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Monte Carlo study of a liquid Ar time projection chamber for long baseline neutrino experiments

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Abstract

This note presents a short description of work done on the Monte Carlo simulation of a multi-kton liquid Ar time projection chamber (LArTPC) for the study of neutrino oscillations with a long-baseline neutrino beam, including new tools for event reconstruction.

1 Introduction

A multi-kton liquid Ar time projection chamber (LArTPC) combines large mass, fine spatial resolution, calorimetry and event imaging capability, and therefore is an excellent candidate as a detector for a long baseline neutrino experiment. In this brief report I present the status of the Monte Carlo simulation, preliminary results for efficiency and background for ν_e appearance, and newly developed tools for automatic event reconstruction.

2 Simulation of neutrino interactions

In this work, following a well-established procedure, the simulation of neutrino interactions in the detector is divided in two separate steps:

1. given a flux of neutrinos, generate neutrino interactions with the proper normalization (Sec. 2.1);
2. propagate final state particles through the detector (Sec. 2.2).

2.1 Cross-sections and rates

This step is done using `NUANCE v3` [1]; the code has been modified to describe neutrino interactions on Ar nuclei, rather than oxygen or carbon. The `NUANCE` code has been coupled to several neutrino fluxes of interest for a long baseline study, giving results consistent with previous independent works [1]. `NUANCE` produces `HBOOK` files which contain, for each event, all the necessary information about the parent neutrino and the final state particles.

2.2 Detector

This step is done using GEANT 3.21. The code [2] has the following salient characteristics:

1. it takes `HBOOK` files from `NUANCE` as input;

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[1] A detailed report in preparation [2]

[2] Thanks to Bill Metcalf of LSU and members of the ICARUS collaboration for providing part of the code used in this work.

2. the geometry of the simulated detector is the one of a 7×10×10 m^3 LAr box (roughly equivalent to 1 kton: 1 kton is a fraction of the full detector, but is more than enough in the present study which deals with local - vertex - information);
3. events are digitized using the standard `GEANT` libraries;
4. this procedure provides a basic event display. Given the imaging capability of a LArTPC, this is - for the time being - an acceptable approximation of a real event display (see fig. 1);
5. MonteCarlo truth information (i.e. momentum and particle ID of the parent neutrino, interaction type, vertex position, momentum and particle ID for final state particles) is recorded event-by-event, together with the "hit level" information;
6. in the specific case of NC π^0 events decaying in two γ's, the first interaction point of each γ from the $\pi^0 \to \gamma\gamma$ decay is recorded.

3 Efficiency and backgrounds

The study of efficiency and background for ν_e appearance is done using MonteCarlo truth information, and is based on two simple requirements for tagging ν_eCC QE interactions:

1. a recoil proton with kinetic energy larger than 50 MeV, to tag a generic neutrino vertex. This lower energy threshold has been experimentally demonstrated [3, 4];
2. an electron coming from the same vertex as the proton.

Here NC π^0 (with $\pi^0 \to \gamma\gamma$) events are the background under study. The neutrino beam used in this specific study is the foreseen wide-band beam from BNL to Henderson / Homestake, with a proton energy of 40 GeV [3]. In `NUANCE`, NC π^0 events are channels 6 ($\nu_\mu \mathrm{p} \to \nu_\mu \mathrm{p}\ \pi^0$) and 8 ($\nu_\mu \mathrm{n} \to \nu_\mu \mathrm{n}\ \pi^0$). The requirement of a proton in the final state by itself reduces the background by about 50% (i.e. gets rid of `NUANCE` channel 8). The efficiency for QE CC events exceeds 90%. In the next step we tag and reject events where at least one of the two γ's from π^0 decay is separated by more than 2 cm from the interaction vertex. This selection is easily justified from experience with actual neutrino data, as in fig. 2, which prove that a 2 cm gap is easily recognized in a LArTPC. Here only 1% of the NC π^0 events has a "gap" of less than 2 cm. This selection does not reduce

