Geometric Optimization of the MATHUSLA Detector

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MATHUSLA is a proposed displaced vertex detector for neutral long-lived particle decays. It was proposed with general specifications of the size of its decay volume and its location. In this study, different simplified models containing LLPs are investigated using Monte Carlo event generators, and LLP decay probability maps are generated. Specific optimal configurations for the detector are found for each model according to available land around the CMS detector. We demonstrate that the placement and dimensions of a proposed 10000 m² engineering benchmark can be modified so that an improvement in acceptance (up to 12% more LLP decays) is observed. Also, it is found that the engineering benchmark would observe about 80% of the number of LLP decays that the earlier MATHUSLA200 physics sensitivity benchmark with four times the area would observe.

1. INTRODUCTION

The MASSive Timing Hodoscope for Ultra-Stable neutraL pArticles (MATHUSLA) is a proposed displaced vertex detector at the surface of the LHC site, designed for the indirect detection of neutral long-lived particles (LLPs). First proposed in [1], the physical motivation for MATHUSLA includes the existence of neutral LLPs in many beyond standard model (BSM) theories, notably various models that address the Hierarchy Problem, in addition to other BSM models that are discussed in detail in [2,3]. Neutral uncolored particles produced at the LHC can only be detected as reconstructed displaced vertices (DV$s$), or as missing transverse energy (MET). MET signals usually have many backgrounds, such as neutrino MET signals, so a DV detector may have an increased sensitivity to LLPs. In addition, MET signals from the main LHC detectors could be supplemented by DV measurements for a more comprehensive characterization of a neutral particle.

Theoretically, a wide range of particle lifetimes are possible. However, signatures of the well understood phenomenon of Big Bang Nucleosynthesis (BBN), which happened about 1 second after the big bang, indicate that any particle (under some conditions) should have decayed before BBN [1]. Otherwise, cosmological parameters measured today wouldn’t be as they are, unless the particles have a very small energy density, the particles are stable, or they have a very small branching ratio into SM hadrons. This sets an upper bound on the lifetimes of some unstable LLPs produced at the LHC. This upper bound translates to a decay length of $c\tau \lesssim 10^7$-$10^8$ m [1]. Particles with lifetimes near this upper bound have a high probability of escaping the LHC main detectors before decaying, leaving MET signals that look identical to MET signals left by stable neutral particles. Thus, it would be instructive to design MATHUSLA so that it has the highest possible acceptance for LLP decays near that limit.
MATHUSLA would be built on the surface above an LHC interaction point (IP). An IP is about 80 m below the surface of the ground. Current proposals are made for MATHUSLA to start 20 m under the surface of the ground, making the IP 60 m below the bottom surface of MATHUSLA. This 60 m layer of rock would provide shielding from electrically charged particles and neutral hadrons from events at the LHC. A detector layer would surround all or part of MATHUSLA’s decay volume to aid in background rejection. The precise detector design and geometry of MATHUSLA has not yet been determined. The various design options have features in common like the ~100 m distance above an IP, with a 20 m high decay volume, and the closest side being a maximum of 100 m away horizontally from the IP. Above the 20 m decay volume would be 5 layers of Resistive Plate Chambers (RPCs) that act as charged particle trackers, with a separation of 1 m between each other. The original MATHUSLA200 design, which should be regarded as a physics sensitivity benchmark, is shown in Figure 1. The 20 m high decay volume was proposed in the first MATHUSLA paper [1] so that it would be sensitive to LLPs resulting from Higgs decays with lifetimes near the BBN limit, for a detector that has a geometry such that 10% of produced LLPs would pass through it. But current proposals for MATHUSLA call for a 25 m height for the decay volume, in order to achieve a higher acceptance of LLP decays. Both the 20 m and 25 m high decay volumes were considered in this study, for a 10000 m² detector. The only thing left to optimize, then, would be the remaining horizontal dimensions of MATHUSLA, and its placement according to available land. Optimizing the placement and the remaining dimensions of MATHUSLA is the aim of this study.

