Search for Light Dark Matter with LDMX

Torsten Åkesson
Uppsala, 27 Feb 2020

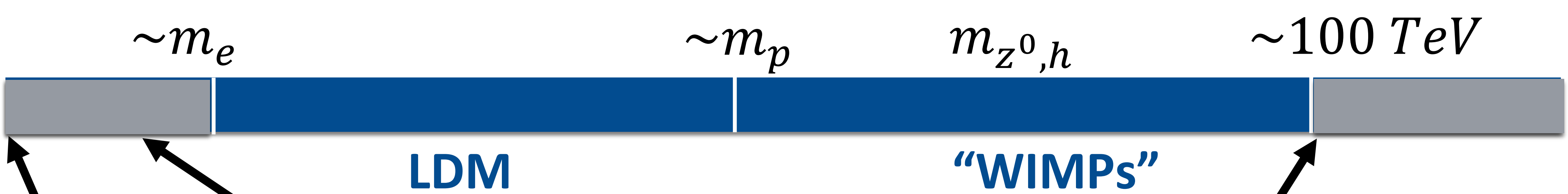
Dark matter; its nature and the thermal origin

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 ~100 TeV



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

Cannot annihilate to the correct relic abundance

Incompatible with structure formation and the hydrogen distribution

(*) 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

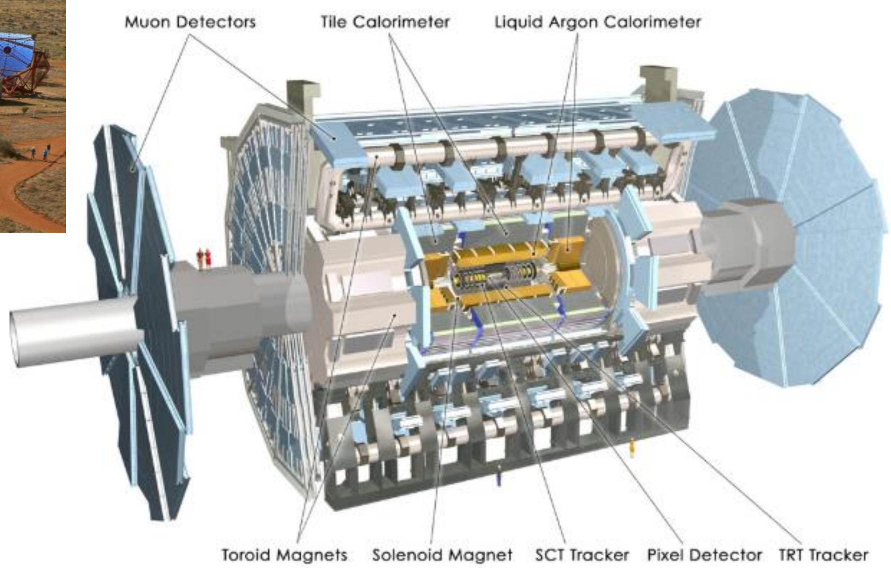
$\sim m_e$ $\sim m_p$ $m_{Z^0,h}$ $\sim 100\ TeV$

LDM **“WIMPs”**

The so-called WIMP miracle makes the range a few GeV – 100 TeV attractive

This range is also motivated by Super Symmetry

Photons from dark matter annihilation in space

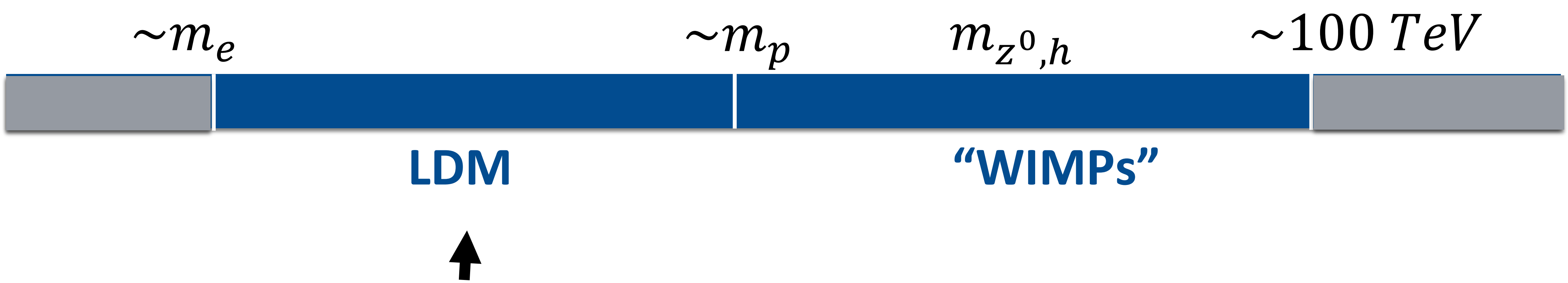


Production of dark matter

Dark matter colliding with matter in an underground detector

Up to now no sign in this range

Thermal dark matter; Light Dark Matter, LDM



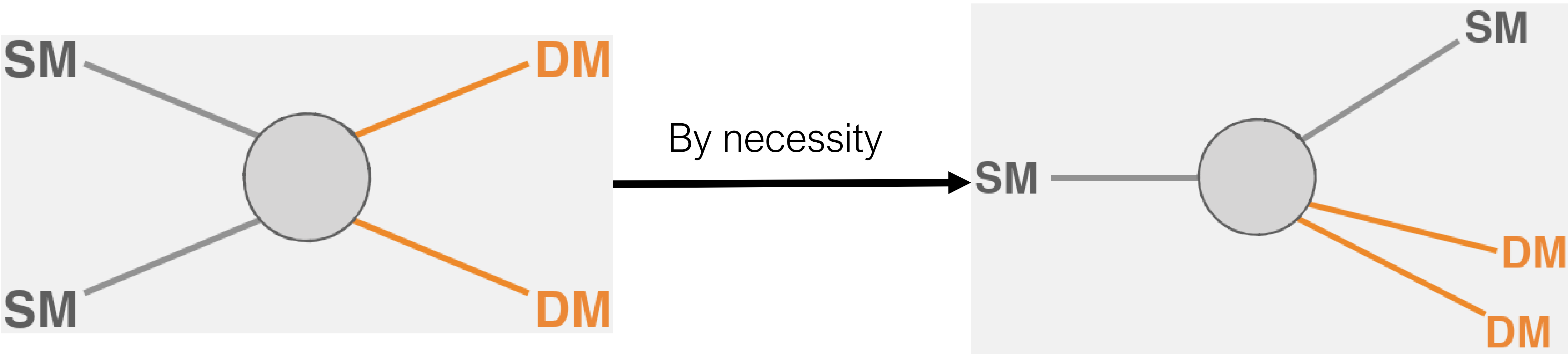
The mass range where we have most known matter is essentially unexplored

Dark matter as such, is a huge Beyond the Standard Model (BSM) phenomenon.

Hints of BSM are all at low energy/low mass, and not at the energy frontier:

- 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

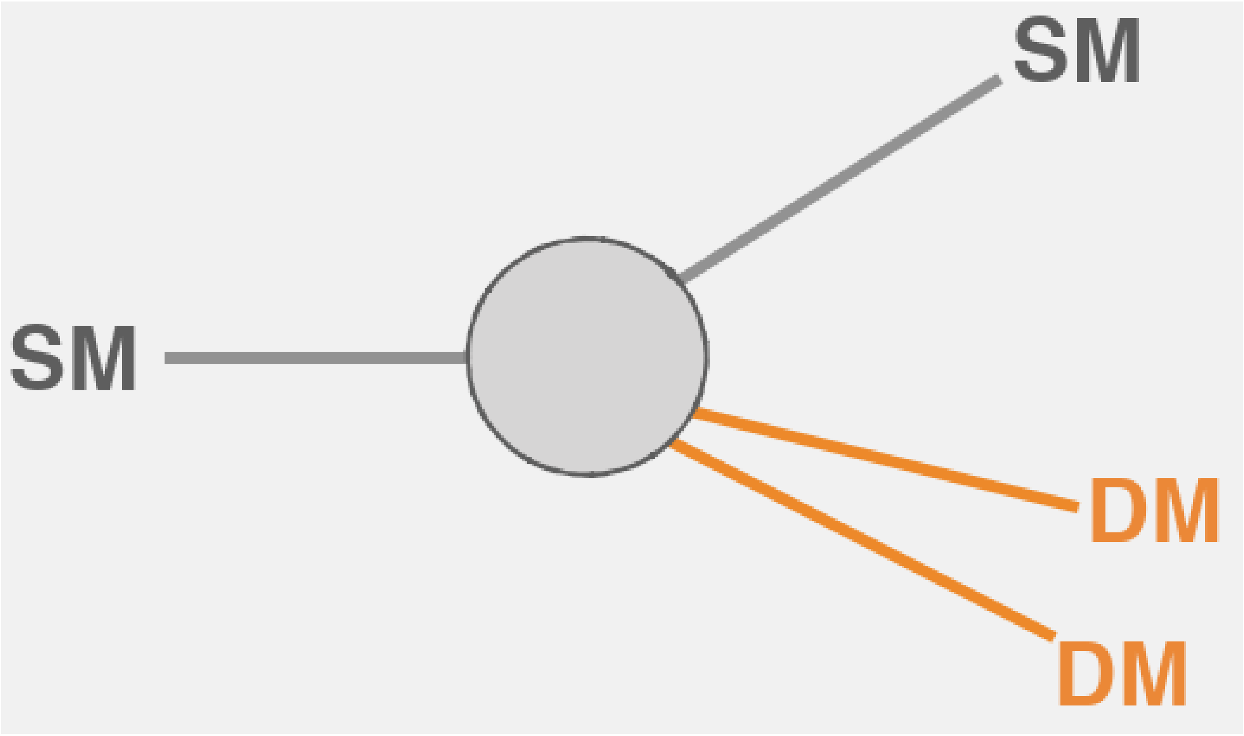


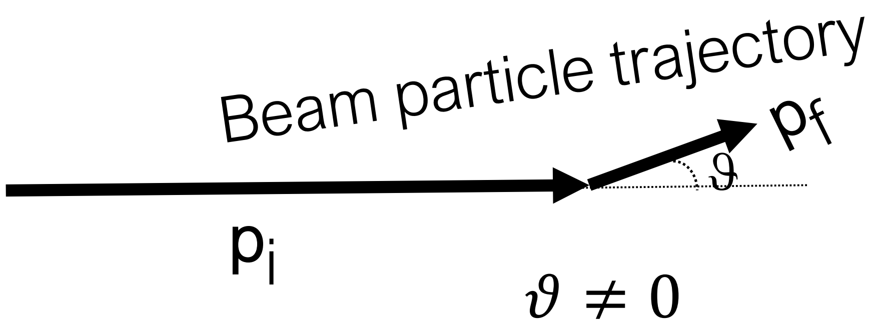
Thermal equilibrium between known and dark matter requires an interaction between them

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

Weak interaction cannot give the observed dark matter abundance, if dark matter particles are light. Light dark matter therefore implies a new interaction.
A hidden sector of physics with very little 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

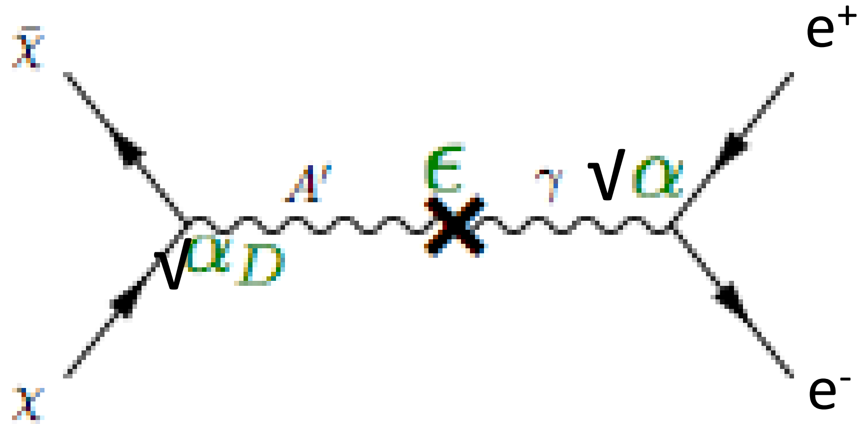
Simplest: A hidden sector QED

- Fine structure constant α_D
- Dark photon **A'**
- Dark matter particles χ

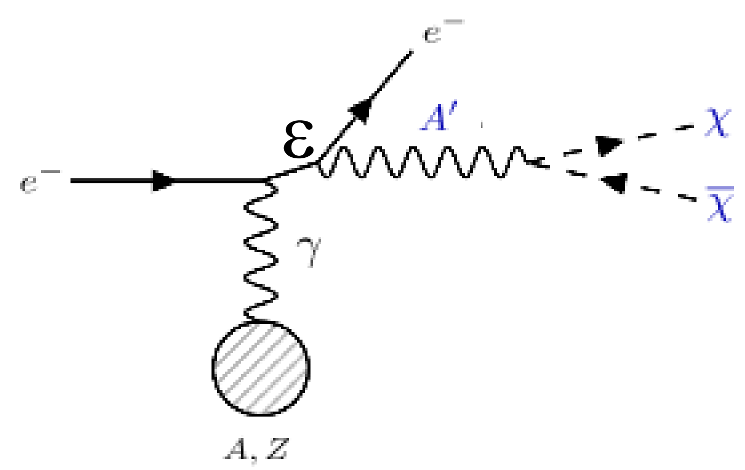
This hidden sector QED connects to the known physics by the A' mixing with the photon (γ) with a small mixing strength ε

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

Thermal equilibrium in the early universe



Reaction in the laboratory

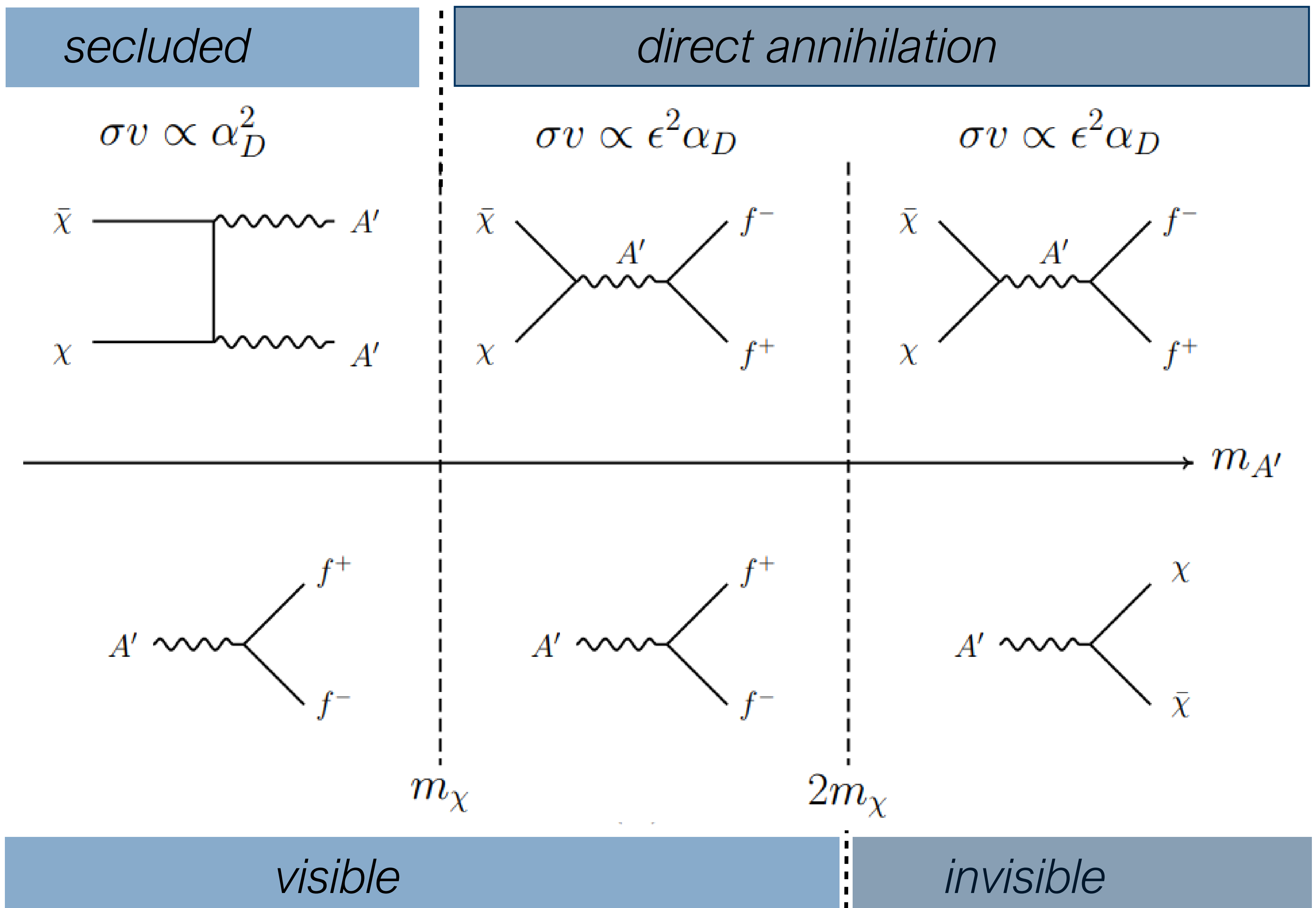


Mass of A' and mass of χ

The main scenario for LDMX

Visibly decaying dark mediator

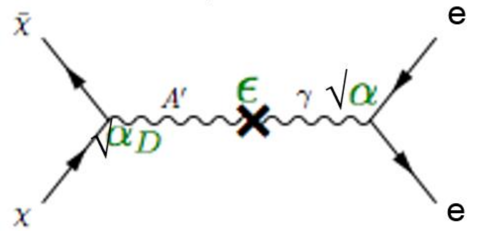
Sub-GeV χ excluded from CMB
(See e.g. T. Bringmann et al, 1612.00845v2)



Thermal equilibrium

In the laboratory

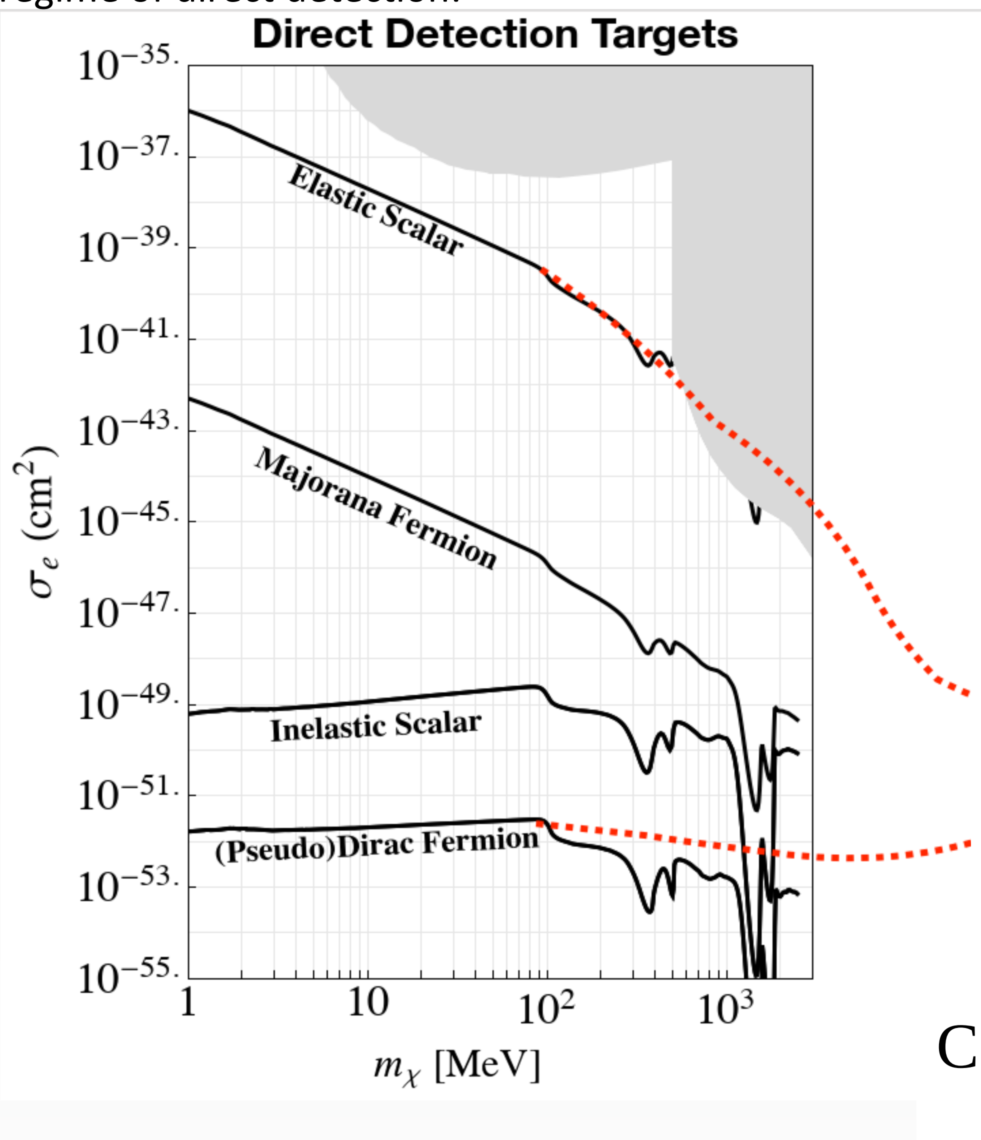
Direct Detection and Accelerator Based Production

