Measuring the Velocity of Elementary Particles

Fundamental Physics in Schools by Remote Learning

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Abstract: Teaching of modern physics requires nuclear and particle detectors that are not always available to high school audiences. A system which allows the measurement of the speed of muon particles detected in cosmic rays is presented. The system was setup at Frascati National Labs of the Italian Institute of Nuclear Physics (INFN) and is being used for hands-on teaching. The system is being upgraded for operation in fully remote control thus enabling e-learning capabilities to a much wider target audience.

1 INTRODUCTION

Experimental experiences on modern physics are of paramount importance to teach at pre-university level, and in general to increase the awareness of a young audience towards the value of fundamental research. Most of the experimental activities concerning nuclear and particle physics, however, make use of instrumentation not easily available to average high schools, although important programmes are being successfully pursued in Italy and elsewhere (Abbrescia, M. et al., 2013).

After an overview on cosmic rays and muon particles, the experimental setup is described in its hardware and software components. Finally, prospects are discussed on the planned upgrade towards fully remote control capabilities to enable e-learning.

2 THE MUON, ELECTRON'S HEAVY BROTHER

The Standard Model describes Nature as composed of particles and forces (Figure 1). The base hypothesis is that to describe Nature the following components are necessary and sufficient: quarks and leptons (organized in three families), the carriers of the four forces, and the Higgs boson.

The muon belongs to the lepton family and has the same properties of the electron, but with a mass 200 times larger. Muons are very important since their detection allowed the Higgs boson to be discovered in 2012 by the CMS and ATLAS experiments operating at the LHC collider of CERN, Geneva (Switzerland).

3 COSMIC RAYS

Muons are abundantly produced by primary cosmic rays interacting Earth's atmosphere (Figure 2).

Primary cosmic rays are high-energy particles of extra-terrestrial origin (from stars, black holes, neutron stars, the Sun, etc) which travel at a speed very close to the speed of light, and hit the Earth's atmosphere.

Most of primary cosmic rays are atomic nuclei, but electrons, positrons and other elementary particles are also present. At sea level, most of the cosmic rays are muons produced by the interaction of primary cosmic rays with the atoms of the atmosphere. The aver-

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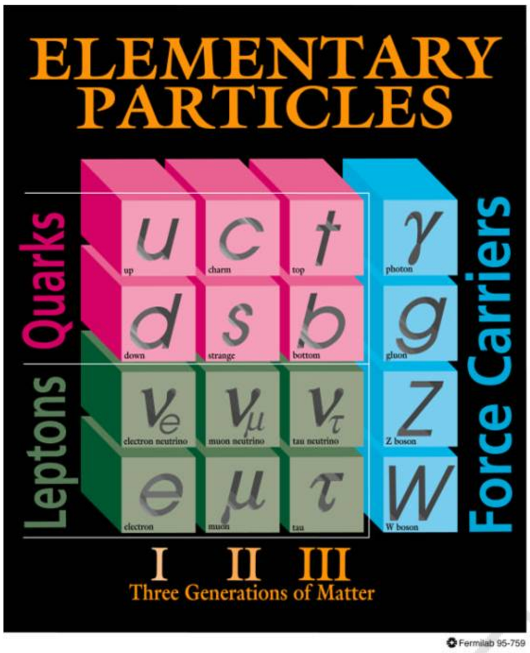

Figure 1: The Standard Model of forces and elementary particles (courtesy of Fermilab).

age rate of muons at sea level is:

$$R_\mu = 100 s^{-1} m^{-2} \tag{1}$$

while the average momentum is:

$$P_\mu = 2\, GeV/c \tag{2}$$

The muon has a mass:

$$m_\mu = (105.698389 \pm 0.000034)\, MeV/c^2 \tag{3}$$

thus yielding a relativistic β factor

$$\beta_\mu = v_\mu / c \cong 0.9986 \tag{4}$$

The muon in cosmic rays detected at sea level, therefore, has speed very close to the speed of light. The setup described utilizes techniques used in modern high energy physics experiments to measure with suitable precision very high particle speeds.

