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Electromagnetic shower reconstruction with emulsion films in the OPERA experiment

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Abstract. OPERA is a neutrino oscillation experiment designed to perform a ν_τ appearance search in the CNGS beam from CERN to Gran Sasso underground laboratory, 730 km from CERN. The identification of the τ lepton produced by a ν_τCC interaction is based on the use the Emulsion Cloud Chamber (ECC) which consists of a modular structure made of a sandwich of passive material plates interleaved with emulsion films. In addition of its very good tracking information capability, used to the detection of short-lived particles, the ECC can be used as a fine sampling electromagnetic calorimeter allowing the study of the $\tau \to e$ decay and the $\nu_\mu \to \nu_e$ oscillation channel. We will report the method developped to reconstruct the electromagnetic showers with ECC and the energy measurement in the 1-10 GeV range.

1. Introduction

OPERA [1] is a long-baseline neutrino oscillation appearance experiment designed to obtain an unambiguous signature of $\nu_\mu \to \nu_\tau$ oscillations in the parameter region indicated by atmospheric neutrino experiments [2, 3, 4]. The detector, located in the underground Gran Sasso Laboratories, plans to detect ν_τ's in the CERN to Gran Sasso (CNGS) ν_μ beam, which is optimised for ν_τ appearance [5]. It may also explore the $\nu_\mu \to \nu_e$ oscillation channel [6], improving the current $\sin^2 2\theta_{13}$ limit [7].

OPERA is an hybrid experiment with electronic detectors, iron magnets (Fig. 1) and Emulsion Cloud Chambers (ECC) (Fig. 2). The ECC combines in one cell the high tracking precision of nuclear emulsions ($\sim$ 1 μm) and the large target mass of the lead plates. The basic element, the "brick", has dimensions of $12.7\times10.2\times7.5$ cm^3; it is a sequence of 56 lead (1 mm thick) and emulsion plates. Each emulsion layer is composed of a pair of 44 μm thick emulsion films on either side of a 205 μm plastic base [8]. The bricks are arranged in "walls" separated by electronic detectors. The lead target has a total weight of $\sim$1.35 ton. Electronic detectors are used to identify the brick where the neutrino interaction occured and to track mainly muons escaping the brick.

Charged particles give a track segment in each emulsion film (*base-track*). The $\sim$1 μm granularity of the emulsions [9] ensures redundancy in the measurement of particle trajectories. If a τ is produced, its decay is detected by measuring the angle (kink) between the τ direction and the charged decay daughter. Furthermore, given its high granularity the OPERA ECC is well adapt for the identification of electromagnetic shower.

