Quantifying Effects Of Final State Interactions On Pion Production In DUNE Using Monte Carlo Event Generators

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Abstract. The analysis of pion production in neutrino-nucleus scattering is crucial to quantify the effect of final state interactions (FSI) in the energy regime of DUNE and other long-baseline neutrino experiments since FSI modify the number of pions that emerge in the final state as compared to the number of pions produced in the initial (primary) state. Not only the number of pions but also their charge gets changed due to the prevailing FSI effects. In the present work, we will study the effect of FSI on pions after their production at the initial neutrino-nucleus interaction vertex using two different Monte Carlo (MC) simulation tools viz. GENIE (version: 3.0.6) and NuWro (version: 19.2.2). Considering the DUNE experimental set-up, we observe pion production in ν_μ and ^{40}Ar nucleus interactions for an event sample of 1 million for each generator. We find that there are some differences in the pion number observed in the primary and final states of two generators and that the differences are above statistical fluctuations. We observe that GENIE (version: 3.0.6) is more responsive (less transparent) to absorption and charge exchange processes as compared to NuWro (version: 19.2.2).

1. Introduction

Neutrinos are the most ubiquitous and perhaps the most fascinating particles in the universe. The unique properties of neutrinos (which are yet not completely understood) make the neutrino research field a challenge and interesting both from conceptual and practical points of view. The behaviour and interactions of these most evasive particles are being studied to understand their nature accurately and to know physics beyond the standard model. The phenomenal experiments done in recent years have made sensational discoveries in neutrino oscillation field [1]. In neutrino oscillations, a neutrino created with one particular flavour can be measured to have a different flavour when observed after some interval of time. Neutrino oscillation physics is administered by oscillation parameters – mixing angles ($\theta_{12}, \theta_{13}, \theta_{23}$), Dirac phase δ_{cp}, and magnitude of mass squared differences Δm^2_{21} (solar mass splitting) and Δm^2_{32} (atmospheric mass splitting). In the recent neutrino oscillation experiments, almost precise determination of mixing angles θ_{12}, θ_{23} and non-zero value of θ_{13} and mass squared differences Δm^2_{21}, $|\Delta m^2_{32}|$ have been made[2, 3, 4, 5]. Nevertheless, some unknown parameters are remained to be found:

1) The sign of Δm^2_{32} (i.e. ordering of neutrino masses). The normal mass ordering or normal mass hierarchy (NH) of neutrino masses is $m_1 << m_2 << m_3$, and their inverted mass ordering

or inverted mass hierarchy (IH) is $m_1 \approx m_2 >> m_3$.

2) Fixing octant of θ_{23} i.e. to determine whether θ_{23} falls in the lower octant $0 < \theta_{23} < \frac{\pi}{4}$ or higher octant $\frac{\pi}{4} < \theta_{23} < \frac{\pi}{2}$. This incapability of an experiment to distinguish between θ_{23} and ($\frac{\pi}{2}$ - θ_{23}) is known as octant degeneracy problem [6].

3) The phase parameter δ_{cp} (Dirac phase) which may take value, -$\pi < \delta_{cp} < \pi$. A value of δ_{cp} different from 0 or π would indicate CP violation in the leptonic sector. This scenario would through light on leptogenesis and baryon asymmetry of the universe[7, 8]. A precise value of δ_{cp} is also required to explain the sterile neutrino phenomenon[9].