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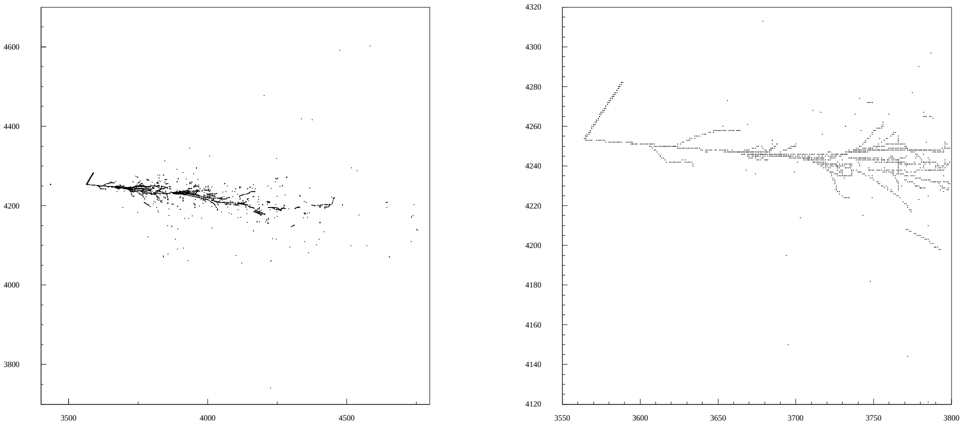
[3] Kindly provided by Milind Diwan and Mary Bishai.



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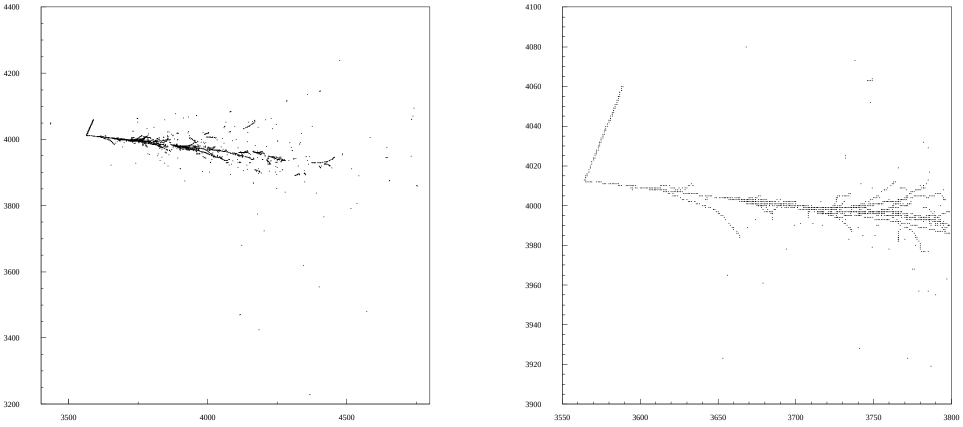

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Figure 1: Images of MonteCarlo generated ν_eCC QE. Left, top: $x - z$ view of the entire event. Left, bottom: $y - z$ view. z is the time coordinate of the TPC. Right: the same, but zoomed on the vertex region. Here the "pixel size" is 2.5 mm.

