Development of High Energy Physics and Prospects for Dark Matter Searches at the HL-LHC

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ABSTRACT

This document outlines the fundamental theory of the Standard Model and the aims and anticipated upgrades of current experimental techniques in high-energy physics. Motivations and requirements for the search for new physics, specifically on searching for dark matter, at the HL-LHC are analyzed and presented. Methodology, constraints, and predicted sensitivity of yields for searching dark matter, based on analyses of simplified models with j+MET, DM+$t\bar{t}$, DM+Wt, DM+$b\bar{b}$ in their final states, are presented.

Keywords: HL-LHC, ATLAS, Dark Matter, Standard Model Limitations, LHC upgrades, BSM, LHC Run-2

1. INTRODUCTION

Standard Model, Limitations, and Beyond Standard Model

In the 20th century, physicists made a remarkable discovery about the basic building blocks of matter. They identified these as "elementary particles" governed by nature's four fundamental forces. These particles are categorized into three generations of spin ½ fermions, consisting of two types: quarks and leptons. Each generation has six particles related in pairs, as shown in Figure 1, along with their corresponding properties. The first generation comprises the lightest and most stable particles, while the heavier and less stable ones belong to the second and third. Quarks come in different "colors," but they combine to form colorless combinations called hadrons because quantum chromodynamics confinement only allows for colorless states. The four fundamental forces, including strong, weak, electromagnetic, and gravity, are believed to result from the exchange of force-carrier particles called bosons. The Standard Model (SM) explains how these forces act on all matter particles.

Despite the SM's extensive testing, it still needs to answer many crucial questions about the universe. One of the main problems is the large discrepancy between aspects of weak force and gravity. Furthermore, there is matter-antimatter asymmetry, and we have yet to unravel the mystery of dark energy and matter. To achieve a more fundamental understanding of the universe, we require additional experimental clues and the development of a "Beyond the Standard Model" (BSM).

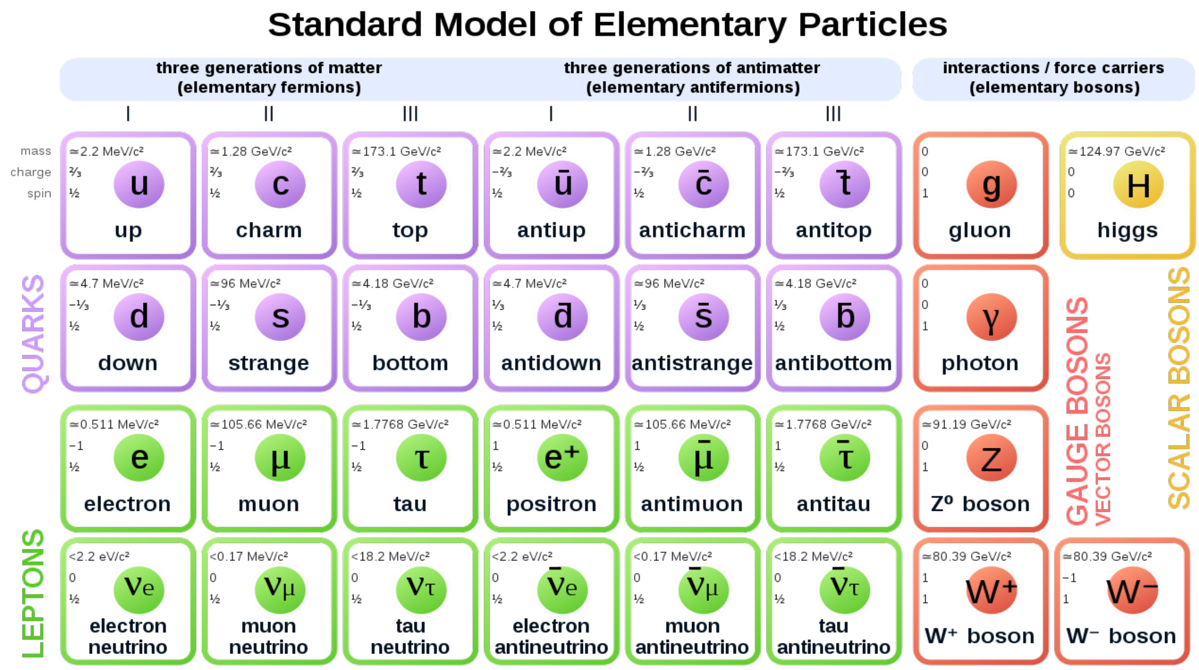


Figure 1: Standard Model of Elementary Particles

1.1 Higgs Mechanism and Electroweak Unification

While experiments show that most fundamental particles have non-zero masses, the SM was naturally written with massless particles. In 1964, the Higgs Mechanism was proposed as a theoretical solution postulating the existence of a "Higgs field" that permeates all space. The existence of a new particle Higgs Boson, discovered in 2012 and confirmed in 2013, completed the conundrum regarding the origin of the mass of fundamental particles.[1]

