

# Measurement of neutron production in atmospheric neutrino interactions at Super-Kamiokande

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We present measurements of neutron production from atmospheric neutrino interactions in water, analyzed as a function of the electron-equivalent visible energy over a range of 30 MeV to 10 GeV. These results are based on 4,270 days of data collected by Super-Kamiokande, including 564 days with 0.011 wt% gadolinium added to enhance neutron detection. The measurements are compared to predictions from neutrino event generators combined with multiple hadron-nucleus interaction models, which describe intranuclear hadron transport and subsequent nuclear de-excitation. Significant variations were observed in the predictions depending on the choice of hadron-nucleus interaction models. Among the models tested, our data favors models that predict relatively fewer secondary neutrons. We also discuss the model-specific features that contribute to these variations.

teraction cross sections and particle kinematics. Modeling these “nuclear effects” is particularly critical for GeV-scale neutrino experiments aiming to measure neutrino oscillation parameters, including CP violation and mass ordering. Outgoing hadrons serve as valuable probes of these effects, and advancements in neutrino detectors have enabled precise measurements of hadron multiplicities and kinematics. For instance, measurements of proton production in neutrino-argon interactions have revealed several discrepancies between observed and predicted kinematic distributions [1].

Detecting neutrons is challenging since they do not leave ionization tracks. Tracking detectors identify neutrons via displaced proton tracks, with detection efficiency limited by the small  $(n, p)$  reaction cross section [2]. This issue is critical with GeV-scale neutrino interactions, where neutrons often carry substantial energy. Misestimating this “missing energy” can bias key measurements, such as the Dirac CP phase [3].

Neutrons can also be detected via the radiative neutron capture  $(n, \gamma)$  reaction, which has no practical energy threshold. Neutrons with kinetic energies of a few MeV or lower are likely to thermalize, undergoing  $(n, \gamma)$  reactions with well-defined timescales and energy signatures that enable clean signal selection. This characteristic historically made neutrons effective tags for antineutrino charged-current (CC) interactions (e.g.,  $\bar{\nu}_\mu p \rightarrow \mu^+ n$ ) compared to neutrino interactions (e.g.,  $\nu_\mu n \rightarrow \mu^- p$ ) [4]. Neutron tagging remains relevant today, for instance, in atmospheric neutrino oscillation analyses, where it enhances sensitivity to both neutrino mass ordering and CP violation, by preventing the cancellation of opposite-sign effects in neutrino and antineutrino oscillation probabilities [5]. Additionally, neutron tagging helps suppress atmospheric neutrino backgrounds for rare events, such as proton decay (e.g.,  $p \rightarrow e^+ \pi^0$  [6]), which in many cases is not expected to produce neutrons, or inverse beta decay ( $\bar{\nu}_e p \rightarrow e^+ n$ ) induced by supernova  $\bar{\nu}_e$ , which typically produces only one neutron. Accurately predicting the number of detectable neutrons from neutrino interactions is crucial for these analyses and requires well-constrained uncertainties in interaction models.

The modeling approach commonly adopted by GeV-scale neutrino experiments is illustrated in Figure 1. Neutrino event generators simulate outgoing hadrons from the initial neutrino interaction, either at the nucleon or quark level, and subsequently model intranuclear hadron transport (often referred to as final-state interactions, or FSI), followed by nuclear de-excitation. Similarly, particle transport codes such as Geant4 [7–9] simulate hadron transport and nuclear de-excitation to describe downstream hadron-nucleus interactions within the detector.

Accurate prediction of the observable neutron multiplicity requires careful consideration of secondary neutron production. For hadron transport in the  $O(0.1\text{--}1)$  GeV energy range, semi-classical Intranuclear Cascade (INC) models [10] are commonly used. These models approximate the process as a series of binary collisions be-

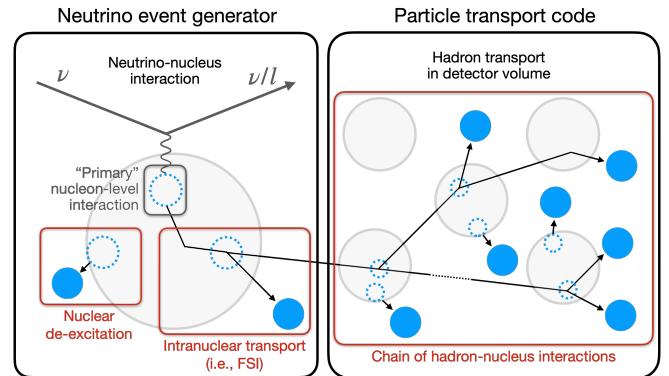


FIG. 1. Schematic of sources of nucleon production in a typical GeV-scale neutrino event simulation setup. Dashed blue circles represent nucleon holes, black arrows represent nucleon trajectories, and solid blue circles represent detectable nucleons ejected from nuclei.

tween a hadron projectile and a quasi-free nucleon within the target nucleus. Subsequent nuclear de-excitation involves an evaporation process that releases neutrons with kinetic energies of a few MeV and also contributes significantly to neutron production at lower energies. Notably, variations in how these models account for nuclear effects often lead to significant discrepancies in predictions [11]. Several studies have measured neutron production from atmospheric or artificial neutrino interactions using water (T2K [12]), heavy water (SNO [13]), and hydrocarbon (MINERvA [14, 15], KamLAND [16]) as target materials. Several of these studies [12, 14, 15] reported deficits in observed neutron signals compared to predictions from neutrino event generators, with the discrepancies often attributed to the inaccuracy of hadron transport models.

In this paper, we present a measurement of neutron production following atmospheric neutrino interactions in water. Using data from events fully contained within the Super-Kamiokande detector from 2008 to 2022, we evaluated the average multiplicity of  $(n, \gamma)$  reactions (or “neutron captures”) as a function of electron-equivalent visible energy, a calorimetric proxy for neutrino momentum transfer. These observations were compared with predictions generated using various models relevant to secondary neutron production.

This paper is structured as follows. Section II provides a brief overview of the SK detector. The selection process for atmospheric neutrino events and neutron signals, along with the estimation of selection performance, are detailed in Sections III and IV. Section V outlines the methodology for determining the average  $(n, \gamma)$  multiplicity per visible energy bin and the associated systematic uncertainties. Section VI introduces the interaction models used for generating predictions. Finally, Sections VII and VIII present a comparison of observations with predictions and discuss the implications of the results.

TABLE I. SK operational phases and neutron-related characteristics. SK-IV, V, VI data were used in this analysis.

Phase	Dates	Livetime [days]	Gd concentration <sup>a</sup> [wt%]	H( $n, \gamma$ ) [%]	Expected ( $n, \gamma$ ) ratio <sup>b</sup> H( $n, \gamma$ ) [%]	Gd( $n, \gamma$ ) [%]	( $n, \gamma$ ) time constant <sup>c</sup> [μs]
SK-I-III	1996-2008	2805.9	-	>99.9	-	-	No data
SK-IV	2008-2018	3244.4	-	>99.9	-	-	204.8 ± 9.8
SK-V	2019-2020	461.0	-	>99.9	-	-	199.8 ± 10.2
SK-VI	2020-2022	564.4 <sup>d</sup>	0.0110 ± 0.0001 [18]	56.1 ± 1.5	43.9 ± 1.5	116.2 ± 2.3	
SK-VII-VIII	2022-present	-	0.0332 ± 0.0002 [19]	29.7 ± 0.7	70.3 ± 0.7	61.8 ± 0.1 [19]	

<sup>a</sup> Based on the amount of dissolved Gd.

<sup>b</sup> Based on the evaluated thermal ( $n, \gamma$ ) reaction cross sections and uncertainties of ENDF/B-VII.1 [17].

<sup>c</sup> Weighted mean of all Am/Be neutron source measurements, explained in Section IV B.

<sup>d</sup> Excludes earlier runs which showed signs of non-uniform Gd concentration, i.e., varying time constant by position.

## 209 II. THE SUPER-KAMIOKANDE DETECTOR

210 Super-Kamiokande (SK) [20] is an underground water  
 211 Cherenkov detector located in Gifu, Japan. It consists of  
 212 two optically separated, concentric cylindrical volumes:  
 213 the inner detector (ID) containing 32.5 ktons of water  
 214 and equipped with 11,129 inward-facing photomultiplier  
 215 tubes (PMTs) and the outer detector serving as a cosmic-  
 216 ray veto. The detector registers a PMT signal with a  
 217 pulse height greater than 0.25 photoelectron-equivalent  
 218 charge as a “hit”. If the number of ID or OD PMT hits  
 219 within a 200-ns sliding time window ( $N_{200\text{-ns}}$ ) exceeds a  
 220 given threshold, an event trigger is issued. The details of  
 221 the detector can be found in [20, 21].

222 Charged particles, namely electrons and muons pro-  
 223 duced by charged-current neutrino interactions, are iden-  
 224 tified through Cherenkov radiation. The radiation is pro-  
 225 jected onto the PMTs as a characteristic ring pattern  
 226 that depends on the particle type and energy. This ring  
 227 pattern serves as the basis for particle reconstruction.  
 228 Neutrons are indirectly identified via Compton-scattered  
 229 electrons resulting from ( $n, \gamma$ ) reactions. In pure water,  
 230 most occur on  $^1\text{H}$ , emitting a single 2.2 MeV gamma-  
 231 ray. With the recent addition of gadolinium (Gd), the  
 232 majority of neutrons are expected to be captured by Gd  
 233 isotopes, resulting in a total gamma-radiated energy of  
 234 around 8 MeV.

235 The  $O(1)$  MeV signal identification performance is sig-  
 236 nificantly influenced by variations in detector character-  
 237 istics. Parameters such as individual PMT gain, tim-  
 238 ing properties, quantum efficiency, and optical absorption  
 239 and scattering in water are continuously monitored using  
 240 cosmic-ray muons and light sources [21]. Additionally,  
 241 the uncertainty in Cherenkov ring energy reconstruc-  
 242 tion (described in Section III B) is evaluated over a wide en-  
 243 ergy range using naturally occurring particles, including  
 244 cosmic-ray muons, Michel electrons, and neutral pions  
 245 produced in neutral-current (NC) atmospheric neutrino  
 246 interactions in water. Figure 2 illustrates the agreement  
 247 between data and simulation in energy reconstruction for  
 248 the Gd-loaded SK-VI phase, which is mostly within 2%  
 249 across the  $O(10\text{-}10^4)$  MeV range and consistent with the  
 250 pure water phase results reported in [5].

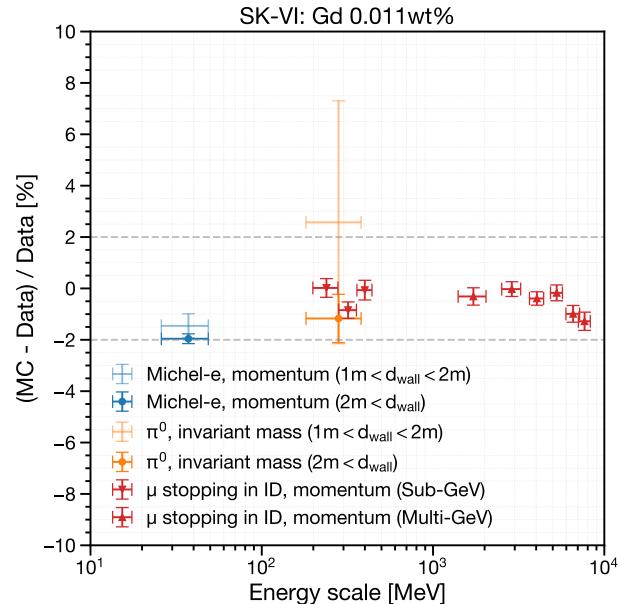


FIG. 2. Comparison of energy reconstruction performance between Monte Carlo (MC) simulation and observed data for naturally occurring particles in the Gd-loaded SK-VI phase. The variable  $d_{\text{wall}}$  represents the distance (in meters) from the reconstructed vertex to the nearest ID photodetector wall. The fiducial volume for this study is defined as  $d_{\text{wall}} > 1$  m.

