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Results from the ICARUS T600 module

A measurement of the μ decay spectrum

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Abstract. We have studied the μ decay energy spectrum from a sample of stopping μ events acquired during the test run of the ICARUS T600 prototype. This detector allows the spatial reconstruction of the events with fine granularity, hence the precise measurement of the μ range and dE/dx with high sampling rate. This information is used to compute the correction factors needed for the calorimetric reconstruction. The Michel ρ parameter is then measured by comparison of the experimental and Monte Carlo simulated μ decay spectra, obtaining $\rho = 0.72 \pm 0.06$ (stat.) ± 0.08 (syst.).

PACS. 13.15.+g Neutrino interactions – 13.35.Bv Decays of muons

1 Introduction

The sample of events in which a muon enters the detector, stops and eventually decays in the detector's sensitive volume –hereafter called *stopping muon* sample– constitutes an important benchmark to evaluate the physics performance of the ICARUS detector. Because of their simple geometry, stopping muon events are relatively easy to reconstruct in space, which allows the computation of the different correction factors needed for the calorimetric reconstruction. Thus, we can study the muon decay spectrum and measure the Michel ρ parameter, which constitutes the first physics measurement performed with the ICARUS novel detection technology, and proves that the technique is mature enough to produce competitive physics results.

Muon decay was first described in a model-independent way by Michel [1], using the most general local, derivative-free, lepton-number conserving, four fermion interaction. For unpolarized muons, the decay probability is given by:

$$\frac{dP}{dx}(x;\rho,\eta) = \frac{1}{N}x^2\left(3(1-x)+\frac{2}{3}\rho(4x-3)+ 3\eta\frac{m_e}{E_{max}}\frac{1-x}{x}+\frac{1}{2}f(x)+\mathcal{O}(\frac{m_e^2}{E_{max}^2})\right) \quad (1)$$

$x = \frac{E_e}{E_{max}}$ is the *reduced* energy (ranging from m_e/E_{max} to 1); E_e and m_e are respectively the total energy and mass of the electron produced in the decay; $E_{max} = 52.8$ MeV is the end-point of the spectrum; $f(x)$ is the term accounting for the first order radiative corrections assuming a local V-A interaction [2]; finally, ρ and η are the so-called Michel parameters, defined in terms of bilinear combinations of the coupling constants of the general four fermion interaction, and hence depending on the type of interaction governing the decay process. For the Standard Model (SM) V-A interaction, the parameters take the values $\rho_{\mathrm{SM}} = 0.75$ and $\eta_{\mathrm{SM}} = 0$.

2 The ICARUS T600 detector

ICARUS T600 [3] is a large cryostat divided in two identical, adjacent half-modules of internal dimensions $3.6 \times 3.9 \times 19.9$ m^3, each containing more than 300 t of liquid argon (LAr). Each half-module houses an internal detector composed by two Time Projection Chambers (TPC), the field shaping system, monitors, probes, PMT's, and is externally surrounded by a set of thermal insulations layers. Each TPC is formed by three parallel planes of wires, 3 mm apart, oriented at $0, \pm 60^\circ$ angles, of 3 mm pitch parallel wires, positioned onto the longest walls of the half-module. The cathode plane is parallel and equidistant to the wire planes at each TPC. A high voltage system produces a uniform electric field, perpendicular to the wire planes, forcing the drift of the ionization electrons (the maximum drift path is 1.5 m).

The ionization electrons produced in the LAr active volume drift perpendicularly to the wire planes due to the applied electric field, inducing a signal (*hit*) on the wires

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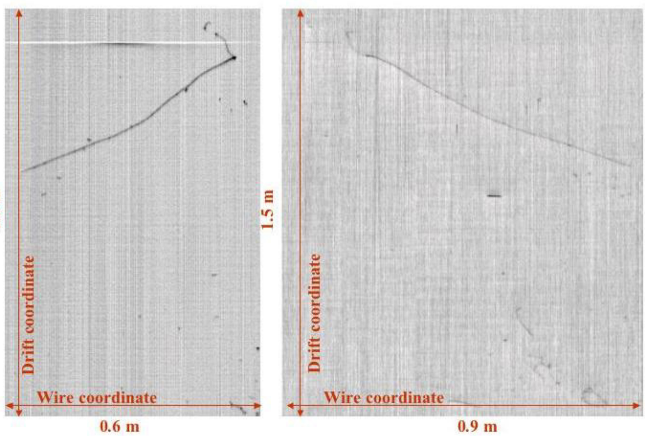

