# Dark Matter searches with long-lived particles
# MVSem : Dark matter theory at Heidelberg University

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This is a summary report of a talk given at University of Heidelberg for the MVSem course "Dark matter theory" under the supervision of Prof. Susanne Westhoff. This was the ninth talk, and the topics covered in the previous talks on dark matter detection, dark matter at colliders and non-thermal dark matter helped to build up to this talk. The goal of this talk was to introduce the dormant nature of LLPs as a Dark matter candidate and discuss the foundations as well as the current affairs of research with respect to them.

Long lived particles (LLPs) started to arise as a potential candidate for Dark matter after the dawn of the WIMP prejudice. Long lived particles have been ubiquitously found in the Standard model of Particle Physics and also have been hypothesized in other theories like the SUSY. This hinted towards considering the potential candidacy of LLPs in Beyond the Standard Model physics (BSM). In this summary, we cover the essential ingredients that essentially make a particle long lived. Based on these ingredients, we discuss a few examples of their possible creation, both thermally and non-thermally. Then, we move towards the detection part and talk about how one could use the present state of the art collider detectors like the CMS/ATLAS in order to find such particles. We talk about various signatures that could be prospectively observed. While doing this, we realize that we are limited in the range of observable lifetimes, that could be used in order to increase our chances for detecting LLPs. Last but not least, various detector proposals that could help us explore this latent parameter space have been discussed.

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## I. BASICS : LIFETIME OF A PARTICLE

### A. Decay rates

Suppose we have a large collection of *decaying particles* at a particular time $t$ : $N(t)$. The *decay rate* $\Gamma$ is the *probability per unit time* that any *given particle will disintegrate*. Giving us, $N\Gamma dt$ to be the *number of particles* that would *decay* in the next instant $dt$. The rate at which the number of particles *decreases* will be given by

$$\frac{dN}{dt} = -\Gamma N \tag{1}$$

$$\text{Solving (1)} \qquad N(t) = N(0)\, e^{-\Gamma t}$$

The *mean lifetime* is given by the reciprocal of the decay rate $\tau = \frac{1}{\Gamma}$. In reality, most particles can decay by several different routes. In such circumstances, the *total decay rate* is the sum of individual rates and so the *lifetime* is given by the following formula

$$\Gamma_{\text{tot}} = \sum_{k=1}^{n} \Gamma_k$$

$$\tau = \frac{1}{\Gamma_{\text{tot}}}$$

*Branching ratios* for $k$'th decay mode can be defined as : $\frac{\Gamma_k}{\Gamma_{\text{tot}}}$.

### B. Parameters affecting the lifetime of a particle

Fermi's golden rule gives us the following formula for the decay rate to a final state $f$

$$\Gamma_f = 2\pi \underbrace{|T_f|^2}_{\propto\alpha} \underbrace{\rho(E_f)}_{\propto\text{mass}}$$

where $|T_f|^2$ is the transition matrix and $\rho(E_f)$ is the phase space distribution for the decay.

#### 1. Small coupling constant

From the Fermi's golden rule, we can see that

$$|T| \propto \alpha$$

the transition matrix is directly proportional to the coupling parameter . This indicates that small coupling leads to a small decay rates, leading to longer lifetimes. This is the reason why particles decaying solely through a strong force will decay faster than particles that solely decay through a weak force.

#### 2. Phase space

*Phase space* is also known as *density of final states.* The phase space factor is purely kinematic ; it depends on the masses, energies, and the momenta of the particles in the final state, and reflects the fact that a given process is more likely to occur the more 'room to maneuver' there is in the final state.

As an example, the decay of a heavy particle into light secondaries involves a large phase space factor, for there are many ways to distribute the available energy. In contrast, the decay of the neutron $(n \to p + e^- + \bar{\nu}_e)$ , there is no extra mass to space. It is tightly constrained and the phase space factor is very small.

Consider an extreme case which is also kinematically forbidden $\Omega^- \to \Xi^- + \bar{K}^0$. Since the final products weigh more than the initial state $\Omega$, there is no phase space available at all and hence the decay rate is zero.