The Higgs Boson affirmed many proposed theories. Following the unification of electricity and magnetism – electromagnetism (EM), the electroweak theory was developed, unifying EM with the weak force. Though the weak force appeared to be much weaker than EM due to the massive sizes, in contrast to the massless photon of the W and Z bosons, the unification of EM and the weak force implies that the forces behave the same at high energies. According to the SM, W and Z bosons acquire large masses via Electroweak Symmetry Breaking (EWSB), a process mediated by the Higgs Mechanism and the Higgs boson. Besides the W and Z bosons, other particles acquire masses via interactions with the Higgs field.

2. EXPERIMENTAL HIGH-ENERGY PHYSICS

2.1 Particle Accelerator – LHC

The largest and most powerful particle accelerator is the Large Hadron Collider (LHC), which enables physicists to examine the accuracy of the SM and explore BSM physics. This circular tunnel, measuring 27km in circumference and located 175m underground, contains superconducting magnets and accelerating structures that propel particles to nearly the speed of light for collision. The collider has four crossing points where accelerated particles collide, corresponding to the locations of the four primary particle detectors: ATLAS, CMS, ALICE, and LHCb, as shown in Figure 2. Many novel discoveries, including the Higgs boson, have emerged from experiments conducted at the LHC.

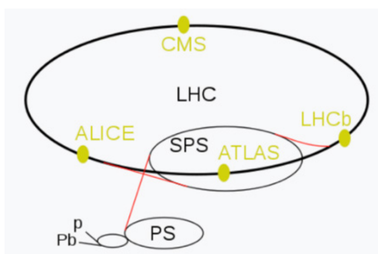


Figure 2: Layout of the LHC Complex. ATLAS, CMS, ALICE, and LHCb are the most significant experiments at the LHC out of all nine, sitting underground in huge caverns on the LHC ring. SPS, PS, p and Pb are the preaccelerators.

2.2 HEP Detectors Technicalities

The study of jets, cones of hadrons, and other particles produced by the hadronization of a quark or gluon show the properties of partons in the collided protons. It provides evidence of new physics that manifests in hadronic final states. Particles traveling through the detector material leave behind characteristic patterns, or "signatures," in different layers, allowing them to be identified through measurements of their energy and momentum. Through delicate detection and measurements of the energy-momentum 4-vectors of the particles and applying physics laws using equations of Special Relativity (SR), physicists can investigate particle collisions and, thus, the nature of the universe.

Electrically charged particles traversing matter lose energy via ionization, electromagnetically knocking loose atomic electrons of matter. Tracking detectors measure the ionization signals along the track of the incident charged particle. The track will then be "reconstructed" using computer algorithms to fit the dots into a line, as seen in Figure 3, which leads to further measurable data. For instance, with the radius of the curvature of the reconstructed track (R), the momentum of the particle (p) can be determined as if the region is immersed in a magnetic field of known strength (B). Particle identification can then be performed by combining measurements of the charged particle's momentum and the rate at which a charged particle traversing matter loses energy (dE/dx). A common detection technique is to infuse gas-filed volume at a high voltage; charged particles passing through will ionize the gas, and free electrons drifting under the influence of the electric field will be collected on nearby wires, leaving detectable signals. Silicon detectors are popular as they provide fine segmentation; charged particles passing through silicon can be detected similarly.

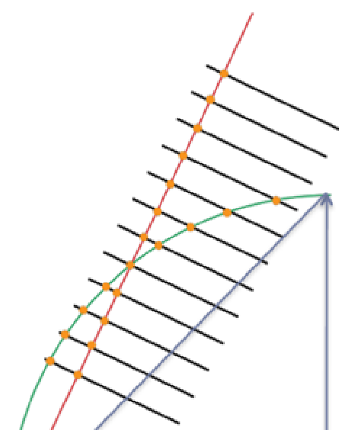


Figure 3: Description of the track reconstruction methodology. The black parallel line represents the layers of detector material. Orange dots represent the ionization signals. The green line represents the reconstructed track of the incident-charged particle.

Electrons and photons undergo radiation rather than ionization. As they travel through matter, they emit an electromagnetic (EM) shower of particles through repeated processes of $e \to e\gamma$ and $\gamma \to e^+e^-$. Heavier particles like hadrons (such as protons) do not radiate energy as readily as electrons and photons. However, they experience a strong force, which allows them to break apart atomic nuclei and produce secondary hadrons, resulting in a hadronic shower. Sampling Calorimeter is a detector that measures the energy of incoming particles by absorbing and measuring the energy deposited through their showers. Calorimeters consist of passive absorbers and active media that convert energy into measurable forms like light or electric charge. EM Calorimeters have a depth of around 20-30 times the length of energy loss of a particle ($X_0$to fully contain EM showers of incoming electrons and photons. Hadronic Calorimeters require more material to contain the more complex hadronic showers fully. Particles like muons and neutrinos that do not experience EM or strong force are measured differently. Muons fly through the detector and are identified and measured for their momentum using a magnetic field. At the same time, neutrinos are inferred from an event's total energy and momentum, where significant missing transverse energy (E_T^{miss}) suggests the presence of neutrinos or other new particles.