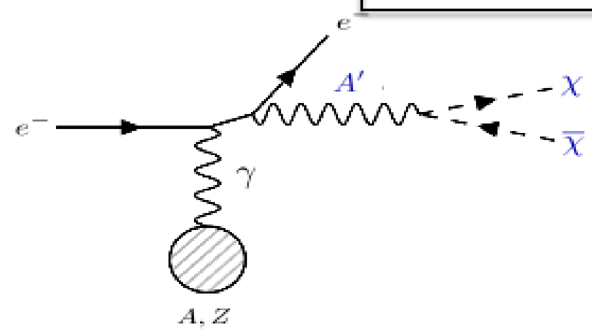


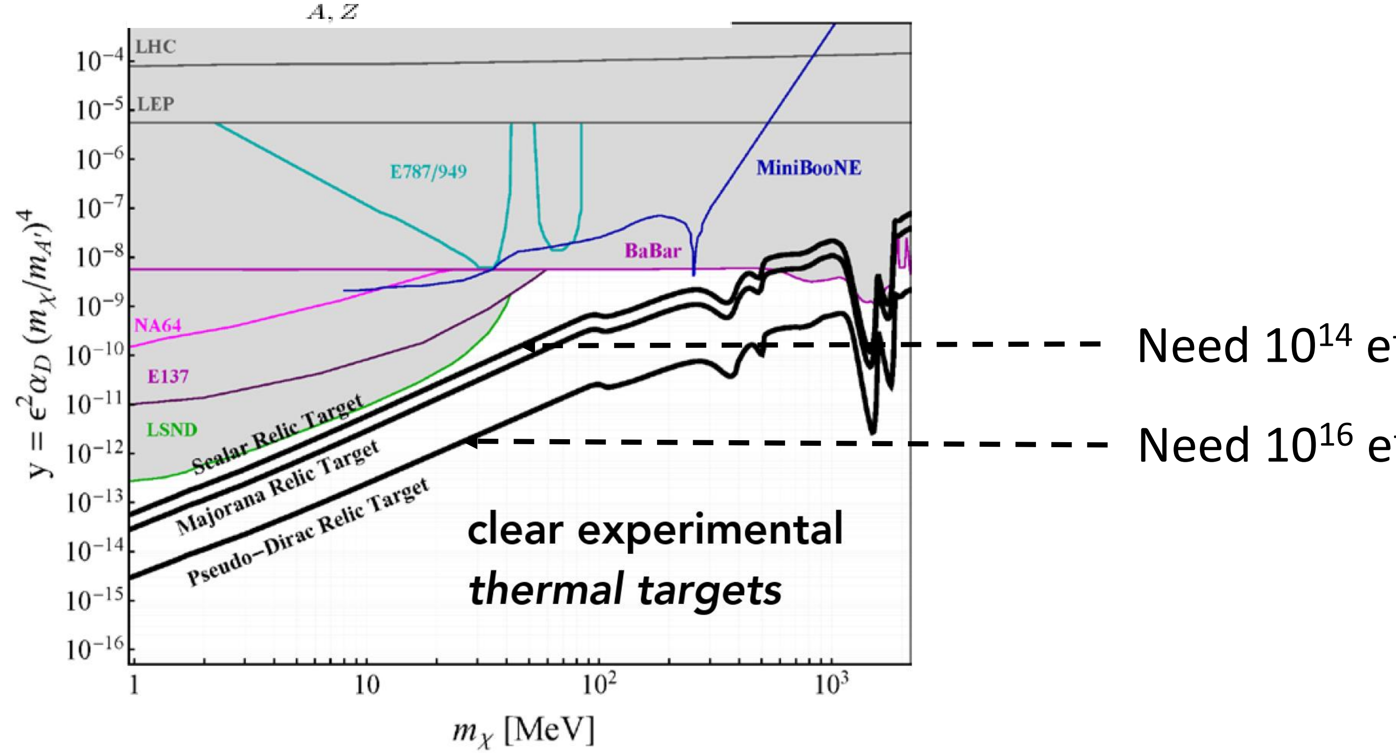
$$\sigma v \sim \varepsilon^2 \alpha_D \frac{m_\chi^2}{m_{A'}^4} = \frac{y}{m_\chi^2};\ y = \varepsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4$$

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

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

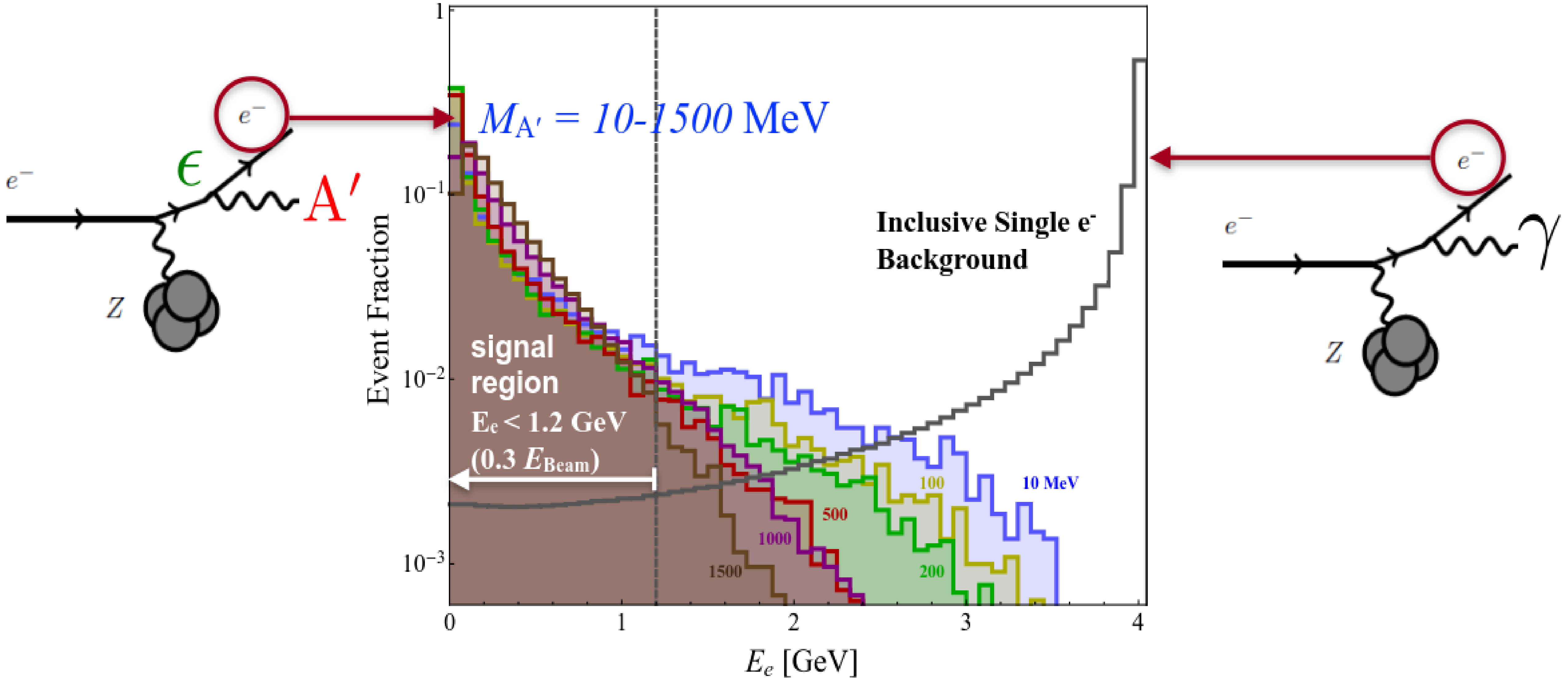






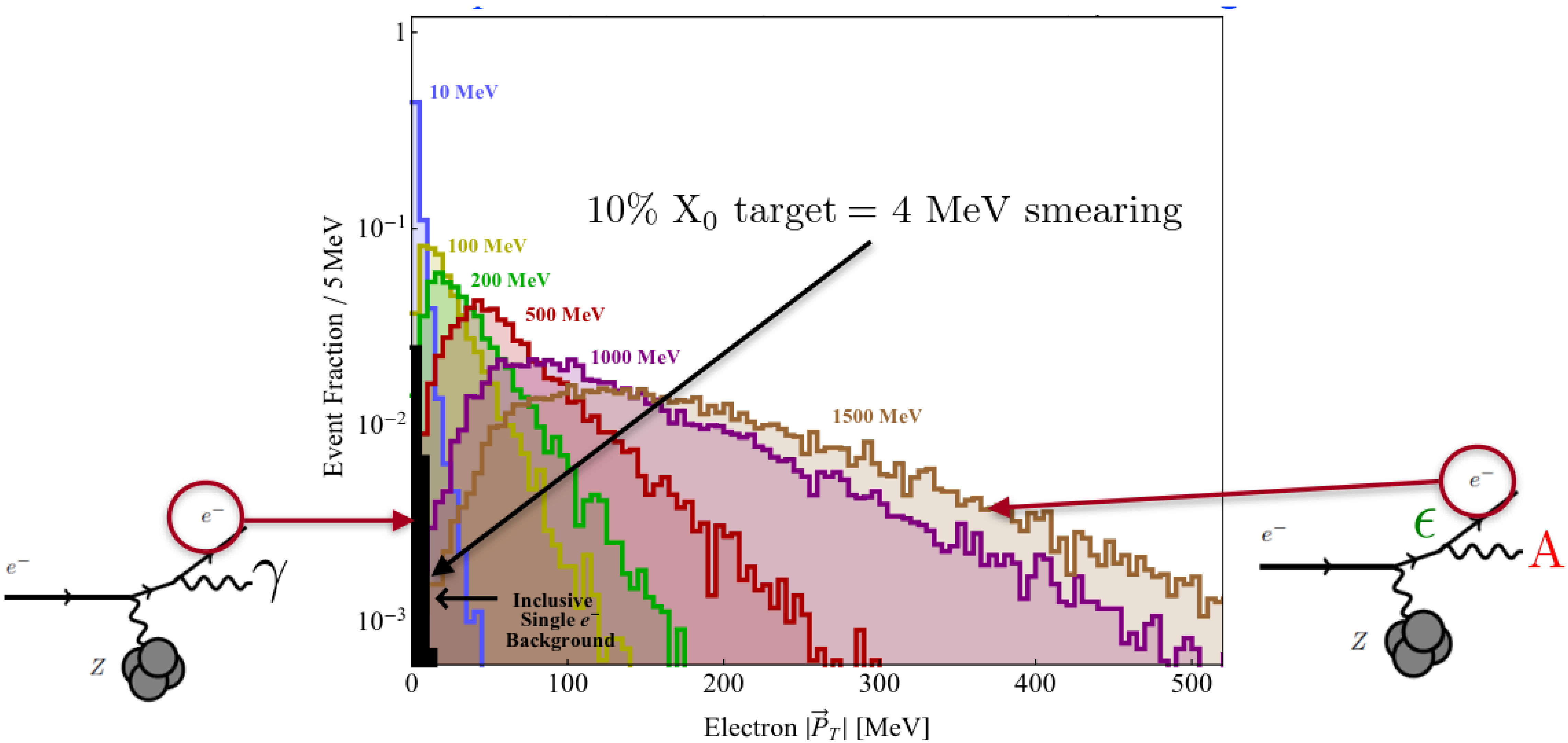
Conservative choice: $\alpha_D = 0.5$ and $m_{A'} = 3m_\chi$

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

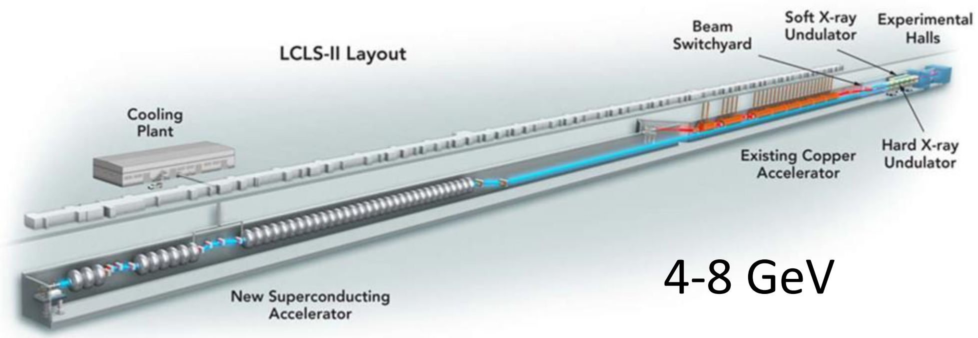
Need 10^{14} - 10^{16} electrons on target

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

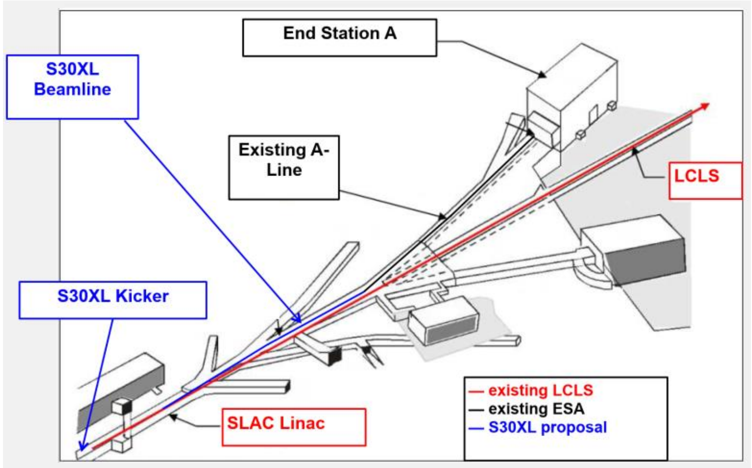
→Low current – high duty cycle – 4-20 GeV – primary electron beam