The detector has operated through eight different phases. Neutron detection began with the fourth phase SK-IV, following the electronics upgrade [22] that allowed extended event recording up to 535 μs after certain ID triggers. This has enabled analysis of delayed neutron captures that occur with a time scale of  $O(10\text{-}100)$  μs following an atmospheric neutrino interaction. Between SK-IV and SK-V, in 2018, the detector underwent refurbishment, during which malfunctioning PMTs were replaced. The later phases, SK-VI, SK-VII, and SK-VIII involved the dissolution of  $\text{Gd}_2(\text{SO}_4)_3$  into the water volume to enhance neutron detection efficiency [18, 19]. Table I summarizes the relevant operational conditions.

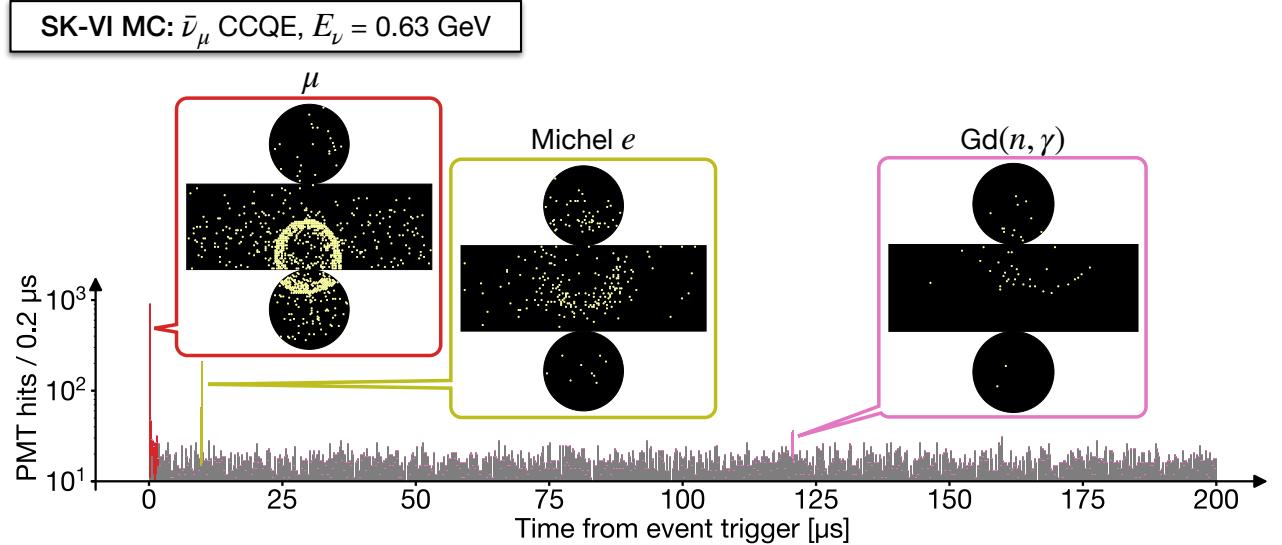


FIG. 3. A PMT hit time distribution for a typical  $\bar{\nu}_\mu$  charged-current (CC) quasi-elastic (QE) interaction with a muon and a neutron as final states. The zero is set at the event trigger. The event displays feature the “prompt” muon signal (red) and the two types of “delayed” coincident signals — Michel electrons from muon decay (olive) and neutron captures on Gd (pink). The gray bars represent randomly recorded background PMT hits. This event was simulated in the SK-VI configuration.

### 265 III. ATMOSPHERIC NEUTRINO EVENTS

#### 266 A. Data reduction

267 We followed a typical selection process for atmospheric  
268 neutrino interactions that are fully contained within the  
269 ID, similar to previous studies conducted at SK [5]. All  
270 events were required to pass the ID trigger with the  
271 threshold  $N_{200\text{-ns}} \geq 58$  PMT hits—roughly correspond-  
272 ing to a 10 MeV electron—followed by the extended 535  
273  $\mu\text{s}$  event window for neutron detection. Background  
274 events arising from cosmic-ray muons, low-energy ra-  
275 dioactivity, and neutrino events with particles exiting the  
276 tank were reduced through OD veto and ID charge cuts.  
277

278 Selected events were reconstructed as described in Sec-  
279 tion III B. To further reject low-energy backgrounds, we  
280 required that the reconstructed vertex be more than 1 m  
281 away from the ID tank wall (defining the fiducial volume  
282 with 23.2 kton of water) and that the visible energy be  
283 larger than 30 MeV. The remaining background contam-  
284 ination, mainly due to corner-clipping cosmic-ray muons  
285 and PMT discharges, was estimated to be below 0.2%,  
286 based on visual inspection [6].

#### 286 B. Reconstruction of prompt Cherenkov rings

287 Figure 3 shows a PMT hit time distribution of a typi-  
288 cal  $\bar{\nu}_\mu$  charged-current (CC) quasi-elastic (QE) event fol-  
289 lowed by a Michel electron and a  $\text{Gd}(n, \gamma)$  reaction, along  
290 with the corresponding event displays. For the “prompt”  
291 radiation due to charged particles (namely, electrons and  
292

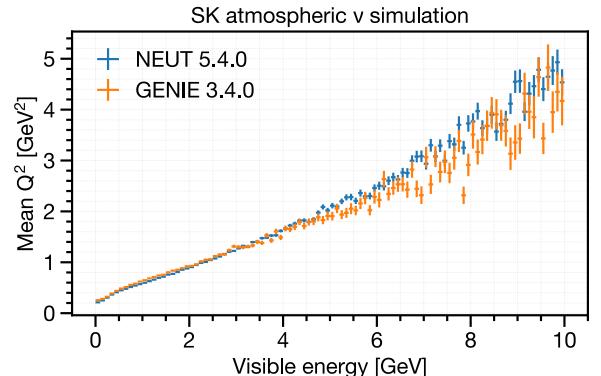


FIG. 4. Average squared momentum transfer ( $Q^2$ ) per visible energy bin for simulated atmospheric neutrino events at SK, compared between two different neutrino event genera-  
tors. NEUT 5.4.0 (blue) uses the baseline setup described in  
Section III C, while GENIE 3.4.0 [23–25] uses the “hN” setup  
as described in Section VI.

293 muons) produced via the primary neutrino interaction,  
294 we followed the typical Cherenkov ring reconstruction  
295 process [26] as applied in previous SK analyses [5, 6].

296 The visible energy of an event is defined as the sum of  
297 the reconstructed kinetic energies of all Cherenkov rings,  
298 assuming each ring originates from an electron. This  
299 calorimetric measure serves as a reliable proxy for neu-  
300 trino momentum transfer, as demonstrated by the pos-  
itive correlation shown in Figure 4.

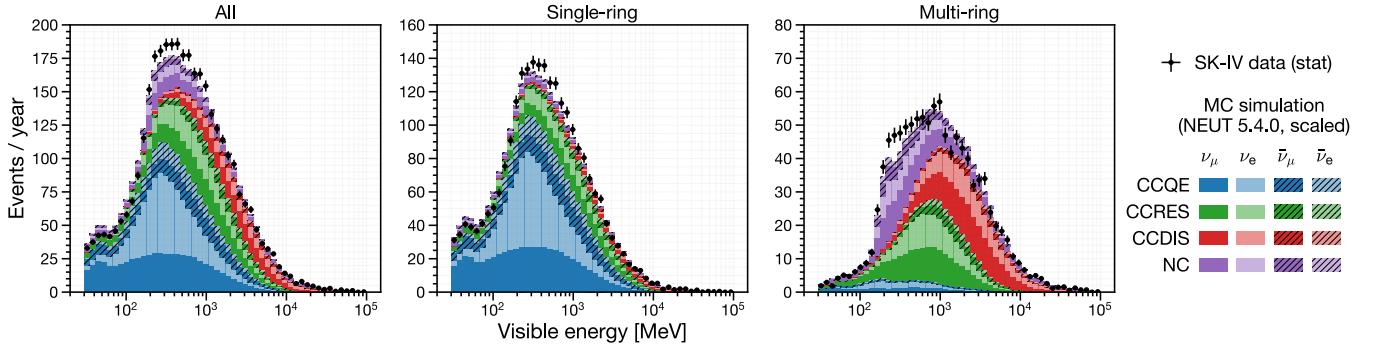


FIG. 5. Visible energy distributions for observed and simulated atmospheric neutrino interactions in water, fully contained within the fiducial volume: all events (left), events with one reconstructed Cherenkov ring (middle), and events with two or more rings (right). CCQE events dominate the single-ring sample, while RES and DIS events dominate the multi-ring sample. The simulation setup is detailed in Section III C. Simulated distributions are scaled to match the SK-IV data to account for neutrino flux uncertainties.

### C. Baseline simulation setup

The simulation of atmospheric neutrino events involves a convolution of the atmospheric neutrino flux, neutrino event generator, and detector simulation.

To determine the incoming neutrino kinematics and event rate, we used atmospheric flux calculations for  $\nu_e$ ,  $\nu_\mu$ ,  $\bar{\nu}_e$ , and  $\bar{\nu}_\mu$  at the detector site, assuming no oscillations, as provided by Honda et al. [27] for neutrino energies ranging from 100 MeV to 10 TeV. Interactions of  $\nu_\tau$  and  $\bar{\nu}_\tau$  were not simulated.

Neutrino interactions in water were modeled using neutrino event generators [28], which compute the cross sections for each interaction channel and sample outgoing particle kinematics. NEUT 5.4.0 [29] was used as the baseline event generator. It covers major interaction channels, including QE scattering with single (1p1h) or double (2p2h) nucleon knockout, single pion production due to  $\Delta$  resonance (RES), and multiple pion production via deep inelastic scattering (DIS). The models used are consistent with the latest SK atmospheric neutrino oscillation analysis [5].

The transport of hadronic final states within the target nucleus (FSI) was modeled separately from the primary neutrino interaction. The transport of low-momentum ( $< 500$  MeV/c) pions was based on Salcedo et al. [30] with parameters tuned to fit external pion-nucleus scattering data [31]. For higher energy nucleons and pions, FSIs were modeled using the INC approach, which includes elastic scattering and single/double pion production. The cross sections for reactions with free target nucleons were sourced from Bertini [32] for nucleon projectiles and from external pion scattering data for high-momentum pion projectiles [33]. The de-excitation of an oxygen target was modeled using tabulated occupation probabilities for nucleon energy states [34] and branch ratios for knockout of each state [35].

The subsequent particle transport in water and detector responses were simulated using GCALOR [36] cou-

pled with Geant3.21 [37]. Propagation of nucleons and charged pions below 10 GeV was simulated based on the Bertini cascade model [38]. For cross sections, GCALOR uses ENDF/B-VI [39] for low-energy (below 20 MeV, or 195 MeV/c in momentum) neutrons, and Bertini-based tabulation [38] for the remaining nucleons and charged pions. The transport of low-momentum pions was separately modeled using the NEUT pion FSI routine to ensure consistency between NEUT and Geant3.

For the transport of low-energy neutrons in the Gd-loaded SK-VI phase, we imported reaction cross sections from the Geant4.10.5.p01 [7–9] NeutronHP database [40] based on ENDF/B-VII.1 [17], replacing ENDF/B-VI for neutron energies below 20 MeV. Additionally, we modeled the gamma-cascade resulting from neutron captures on  $^{155}/^{157}\text{Gd}$  using the ANNRI-Gd model [41, 42].

The characteristics of individual PMTs and the optical parameters in water were adjusted to align with calibration data obtained from light sources and through-going cosmic-ray muons. To accurately account for detector noise, randomly recorded PMT hits were included as background, represented as gray bars in Figure 3.