B-quarks are exceptional in terms of their lifetime and momentum. To identify jets originating from b-quarks, physicists use "b-tagging." B-hadrons typically have a lifetime of ~1 picosecond (ps), resulting in a short travel distance even close to the speed of light. However, special relativity predicts that time dilation increases the time measured for their lifetime and thus the distance they travel. Therefore, a typical b-hadron travels millimetres (mm) before decaying. Although they decay inside the LHC beampipe before reaching the detector, b-tagging is possible by extrapolating charged tracks with sufficient precision to look for evidence that the b-hadron travelled a few mm before decaying. B-tagging has been crucial to many discoveries, including investigations of the Higgs boson. The kinematics of particle pairs produced by the parent of decay, such as the Higgs boson decaying to a pair of b-quarks, can reveal various properties of the parent and is helpful in the search for more new particles.

2.3 ATLAS and CMS

The ATLAS and CMS detectors are crucial components of particle physics research located at opposite ends of the LHC. Despite their differences in design and magnet technology, the two detectors work together to broaden the scope of experiments and confirm findings. Their primary objectives include investigating physics at the TeV scale, making precise measurements of the Standard Model, and searching for Beyond the Standard Model (BSM) physics. The structure of the CMS detector resembles a cylindrical coil made of superconducting cable, which produces a magnetic field with a strength of 4 teslas (T). [2] Figure 4 illustrates the structure of the CMS detector. On the other hand, the ATLAS detector exhibits symmetry in the forward-backwards direction relative to the point of interaction. Its magnetic arrangement comprises a remote superconducting solenoid encircling the inner detector cavity and three sizable superconducting toroids. These toroids, consisting of one barrel and two end-caps, are positioned around the calorimeters in an eight-fold azimuthal symmetry. [3] Figure 5 provides a visualization of the structure of the ATLAS detector.