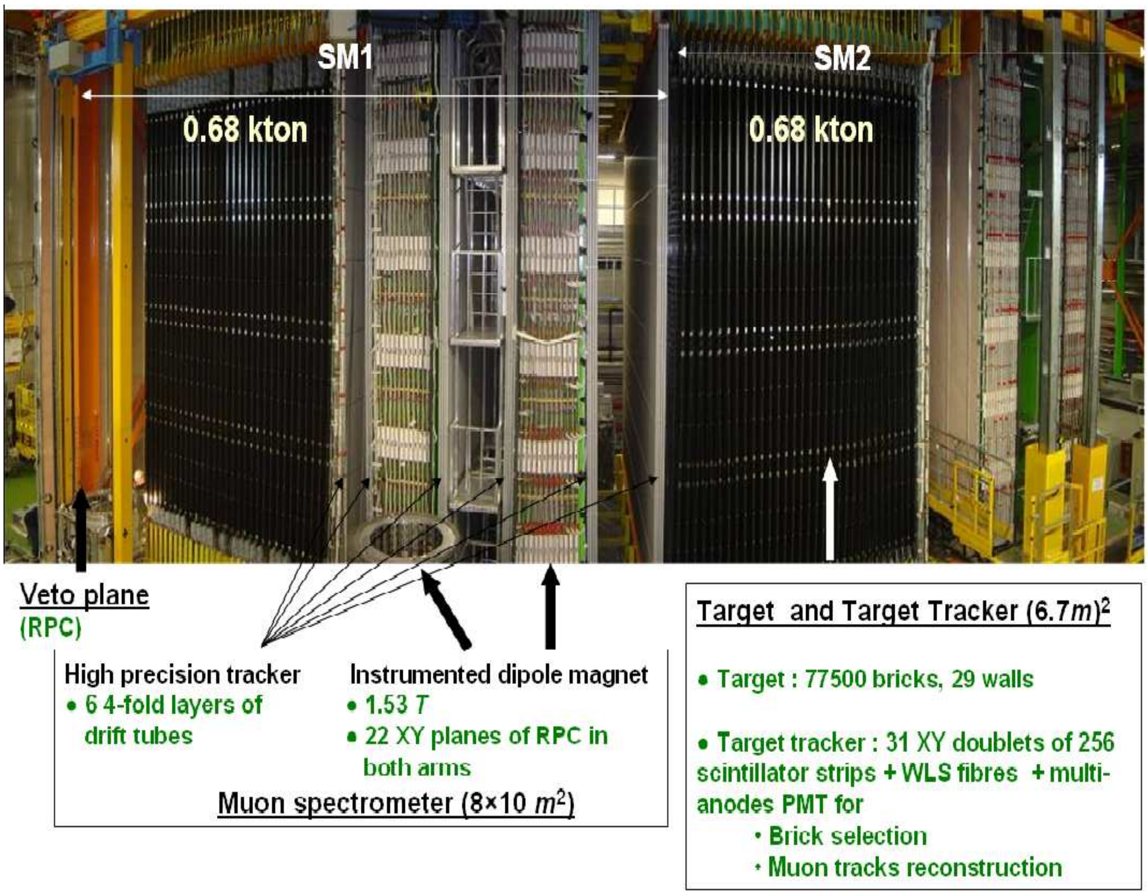

Figure 1. The OPERA detector.

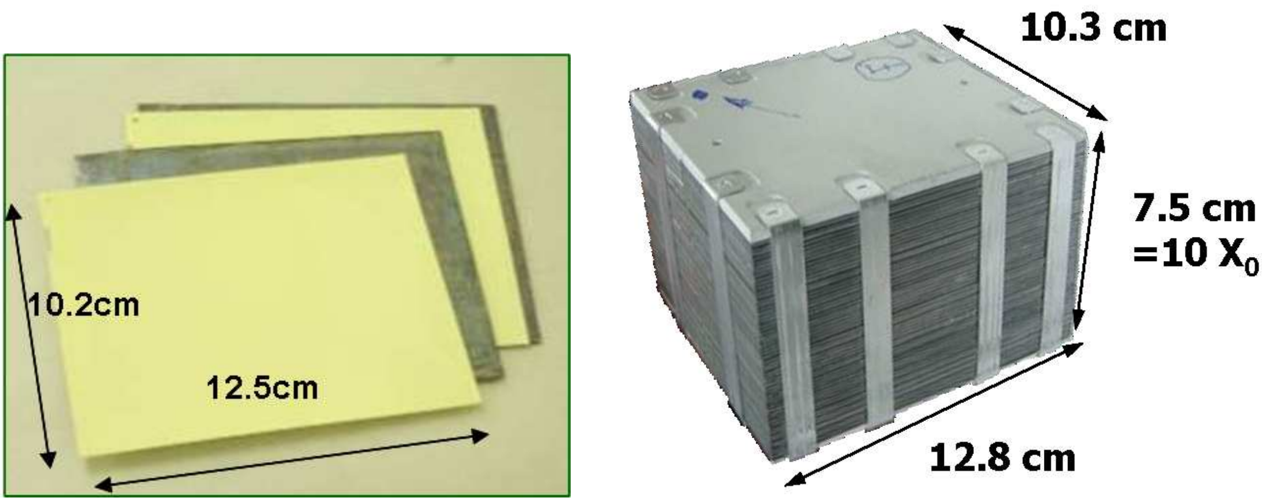

Figure 2. The OPERA Emulsion Cloud Chamber.

