Dark Sector Physics with a Primary Electron Beam Facility at CERN

Abstract

This input is a summary of an Expression of Interest (SPSC-EOI-018) submitted to the CERN Scientific Committee for the SPS accelerator, SPSC.

A primary electron beam facility is proposed with the main motivations being (i) dark sector experiments, and (ii) to enable a suite of development projects in acceleration technology. The facility would deliver a beam to a Light Dark Matter eXperiment, LDMX, which could probe thermal dark matter over a majority of the viable sub-GeV mass range. LDMX can achieve orders of magnitude better sensitivity than any previous or currently envisioned experiment. LDMX uses missing momentum to search for dark matter produced via *dark bremsstrahlung* from in the interaction of electrons in a thin target. This requires a low-current, high repetition-rate electron beam, with optimal energy of $\sim 16\,\mathrm{GeV}$. We propose to create this electron beam at CERN by restoring the SPS's electron acceleration capability.

The proposed facility would also strengthen the CERN accelerator R&D programme. This is desirable on general grounds, but even more-so now when there is some uncertainty about the optimal next step for CERN's future main accelerator.

Contact: Torsten Akesson, Torsten.Akesson@hep.lu.se

I. INTRODUCTION

Only 15% of the observed matter is made of particles described by the Standard Model [1] (SM). The evidence for dark matter (DM) does not give much direct guidance on the masses of its constituents, which could be anywhere from a tiny fraction of an eV up to many solar masses. More constraints can be obtained by focusing on likely scenarios for how the primordial dark matter was created. The most straightforward and simplest scenario is the thermal origin, in which dark matter arose as a thermal relic from the hot early Universe. This scenario only requires small non-gravitational interactions between dark and Standard Model matter, and is viable over the MeV to TeV mass range. The mass region $\sim$MeV to $\sim$GeV is largely unexplored. The fact that most stable forms of ordinary matter are found in this range, argues in favour of exploring this mass range.

A thermal origin for dark matter requires an interaction between dark matter and familiar matter, which implies a production mechanism (of predictable strength) in accelerator-based experiments both in the minimal framework of a four-particle contact interaction and in realistic ultraviolet completions of this scenario by the addition of a new force carrier. The most sensitive way to search for this reaction is to use an electron beam to produce dark matter in fixed-target collisions, making use of missing energy and/or momentum to identify this process [2, 3].

The use of missing energy/momentum to discover new particles goes back to Pauli's 1930 proposal of the neutrino's existence to resolve the apparent non-conservation of energy in beta decays. It took another decade before the observation of neutrino capture. It is now generally accepted that neutrinos make up a small fraction of the dark matter, even though these cosmological relic neutrinos have yet to be detected. This precedent from history is important to remember: much of the parameter space for MeV to GeV mass dark matter is, at present, *only* detectable with accelerator-based experiments because scattering and annihilation signals are parametrically suppressed for non-relativistic dark matter in the halo. Although a discovery of new invisible particles would not unambiguously prove that they are the dark matter (or even cosmologically long-lived), it would mark the beginning of a program of experiments to measure these particles' properties and interactions, which could build a strong case that they are indeed the missing dark matter.

The missing energy and momentum signal of dark matter production is more dramatic in some ways than that of neutrinos, but also more subtle. In typical electroproduction of dark matter particle pairs, the dark matter carries away the vast majority of the incident electron's energy, leading to both a dramatic energy energy loss by the recoiling electron and a sizeable transverse kick. This is a very striking signal, with negligible physics background and instrumental backgrounds that can be managed by a suitably sensitive detector, provided that incident electrons and their reaction products can be individually measured. However, neutrinos are produced in *every* nuclear beta decay event, whereas dark matter will only be produced in a minuscule fraction of electronuclear interactions. Thus, probing dark sector physics to the level of sensitivity needed to explore thermal relic dark matter requires a large integrated luminosity delivered by a low-current, high-duty-cycle electron beam with a modest (5-20 GeV) energy. Only a primary electron beam can deliver this.

An experiment for the purpose of detecting dark matter also has significant sensitivity for millicharged particles, a range of axion-like particles, dark photons, and displaced visible decays of new particles.

The unique accelerator infrastructure, the R&D invested in the development of high frequency linear accelerators and the broad experience in accelerator technology at CERN, can be combined into creating a primary electron beam facility, eSPS, fulfilling the requirements stated above. In addition such an installation could help determining the neutrino nuclear response by measuring electro- and photonuclear reactions.

II. LIGHT DARK MATTER AT ACCELERATORS

If there is an interaction of light dark matter (LDM) with ordinary matter, then there necessarily is a production mechanism in accelerator-based experiments. Dedicated searches for these production reactions thereby provide sensitivity to dark matter couplings to the Standard Model.