500 years of atmospheric neutrino events were simulated for each SK phase and processed as described in Sections III B and III A. The events in the final sample were weighted based on the standard three-flavor oscillation probability in matter [43], using the oscillation parameters fitted with reactor constraints in the previous SK analysis [44] and the PREM model [45] for Earth’s matter density. Corrections for atmospheric neutrino flux accounting for solar activity were also applied.

Figure 5 shows the visible energy distributions of the simulated event sample, demonstrating reasonable agreement with the observations. Single-ring events exhibit a higher fraction of QE interactions and a smaller fraction of DIS compared to multi-ring events. For the same visible energy, multi-ring events are expected to produce more secondary neutrons than single-ring events, due to a higher fraction of DIS interactions.

378 **IV. NEUTRON SIGNAL SELECTION** 432

379 Neutrons produced by atmospheric neutrino interactions in the SK ID are primarily captured by  $^1\text{H}$  or 434  
 380  $^{155}/^{157}\text{Gd}$  isotopes within approximately  $O(100)$   $\mu\text{s}$ , with 435  
 381 expected capture ratios summarized in Table I. Electrons 436 that are scattered by the  $O(1)$  MeV gamma-rays generate 437 Cherenkov photons that form faint rings on the ID tank wall 438 (hereafter referred to as “neutron signal”), as shown in Figure 3. 439

387 Fast neutrons, along with the subsequent gamma-rays 440 and scattered electrons, typically travel only a few tens 441 of centimeters in water. Thus, signal photons can be approximated as originating from a single vertex. While 442 reconstructing this vertex is challenging due to the limited 443 number of PMT hits, *assuming* it to be near another known 444 vertex, such as the reconstructed neutrino interaction 445 vertex, helps identify signals from random PMT coincidences 446 caused by dark current. Remaining Michel electrons from muon decays can be effectively suppressed 447 through cuts based on signal timing and energy. 448

450 **A. Signal selection algorithm** 451

399 The signal selection algorithm is based on Ref. [46], 452 and consists of two stages. 453

401 In the first candidate search stage, we initially subtract 455 the expected photon time-of-flight (ToF) from the individual 456 PMT hit times for a given *assumed* signal vertex, 457 which was provided by the reconstructed neutrino event 458 vertex. Then, we slide a time window of 14 ns width 459 on the ToF-corrected PMT hit times to trigger on the 460 number of included PMT hits. The threshold was 5 for 461 pure water phases SK-IV and V, and 7 for the Gd-loaded 462 phase SK-VI. The search span for each event was [18, 534] 463  $\mu\text{s}$  from the event trigger for SK-IV and V, and [3, 534] 464  $\mu\text{s}$  for SK-VI with a shorter neutron capture time. For 465 overlapping candidates within 50 ns, only the candidate 466 with the largest number of PMT hits is selected. 467

468 In the second candidate classification stage, we extract 469 features of each candidate and use a neural network to 470 classify each candidate into signal and noise based on 471 input features. These features characterize the signal 472 energy, the background hit level, timing spread assuming 473 the vertex, correlation between the input vertex and the 474 hit PMT positions, correlation to the known properties 475 of PMT noise, and angular correlation among hit PMTs 476 relative to the Cherenkov cone opening angle. 477

478 The major changes from the original algorithm [46] include 479 a simplified algorithm, a reduced set of features, 480 and a heuristically tuned neural network architecture. 481 These modifications aim to reduce performance bias between 482 the data and the simulation that is used to train 483 the neural networks. 484

485 Here, we provide the definition and unit of each feature 486 used for the classification of signal candidates, along with 487 their expected distributions as shown in Figure 6. 488

- **NHits**

The number of selected PMT hits within the 14-ns sliding time window.

- **NResHits**

The number of PMT hits within [-100,+100] ns from the center of the 14-ns sliding time window, subtracted from NHits.

- **TRMS** [ns]

The root mean square (RMS) of the ToF-corrected time distribution of the selected PMT hits.

- **FitGoodness**

The normalized likelihood of the ToF-corrected time distribution of the selected PMT hits, given the *assumed* signal vertex and the Gaussian PMT timing resolution of 5 ns.

- **DWall** [cm]

The distance from the *assumed* signal vertex to the nearest tank wall.

- **DWallMeanDir** [cm]

The shorter of the radial and vertical distances from the *assumed* signal vertex to the tank wall, weighted by the mean of the unit vectors connecting the vertex to each hit PMT.

- **BurstRatio**

The ratio of the selected PMTs with a preceding hit within 10  $\mu\text{s}$ , which are likely caused by scintillation within the irradiated PMT glass.

- **DarkLikelihood**

The normalized log likelihood ratio based on measured individual PMT dark rates, given by:

$$\text{DarkLikelihood} = \sigma \left( \log \prod_{i=1}^{\text{NHits}} \frac{r_i}{\langle r \rangle} \right) \quad (1)$$

where  $\sigma$  represents the sigmoid function,  $r_i$  is the dark rate of the  $i^{\text{th}}$  PMT, and  $\langle r \rangle$  is the average dark rate of all ID PMTs.

- **OpeningAngleStdev** [deg]

The standard deviation of the opening angles of cones formed by every possible combination of three hit PMTs and the *assumed* signal vertex.

- **Beta(k)**,  $k \in \{1, 2, 3, 4, 5\}$

$$\text{Beta}(k) = \frac{2}{\text{NHits}(\text{NHits} - 1)} \sum_{i \neq j} P_k(\cos \theta_{ij}) \quad (2)$$

where  $P_k$  is the  $k^{\text{th}}$  Legendre polynomial and  $\theta_{ij}$  is the opening angle between the assumed signal vertex and the  $i^{\text{th}}$  and  $j^{\text{th}}$  hit PMTs.

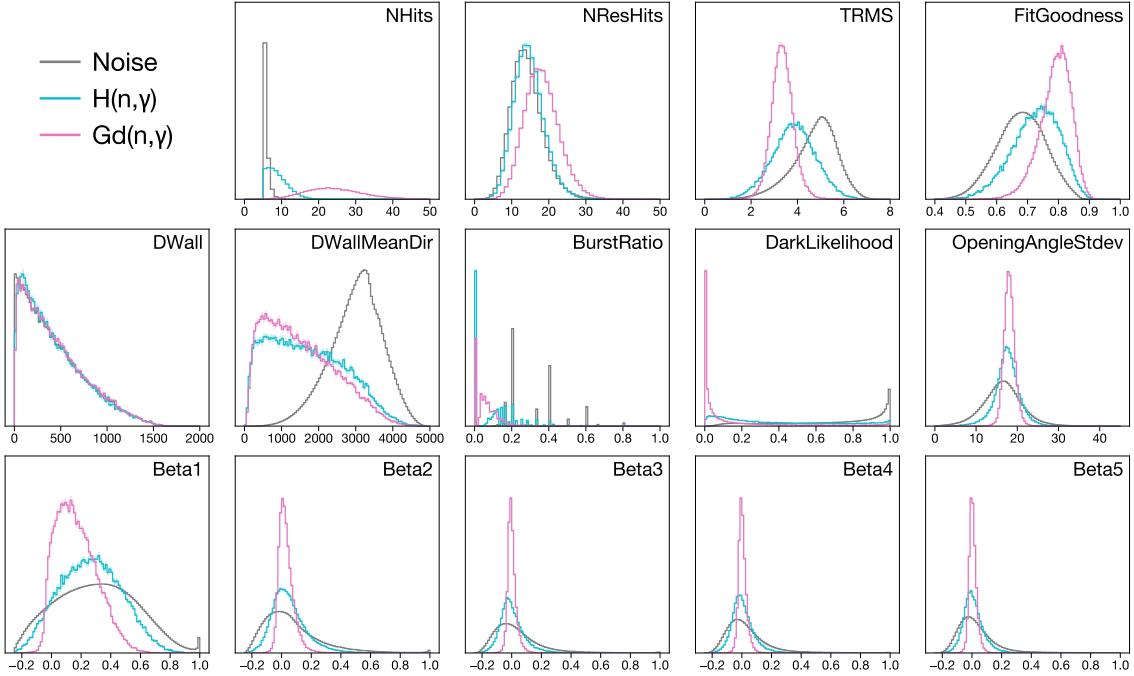


FIG. 6. The features (area-normalized) of neutron signals and noise from the thermal neutron MC simulation used for training the neural network for SK-VI phase.

For training the neural network, we utilized the features and labels of first-stage candidates from a particle-gun simulation of thermal neutrons, with vertices randomized within the ID. Each first-stage candidate, as shown in Figs. 6 and 7, was labeled as signal if it was triggered within 50 ns of the simulated  $(n, \gamma)$  reaction, and otherwise as background. Of the training dataset, 80% was used for updating the neural network weights, while the remaining 20% was reserved for validation.

We implemented a feed-forward fully connected neural network using Keras 2.6.0 [47]. The network consisted of an input layer with 14 features, followed by three dense layers, each comprising 128 ReLU-activated nodes with a 50% dropout rate, and a single sigmoid output node. Weights and biases were initialized following He et al. [48] and optimized by minimizing the binary cross-entropy loss iteratively on minibatches of size 2,048 using the Adam optimizer [49]. The initial learning rate was set to 0.0001. Training was stopped when signal efficiency on the validation set showed no improvement for 5 consecutive epochs. A neural network was trained for each SK phase: SK-IV, SK-V, and SK-VI.

Candidates with a neural network output greater than 0.7 were classified as signals, while those with a large number of PMT hits ( $\text{NHits} > 50$ ) and occurring earlier than the typical neutron capture timescale ( $< 20 \mu\text{s}$ ) were identified as Michel electrons and excluded. The effectiveness of this Michel electron rejection is illustrated in Figure 7. When applied to cosmic-ray muons decaying within the ID, the selection achieved an efficiency of  $98.4 \pm 1.3\%$  and a purity of  $98.7 \pm 0.5\%$ .

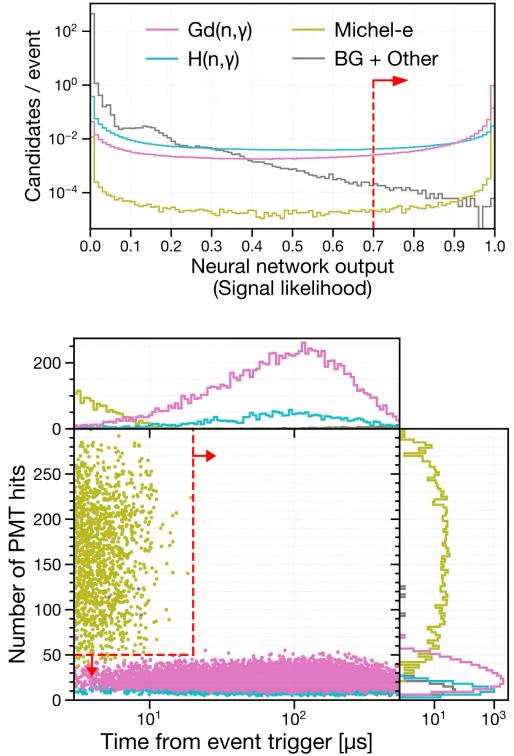


FIG. 7. The neural network response to neutron signals and backgrounds in the SK-VI atmospheric neutrino simulation (top), and the time versus energy distribution of signal candidates passing the neural network selection (bottom). Red arrows indicate the corresponding cut points.

## 506 B. Signal selection performance on calibration data

507 An Am/Be neutron source with a measured total intensity  
 508 of  $236.8 \pm 5.0$  neutrons/s [50] was used to obtain cal-  
 509 ibration data for estimating the signal detection perfor-  
 510 mance. The first excited state of the alpha-absorbed  ${}^9\text{Be}$ ,  
 511 with a roughly 60% branching ratio, emits a fast neutron  
 512 and a 4.44 MeV gamma-ray simultaneously. This source  
 513 was encapsulated with Bismuth Germanate ( $\text{Bi}_4\text{Ge}_3\text{O}_{12}$ ,  
 514 BGO) crystals so that the 4.44 MeV gamma-rays can  
 515 induce scintillation. The setup was deployed in various  
 516 positions within the ID, and events were recorded for 30  
 517 minutes to 1 hour. Events with a trigger charge yield  
 518 corresponding to the 4.44 MeV gamma-ray scintillation  
 519 were regarded as the single neutron control sample.

