MATHUSLA Efficiency Studies*

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(Dated: August 10, 2018)

MATHUSLA is a proposal for a large surface detector to search for neutral ultra long-lived particles produced at the Large Hadron Collider (LHC). It is currently in the design stage. This project involves taking simulated physics events and calculating the geometric acceptance for various detector layouts. The results will be combined with site-specific constraints at the LHC as well as manufacturing practicalities to arrive at the eventual detector layout.

I. INTRODUCTION

Aimed at detecting ultra-long-lived particles (ULLPs), MATHUSLA (MAssive Timing Hodoscope for Ultra Stable neutraL pArticles) was proposed by Chou, Curtin and Lubatti [1] in January 2017 and is currently in the design stage. After a $2.5*2.5*6.5m^3$ test module has been built and tested in ATLAS SX1 building, we are now trying to figure out an economic way to build the real detector.

One important feature of a detector is the percentage of particles emitted that can be detected. This depends on many properties of the detector, such as its material, density, sensitivity, etc. Among others, it is very important to place the detector at the right position so that as many particles travel across the detector as possible. In this study, we build a toy model that assumes a perfect detector to see the particle detection rate of MATHUSLA with respect to ULLPs' decay point because of its detectors' position.

II. DETECTOR GEOMETRY

MATHUSLA of different size were proposed by group members. In this study, we focus on the model of a $100*100*24m^3$ MATHUSLA that is placed 100 meters above the LHC and 100 meters away from the proton-proton collision point along the beams' travelling direction. Figure 1 and figure 2 are layouts of MATHUSLA from different directions.

A realistic module of a detector is of order a few meters. Hence, there are some gaps within the detector and we should have taken them into consideration when we talk about detectors' efficiency. However, since we are only studying the particle detection rate due to the position and the size of MATHUSLA, we will ignore in this study the gap between different modules and treat each detector layer as a perfect $100*100m^2$ detector without any gaps.

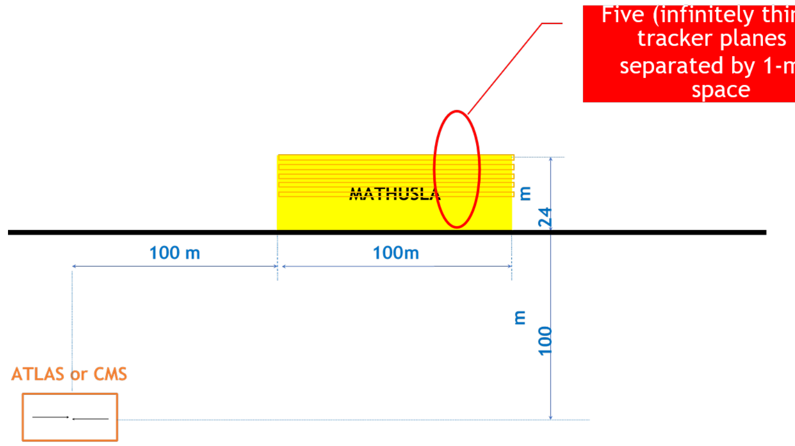

FIG. 1. Side View of Layout

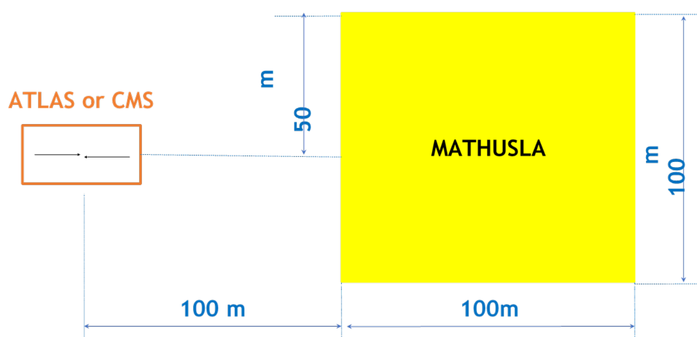

FIG. 2. Top View of Layout

III. DATA SETS

In this study, we are interested in how much we can know about the LLPs from their decaying products. In the worst case scenario, each LLP only decays into two products. Hence, we focus on the events that a LLP decays into two muons to establish a lower bound for the efficiency of MATHUSLA.

