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Searches for ultra long-lived particles with MATHUSLA

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With the current experiments at particle accelerators, no search strategy will be able to observe the decay of neutral long-lived particles with masses above $\sim$ GeV and lifetimes at the limit set by Big Bang Nucleosynthesis (BBN), $c\tau \sim 10^7$–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 the 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 ongoing background studies, and plans for the MATHUSLA detector. The observation of neutral 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.

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1. Introduction

The Large Hadron Collider (LHC) has yet to find convincing signs of new physics beyond the Standard Model (BSM), but many fundamental mysteries are still begging for explanations. Where could the new physics at the LHC be hiding? MATHUSLA (MAssive Timing Hodoscope for Ultra-Stable neutraL pArticles) [1] is a proposal to address a significant gap in the LHC's reach. The existing BSM searches, which mostly focus on energetic final states produced within subatomic distances of the proton collision, may have (literally) been looking in the wrong place. These searches are largely insensitive to neutral *Long-Lived Particles* (LLPs), which are invisible until they decay into visible SM particles some macroscopic distance from the the interaction point (IP). Far from being exotic oddities, LLP signatures are fundamentally motivated in various BSM models [2]. Although dedicated searches for these signatures are ramping up at ATLAS and CMS, trigger and background limitations severely curtail the range of LLP masses, decay modes and lifetimes to which they are sensitive. Particularly challenging are LLPs with *very long lifetimes* that decay dominantly outside of the detector. The LHC could be producing many LLPs with MeV–TeV masses that cannot be produced anywhere else, but that existing detectors cannot discover.

MATHUSLA, a proposed large-scale surface detector located above CMS or ATLAS, can detect LLPs with lifetimes near the cosmological limit of 0.1 s [3], and will extend the sensitivity of the main detectors by orders of magnitude for large classes of highly motivated LLP signatures. As a secondary physics objective, MATHUSLA would also be able to perform cutting-edge cosmic ray physics observations to elucidate the nature of galactic cosmic rays, supernovae and other sources, and help solve important puzzles in astroparticle physics.

The MATHUSLA collaboration has already operated a test stand detector above ATLAS, made significant progress on detailed background and design studies, and presented a Letter of Intent [4] to the LHCC. A significant fraction of the particle physics community came together to make the case for building MATHUSLA (and the importance of LLP searches in general) in a comprehensive white paper [2]. The collaboration is now seeking to construct a MATHUSLA demonstrator detector unit by 2021. The full-scale detector could then become operational by 2025–26.

2. Basic Detector Principles

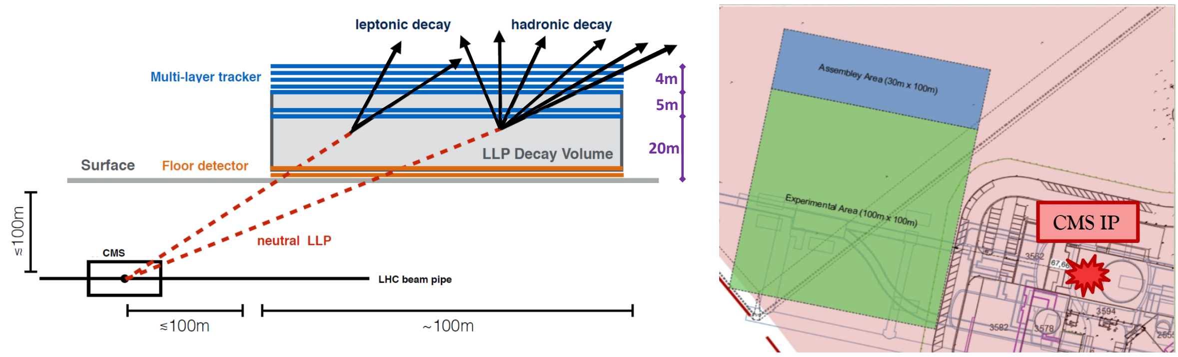

Figure 1: *Left:* Simplified MATHUSLA layout. *Right:* CERN-owned land near CMS (green: experimental area 100 m x 100 m, blue: assembly area 30 m x 100 m) that would be a suitable site for MATHUSLA.

