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*BEAMTEST CHARACTERIZATION OF
THE ENUBET DEMONSTRATOR*

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Everybody lies
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Introduction

The Standard Model of particle physics combines the description of the electrodynamics, the weak interactions and the strong interactions with the classification of all the known elementary particles. Neutrinos are the least known fermions of the Standard Model. Indeed, this is not related to the rarity of neutrinos, but to their interaction with matter. As any other lepton, they do not experience strong interactions, and, having no electric charge, these particles only interact through the weak force. Thus, experimental neutrino physics is quite challenging. Moreover, neutrinos are key ingredients for Beyond Standard Model searches and still a source of unexpected results.

The typical measurements of neutrino features, such as oscillations, are based on the number of specific flavours of neutrinos that appear or disappear after a given distance from their production point, compared to the number of produced neutrinos. In such context, an accurate estimation of the original flux of neutrinos is needed. So far, most beam-based neutrino experiments estimate the original flux of neutrinos by means of models and data on hadron production, with a resulting intrinsic systematic uncertainty of $\sim 10\%$. In order to reduce this uncertainty, a new generation of neutrino beams has been proposed. The results presented in this thesis have been achieved in the framework of the ENUBET project. The goal of ENUBET (Enhanced NeUtrino BEams from Kaon Tagging, ERC-Consolidator Grant-2015, 681647 (PE2)) is to develop the first "monitored neutrino beam", where the neutrino flux can be measured with a 1% precision. The idea is to design a pure and controlled source of electron neutrinos and to monitor the neutrino flux directly inside the decay region by detecting large-angle leptons generated in the K_{e3}^+ three body decay ($K^+ \rightarrow e^+ \pi^0 \nu_e$) using sampling calorimeters based on plastic scintillators and placed inside the decay tunnel. Thus, the tunnel becomes a hollow cylindrical electromagnetic calorimeter with an inner radius of 1 m and a length of 40 m. The sampling calorimeter is composed of alternated arches of iron and plastic scintillators, whose light is collected by wavelength shifting fibers and readout by Silicon PhotoMultipliers.

In October 2022, the ENUBET collaboration performed a beamtest on the

PS extracted T9 beamline at CERN. The main goal of this beamtest was to evaluate the performance of the largest prototype assembled in the ENUBET framework: the Demonstrator, a section of the ENUBET instrumented decay tunnel, 1.65 m long in the beam direction and covering an angle of 45° .

The first chapter of this thesis work gives an overview on the discovery of neutrino, some theoretical background and a brief description of the main neutrino sources, either natural or artificial, and detectors, detailing some of the major historical experiments.

Chapter 2 reviews the ENUBET project and its physics goals. The chapter then moves to the description of the Demonstrator, the largest prototype of the ENUBET detector tested at CERN, which is the subject of this thesis work. The last part of chapter 2 focuses on the April 2023 beamtest at Laboratori Nazionali di Frascati to characterize the readout electronics and the synchronization between the different systems used to collect data.

Chapter 3 discusses the experimental setup of the ENUBET 2022 beamtest, performed on the T9 line at CERN. This chapter presents briefly the detectors and the Data AcQuisition system.

The final chapter is dedicated to the analysis of the performance of the Demonstrator. The linearity and the energy resolution of the calorimeter are presented together with the study of the crosstalk effect and some preliminary results on the particle identification.

Chapter 1

Neutrino Physics

Neutrinos are 1/2-spin electrically neutral particles with a light mass, which are believed to be the most abundant particles in the universe. The three leptonic flavors of neutrinos are produced by many different sources. The main source is the Sun: the fusion reaction of hydrogen into helium produces $\sim 1.8 \times 10^{39}$ electron neutrinos per second that corresponds to a $6 \times 10^{10} \nu/\text{cm}^2/\text{s}$ flux at the Earth surface or about 100 billion neutrinos crossing an average fingernail (1 cm^2) every second [1].

Despite their abundance, neutrinos are however not as well understood as other Standard Model (SM) particles. This is in part due to the fact that they only participate in weak interactions, with cross sections of $\sim 10^{-38} \text{ cm}^2$ at 1 GeV. Present and future experiments in neutrino physics could answer several questions and improve the knowledge on some of the neutrino properties, as its cross section.

This chapter will provide a brief introduction on some aspects of neutrino physics and an overview of the technologies used to detect and study them. For a complete review, see [2].

1.1 The discovery of neutrinos

The first steps towards the discovery of neutrino is represented by Lise Meitner and Otto Hahn's measurements, in 1911, of the continuous β energy spectrum [3]. Such spectrum was in apparent contradiction with the energy conservation law, as it appeared that some energy was lost in the decay process:

$${}^A_Z\text{X} \rightarrow {}^A_{Z+1}\text{X}^* + e^- + \text{nothing else detectable} \quad (1.1)$$

where A and Z are the mass number and atomic number of the decaying

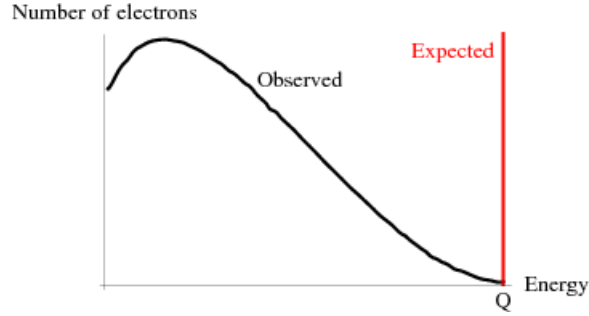


Figure 1.1: Electron spectrum of the β -decay [4].

nucleus, X and X^* are the initial and final elements, respectively and e^- is the electron. In such a decay, it was expected that the electron was emitted with an energy equal to the difference of the parent and daughter nuclear mass, Q . The observed electron spectrum, however, was continuous with an end-point at Q (figure 1.1) in what looks like a violation of the law of energy and momentum conservation.

A few years later, in 1914, James Chadwick confirmed this observation [5] [6], but it was Wolfgang Pauli, in 1930, that postulated the existence of a new particle to solve the dilemma of the β decay. He assumed that in such a decay a new particle (the neutrino) is emitted together with the electron. This causes the continuous energy spectrum of the electron while conserving both energy and angular momentum:



where $\bar{\nu}$ is the new particle, the antineutrino.

In his famous "Radioactive Ladies and Gentlemen" letter dated 4 December 1930 [7], Pauli wrote: "The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant...". Pauli's proposed "neutron" had to have a shallow mass, according to the data from the β -decay of tritium, and should weakly interact with matter in order to leave itself undetected. When, after a short time, Chadwick discovered the neutron (neutral, but strongly interacting and, most importantly, a heavy particle), Enrico Fermi proposed to call the hypothetical Pauli's "neutron" as "small neutron" or neutrino (in Italian) [8].

Only 26 years later, Reines and Cowan performed the first experimental observation of the electron antineutrino $\bar{\nu}_e$ [9] [10], for which in 1995 Reines

received the Nobel Prize¹.

The following decades saw an increasing interest in neutrino research. In 1962 at the Brookhaven National Laboratory (New York City, USA) Lederman, Schwartz and Steinberger detected the interactions of the muon neutrino, establishing that more than one type ("flavour") of neutrino exist. Their experiment [11] showed that the neutrinos obtained in pion decays ($\pi^+ \rightarrow \mu^+ \nu_\mu$) produce muons interacting with matter, but do not produce electrons, which implies that these neutrinos are different from those involved in β^- -decay ($n \rightarrow p^+ e^- \bar{\nu}_e$). The tau neutrino ν_τ first observation followed the discovery in 1975 of its electrically charged partner, the τ lepton [12].

Moreover, in 1968 John Bahcall and Ray Davis performed the theoretical calculations and designed the Homestake experiment to collect and count the neutrinos emitted by the Sun. The experiment was the first to point out a discrepancy between the theoretical number of expected neutrinos and the experimental results generating the "solar neutrino puzzle" [13]. In 1987 the neutrinos coming from the Large Magellanic Cloud were first observed [14] while in 1998 the SuperKamiokande Experiment reported the first evidence of neutrino oscillations [15]. In 2002 the Sudbury Neutrino Observatory finally solved the Solar Neutrino Puzzle [16] while the KAMioka Liquid scintillator ANtineutrino Detector (KamLAND) reactor confirmed the neutrino oscillation hypothesis [17]. In May 2010 the observation of the tau lepton by the Oscillation Project with Emulsion-tRacking Apparatus (OPERA) experiment [18] represented the first direct measurement of the $\nu_\mu \rightarrow \nu_\tau$ oscillations.

Nowadays there are several neutrino physics puzzles still to be solved both from the theoretical and phenomenological point of view [2]. For these reasons, together with the fact that the oscillation phenomenon represents the first evidence of physics beyond the SM, neutrino physics is still an open field.

1.2 Neutrino masses, oscillation and mixing

The Standard Model [19] of particle physics is the theory describing three of the four known fundamental forces (electromagnetic, weak and strong interactions – excluding gravity) in the universe and classifying all known elementary particles. The building blocks of this theory are 1/2-spin elementary particles, quarks and leptons, which interact exchanging several

¹The 1995 Nobel Prize in Physics was awarded "for pioneering experimental contributions to lepton physics" jointly with one half to Martin L. Perl "for the discovery of the tau lepton" and with one half to Frederick Reines "for the detection of the neutrino".

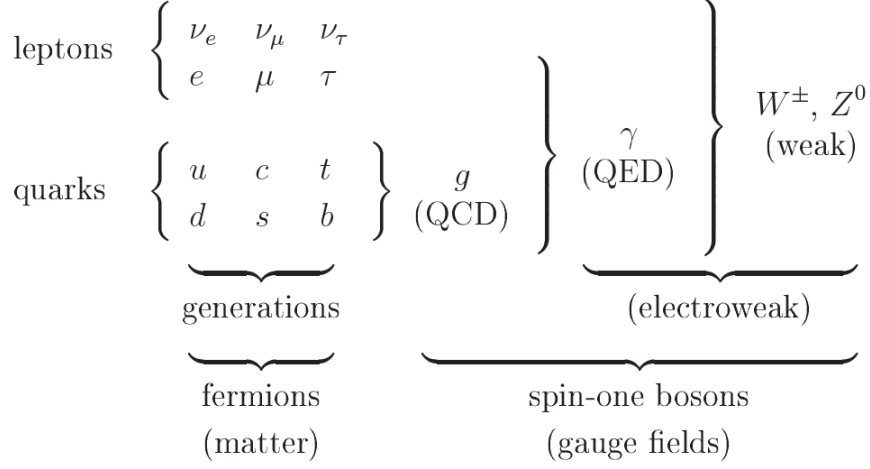


Figure 1.2: The elementary matter and force fields of the SM; the only fields missing from this figure are the spin-zero Higgs boson and the spin-two graviton [21].

types of spin-one bosons [20]. Leaving aside gravity and the spin-zero Higgs boson, they are grouped according to type and generation (or family) in figure 1.2. The next sections will describe the neutrino oscillation, the flavour mixing and some features of the neutrino cross section.

1.2.1 Neutrino oscillation

Quantum mixing is defined as the production of a particle in a state that is a superposition of different mass eigenstates. A consequence of mixing is the ability of the particle to "oscillate", meaning it can be produced in a certain eigenstate of a certain interaction, propagate as a mass eigenstate, then be detected as a different eigenstate of the same interaction.

The neutrino oscillation theory has been first proposed by Pontecorvo in 1957 [22] and subsequently expanded by Maki, Nakagawa and Sakata in 1962 [23]. The related mixing matrix is now known as the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix. Neutrino flavour mixing is defined as a unitary transformation between the eigenbases formed by the neutrino flavour (weak interaction) eigenstates $\{|\nu_e\rangle, |\nu_\mu\rangle, |\nu_\tau\rangle\}$ and the mass eigenstates $\{|\nu_1\rangle, |\nu_2\rangle, |\nu_3\rangle\}$:

$$|\nu_i\rangle = \sum_{\alpha} U_{\alpha i} |\nu_\alpha\rangle \quad |\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle \quad (1.3)$$

where the greek indices (α) indicate the flavour and the latin ones (i) are for the mass eigenstates; U is the 3×3 PMNS matrix.

The U matrix is unitary from the fact that the three flavour (and mass) eigenstates are orthogonal to each other. In addition, the constraints given by its unitarity allow the definition of the $U_{\alpha i}$ elements as functions of three mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$) and one phase (δ_{CP}) [24]:

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & -c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}s_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{pmatrix} \quad (1.4)$$

where $s_{ij} \equiv \sin \theta_{ij}$ and $c_{ij} \equiv \cos \theta_{ij}$.

Flavours are a periodical function of time which means that for a ν_e propagating in space, a measurement in a point near the production point will produce a e^- , but a measurement at a point more distant from the production point will produce a μ^- or a τ^- . To become non-zero, the oscillation probability requires long distances to occur. The reason is that the neutrino masses are close to each other, so a longer time is needed to have the required phase differences between different components; in addition, neutrinos travel at speeds close to the speed of light.

Such oscillations have been confirmed by Super-Kamiokande in Japan [15] [25] and the Sudbury Neutrino Observatory (SNO) in Canada [16] [26]. The data, comparing atmospheric neutrinos produced immediately above the apparatus and also on the far side of the Earth, are consistent with two-flavour oscillations.

Oscillation experiments on neutrinos and antineutrinos produced in the atmosphere, at accelerators, by the Sun and by reactors all provide very good evidence that at least one neutrino is indeed massive. However, the data do not yet indicate which neutrino mass eigenstate is the heaviest and various mass hierarchies are presently allowed. It has been observed experimentally [27] that one state is somewhat separated in mass from the other two, which are instead close. There are essentially two possible hierarchies, as shown in figure 1.3: *normal*, in which there are two lighter states ($m_1 < m_2 \ll m_3$), and *inverted*, in which there are two heavier states ($m_3 \ll m_1 < m_2$). Neither can currently be excluded experimentally.

Due to the two orders of magnitude difference between the two neutrino mass splittings, a measurement is generally able to observe oscillations corresponding to only one of the two values. It is thus often convenient to consider

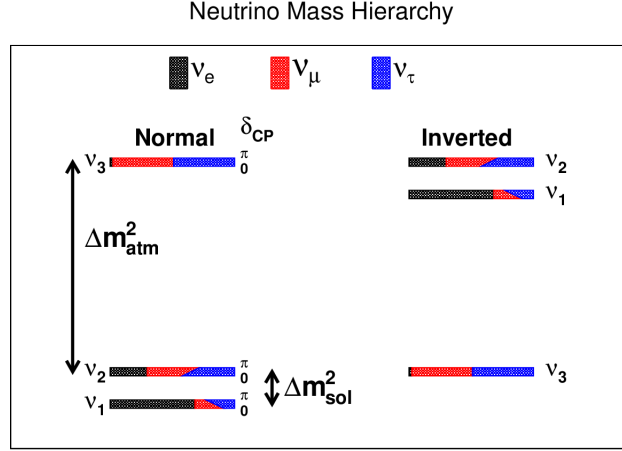


Figure 1.3: Pattern of neutrino masses for the normal and inverted hierarchies. Flavor composition of the mass eigenstates as a function of the unknown CP phase δ_{CP} . $\Delta m_{atm}^2 \sim |\Delta m_{31}^2| \sim |\Delta m_{32}^2|$ and $\Delta m_{sol}^2 \sim \Delta m_{21}^2$ stand for the atmospheric and the solar mass-squared splitting, respectively [27].

an approximate two-flavour model, containing, for instance, only ν_e , ν_μ and ν_1 , ν_2 ; thus equation (1.3) becomes:

$$\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

with the mixing matrix being fully parametrized by a single mixing angle θ . The ν_e to ν_μ oscillation probability amplitude is then

$$\begin{aligned} A(\nu_e \rightarrow \nu_\mu) &= -\cos \theta \sin \theta e^{-iM_1^2 \frac{L}{2E}} + \cos \theta \sin \theta e^{-iM_2^2 \frac{L}{2E}} \\ &= -\cos \theta \sin \theta e^{-iM_2^2 \frac{L}{2E}} \left(1 - e^{-i\delta M_{12}^2 \frac{L}{2E}}\right) \\ &= -2i \cos \theta \sin \theta e^{-i(2M_2^2 - \delta M_{12}^2) \frac{L}{2E}} \sin \frac{\delta M_{12}^2 L}{4E} \end{aligned} \quad (1.5)$$

and the oscillation probability is

$$\begin{aligned} P(\nu_e \rightarrow \nu_\mu) &= 4 \cos^2 \theta \sin^2 \theta \sin^2 \frac{\delta M_{12}^2 L}{4E} \\ &= \sin^2 2\theta \sin^2 \frac{\delta M_{12}^2 L}{4E} \end{aligned} \quad (1.6)$$

where L is the distance from the source to the detector, E is the energy of the neutrino and δM_{12} is the mass splitting.

1.2.2 Dirac or Majorana particle

One of the main open questions about neutrino is the nature of this particle and, in particular, whether it is identical to its own antiparticle. Quarks and charged leptons are called "Dirac" particles because they are not their own antiparticle. A "Majorana" particle, on the other hand, is also its own antiparticle. Neutrinos have not yet been categorized as "Dirac" or "Majorana" particles.

In the Lagrangian formulation of the quantum field theory, a field ψ can be given a mass through a "Dirac term" of the following type [28]:

$$m\bar{\psi}\psi = m\bar{\psi}_L\psi_R + m\bar{\psi}_R\psi_L \quad (1.7)$$

where $\psi_{L,R}$ are the spinor components in the left- and right-handed chirality basis². Equation (1.7) implies that a massive particle must necessarily have both left- and right-handed components; neutrinos are known to be massive, but they appear to be only left-handed and antineutrinos appear to be only right-handed [28].

Two possible interpretations arise:

- right-handed neutrinos (left-handed antineutrinos) exist, but do not participate in weak interactions, which only couple to left-handed particles (right-handed antiparticles)
- neutrinos gain their mass through a different kind of mass term.

A candidate for such a term is the "Majorana term" [28]:

$$-\frac{1}{2}m\bar{\psi}_L^C\psi_L + h.c. \quad (1.8)$$

This term can only appear in the Lagrangian under the assumption that $\psi_R = \psi_L^C \equiv C\bar{\psi}_L^T$ or, in other words, that the considered particle coincides with its antiparticle [30].

A Majorana mass term would solve the neutrino chirality problem, but would also couple neutrinos with antineutrinos, violating the lepton number conservation [29]. This becomes possible *if and only if* neutrinos are Majorana fermions. The important phenomenological implication is that the neutrino is then its own antiparticle and a possible way to confirm such hypothesis is to observe the neutrinoless double β -decay.

²Helicity is defined as $h = \mathbf{p} \cdot \mathbf{s}$, where $\mathbf{p}$ is the momentum and $\mathbf{s}$ is the spin of a particle. The chirality of a particle is determined by whether the particle transforms in a right- or left-handed representation of the Poincaré group [29]. For massive particles, chirality and helicity must be distinguished: it is possible for an observer to change to a reference frame moving faster than the spinning particle, in which case the particle will then appear to move backwards, and its helicity will be reversed.

1.2.2.1 Search for neutrinoless double β -decay

The process of standard double β -decay was proposed in 1935 by Goeppert-Mayer [31] and, although very rare, has now been observed for a number of nuclei [21]. In such a nuclear process, two essentially independent normal β -decays occur more or less simultaneously. There are 35 naturally occurring nuclides for which double β -decay is energetically allowed, of which 14 have been observed. Note though that the double decay can be detected experimentally if the single β -decay channel is forbidden or is highly suppressed.

The first experimental confirmation of such a process (though not its direct observation) dates back to 1950, when Inghram and Reynolds investigated the $^{130}\text{Te} \rightarrow ^{130}\text{Xe}$ decay via a geochemical approach [32]. They measured the excess of ^{130}Xe found in geologically old tellurium ores and deduced an approximate lifetime for this double β -decay mode of 1.4×10^{21} yr. It was not until 1987 that the first direct laboratory observation (at U.C. Irvine, California, USA) of the double β -decay was finally performed [33]. Using a time projection chamber, the team studied the $^{82}\text{Se} \rightarrow ^{82}\text{Kr} + 2\beta^- + 2\bar{\nu}$ decay. They quoted a measured half-life of $(1.1^{+0.8}_{-0.3}) \times 10^{20}$ yr [33].

At that time it was the rarest natural decay process ever observed directly in a laboratory. Since then, a number of experiments have observed the standard double β -decay in other nuclides. All the decays have a very long lifetime with a lower bound of 10^{18} yr.

A Majorana neutrino would theoretically allow a neutrinoless double β -decay ($0\nu D\beta D$) (figure 1.4):

$$(Z, A) \rightarrow (Z + 2, A) + e^- + e^- \quad (1.9)$$

The signature of such a process would be the emission of two electrons, with a total kinetic energy spectrum corresponding to a single line at the decay Q-value. Such a measurement could be used to determine the so-called coherent sum of the three neutrino masses [34]:

$$M_{\beta\beta} = \left| \sum_{i=1,2,3} M_i U_{ei}^2 \right|^2 \quad (1.10)$$

where U is the PMNS neutrino mixing matrix.

Experimental efforts spread over a wide range of detecting techniques, such as HPGe arrays doped with ^{76}Ge (GERDA [35]), Xenon TPC doped with ^{136}Xe (EXO [36]), TeO_2 bolometers doped with ^{130}Te (CUORE [37]), CaF_2 inorganic scintillator crystals (CANDLES [38]) or ^{82}Se tracking calorimeters (superNEMO [39]).

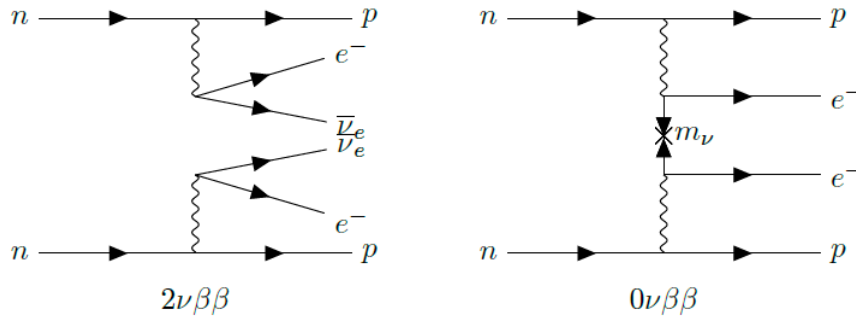


Figure 1.4: Regular (left) and neutrinoless (right) double β -decay [19].

To this day, no $0\nu D\beta D$ event has been observed, and the lower limit on the $0\nu D\beta D$ lifetime of ^{76}Ge is of the order of $\sim 10^{26}\text{yr}$ [34]. The corresponding 90 % Confidence Level (CL) upper bounds on $M_{\beta\beta}$ are 79 – 180 meV (normal and inverse hierarchy respectively) [35].

1.2.3 Neutrino masses

In the SM the masses of the three neutrinos are taken to be zero. This is related to (though not a direct consequence of) the fact that only left-handed neutrinos and right-handed antineutrinos appear to exist in Nature; or rather, only these seem to be present in the observed interactions [21]. A standard Dirac mass term in the Lagrangian describing the propagation of a fermion would implicitly connect left- and right-handed states and would therefore, in principle, be incompatible with such observations [21]. Experimental data, however, provide very strong evidence for oscillations³ between the different neutrino flavours. Such phenomena are possible if and only if at least one of the neutrino species has a non-zero mass.

Along with the electron neutrino and its corresponding antiparticle, the SM includes two other (anti)neutrino flavours, the muon and the tau neutrinos. All the neutrinos are named after their corresponding charged leptons. Neutrinos can couple with a Z^0 boson (Neutral Current (NC) interactions), which changes their quadrimomentum, but does not change their flavour, or with a $W^\pm$ boson (Charged Current (CC) interactions), which mediates the neutrino absorption and emission by or with one of the charged leptons, $e^\pm$, $\mu^\pm$, $\tau^\pm$, as shown schematically in figure 1.5.

³The 2015 Nobel Prize in Physics was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass".

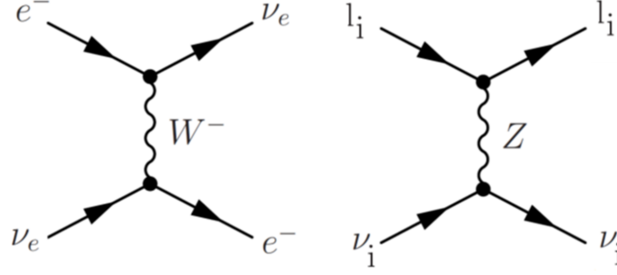


Figure 1.5: Feynman diagrams of charged current (left) and neutral current (right) neutrino interactions with matter. A neutrino of flavour i interacts with its corresponding charged lepton l_i [40].

Experimental data are only able to place upper limits on neutrino masses. By far the most stringent limits are those on the electron neutrino mass coming from the nuclear β -decay studies. In particular, the end-point (in the Kurie plot, figure 1.6) of the β -emission spectrum is lowered if the associated neutrino is massive (by just the energy equivalent to its mass). Recent experimental data on tritium decay provide a 90 % CL upper limit of 1.1 eV [41].

It is interesting to note that a similar, though less stringent, limit is provided by the finite spread in arrival times of the few neutrinos from the *SN1987A* supernova in the Large Magellanic Cloud, approximately 51.4 kpc (~ 170 thousand light years) from the Earth. Bursts of neutrinos were independently detected at three separate observatories. In total, 24 neutrinos were detected over a time interval of less than 13 seconds, a significant deviation from the observed background level: 11 were detected by Kamiokande II (Japan), 8 by IMB (Ohio, USA) and 5 by Baksan (Russia). The analysis of the energy and arrival-time spread provided an upper limit of about 11 eV [42], though a more recent analysis sets a 95 % CL limit of 5.7 eV [43].

Finally, the cosmological limits set a limit on the sum of the three neutrino masses, coming from the Planck Collaboration study of the Cosmic Microwave Background (CMB) spectrum [44]. The latest estimates [44], combining a variety of data, give

$$\sum m_\nu < 0.12 \text{ eV} \quad \text{at 95 \% CL}$$

Moreover the same collaboration obtains the following estimate for the number of neutrino species [44]:

$$N_{\text{eff}} = 2.96^{+0.34}_{-0.33} \quad \text{at 95 \% CL}$$

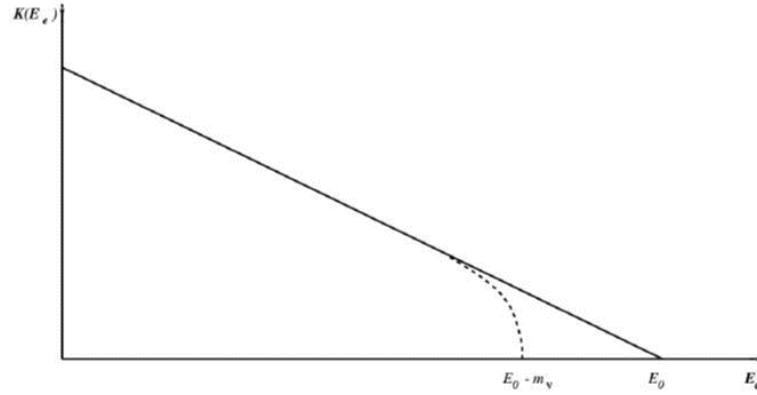


Figure 1.6: Effect of a neutrino mass in the end-point of the lepton energy spectrum of the β -decay [4].

