DARK MATTER SEARCHES AT THE LHC

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The existence of dark matter is one of the greatest yet unsolved mysteries in physics. It has for a long time attracted much notice from astronomers, cosmologists, experimental and theoretical particle physicists alike. This article will attempt to provide an approachable overview of dark matter. In the first part we go over the astronomical evidence of dark matter and delve into other motivations for the introduction of new physics. We then consider a number of theoretical explanations, most notably the famous Supersymmetric Models. After establishing a theoretical basis, we describe the experimental setup in the case of the ATLAS detector at the LHC, after which we more deeply discuss some experimental strategies for dark matter searches at the LHC.

ISKANJE TEMNE SNOVI NA LHC

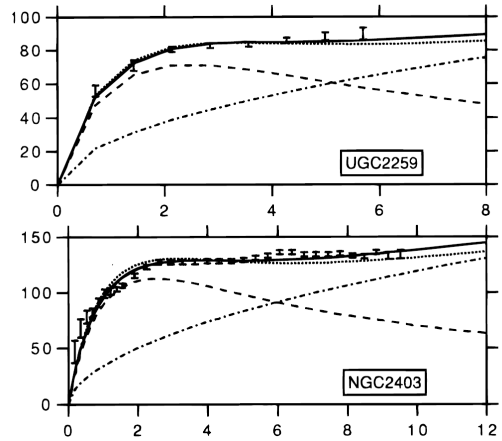
Narava temne snovi do tega dne ostaja eden največjih še nerešenih problemov fizike, zaradi česar predstavlja pomembno raziskovalno področje tako astronomom in kozmologom kot tudi eksperimentalnim ter teoretičnim fizikom osnovnih delcev. V tem članku se bomo poskusili na razumljiv način približati fiziki in raziskavam temne snovi. V prvem delu bomo navedli nekaj dokazov za obstoj temne snovi in drugih motivacij za vpeljavo nove fizike. Nato bomo obravnavali nekaj kandidatov za teoretično razlago temne snovi s poudarkom na dobro znanih Supersimetričnih teorijah. Po zastavljeni teoretični osnovi bomo opisali eksperimentalno sliko takih raziskav v primeru detektorja ATLAS na LHC, nato pa se bomo še malo poglobili v strategije iskanja temne snovi na LHC.

1. Introduction

The concept of dark matter has been known about for quite some time, first noticed in astronomical observations [1]. These go back to the turn of the 19th century, with Lord Kelvin exclaiming that "Many of our stars, perhaps a great majority of them, may be dark bodies" [1] in the context of determining the masses of galaxies. Explicit dark matter studies were later pioneered by Swiss astronomer Fritz Zwicky in the 1930s through observations of galactic cluster dynamics, and became more mainstream in the 1970s with the likes of Vera Rubin, studying galactic rotation curves [1]. It is also around then that the current formulation of the Standard Model of particle physics, which remains our best fundamental theory, came about. The combination of this enigmatic dark matter being unexplained by the Standard Model and its other shortcomings immediately sparked an interest into new theories, attempting to provide an explanation [2]. Soon thereafter, experiments followed, being conducted at colliders like the Tevatron [3] and later the LHC [4], as well as other experiments based on alternative detection schemes. Alas, to date, no signatures of dark matter have been found. Nonetheless, such challenging searches require endurance; progress is still being made and this field of research remains vibrant & ever-evolving [5].

2. Motivations & evidence

The scientific community's vast interest in the nature of dark matter arises from the ample evidence of its existence, as well as the potential it holds for addressing major unsolved problems in physics. The presence of gravitationally-interacting dark matter is most apparent in astronomical observations. An often cited example of this is the problem of *Galactic rotation curves* [6], representations of stars' orbital speeds with respect to the distances from their galaxies' cores. Under the assumptions of Keplerian dynamics one can derive a model of the stars' orbital speeds as $v(r) = \sqrt{GM(r)/r}$, where G is the gravitational constant and $M(r)$ the mass contained within the radius r from the galaxy's core. However, measurements of these curves have shown significant inconsistencies with theory [7], indicating the known measured mass-profiles must be incorrect. In actuality, instead of their speeds declining with their radial distance, the rotation curves "flatten-out", as shown on Figure 1a.



(a) Measurements of galactic rotation curves vs. Newtonian (dashed) and linear potential (dotted). From [7].

(b) Hubble's dark matter map in Galaxy cluster Abell 1689. Lighter shades indicate higher DM density. From [9].