The study of cosmic rays have many implications from practical to theoretical. From an engineering point of view we just remind that all the instruments operating at high altitude such as satellite payloads are more likely to have some circuits to undergo a change of state due to the larger flux at higher altitude. Those changes are well known to happen in a micro-electronic component and typically produce a temporary change of state (single event upset) or more serious permanent changes (single event latchup or burnout) when an incoming cosmic ray interact with the electronic unit. Therefore the knowledge of the cosmic ray flux is important for the electronic design and to provide information on how to counteract the negative action of high energy particles. Also of great concern is the amount of radiation absorption by an astronaut in an interplanetary flight. The radiation dose that would be absorbed is in fact a significant obstacle to human Mars exploration. Also in this case the study of the long term cosmic ray flux is of paramount importance. There are a number of ground based as well as balloon and space borne experiments devoted to the study of cosmic rays. We mention the Alpha Magnetic Spectrometer (AMS) launched on May 2011 and still operating on the International Space Station. It is the largest particle detector orbiting the Earth and has, as main objectives to search for antimatter, dark matter and strangelets (a new hypothetical form of matter obtained with a combination of quark up, down and strange - see Figure 1 for the quark classification). The high precision required for the detectors called for special studies on the stability of the mechanical behaviour of the subsystems (Cusano et al., 2006) and for proposals to use a real time position monitoring (Benussi et al., 2003; Benussi et al., 2007).

4 MUON DETECTORS IN HIGH-ENERGY PHYSICS

The INFN Frascati group and associated collaborators from University of Rome La Sapienza have a deep experience in design, testing, construction, commissioning and operation of muon detectors, with the latest application being the muon detector using Resistive Plate Counters (Colafranceschi et al., 2014) and Gas Electron Multipliers (Abbaneo et al., 2014a) in the CMS experiment at the LHC hadron collider of CERN. Particular care was needed in monitoring gas composition and quality (Abbrescia et al., 2008), so that a gas gain monitoring system was devised (Benussi et al., 2009) and tested (Colafranceschi et al., 2010). Also the possibility of purifying and filtering the gas mixture was experimentally verified (Benussi et al., 2012). Muon detectors using gas are consequently very efficient and precise for both space and time measurements, but besides gas quality control require also careful tuning and monitoring (Abbaneo et al., 2014b; Benussi et al., 2015; Colafranceschi et al., 2013). For this application, a much simpler technique was chosen which utilizes plastic scintillator counters. Scintillation counters do provide suitable efficiency and precision for the measurement aimed to.