520 The observed light yield distribution was compared  
 521 with dedicated simulation, as shown in Figure 8. The  
 522 simulation accounts for continuous source activity and  
 523 pile-up, by reorganizing the simulated detector response  
 524 to Am/Be neutron emission on a single global time axis,  
 525 based on the measured total neutron intensity and the es-  
 526 timated branching ratios to each excited state of alpha-  
 527 absorbed  ${}^9\text{Be}$ . As shown in Figure 8, this simulation  
 528 accurately models event triggers due to ambient neutron  
 529 captures and neutron inelastic interactions within scintil-  
 530 lator crystal. The contamination of such unwanted event  
 531 triggers in the 4.44 MeV gamma-ray event selection was  
 532 estimated to be at a few percent level.

533 Within the selected events in the single neutron con-  
 534 trol sample, signal candidates were obtained following the  
 535 algorithm described in Section IV A, with the *assumed*  
 536 signal vertex set at the source position.

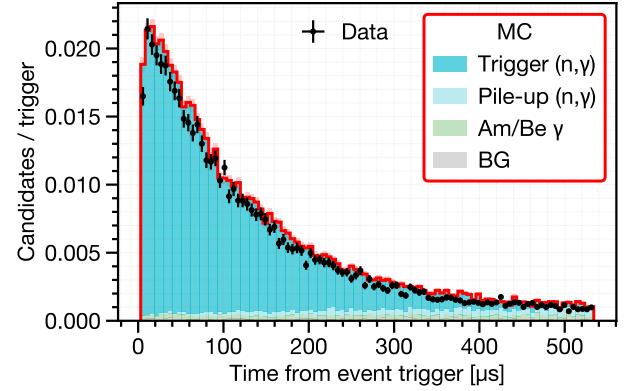


FIG. 9. Exponential decrease of the selected neutron signal candidates as a function of the time from the selected event triggers with the Am/Be neutron source positioned near the ID tank center, in the SK-VI phase. The label “Trigger ( $n, \gamma$ )” indicates captures of neutrons that are produced within 350 ns from the event trigger, while the label “Pile-up ( $n, \gamma$ )” indicates captures of piled-up neutrons without such correlation to the event trigger.

Figure 9 shows an example time distribution of the selected signal candidates. Such distributions of the time  $t$  were fitted with a function  $f$  of the form:

$$f(t) = A(1 - e^{-t/\tau_{\text{thermal}}})e^{-t/\tau_{\text{capture}}} + B \quad (3)$$

where the normalization constant  $A$ , the background constant  $B$ , the neutron thermalization time scale  $\tau_{\text{thermal}}$ , and the neutron capture time constant  $\tau_{\text{capture}}$  are free parameters. The signal efficiency was evaluated as the number of identified signals per selected event triggers, corrected by the constant background term  $B$ . Figure 10 shows the estimated neutron detection efficiencies for various source positions in the ID.

The major sources of systematic uncertainty are summarized in Table II. In the pure water phases (SK-IV and V), the dominant source of uncertainty lies in the potential bias caused by the calibration setup, such as the unwanted event triggers or time correlation of false positives to event triggers, often leading to an overestimation of the background constant  $B$ . The size of this uncertainty was conservatively estimated by comparing the true and estimated signal efficiencies from the simulations and quantifying the fluctuation within each SK phase. In the Gd-loaded phase (SK-VI), the dominant source of uncertainty is in the fraction and the  $\gamma$  emission model of the  $Gd(n, \gamma)$  reaction. The size of these uncertainties is estimated based on the evaluated thermal neutron capture cross-section uncertainties in ENDF/B-VII.1, as well as variations in the estimated signal efficiency when using an alternative photon strength function to describe the Gd continuum gamma cascade in the ANNRI-Gd model [41].

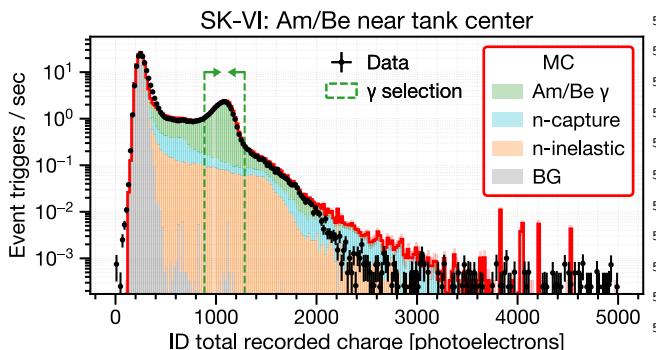


FIG. 8. Distribution of recorded charge within the time window  $[-0.5, 1.0]$   $\mu\text{s}$  relative to event triggers, measured with an Am/Be neutron source positioned near the ID tank center. The black points represent SK-VI data, while the red line shows the simulated prediction. The green dashed arrows indicate the selection window for 4.44 MeV gamma-ray induced scintillation. Roughly 95% of the selected events are attributed to gamma-rays from the Am/Be source (green), with the remaining 5% arising from ambient neutron captures (blue) and neutrons inelastically producing charged particles in the scintillator (orange). The contribution from background events (labeled “BG,” gray) is negligible.

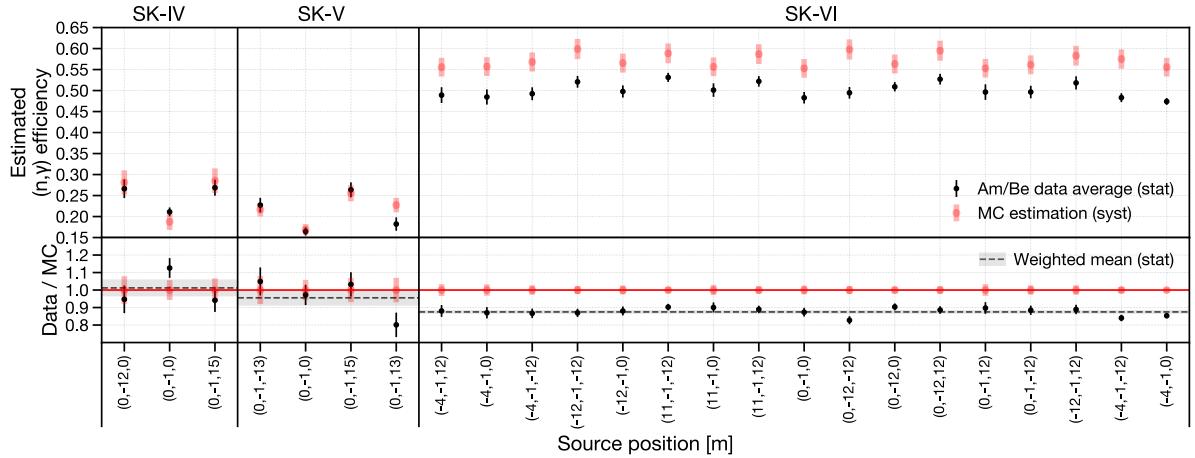


FIG. 10. Estimated  $(n, \gamma)$  signal selection efficiency for each calibration position within the tank. For positions in SK-VI where there are multiple measurements at different dates, the estimated efficiencies were averaged. The systematic uncertainties considered for MC simulation are summarized in Table II.

TABLE II. Major sources of systematic uncertainty in the neutron detection efficiency estimated with the Am/Be neutron source.

Source	SK-IV	SK-V	SK-VI
Am/Be neutron characterization	0.5%	0.9%	0.5%
Detector response	2.2%	3.3%	1.2%
Bias due to calibration setup	6.9%	4.6%	1.1%
Gd( $n, \gamma$ ) fraction	-	-	2.1%
Gd( $n, \gamma$ ) $\gamma$ emission model	-	-	2.6%
Total	7.3%	5.7%	3.8%

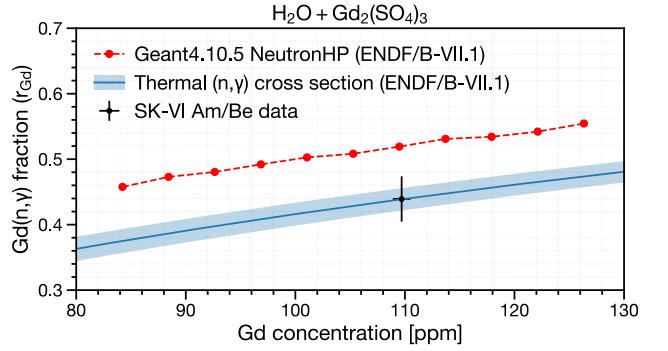


FIG. 11. Predicted Gd( $n, \gamma$ ) fraction in Gd-loaded water as a function of Gd concentration, compared with SK-VI Am/Be data (black). The red dots represent predictions by MC simulation using the NeutronHP model in Geant4.10.5.p01 with neutron cross sections from ENDF/B-VII.1, while the blue line and shades represent evaluation of Equation 4 based on the evaluated thermal  $(n, \gamma)$  cross sections and uncertainties in ENDF/B-VII.1.

The noticeable difference between the observed and predicted signal efficiencies in SK-VI is thought to stem from the overestimation of the Gd( $n, \gamma$ ) fraction in our MC simulation setup. Figure 11 compares the MC-simulated Gd( $n, \gamma$ ) fraction  $r_{\text{Gd}}$  with the analytically evaluated fraction, assuming completely thermalized neutrons:

$$r_{\text{Gd}} \approx 1 - r_{\text{H}} \approx 1 - \frac{n_{\text{H}} g_{\text{H}}(T) \sigma_{\text{H}}(v_{\text{thermal}})}{\sum_i n_i g_i(T) \sigma_i(v_{\text{thermal}})} \quad (4)$$

Here, for the  $i^{\text{th}}$  isotope,  $n_i$  is the number density,  $g_i(T)$  is the Westcott  $g$ -factor for temperature  $T$ , and  $\sigma_i(v_{\text{thermal}})$  is the neutron capture cross section evaluated at thermal neutron speed  $v_{\text{thermal}} = 2200$  m/s.

The value estimated with SK-VI Am/Be data agrees well with the analytical evaluation based on  $g_i$  and  $\sigma_i$  from ENDF/B-VII.1 [51], while both differ from the MC simulation using Geant4.10.5.p01 NeutronHP and ENDF/B-VII.1. The reason seems to be that it considers the thermal motion of hydrogen as free rather than bound in a water molecule [52], thus underestimating the fraction of  ${}^1\text{H}(n, \gamma)$  that competes with the Gd( $n, \gamma$ ) reaction.

To account for such a difference between signal efficiencies evaluated with Am/Be data and MC simulation, we used the weighted mean of the ratios of the two evaluated at all Am/Be source positions as the correction factor. The obtained efficiency correction factor was  $1.01 \pm 0.04$  for SK-IV,  $0.96 \pm 0.04$  for SK-V, and  $0.88 \pm 0.01$  for SK-VI, including both statistical and systematic errors.

The average neutron capture time constants were measured as  $200.4 \pm 3.7$   $\mu\text{s}$  for the pure water phase (SK-IV, V) and  $116.9 \pm 0.3$   $\mu\text{s}$  for the Gd-loaded phase (SK-VI). These results are consistent with ENDF/B-VII.1 predictions of  $204.7 \pm 5.3$   $\mu\text{s}$  and  $114.9 \pm 2.5$   $\mu\text{s}$ , where the errors are derived from evaluated cross section uncertainties. Relative to this, the Geant4 prediction for the Gd-loaded phase was  $112.4$   $\mu\text{s}$ .