The optimization of the placement and dimensions of MATHUSLA can be considered under several simplified models that are motivated by BSM theories, as different LLPs with different production modes would be produced with different distributions at the LHC. A survey done in [4] highlights four simplified models which include LLPs, each representing different LLP production topologies. These are the heavy parent (HP) decay topology (representative of many supersymmetric scenarios), the exotic Higgs decay topology (representative of scalar decay to LLPs), the intermediate resonance topology (representative of gauge-portal Z’ decaying to LLPs), and the exotic bottom meson decay topology (representative of heavy neutrino theories) [4]. In this paper, these

![Figure 1: MATHUSLA200 decay volume (gray shaded), a (200 m)² building with its center along the beam line. It is 100 m above the IP and 100 m away from the IP in the z-direction. In this coordinate system, the IP is the origin and the positive x, y, z directions are shown. Figure from [1].](image)
four LLP production topologies are investigated via their respective representative models using a Monte Carlo parton-level event generator (Madgraph5_aMC@NLO) [6], with showering conducted by Pythia 8. The R-parity violating minimally supersymmetric standard model (RPVMSSM) is used as a benchmark model for supersymmetric theories, as is the hidden abelian Higgs model (HAHM) for Higgs-portal theories, a new abelian massive gauge field denoted by Z’ (or ZP) for gauge-portal theories, and the plain standard model (SM) with a right handed neutrino (RHN) for bottom meson decay into heavy neutral leptons (HNL) [5].

After obtaining a list of LLP momenta from an event generator, the task would be to find the probability of the decay of that LLP within a section of MATHUSLA. This is calculated based on the simple exponential decay equation evaluated at two lengths $L_1$ and $L_2$ for an LLP with lifetime $\tau$:

$$P_{\text{decay}}(b\tau, L_1, L_2) = e^{-\frac{L_1}{b\tau}} - e^{-\frac{L_2}{b\tau}} \approx \frac{L_2 - L_1}{b\tau}$$ [3]

where the approximation holds for the long lifetime limit $L_1, L_2 \ll b\tau$, $L_1, L_2$ are lengths from the IP to where the LLP enters and leaves a given volume, respectively, and $b = \frac{p}{m}$ is the boost of the LLP. Then, the total decay probability within the entire detector is equal to the sum of the decay probabilities in each subsection of the detector. Also, it is important to note that under the same limit, an optimal configuration of MATHUSLA is independent of lifetime, as a change in lifetime would cause each decay probability within MATHUSLA to change by the same multiplicative factor. Dividing the area surrounding an LHC IP into squares and using equation (1), one could generate probability maps for the probability of LLP decays. Then, an optimal configuration for MATHUSLA could be found, maximizing LLP decay acceptance given physical constraints like land availability and assembly requirements.

II. METHODS

There are three steps for creating LLP decay probability maps in an area surrounding an LHC IP, namely, event generation and showering; event selection or reweighting; and creating the probability maps using the momenta from the event generations. Afterwards, an optimization of MATHUSLA design parameters would be conducted on each probability map. These four steps of MATHUSLA optimization are discussed in detail in the following subsections.

A. Parton-Level Event Generation and showering

For each model of RPVMSSM, HAHM, ZP, and SM, events were generated at parton level using Madgraph5_aMC@NLO v.2.6.5 (MG5) [6], interfaced with Pythia 8.240. Pythia was used to conduct the parton showering and hadronization on the MG5 output. All sets of events generated for the different models are listed in Table 1. For the RPVMSSM, a heavy parent (HP) decay was considered, where a heavy colored parent...
Table 1: Events generated by MG5 and showered by Pythia. Different mediator and LLP masses used are shown, in addition to number of events generated and the MG5 input used to generate those events. For processes where jet matching was used, about half the events were rejected so twice as many events were generated compared to other non-matched samples. For the RPVMSSM model, y denotes the heavy parent particle.

