

Neutron reconstruction via blips in liquid argon time projection chambers

Miguel Hernandez Morquecho^{1,*}, Bryce Littlejohn^{2,†}, Paola Sala^{3,‡} and Linyan Wan^{3,§}

¹*University of Minnesota, Minneapolis, Minnesota 55455, USA*

²*Illinois Institute of Technology, Chicago, Illinois 60616-3793, USA*

³*Particle Physics Department, Fermilab, P. O. Box 500, Batavia, Illinois 60510, USA*



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Neutrons are important final-state particles in neutrino interactions, yet they are not considered or reconstructed in most current neutrino liquid argon time projection chamber (LArTPC) physics analyses. In this paper, we present a simulation-based proof-of-concept study of neutron reconstruction in a generic LArTPC detector. Leveraging isolated, MeV-scale energy deposits, or blips, from neutron inelastic scattering, and using realistic blip response from published experimental results, we demonstrate the capability to identify neutrons and to reconstruct the direction and energy of the final-state neutron system in sub-GeV neutrino interactions. We then explore how neutron-related blip attributes can be used to improve physics studies of neutrino interactions, such as enhancing neutrino-antineutrino separation in atmospheric neutrinos and reverse-horn-current beam neutrinos. This study provides an initial quantification of LArTPC neutron reconstruction capabilities, which we expect to improve with future advancements in blip reconstruction, identification, and classification algorithms, as well as the modeling of neutrons.

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I. INTRODUCTION

As neutrino oscillation measurements enter the precision era [1–5], it becomes crucial that we understand neutrino interaction modeling and constrain the significant uncertainties arising from nuclear effects. Modeling these nuclear effects is particularly critical for sub-GeV neutrino interactions, where the energy transfer in the neutrino interaction can be comparable to or dominated by Fermi motion, nucleon-nucleon correlations, and final-state interactions. These sub-GeV neutrinos bear important physics potential, to name a few: CP violation via sub-GeV atmospheric neutrinos [6,7] and beam neutrinos [5,8,9], sterile neutrino searches via beam neutrinos [10], and cross-section studies towards constraining uncertainties in neutrino oscillation studies [11–13]. Outgoing hadrons serve as valuable probes of these effects, among which protons are much more well constrained from experimental data [14–22] compared to uncharged neutrons, due to the

difficulties involved in their detection. In neutrino interactions, a significant amount of momentum in 1 GeV neutrinos is carried by neutrons. Neutron reconstruction therefore possesses crucial importance to recover substantial information loss in the initial neutrino kinematics [23,24].

In neutrino detectors using water Cherenkov or liquid scintillation technology, neutrons typically can be identified and reconstructed via capture on a target nucleus such as hydrogen [25–29] or other doped elements [30–36]. In a liquid argon time projection chamber (LArTPC), however, due to the destructive interference feature in the neutron-argon cross section at ~ 57 keV [37,38], low-energy neutrons in liquid argon have an interaction length of ~ 30 m, indicating that neutron capture on argon, although yielding high energy γ -rays with detectable signatures, is less likely to be contained within a LArTPC detector. Instead, the detection of neutrons can be done via their inelastic scattering off of argon nuclei.

Neutrons from neutrino interactions can inelastically scatter with argon nuclei, leaving the nuclei in excited states and potentially producing secondary neutrons and protons [39,40]. The deexcitation of the remnant nucleus produces γ -rays of a few MeV, which, through Compton scattering and electron-positron pair production, show up in LArTPC data as isolated charge depositions called blips. Several LArTPC experiments have reported evidence of neutron identification, including ArgoNeuT [41] using

*Contact author: hernanm@umn.edu

†Contact author: blittlej@illinoistech.edu

‡Contact author: psala@fnal.gov

§Contact author: lwana@fnal.gov

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blips and MicroBooNE [42] using displaced secondary protons.

In this paper, we conduct a phenomenological study of how neutronic signatures can be implemented to improve high-level neutrino LArTPC physics deliverables. We focus especially on deliverables relevant to sub-GeV neutrinos, where the neutron-carried information is more dominant, yet less studied. Neutron-induced proton emission is much less frequent in this energy range: for example, MicroBooNE's recent study focusing on secondary proton identification reports an efficiency plateauing at $\sim 3\%$ around 250 MeV neutron kinetic energy [42]. This study will therefore primarily center on neutron reconstruction through the use of γ -induced blips.

Our scheme reconstructs the presence, direction, and energy of neutronic final states using a simulated sample with realistic experimental response of blips, which are then purified via a set of simple analysis cuts. These simple neutron attributes are found to improve charge-sign purities for sub-GeV atmospheric and beam neutrino interaction samples. The outcome represents useful starting benchmarks for understanding the utility of blip-based neutron reconstruction in neutrino LArTPCs, which can be expected to improve with more advanced experimental techniques in signal blip reconstruction and selection schemes.

This paper is organized as follows: we first describe the study setup in Sec. II, including neutrino interaction modeling, particle transport simulation, and detector response and reconstruction for blips. Section III talks about the categorization of blips and the analysis selections to reject non-neutron blip background. Neutron reconstruction performance is highlighted in Sec. IV, including neutron identification, energy reconstruction, and direction reconstruction. Section V gives a few examples of physics applications using this neutron reconstruction technique, which demonstrates potential enhancement in neutrino-antineutrino separation tasks in multiple neutrino sources. Section VI discusses systematic uncertainties and the future outlook. Takeaways are summarized in Sec. VII.

II. SIMULATION

The study is set up using sub-GeV atmospheric neutrino flux predicted by the Honda model [43]. For our baseline neutrino samples, final-state particle generation and particle transport is conducted using FLUKA [44], as LArTPC experiments have so far observed best agreement between neutron-related datasets and FLUKA simulation [41]. To explore related systematic uncertainties, in Sec. VI we also investigate alternative neutrino interaction modeling using GENIE-hA [45,46] and GENIE-INCL [47], and alternative particle transportation using the Geant4 package [48]. While neutrons also play an important role in neutral current interactions, in this analysis we focus on charged current

interactions to provide information and inputs to oscillation analyses.

A. Neutrino event generation

FLUKA has its own neutrino interaction generator that embeds the basic neutrino-nucleon interaction in a FLUKA nuclear model called PEANUT [44]. Quasielastic neutrino interactions are sampled according to the Llewellyn Smith formalism [49], accounting for the mass of the produced lepton. At higher energies, the resonant and deep inelastic scattering (DIS) channels open. The production of Δ resonances is modeled following Rein-Sehgal [50]. No other resonance is considered. Care is taken to avoid double counting with the nonresonant DIS channel, with a linear decrease (increase) of the resonance (DIS) probability as a function of the mass of the intermediate hadronic system. The (anti)neutrino-nucleon DIS generator, called NUNDIS, is described in Ref. [51]. However, due to the neutrino energy range considered in this work, the DIS contribution is close to negligible.

Following these neutrino interaction cross-section starting points, the PEANUT model within FLUKA provides initial and final-state interactions. The initial state is described as a Fermi gas with Fermi momentum dependent on the local nuclear density. A Pauli blocking check is performed at each interaction. The coherence length and formation zone are applied to the interaction products to account for the indeterminacy of the location of the products.

The interaction products are then transported in the nucleus according to a generalized intranuclear cascade, followed by a preequilibrium stage and then by equilibrium emission of particles and fragments. Any residual excitation energy is dissipated via the emission of γ -ray cascades. Energy conservation is ensured at each step, exploiting experimental and evaluated data on nuclear masses. γ deexcitation is based as far as possible on existing experimental data on nuclear levels and branching ratios [52]. Outside the coverage of databases, a native statistical model is applied [53]. A validation of the algorithm, with specific focus on the Fermi motion as implemented in PEANUT, is presented in an experimental paper on neutrino interactions in liquid argon [54]. The good agreement of FLUKA simulations with nuclear deexcitation γ data collected in liquid argon is presented in Ref. [41].

Figure 1 shows the energy distribution for primary neutrons and the primary neutron multiplicity from the FLUKA event generation for sub-GeV atmospheric neutrino charged current interactions. The energy distribution has a 2 MeV threshold to avoid the overwhelmingly large evaporation neutron population. This choice is also comparable with prior neutron-related measurements from beam neutrino experiments [55]. The neutron multiplicity figure has a 5 MeV threshold, as required by neutron visibility in a LArTPC, discussed in Secs. IV A and VI A 2.

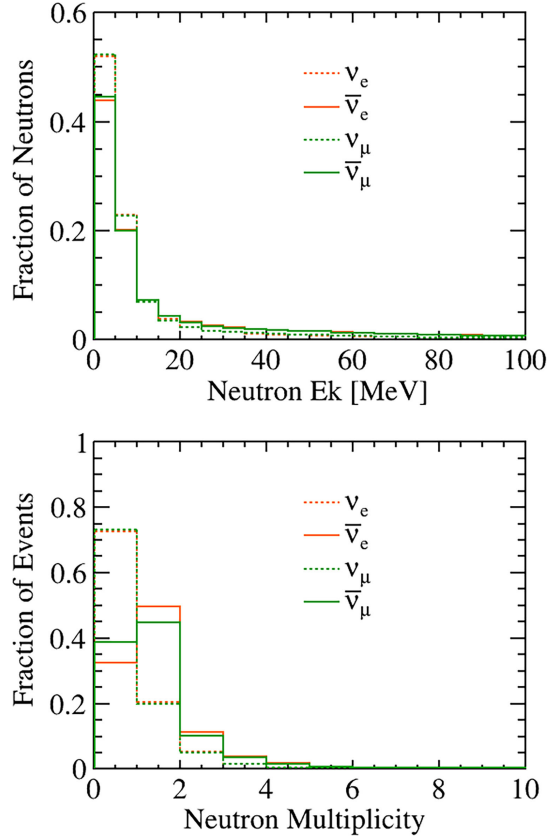


FIG. 1. Neutron kinetic energy distribution with a 2 MeV threshold (top) and neutron multiplicity distribution with a 5 MeV threshold (bottom) from sub-GeV atmospheric neutrinos generated using FLUKA.

B. Particle transport

Following the generation of final-state particles of neutrino-argon interactions, particles must be transported through the liquid argon medium. Final-state products are generated at a single central point in a large homogeneous $4.0 \times 4.0 \times 5.0 \text{ m}^3$ LAr volume, with secondary interaction products above a minimum tracking threshold generated and propagated throughout the entire volume. This LAr volume is comparable in scale to that of the SBND, ICARUS, and ProtoDUNE LArTPC detectors [11,56,57] and to the size of one TPC within a DUNE far detector 10 kT module [58]. When products reach the edge of this simulated volume, they cease being tracked or propagated.

We perform the particle transport in the baseline sample in two stages: FLUKA particle transport, and LArSoft electron transport. For FLUKA particle transport, we select transport settings that prioritize accuracy over reduced CPU usage, such as enabling the production of heavy fragments during evaporation and enabling photonuclear interactions. In particular, the transport of neutrons below 20 MeV is performed with the recent fully correlated pointwise algorithm [59] down to thermal energies. This ensures that γ cascades following neutron interactions are faithfully

reproduced, and that correlations among the interaction products are conserved.

Most neutrino LArTPC simulation and analysis studies perform final-state particle transport using Geant4 implemented within the larger structure of the LArSoft LArTPC analysis framework [60] (see Refs. [15,24,61] for useful descriptions). Since FLUKA is not directly interfaced with LArSoft, we implemented a scheme to transfer FLUKA-generated particles into LArSoft. This transfer is performed at the electron transport phase, with electrons produced but not transported within FLUKA. Truncated electrons are instead propagated within LArSoft and Geant4. Their initial position, momentum, and energy are used as input conditions for transport within the LAr volume in LArSoft, with information from all primaries and secondaries retained for downstream processing and analysis. This approach reduces computational cost while allowing for generation of reconstructed blips in LArSoft with similar data structures for both particle transport paths.

As a cross-check of the two-stage implementation and as a particle transport systematic exercise, we also perform particle transport in an alternative Geant4 setup. We use the Bertini cascade model [62] to simulate hadron-nucleus interactions at intermediate energies, producing secondary particles such as neutrons. Neutrons with energies below 20 MeV are treated using the NeutronHP library [63], a data-driven approach based on evaluated nuclear datasets. These cross-check results are presented in detail in the Appendix and are also described in Sec. VI A 1.

C. Blip reconstruction

Energy depositions from FLUKA-based and Geant4-based particle transport paths are processed by BlipReco, a LArSoft-native reconstruction package first described in Ref. [24] and implemented in recent MicroBooNE MeV-scale analyses [64,65]. The BlipReco package is primarily designed to reconstruct physics quantities of interest from either simulated or real LArTPC wire signals generated by isolated MeV-scale energy depositions, or blips, in LArTPCs. In addition, it processes simulated particle history outputs from LArSoft to generate truth-level physics quantities mirroring those reconstructed from wire signals. Lastly, BlipReco generates truth-level quantities related to the origins of reconstructed blips, such as the identity of the particle that generated a blip's ionization. In this analysis, we avoid simulation and processing of TPC wire signals and leverage only truth-level quantities from BlipReco, similarly to Ref. [24].

When performing blip signal selection and analysis we make use of truth-level analogs to two primary reconstructed blip quantities: energy and 3D position. The true deposited energy associated with a blip is formed by summing all true energy deposited as ionization between the start and end of a charged particle's tracked life. Ionization generated by secondary but connected charged particle trajectories

must be added to this sum, while energy lost via radiative (γ -emitting) processes must be subtracted from it. True 3D positions are defined as the midpoint between contiguous ionization start- and end points. Truth-level blip formation is restricted to low-energy electrons (0–12 MeV kinetic energy) and protons (0–40 MeV kinetic energy).