## 604 V. $(n, \gamma)$ MULTIPLICITY ESTIMATION

605 The average multiplicity of  $(n, \gamma)$  reactions, or neu-  
 606 tron captures, is computed as the average of the ex-  
 607 pected number of  $(n, \gamma)$  reactions estimated on an event-  
 608 by-event basis, as follows:

$$639 \langle N \rangle = \left\langle \frac{N_i^{\text{detected}} - N_i^{\text{BG}}}{\epsilon_i} \right\rangle \quad 637$$

610 Here,  $N_i^{\text{detected}}$  is the count of detected signals,  $N_i^{\text{BG}}$   
 611 is the estimated number of false positives, and  $\epsilon_i$  is the  
 612 estimated signal detection efficiency of the  $i^{\text{th}}$  event.

613 Accurate estimation of  $N_i^{\text{BG}}$  and  $\epsilon_i$  is crucial. While  
 614 Am/Be calibration data provides a basis for these  
 615 estimates, additional factors in atmospheric neutrino  
 616 events—such as neutrino vertex reconstruction accuracy  
 617 and larger neutron kinetic energy—may significantly im-  
 618 pact the performance of signal selection. To better ac-  
 619 count for these effects in the calculation of  $N_i^{\text{BG}}$  and  $\epsilon_i$ ,  
 620 we trained Generalized Additive Models (GAMs) [53] on  
 621 default atmospheric neutrino event simulations. A total  
 622 of six GAMs were constructed across the three SK phases,  
 623 for two output metrics: signal efficiency and false positive  
 624 rate, using the `LinearGAM` class in pyGAM 0.9.0 [54].

625 The input features for the analysis included five re-  
 626 constructed neutrino event variables: visible energy,  
 627 Cherenkov ring multiplicity, the particle type of the most  
 628 energetic ring, and the radial and vertical displacements

629 of the neutrino interaction vertex. GAMs were fitted  
 630 against the distributions of the average simulated output  
 631 metric per bin in the five-dimensional feature space. No  
 632 assumptions were made regarding feature correlations,  
 633 and appropriate smoothing was applied to prevent over-  
 634 fitting. The  $1\sigma$  prediction interval was derived based on  
 635 the statistical uncertainties within each bin.

636 GAMs were trained on the baseline MC simulation,  
 637 as described in Section III C, and tested on a simula-  
 638 tion generated with NEUT 5.1.4, which predicts roughly  
 639 10% lower  $(n, \gamma)$  multiplicity overall. Figure 12 shows the  
 640 performance of the trained GAM in estimating the true  
 641 average signal multiplicity per visible energy bin. Com-  
 642 pared to using a single overall average metric for each of  
 643  $N_i^{\text{BG}}$  and  $\epsilon_i$ , the GAM performs better in reproducing  
 644 the true distribution, especially for multi-GeV bins.

645 The following major systematic uncertainties affecting  
 646 signal counting were evaluated on a bin-by-bin basis:

### (1) Overall signal efficiency scale

647 This includes uncertainties in calibrated efficiency cor-  
 648 rectation factors, as well as neutron momentum and de-  
 649 tector modeling, which are accounted for by compar-  
 650 ing the results across different SK phases as described  
 651 in Section VII.

### (2) Signal selection performance modeling (GAM)

652 This refers to potential errors in the regression model  
 653 used to describe the signal selection performance for  
 654 atmospheric neutrino events. The uncertainty is quan-  
 655 tified as the difference between the true and estimated  
 656 signal multiplicity in a test simulation setup, as shown  
 657 in Figure 12.

### (3) Neutrino event reconstruction

658 This assumes a uniform 2% visible energy resolution,  
 659 as described in Sec. II and Figure 2.

660 Figure 13 illustrates the distribution of fractional un-  
 661 certainties assigned to each visible energy bin. The most  
 662 dominant factor is the overall signal efficiency scale.  
 663

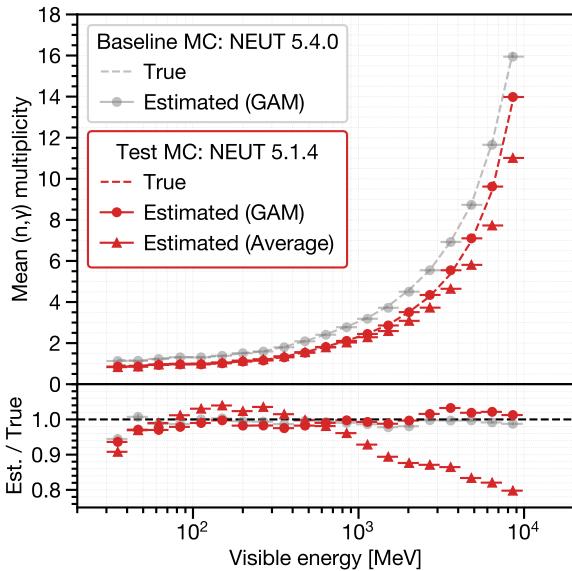


FIG. 12. Comparison of the true (dashed lines) and estimated (circle markers: using GAM, triangle markers: using the overall average signal efficiency and false positive rate) average  $(n, \gamma)$  multiplicity as a function of visible energy, for both baseline and test simulations of atmospheric neutrino events.

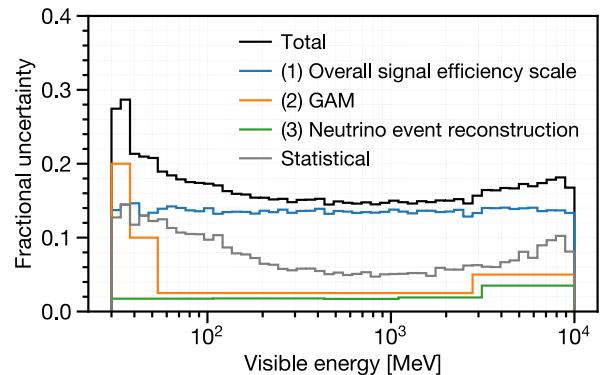


FIG. 13. Fractional uncertainties assigned to the estimated average  $(n, \gamma)$  multiplicity on a bin-by-bin basis.

## 666 VI. TESTED INTERACTION MODELS

667 To compare with the data, we generated predictions  
 668 for the average  $(n, \gamma)$  multiplicity as a function of visible  
 669 neutrino energy using various configurations of neutrino  
 670 event generators and secondary hadron-nucleus inter-  
 671 action models. Six setups of neutrino event generators were  
 672 tested: NEUT 5.4.0, NEUT 5.6.3, and GENIE 3.4.0 with  
 673 G\_18a\_10x\_02\_11b physics tunes [25], where  $x \in a, b, c, d$   
 674 represents FSI models: “hA” [24], “hN” [24], the Geant4  
 675 Bertini cascade model (“BERT”) [55], and the Liège INC  
 676 model (“INCL”) [56].

677 NEUT 5.4.0 was configured as described in Section  
 678 III C, while NEUT 5.6.3 used a modified nuclear bind-  
 679 ing energy, slightly reducing the fraction of CCQE inter-  
 680 actions. GENIE 3.4.0 uses interaction models for QE  
 681 and single-pion production similar to NEUT but features  
 682 distinct FSI and hadronization models. All FSI mod-  
 683 els, except GENIE “hA,” are full INC models based on  
 684 hadron cross sections on free nucleon targets. The Liège  
 685 INC model was paired with ABLA07 [57] for nuclear de-  
 686 excitation. Figure 14 illustrates the outgoing neutron  
 687 momentum distributions for these setups, highlighting  
 688 significant differences below 1 GeV/c. These variations  
 689 and their implications are discussed in Section VIII.

690 Secondary hadron-nucleus interaction models were  
 691 tested using SK detector simulations based on Geant3.21  
 692 and Geant4.10.5.p01. Six configurations were evaluated:  
 693 “SK-IV/V default,” “SK-VI default,” “G3 GCALOR,”  
 694 “G4 BERT,” “G4 BERT\_PC,” and “G4 INCL\_PC.” The  
 695 SK-IV/V and SK-VI defaults differ mainly in their treat-  
 696 ment of low-energy neutron transport below 20 MeV,  
 697 using MICAP (based on ENDF/B-VI) and NeutronHP  
 698 (based on ENDF/B-VII.1), respectively. The “G3  
 699 GCALOR” setup fully relies on Geant3.21 GCALOR,  
 700 differing from the baseline setups that use the NEUT  
 701 pion FSI routine. The Geant4-based configurations (“G4  
 702 BERT,” “G4 BERT\_PC,” and “G4 INCL\_PC”) use the  
 703 NeutronHP model for the low-energy neutron transport.  
 704 For the other hadron transport, “G4 BERT” and “G4  
 705 BERT\_PC” employ the Bertini cascade model, while “G4  
 706 INCL\_PC” uses the Liège INC model. Configurations  
 707 with the “PC” suffix employ the Geant4 Precompound  
 708 model [58] for nuclear de-excitation, whereas “G4 BERT”  
 709 uses a simpler native model [55]. For hadron-nucleus re-  
 710 action cross sections (except for low-energy neutrons), all  
 711 Geant3-based models use Bertini-based tabulation [38],  
 712 while all Geant4-based models use Glauber parametriza-  
 713 tion [59]. Figure 15 compares the average signal mul-  
 714 tiplicity as a function of projectile neutron momentum  
 715 across these configurations, revealing variability in model  
 716 predictions up to 40% for neutron momentum.

717 For each neutrino event generator, a full MC simula-  
 718 tion equivalent to 50 years of atmospheric neutrino obser-  
 719 vation was generated using the baseline detector model  
 720 (“SK-VI default”). To account for variations in sec-  
 721 ondary interactions without additional full simulations,  
 722 we tabulated average signal multiplicities for projectile

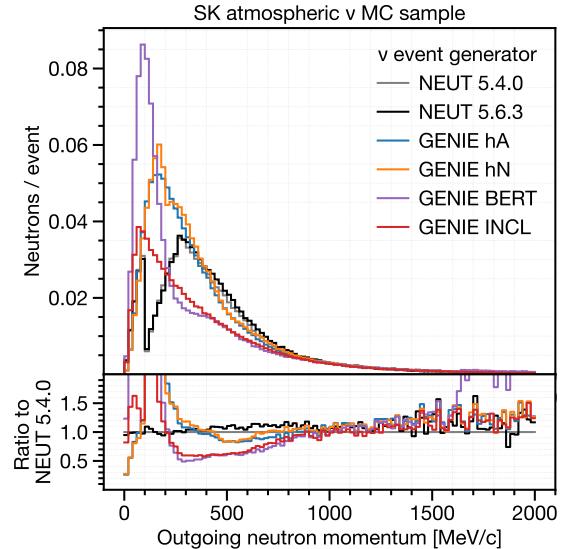


FIG. 14. Model comparison: Outgoing neutron momentum distribution per atmospheric neutrino event in the sample.

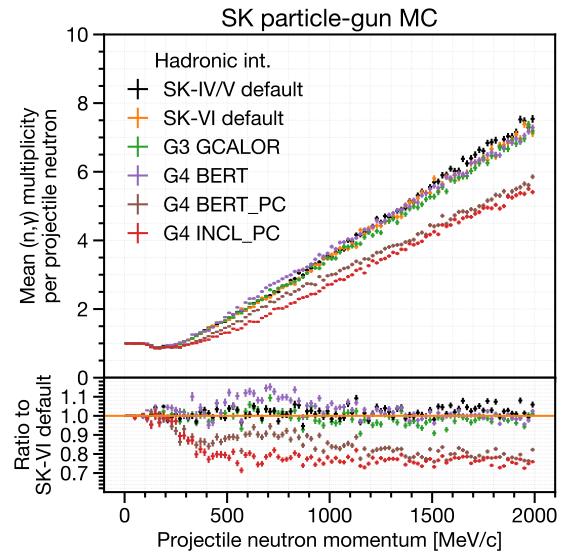


FIG. 15. Model comparison: Average  $(n, \gamma)$  multiplicity per projectile neutron momentum bin, based on simulations using a single-neutron particle-gun setup in water.

hadrons ( $n$ ,  $p$ ,  $\pi^\pm$ , and  $\mu^-$ ) in water up to 10 GeV/c, based on particle-gun MC simulations. Figure 15 shows an example for neutrons.

