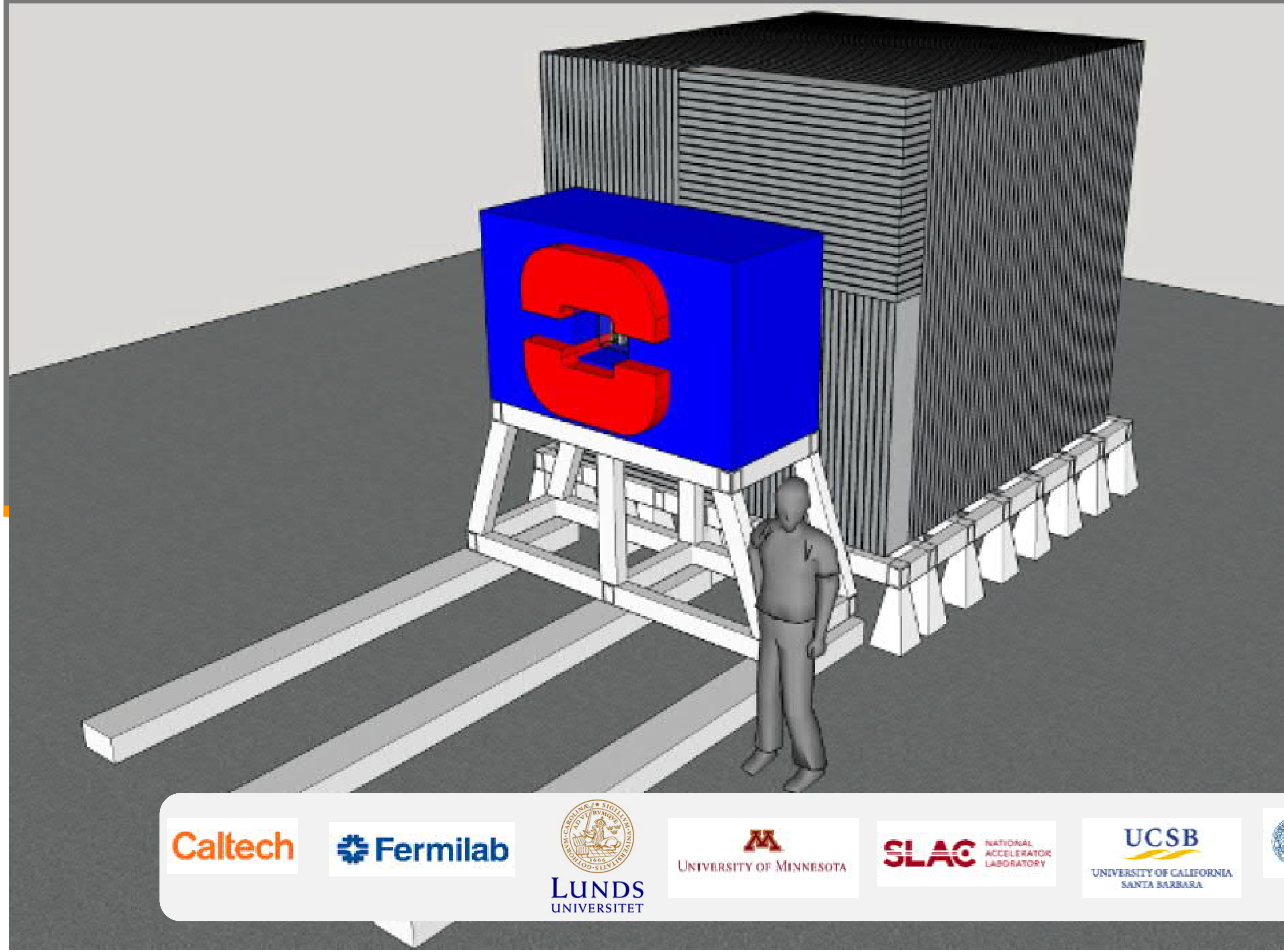
Search for Light Dark Matter with LDMX and a Primary Electron Beam Facility at CERN

Torsten Åkesson

LAL, 3 July 2018

The Light Dark Matter eXperiment, LDMX



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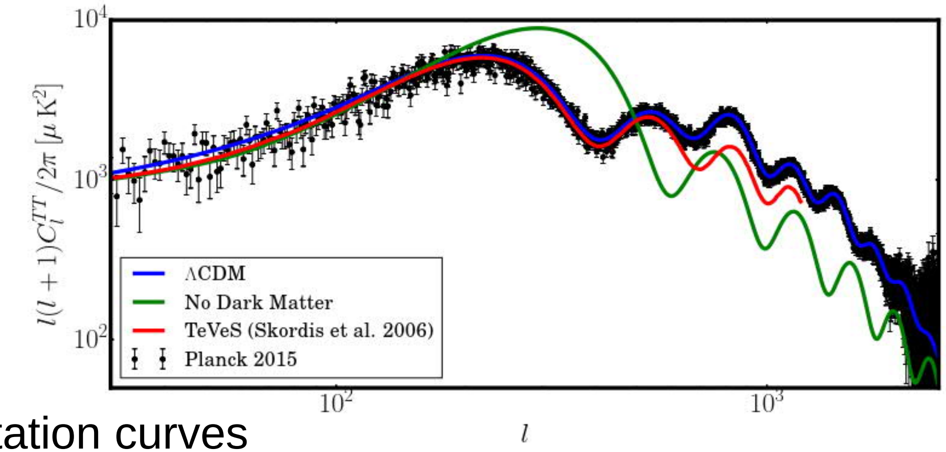
Fermilab
Lunds Universitet
University of Minnesota
SLAC National Accelerator Laboratory
UCSB University of California Santa Barbara
University of California Santa Cruz

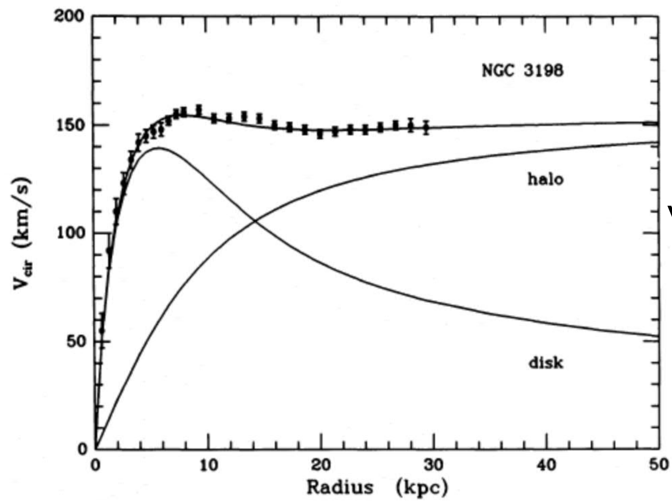
Dark matter; gravitational evidence

CMB (distribution of density fluctuations in the early universe)



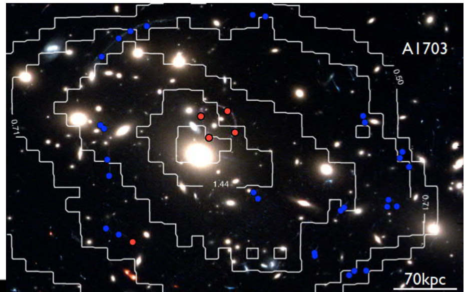
Dynamics in galaxy clusters and galactic rotation curves

The Coma cluster
(Zwicky discovery)



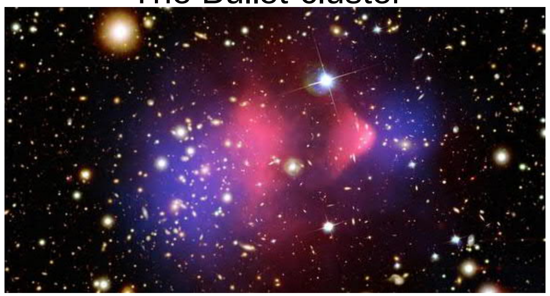
Van Albada et al

Strong and weak gravitational lensing



The lensing effect from the Abel 1703 galaxy cluster

The Bullet cluster



Dark matter; its nature

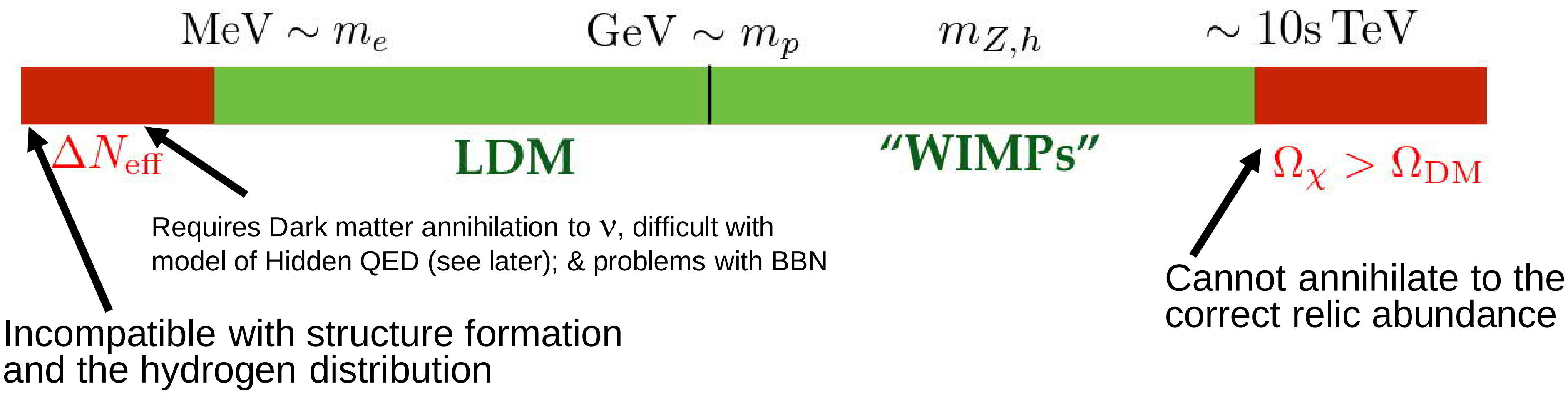
The gravitational observations of Dark matter, give little information on its composition

10^{-22} eV – 100 $M_{\odot}$

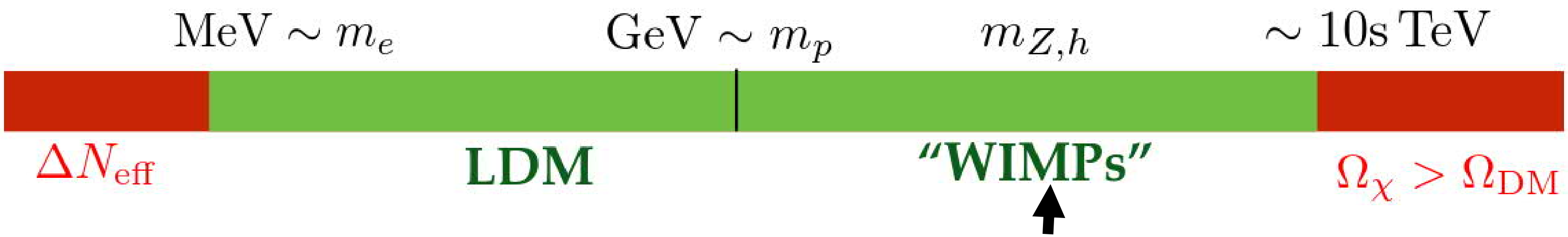
Cosmological scenarios for the origin of Dark matter give different mass ranges.

One attractive cosmological scenario is the thermal origin of Dark matter: Dark matter and Standard Model matter were in thermal equilibrium in the early universe, and Dark matter annihilated into Standard Model particles until the annihilation rate < universe expansion rate, the freeze-out

This gives an allowed mass range ~MeV to ~10 TeV



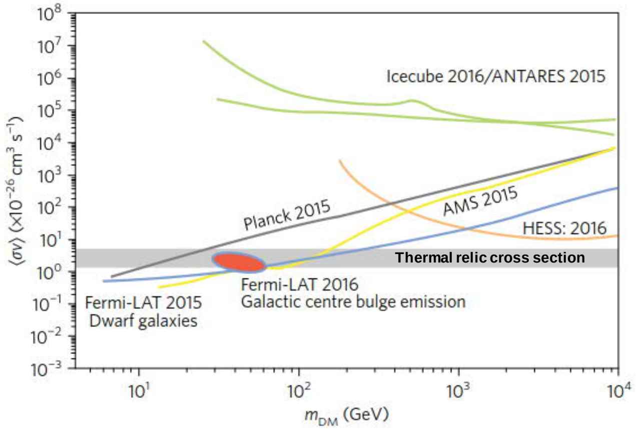
Dark matter; Weakly Interacting Massive Particles

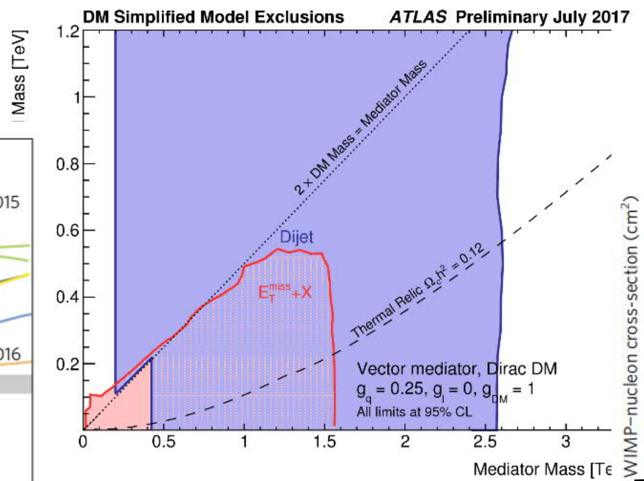


~ many GeV – 10 TeV is an attractive mass range since it produces the correct relic abundance with annihilation based on the strength of Weak Interactions.

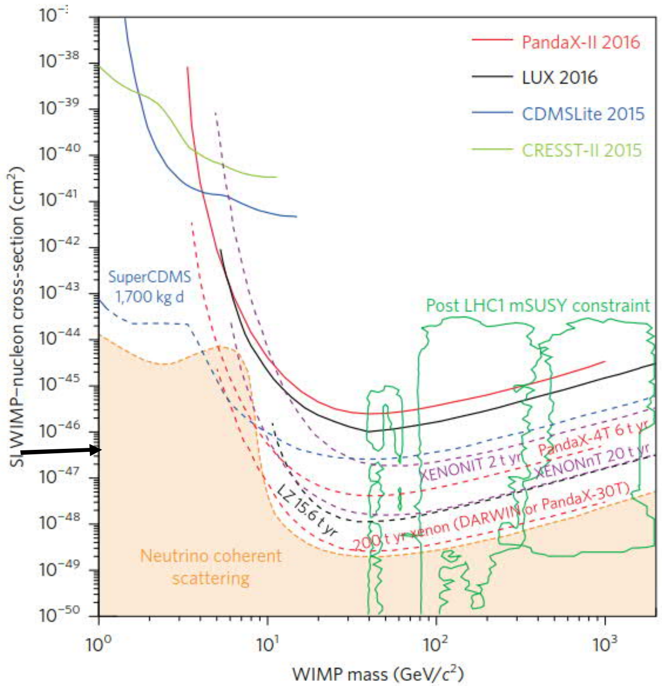
This combined with that Super Symmetry naturally provides such particles has generated a large search effort in this area: Indirect searches, the LHC, direct searches

Nature Physics, 13, Issue 3, 224-231 (2017)



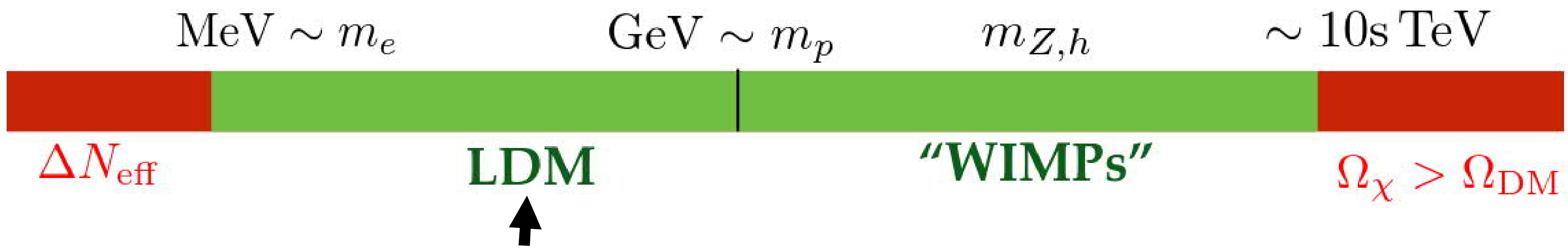


Nature Physics 13, 212-216 (2017)



Up to now no sign in this range. Nevertheless, significant parameter space remains to explored, and will be done

Dark matter; Light Dark Matter, LDM



While there is a large effort in exploring the WIMP range. This is not the case for the range ~MeV - ~GeV, where we have most know matter

Well motivated in scenario where Dark matter is a particle with its own forces and interactions. Also, e.g. result from the Be^*_8 decay indicate that there may be BSM physics in the tenths of MeV area.

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

Study for the simplest possible scenario, a "hidden QED", with the Dark matter particle χ, and a vector mediator A'

Mass of A' and mass of χ

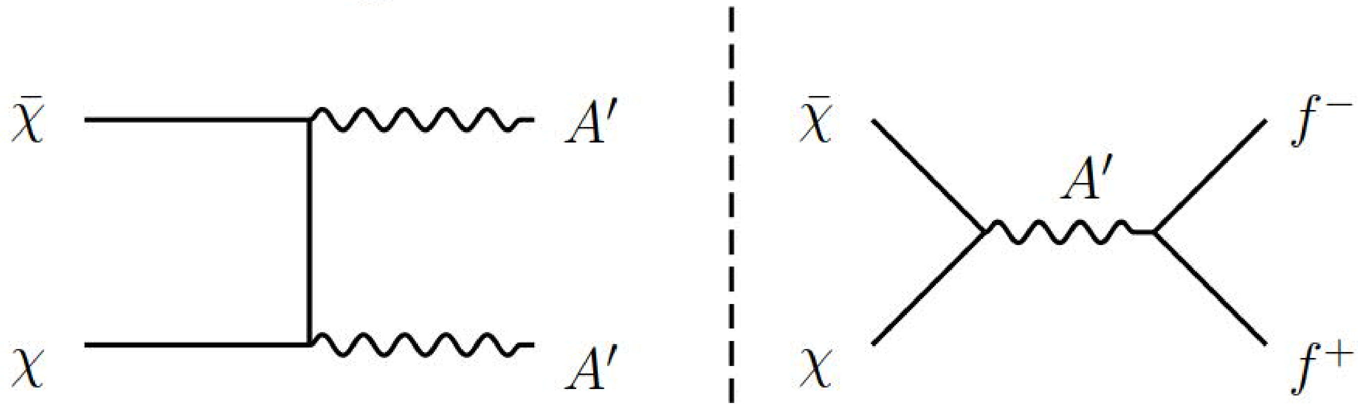
Two different thermal annihilation scenarios for the LDM model, depending on if $m_{A'} < m_\chi$ or if $m_{A'} > m_\chi$

secluded, $m_{A'} < m_\chi$

$$\sigma v \propto \alpha_D^2$$

direct, $m_{A'} > m_\chi$

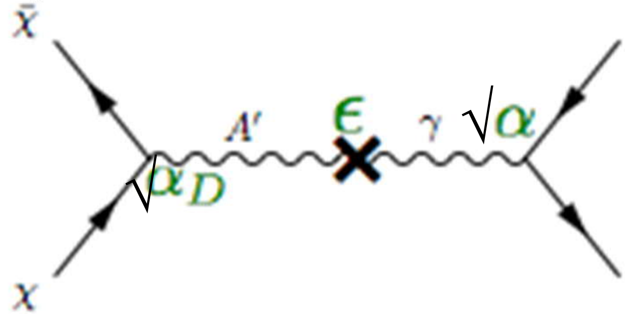
$$\sigma v \propto \epsilon^2 \alpha_D$$



ε is the A' kinetic mixing parameter with the photon, giving the strength with which the A' couples to the electric charge, and therefore couples to the Standard Model

α_D is the Hidden sector Fine-structure constant

CMB-data shows that secluded annihilation into vector mediators is not compatible with sub-GeV Dark Matter (Phys. Rev. D 89, 103508 (2014))