→A primary electron beam dedicated to the experiment

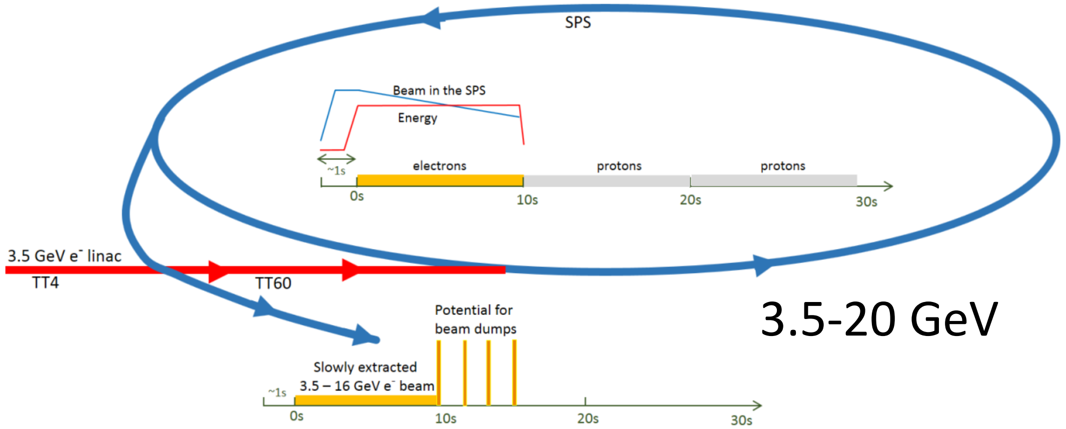
Baseline – SLAC



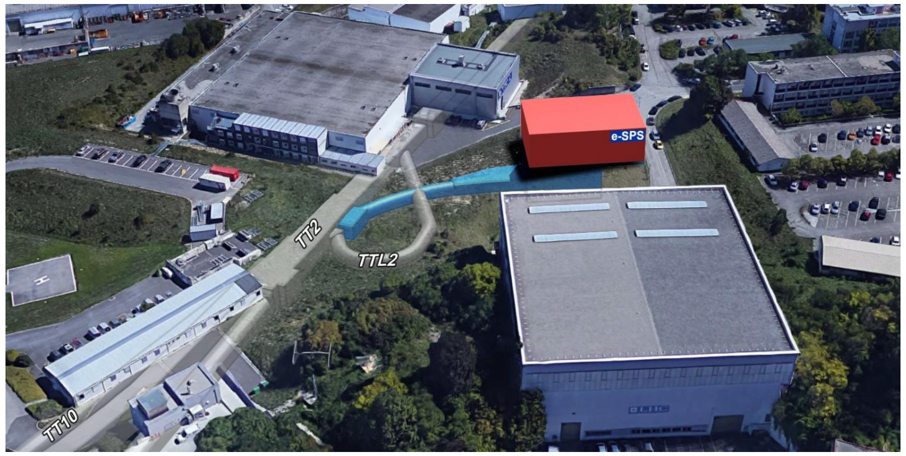
4-8 GeV



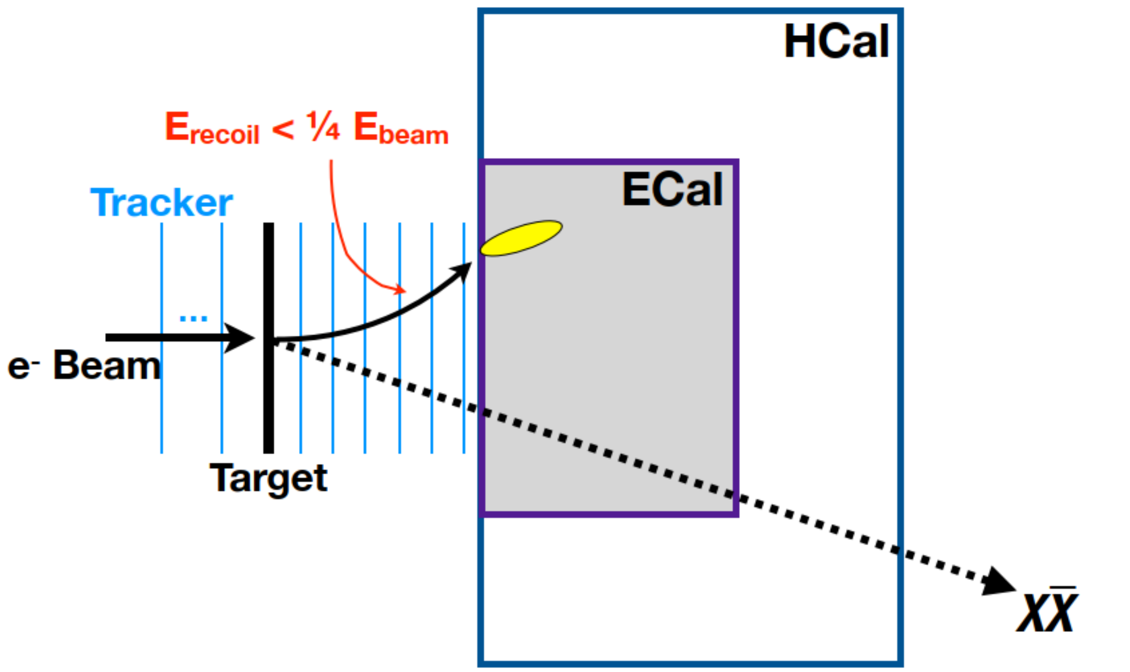
CERN



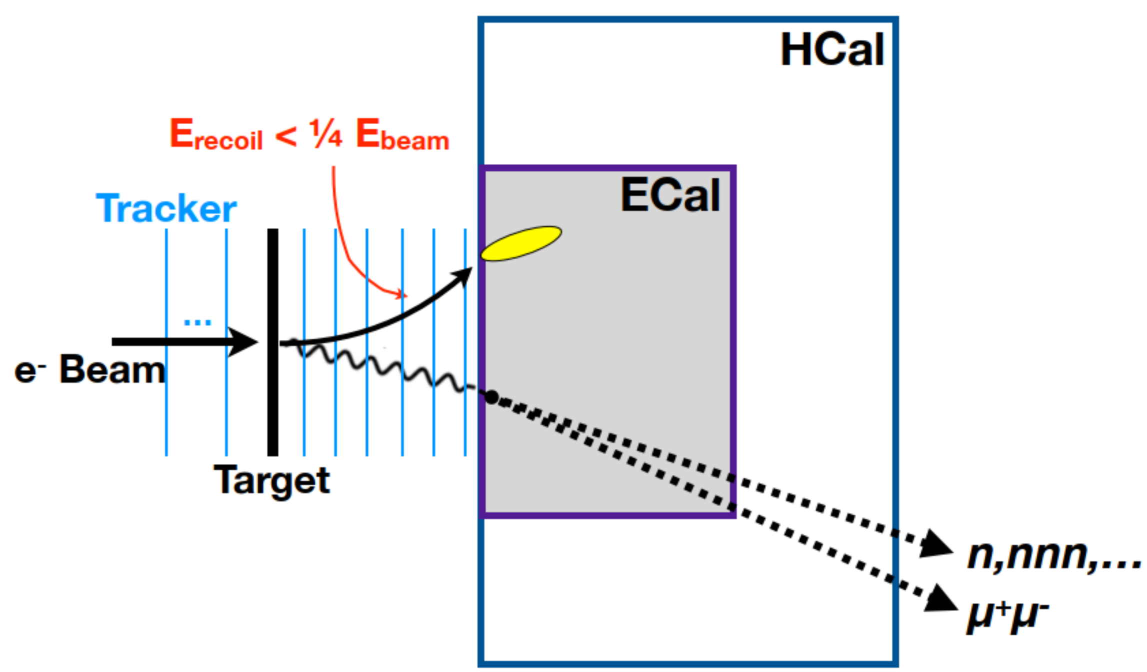
3.5-20 GeV



Basic task for the experiment



Select these



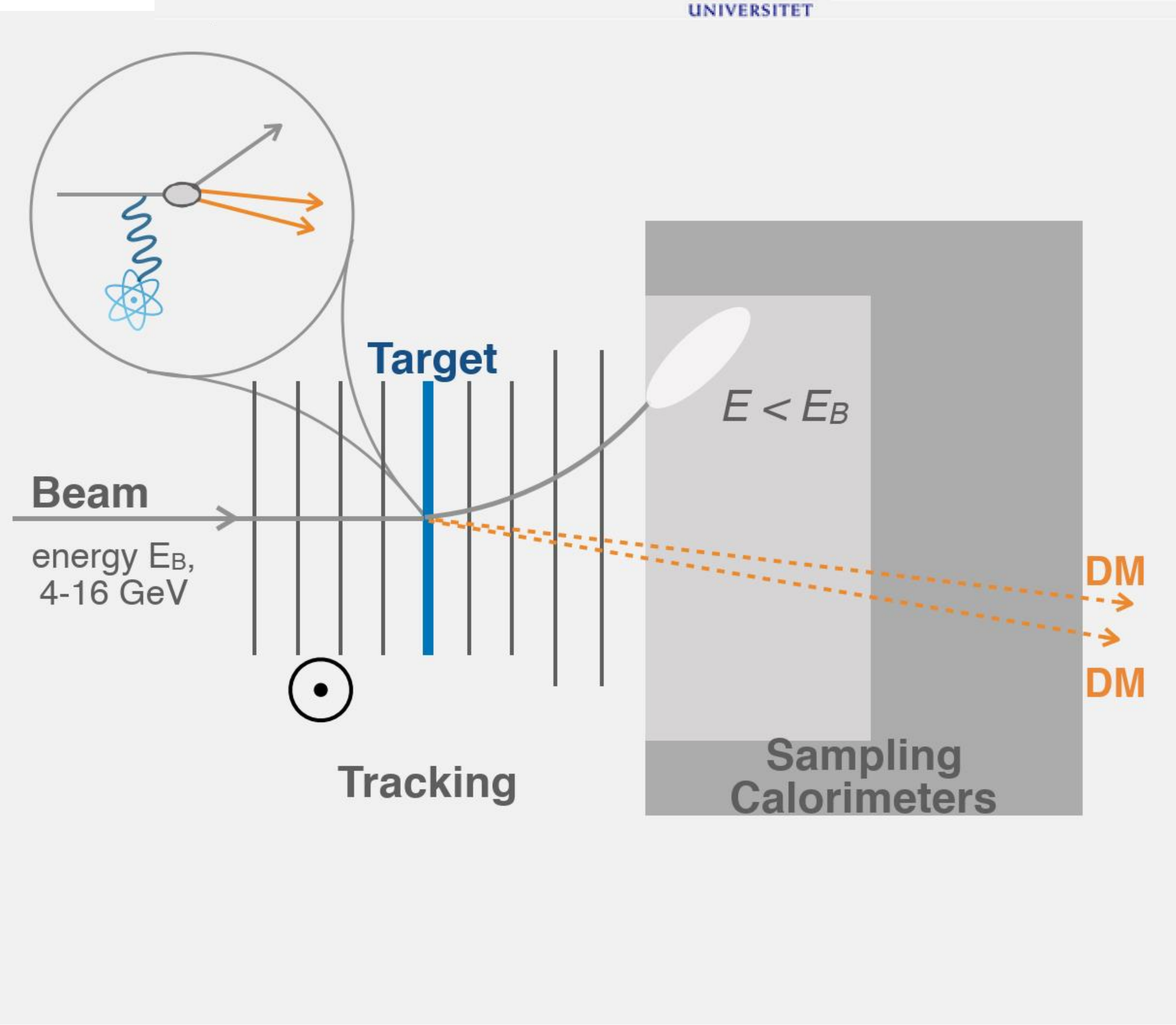
Reject these

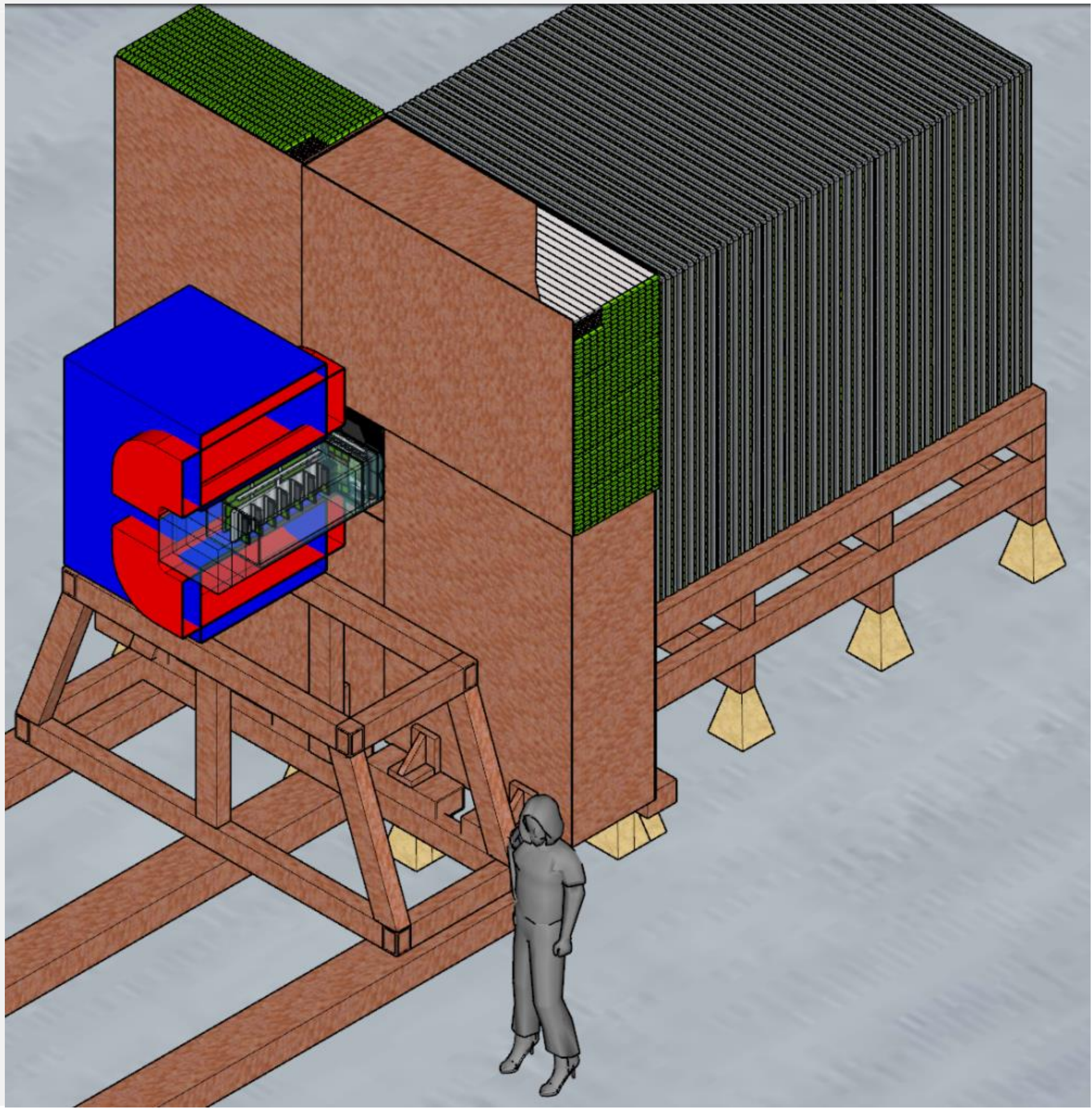
The experiment is to a big degree a question of rejecting these

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

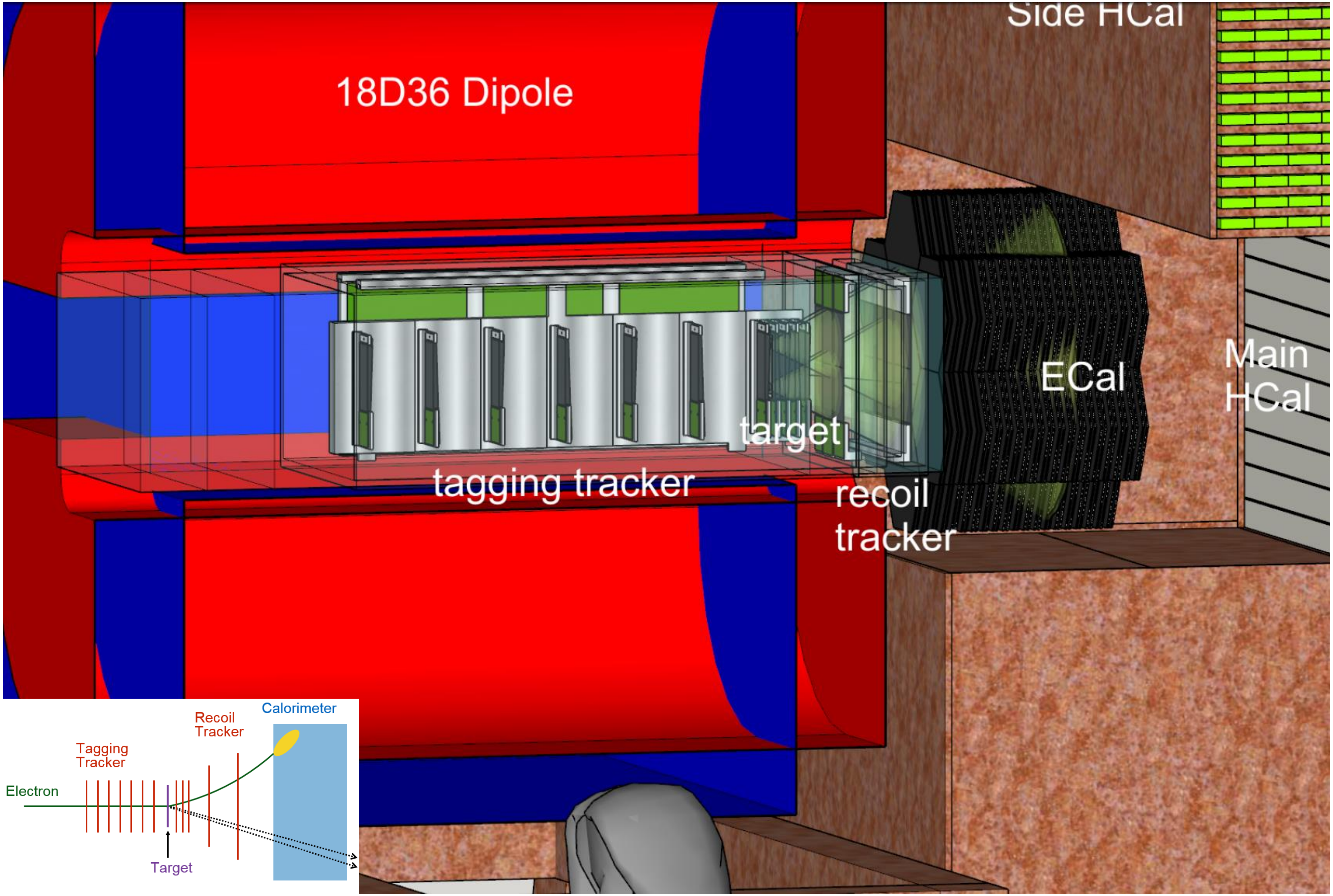
The Light Dark Matter eXperiment – LDMX

Caltech Fermilab Lunds Universitet University of Minnesota UCSB University of California Santa Barbara SLAC National Accelerator Laboratory University of Virginia

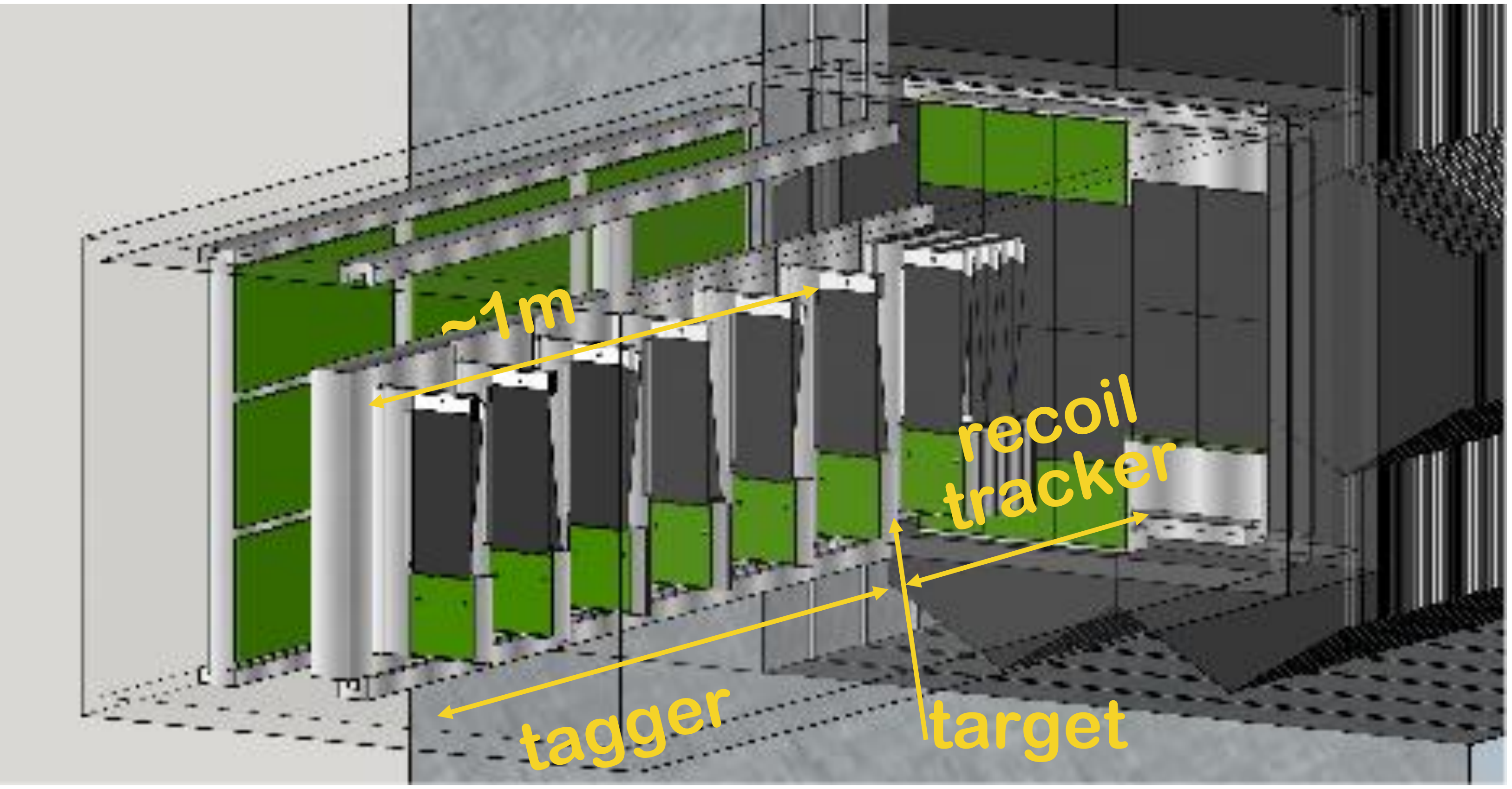


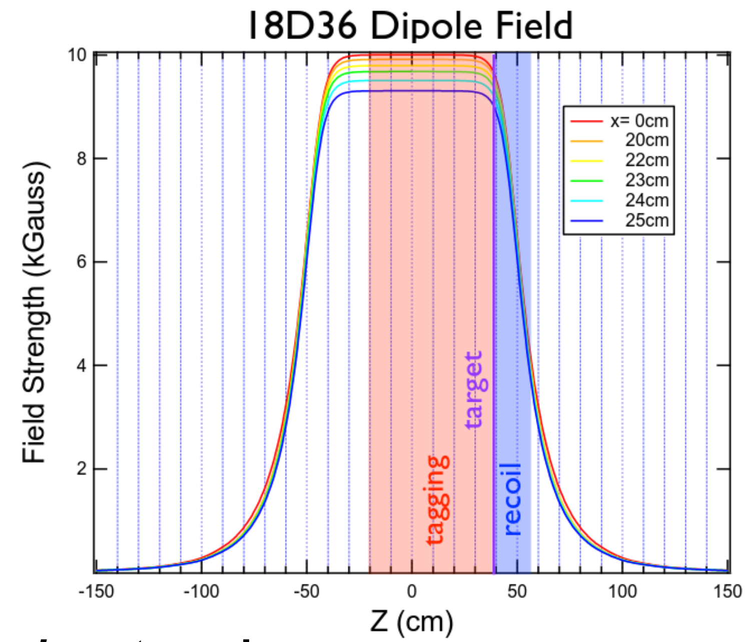


The Light Dark Matter eXperiment – LDMX



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

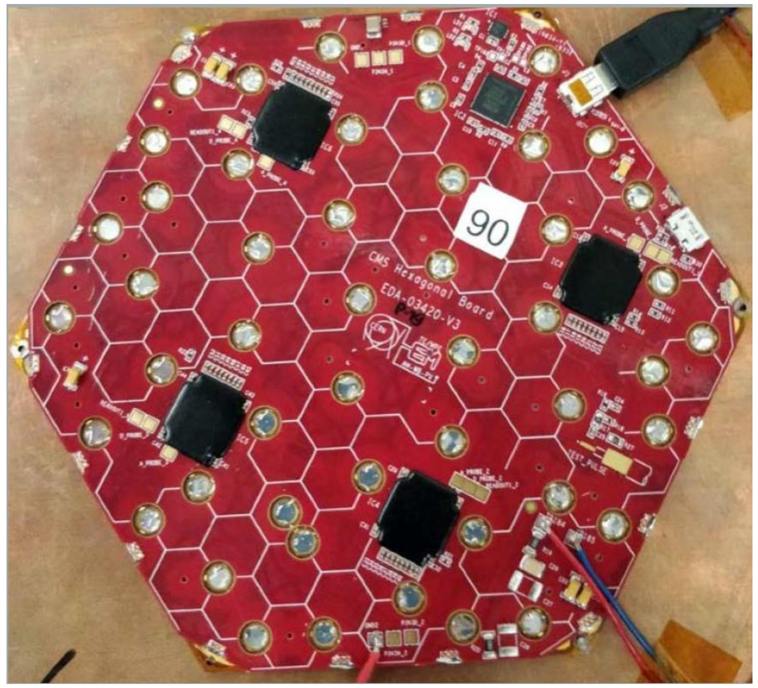
- 18 cm length in fringe field
- 4 stereo layers + 2 axial layers
  - Momentum (50 MeV – 1.2 GeV)
  - Measure p, direction and impact

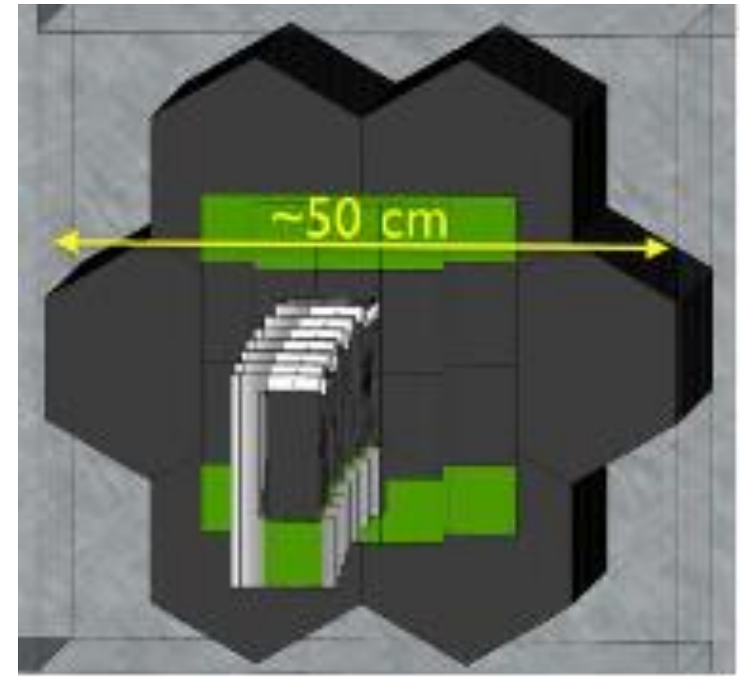
target

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

Electromagnetic Calorimeter - ECal

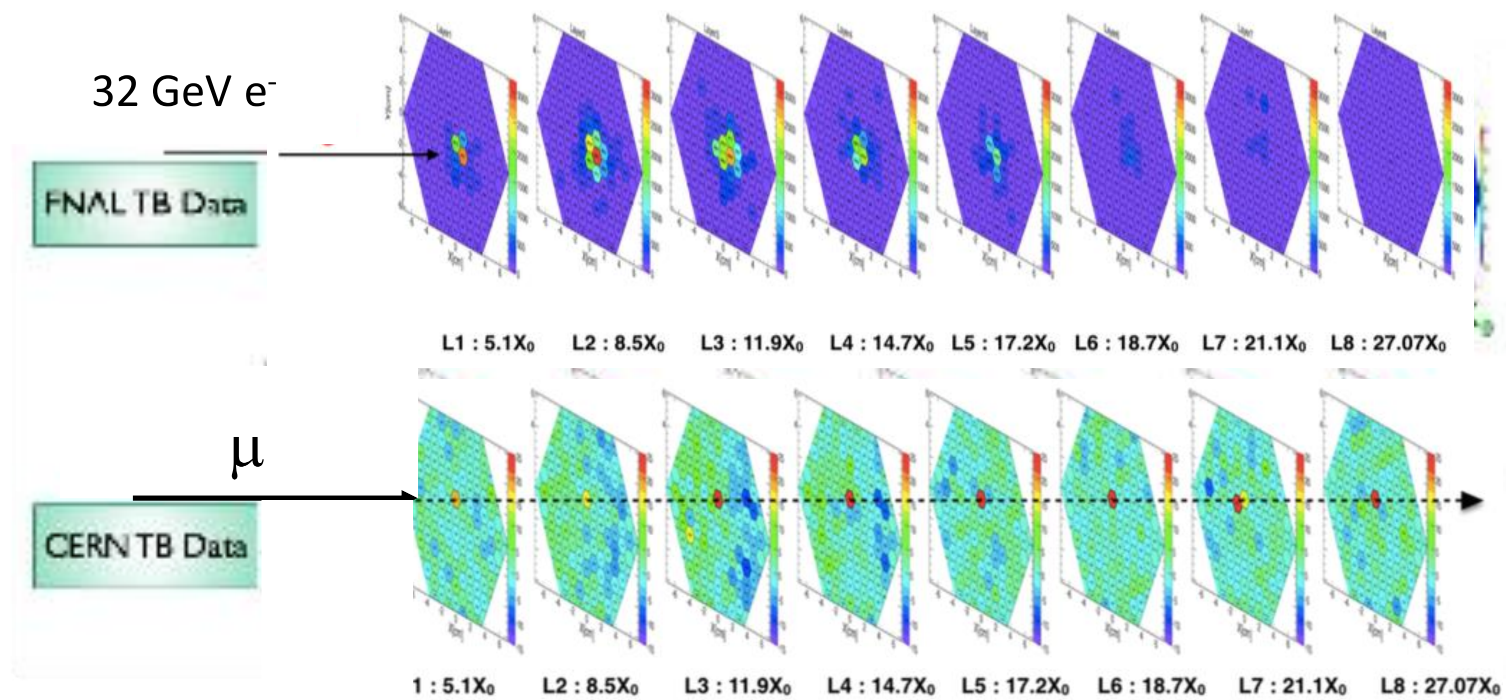
A variant of the forward SiW sampling calorimeter for CMS@HL-LHC