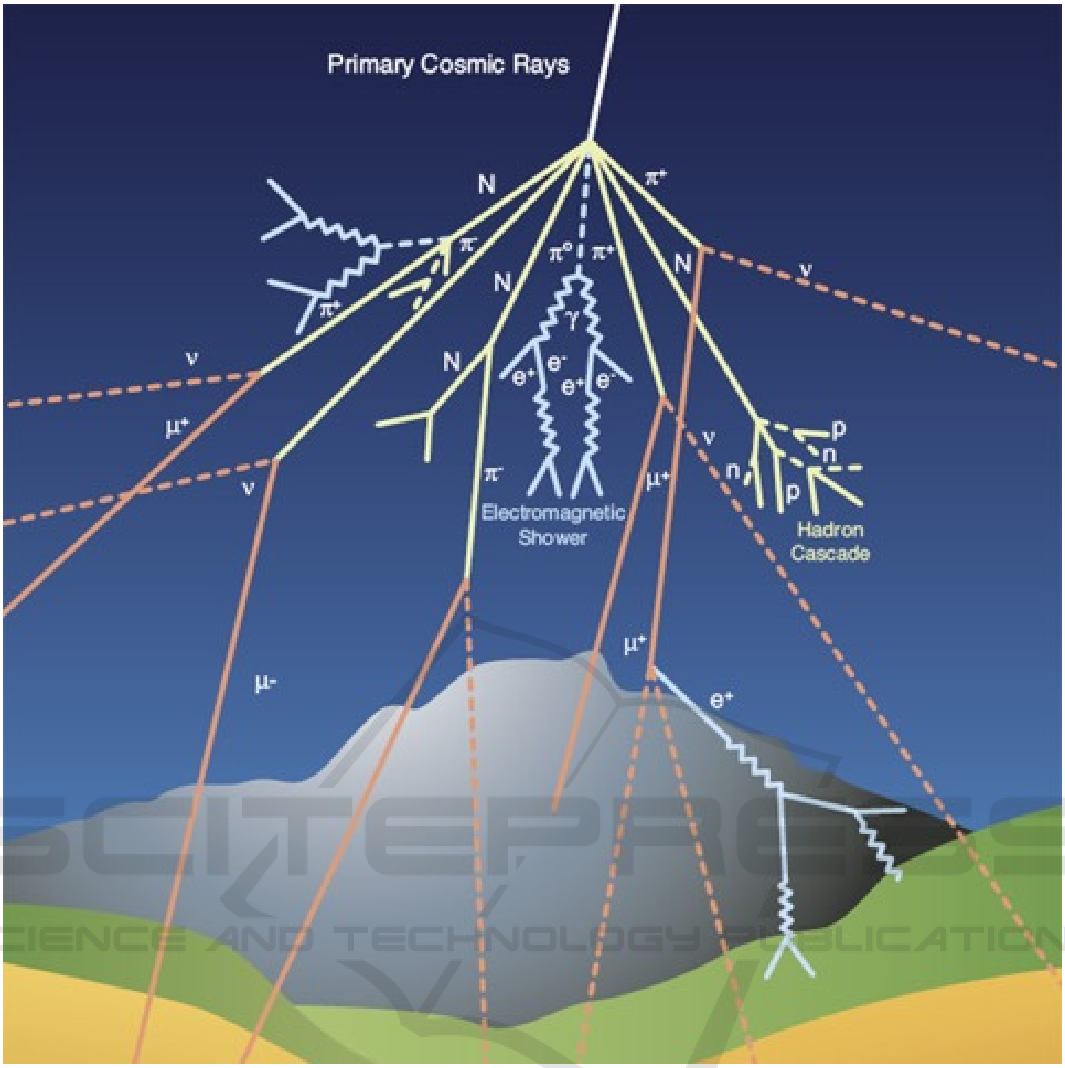

Figure 2: Production of cosmic rays at Earth level following interaction of primary cosmic rays on the atmosphere (courtesy of CERN).

5 EXPERIMENTAL SETUP

The experimental setup (Figure 3 and Figure 4) is composed of two scintillation counters which provide fast electronic signals when crossed by a cosmic ray muon. The distance between counters (L) can be adjusted from 10 cm to 4 m. The speed of the muon crossing both counters is measured by measuring the interval of crossing times Δt.

An exploded view of one scintillation counter is shown in Figure 5. The charged particle crossing the plastic scintillator plate produces a tiny fluorescence light which travels to a clear plastic lightguide and is funnelled to a photomultiplier tube (PMT) which converts the light pulse to an electrical pulse. Both PMT and voltage divider are located inside an iron case (not shown) for electrical, light and terrestrial magnetic field shielding.

The setup is composed of:

- two scintillator detectors (each composed of a 30x30x0.5 cm^3 NE110 plastic scintillator, a 22 cm plexiglass lightguide, a Philips 56AVP PMT provided with a high voltage divider);
- NIM crate, housing discriminator (CAEN mod. 411), logical coincidence unit (CAEN mod. 455), scaler counter (CAEN mod. 145), programmable high voltage supplies (CAEN mod. 470), programmable delay unit (mod.CAEN 108);
- CAMAC crate, housing Status A module (CAEN mod. 236), Time-to-Digital (TDC) Converter (LeCroy mod. 2228), SCSI interface to PC moni-

