Post-Higgs-Discovery Era: WIMPs and Dark Matter

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Abstract

Weakly interacting massive particles (WIMPs) are hypothetical particles that interact via gravity, weak force and other unknown forces. They are predicted to have a mass range between 10 GeV and a few TeV. The WIMP is one of the proposed candidates for dark matter, and, if proven to exist, it would be a gigantic step in cosmology and particle physics. Direct detection such as DarkSide-50 or XENON100 experiments are thought to achieve sensitive results in this next decade. The premise of this dissertation is to discuss the WIMPs involvement with dark matter, their matching properties with the Lightest Supersymmetric Particle (LSP) and their detection.

1 Introduction

Particle physics is a widely researched and discussed topic in the scientific community. It is essentially the study of the fundamental forces and particles that constitute matter and its interactions in our universe. Fundamental particles have changed over the years until modern physics, when the Standard Model appeared. The Standard Model explains all fundamental matter interactions and classifies particles into two fermion groups, leptons and quarks, and two boson groups, gauge and scalar.

With the Higgs boson discovery in 2012, the Standard Model was theoretically completed. However, it is still not able to explain phenomena such matter-antimatter asymmetry, gravity at its most fundamental level, dark energy or dark matter. Standard Model matter can only explain 5% of the entire universe.

There has not been a lack of attempts to explain non-luminous matter although none has been proved yet. Nonetheless, a weakly interacting massive particle or WIMP is in the spotlight of theoretical and experimental physicists around the globe. A step in the right direction would help complete the Standard Model and understand the nature of our universe.

The dissertation starts with an introduction to the Standard Model, followed by the Higgs boson and its discovery. The next section discusses the completeness of the Standard model, which introduces the next topic, dark matter. Once the basis has been set, the text focuses on the main topic, the WIMPs and their detection. The dissertation ends with a discussion and conclusion.

2 Standard Model

The Standard Model is the main model on which particle physics relies. It has been developed and completed throughout the second half of the

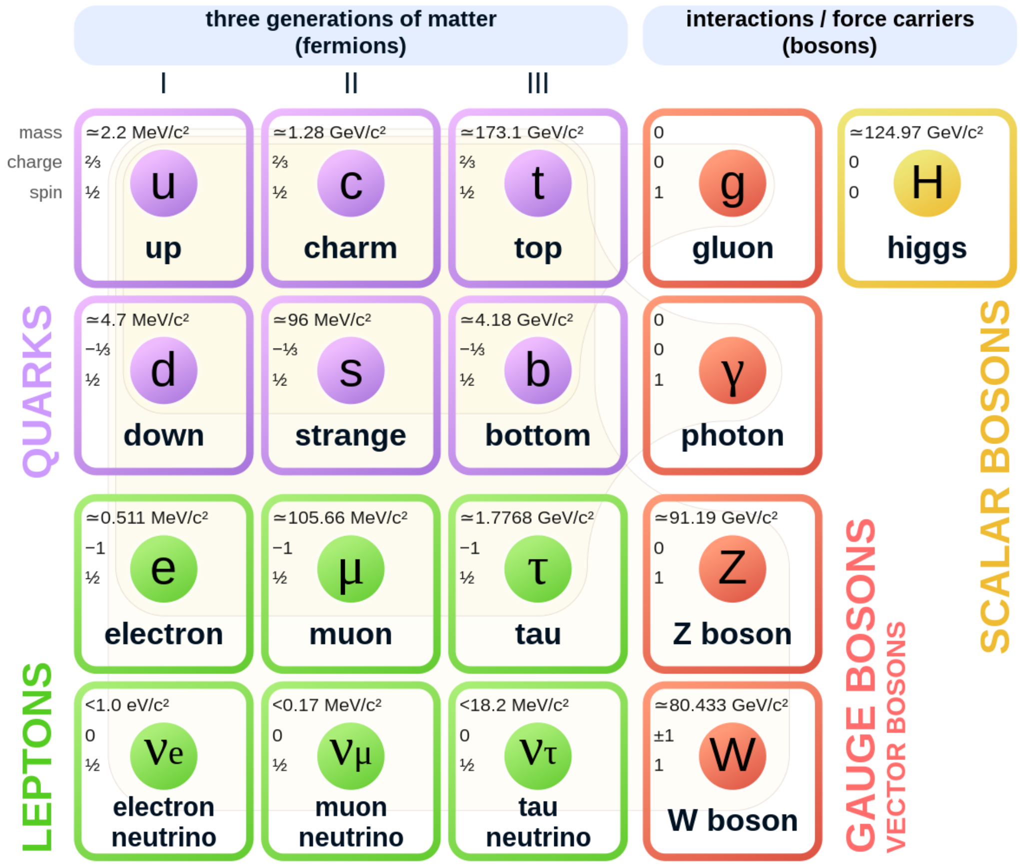

Figure 1: Classification of Elementary Particles according to the Standard Model. From [2]