Figure 1. Examples of proof for the existence of dark matter

This would not be possible if not for the presence of a large amount of massive, invisible – "dark" matter. Other observations also agree with this notion, such as those of dynamics of galaxies in galactic clusters, which orbit their gravitational centers faster as they would otherwise [8], or measurements of gravitational lensing [9] showing a strong effect away from the bulk of visible matter. Dark matter, it seems, plays a key role in gravitationally binding large cosmic structures and must therefore be incredibly abundant. This has also been confirmed by the latest measurements of cosmological parameters – maps of the Cosmic Microwave Background made with the Planck space observatory [10] suggest that dark matter constitutes around 85% of all matter in the Universe. As we have a good understanding about how dark matter behaves on large scales, it would seem the next step is to attempt to describe it on the particle-scale. Unfortunately, the nature of dark matter is such that it is highly improbable to be described by our best theory, the Standard Model of particle physics. This fact alone would present itself as a good reason for research into new physics. What's more, the Standard Model on its own has a few shortcomings yet to be resolved, most notably the *Hierarchy problem*, or the problem of its *Unnaturalness* [11].

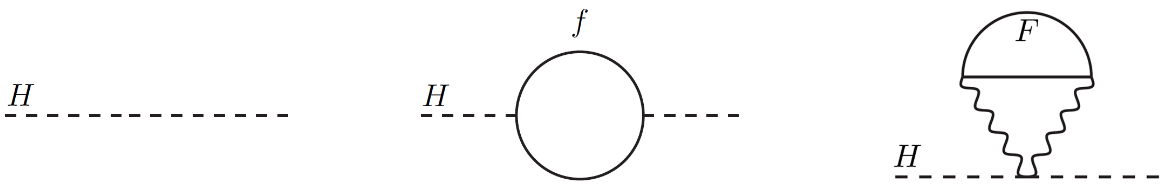


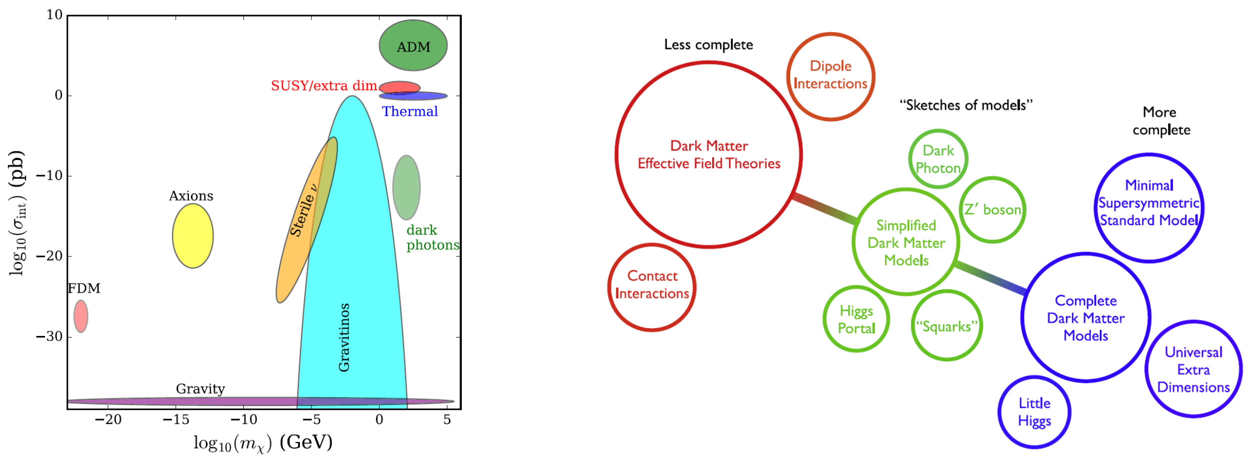
Figure 2. Feynman diagram examples of the 0th, first and second order quantum loop corrections for Higgs mass. The 0th order corresponds to the "bare mass". Reproduced from [12]

A theory is deemed "Natural" if the values of free parameters and their corresponding physical observables are comparable in order of magnitude. Let's consider, for example, a parameter of some (quantum-field) theory m_0 which represents the mass of a particle. It generally follows that the physical measurement of the mass m of such a particle shall not equal to the aforementioned free parameter. The vacuum state is not empty, but rather full of virtual particle-antiparticle pairs, constantly popping in-and-out of existence. In practice, taking into account the effect of these random fluctuations upon the free particle comes in the form of a series of quantum corrections, giving us the "renormalized" mass as a function of the "bare" mass m_0 ($m^2 = m_0^2 + \delta m^2$). Doing these calculations in the framework of the Standard Model (such as in calculating the Higgs boson mass), however, turns out to be problematic. As it happens, the Universe would need to do a lot of fine-tuning to cancel-out these quantum corrections in order for the model mass parameters to agree with the physical masses (meaning $\delta m^2/m^2 \gg 1$, in actuality $\delta m^2/m^2 \gtrsim 10^{34}$), which is why the Standard Model is deemed "unnatural".