The basic layout of MATHUSLA is shown in Fig. 1 (left). An empty air-filled fiducial decay volume is monitored by a robust multi-layer tracking system in the roof of the detector structure and two layers of tracking chambers located about two meters below the roof tracking system. Floor detectors reject interactions occurring near the surface. LLP decays are reconstructed as displaced vertices (DVs) of upwards traveling charged particles. MATHUSLA's position on the surface, separated from the LHC collision by ~ 100 m of rock, shields it from the ubiquitous QCD backgrounds that curtail the ability of the LHC main detectors to discover LLPs. To maintain reasonable geometric acceptance for LLPs ($\sim 5\%$ of solid angle), the detector must be very large, with linear dimensions of $\mathscr{O}(100$ m) and a height of ~ 20 m.

A suitable site for the detector has been identified. CERN owns an available piece of land near CMS [4], see Fig. 1 (right). The original proposal [1], LOI [4], and Physics Case white paper [2] assumed a simplified square detector geometry with an area of 200 m $\times$ 200 m and a height of 20 m for the decay volume, displaced from the IP by 100 m both horizontally and vertically. Since the available CMS site is closer to the IP both horizontally and vertically, a realistic geometry with $\sim 1/3$ the area of this "MATHUSLA200" geometry benchmark can reach the same LLP sensitivity. For this reason we continue to use MATHUSLA200 as a physics reach benchmark, while emphasizing that the final detector design will feature a more optimized, smaller geometry that is cost-efficient and tailored to the available experimental site.

For LLPs with lifetimes $\gtrsim 100$ m, MATHUSLA will have as many LLP decays in its detector volume as will ATLAS or CMS. MATHUSLA is able to resolve DVs from LLPs with masses below $\sim$ GeV (~ 10 MeV) for production in weak-scale processes (B-decays). Crucial to its greater LLP sensitivity is its ability to search for LLP decays without trigger restrictions, unlike the main LHC detectors. Even though MATHUSLA is basically just a large particle tracker without any energy or momentum measurement, it will still be able to measure many important properties of any LLP decays it observes [5]. Final state multiplicity would distinguish between leptonic and hadronic decay modes, while the geometry of the DV can be used to measure the LLP Lorentz boost event-by-event. It would even be possible to use MATHUSLA as a trigger for the main detector. Together with offline correlated information from the main detector, this will allow the properties of any discovered LLP like mass, production and decay mode to be determined.

The dominant background on the surface is cosmic rays (CRs), which are incident on the full detector with a rate in the MHz range, corresponding to $\sim 10^{15}$ charged tracks over the whole HL-LHC run. Their rejection depends on the robust ceiling tracking system, comprised of ~ 5 layers (the required number of layers will be determined by detailed study) with spatial and temporal resolutions in cm and nanosecond range, respectively. If the layers of this tracking system span a vertical distance of a few meters, full 4-dimensional track and displaced vertex reconstruction is possible, which significantly reduces the combinatorial backgrounds since associated tracks must intersect in both space and time to form a vertex. This is an extremely stringent signal requirement even for LLPs with just two charged tracks in the final state, but especially for hadronic LLP decays with $\mathscr{O}(10)$ such tracks. Both Resistive Plate Chambers (RPCs) and plastic scintillators are time-tested technologies that easily meet the specifications needed for stringent background rejection. As argued in [1], since CRs travel downwards and do not inherently form DVs, this signal requirement is expected to allow MATHUSLA to reach the near-zero-background regime.

Other backgrounds are easier to handle. Upwards traveling muons from the LHC do not give a DV or, if they scatter or undergo rare decays that mimic LLP decays, can be rejected by the floor detector. Neutrinos from atmospheric cosmic rays and the LHC scatter off air in the detector volume ~ 100 times during the entire HL-LHC run, but can be rejected with geometrical cuts and timing vetoes on non-relativistic charged tracks associated with the scattering event.

While MATHUSLA leverages the investments of the LHC and extends its physics reach, it is entirely parasitic. Its construction and operation are not expected to interfere with the operation of the LHC's main experiments. MATHUSLA is also an inherently flexible and scalable detector concept, lending itself to modular construction and staged implementation (see Fig. 2).

