# Enhancing ICARUS and REDTOP Software and Hardware: Event Generator Interface Development and Calorimeter Tile Prototype

Erin Visser[1] and Corrado Gatto[2]
[1)] *Michigan State University*
[2)] *Istituto Nazionale di Fisica Nucleare and Northern Illinois University*

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ICARUS (Imaging Cosmic And Rare Underground Signals) is a liquid argon time projection chamber (LArTPC) detector that pursues the sterile neutrino, which relies on accurate simulations of neutrino-argon interactions. REDTOP (Rare Eta Decays To Observe new Physics) is a proposed low-energy, high-intensity meson factory designed to explore rare $\eta/\eta'$ meson decays and probe physics beyond the Standard Model. As a next-generation experiment, this requires both accurate simulations and innovative detector technologies. This project contributes to both ICARUS, from a simulation perspective, and REDTOP, from both a simulation and detection perspective, through the event generation of lepton-nucleon interactions and the physical enhancement of the calorimeter technology within the REDTOP detector. We developed an interface between ACHILLES (A CHIcago Land Lepton Event Simulator), a theory-driven lepton-level event generator, and GENIE, a robust event generator framework used for neutrino physics. By incorporating the precise theoretical cross-section calculations of ACHILLES into the experimental realism of GENIE, the interface allows for improved accuracy of neutrino-nucleon simulations, which can be adapted for the proton beam specifications of the REDTOP meson factory as well as for the ICARUS experiment. In parallel, we developed an improved prototype for the ADRIANO2 (A Dual Readout Integrally Active Non-segmented Option) dual-readout calorimeter tiles for the REDTOP detector. To improve the efficiency of the lead-glass tiles trapping Cherenkov light for energy reconstruction and particle identification, we optimized the application of a highly reflective coating. Through viscosity and thickness control, masking, and a custom spray technique, we refined the coating process to reduce surface defects and improve light yield. Together, these efforts strengthen the ICARUS neutrino program and REDTOP's capability of detecting rare decay events.

## I. INTRODUCTION

The ICARUS experiment is a LArTPC detector within the Short Baseline Neutrino (SBN) Program at Fermi National Accelerator Laboratory[1]. The goal of this experiment is to search for the theoretical sterile neutrino. To predict these signals and discrepancies that support physics beyond the Standard Model, ICARUS leverages the high resolution of LArTPC technology with Monte Carlo simulations, studying neutrino-argon interactions in detail. This project supports ICARUS by developing more accurate neutrino-argon interaction simulations through the integration of ACHILLES and GENIE, two event generators, to produce results that are simultaneously theoretically accurate and experimentally realistic.

The REDTOP experiment is a proposed next-generation meson factory to study rare $\eta$ and $\eta'$ meson decays[2]. The goal of this experiment is to investigate physics beyond the Standard Model, such as light cold dark matter and discrete symmetries violations. To enhance the sensitivity of this detector, REDTOP must employ both precise theoretical models to estimate the background and cutting-edge detector technologies to cope with high event rate and to increase the sensitivity to faint signals.

This project supports REDTOP on two fronts: the development of more accurate event simulations through the integration of the ACHILLES and GENIE frameworks, and the advancement of detector performance via a refined coating method for ADRIANO2 calorimeter tiles. The interface between ACHILLES, a theory-driven lepton-level event generator, and GENIE, an experimentally integrated event simulation framework, enables improved modeling of lepton-nucleon interactions. In parallel, the hardware component focused on optimizing the Cherenkov light yield of ADRIANO2 lead glass tiles, which are central to REDTOP's particle identification and energy resolution capabilities.

Together, these efforts aim to expand the reach of REDTOP in unexplored sectors of the Standard Model. In addition, both are widely applicable to other current and future experiments. The event generator interface will provide a foundation for more accurate physical modeling in neutrino experiments, and the calorimeter prototype is cutting-edge technology for use in a wide array of calorimetry applications.