A new fundamental theory could therefore not only explain dark matter, but potentially also address the other shortcomings of the Standard Model. Thus, this field has attracted considerable attention in the past few decades and will probably continue to do so for a while.

3. Possible candidates

A viable candidate for a dark matter theory must satisfy a number of conditions. From observations, we know that dark matter is massive, otherwise we would not have known of its existence. In the same vein, we know it is almost definitely electrically neutral, as it does not appear to interact with the electromagnetic field (in other words, does not emit / absorb radiation). Similarly, it should be only barely affected by the strong and weak interactions of the SM (very small interaction cross-section σ). All of this also implies that dark matter is stable, or very long-lived. One option is, of course, finding a theory which predicts a new kind of particle to acommodate these conditions. Such particles are often called "WIMP"s – Weakly Interacting Massive Particles [13]. The other option is to evade modifying the ensemble of particles entirely, instead modifying the theory of General Relativity or exploring worlds of a greater number of dimensions [14]. We will focus on the former.



(a) Cross-section (σ) mass (m_χ)"Phase-space" of dark matter candidates. From [15].

(b) Modified from [41]

Figure 3. Visual representations of dark matter theories

To date, an enormous amount of such theories have been put forward [17]. These take a variety of forms and range from less complete approximations to complete overhauls of or entirely novel fundamental theories (as illustrated on Figure 3). Examples of less complete theories would be various effective-field theories [18], building upon the Standard Model through a few added parameters, such as new masses and effective coupling constants. Such theories are often convenient due to their simplicity, but are otherwise flawed, as they are narrow in scope and are accurate in

a limited range of energies. The more complete theories, on the other hand, address a wider range of issues, adding sometimes entire new symmetries and unifying major natural forces. These would be models such as Supergravity [19], which attempts to quantize gravity, or other non-gravitational Supersymmetric theories [12]. These theories have much larger parameter spaces and usually come with their own mathematical formalism.
Many of these theories are increasingly being considered obsolete, as each year brings either no new evidence for their validity or outright exclusion by experimental data. It surely does not help that the unknowable nature of the matter makes measurement and confirmation extremely difficult. But a few endure, remaining popular in discourse, either due to them being more consistent with reality or their potential to solve the hardest unsolved problems in physics. One of the most promising and popular theories (or rather set of theories) in the last few decades have been the Supersymmetric theories [12], which we will explore further in the next section.

3.1 Supersymmetric theories and the MSSM

The key foundation to any supersymmetric theory is the introduction of a new symmetry between fermions (half-integer-valued spin) and bosons (integer-valued spin): *Supersymmetry* (SUSY). As is typical when considering a new symmetry, we introduce the supersymmetry transformation Q. When applied to a fermionic field, this transformation produces a bosonic field and vice versa. These along with their hermitian conjugates $Q^\dagger$ must satisfy an algebra of (anti-)commutation relations, which we call the supersymmetry algebra [20]. Hence, the distinct particle-states fall into one of the different irreducible representations of the supersymmetry algebra. We call these irreducible representations *supermultiplets* and refer to their elements, the fermionic and bosonic states, as *superpartners* to each other. In other words, to satisfy a symmetry between fermions and bosons, each particle must have a superpartner of the opposite class. As implied, there exist many different theories using the supersymmetric principles. Since there is no way for two SM particles to be each others' superpartners, it follows, if supersymmetry holds, that there exist at least as many new SUSY particles as there are ordinary particles. In this sense, the smallest possible expansion upon the SM is described by the *Minimal Supersymmetric Standard Model* (MSSM), which assigns a new SUSY particle for each fermion or boson described by the Standard Model and introduces two additional Higgs doublets [21](Table 1)

(a) Sfermions

Generation 1			Generation 2			Generation 3		
Particle	Mass (GeV)	Charge	Particle	Mass (GeV)	Charge	Particle	Mass (GeV)	Charge
up squark ($\tilde{u}$)	> 379	$+\frac{2}{3}$	charm squark ($\tilde{c}$)	> 379	$+\frac{2}{3}$	top squark ($\tilde{t}$)	> 92.6	$+\frac{2}{3}$
down squark ($\tilde{d}$)	> 379	$-\frac{1}{3}$	strange squark ($\tilde{s}$)	> 379	$-\frac{1}{3}$	bottom squark ($\tilde{b}$)	> 89	$-\frac{1}{3}$
selectron ($\tilde{e}$)	> 73	-1	smuon ($\tilde{\mu}$)	> 94	-1	stau ($\tilde{\tau}$)	> 81.9	-1
e sneutrino ($\tilde{\nu_e}$)	> 95	0	μ sneutrino ($\tilde{\nu_\mu}$)	> 94	0	τ sneutrino ($\tilde{\nu_\tau}$)	> 94	0