1.2.4 Neutrino cross section

The study of neutrinos and their properties is an active area of research. One particularly interesting hypothesis that is being investigated is the role that neutrinos might have played in the observed asymmetry between matter and antimatter in our Universe. To understand this, it is important to study how neutrinos interact with the other particles of the SM, that is, to have a solid knowledge of the cross sections at different energy ranges [45].

Cross sections cannot be easily described by the SM since neutrino masses are very small. The absolute values of the neutrino masses are yet unknown and constrained to very small values ($< \text{eV}$) by cosmological constraints (Planck [44], WMAP [46]) and direct measurements (KATRIN [47], ECHo [48], HOLMES [49], NuMECS [50]). They cannot be derived from neutrino oscillation experiments, since they are sensitive only to the squared mass differences, as described in the previous section.

Neutrinos can be detected via their interaction with electrons or nucleons through weak charged currents. CC interactions are easier to detect since they involve a lepton in the final state and allow for the determination of the neutrino leptonic flavour. NC interactions can only be detected if the final state contains an excited nucleus.

In the following sections, neutrino interaction with matter and some experiments with their results are presented, considering different energy ranges.

Threshold-less processes: $E_\nu \sim 0 - 1 \text{ MeV}$

Threshold-less processes are those involving a neutrino that has zero or almost zero momentum. In this case, there are two possible interactions: coherent scattering and neutrino capture. Nuclear-neutrino interactions were first described by Freedman, Schramm and Tubbs in 1973 [51], about a year after the Conseil Européen pour la Recherche Nucléaire (CERN) discovered neutral currents for neutrino interactions. A neutral current occurs when a neutrino exchanges a neutral Z^0 boson with a quark. Friedman noticed that in some cases the neutrino should interact not with individual quarks or nucleons, but with the entire nucleus at once:

$$\nu + {}^Z_N\text{A} \rightarrow \nu + {}^Z_N\text{A}^* \quad (1.11)$$

The cross section for this process grows as the square of the atomic number A^2 . This reaction has a strong coherent enhancement, but despite that, it is extremely difficult to detect experimentally. This is due to the Heisenberg uncertainty relation: the smaller the momentum transferred from the neutrino to the nucleus, the greater the uncertainty on the coordinates where the interaction took place. This uncertainty becomes comparable to the size of the nucleus at some momentum values.

A measurement of the coherent elastic neutrino-nucleus scattering (CE ν NS) was performed by the COHERENT Collaboration [52]. The detector of the project is based on a Sodium activated Cesium Iodide crystal detector. Whenever the coherent elastic scattering of neutrinos occurs (on the nuclei of cesium or iodine), the nuclei are accelerated, ionize the CsI[Na] scintillator and generate visible photons. 134 ± 22 events were observed, at 6.7σ CL, consistent with the SM prediction.

Neutrino capture is a process similar to the one of the ordinary beta decay and it is sometimes named "enhanced" or "stimulated beta emission" [53]. The neutrino interacts with the target nucleus:

$$\nu_e + {}^Z_N\text{A} \rightarrow e^- + {}^{Z+1}_{N-1}\text{A} \quad (1.12)$$

producing the same observable final states as the ordinary beta decay. The difference between the two processes consists in the fact that the neutrino capture is exothermic, requiring no energy to start the reaction. This low energy process is of great cosmological interest, as it is considered a way to detect cosmological neutrinos [54]. Theorized in 1962 by Weinberg [55], it has recently gained attention also thanks to the advancement of beta decay experiments, which have extended the reach on neutrino mass scales. Unlike the coherent scattering, this process has not been detected yet [56].

Low energy nuclear processes: $E_\nu \sim 1 - 100 \text{ MeV}$

Increasing the energy, the neutrino starts to see each nucleon individually and interact with it via the inverse beta decay:

$$\bar{\nu}_e + p \rightarrow e^+ + n \quad (1.13)$$

Unlike the previously described mechanisms, this one has been studied extensively theoretically [57] and experimentally [58] using neutrinos produced from fission in nuclear reactors. In this case neutrinos are the product of the fission of ^{235}U ($\approx 57\%$ of the total flux), ^{238}U ($\approx 29\%$), ^{239}Pu ($\approx 8\%$) and ^{241}Pu ($\approx 6\%$) [59]. The typical range for the neutrino energy is from the threshold ($E_\nu \geq 1.806 \text{ MeV}$) to 10 MeV , although slightly higher energies ($10\text{--}20 \text{ MeV}$) are of great interest, as this reaction in this energy range is important to understand the supernova explosion mechanism [14]. Theoretically, the inverse beta decay cross section has been predicted with uncertainties around 0.5% .

The neutrinos cross sections in this energy range are an important parameter in many different models, such as reactor neutrino analysis, supernova modelling and neutrino oscillation tests. It is worth remembering that the inverse beta decay was the reaction with which the neutrinos were first detected [10], and, after 60 years, inverse beta decay is still the most exploited reaction for detecting reactor and solar neutrinos. However, the experimental data collected for the study of neutrino cross sections is still limited.

Intermediate energy processes: $E_\nu \sim 0.1 - 20 \text{ GeV}$

Increasing the energy, different neutrino scattering mechanisms come into play. They can be divided into three main categories:

- *elastic and quasi-elastic scattering*: in this process, neutrinos interact with a nucleon (or multiple nucleons) freeing it from the target. In the CC interaction case, the process is known as "quasi-elastic scattering", while it is named "elastic scattering" in the NC case (figure 1.7 top)
- *resonant production*: the interaction with a neutrino can cause a nucleon to reach a resonance state (Δ, N^*), which decays to a variety of mesonic final states (figure 1.7 middle)
- *deep inelastic scattering*: with enough energy, a neutrino can interact with the individual quark constituents of the nucleon. When this happens, the interaction produces a hadronic shower (figure 1.7 bottom).

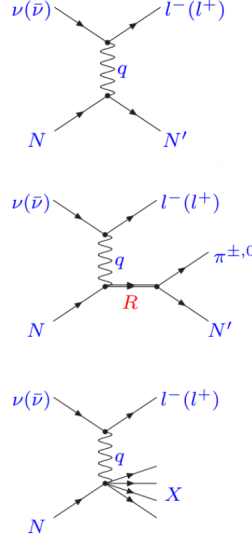


Figure 1.7: Feynman diagrams for the Quasi Elastic scattering (QE) (top), RESonance production (RES) (middle) and Deep Inelastic Scattering (DIS) (bottom).

Experiments measuring neutrino cross sections in the intermediate energy region, mainly exploit the following interactions of muon neutrinos:

$$\nu_\mu + N \rightarrow \mu^- + X \quad (1.14)$$

$$\bar{\nu}_\mu + N \rightarrow \mu^+ + X \quad (1.15)$$

This energy regime is a sort of a transition region between the quasi-elastic scattering (dominant at lower energies) and the deep inelastic scattering (dominant at higher energies) as represented in figure 1.8. Adequate descriptions of the three processes listed above have been formulated, but currently there is no uniform description on how they combine and the transition from one to another.

Data for the neutrino cross sections at these energies have been collected mostly in experiments that provided quite small data samples (from ~ 10 to ~ 1000 events) during the '70s and the '80s, using bubble chamber or spark chamber detectors [45]. However, this energy range has become very interesting after discovering the neutrino oscillations and an increase in the beam intensity in recent decades. New experiments [58] such as Argon Neutrino Test (ArgoNeuT) [60], Mini Booster Neutrino Experiment (MiniBooNE) [61], SciBar Booster Neutrino Experiment (SciBooNE) [62], Main INjector Experiment: nu-A (MINER ν A) [63], Main Injector Neutrino Oscillation Search

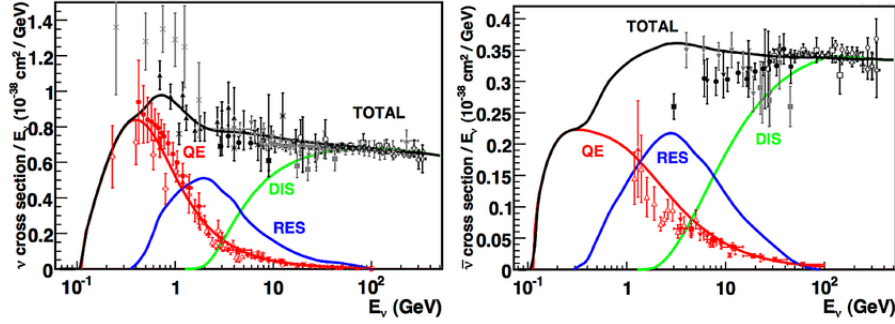


Figure 1.8: The neutrino-nucleon (left panel) and antineutrino-nucleon (right panel) cross sections plotted as a function of the (anti)neutrino energy. The processes that contribute to the total cross section (shown by the black lines) are: QE (red lines), RES (blue lines) and DIS (green lines) [68].

(MINOS) [64], Neutrino Oscillation MAGnetic Detector (NOMAD) [65], KEK to Kamioka (K2K) [66] and Tokai to Kamioka experiment (T2K) [67] are mainly aimed at specific subproblems and a more detailed study of specific interactions and their cross sections.

High energy processes: $E_\nu \sim 20 - 500$ GeV

In this energy range, a neutrino can interact with individual quarks inside a nucleon via the process called deep inelastic scattering (DIS) via a virtual W or Z boson exchange [69]. All the three ν_e , ν_μ and ν_τ DIS interactions are possible. The CC cross section for neutrinos with these energies is shown in figure 1.9.

Data were obtained from various experiments including NOMAD [65], Neutrinos at the Tevatron (NuTeV) [70] and MINOS [64]. It is important to notice that in this region the CC cross section is measured with a precision of a few percent and the visible linear dependence on the energy for neutrinos and antineutrinos confirms the predictions of the quark-proton model.

Ultra high energy processes: $E_\nu \sim 0.5$ TeV – 1 EeV

Being able to detect and study neutrinos with energies of the order of 10^{15} eV and higher could provide additional information on a variety of astrophysical mechanisms that have currently been observed only in the electromagnetic spectrum and via the emission of hadrons. Thanks to the latest technological advancements, this energy range is currently being explored.

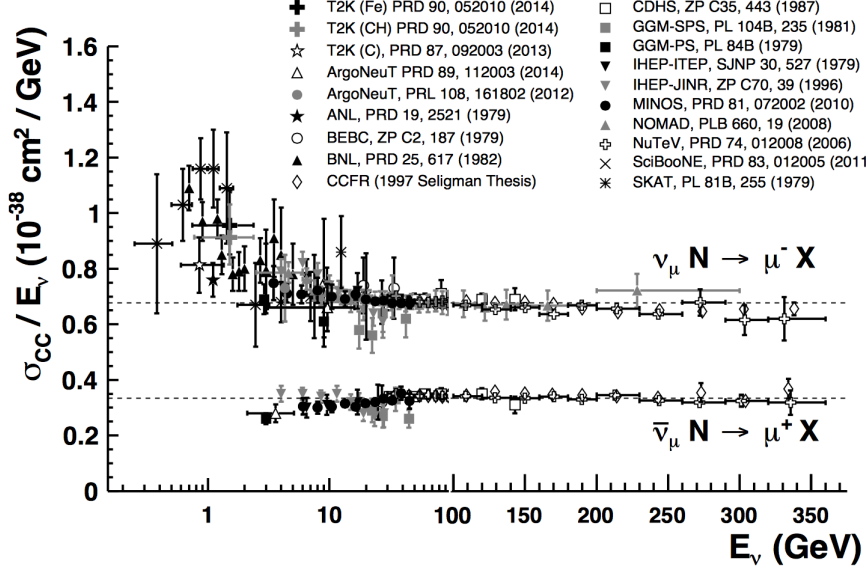


Figure 1.9: DIS neutrino and antineutrino CC cross section ($\nu_\mu N \rightarrow \mu^- X$ and $\bar{\nu}_\mu N \rightarrow \mu^+ X$) divided by the neutrino energy as a function of the neutrino energy [45].

The techniques used to detect these ultra high energy neutrinos include induced events in large volumes of water (Baikal-GVD [71], ANTARES [72], KM3NeT [73]), ice (AMANDA [74], IceCube [75], RICE [76], FORTE [77], ANITA [78]), the Earth atmosphere (Pierre Auger [79], HiRes [80]) and the lunar regolith (GLUE [81]).

In the precision era of neutrino physics, the efforts toward high intensity beams must be complemented by the reduction of systematic uncertainties. The total and differential cross sections in the region of interest for the Deep Underground Neutrino Experiment (DUNE) and Hyper-Kamiokande (0.5 – 5 GeV) are still known with a precision of 10 % or worse [82]. The theoretical models that describe the interactions of neutrinos show large discrepancies with data and the uncertainties in the description of nuclear effects in neutrino scattering play a leading role in the measurement of the oscillation parameters. A new generation of cross section experiments needs [83] [84]:

- neutrino beams with a 1 % precision in the knowledge of the flux at the source since flux uncertainties are the leading systematic contributions to all cross section measurements at the few GeV scale

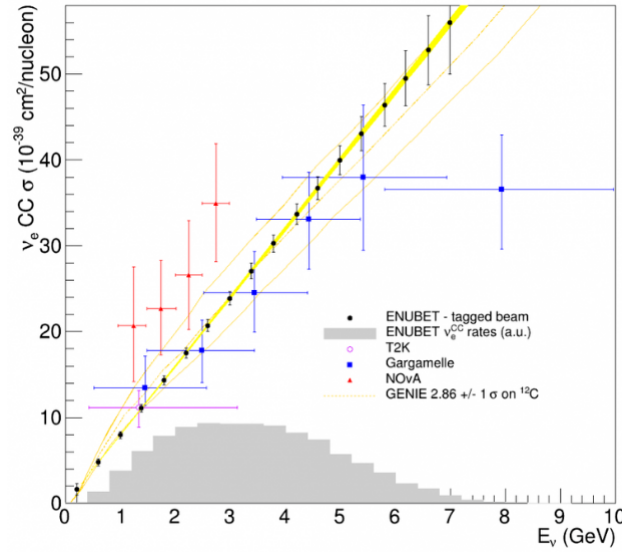


Figure 1.10: ENUBET expected precision on the ν_e cross section measurement (black dots) compared with present measurements (red and blue dots). The red dots are the current uncertainty on the theoretical calculations (GENIE neutrino generator) and the yellow area is the expected systematic error after ENUBET [85].

- an intense and well controlled source of electron neutrinos since future oscillation experiments are mostly based on $\nu_\mu \rightarrow \nu_e$ oscillations and the ν_e cross section is measured directly with a precision worse than 20 %
- detectors capable of reconstructing with high precision the final state particles of ν_μ and ν_e charged current events to determine the total and differential neutrino cross sections in liquid argon (of interest for DUNE) or water (of interest for HyperKamiokande).

These considerations motivated the development of "monitored neutrino beams" and, in turn, the ENUBET proposal [53] for a facility where the only source of electron neutrinos is the three body semileptonic decay of kaons: $K^+ \rightarrow e^+ \pi^0 \nu_e$ (K_{e3}^+). The Enhanced NeUtrino BEams from kaon Tagging (ENUBET) project proposed and described the possibility of measuring neutrino cross sections with an accuracy of 1%. Figure 1.10 shows the expected impact of the ENUBET cross section measurements compared with the present measurement of the ν_e cross section. Such project will be described in chapter 2.

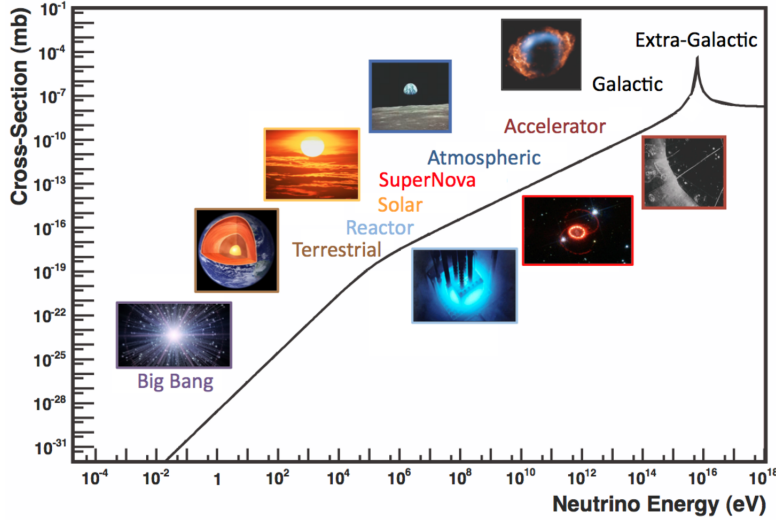


Figure 1.11: Examples of several neutrino sources across decades of energy [45].

1.3 Neutrino sources

Neutrinos, although difficult to detect, are very abundant in the Universe and may hold the answer to many unsolved physical and astrophysical questions. For instance, the cosmic neutrino background is an echo of the Big Bang even older than the cosmic microwave background radiation; it has a number density of about 56 cm^{-3} and is made of neutrinos that decoupled from matter when the Universe was just one second old [86]. Another source of neutrinos is represented by the supernovae or by the Sun, which are natural and "free of charge", but no control over them is possible. Figure 1.11 presents some examples of natural and artificial neutrino sources as a function of the energy of the emitted neutrinos.

To better study the neutrino properties, controlled sources are needed, such as nuclear reactors and particle accelerators.

1.3.1 Natural neutrino sources

Being a common byproduct of most weak processes, neutrinos are emitted in large quantities by plenty of natural reactions. These sources are powerful tools for investigating the different aspects of neutrino physics. The main neutrino sources are the following:

- the Sun is the main source of (electron) neutrinos reaching Earth: their flux is $6.7 \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1}$ at the sea level. They are produced in several

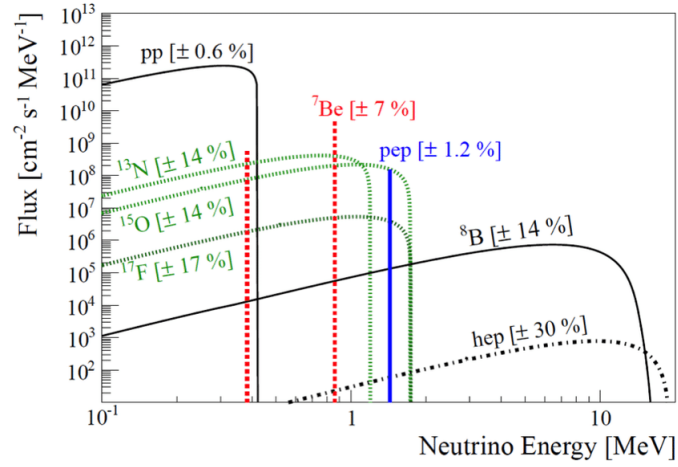
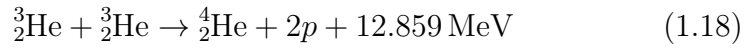
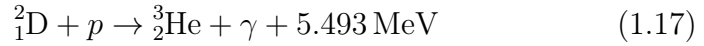


Figure 1.12: Solar neutrino energy spectrum for the main cycles [88].

different nuclear reactions, with the main contributor being the pp cycle (type I branch) [87]:



Apart from the particular pp chain, other nuclear reactions occur and produce neutrinos that are detectable on Earth. In stars more massive than the Sun, hydrogen is converted to helium also via a different sequence of reactions, called the CNO cycle. The main branch of the CNO cycle (type I branch) actually begins with the reaction in equation (1.16) and is followed by [87]:



Their spectrum (figure 1.12) lies roughly in the $0.1 - 10 \text{ MeV}$ range

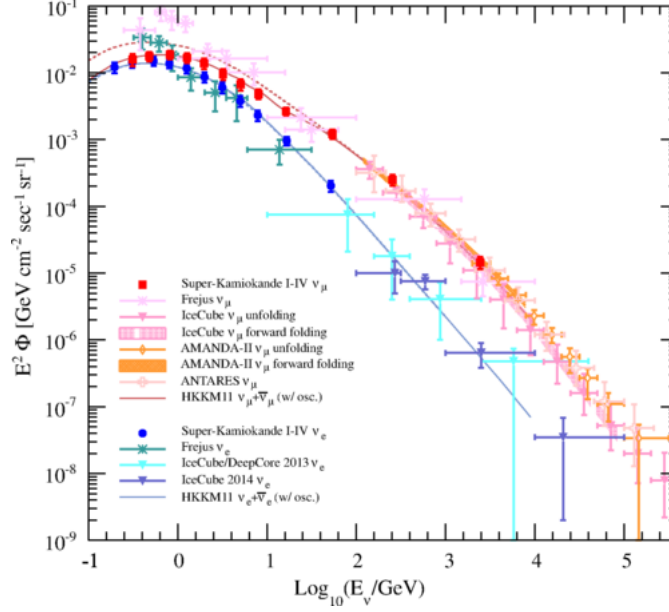


Figure 1.13: Atmospheric ν_μ and ν_e energy spectra [89].

- atmospheric neutrinos are a product of the decay of secondary cosmic rays, mainly

$$\begin{aligned}\pi, K &\rightarrow \mu + \nu_\mu \\ K &\rightarrow \pi + e + \nu_e\end{aligned}$$

They are produced in the upper atmosphere, and can also be observed after crossing Earth, thus offering important information on their eventual interaction with matter. Their spectrum (figure 1.13) covers a few orders of magnitude, up to a few hundreds of GeV

- the nuclear core of a fission reactor produces on average a flux of $\approx 10^{20}$ $\bar{\nu}_e$ per second, resulting from the β -decay of unstable daughter nuclei. The fissioning of ^{235}U produces elements which must release neutrons to approach the line of stability. In modern reactors, the uranium fuel is enriched to a few percent in ^{235}U , but there are also significant contributions to the neutrino flux from the fissioning of ^{238}U , ^{239}Pu , and ^{241}Pu . Considering the typical energies of fission reactions, these (anti)neutrinos are produced mostly in the MeV range (see figure 1.14), and are generally used in short baseline experiments
- supernovae are stars with initial masses of about $8M_\odot$ or more. As time

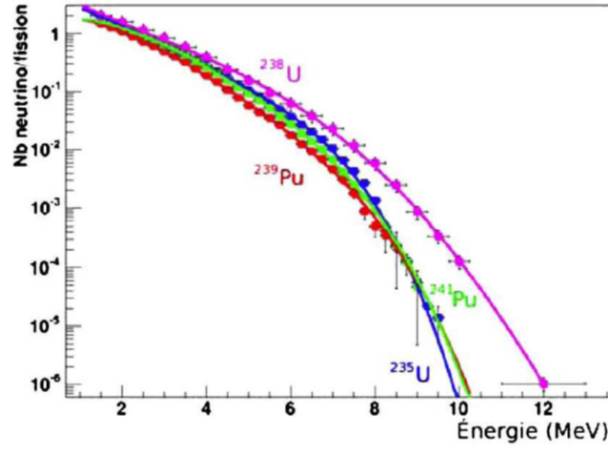


Figure 1.14: Reactor $\bar{\nu}_e$ energy spectra for different isotopes [90].

advances, shells at various inner radii attain the temperatures and the densities required by the reactions that produce progressively heavier elements, up to the production of elements in the "iron group" [87].

As the core of a star reaches the critical mass of about $1.4M_\odot$ of Fe, it collapses in free fall. Once the density reaches nuclear values, the collapse of the central region stops and a shock wave is formed. The high density creates a medium that is opaque even for neutrinos. Once the trapped energy (and lepton number) is able to escape from the core, it does so in the form of the least interacting particles, neutrinos. In a time span of a few seconds, the star releases $\approx 10^{46}$ J in the form of $\approx 10^{58}$ neutrinos, via:

$$\gamma + \gamma \rightarrow e^+ + e^- \rightarrow \nu_e + \bar{\nu}_e, \nu_\mu + \bar{\nu}_\mu, \nu_\tau + \bar{\nu}_\tau \quad (1.25)$$

An example of a predicted supernova neutrino spectrum is shown in figure 1.15.

1.3.2 Artificial neutrino sources

Among the different types of experiments probing the neutrino oscillation phenomenon, accelerator neutrino beams cover an essential role, as they are able to produce directional neutrino fluxes with a given energy and distance from the detector.

Accelerator neutrino experiments start from the extraction of protons from an accelerator. Protons are then directed toward a light target, such

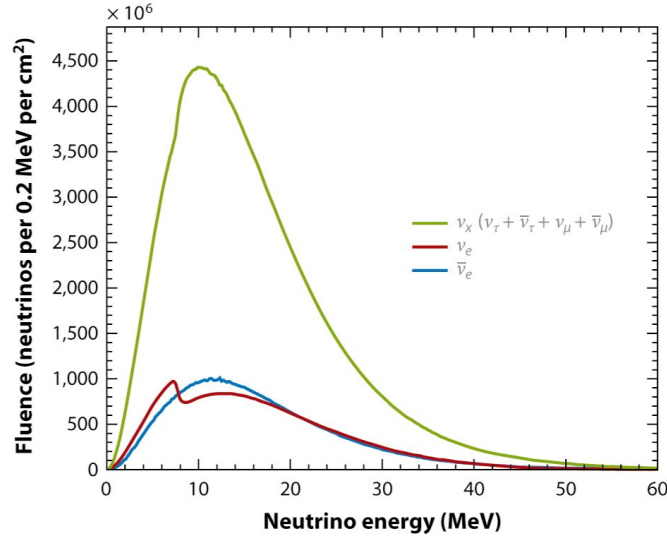


Figure 1.15: Expected supernova neutrino spectra (integrated over 10 s) for the different flavour components [91].

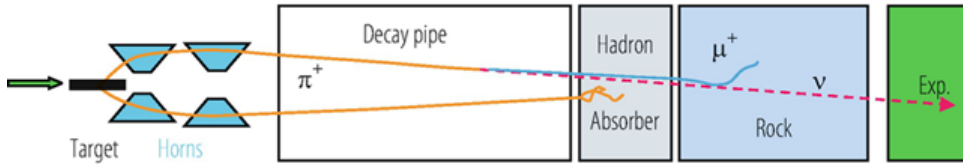


Figure 1.16: Schematic for a typical accelerator neutrino beam setup [2].

as Be, graphite or Al (low Z materials). This results in the production of a secondary particle beam, which is charge- and momentum-selected and focused by a system of magnets. Secondary particles, which are mostly pions and kaons, are then free to decay in what is called a decay tunnel producing neutrinos, as shown in table 1.1 [19].

