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HIGGS BOSON DETECTION USING MACHINE LEARNING

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Abstract — **The Higgs boson is a cornerstone of modern particle physics, playing a crucial role in our understanding of the fundamental forces and particles that make up the universe. To comprehend its significance, let's break down the concepts involved. Fundamentally, the Higgs boson is intimately connected to the Higgs field. The Higgs field is a theoretical framework proposed to permeate all of space, imbuing particles with mass as they interact with it. Imagine it as a sort of cosmic molasses through which particles move, and their interactions with this field give rise to their mass properties. This is a fundamental departure from earlier theories where mass was simply an intrinsic property of particles. The mass of a particle determines how it responds to forces. According to Newton's second law, force equals mass times acceleration. So, a particle with more mass will accelerate less for a given force. This resistance to acceleration is what we typically think of as "mass." Crucially, not all particles possess mass. Photons, for example, are massless particles that travel at the speed of light and play a vital role in the electromagnetic force. However, many other particles, such as electrons and quarks, do have mass, and it's the Higgs field that endows them with this property. The idea of the Higgs boson was proposed in 1964 by a group of physicists including Peter Higgs and François Englert, among others. They postulated its existence as a consequence of the Higgs field. The Higgs boson is essentially a manifestation of the Higgs field's energy, similar to how a photon is a manifestation of the electromagnetic field. This discovery was a monumental achievement in particle physics, confirming a central piece of the Standard Model, which describes the fundamental particles and forces of the universe. For their groundbreaking theoretical work, Higgs and Englert were awarded the Nobel Prize in Physics in 2013. In summary, the Higgs boson and the Higgs field provide a fundamental mechanism for understanding why particles have mass, shedding light on one of the most fundamental questions in physics: the origin of mass itself.**

Keywords— **Higgs Boson, God particle, Standard Model, Elementary particle, Particle collisions, Momentum, Production.**

I. INTRODUCTION

The Higgs Boson, also known as the "God particle," is an elementary particle according to the Standard Model of Particle Physics that interacts with mass. Higgs Bosons have even parity, spin zero, and do not possess electric charge or color charge. The quantum excitation of the Higgs Field generates Higgs Bosons. They are highly unstable and quickly decay into other particles. Higgs fields are scalar fields necessary to break the electroweak symmetry, which gives particles their appropriate mass. These fields exist throughout the universe. The Higgs mechanism, triggered by the Higgs field, interacts with mass as it breaks certain symmetry laws of the electroweak interaction.

This process results in weak force particles like W and Z gauge Bosons acquiring mass at all temperatures below a certain extremely high threshold. The acquisition of mass affects the mobility of the weak Bosons. It also explains why other fundamental particles like fermions have mass. As the Higgs field is scalar, it possesses a non-zero average magnitude in a vacuum. Although the Higgs field exists everywhere, detecting it is challenging. The only feasible method is through its excitation, resulting in the production of Higgs Bosons. However, this necessitates high-energy cyclotrons for colliding particles with high momentum, eventually leading to the rare production of Higgs Bosons.

II. PROPOSED ALGORITHM

In the pursuit of understanding the intricacies of the Higgs Boson and the Higgs field, our research incorporates various models to elucidate their behavior. Specifically, we employ computational frameworks rooted in quantum field theory to simulate the dynamics of particle interactions within the Higgs field. These models leverage sophisticated algorithms to accurately capture the quantum excitation processes that give rise to Higgs Bosons. Furthermore, we utilize statistical models to analyze experimental data obtained from high-energy collisions in particle accelerators. These statistical models enable us to infer the presence and properties of the Higgs Boson based on observed particle decay patterns and energy distributions. By integrating these diverse modeling approaches, our research endeavors to deepen our understanding of the fundamental principles underlying the behavior of the Higgs Boson and its role in shaping the universe. The Models used in this project are :

A) LSTM (Long Short-Term Memory):

- LSTM is a type of recurrent neural network (RNN) architecture designed to address the vanishing gradient problem encountered in traditional RNNs.
- It consists of a chain of memory cells that can maintain information over long periods of time.
- LSTM cells contain three gates: input gate, forget gate, and output gate. These gates regulate the flow of information into and out of the cell, allowing it to selectively remember or forget information.
- LSTM networks are widely used in sequence modeling tasks such as language modeling, speech recognition, and time series prediction.

B) GRU (Gated Recurrent Unit):

- GRU is another type of RNN architecture that simplifies the LSTM by combining the input and forget gates into a single update gate.
- It has two gates: update gate and reset gate. The update gate controls the flow of new information into the memory, while the reset gate determines how much of the past information to forget.
- GRUs are computationally less expensive than LSTMs and are often used when training resources are limited or when simpler models are preferred.
- They are commonly employed in tasks requiring sequential processing, such as machine translation, text generation, and sentiment analysis.