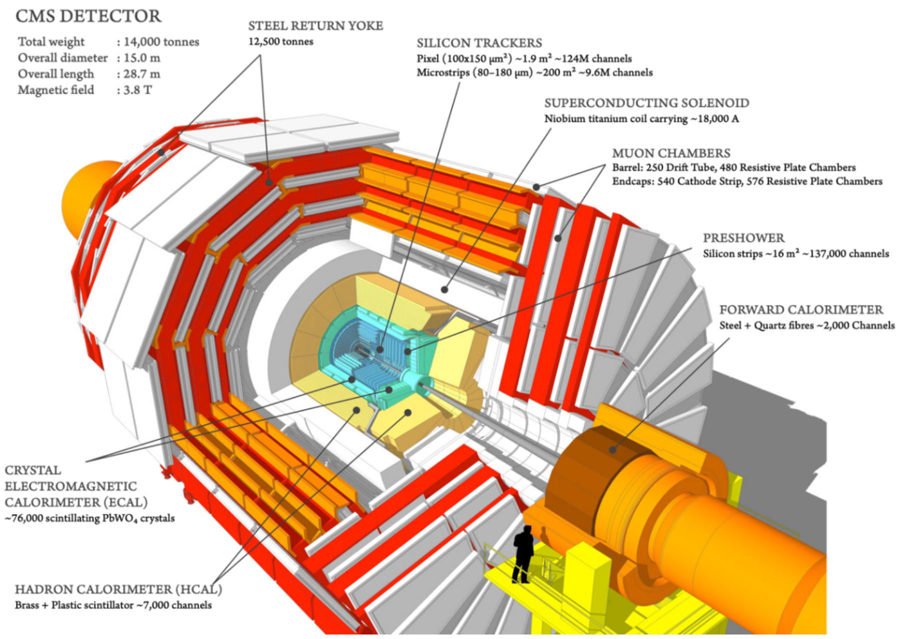
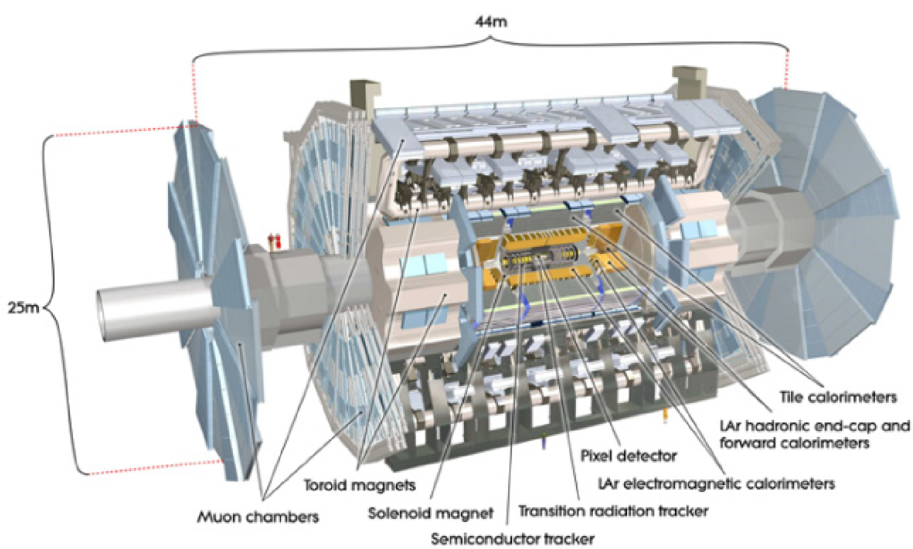
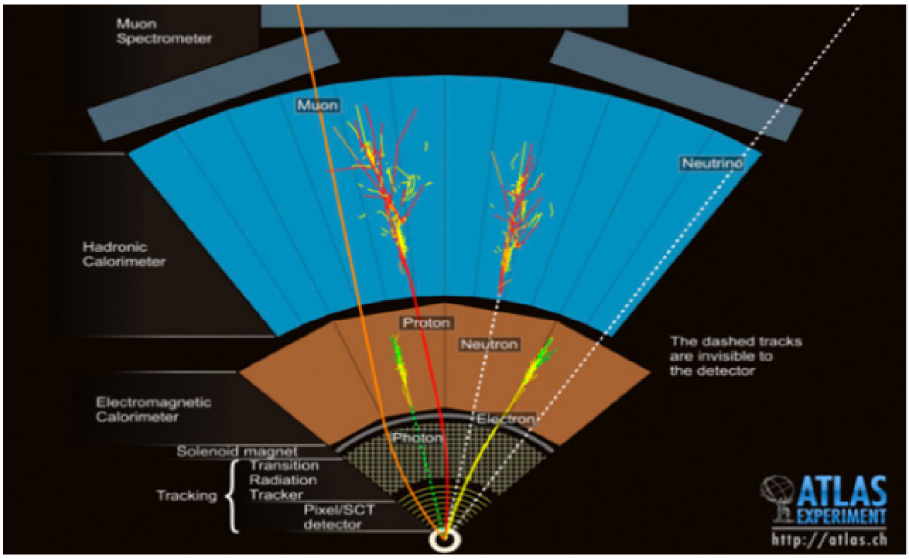


Figure 4: Structure of the CMS detector. The dimensions of the detector are 15m in height and 21m in length. The overall weight of the detector is approximately 14000 tonnes.



(a)



(b)

Figure 5: Structure of the ATLAS detector. The 25m high and 44m long detector weighs approximately 7000 tonnes. (a) presents a cutaway view of the detector. (b) shows the detector level from inside to outside around the collision point.

The ATLAS and CMS experiments have contributed to many crucial discoveries. In 2012, they announced the discovery of a particle of 125 GeV in mass with properties that closely resembled the behaviour predicted in the SM for the Higgs boson, which was confirmed indeed to be the Higgs boson in the subsequent year. The LHC experiments will continue searching for signs of new physics that could point to a more fundamental theory.

3. TECHNICAL UPGRADES

The LHC ran its first collisions in 2010 at a total collision energy of 7TeV and, in 2015, reached 13TeV after improvements until it was shut down in 2018 for further upgrades. To exploit the LHC's full potential, the accelerator complex and detectors must be upgraded to implement the High Luminosity LHC (HL-LHC) for a reliable and efficient machine that delivers an increased integrated luminosity. With the installation scheduled to begin in 2026, the HL-LHC can increase the collision rate by up to a factor of 10 and the number of collisions from 30 to 140 and produce datasets 20 times larger than ever recorded. Increasing the rate and intensity of collisions can lead to new physics via higher chances of direct searches for rarer processes, such as the production of new particles, and indirect searches through improved precision measurements, where deviations from SM predictions can point the direction to the correct BSM theory. The HL-LHC has specific objectives, including exploring the Higgs boson and its connection to EWSB and measuring the top quark's properties - the fermion with the most enormous known mass and most significant Yukawa coupling, and the search for BSM physics, particularly for solutions to dark matter. [4]

The ATLAS detector must undergo upgrades to manage the increased luminosity, data volume, pile-up of simultaneous proton-proton collisions, and radiation in the HL-LHC environment. Table 1 summarises the modifications made to the ATLAS detector throughout the development of the LHC. Figure 6 illustrates the proposed upgrades to specific detector subsystems in response to the HL-LHC.

