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HIDDEN WORLDS of fundamental particles

David Curtin and Raman Sundrum

Spectacular bursts of particles that seem to appear out of nowhere may shed light on some of nature's most profound mysteries.

Why is there something rather than nothing? It's a question so basic and so vast in scope that it seems beyond the realm of quantitative inquiry. And yet surprisingly, it is a question that can be framed and at least partially answered in the study of particle physics.

The standard model (SM) is our current theory of matter and its interactions. Written in the language of relativistic quantum field theory, it has stood up to several decades of tests at high-energy colliders. We know, however, that it cannot be the complete description of the universe, in large part because in several important regards it fails to answer the something-versus-nothing question.

Material existence is connected to three fundamental mysteries. First, why can matter clump to form a rich array of structures without collapsing into black holes? The requisite weakness of gravity arises because the particles that make up everyday matter are incredibly light. In the SM, the mass of all fundamental particles must be less than the electroweak mass, whose value of a few hundred GeV/c^2 follows from the physics of the Higgs boson. However, when the effects of gravity are taken into account, the SM electroweak scale receives quantum contributions on the order of the Planck mass, 10^{18} GeV/c^2. That puzzling discrepancy of scale is called the hierarchy problem. In the SM, a particle's lightness is recovered only thanks to an incredible cancellation among unrelated parameters. There exist more attractive solutions, including supersymmetry and the Higgs boson as a composite particle, that also predict high-energy signatures of new physics at the Large Hadron Collider (LHC).

Second, stuff exists only because at some point in the early universe, there was one extra particle of SM matter for every one billion matter–antimatter pairs. That tiny excess is all that remains today, and it must have been created dynamically in the primordial plasma of the Big Bang. In the SM, that process—baryogenesis—is too weak by many orders of magnitude; evidently, additional particles and interactions must have been present. Theorists have suggested many possibilities, including additional Higgs bosons and modified Higgs couplings that could be detected at the LHC.

Third, strong interlocking evidence from a multitude of astrophysical and cosmological observations suggests that dark matter makes up about 80% of the matter in the universe. We have no definitive knowledge of what it is or how it connects to the SM. The most popular theories predict a tiny interaction of dark matter with ordinary matter. Such a coupling would enable direct detection by nuclear recoils in sensitive detectors and indirect detection in cosmic-ray data that show evidence of dark-matter annihilation into SM particles.

The hierarchy problem, the riddle of matter–antimatter

(GHOST) RIDERS IN THE SKY by Christopher Arabadjis, 2009.

asymmetry, and the nature of dark matter drive much of experimental and theoretical particle physics. Many experimental searches for answers to those mysteries are proceeding vigorously, but so far with null results across the board. That doesn't mean nothing is to be discovered. On the contrary, the null results may well point us toward the true nature of the universe. There could be hidden sectors—additional particles and forces—with only tiny couplings to the SM. Far from being inconsequential, those new sectors can address all three big mysteries. Their signatures are subtle and easily missed, but luckily, their hidden nature is also the key to their discovery. Invisible long-lived particles (LLPs) can be produced at colliders and decay into energetic SM particles after traveling an appreciable distance. Can we catch those revealing flashes?

A tale of two frontiers

Physicists built the LHC in part to access new physics at mass scales higher than those characteristic of the SM. However, new physics may be concealed, not by virtue of high mass, but by very small couplings to the SM. We use the term "hidden sectors" to refer to such disconnected non-SM matter and forces, which can arise robustly within the framework of quantum field theories.

Like the push for higher energy, the investigation of hidden sectors with tiny couplings to visible particles has important historical precedent. Neutrinos are almost massless, and nowadays they are understood to be related to charged leptons (electrons, muons, and taus) through their shared weak interaction. Wolfgang Pauli postulated their existence in 1930 to restore conservation of momentum to beta decay, but their direct detection via scattering off nuclei wasn't achieved until 1956, when large neutrino fluxes from nuclear reactors became available. The discovery of the ghost-like neutrino sector was only the beginning, and those elusive particles still aren't done confusing us. For example, we know that neutrinos have masses and oscillate from one type to another, which is not accounted for in the SM.