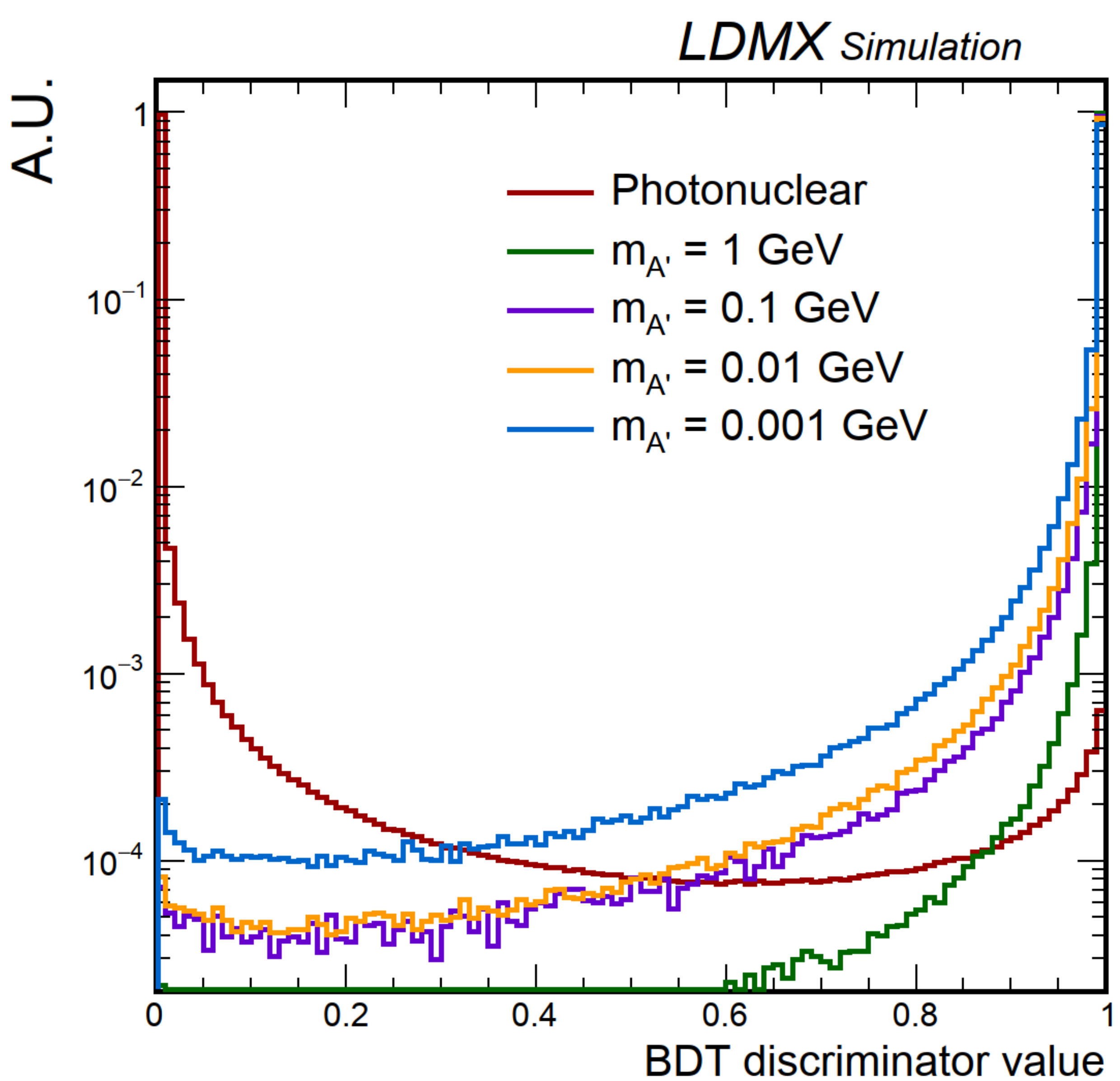


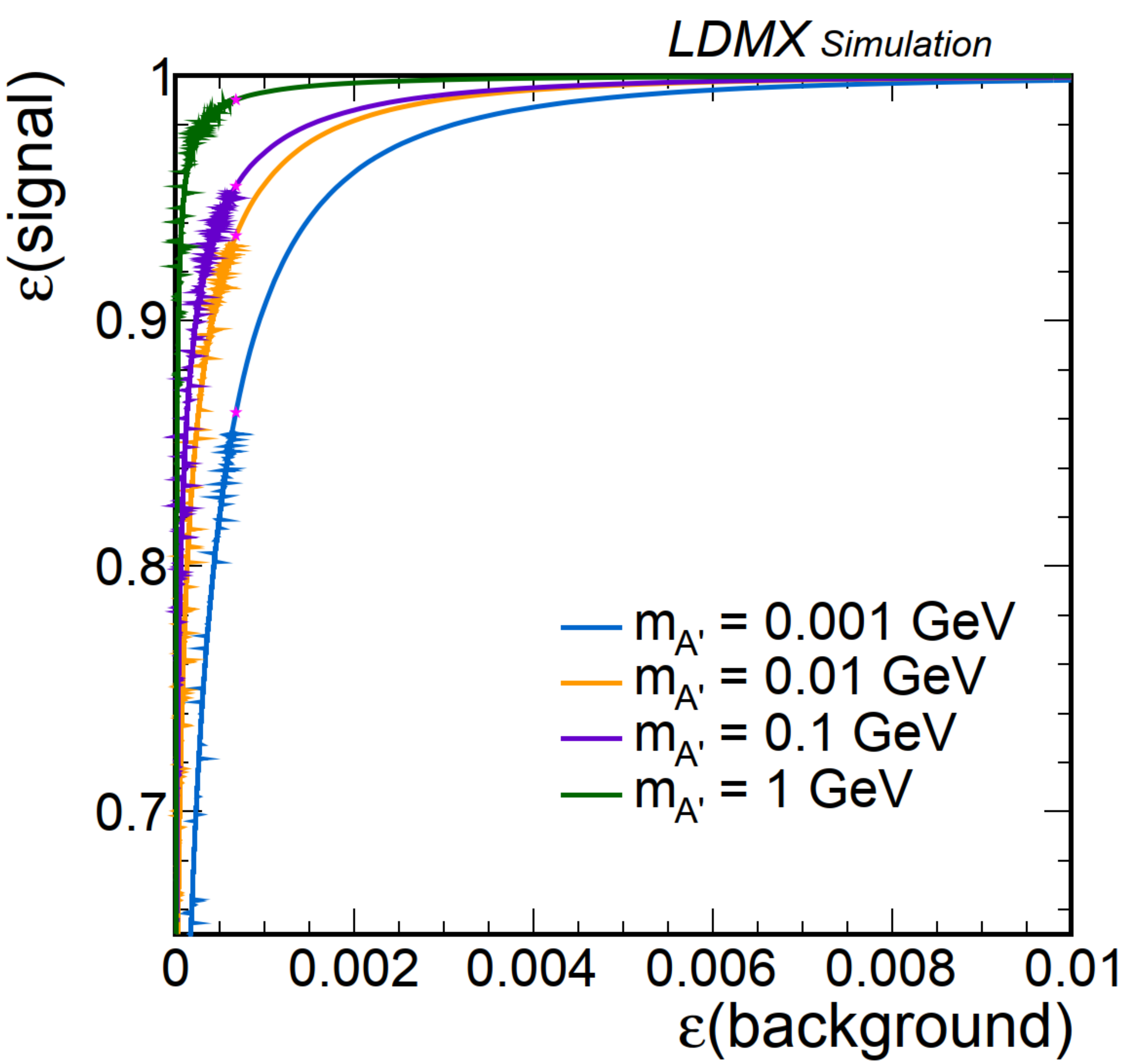
- in LDMX:
  - 40 radiation lengths deep
  - 30 layers, 7 modules each
  - central modules with higher granularity (up to 1000 channels)

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



ECal : Background rejection using a Boosted Decision Tree

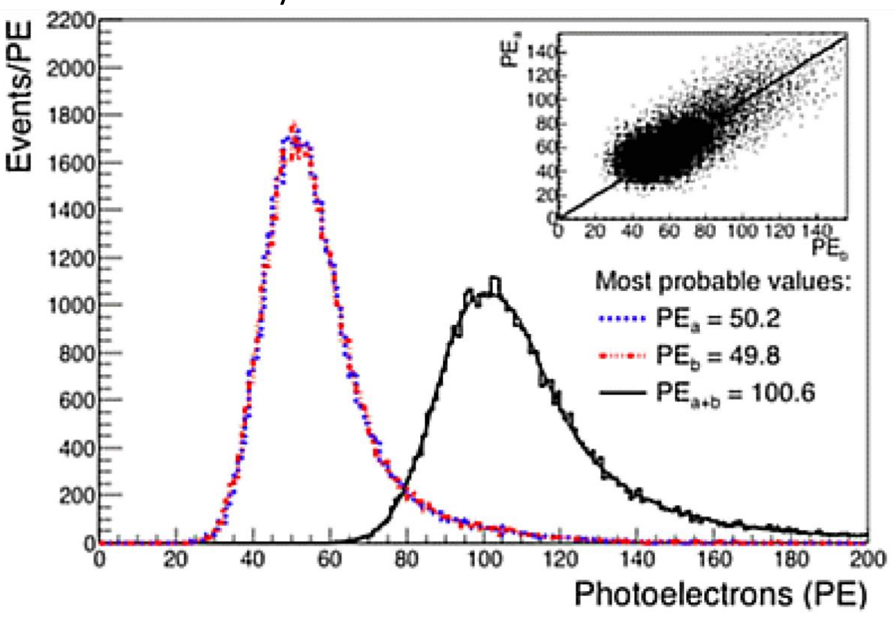


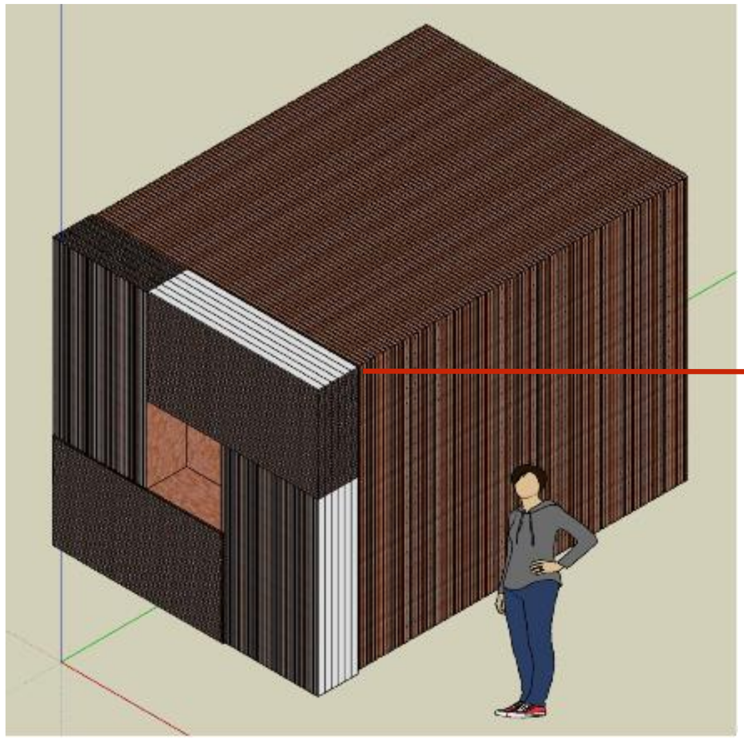


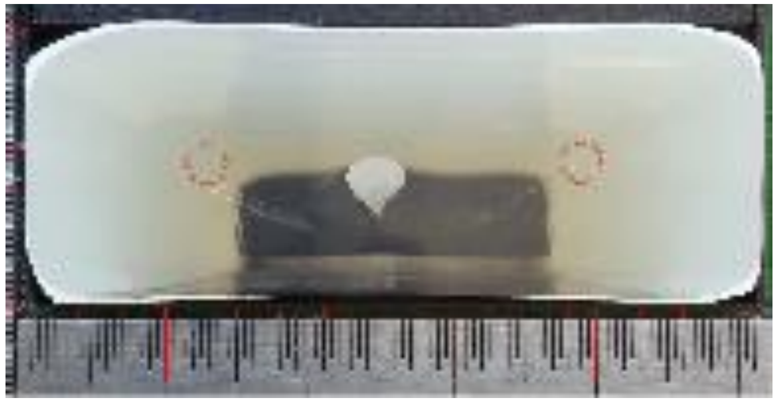
Hadronic Calorimeter - HCal

- 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

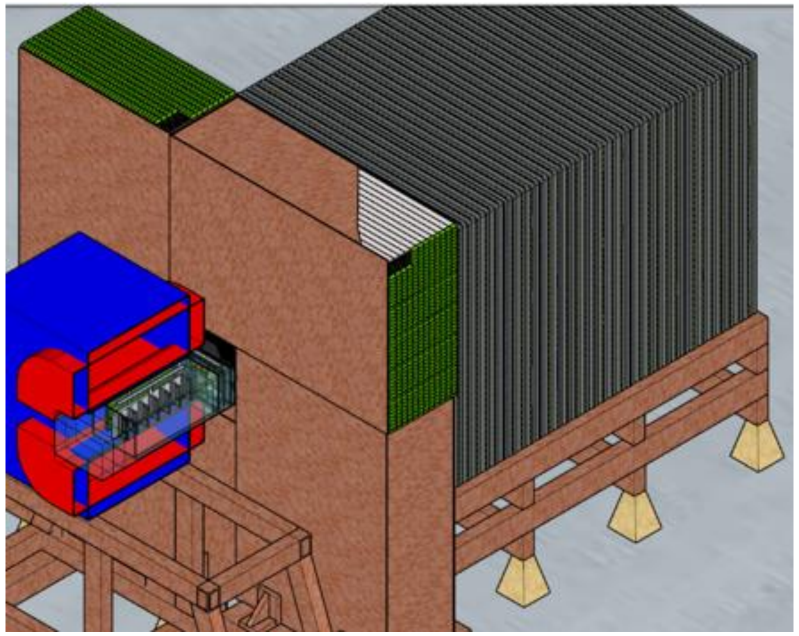






HCal – Optimisation of sampling and depth

Optimisation of the sampling structure and depth



Benchmark example:

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

Absorber thickness?

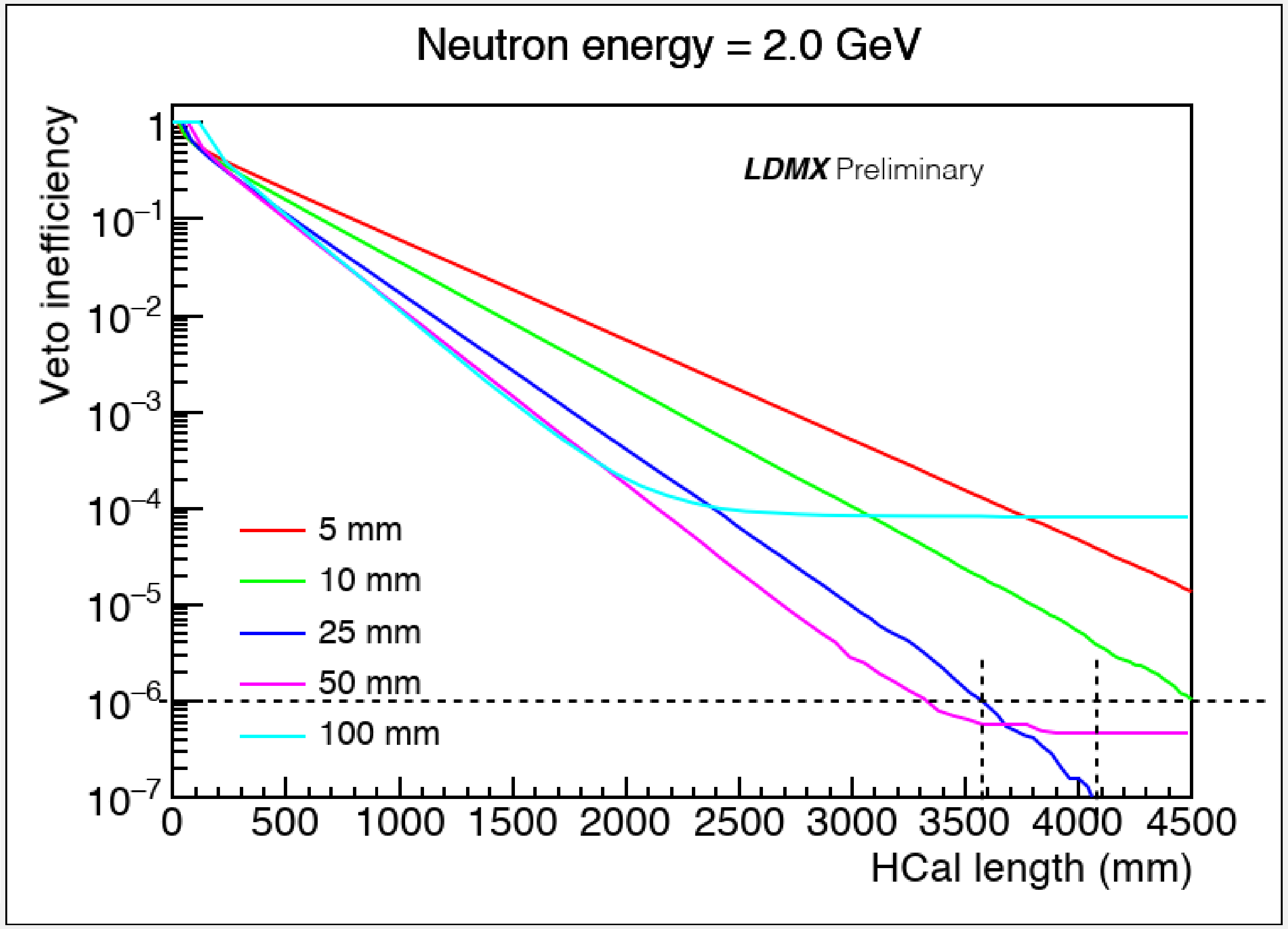
- too thick: neutrons 'get stuck'

  —> no signal in scintillator

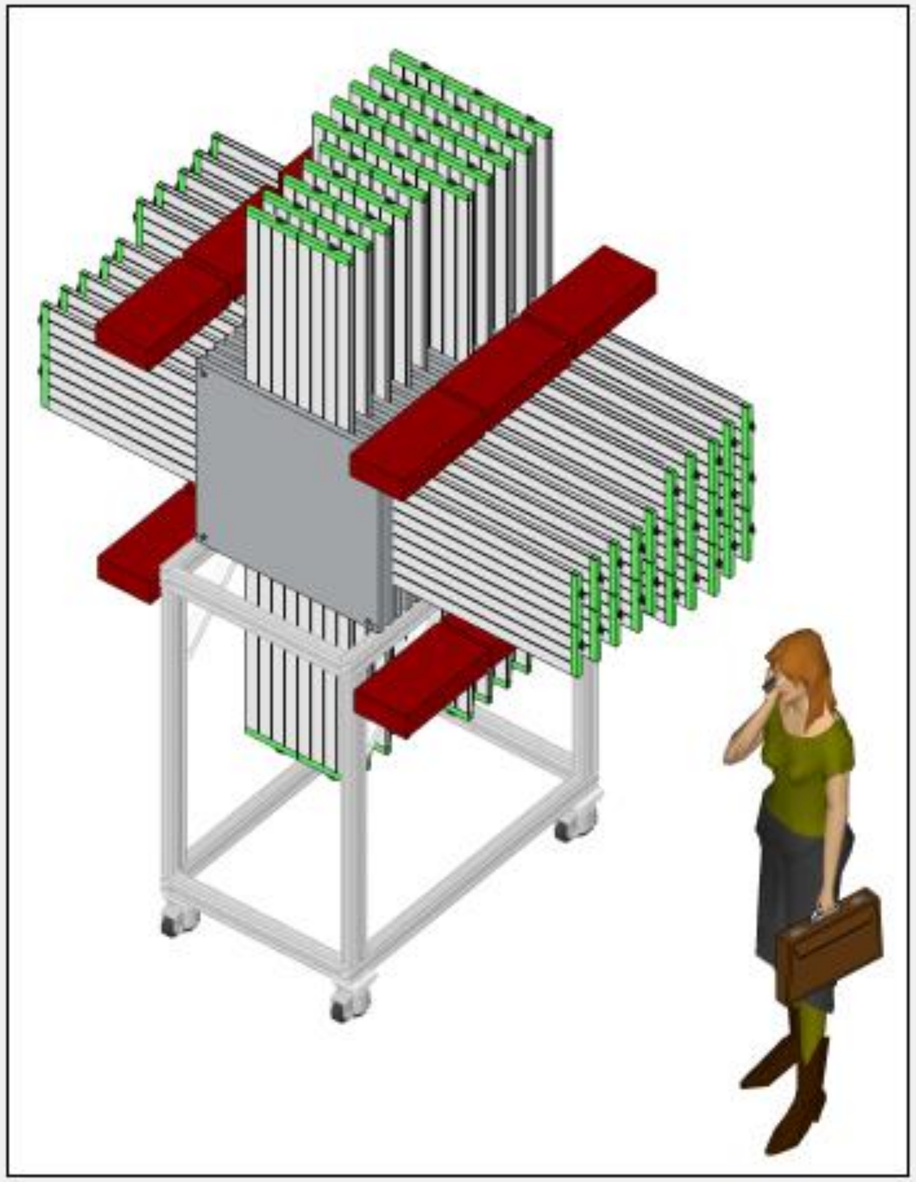
- too thin: detector needs to be very large

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

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



Hcal: Prototype for beamtest 2020. Certify simulation



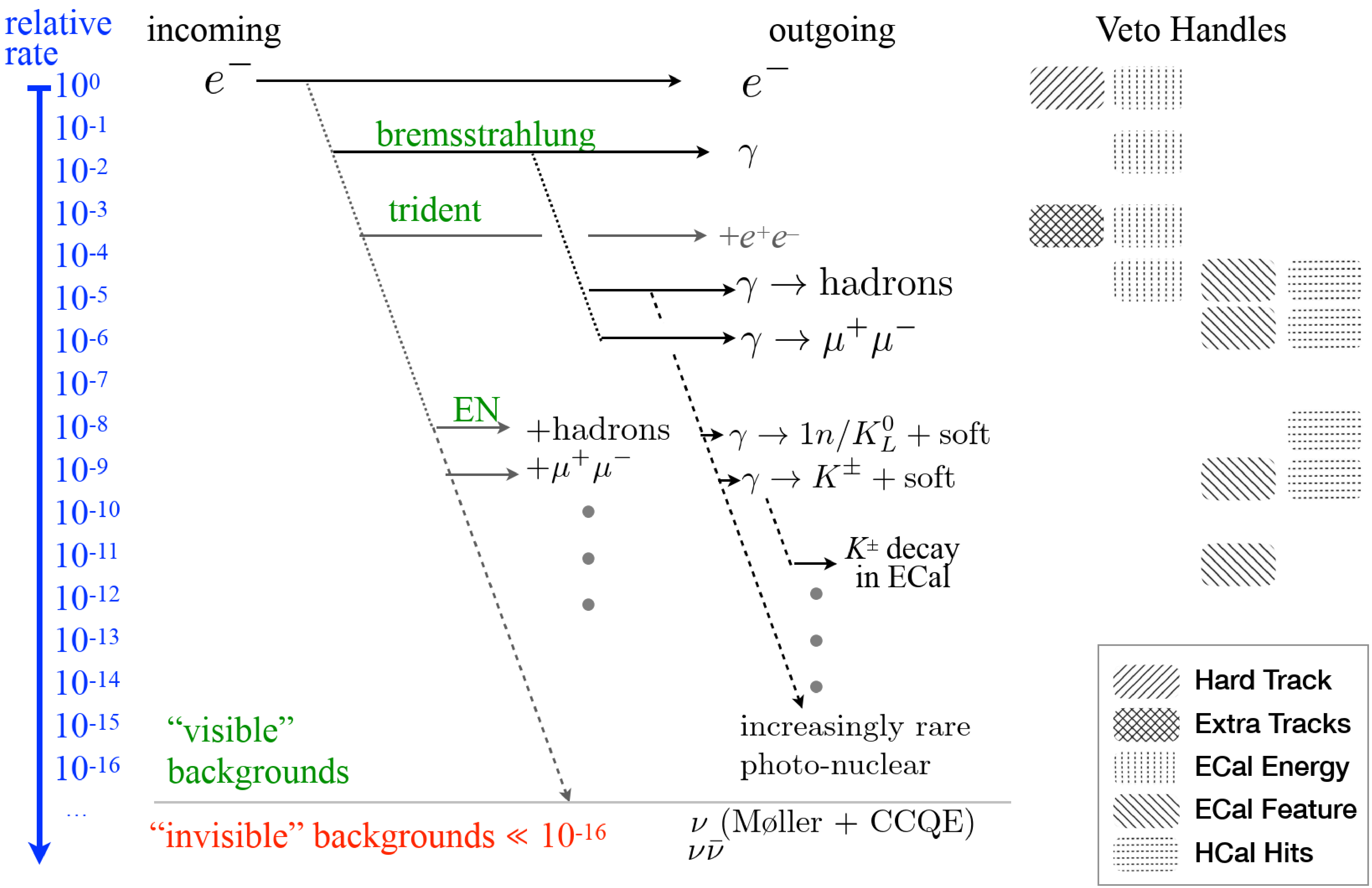
Testbeam

- obtained first funding* for R&D/prototype
- planned for fall 2020
- prototype layout coming together