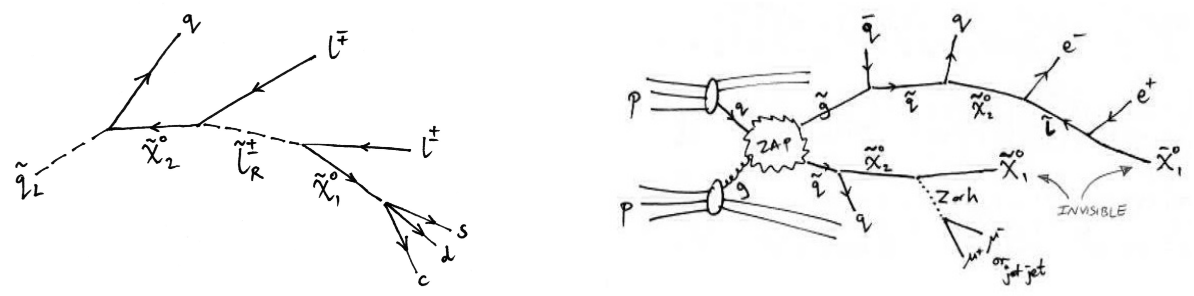
(b) Gauginos

Particle	Mass (GeV)	Description
Neutralinos ($\tilde{\chi}^0_{1-4}$)	> 46	Mixture of photino ($\tilde{\gamma}$), zino ($\tilde{Z}$), and neutral higgsino ($\tilde{H}^0$)
Charginos ($\tilde{\chi}^\pm_{1,2}$)	> 94	Mixture of winos ($\tilde{W}^\pm$) and charged higgsinos ($\tilde{H}^\pm$)
Gluinos ($\tilde{g}$)	> 308	Superpartner of the gluon

Table 1. Masses and charges of sfermions (a) and gauginos (b) in GeV. Reproduced from [17].

The spin-0 superpartners of fermionic particles are called sfermions, their names just being their superpartners' with an added prefix 's-' (up quark → up squark, electron → selectron, etc.). On the other hand, the fermionic superpartners of the bosons are given an added suffix -ino (gluon → gluino etc.). Curiously, two Higgs doublets, one charged and one neutral, must be added to the ensemble

of SM particles, with the physical SM Higgs boson being a linear combination of those of the neutral doublet. This is done to get rid of certain anomalies which would arise otherwise (see Appendix A in [21]). Finally, we classify the charged fermionic superpartners with their mass eigenstates, which we call charginos (typically denoted $\chi_i^{\pm}, i = 1, 2$) and in a similar vein the eigenstates of the neutral superpartners, called the neutralinos ($\chi_i^0, i = 1, 2, 3, 4$).
To understand more about how these new particles would behave, we should consider a new quantum number – *R-Parity* [12][21]. It is defined as $P_R = (-1)^{3B+L+2s}$, where B is the baryon number, L the lepton number and s spin. By this definition, all "normal" SM particles have $P_R = 1$ and their superpartners $P_R = -1$. This leads us to two cases: one in which this new quantum number is conserved and one in which it is not (examples of decay chains in both cases are shown on Figure 4). The latter is quite inconvenient, as nothing would prevent the SUSY particles, presumed to be quite heavier than most SM particles, from just decaying into the SM (see Figure 4a). This would theoretically make them more easily observable, but it consequently prevents the theory from offering a viable dark matter candidate, as we expect it to be paramountly stable. The case of R-parity conservation, however, shows much more promise, since in this case, SUSY particles cannot decay exclusively into those of the SM. Let's make an analogy to the proton. The symmetries of the Standard Model are such that the baryon and lepton numbers B and L are conserved. Consequently the proton, being the lightest of the baryons, does not decay (or at least has a very long life-time). If we follow the same line of reasoning for SUSY particles, we can assume, if R-parity is conserved, that there exists a *Lightest Supersymmetric Particle* (LSP), which should also be very stable. Thus, this supposed electrically neutral and colorless LSP is the SUSY candidate for dark matter.



(a) R-Parity violating chain

(b) R-Parity conserving chain

Figure 4. Examples of processes for both R-Parity cases. Note that in (a), the final products need not contain DM particles.