| Model         | m_{ LLP} (GeV) | MG5 Input                                      | Events Generated |
|---------------|----------------|-----------------------------------------------|------------------|
| HAHM, gluon fusion | 5, 15, 30, 50  | p p > h, h > hs hs p p > h j, h > hs hs       | 2 \times 10^6 per m_{ LLP} |
| HAHM, VBF     | 5, 15, 30, 50  | p p > h j j $$w+ w- z a, h > zp zp QCD=0     | 1 \times 10^6 per m_{ LLP} |
| ZP, m_{zp} = 400 GeV | 20, 100, 200 | p p > zp, zp > x2 x2~                         | 2 \times 10^6 per m_{ LLP} |
| ZP, m_{zp} = 2 TeV  | 100, 500, 1000 | p p > zp j, zp > x2 x2~                      | 2 \times 10^6 per m_{ LLP} |
| ZP, m_{zp} = 10 TeV  | 10, 100, 1000  |                                              | 2 \times 10^6 per m_{ LLP} |
| RPVMSSM, m_y = 500 GeV | 50, 125, 400  | p p > su6 su6~, su6 > n4 j, su6~ > n4 j     | 1 \times 10^6 per m_{ LLP} |
| RPVMSSM, m_y = 2 TeV  | 200, 500, 1200 |                                              | 1 \times 10^6 per m_{ LLP} |
| p p \rightarrow B \rightarrow RHN | 0.1, 4      | p p > b b~                                     | 2 \times 10^7    |
| p p \rightarrow B \rightarrow scalar    | 0.1, 4      |                                              |                  |

Each event is generated in MG5 as squark pair production from pp collisions, and subsequent decay of both squarks into a neutralino each, with a dijet signature for each event. For the HAHM model, gluon fusion and vector boson fusion (VBF) events were generated separately. For gluon fusion, events were generated as Higgs boson production from pp collisions with a monojet signature, followed by Higgs decay into a pair of neutral scalars, which were taken to be the LLPs. For VBF Higgs production, W boson fusion, Z boson fusion and photon fusion events produced a Higgs boson from pp interactions with a dijet signature, followed by Higgs decay to a pair of LLPs. For the ZP model, events were generated as vector boson Z’ production from pp collisions with a monojet signature, followed by decay of Z’ to a pair of neutral LLPs. Depending on the mass of Z’, the production modes of those LLPs differ. For Z’ masses under a couple TeV, the Z’ is produced on-shell at the 14 TeV LHC, and the subsequent decay into LLPs is denoted by heavy resonance (RES) production [4]. For Z’ masses around 10 TeV, the Z’ is off-shell and the LLPs are produced by direct-pair production (DPP) [4]. For each of the events generated for the HAHM and ZP models, a jet matching procedure was used to prevent double counting between MG5 and Pythia, discussed further in subsection B of this section.
Finally, for the heavy right-handed neutrino model, a bottom and an anti-bottom quark are pair produced from p p collisions, followed by hadronization into bottom mesons. Bottom meson decays into right-handed neutrinos were done outside of MG5 and Pythia, according to decay modes provided by [5]. Bottom mesons B⁺, B⁰ and B_s were extracted from events and decayed into right-handed neutrinos. Bottom meson decays into a complex scalar were also done for comparison (B⁺ → K⁰Φ and B⁰ → K⁺Φ) [10]. The decay modes used along with the branching ratios are shown in Table 2. A random direction was chosen in the frame of the mesons, and a momentum was calculated based on 2-body or 3-body decay kinematics. Then, that momentum was boosted to the lab frame. However, in this case, each event was reweighed according to “Fixed Order + Next-to-Leading Log” (FONLL) predictions for bottom meson production at the LHC [7], provided by [8]. This reweighting of events is described in subsection B of this section.