* The Crafoord Foundation &
The Royal Physiographic Society in Lund

PI: Ruth Pöttgen

Background Challenges



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

Simulated sample	**Total events simulated**	**EoT equivalent**
Inclusive EM + PN	1.3×10^9	1.3×10^9
Target $\gamma \rightarrow \mu\mu$	6.3×10^8	8.2×10^{14}
ECal $\gamma \rightarrow \mu\mu$	8×10^{10}	2.4×10^{15}
Target photo-nuclear	8.8×10^{11}	4.0×10^{14}
ECal photo-nuclear	4.7×10^{11}	2.1×10^{14}

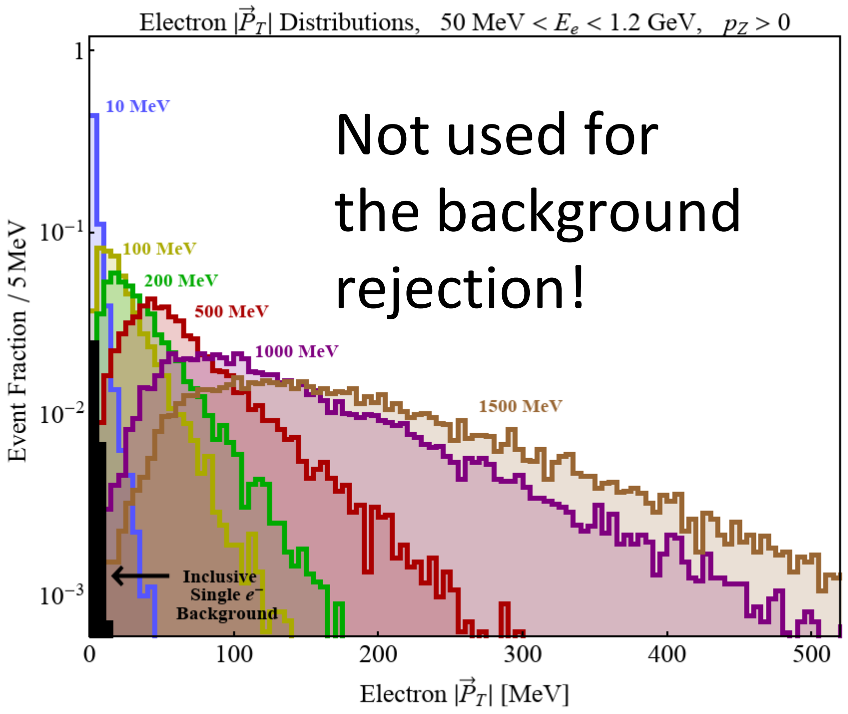
arXiv:1912.05535 and submitted to JHEP

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

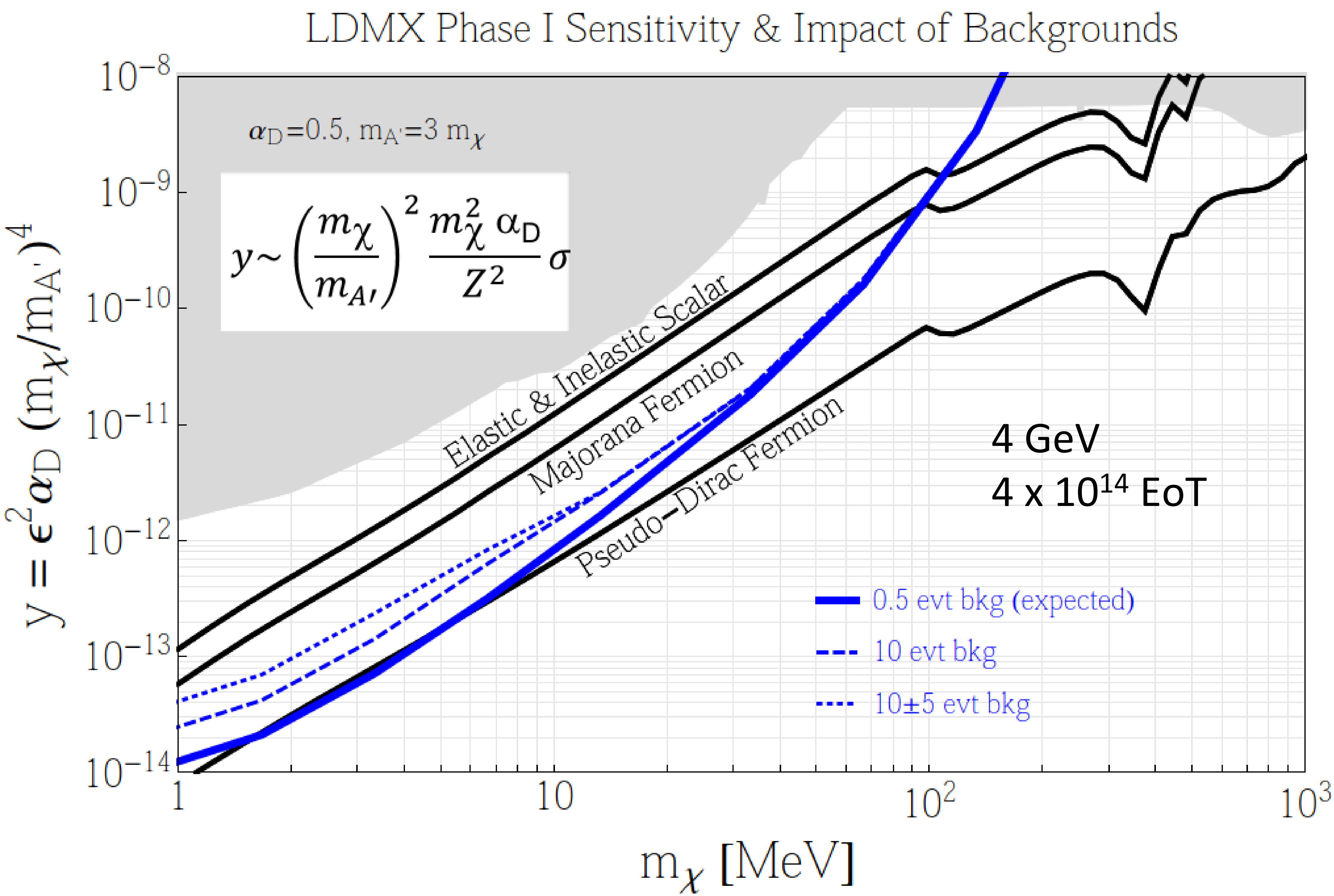


Not used for the background rejection!

	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 submitted to JHEP

Reach at 4 GeV beam energy; LMDX initial run



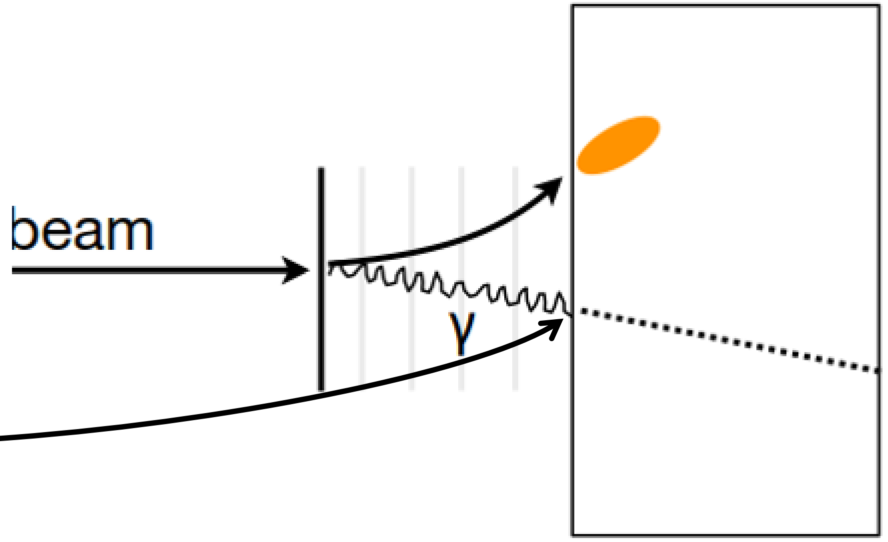
4 GeV

4 x 10^{14} EoT

arXiv: 1808.05219

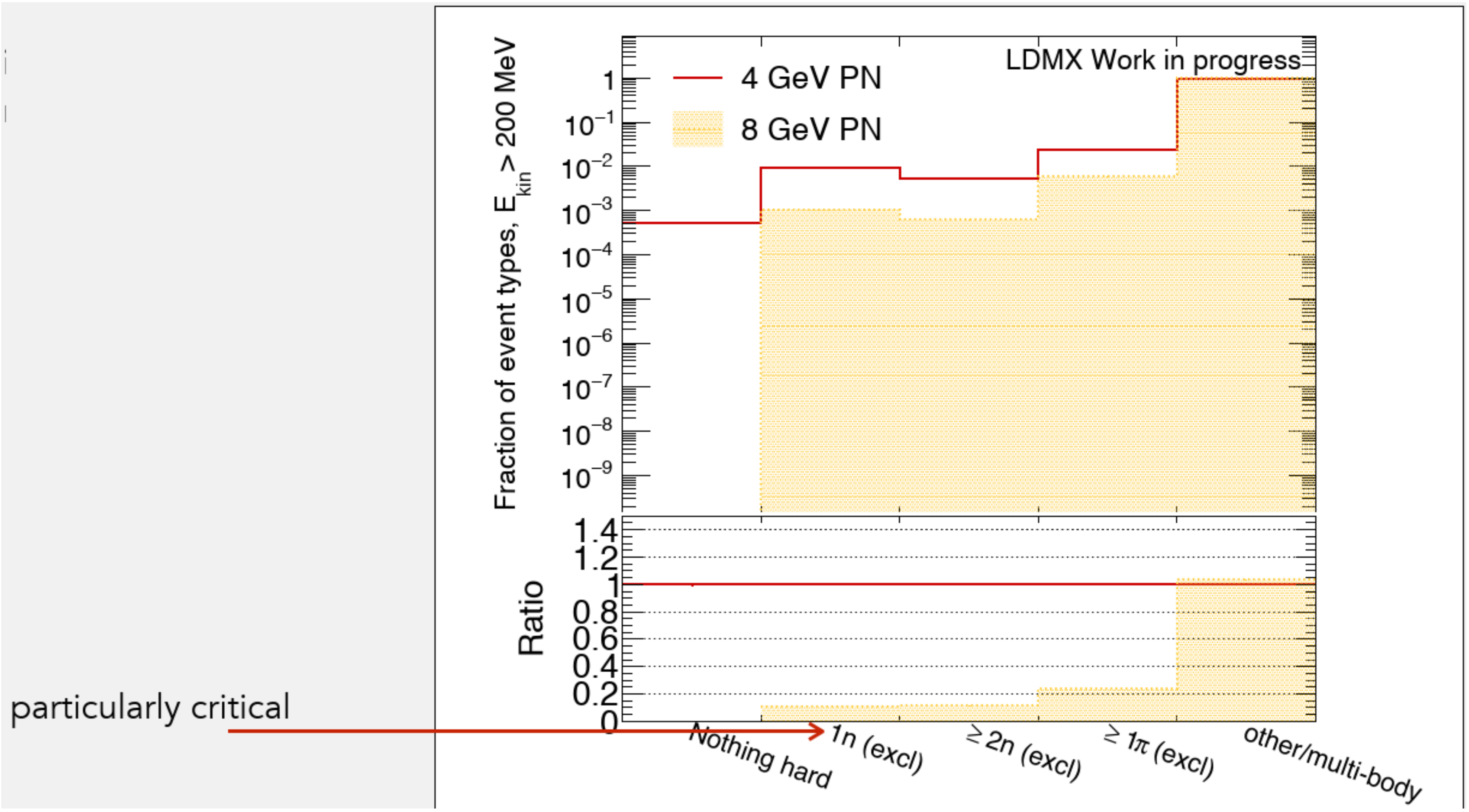
Going to higher energy – background rejection

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



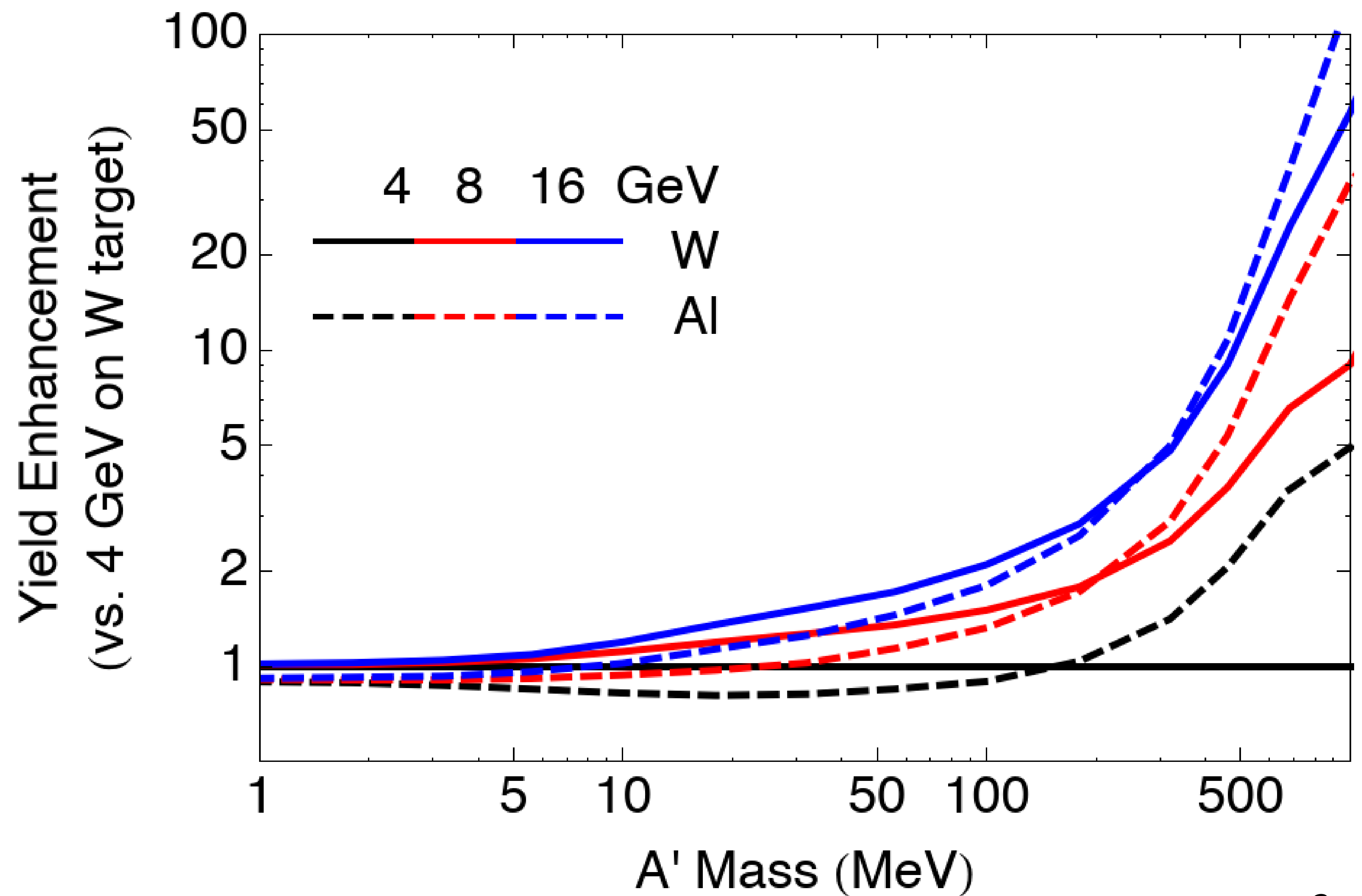
It is much easier for a low energy γ to not be seen, than for a high energy γ:

Higher beam energy strongly increase the background rejection



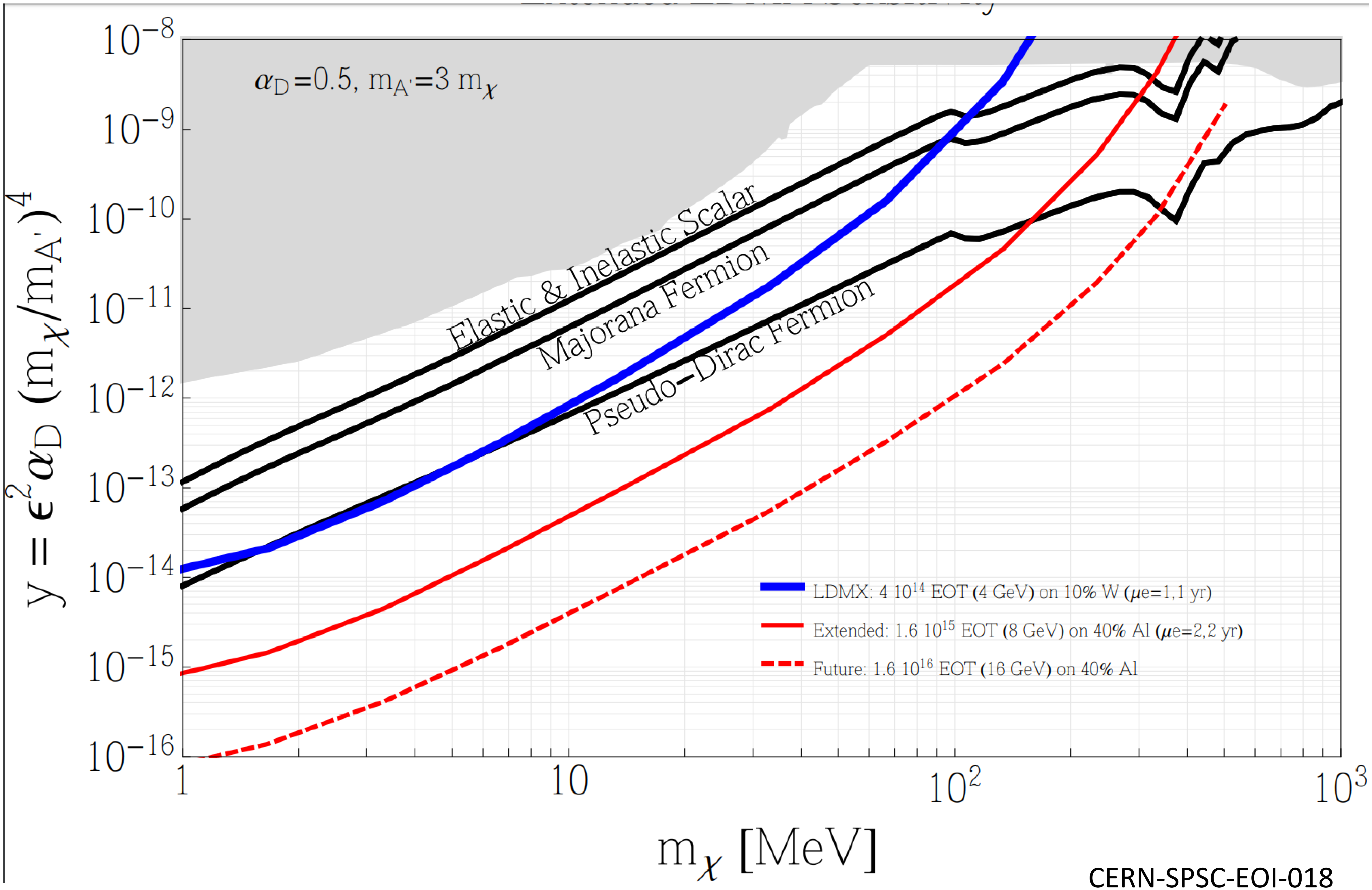
LUNDS UNIVERSITET

Going to higher energy – signal production



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

Going to higher energy – reach



CERN-SPSC-EOI-018

LDMX timeline

- 2019 – mid-2020 : R&D and final design
- Mid-2020 – mid-2021 : Procurement & construction
- Mid-2021 – mid-2022 : Construction
- Mid-2022 – mid-2023 : Installation, commissioning and start data taking
- Mid-2023 – mid-2024 : Data taking and analysis
- Mid-2024 – mid-2025 : Data taking and analysis

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*

The right beam is fundamental for the experiment

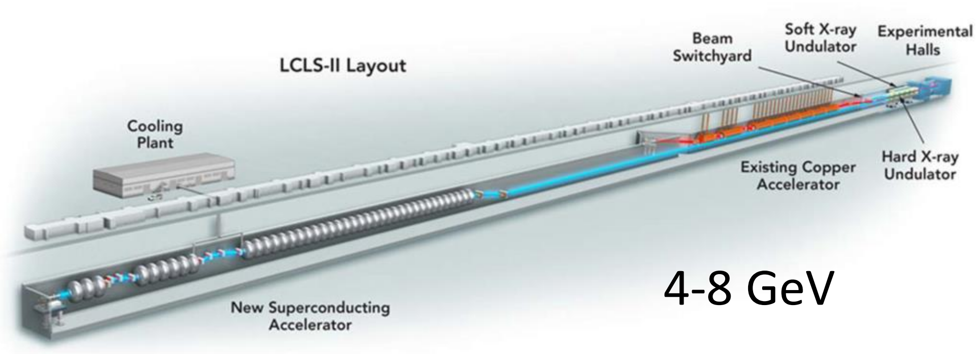
Need 10^{14} - 10^{16} electrons on target

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

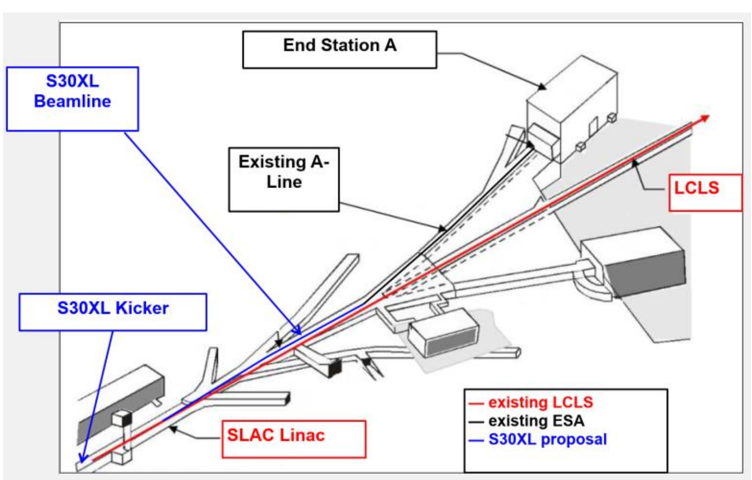
→Low current – high duty cycle – 4-20 GeV – primary electron beam