Accelerator experiments offer access to a wide variety of dark matter interaction types and spins, over the entire sub-GeV dark matter mass range. One strong motivation to expect an interaction with dark matter is that such an interaction offers a simple explanation for the origin of dark matter through its early thermal equilibrium with the Standard Model particles. The strength of this interaction determines when the dark matter froze out of equilibrium, and therefore the residual dark matter abundance. This production mechanism, together with the observed dark matter density, therefore motivates a precise interaction strength for any given dark matter mass.

Models of thermal dark matter in the MeV–GeV mass range require that the interaction governing freeze-out have a cutoff scale below the weak scale. This is, essentially, a simple generalisation of the Lee-Weinberg bound [4, 5]), with two important consequences:

- **Light Forces:** There must be new force carriers at the GeV-scale or below 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; otherwise they would have been produced and detected at LEP or at hadron colliders [6].

These properties single out the hidden sector scenario highlighted in [7–9], which is the focus of considerable experimental activity.

We define the LDM particle to be χ, the $U(1)$ gauge boson A' (popularly called a “dark photon” mediator), and ϵ as the kinetic mixing parameter.

This framework permits two qualitatively distinct annihilation scenarios depending on the A' and χ masses.

- **Direct Annihilation:** A mediator with $m_{A'} > m_\chi$ generates the effective contact interaction for non-relativistic dark matter particles. In the resolved theory, annihilation proceeds via $\chi\chi \to A'^* \to ff$ to SM fermions f through a virtual mediator. This scenario is quite predictive, because the SM-A' coupling ϵ must be large enough, and the A' mass small enough, in order to achieve the thermal relic cross-section. Depending on the mass of the mediator, on-shell mediator production with decay to dark matter or production of dark matter through an off-shell mediator may be the dominant signal in a missing momentum experiment. In each case, the observed DM abundance implies a minimum DM production rate at accelerators. Constraints on this scenario can be extracted from CMB data, but are only relevant for some combinations of DM and mediator spin and couplings. This case will be the focus of the remaining discussion.
- **Secluded Annihilation:** For $m_{A'} < m_\chi$, a new annihilation channel becomes kinematically allowed, and generically dominates. In this case, DM annihilates predominantly into A' pairs [10]. This annihilation rate is independent of the SM-A' coupling ϵ. The simplest version of this scenario is robustly constrained by CMB data [11].

Since the Feynman diagram that governs direct annihilation can be rotated to yield a scattering process off SM particles, the direct detection cross section is uniquely predicted by the annihilation rate in the early universe for each choice of DM mass. Thus, direct annihilation models define thermal targets in the σ_e vs. m_χ plane. Since non-relativistic direct detection cross sections can be loop- or velocity-suppressed in many models, these targets vary by dozens of orders of magnitude in some cases. However, these vast differences