Table 1: Main ATLAS changes corresponding to different phases of the LHC

Upgrade	Shutdown	LHC Luminosity	Main ATLAS Changes
Phase-0 (Run-2)	2013-15	2 x design*	- New inner tracking layer (IBL) - Forward muon system detectors + readout - Trigger: topology at L1, streamlined dataflow
Phase-I (Run-3)	2019-21	3 x design*	- Trigger: more info at L1, tracks at the start of HLT (FTK) - Calorimeter electronics for trigger - New forward muon detectors for trigger (NSW) - The more performant readout system

HL-LHC (Phase-II) (Run-4, …)	2024-26	5-7.5 x design*	- New all-silicon tracking system - Some new muon chambers - All new readout electronics: calorimeters, muons - New trigger architecture + new systems - Higher bandwidth readout system - New detectors in the forward region (HGTD, μ-tagger)
*Original luminosity target: 1 x $10^{34} cm^{-2} s^{-1}$			

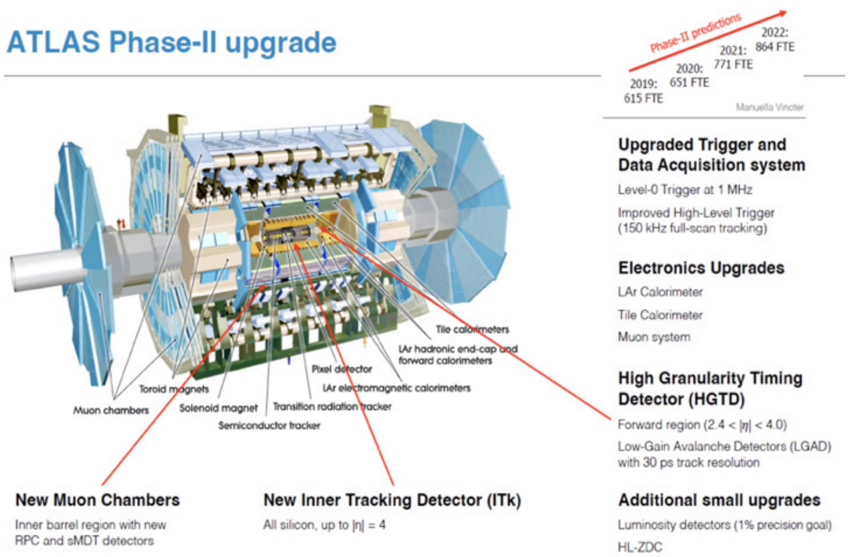


Figure 6: Expected changes to specific subsystems in the ATLAS Phase-II upgrade

The collision point within |η| < 2.5 generates about 1000 particles every 25 nanoseconds, leading to a high track density within the detector. Precise measurements with fine granularity are required to study critical physics processes, and the ATLAS Inner Detector (ID) meets these requirements with its pixel and silicon microstrip semiconductor (SCT) trackers and Transition Radiation Tracker (TRT). The ID is situated in a 2T magnetic field generated by the central solenoid, and its configuration is depicted in Figure 7. It plays a crucial role in identifying particles, tagging the flavour of jets, and reconstructing hadronic decays. [5] However, the current ID cannot handle the robust radiation and occupancy conditions in HL-LHC experiments, necessitating an upgrade.

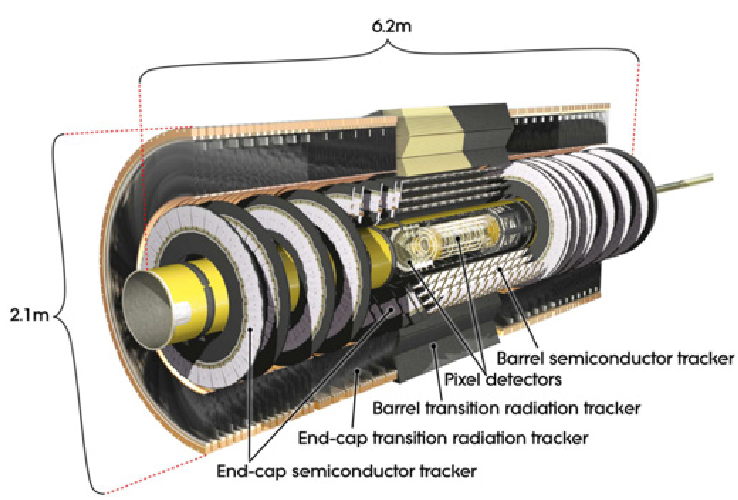


Figure 7: Cut-away view of the ATLAS inner detector. The inner detector is 2.1m in height and 6.2m in length.

