Journal of Physics: Conference Series

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To cite this article: J S Marshall *et al* 2017 *J. Phys.: Conf. Ser.* **888** 012142

The Pandora multi-algorithm approach to automated pattern recognition in LAr TPC detectors

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Abstract. The development and operation of Liquid Argon Time Projection Chambers (LAr TPCs) for neutrino physics has created a need for new approaches to pattern recognition, in order to fully exploit the superb imaging capabilities offered by this technology. The Pandora Software Development Kit provides functionality to aid the process of designing, implementing and running pattern recognition algorithms. It promotes the use of a multi-algorithm approach to pattern recognition: individual algorithms each address a specific task in a particular topology; a series of many tens of algorithms then carefully builds-up a picture of the event. The input to the Pandora pattern recognition is a list of 2D Hits. The output from the chain of over 70 algorithms is a hierarchy of reconstructed 3D Particles, each with an identified particle type, vertex and direction.

1. Introduction

The Pandora Software Development Kit [1] promotes the idea of a multi-algorithm approach to pattern recognition. In this approach, the input building-blocks (Hits) describing the pattern recognition problem are considered by large numbers of decoupled algorithms. Each algorithm targets a specific event topology and controls operations such as collecting Hits together in Clusters, merging or splitting Clusters, or collecting Clusters in order to build Particles. Each algorithm only performs pattern recognition operations when it is deemed safe, deferring complex or unexpected topologies to later algorithms, designed to target such difficulties. The algorithms gradually build-up a picture of the underlying events and collectively provide a robust reconstruction. An overview of the pattern recognition algorithms can be found in [2].

2. Pattern-Recognition Performance

To assess the pattern recognition performance, a matrix of associations between target MCParticles and reconstructed Particles is constructed, as described in [2]. Events are deemed to have a "completely correct" reconstruction if they match exactly one reconstructed Particle to each target MCParticle. MCParticles with at least one matched reconstructed Particle are deemed to be reconstructed, allowing particle efficiency plots to be constructed.

Performance is examined by looking at specific neutrino interaction types in simulated neutrino data from the Booster Neutrino Beam (BNB). The simulated event samples used have been produced by the MicroBooNE experiment for its summer 2016 results. The data samples are based on LArSoft [3] v05-08-00, which includes v2.10.4 of the GENIE [4] Monte Carlo event generator. The sample comprises approximately 100k events with generated neutrino interaction positions located in a fiducial volume of the detector.

Firstly, a subset of BNB CC ν_μ quasi-elastic interactions is considered: those producing exactly one muon and one proton, each with at least 15 true Hits. Table 1 indicates the performance for this interaction type. It shows that 90.7% of muons and 76.4% of protons yield exactly one reconstructed Particle. 71.1% of the events yield exactly one reconstructed Particle for each target MCParticle and are deemed completely correct. A small fraction of muons are not reconstructed and a significant fraction of protons are found not to be reconstructed. The most common mechanism by which target MCParticles are lost is accidental merging of the muon and proton into a single reconstructed Particle. Figure 1 displays the reconstruction efficiencies for the target muon and protons as a function of their number of true Hits and as a function of the true opening angle between the muon and proton.

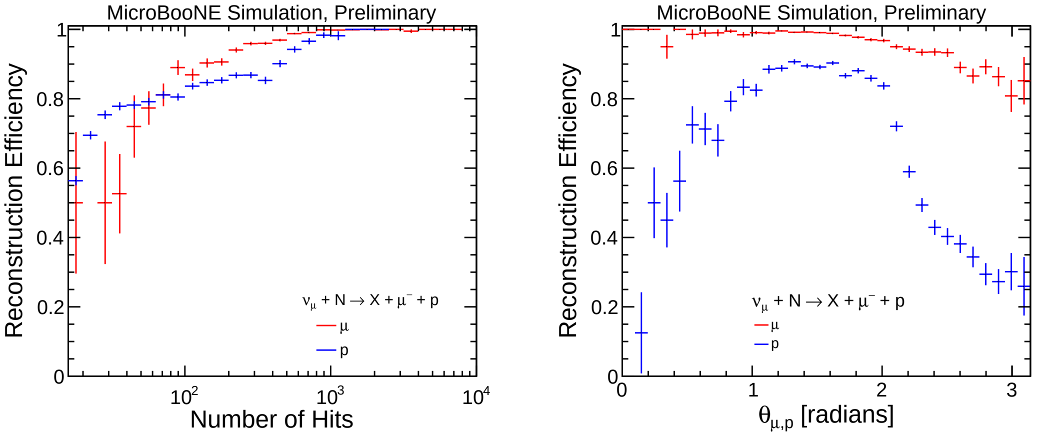

Figure 1: Particle reconstruction efficiencies for CC ν_μ quasi-elastic interactions *(left)* as a function of true Hits and *(right)* as a function of true opening angle between muon and proton.

#Matched Particles	0	1	2	3+
μ	$(2.7 \pm 0.1)\%$	$(90.7 \pm 0.2)\%$	$(6.1 \pm 0.2)\%$	$(0.5 \pm 0.0)\%$
p	$(19.8 \pm 0.3)\%$	$(76.4 \pm 0.3)\%$	$(3.5 \pm 0.1)\%$	$(0.3 \pm 0.0)\%$

Table 1: Performance for CC ν_μ quasi-elastic interactions. The total number of events was 22,102 and 15,718 (71.1%) of these were deemed to be completely correct.

