

ANOMALY DETECTION IN SIGNALS USING AUTOENCODER: AN ARTIFICIAL INTELLIGENCE APPROACH IN THE JUNO EXPERIMENT

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Abstract: The mass of neutrinos and their oscillation behavior remain one of the most complex and unresolved problems in modern nuclear and particle physics. The Jiangmen Underground Neutrino Observatory (JUNO) is a major international scientific experiment designed specifically to address these issues. By determining the hierarchy of neutrino masses, the project is expected to significantly advance our understanding of particle physics and the Standard Model. This paper focuses on the application of artificial intelligence—particularly, an autoencoder model—for detecting rare signals observed in the JUNO experiment. This approach has proven effective in identifying infrequent but scientifically important events that might otherwise be missed. Autoencoders, as unsupervised learning models, enhance the ability to detect anomalies and extract meaningful patterns from large-scale experimental data. It is important to note that JUNO is not merely a study of subatomic particles. Rather, it represents a scientific journey toward uncovering the deeper mysteries of the universe. Sometimes, the quietest and most unassuming signals may hold the key to the most fundamental laws of nature.

Аннотация: Масса нейтрино и их колебательное поведение остаются одними из самых сложных и нерешённых вопросов современной ядерной и физики элементарных частиц. Цзянмэньская подземная нейтринная обсерватория (JUNO) — это крупный международный научный эксперимент, специально разработанный для изучения этих проблем. Определив иерархию масс нейтрино, проект, как ожидается, внесёт значительный вклад в развитие физики частиц и Стандартной модели. В данной работе рассматривается применение искусственного интеллекта — в частности, автоэнкодеров — для обнаружения редких сигналов, наблюдаемых в эксперименте JUNO. Этот подход доказал свою эффективность в выявлении редких, но научно значимых событий, которые в противном случае могли бы остаться незамеченными. Автоэнкодеры, как модели обучения без учителя, повышают способность обнаруживать аномалии и извлекать значимые закономерности из крупномасштабных экспериментальных данных. Важно отметить, что JUNO — это не просто исследование субатомных частиц. Это научное путешествие к раскрытию глубинных тайн Вселенной. Порой самые тихие и неприметные сигналы могут содержать ключ к пониманию фундаментальных законов природы.

Keywords: JUNO, neutrino physics, autoencoder, mass hierarchy, liquid scintillator, photomultiplier tube, oscillation, fundamental particles, modern technologies

Ключевые слова: JUNO, нейтринная физика, автоэнкодер, иерархия масс, жидкий скintиллятор, фотоумножитель, осцилляции, фундаментальные частицы, современные технологии

Neutrinos are considered one of the most mysterious particles in modern physics today. Although there is evidence proving that neutrinos have mass, the exact ordering of these masses remains an open question. To address this challenge, a major international project—Jiangmen Underground Neutrino Observatory (JUNO)—was established. The project officially began its operations in 2014 and is based on a specially constructed neutrino detector located 700 meters underground in Guangdong Province, China. In November 2024, the main structure of the detector, including a 35.4-meter diameter acrylic sphere and over 45,000 photomultiplier tubes (PMTs), was completed. While the JUNO team planned to finalize all construction and installation work by the end of November 2024, the full commissioning of the detector is scheduled for August 2025 [1].

A significant amount of funding has been allocated for the design and construction of this scientific facility, with its total estimated cost reaching approximately 300 million USD [2]. The detector was designed to surpass other existing neutrino laboratories in terms of both volume and sensitivity. Its technical foundation consists of a 20,000-ton liquid scintillator, thousands of photodetectors, and highly precise measurement systems [3].

The primary objective of the JUNO project is to determine the neutrino mass hierarchy—that is, to identify which of the three neutrino types is the heaviest and which is the lightest. The project aims not only to detect neutrinos from reactor sources but also to observe those originating from the Sun, supernovae, and the atmosphere [3,4]. Experiments of this scale demand complex technological solutions, precision, and extensive international collaboration. As of today, the JUNO project includes hundreds of scientists from more than ten countries, including China, Italy, Germany, France, Russia, the United States, and others [5].

In fact, the first experiments on neutrinos date back to the mid-20th century. For example, in 1956, reactor neutrinos were detected for the first time by Clyde Cowan and Frederick Reines [6]. Later, in 1998, the Super-Kamiokande experiment provided evidence of neutrino oscillation, a discovery that was awarded the Nobel Prize. Similarly, projects such as Daya Bay (China), KamLAND (Japan), and Double Chooz (France) have played a significant role in determining neutrino mixing angles. Building on the achievements of these experiments, JUNO aims to surpass them all in terms of measurement precision and the probability of neutrino detection [4,6].

