Nuclear Science and Techniques (2025) 36:39
https://doi.org/10.1007/s41365-024-01604-0

A ROOT-based detector geometry and event visualization system for JUNO-TAO

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Received: 24 June 2024 / Revised: 2 September 2024 / Accepted: 16 September 2024 / Published online: 27 January 2025

Abstract
The Taishan Antineutrino Observatory (TAO) is a satellite experiment of the Jiangmen Underground Neutrino Observatory, located near the Taishan nuclear power plant (NPP). The TAO aims to measure the energy spectrum of reactor antineutrinos with unprecedented precision, which would benefit both reactor neutrino physics and the nuclear database. A detector geometry and event visualization system was developed for the TAO. The software was based on ROOT packages and embedded in the TAO offline software framework. This provided an intuitive tool for visualizing the detector geometry, tuning the reconstruction algorithm, understanding neutrino physics, and monitoring the operation of reactors at NPP. Further applications of the visualization system in the experimental operation of TAO and its future development are discussed.

Keywords Visualization · Geometry · Offline software · JUNO · TAO

1 Introduction

The Taishan Antineutrino Observatory (TAO, also known as JUNO-TAO) [1], a satellite experiment conducted at the Jiangmen Underground Neutrino Observatory (JUNO) [2], is currently under construction in Guangdong, China. TAO is a ton-level liquid scintillator (LS) detector that detects antineutrinos via inverse beta decay (IBD). Its central detector operates at −50°C to reduce the dark noise of a silicon photomultiplier (SiPM) to an acceptable level [3–6]. Located near the Taishan nuclear power plant (NPP), JUNO-TAO is expected to provide a model-independent reference spectrum for reactor antineutrino measurements to JUNO with an energy resolution of approximately 2% at 1 MeV [7–12], which approaches the energy resolution limit of the LS detector. Furthermore, JUNO-TAO aims to provide benchmark measurements for nuclear databases [2], search for sterile neutrinos [13, 14], and verify technologies for reactor monitoring to enhance the reliability of nuclear power plant (NPP) operations and safeguards [15–18].

An event display is a visualization tool that illustrate detector geometry and event data in all phases of any high-energy physics (HEP) experiment [19, 20]. It is used to design detectors, check the detector structure and elements, aid in problem diagnosis through online monitoring during data acquisition, and understand physics in an auxiliary manner during data analysis. The event-display tool also enables physicists to understand the simulation and reconstruction performance when tuning the reconstruction algorithm in software development [21].

A ROOT-based event display was developed for the JUNO-TAO. This included the ROOT package Event Visualization Environment (EVE), which provided an intuitive method for constructing event displays [22–25]. EVE was first developed in the ALICE offline project [26] and has been widely applied in several HEP experiments [27, 28].

This work was supported by the National Natural Science Foundation of China (Nos. 12175321, 11975021, and 11675275) and the Strategic Priority Research Program of the Chinese Academy of Sciences (No. XDA10010900).

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In addition to the primary visual display functions of the detector geometry and event, the software also supports the functions of two-dimensional (2D) hits projection, data association from different formats, and graphical user interface(GUI) control for users to interactively check the detector geometry and event data. Thus, it is an effective tool for TAO experiments to understand neutrino physics and monitor the daily operation of reactors at NPP.

The remainder of this paper is structured as follows. Section 2 briefly describes the software structure and data flow of the TAO event display. Section 3 presents the realized visualization functions. Sections 4 and 5 present the features and performance of a TAO event display and its applications. Finally, Sect. 6 summarizes the study.

2 Methodologies

In this section, we illustrate the structure and data flow of the TAO visualization software. The detector geometry and its description, as well as the event data model in offline software, are introduced. The construction and functional overview of the GUI for realizing user interaction are also expounded.

2.1 Software structure and data flow

An event-display software should provide visualization functions for the detector geometry, displaying different views of detectors, distribution of event hits, and interactive control between the display and users. Similar geometric shapes can be selected to replace the complex detector components. For the JUNO experiment, the Software for Non-collider Physics Experiments (SNiPER) [29], which is a lightweight flexible framework that relies on the external packages Geant4 [30] and ROOT [22], was used to construct the offline software system. JUNO uses the SNiPER framework for developing visual tools [31, 32]. The same framework was constructed for TAO to satisfy the requirements of a consistent software architecture.

As shown in Fig. 1, the TAO event-display software comprised four parts.