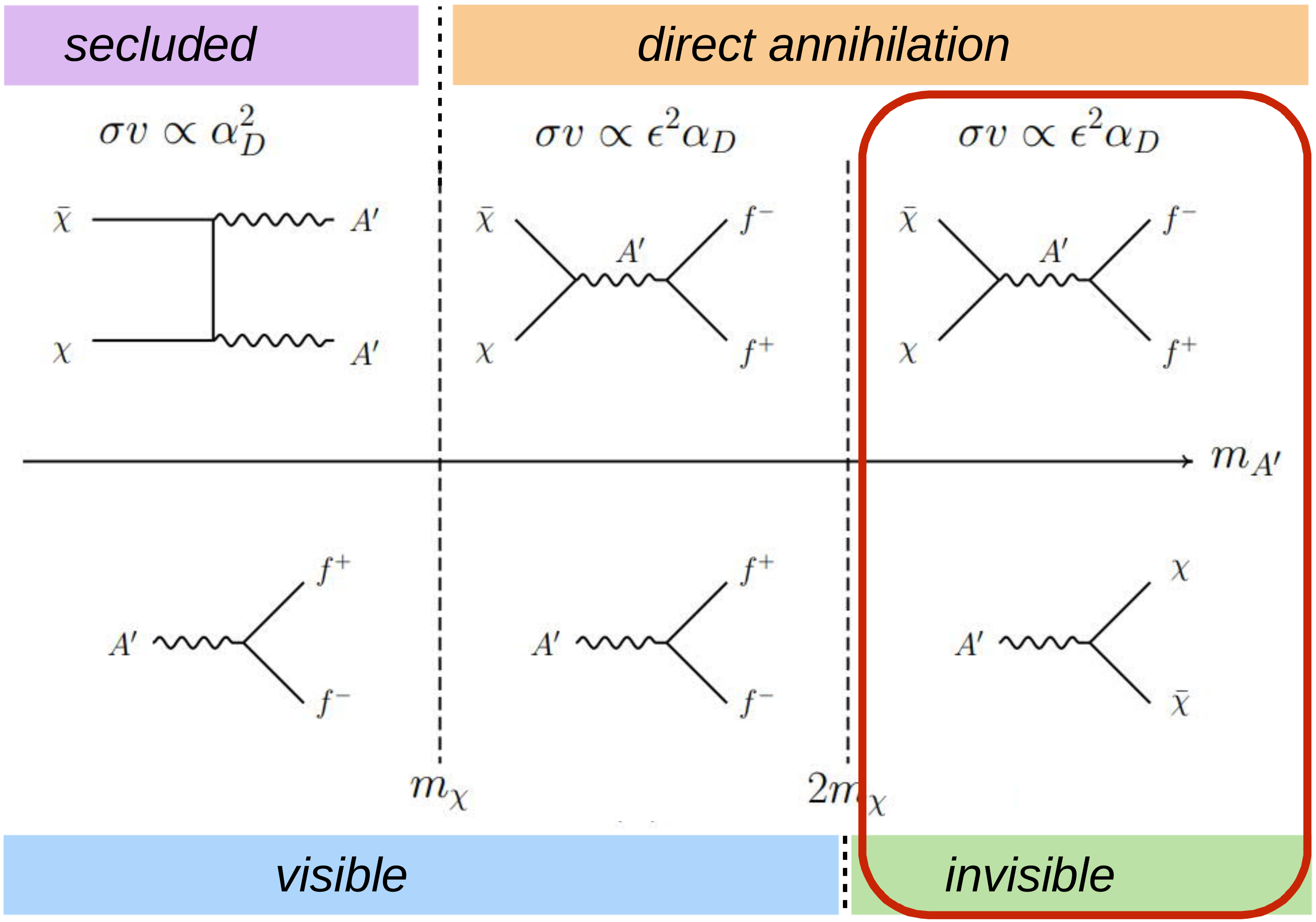


Mass of A' and mass of χ in some more detail

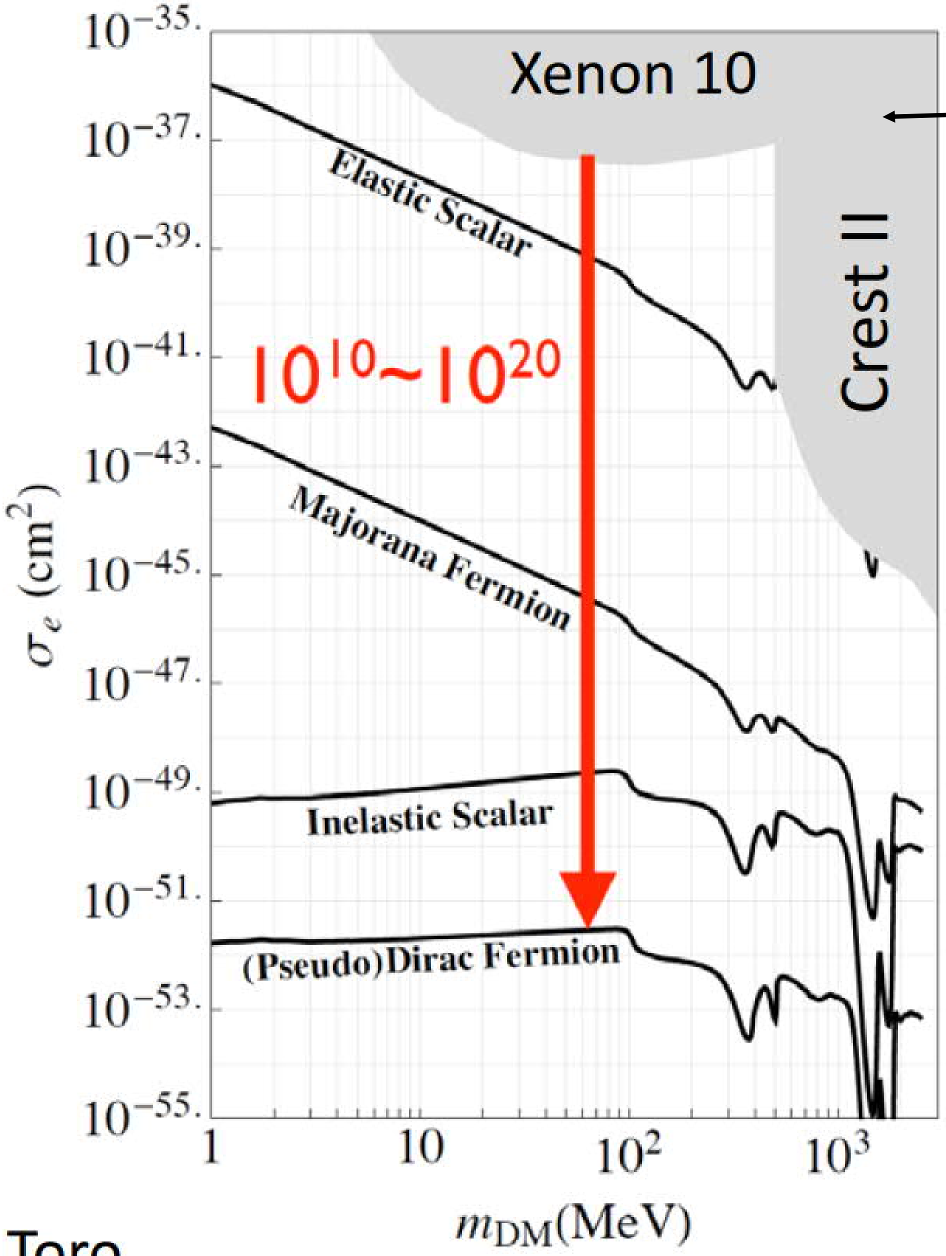
The main scenario for the LDMX experiment

Visibly decaying dark mediator

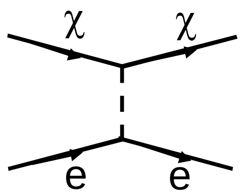
Sub-GeV χ excluded from CMB



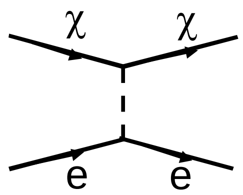
Thermal targets; χ - electron scattering cross sections for direct detection



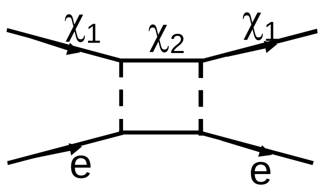
current constraints



Scalar
$\sigma \sim 10^{-39} cm^2$



Majorana
$\sigma \sim 10^{-39} v^2 cm^2; v \sim 10^{-3}$

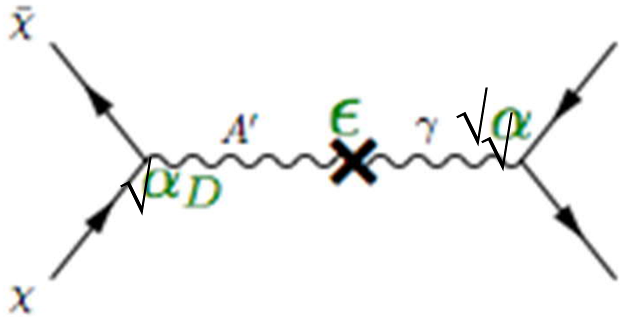


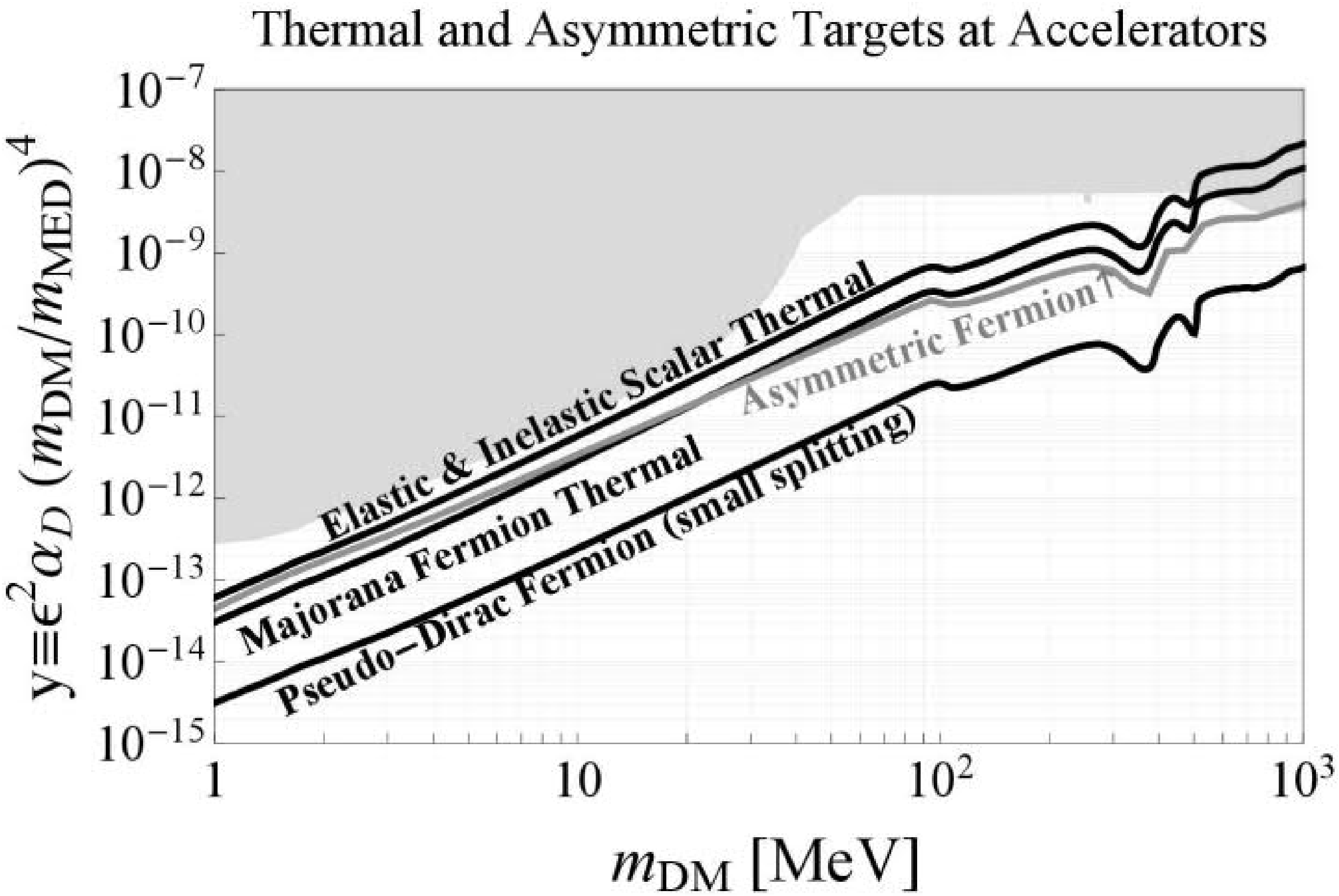
Inelastic
$\sigma \sim 10^{-50} cm^2$
loop diagram

Toro

Thermal Targets; accelerator production

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





$\alpha_D = 0.5$, $m_\chi/m_{A'} = 1/3$ (conservative)

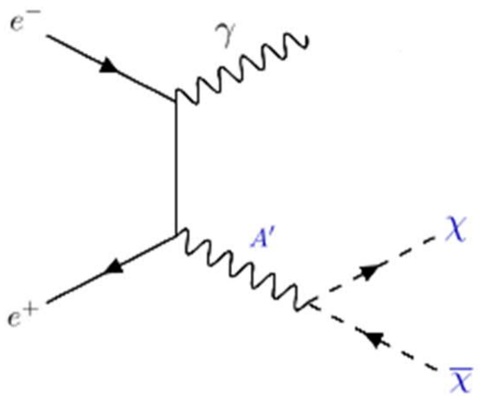
Toro & Krnjaic

Less sensitive to DM-mass and spin, than direct detection

Why fixed-target?

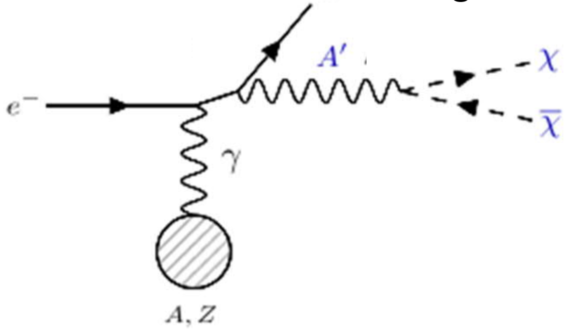
- Maximize DM production & detection; heavy penalty if needing DM-SM interaction twice

$$N \sim \varepsilon^2(1-\varepsilon^2) \approx \varepsilon^2 \gg N \sim \varepsilon^4$$

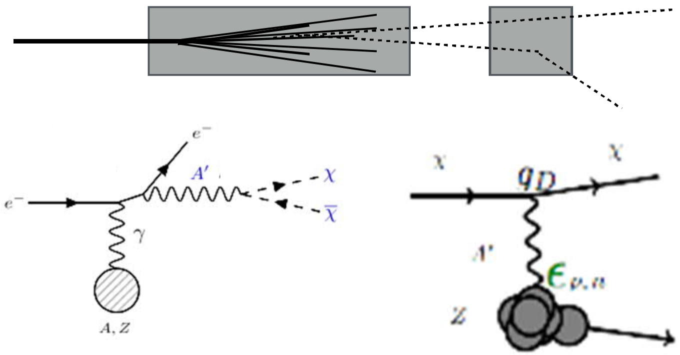


- fixed target

dark bremsstrahlung



- beam-dump



$$\sigma \sim \frac{\varepsilon^2}{E_{cm}^2}$$

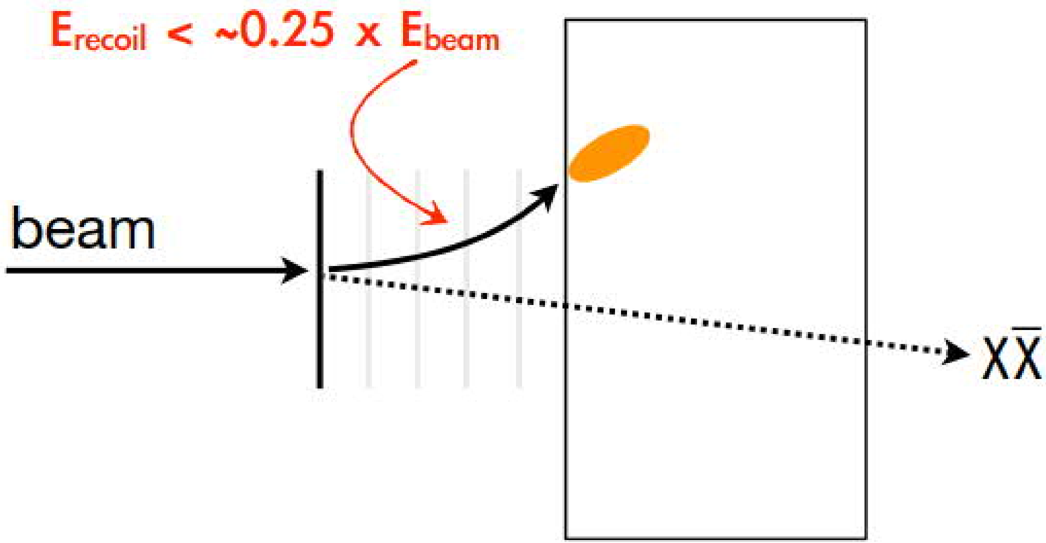
m_χ: 0.1 GeV - ~10 GeV

$$\sigma \sim \frac{Z^2\varepsilon^2}{m_{A'}^2}$$

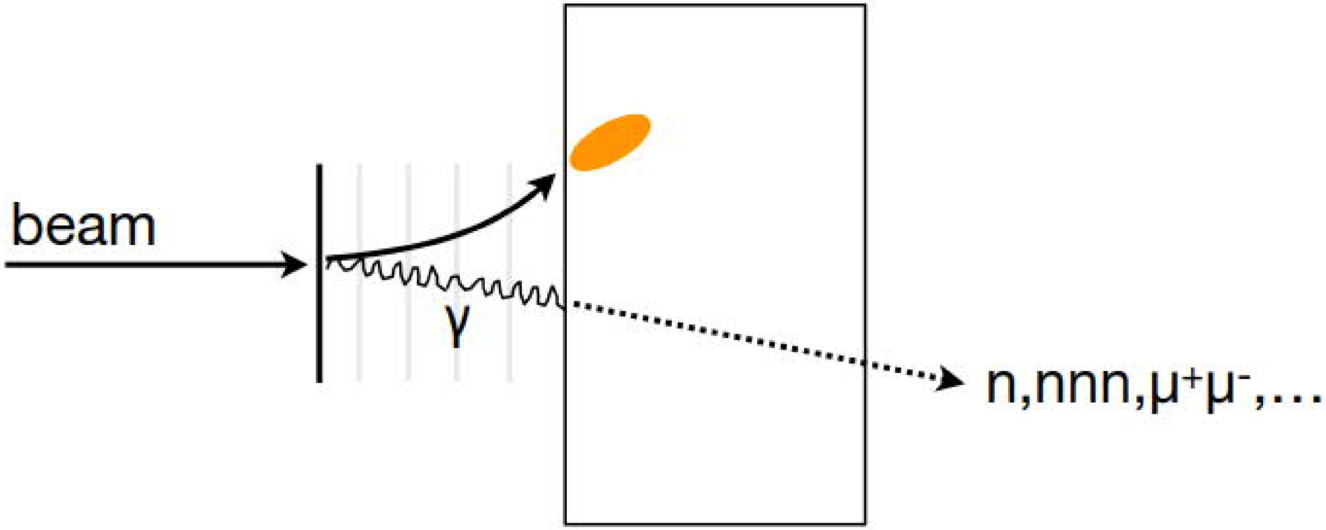
~MeV - ~GeV

Use events where outcome is deduced from the SM-particles in the reaction where Hidden sector particles where produced

Basic task for the experiment



Select these



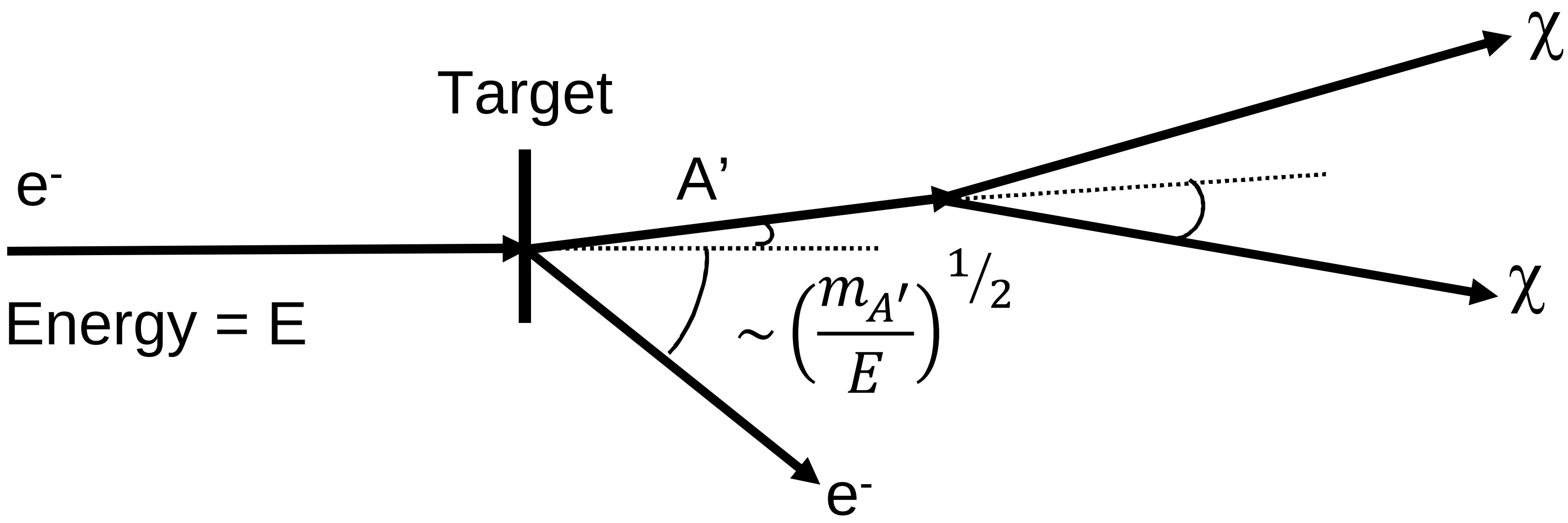
Reject these

Kinematics

$$\frac{d\sigma}{dx} \sim \frac{\alpha^3}{\pi} \frac{\varepsilon^2}{m_e^2 \cdot x + m_{A'}^2 (1-x)/x}$$

$$x = \frac{E_{A'}}{E}$$

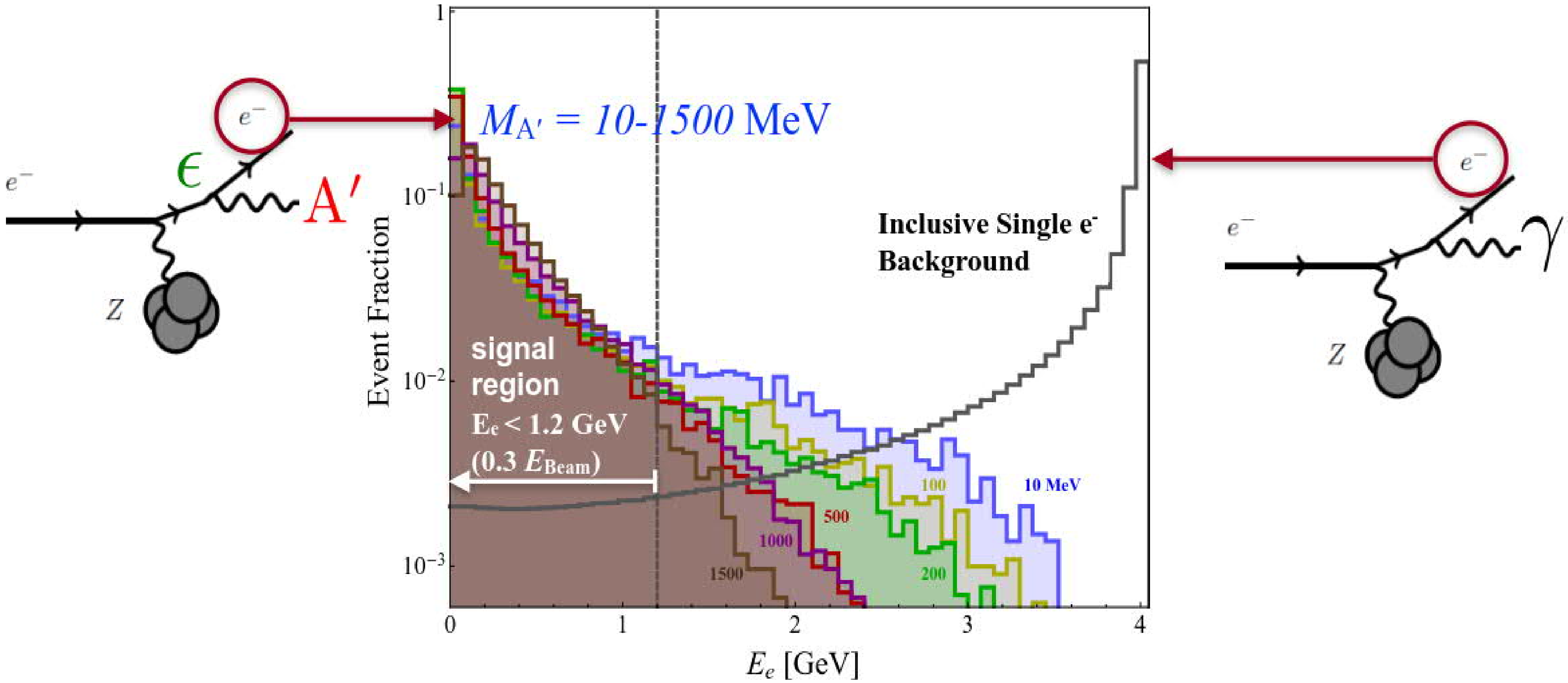
Different kinematics from massless photon bremsstrahlung



A', heavier than e⁻, carries away most of the beam energy

→ recoil electron is soft – large missing energy
→ recoil electron emerges at wide angle – large missing momentum