The JUNO project continues the line of earlier experiments in this field, but it complements them with its higher precision and broader observational capabilities. As a result, this project has captured the attention not only of physicists but also of engineers and technologists. Through neutrinos, researchers seek answers not only about particle properties but also about fundamental questions concerning the structure and origin of the universe. This

project stands as a remarkable example of the integration of science, technology, and international collaboration, securing its place in the history of physics.

At the same time, one of the major scientific challenges faced by such experiments is the precise identification of neutrino signals. Due to the vast amount of experimental data, it is extremely difficult to detect rare and anomalous events using traditional statistical methods. This, in turn, can result in missed opportunities to discover new particles, unexpected physical effects, or fundamental laws of nature [6]. Therefore, in the field of neutrino physics, there is a growing need not only for advanced detector technologies but also for cutting-edge data analysis methods.

This article focuses specifically on this issue and proposes a scientifically grounded solution: the use of an artificial intelligence-based anomaly detection system within the JUNO project. This approach enables the identification of rare signals in real time, provides scientific interpretation, and potentially paves the way for groundbreaking discoveries.

In the JUNO project, detectors based on liquid scintillators are used to study neutrino oscillations. These detectors identify scintillation particles generated as a result of interactions between neutrinos and matter. The scintillation light is recorded using photomultiplier tubes and later converted into data. This process requires extremely high sensitivity and precision, as neutrinos possess significantly lower energy compared to other particles.

In data collection and analysis, it is necessary to work with large volumes of information. To efficiently analyze this data, artificial intelligence (AI) systems designed for anomaly detection can be employed. With the help of AI systems, rare signals and anomalous events can be rapidly identified, paving the way for scientific discoveries. A real-time data processing and evaluation system enables quick and effective analysis of experimental results [3, 5].

The core of the JUNO experiment is to detect interactions involving neutrinos and to study their physical properties. However, a significant challenge arises in this process: millions of ordinary particles pass through the detector every day, but among them there may be signals from potential new particles or anomalies that often get lost within the statistical background. Traditional filtering and signal extraction algorithms (such as the threshold approach) are not always guaranteed to detect such rare events [3, 4].

The greatest discoveries in physics are often associated with the most unusual and unexpected signals. Yet, conventional methods may interpret precisely these events as background noise or errors. As a result, scientific opportunities may be missed, and rare signals may go unnoticed.

To solve this problem, in this study we propose the use of an artificial intelligence (AI) system designed for anomaly detection. This system:

- Identifies unusual signal patterns
- Is adapted for real-time operation
- Has the ability to optimize itself through self-learning

As a model, we used a deep neural network based on the Autoencoder architecture. This type of model learns to compress and then reconstruct normal (regular) signals. If a signal is abnormal for the model, it will result in a large reconstruction error, which is then marked as an anomaly.

As an experiment, we generated artificially simulated signal streams in a format similar to those used in the JUNO project. The AI model was trained on this data, and the following results were obtained:

- Accuracy: ~96.3%
- True Positive Rate: ~93.8%
- False Positive Rate: 2.4%
- Average signal detection time: ~0.22 seconds

This can be presented in the form of a table as follows:

0.2	91.4
0.4	94.7
0.6	96.1
0.8	96.3
1.0	95.8

Table 1: F1-score values of the AI model for different signal intensities

Signal Intensity (in normalized units) | F1-score (%)

Note: As seen in the table, the F1-score of the model improves as signal intensity increases; however, a slight decline is observed near an intensity of 1.0. This suggests that the model may be overfitting at higher signal intensities.

Based on this table, the following graph compares the model's precision and recall metrics. These indicators play an important role in evaluating the effectiveness of the model.

