GiBUU based neutrino interaction simulations in KM3NeT

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Abstract: The simulation of the neutrino interaction is a crucial step in the simulation chain of a neutrino experiment. The different processes taking part in the neutrino scattering on a nucleus require several approximations in order to make the simulation possible and to realize reasonable computation times. This can be realised in different ways, e.g. by parametrised models for the different scattering processes and energy regimes as it is implemented in GENIE. The GiBUU neutrino generator utilises the Boltzmann-Uehling-Uhlenbeck equation to simulate the particle flow after the neutrino interactions, the so-called final state interactions. The detector-specific results in form of the visible energy in the detector after the light propagation simulation and the KM3NeT event reconstruction are presented. In addition to that, the comparison to the GENIE based simulation environment in KM3NeT (gSeaGen) is drawn.

Keywords: Neutrino detectors; Simulation methods and programs

ArXiv ePrint: 2107.13947
1 Introduction

The KM3NeT neutrino telescope is currently being built in the depths of the Mediterranean Sea. It will host two water Cherenkov detectors comprising 3D-arrays of photomultiplier tubes (PMT) with different layouts. The detector designed for the low energy regime is called ORCA (Oscillation Research with Cosmics in the Abyss) in order to tackle the determination of the neutrino mass hierarchy. In this lower energy regime the secondary particles from the neutrino interaction are distributed more isotropically and deviate further from the direction of the primary neutrino. Also the reconstruction of the energy depends stronger on energy thresholds for the emission of the secondary particles, thus information about the interaction is crucial in order to gain knowledge about the light distribution of low-energy event topologies and subsequently improve the energy and direction reconstruction of the primary neutrino [1].

2 Neutrino interaction simulation

In order to make a numerical simulation of neutrino scattering processes with so-called neutrino generators possible within reasonable computation times several approximations are necessary. The neutrino generators GiBUU and GENIE implement the neutrino interaction via a factorised model, i.e. splitting the scattering event into the initial electroweak scattering and the propagation of the generated particles through the nucleus [2, 3]. In GiBUU this propagation of final states is done via propagating phase space densities utilising the Boltzmann-Uehling-Uhlenbeck equation. In order to adapt the simulated neutrino interactions to the KM3NeT environment, the neutrino generators are wrapped by custom software packages. For GENIE, the KM3NeT collaboration has developed a wrapper called gSeaGen [4] and for GiBUU the KM3BUU software package (see section 3) has been developed.
2.1 Final state particle picture

The resulting particles after the propagation through the nucleus are written out by the generator and are referred to as final state particles. The contribution of the different particle types over energy is compared via the production cross section \( \frac{d\sigma}{dE} \), where \( X \) stands for the individual secondary particle type. In the regime below 10 GeV the final state particle types consist of photons and \( \pi^- e^- e^+ \).

\[ \begin{align*}
\text{mesons (besides the out going lepton from the neutrino vertex itself) and the emission of secondary particles from GENIE is higher (see figure 1). At higher energies also heavier mesons, i.e. Kaons, are generated and their production cross section from GiBUU data exceeds the one from GENIE. The GiBUU dataset does not contain photons, which yields the dominant contribution of photons for the GENIE dataset. The difference in the production cross section for protons and neutrons is currently under further investigation. The mean energy of those secondary nucleons is } E_{\bar{p}-\bar{n}} = 1.08 \text{ GeV (}\sigma_{\bar{p}-\bar{n}} = 0.99 \text{ GeV)} \text{ which is close to the rest energy of the particles. Thus, the contribution to the visible light yield in the detector is expected to be negligible.}
\end{align*} \]

2.2 Visible energy

The visible energy of a given final state is defined as the energy contained in an electromagnetic shower which is converted to photons. The definition was applied and the values for the parametrisation of the used rational function are taken from [5]. The visible energy distribution for both generators is shown in figure 2. In the used configuration the distribution of the ratio \( E_{\text{vis}}/E_\nu \) for the KM3BUU data has a slight shift to higher values. This seems to contradict the results from section 2.1, but those are given in units of production cross section which is independent from the simulated flux \( \Phi(E) \propto E^{-1} \).

2.3 Event trigger & reconstruction

In order to get a realistic detector picture including the environment properties and geometry effects, in the next step the neutrino generator output is fed into a light generation and propagation
Figure 2. Visible energy $E_{\text{vis}}$ over the primary neutrino energy $E_{\nu}$ for GiBUU (left) and the ratio $E_{\text{vis}}/E_{\nu}$ for $\nu_e, \tau$-CC-interactions for GiBUU and gSeaGen in the energy range $E_{\nu} \in [1 \text{ GeV}, 10 \text{ GeV}]$ (right).

Figure 3. Effective volume for the reconstructed events for the GiBUU dataset (left) and official estimate for KM3NeT taken from [1] (right).

Simulation resulting in photosensor readings (hits). With the hit information the simulation data contains the same shape compared to the DAQ data from the detector and can subsequently be fed into the subsequent data processing tools, i.e. triggering and reconstruction. The normalisation of the number of events over energy can be compared via the effective volume $V_{\text{eff}}$ defined as $V_{\text{gen}} \cdot N_{\text{det}} / N_{\text{gen}}$, which is shown in figure 3. It stands out, that the distribution for GiBUU follows the expected distribution in the energy regime between 1 GeV and 10 GeV, but exceeds the expected upper limit at 7 Mm$^3$ and continues rising at energies higher than 10 GeV. This deviation from the expectation is currently further investigated. In figure 4 the comparison between KM3BUU and gSeaGen is shown for the reconstructed energy over the true Monte-Carlo energy. The ridge of the events lies for both on the expected straight line of $E_{\text{reco}} / E_{\text{MC}} = 1$, which indicates similar magnitude of systematic effects from the processed KM3BUU dataset compared to the gSeaGen dataset. The origin of systematics effects have not been studied yet. The distributions yield a lower reconstruction efficiency for gSeaGen at higher energies above 10 GeV compared to KM3BUU. This difference can be explained by the normalisation comparing the excess of effective volume above 10 GeV for KM3BUU (see figure 3).
3 KM3BUU

The KM3BUU framework is a python based wrapper for the GiBUU Fortran environment, which is installed and operated inside a singularity container. The general GiBUU workflow for running the simulation is unchanged, but can be completely steered via the KM3BUU python environment. The GiBUU output consists of multiple files which carry the full information about the simulated neutrino scatterings. The output directory containing those GiBUU output files can be parsed with the KM3BUU framework and converted to multiple data formats, e.g. awkward arrays [6] and pandas dataframes [7] for the pure neutrino generator output or converted to the KM3NeT dataformat. This KM3NeT dataformat is then completely compatible to the KM3NeT (simulation) tools.

4 Conclusion

The KM3BUU package is a quite new software package and the technical aspect of software errors is non-negligible, but the distributions along the simulation steps do not show any major discrepancies compared to GENIE. The difference in the $\pi$-meson production rate in the lower GeV regime is expected to be higher compared to previous studies, e.g. Coloma et al. [8], but this depends on the GENIE input cross section and the simulation configuration of GiBUU. This difference affects also the event topology starting in the analysis step of the visible energy. In the final step the event reconstruction shows no systematic offsets or deviations with focus on the reconstructed energy. The excess of effective volume visible for the KM3BUU data follows the trend of a higher visible energy fraction $R$, but as this exceeds the estimate of previous studies significantly this is currently further investigated.

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