## II. ACHILLES-GENIE INTERFACE

### A. Motivation

Since neutrinos are extremely weakly interacting particles, neutrino physicists have developed event generators to simulate neutrino-nucleon interactions. GENIE is a robust neutrino event generator framework with a strong foundation of experimental applications, specifically the ability to incorporate detector geometries and simulate final-state particles[3,4]. However, this event generator relies heavily on experimental data for model tuning, which complicates the ability to extract the underlying physics parameters. ACHILLES, in contrast, is a relatively new standalone event generator driven by theory[5]. ACHILLES incorporates uncertainties and direct nuclear modeling with greater physical accuracy, resulting in more precise cross-section calculations. While ACHILLES stands apart by prioritizing the underlying theory, GENIE is well-integrated with experimental detector geometry and more realistic beam simulation. The motivation arose from a need to bridge this gap between theory and experiment. In this project, we develop an interface between the two generators with the goal of combining the strengths of both, using ACHILLES's precise cross-sectional calculations within the GENIE framework to generate simulations that are both theoretically accurate and experimentally realistic.

ACHILLES is also capable of simulating proton-nucleus interactions. That can be exploited for improving the Monte Carlo studies for the REDTOP experiment.

### B. Generator Comparison

One of the goals of this project is to compare the results of neutrino-Ar scattering, obtained with GENIE standalone vs the ACHILLES+GENIE framework. To begin, we individually configured both generators to produce comparable outputs by standardizing the physical assumptions. To test these models, we apply the simulations to the ICARUS experiment at the Fermilab SBN Program. That is, the beam was defined by the NuMI off-axis flux of ICARUS, the target material as an Argon-40 nucleus, the incoming particles as muon neutrinos, and the GENIE tune as $AR23\_20i\_00\_000$, which was developed for SBN[6]. Additionally, since ACHILLES is a relatively new generator, it has limited interaction modes. Thus, we isolated charged-current quasi-elastic scattering and resonant interactions ($CCQE$+$CCRES$ event generators in GENIE, $QE\_Spectral\_Func$ and $RES\_Spectral\_Func$ nuclear models in ACHILLES). This setup allowed for direct comparisons between the two generators of key quantities that highlight their differences (TABLE I).

TABLE I: Comparison of GENIE and ACHILLES Event Generators

| Feature | GENIE | ACHILLES |
|---|---|---|
| Model Type | Empirical | Theoretical |
| Cross-Section Accuracy | Tuned to experimental data | Direct theoretical modeling with uncertainty quantification |
| Detector Integration | Supports detector geometry | No built-in geometry interface |
| Output Format | Native GENIE ROOT files | HepMC3 ASCII format |
| Strengths | Experimental realism and detector geometry | Precise cross-section calculations and theoretical clarity |
| Limitations | May obscure fundamental physics due to tuning | Limited interaction channels; under development |

When restricted to charged-current quasi-elastic scattering and resonant interactions, we observed that the ACHILLES cross-sectional calculation varied greatly from that of GENIE (TABLE II). This likely reflects the more detailed and accurate nuclear modeling in the theoretical generator. Furthermore, when observing how the cross-sectional calculation varies throughout event generation, we realized that the ACHILLES predictions converged (FIG. 1). That is, the model evaluates each interaction based on consistently improving the underlying physical theory. In contrast, the GENIE cross-section model is empirically tuned to experimental data. While this makes enhances applicability to detectors and beamlines, it means the cross-section is not calculated directly from the underlying physics, rather it samples from pregenerated splines based on existing data and parameter fits. Thus, additional event generation does not improve on the calculation; it just samples more from the same empirical model, and therefore the GENIE estimate does not converge or improve the statistics the way ACHILLES does. Additionally, when observing the energy distribution of muons in the final state, the ACHILLES events display less variation, while GENIE accounts for more spread (FIG. 2). This is likely due to the inclusion of more complex FSI (final-state interactions) modeling and nuclear-medium effects. These simple comparisons showcase the strength of each generator. ACHILLES excels in theoretical precision, while GENIE is stronger for experimental realism and final-state interactions, which further motivates the development of an interface between them.