Two different data sets are used in this study. Both of them contain events of a 125 GeV Higgs-like Boson decaying into two LLPs which subsequently decays into a pair of muons. The mass of the LLPs are chosen to be 15 GeV and 50 GeV respectively in the data sets so

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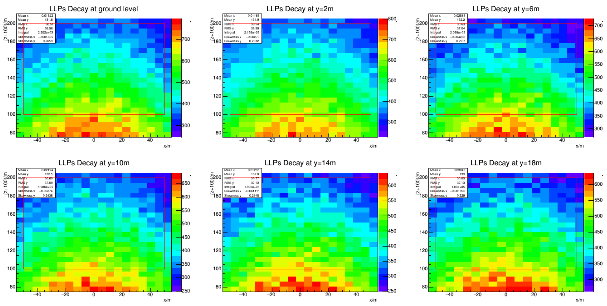

FIG. 3. Number of 15 GeV LLPs decay: x-axis corresponds to the horizontal displacement from the proton trajectory; z-axis corresponds to the perpendicular horizontal displacement from the proton-proton collision point

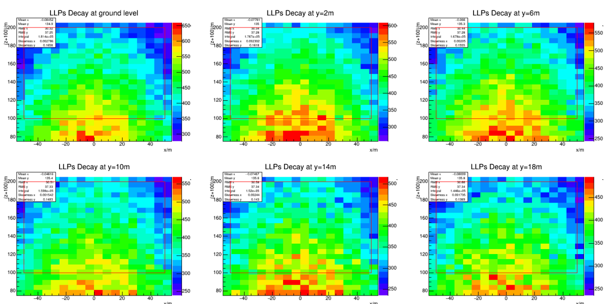

FIG. 4. Number of 50 GeV LLPs decay: x-axis corresponds to the horizontal displacement from the proton trajectory; z-axis corresponds to the perpendicular horizontal displacement from the proton-proton collision point

that we can understand how the mass of the LLPs would affect the efficiency of MATHUSLA.

IV. EFFICIENCY

Simulating with PyROOT, we study the efficiency of MATHUSLA with respect to the position where LLPs decay. For comparison purpose, we include not only the particles decay inside MATHUSLA, but also the ones that decay near MATHUSLA. To exclude cosmic radiation, we only study the muons generated from LLP decaying that happens below the lowest detector plane of MATHUSLA.

Figure 3 and figure 4 show the distribution of particles decay at different height. As expected, more LLPs concentrate at the positions closer to the proton-proton collision point. LLPs have a larger probability to decay near MATHUSLA if it has lower mass and larger momentum.

A. Trigger Efficiency

To trigger a muon, we need it to pass through all five layers of detector planes. Since triggering is a real-time process, it is important to minimize its complexity to reduce the load of the system in real-time. Hence, other than triggering by the whole detector, triggering by one module and triggering by $3*3$ modules were proposed as alternatives, where one module is defined by a $10*10m^2$ block.

From figure 5 to figure 10, we can see the trigger efficiency increases with the decay height. This is not surprising since the solid angel that the muons can travel in for the decaying event to be triggered becomes much larger if the event happens closer to the detector plane than otherwise.

We can also see from the plots that triggering by $3*3$ modules has almost the same efficiency as triggering by the whole detector other than a sharper cut-off at the boundary of MATHUSLA. On the other hand, triggering by one module behaves much worse with a very low efficiency even for the events happen two meters below the lowest detector plane. This indicates that we should probably try to trigger particles in MATHUSLA by $3*3$ modules.

Figure 11 to figure 16 show the same efficiency plot with LLPs having mass only 15 GeV. We can see the same trend of increasing triggering rate with respect to height. Triggering by $3*3$ modules again performs as well as triggering by the whole detector except at the boundary and again it is quite inefficient to trigger by one module.

By comparing the corresponding graphs, we can see that LLPs of mass 15 GeV have much better trigger efficiency than the ones of mass 50 GeV. This is not surprising since smaller mass LLPs have larger momentum by conservation of energy-momentum tensor. Hence, the decay products of smaller mass LLPs tend to move in the direction closer to the LLPs themselves. Since LLPs in MATHUSLA were originally travelling towards the detector planes, there is a larger chance that at least one of the decay products is going to cross all five detector planes.