New hidden sectors can be connected to the SM by small but nonzero couplings called portals. Figure 1 illustrates the most important types. Portal couplings are small for several reasons. For example, symmetries can give rise to quantum mechanical selection rules that force interactions between the SM and a hidden sector to proceed by means of a heavy and therefore hard-to-access mediator state. The mediator is not part of the SM but interacts with both the SM and hidden sectors.

It's possible for some SM states—most importantly the photon and the Higgs boson—to function as a mediator. Although the structure of the theory makes the Higgs-portal and photon-portal couplings smaller than ordinary SM couplings, they are readily made much larger than the couplings of other types of portals. Furthermore, accelerators produce lots of Higgs bosons and photons. In rough analogy to an oscillating neutrino, a photon could transform into a hidden photon and interact with hidden states.[1] The Higgs boson, with a mass of 125 GeV/c^2, is heavy enough to sometimes decay directly into the hidden sector. Such exotic Higgs decays are one of the most promising avenues for producing hidden-sector particles.[2]

Hidden sectors typically contain massive states that would be stable in isolation but that decay into SM particles in the presence of portal couplings. Precisely because the portal is such a tiny keyhole, the decay can take a relatively long time. That is what makes LLPs and their spectacular decays a hallmark of hidden sectors.

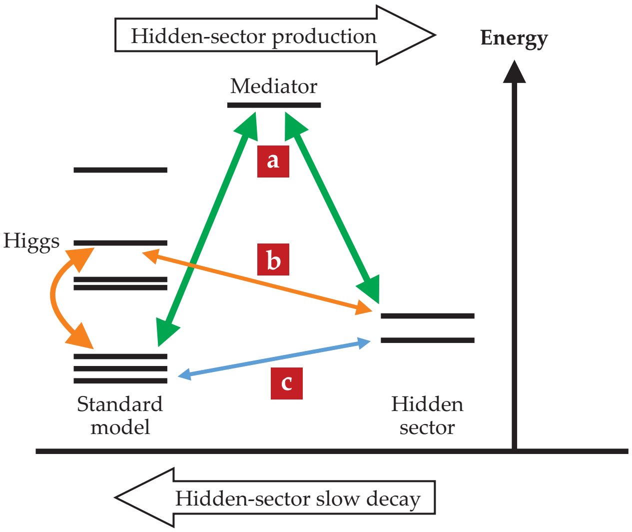

FIGURE 1. PORTALS TO HIDDEN SECTORS. The diagram represents the energies of possible hidden-sector states in relation to those of the standard model. Colored arrows indicate possible transitions between states. At the Large Hadron Collider, hidden-sector states can be created by means of the production and decay of heavy mediators **(a)**, exotic decays of the Higgs boson **(b)**, or small direct couplings **(c)**. Once produced, the states decay through the same portals. Hidden-sector states have long lifetimes because the direct couplings are small or because energy must be borrowed, courtesy of the Heisenberg uncertainty principle, to excite the intermediate mediator or Higgs boson.

Solving mysteries

Searching for the flashes of LLP decays at the LHC and other colliders will be a major enterprise. It will require dedicated analyses and maybe new detectors, but it is well worth the effort. Here are just a few examples of how new sectors with hidden states address the three big mysteries.

Let's start with the hierarchy problem. As shown in figure 2, known solutions cancel the top quark's large quantum contribution to the Higgs (and thus electroweak) mass by introducing partners related to the top by a symmetry. In the case of supersymmetry, the top partners take part in the SM's strong interaction, so they should be produced in large numbers at the LHC.

We haven't found any sign of those partners yet, but another solution, called neutral naturalness,[3] relies on hidden valleys,[4] which are a family of theories that are essentially cousins of quantum chromodynamics (QCD), the theory of the SM's strong interactions. Hidden valleys give rise to low-energy bound states; in analogy to SM protons and pions, they are called hidden hadrons. In theories of neutral naturalness, the top partner does not interact via the SM strong force, but it does interact via those hidden cousins of QCD. A striking signature of that novel interaction involves exotic decays of Higgs bosons to hidden hadrons, which can eventually decay back to SM particles through one of several portals. The result, as shown in the figure, looks like a displaced decay.