The forthcoming version of the ID will consist entirely of silicon and will incorporate several technological advancements based on the current version. The outer cylinder of strips will be located at the maximum radius possible, determined by the poly-moderator, outer support cylinder, detector services, and insertion clearance, to maximize particle trajectory length and minimize resolution variation. The innermost layer will be positioned as close to the beam pipe. By minimizing tracker material, multiple scattering and photon conversion are reduced, leading to improvements in detector occupancy, tracking precision, jet rejection, and granularity. To create a thinner detector, the upgraded ID will utilize smaller pixel sizes and shorter strips in the innermost layers. Simulations indicate that the proposed baseline layout for the Phase-II ID functions effectively even under high pile-up conditions. The fraction of reconstructed vertices remains nearly constant regardless of the number of pile-up events. Compared to the current ID at 0 pile-ups, the upgraded ID's performance in areas such as light jet rejection, transverse momentum, and impact parameter resolution is comparable at high pile-up conditions. Table 2 summarizes some of the critical performance characteristics of this layout compared to the current ID.

Table 2: Performance of the existing ID with IBL and the Phase-II tracker for transverse momentum and impact parameter resolution. σ_x (∞) refers to σ_x for $p_T \to \infty$, to remove the contribution due to material.

Track parameter $\|\eta\| < 0.5$	Existing ID with IBL no pile-up σ_x (∞)	Phase-II tracker 200 events pile-up σ_x (∞)
Inverse transverse momentum (q/p_T) [TeV]	0.3	0.2
Transverse impact parameter (d_0) [μm]	8	8
Longitudinal impact parameter (z_0) [μm]	65	50

4.SEARCHES FOR DARK MATTER

Unlike ordinary matter, Dark Matter (DM) does not interact with the EM field, making it difficult to detect. Figure 8 presents the distribution of matter in the universe. The resultant picture of the universe's content shows that Dark Energy and DM dominate it. DM is not made of the particles of the SM. In the early universe, DM played a central role in forming structures which served as seeds for the clusters of galaxies. The observed structure in the universe provides properties of DM, leading to various approaches to search for them. Experiments at the HL-LHC aim to continue to search for more clues about dark matter.

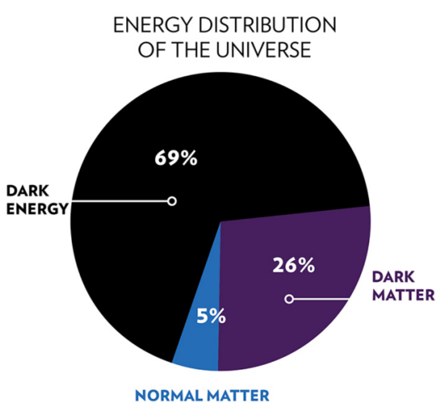


Figure 8: Energy distribution of the three components that make up the structure of the universe. All the ordinary matter we observe only accounts for less than 5% of the universe.

4.1 Proposals and Approaches of Dark Matter Searches

Dark matter is a mysterious substance that scientists believe exists based on the gravitational effect it has on visible matter. According to the theory of general relativity, massive objects cause spacetime to be curved, which results in the bending of light nearby. By observing this lensing effect, physicists can infer the amount and distribution of mass that is responsible for it. For example, scientists have mapped the mass distribution of the Bullet Cluster, two clusters of galaxies located approximately 3.7 billion light years away from Earth, by analyzing the lensing of background galaxies seen in optical images. By examining the X-rays emitted, scientists have identified two different mass distributions, one diffusing more and spreading farther apart. This distribution, now characterized as dark matter, "passes through" collisions without interacting, while ordinary SM matter would diffuse less due to interactions during the collision. Theoretical models of large-scale structure formation suggest that most dark matter is cold dark matter (CDM) because simulations produce galaxy distributions that match what is observed.[6]

Scientists employ various methods to search for dark matter, including direct and indirect detection techniques. One of the most popular approaches is to describe dark matter as a Weakly Interacting Massive Particle (WIMP) and analyze particle production resulting from collisions between proton beams. Presently, high-energy physics

(HEP) experiments strive to detect the production of Cold Dark Matter (CDM) particles, primordial WIMPs generated during the Big Bang that interact with detectors, and particles emitted due to CDM annihilation in the universe. Since a dark matter particle hardly interacts with ordinary matter, it can only be detected indirectly by the significant amounts of E_T^{miss} and $\vec{p}_T^{miss}$ that evade detection by the collision detectors. The High-Luminosity Large Hadron Collider (HL-LHC), a more powerful version of the Large Hadron Collider (LHC), is expected to commence operations in 2025, collecting up to 3000 fb^(-1) of data at √s = 14TeV. Due to its higher luminosity and centre-of-mass energy compared to the previous search conducted at √s = 13 TeV in 2015, researchers anticipate the HL-LHC to deliver greater reach and detector sensitivity for detecting dark matter. [7]