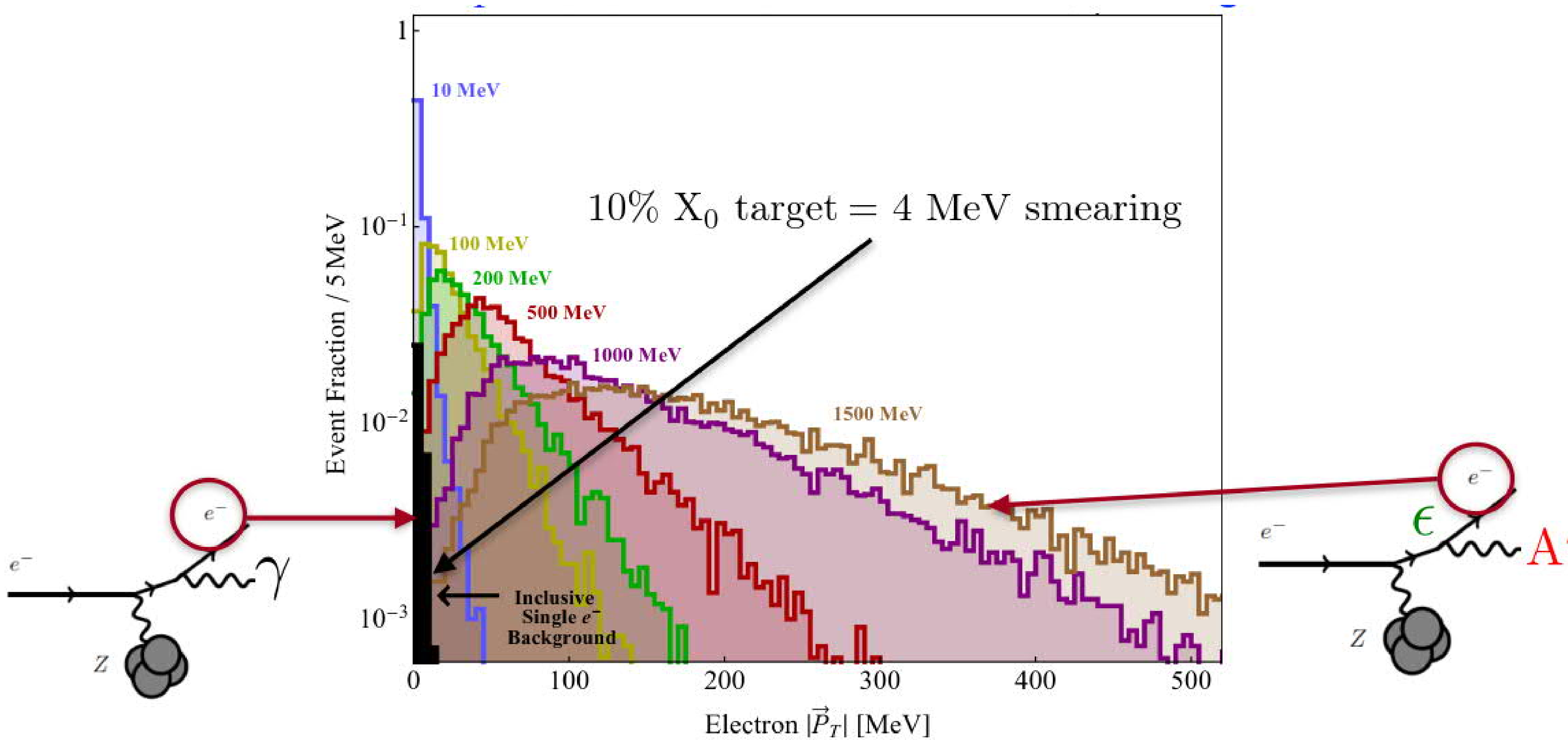
Kinematics: electron energy



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

Measurement pioneered by NA64

Kinematics: electron p_T



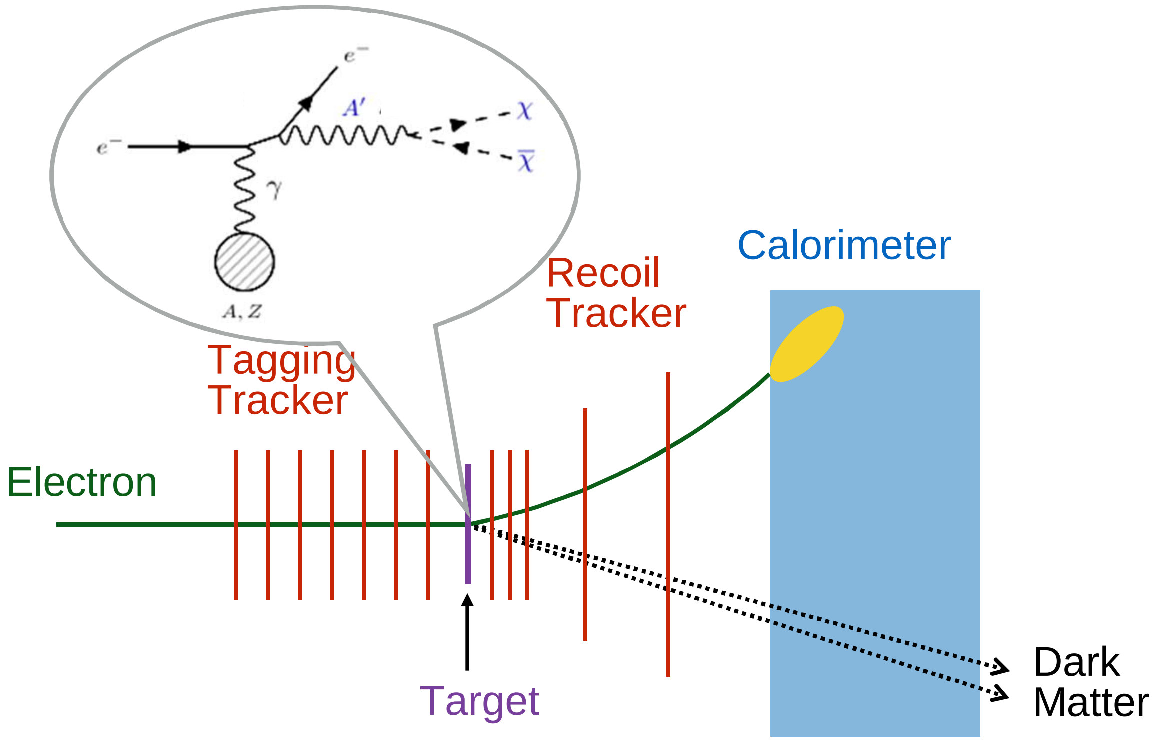
p_T of the recoil electron very different from bremsstrahlung. To measure it require modest E_e and to measure the electron both before and after the target

Thermal relic abundance target requires 10^{14} – 10^{16} electrons on target

Low current – large integrated luminosity – modest energy electron beam

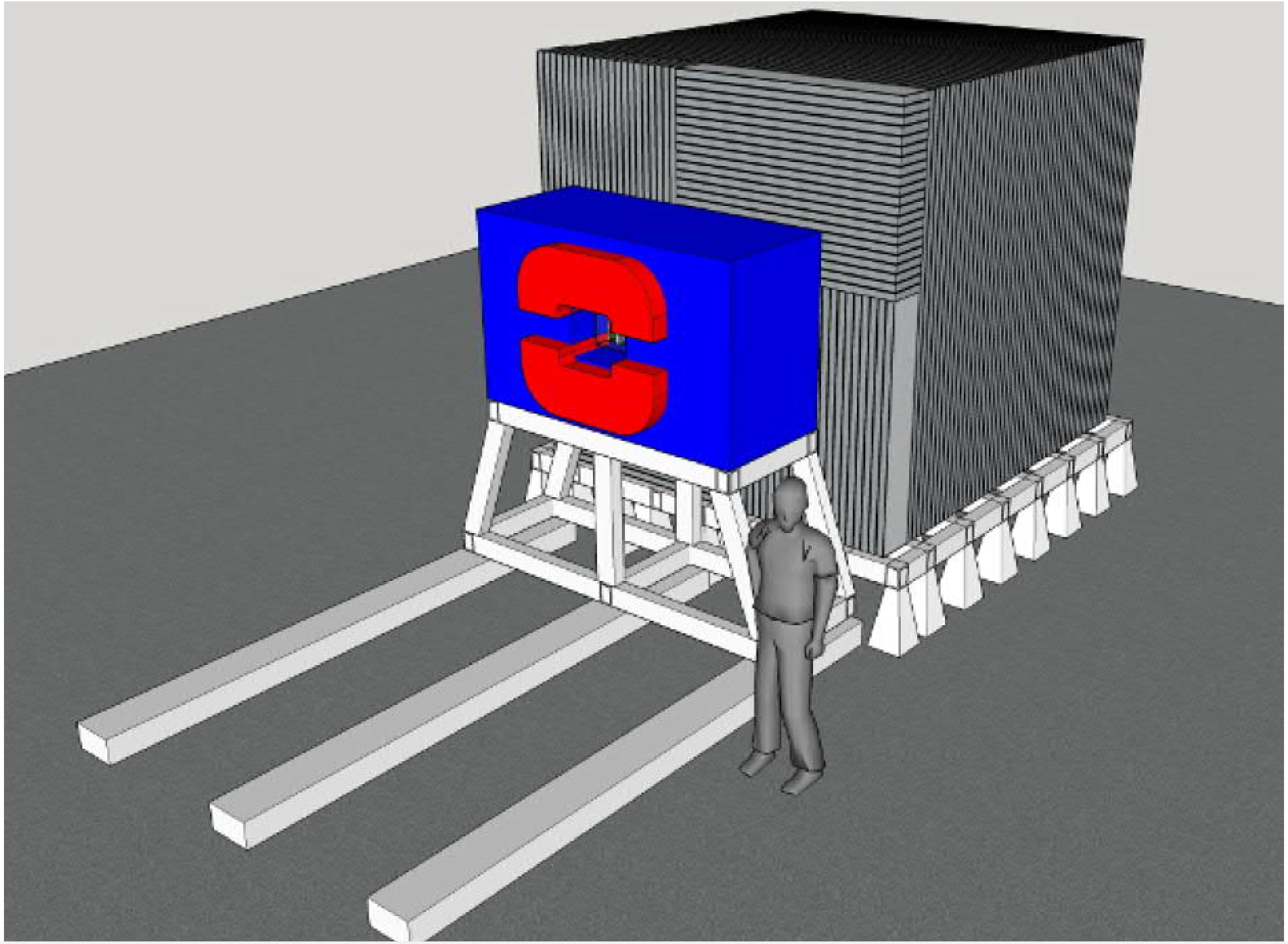
→ Primary electron beam

Conceptual Layout



- phase 1:
  - 4 GeV, ~40 MHz, <n_e>=1
    ~10^{14} EoT
- phase 2:
  - 8 – 16 GeV, ~200 MHz, <n_e>~5
    ~10^{16} EOT

LDMX



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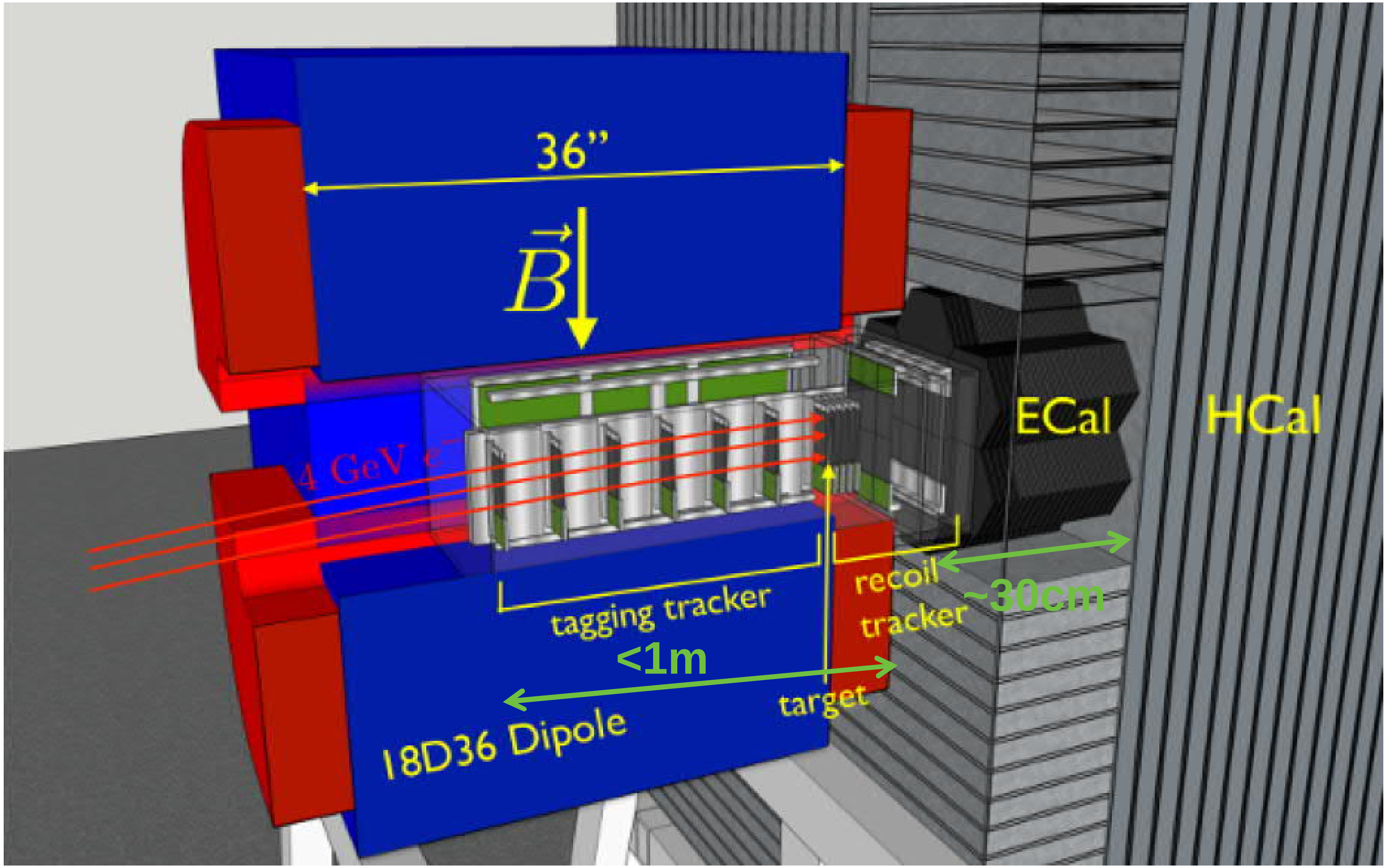
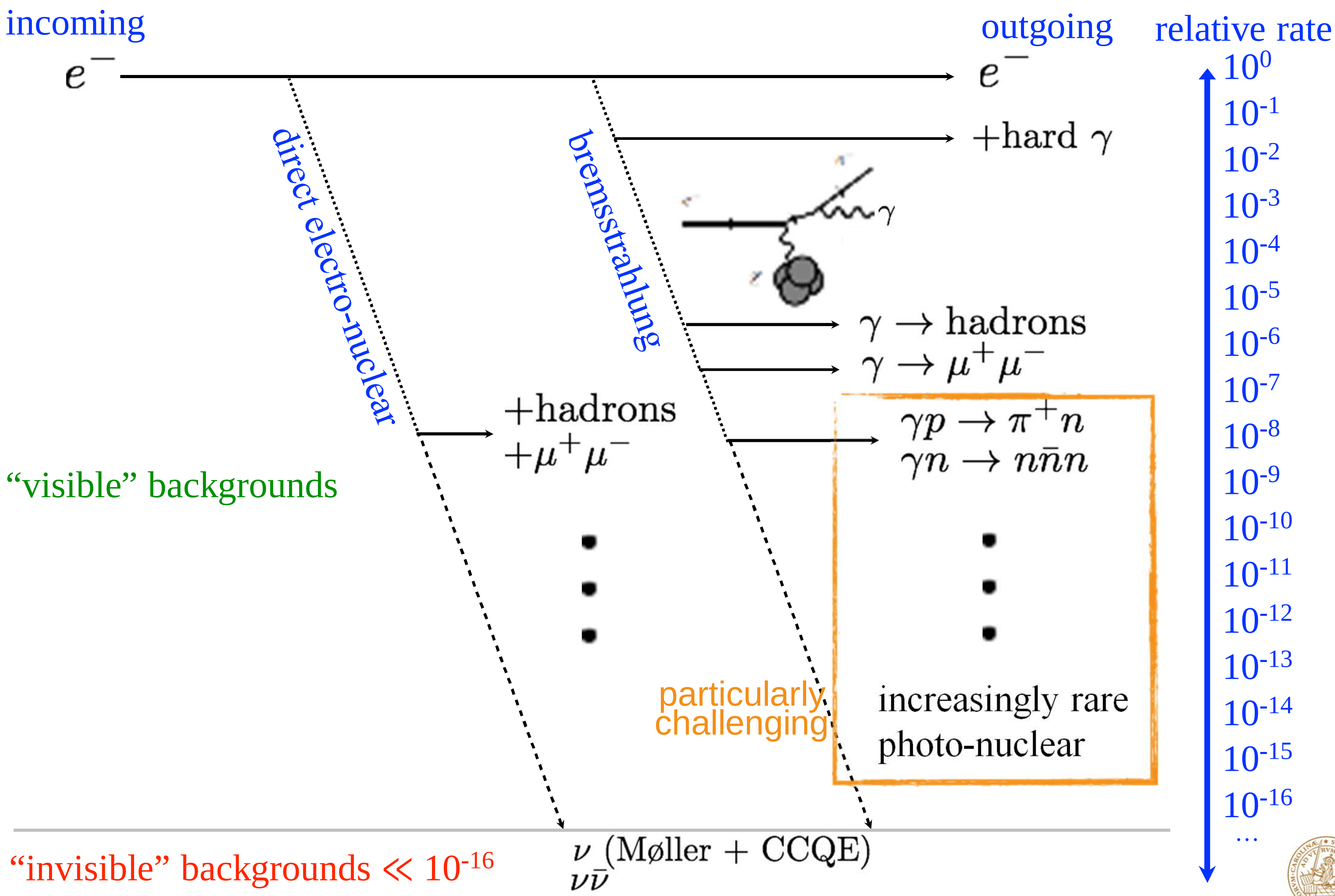
LDMX

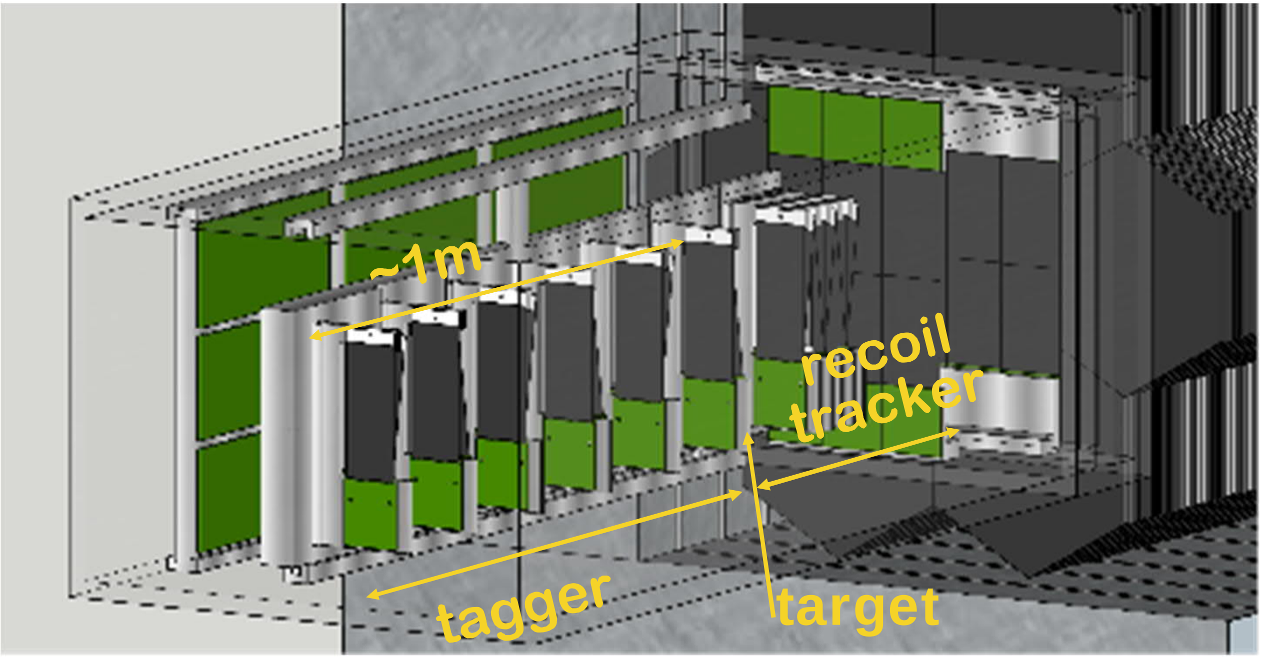


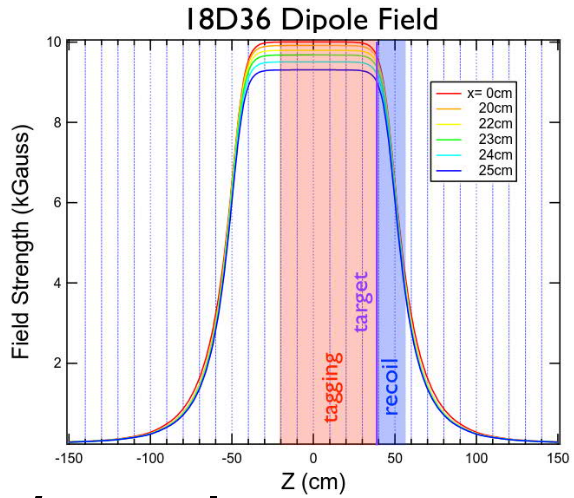
Caltech Fermilab Lunds Universitet University of Minnesota SLAC National Accelerator Laboratory UCSB University of California Santa Barbara University of California Santa Cruz

Background Challenges



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

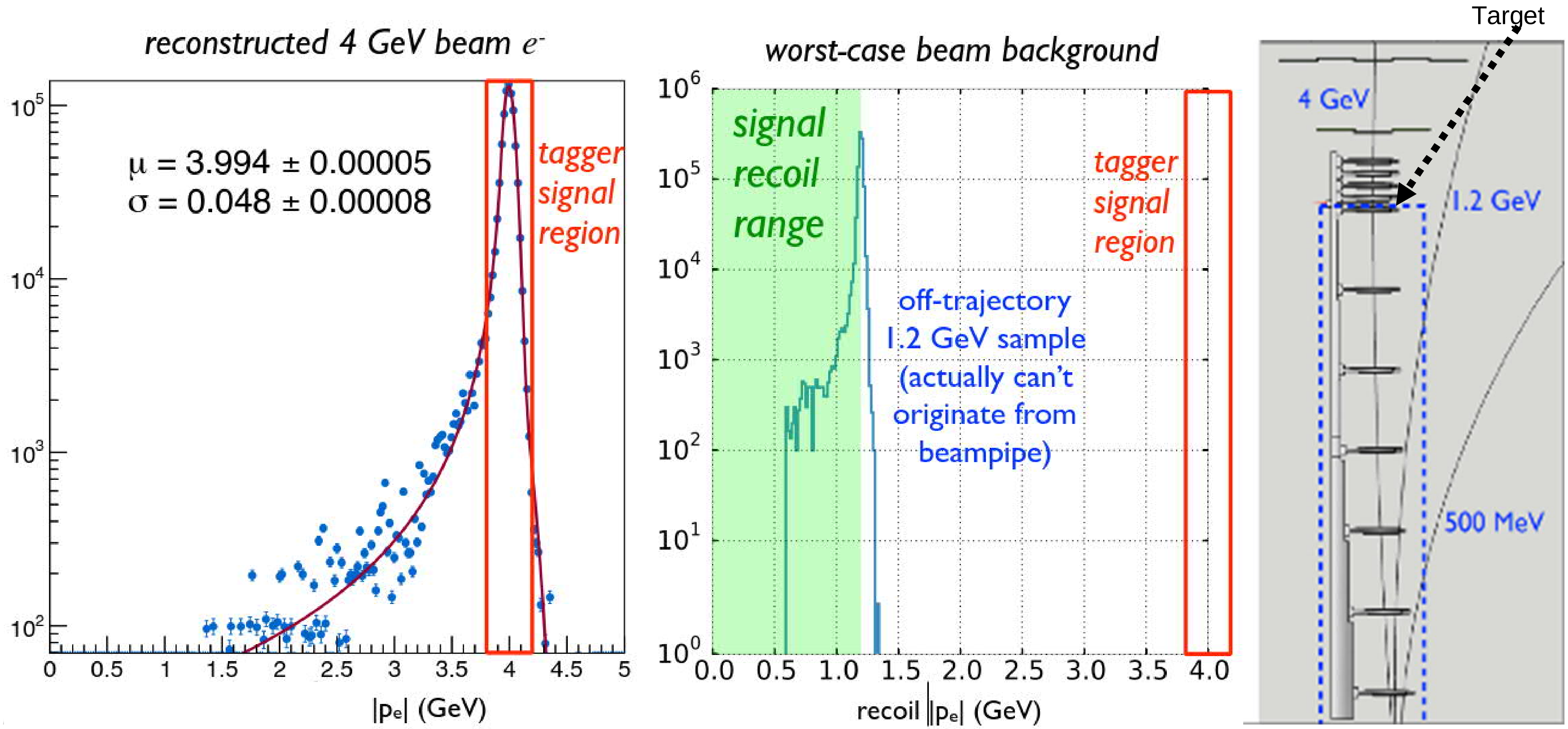
***recoil* tracker**

- 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 tungsten
- balance signal rate and momentum smearing