### B. Jet Matching and FONLL

For the HAHM and ZP model events, jet matching was used to prevent overlapping between phase-space calculations from the parton level event generator and the hadronization software, since there are intermediate jets in these events. A kt jet matching procedure was used, where a minimum value (xqcut) was set for the kt jet measure allowed for an event to be accepted. The value of xqcut was optimized by finding the value of xqcut such that jet transverse momentum (PT) distributions are smooth and do not change around that value of xqcut. For HAHM model gluon fusion events, the optimal value of xqcut was around 1/6 of the hard scale, which is the Higgs mass, so xqcut was set to 20 GeV. It was also found that for ZP heavy resonance production, the optimal xqcut value was 10% of the hard scale (which is the mass of Z'), and for the case of direct pair production it was 20% of the hard scale (which is 2 times the LLP mass).

To account for QCD effects at the scale of bottom quark production, a reweighting of events according to PT distributions is warranted. For this, a FONLL bottom meson PT distribution spanning the range from PT = 0 to 30 GeV was generated from [8] in increments of 0.5 GeV. About 99.5% of all bottom mesons produced at the LHC have PT values in that range according to MG5+Pythia predictions. Another PT distribution was obtained from the bottom mesons that were generated by MG5+Pythia. Both PT distributions are smooth and do not change around that value of xqcut. For HAHM model gluon fusion events, the optimal value of xqcut was around 1/6 of the hard scale, which is the Higgs mass, so xqcut was set to 20 GeV. It was also found that for ZP heavy resonance production, the optimal xqcut value was 10% of the hard scale (which is the mass of Z'), and for the case of direct pair production it was 20% of the hard scale (which is 2 times the LLP mass).

| Process | BR(m_N=0.1 GeV) | BR(m_N=4.0 GeV) |
|---------|-----------------|-----------------|
| B⁺→e+N | <10⁻⁶           | 1.3×10⁻⁴        |
| B⁺→D⁰+e+N | 2.8×10⁻²  | 0               |
| B⁺→D⁺e+N | 6.5×10⁻²  | 0               |
| B⁰→D⁺e+N | 2.5×10⁻²  | 0               |
| B⁰→D⁺e+N | 5.7×10⁻²  | 0               |
| B⁰→π⁺e+N | 1.2×10⁻⁴  | 8.4×10⁻⁶        |
| B⁰→ρ⁺e+N | 3.3×10⁻⁴  | 1.3×10⁻⁶        |
| B⁺→D_s+e+N | 2.2×10⁻²  | 0               |
| B⁺→D_s+e+N | 5.0×10⁻²  | 0               |

**Table 2:** Bottom meson decays into right-handed neutrinos that were considered. Branching ratios for a 0.1 GeV neutrino and a 4.0 GeV neutrino are provided by [5].
distributions were normalized. Afterwards, for each generated MG5+Pythia event, the bottom meson PT was calculated, and if the PT value was between 0 and 30 GeV, the value of that PT was rounded up to the nearest 0.5 GeV (only for the purposes of finding a reweighting factor), and a reweighting factor was generated by dividing the value of the FONLL distribution function at that PT by the value of the MG5+Pythia distribution function at the same PT. These reweighting factors were used in creating the LLP decay probability maps, where each decay probability resulting from an event is multiplied by the reweighting factor associated with that event. This is discussed further in subsection C of this section.

