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Inclusion of GENIE as neutrino event generator for INO ICAL

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Abstract. The iron calorimeter (ICAL) detector is the proposed underground neutrino-physics experiment in the INO cavern. Its main goal is the determination of sign of 2–3 mass-squared difference, Δm^2_{32} $(=m^2_3 - m^2_2)$ in the presence of matter effects, apart from the precise measurement of other neutrino parameters. Like all other neutrino experiments, the INO Collaboration is going to interface its main software code with a neutrino event generator. The GENIE software is best suited for the ICAL experiment. But, it requires a few modifications before being incorporated in ICAL simulation to have better representation of the neutrino flux and to be more user friendly to the INO user. This paper reports all these modifications.

Keywords. Neutrino; India-based neutrino observatory; GENIE.

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1. Introduction

The India-based neutrino observatory (INO) is the neutrino physics experiment to be built under the Bodi hills (9°58′N, 77°16′E) in South India, with at least 1 km rock overburden in all directions. This will be the largest experimental facility of basic science in India which will carry out one of the front-rank experiments in the global field of particle and astroparticle physics. The iron calorimeter (ICAL) detector will be placed in the underground INO cavern, to observe neutrino oscillation pattern over at least one full period.

A 50 kton ICAL detector [1,2] will be set up at INO to study the atmospheric neutrinos. The ICAL will comprise ∼29,000 resistive plate chambers (RPCs [3,4]), interspersed with iron plates, each with 5.6 cm thickness. There will be 151 iron layers, each layer 4 cm apart from one another. Each RPC will cover a surface of 1.84 m × 1.84 m. Thus the detector will cover a dimension of 48 m × 16 m × 16 m. A schematic diagram of the ICAL detector is shown in figure 1.

The main goals of this experiment are the precise measurement of neutrino oscillation parameters including the sign of the 2–3 mass-squared difference, Δm^2_{32} $(=m^2_3 - m^2_2)$ in the presence of matter effects, the value of the leptonic CP phase and last but not the least, the search for any non-standard effect beyond neutrino oscillations. A detailed description of the INO project can be found in [1]. Every neutrino experiment has to analyse its probabilistic results obtainable from the real data. It requires a dedicated neutrino event generator, which generates the Monte Carlo event sample, using the best known neutrino flux and a knowledge of interactions of the neutrinos with electrons, nucleons or nuclei.

The primary goal of ICAL is to determine the ordering of the neutrino mass hierarchy [5,6]. Other physics possibilities, such as precision measurement of $\sin^2\theta_{23}$ and Δm^2_{23} are also important subjects of study at the ICAL. Therefore, a well-suited neutrino interaction generator is necessary for the simulations of atmospheric neutrinos in ICAL.

A Monte Carlo generator simulates neutrino interaction in the detector. This neutrino event is then propagated in the detector, simulating all the processes applicable for real data-taking. Such synthesized events are then analysed to understand and project the physics potentials of the detector.

Several neutrino generators have been devised so far, depending on the varied needs of various neutrino experiments. The GENEVE [7], NEUT [8], NeuGEN [9], Nuance [10], NuWro [11] etc. are some of the Monte Carlo neutrino event generators used primarily

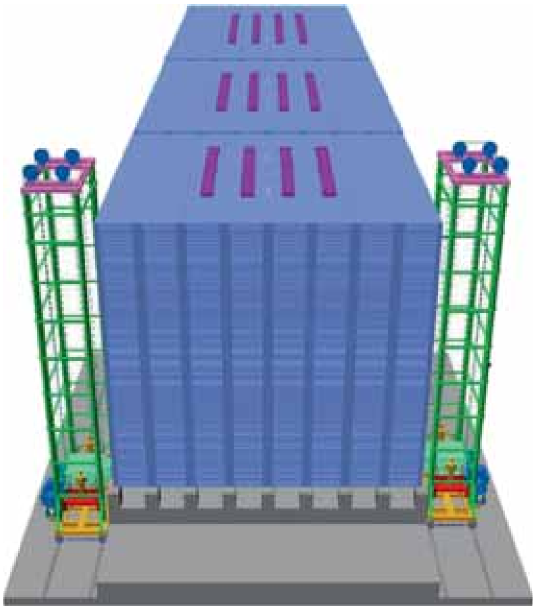

Figure 1. A schematic sketch of the INO ICAL detector.

by the ICARUS Collaboration, Super-Kamiokande and the K2K experiments, the Soudan 2 experiment, the Super-Kamiokande, the MiniBooNE respectively.