20th century and even recently, with the Higgs Boson experimental discovery. This theory describes three out of the four elemental forces, the strong force, the weak force and the electromagnetic force, excluding gravity, and classifies the known elementary particles. [27] Although the Standard Model was experimentally confirmed with the existence of quarks, the experimental discoveries of the top quark, the tau neutrino and the Higgs boson have completed this model theoretically. The elementary particles are classified into two main groups:

2.1 Fermions

Fermions are elementary particles that have a spin of ½ and respect the Pauli Exclusion Principle. Each fermion has its own antiparticle. From Figure 1 we can see that fermions are also grouped into two classes, quarks and leptons.
The six quark categories are: up, down, charm, strange, top and bottom. Up-type quarks have a charge of +⅔, while down-type quarks have a charge of -⅓. A property of quarks is that they have colour charge. They also feel all three fundamental forces, strong, weak and electromagnetic. There are three generations of quarks, each more massive than the previous. The first generation of quarks makes up the proton and neutron, up and down quarks. A quark can have 3 colour states (r, g, b), with antiquarks having the corresponding anti-colour. All three colours mixed together or any colours with their anti-colour produce a net colour charge of zero. Due to colour confinement, free particles must have a net colour charge of zero, Thus, baryons such as protons and neutrons have three quarks, one of each colour. Mesons, on the other hand, have a quark of any colour and an antiquark with the matching anti-colour.[26]
Leptons are also grouped into families and are formed by electron, electron neutrino, muon, muon neutrino, tau and tau neutrino. Leptons can be charge negative (electron, muon and tau) or charge neutral (neutrinos). The charged leptons feel electromagnetic force and weak force, while the neutral ones only feel the weak force and are almost massless. The first generation is where we have our stable matter, electrons and electron neutrinos. [26]
It is important to mention that every fermion has its own antiparticle. For

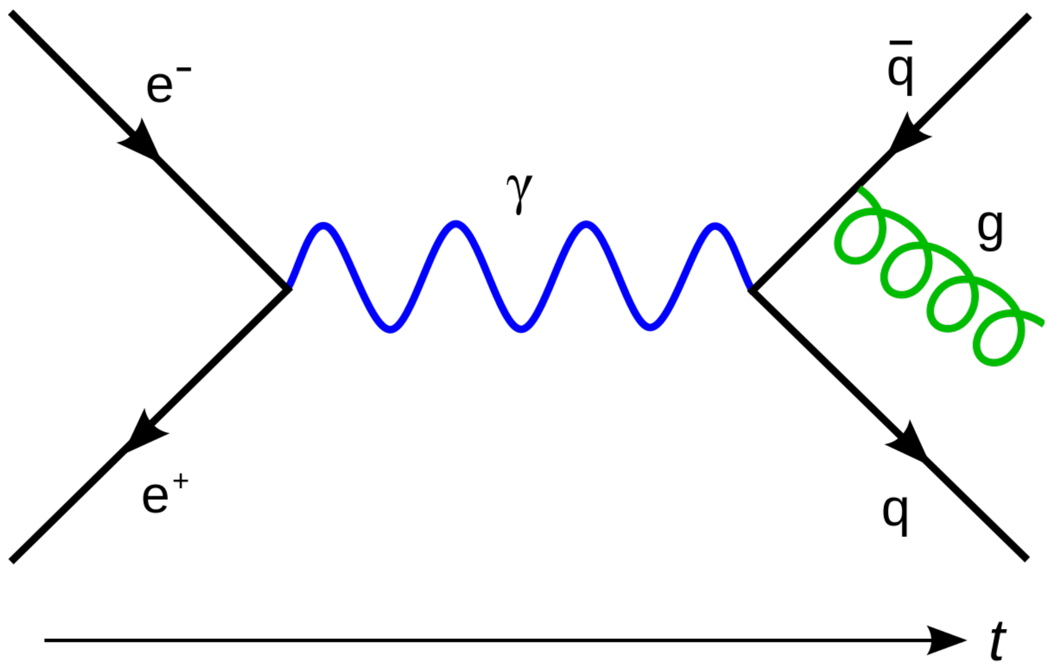

Figure 2: Feynman diagram of an electron and positron annihilating, producing a photon. From [23]

each particle, there is an almost identical fermion with the exact same mass but with the opposite electric charge. Each quark has its antiquark, its electron its antielectron (or positron), and so on.
Figure 2 shows the annihilation of an electron and its antiparticle. Annihilation occurs when an elementary particle collides with its respective antiparticle to create a new particle a photon in this case. [26]

2.2 Bosons

Bosons are the force carriers of the elementary forces and have a spin of 1. The gauge bosons are: gluons, photons, W bosons and Z bosons.
The strong force corresponds to gluons, which are massless. Gluons interact with quarks, creating more complex particles like protons and neutrons.