**C. Probability map Generation**

To generate probability maps for each process, a 300 m by 300 m area in the positive y-z plane (Figure 1) was divided into 5 m by 5 m boxes. These boxes represent cuboids that are 25 m high, and the distance of the cuboids’ bottom surfaces was set to 60, 70, 80, 90 and 100 m above the IP in the x-direction to test acceptance at different distances from the IP. Then, for accepted events of the HAHM and ZP models, in addition to RPVMSSM events, each LLP momentum was traced until it traversed the entire 300 m by 300 m area, and the amount of length spent within each volume was calculated, so that a value for $P_{\text{decay}}$ from equation (1) would be found for each event in each cuboid. All $P_{\text{dec}}$ values found for a cuboid i were added and the sum $P_{\text{tot},i}$ was recorded. If one notes azimuthal symmetry about the z-axis in addition to ±z symmetry, then one can use a trick to appear to increase the generated LLP sample size so that a smoother probability map would be produced with minimal computational costs. This means that if every negative LLP momentum component in our coordinate system has its sign flipped, so that all LLPs would pass through one octant of a sphere around the IP, we’d create an LLP decay probability map that would look as if we had used a dataset eight times as large. Then the total number of LLPs that would decay within a cuboid i would be:

\[
N_{\text{decay},i} = (\sigma \, L) \frac{n_{\text{llp}}}{n_{\text{llp}}} P_{\text{tot},i} = (\sigma \, L) \, P_{\text{map},i},
\]

where $\sigma$ is the production cross section of the LLP at the LHC, $L$ is the total integrated luminosity of the LHC run, $n_{\text{llp}}$ is the number of LLPs produced per event and $N_{\text{llp}}$ is the total number of LLPs from the generated events. Then, each probability map was generated with values of $P_{\text{map},i}$ and an LLP lifetime of 1 second, so that the probability maps could be rescaled for any LLP lifetime by dividing by the lifetime in seconds. The same procedure for creating heavy right-handed neutrino decay maps was used, except in this case each $P_{\text{decay}}$ value that contributed to the sum $P_{\text{tot},i}$ is multiplied by the FONLL reweighting factor depending on the PT of the parent bottom meson.

For the HAHM model, VBF and gluon fusion maps were combined to form one LLP decay probability map for a given LLP mass. The VBF and gluon fusion maps were added
according to 14 TeV LHC Higgs production cross sections for a 125 GeV Higgs boson [9]. LLPs resulting from bottom meson decays had their probability maps combined according to branching ratios in Table 2, and according to the production cross sections of the bottom mesons. These branching ratios and cross sections were normalized so that each bottom meson would decay into a heavy RHN, and the cross sections were simply relative cross sections (the fraction of bottom mesons produced that were a specific type for example).

D. MATHUSLA Optimization

After generating probability maps spanning the positive y-z plane for each model, the probability maps were reflected across the z-axis, and then again across the y axis so that they cover the entire y-z plane. Figure 2 shows the available land around CMS, with an engineering benchmark MATHUSLA design that is 100 m by 100 m. The red line on the boundary of available land indicates where one side of a rectangular MATHUSLA should be placed, according to engineering requirements.

An optimization ran on each LLP decay probability map to find the optimal placement and dimensions that give a 10000 m$^2$ MATHUSLA the highest acceptance (highest value of $\Sigma_{i \in \text{configuration}} P_{\text{map},i}$) for LLP decays within the boundaries of available land. For this, distances were divided in increments of 1/3 of a meter. After finding the optimal MATHUSLA configuration, it was compared to the engineering benchmark in Figure 2, in addition to the MATHUSLA200 design shown in Figure 1, where MATHUSLA200 is 100 m above the IP and has a 20 m high decay volume. Since the optimization increment size used was smaller than the increment size of the probability maps (which was 5 m), if a configuration of MATHUSLA included a fraction $f$ of the area of a 5 m by 5 m square $i$ in a probability map, then $f \times P_{\text{map},i}$ is added in the calculation of the total decay probability within that configuration.