Predictions were made by convolving hadron momentum distributions with momentum-to-multiplicity tables. For each event generator, ratios relative to the baseline detector simulation model (“SK-VI default”) were used to scale the signal multiplicities obtained from the full MC simulation. Figure 16 illustrates the sources of variability in these predictions. Differences across neutrino

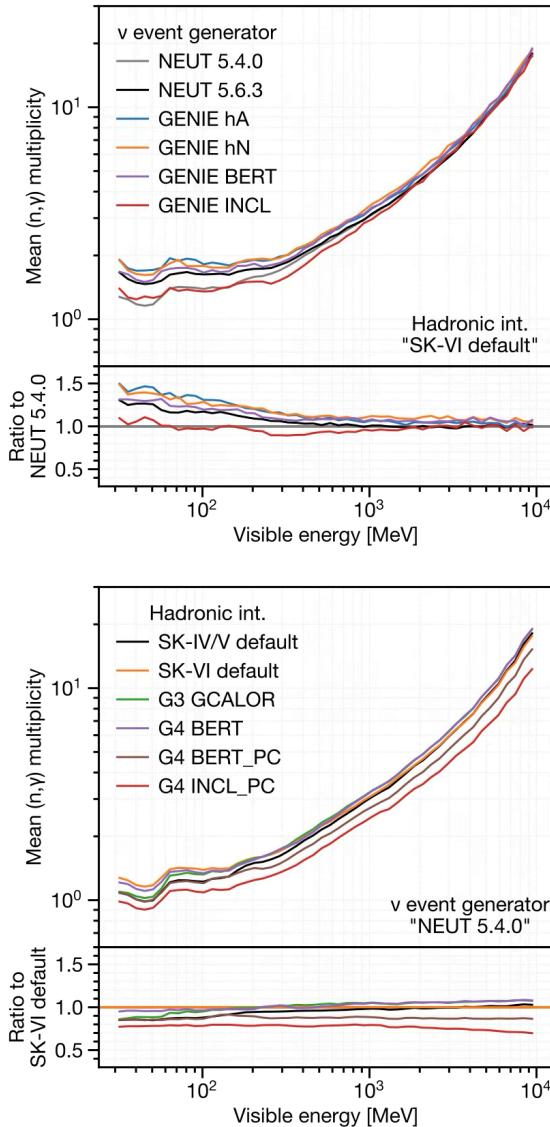


FIG. 16. Comparison of the neutrino event generator options (top) and secondary hadron-nucleus interaction models (bottom) on the predicted average  $(n, \gamma)$  multiplicity. In the top figure, each neutrino event generator option is paired with the baseline secondary interaction model (“SK-VI default”). In the bottom figure, each model is paired with the baseline neutrino event generator (“NEUT 5.4.0”).

event generator configurations are more pronounced at visible energies below 1 GeV, while variability among secondary hadron-nucleus interaction models remains relatively constant. The Liège INC model predicts fewer neutrons than the other FSI models in NEUT and GENIE, as well as the Bertini cascade model and its variants. NEUT 5.4.0 predicts fewer neutrons than NEUT 5.6.3, due to a larger QE fraction. Additionally, the Geant4 Precompound model predicts fewer neutrons than the nuclear de-excitation model native to the Bertini cascade model.

## VII. RESULTS

Table III summarizes the number of atmospheric neutrino events (“ $\nu$  events”) and detected neutron signals (“ $n$  signals”) in the final data sample. The differences in  $\langle N \rangle_{\text{total}}$  are primarily due to uncertainty in the signal efficiency scale.

TABLE III. Summary of atmospheric neutrino events and detected neutron signals in the final data sample.  $\langle N \rangle_{\text{total}}$  denotes the average  $(n, \gamma)$  multiplicity and its systematic uncertainty. Other errors shown are purely statistical.

	SK-IV	SK-V	SK-VI
$\nu$ events	29,942	4,231	5,203
Events/day	$9.23 \pm 0.05$	$9.18 \pm 0.14$	$9.22 \pm 0.13$
$n$ signals	15,705	2,035	5,752
$n$ signals/event	$0.525 \pm 0.004$	$0.481 \pm 0.011$	$1.106 \pm 0.015$
$\langle N \rangle_{\text{total}}$	$2.04 \pm 0.34$	$2.33 \pm 0.27$	$2.36 \pm 0.21$

Figure 17 compares the estimated average  $(n, \gamma)$  multiplicity per visible energy bin across SK phases. To account for uncertainties in outgoing neutron kinematics that affect signal detection efficiency, an independent algorithm using a likelihood fitter [60] was applied to SK-VI data to reconstruct the  $Gd(n, \gamma)$  vertex, providing a reference for the results in Table III. The scale differences between SK phases and the reference are included as systematic uncertainties in the signal efficiency scale, as shown in Table III and Figure 13.

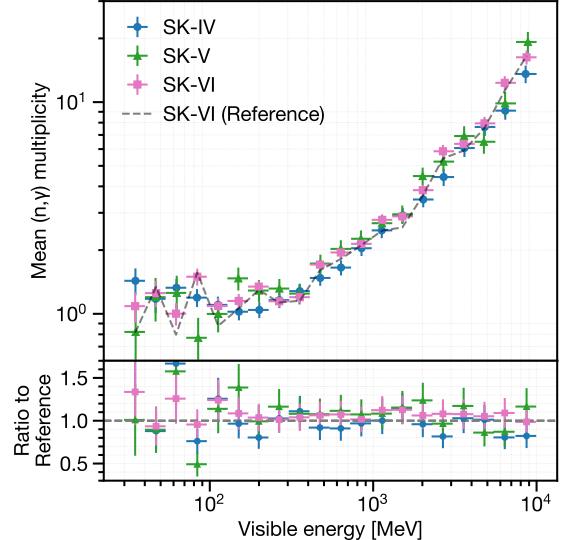


FIG. 17. Comparison of average  $(n, \gamma)$  multiplicity across SK phases, with error bars representing both statistical and systematic uncertainties. The dashed line labeled “SK-VI (Reference)” shows the result from SK-VI data using a reference algorithm whose performance is largely independent of neutron kinetic energy.

The combined data was compared with the SK-VI MC simulation and neutron production estimates in water from SNO [13], as shown in Figure 18. While the combined data matched well with the SNO estimate, it was 20-40% lower than the SK-VI simulation results across different energy ranges. For neutrino events with visible energy greater than a few hundred MeV, where the Cherenkov rings of outgoing leptons are accurately reconstructed, a linear relationship was observed between the visible energy and the average  $(n, \gamma)$  multiplicity.

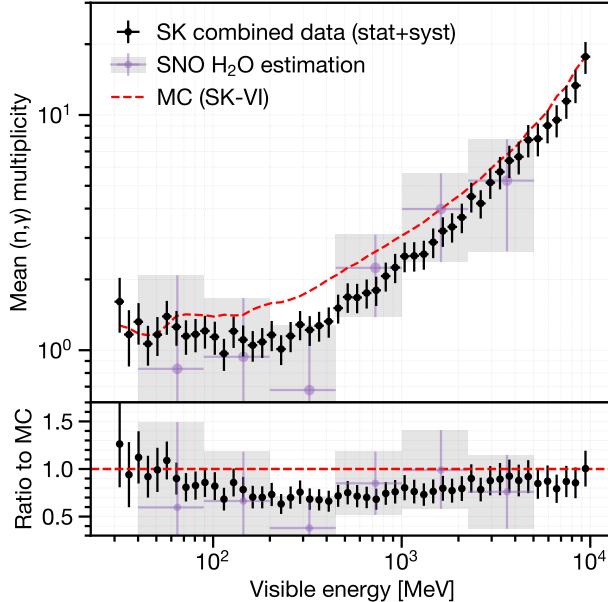


FIG. 18. Average  $(n, \gamma)$  multiplicity estimated for atmospheric neutrino interactions versus visible energy. The black dots and error bars represent combined SK data, including statistical and systematic uncertainties. Purple crosses with shading indicate estimates of neutron production in water derived from SNO measurements using a D<sub>2</sub>O target volume [13]. The red dashed line represents the true average  $(n, \gamma)$  multiplicity per visible energy bin obtained from SK-IV MC simulation.

Figure 19 shows the sources of neutron production in the baseline SK-IV simulation as a function of visible energy, offering insight into the origins of neutron production across different neutrino energy regions. The number of outgoing neutrons from neutrino-nucleus interactions is expected to be nearly constant regardless of visible energy. In events with lower visible energies, the momentum of the outgoing neutrons is small, so each outgoing neutron corresponds almost directly to a  $(n, \gamma)$  reaction. However, at higher energies, the outgoing hadrons gain more energy, leading to an increase in secondary neutron production. This suggests that the  $(n, \gamma)$  multiplicity in lower visible energies is sensitive to the modeling of low-energy nucleon transport within the nucleus, while the linear increase is primarily determined by the choice of secondary hadron-nucleus interaction model.

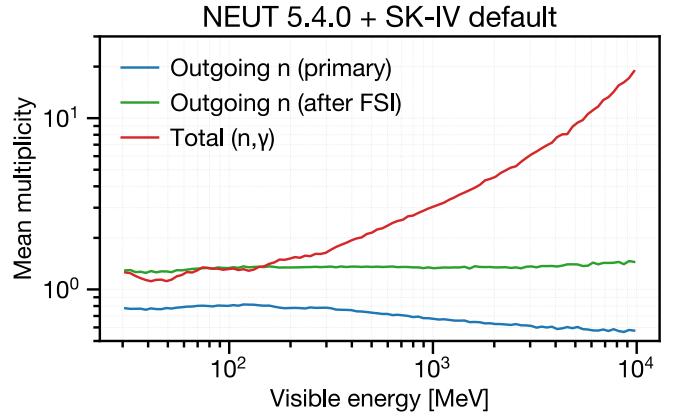


FIG. 19. Mean multiplicity of outgoing neutrons from the primary neutrino interaction (blue) and subsequent FSIs (green) and resulting total  $(n, \gamma)$  reactions (red), in the baseline SK-IV simulation setup.

### A. Effective metrics for model evaluation

The “slope” of the linear increase in the average  $(n, \gamma)$  multiplicity as a function of visible energy was determined through a linear fit over the energy range [0.3, 10] GeV, as shown in Figure 20. Only the vertical statistical uncertainties of the data points were considered in the fit, since the dominant systematic uncertainty arises from the signal efficiency scale. This scale is assumed to be fully correlated across bins, and does not affect the fitted slope.

At lower visible energies, the effects of hadronization in DIS events become negligible, and sensitivity to low-energy nucleon FSI modeling becomes significant. To quantify neutron production in low energy neutrino events, the “low-energy (low-E) multiplicity” was defined as the average  $(n, \gamma)$  multiplicity observed in [0.1, 0.3] GeV visible energy range. Events below 0.1 GeV were excluded due to large systematic uncertainties.

Figure 21 compares the measured slopes and low-energy multiplicities across different SK phases and event types. To ensure a sufficient number of events in each bin for the slope fit and mitigate the influence of outliers, the number of bins was reduced from 50 to 20. While the slope in SK-VI was slightly larger than in SK-IV, the measured values were in general consistent across SK phases within the assumed uncertainties. Both metrics were higher for multi-ring events than for single-ring events, in agreement with MC simulations. This difference arises from the higher fraction of DIS events in multi-ring samples, as shown in Figure 5. In addition, both the slopes and low-energy multiplicities from the combined data were lower than the baseline predictions.