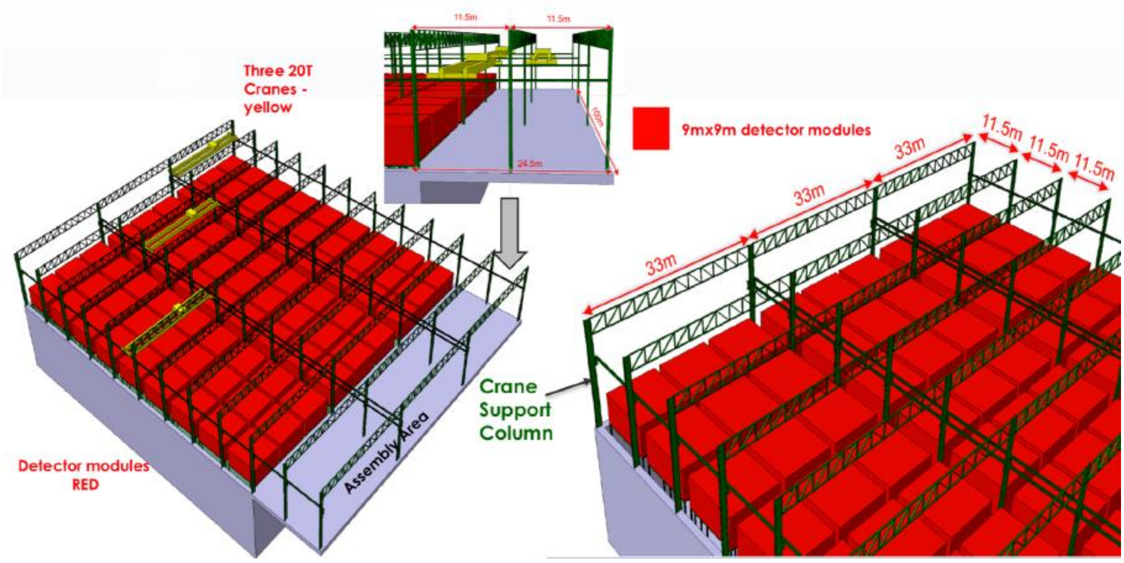

Figure 2: Engineering drawing for an array of 100 modular units.

3. Primary Physics Goal: Discovery of Long Lived Particles

The MATHUSLA white paper [2] discussed the primary physics case in great detail. Three main conclusions form the core motivation for constructing MATHUSLA.

Firstly, LLPs are fundamentally motivated (Fig. 3). They could explain the Hierarchy Problem, Dark Matter, Neutrino Masses and the Baryon Asymmetry of the Universe [2]. Long lifetimes are also ubiquitous in the SM, providing bottom-up motivation for LLPs as a generic BSM signature independent of any particular theory bias.

Secondly, the LHC Main Detectors are blind to large regions of the LLP signature space. For example, searches for LLPs decaying to hadrons (leptons) with less than a few 100 GeV (~ 10 GeV) of visible energy in the event have particularly low trigger efficiency and are highly constrained by QCD and other backgrounds.

Thirdly, MATHUSLA reclaims orders of magnitude in cross section/lifetime reach in these blind spots. The high intensity of LHC collisions yields a large number of B-mesons that can decay to light LLPs, allowing MATHUSLA to probe parameter space in LLP models down to the MeV scale. Meanwhile, MATHUSLA can take advantage of the full LHC collision energy to discover LLPs with weak- or TeV-scale masses. For LLP production cross sections in the pb range, MATHUSLA can probe lifetimes approaching the $c\tau \lesssim 10^7$ m upper limit from Cosmology [3]. A few representative and well-motivated examples are provided here. Fig. 4 (left) compares the sensitivity of MATHUSLA to hadronically decaying *LLPs produced in exotic Higgs decays* to the