To more realistically approximate the response of a real LArTPC to MeV-scale charge depositions for this study, we apply blip response matrices provided by MicroBooNE in Ref. [65]. Each reconstructed blip has its true energy smeared by randomly sampling from the probability density function contained within the response matrix for that true energy value. For blips generated by light or intermediate charged particles ($e^\pm, \pi^\pm, \mu^\pm$), MicroBooNE’s electron response matrix is applied, while for heavy charged particles (p), its proton response matrix is used. Energy-dependent efficiency losses are accounted for similarly by randomly sampling MicroBooNE’s efficiency response for the relevant true energy value. Since MicroBooNE blip efficiencies only approach a maximum of 80%–90% due to the presence of dead wires in their TPC, we optimistically rescale this efficiency to 100% in the $> \text{MeV}$ regime. For blips truly generated by electrons, we optimistically apply the efficiency matrix corresponding to the MicroBooNE’s collection plane, which achieves a reconstruction efficiency of $> 50\%$ of its maximum value around 200–250 keV of electron-equivalent energy deposition.

The truth-level blip ancestry variables used in this analysis are the identity of the particle that generated a blip’s ionization, the identity of the primary (non-neutrino) upstream ancestor of the blip’s producing particle, and the process names of the particle interactions that generated upstream ancestors of interest. Since a large fraction of the FLUKA particle transport process happens outside of LArSoft, care was taken to properly record and parse particle histories in a similar manner for both simulation pathways. When multiple particles with differing identities (such as a γ -induced e^+e^- pair) contribute to a blip’s energy deposition, the particle contributing the most energy is defined to be the true originator. Determination of a blip’s assigned primary upstream ancestor involves backtracking step by step through a blip’s particle parentage until one reaches a primary particle produced directly by the neutrino event generator. There are a few exceptions to this ancestor-assignment process:

- (i) Stopped final-state μ products: if a blip is made by the product of a final-state μ^- nuclear capture, the blip can sometimes be identified not as a “lepton-ancestor” blip, but is instead associated with the upstream parent generated by the μ^- terminating process. Specifically, blips generated by a μ^- nuclear capture neutron or a deexcitation γ -ray are termed n -ancestor blips and γ -ancestor blips, respectively.
- (ii) Secondary n products: if a blip is made by the products of a secondary neutron, it will be identified as an n -ancestor blip. However, the “nonprimary”

nature of this neutron ancestor will also be recorded in some cases. Blips generated by secondary neutrons with an ultimate final-state neutron ancestor retain a “primary” n -ancestor designation.

- (iii) π^0 decay products: in this study, we will disregard all neutrino interactions including a true primary or secondary π^0 . Their inclusion would require additional selection criteria, as well as the modeling of electromagnetic shower topologies in the ν_μ and $\bar{\nu}_\mu$ samples.

Since wire simulation and other high-level reconstruction stages are not implemented, reconstructed track and shower information is not available for this study. Instead, we rely on truth-level energy deposition and ancestry information provided in BlipReco particle histories to relate blips to higher-energy topological features in a neutrino interaction. For example, prior to the blip selection and categorization process, we strike all δ -rays from consideration by rejecting low-energy electrons with a direct $\mu^\pm$ parent and an ionization-related creation process.

III. SIGNAL AND BACKGROUND BLIP CATEGORIES

To reconstruct neutron information in a neutrino interaction with blips, the first step is to identify blips with primary neutron origins from other neutrino-related and ambient blip backgrounds. This section describes the features of blips from different origins, including the primary neutron signal, and backgrounds including non-primary neutrons, other blips from neutrino interactions, and blips from non-neutrino sources.

A. Backgrounds from final-state leptons

A significant fraction of blips in charged-current neutrino interactions have lepton-associated origins. For electron-flavored charged-current neutrino interactions, the primary lepton-associated blips compose 77% (75%) of the total count from ν_e ($\bar{\nu}_e$) charged current interactions via electromagnetic showers, and it is usually not feasible to cluster all the energy deposition from the primary electron or γ -rays into the reconstructed shower objects. Muons at sub-GeV energy do not create these showers, but they can release δ -ray e^- from argon atoms via hard scattering, which deposit track-adjacent activity sometimes reconstructed as blips in real LArTPC data. In addition, δ -rays can experience radiative energy losses, with bremsstrahlung photons generating blip activity disconnected from, but nearby, a μ track. In ν_μ ($\bar{\nu}_\mu$) charged current interactions, blips from this radiative process and from Michel electrons account for 14% (37%) of the total count.

To remove lepton-associated blip activity, we introduce two lepton-related topological selections, as shown in Fig. 2. In $\nu_e/\bar{\nu}_e$ charged current interactions, we apply a cone-shaped angle cut to the electron shower, removing blips within a 45° cone from the shower direction, as shown

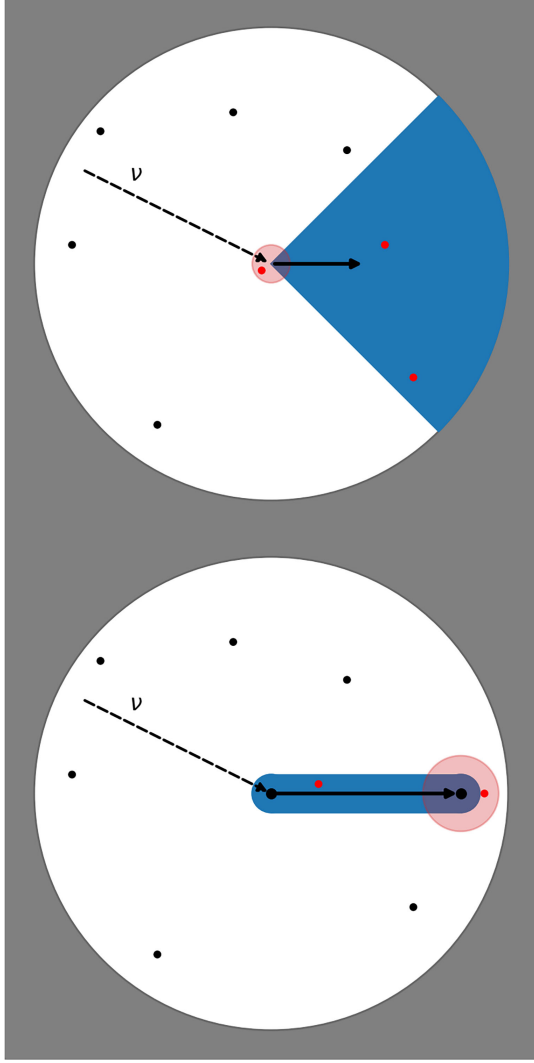


FIG. 2. Cartoon illustrating applied topological selection cuts. Top: cone cut around the shower (blue), and γ cut around the primary vertex (pink) for $\nu_e/\bar{\nu}_e$ events. Bottom: PoCA cut around the track (blue), and γ cut around the end of the muon track (pink) for $\nu_\mu/\bar{\nu}_\mu$ events.

in the blue region in the top subfigure in Fig. 2. In ν_μ and $\bar{\nu}_\mu$ charged current interactions, we connect the primary interaction vertex and the end point of the muon track with a line segment as an approximation to the muon track, and require the point of closest approach (PoCA) [66] distance between the blip and the line segment to be larger than 20 cm, as shown in the blue region in the bottom subfigure in Fig. 2.

These topological cuts can be applied to other tracks and showers in the neutrino interactions. For the sub-GeV atmospheric neutrino sample we consider, protons and charged pions can both form tracks in addition to the muon track, while the major contribution to showers is from the primary electron in the charged current interactions. Therefore, we apply the PoCA cut to all major kinds of particle tracks (proton, charged pion, and muons),

while only applying the cone cut to the primary electron shower. After these cuts, lepton-associated blips account for 25% (19%) in ν_e ($\bar{\nu}_e$) charged current interactions and 11% (22%) in ν_μ ($\bar{\nu}_\mu$) charged current interactions. The same lepton cut can be applied in experimental studies with reconstructed shower direction and detailed tracking.

B. Backgrounds from nuclear deexcitation γ s

After lepton-related PoCA or cone topological selections, the blip distribution as a function of the distance to the primary vertex is shown in Fig. 3. At locations close to the neutrino vertex, a majority of blips appear to have γ -related ancestry. The major contributor to this category is primary deexcitation γ -rays from the struck nucleus hosting the neutrino interaction. Blips from primary γ -rays are more densely populated near the primary vertex, since the interaction lengths of MeV-scale γ -rays are shorter than that of energetic neutrons in liquid argon. To reject these primary γ -rays blips, we implement a cut removing blips less than 20 cm away from the neutrino interaction vertex.

For the ν_μ charged current interactions pictured in Fig. 3, one can observe a higher blip contribution from nonprimary neutrons. In addition, γ -related blips tend to be distributed towards a larger distance range from the primary vertex than for the other three neutrino channels. These features reflect the presence of deexcitation products of stopped μ^- -argon nuclear capture. To remove blips from capture γ -ray products as well as Michel electrons, we require blips to be at least 40 cm away from the end point of muons in ν_μ charged current interactions.

C. Backgrounds from nonprimary neutrons

Nonprimary neutrons not directly from the neutrino interactions can be produced during the propagation of final-state particles, most notably by the hadronic interaction of protons and pions with the argon nuclei, and also nuclear processes such as μ^- capture and deexcitation. The signatures of these neutrons are identical to primary neutrons and are indistinguishable except for their spatial distribution: secondary neutrons are more prone to be near the production vertex, which is typically different from the neutrino interaction vertex. Due to the long interaction length of neutrons in liquid argon, it is not feasible to design a simple removal cut for these nonprimary neutrons, especially for sub-GeV neutrino interactions where the spatial spread of the event is often smaller than or comparable to the neutron interaction length. Instead, nonprimary neutrons may be statistically accounted for in certain analyses using correlated indicators, such as the existence of nonmuon originated Michel e^+ s (indicating the potential presence of stopped π^+ s), kinked tracks (indicating inelastic nuclear scattering), or tracks featuring no Bragg peak (indicating nuclear absorption in flight).

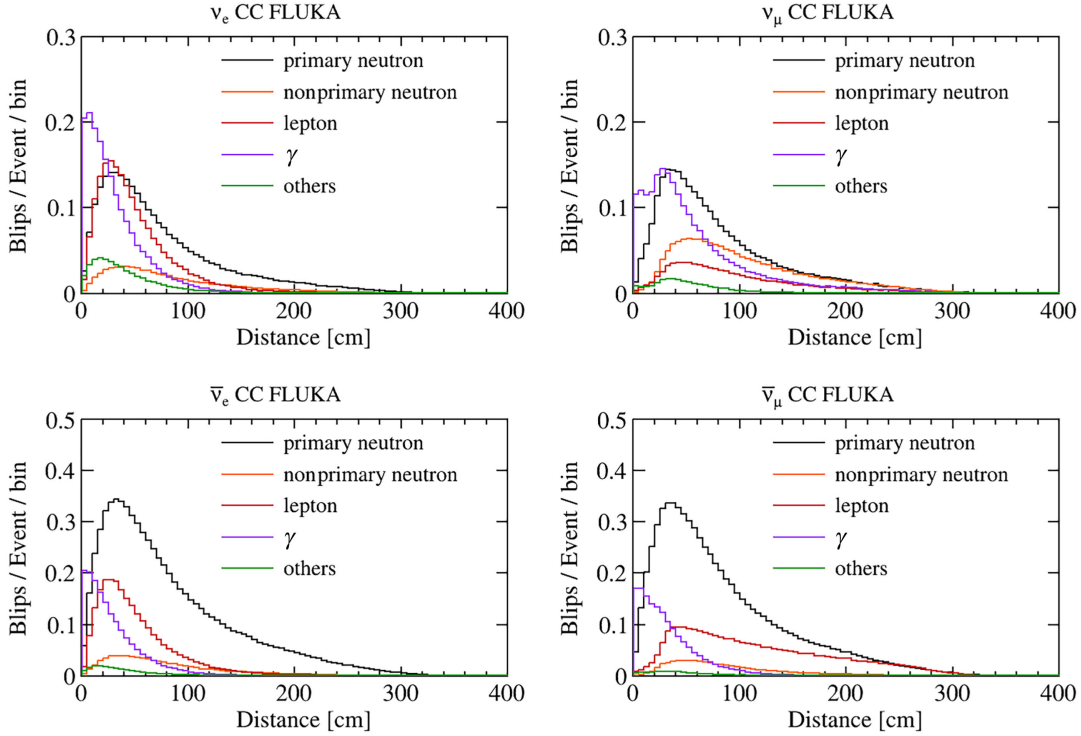


FIG. 3. Distributions of distances between each blip and its primary neutrino interaction vertex for ν_e (top left), ν_μ (top right), $\bar{\nu}_e$ (bottom left), and $\bar{\nu}_\mu$ (bottom right). The PoCA cut for $\nu_\mu/\bar{\nu}_\mu$ s and the cone angle cut for $\nu_e/\bar{\nu}_e$ s is applied, while lepton vertex and end point aimed at reducing deexcitation γ -ray populations are not applied.

Since this analysis represents a simple, general demonstration of neutron reconstruction capabilities, we do not implement any specialized cuts to reduce this background category.

D. Backgrounds from non-neutrino sources

Non-neutrino originated radiation can deposit energy in liquid argon and generate blips. These energy depositions typically come from TPC-internal or TPC-external natural radioactivity or cosmogenic activity. In the on-surface MicroBooNE neutrino LArTPC experiment, it has been demonstrated that β -decays of ^{39}Ar in the LAr bulk dominate blip production at energies < 0.5 MeV, cosmic rays dominate at energies > 3 MeV, and $^{238}\text{U}/^{232}\text{Th}/^{40}\text{K}$ β -decays mostly at or outside the surfaces of the LAr bulk dominate between these energy ranges [65]. Of these three populations, the low-energy ^{39}Ar component is the highest-rate contributor, particularly in regions removed from the TPC field cage edges. For cosmogenic activity or activation from cosmic-ray muon interactions, rates of blip production will be much reduced for underground sites relative to that demonstrated in MicroBooNE, and could be further reduced using time and spatial correlations with reconstructed cosmic-ray muon tracks. For natural radioactivity, most are introduced by materials near the detector boundary, such as field cage, photosensor, and electronics,

and can be reduced by introducing a spatial fiducial volume cut. The remaining major background for neutron reconstruction is the intrinsic radioactivity from ^{39}Ar .

