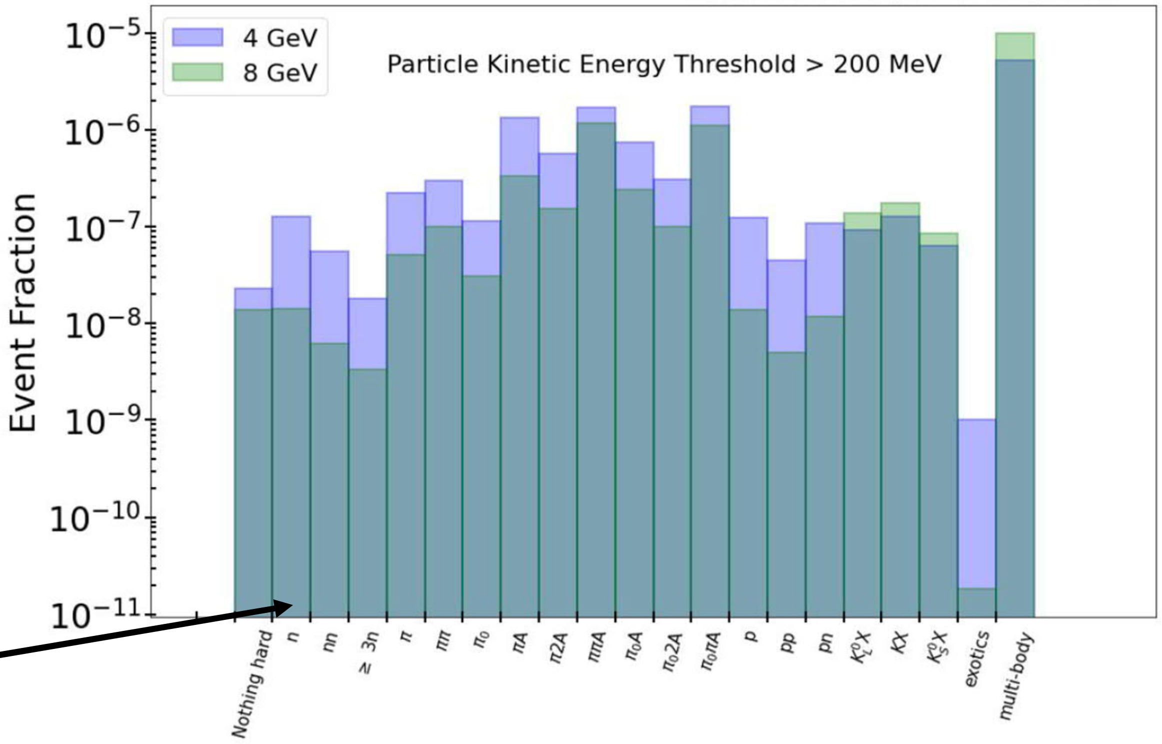
Going to higher energy – background rejection

LDMX challenge is to reject these →
i.e. to not miss a single bremsstrahlung



It is much easier for a low energy γ to not be seen, than for a high energy γ:

