Explore the lifetime frontier with MATHUSLA

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Abstract: The observation of long-lived particles at the LHC would reveal physics beyond the Standard Model and could account for the many open issues in our understanding of our universe. Long-lived particle signatures are well motivated and can appear in many theoretical constructs that address the Hierarchy Problem, Dark Matter, Neutrino Masses and the Baryon Asymmetry of the Universe. With the current experiments at the particle accelerators, no search strategy will be able to observe the decay of neutral long-lived particles with masses above GeV and lifetimes at the limit set by Big Bang Nucleosynthesis, $c\tau \sim 10^7$–$10^8$ m. The MATHUSLA detector concept (MAssive Timing Hodoscope for Ultra-Stable neutral pArticles) will be presented. It can be implemented on the surface above ATLAS or CMS detectors in time for the high-luminosity LHC operations, to search for neutral long-lived particles with lifetimes up to the BBN limit. The large area of the detector allows MATHUSLA to make important contributions also to cosmic-ray physics. We will also report on the analysis of data collected by the test stand installed on the surface above the ATLAS detector, the on-going background studies, and plans for the MATHUSLA detector.

Keywords: Large detector systems for particle and astroparticle physics; Particle tracking detectors
1 Introduction

Long-lived particles (LLPs) occur in many extensions to the Standard Model (SM) with lifetimes that can be as long as the Big Bang Nucleosynthesis (BBN) bound of about $c\tau \lesssim 10^7$–$10^8$ m [1]. Examples of models where such particles are predicted which can be produced at the Large Hadron Collider (LHC) include: Supersymmetric (SUSY) models such as RPV SUSY [2] and Stealth SUSY [3], models addressing the hierarchy problem such as Hidden Valleys [4], and models addressing dark matter [5].

The main experiments at the LHC have extensive programs to search for such particles, covering lifetimes from a few centimeters to tens of meters. Searches for LLPs decaying into final states containing jets were carried out at the Tevatron ($\sqrt{s} = 1.96$ TeV) by both the CDF [6] and D0 [7] collaborations, at the LHC by the ATLAS and LHCb collaborations in proton-proton collisions at $\sqrt{s} = 7$ TeV [8, 9], by the ATLAS, CMS and LHCb collaborations at $\sqrt{s} = 8$ TeV [10–14] and more recently by the CMS and ATLAS collaborations at $\sqrt{s} = 13$ TeV [15–17]. To date, no search has observed evidence of Beyond the Standard Model (BSM), neutral LLPs. However, their reach is limited by different factors such as the trigger, the presence of backgrounds from the collision or beam effects, and ultimately by the size of the detectors. For example, searches for LLPs decaying to hadrons (leptons) with less than a few 100 GeV ($\sim 10$ GeV) of visible energy in the event have particularly low trigger efficiency and are highly constrained by QCD and other backgrounds. These limitations could risk missing a discovery should LLP with a lifetime close to the BBN be created at the LHC collisions.

MATHUSLA (MAssive Timing Hodoscope for Ultra-Stable neutral pArticles) [18] is a proposed large-scale surface detector to be located above ATLAS [19] or CMS [20] to study LLP produced by the High-Luminosity LHC (HL-LHC) [21]. The $\sim 90$ m of rock between the interaction point (IP) and the detector’s decay volume on the surface gives enough shielding for
MATHUSLA to work in a clean environment. Being a background-free experiment increases the sensitivity to LLP lifetimes up to lifetimes of $10^7\,\text{m}$ and extends the sensitivity of the main detectors by orders of magnitude. LLP decays would be reconstructed as displaced vertices of upwards traveling charged particles. As a secondary physics objective, MATHUSLA would also be able to perform cosmic-ray physics measurements and help solve important puzzles in astroparticle physics.

A white paper describing the need for a detector like MATHUSLA was published by a large number of experimentalists and theorists in 2018 [22]. The MATHUSLA collaboration has made significant progress on the detailed background and design studies and presented a Letter of Intent [23] to the LHCC. A test stand with a detector layout similar to the one envisioned for the MATHUSLA detector was assembled in the surface above ATLAS and took data during 2018, analysis of which is ongoing. The results will provide empirical information on potential backgrounds coming from the LHC as well as from cosmic rays. The collaboration is now seeking to construct a MATHUSLA demonstrator detector unit by 2021. The full-scale detector could become operational by 2025–26.