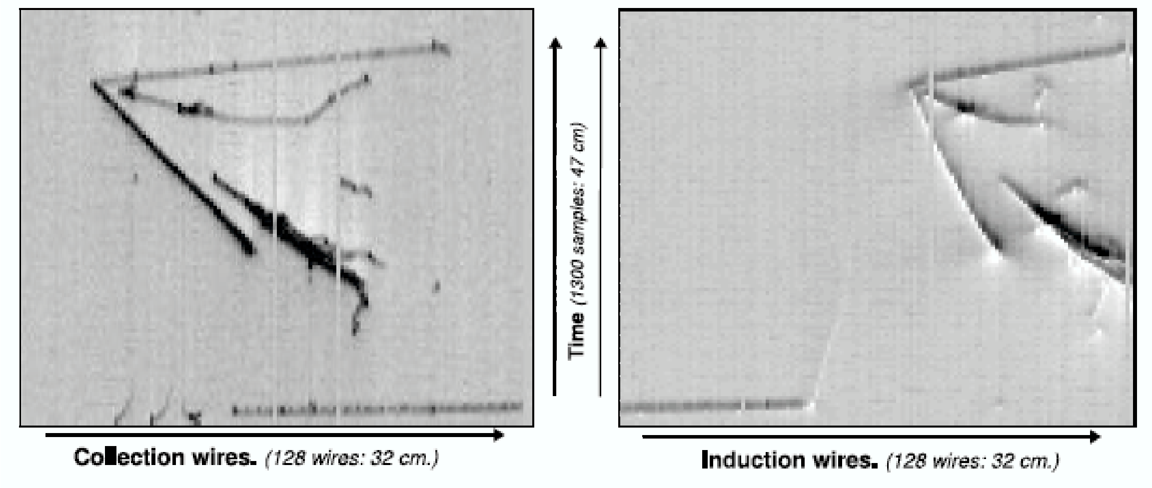

Figure 2: ν_μCC π^0 event recorded in a 50l TPC on the WANF neutrino beam [4].

the efficiency for ν_eCC QE interactions, since the electron leaving from the same vertex as the proton shows no "gap" whatsoever. Therefore the efficiency for ν_eCC QE is 90%.

Two points are worth noting:

1. the separation between the neutrino vertex and the closest γ conversion point is roughly (neutrino)-energy independent, because it depends only on the cross section for gamma-rays which is almost saturated arounf 100 MeV;
2. no attempt has been done to apply kinematics contraints, which on the other hand would be energy dependent.

Combined with the requirement of a proton with at least 50 MeV kinetic energy to tag the vertex, only 0.5% of the NC π^0 (with the π^0 decaying in two γ's) is not rejected. For conventional beams, the background from NC π^0 is therefore easily reduced one order of magnitude below the level of the intrinsic ν_e ($\sim$5%).

Not considered here are different techniques (presented elsewhere [5]), which may further enhance the rejection power. In particular, we are actively working on the implementation of an algorithm to separate single electrons from (overlapping) e^+e^- pairs using the energy deposition in the first few centimeters of the track (dE/dx).
The efficiency for ν_eCC QE interactions is high (here we quote a conservative 90%), due to the very clean topology of the events. A similarly high efficiency is easily obtained using other low multiplicity channels, in particular ν_eCC π^+ interactions, which present little additional complication when compared to ν_eCC QE.

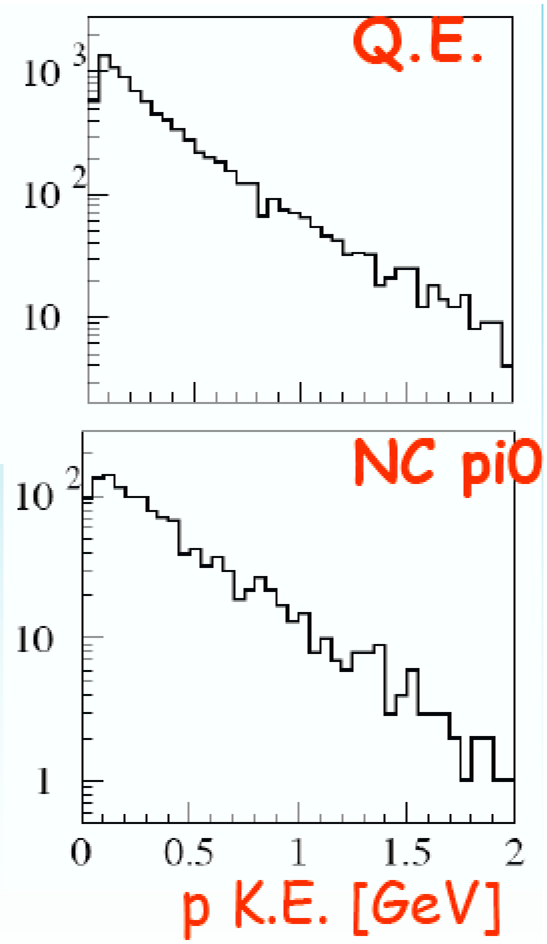

Figure 3: Kinetic energy for the leading proton in CC QE interactions (top) and NC π^0 interactions (bottom).