GENIE is also a Monte Carlo neutrino event generator, with its physics list and the neutrino cross-sections being consistently updated in the current period. The significant features of this generator are discussed in the next section. The incorporation of GENIE as the neutrino event generator for INO ICAL code [12] has become necessary, owing to the absence of further updates in Nuance. Hence, the transition from Nuance to GENIE in the realm of INO–ICAL simulations is required to ensure better and more appropriate studies of the ICAL.

Therefore, GENIE is to be used for simulations and analyses of the atmospheric neutrinos at the INO. We prepare a GENIE@INO package, which is a modified version of the readily available GENIE and includes some additional options which are advantageous to any user. In this paper, we discuss the necessity and the details of these ameliorations.

2. GENIE

Generates Events for Neutrino Interaction Experiments (GENIE) is a ROOT-based universal, object-oriented/C++ neutrino MC generator. GENIE aims to become a 'canonical' Monte Carlo neutrino event generator with wide applicability [13]. The origins of the code came from the Soudan experiment [14] and later, MINOS [15] was its primary applicant.

Current neutrino experiments use detectors with complicated structures or geometries, multiple materials and a wide variety of elements. The neutrinos of different flavours which are incident on the detector cover a wide energy spectrum (from 1 MeV to 1 PeV). GENIE is an evolving Monte Carlo generator whose validity extends to all nuclear targets and neutrino flavours. It covers energy scales from MeV to hundreds of TeV. So, naturally it needs to take care of elementary cross-sections, which it does by accepting an external *.xml* file. This list of cross-sections is also generated by GENIE by considering neutrinos of different energies impinging on every possible target element present in the detector.

It makes appropriate application of the hadronization models, the principles of nuclear physics, and various other physics phenomena in their corresponding ranges of validity. It continues to evolve as it attempts to smoothen out the merging and tuning of the models, while avoiding double counting or discontinuities. The GENIE event generator gives the output in a standard root file in GHEP (STDHEP-like) event record format [13]. It also provides an option to convert the standard format to conventional and customized formats like that of the Nuance, or the format required by T2K [16], NuMi [17] etc. Therefore, GENIE is the most favoured neutrino event generator in the current scenario.

3. Impediments of GENIE@INO

GENIE as known and explained briefly in the earlier section, is itself a ready-to-go neutrino event generator software and one can use it independently. However, with the need arising to use GENIE instead of Nuance (later discussed in §4.1 and figures 8 and 9) in the INO simulation algorithm, certain modifications are required in the source code, to make a GENIE–INO user-friendly package, which can be used at ease, to generate neutrino events. These events can then be directly used for simulations by using the already existing ICAL code [12].

3.1 *Azimuthal angle dependence of the flux*

GENIE uses the two-dimensional ν-flux information in E_ν and $\cos\theta$ bins (2D). The neutrino fluxes at INO site given by HONDA [18] depend on the azimuthal angle (ϕ) also, which is shown in figure 2. If ICAL reconstructs ϕ of the incident neutrinos to significant accuracy, we can observe and study the east–west effects of the flux over the periods/seasons.