2 The MATHUSLA detector

2.1 Basic detector principles

LLP near the BBN lifetime bound arising from exotic Higgs decays could be discovered if the detector had a linear size of $\sim 20\,\text{m}$ in the direction of travel with good geometric coverage ($\sim 5\%$ of solid angle), which results in a detector with linear dimensions of $O(100\,\text{m})$. The $\sim 90\,\text{meters}$ of rock between the collision point and the surface eliminates most backgrounds associated with $pp$ collisions. Still, a large background of cosmic muons and backgrounds from high energy muons and neutrinos coming from the IP must be rejected which requires good tracking and vertexing capabilities. The proposed detector, illustrated in the left panel of figure 1 along with two possible displaced vertices from LLP decays, is a large box of $100 \times 100 \times 25\,\text{m}^3$ volume, with a robust tracking system on its upper part, $25\,\text{m}$ air decay volume and a tracking veto on the floor. An additional double-tracking layer $5\,\text{m}$ below the main tracking system allows to enhance the particle position measurement precision close to the floor.

The expected sensitivity for a SM-like Higgs boson producing two long-lived scalars decaying into hadronic jets for the current benchmark geometry in the expected luminosity for the HL-LHC is shown in the right plot of figure 1. The MATHUSLA limit is obtained assuming 4 LLPs decaying in the detector volume in a zero-background regime. It is compared to the exclusion projection for a single displaced vertex search in the ATLAS Muon System considering the background expected at the HL-LHC [24].

The dominant background comes from cosmic rays, with a rate in the MHz range. Their rejection depends on the robust ceiling tracking system, with spatial and temporal resolutions in cm and nanosecond range, respectively. If the tracking layers span a vertical distance of a few meters, full 4-dimensional track and displaced vertex reconstruction is possible, which significantly reduces the combinatorial backgrounds as tracks must intersect in both space and time to form a vertex. Both Resistive Plate Chambers (RPCs) and plastic scintillators are time-tested technologies.
that meet the needed specifications. Since cosmic rays travel downwards and do not inherently form displaced vertices, this signal requirement is expected to allow MATHUSLA to reach the near-zero-background regime.

The expected rate of muons from the HL-LHC collisions is $O(1 \text{Hz})$. They are upwards traveling muons that do not generally produce a displaced vertex and that can be vetoed by the floor tracker. Upward going atmospheric neutrinos are estimated to be of order 10 to 100 per year and most can be rejected using time of flight. Moreover, they can be measured when there are no LHC beams. Neutrinos from LHC collisions are a subdominant background, estimated to be a few events during the entire HL-LHC data taking, and can be rejected with geometrical cuts and timing vetoes on non-relativistic charged tracks associated with the scattering event. A more detailed description of the possible backgrounds can be found in ref. [23], while more precise rate estimates will be released soon from the analysis of the data collected by the test stand described in section 3.

### 2.2 The modular concept

MATHUSLA is designed to be a large area detector, requiring to cover a wide surface with detector material. Building MATHUSLA as an array of independent modules makes it a flexible and scalable detector, easy to adapt to the available land and the specific site conditions. It also allows for a staged integration with an incremental ramp-up. One of the advantages of MATHUSLA is that it is entirely parasitic: its construction and operation are not expected to interfere with the operation of ATLAS or CMS and its staged construction can happen as a completely independent plan from that of the HL-LHC and the experiments upgrade work.

The current design considers individual modules with a volume of $9 \text{ m} \times 9 \text{ m} \times 25 \text{ m}$ and a separation of $\sim 1 \text{ m}$ between modules as shown in figure 2. Each module includes two tracking layers on the floor to act as a veto for charged particles from the IP, an air-filled decay volume of 25 m and 5 tracking layers on the ceiling for track and vertex reconstruction. The extension of the decay volume by a few meters above ground has been decided as well as the inclusion of two extra tracking layers near the upper part of the decay volume to improve tracking and vertexing resolutions. Studies conclude that a scintillator veto surrounding the entire volume is not needed.

The baseline trigger system is driven by units of $3 \times 3$ modules, a choice based on the largest possible inclination angle for MATHUSLA which would be a very safe option for a $100 \text{ m} \times 100 \text{ m}$
The strategy is to collect all detector hits with no trigger selection and separately record the trigger information. The data rate is dominated by cosmic rays, $1/(\text{cm}^2 \text{ minute})$, which gives $\sim 2 \text{ MHz}$ total rate for the main detector. Considering a unit of $9 \text{ m}^2$, two hits per module with 4 bytes per readout, the readout of 9 layers gives $\sim 1 \text{ MB/s}$ per unit. The readout will be based on ASIC chips with a cost target of 1 EUR per channel. The trigger is recorded separately and used for connecting to the CMS detector bunch crossing. By correlating MATHUSLA and CMS detector data, the LLP production mode and mass can be determined or at least constrained; the LLP boost distribution is tightly correlated with LLP mass once a production process is assumed, as demonstrated in ref. [25]. Conservatively assuming a distance from the IP of 150 m and an LLP with $\beta = 0.7$, an optical fibre transmission to CMS with $v_{\text{fibre}} = 0.5 \mu\text{s}/100\text{ m}$ will guarantee the detector around $3.25 \mu\text{s}$ or more to form trigger and get information to CMS Level-1 trigger (at the HL-LHC the CMS trigger will have a latency time of around $12 \mu\text{s}$).