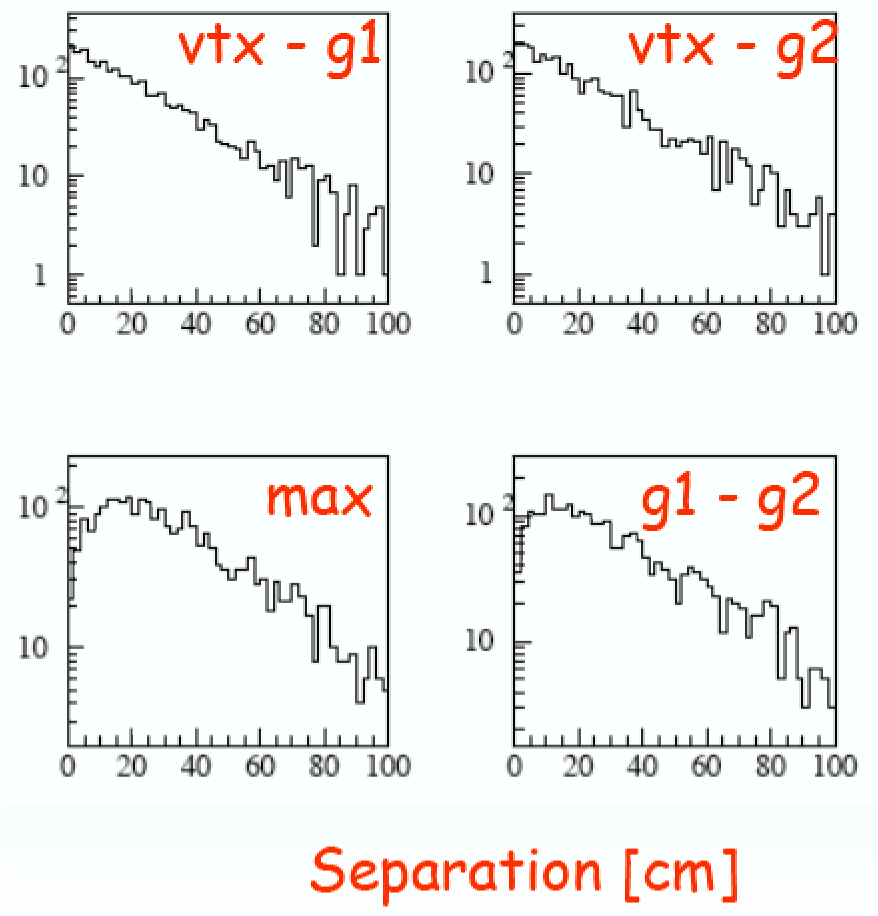

Figure 4: Top, left: separation in cm between the interaction vertex and the first interaction point of the first (arbitrarily defined as such) γ from π^0 decay, π^0 from NC ν_μ interactions. Top, right: separation between the interaction vertex and the first interaction point of the second γ. Bottom, left: maximum between the vertex-to-first-interaction-point separation for the first and second γ. NC π^0 events are rejected if this variable is larger than 2 cm. Bottom, right: separation between the two γ convertion points.

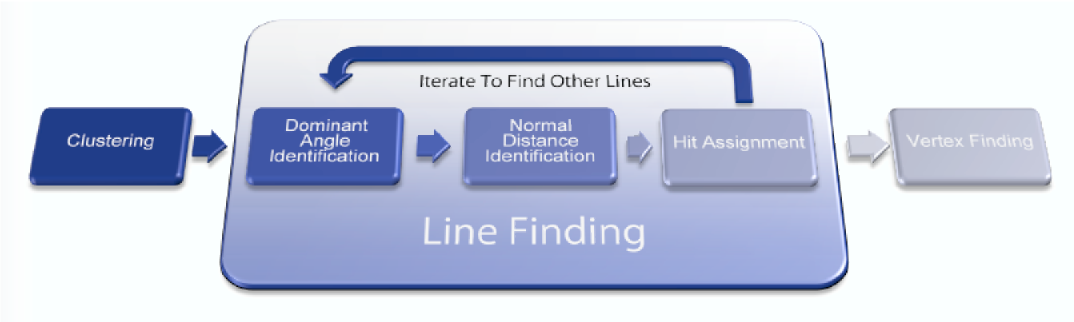

Figure 5: Algorithm skeleton, from [7].