- *Detector geometry* The geometric details of the detector, constructed with Geant4 in detector simulation, are initially saved in a geometry description markup language (GDML) file [33–35]. The GDML file is then transformed into a ROOT file using the GDML-ROOT converter. The geometric information of the detector components within the ROOT file is then accessed via the geometry service [36, 37] and used for the three-dimensional (3D) and 2D construction of detector units with the ROOT EVE package.
- *Event data model* The event data model (EDM) [38] contains three types of information: simulation, calibration, and reconstruction, which is generated by TAO offline software. Consequently, the EDM information is read by the event manager and displayed together with detector geometry. The detailed information on the hits, tracks, and their associations is attributed to the corresponding objects and viewed with the information based on the requirements of users.
- *EVE-based visualization* The detector geometry objects, information of simulation and reconstruction, hit objects, and histograms were implemented with the corresponding visualization objects in the ROOT EVE package. The information of the detector units, including its identifier, position, time and charge of a hit, was also attached to the EVE visualization objects for interactive display.

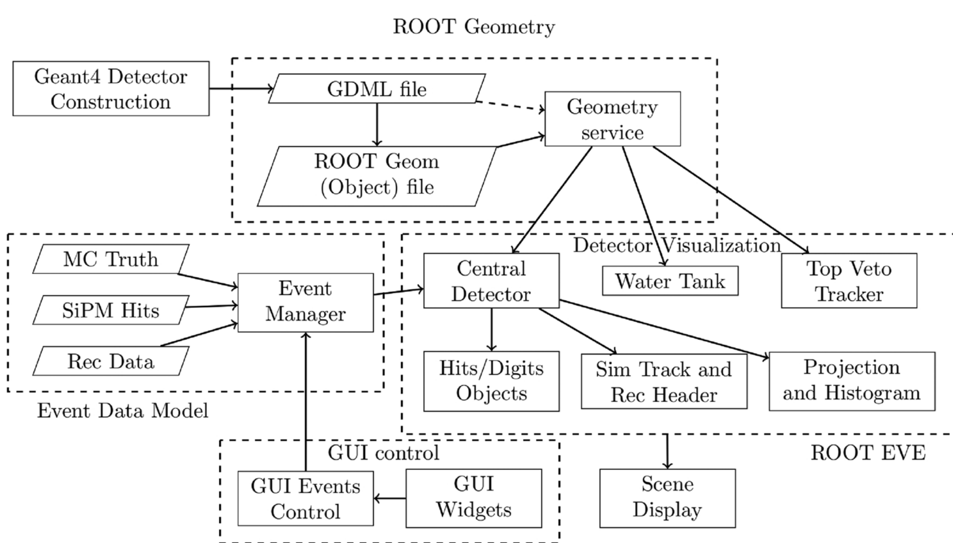

Fig. 1 Architecture and data flow of the TAO event-display software

- *GUI* With the interactive functions realized using the ROOT GUI widgets, the users can access the control of the visualization objects, such as event navigation, switching between different views of the detector. These functions help the users better understand the physics processes in data processing and analysis.

All of these functions were realized with the ROOT packages and within the SNiPER framework, which rendered them easy to implement in the TAO offline software and could be naturally accessed at different stages of data processing, including simulation, reconstruction, and data analysis.

2.2 TAO detector and geometry

The TAO detector was located approximately 44 m from one reactor core(TS-C1) of the Taishan NPP and 217 m from the other reactor core (TS-C2) [12]. It comprised three main subdetectors: the central detector (CD), water tank (WT), and top veto tracker (TVT), as shown in the schematic structure of the TAO detector in Fig. 2.

The CD is a spherical acrylic vessel filled with 2.8 tons of gadolinium-doped LS. This was supported by a spherical copper shell installed with approximately 4,100 SiPM tiles [39], which had a geometric coverage of 94% and exhibits outstanding energy resolution. The residual non-uniformity, degradation in energy resolution, and bias were maintained at 0.2%, 0.05%, and 0.3%, respectively, through calibration [40]. Thus, it could provide a reference spectrum for measuring neutrino mass ordering in JUNO and eliminate potential model-dependent systematic uncertainties from the fine structure in the reactor neutrino spectrum [7].

To veto the cosmic-ray muons and radioactive backgrounds from the environment, the CD was surrounded by the WT, whose interior wall was instrumented with arrays of approximately 300 3-inch photomultiplier tubes(PMT) to record the information of cosmic muons via the detection of Cherenkov light. The TVT, which comprised four layers of plastic scintillators, was designed to detect the tracks and direction of cosmic muons from the top of the CD and WT [41], which is necessary for ground-based detectors. Further details on the TAO detector can be found in [1].