B. Relative Reconstruction Efficiency

To reconstruct an decay event at a certain point in space, we need at least two different trajectories of the decay products. Since a LLP only decays into two muons, the event can be reconstructed if and only if both muons pass through all detector planes. Since reconstruction is done offline, we can do it in whatever way we want. In particular, we can reconstruct by the whole detector to maximize the efficiency.

Figure 17 and figure 18 are the relative reconstruction efficiency of LLPs at different height. First thing we notice is that relative reconstruction efficiency is much better for LLPs with smaller mass. This is expected since if we work in the unit where $c = 1$, for a LLP decays into two muons, if the mass of the original LLP is much larger than its momentum, by conservation of momen-

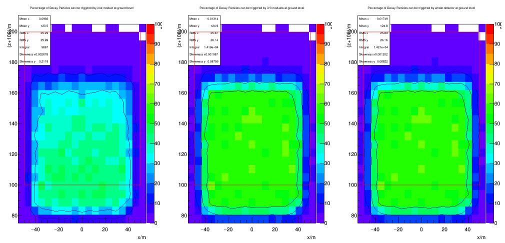

FIG. 5. Trigger Efficiency of 15 GeV LLPs at Ground Level

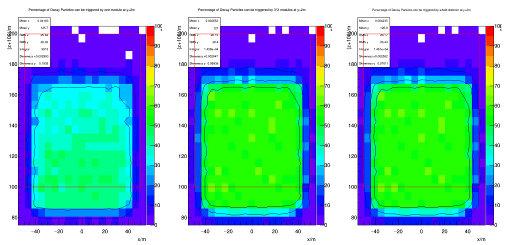

FIG. 6. Trigger Efficiency of 15 GeV LLPs at y=2m

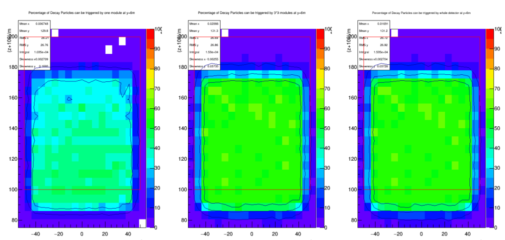

FIG. 7. Trigger Efficiency of 15 GeV LLPs at y=6m

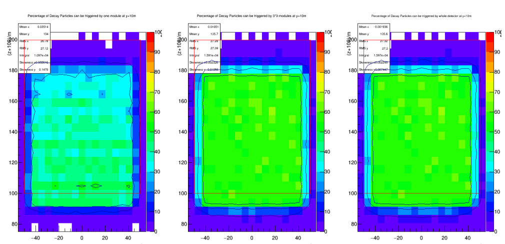

FIG. 8. Trigger Efficiency of 15 GeV LLPs at y=10m

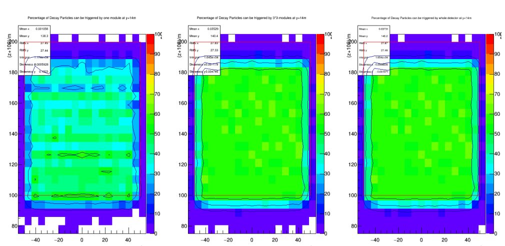

FIG. 9. Trigger Efficiency of 15 GeV LLPs at y=14m

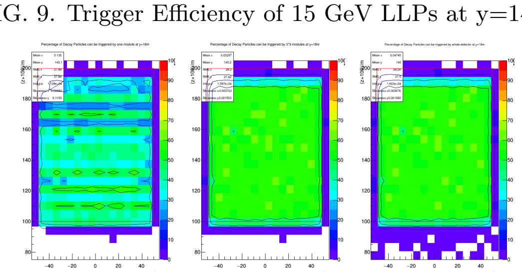

FIG. 10. Trigger Efficiency of 15 GeV LLPs at y=18m

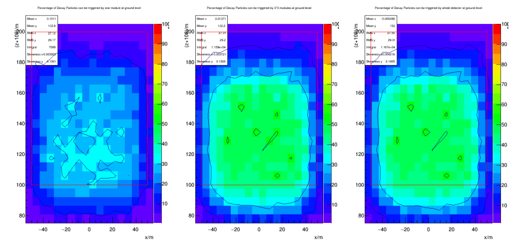

FIG. 11. Trigger Efficiency of 50 GeV LLPs at Ground Level

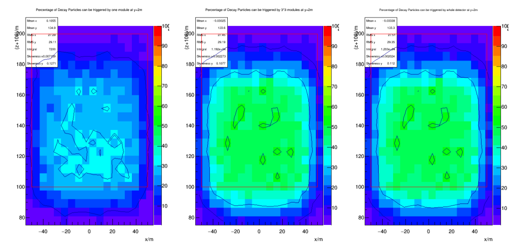

FIG. 12. Trigger Efficiency of 50 GeV LLPs at y=2m