Higher beam energy strongly increase the background rejection

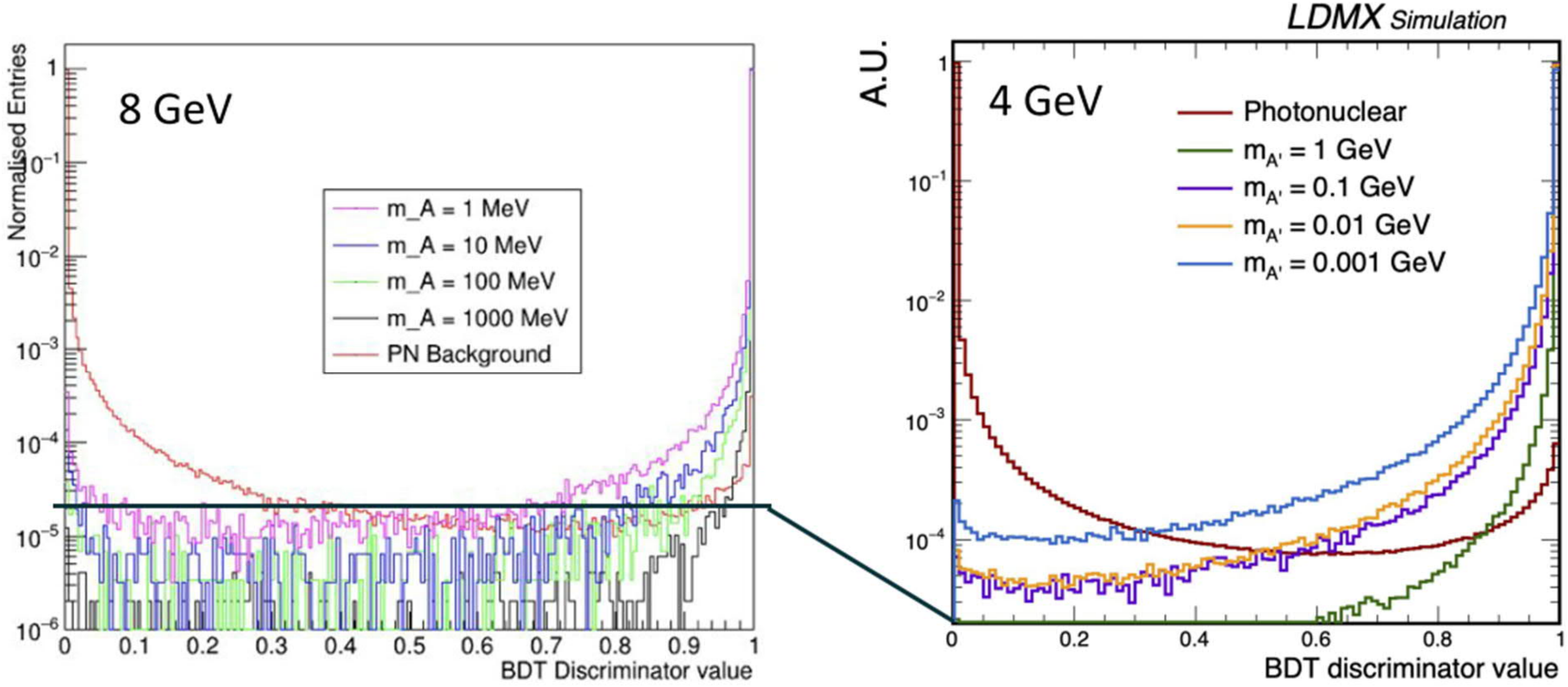


Critical

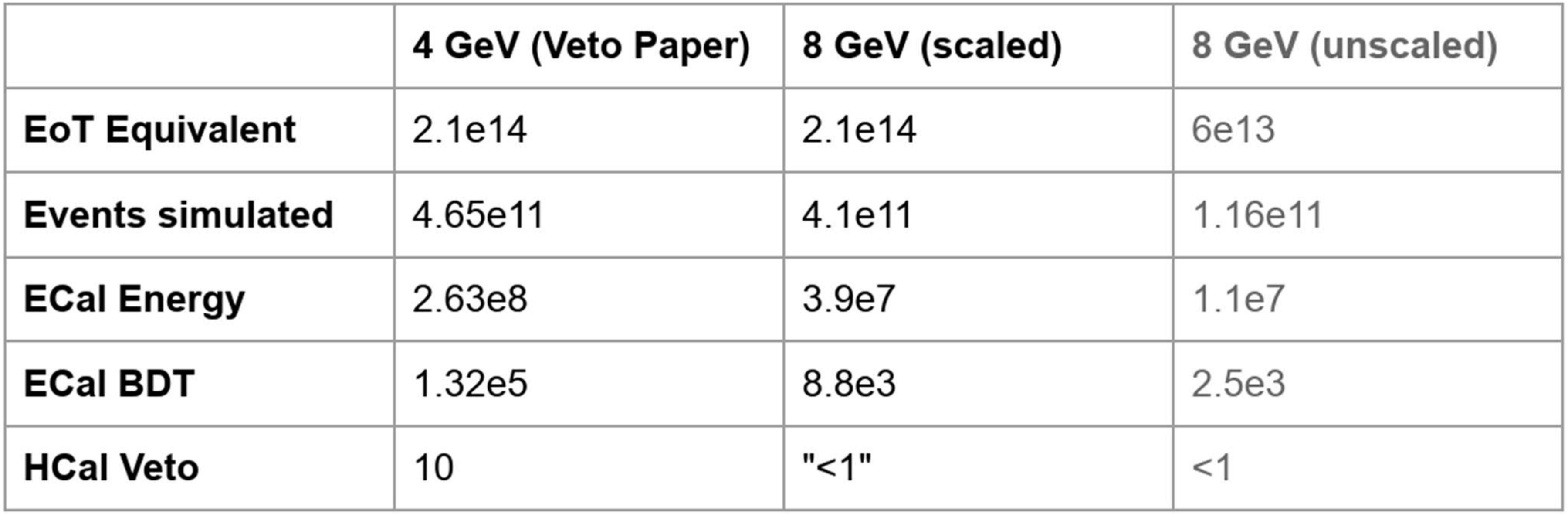
Going to higher energy – background rejection

Apply veto sequence analogously to 4 GeV

- Trigger cut scaled up by ~2 to match signal efficiencies
- BDT discriminator cut: 0.9999 to match signal efficiencies
- Same HCal veto