What about dark matter? Perhaps the best-known candidate

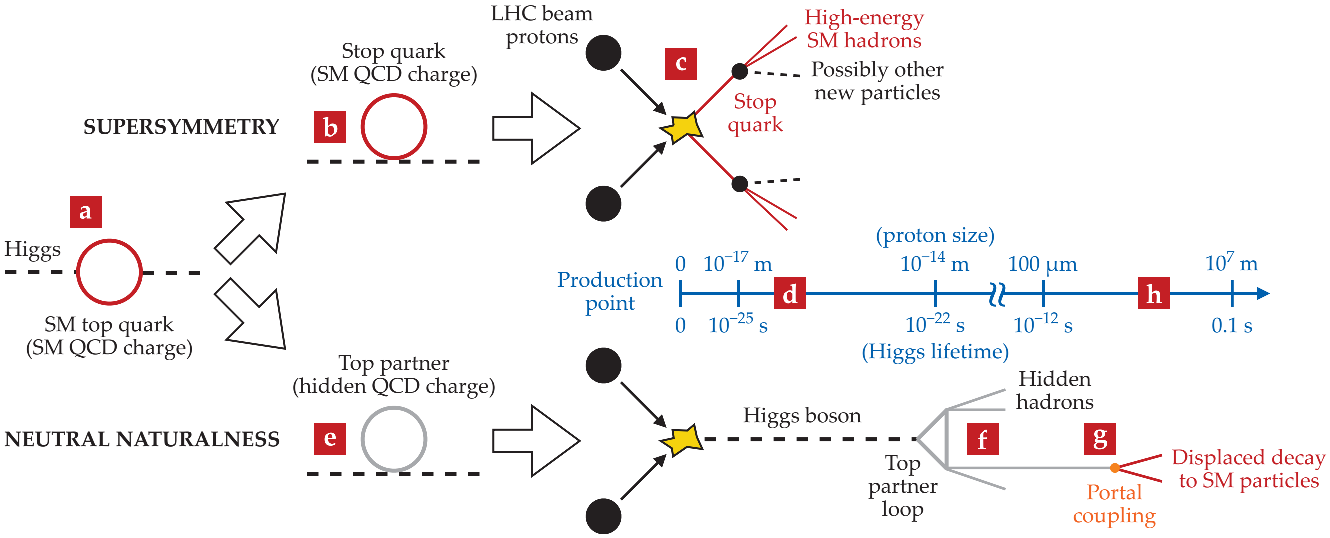

FIGURE 2. SUPERSYMMETRY VERSUS NEUTRAL NATURALNESS. The hierarchy problem in the standard model (SM) arises because quantum processes make large contributions to the Higgs boson mass and there is no natural mechanism for their cancellation. The most important contributions come from top-quark loops **(a)**, intermittent quantum mechanical fluctuations of the Higgs boson into top and antitop pairs. In supersymmetry, the top loop is canceled by a loop of top partners called stops **(b)**, which have a mass comparable to that of the top quark. The stops have the same quantum chromodynamics (QCD) charge as the top quarks—that is, they experience the strong interaction just as the tops do. As a result, they should be copiously produced **(c)** in proton–proton collisions at the Large Hadron Collider (LHC). Stops typically decay into sprays of highly energetic SM particles and possibly new invisible particles within a very short amount of time **(d)**. Neutral naturalness solves the hierarchy problem with top partners that don't have a QCD charge—that is, they don't participate in the SM strong interaction.[3] Under a discrete symmetry, the top quark is reflected by a top partner charged in a hidden QCD **(e)**. Because of the absence of SM QCD couplings, those top partners are not produced in large numbers. However, due to its coupling to the top partners, the Higgs boson acquires a new decay mode that yields hidden QCD hadrons **(f)**. Eventually those hidden hadrons can decay back to SM particles **(g)**. The decay products are well displaced in space and time **(h)** from the original proton–proton interaction point.

is the WIMP (weakly interacting massive particle). As illustrated in figure 3, it freezes out in the early universe when it becomes too diluted to annihilate any further, and its relic abundance is set by its coupling to the SM. If that coupling is the SM electroweak coupling and the mass of the dark matter is close to the electroweak mass, one finds roughly the dark-matter abundance measured today. That confluence is called the WIMP miracle. However, the direct coupling of dark matter with the SM also predicts signatures yet to be seen in direct and indirect detection experiments. Dark matter can be produced at colliders but it is invisible and only reveals itself as a momentum imbalance in a collision.