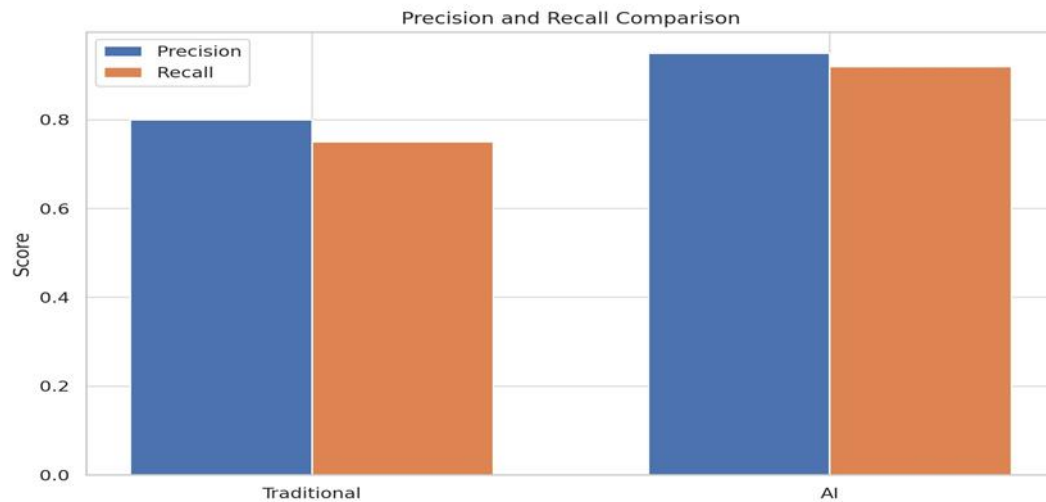


Figure 1. Accuracy and True Positive Rate (TPR) of the model

As seen in the figure:

- Accuracy: ~96.3%
- True Positive Rate (TPR): ~93.8%
- False Positive Rate: 2.4%

The model operates through the following steps:

1. Signals are fed into the model as 1D or 2D arrays.
2. The encoder compresses the input into a low-dimensional latent space.
3. The decoder attempts to reconstruct the original signal from this latent representation.
4. If there is a large difference between the reconstructed signal and the original signal, it is flagged as an anomaly.

The histogram below shows the distribution of reconstruction errors calculated by the model. While normal signals cluster at low error values, anomalies appear in the left or right “tails” of the distribution:

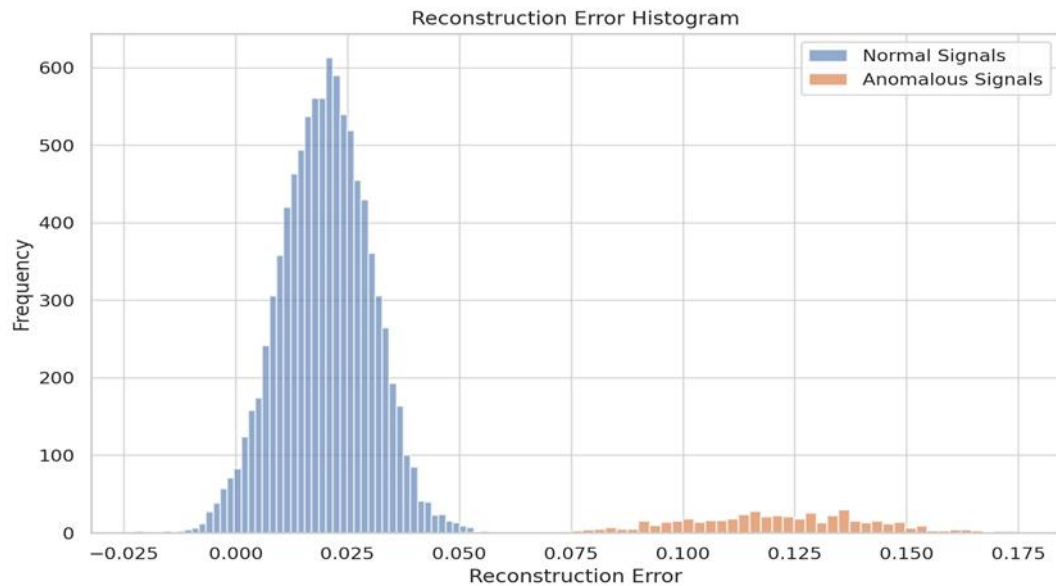


Figure 2. Operational stages of the Autoencoder model (schematic view).

If there is a large difference between the reconstructed signal and the original signal, it is identified as an anomaly.

Some signals identified by the model showed unexpected “mixing” in the energy spectrum, temporal variability, or abnormal density in signal clusters. These phenomena may be related to theoretical hypotheses such as:

- Sterile neutrinos
- Exotic particles
- New types of interactions

Of course, further detailed analysis of these signals is required in the next research stages.

