Enlarging LHC Detectors and Lowering Backgrounds to Discover Long-Lived Particles

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Digest of the paper "New Detectors to Explore the Lifetime Frontier" by John Paul Chou, David Curtin, and H. L. Lubatti [arXiv:1606.06298].

Detecting Particles at the LHC

A great many theoretical proposals have been advanced to address unsolved problems in physics — for example, what makes up the dark matter in our universe, or why the Higgs boson is so light. The vast majority of these scenario predict that there should be additional particles in nature that we have not yet been able to detect experimentally. Some of these hypothetical particles would be "invisible" in the sense that they don't interact sufficiently strongly with normal atomic matter (such as the material in a particle detector) that we would be able to detect them directly. However, if these particles decay in flight into more mundane particles (electrons, photons, *etc.*), we could detect those particles and trace their paths backward in time and space in order determine whether they came from a single decay event.

The Large Hadron Collider (LHC) is one of the most powerful tools we have for detecting long-lived exotic particles. Whether or not we can detect these particles at the LHC, however, depends on how long they travel before they decay. Due to quantum-mechanical uncertainty, it's impossible to say exactly what distance ℓ any individual such particle will travel before it decays. However, we can still get a sense of what the prospects are for detection from knowing the *average* distance L a particle travels after it is produced by particle collisions at the LHC. Assuming for simplicity that each individual such particle is produced with roughly the same speed v, this average is given by $L = v\tau$ where τ is the proper lifetime of the particle. In most scenarios, these invisible particles would be produced at relativistic speeds — i.e., speeds $v \approx c$ very close to the speed of light c. Because of relativistic time dilation, $t_{\text{lab}} = \gamma\tau$ is longer than τ by the relativistic factor $\gamma \equiv (1 - v^2/c^2)^{-1/2}$. Given the size of the the LHC detectors, this leads to a number of possibilities, depending on L — and therefore on the lifetime of the particle.

When a particle travels an extremely short distance $\ell \ll 1$ mm before decaying, a collider detector can't resolve how it traveled, but the particle's presence can often still be inferred from the pattern of particles into which it decayed. By contrast, when a particle travels a distance 1 cm $\lesssim \ell \lesssim$ 1 m, the detector can resolve how far the particle traveled before it decayed, leading to a telltale signal of a long-lived exotic particle — a signal called a "displaced vertex." However, when a particle which travels more than 10 m before decaying, it escapes the collider detector altogether before it decays, so there's no way to detect such an ultra long-lived particle (ULLP) directly. This means that a particle with an average lifetime $L \gg 10$ m therefore has only a tiny probability of decaying within a collider detector. Thus, even if an enormous number of such particles were produced at the LHC, only a few of them would actually decay inside the detector. Since the experimental backgrounds from other, run-of-the-mill physics processes that can mimic a ULLP signal are somewhat large, in many cases it wouldn't be easy to discern such a signal at the LHC.

The MATHUSLA Proposal

There are two ways in which one might try to extend the capabilities of the LHC detectors and allow them to detect even longer-lived particles. First, one might try to make these detectors physically larger. Since they are underground, this might seem impractical. However, by placing an additional piece of detector apparatus on the surface of the Earth above one of the LHC detectors, once can effectively make the spatial extent of that detector larger. The second — and, as it turns out, more important — way in which one might try to extend the capabilities of the LHC detectors is to find ways of reducing the experimental background from standard physics processes that can "fake" a ULLP signal. A recent proposal [1] by particle physicists Chou, Curtin, and Lubatti to create such a surface detector — a detector which the authors christened MATHUSLA (a quasi-acronym for "MAssive Timing Hodoscope for Ultra Stable neutraL pArticles") — aims to accomplish both of these objectives. Signal events at this detector would have essentially no background whatsoever — a fact which would make it ideal for the detection of ULLPs.

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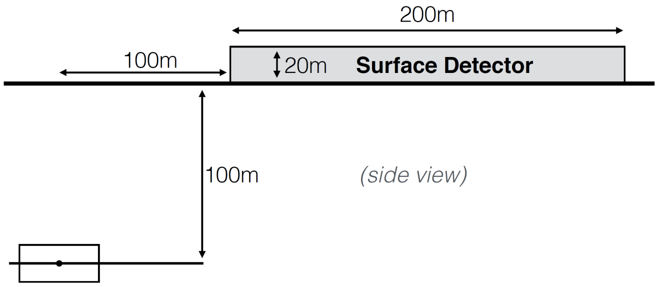

FIG. 1: Side view of the proposed MATHUSLA detector (labeled "surface detector" in the figure). The box 100 m below the ground and to the left of MATHUSLA represents one of the LHC detectors (either ATLAS or CMS).

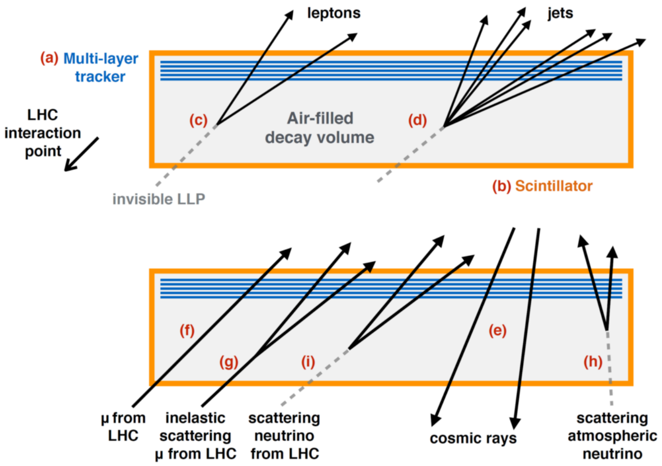

FIG. 2: Design of the MATHUSLA detector.

Support for this proposal has been gaining traction since it was first advanced in 2016. In fact, a prototype of the detector is already under development, and funding is now in the process of being secured for the construction of the full detector.

MATHUSLA would sit on the surface approximately 100 m above one of the LHC detectors (see Fig. 1) and would cover a solid angle large enough to intercept roughly 10% of the ULLPs produced in that detector (this percentage is called the "geometric acceptance" of the detector). It would consist of an enclosed volume of air surrounded by a "shell" made of scintillator tiles which produce a signal when particles pass through them (see Fig. 2). At the top of the detector, but still inside the shell of scintillator tiles, a set of silicon strips which can track the motion of particles produced by ULLP decay within the air-filled volume. The information from the tracking system can be used to reconstruct where inside the detector the particle decayed. Together with the scintillator shell, the tracking system can be used to eliminate backgrounds from other kinds of events which might "fake" ULLP decays.

One important background is from cosmic-rays particles coming from above the detector. Timing information from the scintillators and the tracking system can determine whether the particle which produced the signal was moving upward or downward, allowing one to distinguish these background events from true ULLP decays with very high efficiency. Another important background is from neutrinos which pass upward through the Earth and interact with the material inside the detector, mimicking a ULLP decay. These might be either cosmic-ray neutrinos which pass through the Earth or neutrinos produced by collisions within the LHC detectors. Most of the former kind of neutrinos have very low energies, which means that if one rejects events below a certain energy threshold, one can do a very good job of eliminating this background. The number of "fake" ULLP events produced by LHC neutrinos turns out to be very small, so this background is small as well. Indeed, Chou et al. find that a detection of four signal events over the entire upcoming run of the LHC would be sufficient to claim a discovery.

[1] J. P. Chou, D. Curtin and H. J. Lubatti, Phys. Lett. B **767**, 29 (2017) doi:10.1016/j.physletb.2017.01.043 [arXiv:1606.06298 [hep-ph]].