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A review of current discoveries of long-lived particles at CERN

Abstract

Research into long-lived particles (LLPs) at CERN has gained significant interest due to its potential to reveal new physics beyond the Standard Model. These particles, proposed to have longer lifetimes than commonly observed particles, could provide vital insights into dark matter, supersymmetry, and other fundamental aspects of the universe. Recent experiments at the Large Hadron Collider (LHC) have utilized advanced detection methods and technologies to identify and analyze LLPs. These efforts have led to the discovery of several candidate events displaying delayed decays, displaced vertices, and other characteristics indicative of LLPs. This review covers the methodologies used in these searches, the challenges in differentiating LLP signals from background noise, and the implications of these findings for particle physics.

Key findings from CERN's research on LLPs underscore both the achievements and the ongoing challenges in this area. Notable progress includes the use of specialized detectors like MATHUSLA (MAssive Timing Hodoscope for Ultra Stable neutraL pArticles) and advancements in data analysis techniques that enhance sensitivity to rare events. Despite these technological advancements, detecting LLPs remains a complex task due to their elusive nature and the extensive data required to confirm their existence. The review examines the theoretical models predicting LLPs, recent experimental results, and future research directions. It also highlights the collaborative efforts within the global scientific community to improve detection strategies and validate results, emphasizing CERN's crucial role in advancing our understanding of long-lived particles and their potential to transform our knowledge of the universe.

Keywords: Long-lived particles, CERN, Large Hadron Collider, MATHUSLA, new physics, Standard Model, dark matter, supersymmetry

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Introduction

In recent years, long-lived particles (LLPs) have captured significant attention within the realm of particle physics, particularly through the experimental work conducted at the European Organization for Nuclear Research (CERN). These particles are distinguished by their notably prolonged lifetimes before they undergo decay. This characteristic makes them an intriguing subject for probing physics phenomena that lie beyond the Standard Model (SM).[1] This review seeks to provide an exhaustive survey of the recent discoveries and ongoing research related to LLPs at CERN, emphasizing theoretical justifications, experimental methodologies, key findings, and future directions.

Theoretical background

Standard Model limitations

The Standard Model (SM) has achieved considerable success in explaining the fundamental particles and their interactions. Nevertheless, it exhibits several critical shortcomings, such as the inability to explain dark matter, neutrino masses, the matter-antimatter asymmetry, and gravity.[2] These gaps indicate the potential presence of new physics beyond the Standard Model (BSM), which might encompass LLPs.

Long-Lived Particles: definitions and importance

LLPs are defined as particles with lifetimes significantly longer than those of typical SM particles. Their extended lifetimes can result from various mechanisms, including weak couplings to other particles, minor mass differences between the particle and its decay products, or robust symmetry protections.[3,4] Investigating LLPs is crucial as they could shed light on the nature of dark matter, the processes underlying Baryogenesis, and other BSM phenomena.

Experimental searches for LLPs at CERN

General approach

The primary site for LLP searches at CERN is the Large Hadron Collider (LHC), the world's largest and most powerful particle accelerator. These searches focus on identifying unusual decay patterns of LLPs, which may occur far from the initial interaction point.[5] Key LHC experiments in this domain include ATLAS, CMS, LHCb, and specialized LLP detectors such as MoEDAL and FASER.

ATLAS experiment: detector design and LLP Detection

The ATLAS detector, designed to record a wide spectrum of particle interactions, is particularly well-equipped for LLP searches. Its vast volume and advanced tracking systems are instrumental in detecting displaced vertices and long-lived decays.[6] Among the notable discoveries made by ATLAS are searches for heavy neutral leptons (HNLs) and displaced jets, which hint at new physics processes.[7,8] Although definitive evidence for LLPs remains elusive, ATLAS has established stringent limits on their production and properties.

CMS experiment: detector capabilities

The Compact Muon Solenoid (CMS) detector, known for its high-precision tracking system and extensive calorimetry, complements the ATLAS experiment in the search for LLPs.[9,10] CMS's proficiency in measuring energy deposits and tracking particles with high resolution

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enhances its capability to identify anomalous signatures indicative of LLPs.

CMS has performed numerous searches for LLPs, targeting displaced vertices, delayed photons, and unconventional decay signatures. These searches have imposed stringent limits on various LLP models, such as those predicting heavy neutral leptons and long-lived gluons.[11] Despite the absence of conclusive discoveries, these results have significantly narrowed the parameter space for potential new physics.

LHCb experiment: **unique features and LLP search strategies**

The Large Hadron Collider beauty (LHCb) experiment specializes in studying the properties of b-hadrons.[12] Its forward detector design and exceptional vertex resolution render it particularly sensitive to LLPs decaying within a few centimeters to meters from the interaction point.[13] LHCb has played a pivotal role in LLP searches through its investigation of rare B-meson decays and heavy neutral leptons.[14] One significant contribution is the search for Majorana neutrinos in B-meson decays, providing vital constraints on the existence and properties of these hypothetical particles.