This force is responsible for hadronic and nuclear binding. The electromagnetic force corresponds to photons, which are also massless. This force couples to electric charge and has an infinite range. It is responsible for atomic electron shell structure, chemical bonds and electric circuits, among others. The weak force corresponds to W and Z bosons. W bosons have positive and negative charges and a mass of 80 GeV. Z bosons are neutral and have a mass of roughly 91 GeV. The weak force is responsible for various forms of decay, such as beta decay. It is a weak and short-range force because the mediating particles have mass.
In the Standard Model we also encounter a scalar boson known as the Higgs boson.

3 The Higgs Boson and its discovery

The Higgs boson is a scalar boson in the Standard Model created by the self-excitation of the Higgs field. It is a massive particle (roughly 125 GeV) with zero spin, no electric charge and no colour charge.
The Higgs mechanism relies on spontaneous symmetry breaking, which happens when a physical system, initially in a symmetric state, ends up being in an asymmetric state. In this mechanism, the Higgs field appears, which has a "sombrero-shape" potential with two minima away from zero and is symmetric under rotation. The Higgs field allows the W and Z boson to acquire their masses when they interact with it. Fundamental fermions can also be generated by interaction with the Higgs field. [26]
It was not until 2012 that the Higgs boson was observed and the previous theory from Peter Higgs and François Englert experimentally confirmed. The search for the Higgs boson was mainly done in the European Organisation for Nuclear Research (CERN)in Switzerland. It took more than 30 years and the world's most expensive and large collider at the moment, the Large Hadron Collider (LHC).

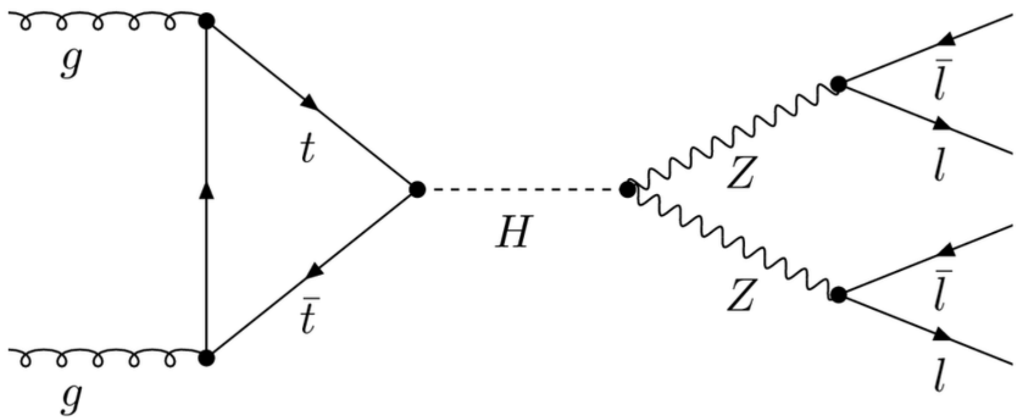

Figure 3: Feynman diagram of the production of the Higgs boson followed by a decay into a pair of Z bosons and its subsequent leptons. From [28]

The LHC consists of a 27 km ring of superconducting magnets that guide the particles through the whole ring. Two beam energies of 6.5 TeV are kept at vacuum and travel in opposite directions at speeds close to the speed of light before they collide. In order to conduct electricity without resistance or loss of energy, magnets must be kept at -271.3ºC. The beams are mainly protons, which are made to collide at four particle detectors (ATLAS, CMS, ALICE and LHCb).

The two detectors that have been looking for the Higgs boson are ATLAS and CMS. These detectors are in charge of detecting the decay products originating from the hadron collisions. ATLAS detector has an onion-like structure with different detector parts surrounding the collision point. Each layer is assembled according to how the different particles interact with different material.