Since the beta decay spectrum of ^{39}Ar has an end point of 0.56 MeV [67] and only produces true blip energies below this value, we apply a minimum blip energy cut of 0.6 MeV to reduce this background contribution. In anticipation of needing to further reduce residual ^{39}Ar contamination from misreconstruction and blips from other radiogenic contributors, we require all the blips used in this analysis to be contained within 2.5 m of their corresponding neutrino interaction vertex. The expected ^{39}Ar blip count is < 0.1 per neutrino interaction after application of this cut, and we neglect this background source for the remainder of our analysis.

E. Final selected blip populations

After applying the topological background rejection in Secs. III A and III B, using the PoCA and cone cuts, the γ rejection cut at the neutrino interaction vertex, and the muon end point, the reconstructed blip energy spectra from neutrino interactions are shown in Fig. 4. For all channels, neutrons appear to be the dominant producers of blips with > 0.5 MeV reconstructed energy, while final-state leptons contribute more substantially at the lowest blip energies. Neutron blip energy spectra contain a clear edge between

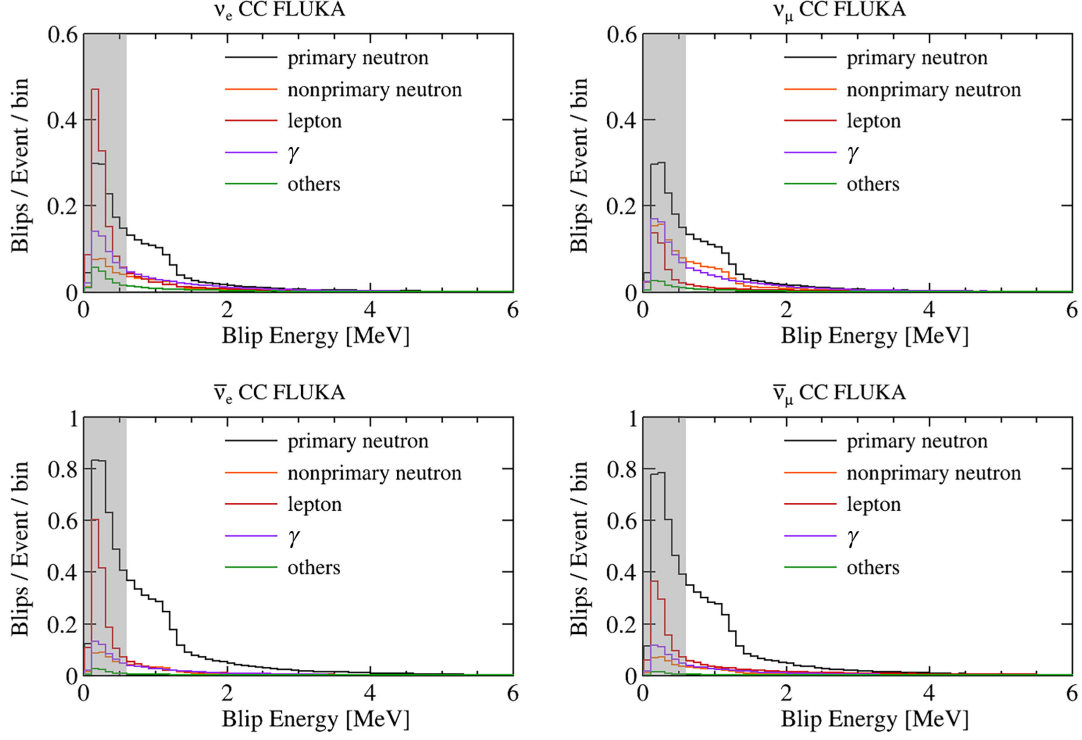


FIG. 4. Reconstructed energy distributions for selected blips from ν_e (top left), ν_μ (top right), $\bar{\nu}_e$ (bottom left), and $\bar{\nu}_\mu$ (bottom right) interactions. All topological cuts, including PoCA cut for $\nu_\mu/\bar{\nu}_\mu$ s and the cone angle cut for $\nu_e/\bar{\nu}_e$ s, the primary vertex cut, and the end-of-muon-track cut, are applied, as shown in Fig. 2.

1.0 and 1.5 MeV, a feature consistent with Compton scattering of 1.46 MeV γ -rays emitted in transitions between the first excited state and ground state of the ^{40}Ar nucleus. Meanwhile, the exponentially falling lepton blip spectra match what one would expect from stochastic radiative energy losses from δ -ray and final-state e^+ or e^- . This validates our 0.6 MeV energy cut in Sec. III D against the ^{39}Ar background.

After the 0.6 MeV energy cut in addition to the topological cuts, the blip multiplicity in the final selected blip sample for each neutrino type is shown in Table I, with breakdowns in each blip type.

In the Appendix, we provide various associated blip distributions, including vertex distance, true energy spectrum, and reconstructed energy spectrum, before and after background rejection cuts, using both the FLUKA and LArSoft-Geant4 particle transports.

TABLE I. Multiplicity of the final selected blip sample for each neutrino type, with each broken down by ancestry category.

	Primary n	Nonprimary n	l	γ	Other
ν_e	1.07	0.29	0.38	0.50	0.15
$\bar{\nu}_e$	3.06	0.35	0.47	0.42	0.07
ν_μ	1.12	0.56	0.20	0.59	0.09
$\bar{\nu}_\mu$	2.98	0.27	0.75	0.41	0.04

IV. NEUTRON RECONSTRUCTION PERFORMANCE

Neutron blips carry information on the existence, multiplicity, and kinematics of final-state neutrons. When multiple primary neutrons are produced in a neutrino interaction, it is highly difficult to separate blips from each of the primary neutrons due to the spread of blips from neutron free path length. We therefore study neutron reconstruction using the entire neutron system, defined as the ensemble of all primary neutrons from a neutrino interaction, instead of individual neutrons. The main goals of neutron reconstruction include the identification of these primary neutrons and the reconstruction of the direction and energy of the neutron system.

A. Neutron identification

For the sub-GeV neutrinos considered in this paper, we split the simulated events in four categories based on the primary neutrino topology in the final states: with protons and no neutrons ($Xp0n$), with protons and neutrons ($XpXn$), with no proton or neutrons ($0p0n$), and with no proton but some neutrons ($0pXn$). We require the neutron categories Xn to have at least one neutron with more than 5 MeV kinetic energy, and the proton category Xp to have at least one proton with more than 30 MeV, for visibility. The blip multiplicity in each category is shown in

Fig. 5. In Fig. 5, we observe an overall tendency for Xn samples to have more blips than $0n$ samples. This tendency is stronger in antineutrino samples than neutrino samples, as neutrons get more energy from antineutrino interactions than neutrino interactions.

To quantify the performance of neutron identification via blips, we consider a simple cut analysis using blip multiplicity only, targeted at separating Xn events from $0n$ events. For each neutrino sample of ν_e , $\bar{\nu}_e$, ν_μ , and $\bar{\nu}_\mu$, we first map signal efficiency (true positive rate) for Xn events and background contamination (false positive rate) for $0n$ events as a function of reconstructed blip multiplicity, also known as a receiver operating characteristic (ROC) curve. An example ROC curve for the pure ν_e sample is shown in Fig. 6. The area under the curve (AUC) listed in Table II is an evaluation of the neutron identification performance, with an AUC of 1 indicating perfect, background-free Xn signal identification, while an AUC of 0.5 indicates no separation. The difference in AUC between ν and $\bar{\nu}$ primarily arises from the higher average summed kinetic energy of final-state neutrons for the latter category, while the reduced AUC for ν_μ comes from the confounding presence of μ^- capture-at-rest blips in both $0n$ and Xn events.

Next, we look to optimize blip cuts events towards the best significance of selecting Xn events in a realistic neutrino sample. To quantify the significance, we use the approximated Asimov significance [68],

$$\sqrt{2[S - B \ln(1 + S/B)]}, \quad (1)$$

where S denotes the number of neutrino interactions with primary neutrons in the final state, Xn , and B denotes the number of neutrino interactions without primary neutrons in the final state, $0n$. Figure 6 shows an example of a mixed $\nu_e/\bar{\nu}_e$ sample, using the $\nu_e/\bar{\nu}_e$ ratio found in sub-GeV atmospheric neutrino fluxes. This process is separately done for $\nu_e/\bar{\nu}_e$ and $\nu_\mu/\bar{\nu}_\mu$ as lepton flavor identification typically performs well in LArTPCs, and the residual contamination can be considered secondary. The best cut is found at three blips for both the $\nu_e/\bar{\nu}_e$ sample and the $\nu_\mu/\bar{\nu}_\mu$ sample.

At this optimized blip multiplicity cut value, we define events with blip multiplicity $>$ best cut to be in a neutron rich subsample (reconstructed Xn sample), and events with blip multiplicity $\leq$ best cut to be in a neutron poor subsample (reconstructed $0n$ sample). We can then evaluate neutron identification performance using a confusion

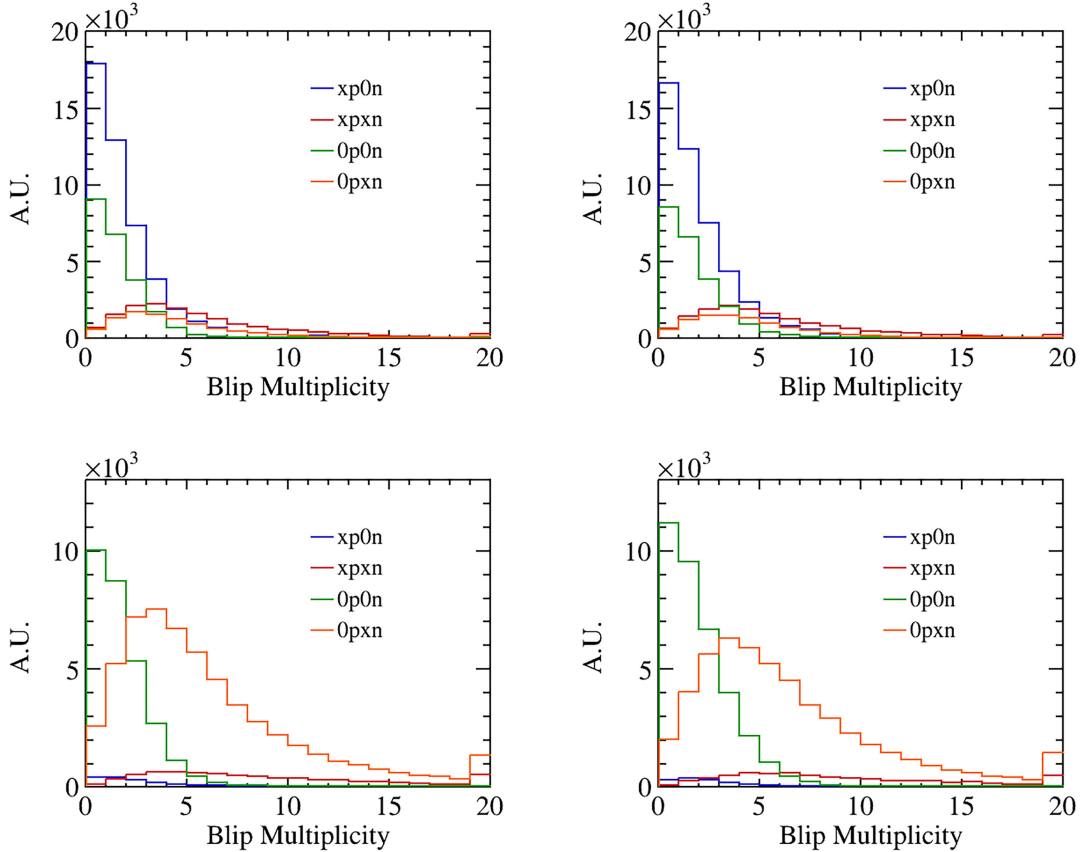


FIG. 5. Blip multiplicity for different final-state topologies in ν_e (top left), ν_μ (top right), $\bar{\nu}_e$ (bottom left), and $\bar{\nu}_\mu$ (bottom right) interactions. The last bin along the x-axis serves as an overflow bin.

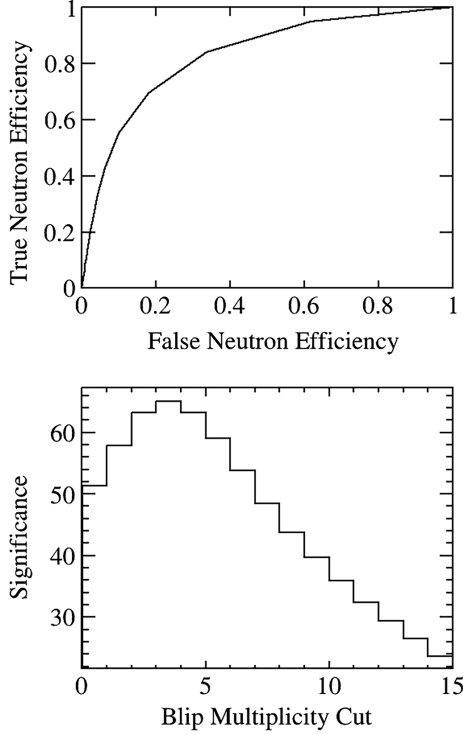


FIG. 6. Top: ROC curve for the blip multiplicity cuts used for neutron identification on the ν_e sample. Bottom: Blip multiplicity distribution used for cut optimization in a mixed $\nu_e/\bar{\nu}_e$ sample. The best cut boundary, whose definition can be found in the text, is determined to be > 3 blips.

matrix, as shown in Table III. It appears that, using blip multiplicity information alone, sub-GeV neutrino events hosting final-state neutrons can be identified with $\sim 70\%$ efficiency, with $\sim 20\%$ of neutron-free events contaminating this category due to the presence of nonprimary-neutron blip activity. This result, while promising on its own, is likely to be improved upon with additional methods that will be discussed in Sec. VIC.