→**A <u>primary</u> electron beam dedicated to the experiment**

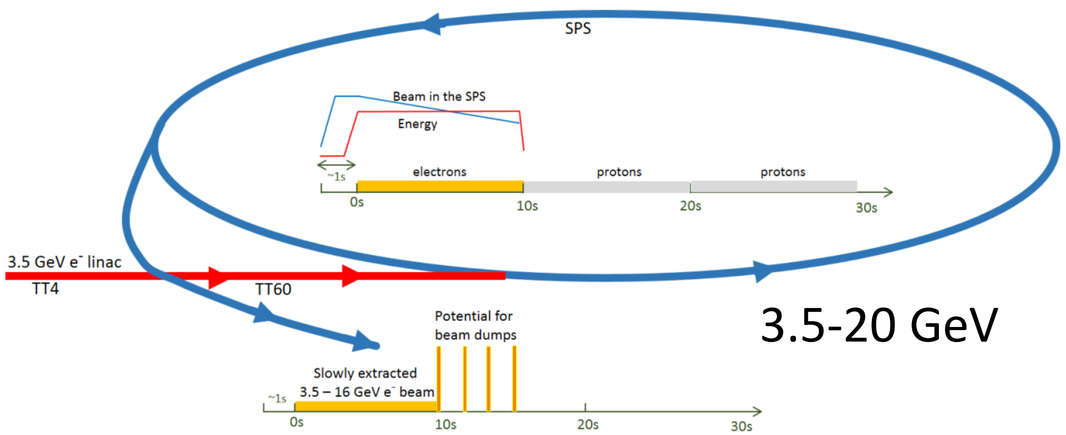
Baseline – SLAC



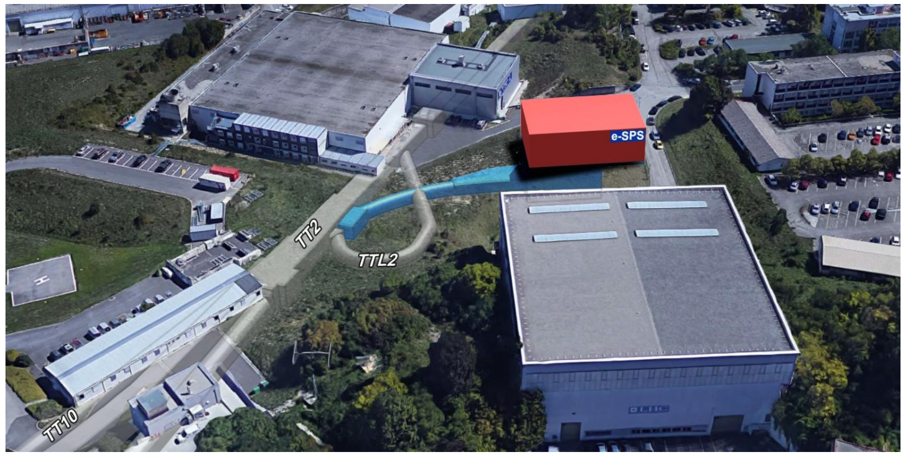
4-8 GeV



CERN



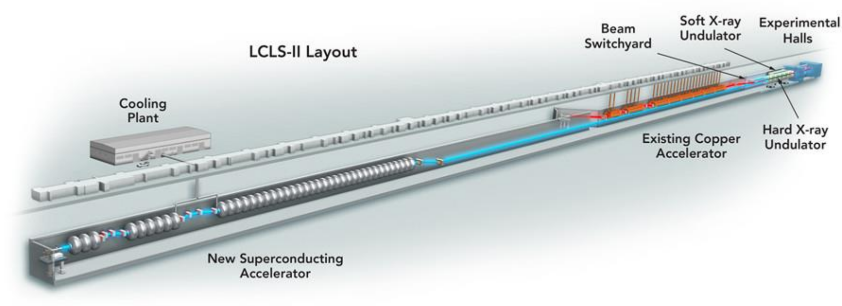
3.5-20 GeV

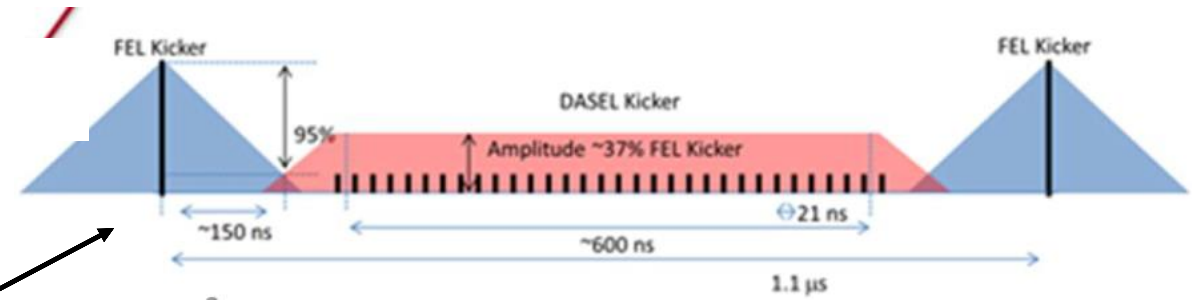


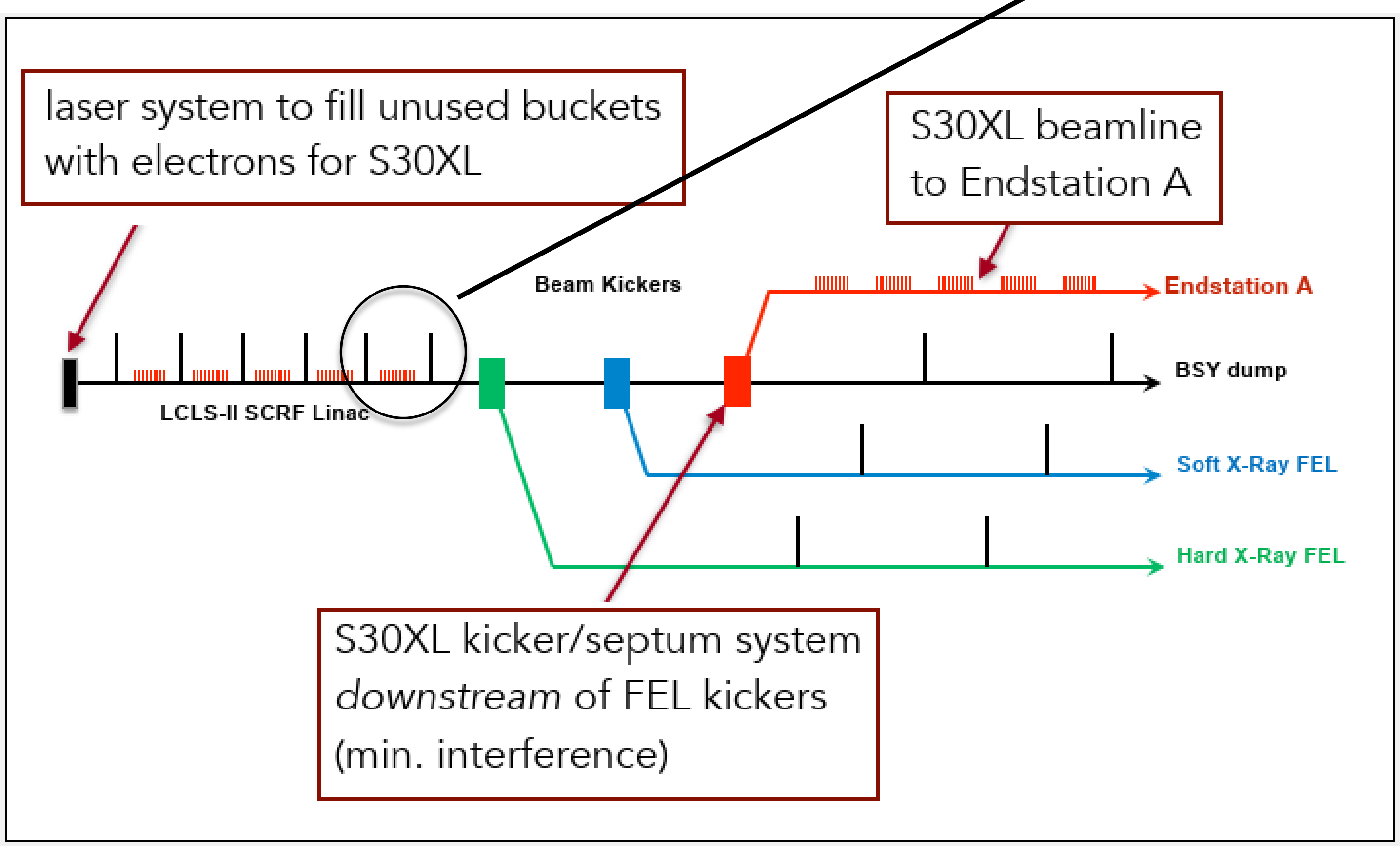
S30XL @ LCLS-II @ SLAC ; parasitic operation

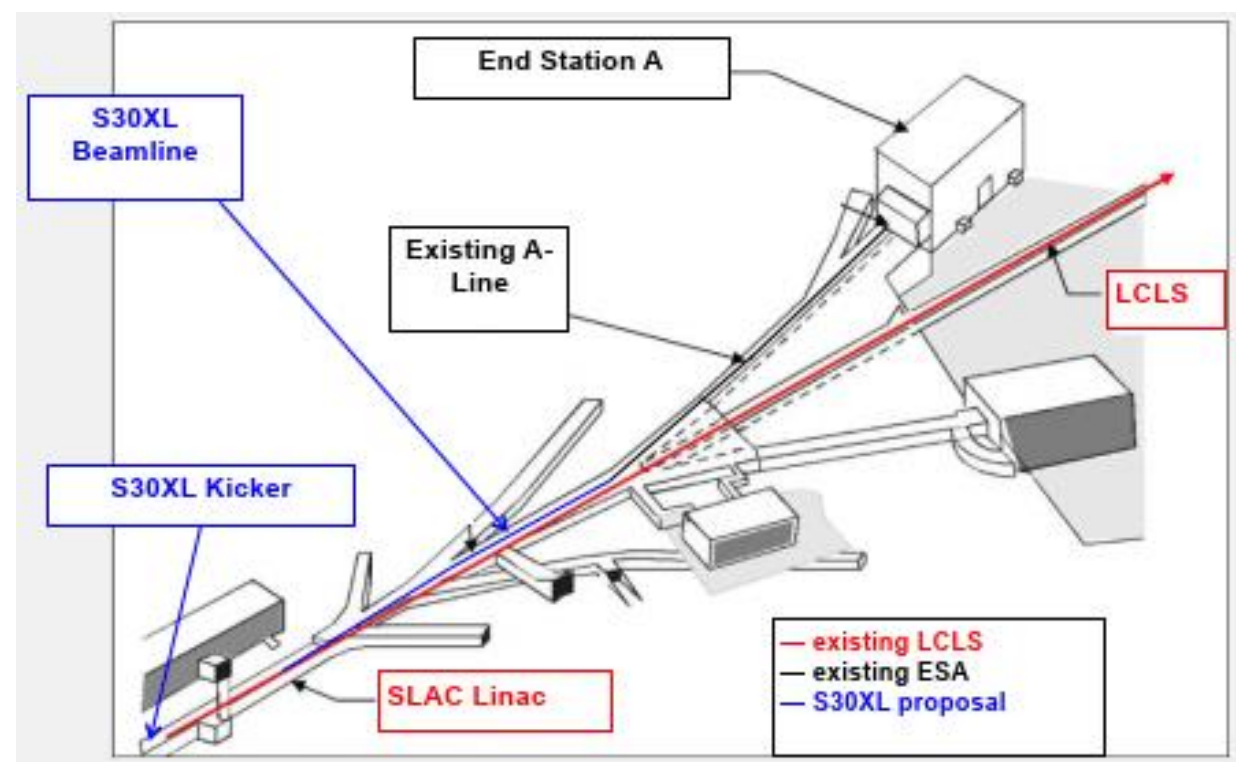
- Fill empty buckets in the continuous wave acceleration by flashing the electron source cathode with a dedicated laser.
- Extract the low-current, high-rate electron beam downstream of the extraction of the electron bunches for photon science
- 4 (8) GeV
  Bunch frequency: 46 MHz (186 MHz)
  4×10^{14} EoT year 1

Linac Coherent Light Source II









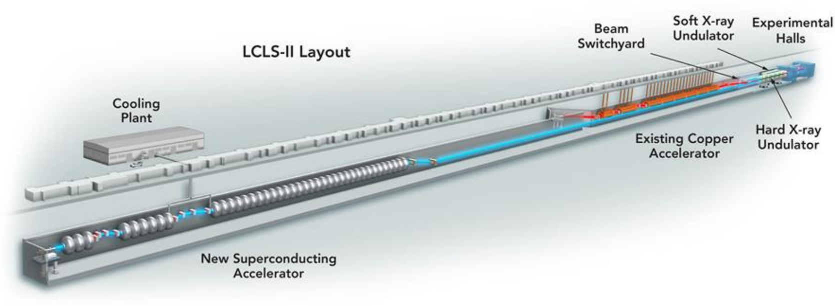
T. Raubenheimer, in Proceedings, 60th ICFA Advanced Beam Dynamics Workshop on Future Light Sources (FLS2018): Shanghai, China, March 5-9, 2018 (2018), p. MOP1WA02.

S30XL @ LCLS-II @ SLAC ; schedule

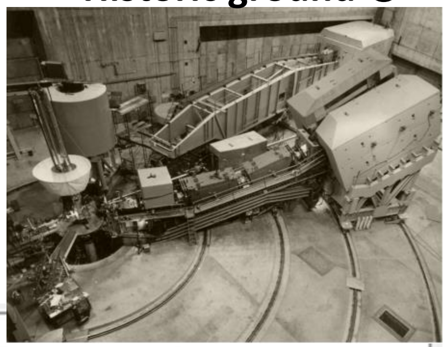
- **Stage-A, March 2021**:
  - S30 Accelerator Improvement Project (kicker & ~100m beamline – ending in beam switchyard)
  - Design underway
  - Successfully reviewed (8-9 January 2020).
  - Installation timeframe: depends on LCLS-II downtime schedule
  - Enable characterization of dark current, long-pulse kicker demonstration, single-electron QED tests, and high-rate single electron test beam
- **Stage-B**:
  - ~100m beamline to connect to existing End Station A line
  - Potentially the laser system from the start

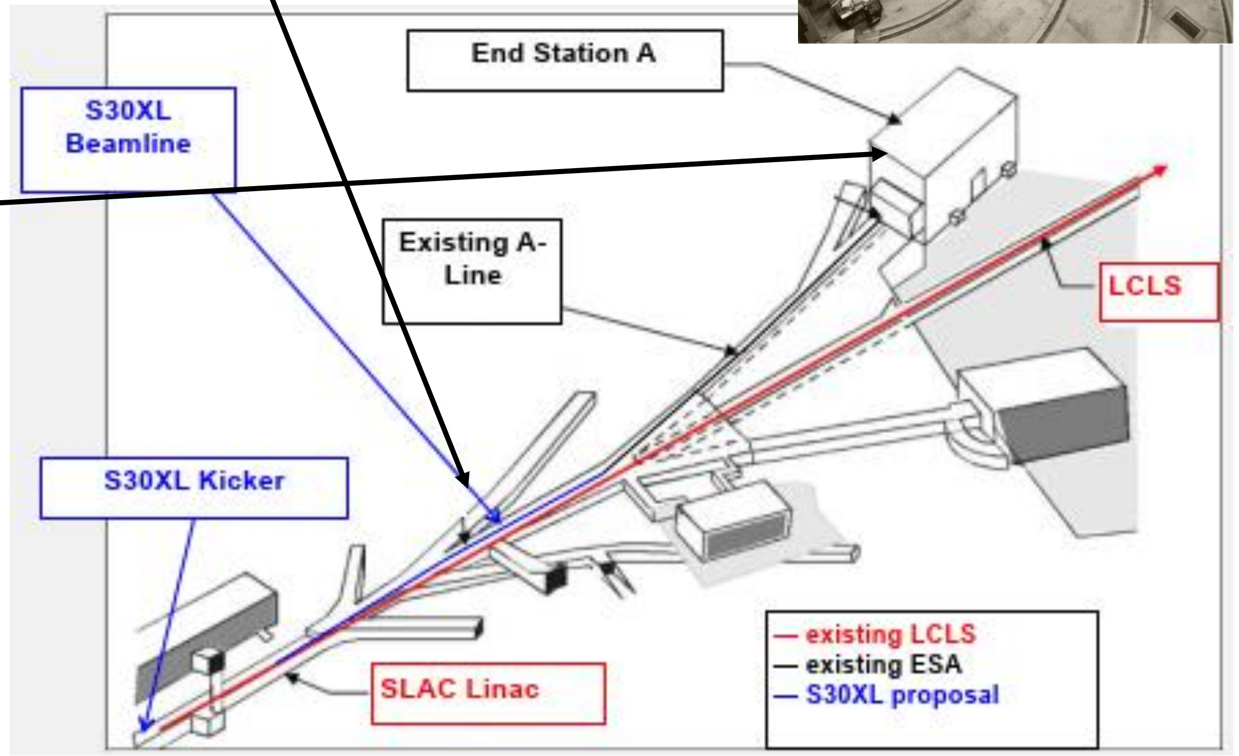
Looks very promising

Linac Coherent Light Source II



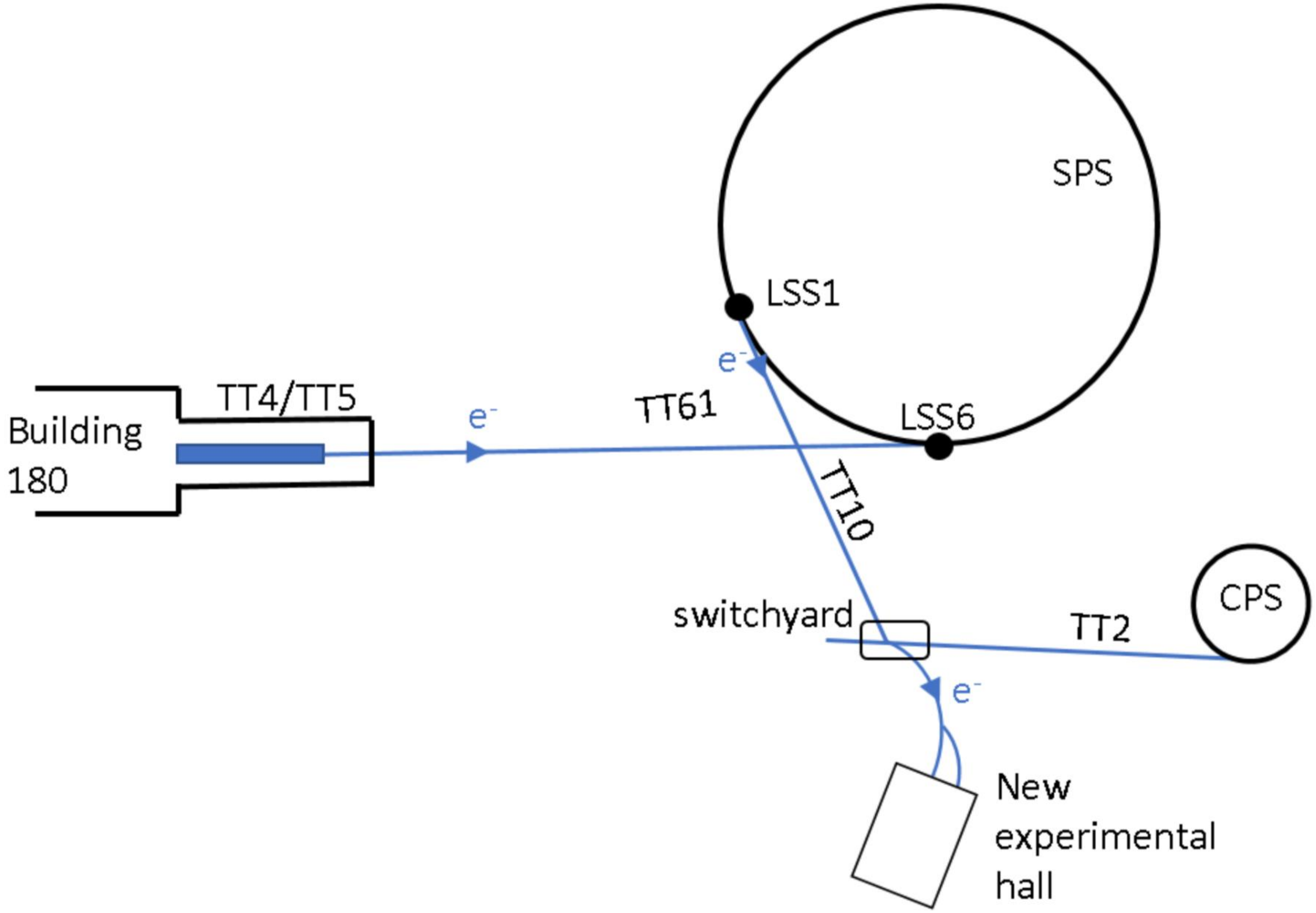
Historic ground ☺





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



- 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 (20) 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

arXiv:1905.07657

eSPS : Status of the EoI process

Review of EoI postponed waiting for ESPP

The CERN DG requested last spring a CDR for eSPS
→ April 2020

eSPS : LINAC – CLIC technology but with klystrons and bunch compressors instead of drive beam

Two acceleration stages

(1)
Already existing Linac:
S-band (3 GHz) RF structures (15 MV/m) to accelerate to 150 MeV to obtain the desired beam parameters

(2)
Linac to be constructed:
X-band (12 GHz) RF structures (66MV/m) to accelerate to 3.5 GeV within 70 m.