[Pg 203-205 : 6]

#### 3. Scale suppression

The *scale suppression* happens when we get the following condition on a decay rate expression ($m$ being the mass of the particle being decayed and $M$ for the mediator),

$$\frac{m}{M} << 1$$

A good example for scale suppression is the Neutron. It's lifetime is stretched due to $\tau_n \approx \left(\frac{m_n}{m_w}\right)^4$ [6], where as the weak coupling constant contributes significantly less in comparison to the contribution from the scale suppression.

Lifetime of particles can be stretched significantly when the parameters above are combined. In some cases, the factors could counter each other and lead to a canceling effect. For example, decay of the top quark happens through the weak force, but still, it is very short lived because of its large mass.

## II. LLPS AS DARK MATTER

LLPs have been predicted by various theories in different domains of theoretical physics.

| | | Small coupling | Small phase space | Scale suppression |
|---|---|---|---|---|
| SUSY | GMSB | | | ✓ |
| | AMSB | | ✓ | |
| | Split-SUSY | | | ✓ |
| | RPV | ✓ | | |
| NN | Twin Higgs | ✓ | | |
| | Quirky Little Higgs | ✓ | | |
| | Folded SUSY | | ✓ | |
| DM | Freeze-in | ✓ | | |
| | Asymmetric | | | ✓ |
| | Co-annihilation | | ✓ | |
| Portals | Singlet Scalars | ✓ | | |
| | ALPs | | | ✓ |
| | Dark Photons | ✓ | | |
| | Heavy Neutrinos | | | ✓ |

Figure 1. Dominant feature that gives rise to long-lived particles in the theoretical models and mechanisms[1]

We saw in I B the physical quantities that affect the lifetime of a particle and could potentially allow them to be long-lived. In the above table, we can see an example stated for each of these parameters. We will elaborate each of these examples in detail for the remaining part of this section.

### A. Small coupling : *Freeze-in DM*

The freeze-in mechanism is effectively the inverse of the well known thermal "freeze-out" mechanism. It works by populating the DM abundance through

$$\underbrace{A}_{\text{Thermal eq. in Early universe}} \longrightarrow \underbrace{\chi}_{\text{DM particle}} + \underbrace{B_{\text{SM}}}_{\text{SM particle}}$$

such decays.

$A$ is in thermal equilibrium with the Universe. Although,the main feature which makes the particle long lived is a very feeble coupling $y_\chi$, such that $\chi$ is thermally decoupled from the plasma. Due to this feeble coupling, such candidates for dark matter particles are also known as *feebly interacting massive particles (FIMPs).* The relic abundance of $\chi$ can be related to $A$ using the following formula [1]

$$\underbrace{\Omega_\chi h^2}_{\text{Cosmo. den. of}\chi} = \frac{10^{27}}{g_*^{\frac{3}{2}}} \frac{m_1 \Gamma_A}{m_2^2}$$

where $m_1, m_2$ are the masses of $\chi$ and $A$ respectively. $\Omega_\chi h^2$ is the cosmological density of $\chi$. $g_*$ is the number of relativistic degrees of freedom at temperatures where $T \approx m_2 = m(A)$ around the $A$ mass. In the standard model, $g_*(100\,\text{GeV}) \approxeq 100$ and $g_*(100\,\text{MeV}) \approxeq 10$.

Assuming $\chi$ constitutes for all the DM in the universe today, i.e. $\Omega_\chi h^2 = 0.11$, one obtains a prediction for the inverse decay width of $A$ by the relevant substitutions and rearrangements of the formula above,

$$\Gamma^{-1}\left(A \to \chi + B_{\mathrm{SM}}\right) \sim \left(\frac{m_1}{100\mathrm{GeV}}\right)\left(\frac{200\mathrm{GeV}}{m_2}\right)^2 \left(\frac{100}{g_*\left(m_2\right)}\right)^{3/2} \times 10^6 \text{ ns} \sim 0.01 \text{ secs}$$

[1]

Giving a lifetime that is detector-stable and can be detected directly if it is electrically charged. This correlation between the cosmological abundance of DM and the lifetime of the particle is what enables us to perform precise collider tests for the freeze-in origin of DM.