A different possibility shown in the figure is that the relic abundance of dark matter is set by the lifetime of a heavy LLP parent that produces dark matter in its decays.[5] The corresponding dark-matter particle has a much weaker coupling to the SM than a WIMP does and is called a feebly interacting massive particle (FIMP). The LLP can be produced at colliders; typical lifetimes are in the millisecond ballpark.

We turn to baryogenesis, which can proceed according to several known mechanisms. In all cases, an out-of-equilibrium process needs to create more matter than antimatter in the plasma of the early universe. A simple way to achieve that imbalance is the out-of-equilibrium decay of a heavy particle. In particular, the scenario of WIMP baryogenesis,[6] as shown in figure 4, piggybacks off the quantitative success of the WIMP miracle. Since the abundances of dark matter and SM matter in our universe are only different by a factor of five, a long-lived WIMP decaying into SM particles could easily generate the required matter asymmetry. The WIMP can be produced at colliders and possibly give rise to LLP signatures.

The above list of theories is certainly not exhaustive; it is meant to illustrate that LLPs and hidden sectors are highly motivated for a variety of fundamental reasons.

Flashes beyond the shrapnel

Long-lived particles can be reliably identified only if we know where they are produced. Unlike dark matter or cosmic rays, which occur naturally, LLPs have to be synthesized at colliders, where experimenters can hope to measure the macroscopic distance from the production point to the flash point of the decay.

If the LLPs have masses below the electroweak scale, they might be produced in high-intensity experiments with lower collision energy than at the LHC. Examples of such experiments include the BaBar search at the PEP-II electron–positron collider,[7] the APEX search at the Thomas Jefferson National Accelerator Facility,[8] and the proposed SHiP (Search for Hidden Particles) experiment at CERN.[9] The abundance of collisions in such investigations allows tiny couplings to be probed by sheer force of numbers.

The LHC, however, is unique in that it allows us to probe hidden sectors when the mediator mass or hidden-sector particle masses are at or above the electroweak scale. The high-luminosity LHC upgrade, planned for the mid 2020s, will increase the number of collisions at the facility by a factor of 10 and is projected to yield 10^8 Higgs bosons over a 10-year period. A tiny Higgs portal can easily force 0.1% of them to decay to hidden-sector states, which would produce plenty of LLPs. Just as the enormous neutrino fluxes at nuclear reactors paved the way to neutrino detection in the 1950s, the combination of high-energy and high-intensity collisions in the current era may

