PROCEEDINGS OF SCIENCE

PoS(ICRC2023)510

Cosmic-ray studies with the MATHUSLA experiment

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The MATHUSLA experiment is designed to investigate the possible existence of particle dark matter in the form of Long-Lived Particles (LLPs) produced in proton-proton collisions at the CERN High-Luminosity Large Hadron Collider (HL-LHC). Since the MATHUSLA detector will cover a wide area of the order of 10^4 m^2, with 9 layers of scintillating-detector planes, it can be used for cosmic-ray studies as well by extending its original set-up with the insertion of a full-coverage layer of Resistive Plate Chambers (RPCs). This will result in a crucial improvement in detecting extensive air showers produced by primary cosmic rays and reconstructing the arrival directions, and will allow detailed studies of parallel-muon bundles. The detection of hadronic showers, and the resulting study of the energy spectrum and composition of cosmic rays, will allow a test of hadronic-interaction models and will extended the investigation of the origin and propagation of primary cosmic rays. In this work, an outline of the MATHUSLA experiment and its potentialities in cosmic-ray studies are presented.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

ICRC2023
38th International Cosmic Ray Conference
The Astroparticle Physics Conference

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1. INTRODUCTION

The search for physics "Beyond the Standard Model" (BSM) motivates the possible existence of so-far-undiscovered Long-Lived Particles (LLPs). The main approaches to this search are the following:

- "top-down": various BSM theories (e.g. supersymmetry) constructed to explain the physics of fundamental interactions naturally include LLPs;
- "bottom-up": LLPs are included in the Standard Model (e.g. muons) and new LLPs can appear via similar mechanisms when adding new particles to the model.

Particles with long lifetime produced in collisions at the Large Hadron Collider (LHC) could be invisible to the main detectors, for several possible reasons:

- if $c\tau \gg$ detector size (where τ is the LLP lifetime) most of such particles escape the detector;
- LLPs which decay inside the detector, but a significant distance away from the interaction point, are difficult to detect;
- if the decay rate of LLPs inside the detector is very small, such particles are swamped by the background.

For such reasons, in order to detect possible LLPs produced in collisions at the LHC, dedicated, suitably designed experiments must be conceived.

2. MATHUSLA: AN EXTERNAL LLP DETECTOR AT THE HIGH LUMINOSITY - LHC

The MATHUSLA (MAssive Timing Hodoscope for Ultra-Stable neutraL pArticles) project foresees the deployment of a surface detector above the LHC interaction point of the CMS experiment [1]. The MATHUSLA detector will not be a part of CMS, and its construction and operation will not interfere with any other LHC experiments. The MATHUSLA structure will rise up to 9 m above the ground and will extend down to about 20 m underground. It will cover a horizontal surface of 100×100 m^2 and the LLP decay volume will have a vertical thickness of 25 m. The detector will have a horizontal displacement of about 70 m and a vertical displacement of about 60 m with respect to the LHC interaction point, as shown in the scheme of Fig. 1.

Due to the experiment large area, it will be deployed using a modular structure: 100 modules, each with a horizontal square area of 10×10 m^2; each module will be further subdivided into four detector units, each with a horizontal square area of 5×5 m^2.

Each module is composed of 6 tracking layers on top, 2 floor layers and 2 mid-level layers, as shown in the scheme of Fig. 2.

The tracking layers will be composed of extruded scintillator bars with wavelength-shifting fibers coupled to Silicon Photo Multipliers (SiPMs). The scintillator bars will be produced by the extrusion facilities at FNAL, already used for several other experiments. The size of each scintillator bar will be either 2.4 m $\times$3.5 cm $\times$1.5 cm with readout at both ends, or 2.5 m long with looped

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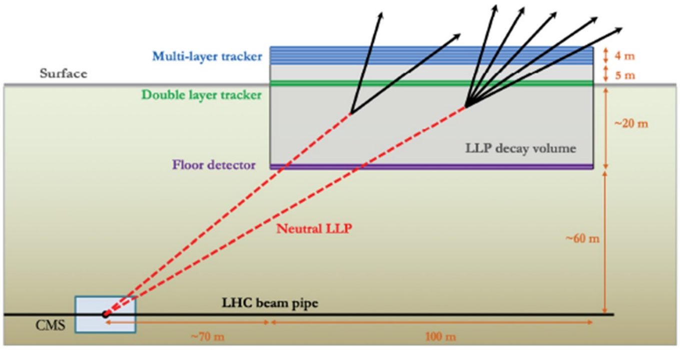

Figure 1: *Schematic vertical section of the MATHUSLA detector and its position with respect to the CMS interaction point at the HL-LHC.*