Next, BNB CC ν_μ interactions with associated charged pion production are considered. Table 2 indicates the performance for this interaction type. The performance for muons and protons is similar to that observed in quasi-elastic events. A loss of efficiency in these events does not tend to mean that a true particle has been missed entirely, but rather that its Hits have been accidentally clustered together with those from a different true particle. The pions typically have a complicated series of true daughter particles and it is a challenge to provide individual reconstructed Particles for each of these and to ensure that the true particle hierarchy is reconstructed perfectly. Figure 2 displays the reconstruction efficiencies for the target muon, proton and pion as a function of their number of true Hits and the distribution of reconstructed vertex positions, relative to the generated neutrino interaction position.

Finally, BNB CC ν_μ interactions with associated neutral pion production are considered, producing exactly one muon, one proton and two photons, from pi-zero decay. Table 3 indicates

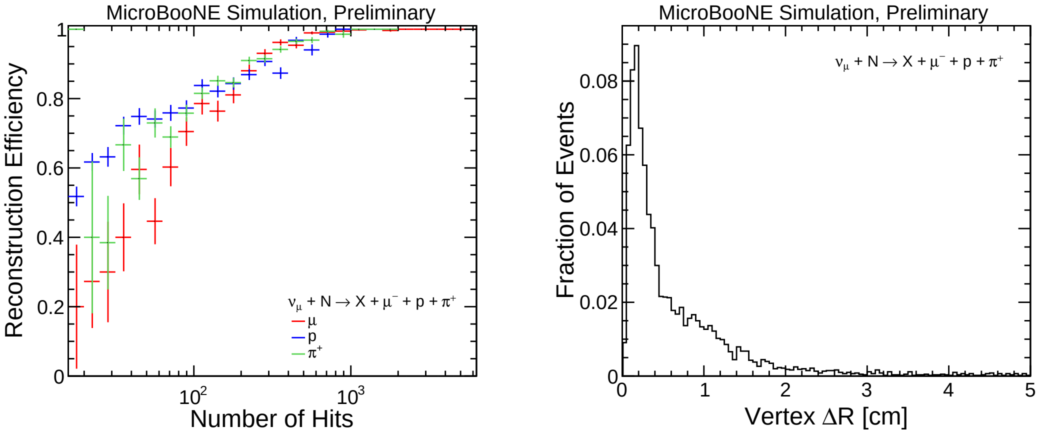

Figure 2: *(left)* Particle reconstruction efficiencies for CC ν_μ interactions with charged pion production as a function of true Hits. *(right)* Vertex resolution for these interactions.

#Matched Particles	0	1	2	3+
μ	$(6.8 \pm 0.3)\%$	$(87.7 \pm 0.4)\%$	$(5.1 \pm 0.3)\%$	$(0.4 \pm 0.1)\%$
p	$(20.5 \pm 0.5)\%$	$(75.0 \pm 0.6)\%$	$(4.0 \pm 0.3)\%$	$(0.5 \pm 0.1)\%$
π^+	$(11.6 \pm 0.4)\%$	$(71.3 \pm 0.6)\%$	$(13.0 \pm 0.4)\%$	$(4.1 \pm 0.3)\%$

Table 2: Performance for CC ν_μ interactions with associated charged pion production. The total number of events was 6,070 and 3,084 (50.8%) were deemed to be completely correct.

the performance for this interaction type. The reconstruction performance for muons and protons remains similar to that seen previously. The slightly larger fraction of lost muons is associated with a new failure mechanism, whereby muons can be merged into showers if the topology is complicated and the vertex reconstruction is poor. As anticipated, the diverse and complex shower topologies lead to both incorrect merging and splitting of Particles. In the Table, γ_1 is defined to be the target shower with the largest number of true Hits and it is matched to exactly one reconstructed Particle in 60.0% of events. In 10.8% of events, no Particle is matched to the largest shower and this failure mechanism is typically associated with small showers being accidentally merged with one of the track Particles. Sparse shower topologies can often mean that the largest shower is reconstructed as multiple, distinct shower Particles.

#Matched Particles	0	1	2	3+
μ	$(7.9 \pm 0.6)\%$	$(87.4 \pm 0.8)\%$	$(4.4 \pm 0.5)\%$	$(0.3 \pm 0.1)\%$
p	$(19.8 \pm 0.9)\%$	$(74.0 \pm 1.0)\%$	$(5.5 \pm 0.5)\%$	$(0.7 \pm 0.2)\%$
γ_1	$(10.8 \pm 0.7)\%$	$(60.0 \pm 1.1)\%$	$(18.2 \pm 0.9)\%$	$(11.0 \pm 0.7)\%$
γ_2	$(35.9 \pm 1.1)\%$	$(51.0 \pm 1.2)\%$	$(10.1 \pm 0.7)\%$	$(3.0 \pm 0.4)\%$

Table 3: Performance for CC ν_μ interactions with associated neutral pion production. The total number of events was 1,874 and 417 (22.3%) of these were deemed to be completely correct.

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