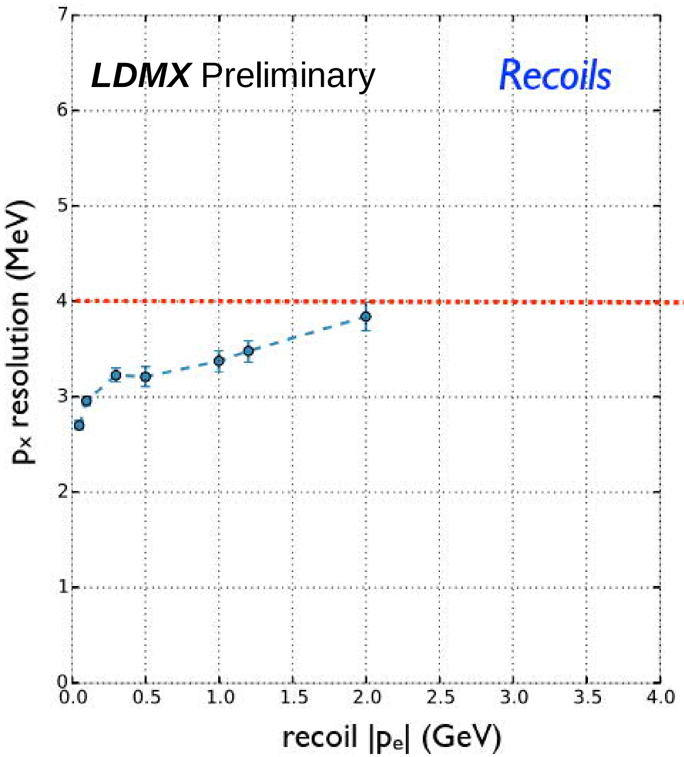
Tagging Tracker

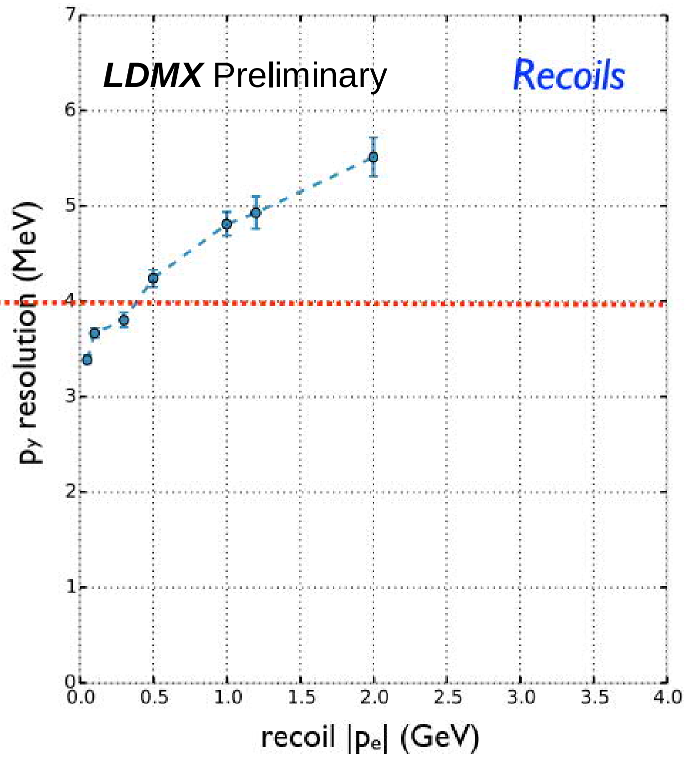


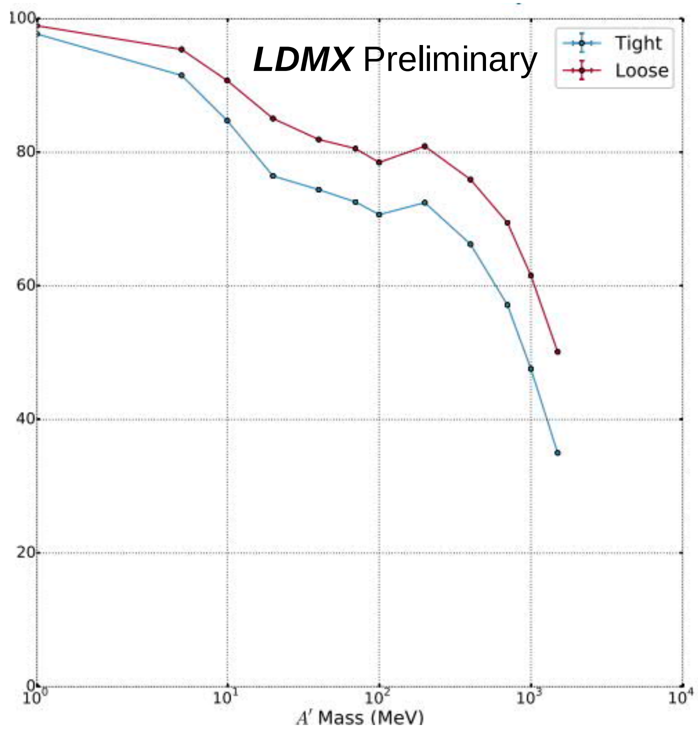
- excellent momentum resolution
- highly efficient in rejecting beam-induced backgrounds

Recoil Tracker

Tagger (p_x, p_y) resolutions at target are (1.0,1.4) MeV
Recoil (p_x, p_y) resolutions are limited by 4 MeV scattering in 10% X_0 target





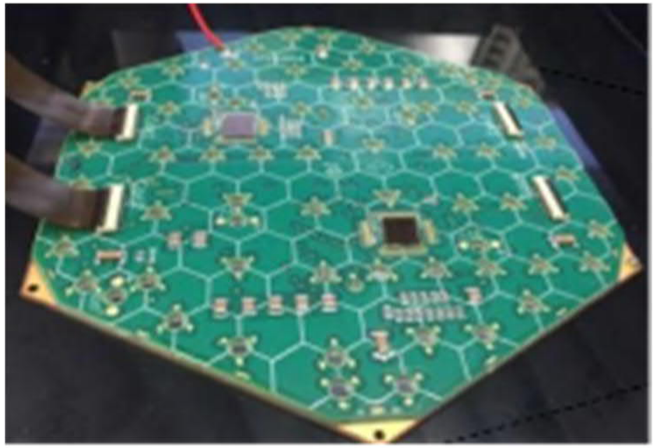


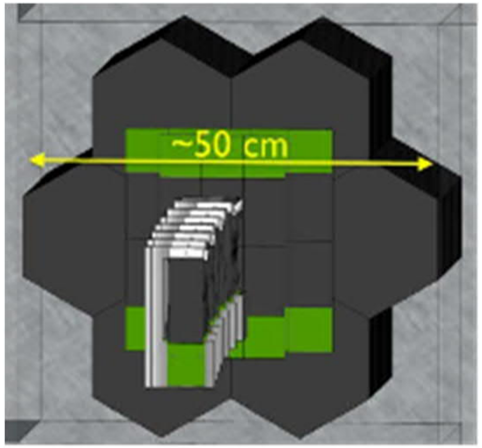
- resolution limited by 4 MeV from multiple scattering in (full) target
- good acceptance over wide mass range

Electromagnetic Calorimeter (ECal)

- ECal shopping list:
  - fast
  - radiation hard
  - dense
  - high-granularity
  - deep (containment)

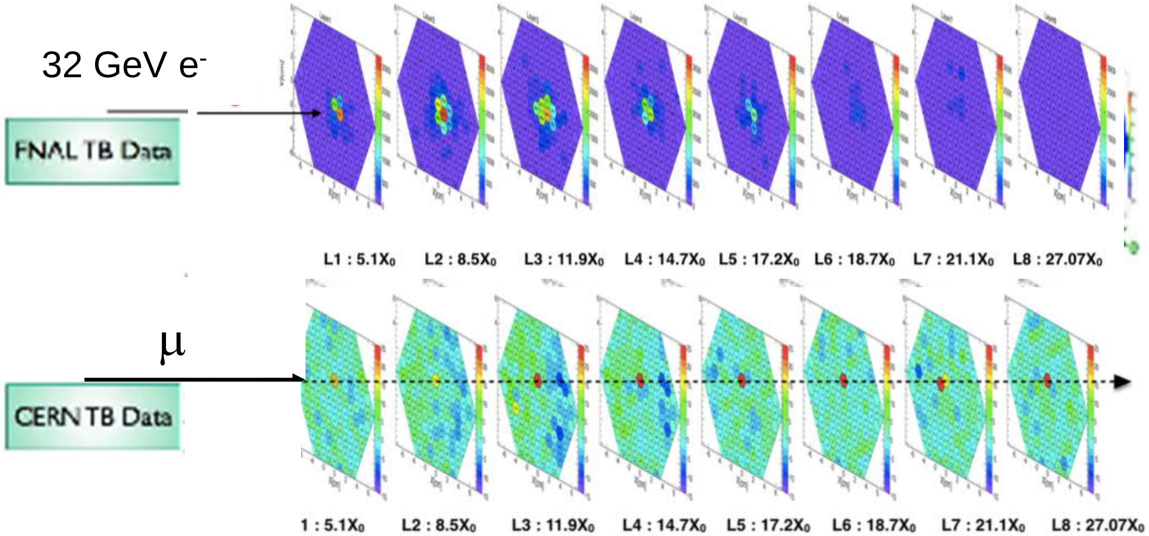
very similar to forward SiW sampling calorimeter for CMS@HL-LHC → design based on this



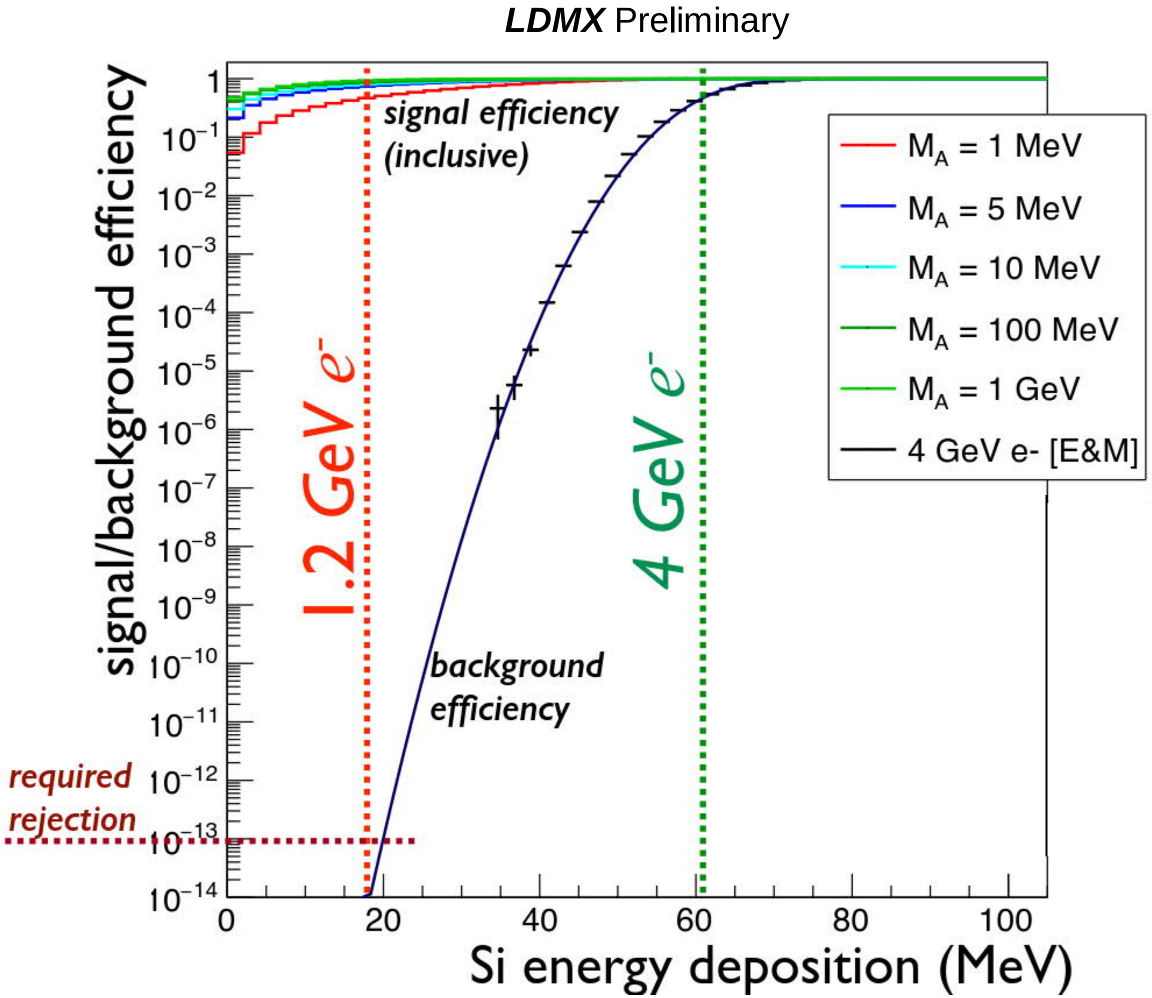


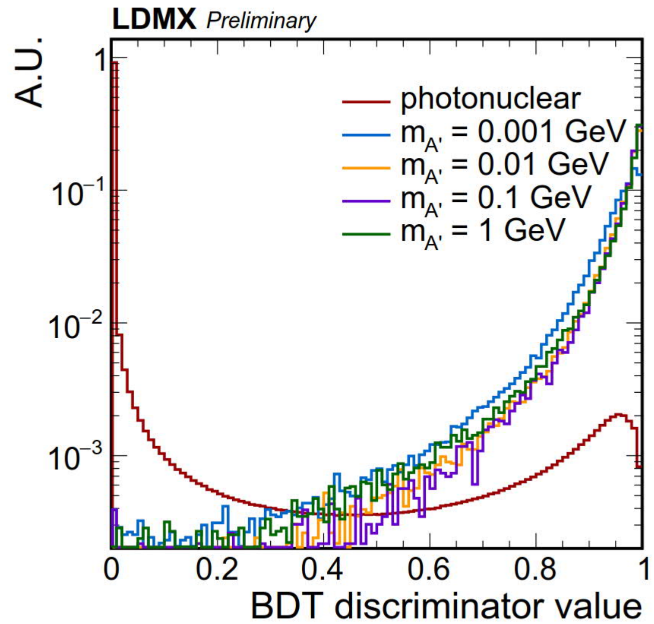
- in LDMX:
  - 40 radiation lengths deep
  - 30 layers, 7 modules each
  - central modules with higher granularity (up to 1000 channels)

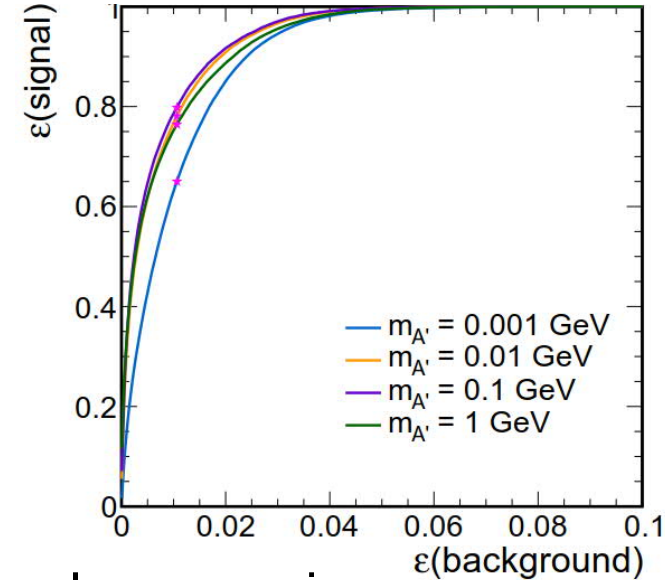
  ECal can track minimum ionizing particles, for rejection of $\gamma \rightarrow \mu^+\mu^-$ and $\gamma \rightarrow$photonuclear events



Electromagnetic Calorimeter (ECal)





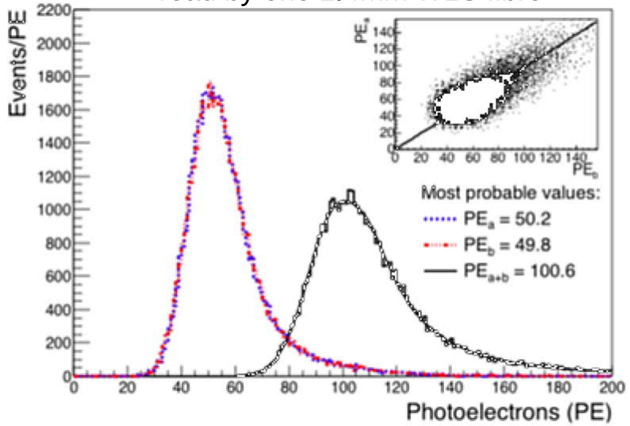


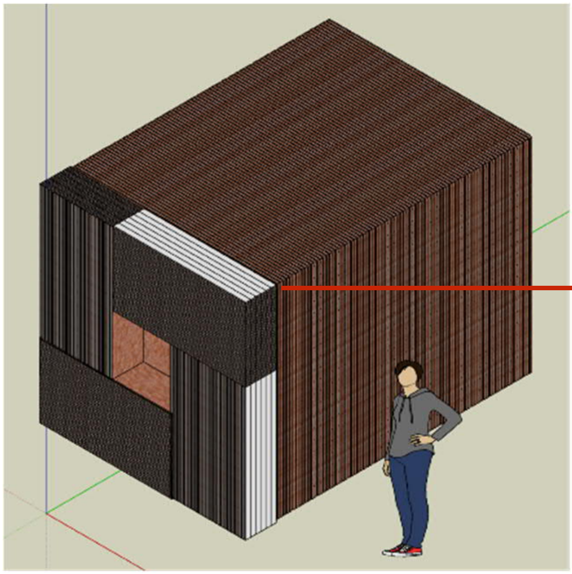
Promising results in terms of background suppression

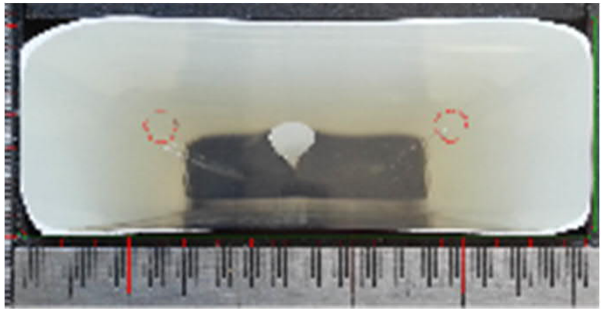
Hadronic Calorimeter (HCal)

- Main task: **Veto background**
  - In particular: photo-nuclear reactions that produce only neutral particles
    - e.g. $\gamma n \rightarrow n n \bar{n}$, or worst case with photo-nuclear reactions where E_{γ} taken by essentially just one neutron
    - Sampling calorimeter with plastic scintillator (extruded polystyrene with WLS fibre) + absorber (steel)
    - Read by SiPM with either mu2e system or the system developed for CMS

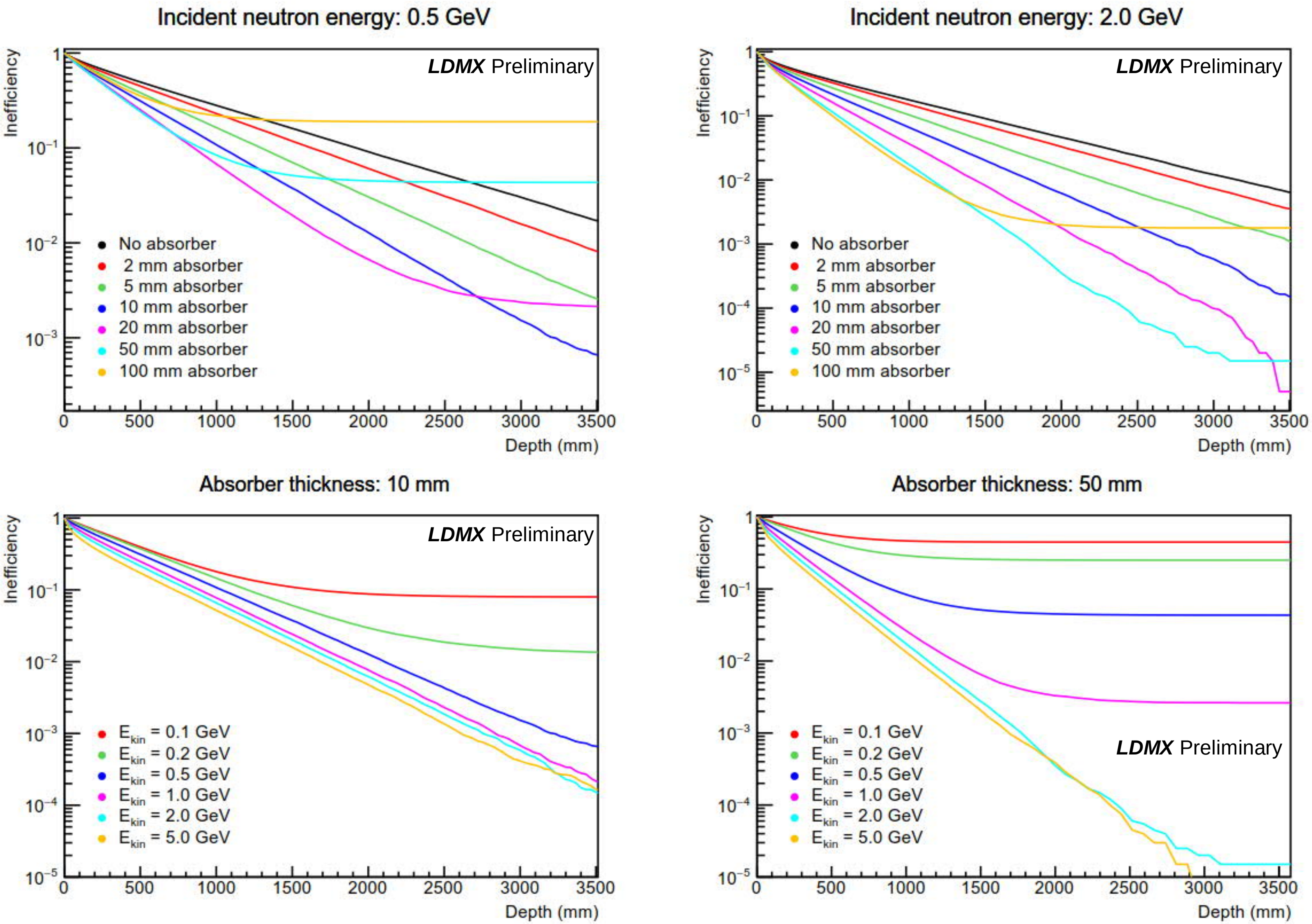
MIP through a 2cm thick, 2m long bar read by one 1.4mm WLS fibre