We are speaking of this LSP generically, as the masses of SUSY particles are unknown. We can outright discount the squarks and gluinos as they have the property of color and would thus interact according to quantum chromodynamics. As for colorless gluino states, they are also very unlikely to be a viable candidate, as they would, similarly to their supersymmetric partners, be expected to form hadronic states. We can also discount the sleptons and charginos by virtue of them being charged. The second-to-last possible option are sneutrinos, but they are deemed highly unlikely by experimental probing of the predicted sneutrino phase-space [22]. This leaves us with the best SUSY candidate for dark matter: the neutralino. This is also the most theoretically developed option for an LSP in most other supersymmetric models [23].
Let's briefly examine other reasons for the potential validity of these models. Supersymmetry is especially popular due to it having the potential to solve the problem of SM unnaturalness [24], briefly mentioned in Section 2. Introducing a fermion-boson symmetry may help to explain why the Higgs mass is measured to be so small. This comes as a consequence of the fermionic and bosonic quantum corrections for mass being of opposite signs, thus largely cancelling each-other and, unlike

in the Standard Model, avoiding the scourge of fine-tuning. Another reason for the exploration of superysmmetric theories is their ability to bring about the unification of the three natural forces at very high energies (gauge coupling unification) [25]. A theory which predicts such an outcome is referred to as a *Grand Unified Theory*, of which discovery has long been sought by many particle physicists.

4. Experimental searches

The validation of any theory is of course conditioned by experimental confirmation. This is especially relevant in this case, considering the sheer amount of candidates. Detecting dark matter is a tricky subject and depends on the source of the measured particles. These can be sourced from the Cosmos, in which case we usually talk about *direct* or *indirect* detection [22]. Direct detection experiments are conceptually not hard to understand and are in some way reminiscent of neutrino experiments. Due to the omnipresence of dark matter throughout the Universe, we can assume there is a constant flow of WIMPs permeating the Earth, often called the ”WIMP wind” [22]. For this reason, a large, massive detector is constructed, preferably located somewhere deep underground to filter out other cosmic particles (such as in the case of neutrino experiments), taking advantage of the WIMPs' small interactive cross-section σ. For this same reason, most of them will simply pass through the detector. However, we can still expect the DM particles to occasionally scatter off the detector's nuclei, depositing energy in the process. This, then, can be measured via vibrations, ionizations or scintillations etc. Examples of such experiments would be the DAMA/LIBRA experiment [27] and the Large Underground Xenon (LUX) experiment [28]. In contrast, indirect detection experiments search for products of dark matter annihilation, assuming such a process is even possible (eg. SUSY neutralinos allow this). Annihilation products vary, some possibilities including high-energy γ rays or neutrinos, both of which we know how to measure, be it via ground-based telescopes or neutrino observatories. Examples of experiments involved in this search include the High Energy Stereoscopic System [29] (system of cosmic γ ray telescopes) or the IceCube experiment [30] (neutrino observatory).

The only alternative to measuring cosmic dark matter is to produce it, achieving this using particle colliders [26]. Taking this path proves to be of difficulty, as we do not know much about either their interactive properties nor their masses. Another thing to consider is that, were we to succeed in producing DM particles, there would be no way to detect them directly. Direct detection schemes, such as those discussed previously, would simply not work in combination with collider production, as the sheer amount of byproduct would overshadow any relevant DM signal. Evidently, the devil lies in the details. Before delving deeper into the specifics of these methods, we should consider the basic principles of our experimental setup, taking under the spyglass the *Large Hadron Collider* and the *ATLAS* experiment.

4.1 The LHC and ATLAS

Built by the European Organization for Nuclear Research (CERN) over a period of 10 years, the Large Hadron Collider (LHC) is the largest and most powerful particle accelerator in the world [31]. It lies at depths ranging from 45 to 170 meters underground and is situated right on the border between France and Switzerland. Its main tunnels contain two adjacent beamlines with radii of 27 km, at the intersections of which lie four large detectors, serving different purposes. The LHC is connected via transfer tunnels to the rest of the CERN accelerator complex, wherein the inital phase of particle-beam acceleration happens. Through them, the beams are injected into the main accelerator ring. In order to guide the particles in orbit, the beam-pipes are fitted with thousands of powerful superconducting magnets. The magnetic dipoles serve to bend the trajectories of the particles, while magnetic quadrupoles bunch them together, tightly collimating the beams. To maintain the superconductivity of the magnets, the beamlines must be kept at operating temperatures of about 1.9 K using a distribution system of liquid helium. These must also be kept at an ultra-high vacuum, as to prevent collisions with gas molecules. The particles are accelerated from their initial speeds using a series of radiofrequency cavities, metallic chambers generating oscillating electromagnetic fields. The beams pass through these cavities as many times as needed until they reach the required energy, their speeds precisely synchronizing with the EM oscillation frequency. This process raises the particles' energies by a factor of 15, from the initial 450 GeV to 6.8 TeV. Finally, before entering the detectors, the beams are collimated further using systems of quadrupoles, ensuring maximum collision rates. What happens then depends on the detector. These conduct different types of experiments, investigating a range of different phenomena. The largest general-purpose detector at the LHC is *A Toroidal LHC Apparatus*, better known as *ATLAS* [32][33]. Schematic illustrations of both the LHC and ATLAS are shown on Figure 5.