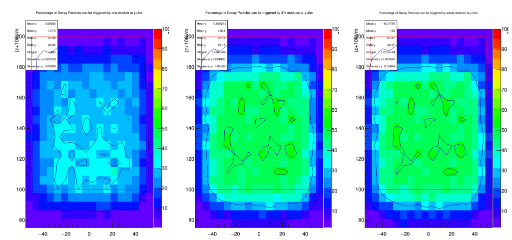

FIG. 13. Trigger Efficiency of 50 GeV LLPs at y=6m

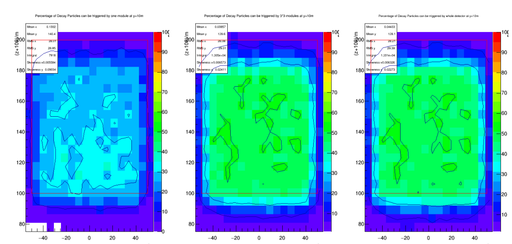

FIG. 14. Trigger Efficiency of 50 GeV LLPs at y=10m

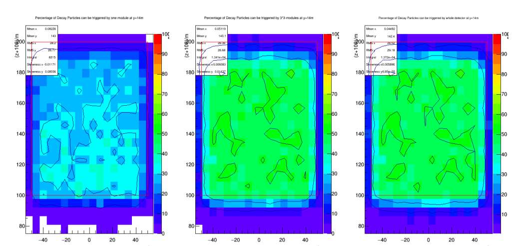

FIG. 15. Trigger Efficiency of 50 GeV LLPs at y=14m

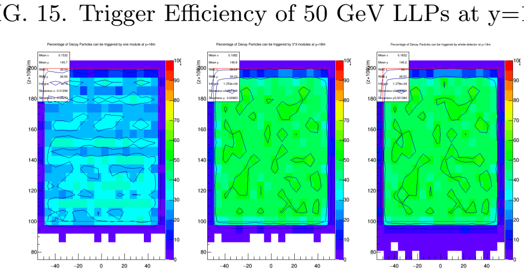

FIG. 16. Trigger Efficiency of 50 GeV LLPs at y=18m

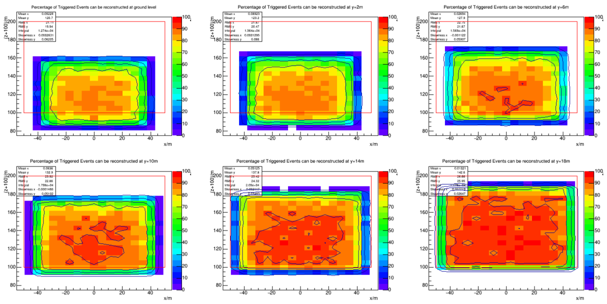

FIG. 17. Relative Reconstruction Efficiency of 15 GeV LLPs: x-axis corresponds to the horizontal displacement from the proton trajectory; z-axis corresponds to the perpendicular horizontal displacement from the proton-proton collision point

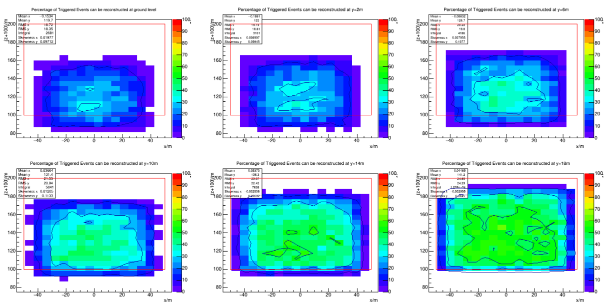

FIG. 18. Relative Reconstruction Efficiency of 50 GeV LLPs: x-axis corresponds to the horizontal displacement from the proton trajectory; z-axis corresponds to the perpendicular horizontal displacement from the proton-proton collision point

tum, the pair of decay products tend to fly out in the opposite direction. If, on the other hand, the momentum of the original LLP is much larger than its mass, both decay particle would tend to move in the direction close to the direction the original LLP travels and in particular, they move close to each other. Since by saying relative reconstruction efficiency, we are only studying whether an event can be reconstructed if it can be triggered, at least one of the muons will pass through all five detector planes. In this case, the other muon is much more likely to go through all five detector planes as well if it travels close to the first muon instead of travelling in the opposite direction.