C) BiLSTM (Bidirectional LSTM):

- BiLSTM is an extension of the LSTM architecture that processes input sequences in both forward and backward directions.
- It consists of two LSTM layers: one processing the input sequence from left to right (forward LSTM), and the other processing it from right to left (backward LSTM).
- By capturing information from both past and future contexts, BiLSTM networks can better understand the context of each input token in sequence modeling tasks.
- They are widely used in natural language processing tasks such as named entity recognition, part-of-speech tagging, and sentiment analysis, where contextual understanding is crucial for accurate predictions.

III. OBJECTIVES

The objectives of the Higgs Boson detection project are focused on creating a robust machine learning model capable of precisely identifying the presence of the Higgs Boson particle within high-energy physics collision data. These key goals encompass:

• Optimize Signal-to-Noise Ratio (SNR): Develop sequence models to enhance the SNR in the data collected from particle collision experiments, thereby improving the detection sensitivity of Higgs Boson signals amidst background noise.

• Event Classification: Design sequence models capable of accurately classifying collision events as either Higgs Boson interactions or background events, leveraging patterns and dependencies within sequential data to discriminate between signal and noise.

• Model Interpretability: Enhance the interpretability of machine learning models used in Higgs Boson detection, enabling researchers to understand the underlying physical principles captured by the models and providing insights into the nature of particle interactions.

• Data-driven Background Estimation: Utilize machine learning models to accurately estimate and model the background noise distribution in particle collision data, allowing for more precise discrimination between genuine Higgs Boson signals and background events.

IV. REVIEW OF LITERATURE

The literature review section comprises three significant contributions to the understanding of the Higgs boson and its detection. Firstly, Roser's presentation, "The Higgs Boson - the search for the particle and the role of simulation" [1], delivered at the Winter Simulation Conference 2014, offers profound insights into the discovery of the Higgs boson and its broader implications. Roser explores the concept of electroweak symmetry breaking, crucial for distinguishing weak and electromagnetic forces, suggesting that the answers to significant physics questions, including dark energy and string theory, depend on understanding the physics at the electroweak scale. The discovery of the Higgs boson in 2012 is portrayed not only as a scientific milestone but also as a philosophical and intellectual triumph. Roser highlights how the prediction of the Higgs boson, based on mathematical symmetry rather than physical necessity, reflects humanity's enduring quest to understand fundamental principles in the universe.

Secondly, Di Ciaccio's contribution, "The Higgs boson discovery and the role of detector technology" [2], presented at the 5th IEEE International Workshop on Advances in Sensors and Interfaces IWASI in 2013, sheds light on the monumental discovery of the Higgs boson and the pivotal role of detector technology. The announcement on July 4, 2012, by the ATLAS and CMS collaborations at the LHC marked a significant breakthrough in particle physics, observing a new particle consistent with the long-sought Higgs boson. The observation's significance, now approaching the 7 sigma level and surpassing the 5 sigma threshold for discovery, along with the measured properties aligning with those of a Standard Model Higgs boson, solidifies the triumph of the Standard Model and deepens our understanding of the Universe. Di Ciaccio emphasizes the immense dedication of experimentalists over two decades in the research and development essential for conceiving and constructing sophisticated apparatus with unprecedented sensitivities.

Lastly, Adhikary, Mukherjee, and Banerjee's paper, "Higgs Boson Detection from Monte Carlo Simulation Tensors using Wide and Deep Networks" [3], presented at the 2023 3rd International Conference on Artificial Intelligence and Signal Processing (AISP) in India, addresses the detection of Higgs bosons through innovative approaches combining Monte Carlo simulation and deep learning techniques. The Higgs boson, characterized by zero spin and coupling to mass, originates from quantum excitation of the Higgs Field. Despite its even parity and absence of electric or color charge, the Higgs boson's inherent instability leads to rapid decay into other particles. The paper introduces Monte Carlo simulation, a probabilistic technique critical for estimating outcomes in processes with unpredictable variables. Specifically, this method is employed to generate a probabilistic dataset encompassing 211 low-level features and 7 high-level features to facilitate Higgs boson detection. However, the authors acknowledge the resource-intensive nature of training deep learning models, often necessitating substantial computational resources.

