At the Frontier of High Energy Physics

Professor Darin Acosta

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Professor Darin Acosta's research at the CMS experiment utilises advanced muon detection, sophisticated trigger systems, and machine learning to deepen our understanding of the Higgs boson and explore the potential existence of dark matter. Based at Rice University in the USA, Professor Acosta's work has long-reaching implications that are fundamental to our understanding of the universe.

Exploring Fundamental Particles and Forces

High-energy physics, also known as particle physics, explores the fundamental particles and forces that constitute the universe. At the forefront of this exploration is the Large Hadron Collider (LHC) at CERN. This is the most powerful particle accelerator in the world, where protons are collided at nearly the speed of light to probe deeper into the laws of nature.

A key component of high-energy physics research involves detecting and analysing the myriad particles produced during these collisions. Many of these particles only last fractions of a nanosecond and require enormous energy even to be produced, so this task requires highly sophisticated detectors and data analysis techniques. Among these detectors, the Compact Muon Solenoid (CMS) is one of the two large general-purpose particle detectors at the LHC that plays a crucial role in searching for new particles and studying the Standard Model of particle physics, which is currently the best description available of the subatomic world.

Muons – elementary particles similar to electrons but with greater mass – serve as an essential probe for detecting rare particle interactions and exploring potential new physics beyond the Standard Model. Professor Darin Acosta of Rice University, a leading figure in this field, specialises in experimental high-energy physics with a focus on the detection and analysis of muon signals. His expertise extends to the development and enhancement of the electronic trigger systems used in particle collider experiments. These systems manage the enormous volumes of data generated during collisions, selecting relevant events for further analysis. This real-time analysis capability is essential for identifying significant physical phenomena amid a vast amount of background noise.

Professor Acosta's research portfolio includes searching for new lepton-quark couplings and rare processes such as the decay of the Higgs boson into dimuons – a process predicted by the Standard Model but with a very low occurrence rate. Through these studies, Professor Acosta and his colleagues aim to test the limits of the Standard Model and potentially uncover new physics that could reshape our understanding of the universe.

Investigating Higgs Boson Decays

The Higgs boson (also known as the Higgs particle) was initially only conceived in 1964 as a theoretical object and a mathematical artefact needed in the Standard Model to make the theory coherent with the world we observe. In particular, the Higgs boson is integral to the mechanism that imparts mass to elementary particles, a fundamental property of matter.

After decades of experiments, its existence was confirmed through the detection of its more common decay modes. However, its decay into muons is exceedingly rare, occurring only about 0.02% of the time, according to theoretical predictions. Detecting and analysing this decay remains very important because it helps verify the consistency of the Higgs mechanism across different fermion families and tests the non-universality of its interaction with lighter particles like muons.

Professor Acosta's involvement in this specific area of research through the CMS experiment at the LHC has focused on improving the sensitivity and accuracy of the detection systems. He has contributed to the development and optimisation of the CMS muon trigger systems, which are crucial for identifying events in which Higgs bosons decay into muons amidst numerous other interactions. These systems use sophisticated algorithms,

including machine learning techniques, to differentiate signal from background noise efficiently.

In practical terms, the detection process hinges on accurately measuring the muons' trajectory and energy, which are influenced by their interaction with the detector's magnetic fields and materials. The CMS detector is equipped with a high-field superconducting solenoid magnet and various subsystems designed to track muons with high precision. The muon systems are specifically designed to identify muons that are able to penetrate through materials that stop most other particles, which is crucial for tracing the paths of muons from the collision point to the detector's outer layers, confirming their origin from decay processes like that of the Higgs boson.

By embedding neural networks within field programmable gate arrays used in the CMS trigger system, Professor Acosta's team has enhanced the system's ability to process and analyse collision data in real time. This technological leap allows for the rapid identification of events where Higgs bosons decay into muons despite the enormous data volumes produced by the LHC.

Advances in Trigger Systems and Machine Learning

The continuous development of trigger systems and the integration of machine learning algorithms represent a significant part of Professor Acosta's contributions to high-energy physics research.

Trigger systems are crucial for managing the data deluge produced by particle accelerators, as they help in selecting potentially interesting events from the billions of particle collisions occurring every second. Traditional trigger systems relied on pre-defined thresholds and simple pattern recognition to filter events, but the complexity and volume of data at the LHC require more sophisticated approaches, especially when the event to detect is relatively rare: a trigger system that doesn't record very often risks missing the rare occurrences of a given event, but a trigger system that records too often risks drowning the researchers in an unmanageable amount of data.

One key development has been the use of neural networks within the Level-1 trigger system – which is the first stage of CMS's data filtering process. These neural networks are implemented on field programmable gate arrays, which are circuits that allow researchers to analyse data directly from the detector hardware with minimal latency and high throughput. This setup actually improves the detection of rare events, such as the decay of the Higgs boson into muons, amid vast quantities of routine collision data.

This also improves the precision of particle tracking and momentum measurement. For example, algorithms based on deep learning have been used to refine the estimation of a particle's trajectory and its originating vertex within the collider. This is particularly important for studies involving displaced vertices, which can be indicative of exotic phenomena like the decay of long-lived particles – a potential signature of new physics.

Beyond enhancements to data acquisition and real-time processing, Professor Acosta's team has also been instrumental in developing offline analysis tools. These tools are used to analyse the data retained by the trigger systems, and techniques such as boosted decision trees and deep neural networks have been employed to distinguish between different types of particle decays, improve background suppression, and enhance signal sensitivity.

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Searching for Dark Matter

Dark matter remains one of the most elusive subjects in modern physics, inferred primarily through gravitational effects on visible matter, radiation, and the large-scale structure of the universe. While it does not emit, absorb, or reflect light, making it invisible and detectable only through its gravitational interactions, physicists are exploring ways to produce dark matter particles, or other dark particles that may only weakly couple to the known particles, directly through high-energy particle collisions at the LHC. The CMS experiment, with its sophisticated detection systems, is particularly well-equipped to search for signs of dark matter through missing energy and momentum in collision events. Anomalous amounts of these missing components, or of long-lived dark particles that weakly decay to known particles like the muon, may suggest the presence of new, non-interacting particles that could be candidates for dark matter.

Having cutting-edge computational technologies pushes the boundaries of what can be discovered at particle colliders, setting new standards for data processing and analysis in scientific research, and helping physicists to find elusive, hard-to-detect objects that are fundamental for our understanding of the universe.

MEET THE RESEARCHER

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Professor Darin Acosta is a physicist specialising in experimental high-energy physics and a faculty member at Rice University. He earned his BSC in Physics from the California Institute of Technology in 1987 and his PhD in High-Energy Physics from the University of California, San Diego, in 1993. His research career began as a postdoctoral researcher at The Ohio State University, followed by a tenure at the University of Florida before joining Rice University in 2021. Professor Acosta is renowned for his expertise in the electronic trigger systems of particle colliders and his pivotal role in integrating machine learning into real-time collision data analysis, which is essential for the CMS experiment at CERN's Large Hadron Collider.

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