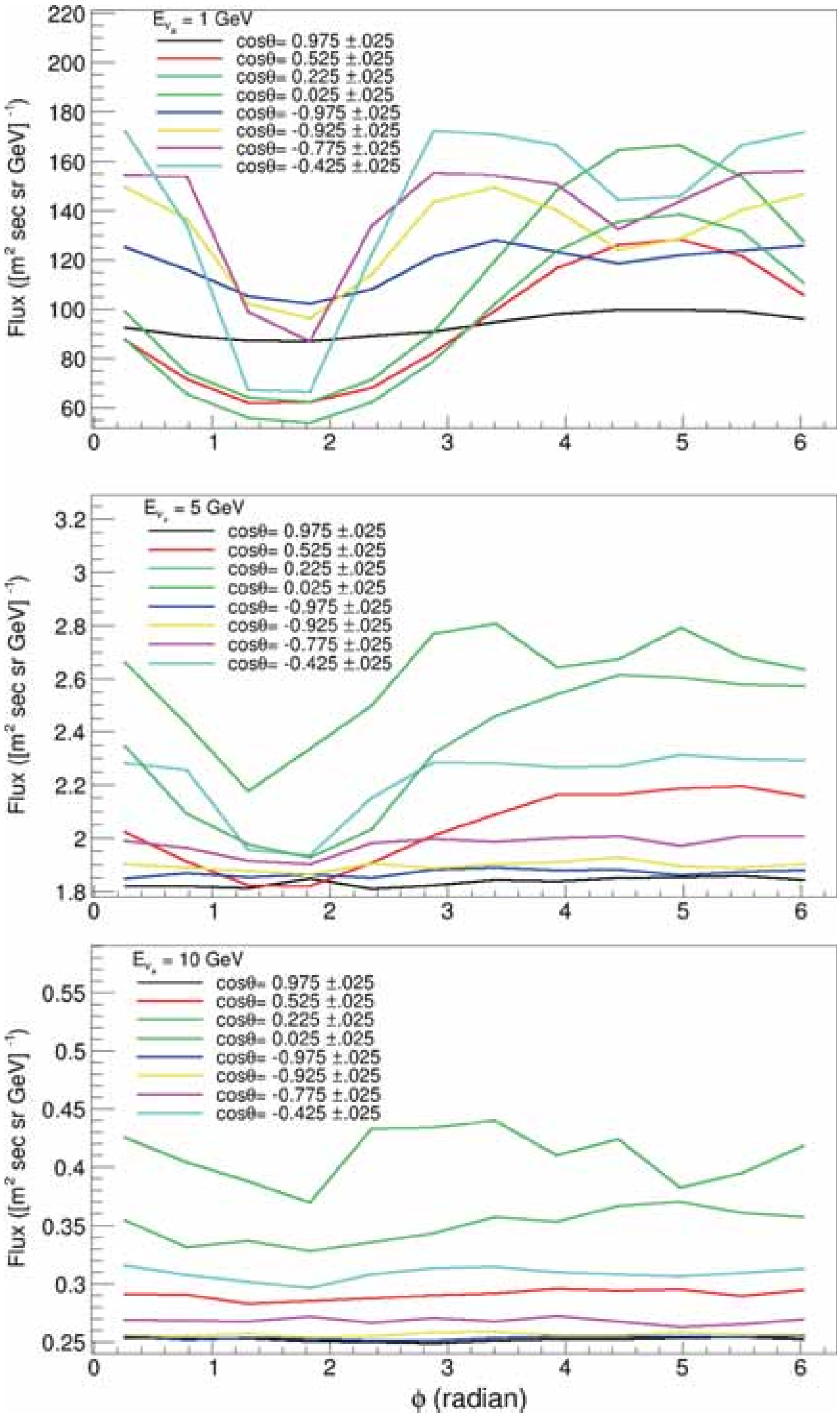

Figure 2. Azimuthal angle distribution of incident neutrino flux at INO site when $E_{\nu_\mu} = 1$ GeV, 5 GeV and 10 GeV for ν_μ.

The asymmetry A can be measured hoping to reproduce the results by SK as per the definition [19]

$$A = \frac{N_\mathrm{E} - N_\mathrm{W}}{N_\mathrm{E} + N_\mathrm{W}}, \tag{1}$$

where N_E (N_W) is the number of events for neutrinos travelling towards east (west).

The effect of asymmetry is observed in low-energy neutrinos of atmospheric origin. The cosmic ray particles enter the atmosphere and the secondary products formed i.e., π/K, are charged particles. They deviate from their original paths due to the geomagnetic field of the rotating Earth. The average drift in the path of an electron/positron is generally given by [20],

$$d = \frac{qh^2 B \sin\chi}{2E_e \cos^2\theta}, \tag{2}$$

where χ is the angle between $\vec{B}$ (magnetic field) and the original velocity of the particle v; q is the electric charge, h is the average vertical height of the electron path, E_e is the average energy and θ is the zenith angle. Similarly, drifts are experienced by π/K and $\mu^{\pm}$s in the Earth's atmosphere. Thus, by observing the azimuthal angle distribution in different bins of the neutrino energy and $\cos\theta$, one can study the changes in the Earth's geomagnetic map, although to a crude approximation.

The orientation of the ICAL detector makes an acute angle with respect to the geographical east direction (figure 3). Therefore, GENIE@INO should include azimuthal information also (3D).

3.2 *Low flux at higher energies*

The cosmic ray power spectra fall as $(dN/dE) \sim E_{\nu}^{-\gamma}$, where $\gamma \sim 2.7$ in our concerned range. Thus, the flux falls rapidly with energy. However, ICAL is interested/sensitive to neutrinos with ∼1–10 GeV

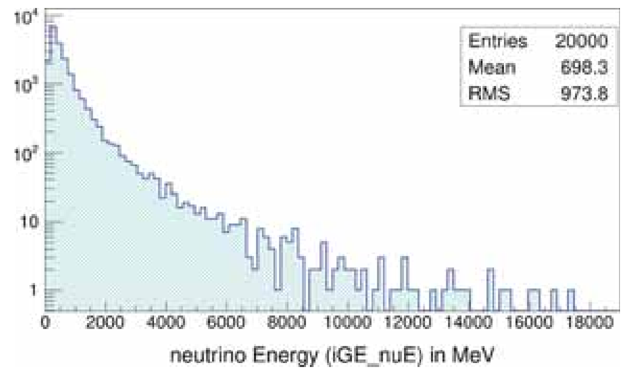

Figure 4. Energy distribution of incident atmospheric neutrinos.

energy. Mass hierarchy discovery potential is large for events with energy of a few GeV. The flux at these energies is rather low, as shown in figure 4.