The neutrino energy is needed to be reconstructed correctly for the study of neutrino oscillations as neutrino oscillation probability is dependent on neutrino energy. Any wrong reconstruction of neutrino energy can give wrong identification of neutrino events, wrong measurement of cross-section and wrong measurement of oscillation parameters. As neutrino beam used in neutrino oscillation experiments is not mono energetic, a complete knowledge of particles in the final state is required for the correct measurement of neutrino energy. Our detector captures the final state particles and these particles, because of nuclear effects, are not identical to the particles produced at the primary vertex thereby making it essential to have absolute knowledge of nuclear effects and final state interactions (a challenging task) for the correct estimation of neutrino energy. The use of heavy nuclear targets in the present and future neutrino experiments will give large event statistics, but at the same time will boost the nuclear effects, thereby reducing statistical errors and shifting the attention to sources of systematic errors. An important source of systematic errors is the uncertainties in the calculation of neutrino-nucleus cross-sections which arises because of the presence of nuclear effects[10, 11, 12]. The up to date comprehension of nuclear effects is not enough to have satisfactory control over systematic errors arising because of nuclear effects [13, 14, 15, 16]. In neutrino-nuclear interactions, the nuclear effects which nuclear environment contains are: Fermi motion of nucleons, nuclear binding energy uncertainties, multi-nuclear correlation, and FSI for the hadrons produced.

In the present work, we have made an attempt to study the effects of FSI on pion production in the DUNE experimental set-up using simulation tools (neutrino event generators), GENIE[17] and NuWro [18, 19]. The comparison of these generators has also been done for similarities and differences. Both the simulation tools (GENIE and NuWro) have incorporated nuclear effects in them but may differ in the incorporation of nuclear models and various neutrino-nucleus interaction processes. In the interactions of neutrino with nucleus, the study of nuclear effects is not a trivial thing as the nucleus is a collection of nucleons that are not independent of each other. Like GENIE and NuWro, there are several generators that include nuclear effects in their codes and use different approximation methods to define different nuclear effects.

The DUNE (Deep Underground Neutrino Experiment)[20, 21, 22, 23] is a third generation Long-Baseline future neutrino experiment in USA. This experiment aims to inspect significant problems in the neutrino physics field i.e. deduction of CP violation phase, octant degeneracy, and neutrino mass hierarchy. In DUNE there is a near detector system (ND system) situated 575 meters downstream of neutrino source at Fermilab in Illinois and a far detector located about 1280 km away from Fermilab at Sanford, South Dakota in USA. The DUNE ND has three primary detector components: A liquid argon time projection chamber (LArTPC or ND-LAr) of mass 50-ton constructed by making use of ArgonCube, a multi-purpose detector (MPD) made up of high pressure gaseous time projection (HPgTPC) enclosed by an electromagnetic calorimeter within a magnet (this detector is also called as ND-GAr), and a SAND (System for on-Axis Neutrino Detection) detector to monitor neutrino flux.
The far detector (FD) of DUNE will be a suit of four similar LArTPCs, every one of which will be having a fiducial mass of at least 40 kilo ton and will be installed in a cryostat with inner

dimensions 15.1 m (width) × 14.0 m (height) × 62.0 m(length) with an entire liquid argon mass of about 17.5 kilo ton. LArTPC is considered as an ideal choice for the DUNE-FD as it will provide excellent tracking and calorimetry performance.

The DUNE neutrino flux, (shown in Fig. 1) and ^{40}Ar nuclei (as target) have been used in our simulation work. The energy spectrum of this flux will have peak value at about 2.5 GeV and the energy range from hundreds of MeV to few tens of GeV. The NuMI (Neutrino at Main Injector) neutrino beamline facility of Fermilab provides the required intense neutrino beam. For this, a protons beam coming from the main injector accelerator is smashed on graphite target which produces mesons (pions and kaons). The produced mesons, after getting focussed, travel through a 200 m long pipe (called as decay pipe), will decay into leptons and neutrinos. The neutrino and anti-neutrino beams can be separated with the help of focussing magnets. The intense (megawatt-scale) muon neutrino (ν_μ) beam produced at Fermilab will travel towards DUNE detectors. Near detector will observe the unoscillated beam spectrum and FD will observe oscillated beam spectrum. The observed systematic uncertainties will help us to fulfil the objectives of DUNE up to a proper extent. The study of pion production at the primary vertex and in the final state gives information about the FSI and systematic uncertainties introduced by it.