The process of interest is the Higgs boson decaying into two Z bosons, which then decay into a lepton-antilepton pair, as we see in Figure 3. The process begins with two protons colliding, creating a Higgs boson. In the detector what is measured is the final, the four charged leptons. Once

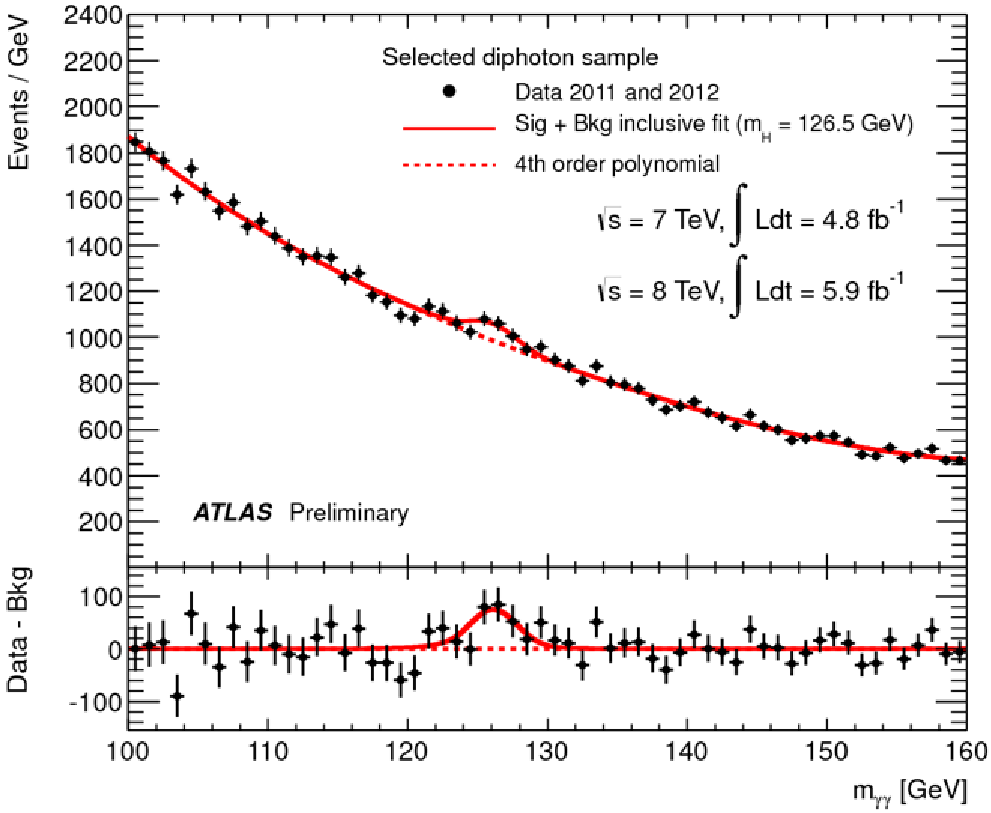

Figure 4: Plot showing the invariant mass from pairs of photons. The excess of events over the background prediction around 125 GeV is consistent with predictions for the Standard Model Higgs boson. From [11]

these products are detected and their properties measured, the invariant mass can be calculated from these measurements. This mass has to be equal to the mass of the Higgs, but only for particles coming from the Higgs decay. For particles coming from other sources, the mass is going to be, in general, background components. This creates a mix of unique results, where in most cases the mass is a background prediction, but in a few cases, it is going to be a fixed value, corresponding to the mass of the Higgs. Carrying out a statistical analysis of the results, a peak will appear as we can see in Figure 4. [11] [12]

4 Is the Standard Model complete? Why are we looking for new particles?

The Standard Model was theoretically completed in 2012 with the last missing piece, the Higgs boson. However, it can still not explain various phenomena.

It is a fact that more matter than antimatter exists in the universe. There are three conditions required to explain this asymmetry: baryon number violation, C and CP violation and the departure from thermal equilibrium. The Standard Model does not contain these ingredients. CP violation in the weak sector is not large enough to explain matter-antimatter asymmetry. [26][6]

Another problem with the Standard Model is that it describes only three out of the four known fundamental forces, missing gravity. This is because, in the subatomic world, gravity is extremely weak. The quantum theory used to describe the microscopic world and the general theory of relativity that describes the macroscopic world are challenging to fit into the same framework. Although it has not been found yet, the graviton could be a suitable candidate for the force-carrying particle of gravity.

In the cosmological field, the existence of dark energy is also a problem for the Standard model, which does not include it. According to the Lambda-CDM model, dark energy is related to a non-zero cosmological constant and it leads to an accelerated expansion of the universe. However, it is still unknown how it impacts and relates to particle physics.