The detector geometry in the TAO offline software was constructed at the stage of Geant4-based detector simulation. The necessary detector information from the simulation was then exported in GDML format, including the CD, WT, and TVT. The GDML file was then converted to ROOT format and used as input for the detector geometry service, providing convenient and consistent storage of detector unit information, such as the position and orientation of each SiPM, position of each plastic scintillator, transformation between the local coordinates of every PMT, and global coordinates of the TAO.

The geometric structure of the TAO detector used in the simulation and reconstruction is illustrated in Fig. 3, which is stored in the GDML file format and displayed using the ROOT OpenGL [42] viewer.

In the TAO experiment, the GDML files were converted to the ROOT format, which rendered it easier for users to learn about the different subdetector structures using the ROOT browser while retaining the advantages of GDML files. The component information of the JUNO-TAO was also stored in a ROOT file. All displayed objects were controlled by ROOT EVE geometry objects and initialized with visualization attributes for later display control. With the

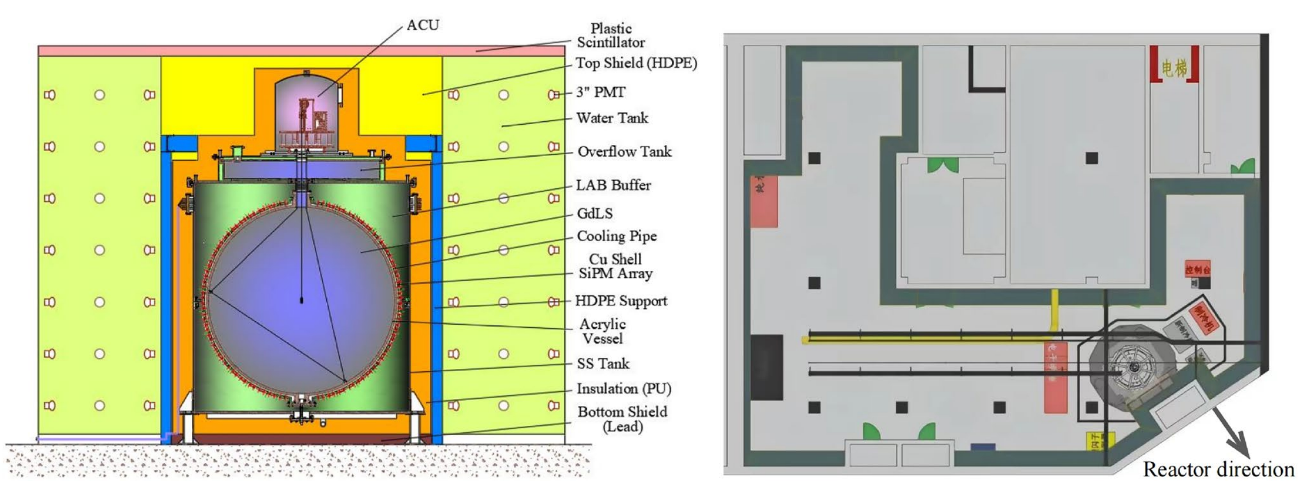

Fig. 2 (Color online) Schematic of the TAO detector. The left figure is the designed structure of the TAO detector. The right figure shows the Taishan Neutrino Laboratory. The footprint of the TAO detector is the black prismatic block located at the bottom right and is approximately 44 m from the reactor core [1]