### B. Small phase space : *Co-annihilating DM*

Co-annihilating DM is a model of a typical freeze-out scenario for DM. Particles are tangled with other particle species with close-enough mass and a large-enough co-annihilation cross-section such that the two freeze-out events are connected.

A key condition is that the second co-annihilating species has a mass such that freeze-out the Boltzmann suppression of its equilibrium number density is not drastic. Mathematically, to beat Boltzmann suppression we need $m_2 - m_1 < T_{\text{freeze-out}}$. This constraint also gives us a tight upper bound (compared to the DM number density) in the kinematically possible states in the final phase space, helping the particle to be long-lived.

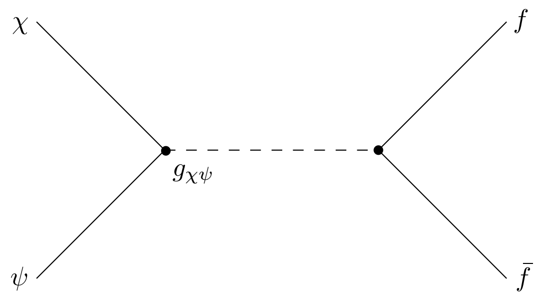


Figure 2. Feynman diagram of an example Co-annihilation scenario

*[1, 5]*

### C. Scale suppression : *Asymmetric DM*

For both the above examples, we have inherently assumed that (i) DM is produced through processes originally in thermally equilibrium, (ii) DM has zero chemical potential. Although, there are several good theoretical frameworks where (i) DM is produced non-thermally (by some out of equilibrium process), (ii) DM is not its own antiparticle. In such frameworks, the relic dark matter density is related to the antiparticle asymmetry, i.e., the Baryon asymmetry in the early universe.

In this section, we consider one of the simplest possibility of a non-thermal DM production scenario. Assume a particle species $\psi$, with $m_\psi > m_\chi$ is produced in the early universe with an abundance $\Omega_\psi$, and $\psi$ decays to $\chi$, which is the stable DM particle, at a temperature when $\chi$ would already be out of equilibrium. . The inherited relic density for $\chi$is then

$$\Omega_\chi \simeq \Omega_\psi \frac{m_\chi}{m_\psi}$$

(up-to some corrections from decay of other thermally produced particles and entropy in their decay processes, hence the "$\simeq$").

## III. SIGNATURE OF LLPS AT LHC

In order to be able to test the theoretical predictions, one needs to be able to find corresponding observations. In this section we talk about the properties of detectors and potential signatures of LLPs that could be observed using them. [5]

### A. Kinematics of LLPs in a detector

The following is a not-to-scale schematic of a typical detector and its sub-components around the collision point at collider experiments.

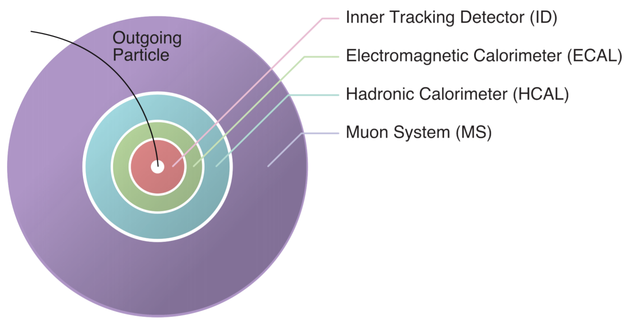


Figure 3. Not to scale schematics of a collider [1]

It is made of 4 major components,

**ID:** (Inner tracking detector) Precision silicon tracking devices work on the same physics principle as gas chambers, although the anode and cathode in a silicon detector are no longer wires but electrodes etched on a thin silicon wafer. Silicon detectors are usually placed right around the beam pipe and provide high resolution position measurements on tracks close to the interaction point. Designed to detect electrically charged particles that are long-lived to transverse the ID. Examples include electron, muon, pion, kaon and proton. The reason why it is called a tracker is that, particles produce a region of ionization in solid-state or gaseous detectors, which are called *hits*. These can be fit into a trajectory called a *track*.