TABLE II: Total cross-section for different event generators, using ICARUS specifications [$10^{-38}$ cm$^2$/Ar].

| Channel | ACHILLES | GENIE |
|---|---|---|
| QE | 8.2601 | 6.8200 |
| RES | 3.2803 | 5.4310 |
| Total | 11.5404 | 12.2510 |

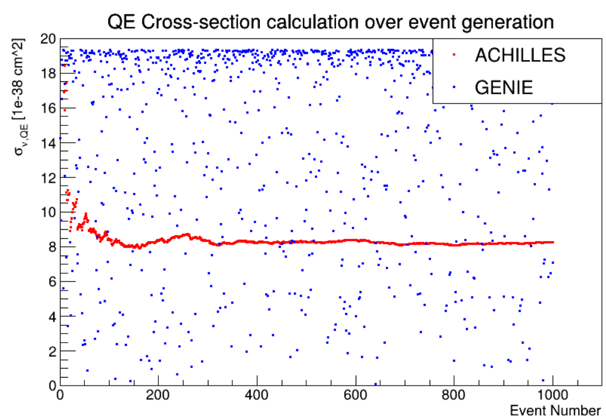



FIG. 1: Cross-section calculation over time for ACHILLES (theoretical convergence) and GENIE (fixed empirical model).

### C. Interface Implementation

To develop this interface, we began by building a foundational understanding of how GENIE processes cross-sectional splines and generates events, and then of how the parameters are structured in ACHILLES. The most crucial aspect of this interface is the fact that ACHILLES events are outputted into HepMC3 ASCII files, and we need to reconstruct the method of spline generation to read the cross-section values from the

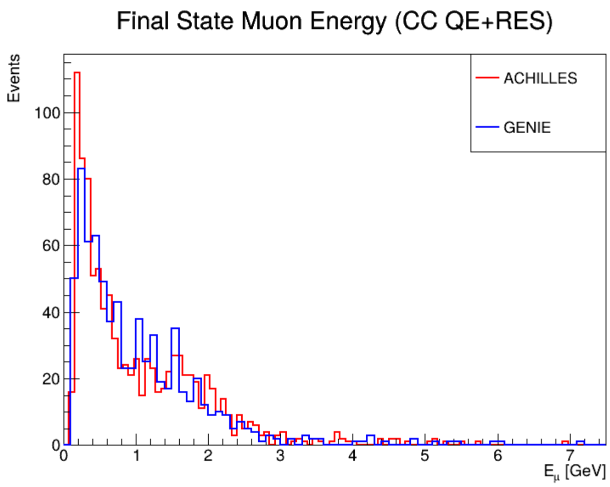



FIG. 2: Final-state muon energy distribution, comparing ACHILLES and GENIE using ICARUS specifications.

HepMC3 file[7]. To do this, we implemented a custom GENIE tool called "HepMC3Lib," in addition to a custom GENIE library called "HepMC3LibraryInterface." Creating this required digging into GENIE's registration system and understanding how GENIE recognizes and calls external generators.

After developing the new event generator, we developed a custom tune to specify the necessary parameters and models. Here, we were able to inject the ACHILLES output file as a common parameter.

The debugging process was a major component of this work. Both GENIE and ACHILLES rely on numerous dependencies and offer extensive configurability, which led to several compatibility issues. Initially, the most significant challenge was that the current version of GENIE defaulted to using PYTHIA6 for hadronization, which is outdated and incompatible with ROOT6. To address this, we pulled and built from two specific commits in the GENIE repository that enabled PYTHIA8 support while maintaining compatibility with other GENIE features.

Another recurring issue was GENIE's internal parameter setup system for event generators. Since the HepMC3LibraryInterface was custom-defined, GENIE would not recognize it unless it was properly registered in the 'TuneGeneratorList.xml' and built with all parameters correctly specified. This involved deep dives into GENIE's generator logic and required careful mirroring of working examples (e.g., EvtLib).

### D. Results and Future Work

Once the interface was successfully developed, we validated it by comparing the event and cross-sections generated by ACHILLES with that obtained by GENIE using the ACHILLES interface. By ensuring that the cross-section values matched identically, we were able to confirm that the two generators were correctly communicating.

Looking ahead, we will advance this interface by configuring GENIE to directly interrogate ACHILLES, bypassing the need for the intermediate steps of running ACHILLES and generating the splines for GENIE. This will require constructing ACHILLES as a shared library loaded for GENIE to access, and then restructuring the build to support calling ACHILLES at runtime.