As there is no way of directly focusing and selecting neutrinos, both the proton energy and intensity and the secondary focusing systems are crucial to produce a neutrino flux with the desired characteristics. A hadron dump at the end of the decay region prevents hadrons and charged leptons from propagating further, allowing only neutrinos to escape, resulting in a neutrino beam. Neutrino detectors are installed downstream of the beamline, along the neutrino trajectory. Figure 1.16 presents a typical layout of a neutrino beam facility.

Electron neutrinos are mainly produced by kaon and subsequent muon

Table 1.1: π^+ , K^+ decays and Branching Ratios [19].

Decay	BR (%)	Comment
$\pi^+ \rightarrow \mu^+ \nu_\mu$	~ 100	Hadron dump
$K^+ \rightarrow \mu^+ \nu_\mu$	63.56(11)	Background
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	5.58(2)	Background
$K^+ \rightarrow e^+ \pi^0 \nu_e$ called K_{e3}^+	5.07(4)	Signal
$K^+ \rightarrow \mu^+ \pi^0 \nu_\mu$ called $K_{\mu3}^+$	3.35(3)	Signal
$K^+ \rightarrow \pi^+ \pi^0 \pi^0$	1.76(2)	Background

decays: $K^+ \rightarrow e^+ \pi^0 \nu_e$ and $\mu^+ \rightarrow e^+ \nu_e$ (with Branching Ratios (BR) $\sim 100\%$). It is essential to optimize the length of the decay region and to use shielding to prevent the muons from decaying. Increasing the meson momentum, the required length of the decay region must increase too: the probability of decay is in fact $P = 1 - e^{-L_{\text{tunnel}}/L_0}$, where

$$L_0 = \begin{cases} 55.9 \text{ m GeV}^{-1} & \text{for } \pi \\ 7.51 \text{ m GeV}^{-1} & \text{for } K \end{cases}$$

As a result, only a portion of the produced mesons decays in the L-length tunnel. Moreover not all the decays produce a valid signal. The "Comment" column of table 1.1 shows which decays are a source of signal or background.

The kinematics of the two-body decay of the mesons ($M^+ \rightarrow \mu^+ \nu_\mu$) can be used to derive the neutrino spectrum. The E_ν energy of the neutrino emitted at an angle θ_0 with respect to the direction of the parent meson is [92]:

$$E_\nu(\theta_\nu) = \frac{(1 - (m_\mu/m_M)^2) E_M}{1 + (E_M/m_M)^2 \theta_\nu^2} \quad (1.26)$$

from which it can be shown that for a non-zero neutrino emission angle θ_ν (the decay angle between the neutrino and pion direction), the neutrino energy loses the strong linear relation with the secondary particle energy, which is present for the on-axis emission. Figure 1.17 shows the neutrino (from a pion decay) energy evaluated with equation (1.26) for different θ_ν values.

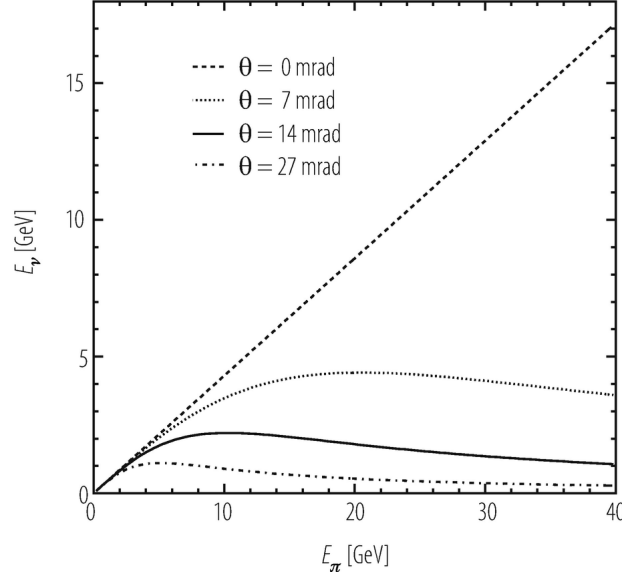


Figure 1.17: Neutrino from pion decay energy for different choices of the decay angle [2].

1.4 Neutrino detectors

The measurement of neutrino masses is based on the kinematic analysis of the reactions involving neutrinos:

$$\nu_l + n \rightarrow l^- + p \quad (1.27)$$

$$\bar{\nu}_l + p \rightarrow l^+ + n \quad (1.28)$$

where a charged lepton $l^\pm$ is produced. When considering medium to high energy (several MeV to ~ 1 GeV), neutrino interactions with a target atom are dominated by CC quasi elastic scattering and the NC neutrino-nucleon elastic scattering cross section is smaller than the quasi elastic one by a factor ~ 10 . For energies higher than ~ 1 GeV, CC deeply inelastic neutrino-parton scattering dominates.

As shown in figure 1.9, the typical values of the total CC cross section are in the $10^{-38} \text{cm}^2 \text{GeV}^{-1}$ range. Other cross sections, such as that of neutrino-electron scattering or inverse β -decay, are typically in the $10^{-43} - 10^{-42} \text{cm}^2 \text{GeV}^{-1}$ range [45].

Given such small cross sections, neutrino detectors are generally rather massive. Their nature is heavily dependent on the physics of the specific experiment, but in general the detection of a neutrino is performed by observing the leptonic (equation (1.27)) or hadronic products of its interaction with the

active medium. The indirect nature of these measurements, coupled with the small cross sections, generally requires a robust background reduction and rejection, as cosmic rays and natural radioactivity can easily mimic the neutrino signals. The following section presents a review of the different detectors and techniques used to detect neutrinos, along with some of the most notable results.

1.4.1 Cherenkov detectors

Cherenkov neutrino detectors are widely used for oscillation experiments and neutrino telescopes. Detectors belonging to this category use the Cherenkov light emitted by charged leptons when they travel through water or ice faster than the speed of light in the medium itself:

$$v \geq \frac{c}{n} \quad (1.29)$$

where v is the particle velocity, c is the speed of light and n is the refractive index of the target material. This light can be detected by an array of photon detectors, positioned around or inside the active medium to obtain the deposited energy, the particle track and an identification of the particle itself.

An example of these types of experiments is the IceCube Neutrino Observatory (IceCube), the South Pole neutrino observatory. It is a cubic-kilometer particle detector located near the Amundsen-Scott South Pole Station⁴ [93].

IceCube is the first gigaton neutrino detector ever built and was primarily designed to observe neutrinos from the most violent astrophysical sources in our universe. The in-ice component consists of 5160 Digital Optical Modules (DOMs), each with a 25 cm PhotoMultiplier Tube (PMT) and associated electronics, as shown in figure 1.18b. The DOMs are attached to vertical "strings", frozen into 86 boreholes, and arrayed over a cubic kilometer from 1450 m to 2450 m depth. The strings are deployed on a hexagonal grid with 125 m spacing and hold 60 DOMs each. The vertical separation of the DOMs is 17 m, as shown in figure 1.18a.

When a neutrino interacts with the ice, it produces electrically charged secondary particles that in turn emit Cherenkov light, as a result of traveling through the ice faster than light.

IceCube is more sensitive to muons than other charged leptons, because they are the most penetrating and thus have the longest tracks in the detector. An electron resulting from an electron neutrino event typically scatters several

⁴It is named in honor of Norwegian Roald Amundsen and Briton Robert Falcon Scott, who led separate teams that raced to become the first to reach the South Pole in 1911.

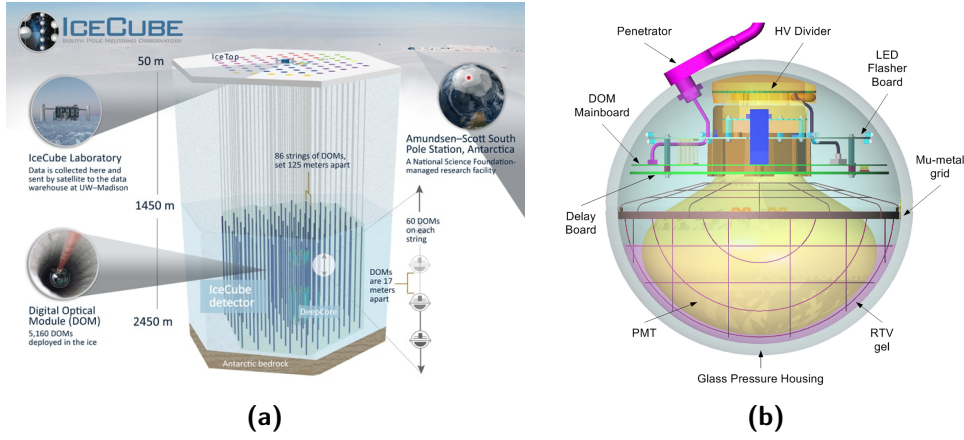


Figure 1.18: (a) Scheme of the IceCube experiment and (b) IceCube DOMs schematic [93].

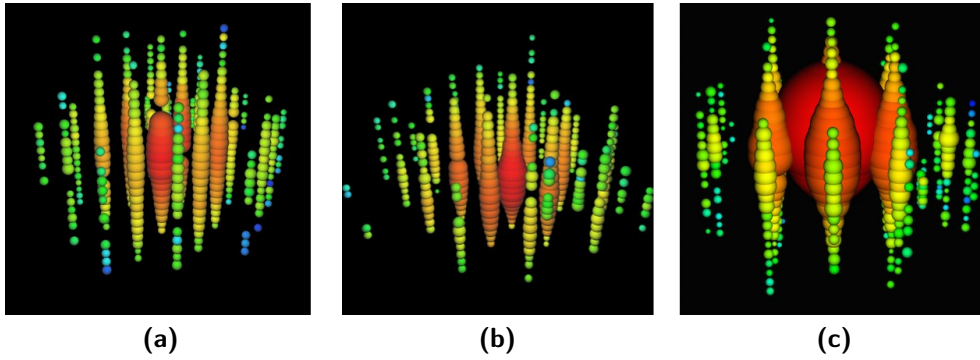


Figure 1.19: Images showing the three "big" events: (a) "Bert" (~ 1 PeV), (b) "Ernie" (~ 1 PeV) and (c) "Big Bird" (~ 2 PeV) [93].

times before losing enough energy to fall below the Cherenkov threshold; this means that electron neutrino events cannot typically be used to point back to sources, but they are more likely to be fully contained in the detector, and thus they can be useful for energy studies [93]. These events are more spherical, or cascade-like, than track-like; on the other hand, muon neutrino events are more track-like. Tau leptons can also create cascade events, but are short-lived and cannot travel very far before decaying, and are thus usually indistinguishable from electron cascades.

A pair of high energy neutrinos were detected in 2013. Possibly of astrophysical origin, they were in the PeV range, making them the highest energy neutrinos discovered to date. Some months later an even more energetic neutrino was discovered. Figure 1.19 shows these three large energy events.

1.4.2 Radiochemical detectors

Radiochemical experiments played a fundamental role in understanding the solar neutrino problem mentioned in section 1.1. Their working principle is as follows:

- suitable target atoms (^{37}Cl or ^{71}Ga) are struck by electron neutrinos, and capture them via the inverse beta decay (equation (1.12))
- the daughter atoms are isolated and put in a small proportional counter
- their electron capture decay is observed through the detection of characteristic X-rays and Auger electrons
- the daughter atom concentration and the incoming neutrino flux are computed.

Due to their nature, these experiments can only observe electron neutrinos, with an energy threshold determined by the initial reaction (814 keV for ^{37}Cl , 233 keV for ^{71}Ga). The critical requirements for these experiments are the following:

- efficient extraction of daughter atoms, which is generally performed through bubbling of the Helium or Nitrogen gas in the tank containing the target in liquid phase
- shielding of the target from cosmic rays, generally performed by building the apparatus under several km-water-equivalent of rock
- shielding of the target from fast neutrons
- minimization of the background radioactivity, which requires the employment of extremely radiopure materials for all parts of the apparatus and the minimization of the active volume in the proportional counter
- minimization of background counts in the proportional counter, which requires active (through anticoincidence scintillators) and passive (through lead or mercury absorbers) shielding from cosmic rays and an event selection through pulse shape discrimination techniques.

One of the most important experiments of this type was the Homestake experiment. It was headed by the astrophysicists Raymond Davis Jr. and John N. Bahcall in the late '60s [13]. Its purpose was to collect and count neutrinos emitted by the nuclear fusion taking place in the Sun. Bahcall performed the theoretical calculations and Davis designed the experiment. After Bahcall

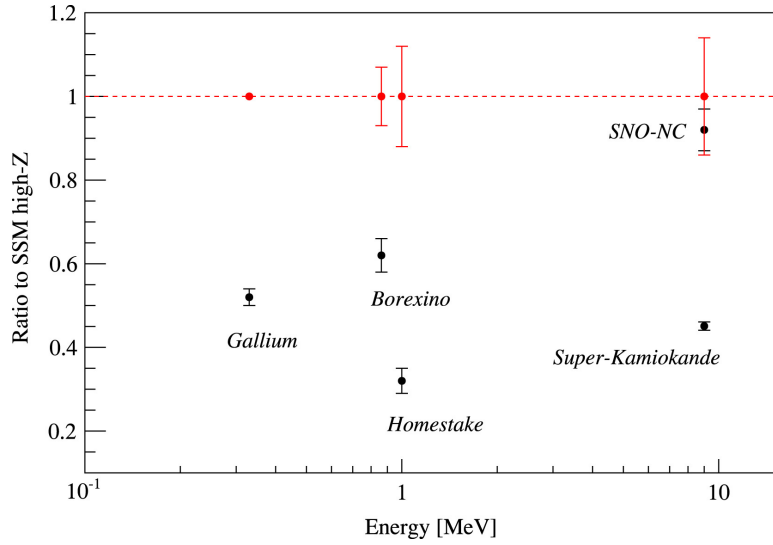


Figure 1.20: Ratio between the solar neutrino flux measured by different experiments and the values predicted by the high-Z Solar SM [97].

calculated the rate at which the detector should capture neutrinos, Davis's experiment turned up only one third of this figure. The experiment was the first to successfully detect and count solar neutrinos, and the discrepancy in the results created the solar neutrino problem.

Following the measurement performed by Homestake, two gallium-based experiments were launched, hoping to get a better estimate of the flux thanks to the lower threshold. These experiments were GALLium EXperiment (GALLEX) [94] in Gran Sasso (Italy) (later upgraded to GNO [95]) and Soviet-American Gallium Experiment (SAGE) [96] in Baksan (Russia). Their results confirmed that the Homestake anomaly was not related to experimental errors and/or to Standard Solar Model errors in predicting the neutrino fluxes. All the Solar Neutrino experiments reported neutrino reductions ranging from ~ 0.3 (Homestake) to ~ 0.6 (Boron solar neutrino Experiment (Borexino)) (figure 1.20). In about a decade, the joint interpretation of many available experimental results, allowed to demonstrate that the neutrino oscillation mechanism was governing the solar neutrino discrepancy and the "solar neutrino puzzle" was solved.

1.4.3 Scintillation detectors

Scintillation neutrino detectors use solid or liquid scintillators to observe and identify the interaction products. The first historical observation of

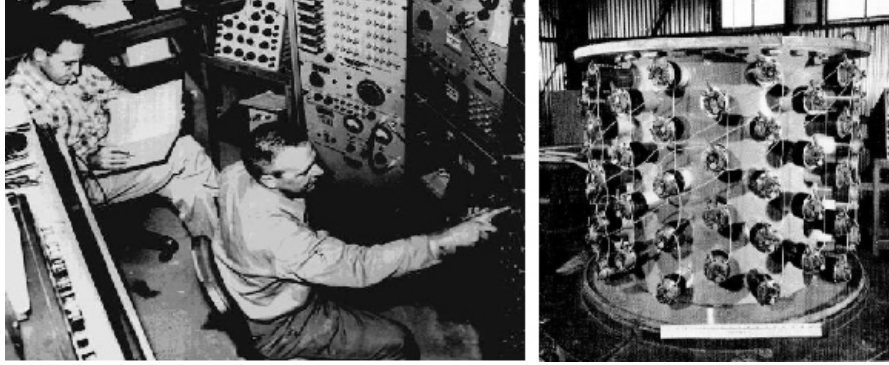


Figure 1.21: Picture of Cowan and Reines at work and the liquid scintillator coupled to PMTs [10].

(anti)neutrinos was made in 1953 by Cowan and Reines [9] [10], using a tank of liquid scintillator coupled to PMTs (figure 1.21). The detector observed the products of the inverse β -decay ($\bar{\nu}_e + p \rightarrow e^+ + n$) of the reactor $\bar{\nu}_e$ by detecting the gamma rays resulting from the positron annihilation and the photons emitted by the capture of neutrons in hydrogen atoms. In order to favour neutron capture, the scintillator was doped with cadmium.

Another example is the KamLAND experiment [17] which performed oscillation measurements with reactor antineutrinos. It consisted of a 1 kTon liquid scintillator volume, positioned at an average of 180 km from 53 different reactors; a schematic diagram is presented in figure 1.22. The scintillator volume was placed in a transparent nylon balloon, suspended in non-scintillating oil and surrounded by PMTs. The cosmic ray veto in this case was an outer water Cherenkov detector, which also reduced the background coming from radioactivity in nearby rocks.

1.4.4 Liquid Argon Time Projection Chambers

A Time Projection Chamber (TPC) is a detector that reconstructs the three-dimensional track of an incoming particle through the drift of the charges produced by ionization in a gaseous or liquid medium. In a TPC, anode and cathode planes generate a drift field of several hundreds V/cm. A field cage (a series of electrodes at growing potentials) improves the uniformity of the field over the whole drift volume. As a particle crosses the detector, it ionizes the active medium. Electrons drift towards the anode, which is composed of N wire planes, with different orientations. The $N - 1$ innermost planes are biased so that the electrons drift past them and produce signals

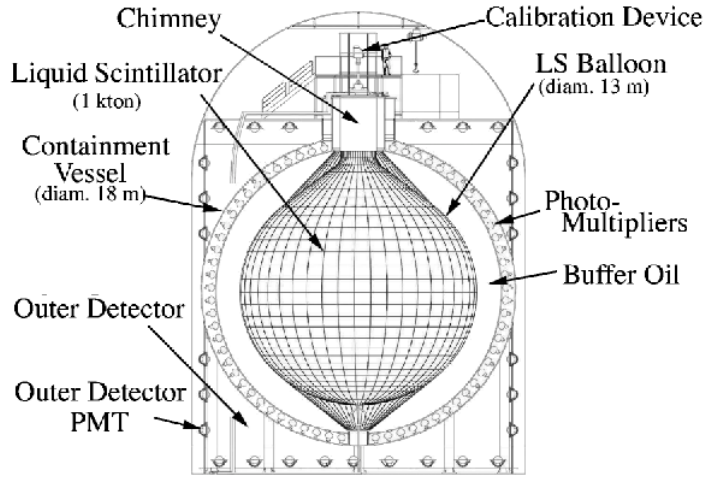


Figure 1.22: Schematic diagram of the KamLAND detector [17].

via induction, while the very last plane collects them. Often, a segmented endcap, positioned behind the last plane, acts as an additional induction plane. A schematic example of a basic TPC is shown in figure 1.23a and a picture of the ICARUS LAr TPC is presented in figure 1.23b.

Using the signals induced in the wires, it is possible to perform a 2D track reconstruction in the plane transversal to the drift direction. The position of the track portion along the drift axis can be computed knowing the drift velocity and the rise time of the anode plane signals with respect to the arrival time of the particle in the active volume. The latter can be easily measured by means of a fast external trigger in the case of a charged particle crossing the detector from outside. Such a strategy cannot be used with neutrinos, which interact - and thus generate a detectable final state particle - inside the active volume.

The solution to this problem is offered by the Liquid Argon Time Projection Chamber (LAr TPC) which produces scintillation light detected by photon detectors positioned inside the active volume, which can be used to determine the interaction time. They provide also information on the time features of the light signal that can be used for particle identification. Liquid Argon has various advantages: since it is a noble element, ionising radiation-produced electrons will not be absorbed as they go toward the detector readout; it is a moderately dense (1.4 g cm^{-3}) element and since it is also moderately priced, large-scale applications are possible. The LAr TPC concept was first proposed in 1977 [98] and applied in Imaging Cosmic And Rare Underground Signals (ICARUS) [99], at Laboratori Nazionali del Gran Sasso (LNGS) (Gran

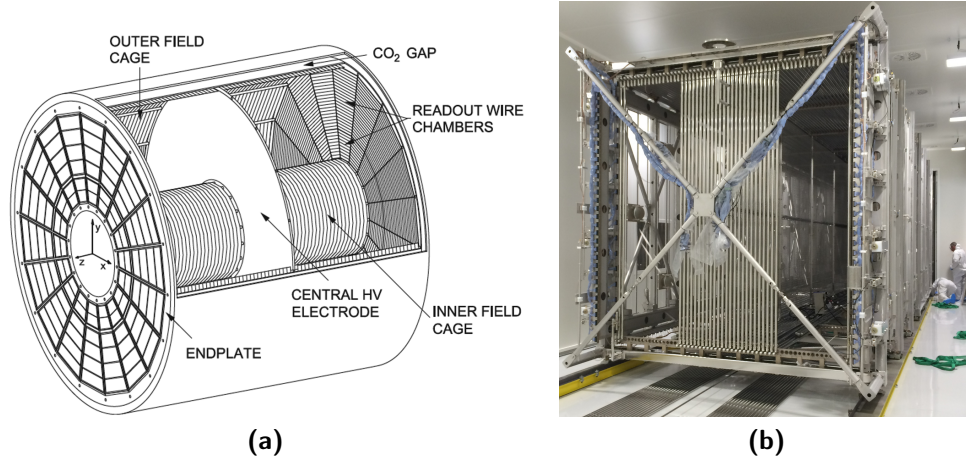


Figure 1.23: (a) Schematic diagram of a TPC detector [100] and (b) picture of the ICARUS LAr TPC detector [100].

Sasso, Italy).

1.4.5 Energy and track detectors

A calorimeter is a type of detector that measures the energy of particles via destructive measurements. In particular, sampling calorimeters consist of alternating layers of an absorber material (typically iron or lead) and an active medium. When a particle enters the calorimeter, it starts a shower in which its energy is deposited in the active layer, collected and measured. Typically, calorimeters are segmented transversely to provide information about the direction of the particle or particles, as well as the deposited energy, while the longitudinal segmentation can provide information about the identity of the particle based on the shape of the shower as it develops.

Examples of sampling calorimeters (iron alternated to organic scintillator planes) are: the NuTeV [70] and MINOS [64] experiments which operate in the 30 – 300 GeV energy range.

Bubble chambers were widely used in earlier neutrino experiments. A bubble chamber consists of a volume of superheated transparent liquid immersed in a magnetic field. When an ionizing particle crosses the liquid, a track of microscopic bubbles is formed. Cameras positioned around the chamber photograph the track and allow a three dimensional reconstruction of the event. The magnetic field is used to compute the particle charge and momentum. The Gargamelle bubble chamber observed neutral currents for the first time [101] in the $\nu_\mu e^-$ scattering: an example is shown in figure 1.24.



Figure 1.24: Example of a track from a neutral current interaction in the Gargamelle bubble chamber [102].

In order to increase the density (and therefore the interaction probability), the 4.8 m long, 1.8 m diameter chamber was filled with heavy freon (CF_3Br).

This thesis work has been performed in the framework of the ENUBET project, whose goal is the measurement of the ν_e flux with a precision of $\sim 1\%$, using a positron tagger consisting of a sampling calorimeter placed in the decay tunnel. This project represents a real milestone for present and future neutrino experiments. The ENUBET project and its largest prototype, the Demonstrator, will be described in chapter 2.

Chapter 2

The ENUBET experiment

Among the main goals of the current and future neutrino oscillation experiments, the measurement of δ_{CP} , the neutrino mass ordering and a better determination of the oscillation parameters can be listed. These goals require a considerable increase in precision and thus a reduction of the systematic errors to a few percent. In fact these measurements need to compute the neutrino interaction event rate, which is the product of three variables: the neutrino flux, the interaction cross section and the detector efficiency.

The ν_e and ν_μ fluxes are typically estimated from a full simulation of the meson beam production and transport from the target to the beam dump and validated by external data. The uncertainties on such values depend mainly on the production of mesons and their transport, which both generate non-negligible systematics. For this reason, neutrino fluxes are subject to considerable uncertainties, of the order of 5 – 10 % [53].

With the development of a monitored neutrino beam, the ENUBET project aims at producing a pure, intense and well-controlled source of electron neutrinos, in order to achieve a $O(1\%)$ precision on the neutrino flux determination [53].

This chapter will provide a description of the ENUBET project and of its features, concentrating in particular on the detectors to monitor the neutrino flux and on the large scale final prototype, the so called Demonstrator.

2.1 The ENUBET project

The idea behind Enhanced NeUtrino BEams from kaon Tagging (ENUBET) (ERC-Consolidator Grant-2015, 681647 (PE2) [103] [104]) is to design a pure and controlled source of electron neutrinos and to monitor the neutrino flux

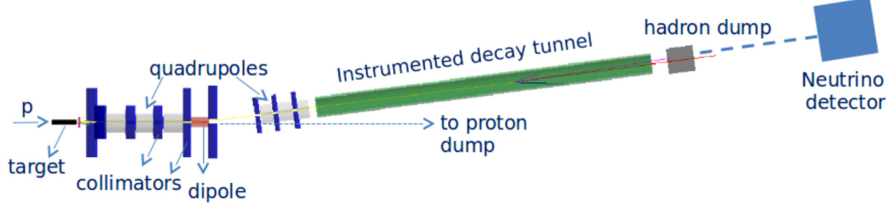


Figure 2.1: Layout of the ENUBET static transfer line [105].

Table 2.1: π^+ , K^+ decays and in the last column if they produce signal or background [19].

Decay		Comment
$\pi^+ \rightarrow \mu^+ \nu_\mu$		Hadron dump
$K^+ \rightarrow \mu^+ \nu_\mu$		Background
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$		Background
$K^+ \rightarrow e^+ \pi^0 \nu_e$	called K_{e3}^+	Signal
$K^+ \rightarrow \mu^+ \pi^0 \nu_\mu$	called $K_{\mu3}^+$	Signal
$K^+ \rightarrow \pi^+ \pi^0 \pi^0$		Background

directly inside the decay region by detecting large-angle leptons generated in the K_{e3}^+ three body decay ($K^+ \rightarrow e^+ \pi^0 \nu_e$) using sampling calorimeters with plastic scintillators placed inside the decay pipe.

In other words, the decay tunnel (tagger) itself is the detector. Figure 2.1 presents the static beamline configuration. The pions and kaons produced by the primary protons hitting the fixed target are focused (with collimators, quadrupoles and dipoles) and transferred through the instrumented decay tunnel. The tunnel is a hollow cylindrical electromagnetic calorimeter with an inner radius of 1 m and a length of 40 m. Figure 2.2a shows a general view of a part of the instrumented tunnel where the K_{e3}^+ decay takes place.