The paper is divided into five sections: Section II comprises an illustration of neutrino interactions and pion production, Section III contains simulation tools GENIE and NuWro with models used by them, Section IV contains results of simulation and finally the conclusions will be given in Section V.

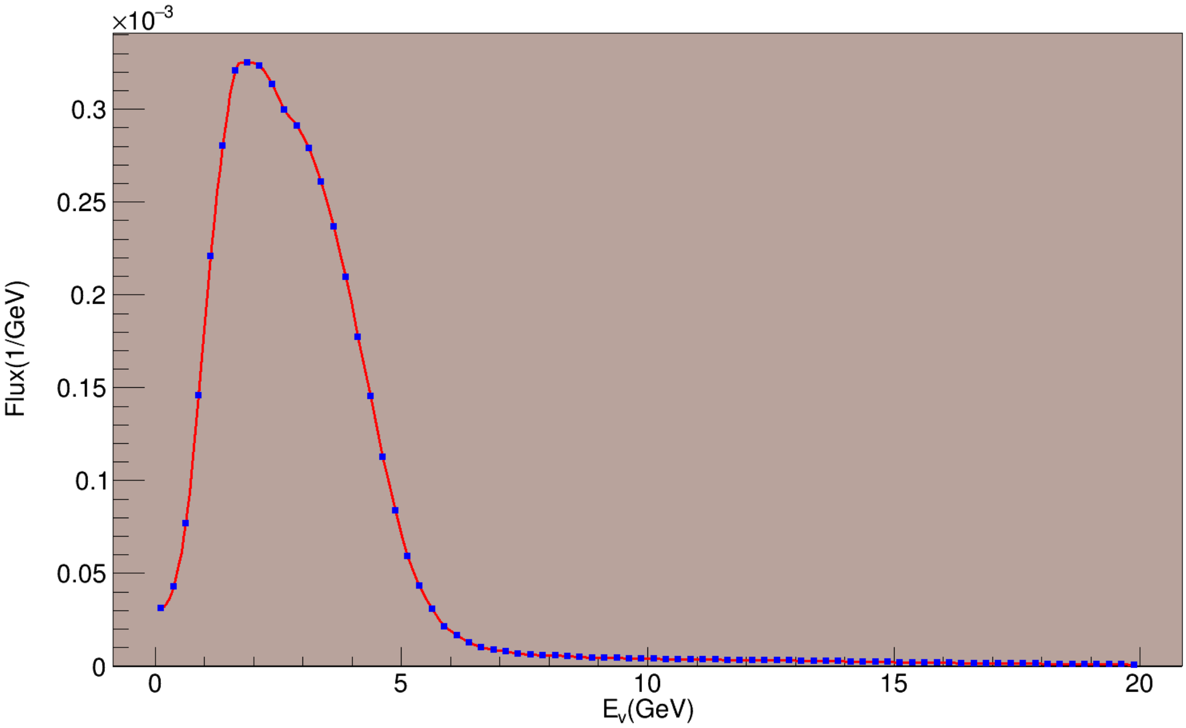

Figure 1. DUNE flux used in the simulation work.

2. Neutrino-Nucleus Interactions

Neutrinos interact with nucleons in the nucleus via weak interactions exchanging $W^{\pm}$ or Z^0 particles. These neutrino interactions can be classified as: neutral current (NC) neutrino interactions and charged current (CC) neutrino interactions.

$$\nu_l + N \longrightarrow l^- + X, \quad \bar{\nu_l} + N \longrightarrow l^+ + X, \qquad CC \tag{1}$$

$$\nu_l + N \longrightarrow \nu_l + N, \quad \bar{\nu_l} + N \longrightarrow \bar{\nu_l} + N, \qquad NC \tag{2}$$

where N = n, p or a nuclear target, l = e, μ or τ, and X = hadrons present in the final state.