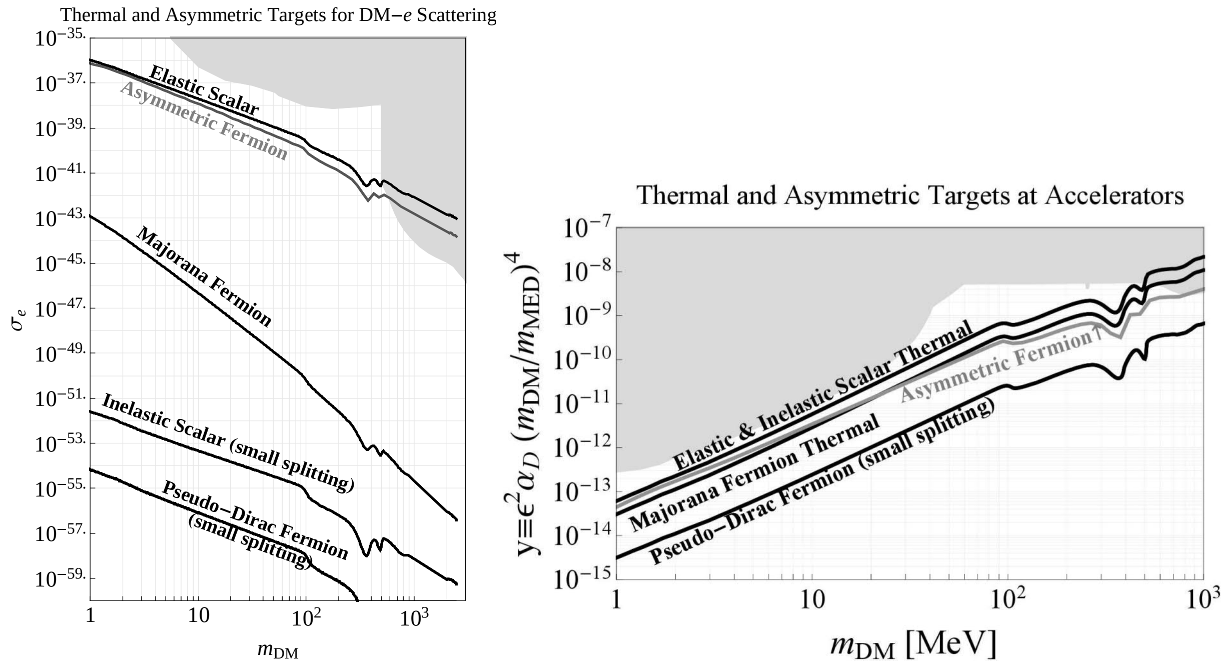


FIG. 1: **Left:** Thermal targets for DM candidates plotted in terms of the electron-recoil direct detection cross section σ_e vs. mass m_{DM}. The appropriate thermal freeze-out curve for each scenario differs by many orders of magnitude in the σ_e plane due to DM velocity suppression factors, loop-level factors, or spin suppression, any of which are significant for non-relativistic scattering. **Right:** By contrast, the dimensionless couplings (captured by y) motivated by thermal freeze-out do not differ by more than a couple of orders of magnitude from one another, as shown in the y vs. m_χ plane. Probing couplings at this magnitude is readily achievable using accelerator techniques, which involve DM production and/or detection, as well as mediator production, all in a relativistic setting. Both plots above are taken from [9] and also show a target for asymmetric fermion dark matter, a commonly discussed variation on the thermal-origin framework.

in the direct detection plane mask the underlying similarity of these models in relativistic contexts where both the scattering and annihilation cross sections differ only by order-one amounts.

To comprehensively study all direct annihilation models on an equal footing, we follow conventions in the literature (see [8]), and introduce the dimensionless interaction strength y as

$$\sigma v(\chi\chi \to A'^* \to f f) \propto \epsilon^2 \alpha_D \frac{m_\chi^2}{m_{A'}^4} = \frac{y}{m_\chi^2} \quad , \quad y \equiv \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4 \quad . \tag{1}$$

This is a convenient variable for quantifying sensitivity because for each choice of m_χ there is a unique value of y compatible with thermal freeze-out independently of the individual values of α_D, ϵ and $m_\chi/m_{A'}$. On the right panel of Fig.1 we show thermal targets for various direct annihilation models plotted in the y vs m_χ plane. Although these are the same models shown on the left panel of this figure, this parameterisation reveals the underlying similarity of these targets and their relative proximity to existing accelerator bounds (shaded regions). Reaching experimental sensitivity to these benchmarks for masses between MeV and GeV would provide nearly decisive coverage of this class of models.

A measurement of missing momentum provides broad sensitivity to light dark matter and other dark sector physics. If the new particles couple to electrons (which is well-motivated), then LDMX can observe them up to a mass of $\sim$ GeV. The sensitivity of LDMX to some of these physics possibilities is described in [12] and discussed more fully in [13]. Among other examples, we explicitly quantify in [12] the LDMX sensitivity to DM produced through an on- or off-shell mediator (including the near-resonance region) or B-L gauge boson mediated DM.

III. MEDIATORS, MILLICHARGES, NEUTRINO PHYSICS, AND NUCLEAR PHYSICS

As described in [12], a primary electron beam facility opens even more possibilities than the ones mentioned above, we give some examples in the following.

A missing momentum search like the one described above is sensitive to a range of other new-physics scenarios, potentially unrelated to dark matter. This includes invisible dark photons and minimal B-L Z' gauge bosons via their invisible decays to neutrino final states. Such a search is also sensitive to the production of millicharged particles (which occurs through off-shell photon exchange), since particles with sufficiently small millicharge Q_χ/e have no additional interactions in the detector.

There are further opportunities beyond a fixed-target experiment, as the majority of the electrons remain in the SPS after the extraction of the long low-current electron spill. These $1-5\times10^{12}$ electrons could be dumped in another beamline in a 23 μs spill. This could allow the accumulation of more than 10^{18} electrons in a year. In fact, if priority was given to such an operation, this fast extraction of the 16 GeV beam could be repeated every two seconds. This provides the potential to search for dark photons decaying into Standard Model particles with a beamdump experiment.

Photo-nuclear and electro-nuclear reactions are major background sources for the dark matter experiment. However, to measure such reactions is important to understand neutrino nuclear response. While LDMX is capable of making several such measurements, there may even be a case to perform a dedicated experiment, given the importance of understanding such reactions for neutrino physics.

Finally, there is a broad use of electron beams for nuclear physics. The electron beam facility proposed here would extend the energy range, but could not reach the same beam intensity as is currently available at Jefferson laboratory in the USA. However, there the requests for beam go beyond what is available.