GENIE contains provisions for weighted event generation for the neutrino beams incident on the target. No such option has been made available for the atmospheric neutrino event generation in GENIE.

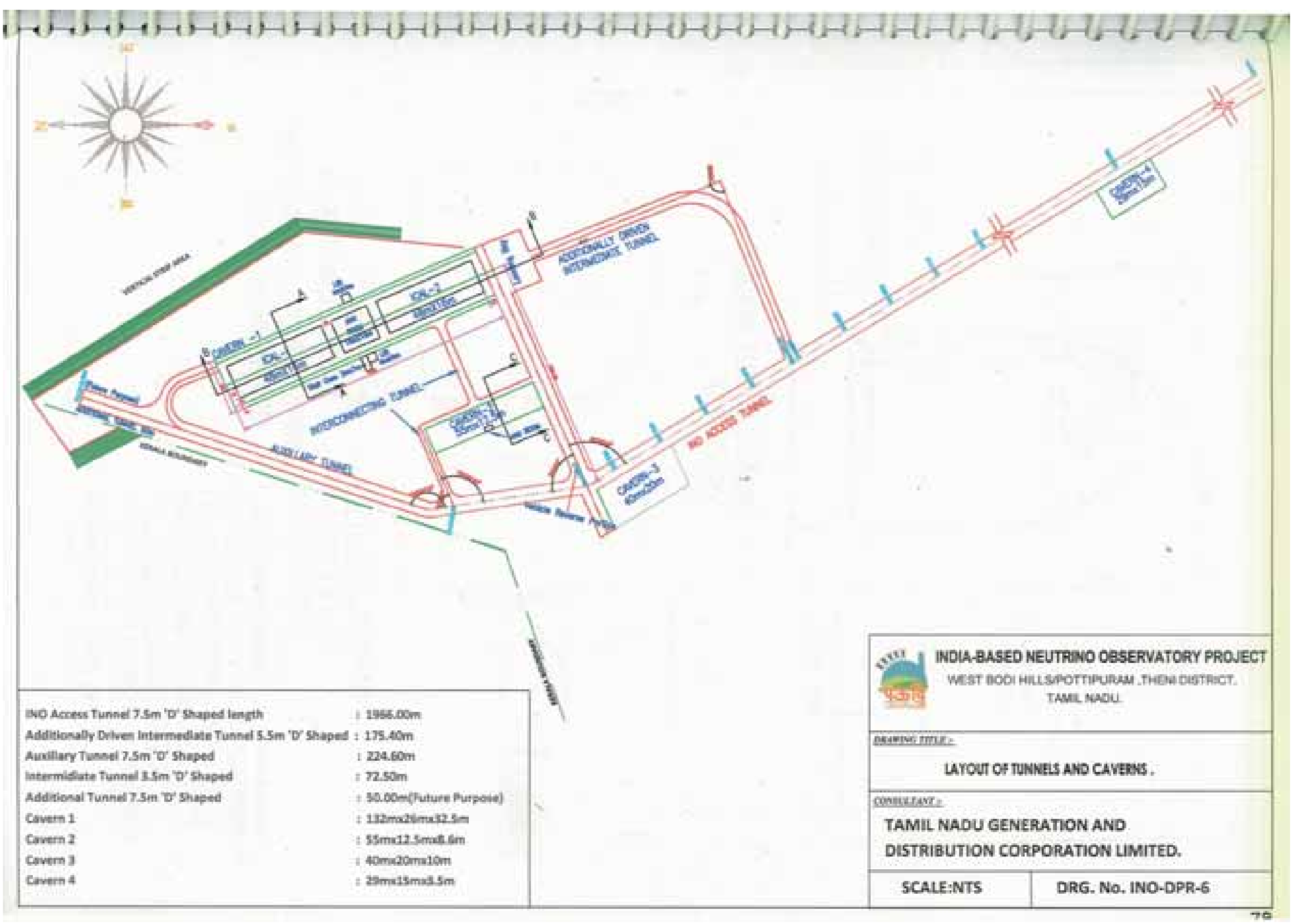

Figure 3. A schematic sketch of the ICAL detector at the INO site.