Furthermore, the Standard Model is not able to describe the totality of the matter in the universe. In fact, 82% of the total matter is not included in this model. This matter is electromagnetically neutral, stable and invisible to eyesight and is known as dark matter. Its nature is still mainly unknown although different particle candidates have emerged in these past decades. ‘

5 Dark Matter

Dark matter, sometimes confused with dark energy, is non-luminous matter that makes up 23% of the entire universe. Standard Model matter includes only 4% of the universe, according to the Lambda-CDM model of cosmology. Dark matter behaves under gravity like Standard Model matter but does not couple as strongly under gauge interactions. It is electromagnetically neutral and can be classified into cold dark matter and hot or warm dark matter. Cold dark matter (CDM) is classified as slow compared to the speed of light, while warm dark matter (WDM) has higher velocities. The current models, such as the previously mentioned Lambda-CDM mode, favour cold dark matter.

In the 1930s, the astronomer Fritz Zwicky noticed a discrepancy between the mass of clusters of galaxies calculated through luminosity and the one based on dynamical estimates, using the virial theorem. [20][6] Around the same time, Jan Oort found that radial velocity does not decrease straight away as we get away from a galactic nucleus as we can see in Figure 5, which could be explained by the existence of massive dark halos surrounding galaxies.

Further evidence of dark matter is gravitational lensing, which is a consequence of general relativity. Einstein postulated that the universe exists in a flexible four-dimensional spacetime, curved by objects with mass. Light is similarly affected, as massive objects lying between a light source and an observer act as a lens, which bends the light. The amount of mass within a cluster can be measured from this distorted image using the Einstein

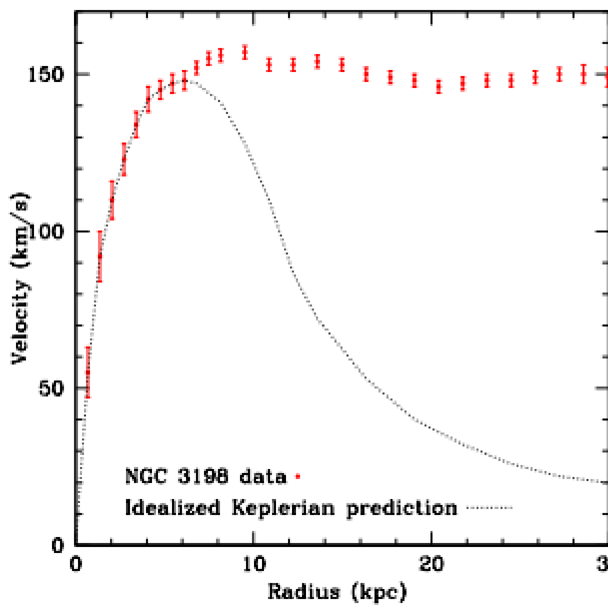

Figure 5: Measured rotational velocities of HI regions in NGC 3198 compared to a Keplerian prediction. From [21]

radius:

$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{d_{LS}}{d_L d_S}} \tag{1}$$

Where G is the gravitational constant, M is the mass of the lens, c is the speed of light, d_L the distance to the lens, d_S the distance to the source and d_{LS} the distance between the lens and the source. Physicists realised that the calculated mass from Equation 1 was much larger than the one from its luminosity. [21] This missing mass corresponds to dark matter.

There is no shortage of candidates for non-baryonic matter. The list includes from Standard Model neutrinos to WIMPs and axions. Standard Model neutrinos have been considered dark matter candidates due to their proven existence. However, due to their low mass and low abundance, this option is not widely supported. Sterile neutrinos were also proposed

as candidates, as they are Standard Model neutrinos but without weak interactions.
Axions are attempts to solve CP violation, they are very light ($\leq 0.01eV$) and weakly interacting. They have an acceptable range of relic density and they are thought to not be in thermal equilibrium in the early universe. [8]
Relic density is the density of a particle at the time of freeze-out, instantly after the Big Bang. Relic abundance can be calculated using the Boltzmann equation. [16]
Massive astrophysical compact halo objects (MACHOs) were one of the first candidates for dark matter. They are astronomical bodies that emit little or no radiation and drift through space. These can be detected through gravitational lensing. However, it is unlikely that these astronomical bodies could make up for the vast majority of dark matter.
Kaluza-Klein excitations of Standard Model fields have also been discussed as a candidate for dark matter. This exotic particle combines baryon-number and Standard Model colour to ensure its stability. Kaluza-Klein particles have an acceptable relic density with mass values in the 10 GeV to a few TeV range. [4]
Finally, one of the most common candidates for dark matter is the weakly interacting massive particle (WIMP).