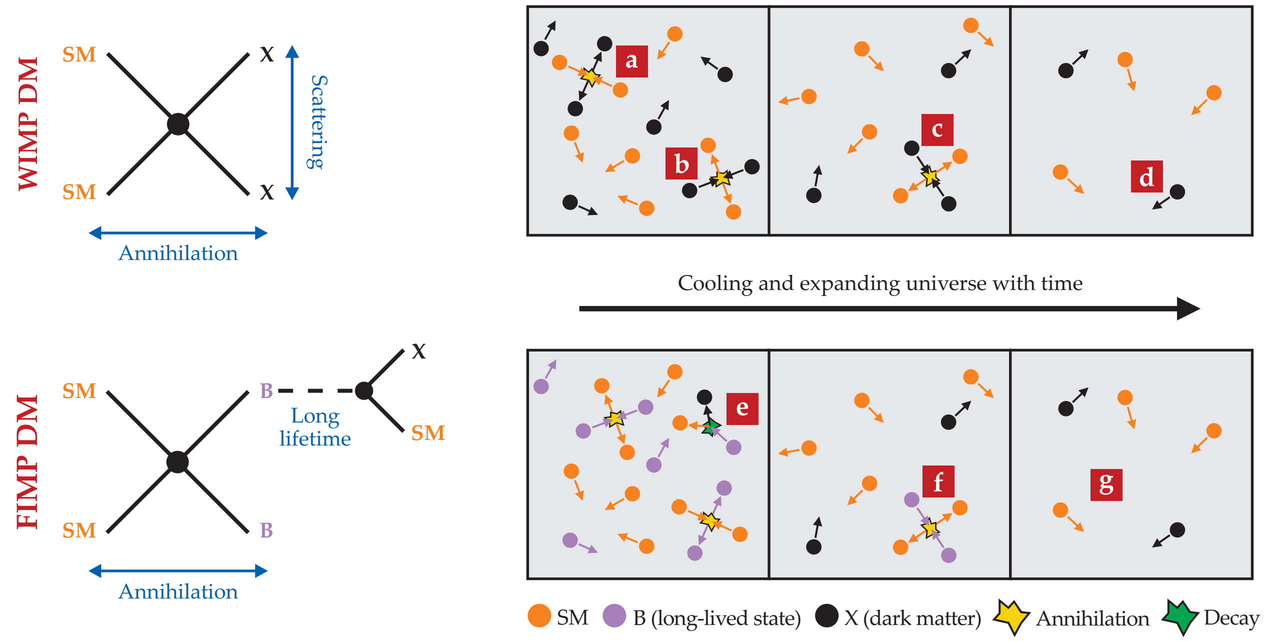

FIGURE 3. DARK-MATTER freeze-out versus dark-matter freeze-in. Early in the history of the universe, the thermal energy is much greater than the rest energy of a dark-matter (DM) particle. In that epoch, standard-model matter (SM) is in thermal equilibrium with dark matter (X); the process SM + SM → X + X **(a)** and the reverse process **(b)** occur at equal rates. As the universe cools, colliding standard-model particles no longer have the energy to create the heavy dark matter, but X still annihilates to SM **(c)**, which drastically reduces the dark-matter abundance. As the universe cools and expands even more, dark matter becomes so diluted that annihilation to SM no longer takes place. The dark-matter abundance is frozen out and survives to this day **(d)**. That relic abundance is dictated by the dark-matter coupling to the standard model, which sets both the annihilation rate in the early universe and the rate for dark matter to scatter off standard-model particles in direct detection experiments. On the other hand, the relic density of feebly interacting massive particles (FIMPs), an alternative to the popular weakly interacting massive particles (WIMPs), is set by a freeze-in mechanism, in which no FIMPs are initially present.[5] A parent particle B has sizable couplings to the standard model and is in thermal equilibrium in the early universe. However, the long-lived B decays into SM and X **(e)**. Even when the universe is much younger than the lifetime of the B, a tiny fraction of Bs still decays, so dark matter steadily accumulates. As the universe cools, the Bs annihilate almost completely away to standard-model particles **(f)**. The frozen-in dark-matter abundance **(g)** survives to the present day. In this FIMP scenario, the dark-matter relic density is set directly by the lifetime of the B, which is typically in the millisecond ballpark.

give us unparalleled access to new hidden worlds, provided we look in the right places.

The main detectors at the LHC are busy places, with lots of hadronic shrapnel flying around. Luckily, neutral LLP decays are a spectacular signature, and the bursts of energy appearing out of nowhere set them apart from the mundane rubble emanating from the collision point. Looking for LLPs represents something of a paradigm shift from the usual approach, exemplified by the top branch of figure 2, to hunting for new physics. As-yet-undiscovered particles with large coupling to the SM would have large production rates. And that ample production is necessary if the particle signals are to be observed above the SM background noise, because the large coupling also makes the particles decay immediately at the collision point. LLP production typically occurs at much lower rates, but each individual displaced decay is so spectacular that backgrounds are orders of magnitude lower than for particles that couple strongly to the SM. Far fewer observed events are needed to claim discovery.

The decay lengths of hidden-sector LLPs could be almost anything from a few hundred microns to astrophysical scales. You might find that a little discouraging: Why should we expect to see an LLP decay in the lab if it could just as well decay near Proxima Centauri? Some detailed theories suggest that LLPs should have relatively short lifetimes, but in any case, there exists a robust ceiling. If the LLP is producible at colliders, it must have been in thermal equilibrium with the SM plasma in the early universe. As the universe cooled, the first elements—hydrogen, helium, lithium, and beryllium—came into being. That formation process, Big Bang nucleosynthesis, took place when the universe was about 0.1–1 second old, and it is exquisitely sensitive to ambient conditions. With few exceptions, LLPs decaying during or after Big Bang nucleosynthesis would disrupt the process and yield inconsistencies with measurements of primordial elemental abundances.[10]

Ongoing searches

Some experiments at the LHC are already looking for LLPs, but much more needs to be done to cover the whole range of accessible masses, lifetimes, and production processes. Figure 5 provides a basic overview of the ATLAS (A Toroidal LHC Apparatus) and CMS (Compact Muon Solenoid) detectors at the LHC and the signatures they might observe.