Further classification of each of these CC and NC interactions is as under:
a) Quasi Elastic and Elastic Scattering: The neutrino may get scattered from the nucleon and eject the nucleon in the process. In case of charged current events, this scattering is quasi-elastic and in case of neutral current events, this scattering is elastic. Taking into consideration the muon neutrinos (ν_μ), the interaction reactions can be written as under:

$$\nu_\mu + n \longrightarrow \mu^- + p, \quad \bar{\nu_\mu} + p \longrightarrow \mu^+ + n, \qquad QE(CC) \tag{3}$$

$$\nu_\mu(\bar{\nu_\mu}) + n \longrightarrow \nu_\mu(\bar{\nu_\mu}) + n, \quad \nu_\mu(\bar{\nu_\mu}) + p \longrightarrow \nu_\mu(\bar{\nu_\mu}) + p \qquad Elastic(NC) \tag{4}$$

b) Resonance Production: A neutrino with proper energy may interact with the nucleus and excites it to a resonance state which then decays into a nucleon and a single pion with in a small fraction of time. Taking into consideration the muon neutrinos (ν_μ), the interaction reactions can be written as:

$$\nu_\mu + N \longrightarrow \mu^- + N^* \longrightarrow \mu^- + \pi + N^{'} \tag{5}$$

Here, N, N' = n or p; $\pi = \pi^+$, π^- or π^0; N^* represents a resonance, most of the time Δ (1232) resonance is produced, but other higher resonances can also be produced. This process is possible for for both CC and NC interactions.
c) Deep Inelastic Scattering: For neutrinos to undergo this type of scattering the energy required is higher than the threshold energies for QE and RES scattering. In deep inelastic scattering (DIS), a neutrino with relatively high-energy undergoes scattering from the quark inside the nucleon with the exchange of W or Z particles and there would be production of lepton and a hadron shower. This type of interaction can take place for both charged current and neutral current processes.
d) Coherent Scattering: There may be interaction of neutrinos with the nucleus as a whole (coherent interaction of nucleus), producing a meson and a lepton in the process. Although this process gives a small contribution towards the pion production.
e) MEC (or 2p-2h) Process: Study of neutrino-nucleus interactions in a few GeV energy regions is complex since there is an overlap of many reaction channels and physics mechanisms [24] etc. 2p-2h or MEC events are high-energy neutrino interaction events and they look like QE scattering events[25]. The signature of a 2p-2h interaction event is $1\mu^-$ and no pion in the final state. The same is the signature of a true quasi-elastic interaction or a resonance interaction with pion absorbed in the nuclear matter. In 2p-2h interaction, a neutrino makes interaction with a correlated pair of nucleon in the nucleus and transfers its energy and momentum to it, thereby ejecting two nucleons from nucleus. The 2p-2h interaction process is also called as meson exchange (MEC) process as during the initial stage of this process, nucleons keep on exchanging a pion. This type of interaction takes place in the energy regime between quasi-elastic and resonance processes.

3. Simulation Tools-GENIE And NuWro

Neutrino event generators form a major simulation tool for the data analysis, the plan and development of detectors, and the measurement of systematic errors. They are used to generate events taking into consideration detector requirements for any experiment. In our simulation studies, we have used version 3.0.6 of GENIE and version 19.2.2 of NuWro which were the latest stable releases at the time this simulation work was being carried out. These are presently being used by many neutrino experiments of Fermilab and other experiments in the world. GENIE has been used by experiments like MINOS[26], MINERvA[27], MicroBOONE[28], T2K[29], NOvA[30] and ArgoNEUT[31]. T2K experiment recently used NuWro for estimating systematic errors while MINERvA experiment recently used NuWro in measuring two-body current distribution and the flux-averaged differential cross-section.

Both GENIE and NuWro are written in C++. GENIE is a modern and most sophisticated package developed by international collaboration taking into consideration ongoing neutrino oscillation experiments. This simulation tool can simulate neutrino events for all neutrino flavours over a wide energy range. NuWro has been recently developed by a group of theoreticians of Wroclaw University. It also works effectively over wide energy range and provides nearly all what is required by modern neutrino experiments.