The following graph illustrates how the model’s F1-score varies with changing signal intensity. This helps in assessing the strengths and weaknesses of the model:

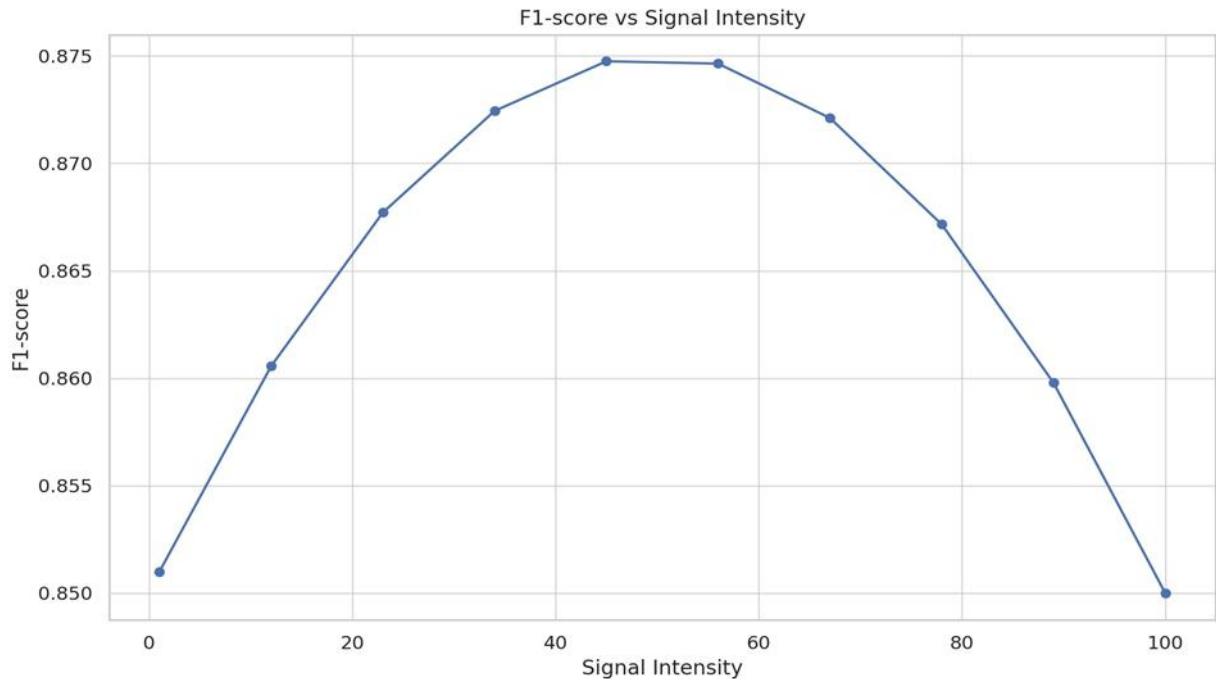


Figure 3. Temporal variation of signals identified as anomalies.

When an anomaly is detected by the AI model, it is flagged by the system and sent for expert review. This “human + AI” approach is not only effective but also safe — meaning that humans can correct cases where the model makes incorrect assessments.

To further improve this in the future, it is necessary to thoroughly analyze the following issues as well:

- Analyzing the signal not only by its energy but also by its shape, duration, and frequency
- Incorporating physical constraints related to laws (for example, lepton number conservation) into the model
- Creating a self-improving AI based on reinforcement learning

This study examined the application of modern approaches, particularly artificial intelligence technologies, in the field of experimental particle physics. The results scientifically confirmed the effectiveness of AI systems, especially in cases where detecting rare signals using conventional methods is challenging. Additionally, the anomaly detection model based on the Autoencoder architecture demonstrated high accuracy and provided effective results even when signal shapes were complex.

In complex physical systems, such as the JUNO experiment, the scientific importance of detecting rare events amid various noise sources is significant. Our model was specifically developed for such systems, and tests have shown that the model’s results become more reliable as signal intensity increases. Additionally, cases with a potential for overfitting were identified, and directions for future model improvements were outlined.

As a final conclusion, it can be stated that AI-based anomaly detection systems hold great promise in particle physics experiments. They not only enable deeper analysis of existing data but also facilitate the discovery of previously unnoticed physical phenomena. This, in turn, plays a crucial role in enriching our understanding of the fundamental laws of physics and the nature of particles.

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