Fig. 1. Run 966 Event 8 Right chamber: muon decay event views corresponding to the Collection (left) and second Induction (right) wire planes.

near which they are drifting while approaching the different wire planes. By appropriate biasing, the first set of planes can be made non-destructive (*Induction* planes), so that the charge is finally collected in the last plane (*Collection* plane). Each wire plane provides a two-dimensional projection (*view*) of the event, where the position in one coordinate is constrained by the hit wire, while the signal timing with respect to the trigger gives the position along the drift direction.

3 Data selection and reconstruction

Data were acquired during the T600 technical run [3]. The off-line data selection was carried out by visual scanning using topological criteria. A total of 5830 triggers were scanned, containing 4548 stopping muon events, out of which 3370 were further selected by the preliminary quality cuts.

The spatial reconstruction of the muon tracks is needed in order to compute the corrections entering the calorimetric reconstruction of the events. A detailed description of the spatial reconstruction tools has been reported elsewhere [3,4].

The ionization charge is precisely measured in the Collection wire plane. The energy associated to a given hit is related to the collected charge by means of

$$E = \frac{CW}{R}\, e^{(t-t_0)/\tau_e}\, Q \qquad (2)$$

where C is the calibration factor [5]; $W = 23.6^{+0.5}_{-0.3}$ eV is the average energy needed for the creation of an electron-ion pair [6]; R the electron-ion recombination factor; $(t-t_0)$ the time of drift of the electrons; τ_e the drift electron lifetime, which parametrizes the attachment of drift electrons to impurities in LAr; and Q the measured charge. R, t_0 and τ_e are extracted from the reconstructed muon tracks [4,7], essentially by tuning them so that the measured energy corresponds to the theoretical expectation

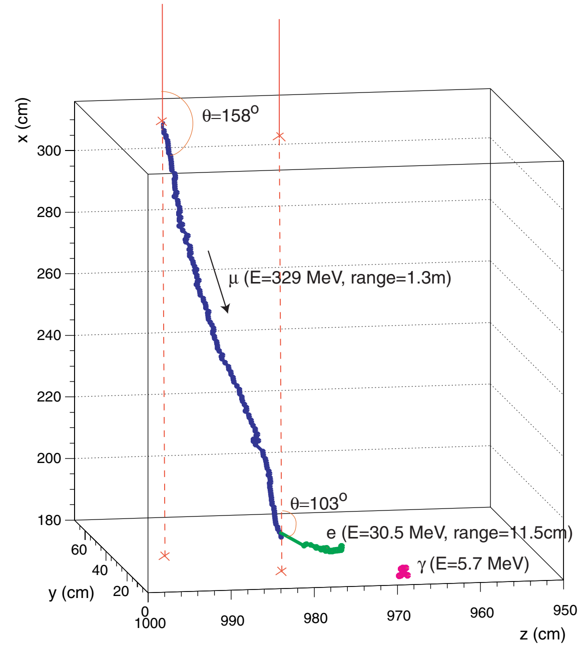

Fig. 2. Run 966 Event 8 Right chamber: fully reconstructed muon decay event.

for stopping muons. This method determines the electron energy in a bias-free way, since all the correction parameters are tuned using exclusively muon tracks. For τ_e we have obtained values ranging from 1.2 to 1.7 ms (depending on the data taking period), meaning free paths for drift electrons between 1.9 and 2.6 m, to be compared with the maximal drift distance 1.5 m. The measured recombination factor is $R_{\rm mip} = 0.640 \pm 0.013$ for minimum ionizing particles and R^{-1} linearly increasing with slope 0.11 ± 0.01 cm/MeV.

Figure 1 shows the initial two-dimensional projections of a typical stopping muon event, produced by the Collection and the second Induction planes, respectively. On Figure 2, the fully reconstructed event is shown.

4 Results

A total of 1858 electrons are available for the determination of the Michel ρ parameter. The measured spectrum corresponds to the fraction of the electron energy lost by ionization in LAr since no attempt to recover the energy loss by bremsstrahlung radiation has been carried out. We compare the spectrum with the one obtained for a Monte Carlo (MC) simulated event sample, containing 10000 electron events from muon decays, generated using FLUKA [8]. The simulation includes all detector effects except for the presence of impurities, whose effects are evaluated from data and included in average in the final MC distribution [7]. The measured and simulated energy spectra are compared in Figure 3. They are found to be in good agreement ($\chi^2/ndf = 14.0/20$).