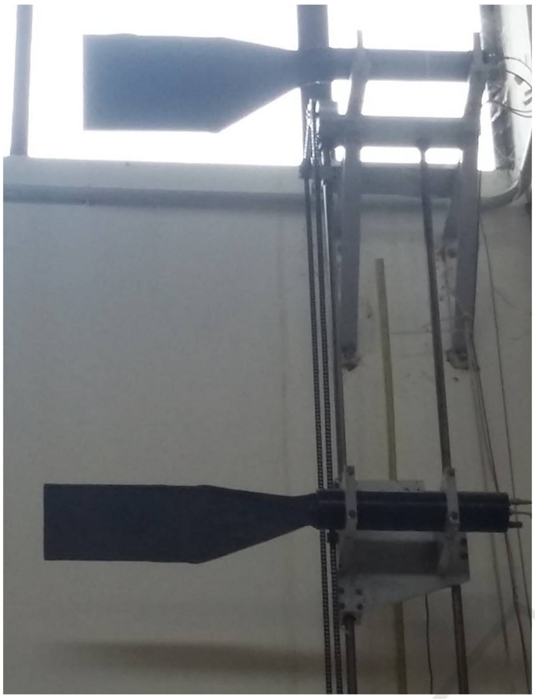

Figure 3: Experimental setup: adjustable distance scintillation counters, lightguides, photomultiplier, high-voltage supply and signal cables.

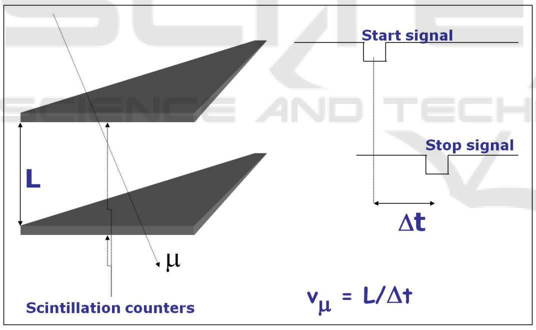

Figure 4: Principle of measurement of cosmic ray muon speed.

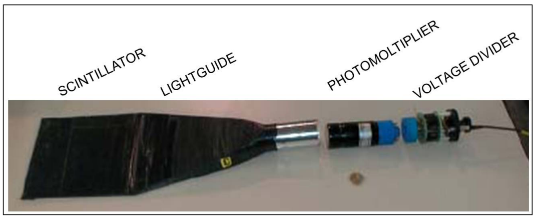

Figure 5: Exploded view of one of scintillation counters and readout electronics.

toring and control;

- PC software for data acquisition (LabVIEW).

A block diagram of the setup is reported in Figure 6.

Scintillation detectors are set at an adjustable distance *L*. A cosmic ray muon crossing the scintillator produces a fluorescence light pulse converted to electric pulse by the PMT. The PMT signal, once discriminated and converted to digital, is delayed (200 ns for upper PMT and 100 ns for lower PMT). The two signals are fed to the coincidence unit which performs a logic AND operation. This selection is necessary to select the particle crossing both detectors, and rejecting crossing due to two particles. The coincidence unit has three outputs. OUT1 is sent to a scaler counter, OUT2 to the Status A module, OUT3 to the common start input of the TDC. The common stop input of TDC is fed by the lower PMT signal. Both TDC and Status A are readout by the PC via SCSI interface.

6 REMOTE E-LEARNING

The system can be accessed remotely so that it will allow the students to verify the existence of cosmic rays. The students will connect either remotely to the experiment console via a Virtual Network Computing (VNC) software so that they will have access to the experiment. By managing the privileges it will be possible to give the students the possibility either to govern the experiment or simply to watch the remote computer console. The teacher will guide them through a webcam connection. Webcam can also be used to show the detector and the relevant electronics. The teacher will start with the observation that there are entities which leave a signal on the detector and that the theoretical physicists in the recent past, taking into account the many subatomic particles produced in several other experiments, organized them in the very elegant reduced set of particles called the standard model. Later going more in depth into the topic, he will describe the particles that are actually traversing the detector by introducing the property of the muons and by illustrating the way they are originated in the upper atmosphere by the primary cosmic rays. The short lifetime of muons (microseconds), that are generated in the upper atmosphere, would not allow them to reach the ground according to Galilei-Newton mechanics, because in few microseconds, even light will travel only about 1 km. Checking experimentally, with the devise described above, that the speed of muons is very close to the speed of light, will allow the teacher to touch the concept of Special Relativity. In fact according to that theory, time is relative to the observer and is not an absolute quantity, so for the muons moving very fast, time flows differently and that allow them to reach the ground and thus being