IV. A PRIMARY ELECTRON BEAM FACILITY AT CERN

The overall scheme

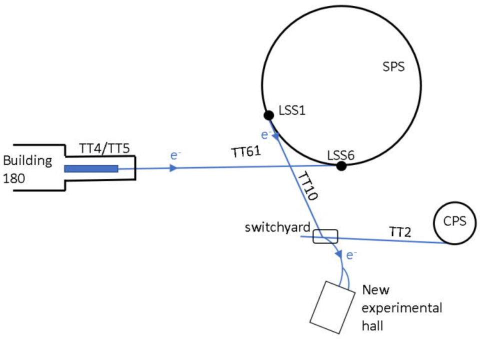


FIG. 2: Schematic of the primary electron beam facility.

Recent interest in light dark matter searches using GeV electrons has stimulated a new study of how such a beam could be provided at CERN. The basic requirement is a very long spill of low intensity electrons feeding the Light Dark Matter eXperiment (see Sec. V).

The present proposal is to use the Super Proton Synchrotron (SPS) simultaneously as an accelerator and as a very long pulse stretcher to provide such a beam. The SPS has, in the past, accelerated electrons and positrons from 3.5 GeV to 22 GeV when it was used as the injector to the Large Electron–Positron collider (LEP) [14], although most of the equipment required has now been dismantled.

The electron injector would be replaced by a 3.5 GeV compact high-gradient linac based on Compact LInear Collider (CLIC) [15] technology injecting pulses of 200 ns duration into the SPS, filling the ring at 100 Hz on a 700 msec duration plateau.

The beam would then be accelerated to 16 GeV, limited by the voltage from twelve Radio Frequency (RF) cavities still available from the LEP days, which would have to be reinstalled. The electrons would then be extracted on a long flat top at 16 GeV using slow resonant extraction. The flat top duration depends on the time available inside an SPS supercycle where other users are fed with beams inside the same supercycle. A reasonable assumption would be a 10 s flat top inside a 32 s supercycle, although the spill could be longer if needed.

The extracted beam would be transported along an existing beamline to an experimental area. A fast extraction is also possible, when the whole beam is extracted from the machine in one revolution (23 μs) to feed a possible *beam dump type* experiment. Most of the hardware apart from the 3.5 GeV linac already exists.

The main elements of the facility

The main components of the facility, shown schematically in Fig. 2, are introduced below. Much more details about each component in the list below, and the studies made for their performance and implementation, can be found in [12].

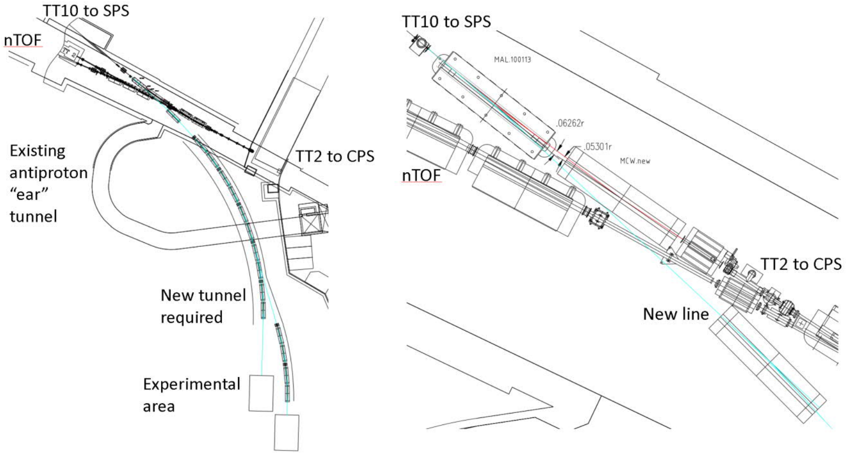
- **The 3.5 GeV compact linac** would be built using the technology developed for CLIC at 12 GHz, but with klystrons as power source instead of the two-beam acceleration method proposed for CLIC. An ideal location would be in Transfer Tunnel 4 and 5 (TT4 and TT5) at the entrance to the West Hall (building 180), and connected to the SPS by the TT60 tunnel complex. A 0.1 GeV S-band photo-injector would provide a 200 nsec pulse with a very flexible bunch structure inside the pulse. High gradient X-band (12 GHz) RF accelerating structures are used in the main linac in order to make it compact and accelerate the beam from 0.15 GeV up to 3.5 GeV within 70 m. High gradient X-band RF systems are operated at CERN: Xbox1, 2 and 3, as well as in several linac based light sources: SwissFEL, FERMI, and LCLS, where it is used for beam manipulation and beam diagnostic purposes. The RF-elements, the most costly part of the linac, are well known operationally, installed in several of these facilities and available commercially. Distribution components, control systems and software are available. An average loaded acceleration gradient of 75 MeV/m (95 MeV/m unloaded) has been chosen as a compromise between making the main linac as short as possible and reducing the required peak power and associated number of klystrons. The design of the linac is similar to the one adopted for the EuSPARC facility at Frascati [16]. X-band structures with similar parameters, usually more demanding, are regularly designed, built and successfully tested. Prices, time-scales and industrially capabilities are hence well established.