The main particles in the decay tunnel are positrons, charged pions, π^0 s (which decay into two photons) and muons. The electron neutrino component is determined by monitoring the large-angle positrons from the K_{e3}^+ decays in the decay tunnel. For this reason, the tagger has to detect positrons and distinguish them from photons, in order to identify the K_{e3}^+ decay.

The spectra of the particles entering the decay tunnel are shown in figure 2.3. However, not all the particles will produce a signal: most of them will be a source of background (table 2.1). The signal is given by the photons and positrons which produce electromagnetic showers in the layers of the electromagnetic calorimeter.

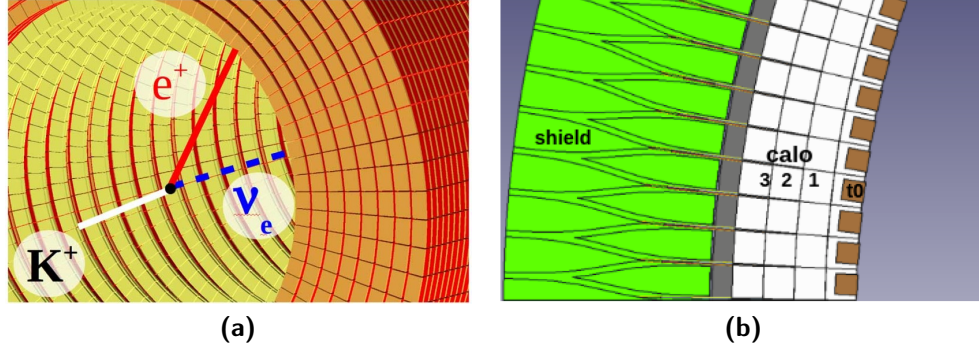


Figure 2.2: (a) A general scheme of the ENUBET decay tunnel with the K^+_{e3} decay. (b) The tagger layout, from right to left: the photon-veto (t_0) layer, three layers of the electromagnetic calorimeter (calo 1, 2, 3) and the Borated PolyEthylene (BPE) shield [85].

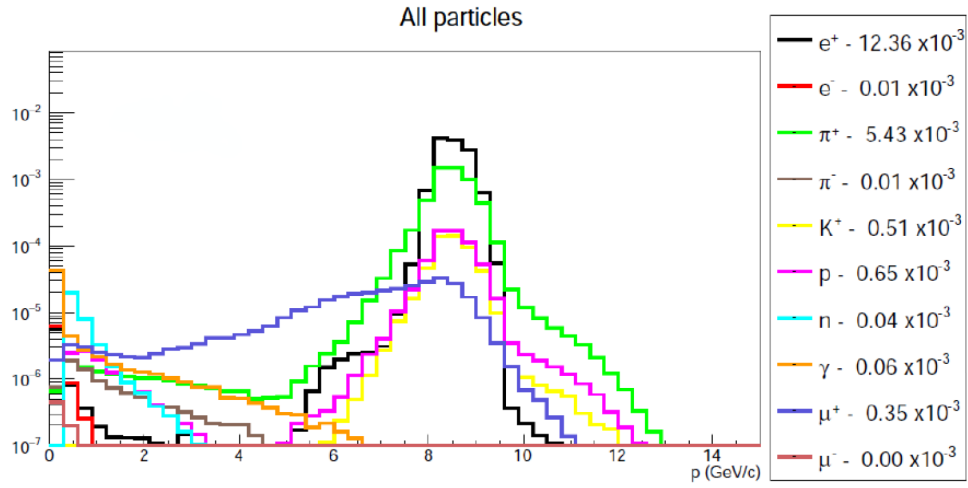


Figure 2.3: Particle spectra at the decay tunnel entrance normalized to the number of protons on target [106].

The ENUBET electromagnetic calorimeter is a longitudinally and radially segmented calorimeter. It is fast (recovery time ~ 10 ns) and is cost-effective [107]. Moreover, being segmented both longitudinally and laterally, it has a good space resolution and particle identification capability [108] [109].

The segmented calorimeter is made of elementary units called Lateral readout Compact Modules (LCM). Each LCM (figure 2.4) consists of five 1.5 cm thick iron slabs, coated with zinc, interleaved along the longitudinal direction with 0.7 cm thick layers of plastic scintillator (made of Polyvinyltoluene). These active layers are segmented along the radial direction and consist of three $3 \times 3 \times 0.7$ cm³ scintillator tiles, for a total transversal area of 9×3 cm². In order to detect positrons and distinguish them from photons, the two upstream active layers are instrumented with an additional tile placed in the innermost radial layer, the so called t_0 photon veto layer (figure 2.4a). Photons produced in the decay tunnel, will not give a hit in the t_0 layer associated with an energy deposit in the calorimeter, and will not be misidentified as positrons. On the other hand, if there is material at an inner radius with respect to the t_0 layer, such as the beampipe, and photons convert by interacting with it, they constitute a source of background, because the ENUBET positron tagger does not exploit the time correlation among particles. The t_0 layer is an inner layer of the instrumented decay tunnel and comprises two plastic scintillator tiles ($3 \times 3 \times 0.7$ cm³) every 7 cm.

The optical readout scheme of the LCM tiles ensures optical isolation between the modules. Each tile is read out by two WaveLength Shifting (WLS) fibers, that exit the detector in the outward radial direction (figure 2.4a). The fibers have a diameter of 1 mm and are glued into the grooves (1 mm deep with a squared shape) hosted by the scintillator tiles.

There are two types of grooves:

- "Readout" grooves to which the fibers are glued for light collection
- "Transit" grooves hosting the readout fibers coming from the other tiles; they must not collect light from the tile they are crossing.

Each tile has a different layout in terms of the number of readout and transit fibers. This means that the scintillator tiles need to host also the fibers that read the other tiles. The readout scheme is shown in figure 2.5. Since there are also the t_0 veto tiles, the LCM can be seen as composed of three layers of "triplets" (electromagnetic calorimeter only, figure 2.4a) and two layers of "quadruplets" (electromagnetic calorimeter and t_0 tiles, figure 2.4a). The triplet, composed of tiles 4, 5 and 6 (figure 2.5) must host 3 couples of fibers. The readout grooves, marked in green, on tile 5 are on the back face and correspond to the transit grooves (for fibers reading tile 4) on the front

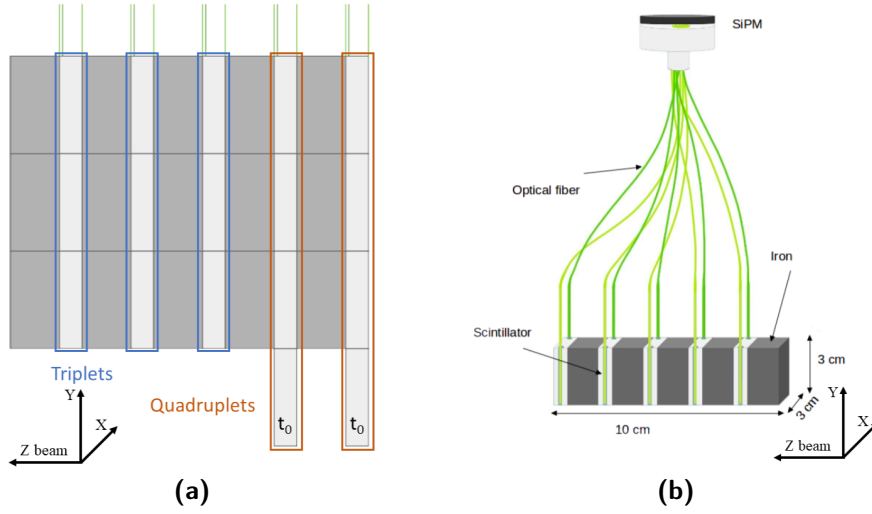


Figure 2.4: (a) WLS fibers run along the face of the scintillators and absorber planes with the same longitudinal position in the different radial channels [110]. (b) Layout of one LCM with fibers [111].

face. For tile 6 the readout grooves must be placed in a slightly offset position (2 mm away) with respect to the transit grooves (that host fibers reading tile 4). The same pattern is used for the quadruplet (figure 2.5), with the further complication of having a fourth tile from the t_0 layer that must be included in the design. The tiles were produced by Stylplex [112] and were painted with a diffusive TiO_2 -based coating to increase the light collection efficiency. An example is shown in figure 2.6.

The WLS fibers convey the collected light to Silicon PhotoMultipliers (SiPM), which perform the readout. The t_0 tiles are readout individually by

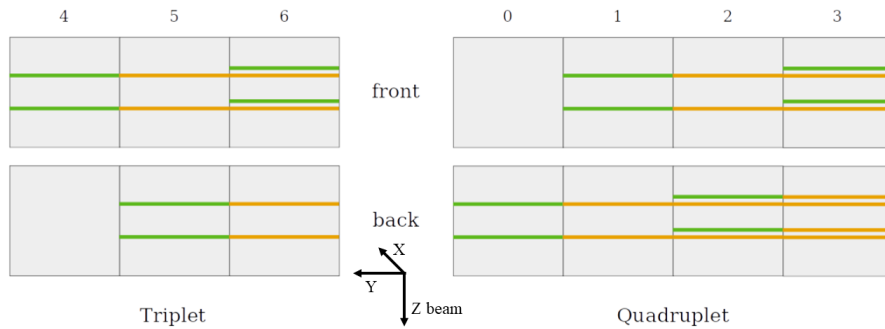


Figure 2.5: Grooves for fibers routing across the scintillator tiles: readout grooves (green) and transit grooves (orange) [110].

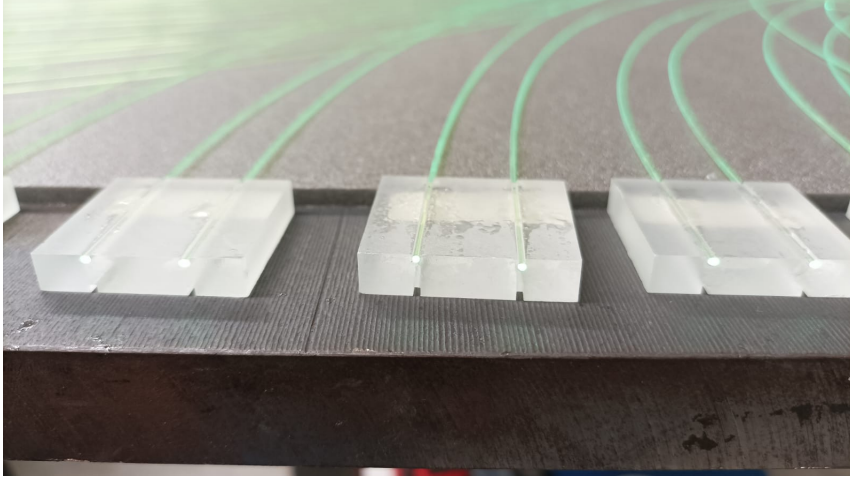


Figure 2.6: Example of scintillator tiles with WLS fibers. The tile is an example of tile 1 of figure 2.5 because it has two WLS fibers in the readout grooves in the front and two transit grooves in the back.

Hamamatsu S14160-3050HS SiPMs (with an area of $3 \times 3 \text{ mm}^2$ and a pixel pitch of $50 \mu\text{m}$). The remaining tiles of each LCM are grouped according to their radial layer; the fibers of each group are then bundled and readout by a single Hamamatsu S14160-4050HS SiPM (with an area of $4 \times 4 \text{ mm}^2$ and a pixel pitch of $50 \mu\text{m}$) [113].

A readout scheme with the WLS fibers exiting the detector radially has the advantage of reducing considerably the risk of radiation damage for the SiPMs, induced by the fast neutrons generated in hadronic showers. With this solution, the SiPMs are far from the region of the calorimeter more subject to radiation. Moreover, the neutron radiation damage has been reduced by a factor of ~ 20 positioning a shielding [114]. The shield, made of BPE, is located above the calorimeter (figure 2.2b) and has a thickness of 30 cm. The fibers cross the shield and are coupled with the SiPMs outside the high radiation inner area [115] [116] [117].

Table 2.2 summarizes the materials used for the Demonstrator construction.

The final prototype that the ENUBET Collaboration is required to build is a $3 \text{ m} \times \pi$ calorimeter with an energy resolution of $\leq 20\%/\sqrt{E}$, in order to achieve a $O(1\%)$ precision on the neutrino flux determination [53] [118]. Many prototypes were built and tested during the past years [111] [119] [120] [121] [122] [123] to choose the calorimeter configuration (from shashlik to sampling), the materials and the assembly procedure. The following section

Table 2.2: Materials used for the Demonstrator construction.

Part of the Demonstrator	Material	Manufacturer
Outer arches	BPE	LNF
Inner arches	Iron	LNF
Fibers	WLS plastic	Kuraray
Tiles	Polyvinyltoluene	Stylplex
Tiles coating	TiO ₂ paint	–
Optical isolation coating	Aluminum-based paint	–

will describe the latest prototype (Enubino) and its results while in the last section the Demonstrator will be presented.

2.1.1 Enubino

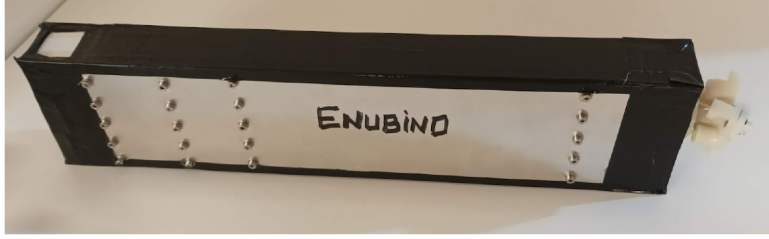
The development of a 40 m long instrumented tunnel has required dedicated feasibility studies. The first prototypes tested by the ENUBET collaboration were shashlik calorimeters with the readout WLS fibers running perpendicularly across the tiles. Many tests have been performed at CERN and at Laboratori Nazionali di Frascati (LNF) to evaluate their performance. The shashlik configuration was discarded, due to some critical issues: the low light collection efficiency and the radiation damage to the SiPMs caused by fast neutrons. As a result, the lateral light readout system replaced the shashlik option.

Enubino is the final prototype of the ENUBET tagging calorimeter before the assembly of the large number of channels one. It employs a light readout technique that was tested with cosmic rays at the INFN Laboratori Nazionali di Legnaro (LNL) and with particle beams at the CERN PS East Area, in order to assess its performance [110] [124]. The Enubino prototype is fundamentally composed of a single LCM, as described in section 2.1. A picture of Enubino is shown in figure 2.7.

Enubino has been tested in November 2021 on the T9 beamline of the CERN PS East Area facility with a 15 GeV beam. The light collection efficiency of Enubino has been evaluated considering the Minimum Ionizing Particles (MIP) impinging on the calorimeter or on the t_0 tile and crossing the entire module (all the 5 scintillator tiles of the LCM). Enubino has an efficiency of $\sim 96\%$ (figure 2.8). Moreover also its response uniformity was evaluated using MIPs. The uniformity was estimated by computing the MIP peak of the signals generated in each tile and evaluating if all the tiles have the same uniform response. In addition, the new light readout scheme that uses



(a)



(b)

Figure 2.7: (a) A plane of the Enubino detector and (b) the Enubino detector.

frontal grooves instead of lateral grooves, which was motivated by the need for large-scale production of the scintillators, has been successfully tested [110].

2.2 The ENUBET Demonstrator

The Demonstrator is a section of the ENUBET instrumented decay tunnel. This prototype is 1.65 m long in the z direction, which corresponds to 15 LCMs, and it is composed of arches of iron and plastic scintillators spanning 90° . This modular design could be extended then to a full 2π object.

The Demonstrator is housed in a custom structure (figure 2.9) with four extendable legs allowing the calorimeter tilting (in order to simulate the 60 mrad impact angle of the positrons inside the ENUBET decay tunnel to identify the K_{e3}^+ decay) and it is composed of 75 iron planes (1.5 cm thick and 11 cm high) alternated with 75 scintillator planes. Above them, the BPE arches (2.25 cm thick and 30 cm high) are placed (figure 2.10a). The iron components are made of single slabs, that have been milled in their central part in order to better accommodate the painted scintillator tiles (figure 2.10b).

The 0.7 cm scintillator tiles from Stylplex [112] have a trapezoidal shape in order to avoid dead regions. The Y11 WLS fibers produced by Kuraray [125] have been cut (figure 2.11a), smoothed with sandpaper (figure 2.11b), for a better adhesion of the paint coating, and then glued in the grooves (which

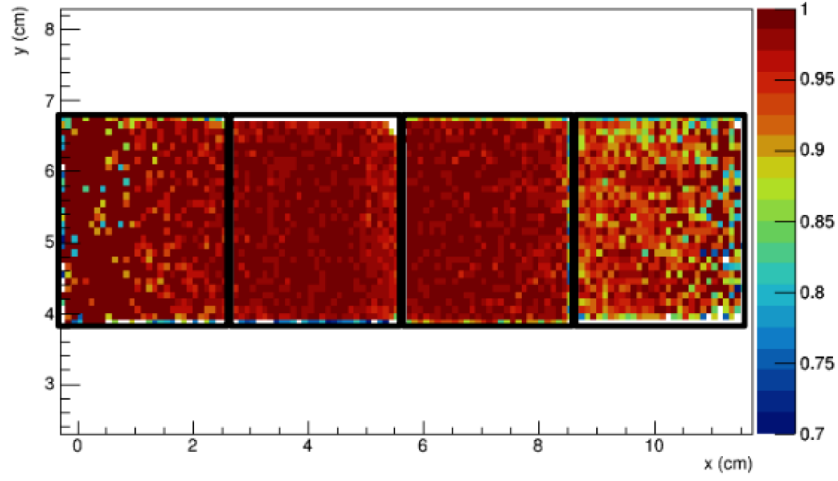


Figure 2.8: Enubino efficiency map [110].



Figure 2.9: Demonstrator cradle at LNL.

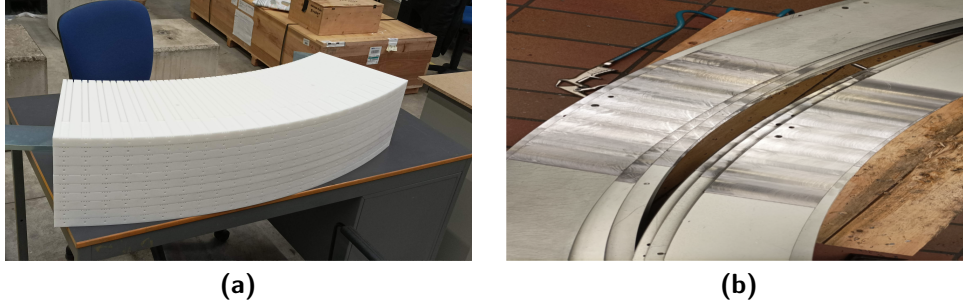


Figure 2.10: (a) The BPE arches and (b) the iron inner arches.

have a square shape) in each tile (2 fibers for each tile). The risk of obstructing the grooves with the TiO_2 coating has been reduced by painting the tiles with two layers of the TiO_2 -based paint watered down (figure 2.11c). An additional layer of Aluminum-based paint was added to the "transit" grooves for safer optical isolation (figure 2.11d).

After the planes assembly (figure 2.12a), the tiles were positioned according to the triplet/quadruplet scheme, over each iron layer, as shown in figure 2.12b. Only the 45° central part was instrumented, for mechanical reasons and for the availability of the different pieces.

The planes were finally inserted in the Demonstrator structure (figure 2.13).

To ensure the correct bundling of the fibers, a 3D printed plastic guide called "fiber concentrator" (figure 2.14), was positioned on top of the neutron shield. Every concentrator bundles the WLS fibers coming from the same type of tile from 5 planes. 80 concentrators have been placed.

The fibers were glued into place and then levelled for a good fiber to SiPM coupling. The Demonstrator consists of 400 readout channels: 240 calorimetric channels and 160 t_0 tiles. The Hamamatsu SiPMs were hosted on custom Printed Circuit Boards (PCB) called FEBs (figure 2.15) that were fixed on the top of each fiber concentrator. The SiPMs identified as S1, S2 and S3 in figure 2.15b read 10 calorimetric fibers each coming from the 5 planes of one LCM: 3 from the triplet tiles and 2 from the quadruplet tiles (figure 2.5). The SiPMs identified as S4 and S5 read the t_0 tiles of the quadruplets (2 fibers each) (figure 2.5) which are the veto tiles.

The anodes and the cathodes of the 5 SiPMs on a FrontEnd Boards (FEB) are connected to the FrontEnd Readout System (FERS) via Hirose U.FL coaxial cables [126]. To allow this connection, a metal structure has been assembled over the concentrators as shown in figure 2.16.

The Demonstrator (figure 2.17) has been tested on the PS T9 beamline at CERN. The Demonstrator has been positioned on a rail to properly move

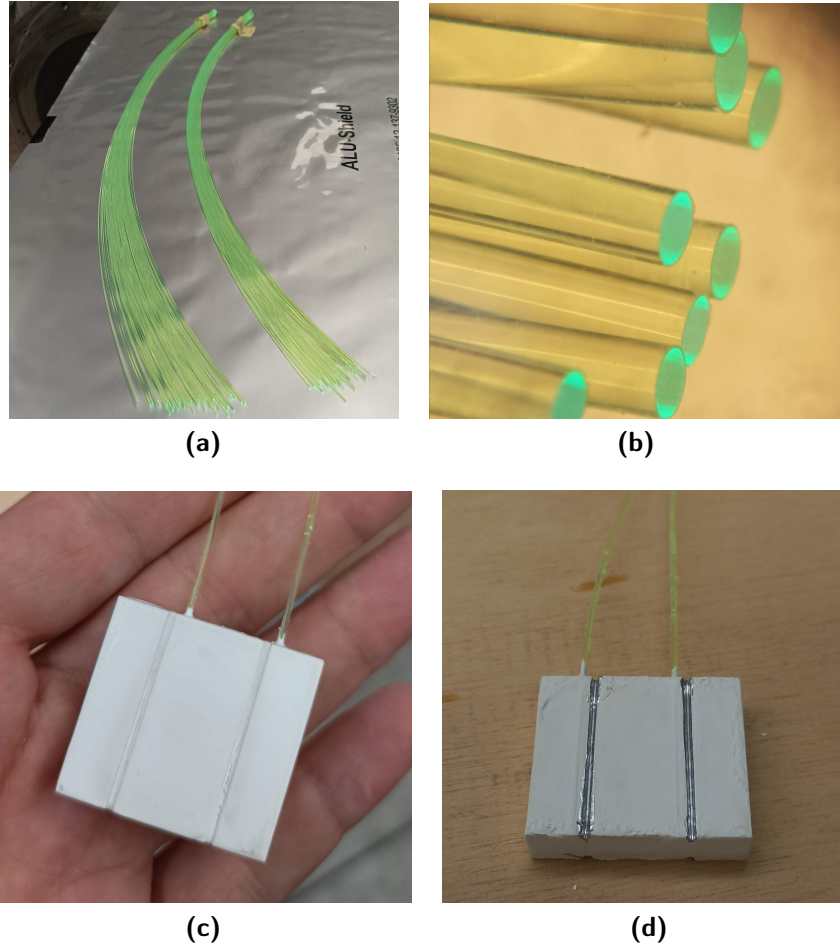


Figure 2.11: (a) The WLS fibers, (b) the polished fibers, (c) the tiles painted with TiO_2 and (d) the grooves painted with Aluminum-based paint.

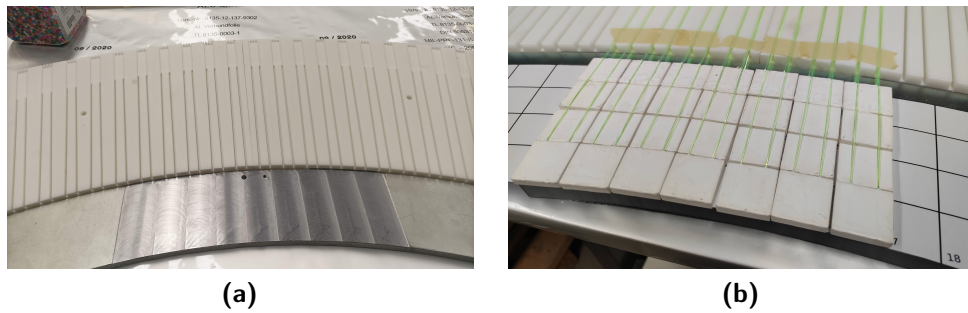


Figure 2.12: (a) An assembled plane and (b) a plane of quadruplets.

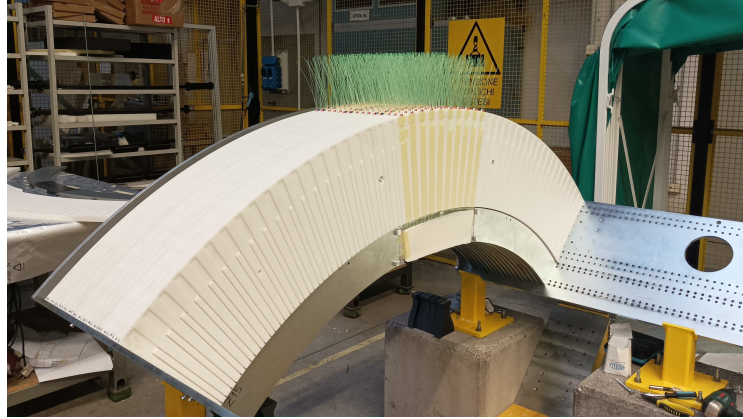
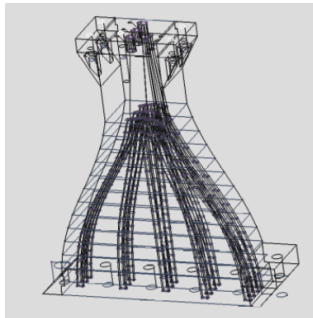


Figure 2.13: Instrumented planes in the Demonstrator cradle.



(a)



(b)

Figure 2.14: (a) The concentrator design and (b) 80 concentrators installed on the Demonstrator.