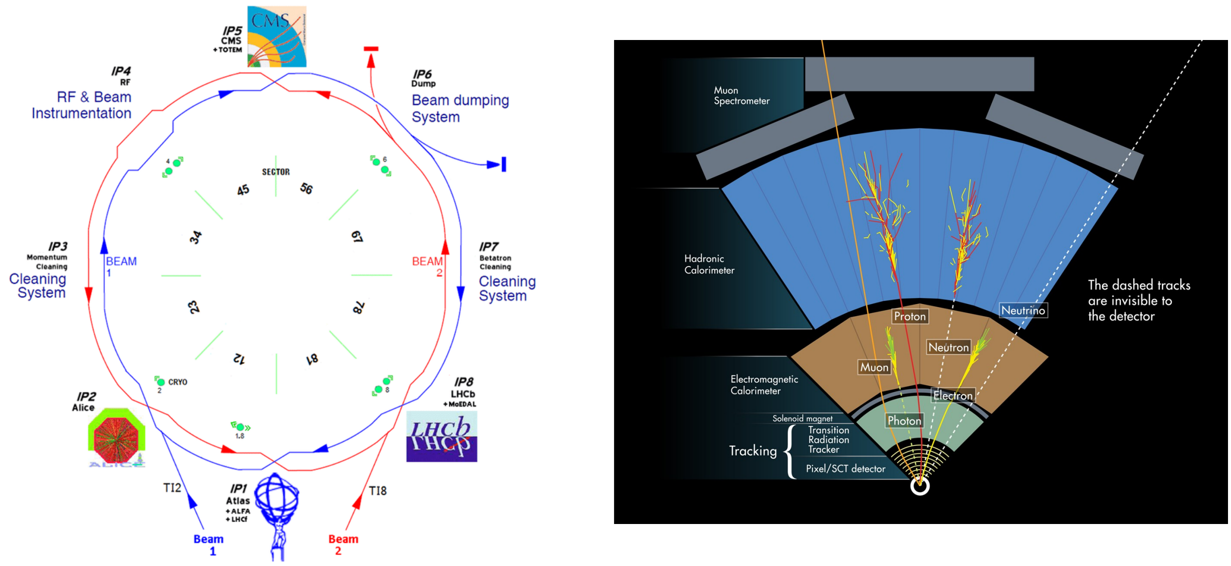


Figure 5. Layouts of the LHC and the ATLAS detector. From [34] and [35], respectively.

To provide a complete observation of a given process, particle detectors must be able to measure a variety of quantities. In short, to recognize the process which took place, we need to measure their locations, which we call vertices, and from there track the products' trajectories, measuring their speeds, momenta and other properties, relevant to particle identification. The specifics of the geometry and types of smaller working parts depend on the purpose of the detector itself. Let us now focus on the ATLAS detector. The particle beams collide in the center of the detector, the products of their collisions flying in all directions. Hence, the detector itself is cylindrical in shape, with the particles colliding in its center. The purpose of measuring the many different properties of the final products requires the detector to consist of several different subsystems, constructed around the beam axis in layers. These are as follows [32][33]:

1. In the immediate vicinity of the collision point is the *Pixel vertex detector*. It consists of millions of small silicon pixels. During the traversal of this detector type, charged particles deposit energy inside the silicon (being a semi-conductor) by creating electron-hole pairs. This allows us to identify the vertices and immediate product trajectories with good precision.

2. Surrounding the vertex detector is the *Semiconductor tracker*. Particles pass through layers of detector strips, also made of silicon, thus depositing energy via the same mechanism as mentioned. Its purpose is to further track charged particle tracks.

3. The next layer is the *Transition radiation detector*. It takes advantage of transition radiation; as charged particles pass through an optically non-homogenous medium, they emit electromagnetic radiation in the X-ray region, the intensity of which depends on the particle's charge and Lorentz γ factor. Inside are straws containing gas, which are surrounded by a material of variable refractive index. The transition radiation emitted after a charged particle passes through the detector ionises the gas inside the straws, providing a measurement of location and information about the type of the particle.