- **Transfer and injection to the SPS** would be done via the TT61 previously used to transport protons to the west area, the electrons being injected in the opposite direction to the protons. A new 3.5 GeV kicker with a flat top of 200 nsec and a 100 Hz repetition frequency would be installed at the SPS injection point in Long Straight Section 6 (LSS6). The ring would be filled in about 700 milliseconds.

- **Acceleration in the SPS**. Compensation for the synchrotron radiation loss from electrons requires a much higher voltage than is available in the SPS for proton acceleration. In addition, the SPS cavities are directional so cannot easily be used to accelerate particles in the opposite direction. Acceleration to 16 GeV requires 10 MV of total RF voltage. Twelve RF cavities from the LEP era still exist and are in good condition. They would have to be reinstalled in their former locations (still free) with new power amplifiers. They are equipped with very powerful damping systems so they will not affect high-intensity proton operation (already proven). The total voltage then available (12 MV) would be sufficient to reach 16 GeV with ample margin. The maximum energy achieved in the SPS as LEP injector was 22 GeV with the whole straight section filled with 32 cavities [14]. At this energy, other factors need to be taken into consideration including heating of the vacuum chamber and irradiation of the SPS dipole coils by synchrotron radiation penetrating the vacuum chamber. Replacing the RF cavities with superconducting cavities is not an option since they would present much too high impedance to the proton beams in the supercycle. Nevertheless, by adding new standing-wave cavities in the remaining free locations, one could imagine an eventual upgrade to higher energy. The performances, hardware and implementation times needed for the SPS adaptations are further described in [12].

- **Resonant extraction** at 16 GeV can be done by exciting the third integer resonance using existing sextupoles [17]. Quantum excitation due to synchrotron radiation would provide a powerful method of pushing particles into resonance with no dynamic variation of the tune being required as is the case for the proton beam. The intensity and duration of the spill can be controlled down to very low currents by adjusting the distance in tune of the beam from the resonance A new extraction channel using similar hardware as for proton extraction must be installed in LSS1. Fast extraction through the same channel could be performed using existing SPS kickers if needed for a beam dump experiment. Preliminary result simulations supporting this scheme are available in [12].

- **Transport to the detector**. The beam will be extracted into TT10, the beamline which is also used to inject protons into the SPS. The TT10/TT2 switchyard magnets would not be powered during electron extraction so that the beam can be directed to a new experimental area. Quadrupoles would be used to blow up the beam to match the detector requirements. Figures 3(a) and 3(b) show the switchyard region at the end of the TT10 line.



(a) (b)

FIG. 3: Layout of the switchyard region (a) and a zoom around the beamlines junction (b) with the proton trajectory in red and electron trajectory in cyan.

- **The instrumentation** needed for the source and linac systems, the transfer line and SPS injection, for position-, profile- and intensity measurements in the SPS ring, and for the SPS extraction and transfer line to the experimental hall, has been studied. The parameters cover a wide range but solutions are identified and described in [12].

- **Civil Engineering (CE)**. The civil construction required for the whole project would be a new small experimental hall housing one or two experiments, located just outside the TT2. Fig. 4 shows a visualisation of the proposed facilities showing the connection to TT2, extraction tunnel, detector pit and experimental hall. The CE study has covered the tunnelling requirements to house the extraction beam lines along with creation of the space required for an experimental hall, surface building and associated services, drainage, access and parking. The changes required in the TT4 and TT5 were also reviewed to determine whether any CE enabling works were required and it was confirmed they are not.

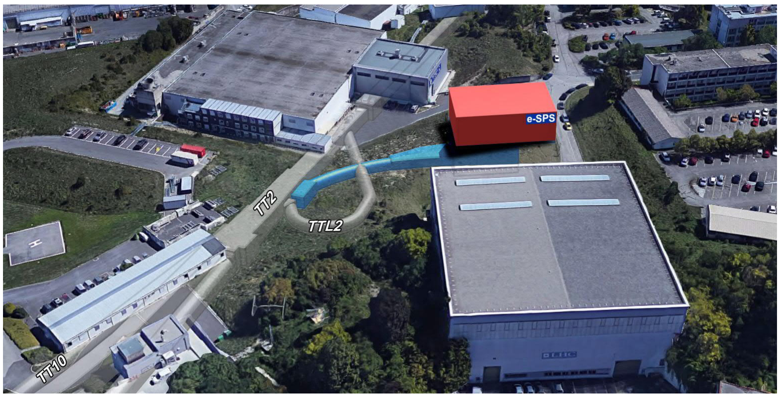


FIG. 4: Visualisation of the proposed underground (shown in blue) and overground (shown in red) facilities

In addition to the technical studies for each of these elements the relevant groups have provided cost and schedule estimates as summarized in appendix B 1. There is an important accelerator R&D programme possible with the facility described above. These opportunities are summarized in section VI below.