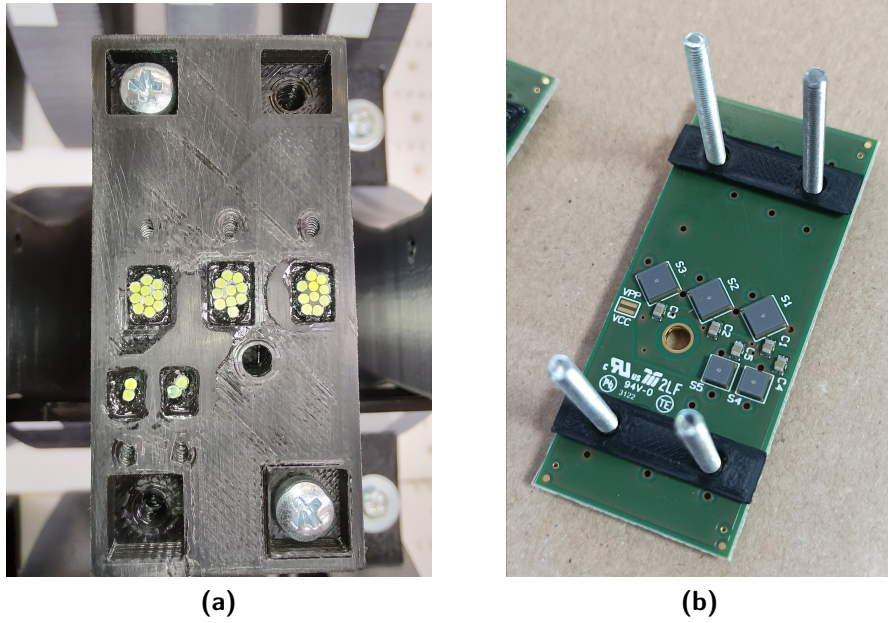


Figure 2.15: (a) The fibers glued on a concentrator and (b) a PCB with 5 SiPMs.

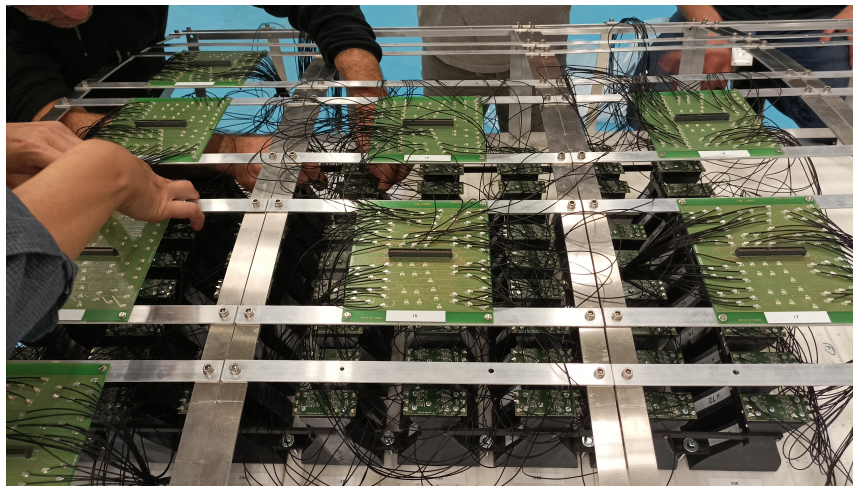


Figure 2.16: Metal structure with the interconnection boards and the Hirose cables.



Figure 2.17: The assembled Demonstrator at LNL.

it and on four extendable legs allowing the calorimeter tilting (figure 2.17). The analysis of the collected data is the main topic of this thesis work; the analysis procedure and the results will be described in chapter 4.

2.2.1 Demonstrator electronics

The frontend electronics used for the tests of the ENUBET Demonstrator is the FERS-5200 (A5202 model) by CAEN. It consists of a FrontEnd Readout System (figure 2.18a) designed to readout large arrays of detectors, such as SiPMs, multi-anode PMTs and silicon strip detectors [127].

Each unit is a $\sim 7 \times 17 \text{ cm}^2$ board which houses 64 channels and includes the FrontEnd ASIC (Application Specific Integrated Circuit (ASIC)), A/D converters, trigger logic, synchronization, local memory and the readout interface. Moreover, it has 4 coaxial connectors (2 inputs and 2 outputs) for programmable control signals.

The ASIC is based on two Citiroc-1A chip produced by Weeroc [128]. It is a 2×32 channel analogue frontend ASIC dedicated to the readout of SiPMs. Each of the 32 inputs features a low power 4.5 V range 8-bit Digital to Analog Converter (DAC) to adjust the SiPM bias-voltage channel by channel to correct for the gain and noise non-uniformity of the system. The ASIC can perform two measurements in parallel with different gains in order to

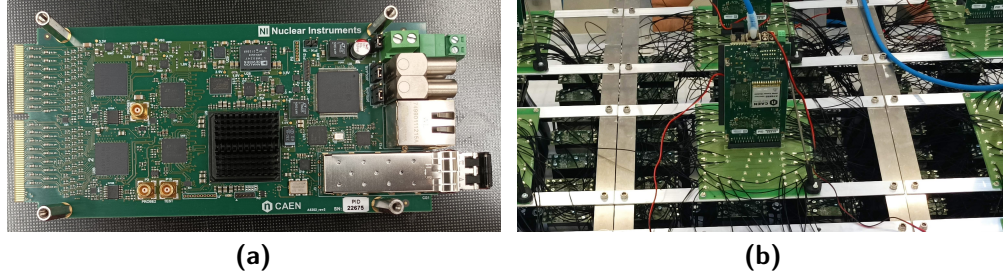


Figure 2.18: (a) A FERS board and (b) the FERS assembled on the Demonstrator.

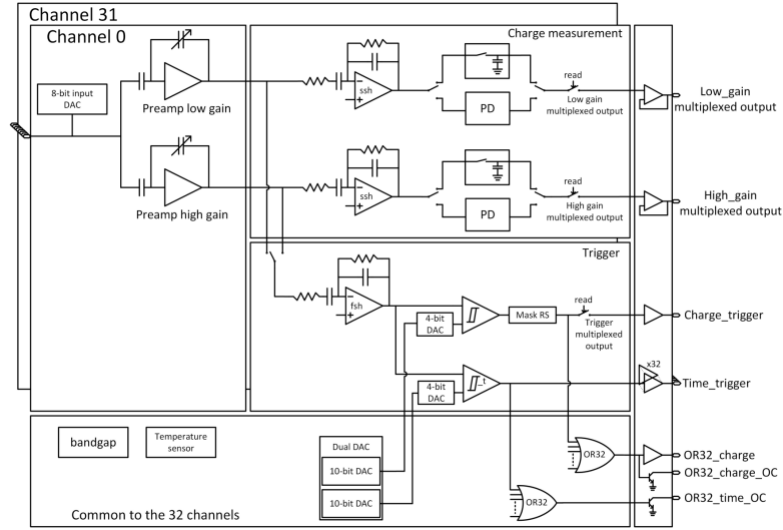


Figure 2.19: The slow shaper, fast shaper and peak detector schematic [128].

maximize the dynamic range. The possible settings are Low Gain (LG) and High Gain (HG), whose ratio is 1 to 10. For each channel, two parallel AC coupled voltage preamplifiers are embedded to ensure a dynamic range from 160 fC to 400 pC. Each preamplifier is followed by a shaper with an adjustable time constant to filter the signal bandwidth and optimize the signal-to-noise ratio. Two types of shapers can be chosen: a slow shaper (SSH) and a fast shaper. The signal from the two shapers can be sampled using a Sample & Hold or a Peak Detector (PD). The stored charge information is readout serially using two analog multiplexed outputs, one for the low gain and one for the high gain. The schematics of the slow shaper, the fast shaper and the peak detector are presented in figure 2.19.

Janus is the open source software used for the control and the readout of

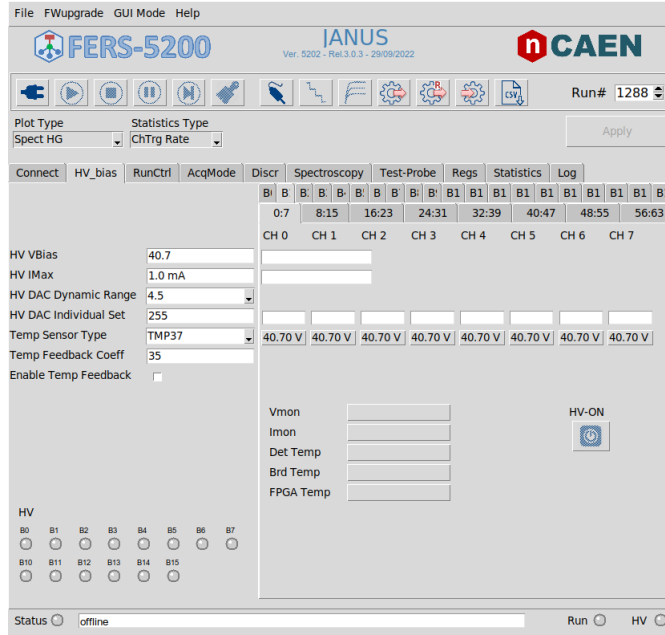


Figure 2.20: The Janus interface.

the FERS boards. The FERS is connected via Ethernet to the PC [129]. A picture of the Janus interface is presented in figure 2.20.

In order to couple the U.FL Hirose connector of the SiPMs to the A5202 boards, an intermediate step is needed, which is the interconnection board. The FERS, reading 400 Demonstrator channels, have been assembled on the interconnection board and holded by a support. In addition a fan has been mounted to prevent the overheating of the electronics (figure 2.18b).

To understand some of the Janus software features and the synchronization between the FERS readout and the tracking system one, in April 2023 a beamtest has been performed at LNF with a small prototype.

2.2.2 The April 2023 beamtest at LNF

The main goal of this beamtest was to better understand the behaviour of the ENUBET Demonstrator SiPMs with different settings of the CAEN A5202 boards: the LG and HG amplification and the shaping time of the shaper output signal. Moreover, during the October 2022 beamtest, some problems arose in the synchronization of the events between the two independent Data Acquisition (DAQ) systems: the tracking system and the FERS (more details are presented in section 3.1.6). During this beamtest, a new synchronization

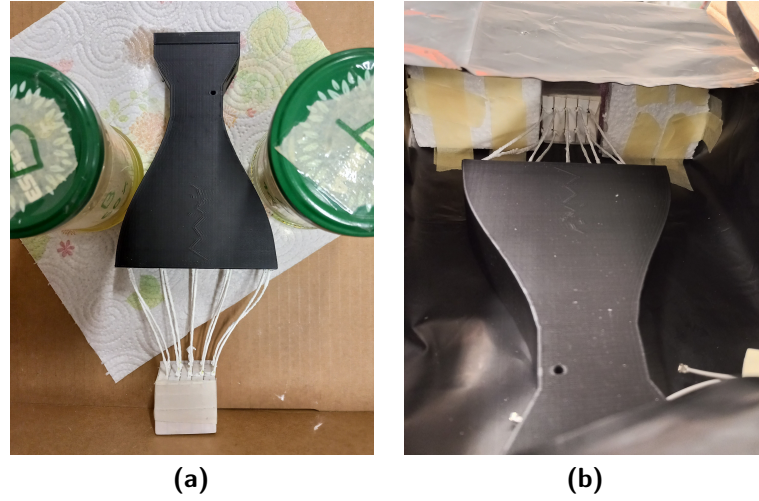


Figure 2.21: (a) Assembly of the WLS fibers in the concentrator and (b) the prototype positioned in the black box.

algorithm has been tested. Data were acquired with a 450 MeV electron beam.

The small prototype consisted of 5 scintillator tiles each one interfaced to a SiPM mounted on a PCB. Two WLS fibers for each tile have been bundled in the concentrator, cut, glued and smoothed as described in the previous section. The prototype has been positioned in a black box as shown in figure 2.21.

The black box with the prototype has been positioned on a controlled movable table (figure 2.22a) in front of a $1.92 \times 1.92 \text{ cm}^2$ double side silicon strip telescope (Si 1) and two $1.92 \times 1.92 \text{ cm}^2$ single side silicon strip telescopes (Si 2 for the y direction and Si 3 for the x direction) for the particle track reconstruction (figure 2.22b), as described in [130]. Figure 2.23 presents a simplified scheme of the experimental setup. The SiPMs were readout by two FERS: 3 tiles by the first one and the other two by the second one.

2.2.2.1 Position scan

In order to test the new configuration which allows the synchronization of the events between the tracking system and the two CAEN A5202 modules, a position scan has been performed. The trigger signal of the system was generated by the silicon detectors and sent in parallel to both the A5202 boards. The prototype has been tested with the beam impinging on the side (figure 2.24) and all the tiles were scanned with the beam. The LG

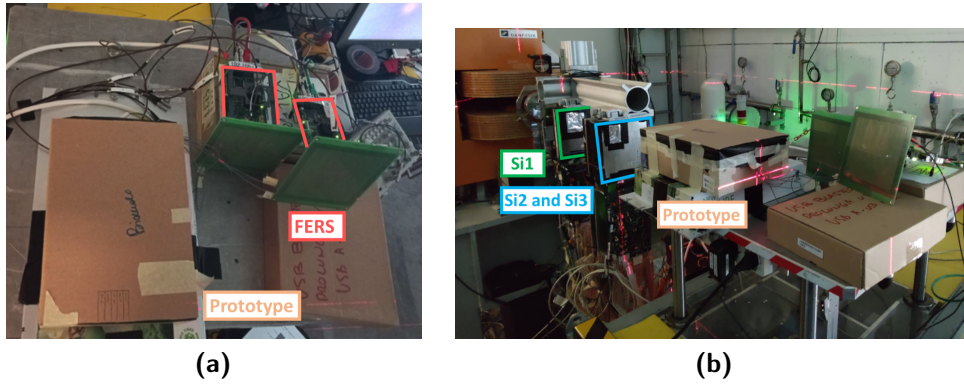


Figure 2.22: (a) Prototype on a movable table connected with 2 FERS and (b) the experimental setup.

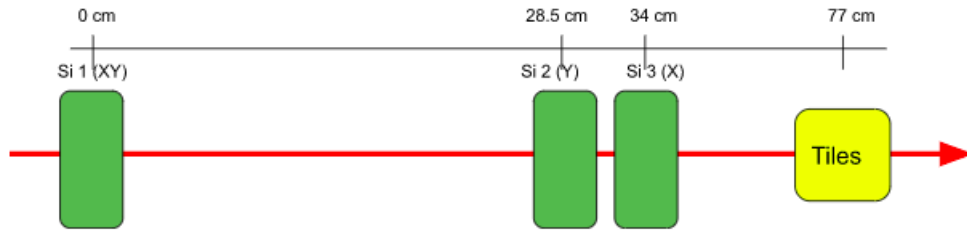


Figure 2.23: Experimental setup at LNF. The labeling notation used here is described in the text. The reported distances were measured from the center of Si 1 to the center of each element.

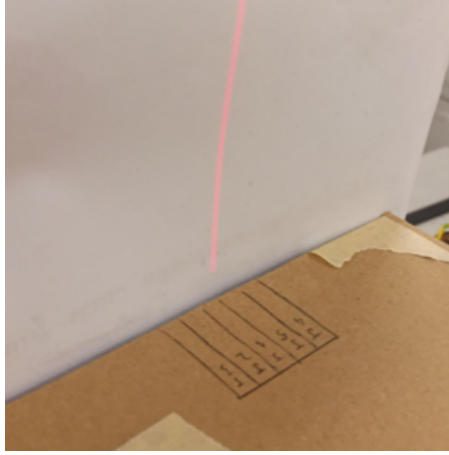


Figure 2.24: Alignment of the prototype for the position scan.

amplification was set to 35.

The silicon strip telescopes located on the beamline were manually aligned in the plane perpendicular to the beam axis. However, small offsets still existed from module to module, thus requiring an offline compensation. In order to align the second detector to the first one, the incidence angles of the electrons were computed for each event, along both the x and y axis:

$$\begin{cases} \theta_x = \arctan \frac{\Delta x}{\Delta z} \\ \theta_y = \arctan \frac{\Delta y}{\Delta z} \end{cases} \quad (2.1)$$

where Δx and Δy are the differences between the hit positions measured by the first silicon tracker and the hit positions measured by the second tracking system. Δz is the distance between the modules, along the z axis (that is the beam axis).

The distributions of the incidence angles, before the alignment, were fitted with a gaussian function (figure 2.25). The alignment was performed by subtracting the tangent value of the mean values of the gaussian functions from the measured incidence angles. The divergence of the 450 MeV electron beam along the x and y axes was computed as the standard deviation of the gaussian function fitted on the incidence angles distributions (figure 2.25). Figure 2.26 presents the projection on the prototype plane of the reconstructed beam profile in x and y .

The correct synchronization of the events has been studied computing the efficiency map for each tile. The efficiency map of a tile is the spatial

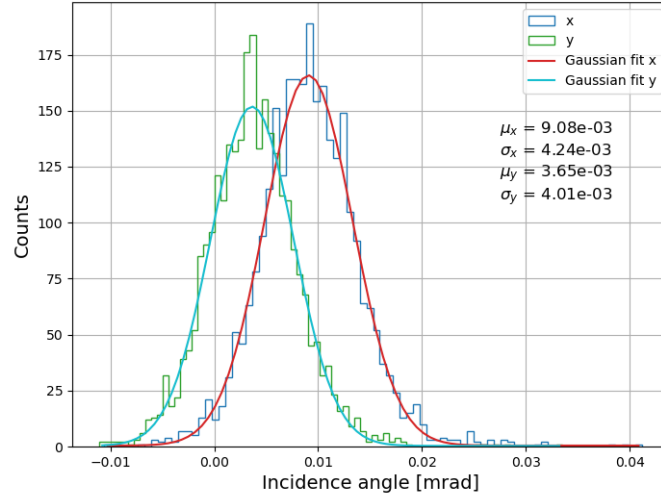


Figure 2.25: Frequency distributions of the electron incidence angles along the x (blue) and y (green) axis and the gaussian fits for the x (red) and the y (cyan) axis before the offline compensation.

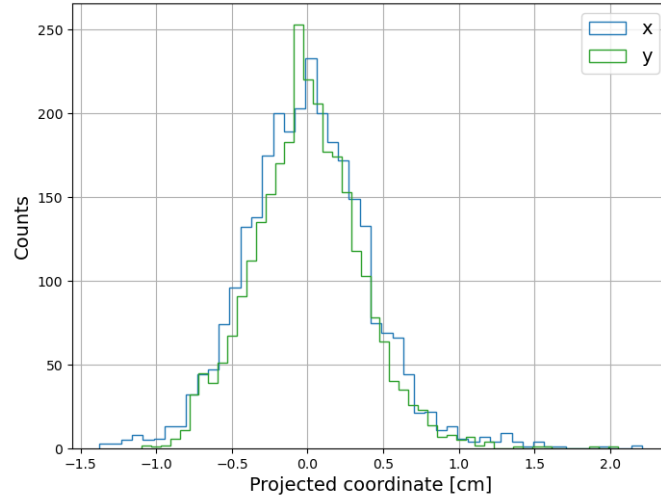


Figure 2.26: Reconstructed profile plot of the 450 MeV electron beam once aligned the detectors.

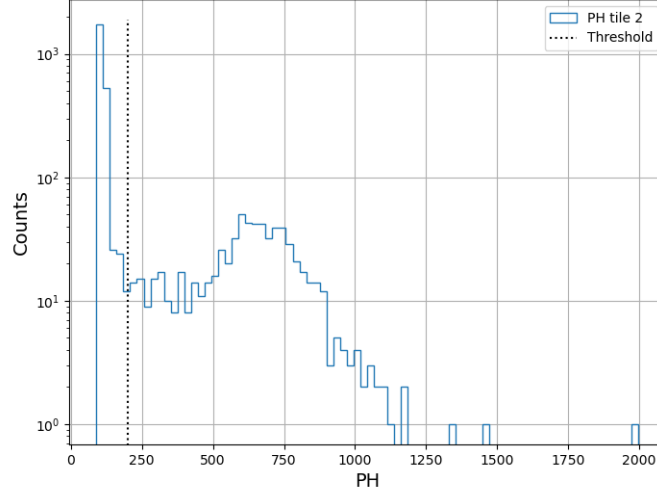


Figure 2.27: PH of the central tile of the prototype. The dotted black line is the threshold.

distribution of the fraction of the events detected by the prototype with respect to the total number of events that have crossed the tiles. In order to compute the map the following steps have been performed:

- the particle track hit on the prototype has been reconstructed
- a 2D histogram of the hits has been produced
- a threshold on the Pulse Height (PH) of each SiPM has been set in order to define the particle events
- a 2D histogram of the events with the PH larger than the threshold has been produced
- the efficiency map is defined as the ratio bin by bin of the two 2D histograms.

Figure 2.27 shows an example of the histogram of the PH for the second tile: considering the pedestal on the left, a threshold can be set at 200 ADC counts. Figure 2.28 presents the efficiency map of the 5 tiles of the prototype.

In table 2.3 the mean efficiency of each tile is presented. Independently from the good values, the fact that the plot in figure 2.28 allows to reconstruct the shape of each tile is a clear indication that the two systems are

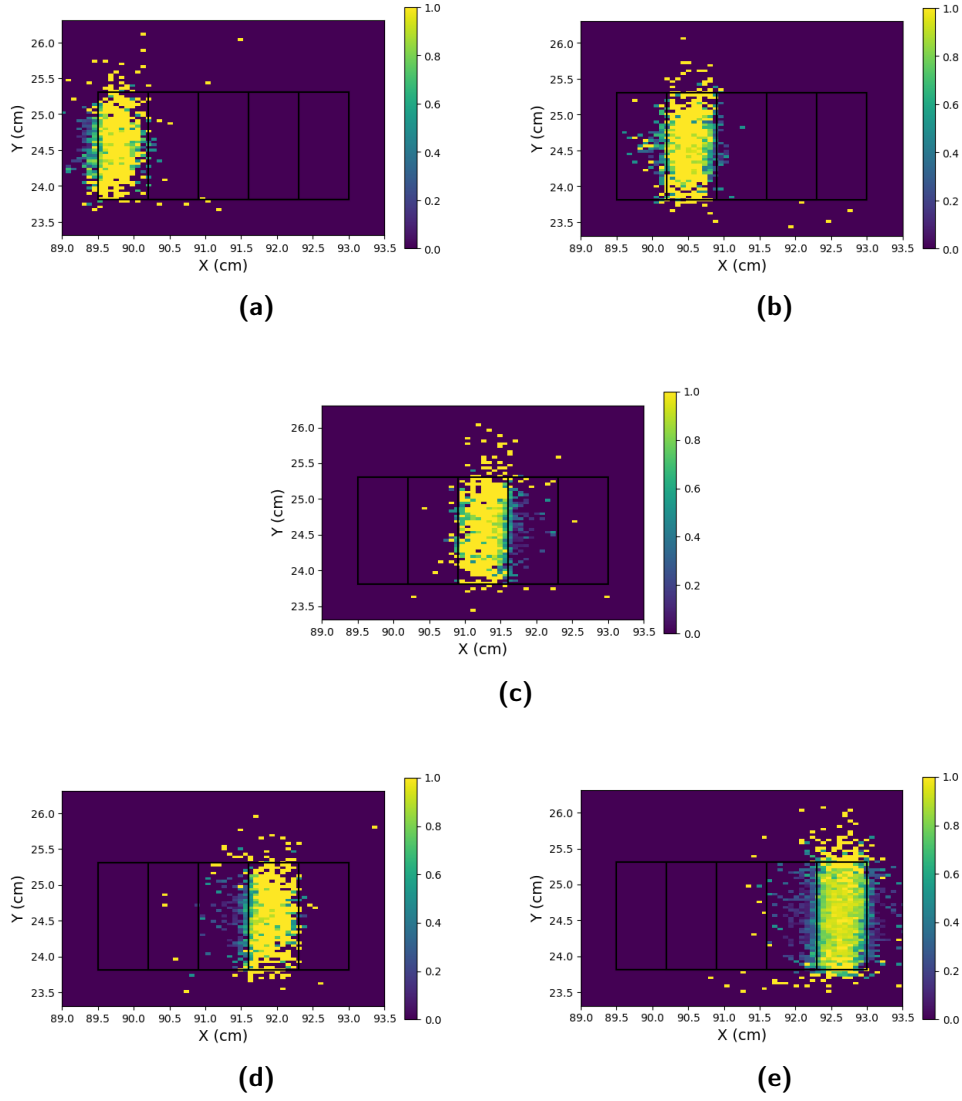


Figure 2.28: Efficiency map of the 5 tiles. The position of the tiles is indicated with the black squares.

Table 2.3: Efficiency values of the tiles.

Name	Efficiency [%]
Tile 1	95.12
Tile 2	95.47
Tile 3	95.08
Tile 4	96.41
Tile 5	91.38

synchronized. In fact, this means that the hit position (reconstructed by the tracking system) and the PH (measured by the FERS) are correctly matched.

2.2.2.2 LG and HG scan

The Janus software allows to define the value of the LG and the HG amplification chains. Both values have a range from 0 to 63 in a non linear scale. The selected values for the gain scan (both for LG and HG) were 5, 10, 15, 25, 35 and 40.

The prototype was centered to have the beam on the central tile (green tile of figure 2.29). For each gain, the histogram of the PH of the central tile has been computed and fitted with a gaussian function. Moreover, due to the asymmetric shape of the plot, the plot itself has been fitted with a Landau function. An example of the two fits for the central tile with $HG = 10$ is presented in figure 2.30.

The μ parameters of the gaussian and Landau fits have been plotted as a function of the gain and fitted with the following function:

$$y = \frac{a}{b - x} + c \quad (2.2)$$

where x are the gain values, y are the μ values of the PH fit and a , b and c the parameters of the fit function. As reported in the Janus documentation the parameters should be $a = 60$, $b = 64$ and $c = 0$ [129].

Figure 2.31 presents the fit with equation (2.2) of the HG and LG scans. In both the scans, the data for gain 40 were excluded from the fit (gray points in figure 2.31) because of the low statistics in the PH histograms which did not allow a good fit. The values with their errors for the fit parameters computed with equation (2.2) are reported in table 2.4. It can be noticed that the trend of the measured curve is similar to the theoretical one, but the values are different. Moreover, as reported in table 2.4, the a and c parameters are in agreement with the theoretical ones within 1σ (except for the LG Landau fit) and the b parameter is in agreement with the theoretical one within 2σ .

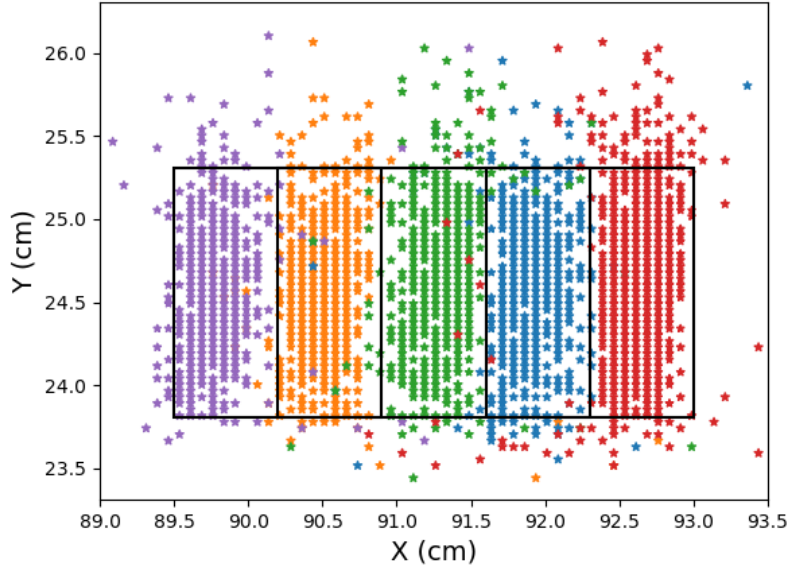


Figure 2.29: Overlap of the efficiency maps of the 5 tiles, indicated in black.