This work also has application to the REDTOP experiment. By adapting the event generators to simulate a proton beam rather than a neutrino beam, this interface can be used for accurate simulations of collisions within the REDTOP detector.

## III. ADRIANO2 TILE PROTOTYPE

While the software project was based on neutrino physics theory, the ADRIANO2 tile prototype project was exploring new hardware for collider physics and rare-meson decays.

### A. ADRIANO2 in REDTOP

Within the REDTOP detector, ADRIANO2 is a high-granularity, dual-readout calorimeter composed of alternating tiles of lead-glass and scintillating plastic, with SiPMs directly coupled to the tiles (FIG. 3). The goal is to measure the electromagnetic showers, separating Cherenkov and scintillation light, for efficient particle identification and accurate energy reconstruction. For this project, we focused on the lead-glass tiles, which generate Cherenkov light when fast, charged particles pass through, and this light is collected by SiPMs (Silicon Photomultipliers).

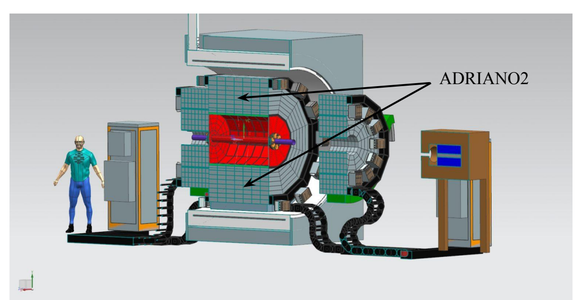



FIG. 3: ADRIANO2 Dual-Readout Calorimeter in the REDTOP Detector.

### B. Materials and Methods

We aimed to maximize Cherenkov light yield by improving the reflectivity and uniformity of the tile surface coating. For the paint, we selected a commercial, water-based barium sulfate coating that exhibits very high reflectance, over 97% in the visible spectrum: the Avian-B White Reflectance Coating by Avian Technologies[8]. Then, we customized the application technique to minimize the formation of bubbles and ensure a smooth, uniform layer, both of which are critical to prevent light scattering and the degraded energy measurement that results from the former.

To develop this technique, we first focused on determining the most successful combination of dilution of Avian-B and air pressure for the air gun used for application. To determine this pair, we conducted tests with a commercial paint. We diluted the paint to 5%, 7.5%, and 12.5% with ethyl alcohol 200 proof, and tested spraying at 40 PSI, 50 PSI, and 60 PSI on a black gloss background. We were looking for the combination that produced the most even spray without extensively separating, cracking, bubbling, or splattering. Our observations led us to choose the spray setup of 7.5% dilution at 50 PSI. To replicate this dilution with Avian-B and ethanol, we conducted viscometer measurements using the NDJ-8T viscometer by Bonvoisin. This replication resulted in a 50% dilution of Avian-B in ethanol.

After setting up the paint gun at 50 PSI, we then began to test the spray pattern of the 50% Avian-B dilution on spare glass. If the spray was too intense, the coating would spread out, pool up, or splatter. If the spray was too light, the coating would not evenly cover the tile. That is, either extreme would result in surface inconsistencies that could scatter light and lead to inefficient energy reconstruction.

After we successfully determined the right intensity for spraying, we then began to test and standardize the thickness of the coating. Previous ADRIANO2 prototypes served as a baseline for the minimum thickness, which we measured with the Starrett thickness gauge as 0.319*mm* (FIG. 4). After each layer of coating, we waited 15 to 20 minutes for it to dry. This patience is a crucial step to ensure uniformity, as piling on the layers could result in inconsistent drying and potential clumping. After every 5 layers on the spare glass, we would measure the thickness until the minimum thickness was reached. This resulted in standardizing the number of layers as 27, to ensure consistency across tiles. After 27 coats on the surface with the window, the tiles were left to dry for 3 days, then flipped for the opposite surface and sides to be coated.

Furthermore, a key aspect of the lead-glass tiles is the SiPMs directly coupled to the surface. To ensure the most efficient read out, the windows for the coupling area have to be kept as clean as possible. To maintain this, 3D-printed masks were developed to shield the SiPM windows, protecting them from contamination during coating to ensure clean readout (FIG. 5).