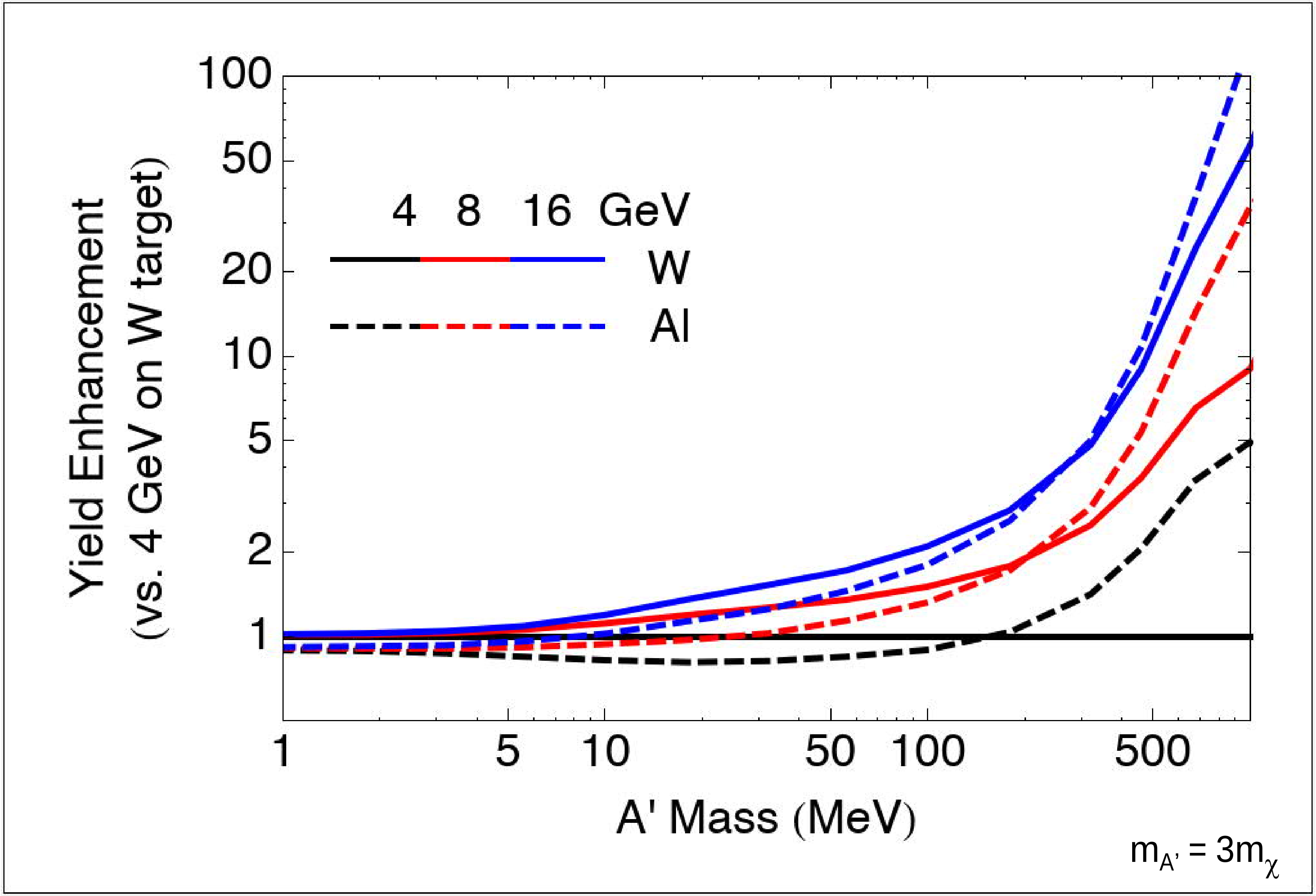
Going to higher energy – background rejection



	4 GeV (Veto Paper)	8 GeV (scaled)	8 GeV (unscaled)
EoT Equivalent	2.1e14	2.1e14	6e13
Events simulated	4.65e11	4.1e11	1.16e11
ECal Energy	2.63e8	3.9e7	1.1e7
ECal BDT	1.32e5	8.8e3	2.5e3
HCal Veto	10	"<1"	<1