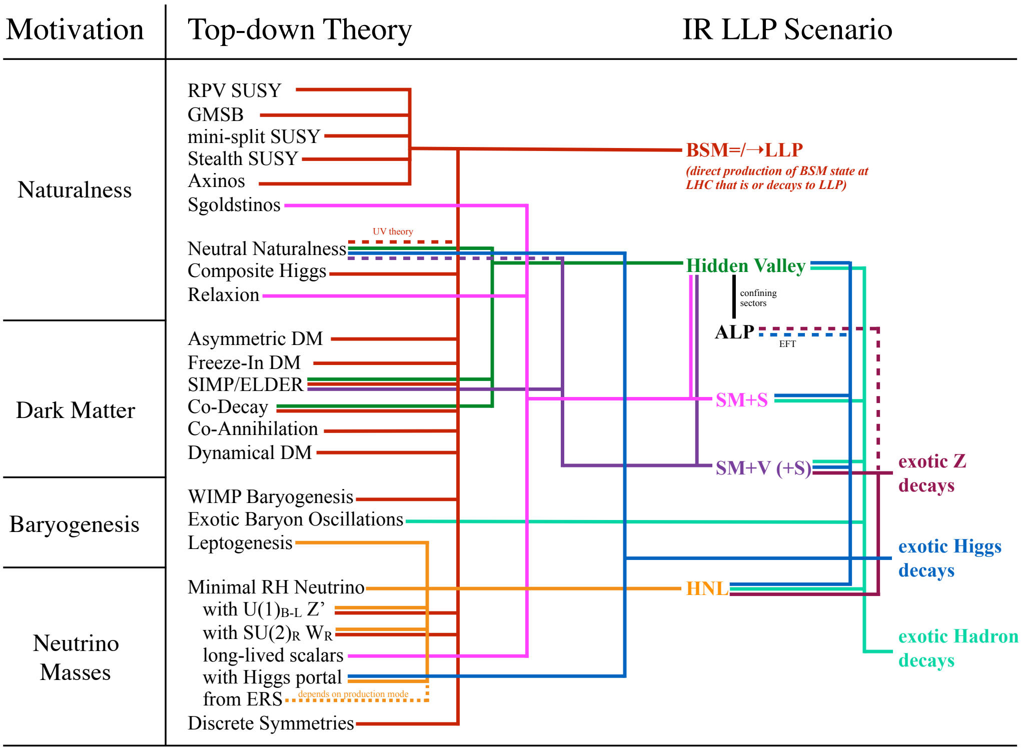

Figure 3: Summary of some top-down theoretical motivations for LLP signals at MATHUSLA [2].

projected sensitivity of an ATLAS search in the muon system. *MATHUSLA can probe three orders of magnitude smaller LLP production rates (or longer lifetime) than the LHC main detectors.* This is one of the most important LLP benchmarks, since it could provide the smoking gun for many BSM theories like Neutral Naturalness or general Hidden Valleys. Figure 4 (right) demonstrates MATHUSLA detection capabilities for *Long-lived Higgsinos with masses exceeding a TeV*, which arise in theories including gauge mediation, supersymmetric axion models, and R-parity violation. The ability of MATHUSLA to probe LLPs in the MeV-GeV range, including *dark scalars or right-handed neutrinos*, via their production in exotic decays of B-mesons is shown in Fig. 5.

4. Secondary Physics Goal: Study of Cosmic Rays

The MATHUSLA design is driven by the tracking requirements of distinguishing upward-going LLP decay products from downward-going cosmic rays (CRs), so it is not surprising that MATHUSLA can act as a cutting-edge CR telescope. The qualitative CR physics case was discussed in [2], with more detailed studies in progress. MATHUSLA's large area gives it good efficiency for extended air showers from $\sim 10^{14}$–10^{18} eV primary CRs. Its combination of high-resolution directional tracking, near-full-area coverage, and proximity to ATLAS or CMS for correlated shower core measurements would be highly valuable in this crucial energy window. The main features in the spectrum of Galactic CRs show up in this energy window: the *"knee"* at $\sim$ 3–4 PeV, and a second knee at $\sim$ 100 PeV. Below the first "knee" ($E_{pr} \sim 10^{15}$–10^{16} eV), the spectrum is dominated by galactic sources such as supernovae. The precise energy spectrum shape, anisotropy, and elemental composition provide crucial information on the distribution of these sources and the astrophysics that drives them. At $E_{pr} \sim 10^{17}$–10^{18} eV, galactic CRs taper off and extragalactic