### 2.3 Current geometry proposal

CERN owns an available piece of land near CMS that would be a suitable site for the detector [23]. The MATHUSLA collaboration is working with Civil Engineers from CERN to define the building and the layout of the detector. Figure 3 shows the details on the planned position (left) and the size of the detector (right).

The current proposal contemplates a $100 \text{ m} \times 102 \text{ m}$ experimental area located on the surface of CMS together with a $30 \text{ m} \times 100 \text{ m}$ adjacent area for the detector assembly. The total height of
The original MATHUSLA proposal [18] assumed a distance of 100 m from the IP both horizontally and vertically. Reducing these distances as explained above, the current proposal can reach a similar LLP sensitivity as the original detector with a final detector design more optimised, with smaller geometry that is cost-efficient and tailored to the available experimental site.

Figure 4 shows the details on the proposed geometry. An enclosed building would contain an experimental area, an assembly area and a system of cranes. The $9 \times 9$ modules would be arranged in three arrays, each of which would be served by an independent 20 T crane, reaching the assembly area for construction and maintenance.

3 The MATHUSLA test module

The MATHUSLA detector has been conceived to be a background-free detector, a hypothesis that can be confirmed by making use of a test stand detector. A test stand with a layout similar to the one envisioned for MATHUSLA was installed in the surface area above the ATLAS IP, taking data with different beam conditions during 2018. Data taken during periods with no beams present in the LHC provide a good measurement of the background from cosmic rays. Data collected with collisions at the LHC can give an estimate of the background expected from the LHC. A precise measure of the charged particle flux in the test stand will provide the veto efficiency requirement for the main detector to guarantee that no cosmic particles fake charged particles coming from the LHC. All this information can be used to optimise the design of the main detector.
Figure 5. Left: 3D model of the MATHUSLA test stand. Right: photo of the final assembled structure installed above the ATLAS IP. The green dots identify the two scintillator layers used for triggering, while the red dots mark the three RPC double-layers used for tracking.

Following the concept of the main detector, the test stand is composed of one external layer of scintillators in the upper part and one in the lower part with six layers of RPCs between them as shown in figure 5. The overall structure is \( \sim 6.5 \) m tall, with a base of \( \sim 2.9 \times 2.9 \) m².

Events are selected by a trigger system that requires a hit in one of the scintillator layers followed by a hit in the opposite scintillator layer within a time window. The test stand has collected a total of 680 hours with the detector fully operational, corresponding to a total number of tracks of around 90 M, after data quality requirements. Tracks are then reconstructed using a minimum \( \chi^2 \) fit using spatial and time information from the RPC and scintillator hits.

The geometry and material of the ATLAS cavern, the test stand, and its surroundings were modelled with GEANT4 [26]. The material of the ATLAS detector is equivalent to approximately 10 interaction lengths. The rock between ATLAS and the test stand was approximated by 36.45 m of a marl/sandstone mix, 18.25 m of a mix of kaolinite and calcium carbonate, and 25.51 m of sandstone. Both the scintillation counters and the RPCs, as well as parts of the supporting structure, are included in the simulation. Downward cosmic ray particles were generated by sampling energies and zenith angles from distributions predicted by PARMA4.0 [27], an analytical model for estimating cosmic ray fluxes on Earth. The particles were simulated in the GEANT4 model of the test stand and detector hits were recorded. The dominant LHC pp collision processes that can produce particles reaching the test stand are the \( W, Z, c\bar{c}, b\bar{b}, \) and \( t\bar{t} \). All these processes were simulated using PYTHIA 8.2 [28]

Tracks are identified as upwards- or downwards-going by the fit. Figure 6 shows the distribution of tracks as a function of the reconstructed zenith angle and a comparison to the expected distribution from a simulation. Data are separated in periods when no beam was present in the LHC (runs with no beam, blue line) and periods when there were collisions at the LHC (runs with beam, red line).