6 WIMPs

Weakly interacting massive particles are hypothetical particles which interact via gravity, weak force and others, potentially from outside the Standard Model, which could be weaker than the weak force. This hypothetical particle is one of the leading candidates for dark matter and it is thought to have a mass range between 10 GeV and several TeV. [6] Recent studies have gotten sensitive results of a potential 70 GeV WIMP. [29]
If we consider WIMPs as the dominant form of dark matter, their number

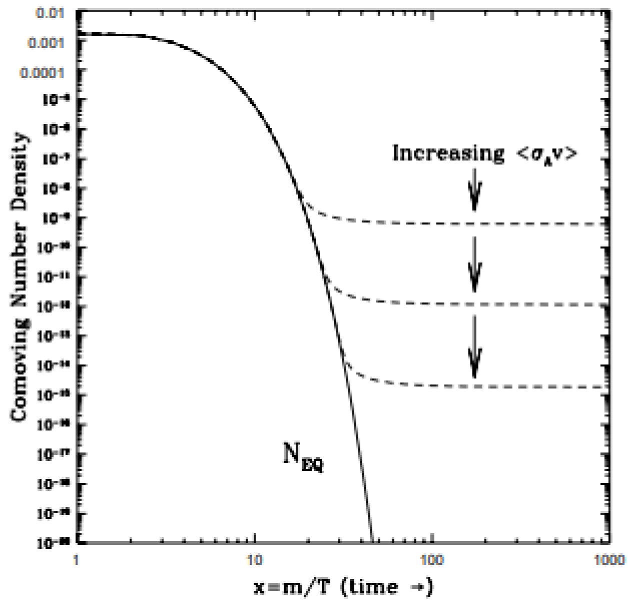

Figure 6: Number density of WIMPs in the early Universe. The dashed curves are the actual abundance, and the solid curve is the equilibrium abundance. From [25]

can be estimated from dark matter density. This reveals that around 10^5 WIMPs per second will pass through every cm^2 of the surface of the Earth. By assuming a mass in the mentioned range, the velocities of WIMPs will be of the orders of baryonic matter velocities, $10^{-3}c$. [26]

Figure 6 shows numerical solutions to the Boltzmann equation which determines the WIMP abundance in the early Universe. From the Boltzmann equation, the value of the cross section is found to be 10^{-9} GeV^{-2}. Surprisingly, this is the value expected from an electroweak cross section, suggesting that if an undiscovered massive particle with electroweak interaction exists, it should have a relic density of unity and be a suitable dark-matter candidate. Relic density is the density of a particle at the time of freeze-out, instantly after the Big Bang, where Standard Model matter to dark matter flow was reciprocal. [25] The issue is that WIMPs do not correspond to any known particles, so new types of particles have to be postulated.

One possibility is the WIMP miracle, which is the coincidence of the WIMP properties with a new supersymmetric particle. The simplest and most consistent supersymmetry model is the Minimal Supersymmetric Standard Model (MSSM), which is an extension of the Standard Model where all particles have a partner with the same quantum numbers except for a spin difference of a half. Each boson has a fermion as a partner and vice versa. MSSM particles contribute to making a light Higgs boson, as its interactions with the Standard Model particles make it very heavy. Furthermore, this model relies on R-parity, which is a supersymmetry concept where baryon and lepton numbers are not conserved. It can be represented by:

$$R = (-1)^{3B+L+2s} \tag{2}$$

Where B is the baryon number, L is the lepton number and s is the spin. Following Equation 2, Standard Model particles have an R-parity of 1, while supersymmetric particles have an R-parity of -1. Just like proton stability is determined by the baryon number, R-parity determines that the lightest $R = -1$ state is stable. This allows the lightest supersymmetric particle (LSP) to be a suitable candidate for cold dark matter, where in many models is the neutralino. [17] [19] [9] Other particles such as the sneutrino were excluded as they could not have to have a mass between a few GeV and several TeV to be stable. The neutralino has a spin of a half and is formed by the wino (the supersymmetric particle of the W boson), the bino (the superpartner of a gauge field that corresponds to weak hypercharge) and two Higgsinos (superpartners of the Higgs boson). Its four eigenstates are: $\tilde{N}_1^0$, $\tilde{N}_2^0$, $\tilde{N}_3^0$ and $\tilde{N}_4^0$. [19] As neutralinos are its own antiparticles, they are Majorana fermions. They can annihilate into W^+ and W^- pairs by exchange of Z^0, h^0 and H^0 bosons as we see in Figure 7. H^0 and h^0 are two CP even neutral bosons from the Two-Higgs-doublet model. [22]