**ECAL:** (Electromagnetic Calorimeter) ECALs are designed to measure the energy of electromagnetic particles (both charged and neutral) and their position. This is done by constructing them using a heavy, high Z material to initiate an electromagnetic shower to totally absorb the energy and stop the particles. The important parameter for the material used in electromagnetic calorimeters is the radiation length $X_0$, and have typical values of $15 - 30\ X_0$. Additionally, it is key to have as little material before the calorimeter as possible (this means the tracker) so that the particles do not radiate before they reach it. After passing the tracker, the particles enter the ECAL. It is designed to measure the energy deposits of photons, electrons and positrons.

**HCAL:** (Hadronic Calorimeter) The purpose of HCALs is to measure the energy of heavy hadronic particles. They are similar to electromagnetic calorimeters but bigger. The most important use of a hadronic calorimeter is to measure the energy of dense jets of particles.

**MS:** (Muon system) Muons are extraordinarily penetrating and therefore the detectors for identifying them are the outer-most layer of a collider detector. Any charged particle that makes it through that many interaction lengths of material is identified in the muon chamber. These detectors are made up of several layers of tracking chambers as seen in fig(4). Their primary purpose is to measure the momentum and charge of muons. The measurements from the muon chambers are combined with the tracks reconstructed with the inner tracker to fully reconstruct the muon trajectory.

A neutrino, which does not have any of the properties that the systems are sensitive to, passes undetected through all the layers. Although, one can use missing transverse momentum to predict their path through the layers. Also, a background magnetic field is responsible for curving/bending the track of charged particles. Using the parameters of such bending, it enables one to calculate energy and momentum of such particles.

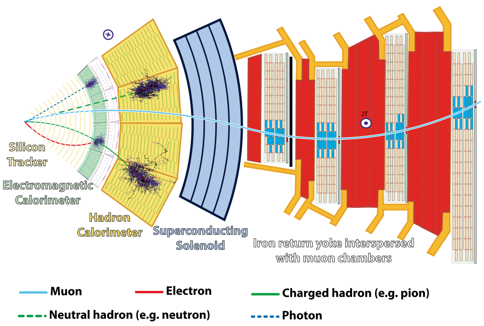


Figure 4. Transverse cross-section of a detector [4]

## B. Decays within the tracker

Traditional detectors (varying to a certain extent) are sensitive to particles having lifetimes around the scales of $\sim$ 25 ns which corresponds to a $c\tau$ = 7500 mm. Looking blindly at this number would make one think that it is impossible to detect LLPs or their decays within such conventional detectors. One has to realize that the decay probability exponentially decreases. The data-visualized interpretation of this can be see in fig(5). Let us select one point on the lower figure and analyze it in order to understand what is this data telling us. Look at the coordinate ($10^2$ GeV, $10^3$ mm). Eyeballing the color and associating the value associated to it is approximately 0.3. This number tells us the *fraction of events* for such a particle that decay within 30 cm from the production point. This means that approximately 30% of the decay happens within 30 cm for a particle that has a decay length of 100 cm. This means that in-principle it is possible to detect hits for particles that are much long lived in such a detector.