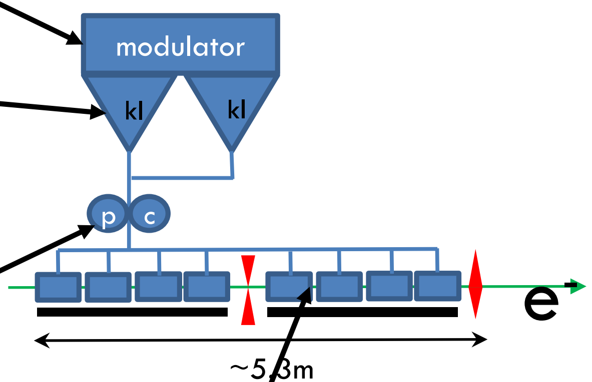
Modulator

Klystron

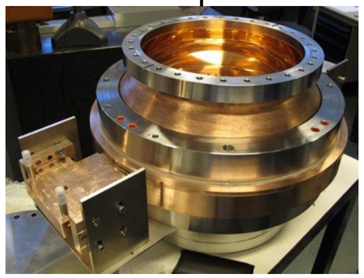
One RF unit

Accelerates 200 ns bunch train up to 264 MeV

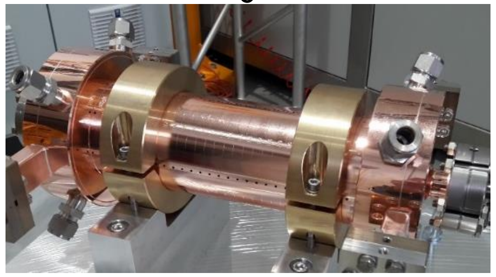
All components are available to purchase or fabricate

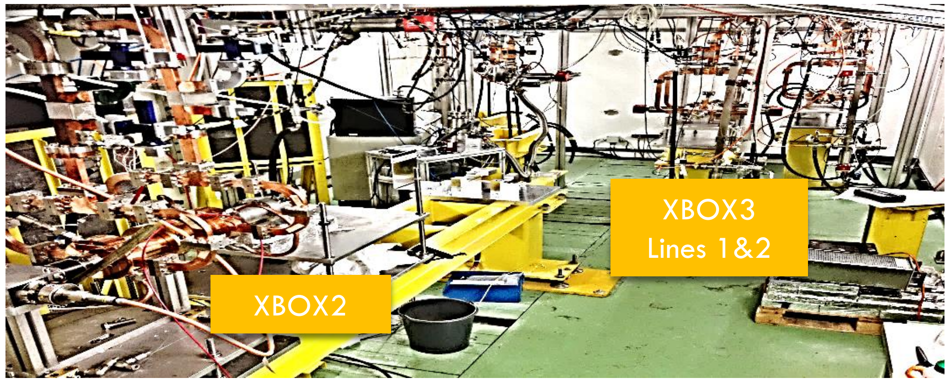


Pulse compressor



Accelerating structure

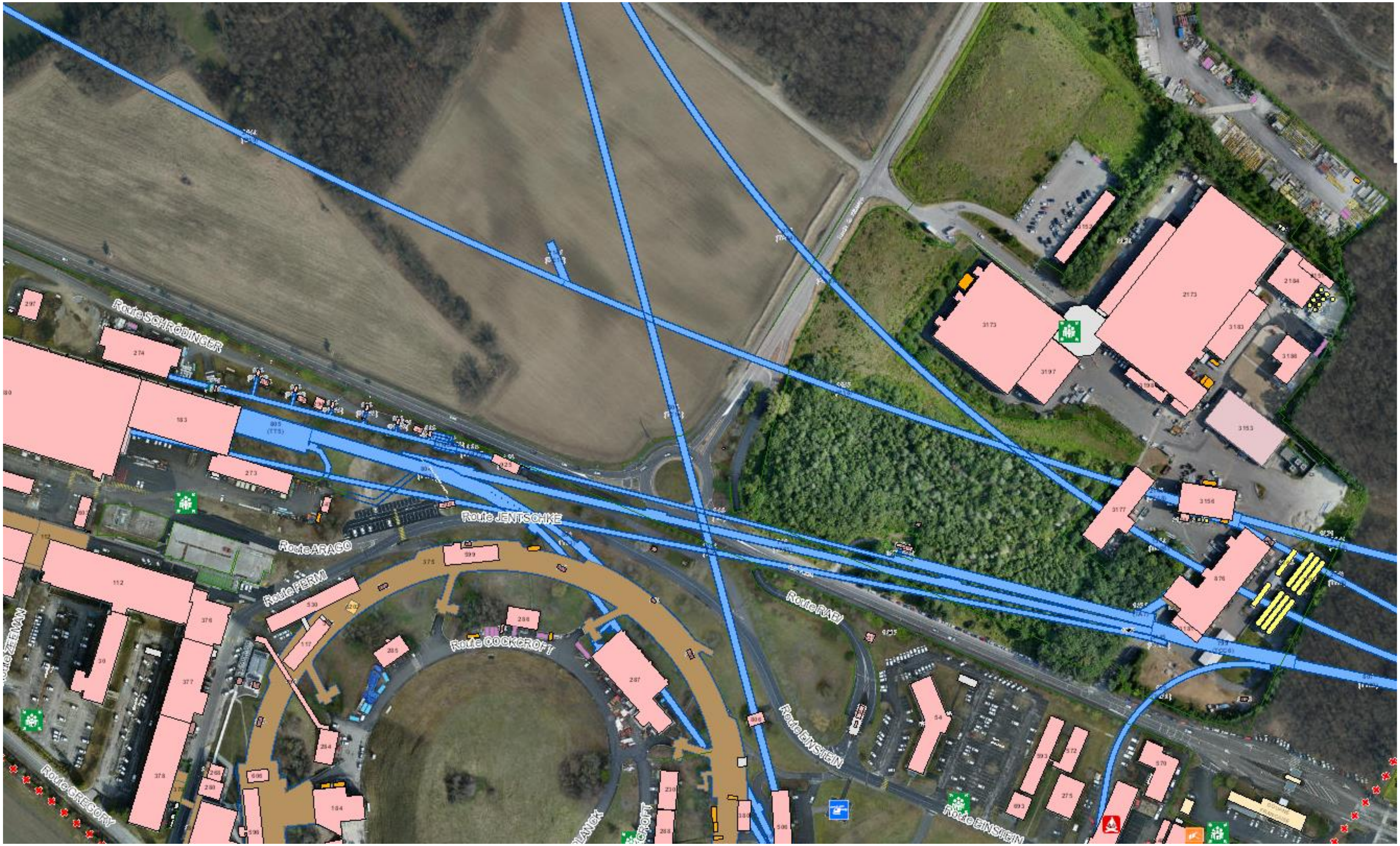




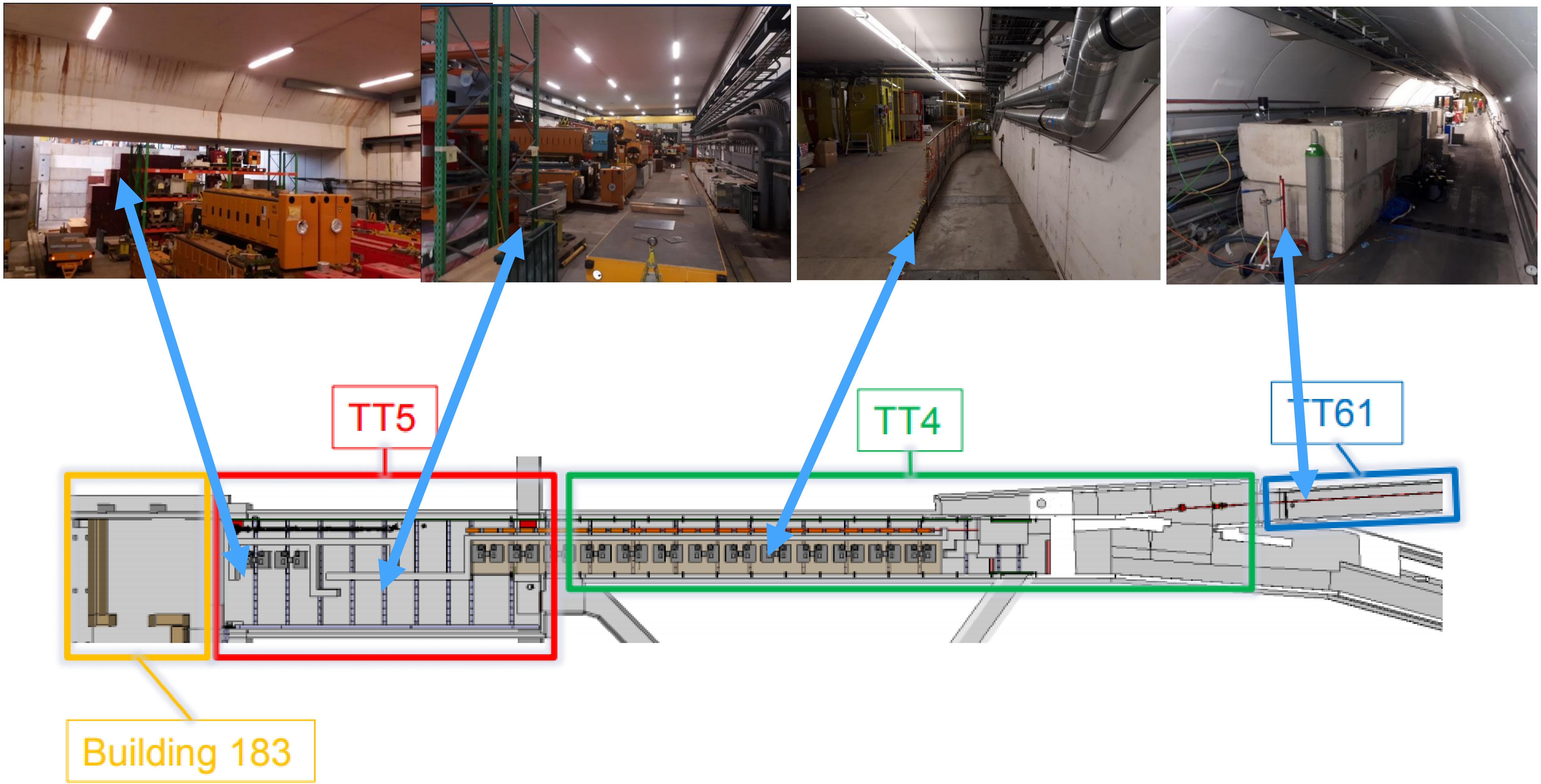
Assembled systems in continues operation at CERN since many months

RF DESIGN OF THE X-BAND LINAC FOR THE EUPRAXIA@SPARC_LAB PROJECT
M. Diomede Et al., IPAC18

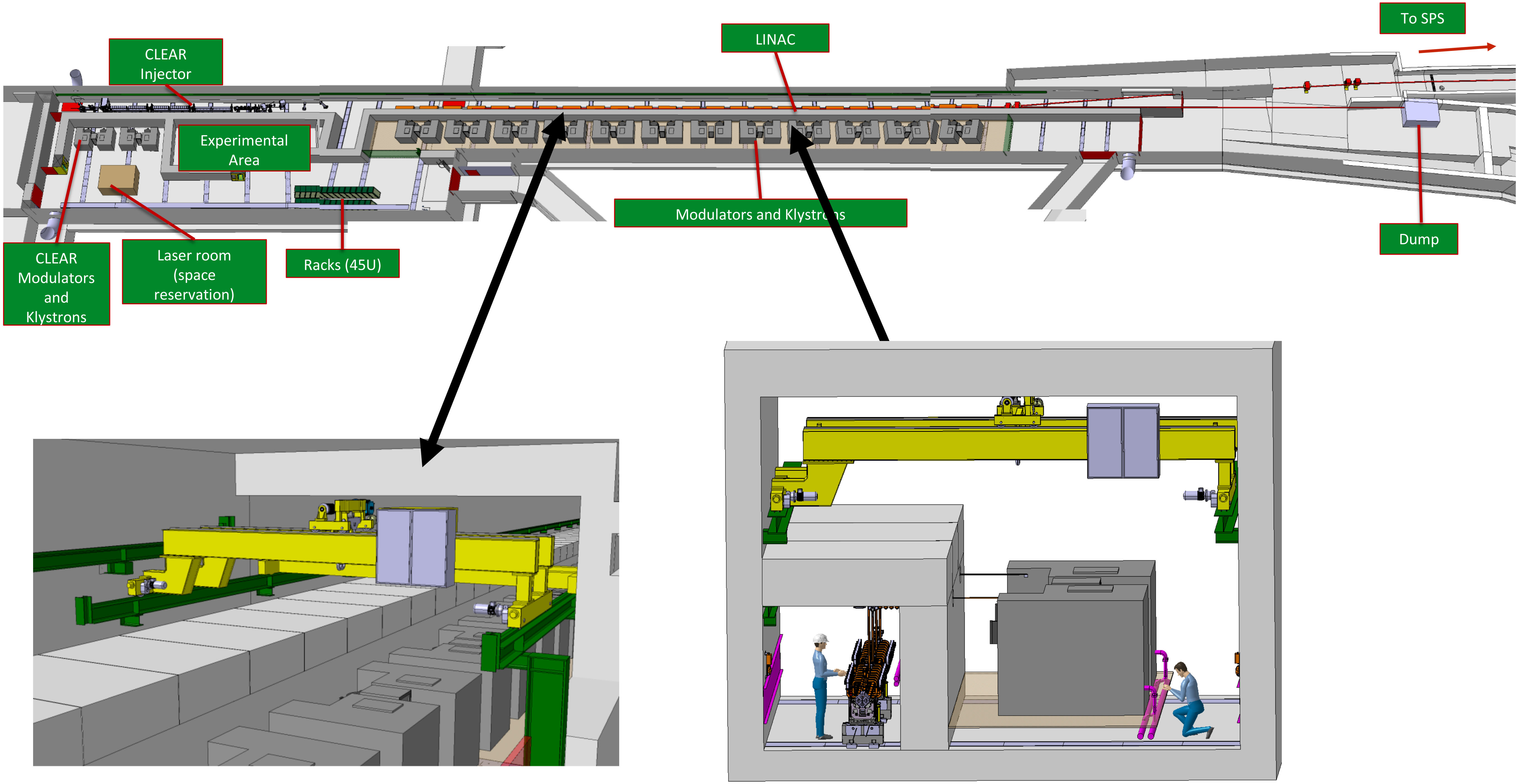
LINAC – Location



LINAC – Status of its location today



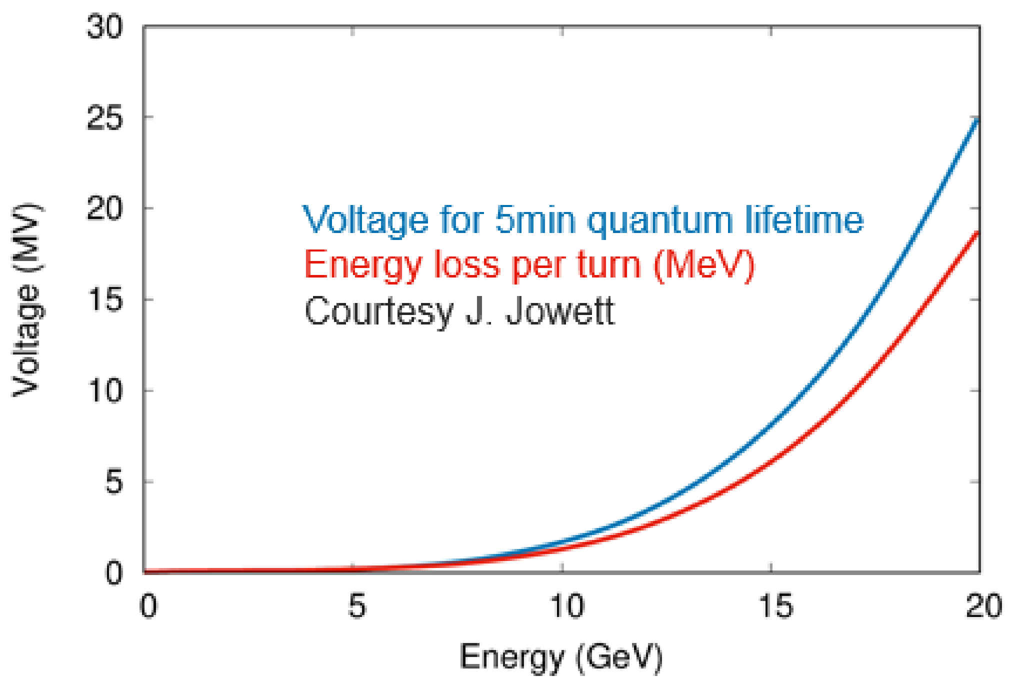
eSPS : LINAC – Status of its location tomorrow

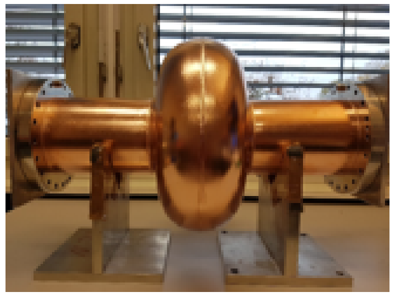


eSPS : SPS – RF system

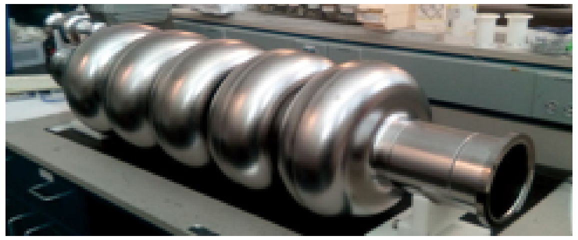
(20 GeV)

- Acceleration to 16 GeV can safely be achieved, need ~10 MV
- Studies show that a superconducting RF system is the most appropriate. The preferred frequency is 800 MHz – two options seem possible in this case (see below)
- Installation in LSS6 (LHC extraction region) is the preferred location to exploit the existing infrastructure from the crab cavity installation.
- Use the mechanical bypass, a pulsed bypass, or inline

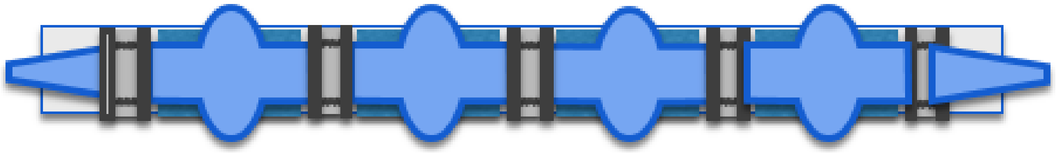




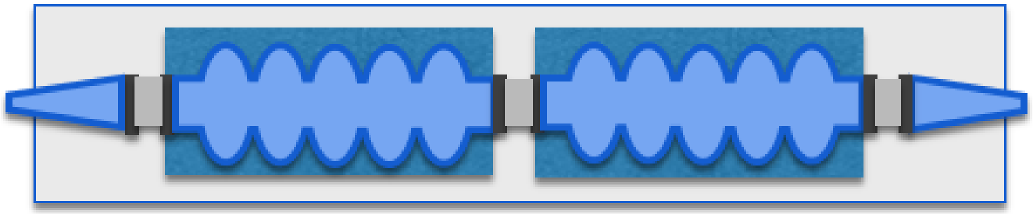
FCC-800 MHz prototypes



Sample Configuration (10 MV)