In GENIE, the nuclear model used is the relativistic Fermi gas (RFG) model (as suggested by Bodek and Ritchie [32]) while in NuWro, local Fermi gas (LFG)has been used. QE scattering is modelled using Llewellyn Smith model [33] in both the generators. Further, in GENIE, the latest BBBA07 [34] vector form factor is used while in NuWro the latest BBBA05 [35] vector form factor has been used. For RES interactions, GENIE considers contribution from Δ resonance and from other resonance individually on the basis of Rein-Sehgal model[36] while NuWro uses the Adler-Rarita-Schwinger model [37] for RES interactions. For DIS events, GENIE uses the Bodek and Yang model [38] while NuWro employs the Quark-Parton model [39]. For coherent (COH) pion production, GENIE uses the Rein-Sehgal model with an updated PCAC formula [40] while NuWro uses the Rein-Sehgal model[41]. In GENIE, we use variable values of axial mass (M_A) between 0.99 - 1.2 GeV/c^2 while in NuWro we use variable values of axial mass between 0.94 - 1.03 GeV/c^2.

4. Results And Discussion

1 million similar set of events have been generated using DUNE flux and ^{40}Ar target, for both GENIE and NuWro. The number of pion produced in the initial and in the final state were obtained on the event by event basis for both the generators. The results obtained are put in the form of topology tables for initial (primary) and final states. Evidently, a primary state shows the pions which are created at primary vertex while a final state shows the pions which are obtained after secondary interactions may have taken place. The simulation results for a million events are shown in Table 1 and Table 2 respectively for GENIE and NuWro. A comparison plot for the pions produced event-wise in primary and final states for two generators is shown in Figures 2 and 3 (left panel for GENIE and right panel for NuWro). Thus in both the generators the number of pions in the initial states is different from the number of pions in the final states due to FSI. For example, the total number of π^+ produced in the initial state of GENIE (table 1) is 382806 while the total number of π^+ noticed in the final state is 237662. This is to be taken into account in real detectors, as they observe the particles produced in the final state and thus can give misinformation about the pions produced in the primary vertex.

From table 1 and table 2, it is observed that apart from many similarities, there are some large dissimilarities in the number of pions in initial and final states for the two generators. For example, the number of π^+ noticed in the final state corresponding to π^0 in the initial state is

Table 1. Occupancy of primary and final states for one million events simulated using GENIE(v-3.0.6) event generator. The different topological groups shown for primary and final states are made on the basis of number of pions produced event-wise. The default values of axial masses taken are: M_A^{QE} =0.99 GeV/c^2, M_A^{RES} =1.12 GeV/c^2, M_A^{COH} = 1.0 GeV/c^2.

	Primary Hadronic States											
Final states	0π	$1\pi^0$	$1\pi^+$	$1\pi^-$	$2\pi^0$	$2\pi^+$	$2\pi^-$	$\pi^0\pi^+$	$\pi^0\pi^-$	$\pi^+\pi^-$	$\geq 3\pi$	total
0π	203671	21697	66643	280	196	429	0	1357	23	364	326	294986
$1\pi^0$	2333	75872	39372	251	2431	499	0	7470	74	358	1513	130173
$1\pi^+$	3773	6792	212562	245	82	3263	0	7051	05	2300	1588	237662
$1\pi^-$	717	6570	2733	904	97	11	0	390	47	2197	702	14368
$2\pi^0$	19	3029	6565	65	7222	181	0	3628	37	194	2892	23832
$2\pi^+$	18	369	3109	26	13	8947	0	1511	0	127	2408	16528
$2\pi^-$	02	85	23	01	08	01	0	05	12	12	132	281
$\pi^0\pi^+$	118	5586	11313	149	664	1721	0	40002	22	1223	5355	66153
$\pi^0\pi^-$	16	3041	1715	149	688	17	0	489	236	1184	1886	9421
$\pi^+\pi^-$	83	9882	30571	735	317	480	0	3458	32	15319	4806	65683
$\geq 3\pi$	388	5759	8200	1419	2854	3478	0	15451	966	7237	95162	140914
total	211138	138682	382806	4224	14572	19027	0	80812	1454	30515	116770	1000000

Table 2. Occupancy of primary and final state hadronic systems for one million events simulated using NuWro(v-19.2.2) event generator. The different topological groups shown for primary and final states are made on the basis of number of pions produced event-wise. The values of axial masses taken are: M_A^{QE} =0.99 GeV/c^2 and M_A^{RES} =1.12 GeV/c^2.