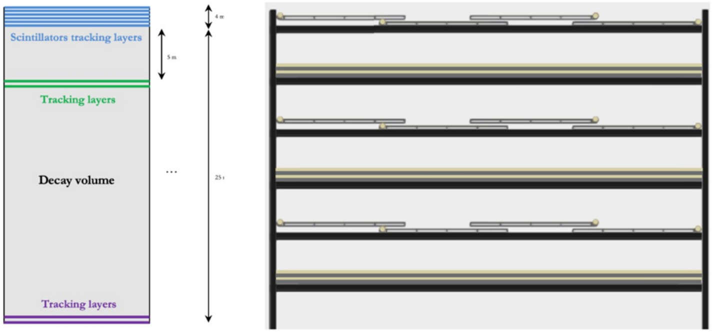

Figure 2: *Schematic vertical section of a MATHUSLA module (left), and details of the layout of its uppermost tracking layers (right).*

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fiber as the readout at one end. The expected transverse spatial resolution is about 1 cm, and the expected longitudinal spatial resolution (related to the resolution of the time difference between two ends) is about 15 cm. A test of the 5-m scintillator bars gave a 1-ns time resolution for cosmic-ray hits. R&D activities are going on concerning several items: wavelength-shifting fibers (attenuation, light collection), SiPMs (dark counts), scintillator-bar geometry.

The identification of LLP decays in MATHUSLA will be based upon the following considerations:

- since there will be no magnetic field in the decay volume, MATHUSLA will not be able to measure the particle momentum or energy, but the reconstruction of decay vertices geometrically compatible with long-lived neutral particles coming from the LHC interaction point will allow to evaluate the LLP Lorentz boost (Fig. 3);
- the synchronization of the MATHUSLA LLP candidate events with the CMS Level-1 trigger

will allow off-line event-info correlation so that it will be possible to classify the LLP production mode.

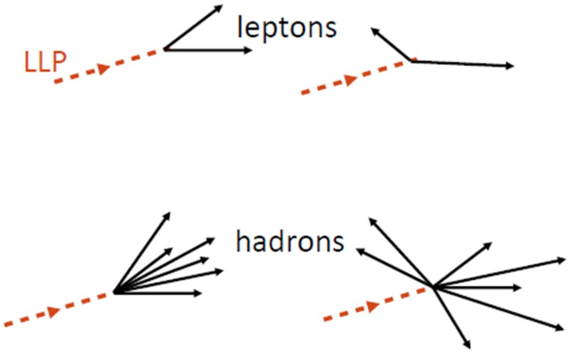

Figure 3: *Schemes of possible LLP decay vertices, in the case of two-body leptonic decay and many-body hadronic decay.*

Based on that, two analysis steps follow:

- if the production mode is known, then the LLP mass can be derived from the experimental boost distribution;
- if the LLP mass is known, then the LLP decay mode can be established from the experimental track multiplicity.

Under specific hypotheses, the combined MATHUSLA+CMS analysis could obtain some model parameters (e.g. mass of the parent particle, LLP mass) with just 100 observed LLP events.

In the search for new particles, a precise, reliable evaluation of the backgrounds is mandatory. A preliminary consideration in this respect is that LLP displaced vertices have to satisy many stringent geometrical (~ 1 cm precision) and timing (~ 1 ns precision) requirements. Fig. 4 shows a schematic vertical section of MATHUSLA with examples of the main possible background events. These requirement, plus a few extra geometrical and timing cuts, will provide almost negligible background for neutral LLP decays (less than 1 background event per year expected). Here are more details about the expected background events:

- the background due to cosmic rays was estimated with Test-Stand measurements performed on the surface above the LHC P1 interaction point in 2018; about 3×10^{14} downward-going tracks are expected in MATHUSLA over the whole HL-LHC run: these can be distinguished from LLPs by using timing cuts; about 2×10^{10} upward-going events due to cosmic-ray inelastic backscattering from the floor or to the decay of stopped muons in the floor are expected in MATHUSLA over the whole HL-LHC run: a negligible fraction of these could produce fake decay vertices in the MATHUSLA decay volume; possible rare K_L^0 produced in the floor can be vetoed with various strategies, which are under study;

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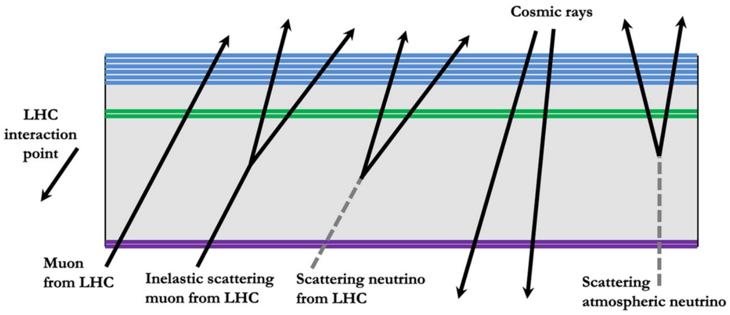