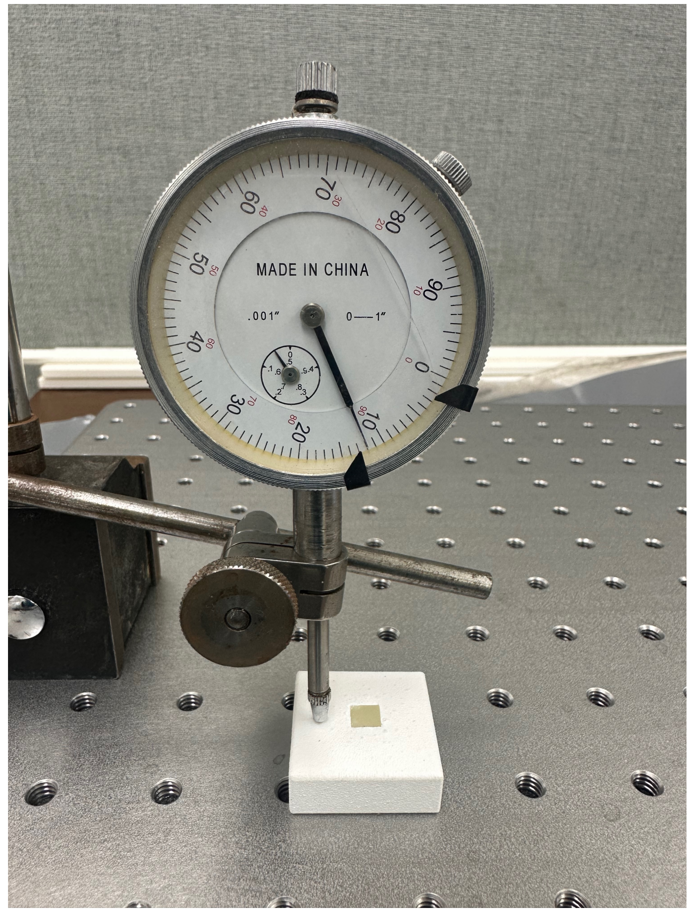



FIG. 4: Thickness measurement of the previous ADRIANO2 tile prototype as a baseline.

### C. Technical Challenges and Solutions

One main challenge we faced with this process was contamination of the SiPM window, either through leakage under the mask or from imperfect mask removal (FIG. 6). To mitigate the latter, we used a scalpel to separate the mask from the coating and prevent the coating from peeling or flaking with mask removal. However, the former was not realized as an issue until post-mask removal. To accommodate this challenge afterwards, we developed a delicate clean-up process to remove spurious coating from the SiPM window.

Another challenge we faced was the formation of bubbles under the layers. These bubbles decrease the reflectivity of the coating by resulting in scattering of the Cherenkov light, and, consequently, a degraded SiPM signal readout (FIG. 7). To prevent this issue, we focused heavily on a controlled, consistent application technique. This method also included continuous and slow stirring of the paint between layers, as separation of the Avian-B and ethanol would result in non-uniform viscosity and shaking to mix would introduce air into the mixture.

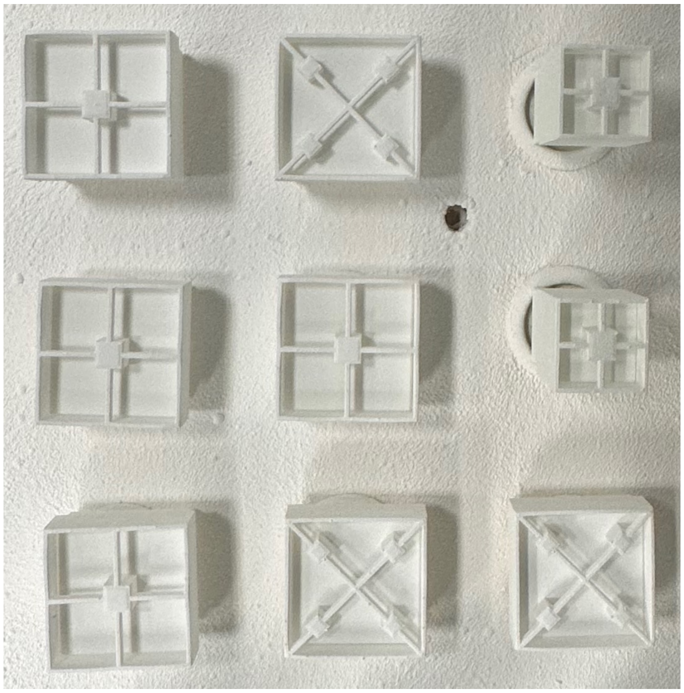
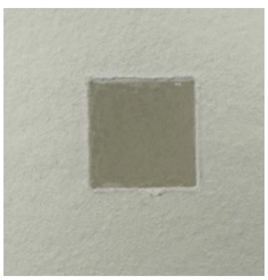
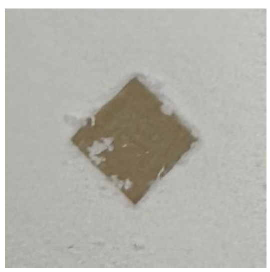