3.3 *Event generation for a certain exposure time*

Atmospheric neutrino experiments like INO require to decide their runtime, which largely (though indirectly) depends on the length of exposure of the detector to the atmospheric neutrino fluxes. GENIE has been used to generate a fixed number of ν interactions. There was no effective provision to generate atmospheric ν events for a certain exposure time. This is very necessary for atmospheric neutrino experiments.

3.4 *ICAL-customized output*

Every experiment has its own objective and methods of analysis. GENIE has provisions to give output in the customized formats for different experiments like T2K, NuMI, JPARC etc. Simulations for the INO experiment require the output in its own facilitating format. This either demands us to understand the analysis parameters of other experiments, or to have an exclusive format for INO.

4. Solutions

In order to overcome the shortcomings mentioned in the earlier section, we modify the GENIE source code to include the following aspects. This not only results in a 'ready-to-go' GENIE@INO package but also ensures a better understanding of the neutrino event generator being used at INO.

4.1 *Accept the information of azimuthal angle in flux tables*

The Nuance@INO has so long been using the SK flux, which has energy (E_ν) and $\cos\theta_\nu$ dependence only [2]. However, the Honda flux at the INO site depends on the azimuthal angles too, divided into bins of 30. GENIE had the provision to use the former type of flux files, be it the FLUKA [21] format or the BGLRS [22] format. So, in order to include all the available information into ICAL studies, the source code of GENIE

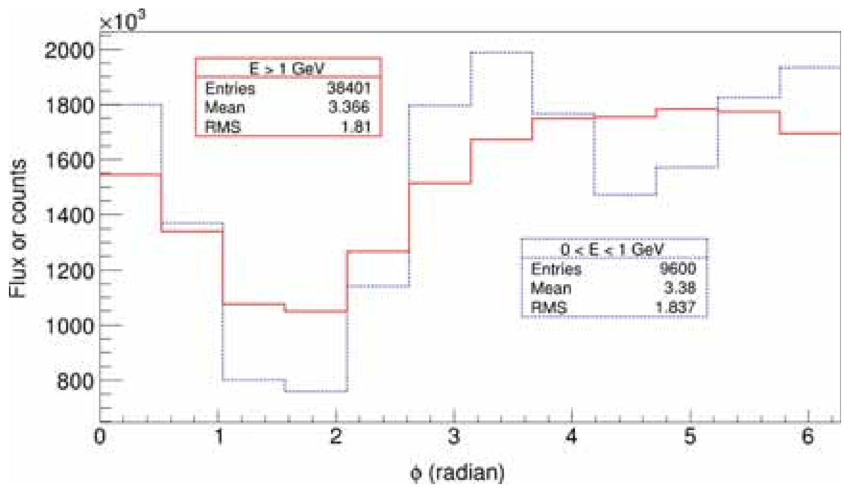

Figure 5. Azimuthal angle of incident neutrinos at ICAL@INO with the 3D flux at the INO site.

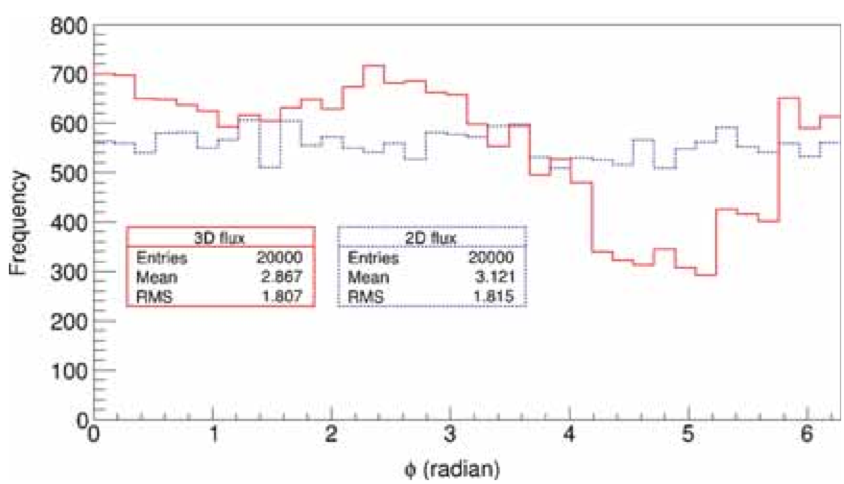

Figure 6. Azimuthal angle of ν_μ at ICAL@INO with flux averaged over ϕ vs. the 3D flux, both by HONDA at INO site.

has been modified to read such flux files which contain azimuthal angle dependencies too. It has been observed that there is observable variation of neutrino flux along the azimuthal direction, which is shown in figure 5.