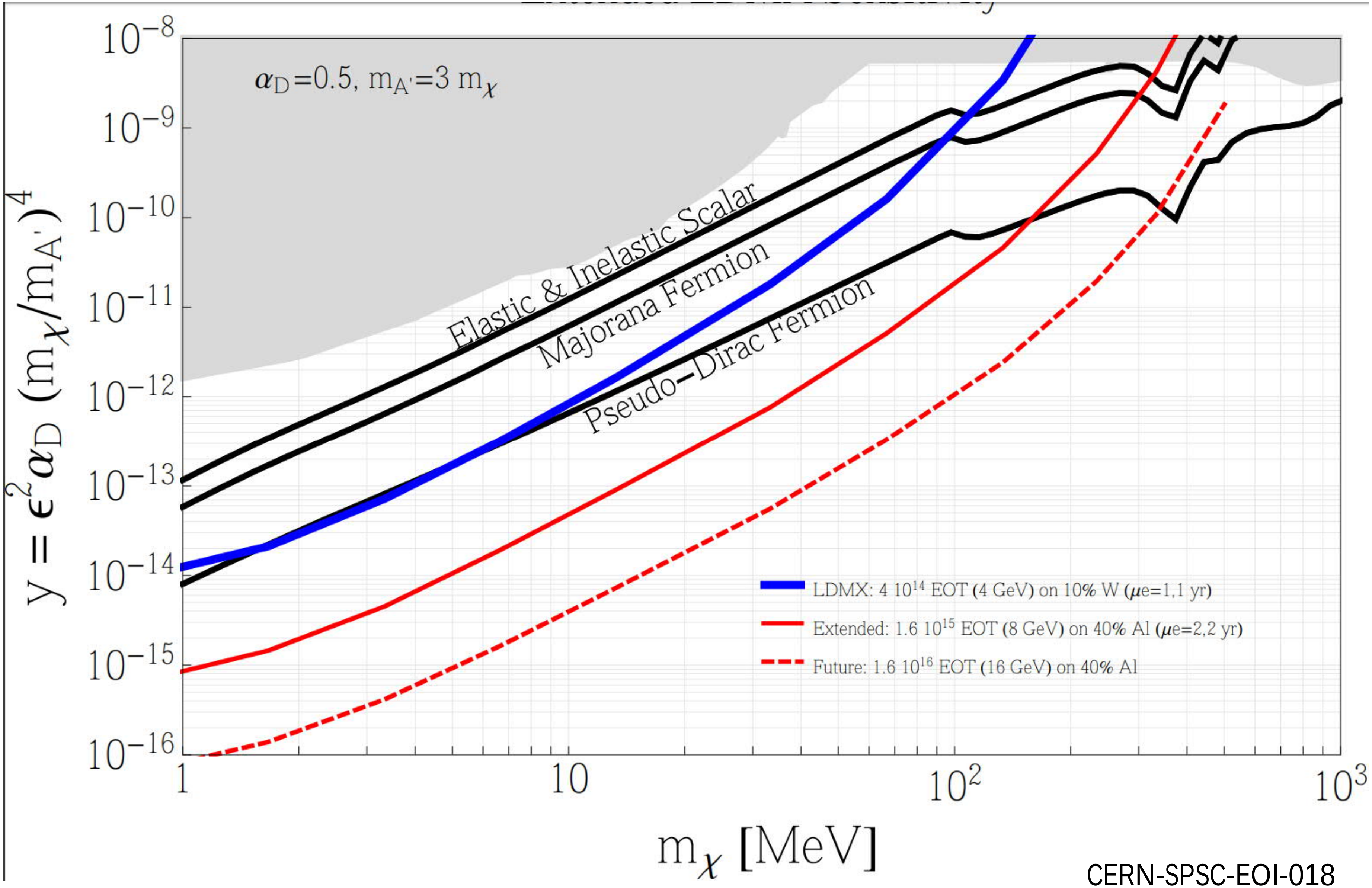
Indications of large improvement in veto capabilities

Going to higher energy – signal production



$m_{A'} = 3m_\chi$

Going to higher energy – reach

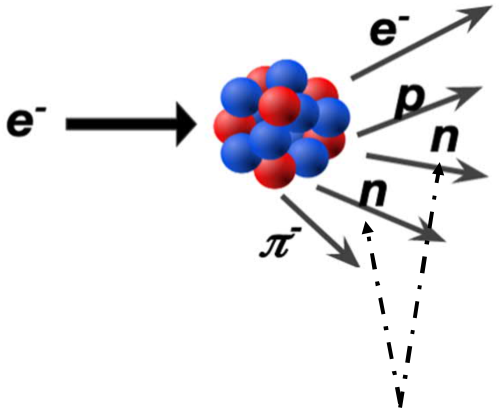


CERN-SPSC-EOI-018

Not covered in this talk

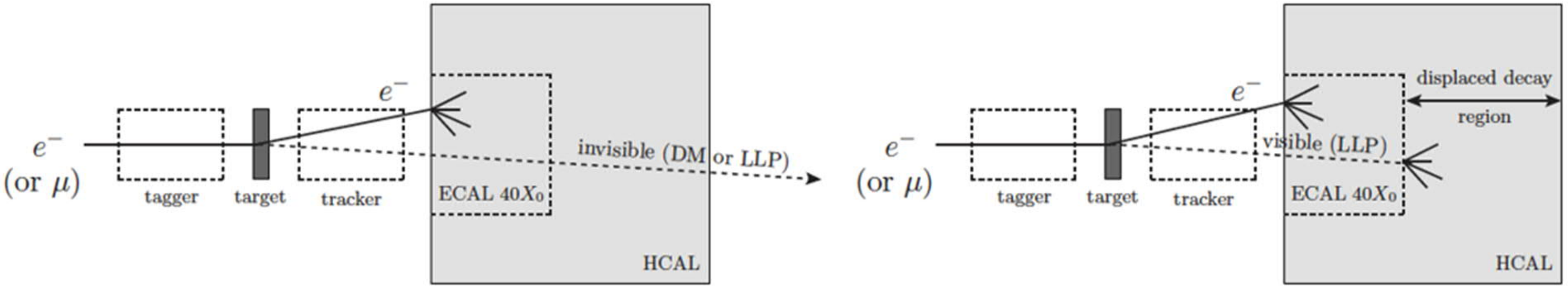
Supporting measurements for the global neutrino program