FIG. 5: Tile coating setup with SiPM masks.



(a) Clean window.



(b) Contaminated window.

FIG. 6: Painted tiles showing clean vs. contaminated SiPM window.

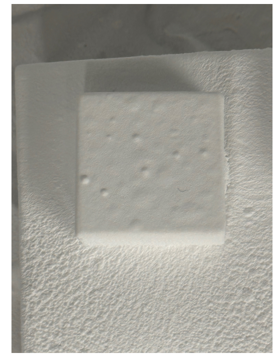
### D. Future Work

Moving forward, we will measure the Cherenkov light yield under cosmic ray testing and compare to previous prototypes, to quantify the improvements of this new tile prototype. Additionally, we will work towards improving the masks to prevent contamination of the SiPM window altogether. Another future development would be to conduct durability testing of the coatings, to predict how well they will perform under the high-intensity proton beam.

## IV. CONCLUSION

From the software approach, this project incorporated the lepton-level cross-section calculations from ACHILLES into the GENIE framework, enabling more physically accurate simulations compatible with realistic neutrino as well as proton fluxes and detector geometries. This interface provides a foundation for improving cross-section predictions and generation of final state particles in current and future experiments, specifically the ICARUS and the REDTOP experiments.

(a) Smooth coating.



(b) Coating with interfering bubbles.

FIG. 7: Painted tiles comparing uniform coating vs. coating with bubbles.

From the hardware approach, this project established a reliable and consistent procedure for coating ADRIANO2 calorimeter tiles, identifying common issues and mitigation strategies. Improvements to light collection support REDTOP's energy resolution and particle identification requirements.

## V. ACKNOWLEDGMENTS

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## VI. REFERENCES

[1] P. Abratenko et al. ICARUS at the Fermilab Short-Baseline Neutrino program: initial operation. *Eur. Phys. J. C*, 83(6):467, 2023.
[2] Corrado Gatto. The REDTOP experiment: a low energy meson factory to explore dark matter and physics beyond the Standard model. *PoS*, CD2021:043, 2024.
[3] C. Andreopoulos et al. The GENIE Neutrino Monte Carlo Generator. *Nucl. Instrum. Meth. A*, 614:87–104, 2010.
[4] Costas Andreopoulos, Christopher Barry, Steve Dytman, Hugh Gallagher, Tomasz Golan, Robert Hatcher, Gabriel Perdue, and Julia Yarba. The GENIE Neutrino Monte Carlo Generator: Physics and User Manual. 10 2015.
[5] Joshua Isaacson, William I. Jay, Alessandro Lovato, Pedro A. N. Machado, and Noemi Rocco. ACHILLES: A novel event generator for electron- and neutrino-nucleus scattering. 5 2022.

[6] Júlia Tena-Vidal et al. Neutrino-nucleon cross-section model tuning in GENIE v3. *Phys. Rev. D*, 104(7):072009, 2021.
[7] Andrii Verbytskyi, Andy Buckley, David Grellscheid, Dima Konstantinov, James Monk, Leif Lönnblad, Tomasz Przedzinski, and Witold Pokorski. Hepmc3 event record library for monte carlo event generators. *Journal of Physics: Conference Series*, 1525:012017, 04 2020.
[8] Avian Technologies LLC. Avian-b white reflectance coating.