V. A LIGHT DARK MATTER EXPERIMENT, LDMX

An initial design study for a Light Dark Matter eXperiment (LDMX) has been presented in [18]. The experiment shown in Figure 5 is designed to identify final states of electron on target interactions that are consistent with the production of DM particle-antiparticle pairs via a vector mediator. Most of the energy is typically carried away by the DM, resulting in a soft recoiling electron with a large transverse momentum. LDMX reconstructs the kinematics of each beam electron both up- and down-stream of the target. Calorimetry, consisting of a high-granularity electromagnetic calorimeter and a hadron calorimeter with high neutron detection efficiency is used to veto events containing additional photons, charged particles or neutral hadrons.

Detailed studies have been carried out for Phase I with 4×10^{14} electrons on target at a beam energy of 4 GeV. These showed that the backgrounds are reduced to 0.5 events while retaining good signal efficiency for 4×10^{14} electrons incident upon a $0.1X_0$ tungsten target at an average rate of one 4 GeV electron per 20 ns. This could be achieved in $\sim$1 year of operation with a live time of $\sim 10^7$ seconds. As seen in the blue line in Fig. 6, this probes much of the uncovered thermal freeze-out parameter space for Scalar and Majorana dark matter.

For coverage of other DM candidates such as Pseudo-Dirac Fermions, more challenging mass ratios, off-shell mediators and other challenging model spaces, we extrapolate the Phase I performance to consider what might be achieved in a Phase II of the experiment that could take advantage of different beam energies and luminosities, as well as changes to the experiment itself. We find that LDMX can cover the pseudo-Dirac fermion relic target for the mass range m_χ: $(0.01, 150]$ MeV by means of modest and/or very accessible extensions of the Phase I experiment, while for the highest mass range, $(150, 300]$ MeV, more significant changes may be required.

The modest changes we alluded to above are: (i) increased target thickness from $0.1X_0$ to $0.15X_0$ and

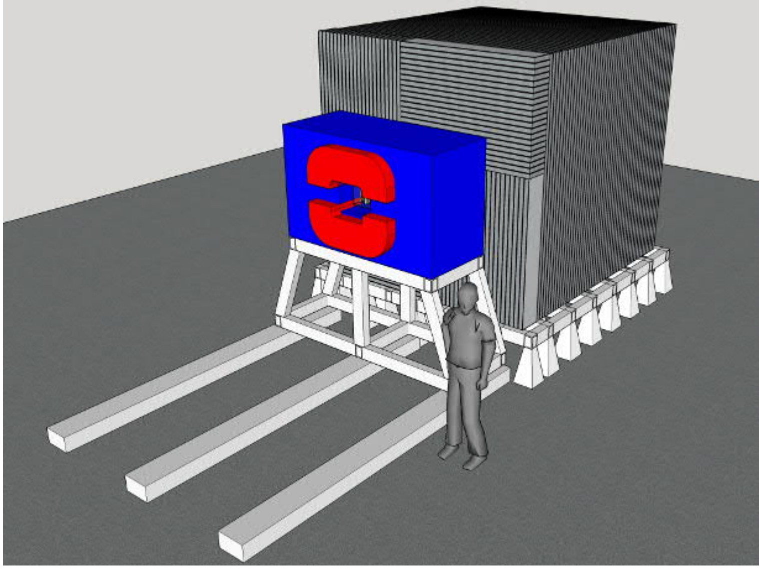


FIG. 5: An overview of the LDMX detector showing the full detector apparatus with a person for scale.