	Primary Hadronic States											
Final states	0π	$1\pi^0$	$1\pi^+$	$1\pi^-$	$2\pi^0$	$2\pi^+$	$2\pi^-$	$\pi^0\pi^+$	$\pi^0\pi^-$	$\pi^+\pi^-$	$\geq 3\pi$	total
0π	207585	16834	59163	648	117	144	0	1378	10	677	75	286631
$1\pi^0$	2965	83140	16090	136	1626	69	0	9975	124	452	731	115308
$1\pi^+$	4702	3748	217392	20	50	1653	0	9352	4	4841	555	242317
$1\pi^-$	2058	4314	3357	6722	69	25	4	482	93	5104	370	22598
$2\pi^0$	425	1783	968	2	7110	14	0	3188	38	112	2568	16208
$2\pi^+$	61	137	2744	0	06	5856	0	2053	0	320	13331	12508
$2\pi^-$	34	129	105	30	09	01	07	38	41	311	123	828
$\pi^0\pi^+$	271	1961	4680	08	336	491	0	77815	08	1602	4760	91932
$\pi^0\pi^-$	188	1379	790	58	414	08	0	966	1383	1745	2912	9843
$\pi^+\pi^-$	327	1225	5004	63	24	134	0	2929	26	44524	4742	58998
$\geq 3\pi$	186	1574	3063	40	776	526	0	8358	103	4394	123809	142829
total	218802	116224	313356	7727	10537	8921	11	116534	1830	64082	141976	1000000

39372 in GENIE whereas the relative number is 16090 in NuWro, a difference of 59% is there. The reason is that DUNE flux has the peak around 2.5 GeV and for this energy region QE, RES, and DIS processes make significant contribution toward the total cross-section. Whereas to describe these processes individually, the models used are usually common in different generators, even then there are differences in the way in which a particular generator handles the merging of relative contributions from these processes. This in combination with assumed nominal values for some input parameters and nuclear environmental models used by each generator can produce the observed differences. As discussed in Section 2, RES, and DIS processes are expected to produce events with pions in initial and final states while QE processes generally produce events without pions in initial and final states.

From table 1 and table 2, it is observed that both the generators have almost similar 0π

topologies. The total number of events with 0π in the primary state is 211138 and in the final is 294986 for GENIE while the corresponding numbers in NuWro are respectively 218802 and 286631, the difference is less than 4% for each state. As QE events, generally give 0π topologies, it is observed that both the generators give almost similar results for QE events. Also, both the generators have a larger number of events with 0π in the final state than in the primary state, as seen from Figures 2 and 3. This shows that during their propagation in the nuclear environment, the probability of pion absorption is more than probability of pion creation. The first column of each table (tables 1 and 2) is 0π primary state column for each generator. The number of events that have 0π in the primary state and π^0 in the final state is 2333 for GENIE while the relative number is 2965 for NuWro; the number of events that have 0π in the primary state and π^+ in the final state is 3773 for GENIE while the relative number is 4702 for NuWro and so on. Since all these events were with no pions in the initial state, these differences indicate that different hadron transport models have been used by GENIE and NuWro generators.