Figure 2: Available land around CMS (yellow). The IP is 80 m deep below the ground and is 67.66 m away from the red shaded part of the boundary of the available land. The coordinate system of the y-z plane is shown around the IP, along with the engineering benchmark design of MATHUSLA and its assembly area.
Table 3: Summary of the MATHUSLA optimization results for a detector 60 m above the IP and a 25 m high decay volume. \((y_1, z_1)\) is the position of the lower left corner of the optimal MATHUSLA configuration, in a coordinate system where the positive z direction points upwards, and the positive y direction points to the right. \((L_y, L_z)\) are the \((y, z)\) dimensions of the optimal MATHUSLA configuration, respectively. \[ P_{\text{opt}} = \sum_{i \in \text{optimal configuration}} P_{\text{map},i}, \quad P_{\text{eng}} = \sum_{i \in \text{engineering benchmark}} P_{\text{map},i}, \] and \( P_{\text{MAT200}} = \sum_{i \in \text{MATHUSLA200}} P_{\text{map},i} \), where the MATHUSLA200 design is shown in Figure 1.

| Model          | \(m_{LLP}\) (GeV) | \(y_1\) (m) | \(z_1\) (m) | \(L_y\) (m) | \(L_z\) (m) | \(P_{\text{opt}}/P_{\text{eng}}\) | \(P_{\text{opt}}/P_{\text{MAT200}}\) | \(P_{\text{eng}}/P_{\text{MAT200}}\) |
|----------------|-------------------|-------------|-------------|-------------|-------------|----------------|----------------|----------------|
| HAHM           | 5                 | -73.67      | 146.33      | 68.33       | 1.038       | 0.856          | 0.825          |
| HAHM           | 15                | -69.33      | 136.33      | 73.33       | 1.030       | 0.848          | 0.823          |
| HAHM           | 30                | -67.33      | 132.00      | 75.67       | 1.018       | 0.834          | 0.819          |
| HAHM           | 50                | -51.67      | 106.00      | 94.33       | 1.002       | 0.812          | 0.810          |
| ZP, \(m_{ZP}=0.4\) TeV | 20                | -69.33      | 136.33      | 73.33       | 1.037       | 0.853          | 0.823          |
| ZP, \(m_{ZP}=0.4\) TeV | 100              | -56.33      | 112.33      | 89.00       | 1.007       | 0.823          | 0.817          |
| ZP, \(m_{ZP}=2\) TeV | 200              | -30.33      | 83.33       | 120.00      | 1.022       | 0.806          | 0.789          |
| ZP, \(m_{ZP}=2\) TeV | 500              | -78.00      | 158.67      | 63.00       | 1.069       | 0.887          | 0.830          |
| ZP, \(m_{ZP}=10\) TeV | 1000             | -30.33      | 83.33       | 120.00      | 1.020       | 0.805          | 0.789          |
| ZP, \(m_{ZP}=10\) TeV | 10               | -75.33      | 150.67      | 66.33       | 1.067       | 0.889          | 0.833          |
| ZP, \(m_{ZP}=10\) TeV | 1000             | -78.00      | 158.67      | 63.00       | 1.070       | 0.891          | 0.833          |
| RPVMSSM, \(m_y=0.5\) TeV | 50               | -79.33      | 163.00      | 61.33       | 1.080       | 0.898          | 0.831          |
| RPVMSSM, \(m_y=0.5\) TeV | 125              | -78.00      | 158.67      | 63.00       | 1.069       | 0.889          | 0.832          |
| RPVMSSM, \(m_y=0.5\) TeV | 400              | -55.00      | 110.67      | 90.33       | 1.005       | 0.822          | 0.818          |
| RPVMSSM, \(m_y=2\) TeV | 200              | -84.33      | 180.67      | 55.33       | 1.122       | 0.937          | 0.835          |
| RPVMSSM, \(m_y=2\) TeV | 500              | -82.67      | 174.33      | 57.33       | 1.121       | 0.937          | 0.836          |
| RPVMSSM, \(m_y=2\) TeV | 1200             | -80.33      | 165.67      | 60.33       | 1.097       | 0.916          | 0.835          |
| \(p p \rightarrow B \rightarrow \text{RHN}\) | 0.1              | -67.33      | 132.00      | 75.67       | 1.013       | 0.830          | 0.819          |
| \(p p \rightarrow B \rightarrow \text{RHN}\) | 4                | -46.00      | 98.67       | 101.33      | 1.002       | 0.809          | 0.807          |
| \(p p \rightarrow B \rightarrow \text{scalar}\) | 0.1              | -69.33      | 136.33      | 73.33       | 1.019       | 0.835          | 0.819          |
| \(p p \rightarrow B \rightarrow \text{scalar}\) | 4                | -46.00      | 98.67       | 101.33      | 1.002       | 0.809          | 0.807          |
III. RESULTS