- Neutrino experiments, e.g. DUNE, rely heavily on generator modelling of neutrino - nucleon scattering
- Inclusive and exclusive electron-nucleon scattering measurements can reduce modelling uncertainties



Sensitivity to a wide range of dark (and almost dark) signatures

- Missing momentum search covers more models
- Visible signatures provide a complementary search strategy. Detailed studies are needed for these signatures



The right beam is fundamental for the experiment

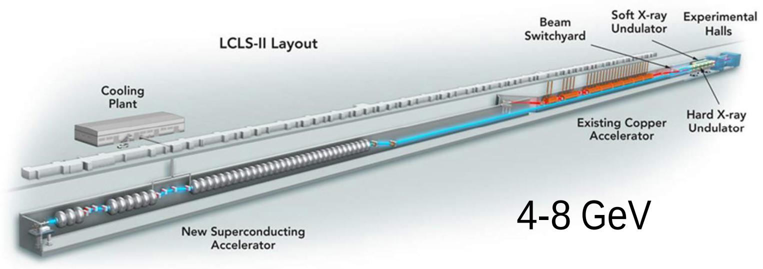
Need 10^{14} - 10^{16} electrons on target

To measure the p_T of the recoil electron requires modest beam energy and to measure the electron both before and after the target

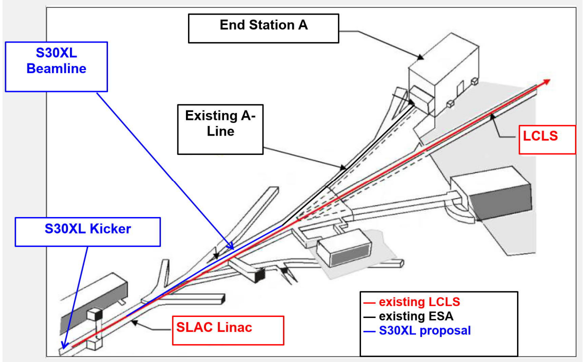
→Low current – high duty cycle – 4-20 GeV – primary electron beam

→A primary electron beam dedicated to the experiment

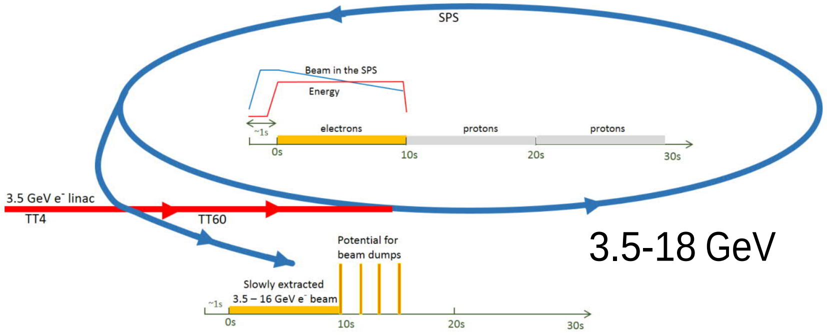
Baseline – SLAC



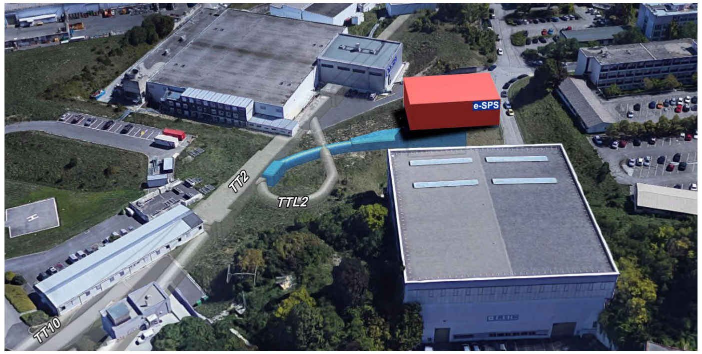
4-8 GeV



CERN – potential future high energy version?