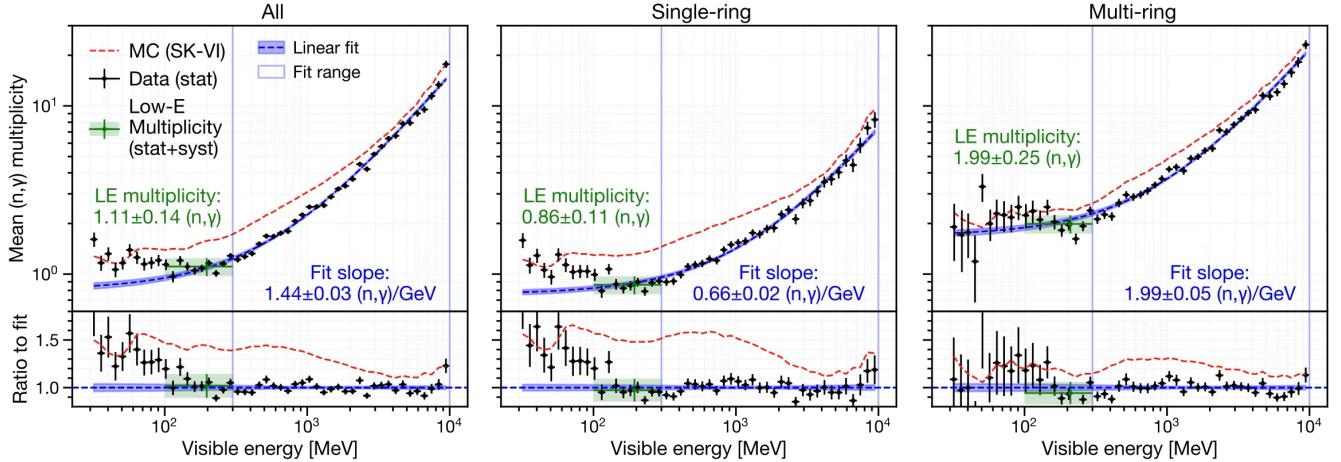


FIG. 20. The average  $(n, \gamma)$  multiplicity as a function of the visible energy of neutrino events observed in the combined data, shown for all events (left), single-ring events (middle), and multi-ring events (right). The red dashed lines denote the predictions from the full MC simulation in the SK-VI baseline setup. The blue dashed lines represent the fitted linear functions, with the blue-shaded regions indicating the  $1\sigma$  prediction intervals. The fit was performed over the energy range [0.3, 10] GeV, with data points weighted by the inverse of their statistical errors. The green data points with error bars represent the low-energy multiplicity, defined as the average  $(n, \gamma)$  multiplicity in [0.1, 0.3] GeV range.

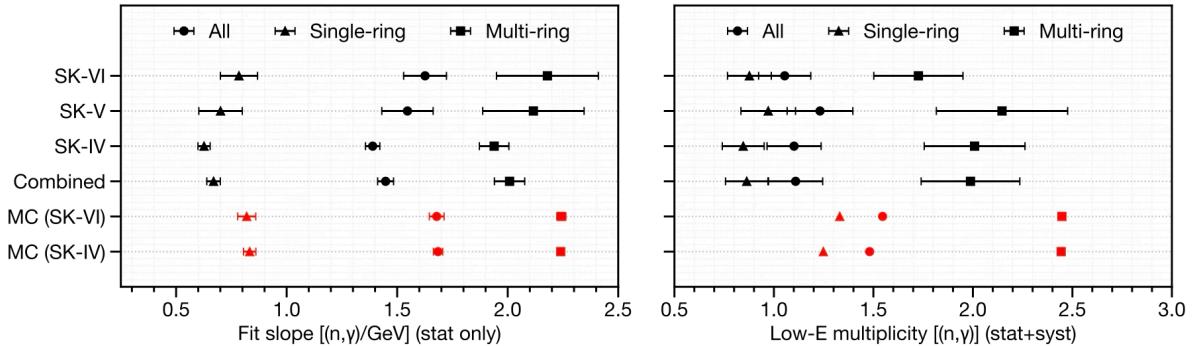


FIG. 21. The measured slopes (left) and low-energy multiplicities (right) across different SK phases and event types. The low-energy multiplicities are defined as the average  $(n, \gamma)$  multiplicity observed within the visible energy range of [0.1, 0.3] GeV. In the left panel, the error bars represent statistical uncertainties only, whereas in the right panel, the error bars account for the full systematic uncertainty, including the signal efficiency scale error. The MC predictions (red) in the right panel correspond to the “true” average  $(n, \gamma)$  multiplicity, rather than the efficiency-corrected values.

## B. Comparison with model predictions

817  
 818 Predictions from various model combinations (ex-  
 819 plained in Section VI) were compared with the combined  
 820 data, as shown in Figure 22. A notable feature in the  
 821 data is a valley in the [0.1, 0.3] GeV region, which is  
 822 less pronounced in the baseline simulation. The largest  
 823 discrepancy between the data and predictions occurs in  
 824 this region. This valley is only reproduced when us-  
 825 ing models that predict fewer neutrons than the base-  
 826 line for both FSI and secondary interaction models, such  
 827 as “GENIE INCL” and “G4 BERT\_PC.” The bottom  
 828 panel of Figure 22 highlights this, by comparing the  
 829 data with predictions from specific FSI models (“GENIE  
 830 hN,” which predicts more neutrons, and “GENIE INCL,”  
 831 which predicts fewer neutrons) and secondary interac-  
 832 tion models (“G4 BERT,” which predicts more neutrons,  
 833 and “G4 BERT\_PC” and “G4 INCL\_PC,” which predict  
 834 fewer neutrons). Among all tested combinations, “GE-  
 835 NIKE INCL” and “G4 BERT\_PC” provide the best agree-  
 836 ment with data, showing the lowest chi-squared statistic  
 837 when considering statistical errors only.

838 Figure 23 compares the measured slopes and low-  
 839 energy multiplicities with model predictions. The pre-  
 840 dictions show three distinct groups of slopes: the  
 841 “G4 INCL\_PC” model gives the smallest slopes, “G4  
 842 BERT\_PC” predicts intermediate slopes, and other vari-  
 843 ants of the Bertini cascade model produce the largest

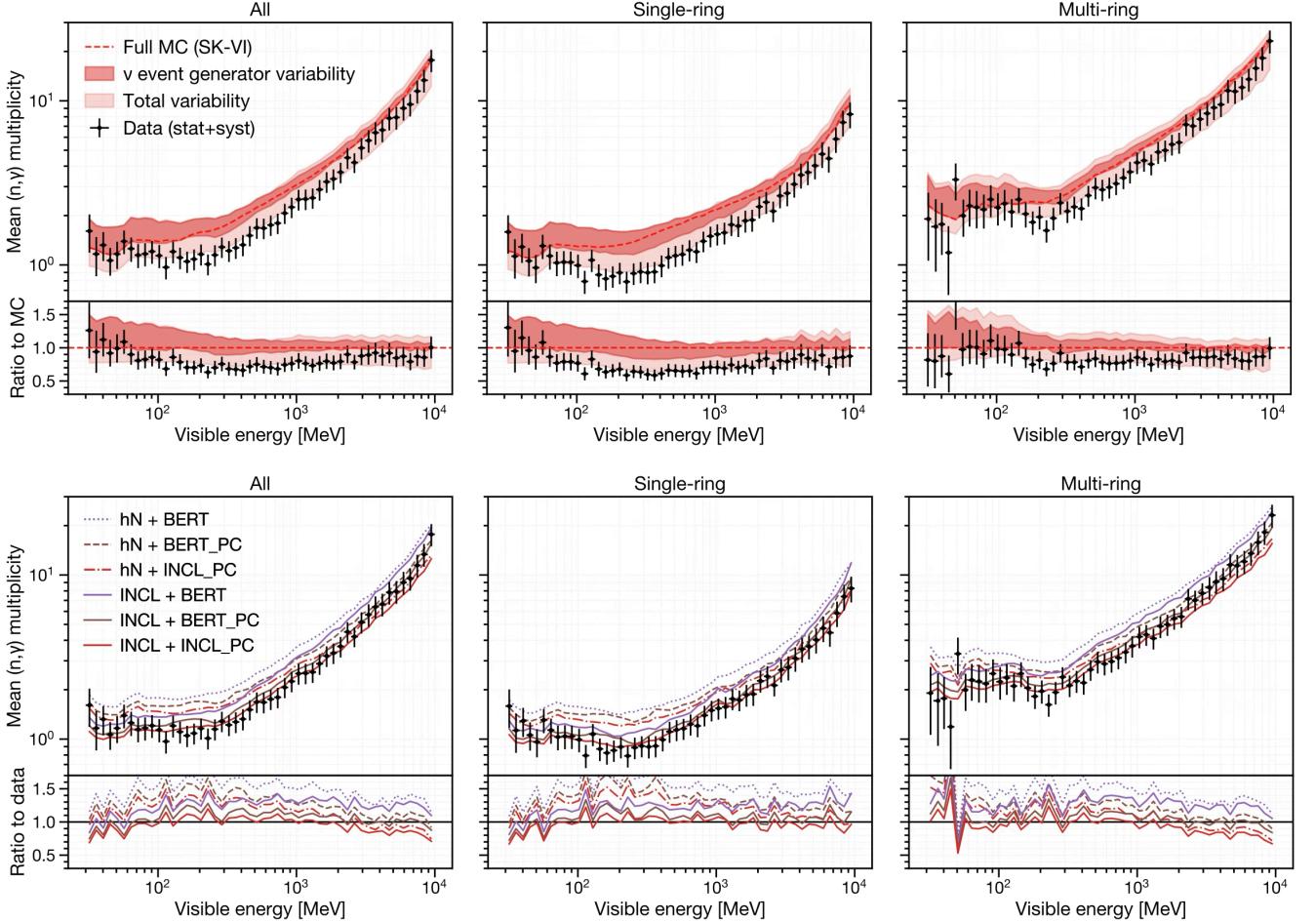


FIG. 22. Comparison of various model predictions with the combined data, showing the average  $(n, \gamma)$  multiplicity as a function of atmospheric neutrino event visible energy for all events (left), single-ring events (middle), and multi-ring events (right). The black dots with error bars represent the combined data, including both statistical and systematic uncertainties. In the top panel, the combined data are compared to the prediction intervals of the models. Thicker shaded regions represent the range of predictions obtained by varying only the neutrino event generator options while keeping the secondary hadron-nucleus interaction model fixed to the baseline (“SK-VI default”). Lighter shaded regions indicate the broader range of predictions from all model combinations. The bottom panel shows corresponding plots for specific model choices that are based on GENIE and Geant4, including the one (“INCL + INCL\\_PC”) that shows the overall best agreement with the combined data.

slopes. The slope observed in the single-ring data better<sup>857</sup>  
 matches the “G4 INCL\\_PC” predictions, while the slope  
 in the multi-ring data is closer to the “G4 BERT\\_PC”  
 predictions. This distinction is most evident in the bot-  
 tom panel of Figure 22, where “G4 INCL\\_PC” matches  
 well with sub-GeV single-ring data, and “G4 BERT\\_PC”  
 is a better fit for multi-GeV multi-ring data.  
 858

For low-energy multiplicities, the two versions of  
 NEUT and ”GENIE INCL” are preferred, as they pre-  
 dict lower neutron production. In contrast, models  
 such as GENIE’s “hA,” “hN,” and “BERT” overestimate  
 low-energy multiplicities, producing values significantly  
 higher than the uncertainty in signal efficiency.  
 851 862 863 864 865 866 867

## VIII. DISCUSSION

Overall, our data favor models that predict relatively lower neutron production. In this section, we examine key features of these models that affect neutron production, with reference to Figure 14 that highlights differences in nucleon momentum distributions across various neutrino event generators. By qualitatively comparing the variations among the INC models and nuclear de-excitation models used in these generator options, we discuss potential sources of the observed differences in their predictions.  
 859 860 861 862 863 864 865 866 867