Many theories, with and without hidden sectors, predict LLPs that interact electromagnetically or strongly, and those particles can show up in several detector subsystems.[11] For ex-

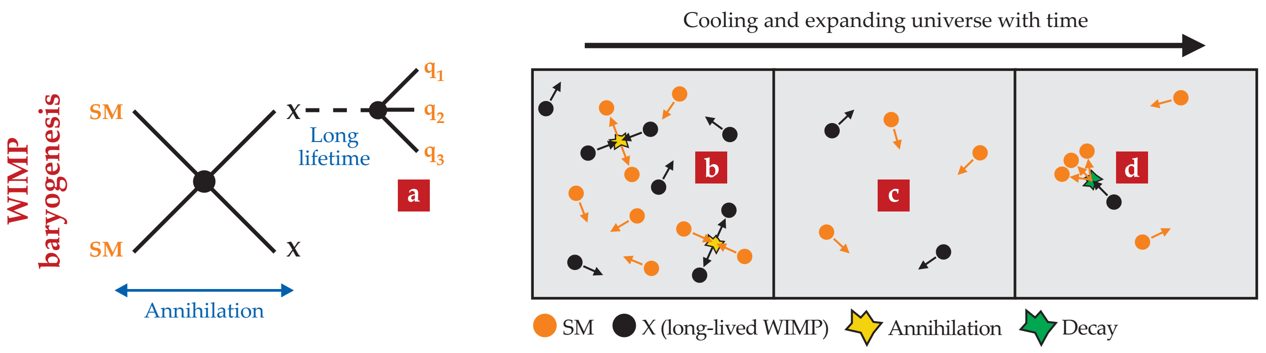

FIGURE 4. WIMP BARYOGENESIS. The creation of matter over antimatter is favored by the decay **(a)** of a metastable weakly interacting massive particle (WIMP) X into standard-model (SM) quarks (q).[6] At early times, X is in thermal equilibrium with the matter-antimatter-symmetric thermal bath **(b)**, and as with conventional WIMPs, it eventually freezes out as the universe expands and cools **(c)**. When the universe is about as old as the lifetime of the X, the particle decays out of equilibrium and creates the matter excess **(d)** that survives today.

ample, due to its high mass, the LLP could deposit a lot of energy in a calorimeter, or it could leave a kinked track if it decays while it traverses the detector.

It is also possible for stable hidden-sector particles to be electrically millicharged—that is, to have an electronic charge that's just a tiny fraction of the electron's. It happens when states interact with each other via a massless hidden photon that oscillates into the SM sector through the photon portal. Millicharged states are extremely difficult to detect because they are only weakly ionizing when they pass through matter. However, their traces could be observed with a dedicated detector like MilliQan, which would be situated in a tunnel, close to one of the main detectors.[12]

Neutral LLPs are challenging to isolate at the LHC, since the detectors there weren't primarily designed for such particles. However, if the LLPs decay to charged particles, the tracking systems can reconstruct displaced vertices,[13] such as is shown in figure 5. The signals are spectacular, but there is some SM background: Extremely rare events involving production of highly energetic SM hadrons, peculiar configurations of long-lived SM hadron decays, and detector hiccups can conspire to fake a displaced vertex. Such a chain of coincidences can be a problem only because of the enormous rate of SM strong-interaction events, which produce multitudes of hadrons at the LHC.

The obvious challenges are neutral LLPs with decay lengths much larger than the detector size; only a small fraction of those will decay in the detector. The ATLAS detector is able to look for displaced vertices in its largest subdetector, the muon system. If the LHC produces enough LLPs, the ATLAS team can afford for the large majority to escape, and their searches can have sensitivity to decay lengths in the kilometer range.[14] But for particles with longer lifetimes and hence lower chances of decaying in the main detector, strong-interaction background swamps the signal. How can we probe those especially long-lived particles?

The lifetime frontier

Big Bang nucleosynthesis limits the lifetime of an LLP to less than 0.1–1 second, but that still allows an LLP produced at an accelerator to travel all the way to the Moon. We won't catch them all. Luckily, we don't have to. Being able to observe just one in a million of those limit-testing LLPs would already allow us to probe the most important new physics scenarios.