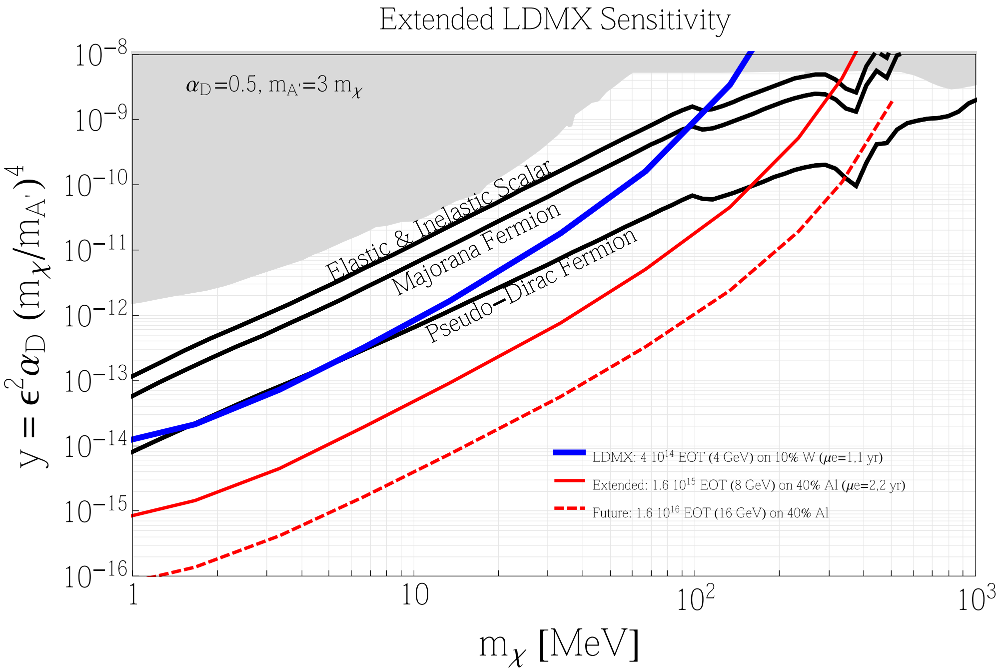


FIG. 6: The blue line is the sensitivity of the Phase I LDMX reference study discussed in [18], that conservatively assumes 0.5 background events for 4×10^{14} EOT. A scaling estimate of the sensitivity of the configuration for the mass range $150 \leq M_\chi < 300$ is illustrated by the solid red line. The dashed red line represents a similar estimate of the projected reach for $\mu_e \sim 12$ and roughly 3 years of running. For the latter two examples we have again assumed low background, consistent with reductions in yields of potential background sources, and better rejection, while increasing the effective luminosities to 1.6×10^{15} and 1.6×10^{16} EOT, respectively.

$0.4X_0$, (ii) an 8 GeV electron beam, and (iii) doubling the number of electrons per 20 ns to $\mu_e = 2$. For $(0.075, 300]$ MeV we also consider: (iv) use of an Aluminium target.

The full red line in Fig. 6 shows the extended reach obtained by the changes (i), (ii), (iii) and (iv) described above. The proposed beamline at CERN would provide a beam energy as high as 16 GeV, or more. An implementation of LDMX with 16 GeV beams, without increasing the beam intensity, would provide substantially more reach to higher masses.

We now consider the impacts of the unique ability of a CERN beamline to provide 16 GeV electrons on target, and increasing the electron multiplicity per 20 ns to higher values than $\mu_e = 2$. Obviously the increase in beam energy translates directly into higher production cross sections for signals involving higher mass states, and the increase in beam intensity would improve the sensitivity across the whole mass range.

One way to deal with higher electron multiplicities is to spread the electrons out in both space and time. A broader target region with $\Delta x \times \Delta y = 20$ cm$\times 1.4$ cm would provide roughly a factor of two increase in area over Phase I. This could allow an equivalent increase in μ_e without increasing the average density of objects in the detector. As for spreading the beam in time, the electrons could be spaced in 4 bunches with 5 ns bunch spacing for each 20 ns sampling. For the cases where the average electron multiplicity is two or more, one could spread the electrons over the second and third bunches where the charge collection efficiency is highest for 20 ns front-end readout. With no new components, the tracker and calorimeters can comfortably distinguish a 5 ns difference, adding another dimension to help resolve overlapping objects. In addition, the individual bunches would have a spread with an rms of order 150 ps. We expect to achieve timing resolutions of order 40-50 ps in the electro-magnetic calorimeter, provided the signal to noise ratio is very high [19]. The use of the 5 ns bunch spacing and timing within the bunches could provide more than 8 time bins.

In summary, if the LDMX described in [18] were to be enhanced to handle these running conditions, as argued above, then a sensitivity as shown by the dashed red line in Fig. 6 would be achieved, by means of spatially and temporally distributed electron beams with double the energy to 16 GeV.

VI. OPPORTUNITIES FOR ACCELERATOR STUDIES AND R&D WITH THE FACILITY

The primary purpose of the eSPS accelerator facility described in section IV above is to provide an electron beam optimized for LDMX. However, in addition the 3.5 GeV electron linac and the re-introduction of electrons in the SPS provide CERN with completely new possibilities for accelerator project development for its future programme and for general accelerator R&D.

During LDMX running the linac beam at 3.5 GeV is used less than 5% of the time for injection into the SPS and is available for other uses the rest of the time. A brief guide to the possibilities are given below. The added possibilities for accelerator studies that open up by adding positron production at the end of the 3.5 GeV linac as described in [12] are also included in the summary. More detail about the different aspects of the accelerator studies and future project development described below can be found in [12].