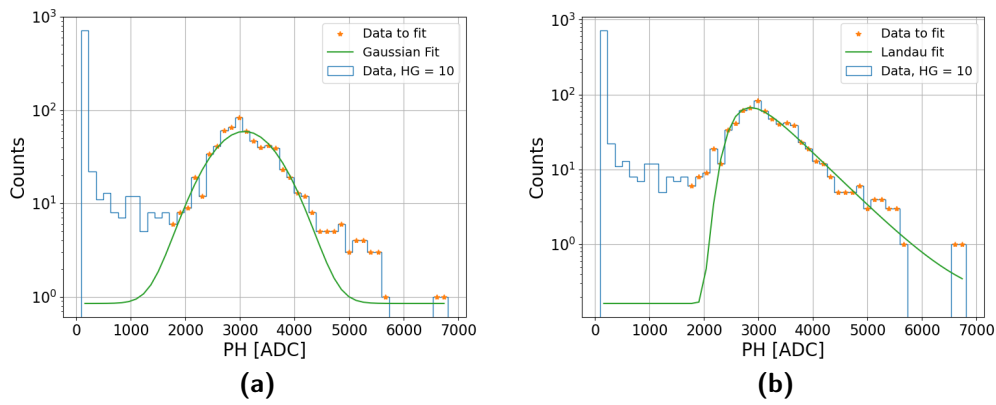


Figure 2.30: Central tile PH (a) gaussian fit and (b) Landau fit.

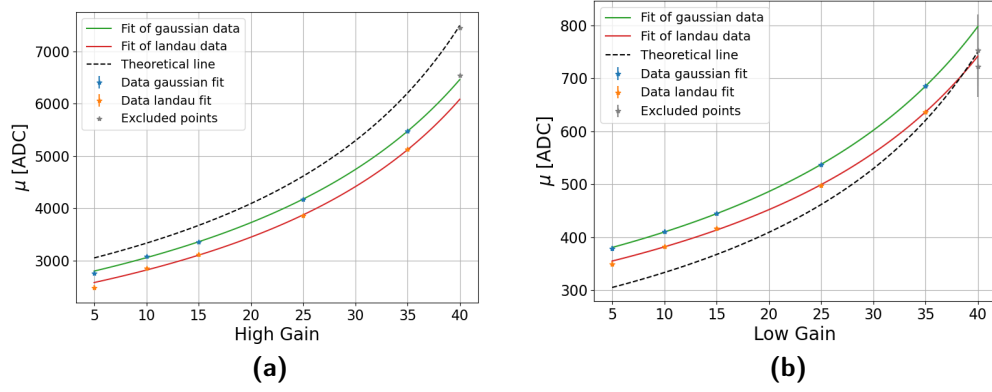


Figure 2.31: Fit with equation (2.2) of the (a) HG scan and the (b) LG scan.

Table 2.4: Parameters value and respective errors of the gain fit with equation (2.2).

Values	$a \pm \delta a$	$b \pm \delta b$	$c \pm \delta c$
Theoretical	60	64	0
HG gaussian fit	62 ± 15	69 ± 3	-0.07 ± 0.10
HG Landau fit	60 ± 10	67 ± 3	-0.06 ± 0.10
LG gaussian fit	53 ± 8	69 ± 3	0.09 ± 0.09
LG Landau fit	52 ± 7	68 ± 3	0.11 ± 0.08

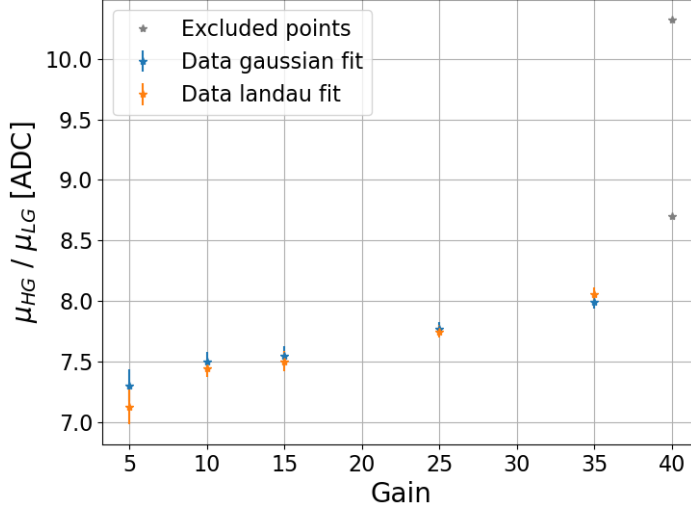


Figure 2.32: Ratio of the μ parameters for HG and LG.

Finally, the ratio between the μ parameters of the gaussian and Landau fits for HG and LG has been computed to verify the 1 to 10 ratio between the two gains (figure 2.32). It can be seen that the ratio is in the range from 7 to 8.5 and it increases with the gain. In addition the curve presents a plateau shape between gain 15 and 25.

2.2.2.3 Shaping time scan

The Janus software allows to define the time constant of the Slow Shaper circuit for the LG and HG amplification chains. 7 different values are available between 12.5 ns and 87.5 ns with a 12.5 ns step. The selected values for the shaping time scan (with LG and HG set to 10) were 25 ns, 50 ns and 75 ns.

For the scan, the prototype was centered to have the beam in the central tile (green tile of figure 2.29). The histogram of the PH of the central tile has been computed and fitted with a gaussian function, for each shaping time, to obtain the μ parameters that were then plotted as a function of the shaping time itself. Figure 2.33 presents the two plots for LG and HG. A decrease of 1.52 ADC/ns for LG and of 4.75 ADC/ns for HG has been measured.

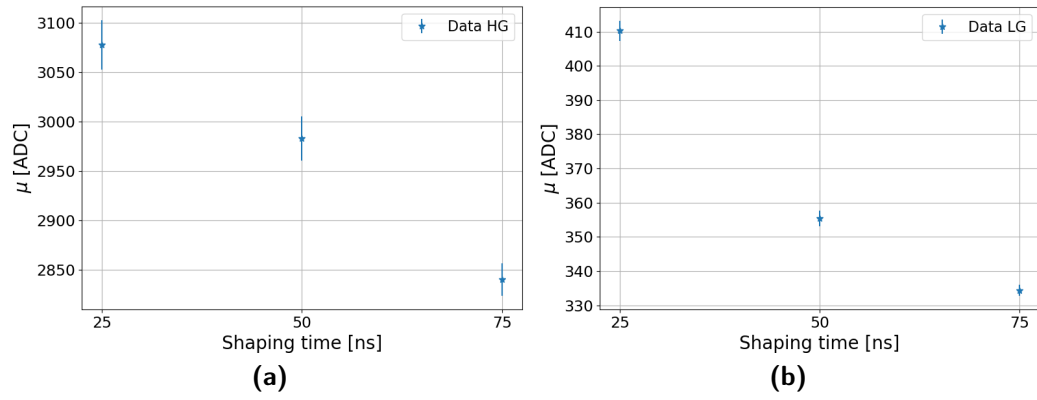


Figure 2.33: μ parameter of the gaussian fit as a function of the shaping time (a) for HG = 10 and (b) for LG = 10.

Chapter 3

The October 2022 Demonstrator beamtest at CERN

In October 2022 the ENUBET collaboration performed a beamtest at the CERN PS East Experimental area (T9 beamline), before the development of the 40 m decay tunnel. The goal of this beamtest was to evaluate the performances of the Demonstrator introduced in section 2.2. This chapter describes the experimental setup and the detectors installed in the beamline. The beamtest data analysis and results will be presented in chapter 4.

3.1 Experimental setup

The ENUBET 2022 beamtest was performed on the CERN East Area T9 extracted beamline (figure 3.1). The East Area is a multi-purpose facility, where fixed target experiments may be temporarily installed. The beam that can be delivered to such experiments is either the primary PS proton beam, featuring a momentum of $24\text{ GeV}/c$ (only to the irradiation facility), or a secondary mixed hadron beam, with a momentum of $1 - 15\text{ GeV}/c$. It is also possible to produce tertiary electron beams with a momentum of $0.5 - 6\text{ GeV}/c$ [131]. The beam composition and the features of the transported particles, namely the momentum and the polarity, are a function of the configuration of the target station, the collimator settings and also the materials present on the beamline. The beam structure foresees typical intensities of the order of $10^4 - 10^5$ particles per extraction cycle (spill) delivered during a burst of 400 ms with a repetition period of 20 – 30 s depending on the machine cycle. More details about the T9 beamline are given in [132].

Figure 3.2 presents a simplified scheme of the experimental setup installed

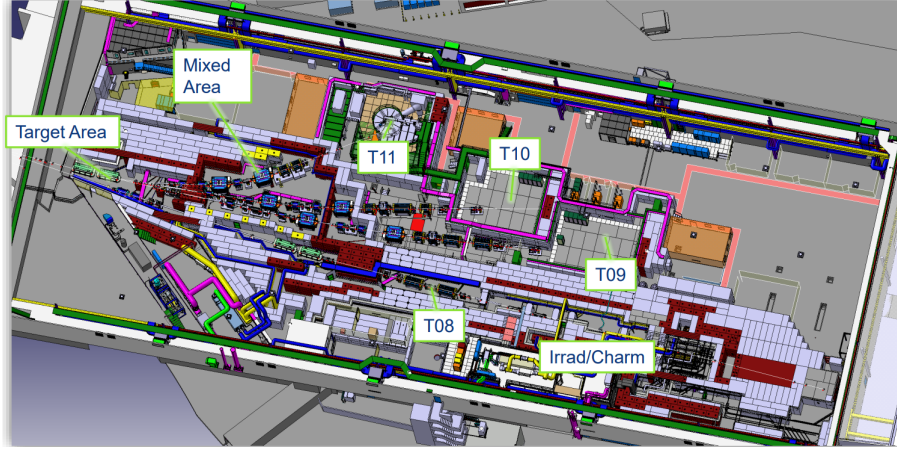


Figure 3.1: Layout of the experimental area of the T9 extracted beamline [133]. The beam is delivered from the Target area to the T09 area in the middle of the picture, from left to right.

on the T9 line. The following detectors were placed on the beamline, in order of position:

- Two Cherenkov detectors (Cher1 and Cher2), which were used to study the beam composition (section 3.1.1)
- A plastic scintillator (S1), which generated the trigger (section 3.1.2)
- Two silicon chambers (Si1 and Si2) to reconstruct the trajectories of the incident particles (section 3.1.3)
- The Demonstrator detector (DEMO) (section 3.1.4)
- Two plastic scintillators (S2 and S3), used as muon catchers (section 3.1.5).

3.1.1 The Cherenkov detectors

The two Cherenkov counters are part of the fixed T9 beamline setup, each consisting of a Cherenkov threshold selector and a PMT. The upstream counter was Cher1 (BCA - XCET044 model) while the downstream one was Cher2 (BCA - XCET048 model) (figure 3.3). They were placed against the shielding wall, close to the end of the beam pipe. From the control room, it was possible to select the gas type (nitrogen or carbon dioxide) and

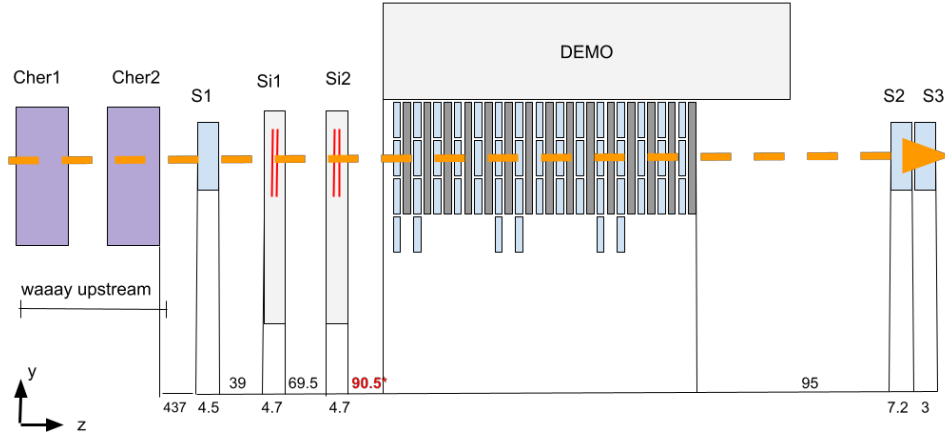


Figure 3.2: Experimental setup installed on the T9 extracted beamline. The labeling notation used here is described in the text. Only the first 3 LCMs are drawn.

its pressure. The operating pressures of the two detectors were selected so that [132]

- both Cher1 and Cher2 were sensitive to electrons
- only Cher1 was sensitive to muons
- none of them detected the remaining beam particles.

3.1.2 The plastic scintillator trigger

The trigger of the DAQ system was provided by a plastic scintillator (S1), which featured a thickness of 4cm and an active area of $10 \times 10 \text{ cm}^2$. The scintillator was mounted on a tripod 39 cm upstream the first silicon chamber (Si1, figure 3.4) and readout by a standard high voltage PMT.

3.1.3 The tracking system

The tracking system was located between the plastic scintillator trigger and the Demonstrator and was composed of two so called "beam chambers" (Si1 and Si2). Each of them consists of 2 single-side microstrip detectors, arranged in a $x - y$ configuration. They are $410 \mu\text{m}$ thick, with a $9.5 \times 9.5 \text{ cm}^2$ active area. The strip pitch is $121 \mu\text{m}$, although the readout is performed with a floating strip configuration, that is with a pitch of $242 \mu\text{m}$ to improve



Figure 3.3: The Cher1 Cherenkov counter placed against the shielding wall, close to the end of the beam pipe.



Figure 3.4: The S1 plastic trigger scintillator (orange) and the Si1 and Si2 silicon chambers (light blue). The red laser was used for the alignment of the system.

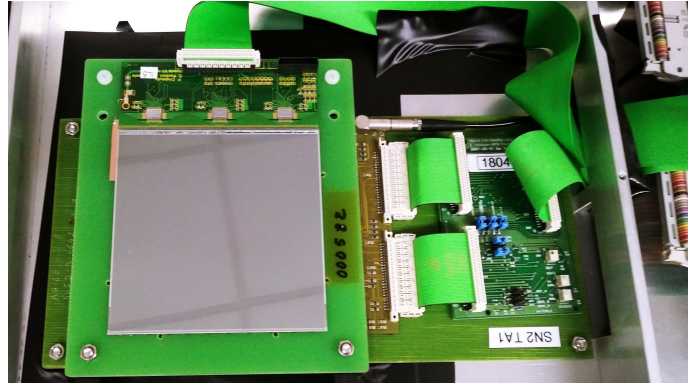


Figure 3.5: Picture of the inside of a silicon beam chamber: a single AGILE detector is visible, while the one with the strips in the other direction is placed below it.

the spatial resolution which is of the order of $30\text{ }\mu\text{m}$ [134], while maintaining under control the power consumption. One side of the beam chamber is visible in figure 3.5.

Each detector is readout by 3 ASICs (TA1), directly bonded to the strips, that perform amplification, shaping, sample & hold and mutiplexing of the analog outputs of the different strips on a single output channel. Each ASIC processes the signals of 128 strips.

The frontend readout and the DAQ were performed by an array of custom boards featuring an Altera Field Programmable Gate Array (FPGA):

- The frontend is a repeater board which provides the power to the ASICs, the bias to the detector, the digital signals (coming from the VME Readout Board (VRB)) to the ASIC and amplifies the multiplexed output of the ASICs sending it to the Analog to Digital Converter (ADC) board. The frontend electronics circuits and the ADC boards are mounted inside the box (Si1 and Si2 in figure 3.4)
- The ADC board performs the analog to digital conversion of the strip signals. The ADC receives the control signals from the VRBs and sends the digitized strip signals to the VRBs
- The VRBs receive the digitized signals from the ADC, send the control signals to the ADC and to the two repeater boards (a VRB deals with one silicon detector), receive the external trigger, produce a "BUSY" TTL signal when they receive a trigger, send and receive data to/from the PC via the Versa Module Eurocard (VME) BUS interface. The

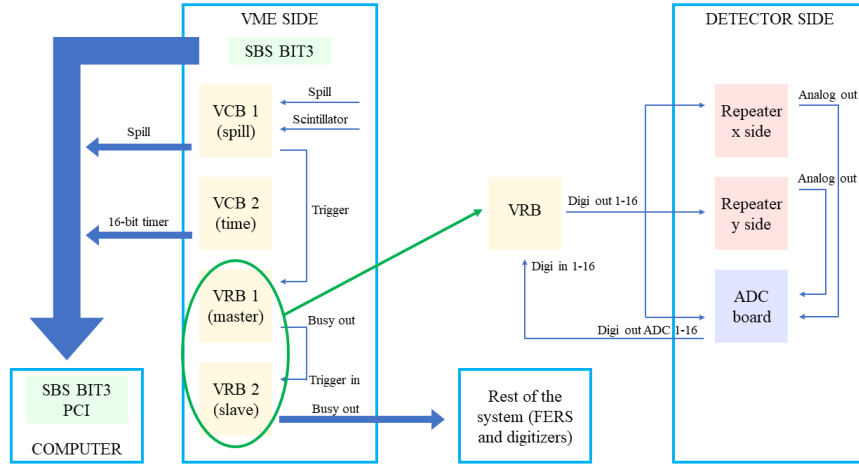


Figure 3.6: Schematic view of the electronics chain.

communication between VRBs, ADC and repeaters is done via differential digital signals. In the beamtest system, one VRB acted as "master" and received the trigger for the whole system from a VME Cyclone Board (VCB). Its BUSY signal was then used as the trigger for the other VRB. The BUSY of the second VRB was duplicated and used as a trigger for the rest of the system (the FERS reading the Demonstrator and the digitizers)

- The VCB is a multi purpose board whose action depends on the FPGA code. The 2022 system employed two VCBs: the first one received the spill signal and communicated it to the DAQ, the second one had a high precision clock to generate the event timestamp for the data of the silicon detectors and the digitizers.

Figure 3.6 presents the schematic view of the electronics chain. More information about the elements of the frontend and the DAQ can be found in [130].

3.1.4 The Demonstrator

The Demonstrator has been presented in section 2.2. Once placed in the T9 area and after having connected all the systems, a plastic cover and a cloth cover were placed above the Demonstrator itself (figure 3.7) in order to minimize the light entering.



Figure 3.7: The Demonstrator covered with a plastic and cloth cover.

The Janus software was used to control the FERS. In "spectroscopy mode" the trigger signal opens a time window (hold delay) wherein a peak sensing is performed and the maximum of the signal is sampled, communicated to the computer and saved to disk by Janus, along with the timestamp (provided by an internal clock in each A5202) of the event. This is done for all the channels, but it is performed independently for each FERS.

The external trigger was sent to the T0 coaxial input of the first FERS and then replicated onto its T0 coaxial output. The output was sent to the second FERS and so on. The in/out connectors were set to "bypassed" (via a dedicated jumper) to minimize the delay on the signal. Janus performed a periodic "synchronization" of the FERS internal clocks by sending a signal along a daisy chain made with the T1 in/out coaxial connectors.

During the beamtest, a limited number of the demonstrator channels was readout by digitizers. This was done because:

- the previous beamtests employed the digitizers for the readout of the whole prototype, making it a well tested system, as opposed to the FERS system (used for the first time)
- the digitizers sample the whole waveform (with a number of samples set by the user; in this case 512 samples), thus allowing a better insight on the shape and behaviour of the signal. On the other hand, the FERS system stores only the peak of the waveform.

7 CAEN waveform digitizers were employed: two CAEN DT5730 [135] and five CAEN V1720 [136]. One of the two DT5730 was used for the readout

Table 3.1: Features of the digitizers used in the ENUBET 2022 beamtest [135] [136].

Item	DT5730	V1720
Number of readout channels	8	8
Resolution [bits]	14	12
Maximum sampling frequency [MS/s]	500	250
Full scale range [V]	0.5 or 2	2

of several signals: the trigger scintillator, the Cherenkov detectors and the muon catchers. The other DT5730 boards and all the V1720s were used to read part of the Demonstrator. The features of the digitizers are presented in table 3.1. The control and the readout of the digitizers were performed by the DAQ software via an optical fiber interface (the CAEN A3818 PCI Express CONET2 Controller [137]). The A3818 PCI board and the digitizers were connected by an optical fiber daisy chain.

3.1.5 The muon catcher

On a DESY table (a vertical and horizontal movable platform controlled from outside the experimental area), 95 cm downstream of the Demonstrator, two plastic scintillator detectors were placed to detect muons, thus improving the information provided by the Cherenkov detectors.

The S2 detector (figure 3.8) had an active volume of $12.5 \times 19.3 \times 3 \text{ cm}^3$ made up by 12 plastic scintillator bars, readout by WLS fibers coupled to a single PMT [138]. Each bar had an area of $1.5 \times 1.9 \text{ cm}^2$ and was 19.3 cm long. Each bar was readout via two 1 mm Kuraray WLS Y-11 (200M) fibers [125]. In each module, the fibers were optically coupled to a $2.2 \times 2.2 \times 5 \text{ cm}^3$ Hamamatsu H6780 PMT module [113]. The box was an aluminum frame, with wooden boards on the front and on the back (only the wood was on the beam).

The S3 detector (figure 3.8) had an active volume of $10 \times 10 \times 1.3 \text{ cm}^3$ made by a plastic scintillator coupled to a lightguide, which was in turn coupled to a PMT. The box was in 3D-printed PLA plastic.

3.1.6 The Data Acquisition system

The DAQ system of the ENUBET 2022 beamtest was based on the VME standard [130]. The data trigger logic was the following (figure 3.9):

- the spill signal was received from the control room (SPILL)

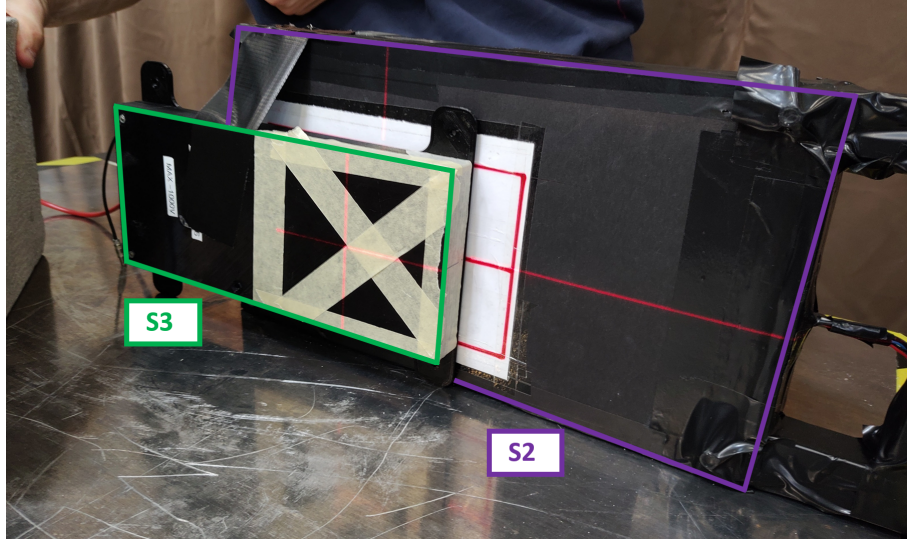


Figure 3.8: The S2 muon catcher detector (purple) and the S3 muon catcher detector (green) positioned on the DESY table. The red laser was used for the alignment of the system.

- the S1 trigger scintillator signal was discriminated (S1D)
- the S1D and SPILL signals were fed to a NIM coincidence board to acquire events only during the spill (NIM)
- the VRB acquisition boards produced a "Master Trigger" with a coincidence between the NIM trigger and the not busy of the silicon chambers, $MT = NIM \text{ AND } NOT(BUSY \text{ Si})$
- the MT trigger was sent to the beam chambers, the digitizers and the FERS
- when not enabled, MT was set to logic 1 by default.

The whole system was controlled by two main softwares: Janus controlled the FERS and a custom architecture controlled the silicon detectors DAQ and the digitizers. The custom software employed VME BUS communication C libraries to communicate with the VME boards (VRBs and VCBs) and C++ libraries provided by CAEN to communicate with the digitizers.

The DAQ software allowed to set the parameters of the system (addresses and configurations of the VME boards, number and configurations of the

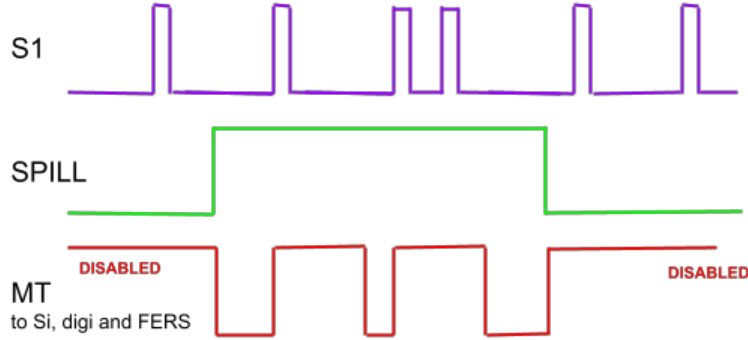


Figure 3.9: Scheme of the trigger logic.

digitizers), to perform the "pedestal" run¹ and to start and stop a regular run.

Once the run was started, the system waited until the first VCB detected the start of a spill. Within the spill, it waited for the master VRB to receive a trigger then read the event timestamp from the second VCB. Once the digitizers and the ADC have performed the readout, the master VRB reset the boards and the digitizers and waited for the next trigger. The silicon digitized signals were stored in the VRBs memories while the digitizer waveforms were stored in DAQ arrays. At the end of a spill, the system saved everything to disk, together with the event timestamps.

The data were saved in hbook ntuples [140], containing, for each event: the PH of the microstrips (384×2 sensors $\times 2$ silicon detectors), the timestamp and the waveforms of the digitizers (512 samples $\times 8$ channels $\times 7$ digitizers). The pedestal data from the pedestal runs were processed by a PAW routine [141]. The pedestal and RMS values were saved in ASCII files.

The hbook data were processed by a Fortran77 routine for the so called "online stripping", that applied a clustering algorithm to the microstrip signals to select the single particle events. For each event the algorithm identifies the "cluster" that is the group of strips detecting the passage of a particle and thus having a signal higher than a threshold set on the basis of the strip RMS. The digitizers data were analyzed by the DAQ software itself and the baseline, the maximum PH and the time of the maximum were saved in the ntuples.