The azimuthal angle dependence of the flux gives a non-uniform ϕ distribution at the ICAL detector, as in figure 6. (Please note the inversion of ϕ distribution, which is due to the convention of inverse coordinate system in ICAL with respect to HONDA coordinate system.)

Significant difference can be noted if the 3D enhanced information is used, instead of the flux averaged over ϕ (2D). The ϕ distribution in the case of 2D is comparable to that of the neutrinos around or above 10 GeV, as shown in figure 7. The ICAL detector is sensitive to neutrinos above 1 GeV, where the signature of ϕ is well-realizable.

So, inclusion of the ϕ-dependent flux information is absolutely necessary for the study of atmospheric neutrinos at INO.

Besides the already available flux-file options, i.e. the FLUKA and the BGLRS, a third option called FLUKA3D has been introduced.

A comparison of the $\cos\theta$ and ϕ distributions in the three cases of ICAL events sample generated by: (i) Nuance using the SK flux; (ii) GENIE using the above-mentioned SK flux and (iii) GENIE using the flux at the INO site, is shown in figures 8 and 9.

The distributions of ϕ and $\cos\theta$ in figures 8 and 9 further support the use of GENIE over Nuance, and also highlight the importance of using the INO flux tables over that of the SK site. A complementary assurance of this fact can be found in [2].

4.2 *Weighted event generation of atmospheric neutrinos*

The neutrino flux being very high at low energies, the fraction of the total number of events in the high-energy range is less. If one is interested in studying

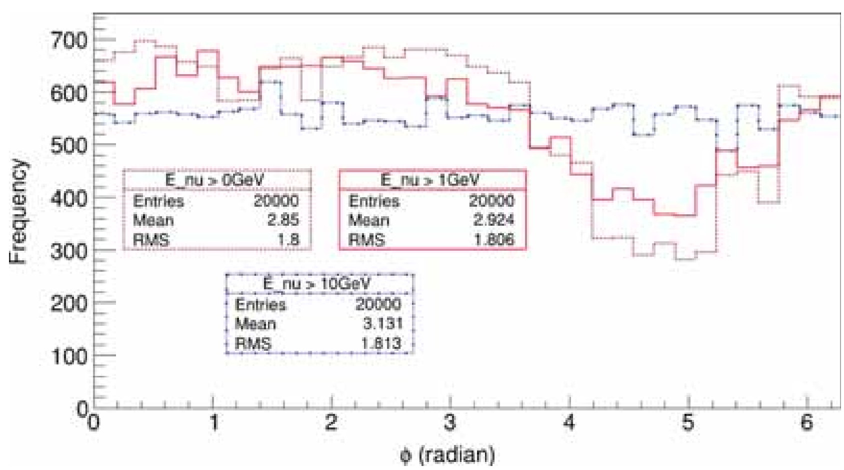

Figure 7. Azimuthal angle of ν_μ at ICAL@INO with the 3D flux. Comparison of the ϕ distributions for relevant energy ranges are also shown.

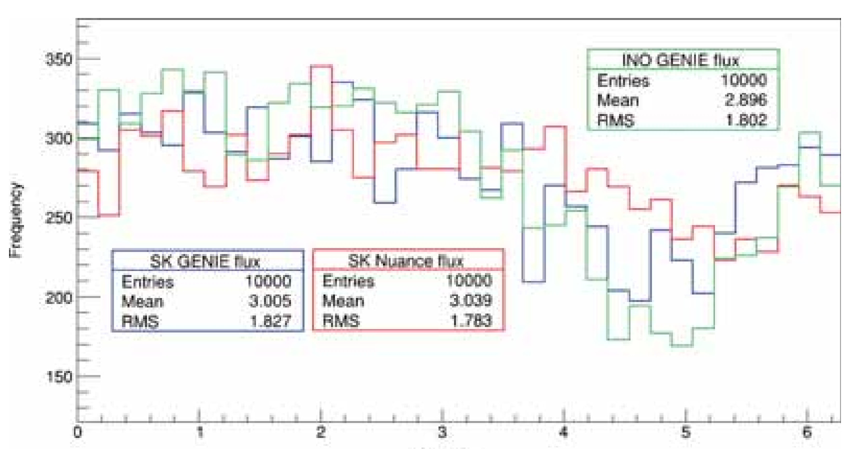

Figure 8. Comparison of the azimuthal angle distributions of ν_μ at ICAL@INO with the 3D flux in the three different cases (mentioned above) in the energy range 0.1–10 GeV.