V. DESCRIPTION AND ANALYSIS

The project "Higgs Boson detection using machine learning" focuses on leveraging sequence models, including BiLSTM, GRU, LSTM, and combinations like LSTM + GRU and BiLSTM + GRU, to identify and analyze signals indicative of the presence of the Higgs boson in experimental data. Machine learning techniques are applied to data collected from particle collision experiments, such as those conducted at the Large Hadron Collider (LHC). These experiments produce vast amounts of data, and traditional analysis methods may struggle to extract meaningful patterns. Sequence models, particularly recurrent neural networks (RNNs) like LSTM (Long Short-Term Memory), GRU (Gated Recurrent Unit), and their bidirectional variants (BiLSTM), are well-suited for analyzing sequential data, making them ideal candidates for this task. There are two types of events:- Signal and Background

- Signal event:- An event where a Higgs decay pattern is observed (true positive)

- Background event:- An event which is similar to the pattern of Higgs decay(false positive)

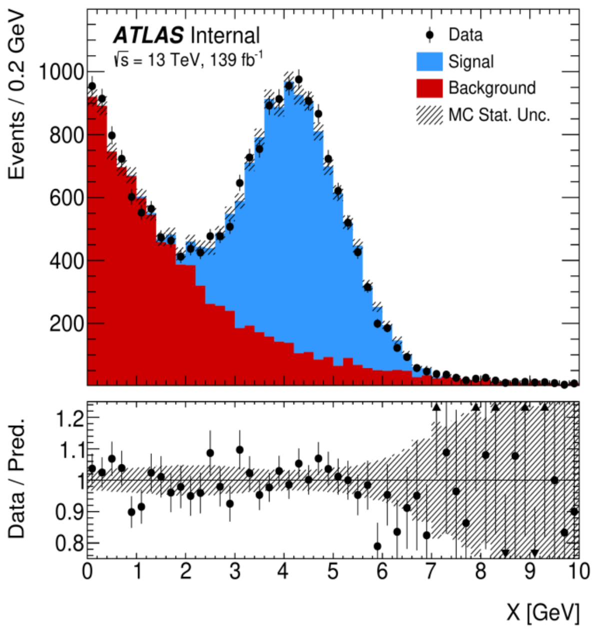

Fig.1 Basic Graph Representation of Signal and Background Events

VI. IMPLEMENTATION

The implementation of the Higgs boson detection project involves several crucial steps to effectively develop and execute the machine learning model. Here's a detailed outline of the methodology for implementing the project:

- Data Collection and Preprocessing: Acquire labeled collision data (signal/background events for Higgs Boson) from the ATLAS Open Portal and preprocess it into a suitable format for training the model.
- Feature Engineering: Extract and engineer features from the collision data to represent particle interactions effectively. This includes crucial features such as particle momenta (px, py, pz), energies, and other relevant properties.
- Model Selection: Choose an appropriate machine learning model architecture for Higgs boson detection, considering options such as LSTM, BiLSTM, or GRU, based on the dataset's characteristics and the task's complexity.
- Model Training: Train the selected model on the preprocessed data to learn the patterns and characteristics of Higgs boson events. Implement techniques to handle potential class imbalance, such as oversampling or undersampling.
- Model Evaluation: Assess the trained model's performance using various metrics such as accuracy, precision, recall, and F1-score on a validation dataset to gauge its effectiveness.

- Hyperparameter Tuning: Optimize the model's hyperparameters, including learning rate, batch size, and number of layers, to enhance its detection accuracy and generalization capability.
- Testing and Validation: Validate the model's performance on unseen data to ensure its ability to generalize to new collision events and verify its effectiveness in real-world scenarios.

Furthermore, following the model training phase, we computed performance metrics including accuracy and AMS (Approximate Median Significance) to assess the model's efficacy in event classification and the detection of Higgs boson signals within background noise. These metrics offer valuable insights into the model's performance and its practical relevance in the field of particle physics research.

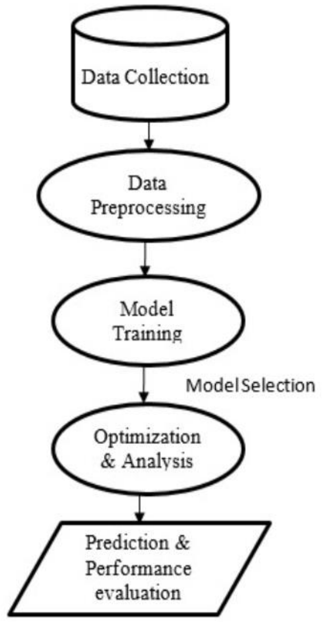

Fig.2 Flowchart of the System

VII. CONCLUSION

In conclusion, the application of machine learning techniques for Higgs Boson detection represents a significant stride towards unlocking the mysteries of particle physics. Our research has showcased the effectiveness of machine learning algorithms in discerning Higgs Boson events amidst complex particle collision data. While our findings demonstrate promising results, there remains ample room for further exploration and refinement. Future research endeavors should focus on enhancing the accuracy and robustness of detection models, exploring innovative feature engineering approaches, and addressing challenges such as class imbalance and model interpretability. Additionally, efforts should be directed towards seamlessly integrating machine learning methodologies into experimental frameworks for real-time Higgs Boson detection in high-energy physics experiments. By advancing our capabilities in Higgs Boson detection through machine learning, we can deepen our understanding of fundamental particle interactions and pave the way for groundbreaking discoveries in the realm of particle physics.

VIII. REFERENCE

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