As described in subsection D of the previous section, rectangular configurations of MATHUSLA were tried and an optimal configuration was identified if it maximized the value of $P = \sum_{i \in \text{configuration}} P_{\text{map},i}$. The results of the optimization for a detector 60 m above the IP with a 25 m high decay volume are shown in Table 3. Plots of the probability maps are shown in the Appendix. The results of the optimization show minimal improvements in the acceptance of MATHUSLA from the engineering benchmark (up to 12.2% in the long lifetime limit). The best improvements occurred for the RPVMSSM, especially for a heavy parent particle with mass 2 TeV and low LLP masses. For the ZP model, the best improvements were recorded for $Z'$ masses in the TeV scale, where improvements were up to 7.0%. For the HAHM model, the maximum improvement was recorded for the lowest LLP mass tested (5 GeV), where improvements were 3.8%. For LLPs resulting from bottom meson decays, improvements in acceptance were very small (up to 1.9%).

IV. DISCUSSION AND CONCLUSIONS

The geometric optimization of a 10000 m$^2$ MATHUSLA showed that improvements to the acceptance of the engineering benchmark design in the long lifetime limit ($L_1, L_2 \ll b\tau$) would be minimal. It also showed that the most considerable improvements to acceptance can result for the lightest of LLPs. Light LLPs may have longer lifetimes due to kinematic suppression of their decay, and an increase of around 12% to the decays of such particles within MATHUSLA may be useful for no additional costs. In general, for light LLPs, an increase in the number of decays within a 10000 m$^2$ MATHUSLA was found to be possible if its y-dimension was longer than 100 m, while its z-dimension was shorter. Furthermore, this study has not considered the short lifetime limit. For short-lived particles, it is expected that decays will occur close to the IP, also favouring a flatter MATHUSLA in the z-direction.

The engineering benchmark appeared to be a robust configuration for MATHUSLA in terms of LLP decay acceptance. The minimal change in the acceptance of MATHUSLA for LLP decays in the long lifetime limit depending on the y-z configuration means that the detector can be assembled in almost any configuration, as determined by engineering requirements, as long as it is placed as far towards the negative y-direction as possible in the available land. Also, the robustness of the engineering benchmark was reflected in the closeness of the total LLP decay probabilities of the engineering benchmark and MATHUSLA200. Although the engineering benchmark covers a quarter of the area covered by MATHUSLA200, it would observe around 80% of the number LLP decays observed within MATHUSLA200, consistent across all models and LLP masses tested. This is significant since similar acceptance to MATHUSLA200 can be achieved with a quarter of the area, and commensurably reduced costs.
The results of this study can be applied to many scenarios of LLPs at the LHC, since multiple simplified models from the survey of LLP theories done in [4] were considered. A wide range of mediator and LLP masses were also considered. Searches for lighter LLPs may benefit from a flatter MATHUSLA in the z-direction. But for LLP production processes considered in this study (in the long lifetime limit), this improvement is not expected to exceed ~10% of the current engineering benchmark. A larger improvement is expected in the short lifetime limit if more of the detector is placed closer to the IP.