Here we will focus on the electromagnetic shower reconstruction, the electron/pion separation and the shower energy estimation achievable in an OPERA ECC. Several algorithms have been developed in order to fullfill the requirements of the OPERA analysis; minimize the misidentification of pion to electron and maximize the electron efficiency for an energy greater than 1 GeV.

2. The shower reconstruction

A good electron-pion separation may be obtained by studying the different behavior of these particles in passing through an OPERA brick. At the energies of interest (1 - 10 GeV) an electron loses energy essentially through bremsstrahlung processes while charged pions lose energy mainly via ionization. An electron quickly develops an electromagnetic shower in 10 X_0 of an ECC brick. The total number of base-tracks and the longitudinal and transverse profiles of the showers can be used for particle identification.

The algorithm for the shower reconstruction has already been described in [10]. Here we will briefly report the reconstruction method and give the new results obtained using of a most realistic background.

The principle of the reconstruction algorithm is to collect base-tracks inside a given cone using connection criteria on the position and the slope. The angular displacement $\delta\theta$ and the position displacement δr are optimize in order to keep background at around 5% of the total number of the collected base-tracks. In the present study we used as background scanned data, extracted from a brick placed inside the OPERA detector during the october 2007 run and exposed to cosmic rays for alignement. This kind of background is the one we will have in the OPERA experiment and is then more realistic than the previous one we used which was extracted from a brick exposed to test beam. As this new background was found to be lower, we were able to open up the connection criteria in the shower reconstruction algorithm. An adequate background rejection is achieved with $\delta\theta < 150\ mrad$ and $\delta r < 150\ \mu m$. In addition the maximum radius allowed for the cone is set to 800 μm.

A reconstructed showers electron at 6 GeV are shown in Fig. 3. It is worth to note that a not-showering event (as a passing-through pion) would be reconstructed by this algorithm, even if not accompanied by any shower.

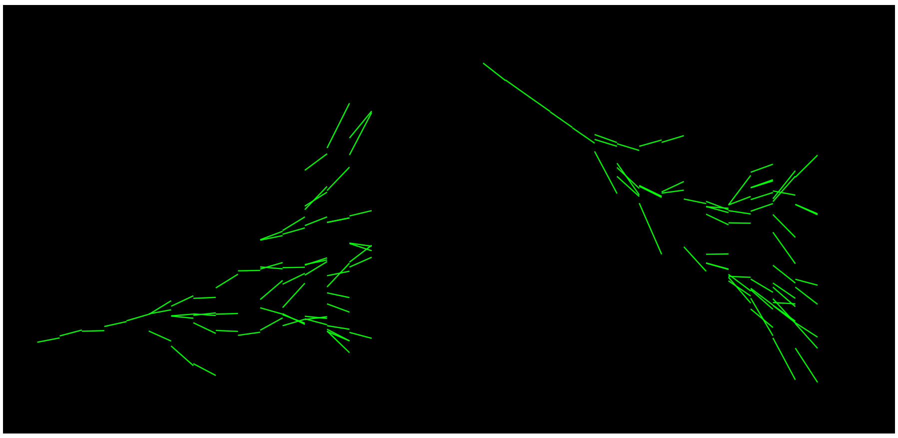

Figure 3. xz projection (left) and yz projection (right) of a reconstructed shower generated by a 6 GeV electron extracted from the brick exposed to an electron beam at DESY. 20 emulsions are used which corresponds to 19 lead layers (∼3.3 X_0). Each green dash corresponds to a base-track attached to the reconstructed shower.

2.1. Neural network analysis

The classification in terms of particle identities is demanded to a Neural Network (NN) [11]. Then, each event which has been reconstructed by the shower algorithm will be used to feed a NN. As it is shown in Fig. 4, the longitudinale profile of electrons and pions is very different as well as the number of base-tracks in the reconstructed shower. These informations are used as input values to feed the NN. More details of the NN method can be found in [10].