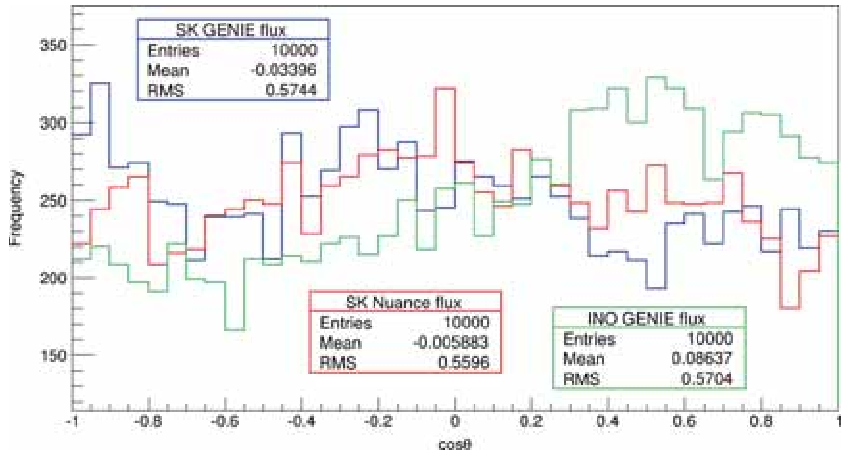

Figure 9. Comparison of the $\cos\theta$ distributions of ν_μ at ICAL@INO with the 3D flux in the three different cases (mentioned above) in the energy range 0.1–10 GeV.

the effect of these high-energy events, along with the lower-energy ones, one faces the problem of low statistics in the higher energy region, or may tediously generate events in different energy bin and then merge them according to their cross-sections. So the option of weighted atmospheric event generation is introduced. An optional tag "-w *weight*" in the gevgen_atmo command is introduced. It generates events with the flux multiplied by the energy raised to a power "*weight*" instead of zero. The minimum and maximum limits of the weight values have been set to be $\{-1, 5\}$. The default is undoubtedly 0. However, it is suggested to keep the weight values limited between 0.0 and 2.2. If weights above this range are considered, the number of events in the lower energy range reduces tremendously. This effect is not required for studying the events at the INO detector. A comparison of generated neutrino spectra with different weights is shown in figure 10 and the steps to obtain this are given below:

(a) Weight, w, is read through command line,
(b) this value is transferred to the ν-flux reading function,
(c) neutrino fluxes are modified by the multiplicative factor E^w,
(d) neutrino from this modified flux table is selected and
(e) the usual event generation process is continued.

The individual event weights, i.e. the energy raised to the power of the weight value, as well as the energy–weight histogram (in case one would want to calculate weight for an energy independently) is made available in the modified GENIE output file.

4.3 *Exclusive output format for INO*

The GENIE output is first written in a root file in the 'ghep' format, which then supports the option of converting it into various generic formats like 't2k-root/txt format', 'numi-format', 'nuance-tracker' format etc. A

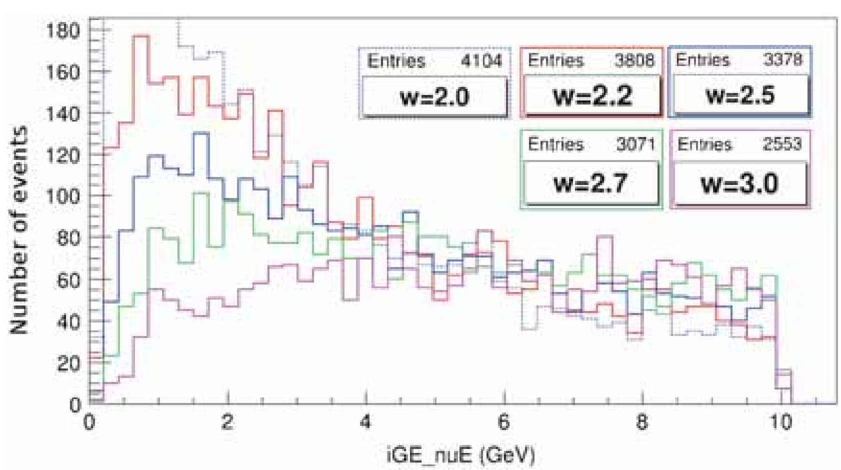

Figure 10. Comparison of the energy distributions of the generated neutrino events using different weights.

new option called the 'nu_INOGEN_rootracker' has been introduced to obtain the output in a root format which is customized for INO–ICAL code. Unlike the standard GENIE output in SI units, the modified output has the length in mm, time in ns and momenta or energy in MeV, which are the default units of the GEANT4. The interaction identification (id) codes have been made directly available as another parameter against every event. The target nuclei and the kinematics of the unstable particles ($\tau < 10^{-10}$ s) have been enlisted too along with all stable particles produced in each interaction.