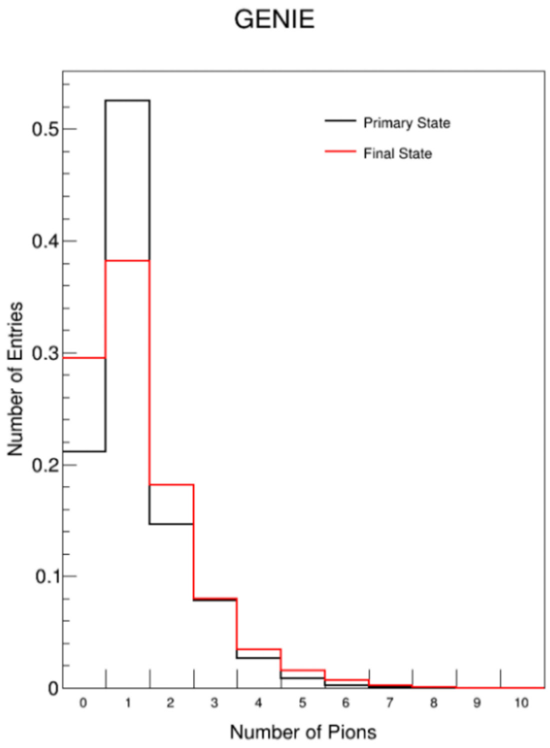

Figure 2. The Fig. shows the number of pions observed on the event by event basis in initial and final states for GENIE simulation tool (red line for final state and black line for initial/primary state).

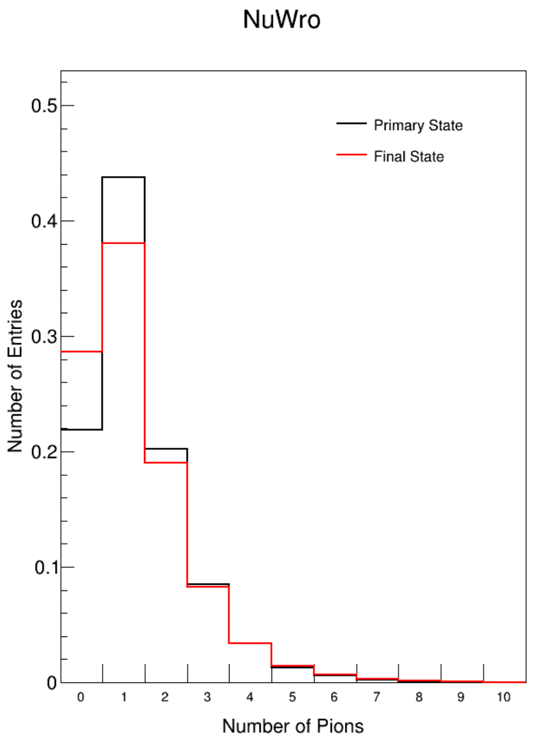

Figure 3. The Fig. shows the number of pions observed on the event by event basis in initial and final states for NuWro simulation tool (red line for final state and black line for initial/primary state).

For comparison and ready-made information, we have compiled table 3. This table contains the percentage of events with 0π, $1\pi^0$, $1\pi^+$, $1\pi^-$, 1π, and $>1\pi$ both for primary and final states and for both GENIE and NuWro. A clear observation is that GENIE supports the single pion production while multiple pion production is favoured in NuWro. Important information about FSI can be extracted from tables 1 and 2 with the help of a summary table (table 4). table 4 shows directly the topology changing effects due to intranuclear transport of pions for both GENIE and NuWro. In this table, we have shown from all the events with an initial

Table 3. Simulated percentage of events with zero pion (0π), exactly one pion (1π) and more than one pion ($>1\pi$) for GENIE and NuWro generators. The results after FSI are shown by the values in the brackets.

Pions	GENIE	NuWro
0π	21.1% (29.5%)	21.9% (28.7%)
$1\pi^0$	13.9% (13%)	11.6% (11.5%)
$1\pi^+$	38.3% (23.8%)	31.3% (24.2%)
$1\pi^-$	0.4% (1.4%)	0.7% (2.3%)
1π	52.6% (38.2%)	43.7% (38%)
$>1\pi$	26.3% (32.3%)	34.4% (33.3%)

Table 4. Simulated percentage of events with single pion or no pion in the final state if there was single pion in the primary state, using GENIE and NuWro event generators.