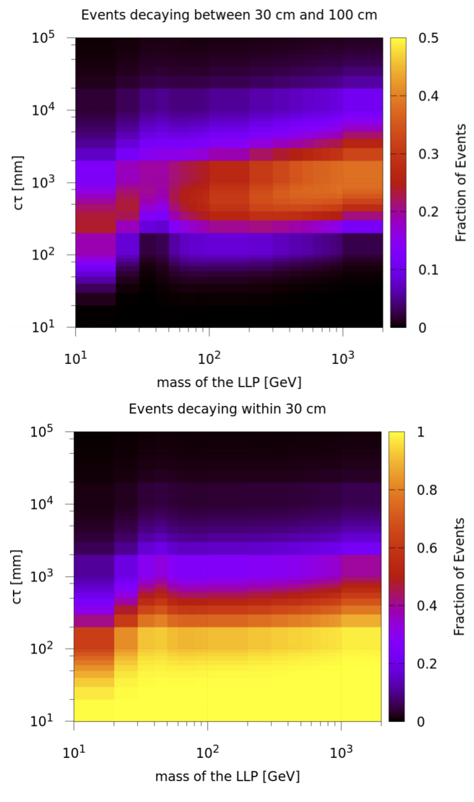


Figure 5. Fraction of LLPs decaying within 30 cm (Top) and 30-100 cm (Bottom) as a function of mass and decay length [2]

A particle having lifetime $\tau$, will cover the transverse distance

$$d_T = \gamma\beta c\tau$$

in the lab frame of reference. In the formula, $\gamma = \frac{1}{\sqrt{1-\beta^2}} = \frac{E}{m}$ and $\beta = \frac{v}{c} = \frac{|\vec{p}_T|}{E}$ are the parameters. Using this, the exponential decay formula, one can calculate the probability of the decay based on the dimensions of a spherical detector using the following formula,

$$P_{\text{dec}} = \frac{1}{4\pi}\int_{\Delta\Omega} \mathrm{d}\Omega \int_{L_1}^{L_2} \mathrm{d}L \frac{1}{d} e^{-L/d}$$
$$\text{where} \quad d = \frac{|\vec{p}_T|}{m} c\tau$$

and $L_1$,$L_2$ are the distances between the interaction point where the LLP enters and exits the detector volume respectively. $\Delta\Omega$ is the detector volume. [2, 9]

## C. Direct detection

In this section, we talk about two signatures of particles in the detectors which potentially enables us to observe the LLPs directly.

### 1. *Anomalous ionization*

A charged LLP (CLLP) is directly detectable from the tracks that forms in the ID. If the mass of the CLLP is heavier than that of a proton, its speed $\beta$ will be markedly lower than that of any track-forming SM particle of the same momentum. The average ionization energy loss per unit distance traveled by a charged particle in material of a particular density has a $\beta$ dependence given by the Bethe-Bloch formula,

$$\left\langle \frac{dE}{dx} \right\rangle \sim -\frac{z^2}{\beta^2} \cdot \left[ \ln\left(\frac{\beta^2}{(1-\beta^2)}\right) - \beta^2 + C \right]$$

where C is a near-constant that depends on the properties of the material traversed and z is the electric charge of the traversing particle. Thus, a CLLP that is slow-moving or has charge greater than 1 can be identified via anomalously large $\langle \frac{dE}{dx} \rangle$. [1]

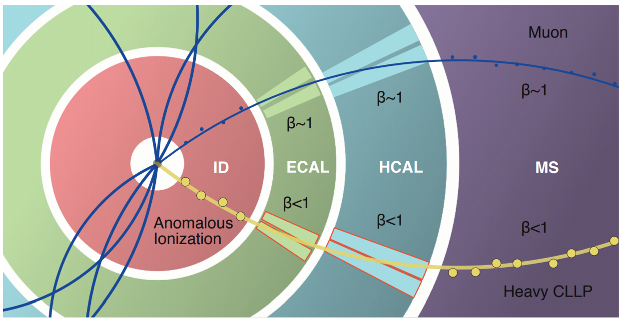


Figure 6. Anomalous ionization of a heavy CLLP [1]

### 2. *Delayed detector signals*

A heavy LLP traveling at low speed relative to a SM particle of the same momentum takes more time to cover the distance from its production vertex to a distant detector subsystem, particularly the calorimeter or MS. This "late" arrival constitutes a unique LLP signature. Measurement of the time of flight provides a measurement of the speed of the LLP candidate and, in conjunction with its momentum measurement, gives the LLP mass. [1]

## D. Indirect detection

In the following section, we talk about two signatures of particles in the detectors which potentially enables us to observe the decay of LLPs, hence *indirectly*.