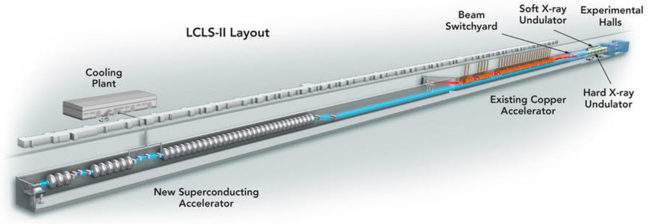
3.5-18 GeV

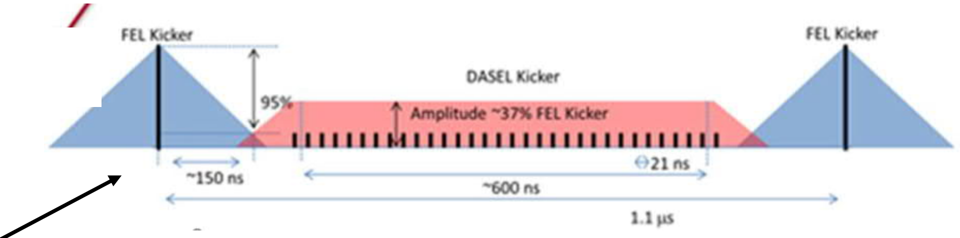


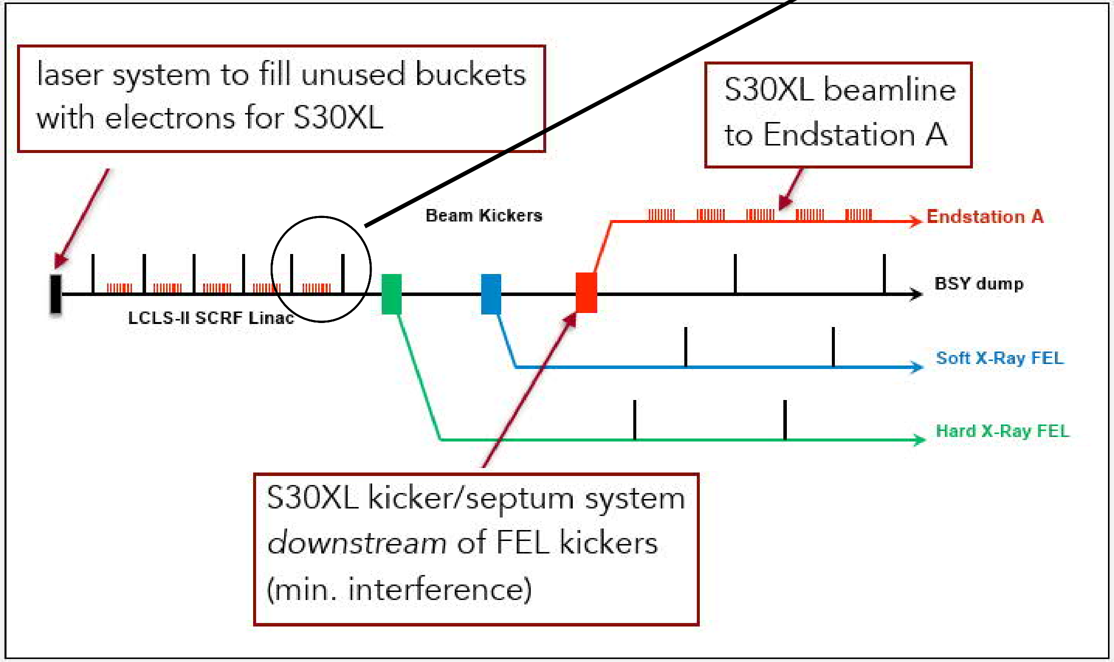
S30XL @ LCLS-II @ SLAC ; parasitic operation

- Fill empty buckets in the continuous wave acceleration by flashing the electron source cathode with a dedicated laser.
- Extract the low-current, high-rate electron beam downstream of the extraction of the electron bunches for photon science
- 4 (8) GeV
  Bunch frequency: 46 MHz (186 MHz)
  4x10^{14} EoT year 1

Linac Coherent Light Source II

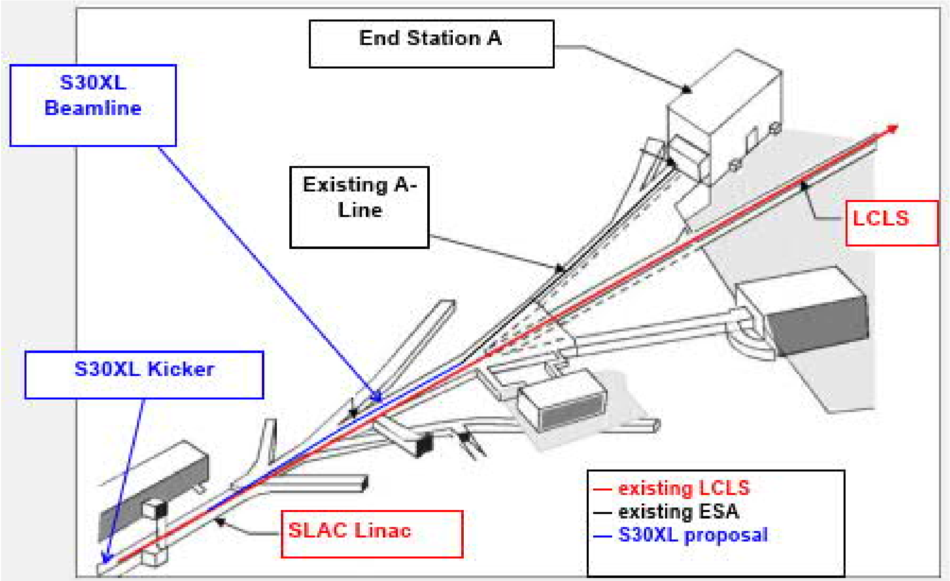





laser system to fill unused buckets with electrons for S30XL

S30XL beamline to Endstation A

S30XL kicker/septum system *downstream* of FEL kickers (min. interference)