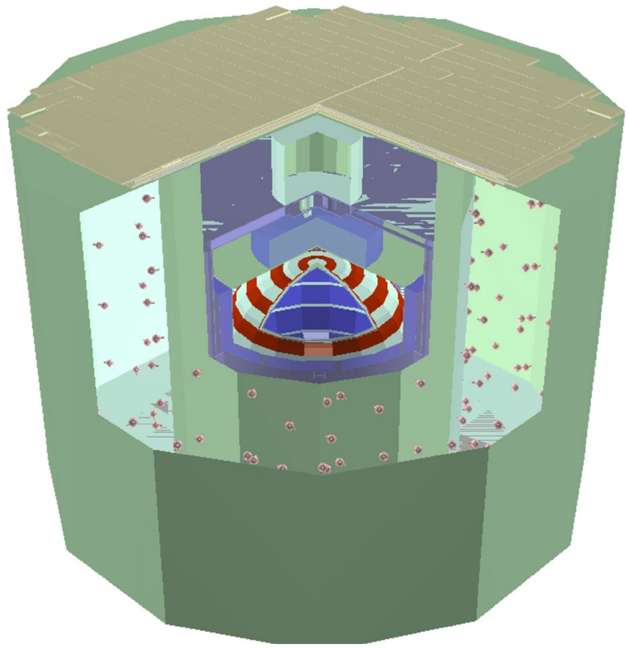

Fig. 3 (Color online) Geometric structure of the TAO detector exported from GEANT4 simulation and displayed with ROOT OpenGL viewer. The brown top layers are TVT, the sphere in the center is CD, and the outer perimeter comprises PMTs installed in WT

detector data exported by the geometry service, the visualization of the subdetectors could be quickly constructed with fundamental 3D models of geometric shapes, such as boxes, cones, spheres, and cylinders.

2.3 Event data model

The event data model (EDM) offers a comprehensive array of event data information, which is represented as ROOT-based persistent data objects and flows between different stages and applications, such as SimEvent from detector simulation, ElecEvent from electronics, CalibEvent from calibration, and RecEvent from the reconstruction output. The data were structured within a similar framework that aligned with the EDM in the JUNO offline software [38, 43].

The software structure of the event display indicates that reading different data files through the event manager distinguishes the types of data that these files contain. In the event display of the TAO, various data files, such as SimEvent, CalibEvent, and RecEvent, are read simultaneously. The event data objects are initialized with the corresponding ROOT EVE objects, such as the time and charge of the fired PMT hits, reconstructed vertex and energy, Monte Carlo (MC) truth information of each particle, and photon propagation paths if provided. This information is used in the subsequent development of event-display functions and display control from the ROOT GUI.

Because there are approximately 4,100 SiPMs, 300 PMTs, and four layers of TVT scintillators in the TAO, constructing all the corresponding EVE objects is time-consuming. Moreover, it is impractical to perform such construction each time for each event. Instead, to display event-by-event more efficiently, the key is to construct all detector units corresponding to EVE objects only once at the initialization stage of the event-display software, and then changing the visualization attributes of each detector unit object according to its fired status in a specific event. For example, SiPMs can be displayed in different colors according to the number of photons on the SiPM or the time of the earliest arriving photons. The text information associated with this SiPM in the EVE is also updated from the EDM information. Thus, the ROOT EVE can directly control the visualization of each event more efficiently, as shown in Fig. 4.

2.4 EVE-based visualization

EVE is a ROOT module based on an experiment-independent part of the event display in the ALICE experiment [23, 26] and has been used to perform high-level event visualization, debugging of simulation and reconstruction codes, and raw data visualization. The EVE package provides a standard platform for different experiments to visualize the detector geometry and event information, combined with the GUI package to create an intuitive event-display control window.

As shown in Fig. 4, the default control panel of the EVE on the left side of the window including displaying the detector and event information and controlling the visual effects and settings. Certain new features and functions specifically for TAO event displays were developed and deployed with the corresponding widgets on the right panel, including event navigation, simulation and reconstruction displays, hit objects, and histograms. These functions were also linked to the EVE visualization objects for interactive displays. Further details on the visualization effects and functions are discussed in Sect. 3.

2.5 GUI

The GUI is an interface for interactive communication between the display and the users. The TAO event-display GUI was implemented to display the detector geometry, event data, and functional widgets for control. Users can control the visualization effects of the event and detector components by clicking on the functional buttons on the GUI panel. The GUI interface was constructed by combining the ROOT EVE and GUI packages. EVE provided visualization functions, whereas the GUI constructed a window panel and widgets to control these functions, as shown in Fig. 4.