### 1. *Displaced tracks*

Tracks of charged particles emitted in the decay of a LLP are often measurably inconsistent with originating from the beam spot, the spatial region where beam-particle collisions take place. Such a track is illustrated in fig(7). The degree of consistency is typically determined from the track's transverse impact parameter $d_0$. This is the shortest distance, measured in the $(x, y)$ plane transverse to the beams, between the track and the hypothesized position of the collision. This position is taken to be either the interaction point (IP) at the center of the beam spot or the primary vertex (PV), which is the point from which reconstructed tracks originating from the collision appear to emanate in a particular event. [1]

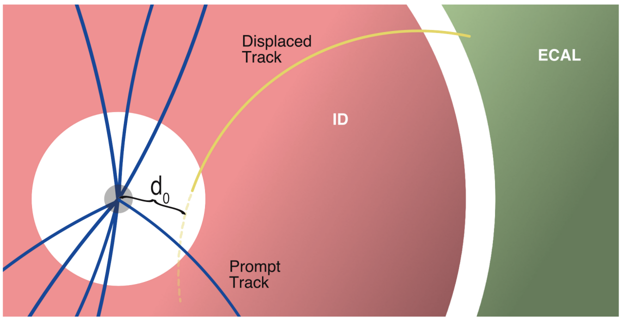


Figure 7. A displaced track with a large transverse impact parameter $d_0$ in addition to a standard prompt track[1]

### 2. *Displaced vertices*

When several LLP-daughter tracks are detected, their common point of origin constitutes a displaced vertex (DV), with a position $\sim r_{\text{DV}}$ and corresponding co-variance matrix that can be determined by a vertex-fitting algorithm. Such a DV is illustrated in fig(8). Since the vertex involves several tracks, the distance $|\sim r_{\text{DV}}|$ of the vertex from the IP or from the PV is determined more precisely than $d_0$ and directly represents the relevant decay length. [1]

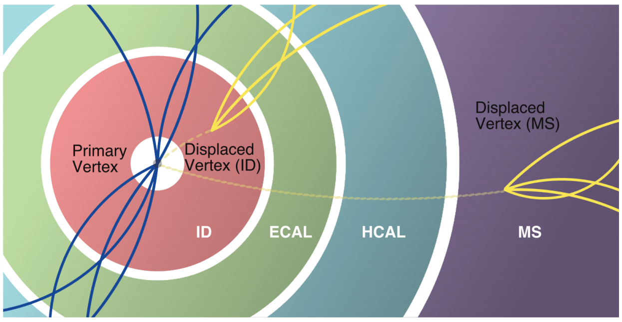


Figure 8. Primary vertices formed with primary tracks. Displaced vertices in both ID and MS are shown [1]

## IV. SEARCH FOR LLPS IN COLLIDER EXPERIMENTS

### A. MATHUSLA

Massive Timing Hodoscope for Ultra-stable neutral particles aka MATHUSLA, is an proposed enormous tracking detector that would sit at the surface roughly 100 m above the CMS or ATLAS. It is proposed to have the dimensions of $200 \times 200 \times 20$ m$^3$. The goal of this detector is to detect the decay products of neutral long lived particles (NLLPs) into pairs of charged particles. The positioning of this humongous box-like detector will be extremely important as we want the NLLPs to decay within this volume. At the top of the box, there will be detectors that will measure the leptonic and hadronic particles as a result of this decay. Using this, signatures for displaced vertices can be reconstructed. This parameter space cannot be probed by conventional detectors around a typical collider experiment. On top of this, we also have the benefit of having low SM background. Initial estimates indicate that with 3000 fb$^{-1}$ of data, MATHUSLA would be sensitive to LLPs with lifetimes up to $\tau \leq 10\,\mu$s limits obtained from Big-Bang Nucleosynthesis for some model. [1][9]