TABLE II. AUC for the ROC curve of the blip multiplicity selection in neutron identification, with breakdowns in neutrino types.

	ν_e	ν_μ	$\bar{\nu}_e$	$\bar{\nu}_\mu$
AUC	0.83	0.82	0.85	0.85

TABLE III. Confusion matrix for $\nu_e/\bar{\nu}_e$ s (left) and $\nu_\mu/\bar{\nu}_\mu$ s (right).

	True 0n		True Xn		
Reco Xn	0.18	0.71	Reco Xn	0.21	0.74
Reco 0n	0.82	0.29	Reco 0n	0.79	0.26

B. Direction and energy of the neutron system

In this section, we aim to compare the true direction and energy of final-state neutron systems with comparable quantities reconstructed from blip-based information. This is the first quantification of this kind performed in the literature for directional reconstruction. While blip-based neutron kinetic energy reconstruction capabilities were investigated in Ref. [24], this is the first exploration above a few 10 s of MeV—an energy regime particularly relevant for GeV-scale neutrino interactions.

For directionality, we consider the direction of the neutron system along the true momentum vector $\vec{P}_n$, as follows:

$$\vec{P}_n = \sum \vec{P}_i^n, \quad (2)$$

where $\vec{P}_i^n$ is the momentum of every primary neutron i above 5 MeV in the neutron system. We then assign vectors $\vec{V}_j^b$ from the primary interaction vertex to each blip j after the background reduction cuts discussed in Sec. III, and take the sum of these vectors $\vec{V}_b$, as follows:

$$\vec{V}_b = \sum \vec{V}_j^b, \quad (3)$$

as the reconstructed neutron system direction. The direction reconstruction performance is quantified as the inner angle θ between $\vec{P}_n$ and $\vec{V}_b$, as follows:

$$\theta = \arccos(\vec{P}_n \cdot \vec{V}_b / |\vec{P}_n| |\vec{V}_b|). \quad (4)$$

Different directionality reconstruction, for example, weighting blip vectors with blip energy, are also explored and are observed to change the result slightly, but does not present any significant improvement in performance.

Figure 7 shows the direction reconstruction performance in the inner angle θ for $\bar{\nu}_e$ interactions as a function of the

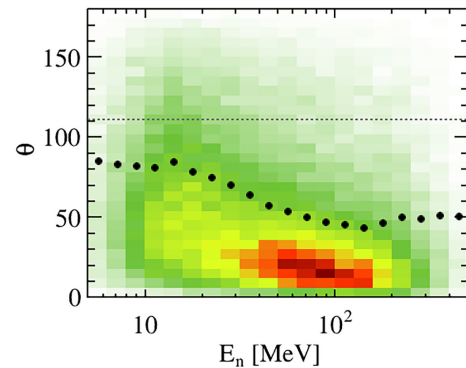


FIG. 7. Direction reconstruction inner angle θ as a function of the neutron system energy, using blip information in $\bar{\nu}_e$ events. Black points indicate the 68% percentile resolution from the contour. Gray dashed lines indicate the 68% percentile resolution if no directional information is obtained.

neutron system energy E_n , where $E_n = \sum E_n^i$, and E_n^i is the kinetic energy of each neutron above 5 MeV in the neutron system. Besides these $\theta - E_n$ distributions indicated by the colored contours in Fig. 7, the 68% percentile, or the resolution in θ , is also plotted. Similar performance is observed in neutron systems from $\bar{\nu}_e$, ν_μ , and $\bar{\nu}_\mu$ events. At 100 MeV kinetic energy, the direction of the neutron system can be reconstructed with $\sim 40^\circ$ angular resolution. While the performance is not as good as for high-energy electromagnetic showers or muon tracks, it is a meaningful outcome that demonstrates that blips can uncover the ability to perform differential cross-section measurements as a function of neutron angular kinematics for $\nu - \text{Ar}$ interactions.

For energy reconstruction, we consider E_n , the sum of kinetic energy of each neutron above 5 MeV in the neutron system. The reconstruction estimator is constructed as the naïve sum of the energy of the blips in MeV, $E_{\text{blip}} = \sum E_j$, where E_j is the reconstructed energy of blip j in MeV. We also tried different estimators, including removing the blip energy weight, or adding a distance-to-vertex weight, none of which significantly outperforms the naïve sum.

Figure 8 shows the energy correlation between the sum of blip energy and the energy of the neutron system in $\bar{\nu}_e$ s. The observed correlation between true and reconstructed neutron energy indicates that blip-based neutron

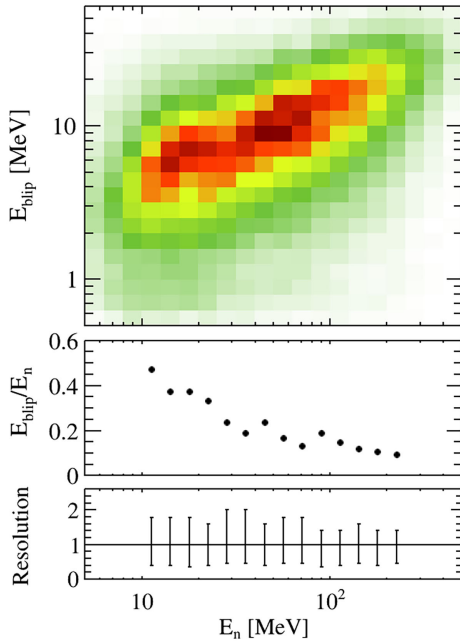


FIG. 8. Energy reconstruction for the neutron system using blip information E_{blip} as a function of true neutron system energy E_n in $\bar{\nu}_e$ events. Top: two-dimensional correlation. Middle: ratio of E_{blip}/E_n , where the peak in the E_{blip} in a given E_n bin is taken as the numerator, and the center of the E_n bin as the denominator. Bottom: asymmetric relative resolution, defined as 68% of population on one side of the peak in E_{blip} .

TABLE IV. Summary of demonstrated neutron identification and reconstruction performances in Sec. IV.

Identification efficiency in subGeV $\nu_e/\bar{\nu}_e$'s	0.71
Background inefficiency in subGeV $\nu_e/\bar{\nu}_e$'s	0.18
Angular resolution at 100 MeV	40°
Energy resolution at 100 MeV	50%
Dominant uncertainties	Sec. VI A 1

calorimetry is possible in LArTPC neutrino interactions, as further discussed in Sec. VB. The middle panel of Fig. 8 shows that across the energy range considered, the summed energy of all signal blips accounts for $\leq 50\%$ of the total neutron energy. Instead, most energy is lost in a variety of different processes: elastic neutron-argon scattering, binding energy losses from nucleon emission, unreconstructed charge below blip reconstruction thresholds, reconstructed blips excluded from the signal sample, and neutron escape from the 2.5m radius. Energy losses are fairly evenly split between these various categories. The bottom panel of Fig. 8 shows the fractional resolution as a function of true neutron energy. Above 100 MeV kinetic energy, the energy of the neutron system can be reconstructed with $\sim 50\%$ energy resolution.

A summary of the results in this section is presented in Table IV.

V. PHYSICS APPLICATIONS

In this section, we discuss two example physics use cases of blip-based neutron reconstruction: neutrino-antineutrino separation, and neutrino kinematic reconstruction.

A. Neutrino antineutrino separation

1. Separation in atmospheric neutrinos

Separation of neutrinos from antineutrinos is an important topic in atmospheric neutrinos, especially for the purposes of improving CP violation and mass ordering sensitivities. Neutron reconstruction is a typical approach towards neutrino antineutrino separation [69]. The recent Super-Kamiokande atmospheric study has demonstrated that with a modest 26% efficiency in neutron identification, an improvement in the sample purity and thus the mass ordering sensitivity can be seen [29,70].

Charge conservation implies that in neutrino interactions, statistically speaking, neutrinos tend to produce more protons, and antineutrinos tend to produce more neutrons. In LArTPCs, the high image resolution enables the separation of ν s and $\bar{\nu}$ s by the identification of protons in final-state particles in neutrino interactions. In the sub-GeV atmospheric neutrino charged current interaction samples used in this analysis, assuming a perfect identification of protons above 30 MeV energy, for electron-flavor neutrinos, one can obtain 98% ν purity by requiring

TABLE V. Efficiency (normalized per neutrino type) and purity (normalized per topology) in each reconstructed topology category assuming atmospheric ν_e and $\bar{\nu}_e$ charged current events composition.

Topology	Efficiency		Purity	
$0p$	0.34	0.90	0.72	0.28
Xp	0.66	0.10	0.98	0.02
$0pXn$	0.10	0.49	0.57	0.43
$0p0n$	0.24	0.41	0.80	0.20
$XpXn$	0.22	0.08	0.95	0.05
$Xp0n$	0.44	0.02	0.99	0.01
	ν_e	$\bar{\nu}_e$	ν_e	$\bar{\nu}_e$

at least one reconstructed proton Xp , and 28% $\bar{\nu}$ purity by requiring no reconstructed protons $0p$, as shown in the top rows in Table V. The performance is satisfactory for ν s but much less so for $\bar{\nu}$ s, due to both the flux composition and the cross section.

The purity of the $\bar{\nu}$ sample can be enhanced by using neutron identification with blips. We look at the sub-GeV atmospheric neutrino charged current interaction samples to demonstrate this capability. Using the blip multiplicity cuts for different flavor samples developed in Sec. IV A, we can construct a topological classification of Xn and $0n$, where Xn denotes a reconstructed neutron rich category with blip multiplicity above the cut (three blips for $\nu_e/\bar{\nu}_e$ s and three blips for $\nu_\mu/\bar{\nu}_\mu$ s, as detailed in Sec. IV A), and $0n$ denotes a neutron-poor category with blip multiplicity otherwise, in addition to the Xp and $0p$ categories. The $\nu_e/\bar{\nu}_e$ efficiencies in each topological category are listed in the left columns in Table V. Placed in the context of atmospheric neutrinos, with the expected atmospheric neutrino flux composition and the corresponding $\nu_e/\bar{\nu}_e$ charged current interaction rate, we obtain the purity in each reconstructed topological category as shown in the right columns of Table V. The $\bar{\nu}_e$ purity can be enhanced from 28% in the $0p$ sample to 43% in the $0pXn$ sample, at 49% efficiency. Super-Kamiokande reported in its atmospheric neutrino oscillation analysis [70] a $\bar{\nu}_e$ charge purity of 38.7% at 43.6% efficiency in the SK IV–V $\bar{\nu}_e$ -like $1n$ sample. Our result indicates a potential increase in both purity and efficiency compared to the reported Super-Kamiokande result. Moving the blip multiplicity cut up to 5 towards better purity, it is feasible to achieve $\sim 50\%$ with 30% efficiency, from blip information alone.

For $\nu_\mu/\bar{\nu}_\mu$ separation, further identification can be pursued via the Michel electron from muon decays. The SBND experiment has demonstrated a Michel electron selection with machine learning reconstruction achieving an efficiency of $\sim 80\%$ [71], with potential improvement using the complementary muon capture-at-rest feature [24]. While the separation performance via blip identification is similar to $\nu_e/\bar{\nu}_e$ s, with the requirement of reconstructed Michel electrons (denoted as $1m$), assuming a Michel

TABLE VI. Efficiency (normalized per neutrino type) and purity (normalized per topology) in each reconstructed topology category assuming atmospheric ν_μ and $\bar{\nu}_\mu$ charged current events composition, taking into consideration Michel electron reconstruction efficiency at 80%.

Topology	Efficiency		Purity	
$0p1m$	0.07	0.72	0.34	0.66
$1p1m$	0.13	0.07	0.91	0.09
$0pXn1m$	0.02	0.40	0.23	0.77
$0p0n1m$	0.05	0.33	0.44	0.56
$XpXn1m$	0.05	0.06	0.82	0.18
$Xp0n1m$	0.08	0.01	0.97	0.03
	ν_μ	$\bar{\nu}_\mu$	ν_μ	$\bar{\nu}_\mu$

electron selection efficiency of 80% [71], we obtain the event numbers in each reconstructed topological category as shown in Table VI. The $\bar{\nu}_\mu$ purity can be enhanced from 66% in the $0p1m$ sample to 77% in the $0pXn1m$ sample.

2. Separation in beam neutrinos

The same approach can be deployed to beam neutrinos with reverse horn current (RHC), where we have the same challenge of separating $\bar{\nu}$ s from ν s due to the less pure $\bar{\nu}$ beam compared to ν s beam in the forward horn current mode. Take the Booster Neutrino Beam (BNB) [72] as an

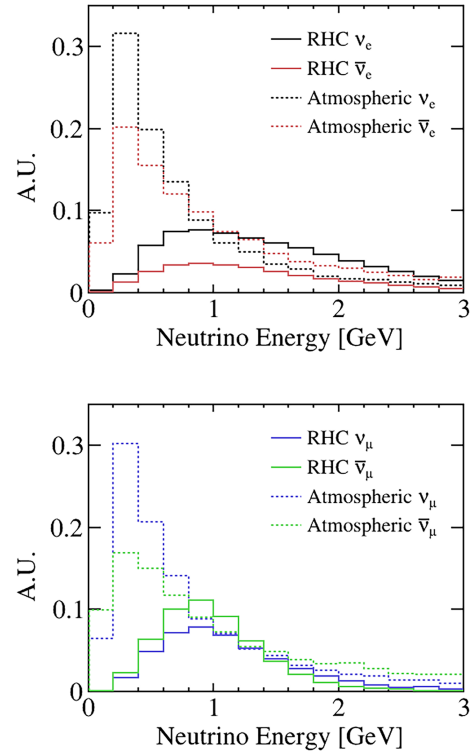


FIG. 9. Energy spectra of $\nu/\bar{\nu}$ interactions in atmospheric neutrinos (dashed lines) and in BNB RHC beam neutrinos [11], normalized by flavor in each neutrino source. Top: ν_e (black) and $\bar{\nu}_e$ (red). Bottom: ν_μ (blue) and $\bar{\nu}_\mu$ (green).