Figure 4: *Schematic vertical section of the MATHUSLA setup with the main possible backgrounds to LLP detection.*

- the background due to upward-going muons from HL-LHC collisions reaching MATHUSLA will amount to $\sim 10^{11}$, mostly from W and $b\bar{b}$ decays, from 3 ab^{-1} of HL-LHC collisions; most of these tracks can be vetoed with floor detectors, with just a very tiny fraction generating displaced vertices due to scattering or rare decays; overall, this kind of background can be handled without difficulty;

- the background due to charged tracks generated by neutrino scattering in the MATHUSLA decay volume can be estimated realiably: neutrinos from HL-LHC collisions are expected to produce $\ll 1$ fake decay vertex per year, and atmospheric neutrinos are expected to produce ~ 30 fake decay vertices per year, which can be reduced to less than one with geometrical and timing cuts.

The sensitivity of MATHUSLA to LLP detection depends on the physical properties of the LLP (e.g. mass, lifetime, production cross section) and on the detector geometry. Here are the expected MATHUSLA sensitivities to a few LLP benchmark models.

- hadronically-decaying LLPs produced in exotic-Higgs decay; the process $pp \to h \to XX$ can be studied with sensitivity improved by a factor of $\sim 10^3$ with respect to the LHC main detectors;

- in scenarios where the long-lifetime limit is accessible ($\gtrsim 100$ m), MATHUSLA is complementary to other planned experiments for LLP detection;

- LLP two-body decay to a Standard-Model particle and a “Dark-Matter” particle, as foreseen by a “freeze-in” Dark-Matter model, where the LLP (χ_2 mass eigenstate of the model) existed in thermal equilibrium with primordial plasma, then decaying to a final state including a Dark-Matter particle (χ_1 mass eigenstate of the model) [2].

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3. PROPOSAL FOR AN ADDITIONAL LAYER OF RESISTIVE PLATE CHAMBERS IN MATHUSLA

The good performance and the important scientific results of the ARGO-YBJ experiment [3], based on a full-coverage single layer of Resistive Plate Chambers (RPCs), suggested the possibility of exploiting the wide area covered by the MATHUSLA experiment to install a full-coverage layer of RPCs. This additional layer of detectors can obviously provide additional information to the LLP measurement of the MATHUSLA experiment, and can contribute to specific studies in cosmic-ray physics which could not be easily done with other experiments.

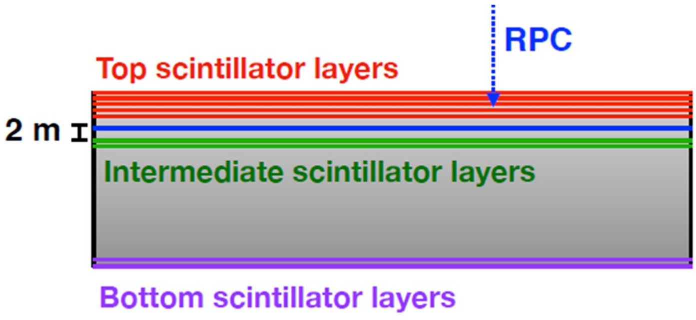

Figure 5: *Schematic vertical section of the MATHUSLA setup with the insertion of the proposed RPC layer.*

RPCs provide the following additional information:

- Lower multi-hit probability in one strip due to the finer segmentation of the RPC read-out strips
- Estimation of the pulse charge from the "time-over-threshold" measurement; this gives an approximate evaluation of the hit multiplicity in one strip provided the number of simultaneous hits is significantly greater than one.
- Crucial information for cosmic-ray studies with MATHUSLA: linear response for hit density up to more than 10^4 hits/m^2 in the detection of air-shower cores thanks to the "big-pad" analog readout [4], to be compared to the saturated response (at high hit density) of a digital strip readout.

Here are the main features of the RPCs that would be used in MATHUSLA:

- Big-Pad size: 1.1×0.9 m^2; the big-pad signal is proportional to the local charge density crossing the detector;
- Read-out strip area: 242 cm^2 (11-mm pitch);
- Operating mode: saturated avalanche;
- Gas-gap width: 1 mm (as the ATLAS BI RPCs).

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4. COSMIC-RAY PHYSICS WITH MATHUSLA

We already pointed out the features of the additional RPC layers connected to cosmic-ray studies with MATHUSLA. Nevertheless, there are a few important constraints to such studies: the very modest altitude of the experimental site (374 m above sea level), and a sensitive area not exceeding 10^4 m^2.