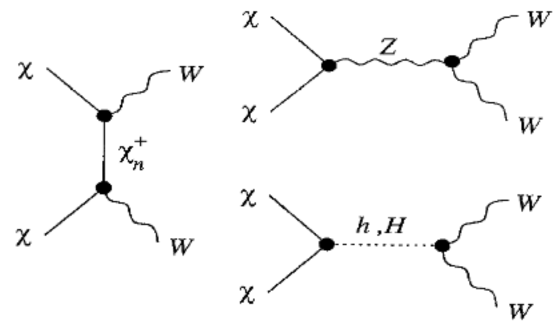

Figure 7: Diagrams of neutralino annihilation to $W^+ \, W^-$ pairs. From [24]

Another possibility is the vector gauge boson W_D. This vector boson is produced through the standard freeze-out processes $SM + SM \leftrightarrow W_D + W_D$, allowing the WIMP to stay in thermal equilibrium. However, the W_D model also includes another component, the Feebly Interacting Massive Particle (FIMP). The FIMP, created through ÚV freeze in processes $H_i + H_i \rightarrow FIMP + FIMP$, where $i = 1, 2$. It has a much smaller interaction than the electroweak and has small couplings. [15] Contrary to freeze-out, FIMP freeze in processes interact weakly with luminous particles and do not achieve thermal equilibrium with the early universe fluid.[7] Some models even consider the annihilation of gluons into FIMPs by exchanging gluophilic Z'. [10] Z' represents a possible mediator between dark matter and baryonic matter. [18]

7 WIMP detection

Most of the experiments to detect WIMPs involve direct detection, indirect detection through observation of energetic neutrinos and through their production at the LHC.

The production of dark matter in an accelerator would be a gigantic step in particle physics. If we assume that R-parity is conserved, the neutralino could be looked for in an accelerator. When supersymmetric particles are created, they will decay to the lightest supersymmetric particle (LSP) and escape the detector, like the Standard Model neutrino. The LSP could be detected as missing energy and momentum, as it leaves the collision spaces. On the other hand, mono-jet searches at the LHC could hypothetically include a space for the FIMP candidate. Feeble dark matter interactions consistent with freeze in mechanism could be accomplished with this model. [10]

WIMP WIMP annihilation is also a valid indirect detection technique. Its annihilation rate is proportional to the square of dark matter density and its products include gamma rays, neutrinos and antimatter particles. These gamma rays are found most frequently in the galactic center. They originate when the WIMP annihilation produces a quark and antiquark pair, which also produces a particle jet, releasing gamma rays. Neutrinos from WIMP annihilation are mainly in stars, where annihilation and capture rates are at equilibrium. These neutrinos can then be studied, as they interact weakly and escape the Sun. [21] A recent analysis of gamma rays in the Fermi-Large Area Telescope (Fermi-LAT) may have achieved indirect detection of a 70 GeV WIMP, as its mass and cross section are consistent with theoretical calculations. [29]

Direct detection experiments search for low energy nuclear recoils made in WIMP collisions with atomic nuclei, with low energy thresholds, large detector masses and ultra-low backgrounds. One of the most promising experiments is XENON100, located at the Laboratory Nazionalo del Gran Sasso (LNGS), Italy. It operates a dual-phase xenon time projection chamber (TPC), at liquid and gas states. Ionised electrons are drifted through an electric field to the liquid-gas boundary and extracted in the last phase. UV-sensitive photomultiplier tubes observe these events, allowing the rejection of background events. In the end, nuclear recoils are induced by