Indeed, for a Higgs-like Boson that decays into two 15 GeV LLPs, the mass of the LLPs are much smaller comparing to their momentum, hence we see almost perfect relative reconstruction rate when these LLPs decay in the middle of MATHUSLA close to the lowest detector plane.

We can also see that in both cases, relative reconstruction efficiency increases with decay height. This is also reasonable since even for a very small angular deviation, if both muons travel a long distance, their spacial separation will still become large. If a LLP decays very close to the detector plane, its decay products do not have the chance to be separated too much before they hit the detector plane so the relative reconstruction efficiency is much better.

V. SUMMARY

From our study, for the simplest 'bi-products' cases, MATHUSLA performs much better especially in relative reconstruction efficiency with lighter LLPs. In general, if a LLP decays into multiple charged particles, we expect both the trigger efficiency and the relative reconstruction efficiency to be better.

For practical purpose, we can use $3*3$ module triggering to avoid high complexity in the triggering process with a very low loss rate of triggered events. Of course, the final decision should be made depending on the complexity of the triggering algorithm and all the other relevant factors.

VI. FURTHER STUDY

Due to time constrain of the summer student program, we have only studied a toy version of MATHUSLA's detecting efficiency. If we do want to study efficiency of the real-life MATHUSLA, we should try to do it more carefully.

First, we should try to plot the corresponding efficiency pictures with LLPs decaying into multiple hadrons and confirm with ourselves that indeed the efficiency is higher for 'multi-products' cases. This part is in fact ongoing but due to the fact that it takes much more CPU time to run the code with multiple decay products, we have now only run the code with a small fraction of the entries. Everything looks promising with this small fraction of the entries but still, we should run the code with the whole input files if we want to have better understanding on the detection efficiency of MATHUSLA in hadronic decay.

Second, as we have discussed before, a real-life detector has gap between its modules. Detail of the gaps depends on the technology we can afford. At some point, we need to introduce gaps into our simulation so that we can understand better how much they will affect the efficiency of MATHUSLA.

MATHUSLA was proposed originally with the size of $200*200*24m^3$. The fact that we choose $100*100*24m^3$ MATHUSLA to do the simulation does not exclude the probability for it to be built with a different size. It is necessary to take it into consideration and try to understand how the efficiency will be affected by the size of MATHUSLA. Also, there is no rule saying that we have to build MATHUSLA as a square. Hence, we should as well try rectangle or even circle, triangle to see how efficiency is affected by its shape.

In our simulation, MATHUSLA is placed along the axis where the proton beams travel and its front is 100m away from the proton-proton collision point. Again, there is no specific rule for it to stay this way and we might as well put MATHUSLA anywhere on the ground. Of course we cannot put it right above the collision point to overtake the control center, and we shall not put it very far away from the collision point or most particles will never pass through the detector. However, there is still a large range of places for us to place MATHUSLA and we do want to study how the location of MATHUSLA can affect its efficiency so that even if we cannot put it at the most ideal place due to real-life constrain, we can still put it at an 'efficient place'.

A lot more can be done if we want to have better understanding in how MATHUSLA works. But overall speaking, MATHUSLA has a promising efficiency in studying ULLPs.

VII. ACKNOWLEDGEMENT

Many thanks to Dr. Charles C. Young from SLAC National Accelerator Laboratory for providing guide on this summer project and Dr. Jos Francisco Zurita from Karlsruher Institut fr Technologie for helping on this summer project. Thanks to Prof. Luis Roberto Flores-Castillo, Prof. Ming-Chung Chu from CUHK for providing generous help and recommending me to join CERN summer student program. The funding and supports are also provided by CERN summer student project and CN Yang Scholarship, CUHK.

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[1] H. J. Lubatti John Paul Chou David Curtin. "New Detectors to Explore the Lifetime Frontier". In: *Physics Letters B* 767 (2017), pp. 29–36.