The FERS data were saved independently in a binary file, containing both

¹Pedestal data for all the strips are collected in dedicated runs (~ 200 random trigger events) and then analyzed offline to compute the pedestal value for each strip (mean value of the distribution of all the events) and the noise Root Mean Square (RMS) before and after the subtraction of the common mode [139].

the LG and HG PHs of all the channels of each FERS and the corresponding event timestamps.

A Python routine² [142] converted the Janus binary data and the ASCII data to root TTrees and saved them in rootfiles [143]. Finally, a custom software³ used the FERS and Si DAQ event timestamps to match the data of the two independent systems and saved the merged data in the final root TTrees.

²Developed by Valerio Mascagna (Università degli Studi di Brescia & INFN-PV)

³Developed by Valerio Mascagna (Università degli studi di Brescia & INFN-PV), Michelangelo Pari (Università degli Studi di Padova & INFN-PD) and Leon Halić (Institut Ruđer Bošković, Zagreb, Croatia)

Chapter 4

Preliminary characterization of the Demonstrator

The characterization of the Demonstrator and of its behaviour was performed in October 2022 on the T9 beamline at CERN with electron and hadron beams. After the alignment of the tracking system, the linearity and energy resolution of the Demonstrator were computed and also the crosstalk effect was studied. Furthermore, some preliminary tests of particle identification were done. In this chapter, the data analysis procedures and the results are presented.

4.1 Preliminary analysis

This section is dedicated to the description of the analysis performed before the main data analysis, namely the offline alignment of the tracking system, the characterization of some of the used beams, the definition of the fiducial cuts and the equalization of the 400 readout channels of the Demonstrator.

4.1.1 Alignment of the tracking system

While installing the setup, the beam chambers located on the beamline were manually aligned in the plane perpendicular to the beam axis. However, small offsets could still exist from module to module, thus requiring an offline compensation. In order to align the second detector to the first one, the incidence angles of the beam particles were computed for each event along both the x and y axis with equation (2.1).

The distributions of the incidence angles, before the alignment, were fitted

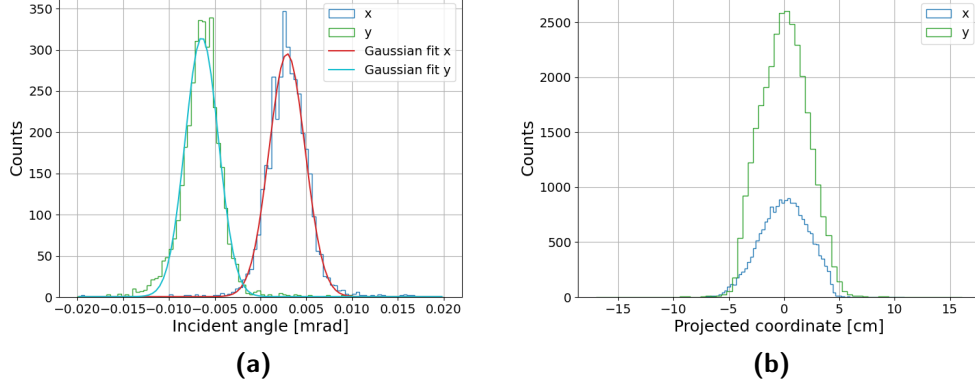


Figure 4.1: (a) Frequency distributions of the particle incidence angles along the x (blue) and y (green) axis and the gaussian fits for the x (red) and the y (cyan) axis before the offline compensation and (b) reconstructed profile plot of the 3 GeV beam centered on 0 cm projected on the first z layer of the Demonstrator.

with a gaussian function. The two distributions were not centered on 0, meaning that the two beam chambers were not perfectly on axis with respect to the beam. The alignment was performed by subtracting the tangent value of the mean values of the gaussian functions ($\mu_x = 2.91$ mrad and $\mu_y = -6.41$ mrad) from the previous coordinate:

$$\begin{cases} x' = x - D \cdot \tan \mu_x \\ y' = y - D \cdot \tan \mu_y \end{cases}$$

where x and y are the non-aligned coordinates, D is the distance between the two silicon chambers, μ_x and μ_y are the mean values of the angle distributions. The divergence of the beam along the x and y axes was computed as the standard deviation of the gaussian function fitted on the incidence angles distributions (figure 4.1a). Figure 4.1b presents the projection on the first z layer of the Demonstrator of the reconstructed beam profile in x and y centered on 0 cm after the alignment.

Moreover, since the beam was not wide enough to cover the whole Demonstrator in a single run, a position scan was performed. Figure 4.2 presents how the Demonstrator has been scanned with the beam and the beam projections on the Demonstrator plane (figure 4.2b) for a total of 2 positions along the y axis and 7 along the x axis. For the scan along the x axis, the Demonstrator has been moved with the rail it was located on; for the two positions along

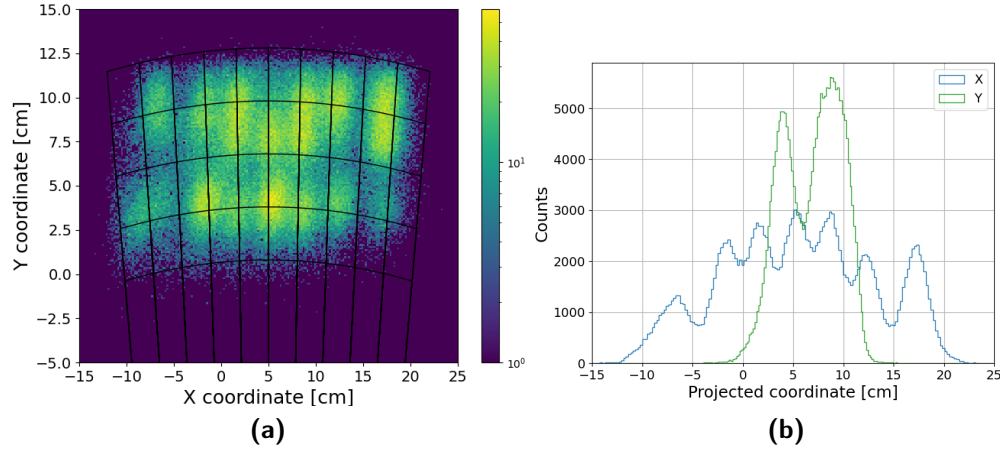


Figure 4.2: (a) Scan with the beam on the Demonstrator and (b) projection of the beam on the Demonstrator plane.

the y axis, the height of the beam was modified through the magnets of the beamline and for the tilt run, the four extendable legs were raised and lowered (figure 2.17).

4.1.2 Beam composition

In this section, the beam composition of some of the secondary electron and hadron beams is presented. The events were selected with a time cut considering that both Cher1 and Cher2 were sensitive to electrons, only Cher1 was sensitive to muons and none of them detected the remaining beam particles (figure 4.3a). Furthermore, a PH cut was obtained from the 2D histogram of the Cherenkov detectors PHs (figure 4.3b). The beam composition is presented in table 4.1. In the column "Other events" the other particle types in the beam (for instance pions) and non physical events (for instance noise of the Cherenkov detectors) are included.

4.1.3 Fiducial cuts

In order to adequately select the data for the following steps in the analysis, two different fiducial cuts (selections on the (x, y) position hit by the tracks) were defined:

- Equalization fiducial cut: this cut was performed for each single tile to select only the particles which have a trajectory fully contained along the LCM. For this reason, the 5 GeV hadron beam was used since pions

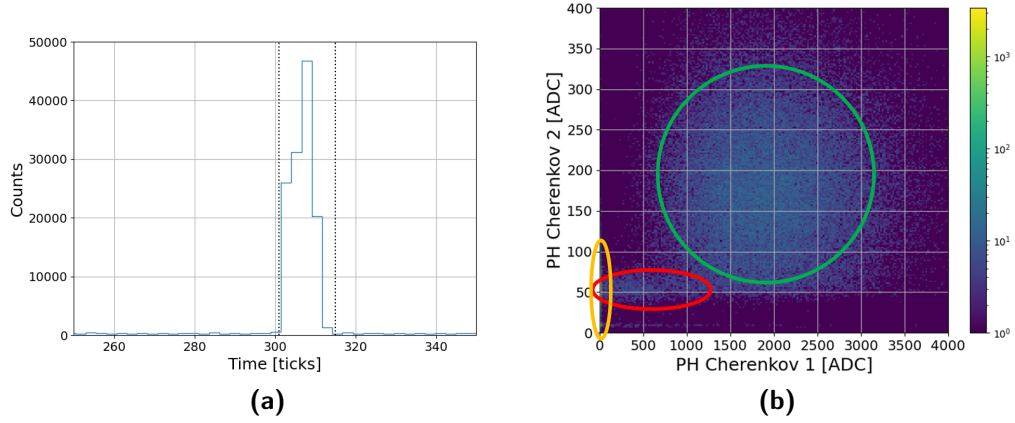


Figure 4.3: (a) Histogram of the arrival times: 1 tick corresponds to 2 ns. The dotted lines indicate the selected region. (b) 2D histogram of the Cherenkov detector PHs and the areas where the electrons (green region), muons (red region) and pions (orange region) should be.

Table 4.1: Composition of some of the secondary electron and hadron beams. In the column "Other events" the other particle types in the beam and non physical events are included.

Beam type	Energy [GeV]	Particle percentage [%]		
		Electrons	Muons	Other events
Electron beam	1	78.81	4.73	16.46
	3	61.99	4.29	33.72
	5	69.26	8.59	22.15
Hadron beam	3	0.19	1.55	98.26
	5	8.99	1.49	89.52

have a high probability to cross the first 2 or 3 layers in z without decaying given their nuclear interaction length is 16.77 cm [19]. In order to ensure the full containment, a $1.5 \times 1.5 \text{ cm}^2$ area centered in the Center Of Gravity (COG) of the tile was selected; figure 4.4 presents an example of the selected area of a tile. The COG has been estimated as the mean value of the projected events with an efficiency larger than 80 % in both directions. Moreover, the track of the particle has to cross the whole LCM. Thus the fiducial cut was applied both to the upstream layer and to the downstream layer of the LCM. If the tile had a low or not uniform efficiency or was located too downstream (where the efficiency map is affected by the smearing of hadrons interacting with the Demonstrator and the silicon track is no more the real particle trajectory), the ideal geometry of the detector has been used.

- **Linearity fiducial cut:** this cut was applied on the entire Demonstrator to contain the most significant part of the electromagnetic shower. The particle with a defined energy (fixed by the information provided by the T9 beamline) was selected with a position cut defined by the Molière radius. Such a parameter depends on the material and defines the scale of the transverse dimension of the fully contained electromagnetic shower. It is defined as the radius of the cylinder which contains, on average, 90 % of the shower energy deposit. It is related to the radiation length X_0 ¹ by the approximate relation $R_M = 0.0265 X_0 (Z + 1.2)$, where Z is the atomic number. For iron, the Molière radius is $R_M = 1.719 \text{ cm}$ [19]. In this case, the fiducial cut was defined to select the events which have an impact point falling within 2 Molière radii (which contain, on average, 95 % of the shower energy deposit) from the edges of the calorimetric tiles of the LCMs. Figure 4.5 presents an example of the selected area in the first layer of the Demonstrator.

4.1.4 Equalization

The Demonstrator consists of 400 readout channels: 240 calorimetric channels and 160 t_0 tiles readout by two different types of SiPMs. Every SiPM, which performs the readout of one channel, could have a different response, so an equalization procedure of the SiPMs is needed.

A dedicated algorithm² performed the equalization. For each channel, the MIP events, which have a trajectory in the region defined within the

¹The radiation length (X_0) is the average distance necessary to reduce the energy of an electron (positron) by a factor $1/e$, due only to radiation emission [144].

²Developed by Luca Bomben (Università degli Studi dell'Insubria & INFN-MiB).

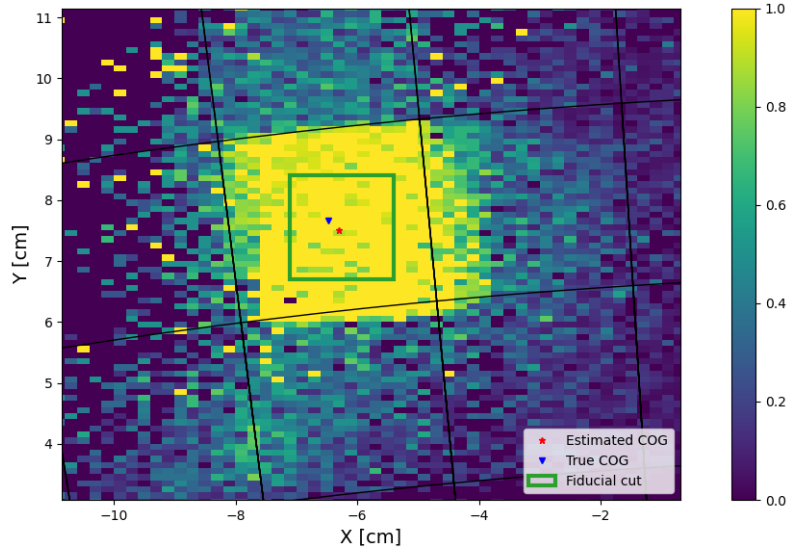


Figure 4.4: Example of the equalization fiducial cut on a tile (green). The red star is the estimated COG and the blue triangle is the expected center of the tile, given the ideal detector geometry. The distance between the two points is ~ 1 mm indicating that the COG was well estimated.

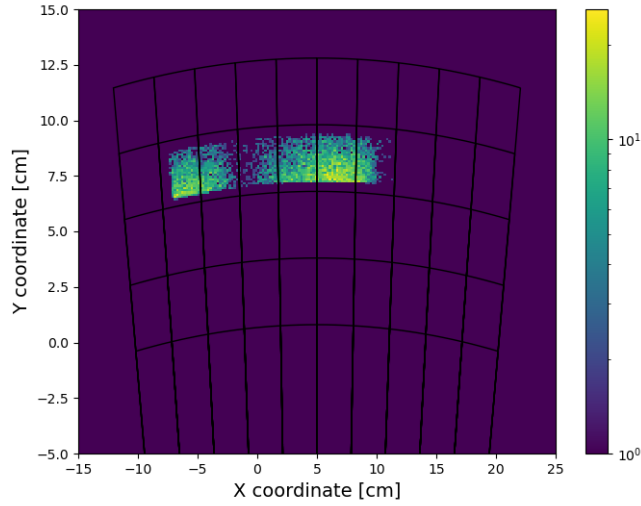


Figure 4.5: Events selected with the linearity fiducial cut. The area contains the events with a track falling within 2 Molière radii from the edges of the calorimetric tiles of the LCMs.

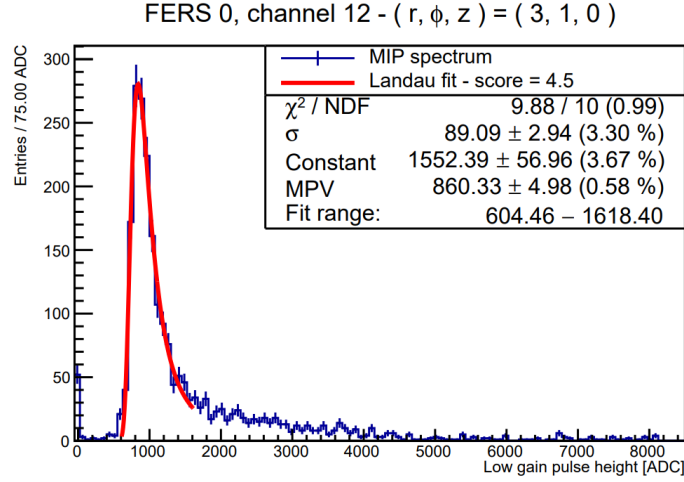


Figure 4.6: Example a of MIP peak fitted with a Landau function for a t_0 tile.

equalization fiducial cut, have been selected. The MIP peak has been fitted with a Landau function (two examples are presented in figure 4.6) and then every channel has been equalized with the following equation:

$$PH' = \frac{PH - baseline}{peak - baseline} \quad (4.1)$$

where PH is the pulse height of a selected channel, PH' is the equalized pulse height, $peak$ is the Landau MIP peak and $baseline$ is the baseline value of the same channel.

4.2 Linearity and resolution

To find the correspondence between the PHs (in ADC counts) and the energy deposited in the Demonstrator (in GeV) by the incoming particles, a calibration with electron beams was performed.

The events were acquired with electron beams at a fixed energy (E_{GeV} from 1 GeV to 5 GeV) and then the linearity fiducial cut was applied to remove the electromagnetic showers not fully contained in the Molière area. The equalized PH spectra of the selected events were fitted with a Crystal Ball function, which consists of a gaussian core with two different exponential

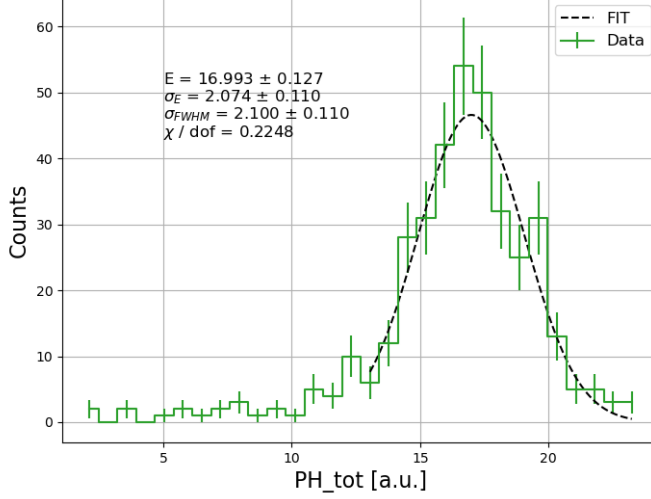


Figure 4.7: PH spectrum for a beam of 2 GeV and fit with a Crystal Ball function.

tails:

$$f(\bar{E}, E, \sigma_E, k_L, k_R) = \begin{cases} \exp\left(\frac{k_L^2}{2} + k_L \frac{\bar{E} - E}{\sigma_E}\right) & \text{if } \frac{\bar{E} - E}{\sigma_E} < -k_L \\ \exp\left(-\frac{(\bar{E} - E)^2}{2\sigma_E^2}\right) & \text{if } \frac{\bar{E} - E}{\sigma_E} \in [k_L, k_R] \\ \exp\left(\frac{k_R^2}{2} - k_R \frac{\bar{E} - E}{\sigma_E}\right) & \text{if } \frac{\bar{E} - E}{\sigma_E} > k_R \end{cases}$$

where E and σ_E are respectively the mean value and the standard deviation of the gaussian core. The k_L and k_R parameters define the left and right border between the gaussian core and the exponential tail. An example of a PH spectrum and its fit are presented in figure 4.7.

The fit parameters allowed to compute the energy resolution for each energy:

$$R = \frac{\sigma_E}{E} \quad (4.2)$$

A linear regression was performed on the (E_{GeV}, E) pairs, thus obtaining the calibration line parameters p_1 and p_0 :

$$E = p_1 \cdot E_{\text{GeV}} + p_0 \quad (4.3)$$

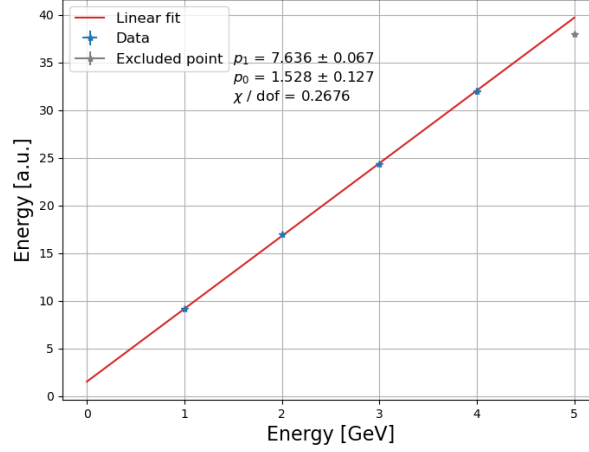


Figure 4.8: Linearity of the Demonstrator in the 0 – 5 GeV range. The 5 GeV point (gray star) was excluded from the fit.

The 5 GeV point was excluded from the fit due to the deviation from the linearity. Such deviation could be explained by several factors:

- possible partial containment of the electromagnetic shower in the selected tile
- saturation of the electronics
- systematic error on the baseline subtraction of the downstream channels
- possible systematic errors on the peak sampling performed by the FERS.

Figure 4.8 presents the calibration fit of the Demonstrator. To verify the goodness of the calibration, the relative distance between the calibrated points and the true value of the energy of the beam has been computed (figure 4.9): the values are smaller than 1 %.

The dependence of the energy resolution on the beam energy (E_{GeV}) was modeled as [108]:

$$R = \frac{a}{\sqrt{E_{\text{GeV}}}} \oplus c \quad (4.4)$$

where $\oplus$ is the quadratic sum, a the stochastic term and c the constant term. The noise term (b/E_{GeV}) was not considered due to the low statistics, so the data have been fitted with a simplified model. The resolution curve is shown in figure 4.10. The energy resolution values go from 18.14 ± 0.74 % at

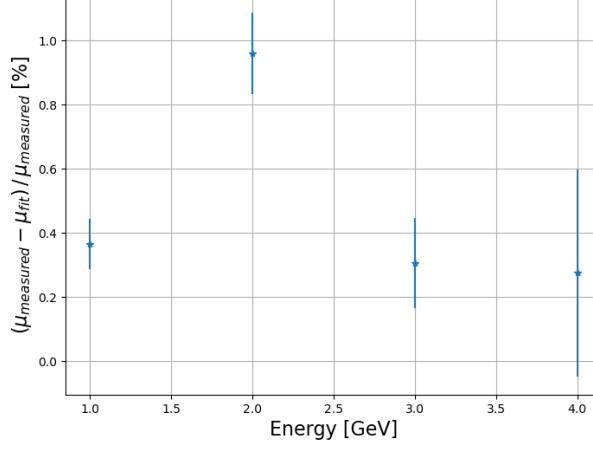


Figure 4.9: Residual plot of the linearity of the Demonstrator in the 1 – 5 GeV range.

1 GeV to $8.99 \pm 0.41 \%$ at 5 GeV. The stochastic term is $17.25 \pm 0.91 \%$ and the constant term is $4.69 \pm 0.32 \%$. These results are in agreement with the previous ones obtained on the other prototypes and reported in [145], [111] and [123].

4.3 Crosstalk

Optical crosstalk occurs when the light produced in a scintillator tile travels to a neighbouring one and might then be picked up by one of its readout fibers. This would generate a signal in the wrong tile, affecting the performances of the calorimeter.

The crosstalk effect has been studied only for the first z layer and with muon events which have a track in the equalization fiducial cut (an area of $1 \times 1 \text{ cm}^2$, instead of the $1.5 \times 1.5 \text{ cm}^2$, was also tested, but led to the same results). Muons have been selected thanks to their MIP behavior, since they do not produce electromagnetic showers, as electrons and pions, which could produce a signal in adjacent tiles due to the secondary particles of the shower and not to crosstalk.

Moreover, in order to increase the statistics, MIP like events of electrons and pions have been considered, that is events with an equalized PH in the range $0.7 - 2.5$ MIPs. Figure 4.11a presents the Cherenkov biplot from which it could be seen that these events are mostly pions and muons with very few

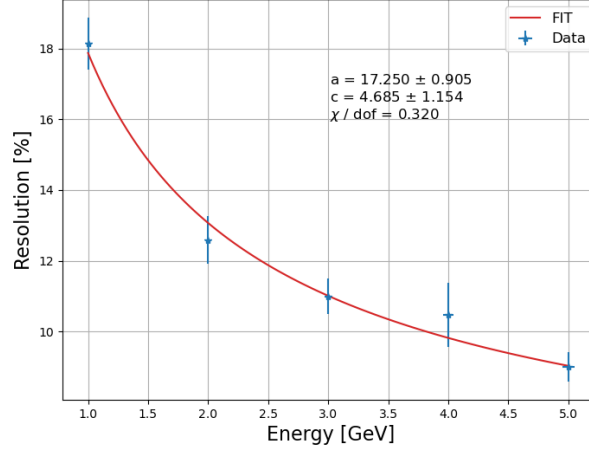


Figure 4.10: Energy resolution of the Demonstrator in the 1 – 5 GeV range.

residual electrons. Figure 4.11b presents the PH spectrum with the selection range.

For a chosen tile (reference tile), events with a PH larger than 0.7 MIPs were selected. Then the PH spectra of the events which generate a signal in neighbouring tiles have been computed. Figure 4.12 presents an example where tile $(R, \phi, z) = (3, 1, 0)$ is the reference tile. The other spectra are the tiles with the same R or adjacent ϕ . It can be noticed how the crosstalk contribution in neighbouring tiles is consistently below 1 MIP signal.

To better understand the crosstalk, another parameter has been evaluated, that is the mean value of the ratio between the PH of two channels:

$$ratio_{PH} = \langle (PH_2/PH_1)[PH_1 \geq 0.7 \cdot \text{MIP}] \rangle \quad (4.5)$$

where $PH_1(R, \phi, 0)$ is the reference channel and $PH_2(R', \phi', 0)$ is another channel of the same layer. Figure 4.13 presents an example where tile $(R, \phi, z) = (3, 1, 0)$ is the reference tile and the $ratio_{PH}$ parameter is computed for all the other tiles of the first z layer. Excluding the t_0 tiles ($R = 0$ and $R = 1$ in the used convention), the neighbour tiles have a few percent of crosstalk and below a MIP signal. The t_0 tiles should not be considered for the crosstalk because they are not part of the electromagnetic calorimeter and do not measure the energy of the particles.

Moreover, for the t_2 tiles ($R = 3$ in the used convention) the mean of the $ratio_{PH}$ of its first neighbours has been evaluated. For example, the mean of the $ratio_{PH}$ value of the right channel of all the t_2 tiles has been computed.

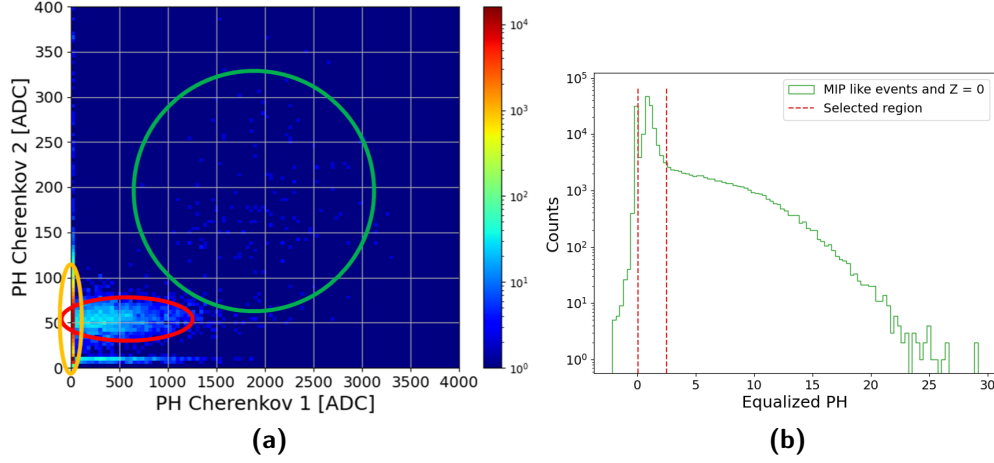


Figure 4.11: (a) Cherenkov biplot of the selected events for the crosstalk study with the electrons (green region), muons (red region) and pions (orange region) events. (b) PH spectrum of the selected events.