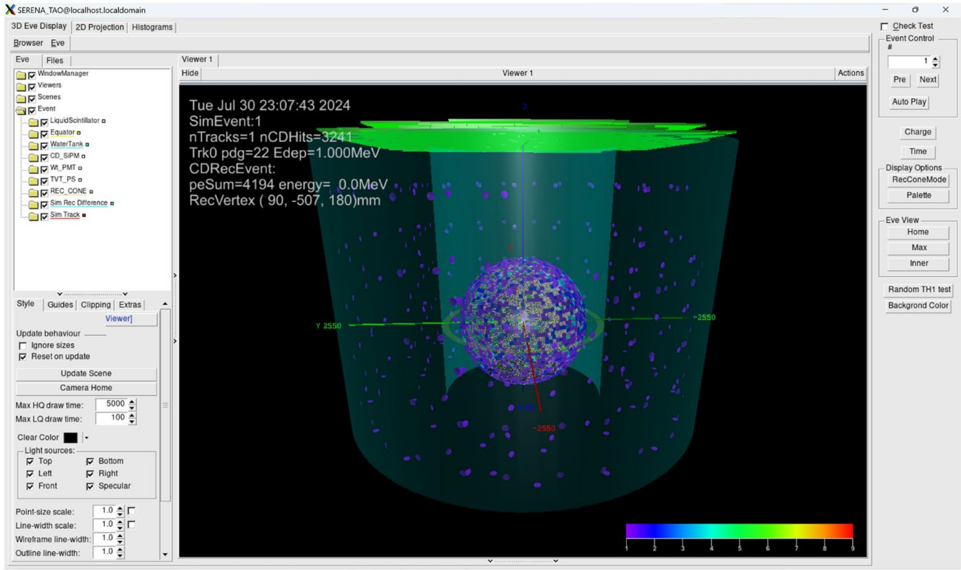

Fig. 4 (Color online) GUI of the TAO event-display software and display of a gamma event in the TAO detector

The central window is the primary body of the event display, which includes the display of the detector's geometric structure, hit information, and photon tracks. It was constructed based on the OpenGL module to implement the data presentation and interaction layers. In the upper-left corner, detailed event information is displayed to help physicists understand the event in the simulation and reconstruction, such as the identifier of a specific event, its production date and time, total number of hits in this event, deposited energy, reconstructed event vertex, and MC truth.

As shown in Fig. 4, both 3D display and 2D projection display were provided and can be switched between different tabs in the upper left of the GUI window. In the left panel of the GUI window, the default functions were provided by the ROOT EVE, such as the orientation of objects and setting the background color of the display window. In the right panel of the GUI window, functional buttons were defined for event display, such as event sequence control, charge and time display, and event-view mode. Users can control the display of events in the detector through the GUI window and panels, and scan the events individually to check more detailed event information for reconstruction algorithm tuning and physics analysis.

3 Visualization

This section presents the realization of the visualization functionalities, including the visualization of the detector geometry, hits, comparison of the reconstruction output, and 2D histograms.

3.1 Detector units

As mentioned in Sect. 2.1, all the detector geometry information is converted from the GDML file and used as the input for the TAO event display. However, it is challenging to visualize all geometric details of every detector unit. Graphical processing power requirements are typically beyond the computer hardware limits of most end users. However, analyzers may not be interested in the exact shape of every detector unit, such as the PMT but prefer to focus more on its spatial position and firing status.

Therefore, the detector units were optimized for visualization. The units of the detectors with complex structures were replaced with similar simple geometric shapes. For example, the SiPM and plastic scintillator are represented by box objects (TEveBox), and the PMTs are simplified into a set of conical objects, rendering the detector visualization smoother on most end-user computers. With such an implementation, the performance and interactive response speed of the event-display software were greatly improved.

As shown in Fig. 5, the blue sphere represents the visualization effect of the CD comprising 4,100 SiPMs. The light blue cylinder indicates the approximate shape of the WT with 300 3-inch PMTs, which are represented by small purple cones embedded in the WT. The green TVT on top comprises four layers of plastic scintillators that are approximately cuboid.

Every detector object is selectable and pickable. For example, when the cursor moves over any SiPM or PMT, it is selected based on the highlighted visualization effect. Meanwhile, a text box pops up to show its spatial position and identifier, helping users obtain detector unit information,