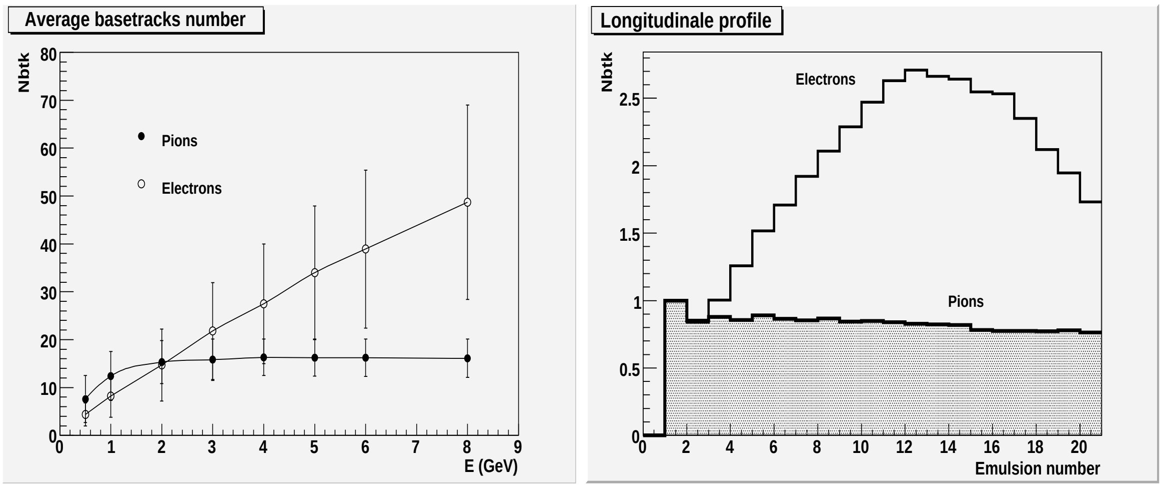

Figure 4. Left: Average number of base-tracks in reconstructed showers versus the energy for simulated pions and electrons. Right: Mean longitudinale profile for simulated electrons and pions at 4 GeV.

2.2. Results of the electron/pion separation

A good method for e/π separation should provide a high probability to correctly identify one type of particle and a small probability to misidentify the other type. To do that, we apply a threshold on the output neuron value in order to separate both particle type (see Fig. 5).
The electron efficiency, $\epsilon_{e\to e}$, and the pion contamination, $\eta_{\pi\to e}$, are defined as follow:

$$\epsilon_{e\to e} \equiv \frac{n_{e\to e}}{N_e} \; \eta_{\pi\to e} \equiv \frac{n_{\pi\to e}}{N_\pi}$$

Where $n_{e\to e}$ and $n_{\pi\to e}$ correspond to the number of electrons, respectively pions, having an output value above the threshold. N_e and N_π are defined as: $N_e \equiv n_{e\to e} + n_{e\to\pi}$ and $N_\pi \equiv n_{\pi\to\pi} + n_{\pi\to e}$, they correspond to the total number of electrons respectively pions seen by the neural network. Using an equivalent definition we can also compute $\epsilon_{\pi\to\pi}$ and $\eta_{e\to\pi}$.
The threshold value will be chosen in order to have $\eta_{\pi\to e}$ as low as possible (< 1-2%) keeping $\epsilon_{e\to e}$ maximal (> 80-90%).

To train the NN, we used 18108 pions and 17988 electrons at randomized energy spectrum from 0.5 to 6 GeV. The validation sample, with different events from training sample, contains 1000 pions and 1000 electrons at each following energy 0.5, 1, 2, 3, 4, 5, 6, 8 GeV.
The results show a good discrimination for energy ≥ 1 GeV, indeed the pion contamination $\eta_{\pi\to e}$ is 1.0% at 1 GeV with an electron efficiency $\epsilon_{e\to e}$ around 80%. At higher energies, $\eta_{\pi\to e}$ diminishes below 1% and $\epsilon_{e\to e}$ is above 90%. For the lower energy, 0.5 GeV, the contamination remains high, 7-10%, with an efficiency around 65%. All the results are summarized in table 1.