We measure ρ while constraining η within its experimentally allowed interval ($-0.020 < \eta < 0.006$) [9]. The

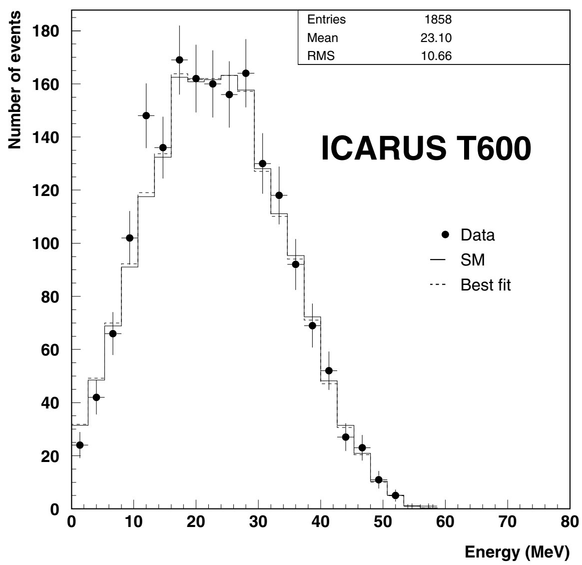

Fig. 3. Muon decay spectra in the ICARUS T600 detector. The plot shows the measured distribution (dots) compared both to the SM expectation (solid line) and the best fit with ρ and η as free parameters (dashed line).

spectrum for an arbitrary pair of values, ρ and η, is built by weighting the MC events with a factor $\frac{\frac{dP}{dx}(x_{\mathrm{MC}};\rho,\eta)}{\frac{dP}{dx}(x_{\mathrm{MC}};\rho_{\mathrm{SM}},\eta_{\mathrm{SM}})}$, where $x_{\mathrm{MC}} = E_{\mathrm{MC}}/E_{max}$, and E_{MC} is the generated energy. We extract the value of ρ as that for which the best fit between the simulated and measured energy spectra is obtained, which yields $\rho = 0.72 \pm 0.06$, where the error is of statistical origin and includes the correlation with η. Figure 3 shows the spectrum for the best fit of ρ.

There are two types of source of systematic uncertainties that can affect this measurement, namely: an underestimation of the energy resolution and a systematic shift in the global energy scale. With the help of the MC sample, the contributions to the total systematic error are estimated in ± 0.01 and ± 0.08, respectively. Therefore, the total error is dominated at this level by the systematics due to the uncertainty on the energy scale, which stresses the importance of a fine calibration of the detector. The final result is:

$$\rho = 0.72 \pm 0.06 \text{ (stat.)} \pm 0.08 \text{ (syst.)} \tag{3}$$

compatible within the error bounds with the V-A value.

The Michel parameter ρ from μ decays has been measured in the the late 60's by several authors [10] with a precision of about 0.4%. Such results have been obtained using dedicated experiments involving data samples of typically several hundred thousand events. More recently, the data from electron-positron colliders have been used to measure the Michel parameters of the purely leptonic τ decay [11]. These measurements have an accuracy of about 5% and are based on the analysis of samples typically amounting up to several ten thousand events. Our new result is not competitive with those obtained from μ decay, and barely with those obtained from τ decay. However, it must be remarked that this result has been obtained using 1858 muon decay events with a non optimized experiment. This result stresses the capabilities of the ICARUS technology to produce robust physics results.

5 Conclusions

We have performed the first physics measurement with the ICARUS LAr TPC detection technique, the Michel ρ parameter, from the detailed study of muon decay spectrum using the stopping muon event sample from the ICARUS T600 detector test run. We have obtained $\rho = 0.72 \pm 0.06$ (stat.) ± 0.08 (syst.), in agreement with the SM value. This measurement involves the exploitation of both the spatial and calorimetric reconstruction capabilities of the detector. Therefore, the obtained result constitutes a proof of the matureness of the detection technique to produce high quality physics results, in particular for neutrino physics when it will be installed in the Gran Sasso underground laboratory.

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