Hadronic Calorimeter (HCal); ongoing optimization

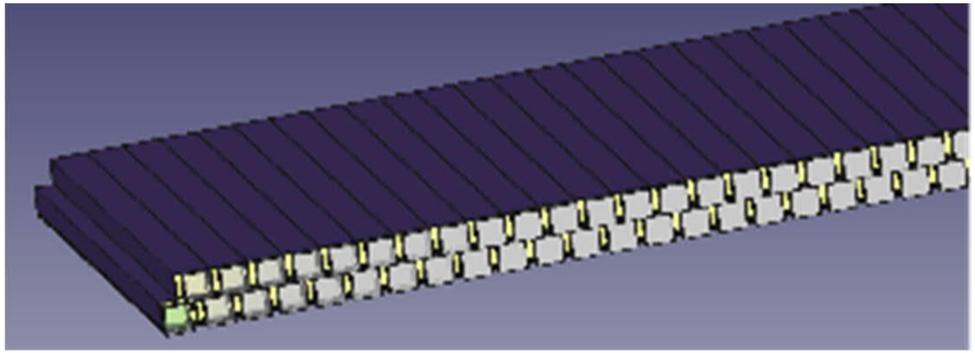


- Simulation studies show potential to get background free for 4×10^{14} EoT

Trigger

- use missing energy signature
  - reject ~beam-energy signals (non interacting e^-, bremsstrahlung,…)
  - use energy deposition in first 20 ECal layers

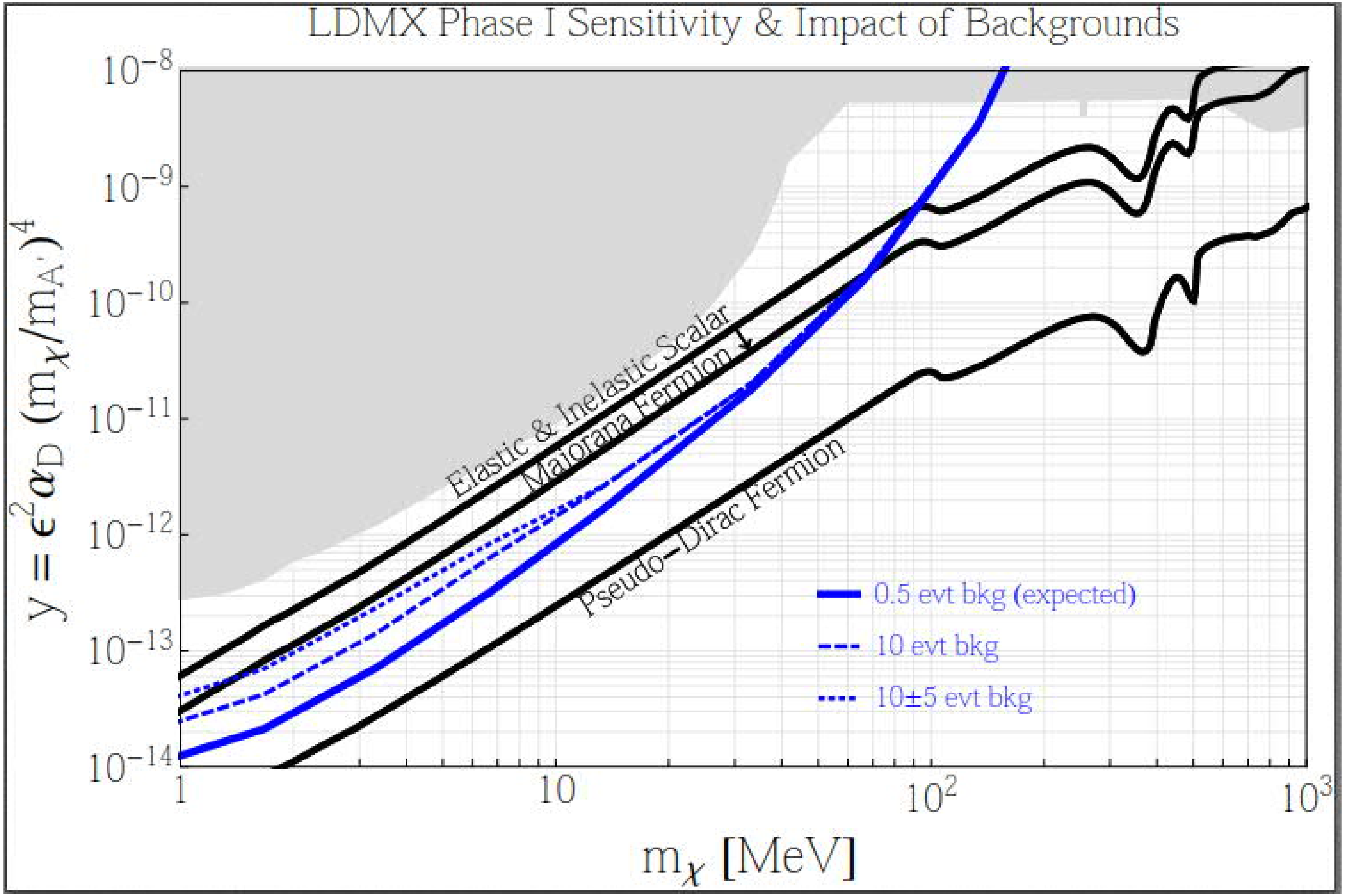
- to avoid triggering on empty bunches: (segmented) scintillator behind target
  - also helps getting an estimate of actual number of electrons
    - crucial for phase 2



46 MHz bunch frequency, 1 e^-/bunch

Trigger	Prescale factor	Rate (Hz)
Physics Trigger	1	*4000*
Background-Measurement Triggers		*500*
ECAL Missing-Energy > 1 GeV	5000	100
HCAL hit > 2 MIP	1000	100
HCAL hit > 20 MIP	1	100
HCAL MIP track		200
Detector-Monitoring Triggers		*500*
Zero-bias (trigger scintillator ignored)	4.6×10^5	100
Beam-arrival (trigger scintillator)	1.5×10^5	300
Empty-detector (trigger scintillator veto)		100
Total Trigger Budget		5000

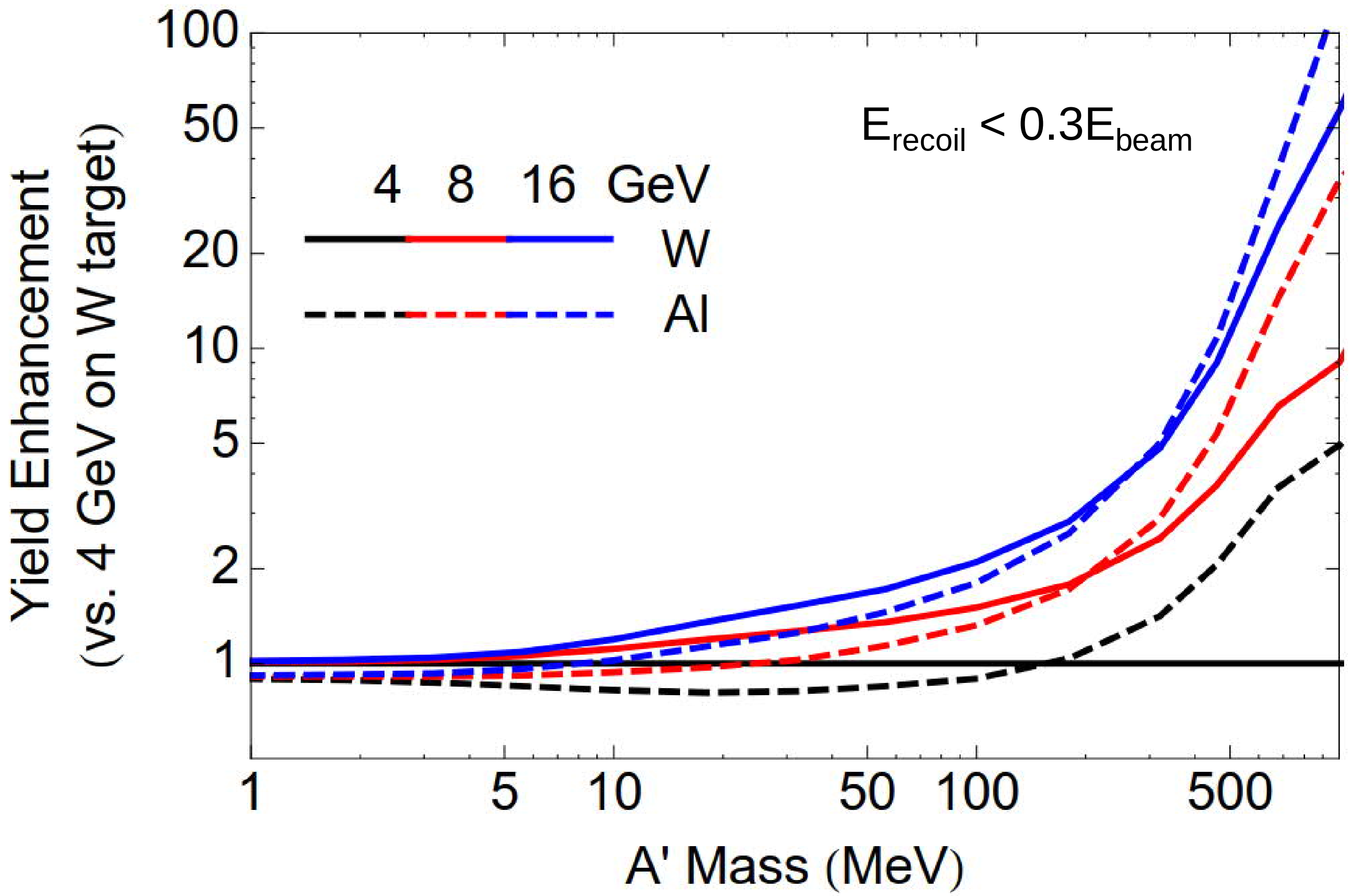
Projected sensitivity for phase-1



Projected sensitivity for 4 × 10^{14} 4 GeV electrons on target

Towards phase-2: Higher beam energy and varying target

Beam energy and target material affect the A’ production cross-section, especially at high $m_{A'}$



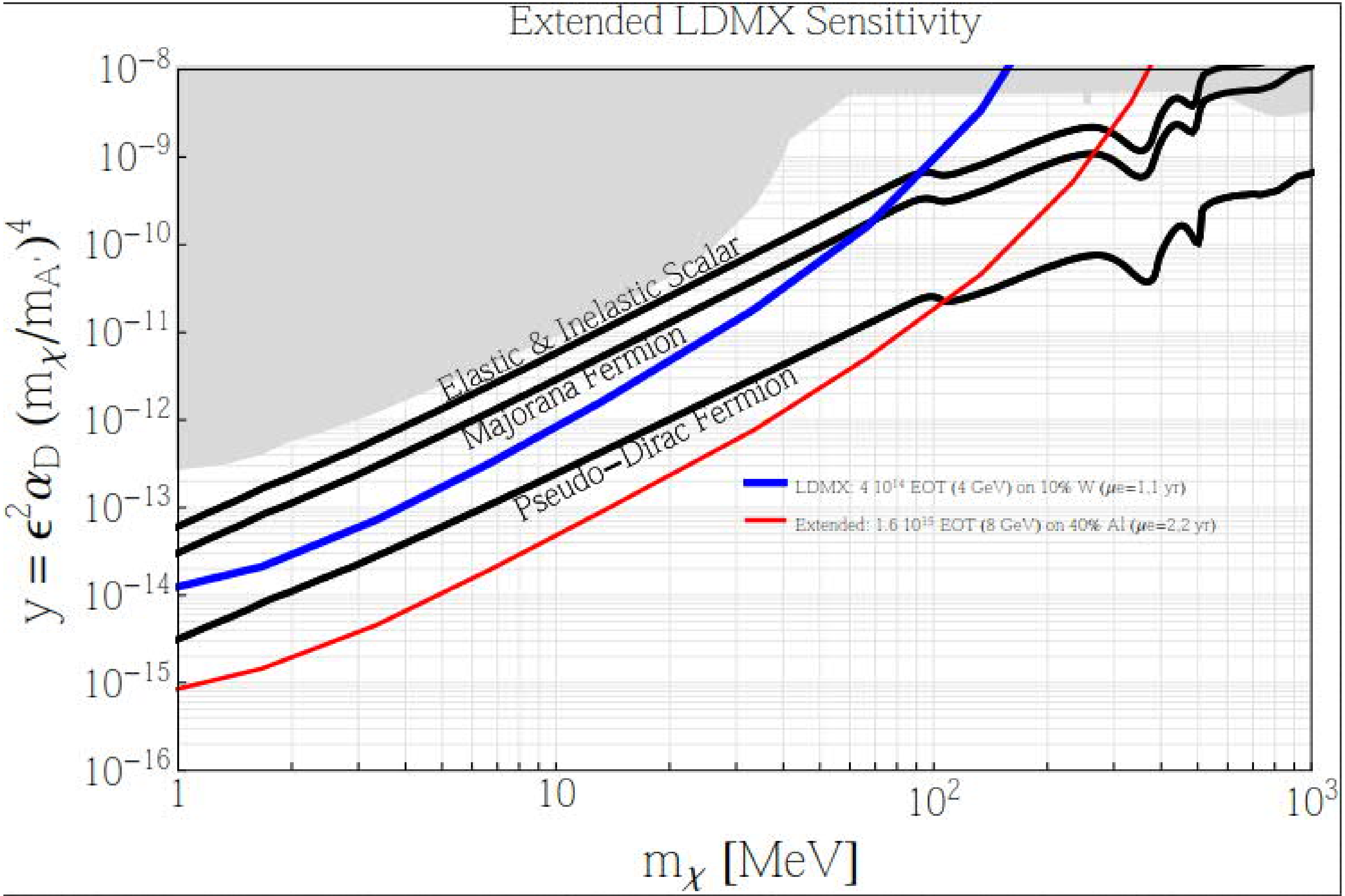
Towards phase-2: Higher beam energy and varying target

- To reach the pseudo-Dirac fermion target:
  - *Factor needed* – needed increase in luminosity relative to Phase-I
  - *Factor achieved* – the increase for a combination of changes to the Phase-I experiment

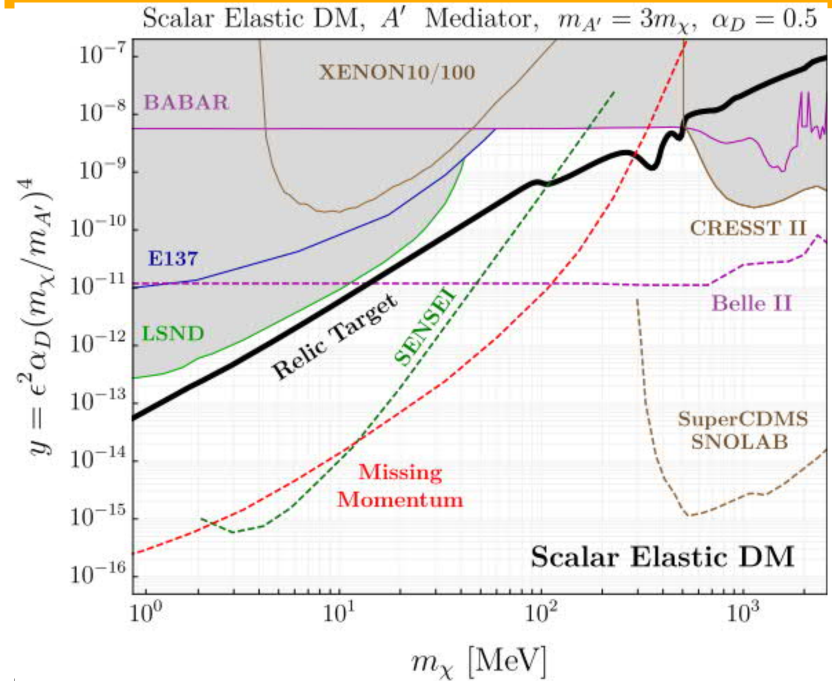
Mass Range [MeV]	Factor needed	E_e [GeV]	E_e Factor	Target $[X_o]$ $Mat'l$	Target Factor	μ_e	Years running	Factor achieved
$0.01 \leq M_\chi < 20$	3	-	1	0.2 W	2	1	1.5	~3
		-	1	0.1 W	1	2	1.5	
		-	1	0.15 W	1.5	2	1	
$20 \leq M_\chi < 80$	6	8	1.5	0.1 W	1	2	1.5	~6
		8	1.5	0.15 W	1.5	1	2	
		4	1	0.15 W	1.5	2	2	
$80 \leq M_\chi < 150$	10^2	8	4	0.4 W	4	2	4	$\sim 10^2$
		* 8	4	0.4 Al	8	2	2	
		16	16	0.4 W	4	1	2	
		16	16	0.4 Al	8	1	1	
$150 \leq M_\chi < 300$	3×10^3	8	4	0.4 Al	8	2	4	$\sim 2 \times 10^2$
		16	16	0.4 W	4	2	4	$\sim 5 \times 10^2$
		16	16	0.4 Al	8	5	5	$\sim 3 \times 10^3$

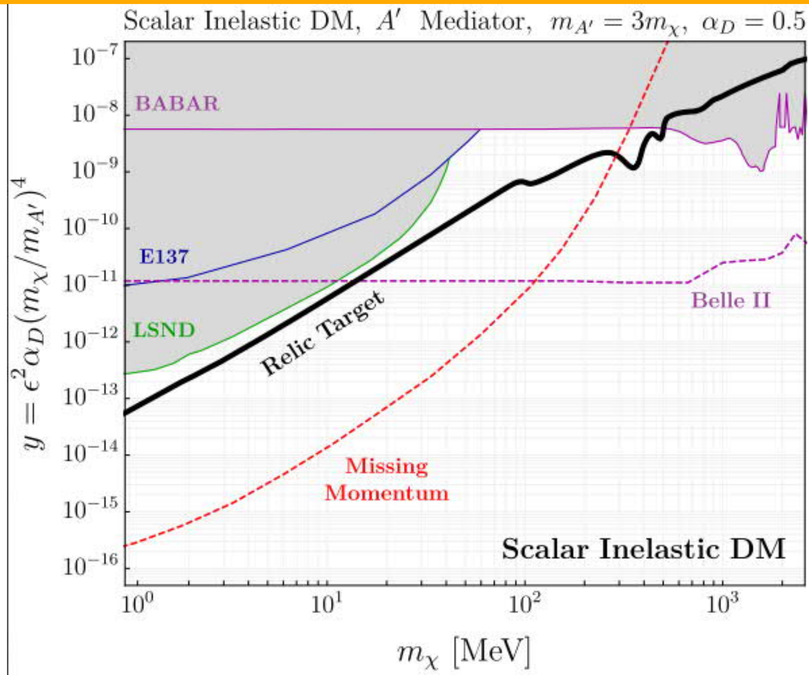
Projected sensitivity for phase-2’ ; conservative estimate from phase-1 studies

Projected sensitivity for 1.6×10^{15} 8 GeV electrons on target

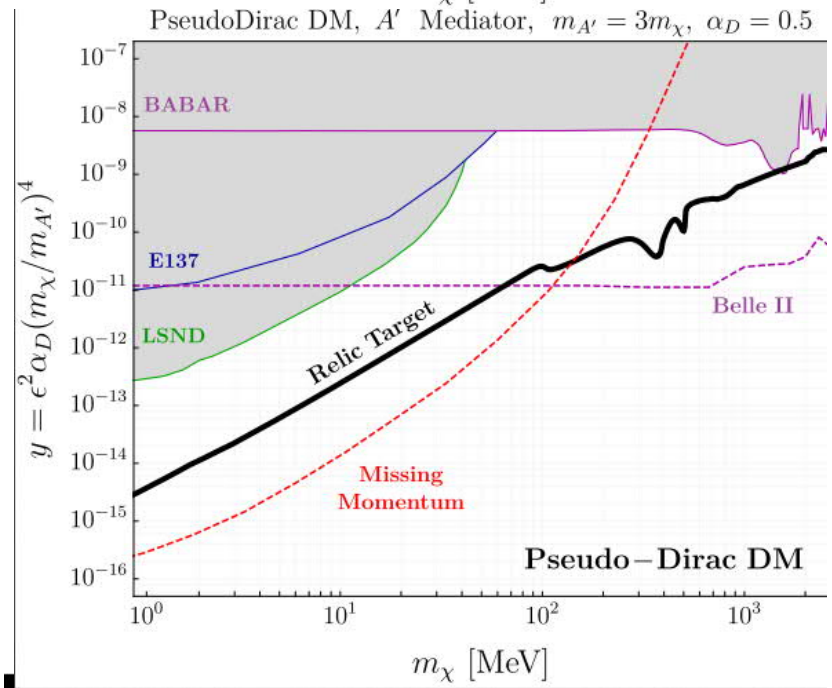


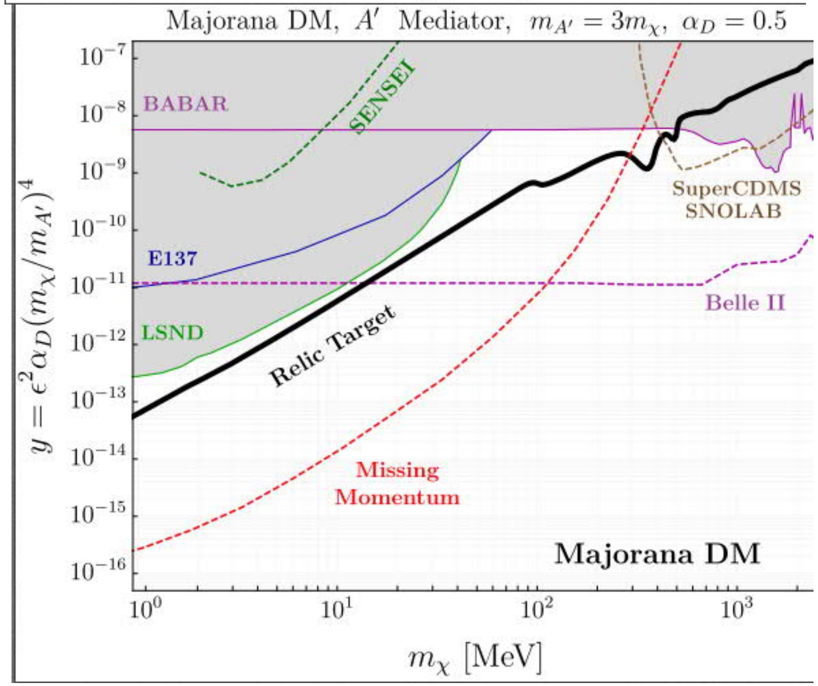
Projected sensitivity for phase-2 ; fully using the available $\int \mathcal{L}\, dt$