A. Summary of opportunities

Four main directions for accelerator R&D and studies with the eSPS facility can be identified:

- **Studies with relevance for future facilities.** The X-band linac and operating the SPS with electrons open key strategic possibilities for future e^+e^- facilities at CERN. First of all, the construction and operation of the linac is in itself a natural next step for the X-band high-gradient technology towards a Compact LInear Collider (CLIC) [15]. The resources needed are similar to what has been invested annually during the last decade in the CLIC study. In addition the FCC-ee [20], LEP3 [21] and LHeC [22] concepts rely on electron and positron injectors with important challenges that could be addressed with the eSPS facility. Studies of positron production at the end of the X-band linac is an interesting future addition which would benefit any future e^+e^- collider, linear or circular, inside or outside CERN. New ideas being discussed in this context include an implementation of the LEMMA [23]) (Low EMittance Muon Accelerator) concept for a muon collider, where positron production and target studies will be crucial.

- **Plasma acceleration.** The facility opens the possibility of a significantly broader plasma acceleration programme in line with European priorities for this field, primarily addressing key challenges as needed for the potential use of the technology in colliders. Use of the linac electron beam is considered for plasma acceleration as both driver and probe. As mentioned, positron production studies are of vital interest for any e^+e^- machine, as well as new muon collider concepts, but such a positron beam would also provide unique opportunities for studies of plasma acceleration of positrons.

- **General accelerator R&D.** The 3.5 GeV electron linac will provide a test bed for general accelerator R&D covering a wide range of topics, and serving an important user community in its own right. Many of the general accelerator studies that can be envisaged are natural continuations of the studies currently carried out in the CLEAR facility [24]. Examples are high gradient and plasma lens studies, instrumentation and impedance studies, medical accelerator developments for example for VHEE [25] irradiation, component irradiation, THz acceleration, and educational activities. With the eSPS linac parameters, the capabilities are significantly increased with respect to what can be done today in the CLEAR facility.

- **Use of a low emittance SPS electron beam.** The use of the SPS electron beam is also possible but will be in competition with other users of the SPS. For the SPS beam one can take advantage of a small equilibrium emittance optics using the existing SPS lattice. Low emittance ring studies and the use of SPS as a damping ring can be pursued, as have been considered for both linear and circular future e^+e^- machines at CERN. One could also consider pursuing of final focus studies beyond the ATF2 [26] if this becomes a priority. A realistic implementation of the latter is not studied at this point.

B. Resources and accelerator user community

The eSPS facility can significantly extend the strategic possibilities for future machines at CERN, provide important input to their technological development, and serve as a unique user facility for general accelerator R&D. The possibility of achieving these goals at an annual resource level which is compatible with the yearly investments in CLIC technology made in recent years, profiting of the technological results obtained in the CLIC-studies and the experience from running with electrons in the SPS during the LEP era, while performing physics studies that are essential to pave the way towards future larger machines, is very attractive and a unique opportunity for the organization at this time.

The scientific and technical community capable to contribute to and interested in the X-band machine development and construction, as well as the accelerator user community, are both large. The potential links between the eSPS facility and X-band accelerator developments outside CERN are many, in particular the on-going design study for an X-band based FEL (CompactLight) [27] and the collaboration with INFN-LNF for building a 1 GeV X-band linac [28] as part of the LNF EuPRAXIA [16] efforts. These ongoing developments already provide a network of 25 collaboration partners, many of which are developers and users of X-band technology in their local facilities. One can also expect many additional CLIC collaboration partners to actively direct their collaboration efforts towards studies and technology developments directly applicable in the eSPS linac. As shown above, it is not only the CLIC collaboration partners that will engage in this facility, but also AWAKE [29] collaboration partners and CLEAR users would be ready to pursue the facility build-up and its scientific programme in the area of accelerator R&D. Both these communities are very large, in particular the very large novel accelerator technology community consider test-facilities at CERN crucial for making these technologies applicable for high energy colliders.

VII. CONCLUSIONS

This ESPP input presents a programme of highly motivated physics and accelerator R&D that is very well matched to existing accelerator expertise and accelerator infrastructure at CERN. It also draws heavily upon CERN investments in R&D for linear accelerators and for detector R&D, such as that which is underway for the high luminosity upgrades of the LHC experiments.

The proposed new accelerator facility and LDMX experiment would make it possible to search for evidence of thermal dark matter production over the majority of the highly motivated sub-GeV mass range, with orders of magnitude more sensitivity than any previous or currently-envisioned experiment. As such, it would access a wide array of DM models that could not otherwise be probed, or probed as comprehensively, by other means. Depending on the results it obtains, the experiment could be the first of a sequence of intensity frontier experiments targeting physics at low mass with weak coupling to the Standard Model.

The proposed facility would also strengthen the CERN accelerator R&D programme. This is desirable on general grounds, but even more-so now when there is some uncertainty about the optimal next step for CERN's future main accelerator.

In the case of a positive result on light dark matter, the landscape of particle physics experimentation would shift toward a greatly increased emphasis on the intensity and cosmic frontiers. Since the primary electron beam facility proposed here can be pursued on a short time-scale and for a relatively modest cost when compared to that of a major collider, we believe that there is a strong case for CERN to adopt this program and to facilitate its realization as quickly as possible.

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