TABLE VII. Purity (normalized per topology) in each reconstructed topology category assuming BNB RHC charged current events composition, taking into consideration Michel electron reconstruction efficiency at 80% with 1m requirement only for ν_e s and $\bar{\nu}_\mu$ s.

Topology	$\nu_e/\bar{\nu}_e$ Purity		$\nu_\mu/\bar{\nu}_\mu$ Purity	
0p(1m)	0.48	0.52	0.08	0.92
1p(1m)	0.94	0.06	0.61	0.38
0pXn(1m)	0.32	0.68	0.05	0.95
0p0n(1m)	0.59	0.41	0.11	0.89
XpXn(1m)	0.87	0.13	0.43	0.57
Xp0n(1m)	0.98	0.02	0.84	0.16
	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$

example. The similarity in flux and event rate energy spectra indicates applicability of our established methods, as shown in Fig. 9, with the caveat of missing events above 1 GeV neutrino energy. Reweighting the simulated atmospheric neutrino components to that of BNB RHC [11] and applying the same procedure of neutron-enhanced neutrino-antineutrino separation, we obtain an estimated $\nu_e/\bar{\nu}_e$ separation performance as in Table VII. The $\bar{\nu}$ purity from BNB RHC is better compared to atmospheric neutrinos because of both the more dominant $\bar{\nu}$ components and the energy spectra peaking at higher energy, enabling more high-energy neutrons to be detected and reconstructed via blips. With beam neutrinos, the separation of $\nu/\bar{\nu}$ can include more information such as the angle between the lepton direction and the beam direction, indicating helicity suppression. It is typically handled using multivariate analysis techniques, and the addition of neutron information from blip reconstruction offers a power additional differentiating variable in this kind of framework.

B. Neutrino direction and energy reconstruction

We typically rely on the lepton information (for example, Ref. [12,73]) or leptonic energy plus information from final-state protons and mesons (for example, Refs. [17,74]) to represent the incoming neutrino kinetics in a LArTPC. For neutrino interactions producing neutrons in their final states, the reconstruction of the neutron system could in principle enhance neutrino direction and energy reconstruction by adding the missing neutron information back. We therefore study neutrino energy and direction reconstruction using the neutron information with the technique described in Sec. IV B.

To focus on the impact of neutron system reconstruction, we study a subsample of $\bar{\nu}_e$ reconstructed as Xn, with true primary neutrons above 5 MeV in the final state. We first construct a toy reconstruction without neutron information as the evaluation baseline with

$$\vec{P}_\nu^{\text{rec}} = |\sum \vec{P}_i|, \quad (5)$$

where P_i is the smeared momentum of each particle i above the corresponding threshold using an assumed resolution. For the sub-GeV atmospheric neutrino sample used in this analysis, we include the particles of es , μs , $\pi^\pm s$, and ps , with corresponding kinetic energy thresholds at 10 MeV for the leptons and 30 MeV for the hadrons, assumed energy resolutions at 5% for leptons and 10% for hadrons, and assumed angular resolutions at 2° for leptons and 10° for hadrons. This toy reconstruction performance is chosen to be comparable with a few phenomenological studies [6,7] and experimental observations [19].

Figure 8 shows the correlation between the sum of blip energy and the energy of the neutron system. It can be fit by quadratic functions

$$E_n^{\text{rec}} = 27.8 \text{ MeV} + 3.41 \times E_{\text{blip}} - 0.0164 \text{ MeV}^{-1} \times E_{\text{blip}}^2, \quad (6)$$

for $\nu_e/\bar{\nu}_e$ s, and

$$E_n^{\text{rec}} = 25.4 \text{ MeV} + 4.44 \times E_{\text{blip}} - 0.0045 \text{ MeV}^{-1} \times E_{\text{blip}}^2, \quad (7)$$

for $\nu_\mu/\bar{\nu}_\mu$ s, where E_n^{rec} represents the reconstructed energy of the neutron system. The reconstructed neutrino energy is therefore assigned as

$$E_\nu^{\text{rec,n}} = |\vec{P}_\nu^{\text{rec}}| + E_n^{\text{rec}}, \quad (8)$$

requiring reconstructed neutron energy $E_n^{\text{rec}} > 0$. Figure 10 shows the energy reconstruction performance with and without the blip-based neutron reconstruction as a function of the incident neutrino energy E_ν . With the addition of neutron information, we see a smaller bias in neutrino energy, as well as a larger resolution. The bias reduction comes from neutron kinematics completing the energy deposition from neutrino interactions in LArTPCs, as noted or quantified previously in the literature in both higher-energy (4 GeV $\nu_e/\bar{\nu}_e$ [23]) and lower-energy (<100 MeV ν_e [24,75,76]) neutrino contexts. The worse resolution is driven by the large uncertainty in the energy of the neutron system, as seen in the width of Fig. 8. It indicates that the energy scale uncertainty from missing neutrons is smaller than the neutron energy resolution currently achieved.

On directionality, the performance is evaluated using the inner angle θ between the true neutrino direction and the reconstructed neutrino direction along the momentum direction. The neutrino direction with neutron information is constructed along the direction of the momentum with neutron information,

$$\vec{P}^{\text{rec,n}} = \vec{P}^{\text{rec}} + \vec{P}_n^{\text{rec}}, \quad (9)$$

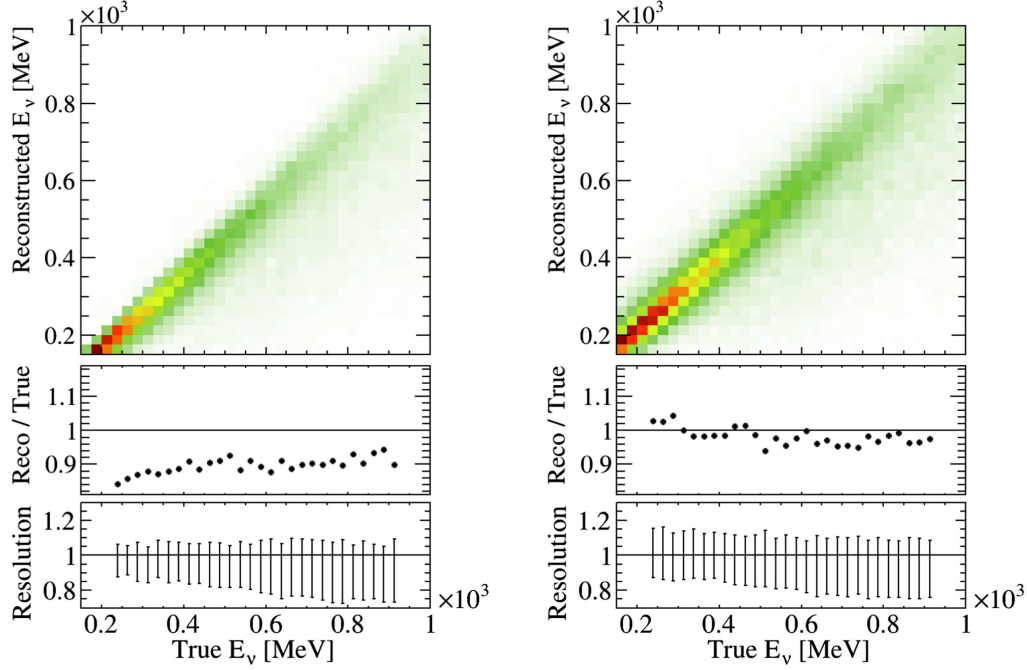


FIG. 10. Energy reconstruction performance for $\bar{\nu}_e$ with at least one primary neutron above 5 MeV, without (left) and with (right) blip information. Top: Two-dimensional response matrix relating true neutrino energy to reconstructed neutrino energy. Middle: Ratio of reconstructed to true neutrino energy, where the peak in the reconstructed E_ν in a given true E_ν bin is taken as the numerator and the center of the true E_ν bin is taken as the denominator. Bottom: Asymmetric relative resolution defined as 68% of the population on each side of the peak.

where we define $\vec{P}_n^{\text{rec}}$ as a vector with the direction of the reconstructed direction of the neutron system $\vec{V}_b/|\vec{V}_b|$, and the magnitude of $|\vec{P}_n^{\text{rec}}| = \sqrt{E_n^{\text{rec}2} - M_n^2}$, in which M_n is the neutron mass, and E_n^{rec} is the reconstructed energy of the neutron system, requiring $E_n^{\text{rec}} > 0$. This definition implies an assumption of neutron multiplicity being 1, although the neutron multiplicity in the neutron system is unknown. The choice is justified as in a large number of events, there is one leading energetic neutron generating the majority of blips. Figure 11 shows the direction reconstruction performance with and without blip-based neutron reconstruction as a function of neutrino energy E_ν . The modest enhancement from neutron information in directional reconstruction can be seen in the lower end of the neutrino energy spectrum below 300 MeV, where the angular resolution is improved from $\sim 100^\circ$ to $\sim 90^\circ$.

In both the neutrino energy and neutrino direction reconstruction, we see that including blip information gives a composite result of a smaller bias and a larger spread, the former indicating the importance of including the neutron information, and the latter indicating the limited precision in our simple neutron reconstruction scheme. One can expect potential future improvements in neutron reconstruction as discussed in Sec. VIC to enhance the precision and further benefit neutrino kinetic reconstruction. With the current performance, however, the most robust use of blip information is likely in event

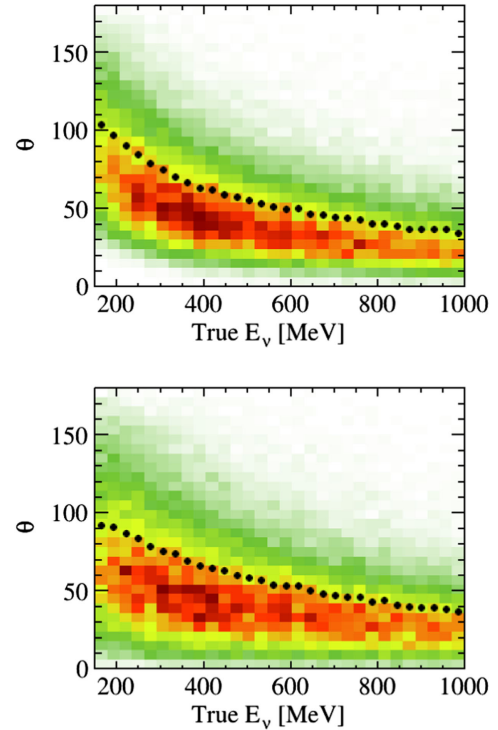


FIG. 11. Direction reconstruction for $\bar{\nu}_e$ s with at least one primary neutron above 5 MeV, without (top) and with (bottom) blip information. Black points indicate the 68% percentile, or the resolution.

classification and sample categorization through neutron identification. As shown the left figure in Fig. 10, the Xn (neutron-rich) sample exhibits a $\sim 10\%$ energy scale bias. Thus, even in the cases which do not require neutrino-antineutrino separation, such as the highly ν -pure FHC beam samples, neutron identification via blips can be used to divide the data into neutron-poor (small energy-scale uncertainty) and neutron-rich (large energy-scale uncertainty) subsamples. Dedicated neutron kinetic reconstruction will be especially valuable in physics cases where hadronic activity is directly relevant, such as hadrophilic dark matter searches [77–79]. In addition, the neutron kinetic reconstruction could serve as a nuisance-constraining variable in oscillation analyses [70].

It should be noted that while we demonstrate potential benefits of neutron reconstruction with blips, the resulting performance gain in neutrino physics analyses, such as oscillation studies and rare event searches, is subject to significant systematic uncertainty in neutron production modeling, as discussed in Sec. VI A 2.

VI. DISCUSSION AND OUTLOOK

A. Systematic uncertainties

1. Neutron propagation and interaction

Different energy depositions and blip multiplicities will originate from different modeling of neutron propagation, inelastic scattering, and argon nucleus deexcitation. As discussed in Sec. II B, after the neutrino interaction generation using FLUKA, we have the choice to propagate the produced final-state particles using different packages. While this paper adopts FLUKA for particle transport as the central value sample used in the studies presented in Secs. III–V, we also deployed a LArSoft-based Geant4 particle transport using the Bertini cascade model, with high-precision modeling for low-energy neutrons using the NeutronHP library [63].

We investigated the outcomes of applying the same set of blip background reduction cuts and neutron reconstruction algorithm developed with FLUKA propagated sample to the Geant4 propagated sample, as a systematic uncertainty evaluation process. To illustrate, Table VIII shows the neutron identification confusion matrix previously

discussed for FLUKA in Sec. IV A and Table III, with Geant4 and FLUKA results shown side by side. The true neutron efficiency with primary neutrons in both flavor samples are quite comparable between Geant4 and FLUKA particle transport, as is the rejection inefficiency for no primary neutrons in electron-flavor final states, with $\leq 5\%$ relative differences. For muon-flavored final states, a more substantial difference, 28% versus 21%, is likely due to inaccurate Geant4 modeling of deexcitation products of the μ^- capture at rest process, as noted by the LArIAT experiment [80].

2. Neutron production

It is challenging to model neutron and proton production from neutrino interaction on argon, due to the complexity of the argon nucleus. To show the differences in the neutrino interaction modeling, we use an alternative neutrino generator GENIE [45] in addition to the FLUKA generator, and compare the neutron distributions from the generator predictions using the same neutrino flux. We also consider GENIE with the INTRANUKE effective intranuclear rescattering model hA [46], and Liège Intranuclear Cascade (INCL) model [47], as final-state interaction variations. The FLUKA generator predictions are shown in Fig. 1, while the GENIE generator predictions are shown in Fig. 12.

The top row in Fig. 12 shows the resulting differences in neutron kinetic energy distributions for sub-GeV atmospheric neutrinos, with a 2 MeV threshold to avoid the overwhelmingly large population of mostly invisible evaporation neutrons (the same treatment as in Fig. 1). There is a strong model discrepancy in low-energy neutron production below 5 MeV kinetic energy, which motivates our signal definition with the 5 MeV threshold in Sec. IV A, in addition to visibility considerations.