fast neutrons and WIMP nucleus scatters, and electronic recoils can be distinguished. [14]
Other popular cryogenic noble liquid detectors are WArP and Dark Side, both using argon and located at the LNGS. Liquid argon, with extremely low quantities of the isotope ^{39}Ar, has got a very good yield and its electrons need 20 eV to produce scintillation photons. Scintillation occurs when luminescent materials are excited by ionizing radiation and emit the absorbed energy in the form of light. This light is then emitted at 128 nm in the Vacuum Ultraviolet Regions. Contrary to liquid xenon, argon's scintillation light components are widely separated, as they have very different decay times. This improves the identification of nuclear recoils against the background beta and gamma emissions. Liquid argon has a high electron mobility, is available at large quantities and can be easily purified of electronegative impurities. These properties allow long drift distances for free electrons. Its low mass compared to other materials such as germanium and xenon, results in a lower cross-section for elastic scattering of nuclei, which is proportional to A^2. [3]
DarkSide-50 detector consists of a three detector system, as we see in Figure 8. The inner grey cylinder is the Liquid Argon Time Projection Chamber (LAr TPC) and is in charge of detecting dark matter. LAr TPC can reject gamma and beta backgrounds in favour of nuclear recoils expected from WIMP scattering. The sphere is the Liquid Scintillator Veto (LSV), which serves as a shield and suppresses unwanted backgrounds such as radiogenic and cosmogenic neutrons, γ rays and cosmic muons. The outer cylinder is the Water Cherenkov Detector (WSD), which also shields and suppresses background cosmic muons. It is a tank filled with high-purity water. This detector is proven to be able to run for over two decades with underground argon, without any ^{39}Ar background. Recent WIMP searches in this detector, give a cross section limit as low as $6.1 \times 10^{-44} cm^2$, one of the best results achieved with argon. [13] [5]

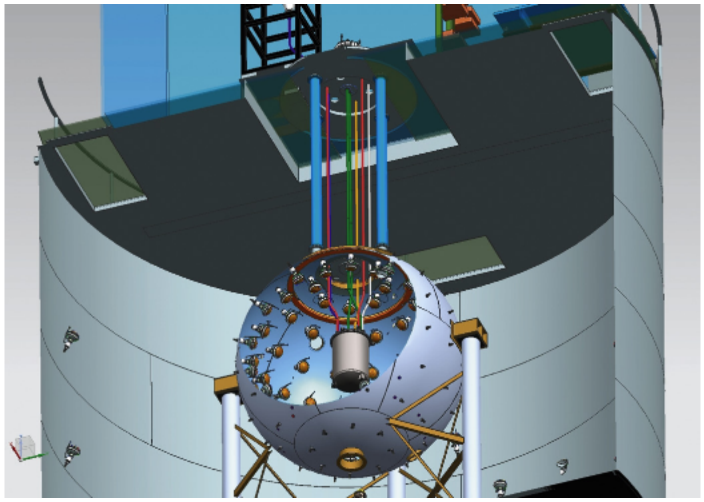

Figure 8: The nested detector system of DarkSide-50 at the LNGS. From [13]

8 Discussion

The outcome of this research has been to establish the WIMP as an appropriate candidate for dark matter and to provide insight into its hypothetical properties. Many theorists believe supersymmetry is the key in the understanding of WIMPs, which could hypothetically be neutralinos. However, the freeze in FIMP is getting more significant in recent papers and experiments, especially when paired with a vector gauge boson W_D WIMP. When comparing direction detection using liquid noble gases such as xenon or argon, it is observed that argon's properties are more suitable for WIMP detection. Furthermore, experiments such as DarkSide-50 have gathered sensitive results in WIMP detection from liquid argon. A cross section limit of $6.1 \times 10^{-44} cm^2$ has been achieved. The implications of such a low cross section limit are the increase in precision when detecting WIMP beams. There is even evidence of a possible 70 GeV WIMP, from gamma rays analysis at Fermi-LAT.

However, it will still take a few years until sensitive results on this hypothetical particle are achieved. The Future Circular Collider at CERN could be the final solution to the dark matter mystery. The collider is planned to be almost 4 times larger than the LHC and to reach collision energies of around 100 TeV. [1]

9 Conclusion

The Standard Model classifies all known fundamental particles and three fundamental forces. The 2012 Higgs boson experimental discovery completed the Standard Model theoretically. However, we are still unable to fully comprehend more than 90% of our universe, especially dark matter, proven to be in much more quantity than baryonic matter. Cold dark matter, which is the most common, is non-luminous, neutral and stable. Although not proven yet, one of the most relevant theories for cold dark matter is the weakly interacting particle. WIMPs interact via gravity, weak force and potentially other feeble forces, outside of the Standard Model. As it has been discussed, the WIMP properties match with the Lightest Supersymmetric Particle, thought to be the neutralino. This supersymmetric particle relies on R parity and is formed by other electroweakinos. Even though it annihilates into W^+ W^- pairs, experimental physicists have still not found this particle. Nowadays, direct detectors such as DarkSide-50 and indirect detectors like the Fermi-LAT seem to be getting close to decisive results on this topic. A Post-Higgs discovery is bound to strike the scientific community and put some light into dark matter and its fundamental particle, the WIMP.

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