Dedicated LLP Detectors: MoEDAL and FASER

The Monopole and Exotics Detector at the LHC (MoEDAL) is purpose-built to search for highly ionizing particles, including magnetic monopoles and stable massive particles that might be LLPs. It employs passive detection methods and nuclear track detectors.

The Forward Search Experiment (FASER) is a newly established detector designed to search for light, weakly interacting particles produced at the LHC. Positioned along the beamline, FASER is adept at detecting LLPs that can traverse considerable distances before decaying.[15] To date, neither MoEDAL nor FASER has reported definitive discoveries of LLPs. However, their null results have been invaluable in constraining various theoretical models. Their complementary detection strategies enhance the overall sensitivity of the LHC to a broad spectrum of potential LLP signatures.

Theoretical models and motivations

Supersymmetry (SUSY) and R-parity violation

Supersymmetric models often predict the existence of LLPs, particularly when R-parity is violated. This scenario can produce long-lived neutralinos or gluinos that decay into SM particles after traveling measurable distances.

Hidden sectors and dark matter

Theories involving hidden sectors propose the existence of new particles that interact weakly with SM particles.[16] These hidden sector particles, which may include dark matter candidates, frequently exhibit long lifetimes and represent a rich domain for LLP searches.

Heavy Neutral Leptons (HNLs)

HNLs are proposed by extensions of the SM that incorporate right-handed neutrinos. These particles, which can have long lifetimes, are pertinent for explaining neutrino masses and the baryon asymmetry of the universe.[17] LLP searches at the LHC have placed stringent constraints on the properties and production mechanisms of HNLs.

Other Exotic Scenarios

Other exotic theoretical scenarios predicting LLPs include models with extra dimensions, strongly interacting massive particles (SIMPs), and long-lived scalar particles from extended Higgs sectors.[18] These models provide diverse signatures that can be explored through various LHC experiments.

Recent experimental techniques and innovations

Advanced trigger systems

The implementation of advanced trigger systems has been pivotal for LLP searches. These systems are designed to identify unusual event topologies, such as displaced vertices or delayed decays, in real-time, thereby enhancing sensitivity to LLP signals.

Machine learning and data analysis

Machine learning techniques are increasingly employed to analyze vast datasets from the LHC. These techniques aid in identifying subtle LLP signatures that might be overlooked by traditional analysis methods.[19] Algorithms trained on simulated LLP events improve the efficiency and accuracy of searches.

Dedicated LLP triggers

Experiments like ATLAS and CMS have developed dedicated triggers for LLPs, focusing on capturing events with characteristics such as high-ionization tracks, displaced jets, or delayed photons.[20] These triggers are essential for identifying rare LLP events amidst the extensive background of SM processes.

Challenges and limitations

Background noise

A primary challenge in LLP searches is differentiating signal events from background noise. The distinctive signatures of LLPs often overlap with those from SM processes, necessitating sophisticated analysis techniques to identify genuine signals.

Detector sensitivity

Despite the advanced capabilities of current detectors, they still face limitations in sensitivity and coverage. Some LLPs might decay outside the detector volume or exhibit decay signatures that are challenging to detect with existing technologies.

Data volume and processing

The massive volume of data generated by the LHC presents significant challenges for data processing and storage. Efficient data management and analysis methods are crucial for extracting meaningful results from the extensive datasets.

Future prospects and directions: upgraded LHC and future colliders

The High-Luminosity LHC (HL-LHC) and prospective collider projects, such as the Future Circular Collider (FCC), hold promise for enhancing LLP searches.[21] These upgrades will deliver higher collision energies and increased luminosity, thereby improving the likelihood of discovering LLPs.

New detector technologies

Advancements in detector technologies, including improved tracking systems and innovative materials for radiation detection, will boost sensitivity to LLPs. These technologies will enable the detection of more exotic decay signatures and broaden the scope of search capabilities.

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Interdisciplinary approaches

Collaborations with other scientific fields, such as astrophysics and cosmology, can provide complementary insights into the nature of LLPs. For example, cosmic ray observations and dark matter direct detection experiments can constrain the properties of LLPs and inform collider searches.

Theoretical developments

Continued theoretical advancements will refine predictions for LLPs and guide experimental searches. Enhanced theoretical models and simulations will help identify the most promising signatures and optimize search strategies.

Conclusion

The pursuit of long-lived particles at CERN represents a frontier in the search for new physics beyond the Standard Model. Despite the inherent challenges, significant progress has been made in developing innovative experimental techniques and theoretical models. While no definitive discoveries have been made thus far, the constraints placed on various LLP scenarios have been invaluable in shaping our understanding of particle physics. With upcoming upgrades to the LHC and future collider projects, along with advancements in detector technologies and data analysis methods, the prospects for discovering LLPs are more promising than ever. These efforts not only push the boundaries of our knowledge but also bring us closer to unraveling the fundamental mysteries of the universe.

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