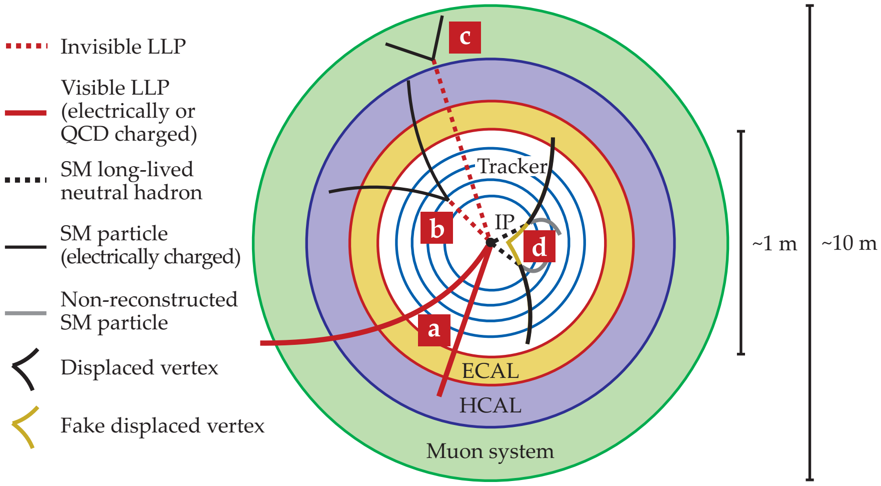

FIGURE 5. SEARCHES FOR LONG-LIVED PARTICLES (LLPs) at the Large Hadron Collider (LHC). Shown here is a schematic cross section, transverse to the beam, of the ATLAS and CMS detectors; the inner layers are enlarged to show detail. The tracker layers detect passing charged particles, and the track curvature in the magnetic field reveals a particle's momentum. The calorimeters labeled ECAL and HCAL measure energy of electrically charged particles and hadrons, respectively, and the muon system detects muons. Particles are produced in collisions at the interaction point (IP). Electrically charged LLPs or strongly interacting LLPs charged under quantum chromodynamics (QCD) leave signals **(a)** in many detector layers. Neutral LLPs are invisible but can decay to standard model (SM) particles in the tracker **(b)**. The tracks of the decay products meet at a displaced vertex. The muon system of the ATLAS detector can also reconstruct displaced vertices **(c)**. A rare but important background to neutral LLP searches consists of fake displaced vertices that occur due to various freak coincidences. For example, the tracker might fail to detect all the decay products of a few long-lived SM hadrons. Such an event is extremely rare, but it can lead to a fake displaced vertex, shown as yellow intersecting lines **(d)**.