The bottom row in Fig. 12 shows the neutron multiplicity above 5 MeV kinetic energy cut. We observe the general tendency of $\bar{\nu}$'s producing more neutrons than ν 's as expected. In addition, GENIE-INCL tends to predict a lower multiplicity than from GENIE-hA even with the 5 MeV kinetic energy threshold. This is due to GENIE-INCL having a similar neutron spectrum and multiplicity to FLUKA shown in Fig. 1, leaning towards lower energy compared to GENIE-hA. While we can raise the neutron energy threshold further to mitigate this discrepancy in the predictions, in order to use neutron information in studies such as neutrino oscillation and cross-section analyses, the reconstruction should aim to cover as much phase space as possible. The uncertainty in low-energy neutron production therefore poses a significant challenge to use neutron information in neutrino reconstruction. It requires more experimental data on nucleon multiplicity in LArTPC experiments, and more data-to-model comparison as well as model parameter tuning, calling for a collaborative effort

TABLE VIII. Comparison of neutron identification efficiency for $\nu_e/\bar{\nu}_e$'s (top) and $\nu_\mu/\bar{\nu}_\mu$'s (bottom).

		Neutron eff.	Non-neutron ineff.
$\nu_e/\bar{\nu}_e$	FLUKA	0.71	0.18
	Geant4	0.71	0.19
$\nu_\mu/\bar{\nu}_\mu$	FLUKA	0.74	0.21
	Geant4	0.75	0.28

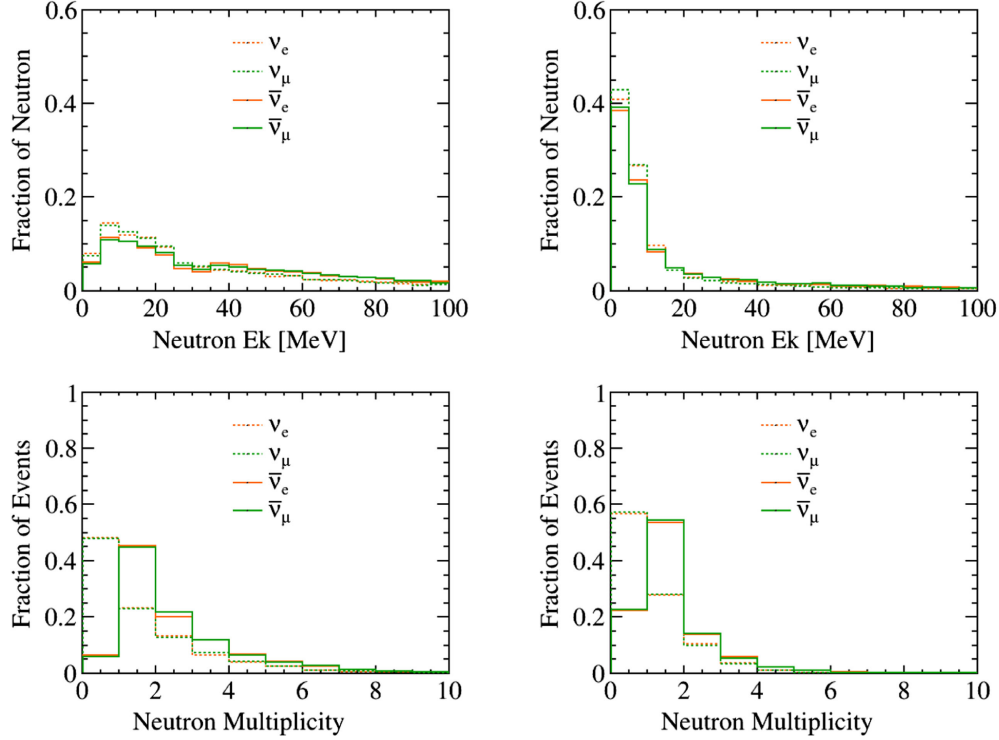


FIG. 12. Neutron kinetic energy distribution with a 2 MeV threshold (top) and neutron multiplicity distribution with a 5 MeV threshold (bottom) from sub-GeV atmospheric neutrinos generated using GENIE-hA (left) and GENIE-INCL (right).

from neutrino experiments, neutrino cross-section model developments, and nuclear physics experts.

B. LArTPC detector applicability

The blip threshold and energy resolution, or more generally, the blip detector response, is impacted by the drift distance, wire pitch, and noise environment. We discuss below the impact of detector parameters on our neutron blip selection and analyses:

- (i) Drift loss: due to the impurity in LAr, the ionization electrons suffer a loss during the drift to the anode. This effect can be characterized as

$$Q_a = Q_0 e^{-t/\tau_e}, \quad (10)$$

where Q_a is the detected charge, Q_0 is the deposited charge, t is the drift time from blip to the anode, and τ_e is the so-called electron lifetime, a parameter indicating the purity of LAr. If t , or equivalently the blip distance to anode along drift direction (usually called x -coordinate), is unknown, the charge loss can result in an uncertainty during reconstruction from Q_a to Q_0 . However, for blips originating from neutrino interactions, such as the neutron blips and the backgrounds discussed in Secs. III A, III B, and III C, t can be reconstructed with good precision assuming the blip is simultaneous (within ~ 1 us) with the neutrino interaction, and thus our selection and analyses are not

subject to this uncertainty. With known t , the charge loss induces a very mild impact on energy response smearing [64] and blip threshold due to the loss of ionization electron statistics, the latter of which is further mitigated by the 0.6 MeV blip energy cut for ^{39}Ar background rejection, as discussed in Sec. III D.

- (ii) SNR: the SNR observed in the TPC waveforms limits the blip reconstruction threshold. The 0.6 MeV blip energy cut for ^{39}Ar background rejection discussed in Sec. III D makes our selection not sensitive to the intrinsic SNR limited blip reconstruction threshold. This is true for LArTPC detectors such as MicroBooNE, SBND, and ProtoDUNE, with an SNR of $\gtrsim 20$ on the collection plane in raw data [81–83]. For future detectors such as the DUNE far detectors, maintaining a similar SNR should be sufficient for neutron blip purposes. We note that when the SNR of an LArTPC is too low, the blip energy threshold could become noise limited rather than background limited. As an example, it will be a challenge to achieve blip-enhanced neutron reconstruction and physics application in warm electronics detectors such as ICARUS, which has a relatively low SNR of 10.8 on the collection plane [84], due to noise from the long distance analog signal transmission.
- (iii) Wire pitch: wire pitch impacts the charge deposition per wire, and thus impacts the blip reconstruction threshold. LArTPCs with a 5 mm pitch, such as ProtoDUNE [83] and DUNE [85], collect more charge per wire, and could

use a less-stringent requirement on SNR to achieve the same blip reconstruction threshold, compared to the 3 mm pitch LArTPCs such as MicroBooNE [81] and SBND [11]. However, as mentioned above, with the 0.6 MeV blip energy cut for ^{39}Ar background rejection, the blip selection in this paper is not sensitive to the intrinsic blip reconstruction threshold. The change of position precision between a 3 mm pitch and a 5 mm pitch is negligible compared to the 20 cm and 40 cm selection cuts in Secs. III A and III B.

In addition to detector response, the background rate also limits the level information extractable from blips. As discussed in Sec. III D, we consider radioactivities commonly existing in the LAr bulk region while assuming the radioactivities from TPC structures are removable from a fiducial volume cut. Cosmogenic backgrounds are not considered in this work. For deep-underground detectors, a generous rejection cut near the detected cosmic-ray muon track in time and space can reject most of the cosmogenic backgrounds. For surface detectors or near-surface detectors subject to significant cosmogenic backgrounds, spallation must be studied in further detail to balance the acceptance and the background rejection efficiency, as demonstrated in other neutrino detectors [86–89].

C. Neutron reconstruction improvements

In this paper, we demonstrated a working framework for neutron reconstruction via blips in LArTPCs using a simple and intentionally conservative approach. The current cuts are set to keep the performance robust when applied to various LArTPC performances. To name a few, the 20 cm PoCA cut is robust against the $\lesssim 1$ cm vertex resolution in this energy range [90]. The 45° cone cut is robust against the $\lesssim 10^\circ$ shower angular resolution in this energy range [90], given the $\lesssim 30^\circ$ intrinsic visible opening angle from the Molière radius [91].

Looking forward from this first demonstration, we see ample room for improvement in performance along many stages of the analysis process in experimental application, with the detector and reconstruction performance of a specific detector. Here, we list some clear areas of future improvement:

- (i) PoCA cuts for $\mu^\pm$: the current PoCA cut applied along a line segment connecting the start- and end points of a track could miss rejection of background blips if the track has been scattered, which can be recovered by a more realistic track reconstruction, removing blips within PoCA distance of all hits clustered in any track, not necessarily along a line segment.
- (ii) Shower cuts for $e^\pm$: shower exclusion is also highly simplified: a selection based on a more informed approach adapted from established electromagnetic calorimetric techniques, such as the Molière radius [91], could potentially provide better treatment of this blip category.
- (iii) Radiogenic reductions: to reject the dominant non-neutrino induced blips from ^{39}Ar decays, we removed

all low-energy blips from this study, which substantially reduces blip statistics. One can imagine a broad array of potential analysis improvements using topology-based discrimination.

- (iv) Blip proximity to features of interest: as mentioned in Sec. III C, beyond the muon PoCA cut, shower cone cut, and neutrino vertex and muon end point cuts, no effort was made to reject nonsignal blips featuring correlations with high-energy event features, such as kinked tracks, Michel e^- stubs, tracks missing a Bragg peak, and so on.
- (v) Secondary protons: our analysis provides no special consideration of p -generated blips. While they are produced far more rarely than γ -induced neutron blips, they are a far more unambiguous indication of the existence of an energetic neutron. Proper leveraging of p -induced blips may be particularly helpful for higher energy neutrino interactions featuring more energetic neutrons.
- (vi) Light-based neutron reconstruction: our analysis does not consider any information provided by a LArTPC's scintillation light collection subsystem. Light-based LArTPC information offers the potential benefit of fast timing, which may be helpful in better excluding out-of-time radiogenic energy depositions or in establishing neutron kinematics using orthogonal time-of-flight techniques.

Future improvements addressing these points will be likely to achieve substantial enhancement in neutron reconstruction capabilities beyond what we demonstrate in our study. In particular, application of artificial intelligence/machine learning (AI/ML) techniques to the problem of neutron reconstruction is well motivated in the context of the multidimensional blip attribute phase space provided by an LArTPC image. In addition to potentially enhancing blip response in signal processing [92–94], AI/ML techniques can more fully leverage correlations in interblip spacing, energy, location with respect to other key event topology features, and more.

VII. SUMMARY

We construct a simulation-based study of neutron reconstruction using blip information in a generic LArTPC detector. Using realistic blip responses from published experimental results, we demonstrate that blip counts from sub-GeV neutrino interactions with primary neutron production are statistically significantly higher than those from neutrino interactions without primary neutrons, and that these blips can be used to reconstruct attributes of these primary neutrons. With a straightforward and simplistic signal blip selection and a neutron identification scheme based solely on signal blip counting, we demonstrate identification of neutrons at $\sim 70\%$ efficiency with $\sim 20\%$ inefficiency caused by blip contributions from nonprimary neutrons or non-neutron contaminations. Although

individual neutrons in the same neutrino interaction cannot be identified separately, the energy and direction of such a neutron system can be reconstructed at $\sim 50\%$ energy resolution and $\sim 40^\circ$ angular resolution at ~ 100 MeV. We then apply these capabilities in the context of reconstructing attributes of sub-GeV neutrino interactions in an LArTPC. We find that in the context of atmospheric neutrinos and BNB reverse-horn-current (antineutrino mode) beam neutrinos, the addition of simple blip-based neutron information can potentially improve neutrino-antineutrino separation capability, which can provide potential new handles to neutrino oscillation studies and neutrino cross-section constraints, particularly for atmospheric $\bar{\nu}_e$ s. Demonstrations in this paper should be seen as a jumping-off point in a long-term project of neutron reconstruction improvements in LArTPCs, as opposed to a demonstration of maximal capabilities. AI-informed reconstruction techniques capable of identifying and exploiting multidimensional correlations are well matched to the diverse and multifaceted nature of low-energy activity in LArTPC images.

Blip features are subject to systematic uncertainties due to the insufficient modeling and experimental data on neutron-argon interactions as well as neutron production in neutrino interactions. With different neutron propagation modeling in FLUKA and Geant4, we note $\sim 5\%$ differences in neutron identification efficiency and $\sim 25\%$ differences in background contamination. Thus, further application of neutron reconstruction to neutrino physics deliverables faces challenges from neutrino interaction modeling, neutron production uncertainties, hadronic interaction modeling, and nuclear deexcitation modeling. Since these uncertainties are more pronounced at lower energy and higher neutron multiplicity, these uncertainties can be mitigated by treating neutrons as a system without counting individual neutrons and by requiring energy thresholds aimed at excluding consideration of low-energy neutronic final states. However, these limitations should be best resolved via dedicated efforts toward experimental measurements and subsequent neutron model tuning.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [95].

APPENDIX: FLUKA SIMULATION

Before any selection, using the FLUKA simulation, the blip distribution in true energy is shown in Fig. 13, and the reconstructed energy and distance to primary vertex is shown in Figs. 14 and 15.

In summary, the blip selection for $\nu_\mu/\bar{\nu}_\mu$ s are:

- (i) PoCA > 20 cm
 - (ii) The distance between blip vertex and primary neutrino interaction vertex is between range 20-250 cm
 - (iii) The distance between blip vertex and the end of the muon track is > 40 cm
 - (iv) The reconstructed blip energy is > 0.6 MeV,
- and the blip selection for $\nu_e/\bar{\nu}_e$ s are:
- (i) Cone angle > 45 degree
 - (ii) The distance between blip vertex and primary neutrino interaction vertex is between 20 cm to 250 cm
 - (iii) The reconstructed blip energy is > 0.6 MeV.

After all the selections, the remaining blip distribution in reconstructed energy and distance to primary vertex is shown in Figs. 16 and 17.