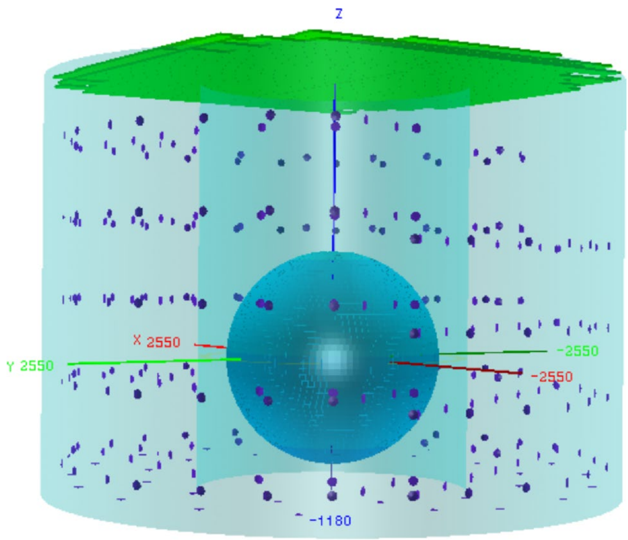

Fig. 5 (Color online) Visualization of the TAO detector geometry in event-display software. The light blue cylinder indicates the WT. The purple points in the WT indicate veto PMTs. The blue sphere is composed of SiPMs in the CD. The top green bars indicate the four layers of plastic scintillators in the TVT. The numbers at the x, y, and z positions represent the set boundaries of the coordinate axes, with the unit being millimeters. This provides a visual understanding of the dimensions of the detector

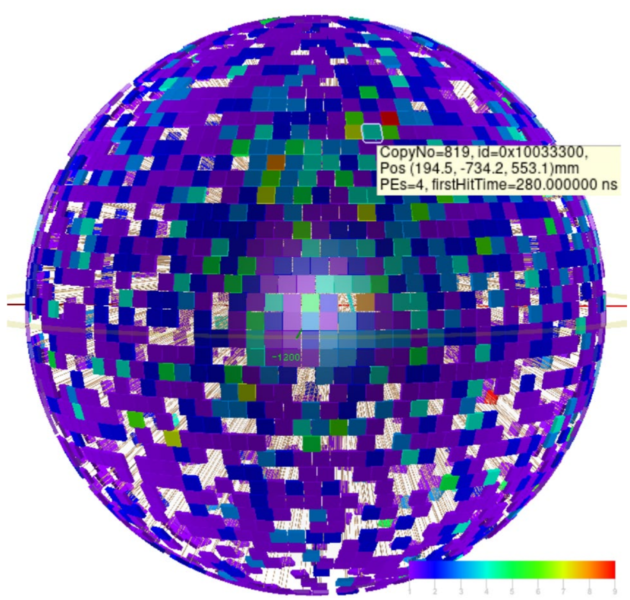

Fig. 6 (Color online) Charge distribution of SiPM hits in an event, represented with different colors. The red SiPMs have more photon hits, while the blue and purple SiPMs have fewer hits, as illustrated in the legend

as shown in Fig. 6. The display properties of the detector units can be flexibly set by the EVE panel on the left side. For example, users can control whether to display a subdetector by switching the subdetector on or off on the left panel.

3.2 Hits information

The critical function of a visualization involves displaying hits distribution. With approximately 4,100 sensitive SiPMs in the CD, the photon detection efficiency exceeded 50%. The event-display software provided two modes to show the hit information of the detector units: the number of photon hits on the SiPM(charge) and the time of the first hit on the SiPM(time). The charge distribution of an event in the CD is shown in Fig. 6. The SiPMs can be distinguished based on their unique identifiers. The detector units that were fired with hits are visually represented by a specific color. Meanwhile, the detector units that were fired by any hit are set invisible, allowing for a clear visualization of the hit distribution in the entire detector.

Charge and time distributions play an important role in tuning the reconstruction algorithm. For example, the charge-weighted vertex reconstruction algorithm uses the hit charge distribution of the SiPMs to reconstruct the event vertex. The time distribution was used to calculate the spatial position of the maximum likelihood from an event vertex to every SiPM hit [1, 44]. The charge and time distributions in the event display provide an intuitive way to help software developers understand the reconstruction algorithms. In addition, charge and time distributions help physicists understand the reaction processes while analyzing an event.

3.3 Simulation and reconstruction information

MC simulation is critical for the design of detectors, helping physicists check the design performance of detectors and tune algorithms. The reconstruction algorithm employs the hit information received by the detector to reproduce the true information of an event as closely as possible to the real process [21, 45, 46]. When experimental data are not available, the MC simulation is a good approach for testing the performance of the reconstruction algorithm.