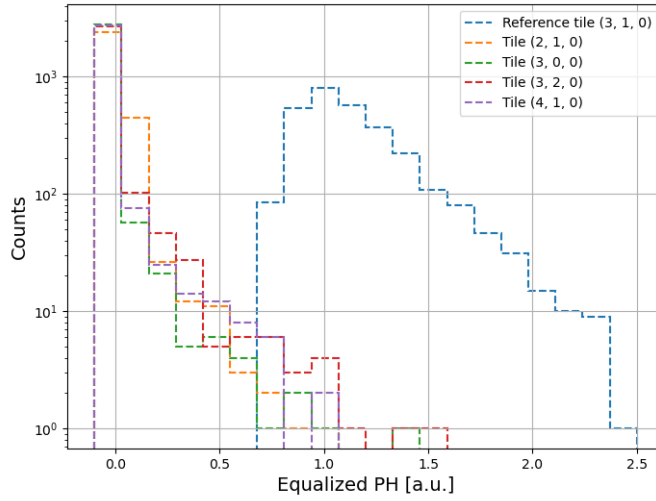


Figure 4.12: The PH spectrum of the reference tile (blue) and the spectrum of the neighbour tiles with the same R or adjacent ϕ .

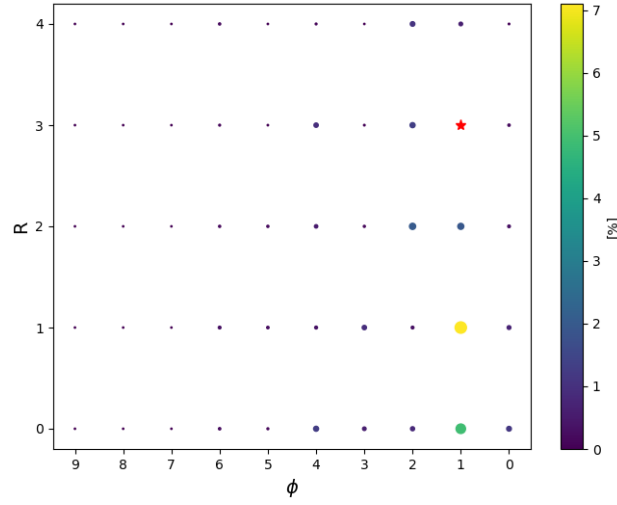


Figure 4.13: Crosstalk effect for tile $(3, 1, 0)$ as reference (red star). The value in the colorbar and the size of the markers are proportional.

Table 4.2: Mean of the $ratio_{PH}$ values for the first neighbours of the t_2 tiles.

1.90 %	1.11 %	0.84 %
1.42 %	t_2 tile	1.37 %
1.59 %	3.60 %	0.48 %

Table 4.2 presents the results for the mean of the first neighbour around the t_2 tile. Also in this case the crosstalk is smaller than 4 %.

Finally, a plot of the $ratio_{PH}$ of the reference tile and its neighbours (same R or adjacent ϕ) as a function of the PH of the reference tile has been computed. An example of this plot for tile $(R, \phi, z) = (3, 1, 0)$ is presented in figure 4.14. Most of the channels present a few percent of crosstalk and always smaller than 5 %.

In conclusion, all the tests reported a few percent of crosstalk for all the tiles of the first z layer, indicating that the optical isolation between neighbour tiles is good enough.

4.4 Preliminary Particle Identification analysis

At the end of the beamtest, the Demonstrator has been tilted with angles of 50 mrad, 100 mrad and 200 mrad to try to reproduce the incidence angle of

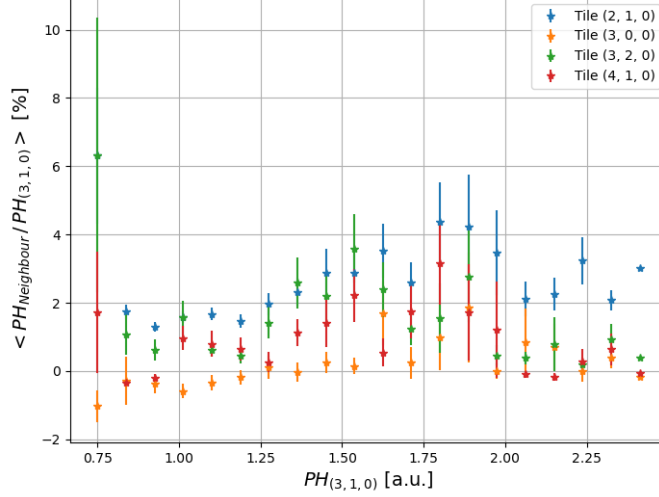


Figure 4.14: Plot of the PH of the reference tile (3, 1, 0) versus the $ratio_{PH}$ of the neighbour tiles.

particles in the final configuration of the future ENUBET detector (figure 4.15). These tilted angle runs (electron and hadron beam of 5 GeV) can be used to perform a preliminary Particle IDentification (PID) analysis, to tentatively estimate the PID capabilities of the final detector.

For a given event, the PHs of the tiles were equalized and a threshold of 1.25 MIP was set to define which channels may have detected a particle. The particle type was identified thanks to the Cherenkov detectors:

- Figure 4.16a presents an example of an electron event with a tilt angle of 50 mrad. Figure 4.16b presents the deposited energy as a function of z : it can be seen that the electromagnetic shower is completely contained within three layers in the z direction
- Figure 4.17a presents an example of a muon event with a tilt angle of 200 mrad: the particle crosses the detector in a straight line, without producing showers. Figure 4.17b presents the deposited energy as a function of z : the particle deposited energy in almost every layer
- Figure 4.18a presents an example of a heavy hadron event with a tilt angle of 50 mrad. Figure 4.18b shows the deposited energy as a function of z : it can be seen that the electromagnetic shower develops at a larger depth inside the Demonstrator.



Figure 4.15: Demonstrator tilted of 200 mrad.

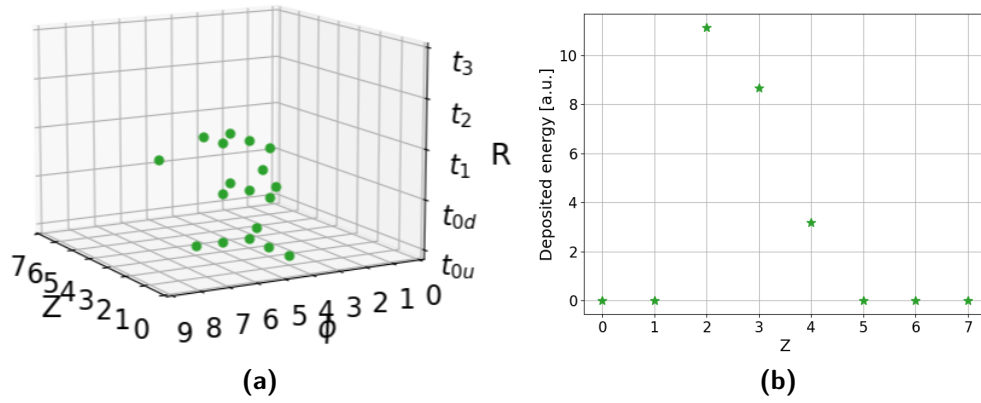


Figure 4.16: (a) Tiles over threshold display and (b) energy deposit as a function of z for an electron event.

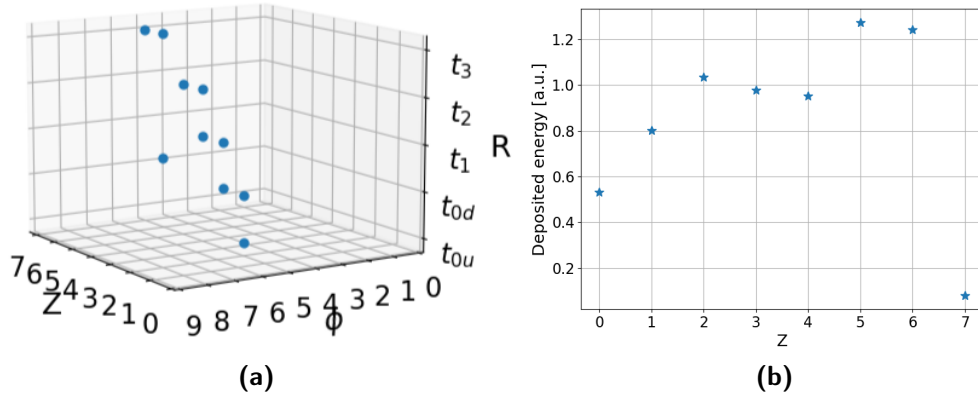


Figure 4.17: (a) Tiles over threshold display and (b) energy deposit as a function of z for a muon event.

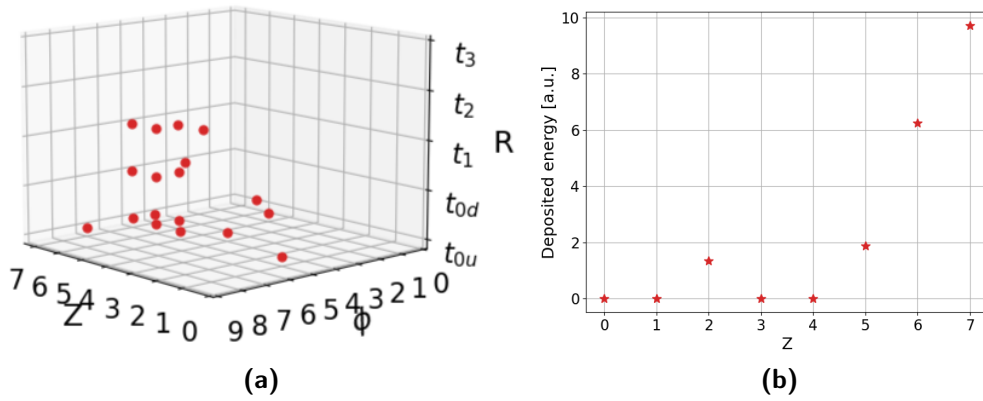


Figure 4.18: (a) Tiles over threshold display and (b) energy deposit as a function of z for a heavy hadron event.

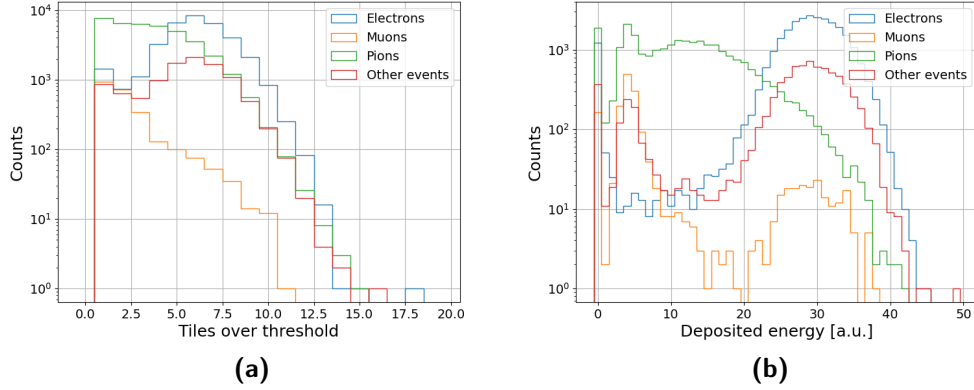


Figure 4.19: (a) Number of tiles over threshold and (b) deposited energy in the z , $z - 1$, $z + 1$ and $z + 2$ layers, with z the one which has the largest number of tiles over threshold.

Two parameters have been evaluated to define a way to identify the particle type: the total number of tiles over threshold (figure 4.19a) and the sum of the PHs in the z layer which has the largest number of tiles over threshold, the previous one (layer $z - 1$) and the two following layers (layer $z + 1$ and $z + 2$) (figure 4.19b).

Figure 4.20a presents the biplot of these two parameters. Three spots can be distinguished: the upper one is mainly composed of electron events (green region of figure 4.20b), the middle one of heavy hadrons (orange region of figure 4.20b) and the lower one of muons (red region of figure 4.20b). This discrimination was performed using the Cherenkov detectors. As shown in figure 4.21c, a large fraction (63 %) of the events previously classified as "other events" (figure 4.19) populate the electron region. It is indeed reasonable to think that these events correspond to electrons that were detected only by the second Cherenkov and not by the first one, perhaps due to the inefficiency of the latter.

To distinguish electron events from the heavy hadron events, a threshold was set (red line in figure 4.21). The events over this threshold are classified as electrons and the ones under the threshold as heavy hadrons. The performance of the event classification is presented in table 4.3. The values of the true positive (TP), true negative (TN), false positive (FP) and false negative (FN) were estimated. Then, the true positive rate ($TPR = TP/(TP + FN)$), true negative rate ($TNR = TN/(TN + FP)$), false positive rate ($FPR = FP/(FP + TN)$) and false negative rate ($FNR = FN/(FN + TP)$) were evaluated. Moreover, to estimate the goodness of the classification, the

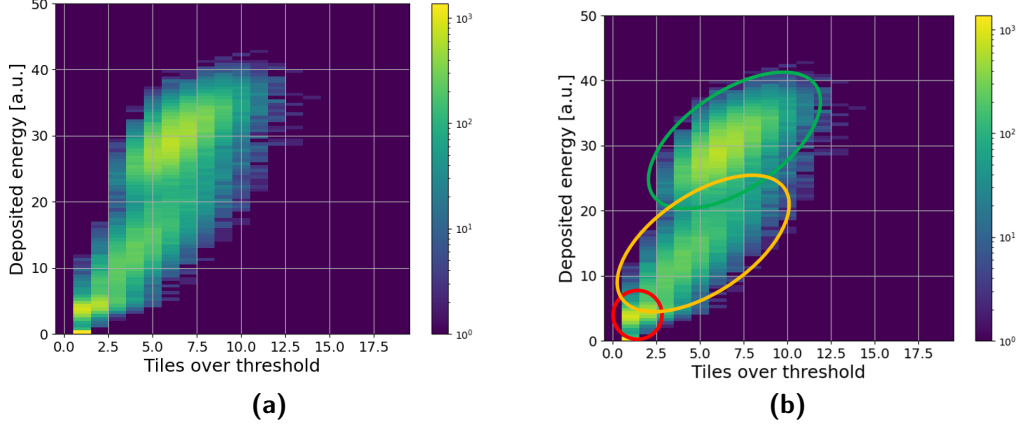


Figure 4.20: (a) Biplot of the two parameters: (b) three spots can be distinguished: the upper one is mainly composed of electron events (green region), the middle one of heavy hadrons (orange region) and the lower one of muons (red region).

Table 4.3: Performance of the classification of electrons and heavy hadrons.

Particle type	TPR	TNR	FPR	FNR	Accuracy	Precision
Electrons	72.93 %	81.91 %	18.09 %	27.07 %	78.27 %	73.28 %
Heavy hadrons	59.33 %	92.58 %	7.42 %	40.67 %	76.74 %	87.91 %

accuracy and precision³ were computed.

The identification performed with the Cherenkov detectors was used as "true value" for the classification, while the predicted values correspond to the estimate performed via the described algorithm. These results led to an accuracy of 78.27 % and a precision of 73.28 % in classifying electrons and an accuracy of 76.74 % and a precision of 87.91 % in classifying heavy hadrons.

These preliminary results show how, even with an extremely basic discrimination, it is already possible to distinguish electrons and heavy hadrons. ENUBET intends to develop a PID algorithm based on a neural network; a prototype of this algorithm has been tested with simulated data and will be adopted for the beamtest data.

³The accuracy of a measurement system is the degree of closeness of the measured quantity to its true value; it is defined as $(TP + TN)/(TP + TN + FP + FN)$. The precision of a measurement system is how close the measurements are to each other; it is defined as $TP/(TP + FP)$ [146].

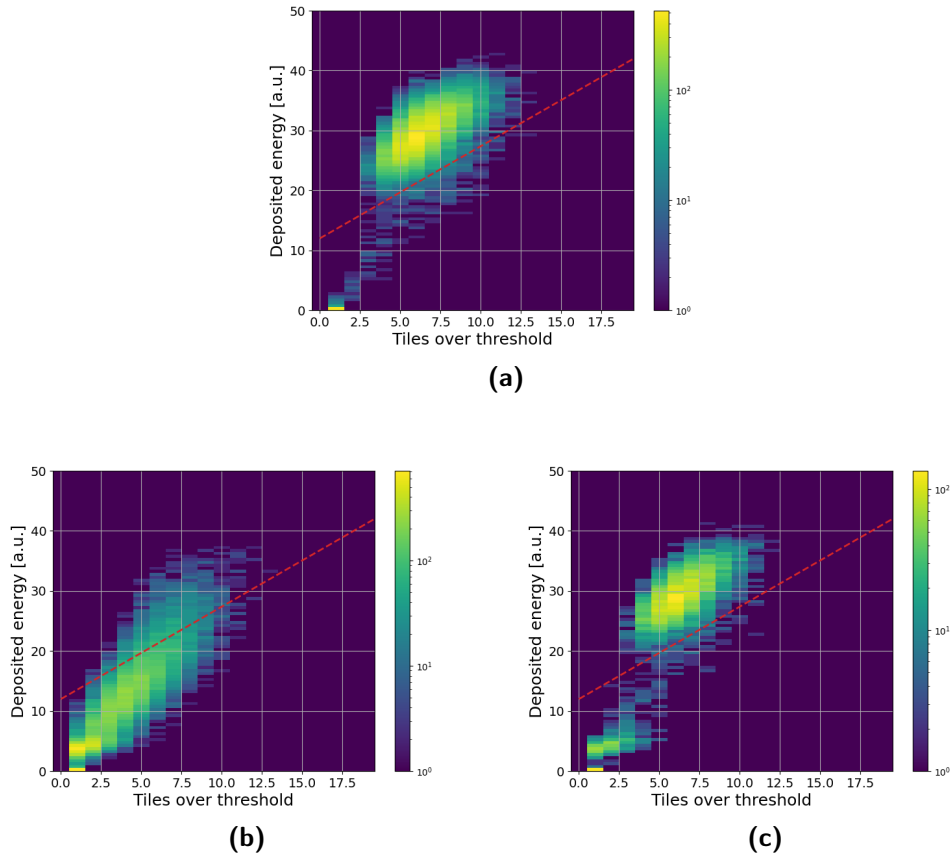


Figure 4.21: Biplot of the two parameters for (a) the electron true events, (b) the heavy hadron true events and (c) the other particle true events. The red line is the chosen threshold. An overlap of the electron and heavy hadron areas can be noticed.

Conclusions

This thesis work has been performed in the framework of the ENUBET project. The goal of the ENUBET project is to develop a monitored neutrino beam with a 1 % precision on the measurement of its flux. The idea is to design a pure and controlled source of electron neutrinos and to monitor the neutrino flux directly inside the decay region by detecting large-angle leptons generated in the K_{e3}^+ three body decay using sampling calorimeters based on plastic scintillators readout by SiPMs and placed inside the decay tunnel. In practice, the tunnel will be a hollow cylindrical electromagnetic calorimeter with an inner radius of 1 m and a length of 40 m.

The development of a 40 m long instrumented tunnel has required dedicated feasibility studies. The first prototypes tested by the ENUBET collaboration were shashlik calorimeters. Many tests have been performed at CERN and at LNF, but this configuration was discarded. As a result, the lateral light readout system replaced the shashlik option.

The largest prototype, the Demonstrator, is a section of the ENUBET instrumented decay tunnel, 1.65 m long in the beam direction and spanning 45° in the transverse plane. The sampling calorimeter is composed of 75 alternated arches of iron and 75 plastic scintillator layers. These active layers are segmented along the radial direction and consist of three $3 \times 3 \times 0.7 \text{ cm}^3$ scintillator tiles, for a total transversal area of $9 \times 3 \text{ cm}^2$. In order to detect positrons and distinguish them from photons, the two upstream active layers are instrumented with an additional tile placed in the innermost radial layer, the so called t_0 photon veto layer. The Demonstrator consists of 400 readout channels: 240 calorimetric channels and 160 t_0 tiles readout by WLS fibers coupled to SiPMs.

The core of this thesis work is the characterization of the Demonstrator. To reach this goal, the ENUBET collaboration performed a beamtest on the T9 extracted beamline at CERN in October 2022 exposing the Demonstrator to a beam of high energy electrons and hadrons. The experimental setup employed in this test was composed of two Cherenkov detectors, a plastic scintillator for the trigger, a high resolution tracking system, the Demonstrator

and two muon catchers.

The procedure to analyse the data has required several steps, namely the offline alignment of the tracking system, the characterization of the used beams, the definition of fiducial cuts and the equalization of the 400 readout channels of the Demonstrator. Once completed this preliminary phase, the linearity of the Demonstrator was computed plotting the mean value of the equalized PH spectra fitted with a Crystal Ball function as a function of the beam energy. A small deviation was found for the 5 GeV point, that could be explained by a partial containment of the electromagnetic showers or by systematic errors related to the signal sampling, such as saturations or non linearities in the readout chain. The linearity measurement has allowed to compute the energy resolution that resulted to be in the range from $18.14 \pm 0.74\%$ at 1 GeV to $8.99 \pm 0.41\%$ at 5 GeV, in agreement with the previous values reported in [145] and [111].

One of the key elements to be studied, for such a detector, is represented by the optical crosstalk, that occurs when the light produced in a scintillator tile travels to a neighbouring one and might then be picked up by one of its readout fibers. This would generate a signal in the wrong tile, affecting the performances of the calorimeter. The crosstalk effect has been studied for the first z layer and measured values of a few percent ($< 5\%$) between neighbour tiles have been obtained.

Finally, the tilted angle runs were used to perform a preliminary PID analysis, to tentatively estimate the PID capability of the final detector. These tests led to an accuracy (the degree of closeness of the measured quantity to its true value) of 78.27% and a precision (how close the measurements are to each other) of 73.28% in classifying electrons and an accuracy of 76.74% and a precision of 87.91% in classifying heavy hadrons.

These characterization results are particularly relevant because they point out that this prototype has achieved the goals foreseen by the ENUBET collaboration. Moreover, a further development of the Demonstrator design was done, extending it in the ϕ direction from 45° to 90° and in the beam direction by placing other arches of scintillator and iron. The performance of this new system has been evaluated in a dedicated beamtest in August 2023 and data are being analyzed.

This thesis work has established a systematic way to analyse the beamtest data and the obtained results represent the benchmarks for future studies.

Acronyms

ADC Analog to Digital Converter

AMANDA Antarctic Muon And Neutrino Detector Array

ANITA ANtarctic Impulsive Transient Antenna

ANTARES Astronomy with a Neutrino Telescope and Abyss environmental
RESearch project

ArgoNeuT Argon Neutrino Test

ASIC Application Specific Integrated Circuit

Baikal-GVD Baikal Gigaton Volume Detector

Borexino Boron solar neutrino Experiment

BPE Borated PolyEthylene

BR Branching Ratios

CANDLES CALcium fluoride for studies of Neutrino and Dark matter by
Low Energy Spectrometer

CC Charged Current

CERN Conseil Européen pour la Recherche Nucléaire

CL Confidence Level

CMB Cosmic Microwave Background

CNO cycle Carbon–Nitrogen–Oxygen cycle

COG Center Of Gravity

CUORE Cryogenic Underground Observatory for Rare Events

DAC Digital to Analog Converter

DAQ Data AcQuisition

DIS Deep Inelastic Scattering

DOM Digital Optical Module

DUNE Deep Underground Neutrino Experiment

ECHo Electron Capture in ^{163}Ho

ENUBET Enhanced NeUtrino BEams from kaon Tagging

EXO Enriched Xenon Observatory

FEB FrontEnd Boards

FERS FrontEnd Readout System

FORTE Fast On-orbit Recording of Transient Events

FPGA Field Programmable Gate Array

FWHM Full Width at Half Maximum

GALLEX GALLium EXperiment

GERDA GERmanium Detector Array

GLUE Goldstone Lunar Ultrahigh-energy neutrino Experiment

GNO Gallium Neutrino Observatory

HG High Gain

HiRes High Resolution Fly's Eye Experiment

HOLMES ^{163}Ho decay to Measure the Electron Neutrino Mass

HPGe High Purity Germanium

ICARUS Imaging Cosmic And Rare Underground Signals

IceCube IceCube Neutrino Observatory

INFN Istituto Nazionale di Fisica Nucleare

K2K KEK to Kamioka

KamLAND KAMioka Liquid scintillator ANtineutrino Detector

KATRIN KARlsruhe TRItium Neutrino experiment

KM3NeT Cubic Kilometre Neutrino Telescope

LAr TPC Liquid Argon Time Projection Chamber

LCM Lateral readout Compact Module

LG Low Gain

LNF Laboratori Nazionali di Frascati

LNGS Laboratori Nazionali del Gran Sasso

LNL Laboratori Nazionali di Legnaro

MINERvA Main INjector ExpeRiment: nu-A

MiniBooNE Mini Booster Neutrino Experiment

MINOS Main Injector Neutrino Oscillation Search

MIP Minimum Ionizing Particle

NC Neutral Current

NOMAD Neutrino Oscillation MAgnetic Detector

NuMECS Neutrino Mass via Electron Capture Spectroscopy

NuTeV Neutrinos at the Tevatron

OPERA Oscillation Project with Emulsion-tRacking Apparatus

PCB Printed Circuit Board

PH Pulse Height

PID Particle IDentification

PMNS Pontecorvo-Maki-Nakagawa-Sakata

PMT PhotoMultiplier Tube

pp chain proton-proton chain

QE Quasi Elastic scattering

RES RESonance production
RICE Radio Ice Cherenkov Experiment
RMS Root Mean Square
SAGE Soviet-American Gallium Experiment
SciBooNE SciBar Booster Neutrino Experiment
SiPM Silicon PhotoMultiplier
SM Standard Model
SNO Sudbury Neutrino Observatory
superNEMO super Neutrino Ettore Majorana Observatory
T2K Tokai to Kamioka experiment
TPC Time Projection Chamber
UCM Ultra Compact Module
VCB VME Cyclone Board
VME Versa Module Eurocard
VRB VME Readout Board
WLS WaveLength Shifting
WMAP Wilkinson Microwave Anisotropy Probe

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