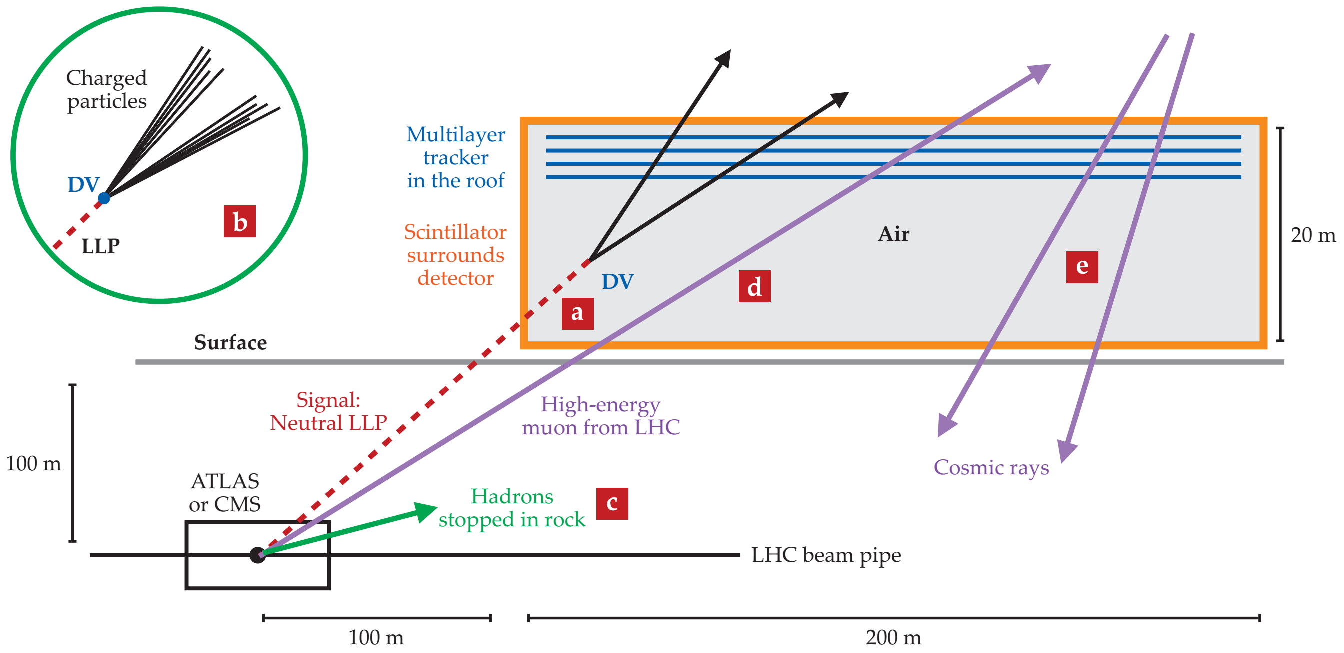

FIGURE 6. THE MATHUSLA DETECTOR for catching long-lived particles (LLPs) at the lifetime limit. The MATHUSLA concept[15] envisions a 200 m × 200 m × 20 m detector on the ground above the Large Hadron Collider (LHC), offset from the ATLAS or CMS collision points. An LLP produced at the LHC travels upwards and decays in the air-filled decay volume **(a)**. The inset **(b)** shows a simulated LLP with mass of 20 GeV decaying into a quark and an antiquark that give rise to an upward-traveling shower of about 10 charged standard-model particles. The particle shower is detected by trackers in the roof; tracker data enable the reconstruction of a displaced vertex (DV). The spectacular nature of this signal is vital for background rejection. Standard-model hadrons produced in the collision are stopped in subsurface rock **(c)**. A scintillator surrounding the detector volume ensures the DV is not falsely constructed from upward-traveling charged muons **(d)** penetrating the rock. Cosmic rays **(e)** are constantly incident on the whole detector, but they do not yield a reconstructed DV, and they can be reliably distinguished by their direction of travel. Rare backgrounds such as cosmic-ray neutrinos scattering off air (not shown) can be rejected due to the geometry and timing of their final states, which are quite different from what would be observed for the signal shown in the inset.

The main LHC detectors can't pull off such observations, but a dedicated LLP detector might; a preliminary concept has recently been proposed by one of us (Curtin), and collaborators.[15] The MATHUSLA (Massive Timing Hodoscope for Ultra-Stable Neutral Particles) detector, a gigantic tracker named after the long-lived biblical character, is shown in figure 6. Situated on Earth's surface rather than underground, it is shielded from troublesome SM hadrons produced in LHC collisions. Backgrounds, which are currently being studied in detail, can be nearly perfectly rejected. Since the instrumentation is relatively simple, MATHUSLA could be built in time for the high-luminosity LHC upgrade.

Many hidden sectors could go undiscovered at the LHC without a dedicated LLP detector, and the achievable sensitivity of MATHUSLA is remarkable. For example, if the Higgs boson decays to very long-lived particles 10% of the time, the high-luminosity LHC main experiments will be able to detect a deviation from SM predictions of its couplings, but they will not be able to determine if they had just discovered dark matter or LLPs. MATHUSLA could catch those LLPs decaying, even if their lifetimes are near the Big Bang nucleosynthesis limit. For shorter lifetimes, corresponding to decay lengths down to 100 m or so, MATHUSLA's sensitivity would enable the detection of LLPs with production rates three orders of magnitude smaller than what the ATLAS or CMS detectors could discover on their own.

We're in for an exciting ride. The LHC is the accelerator of our time, and both theoretical and experimental clues point toward new physics near its operating energy at the TeV scale. Null results to date don't invalidate those hints; they may simply be pointing us toward the brave new world of hidden sectors. Much work is needed to take advantage of the unique opportunities the LHC provides, but if the necessary searches and detector ideas are implemented now, we have every reason to hope for spectacular discoveries in the years to come.

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