These three elements together are called the *Inner detector* and are surrounded by a large solenoid magnet, providing a powerful magnetic field parallel to the beam axis. This magnetic field is key to particle identification, as the curve of their trajectories provide information about the particles' momenta and their charges. The detector consists of a further three subsystems, being two calorimeters and a muon spectrometer:

4. The *Liquid Argon Calorimeter* is an electromagnetic calorimeter, designed for measuring mainly the energy of photons and electrons. It has a layered structure, alternating between metal and liquid argon. At high energies, photons react with the heavy atoms in the metallic layers via electron - positron pair production. These pass through to the layers of argon, where ionization ensues, and the severed electrons produce new photons via *Bremsstrahlung* (braking radiation). This process repeats layer-by-layer, resulting in an electromagnetic shower. In the process, currents from the argon layer are measured, enabling us to reconstruct the electromagnetic shower and finding out the energy of the intial photon or electron.

5. Although some (charged) hadrons do get caught in the EM calorimeter, a separate device must be used for their energy measurements. The working of the *Tile Hadronic Calorimeter* is similar in concept, albeit with alternating layers of steel and those of plastic scintillators. Strongly interacting particles (hadrons) pass through the steel layers, in the process producing showers of new particles. These in turn, when passing through the scintillators, produce measurable photons. This process continues until their energy is dissipated. From these deposited energies we then reconstruct the energy of the original particle.

6. The final layer is the *Muon Spectrometer*. Measuring muons must be done separately, as unlike in the case of electrons, their *Bremsstrahlung* is negligible and therefore do not produce electromagnetic showers as well. They also do not interact strongly in the hadronic calorimeter. This does in effect make identifying them easier; if a particle has passed through all previous layers, it is probably a muon. What remains is measuring their momenta, which is achieved using a similar tracking scheme as in the inner detector and then analyzing their trajectories in a magnetic field.

All of these detection systems work in tandem to continuously produce an abundance of data. The measurements of all of the particles, which can be tracked back to a single vertex, give us the necessary information for reconstructing the process. To unravel this information, complex methods of data analysis are needed. For this reason, powerful computational tools such as deep learning algorithms are employed, classifying and filtering out events for further analysis in split seconds. These are also used for simulating events given theoretical models or calculating background signal estimations for comparison with experiment.

In searching for new physics, certain assumptions must be made. If we have an inkling of what we're searching for is supposed to look like, we can gaze into the experimental data and search for signatures of our object of interest. Luckily, we have some general constraints to consider when searching for dark matter. It is certain that any produced WIMPs will escape detection. In practice, a WIMP-producing event could be recognized as appearing to violate energy conservation. For this purpose, we define a quantity named *missing transverse energy* [36], defined as $\not{E}_T = -|\sum_i \vec{p}_{Ti}|$ where $\vec{p}_{Ti}$ denotes the transverse momentum of the i-th product in a process. We limit ourselves to transverse momenta (perpendicular to beam) because, despite the beams' energies being equal, the longitudinal component need not exactly equal zero. This comes as a consequence of the quarks constituting the protons in the beams sharing the momentum, which can lead to imbalances when these protons break up. In contrast, the initial transverse momenta will always equal to zero, which allows us to check for the conservation of this quantity. Registering a missing energy signature hence may imply the existence of some particle not accounted for, in our case, a possible dark matter particle. Most theoretical models, such as the R-parity conserving case in the MSSM and other SUSY models, predict DM production together with a significant amount of SM particles. Furthermore, we have reached such a good understanding of how the SM particles interact, that we could in theory reliably predict even very small missing energy signatures, should these arise (as we do with eg. SM neutrinos). These facts provide a solid basis for DM searches via $\not{E}_T$. Processes which would be characterised by noticeable $\not{E}_T$ vary. One such example are *Mono-X* processes , into which we will take a closer look.

4.2 Mono-X searches

Mono-X processes describe processes in which a single DM particle or particle-antiparticle pair is produced in association with a single SM particle, its non-zero p_T providing a missing-energy signature for the DM particle [37]. These searches are especially convenient, as they leave a smaller margin of error for $\not{E}_T$ detection. Also worth mentioning is the fact that when analysing data in cases of different SM products X, different background signals must be considered, making some more or less viable for detection. In order to model and test these processes, effective field theories are frequently developed, as they are easily malleable to account for specific phenomena [18].

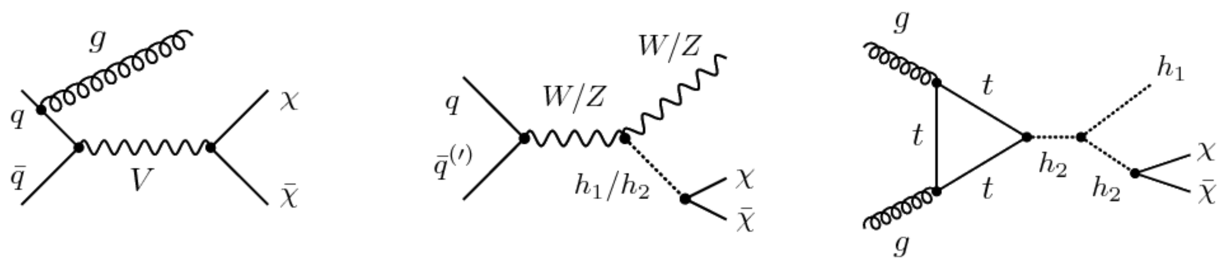


Figure 6. Examples of Feynman diagrams for mono-jet/V/Higgs producing processes. DM particles denoted by χ. Modified from [41].