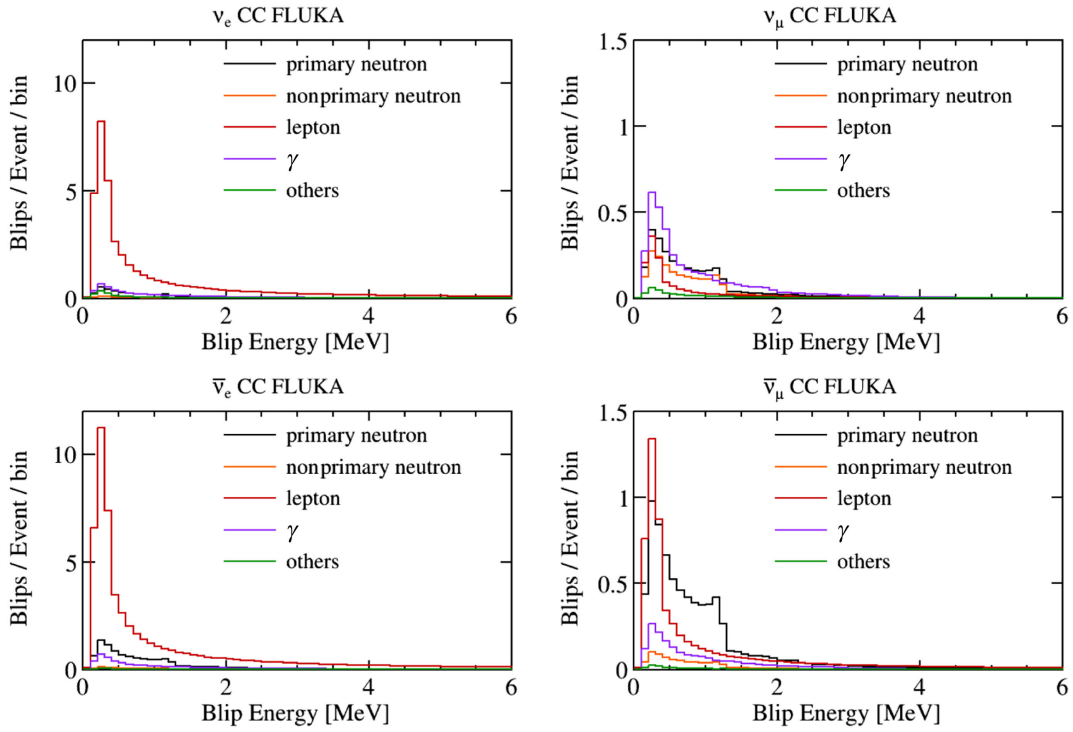


FIG. 13. Distributions of the true blip energy for ν_e (top left), ν_μ (top right), $\bar{\nu}_e$ (bottom left), and $\bar{\nu}_\mu$ (bottom right). No cut is applied.

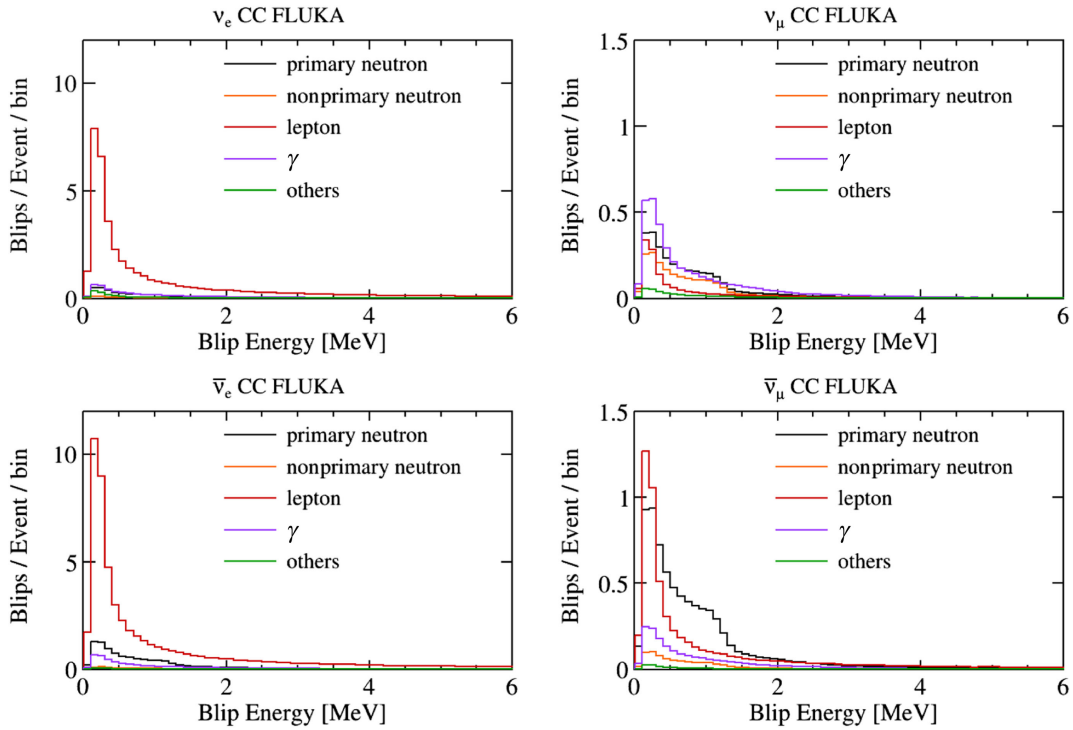


FIG. 14. Distributions of the reconstructed blip energy for ν_e (top left), ν_μ (top right), $\bar{\nu}_e$ (bottom left), and $\bar{\nu}_\mu$ (bottom right). No cut is applied.

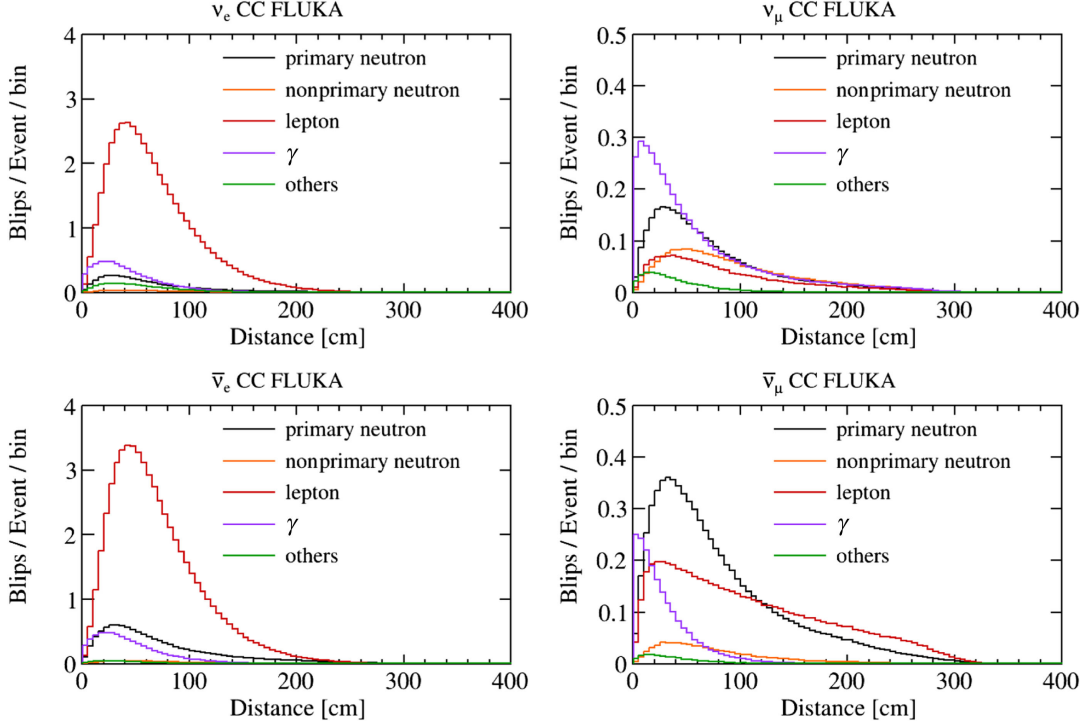


FIG. 15. Distributions of the distance from the blip to the primary vertex for ν_e (top left), ν_μ (top right), $\bar{\nu}_e$ (bottom left), and $\bar{\nu}_\mu$ (bottom right). No cut is applied.

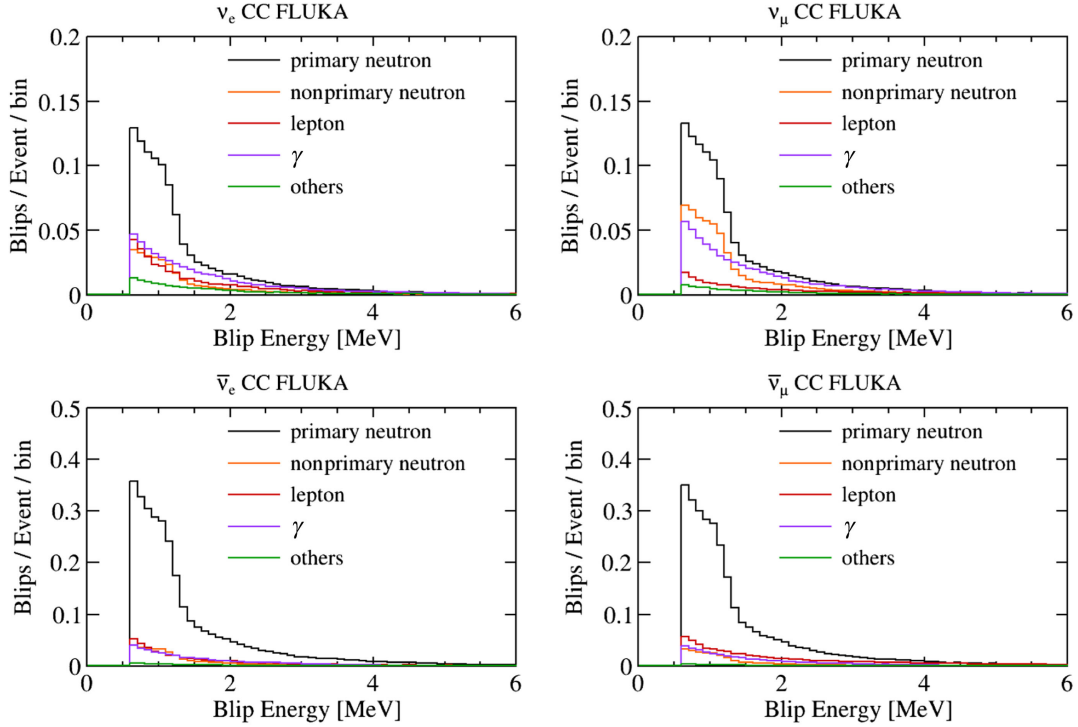


FIG. 16. Distributions of the reconstructed blip energy for ν_e (top left), ν_μ (top right), $\bar{\nu}_e$ (bottom left), and $\bar{\nu}_\mu$ (bottom right). All cuts are applied.

1. Geant4 simulation

Using the alternative Geant4 simulation, the blip distribution in true energy is shown in Fig. 18, and the reconstructed energy and distance to primary vertex before any selection is shown in Figs. 19 and 20.

After all the selections, the remaining blip distribution in reconstructed energy and distance to primary vertex is shown in Figs. 21 and 22.

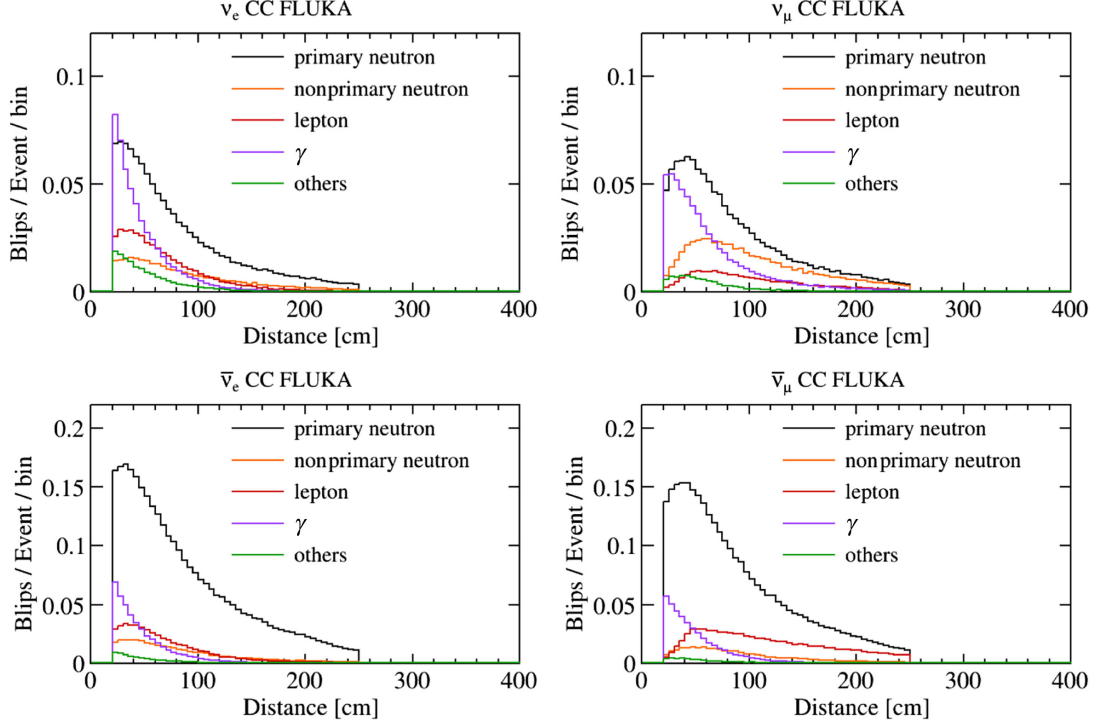


FIG. 17. Distributions of the distance from the blip to the primary vertex for ν_e (top left), ν_μ (top right), $\bar{\nu}_e$ (bottom left), and $\bar{\nu}_\mu$ (bottom right). All cuts are applied.