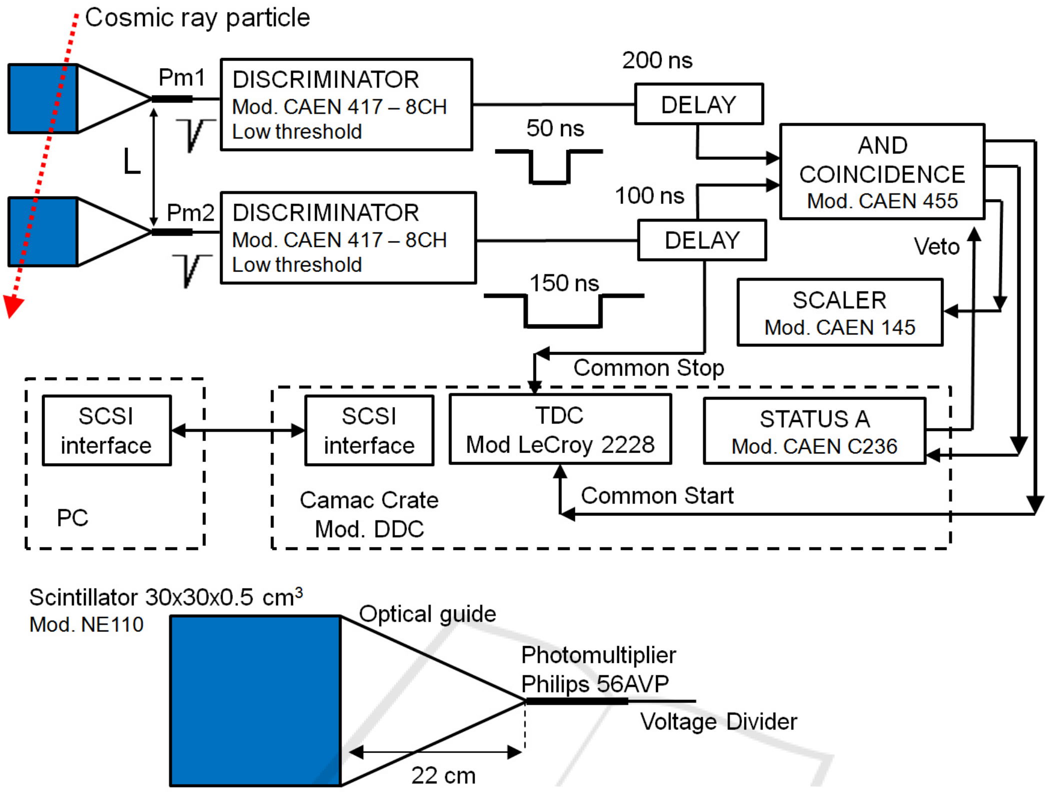

Figure 6: Block diagram of experimental setup.

observed by our detector.

From a technological point of view it is also of interest the working principle of the detectors and of the measurement chain used in the set-up described. Explaining the detectors will provide the opportunity to extend the concept of observation that, for extremely small entities, changes significantly. The biggest particle detectors are mounted on the LHC ring at CERN and they can be considered the most powerful microscopes because they allow to explore far beyond than any electron microscope can reach. Furthermore, for students in informatics, it can be shown how particle physics laboratory have to manage the huge amount of information derived, for instance, by the products of collisions of protons inside the colliders such as LHC at CERN. From that data analysis it was possible to observe the Higgs boson which by the way, as mentioned earlier, was observed thanks to its decay products that were muons.

7 CONCLUSIONS

A system is in operation at Frascati National Labs of INFN for the measurement of speed of muon particles in cosmic rays. The measurement is targeted to an audience of high school level students and teachers. The present setup is able to collect and analyse data. Data Analysis includes the optimization and tuning of detectors, full statistical treatment of results including the evaluation of statistical and systematic errors. The remotization of controls and data acquisition of the system is being pursued. Once operationally remotized, the system will provide remote e-learning of a real measurement of elementary particles fundamental properties such as their speed.

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