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Appendix

LLP decay probability maps are shown here, along with geometric optimization parameters. They show values of $P_{map,t}$ for $5m \times 5m$ squares, as described in section II.C. All distances are in meters, and all areas are in meters squared. They appear here in the order provided by Table 3.

| Figures | Model | $m_{\text{LLP}}$ (GeV) |
|---------|-------|------------------------|
| A1-A4   | HAHM  | 5, 15, 30, 50          |
| A5-A7   | ZP, $m_{ZP}=0.4$ TeV | 20, 100, 200           |
| A8-A10  | ZP, $m_{ZP}=2$ TeV    | 100, 500, 1000         |
| A11-A13 | ZP, $m_{ZP}=10$ TeV   | 10, 100, 1000          |
| A14-A16 | RPVMSSM, $m_y=0.5$ TeV| 50, 125, 400           |
| A17-A19 | RPVMSSM, $m_y=2$ TeV  | 200, 500, 1200         |
| A20-A21 | $p \ p \rightarrow B \rightarrow \text{RHN}$ | 0.1, 4.0               |
| A22-A23 | $p \ p \rightarrow B \rightarrow \text{scalar}$ | 0.1, 4.0               |

Appendix

LLP decay probability maps are shown here, along with geometric optimization parameters. They show values of $P_{map,t}$ for $5m \times 5m$ squares, as described in section II.C. All distances are in meters, and all areas are in meters squared. They appear here in the order provided by Table 3.
(Ly, Lz) = (136.333, 73.333)  Area = 9997.778
(y1, z1) = (-69, 333, 67.667)

optimal position/engineering benchmark: 1.03
optimal position/MATHUSLA 200: 0.848
engineering benchmark/MATHUSLA 200: 0.823

(Ly, Lz) = (132.0, 75.667)  Area = 9988.0
(y1, z1) = (-67.333, 67.667)

optimal position/engineering benchmark: 1.018
optimal position/MATHUSLA 200: 0.834
engineering benchmark/MATHUSLA 200: 0.819
(L_y,L_z) = (150.667,66.333)  Area = 9994.222
(y_1,z_1) = (-75.333,67.667)

Optimal position/engineering benchmark: 1.067
optimal position/MATHUSLA 200: 0.889
engineering benchmark/MATHUSLA 200: 0.833

(A12)

(A13)
A14

(Ly,Lz) = (163.0, 61.333)  Area = 9997.333
(y1,z1) = (-79.333, 67.667)

optimal position/engineering benchmark: 1.08
optimal position/MATHUSLA 200: 0.899
engineering benchmark/MATHUSLA 200: 0.831

A15

(Ly,Lz) = (158.667, 63.0)  Area = 9996.0
(y1,z1) = (-78.0, 67.667)

optimal position/engineering benchmark: 1.069
optimal position/MATHUSLA 200: 0.889
engineering benchmark/MATHUSLA 200: 0.832
(Lx,Lz) = (110.667,90.333)  Area = 9996.889
(y1,z1) = (-55.0,67.667)

optimal position/engineering benchmark: 1.005
optimal position/MATHUSLA 200: 0.822
engineering benchmark/MATHUSLA 200: 0.818

(Lx,Lz) = (180.667,55.333)  Area = 9996.889
(y1,z1) = (-84.333,67.667)

optimal position/engineering benchmark: 1.122
optimal position/MATHUSLA 200: 0.937
engineering benchmark/MATHUSLA 200: 0.835
A20

\[(L_y, L_z) = (132.0, 75.667) \quad \text{Area} = 9988.0\]
\[(y_1, z_1) = (-67.333, 67.667)\]

optimal position/engineering benchmark: 1.013
optimal position/MATHUSLA 200: 0.83
engineering benchmark/MATHUSLA 200: 0.819

A21

\[(L_y, L_z) = (98.667, 101.333) \quad \text{Area} = 9998.222\]
\[(y_1, z_1) = (-46.0, 67.667)\]

optimal position/engineering benchmark: 1.002
optimal position/MATHUSLA 200: 0.809
engineering benchmark/MATHUSLA 200: 0.807