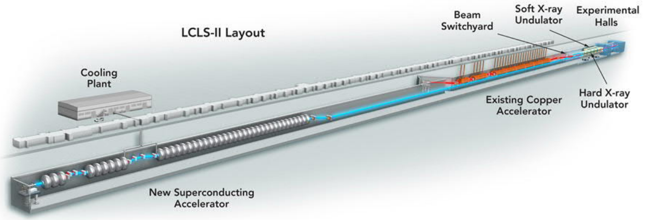


T. Raubenheimer, in Proceedings, 60th ICFA Advanced Beam Dynamics Workshop on Future Light Sources (FLS2018): Shanghai, China, March 5-9, 2018 (2018), p. MOP1WA02.

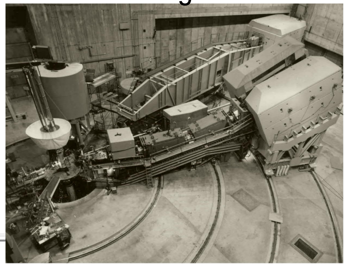
S30XL @ LCLS-II @ SLAC ; schedule

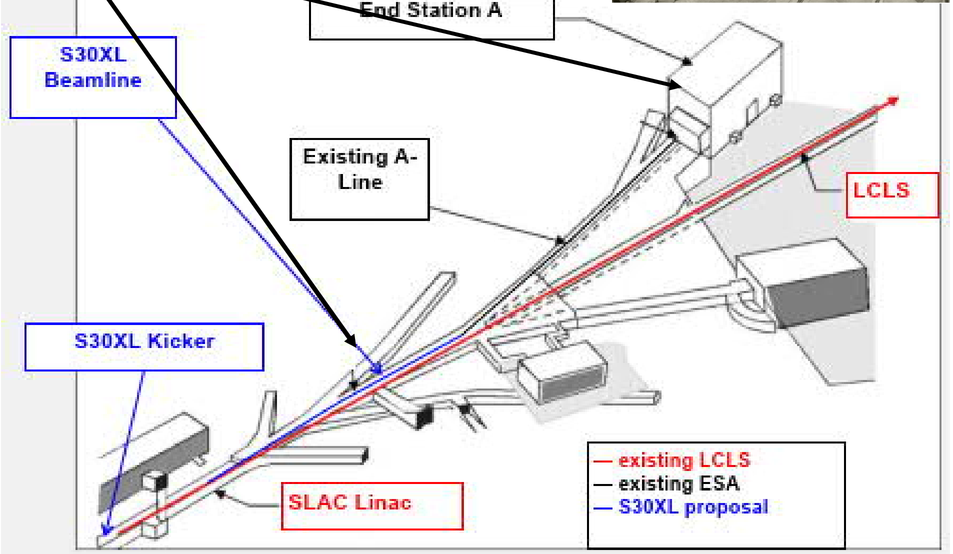
- Stage-A:
  - S30 Accelerator Improvement Project (kicker & ~100m beamline – ending in beam switchyard)
  - Under construction
- Stage-B:
  - ~100 m beamline to connect to existing End Station A line
  - Beam planned to start October 2023, and run with no long interruptions until March 2025
- Stage-C (funding 1.05 M$ to be approved):
  - Dedicated laser on the photo-cathode to improve the control of the electron emission into the beam.
  - Can be constructed while the beam is delivered to ESA. Needs just 1-2 weeks interrupt for final connection
- 8 GeV:
  - Beam interruption March 2025 – Feb (June?) 2026 for LCLS-II upgrade to 8 GeV