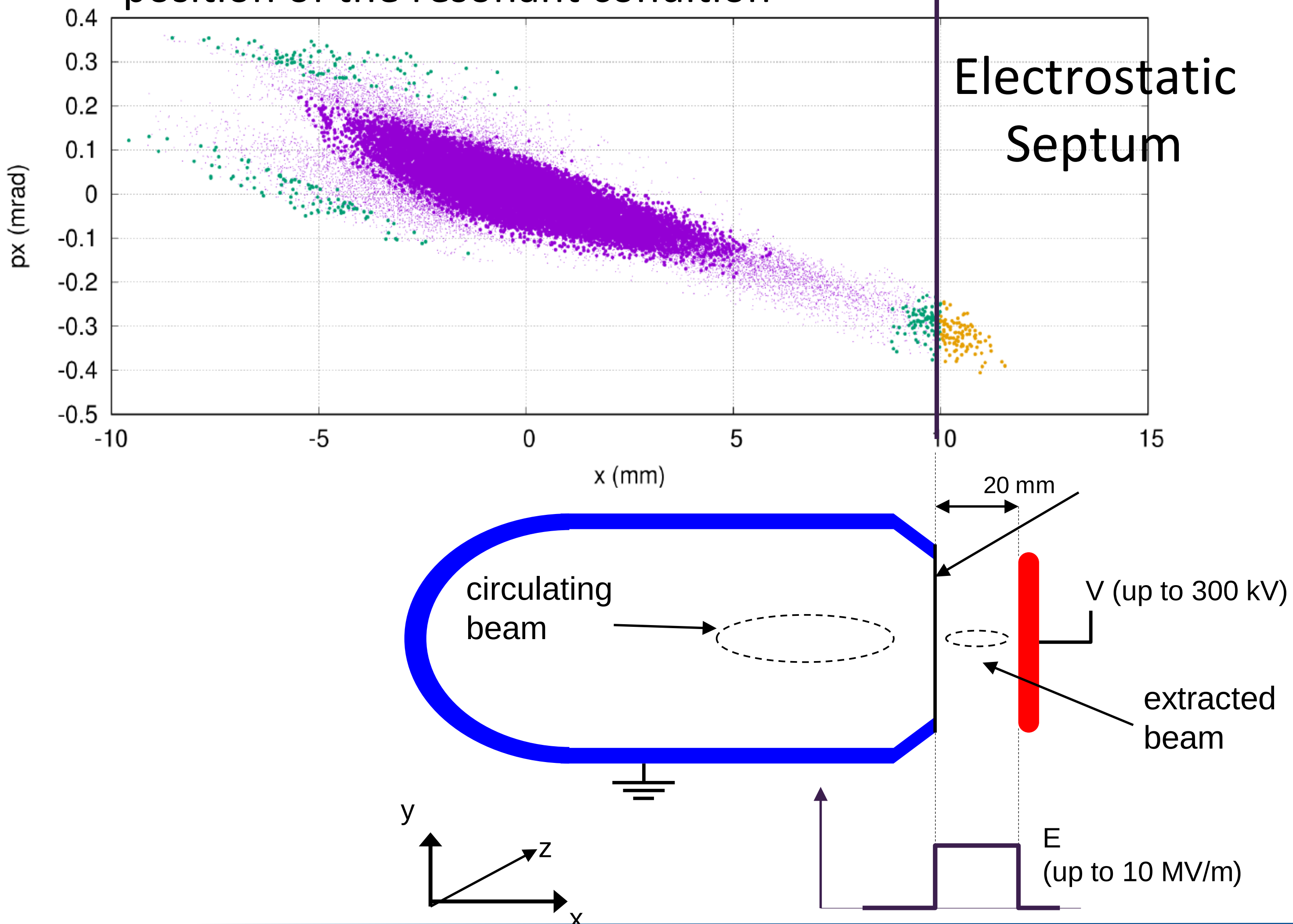
Four 1-cell in a CM ~ 5m

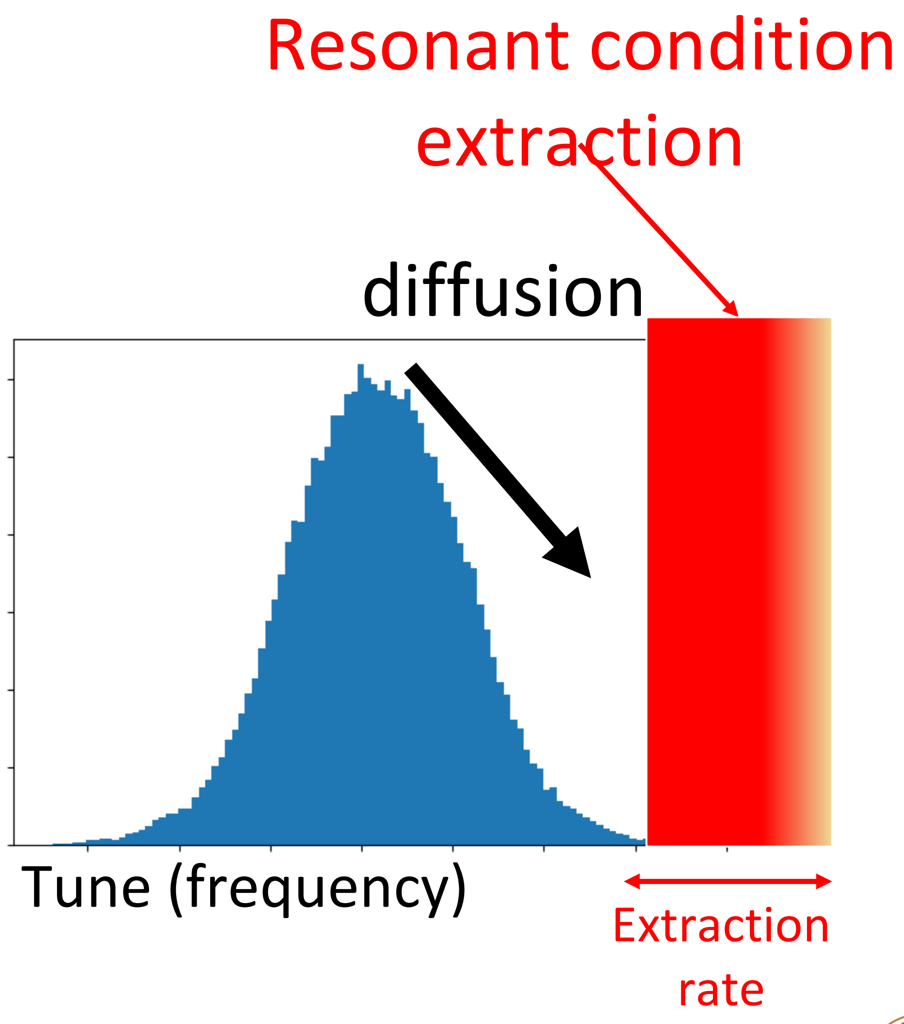


Two 5-cells in a CM ~ 5m

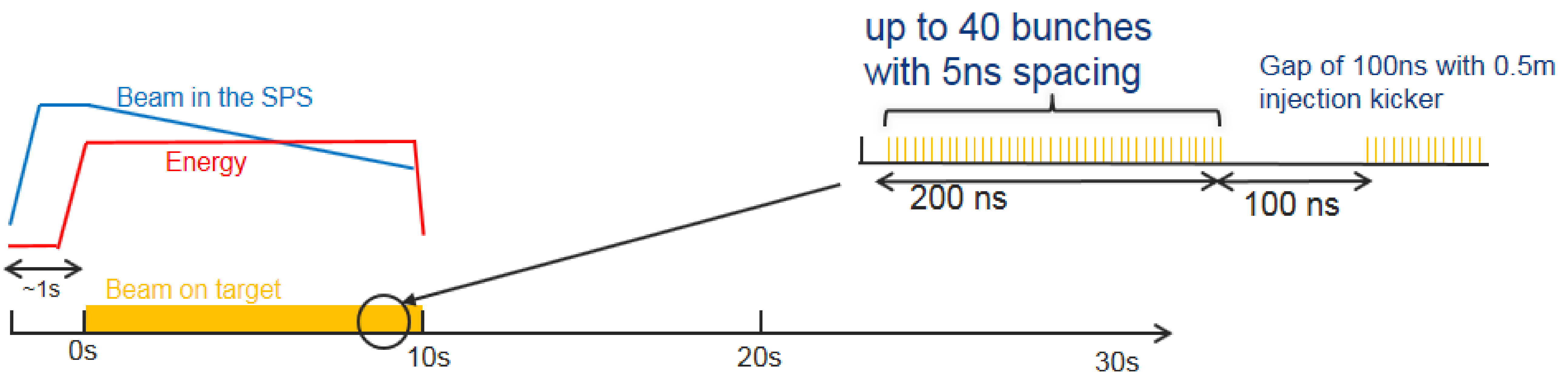
eSPS : Slow extraction

- Spread in oscillation frequency within the beam follows
  - Transverse distribution
  - Longitudinal distribution in presence of chromatic lattice
- Position of the resonant condition is set by the machine
- Synchrotron radiation constantly diffuse the particles to fill the tail in the distribution
- The extraction rate can be controlled by changing the position of the resonant condition



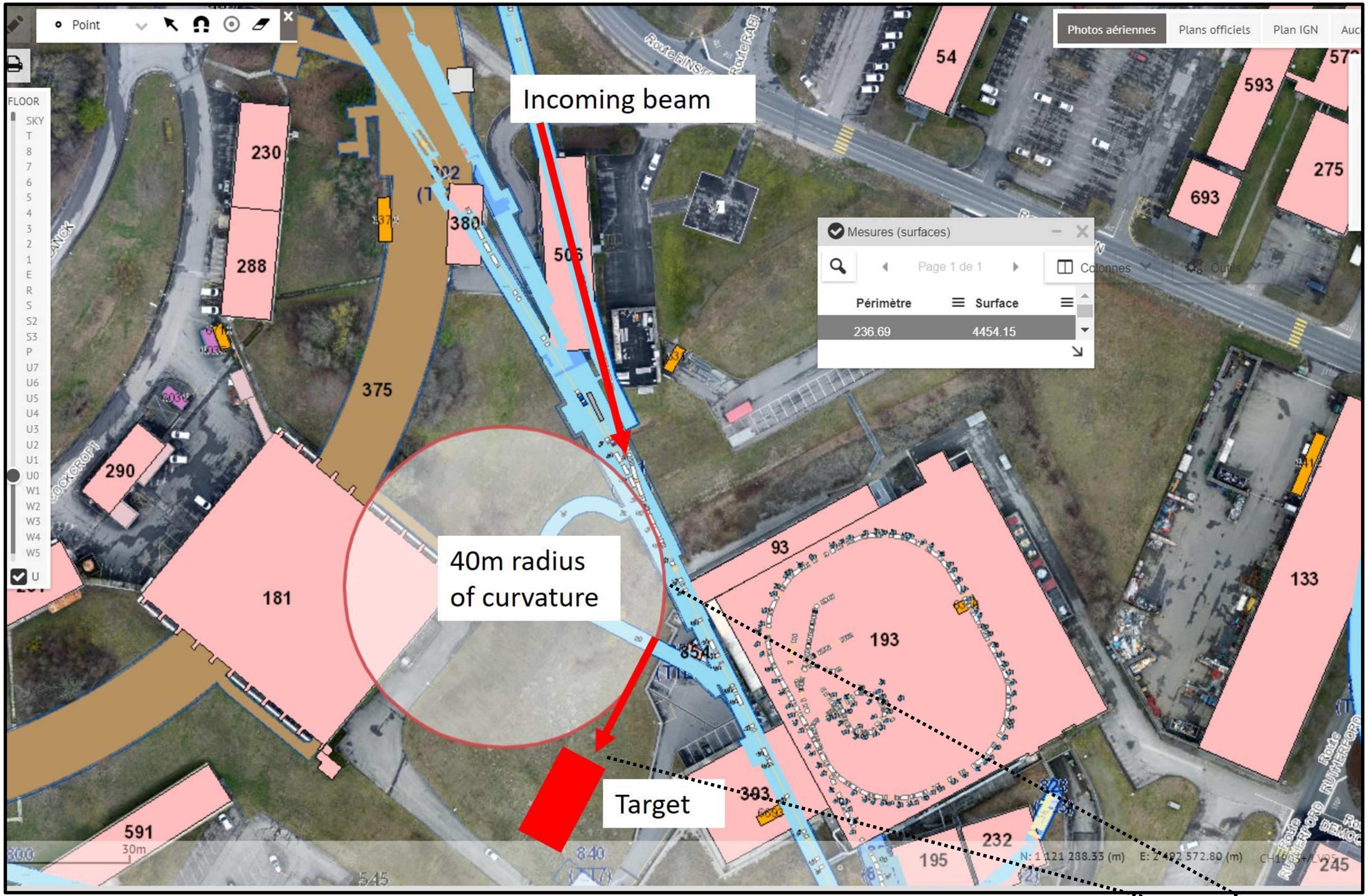


eSPS : Structure of extracted beam



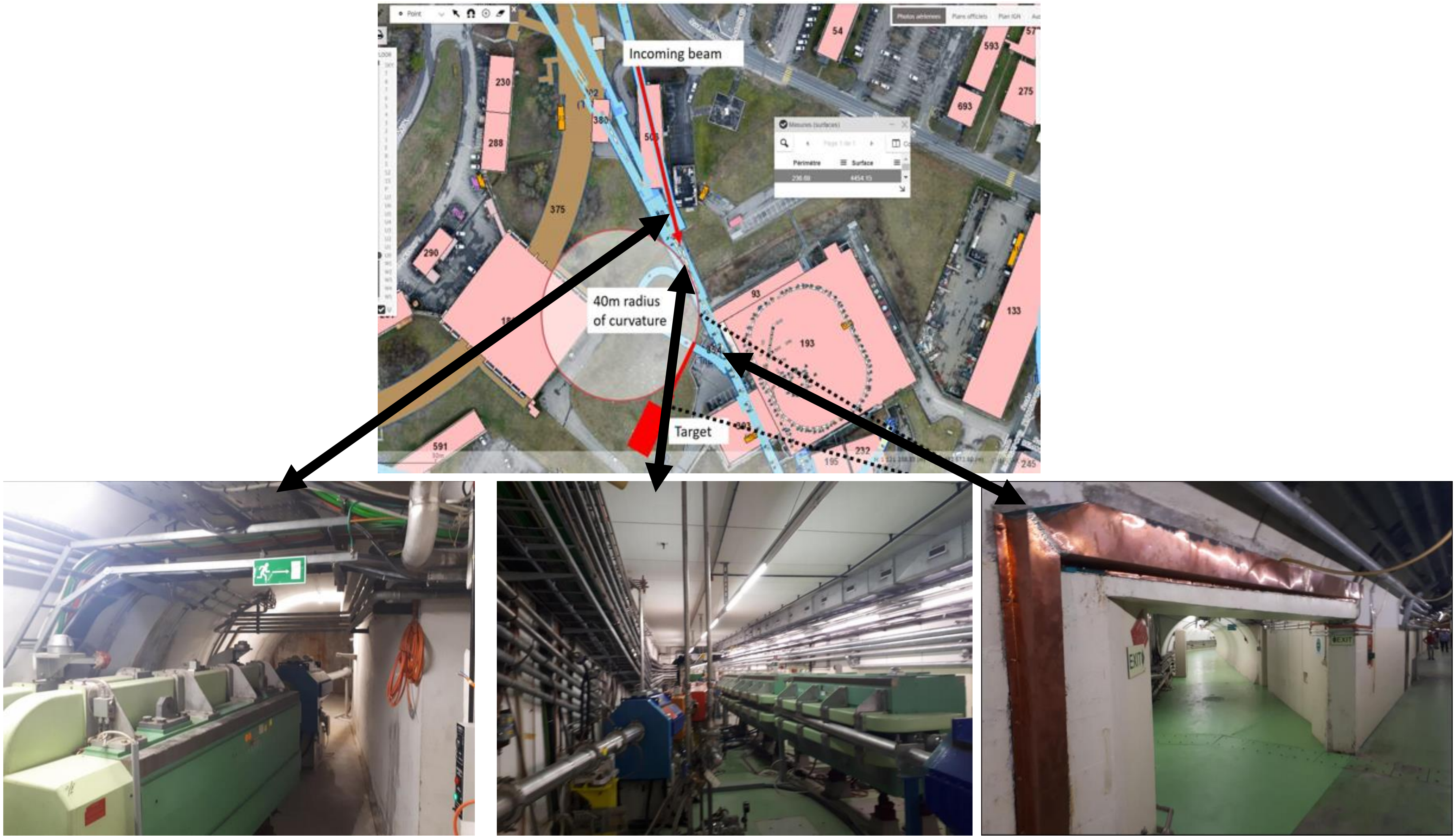
- Flexibility
  - Bunch spacing 5ns, 10ns, … 40ns
  - Average electrons per bunch can be chosen from <1 to anything
  - Transverse beam spot on target from very small up to hundred cm^2
- This flexibility can deliver the needs of LDMX
  - Phase 1 : 10^{14} electrons
  - Phase 2 : 10^{16} electrons

Extracted beam and experimental area

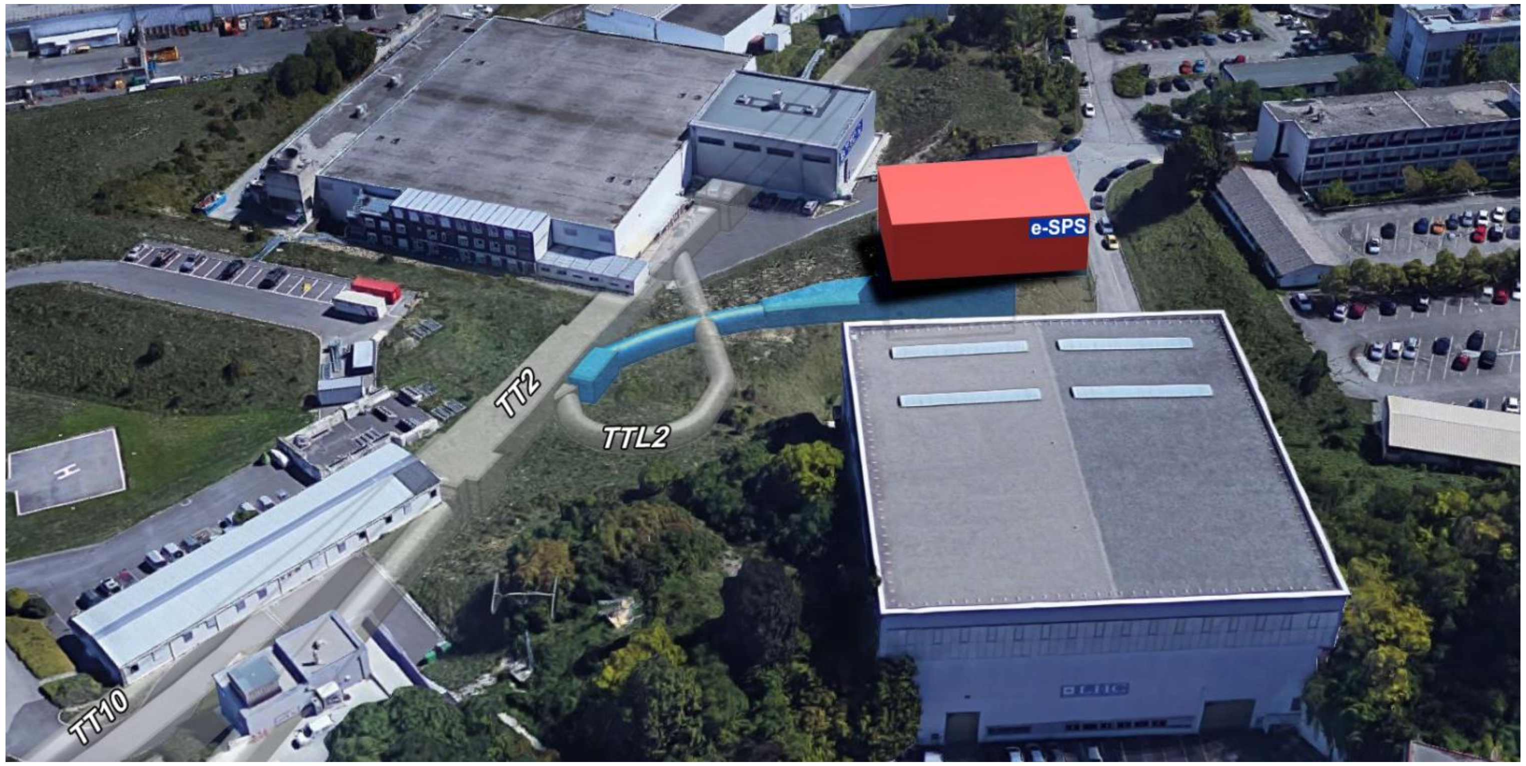


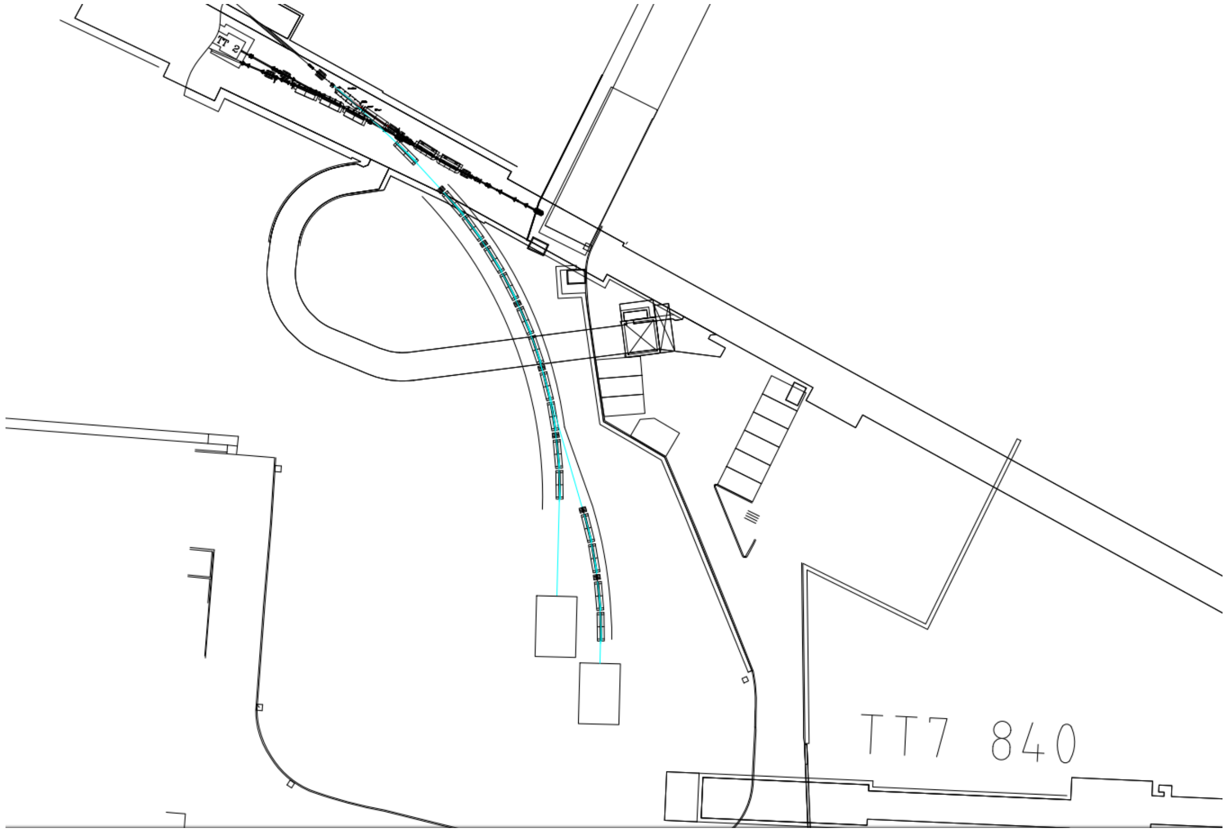
- In total ~50 m new tunnel

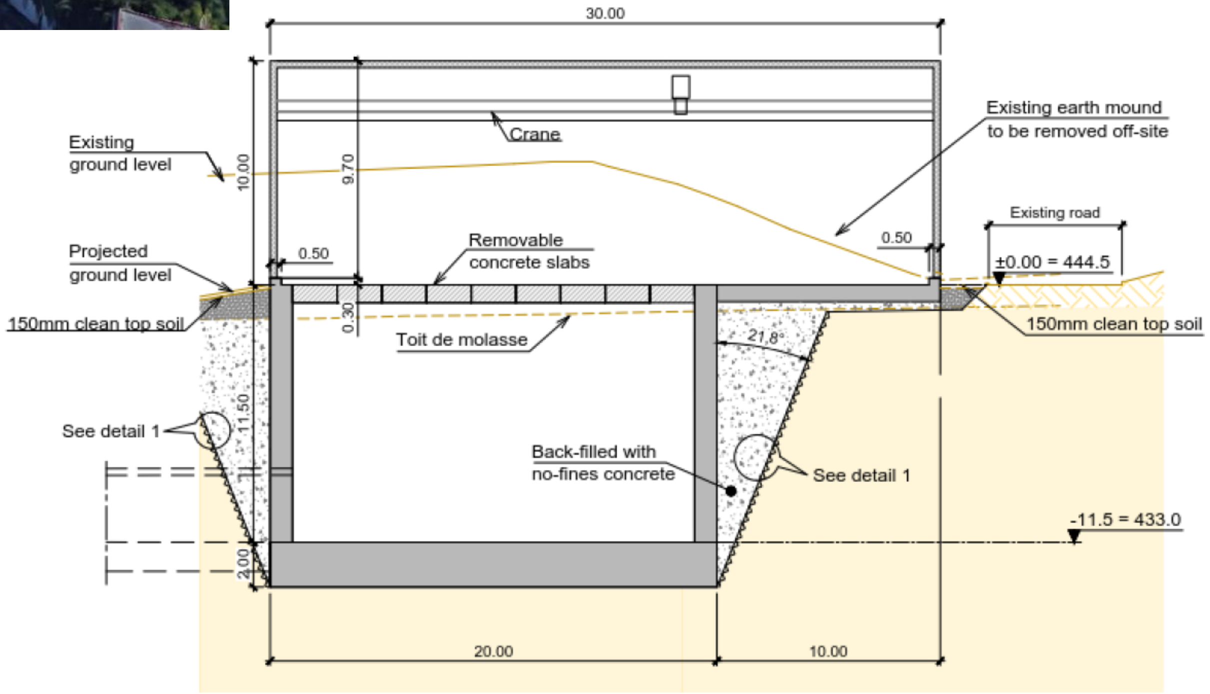
Extracted beam and experimental area



eSPS : Experimental area







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

- If nothing unforeseen would happen then we get the SLAC beam as planned
- My assessment: If the overall CERN strategy requires a large scale X-band linac, then a large prototype will be needed, and then we have good chances to get the eSPS