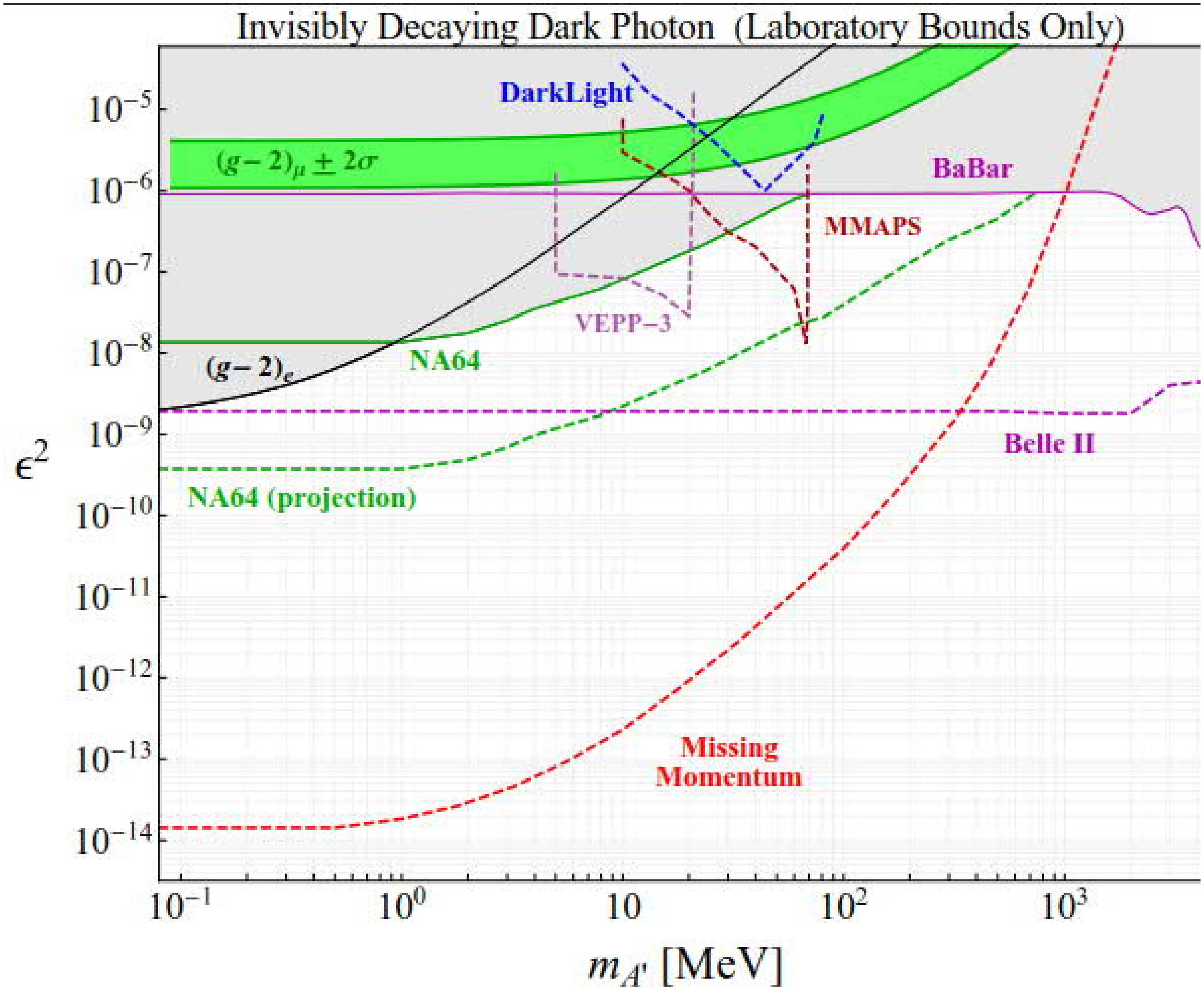


- α_D = 0.5, $m_{A'}/m_\chi$ =3 (conservative, weakest bounds)

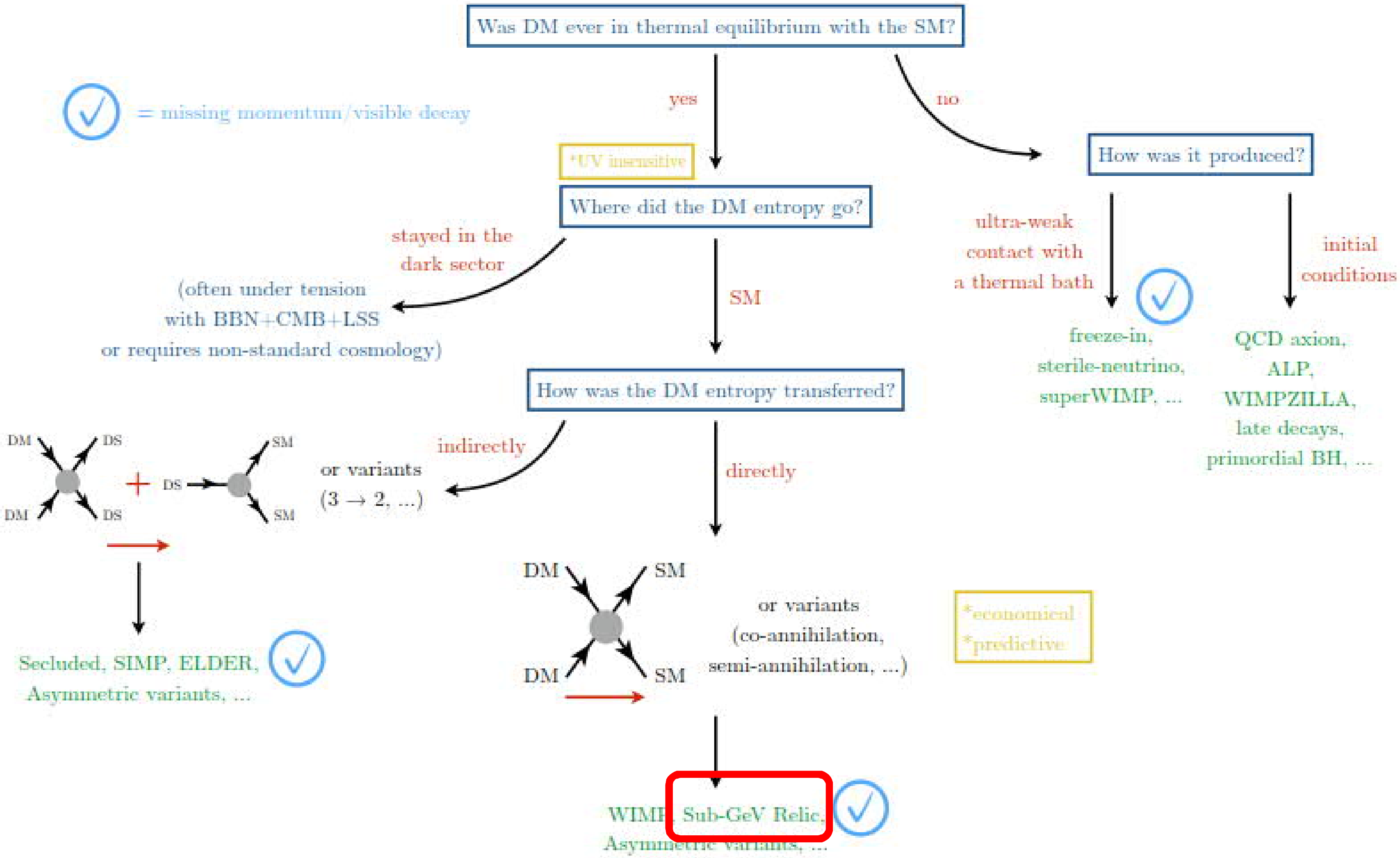




Sensitivity invisibly decaying mediator without DM interpretation



Other BSM physics topics



Asher Berlin et al, “Dark Matter, Millicharges, Axion and Scalar Particles, Gauge Bosons, and Other New Physics with LDMX”, soon to be posted on arXiV

Other BSM physics topics

- DM with quasi-thermal origin
  - Asymmetric
  - Strongly-Interacting Massive Particle (SIMP)
  - Elastically Decoupling Relic (ELDER)
- New invisibly decaying mediators in general, improve sensitivity for Dark Photon
- Displaced vertex signatures
- Milli-charged particles

- Photo- and electro-nuclear processes (for future neutrino experiments)

Preliminary assessments show the LDMX will also be sensitive here, but, studies of this potential is just starting, so too early to report now

Please see: Asher Berlin et al, "Dark Matter, Millicharges, Axion and Scalar Particles, Gauge Bosons, and Other New Physics with LDMX", soon to be posted on arXiV

Collaboration and Preliminary Design Report

Light Dark Matter eXperiment (LDMX)

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John Jaros,[5] Robert Johnson,[6] Gordan Krnjaic,[7] Jeremiah Mans,[4] Takashi Maruyama,[5]
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(Dated: June 15, 2018 : To be posted on LDMX Confluence Page)

We present an initial design study for a small-scale accelerator experiment to discover sub-GeV dark matter, probing dark matter couplings to electrons well beyond that motivated by thermal freezeout, and over a large mass range. The experiment, referred to as the Light Dark Matter Experiment (LDMX), would also be sensitive to a range of visibly and invisibly

The draft Preliminary Design Report has become sufficiently mature to be made public:
https://confluence.slac.stanford.edu/pages/viewpage.action?pageId=210534721

LDMX outlook

- Preliminary design report essentially converged
- Some more optimization needed for the hadron calorimeter
- Aim for detector prototyping during 2019
- Could start construction already 2020/2021 pending funding
- Potential for additional sub-GeV physics channels being explored
- More studies required for phase-2, but just based on the phase-1 studies it seems clear that most of the phase-2 goals can be reached without major technical developments

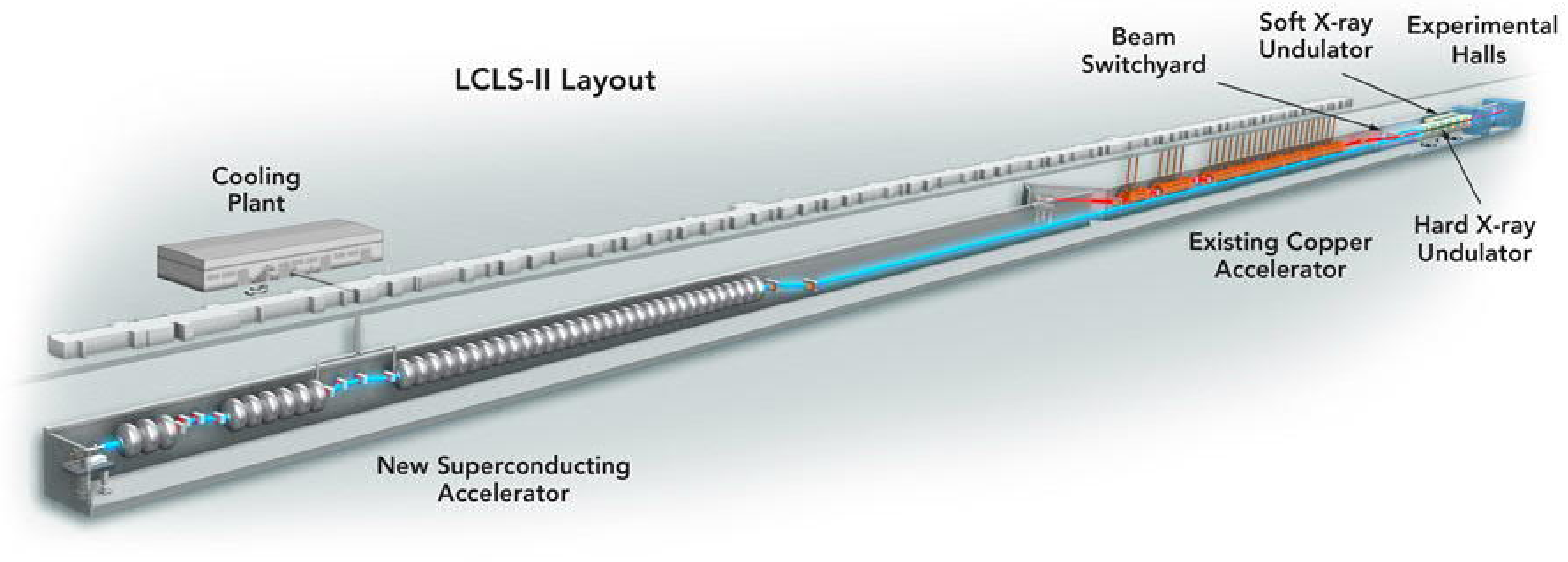
Excellent potential to probe thermal targets in MeV - GeV range

Sensitive to a range of sub-GeV physics

a Primary Electron Beam Facility at CERN

Beam for the LDMX baseline planning: DASEL

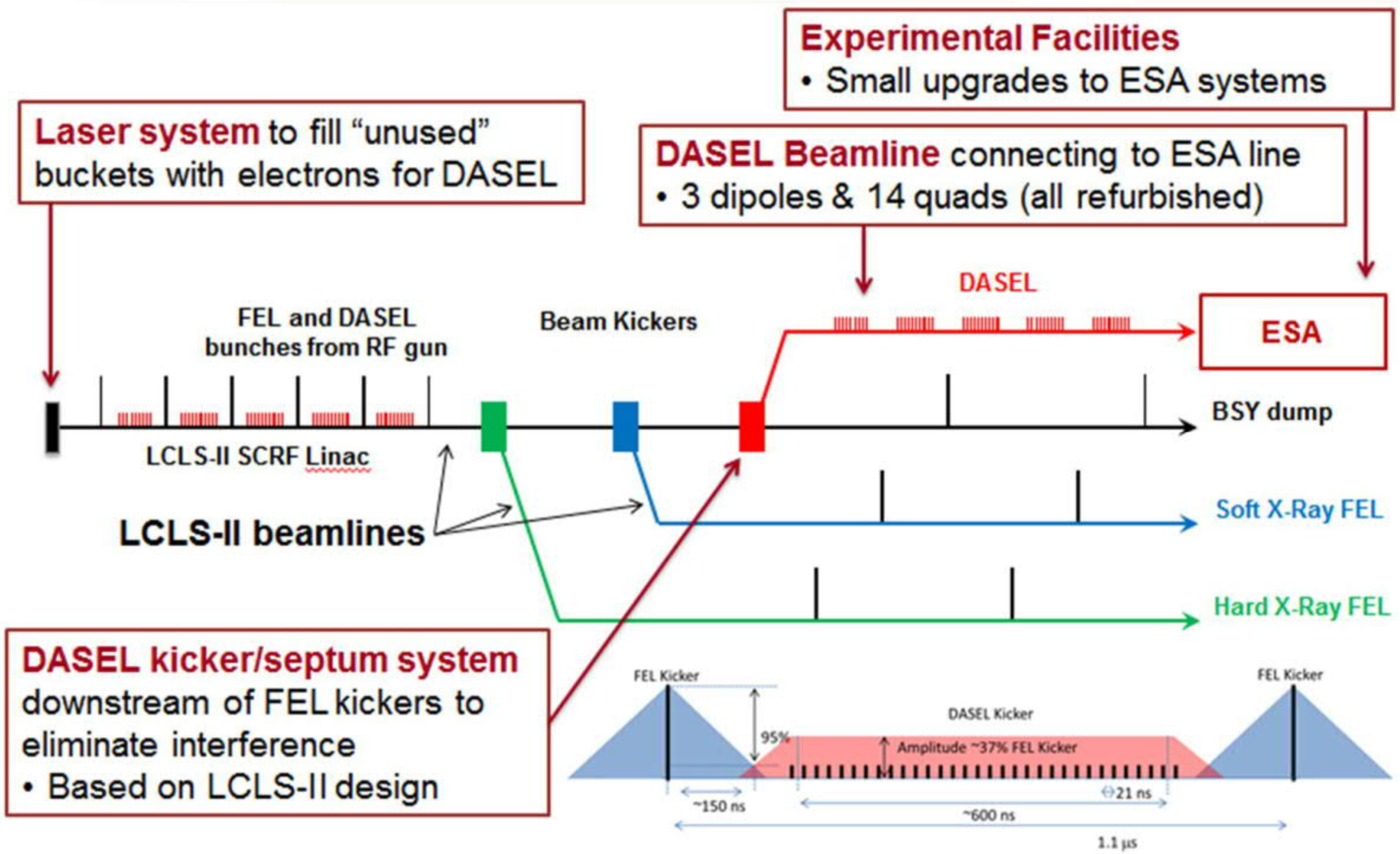
- Dark Sector Experiments at LCLS-II (Linac Coherent Light Source II) at SLAC; parasitic operation



Beam for the baseline planning: DASEL

- Dark Sector Experiments at LCLS-II (Linac Coherent Light Source II) at SLAC; parasitic operation

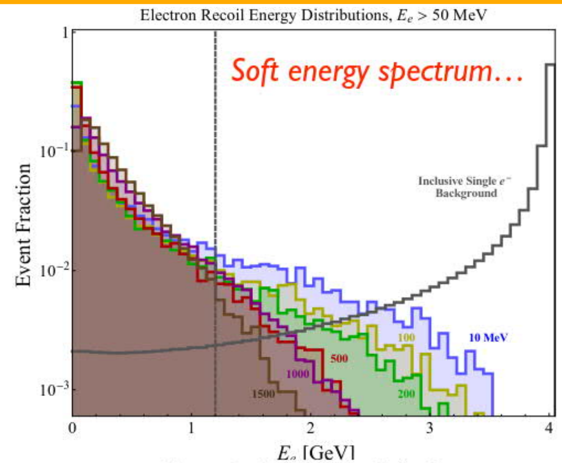
T. Raubenheimer

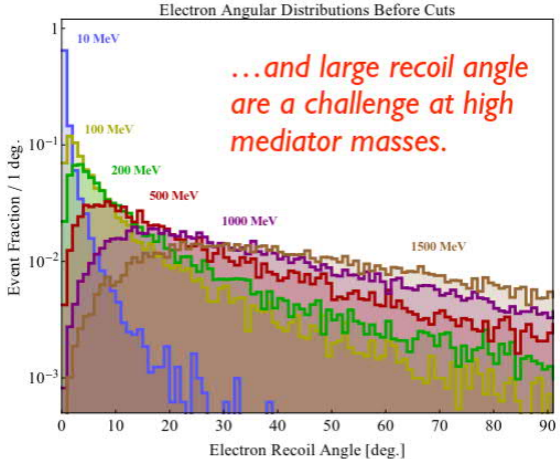


- First 4 and later 8 GeV; 46 MHz (phase-1, 4×10^{14} EoT), 186 MHz (phase-2, 10^{16} EoT)

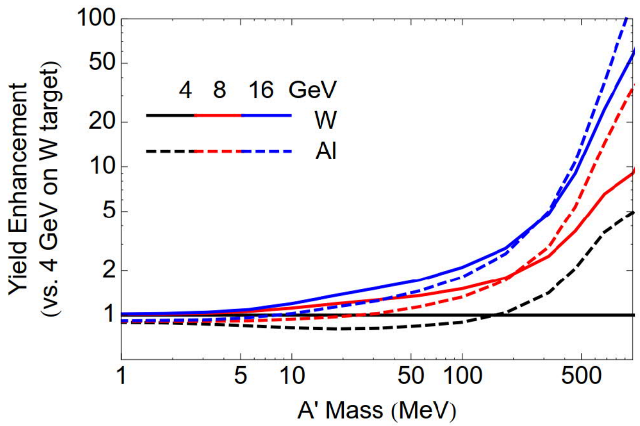
An Electron Beam Facility at CERN

- DASEL starts by delivering a 4 GeV electron beam; 4 GeV is not optimal
  - Higher energy makes it easier to reject photo-nuclear reactions (more difficult to hide the γ-energy)
  - Higher energy increases the yield and acceptance at higher $m_{A'}$
- Optimal beam energy around 15 GeV
  - At the time of LEP, CERN SPS accelerated electrons up to 22 GeV and injected into LEP
  - Could this capability be reactivated?
- Addressed by the Physics Beyond Colliders working group, PBC-acc-e-beams