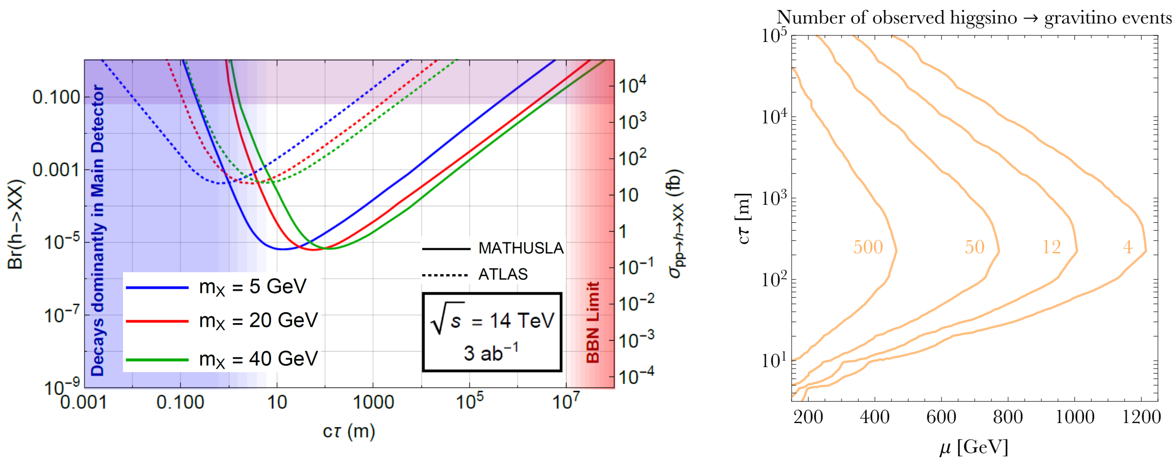

Figure 4: MATHUSLA reach for weak- and TeV-scale LLP decays at the HL-LHC. *Left*: Exotic Higgs decays to LLPs, MATHUSLA (solid) versus LHC main detectors (dashed) [6]. Plot from [1]. *Right*: Long-lived Higgsinos in supersymmetric models. Contours show the number of Higgsino decays in MATHUSLA as a function of Higgsino mass μ and decay length $c\tau$. Plot from [2].

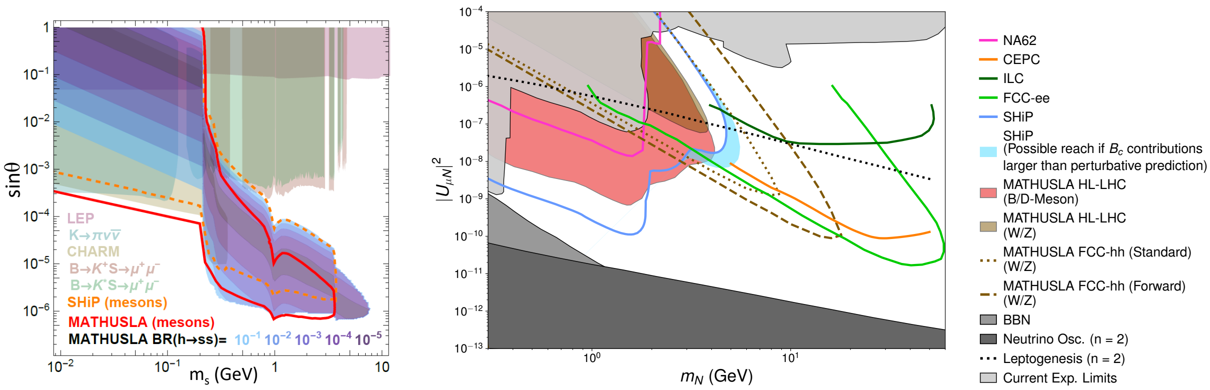

Figure 5: Projected MATHUSLA sensitivity [2] to low-mass LLPs at the HL-LHC. *Left*: "Dark Scalar" LLPs in the minimal SM+S extension, where a scalar of mass m_S has mixing $\sin\theta$ with the 125 GeV Higgs boson. Red: sensitivity to B-meson decays. Blue-purple: minimum BR$(h \to ss)$ value to which MATHUSLA would be sensitive. Dashed orange: projected constraint from the SHiP experiment. *Right*: Right-Handed Neutrino LLP simplified model, where the mixing with active neutrinos is dominated by the 2nd generation.

sources dominate. This transition region is of great interest for studying the magnetic field that confines charged particles within our galaxy, as well as the characteristics of extragalactic sources and charged particle propagation in the intergalactic medium. Our understanding of this part of the CR spectrum is constrained by the available statistics; MATHUSLA's measurements could help resolve long-standing puzzles and inconsistencies between other CR experiments.

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