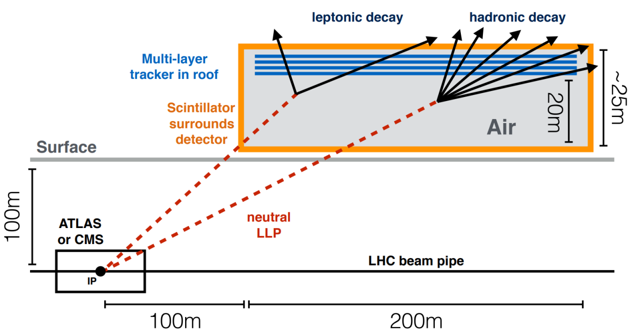


Figure 9. Simplified detector layout showing the position of the 200 m × 200 m × 20 m LLP decay volume [9]

### B. FASER

The FASER experiment has been inaugurated in May 2021 and is situated 480m (initially planned at 150m) downstream from the IP of the ATLAS or CMS experiment, beyond the point at which the beams curve away. Placed at 0 degrees relative to the collision axis, hoping to also detect neutral LLPs or their decay products. There is a significant amount of shielding from the SM background due to layers of rock and concrete.

At the entrance to the detector, two scintillator stations are used to veto charged particles coming through the cavern wall from the ATLAS interaction point; these are primarily high-energy muons. The veto stations are followed by a 1.5-m-long dipole magnet. This is the decay volume for long-lived particles decaying into a pair of oppositely charged particles. After the decay volume is a spectrometer consisting of two 1-m-long dipole magnets with three tracking stations, which are located at either end and in between the magnets. Each tracking station is composed of layers of precision silicon strip detectors. Scintillator stations for triggering and precision time measurements are located at the entrance and exit of the spectrometer.[10][1]

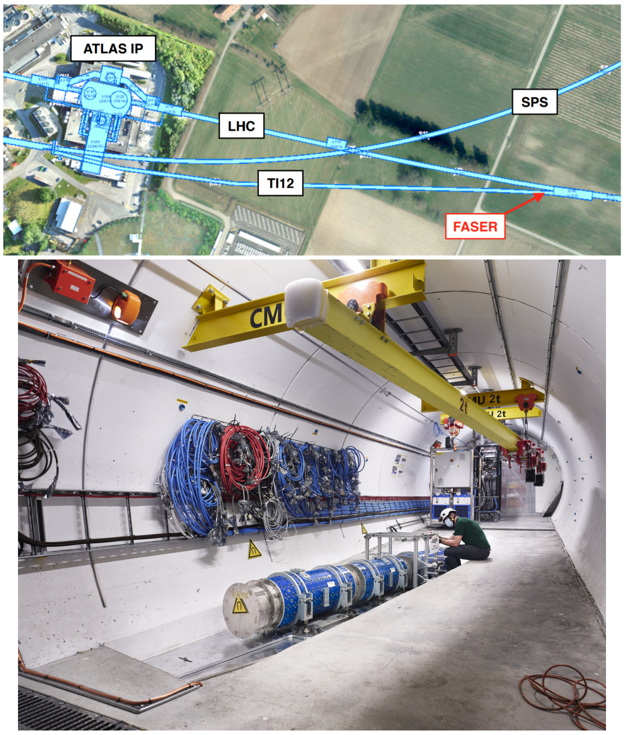


Figure 10. Top : Location of FASER from the ATLAS IP, Bottom : Installation of FASERs three magnets in Nov 2020[10][10]

## V. CONCLUSION

LLPs have given us a new domain to explore the particle approach to Dark matter. Being prevalent in existing theories, a lot of the physical interpretations from the SM can be adopted for BSM while discussing this approach. Traditional collider detectors can be used to test a very limited parameter space for LLPs as DM. Upcoming detector proposals have been coming up with innovative ways to expand the sensitivity beyond that of currently existing detectors. In order to increase the chances for LLP detection, it is best to have low SM background, which enables one to veto out the signatures of known particles. This helps to identify and theorize the signatures of LLPs with much for sensitivity.

It is a very young field and shows a lot of promise. Detection of such particles and matching them with corresponding theories could be potentially a ground breaking as it can influence several other parts of particle physics and cosmology.

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