4.2 Estimated Sensitivity for HL-LHC Dark Matter (characterized as WIMPS) Search

WIMPs are elementary particles hypothesized to interact with gravity and forces outside the Standard Model (SM) with equal or weaker strength than the weak force. They are believed to have formed in the early Universe through thermal creation, similar to SM particles. [8] WIMPs were created and annihilated at high temperatures into lighter particles, behaving as relic dark matter particles. However, as the Universe cooled and expanded, the average thermal energy decreased, and creating dark matter particle-antiparticle pairs became impossible. Despite this, annihilation continued, leading to an exponential decrease in the number density of DM particles. [9] This implies that particles with larger interaction cross sections would have a lower number density, as they would continue to annihilate for longer. According to this model, if the DM particle is a remnant particle, the interaction cross-section governing the particle-antiparticle annihilation cannot be more than the cross-section for the weak interaction. This is because of the presently estimated abundance of DM in the Universe. This is why WIMPs are believed to have characteristics similar to those of weakly interacting massive particles. Physicists can detect WIMPs by looking for the byproducts of their annihilation or by creating them in particle accelerators.

Discovering the nature of DM is an important problem in physics. The characterization of DM in the form of WIMPSs will be one of the top priorities of the HL-LHC. The LHC has been performing collider searches for dark matter and its mediators. One of the most common searches is the monojet search with j+MET in the final state. There are two simplified models of them, whose Feynman diagrams are shown in Figure 9:

- s-channel DM pair production with an axial vector mediator with the couplings of the mediator to DM (g_{DM}) = 1.0 and to the SM (g_{SM}) = 0.25
- s-channel production with a pseudoscalar mediator with the couplings of the mediator to DM (g_{DM}) = 1.0 and to the SM (g_{SM}) = 1.0

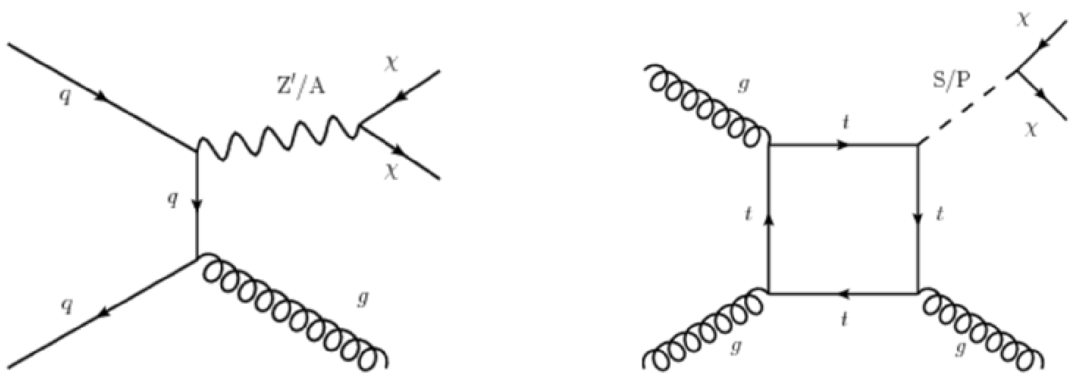


Figure 9: Feynman diagrams of DM pair production for an axial vector and pseudoscalar mediated interaction.

The study aims to analyze the accelerator constraints on DM searches by simulating the projections of two coupling scenarios using detector performance specifications from the CMS Phase-2 technical proposal. The event selection criteria, consisting of jets and E_T^{miss}, are presented in Table 3, and the analysis is based on LHC Run-2 monojet events. Further details about the simulation can be found in Ref. [10]. The reach of mediator mass is highly dependent on the precise knowledge of systematic uncertainties. The study shows that without any improvement, the mediator mass can reach up to 2.5 TeV, but if the systematics improve by ¼, then the sensitivity will increase by 20% to 3 TeV. [10] So far, results of searches for DM at the LHC have demonstrated that colliders can place significant constraints on spin-dependent interactions and velocity-suppressed scattering cross-sections. However, with the HL-LHC's upgraded detectors, there will be a remarkable gain in new physics reach, which could lead to further breakthroughs in the search for DM.

Table 3: Summary of the event selection criteria used to select monojet events for the analysis.