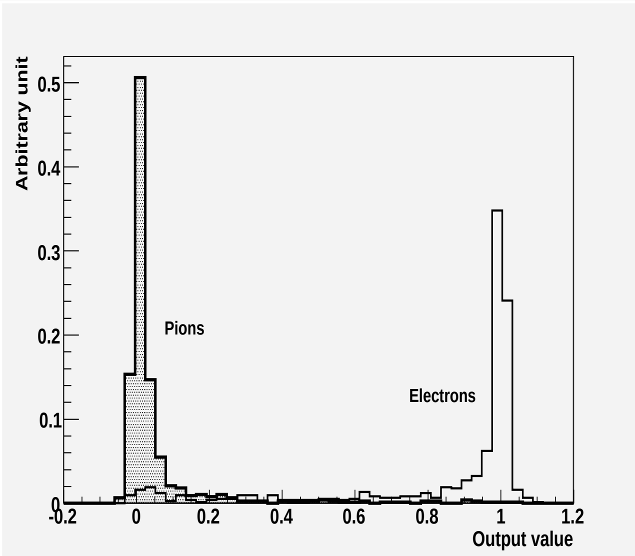

Figure 5. Output value given by the neural network for simulated pions and electrons at 2 GeV. Choosing an output value of 0.6, for instance, allows to well separate both particles. The small pion part above 0.6 will give the pion contamination.

E (GeV)	$\epsilon_{e\to e}$ %	$\eta_{\pi\to e}$ %	$n_{e\to e}/N_e$ %	$n_{\pi\to e}/N_\pi$ %	$\epsilon_{e\to e}$ %	$\eta_{\pi\to e}$ %
	20 sheets		30 sheets		50 sheets	
0.5	62.2 ±2.0	7.4±1.0	66.2±2.0	9.0±1.1	66.4±1.9	9.9±1.2
1	77.4± 1.4	1.0 ±0.3	79.9±1.4	1.0±0.3	79.8±1.4	1.0±0.3
2	91.3±0.9	0.2± 0.2	92.2±0.9	0.2±0.2	92.7±0.9	0.2±0.2
3	95.5±0.7	<0.3	96.6±0.6	<0.3	96.5±0.6	<0.3
4	96.2± 0.6	0.2 ±0.2	97.0±0.6	0.1±0.1	97.0±0.6	0.3±0.1
5	98.8 ±0.4	0.3±0.2	98.9±0.3	0.5±0.2	98.9±0.3	0.5±0.2
6	98.2± 0.4	0.2±0.2	98.2±0.4	0.4±0.2	98.0±0.5	0.4±0.2
8	98.8 ±0.4	0.4 ± 0.2	99.2±0.3	0.6±0.3	98.8±0.4	0.6±0.3

Table 1. Electron efficiency and pion contamination for the simulated data with added background extracted from real data using 20, 30, 50 sheets. The output NN value is fixed at 0.73, 0.7, 0.73 respectively. The upper limits (95% C.L.) for the 3 GeV case have been computed assuming a binomial distribution [12]. We computed an upper limits since none of the pion has been misidentified as an electron.

3. Electromagnetic shower energy estimation

An algorithm for the shower energy measurement has been developped and is currently under optimisation. Here we briefly present some preliminary results.

The algorithm is based on exactly the same NN structure as the one used for the e/π separation (section 2.2) except that as ouput we demand the NN to calculate the energy value (known from simulation during the training phase of the NN). As preliminary results we give the obtained resolution for simulated electrons reconstructed in 41 emulsions plates (Fig. 6):

$$(\frac{\sigma_E}{E})^2 = (\frac{49\%}{\sqrt{E}})^2 + (\frac{24\%}{\sqrt{E}})^2$$