A subcategory of Mono-X searches are *Mono-V* searches, where V denotes a SM vector boson (γ, Z, W) [38][39]. Such searches are considered particularly when testing theories which predict direct DM - gauge boson coupling. The simplest is the case of $V = \gamma$, as a photon with high p_T should be relatively easy to identify. Moreover, background levels for mono-photon events are predicted to be relatively low, although fake events are prone to be registered due to various detector anomalies. When $V = Z, W$ are considered, we typically look for lepton signatures. Z bosons' decay chains usually result in di-lepton (l^+l^-) products, the detection of which generate clean signals, partly due to the their large rest masses ($\sim 80\,\text{GeV}$). W bosons, on the other hand, are characterised by

lepton-neutrino decays. Since neutrinos are also weakly interacting and evade detection, they add to the missing transverse momentum measurement. This makes such a detection scheme a bit more difficult, as the measurements would appear quite similar to those of just an ordinary W decay.
Another often considered option are *Mono-jet* processes [40]. We use the word "jet" to mean a narrow cone of hadrons. This case arises when one of the initial particles (in this case a quark) emits a gluon prior to interacting. As colored gluons do not exist in the form of free particles, they form other colored objects around them, thus resulting in a plethora of colorless hadronic states. This can lead to the creation of one or a number of jets. Mono-jet processes are usually harder to model and hence identify, this issue arising also when estimating the respective background signals. These factors put a relatively higher lower limit on the $\not{E}_T$ signatures for accurate measurements.
Another interesting case is that of *Mono-Higgs* events [42]. A common signature of the Higgs boson are di-photon ($\gamma\gamma$) products, in which case measurement with small background signals can be made (It is also via this process that the Higgs boson was first discovered). Mono-Higgs searches by searching for $b\bar{b}$ final products have also been proposed, though these are expected to be burdened by larger background signals.

A variety of other experimental strategies are used for DM detection, for example via multi-jet resonances, top quark - W boson pairs, single top quark production and many more, each being supported by various theoretical models. New searches are being proposed and conducted regularly, though we must admit that concrete signs of DM production are as of now yet to be observed (as in the examples shown on Figure 7).

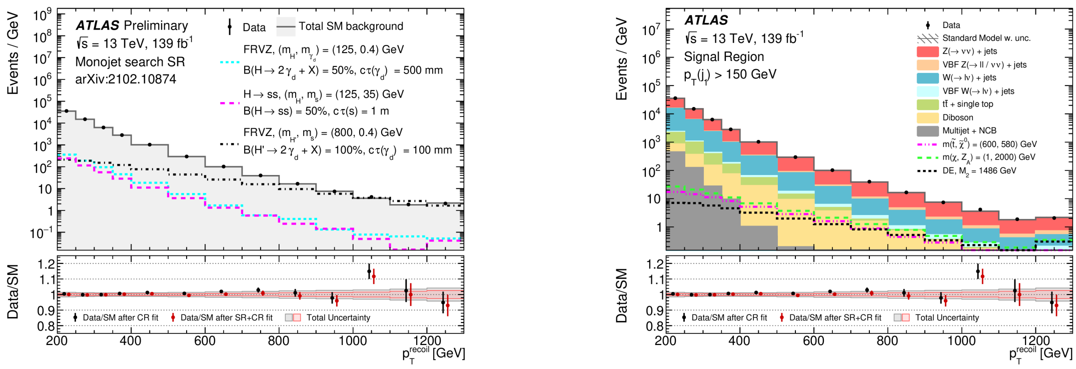


Figure 7. Examples of measurements vs. theoretical predictions via different channels of DM production (dotted) with respect to $\not{p}_T$ [43] [44]. Data points consistent with SM background indicate no DM production.

5. Conclusion

It seems the long history of research into dark matter is not ready to come to a close just yet. In this article, we have attempted to present the basic principles behind the searches for dark matter, with examples peppered throughout. But one would be wrong to understate the scale of this field of research. Even now, new theoretical and experimental advances are being made with each passing year. Thus, we leave off with a thought of vigilance and optimism in our pursuit of future discoveries.

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