Event selection	
AK4 jets	$p_T(j_1) > 250$ for AV (200 for PS), $\|\eta\| < 2.5$
$\Delta\phi$ (jet, E_T^{miss})	$\Delta\phi > 0.5$
veto electrons	$p_T > 10$, $\|\eta\| < 2.4$
veto muons	$p_T > 10$, $\|\eta\| < 2.5$
veto taus	$p_T > 18$, $\|\eta\| < 2.3$
b-jet veto	'Loose', $p_T > 15$, $\|\eta\| < 2.5$
E_T^{miss}	$E_T^{miss} > 200$ GeV

4.3 Dark Matter Produced in Association with Heavy Quarks at the HL-LHC

One strategy to identify DM particles involves generating them in a controlled laboratory setting, and the LHC is investigating ways to create these particles via proton beam collisions. This segment explores the possibility of detecting DM particles created together with heavy quarks at the HL-LHC, utilizing two simplified models in which the DM candidate is a weakly interacting Dirac fermion. Heavy flavour quarks are sensitive to the location where the DM and SM sectors interact through the exchange of a spin-0 mediator. The research is categorized based on whether the mediator is a scalar or pseudoscalar: DM production in combination with a pair of bottom quarks and DM production in association with one or two top quarks. The research focuses on three signatures; each displayed as a tree-level diagram illustrated in Figure 10. These signatures provide valuable insights into the likelihood of producing DM particles and represent a promising avenue for further research at the LHC.

DM+$t\bar{t}$ two tops decaying di-leptonically

DM+Wt one top produced in tandem with a W-boson, both decay leptonically

DM+$b\bar{b}$ two bottoms decaying di-leptonically

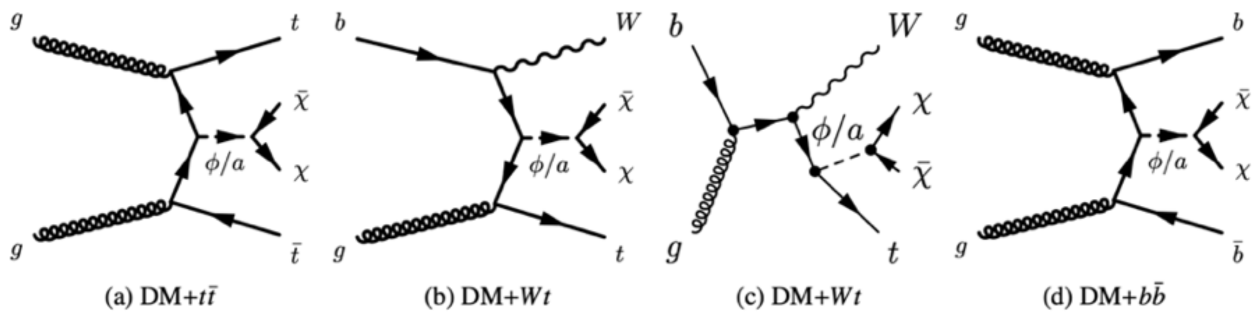


Figure 10: Representative tree-level diagrams for the production of dark matter (χ) in association with (a-c) top quarks and (d) bottom quarks following the exchange of either a colour-neutral scalar (φ) or pseudoscalar (α) particle.

This study focuses on the sensitivity analysis of the upgraded ATLAS detector with 200 interactions per bunch crossing to detect dark matter (DM) particles produced during proton collisions. The analysis utilizes parameterizations derived from performance studies, and background samples are simulated from the upcoming particle accelerator and detector upgrades. The DM signal samples follow LHC Run-2 models with a collision energy of 14TeV, replicated by event weight application. The analysis selects events with either the bottom or top quarks by reconstructing jets, muons, electrons, and missing transverse momentum $\vec{p}_T^{miss}$. Exclusion limits at a 95% Confidence Level (CL) are derived for mediator masses ranging from 10 to 500 GeV, with systematic uncertainties commensurate with recent projections assumed. The exclusion potential at the HL-LHC improves by about 3 to 8.7 for scalar and pseudoscalar masses created with bottom quarks, with a DM mass of 1 GeV and assuming unitary couplings. The colour-neutral scalar mediator's expected exclusion mass range runs from 80 GeV to 405 GeV for final states with one or two leptonically decaying top quarks. For pseudoscalar masses, the exclusion range goes up to 385 GeV. Ref [11] includes the methodology for event selection.

5.CONCLUSION

The High-Luminosity LHC upgrade can potentially enhance the search for rare particles and phenomena across all significant experiments at CERN. The focus of current efforts in the field of high-energy physics (HEP) is to improve Standard Model (SM) measurements, investigate the properties of the newly discovered Higgs boson, and search for beyond-the-Standard

Model (BSM) physics. The HL-LHC upgrade will significantly expand the reach and sensitivity of HEP experiments, paving the way for discoveries. However, the HEP community is also exploring the possibility of constructing accelerators beyond the HL-LHC to answer more complex questions. One such proposal is the Circular Electron-Positron Collider. It is designed to operate as a 240 GeV Higgs factory to provide precise measurements of the Higgs boson and its interactions with other particles. This collider is planned for construction in China. Advancements in technology and the ongoing exploration of particles and theories will lead to a deeper understanding of the fundamental workings of the universe.

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