4.4 *Activating the option of exposure time*

The provision to generate the atmospheric ν events for a certain exposure time has now been introduced. We can now generate the ν-interaction data for any length of exposure to the atmospheric neutrinos, using any detector geometry.

We used the following equation to define the number of interactions:

$$N = \sum_{n}\sum_{E_\nu}\sum_{\cos\theta}\sum_{\phi}\sum_{\text{material}}\left[\frac{\mathrm{d}N}{\mathrm{d}E_\nu}\Phi_\nu(E_\nu,\cos\theta,\phi) \times \sigma(E_\nu)\frac{\rho_l \times N_\mathrm{A}}{A} \times \Delta E\right]\frac{1}{n}4\pi\pi R_T^2, \quad (3)$$

where N is the rate of interactions, N_A is the Avogadro's number, A is the atomic number of the target nucleus, ρ_l is the pathlength of the neutrino in the INO detector of the target nucleus A, n is the number of iterations and R_T is the radius of the hypersurface of the neutrino gun of the generator.

The scaled equivalent (number of generated events weighted with the inverse scale factors) which was used to change the nutrino flux (E^{-w}) for different weight factors are given in table 1, where the total number of iterations used for this calculation is 10000. The total generated event is ∼3.1 times the true number for $w = 2$.

We need to decide the number of iterations (in eq. (3)) to have an accuracy better than 1%. As can be observed from figure 11, the variation in the value of the calculated rate of interactions is 0.3%, for iterations beyond $n = 2 \times 10^7$. So, we can use $\sim 2\times 10^7$ iterations to calculate an acceptable value of rate of interactions.

Table 1. Consistency check with different weight factors to obtain the number of events in one year. The scaled equivalent for $w = 2$ is 35281.

Weights	0	0.5	1.0	1.5	2.0	3.0
$\nu_\mu+\bar{\nu}_\mu+\nu_e+\bar{\nu}_e$	11529	11681	11759	11865	11746	11596

5. Summary

A neutrino event generator is a vital component in the simulation studies of a neutrino experiment. INO has chosen to adopt GENIE as the neutrino event generator, after having used Nuance so far. This required us to make an INO-user friendly version of GENIE. One can readily use the results of the 'GENIE@INO' and apply them into the ICAL simulation studies. However, in the process, it has led us to include four new options in the GENIE code, three of which may also be used for any other atmospheric neutrino experiments. The four new

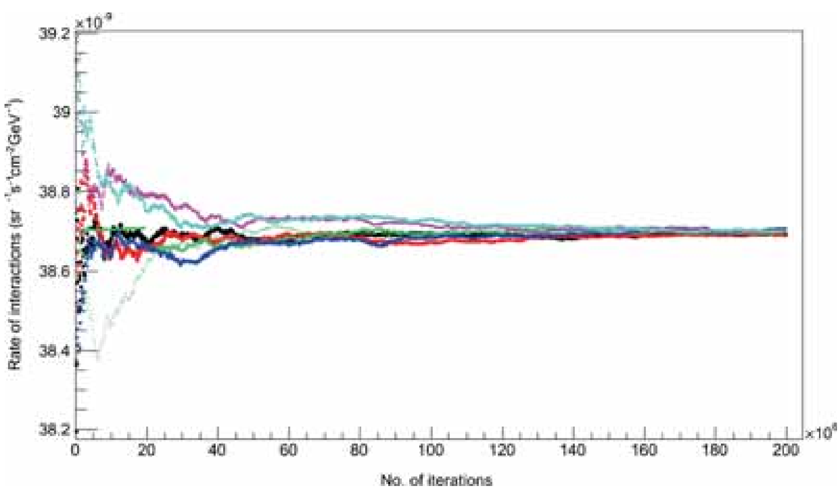

Figure 11. Expected flux rate for different number of iterations. The colours represent the execution of the program with different seeds of random number generation.

options in the GENIE neutrino event generation, which are available at the GENIE@INO version are:

(1) FLUKA3D: To include the 3D atmospheric neutrino flux information, i.e., the energy, the $\cos\theta$ and the ϕ,
(2) -w energy-weight: Option for weighted atmospheric event generation, i.e., more high-energy neutrino event generation, defying the exponential fall of the ν-energy spectrum,
(3) nu_INOGEN_rootracker: Command to get exclusive INO-customized output and
(4) -e exposure: To generate events for a desired exposure time of the detector.

The third option is obviously more useful to an INO user, unless, one chooses to use the INO-specific output format for one's analysis. The other options are helpful to any user. A very significant modification is the inclusion of the acceptability of an entirely new flux file format in this version of GENIE. Thus, this package is ready to accommodate any format of flux-files in GENIE.

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