4 Event reconstruction

The work done on event reconstruction will be described thoroughly in [6]; this section is based on the content of [7], which also describes foreseen future developments. The work described here is still an early development, and has been pursued independently of other existing packages with similar capabilities [8]. The final goal of this reconstruction package is to provide automated identification of neutrino interactions, particle identification for the final state particles, and measurement of momentum for the final state particles.

The current software is implemented in C++, within the `ROOT` framework, and is designed to reconstruct linear tracks, through a parameterization by angle. Linear tracks are the ingredients to reconstruct ν_μCC QE, CCπ^+ and - in general - low multiplicity events. The schematic of the procedure is shown in fig. 5, and various results are shown in fig. 6, 7, 8. The algorithm has been applied to MonteCarlo data, described in Sec. 2. It efficiently identifies primary and secondary vertices, and reconstructs the direction of the momentum for “sufficiently long and straight” tracks within 2 degrees (RMS), which is already sufficiently accurate for a first pass filter. It is worth stressing that this is done in a *fully automated way*. Moving away from analyses based on several steps of hand scanning and visual inspection of the recorded events is crucial when considering the huge amount of data that will be produced by a multi-kton LArTPC.

5 Conclusions

Preliminary results from MonteCarlo simulation and reconstruction for a kton-size LAr TPC have been presented. The study of the NC π^0 background for ν_e appearance searches shows that, given the fine spatial resolution of the detector, such background can be reduced below to the level of associated with the intrinsic $\nu_e$component of a conventional

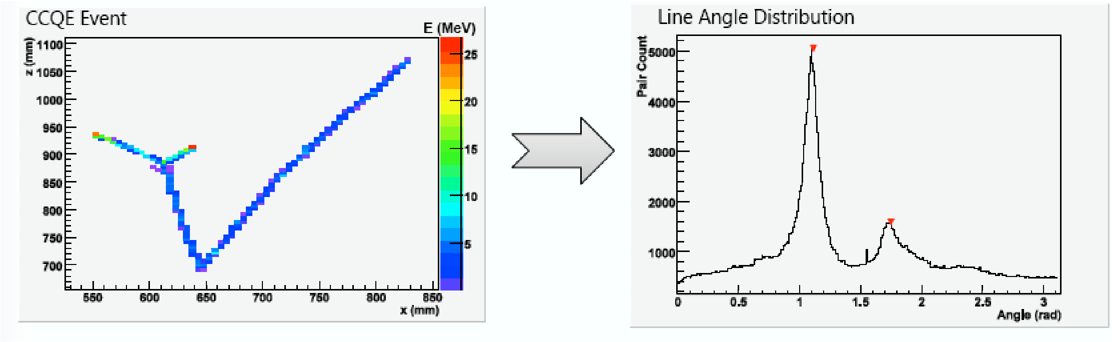

Figure 6: Line angle identification, from [7].