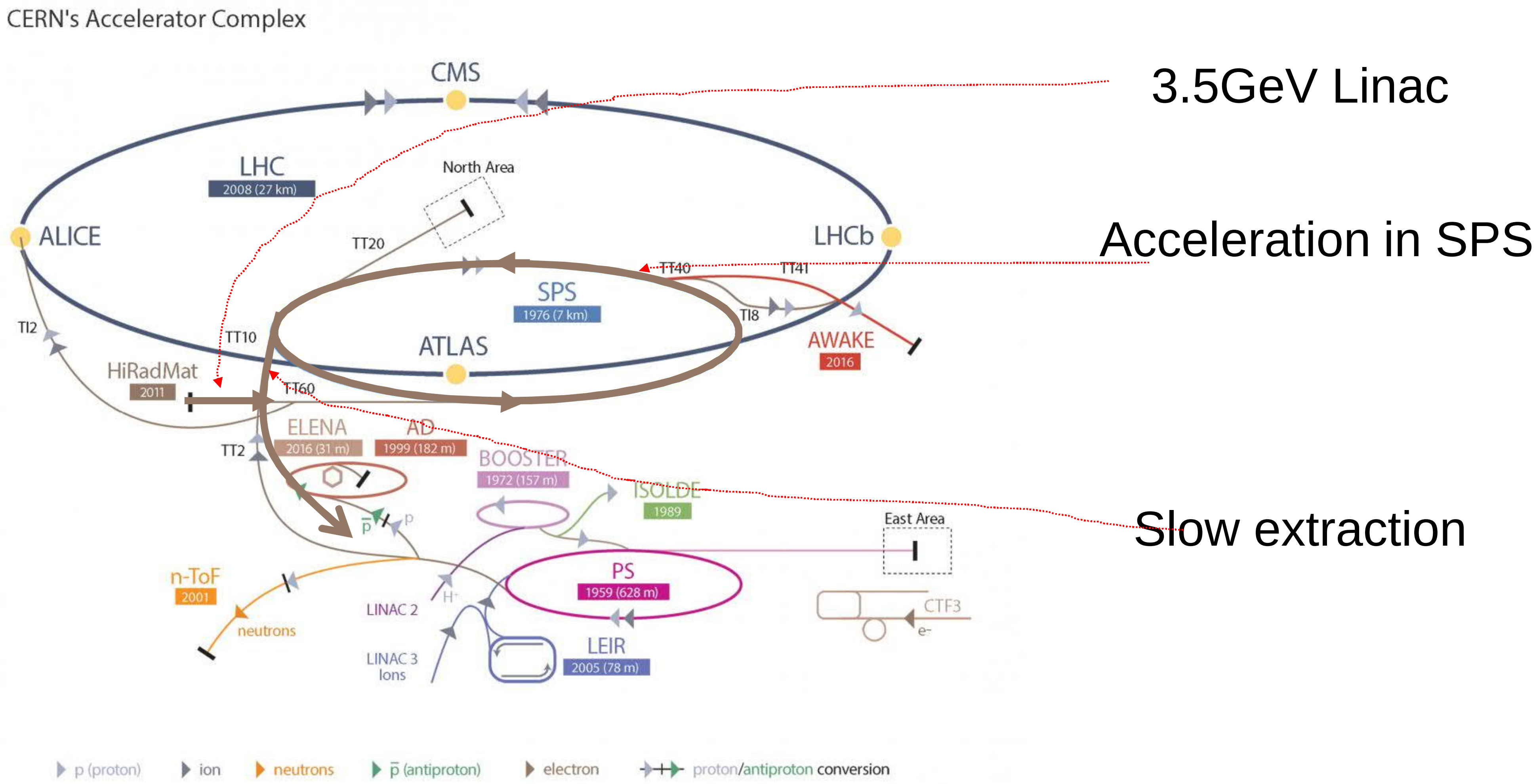


$\sim \left(\frac{m_{A'}}{E}\right)^{1/2}$

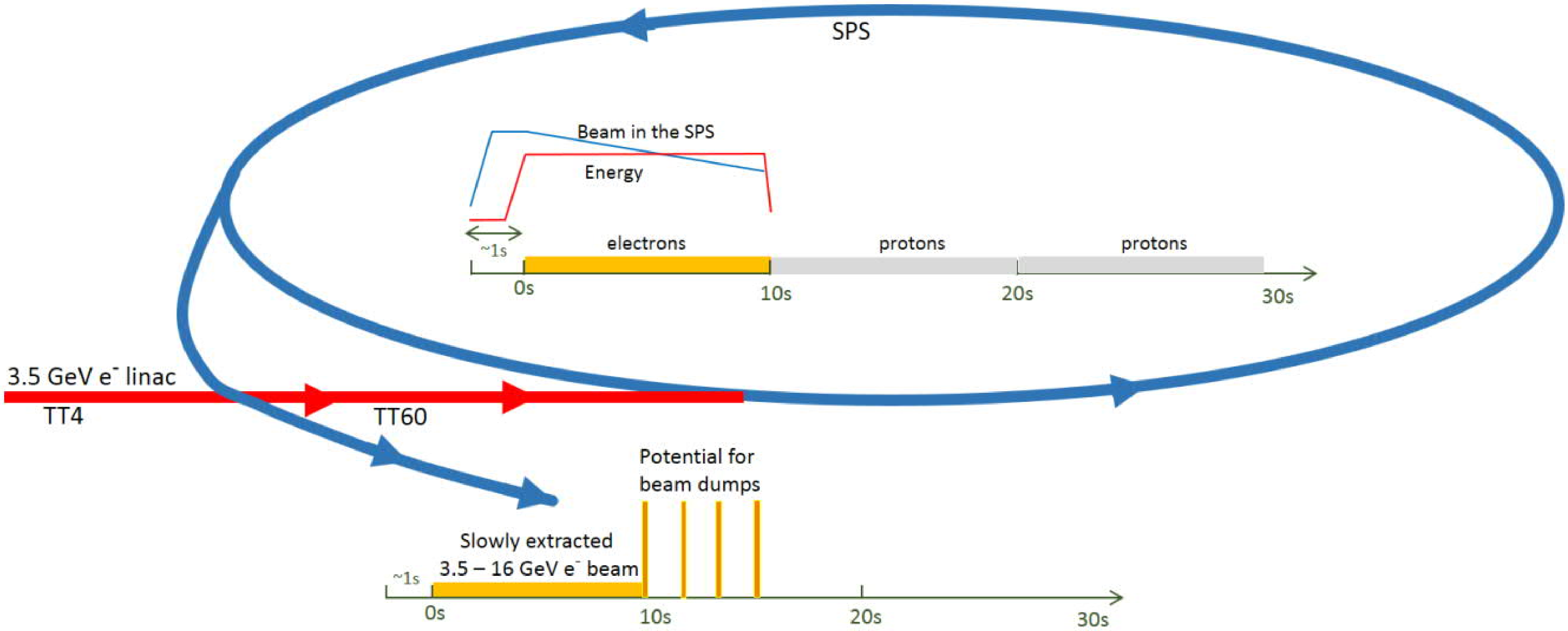


Relative yield

An Electron Beam Facility at CERN

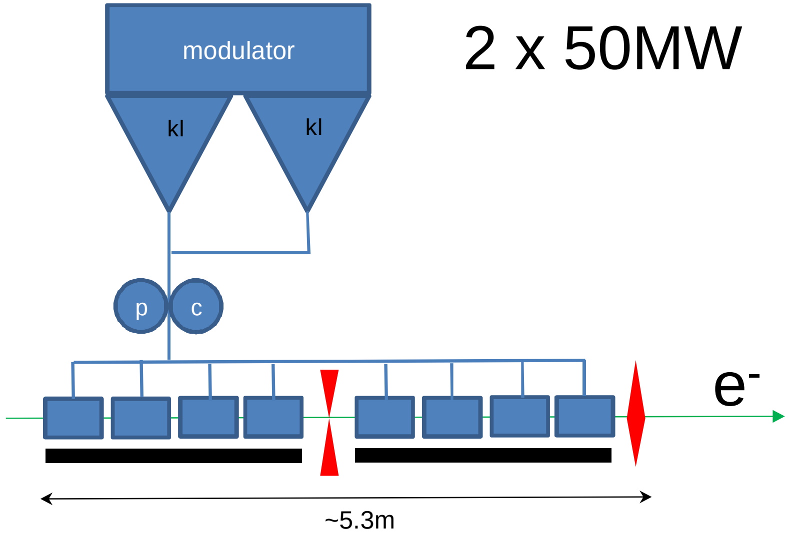


An Electron Beam Facility at CERN

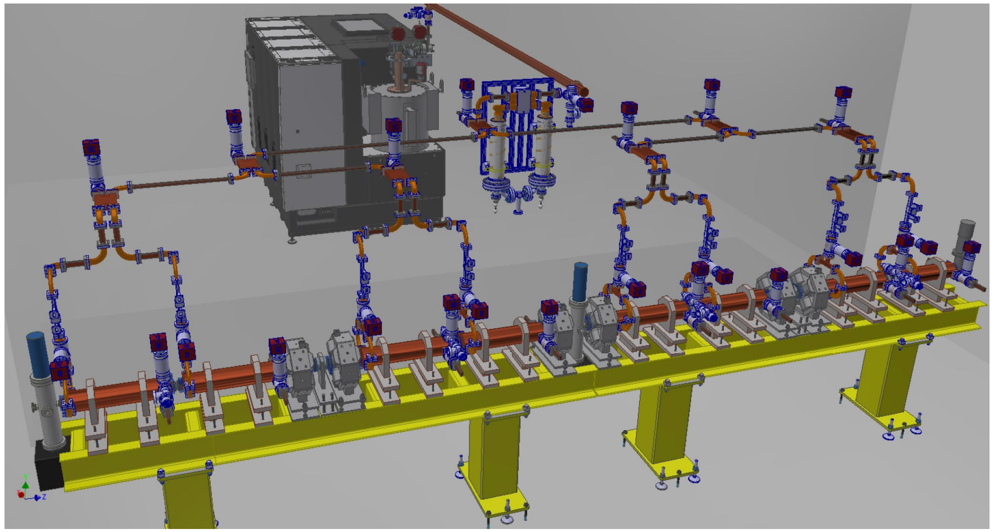


Linac parameters

- 0.1GeV S-band injector (~3 GHz)
- 3.4GeV X-band linac (~12 GHz)
  - High gradient CLIC technology
  - 13 RF units to get 3.4 GeV in ~70 m [1]



Possible parameters	
Energy spread (uncorrelated*)	<1MeV
Bunch charge	52 pC
Bunch length	~5ps
Norm. trans emittance	~10um
N bunches in one train	40
Train length	200 ns
Rep. rate	100 Hz



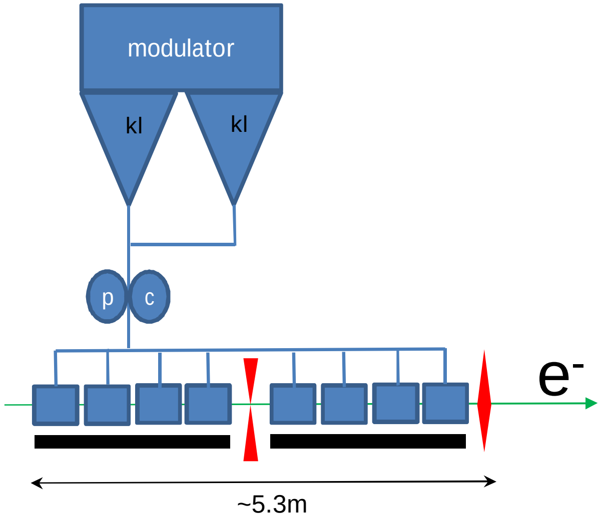
RF DESIGN OF THE X-BAND LINAC FOR THE EUPRAXIA@SPARC_LAB PROJECT
M. Diomede Et al., IPAC18

Linac components are available

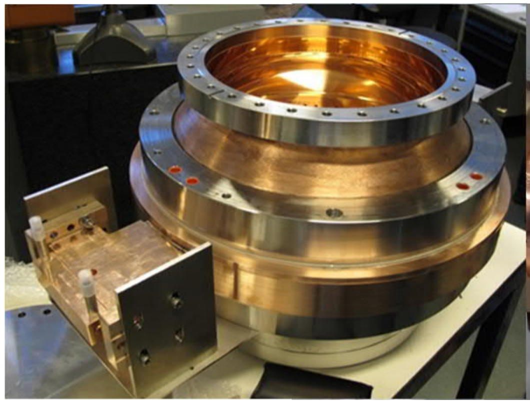
- Examples

Klystron

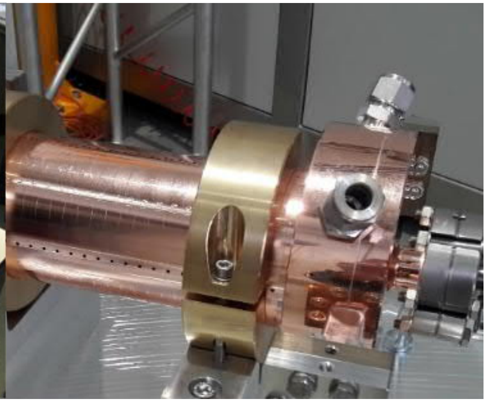
Modulator



- One RF unit accelerates 200 ns bunch train up to 264 MeV



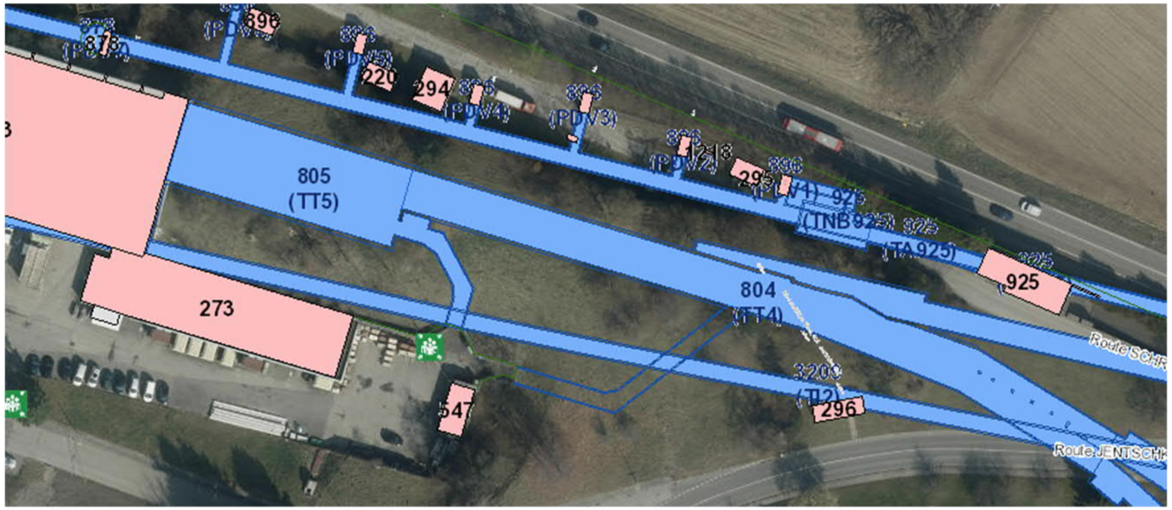
Pulse compressor

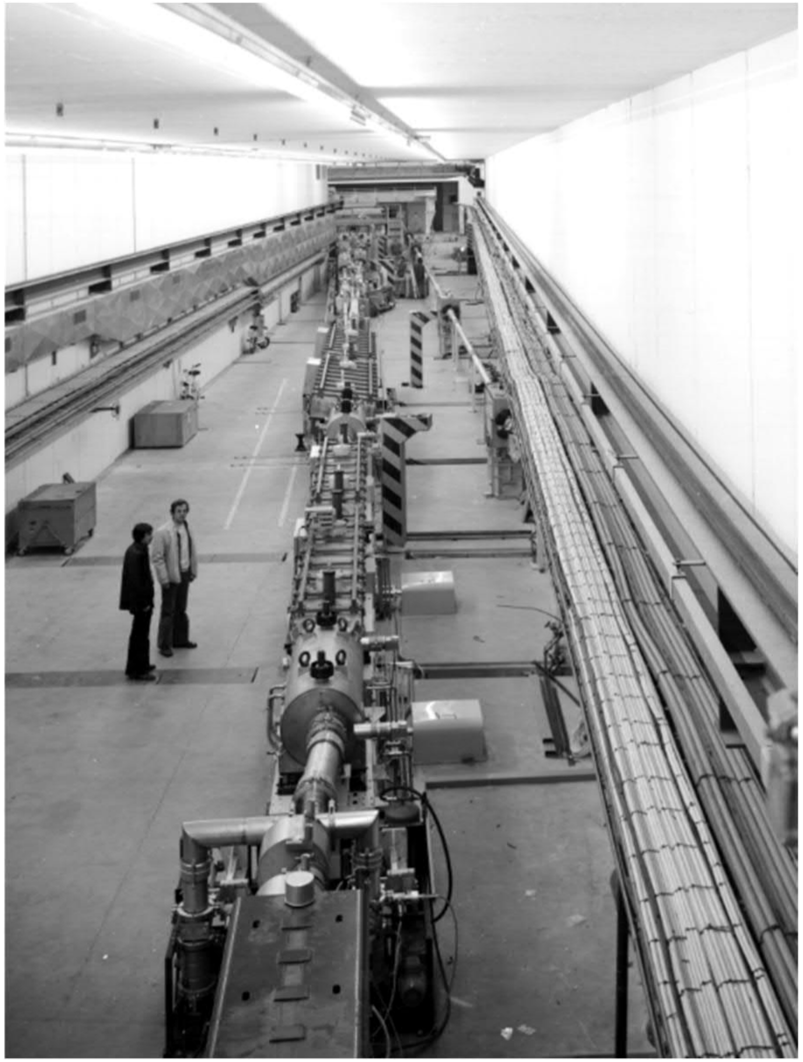


Accelerating structure

Linac in TT5/TT4

- To be installed in the available transfer tunnels TT4, in line with the SPS





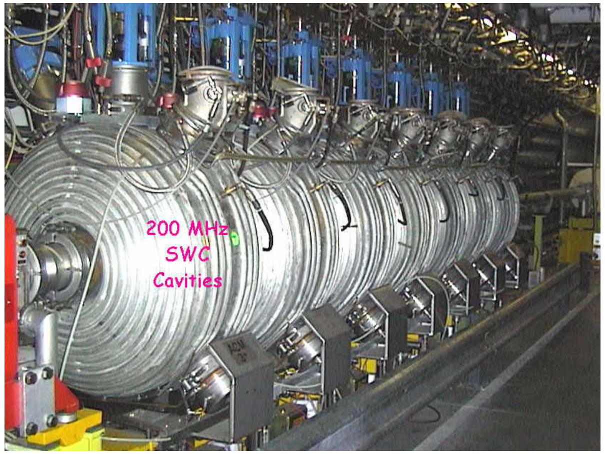
Injection into the SPS

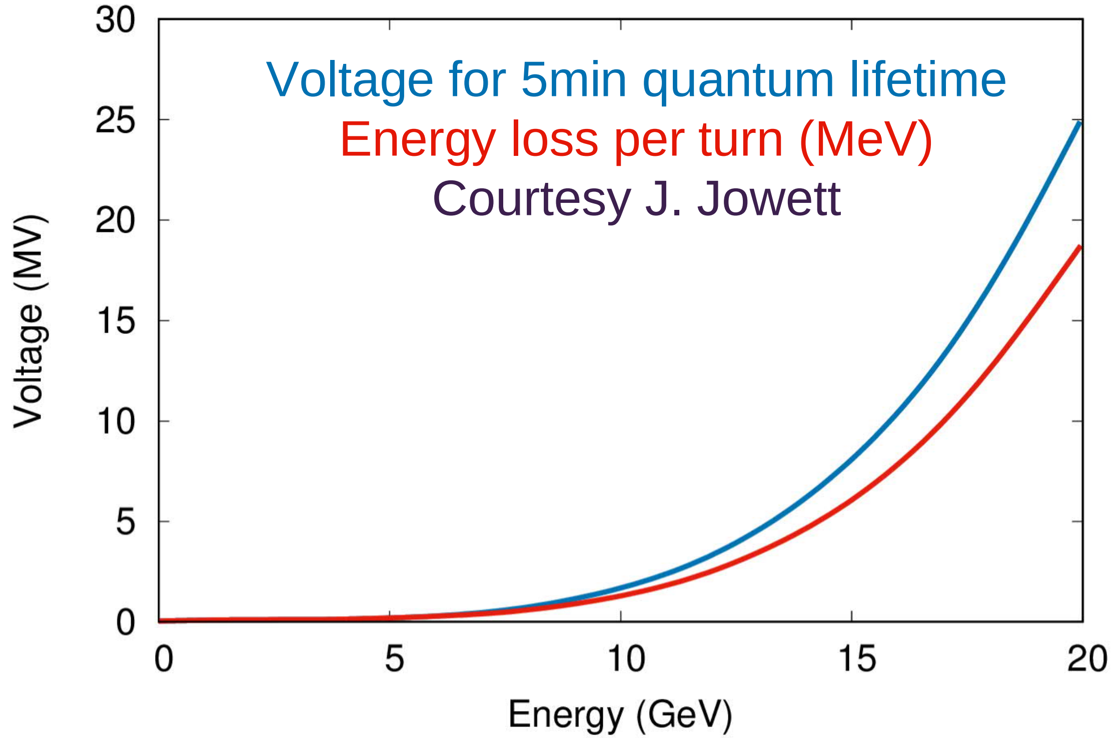
Bunch to bucket injection in
the 200 MHz SPS longitudinal
RF structure.

Total of 75 trains of
40 bunches
3000 bunches giving
10^{12} electrons in the ring

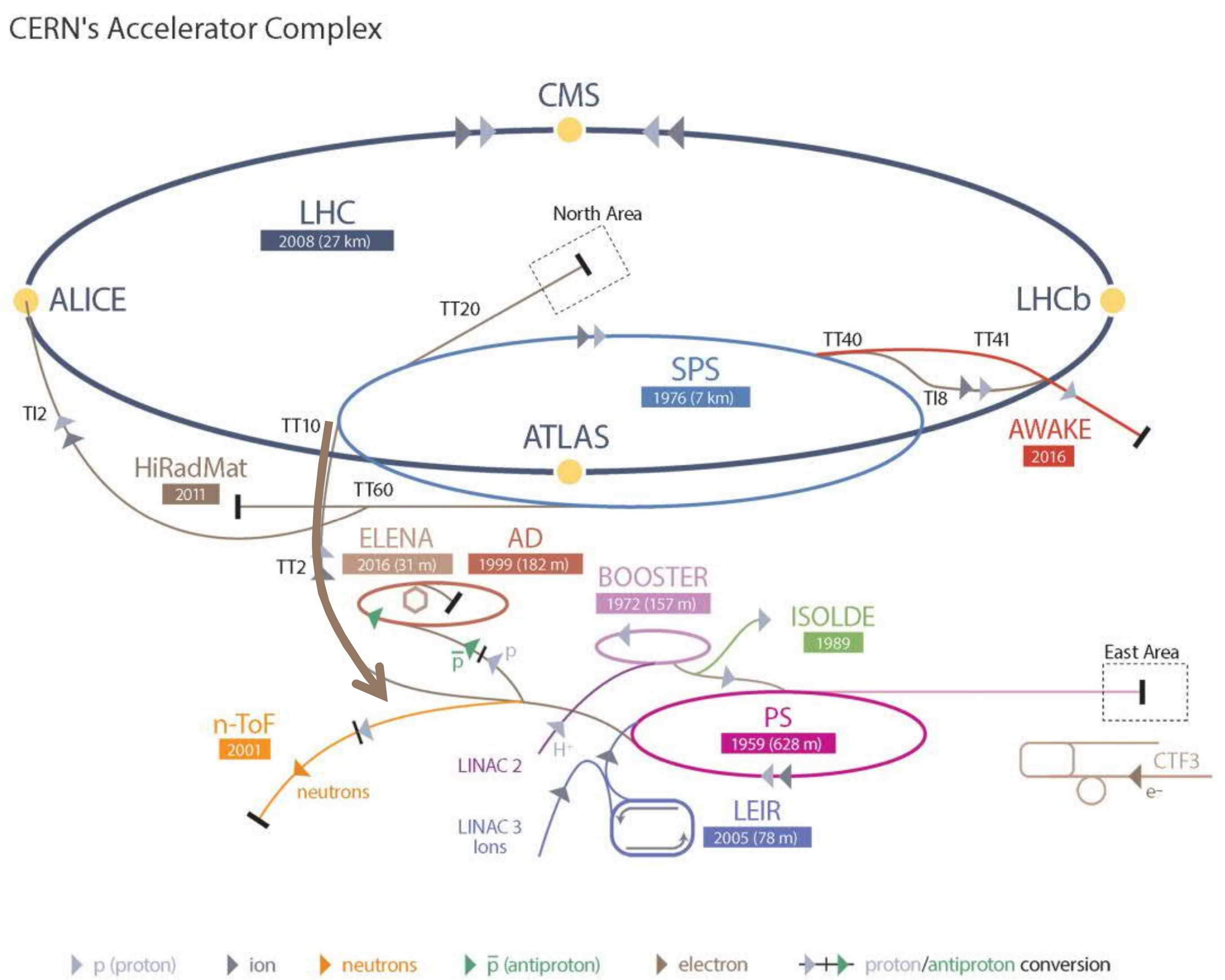
SPS RF system

- Acceleration to 16 GeV can safely be achieved
- Existing 200 MHz cavities from LEP era to be re-installed
  - Need 10MV for 16GeV electrons
  - (13) 200 MHz Standing Wave Cavities [1 MV per cavity] are available
- Space is available to install them
- 5ns, 10ns, … 40 ns longitudinal structure is imposed by the available cavities