Process	GENIE	NuWro
$\pi^0 \longrightarrow \pi^0$	55%	72%
$\pi^+ \longrightarrow \pi^+$	56%	69%
$\pi^0 \longrightarrow 0\pi's$	16%	14%
$\pi^+ \longrightarrow 0\pi's$	17%	19%
$\pi^0 \longrightarrow \pi^+$	5%	3%
$\pi^0 \longrightarrow \pi^-$	5%	4%
$\pi^+ \longrightarrow \pi^0$	10%	5%

state topology, the fraction of those which have both initial and final state topologies. In the table, rows one and two give the percentage of events with a single pion in the final state corresponding to a single pion in the initial state. The percentage of events is more than 50 for both the generators which indicate that there are more chances that pions produced at the initial vertex will not undergo re-interaction and appear in the final state as such. Rows 3rd and 4th give the percentage of pions absorbed after being created at the primary vertex. The remaining three rows show the effect produced by charge exchange processes. The table gives transparency (or response) of the nucleus for GENIE and NuWro generators. It is seen that the current version of GENIE has lower transparency (more response) than the current version of NuWro.

Table 5. The ratio $1\pi^+/0\pi$ for GENIE(v-3.0.6) and NuWro(v-19.2.2) using DUNE flux and ^{40}Ar target

Generator	$1\pi^+/0\pi$ (Total of initial state)	$1\pi^+/0\pi$ (Total of final state)	Change observed after FSI
GENIE	1.8	0.81	55%
NuWro	1.4	0.85	39%

Thus, both the generators give almost similar results, considering the complex nature of nuclear effects. Since the single pion production events is the main background channel in oscillation experiments, a study of these modes is important. The ratio of CC$1\pi^+$ to CCQE (0π) cross-sections for both the generators is calculated from corresponding numbers in tables

1 and 2 and is shown in table 5. The ratio can be approximately compared with the results for MiniBooNE data corrected for FSI, the value is (1.318±0.247) for neutrino energy (2.1±0.3)GeV [42].

5. Summary and Conclusions

We have presented an analysis of the effects of FSI on pion production using GENIE and NuWro tools in the DUNE experimental set-up. The beam used is ν_μ and the target is ^{40}Ar. It is clear from tables 1 and 2 that two generators show differences in pion topologies both for initial and final states which may be due to dissimilarities in input parameters and execution of models in two generators. It is also clear that FSI create differences in the number of pions produced in the initial and final states which is to be taken into account as detectors observe only final state particles. The differences shown by two generators can also be noticed in Figures 2 and 3. It is clear from table 3 that both the simulation tools reveal almost identical effects of FSI on pions while their transport through nuclear matter.

Both GENIE and NuWro have more numbers of 0π events in the final state than the initial state as is clear from tables 1 and 2 and also from Figures 2 and 3. This concludes that during their intranuclear transport, it is more likely that a pion may get absorbed than its creation. Also both the generators show almost similar 0π topologies which concludes that QE events have almost the same cross-sections for both GENIE and NuWro. Table 5 shows that NuWro has a lower cross-section for single π^+ production than GENIE. Using the summary table (table 4), it becomes clear that NuWro shows high transparency for pions than shown by GENIE. Taking into consideration the complex nature of nuclear effects and FSI, one can say that both the generators are giving quite a similar results.

The results of this analysis indicate that for experiments like DUNE, we should have authentic accuracy of nuclear models to be used in simulation tools like GENIE and NuWro. This means an apostolic neutrino event generator is required as a simulation tool. A clear understanding of physics beyond neutrino-nucleus interactions is required to understand the nuclear effects. Present analysis was done with 100% detector resolution. In the future, we will apply detector threshold cuts for the DUNE detector and include some more generators in the analysis.

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