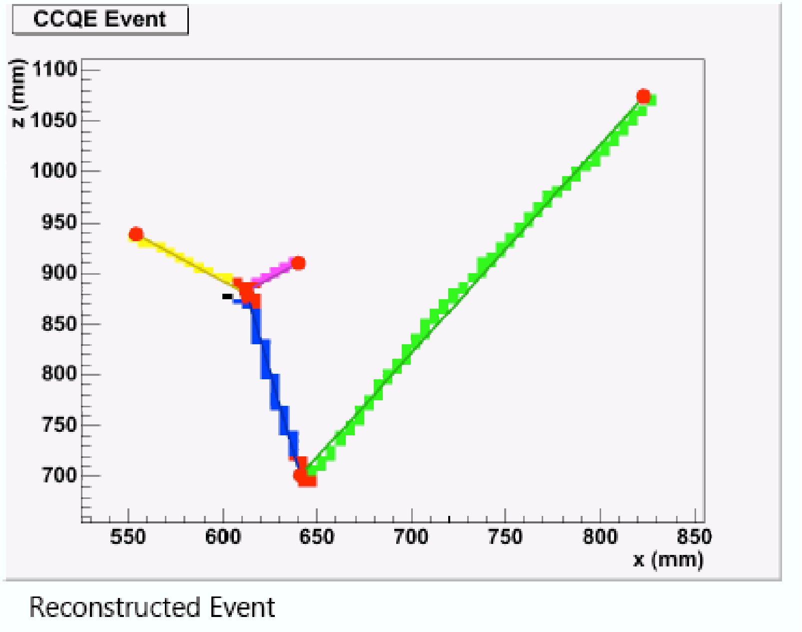

Figure 7: Final event reconstruction for a ν_μCC QE event, with the proton producing a secondary vertex. From [7].

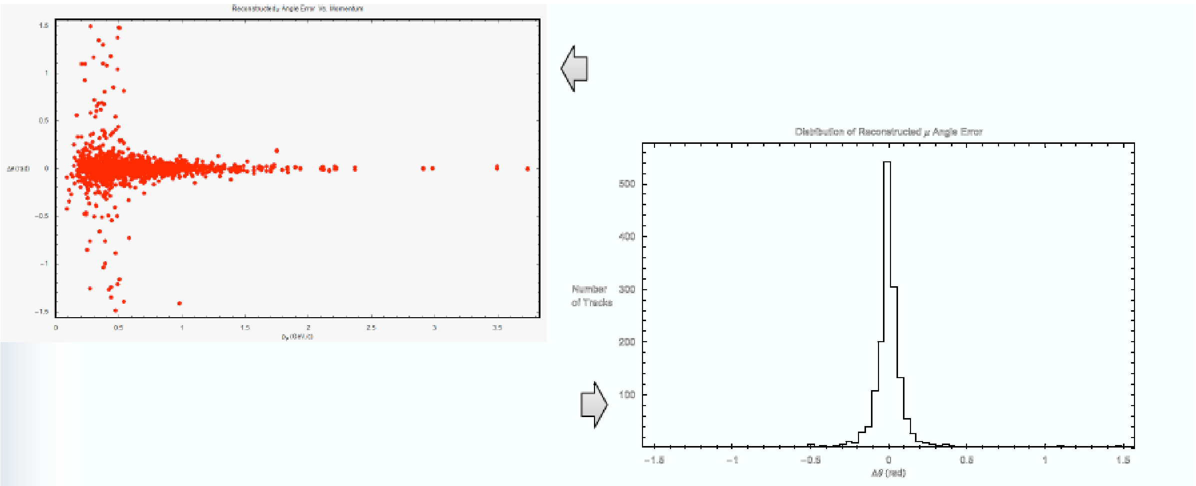

Figure 8: Left: difference between the reconstructed direction and the direction of the momentum of the muon (rad) from ν_μCC QE events, plotted *vs.* the momentum of the muon (GeV/c). Right: histogram of direction differences. From [7].

neutrino (ν_μ) beam. New work on automatic tools for reconstructing events in a LAr TPC has been quickly introduced.

References

[1] D. Casper, hep-ph:/0208030

[2] B. T. Fleming, in preparation

[3] A. Curioni, hep-ex/0603009

[4] ICARUS-Milano Collaboration, submitted

[5] E. Kearns et al., "A proposal for a detector 2 km away from the T2K neutrino source", submitted to the US NUSAG Committee, 20 May 2005

[6] C. Anderson et al., in preparation

[7] C. Anderson, talk given at "Neutrino Physics with LArTPCs Workshop", Yale, July 2006

[8] ICARUS Collaboration, NIM A, 527, 329 (2004)