An important function of the event display involves comparing the differences between the reconstruction and MC truths in the simulation to tune the accuracy of the reconstruction algorithms and to diagnose the reconstruction results event-by-event to identify potential problems. For instance, in the context of Inverse Beta Decay (IBD) events involving the positron's deposited energy vertex, discrepancies between the true vertex in MC and the reconstructed vertex can be effectively analyzed using event-display software. This enables the observation of the distribution characteristics of such events, facilitating the targeted improvement of the reconstruction algorithm. During event simulations, such as muon events in cosmic rays that yield a substantial

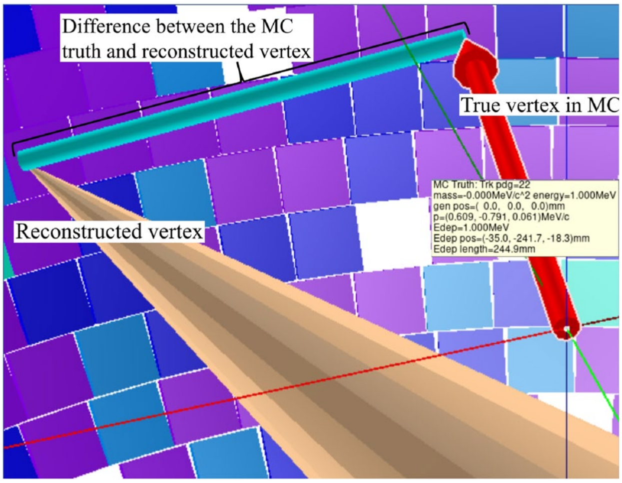

Fig. 7 (Color online) Comparison of the reconstructed vertex with MC truth in a simulated positron event

number of photons, the event-display software facilitates the examination of charge and timing distributions within SiPMs. The TAO event-display software can simultaneously present various types of information regarding an event by reading different types of data, such as showing the reconstruction and simulation results together, such that users can visually compare the associations between them.

The difference between the reconstructed vertex and MC truth from a simulated positron event, which was synchronously extracted from the simulation and reconstruction output data files, is shown in Fig. 7. The tail of the red arrow represents the true production vertex position, and the head of the red arrow indicates the position of the positron annihilation from the MC truth. The apex of the brown cone is the reconstructed event vertex. The blue line connecting the head of the red arrow and the apex of the cone illustrates the difference between the reconstructed and MC truths.

A shorter blue line indicates a better reconstruction performance. For perfect vertex reconstruction, the length of the blue line should be zero, and the reconstructed vertex should merge at the same point as the true vertex. The text box shows the detailed reconstruction or MC truth when the user moves the cursor over the red or blue lines to obtain more information.

3.4 2D projection

In addition to the 3D visualization of the detector and event data, 2D projection is helpful for data analysis. For example, the 2D event displays of CMS [27] and BESIII [47, 48] can help physicists understand the data analysis processes more easily.

The 2D projection of the CD SiPMs synchronously read the geometry of the CD SiPM hits. The ROOT EVE provides two default cross-sectional projection views: x-y and z-r views. However, it does not provide much helpful information regarding the distribution of hits because the CD is a symmetric sphere. The Aitoff projection method [49] was implemented for 2D projection views. It projects the entire surface of a sphere onto a 2D plane plot, such as spreading the Earth onto a flat surface.

The 2D charge distribution projection of CD is shown in Fig. 8. Solid markers with different colors represent the number of photons hitting the SiPM. Red indicates that more photons hit the SiPM. The gray dots represent SiPMs without any hits. In the 2D projection view, the X and Y coordinates represent the projection of longitude and latitude of the CD sphere, respectively.

4 Features and applications

The TAO event-display software provides a concise and convenient interactive control interface between users and visualization of event data. Certain features and applications of the visualization software are as follows:

Application in detector commissioning Event displays play an important role in detector commissioning by enabling users to gain insight into the performance and operational status of the detectors. Through the analysis of events, users can identify potential issues and evaluate detector performance, facilitating debugging and repair efforts. Furthermore, visualization of the detector assists in optimizing the detector performance and enhancing the efficiency and accuracy of data collection.

Visualization monitoring tool During detection and experimental operations, the event display helps scientists monitor and analyze experimental data in real time [18, 50, 51]. It is used for the visualization and interpretation of particles interacting with a TAO detector, thereby enabling

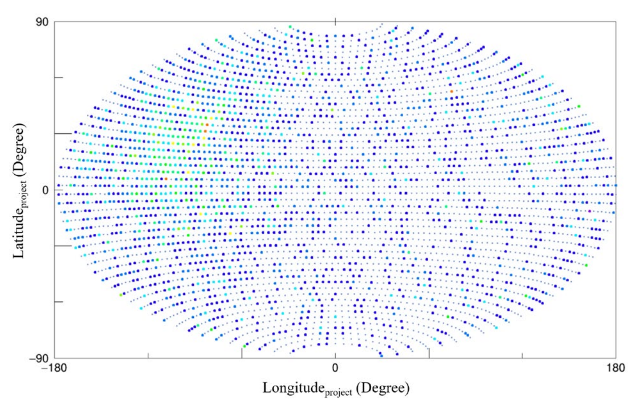

Fig. 8 (Color online) 2D projection view of an event in CD. Each maker represents a SiPM with different colors indicating the different number of photon hits on it

researchers to swiftly discern critical features and patterns within the data. By displaying and analyzing the events from the reactor in real time, researchers can perform timely modifications to the experimental parameters and data collection strategy and optimize the detector performance to ensure high-quality experimental data acquisition.