Linac Coherent Light Source II



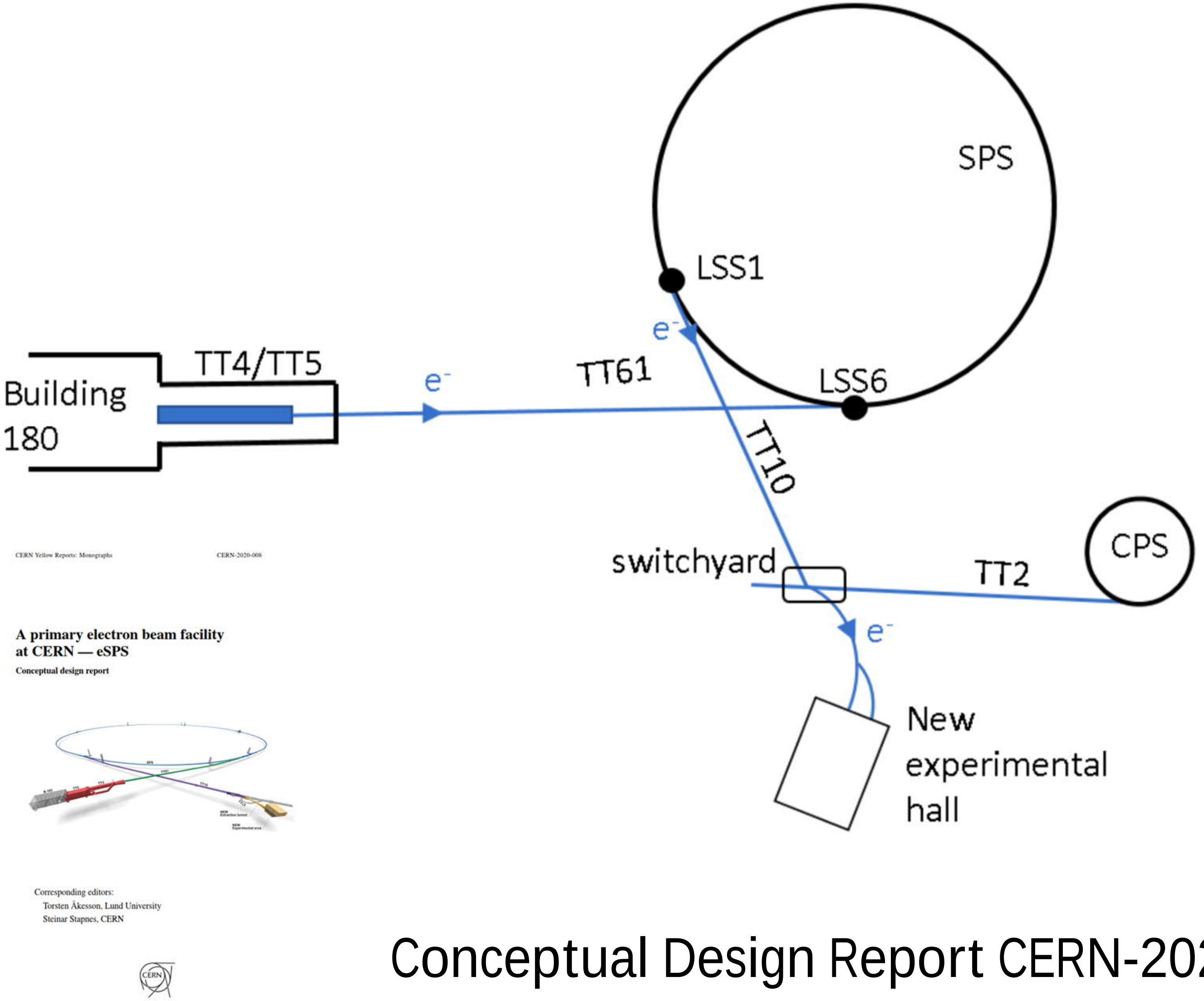
Historic ground ☺





T. Raubenheimer, in Proceedings, 60th ICFA Advanced Beam Dynamics Workshop on Future Light Sources (FLS2018): Shanghai, China, March 5-9, 2018 (2018), p. MOP1WA02.

An Electron Beam Facility at CERN – eSPS



CERN Yellow Reports: Monographs
CERN-2020-008

A primary electron beam facility at CERN — eSPS
Conceptual design report

Corresponding editors:
Torsten Åkesson, Lund University
Steinar Stapnes, CERN

- X-band based 70m LINAC to ~3.5 GeV in TT4-5
- Fill the SPS in 1-2s via TT60 (bunches 5ns apart)
- Accelerate to ~16 (18) GeV in the SPS
- Slow extraction to experiment in 10s as part of the SPS super-cycle
- Bring the beam to the Meyrin site using TT10

Conceptual Design Report CERN-2020-008

arXiv:2009.06938v3

The Knut & Alice Wallenberg project: Light Dark Matter


Riccardo Catena
Theoretical Physics, Chalmers


Jan Conrad
Astroparticle Physics, SU


Caterina Doglioni
Particle Physics, LU


Stefan Prestel
Theoretical Physics, LU


Ruth Pöttgen
Particle Physics, LU


Luis Sarmiento
Nuclear Physics, LU

- WP1 The Light Dark Matter eXperiment, LDMX: *Lund University Particle Physics*
- WP2 Simulation: Signal generation and integration in PYTHIA, PYTHIA-GEANT4 integration, and simulation of electronuclear (eN) and photonuclear (γN) reactions, all crucial for LDMX. *Chalmers Theoretical Physics, Lund University Theoretical Physics, Lund University Particle- and Nuclear Physics*
- WP3 Data interpretation: Making a statistical inference package for LDMX, and making global fits. *Lund University Particle Physics, Chalmers Theoretical Physics, Stockholm University Astroparticle Physics*
- WP4 Detector material evaluation for direct detection: Preparing for a future direct detection experiment guided by the outcome of the above activities. *Chalmers Theoretical Physics and Stockholm University Astroparticle Physics*

Summary

- A convincing case to search for light dark matter
  - Accelerator experiment and direct detection experiments are complementary
- The LDMX concept has strong potential
- The beam is fundamental and we will get it
  - In preparation for using the SLAC beam under construction
  - Potential for a high energy version at CERN by reactivating the SPS as an electron accelerator