In the case of downwards-going tracks (left), the angular distributions in runs with and without beam match perfectly. They are also compatible with the cosmic-ray simulation distribution (grey
Figure 6. Distribution of reconstructed tracks as a function of the zenith angle. Data events in runs with (no) beam are shown as (blue) red lines. Left: downwards-going tracks, overlaid is a simulation of cosmic-ray events. Right: upwards-going tracks, overlaid is a simulation of particles coming from the ATLAS IP. Multiple scattering has not been taken into account in the simulations.

area) where multiple scattering of particles in the detector material is found to be negligible. The number of downward cosmic ray tracks increases with zenith angle from $0^\circ$ to $10^\circ$ due to the increasing solid angle. The distribution peaks at about $10^\circ$ and decreases at higher zenith angles as the geometric acceptance of the test stand diminishes. The fluctuations in the number of tracks as a function of azimuthal angle also reflects the geometric acceptance of the test stand. This distribution confirms that the downwards-going tracks are properly reconstructed.

In the case of upwards-going tracks (right), there are two components to take into account. The first component comes from cosmic ray inelastic backscattering. Upward particles generated by cosmic rays can be produced by interactions with material in the test stand or in the floor of the SX1 building. These upward particles are emitted across the entire geometric acceptance of the test stand. From these runs without beam, a ratio that relates the rate of upward inelastic backscattering to the rate of incident downward cosmic rays is estimated to be around $7 \cdot 10^{-5}$. The second component of upward tracks comes from muons created in LHC pp collisions. Since the test stand operated almost directly $80\text{ m}$ above the ATLAS IP, tracks from these muons are expected to be concentrated at small zenith angles. The measured rate of muons from the IP scales linearly with luminosity and is consistent with Monte Carlo simulated rates.

4 MATHUSLA as a cosmic-ray telescope

MATHUSLA has all the qualities needed to act as an excellent cosmic-ray telescope. MATHUSLA's large area provides good efficiency for extended air showers from primary cosmic rays. Its combination with high-resolution directional tracking and proximity to ATLAS or CMS for correlated shower core measurements could allow more detailed studies of the core structure, crucial to determine the atomic number of the primary cosmic particles. These measurements, which do not interfere with the primary goal of LLP discovery, represent a “guaranteed physics return” on the investment of the detector, as well as an opportunity to establish a cosmic-ray physics program. The qualitative cosmic-ray physics case was discussed in [22].
Current studies are investigating the possibility of adding an RPC plane with digital and analog readout. The digital readout might allow to improve the measurement of the spatial and temporal structure of an Extensive Air Shower (EAS), and perform low-density measurements. The analog system has the advantage of allowing to measure the high density of particles up to $10^4/m^2$, expanding the measurements of cosmic rays beyond the knee. An additional RPC layer could allow to precisely measure the shower front by having a good time-spatial determination of it. This could improve the determination of the core and the arrival direction of the shower, important for vertical EAS, where the saturation effects in the scintillation planes can lower the core and arrival direction precision. On the other hand, with measurements of the density of charged particles, the lateral distribution function (LDF) of charged particles can be obtained event-by-event, which can help to determine the energy scale of the primary cosmic ray and the composition of the cosmic ray nuclei. The energy scale can be estimated from the amplitude of the lateral distribution, and the primary composition could be studied by using the steepness of the LDF (the lighter and more energetic the air shower, the bigger the steepness of the LDF). Moreover, one RPC layer can improve the measurements of the vertical and inclined events on the energy and the deposited charge. All these additional information could allow the reconstruction of the all particle energy spectrum from vertical and inclined events up to 100 PeV, obtain large scale anisotropy maps in arrival directions of the cosmic rays, measure small scale anisotropies in arrival directions, and search for point sources. Moreover, they will also allow testing, more precisely, the hadronic interaction models.

5 Conclusions

LLPs occur in a wide variety of BSM scenarios addressing the most fundamental mysteries of particle physics. In this document, I presented the MATHUSLA detector that could extend the sensitivity to long decay lifetimes by orders of magnitude compared to LHC detector searches. Moreover, MATHUSLA could act as a cosmic-ray telescope, and it could perform very precise cosmic-ray measurements up to the PeV scale. A small-scale experiment, the MATHUSLA test stand, was constructed and installed on the surface above the IP of the ATLAS detector at Point 1 of the LHC and collected data throughout 2018. The data recorded when LHC beams were in collision and when they were not in collision is dominated, as expected, by downward-going cosmic rays. Upward-going tracks, identified by timing, have two components. One is the background from cosmic ray inelastic backscattering that has an observed angular distribution consistent with the observed downward cosmic-ray angular distribution because both are determined by detector acceptance. The second source of observed upward-going tracks is shown to be consistent with expected muons from LHC collisions, which have a significantly narrower angular distribution that is determined by the small solid angle subtended by the test stand. The test stand results confirm the background assumptions in the MATHUSLA proposal and give confidence in MATHUSLA’s projected physics reach.

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