Scan of rare signal events The TAO event-display software supports two modes of visualization: 3D display and 2D projection, as shown in Figs. 6 and 8. After the removal of a significant portion of the background, which includes ambient neutrons induced by cosmic-ray muons and radioactive backgrounds from the environment [52, 53], rare signal events, such as reactor antineutrino events and other signal neutrinos [14], can be displayed within the detector in both visualization modes. This facilitates an intuitive understanding of the physical processes to aid the analysis of rare events. The ultimate performance of the detector relies on event reconstruction. To satisfy the requirements of the ultrahigh-energy resolution of the TAO, it is necessary to fully utilize the charge and time information from the SiPM and employ additional new technologies for reconstruction [54, 55]. The event display supports the intuitive reconstruction of the vertex and energy within the detector for comparison, as shown in Fig. 7.

Nuclear power plant monitoring As a neutrino detector located close to the Taishan NPP, the TAO can also serve as an NPP-monitoring apparatus. Visualization software will be instrumental in monitoring the operation, not only for the TAO but also for the NPP [16, 17]. Because of the advantages of monitoring a single reactor and the superb energy resolution of $<2\%$ at 1 MeV [1], the TAO experiment and its visualization tool provide a novel and unique approach for NPP monitoring in addition to the currently existing tools.

Future developments An event display based on the ROOT is integrated into the offline software system as a module, which is commonly set up on servers running the LINUX operating system. Furthermore, JUNO has developed event-display software using ROOT and Unity [31, 32]. Unity is adaptable for multi-platform use, including Windows, LINUX, MacOS, and web browsers. For TAO, visualization can also be developed using Unity and Virtual Reality(VR) applications [56]. More efforts are expected to implement the Unity-based event display for TAO, including automatic detector geometry conversion [57] and event data conversion from the ROOT format generated in the offline software to the format readable by Unity.

5 Performance

In experimental evaluations conducted on a local computing system equipped with an Intel Core i7 CPU, the TAO event-display software demonstrated sufficient computational power to effectively process standard IBD events, achieving a display refresh rate exceeding 10 frames per second. The typical memory usage for visualizing IBD events in a TAO event display was approximately 890 MB, encompassing the import and display of simulation, calibration, and reconstruction data files. Nevertheless, the operational efficiency of the software when accessed remotely is significantly contingent upon the latency experienced by users and the computing server.

Scientific Linux is the predominant platform utilized for executing TAO offline software, and event-display software has undergone rigorous testing and exhibits robust performance on remote client systems such as Linux, Windows, and Mac. The event-display software was incorporated into the TAO offline software framework, enabling streamlined interfacing with the online DAQ system for real-time monitoring and event visualization following the requisite adaptations.

6 Summary

The visualization technique is a valuable tool for HEP detector design, offline software development, and data acquisition. It can be utilized as an online data-monitoring tool during data acquisition and plays an important role in enhancing the performance of detector simulation, reconstruction, and physics data analysis. As a detector situated in close proximity to the reactor, the visualization of the JUNO-TAO can serve research needs in neutrino physics and aid users in monitoring the operation of NPP.

With the construction of the JUNO-TAO experiment, the event-display software was successfully developed, and more features are expected to be added in future updates. Furthermore, Unity-based event-display software is also being designed and developed, with significant potential for developing more advanced features and applications, such as online monitoring and VR programs. Following the successful application of the visualization software for JUNO-TAO, the visualization software based on ROOT and Unity will be implemented in a broader range of future HEP experiments.

Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Ming-Hua Liao, Kai-Xuan Huang and Jia-Yang Xu. The first draft of the manuscript was written by Ming-Hua Liao, Yu-Mei Zhang and Zheng-Yun You, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data availability The data that support the findings of this study are openly available in Science Data Bank at https://cstr.cn/31253.11.sciencedb.j00186.00386 and https://doi.org/10.57760/sciencedb.j00186.00386

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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