Taking everything into account, cosmic-ray studies with MATHUSLA will be focused on the following items [5]:

- Study of the cosmic-ray energy spectrum and composition (measurement of the atomic number Z of the primary particle);
- Bundles of parallel muons. They can be observed when the electro-photonic component of the shower is absorbed before the shower hits the detector ("pure muonic shower"). For vertical showers they can be seen only at low energy, while for inclined or almost horizontal showers they can be observed also at high or very high energy due to the larger thickness of the atmosphere. This study is crucial both again for cosmic-ray composition studies and for discriminating among the predictions of different high-energy hadronic interaction models.

The space-time-charge information provided by the RPC big pads allow the EAS front reconstruction, its inclination with respect to the horizontal plane and the local hit density.

As an example of the RPC-plane response to an extensive air shower, Fig. 6 shows the bidimensional distribution of the induced charge on the RPC big pads in one simulated event (primary proton of 263 GeV with a zenith angle of 11.37°) and the bidimensional map of the big-pad time delays with respect to the first hit in the event (preliminary result).

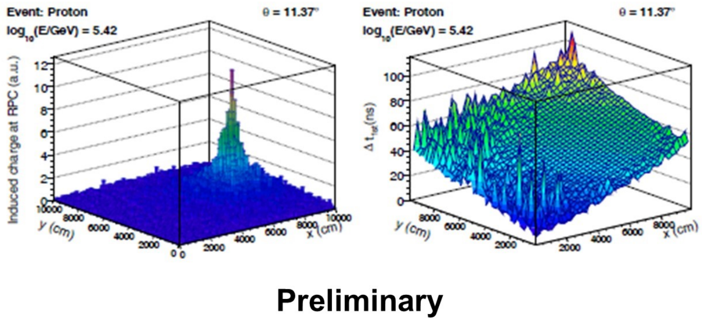

Figure 6: *PRELIMINARY. Left: bidimensional distribution of the induced charge on the RPC big pads in one simulated event (primary proton of 263 GeV with a zenith angle of* 11.37°*). Right: bidimensional map of the big-pad time delays with respect to the first hit in the event.*

If the EAS arrival direction is greater than about 65°, muons are the main component of the EAS. At the MATHUSLA site, inclined EAS from H and Fe primary nuclei between ~ 1 and

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~ 100 PeV have an average muon content of about (80 ± 1) %, as predicted by QGSJET-II-04 MC simulations (preliminary result).

The average value and the spectrum of the local muon density D in MATHUSLA for inclined EAS events generated by H and Fe primaries in the 1 to 100 PeV energy range have been simulated and studied using several high-energy hadronic interaction models, assuming that the primary energy spectra have a behaviour $\sim E^{-2}$. Above 10 PeV the local magnitude of D increases linearly with the primary energy in log scale and it is greater for heavy primaries than for light ones. The D spectra for EAS with a high content of muons are harder than the D spectra for EAS with a low muon multiplicity, and a slight spread is observed depending on the high-energy hadronic interaction model: so, such curves can be used to test the prediction of different models and discriminate among them. The preliminary results of the simulation studies are shown in Fig. 7.

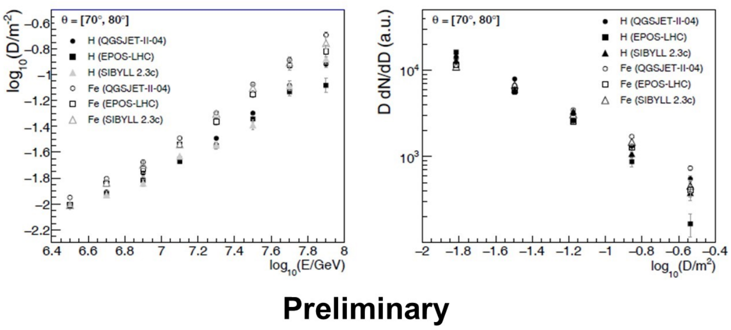

Figure 7: *PRELIMINARY. Left: local muon density reaching MATHUSLA vs. primary energy, in log-log scale, for showers induced by protons (H) and iron nuclei (Fe) according to several hadronic-interaction models. Right: muon-density spectrum on MATHUSLA vs. primary energy, for showers induced by protons (H) and iron nuclei (Fe) according to several hadronic-interaction models.*

5. THE MATHUSLA PROGRESS STATUS AND CONCLUSIONS

The MATHUSLA Technical Design Report is being written and is expected to be presented to CERN by the end of 2023, followed by a prototype module and the full detector for the HL-LHC run.

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