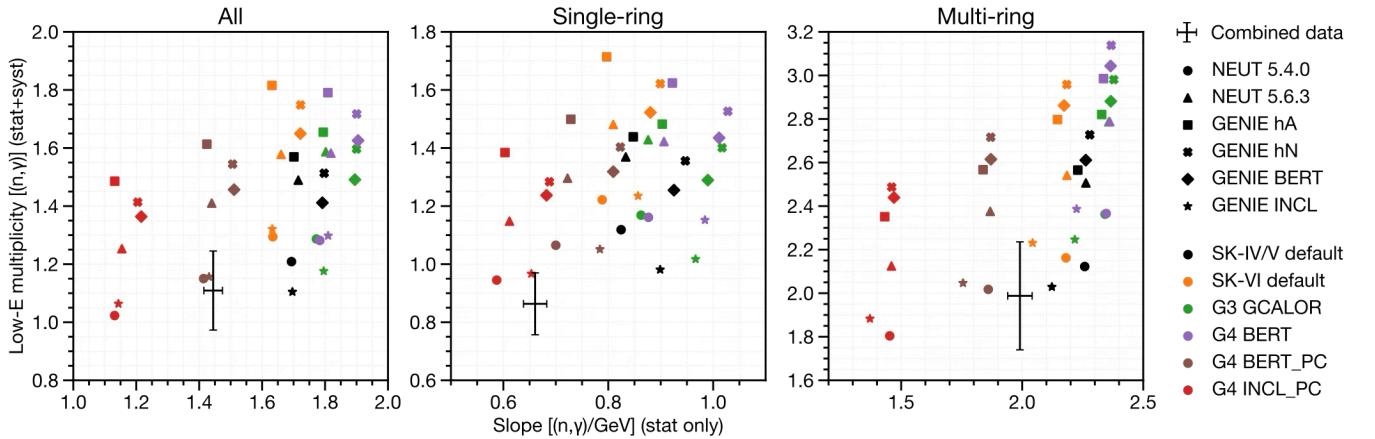


FIG. 23. Scatter plots of fitted slopes and low-energy multiplicities in model predictions and data (black crosses, error bars include systematic uncertainty in low-energy multiplicity and statistical uncertainty in slope), shown for all events (left), single-ring events (middle), and multi-ring events (right). Shapes represent neutrino event generator options used, while colors indicate the secondary hadron-nucleus interaction model used.

868

### A. Nuclear de-excitation

Nuclear de-excitation models play a critical role in predicting the total  $(n, \gamma)$  multiplicity per secondary interaction, as they govern the production of very-low-energy neutrons, which directly contribute to  $(n, \gamma)$  reactions. One notable feature in Figure 14 is the significant peak in the “GENIE BERT” prediction for neutron momenta below 250 MeV/c. This peak arises primarily from the nuclear de-excitation model in the Geant4 Bertini cascade [55]. A key characteristic of this model is its restriction on Fermi breakup, which is disallowed for nuclear targets with mass numbers greater than 11 [55], including oxygen (and also carbon, which is particularly relevant to past MINERvA studies [14, 15]). The more recent Geant4 Precompound model [58] allows Fermi breakup for mass numbers up to 16, including oxygen. This additional fragmentation mechanism is expected to reduce the number of “single” neutrons contributing to  $(n, \gamma)$  signals. Further differences between these models include variations in nucleon absorption (inverse reaction) cross sections and level density parameters [58], which may impact single-neutron production in the statistical evaporation process. Similarly, the ABLA07 model, used in the “GENIE INCL” option, predicts neutron emission rates comparable to those of the Geant4 Precompound model and the NEUT oxygen de-excitation model. Conversely, the “GENIE hA” and “hN” options omit nuclear de-excitation altogether.

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### B. Pauli blocking

Another key difference among the models lies in their treatment of “Pauli blocking,” a quantum mechanical effect that prohibits nucleons from occupying the same quantum state, as dictated by the Pauli exclusion prin-

ciple. For instance, NEUT and the “GENIE BERT” options implement strict Pauli blocking, which forbids all nucleon scattering below the oxygen Fermi momentum of 225 MeV/c, modeling the nucleus as a degenerate Fermi gas. This strict treatment manifests in NEUT as a characteristic dip in the corresponding energy range, as illustrated in Figure 14. By contrast, the Liège INC model applies a probabilistic approach to Pauli blocking during the cascade, accounting for nucleon holes created by prior cascade steps. This results in smoother neutron distributions near the Fermi momentum. In comparison, the “GENIE hA” and “hN” models omit Pauli blocking entirely, leading to significantly higher predicted neutron production than either NEUT or “GENIE INCL.”

### C. Other considerations

The Liège INC model and the Geant4 Bertini cascade model, which apply corrections such as nucleon-nucleon repulsion and interaction correlations across cascade steps, predict lower neutron production at intermediate energies (250–1000 MeV/c) compared to the other options shown in Figure 14. This difference in outgoing hadron momentum distribution should affect the number of secondary interactions. The impact of these differences on the observed neutron multiplicity is particularly evident in low-energy single-ring events, where “GENIE hN” and “GENIE INCL” yield significantly different predictions, as shown in Figure 24.

For low-energy single-ring events, the secondary hadron-nucleus interaction model plays a smaller role in determining the total neutron multiplicity due to the limited hadron momentum and the resulting suppression of secondary interactions. Also at lower visible energies, neutron production is expected to be dominated by outgoing neutrons. In contrast, for multi-GeV multi-ring

events, which indicate significant pion production, outgoing high-energy pions are expected to dominate neutron production, as seen in Figure 24, increasing the contribution from secondary interactions. The underprediction of neutron multiplicity in multi-ring events by the Liège INC model (“G4 INCL\\_PC”), as shown in Figure 22, along with its smaller slope compared to the Bertini cascade model (“G4 BERT\\_PC”), is largely attributed to its underprediction of secondary neutrons induced by pion projectiles over 500 MeV/c, where multiple pion production is relevant. Meanwhile, variations in low-energy neutron reaction cross section datasets (e.g., ENDF/B-V and ENDF/B-VII.1), low-energy pion-nucleus interaction models (e.g., adoption of NEUT’s low-energy pion FSI model), or hadron-nucleus reaction cross sections (e.g., Bertini [38] and Glauber [59]) appear to have a relatively minor impact on neutron production predictions.

## IX. SUMMARY

Accurately modeling neutron production in neutrino interactions is essential for characterizing incoming neutrinos, which is crucial for advancing precision measurements of neutrino oscillation parameters and rare event searches involving neutron tagging. Recent studies have suggested potential inaccuracies in the modeling of secondary hadron-nucleus interactions.

This paper reports a measurement of total neutron production following atmospheric neutrino interactions within the water volume of the Super-Kamiokande (SK) detector. In SK, neutrons with kinetic energies below a few MeV are typically captured by surrounding nuclei, such as  $^1\text{H}$  or  $^{155}/^{157}\text{Gd}$ , releasing 2–8 MeV of energy through gamma-ray emissions. These radiative neutron captures ( $(n, \gamma)$  reactions) were identified using a detection algorithm that combines a simple low-energy trigger with a neural network binary classifier, calibrated with an Am/Be neutron source. Event-by-event neutron capture multiplicity was estimated using a multivariate non-linear regression technique. Atmospheric neutrino events were binned by their electron-equivalent “visible energy,” a semi-calorimetric proxy for neutrino momentum transfer, in the range of [0.03, 10] GeV. The average neutron capture multiplicity in each visible energy bin was compared against predictions from various combinations of neutrino event generators and secondary hadron-nucleus interaction models.

The extensive dataset provides strong discriminative power for evaluating hadron-nucleus interaction models. Variability in model predictions across the energy range was found to be as large as 50%. Notably, the variability in FSI model predictions was more pronounced in the sub-GeV range, while variability from secondary hadron-nucleus interaction models dominated in the multi-GeV range. The observed data, which showed fewer neutron signals than predicted by the baseline simulation, could only be explained by using FSI and secondary interac-

tion models that predict relatively lower neutron production. For example, the Liège INC model for intranuclear hadron transport and the Geant4 Precompound model for nuclear de-excitation produced lower neutron predictions that aligned more closely with the observations. In contrast, the widely used Geant4 Bertini cascade model, when coupled with its native nuclear de-excitation model, significantly overestimated neutron production beyond the estimated uncertainties. Qualitative comparisons suggest that the major sources of variation in neutron production predictions stem from the modeling of nuclear de-excitation, Pauli blocking, and corrections beyond the semi-classical treatment in INC models. This study highlights the critical role of hadron-nucleus interaction models in predicting total neutron production from neutrino interactions.

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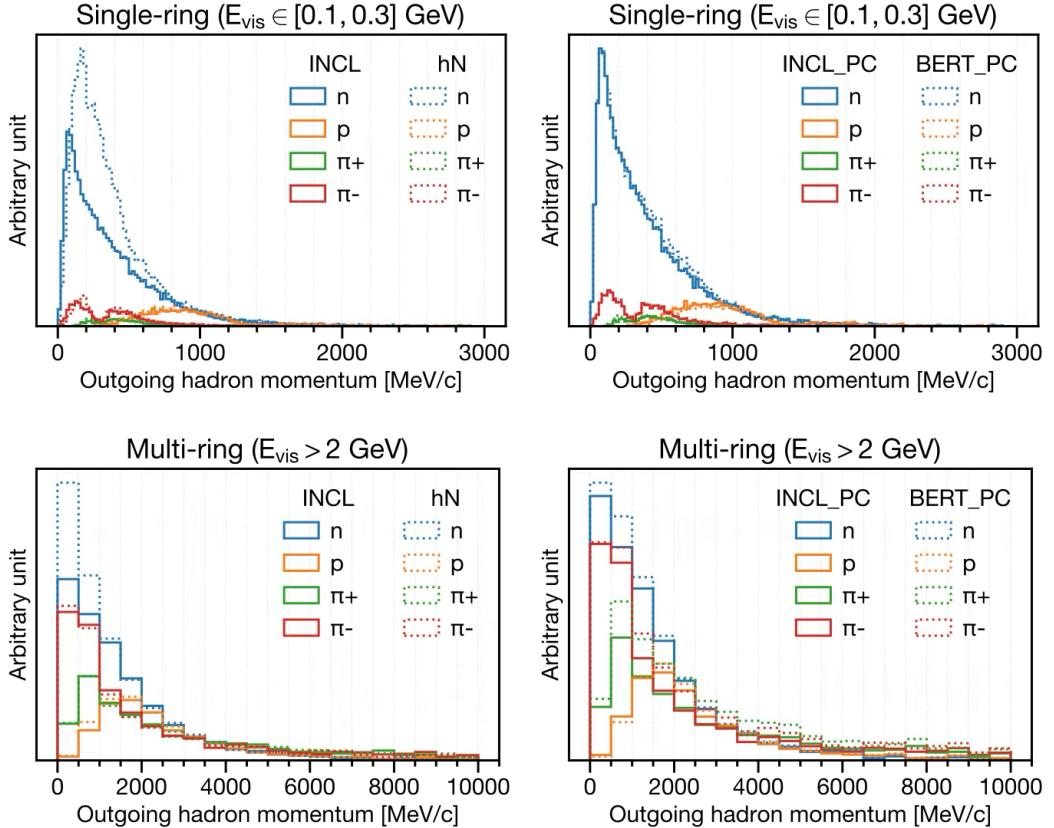


FIG. 24. Momentum distributions of outgoing hadrons predicted by neutrino event generators, weighted by the average ( $n, \gamma$ ) multiplicity per projectile hadron momentum bin as predicted by secondary hadron-nucleus interaction models. The area under each histogram bin represents the average contribution of a specific hadron at a given momentum to the observable ( $n, \gamma$ ) multiplicity. The top panels show predictions for single-ring events with visible energy ( $E_{\text{vis}}$ ) in the range [0.1, 0.3] GeV, while the bottom panels correspond to multi-ring events with visible energy above 2 GeV. The left plots compare two different cascade models for final-state interactions (“GENIE INCL” and “GENIE hN”) coupled with the secondary hadron-nucleus interaction model “G4 INCL\\_PC,” whereas the right plots compare two secondary interaction models (“G4 INCL\\_PC” and “G4 BERT\\_PC”) coupled with the neutrino event generator option “GENIE INCL.”

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