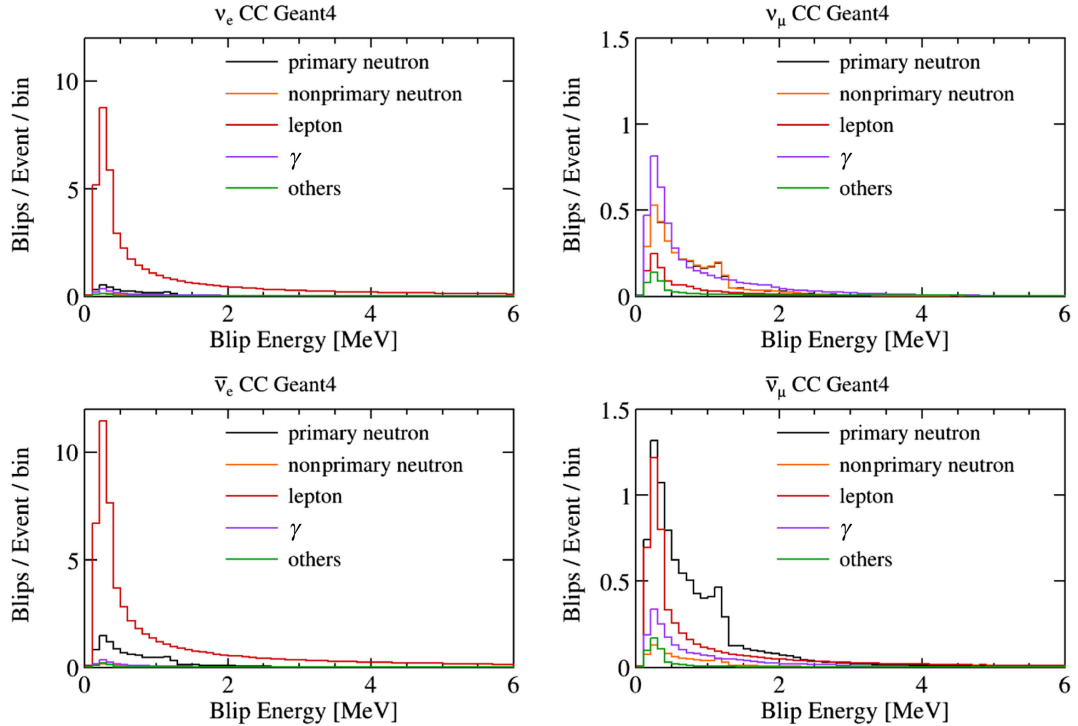


FIG. 18. Distributions of the true blip energy for ν_e (top left), ν_μ (top right), $\bar{\nu}_e$ (bottom left), and $\bar{\nu}_\mu$ (bottom right). No cut is applied.

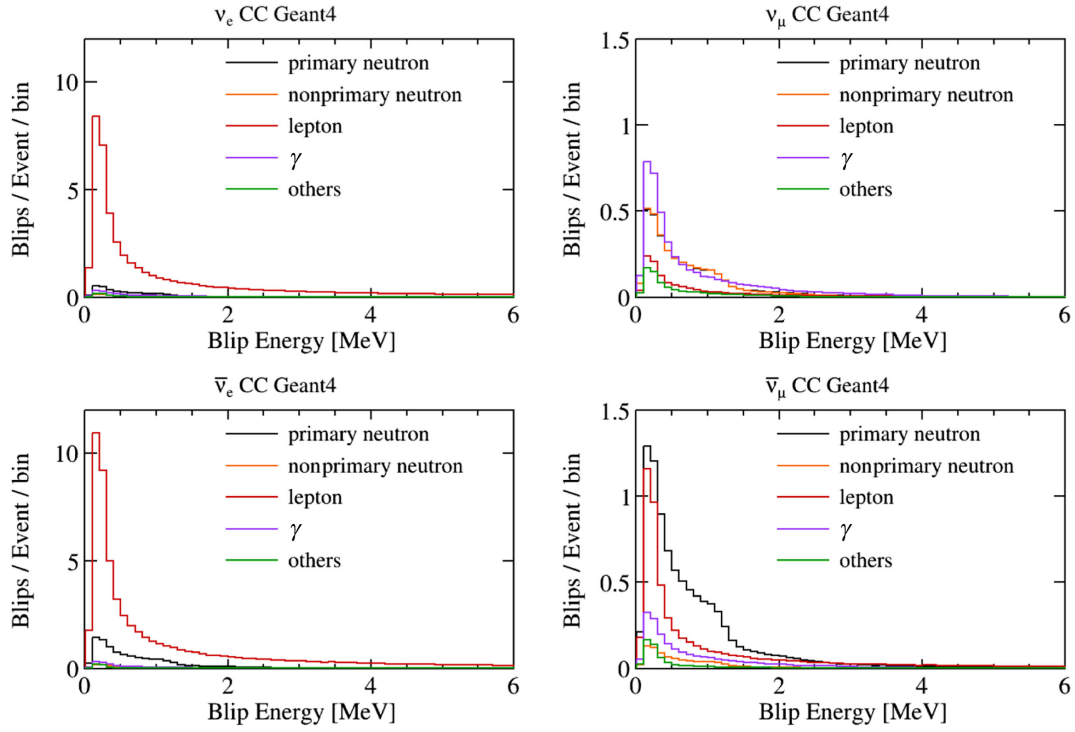


FIG. 19. Distributions of the reconstructed blip energy for ν_e (top left), ν_μ (top right), $\bar{\nu}_e$ (bottom left), and $\bar{\nu}_\mu$ (bottom right). No cut is applied.

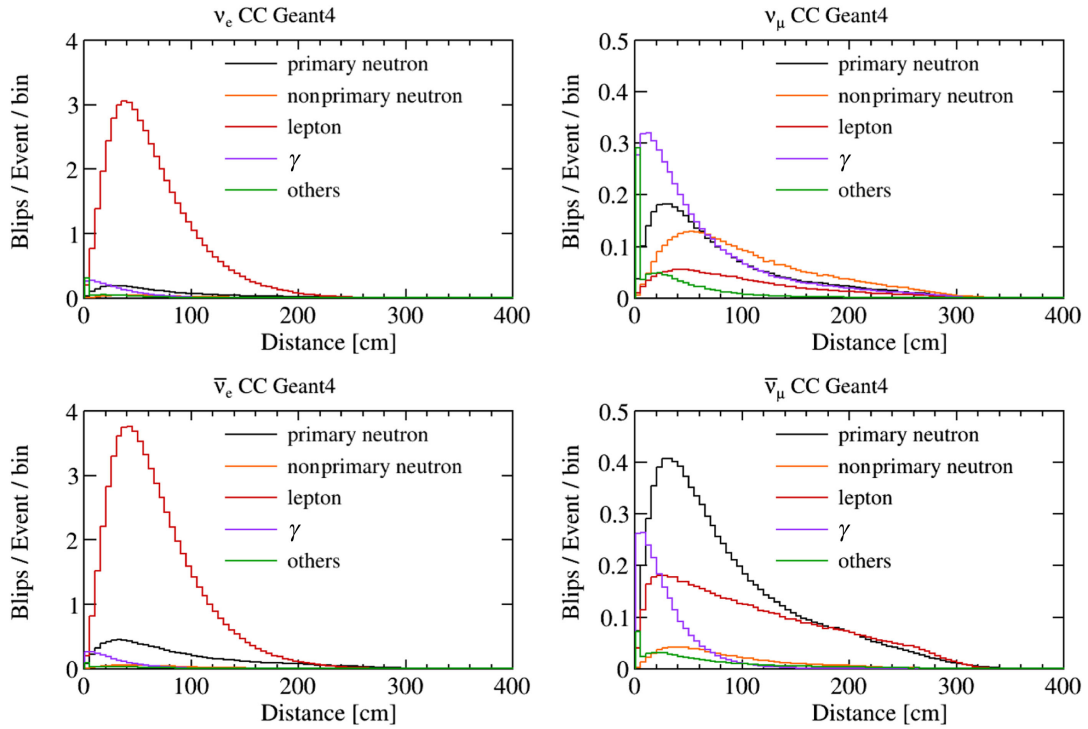


FIG. 20. Distributions of the distance from the blip to the primary vertex for ν_e (top left), ν_μ (top right), $\bar{\nu}_e$ (bottom left), and $\bar{\nu}_\mu$ (bottom right). No cut is applied.

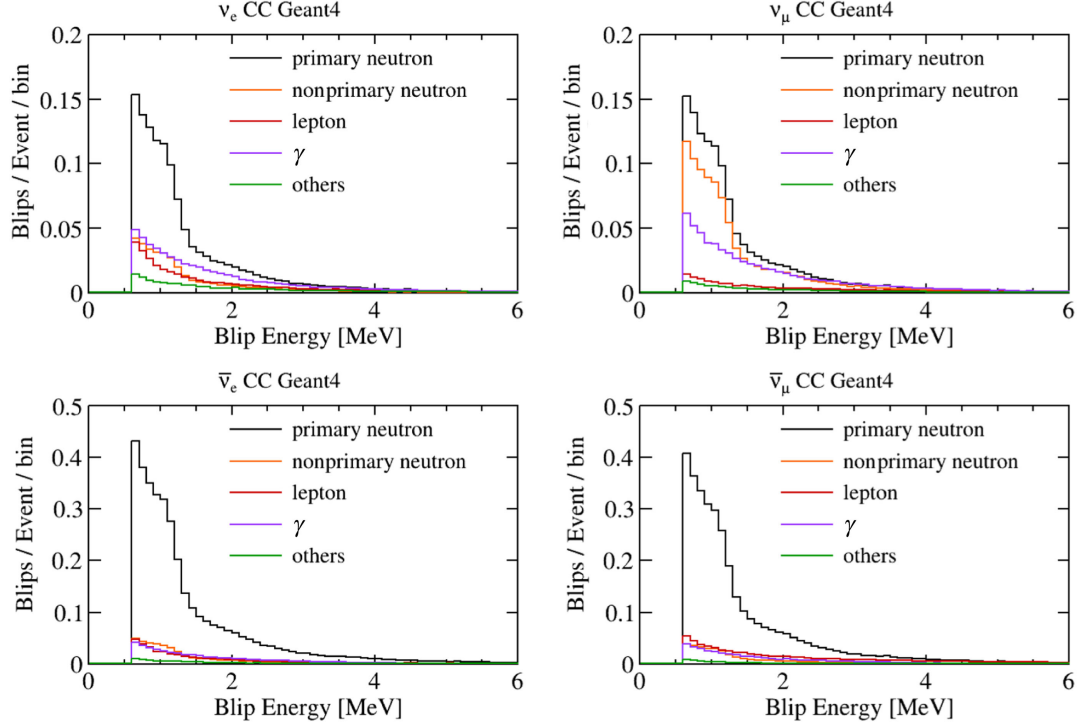


FIG. 21. Distributions of the reconstructed blip energy for ν_e (top left), ν_μ (top right), $\bar{\nu}_e$ (bottom left), and $\bar{\nu}_\mu$ (bottom right). All cuts are applied.

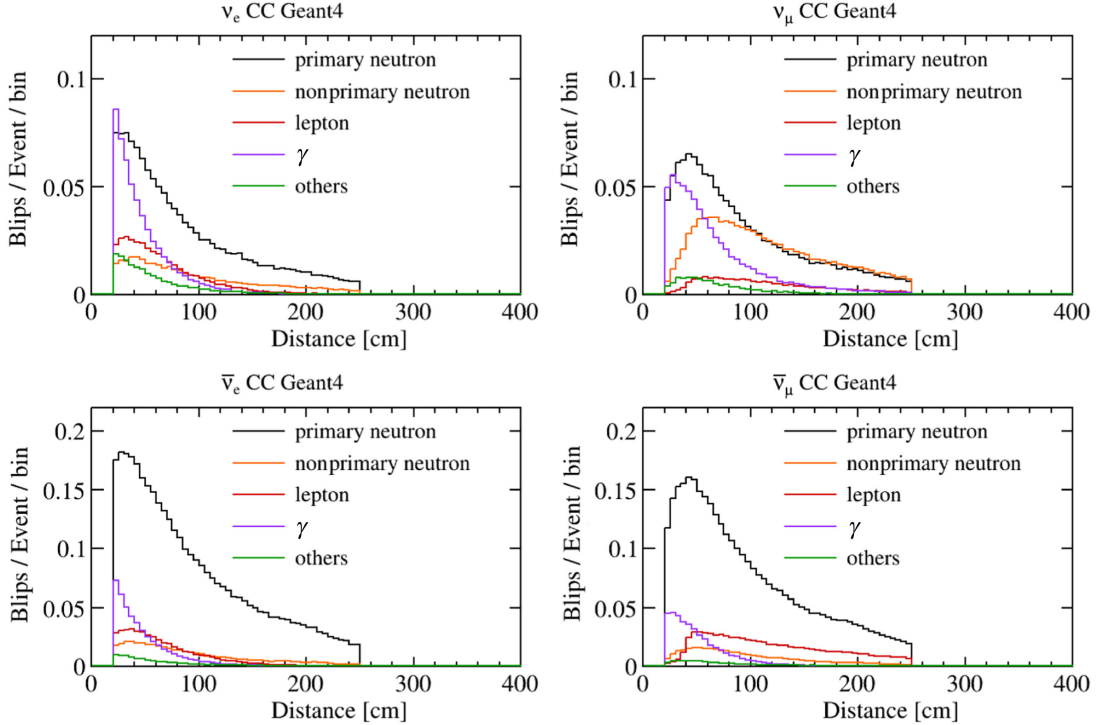


FIG. 22. Distributions of the distance from the blip to the primary vertex for ν_e (top left), ν_μ (top right), $\bar{\nu}_e$ (bottom left), and $\bar{\nu}_\mu$ (bottom right). All cuts are applied.

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