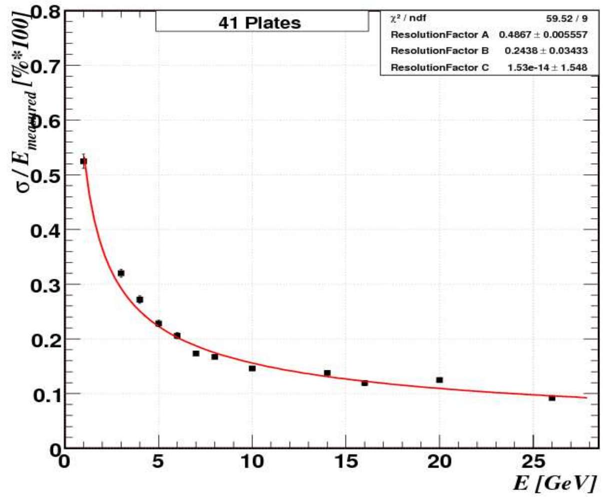

Figure 6. Energy resolution versus the energy for simulated data with background addition reconstructed in 41 emulsion plates.

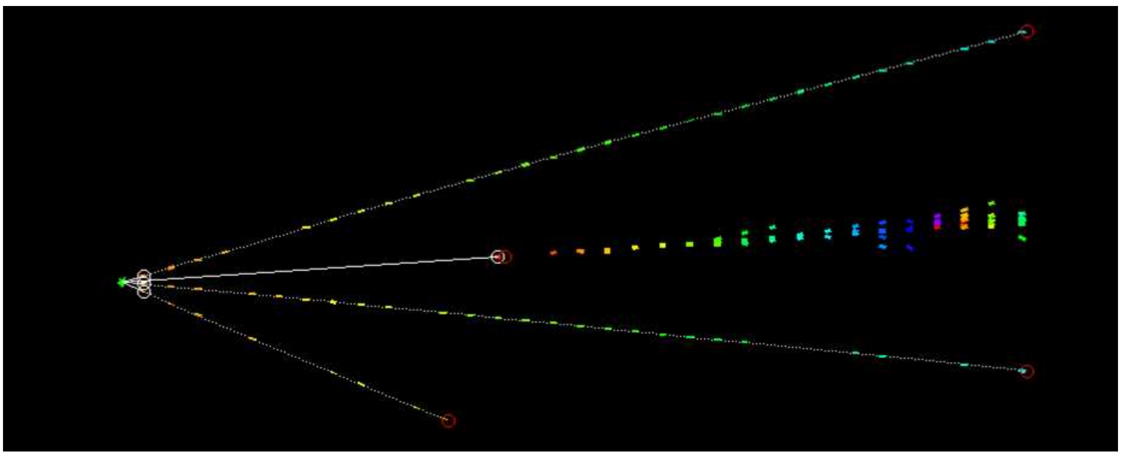

Figure 7. A first reconstructed $\nu_\mu CC$ event recorded during the october 2007 run in the OPERA detector. The 3 long straight tracks are direcltly attached to the primary vertex (the upper one is the μ). The colored shower in the middle is a gamma conversion coming from a π^0 decay and is also well attched to the primary vertex.

4. Conclusion

An algorithm for electron shower reconstruction have been developed and was used to study the e/π separation and the shower energy measurement in the OPERA brick. A method based on a Neural Network, using the electromagnetic shower properties was tested on simulated data with realistic background addition showing that in the OPERA case background, the pion contamination is below 1% for energies ≥ 2 GeV with an electron efficiency greater than 90%. At lower energy, around 1 GeV the pion contamination is ~ 1 % for an efficiency close to 80%. Some preliminary results on the energy resolution gives $\frac{\sigma_E}{E} \sim \frac{50\%}{\sqrt{E}}$.

Although the presented results here are within the requirements for the OPERA kinematical analysis, it would be interesting to increase the efficiency and the energy resolution at low energy. Some improvement are still under investigation to improve the reconstruction at low energy (<1 GeV). This will allow for instance to diminish the background for both $\tau \to e$ and $\nu_\mu \to \nu_e$ analysis coming from π^0 decay in the hadronic shower.

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