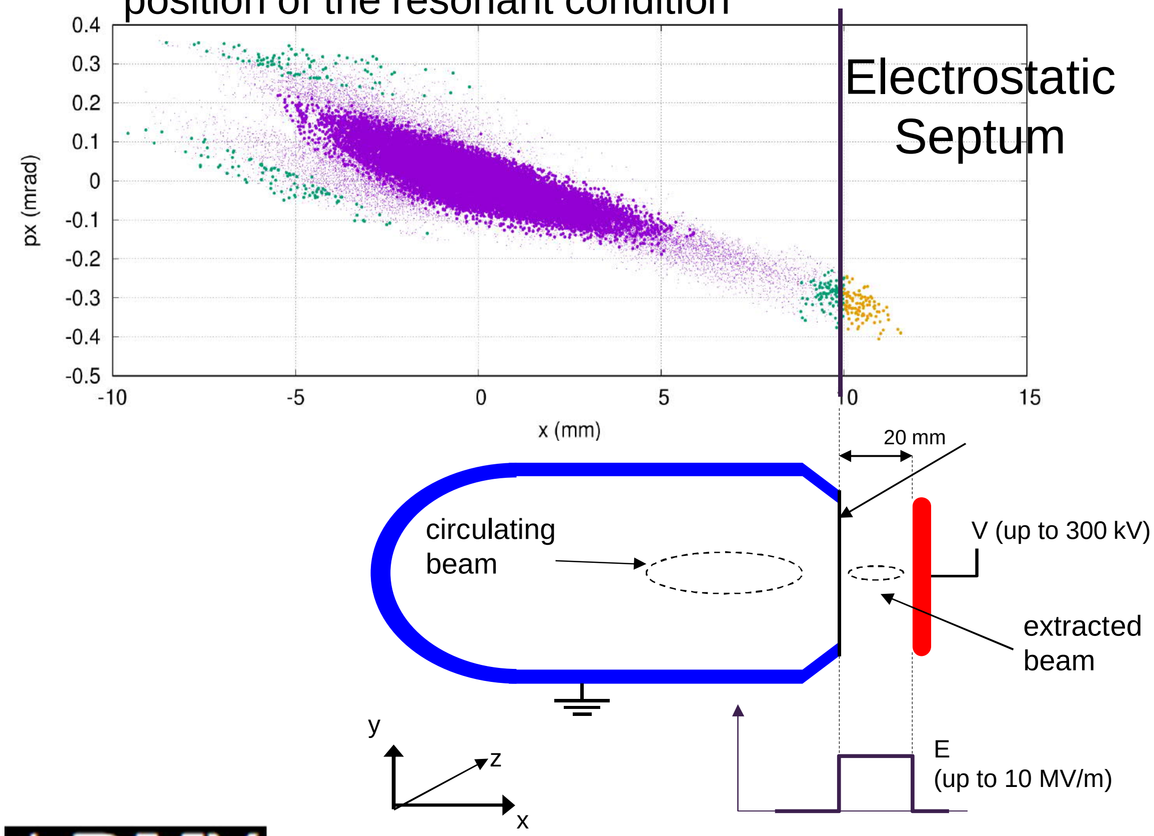


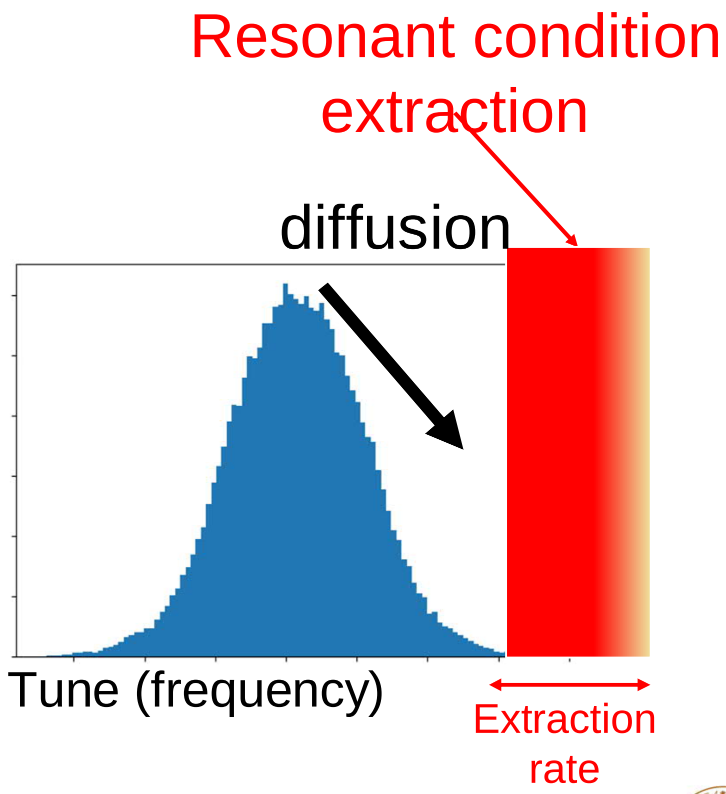
Slow extraction to experiments



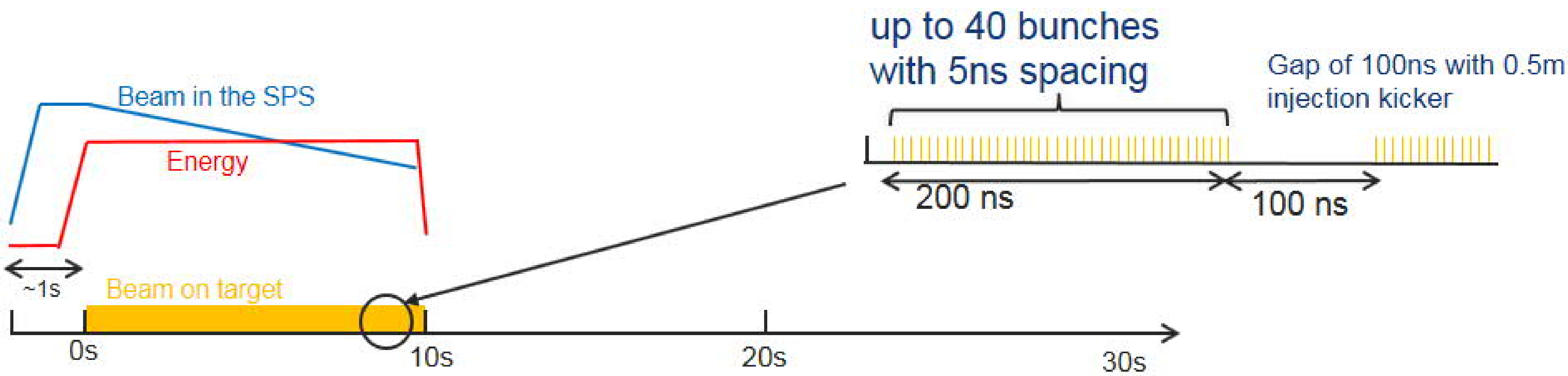
Slow extraction principle, in frequency space

- 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





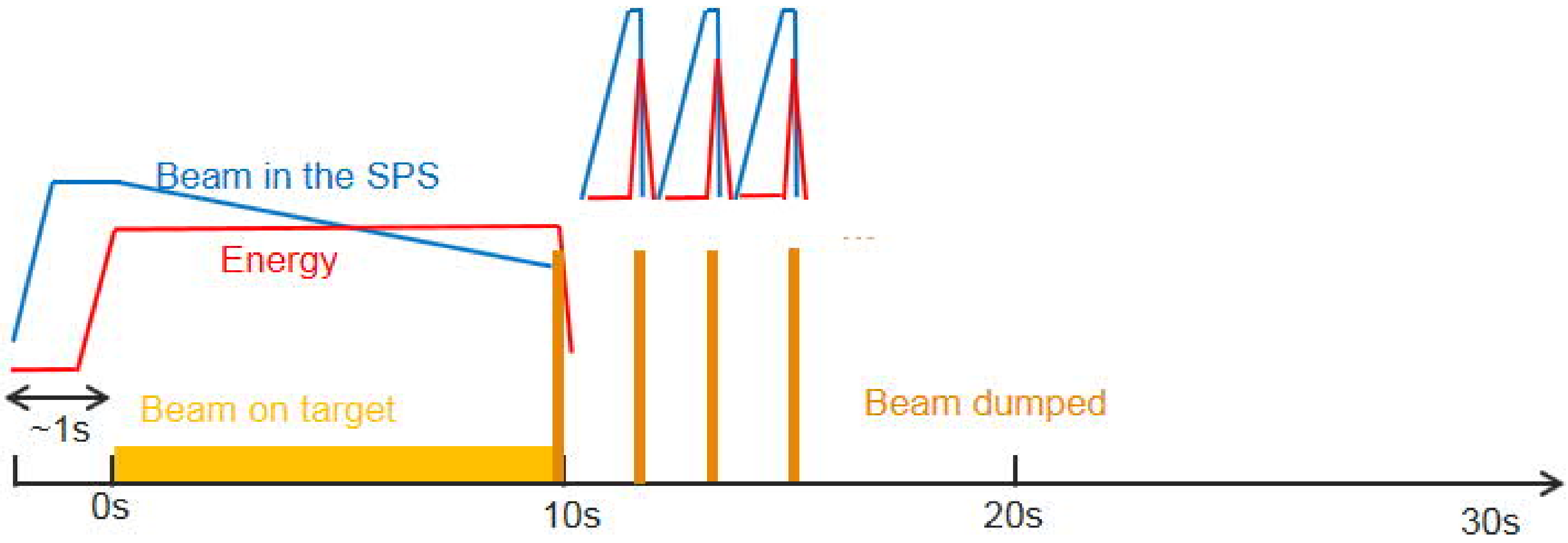
Structure of extracted beam



- 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

Beamdump with potential for 1-3 x 10^{18} electrons per year

- After this beam has been delivered there is still a lot of electrons in the SPS
- These can quickly be dumped into a separate beam line
  - 10^{12} electrons within 23µs, possibly up to 4 times more



Such a dump could be repeated every 2 s

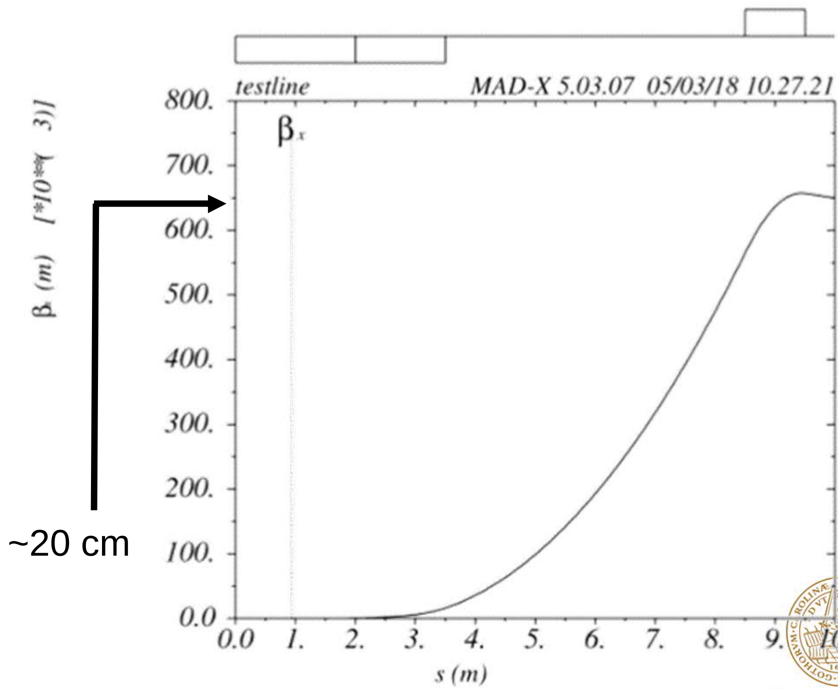
Beam transfer line from the SPS to experiments

- Uses existing TT10 line, designed to transport 10/20 GeV beams, followed by a new 50 m line to the hall

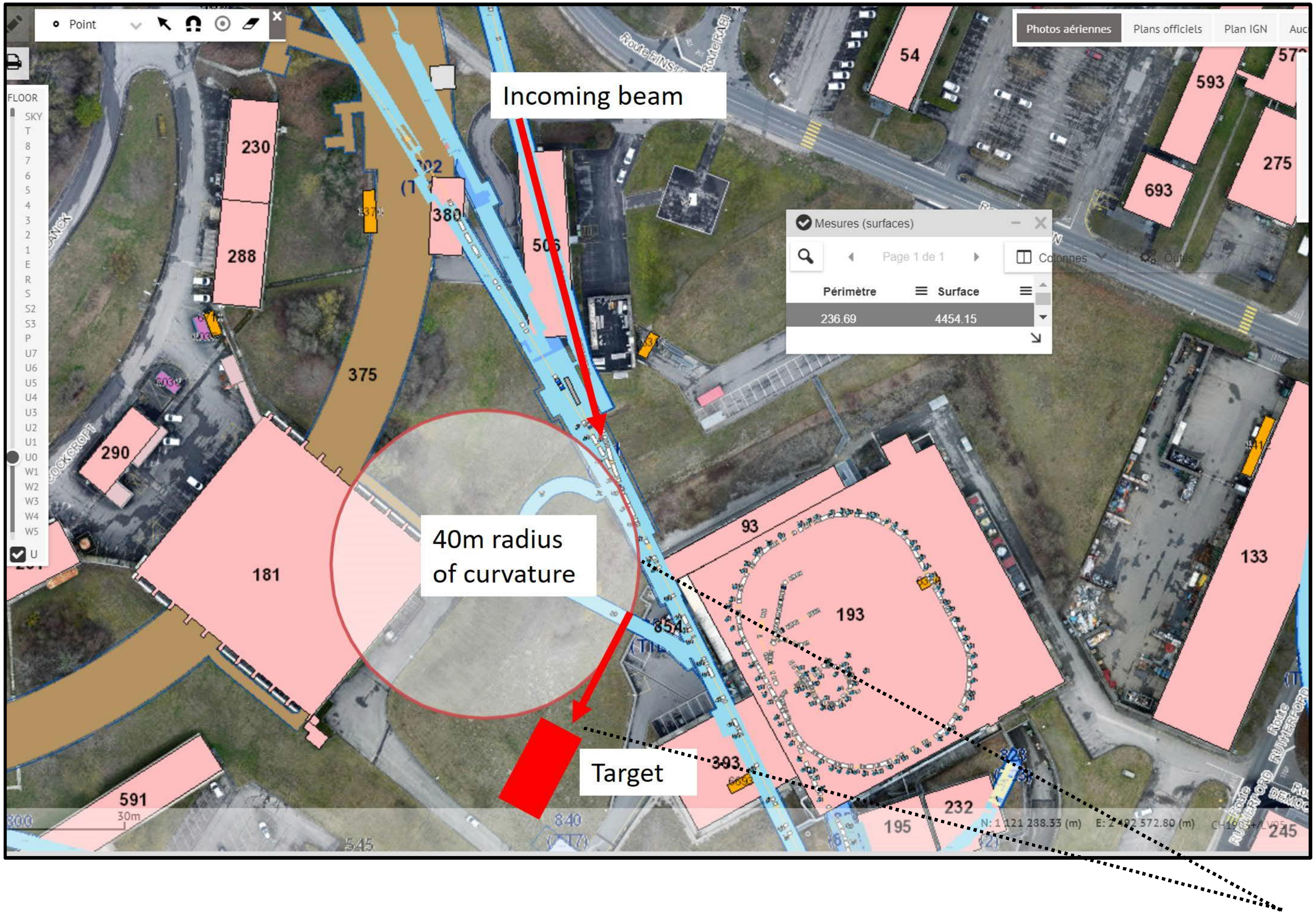
- Collimation in the line for control of beam distribution and intensity

    - ~ Gaussian beam profile can be made almost flat by collimation

- Beam size might be increased greatly at the target
    - Size of beam-spot chosen to deliver number of electrons/cm^2/bunch-crossing on target
    - For instance a 2cm vertical and 20 cm horizontal beam is feasible
    - There is flexibility on the choice of both horizontal and vertical beam sizes



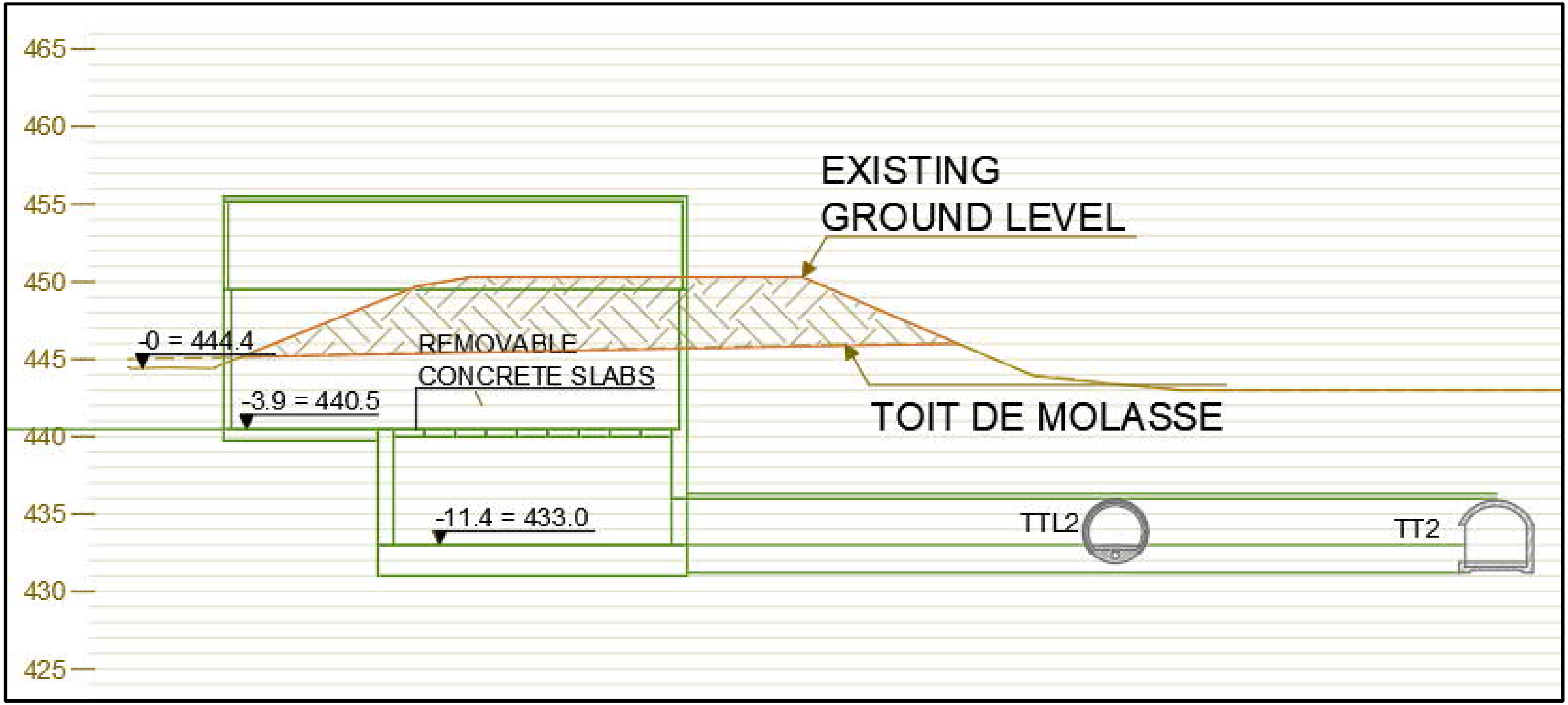
Extracted beam and experimental area



- In total ~50 m new tunnel

Extracted beam and experimental area

- Experiment hall



Extracted beam and experimental area

- Location of the experiment hall

Potential use of such a facility

Particle Physics and Nuclear Physics

- 10^{14} electrons per year with a 20 ns bunch spacing and one electron per bunch/10^{16} electrons per year with a 5 ns bunch spacing and 22 electrons per bunch
  - Explore dark matter interactions with a sensitivity that extends several orders of magnitude below the required sensitivity predicted by the thermal relic targets for representative dark matter candidates coupled to a dark photon in the sub-GeV mass range

- Fast beam dump giving 1-5 x 10^{12} electrons per 23 μs dump resulting in 1-3 x 10^{18} electrons per year for an experiment, e.g. searching for dark photons decaying to Standard Model particles

- Nuclear physics: A European facility extending the energy range available at Jlab; study of the momentum and spin distributions of sea quarks and in particular of gluons in the nucleons, the study of the excitation spectrum of nucleons and hyperons, and the prospect to produce mesons with exotic composition and/or exotic quantum numbers.

Potential use of such a facility

Accelerator Physics

- Linac: a CLIC prototype A natural next technology step (together with INFN and others for X-band linacs). Technology needs a larger scale implementation. To build the eSPS injector is elegant and efficient compared to building 5-6 modules just for laboratory/beam testing.

- Relevant also for other potential future facilities using electrons like FCC-ee, a Z, W, H and top factory, covering beam energies from 45.6 to 175 GeV. To run the collider at the Z-mass is the most challenging for the injectors due to the high total charge and low equilibrium emittance in the collider. The linac relevant also for R&D towards circular e+e- machines.

- Use for plasma studies with electrons
  - Use electron (3.5GeV) beam as driver and/or probe

- Opens for R&D (positron production for example) towards Lemma ($e^+e^- \rightarrow \mu^+\mu^-$ close to production threshold) as muon source for future muon accelerator/collider?

- General accelerator R&D as in CLEAR today (https://clear.web.cern.ch)
  - Plasma-lenses, impedance, high grad, medical, training, instrumentation, THz, ESA irradiation

- General Linear Collider related studies
  - Example: damped beam in SPS for final focus studies (beyond the KEK ATF2). Relevant for CLIC but Europe/CERN could also contribute to an ILC with such studies; an ATF3.

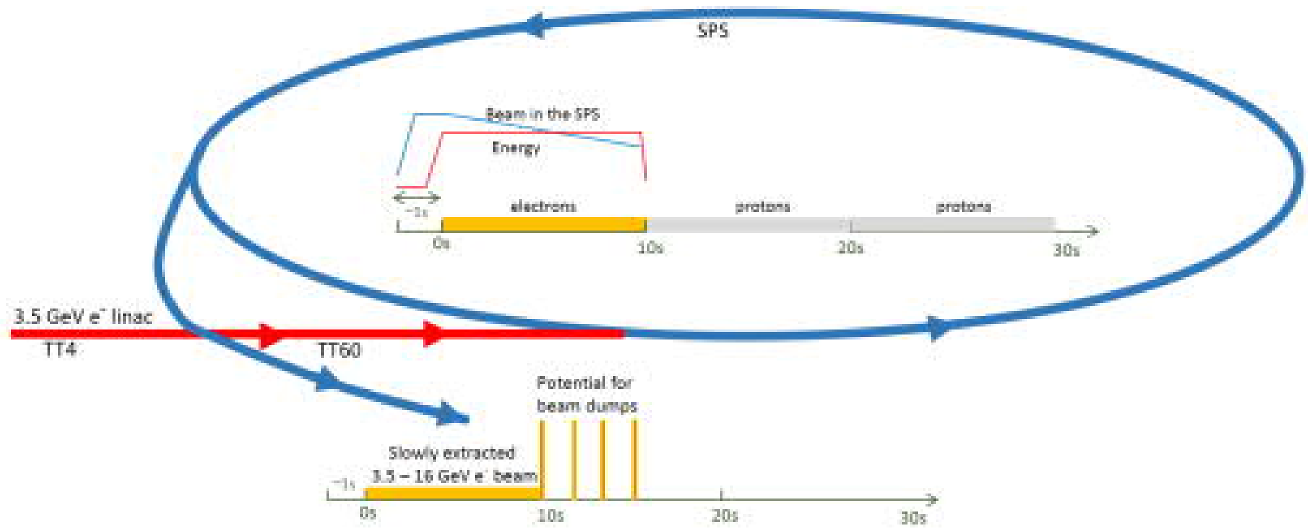
Short write-up of the concept

A primary electron beam facility at CERN

T. Åkesson [1], Y. Dutheil [2], L. Evans [2], A. Grudiev [2], Y. Papaphilippou [2], S. Stapnes [2]
On behalf of the *PBC-acc-e-beams** working group

[1]Lund University, Lund, Sweden
[2]CERN, Geneva, Switzerland

Thursday 31st May, 2018



- arXiV-1805.12379

eSPS outlook

Existing accelerator infrastructure at CERN, CERN experience with beam-manipulation, and results from the CLIC R&D can give Europe a primary electron beam facility with potential for:

1 A range of experiments for Hidden sector/Dark matter research

2 Nuclear physics like at Jefferson laboratory

3 A significant CLIC linac prototype

4 Tool for strategic and generic accelerator R&D at CERN