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Monitored neutrino beams and the next generation of high precision cross section experiments

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Abstract. The main source of systematic uncertainty on neutrino cross section measurements at the GeV scale originates from the poor knowledge of the initial flux. The reduction of this uncertainty to 1% can be achieved through the monitoring of charged leptons produced in association with neutrinos. The goal of the ENUBET ERC project is to prove the feasibility of such a monitored neutrino beam. In this contribution, the final results of the ERC project, together with the complete assessment of the feasibility of its concept, are presented. An overview of the detector technology for a next generation of high precision neutrino-nucleus cross section measurements, to be performed with the ENUBET neutrino beam, is also given.

1. Monitored neutrino beams

The realization of the first monitored neutrino beam, to push the precision of neutrino-nucleus cross section measurements at the 1% level, is the aim of the ENUBET R&D project [1, 2]. Funded in 2016 by the European Research Council (ERC), since April 2019 the project is also part of the CERN Neutrino Platform framework (NP06/ENUBET), and recently has been included in the Physics Beyond Colliders (PBC) initiative. The reasons for the interest of the community to improve our knowledge on neutrino-nucleus interactions are different, and are also supported by the European Strategy for Particle Physics. Currently, the interaction rates are known with an uncertainty of the order of 10-30%, and this affects our theoretical knowledge, being not able to disentangle different neutrino interaction models. Therefore, precision measurements would shed light on the neutrino interaction mechanisms. Moreover, next generation of long-baseline experiments would definitely benefit from high precision cross section measurements, boosting their sensitivity to the neutrino oscillation parameters and enhancing their discovery potential.

Being the neutrino cross section systematics dominated by the knowledge of the neutrino flux, the aim of ENUBET is to directly reduce this uncertainty by designing a highly controlled narrow band neutrino beam, where leptons from meson decays are measured in the decay tunnel. This technique, dubbed as lepton monitoring [3], would allow to measure the neutrino cross section with 1% precision and the neutrino energy at 10% level.

Even if the idea sounds quite simple, technologically the task is challenging. As a matter of fact, an instrumentation of the harsh environment of the entire decay tunnel is needed for the purpose of monitoring the leptons. At the same time, the cost must be limited with respect to the total beamline cost. Of course, a specific design of the mesons transfer line is required, being a standard beamline, as those conceived for long-baseline experiments, not suited for the monitoring technique.

2. Transfer line and neutrino flux

The ENUBET transfer line is designed to transport at the decay tunnel entrance a beam of central momentum value of 8.5 GeV and 10% momentum bite. Two dipoles are employed and allow a total bending angle of about 15 degrees, together with a set of quadrupoles along the line for the beam focusing [4]. The large bending angle allows for a better separation of the backgrounds from the signal. A complete simulation with standard tools is performed: TRANSPORT for the optics optimization, G4beamline for particle transport and interactions, FLUKA for irradiation studies. With the final design of the beamline a total meson flux of 4.13×10^{-3} π^+/POT and 0.34×10^{-3} K$^+$/POT at the tunnel entrance is achieved.

During the last year, the Collaboration achieved an important goal, by implementing the full facility in Geant4 simulation. In fact, a complete control over all parameters and a full access to the particle histories is mandatory for the assessment of the systematics on the neutrino flux, and is possible with the complete Geant4 simulation.

Some optimization studies are still being performed to explore the possibility of enhancing even more the meson flux at the tunnel entrance and to decrease the background on the

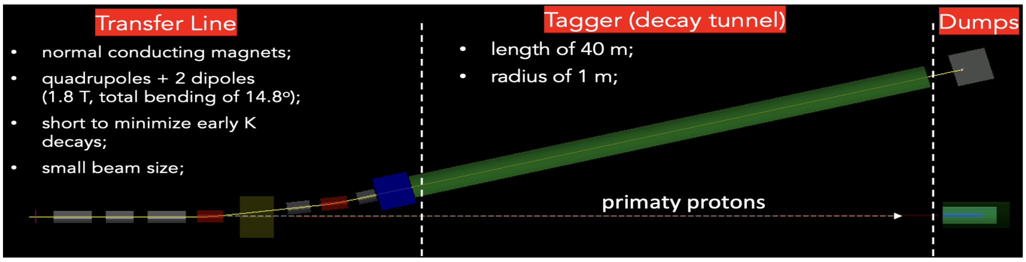

Figure 1. Schematics of the ENUBET facility. On the left side are shown the two dipoles (red boxes) and the quadrupoles set (grey boxes). Central side shows the 40 m long decay tunnel (green box). Right side shows the hadron (top box) and proton (bottom box) dumps. Shielding and collimators are not shown.

instrumented decay region [5]. The strategy is to scan the collimation parameter space to find the point that maximizes a figure of merit (FOM), and exploits the Geant4 implementation of the facility together with a framework based on a genetic algorithm developed for optimization studies. Preliminary results show that a gain of about 28% in the meson flux at tunnel entrance and reduced backgrounds can be obtained. Next step is to improve the definition of the FOM to take into account shape information in the signal and background distributions.

With the designed transfer line, the goal statistics of 10^4 ν_e^{CC} events at the detector can be achieved in about 3 years of data taking. This is under the assumption of the 400 GeV proton beam of the SPS at CERN, providing 4.5×10^{19} POT/year, and a ProtoDUNE-like detector, 500 tonnes of mass placed at 50 m from the decay tunnel end. The energy distribution of the ν_e^{CC} events at the detector is such that above 1 GeV a fraction of 80% of the total ν_e^{CC} rate is produced by decays in the tunnel volume. This is the neutrino component that can be directly monitored through the calorimeter instrumenting the tunnel walls. The neutrino components that cannot be monitored are produced mainly in the proton dump (below 1 GeV) or in the straight section of the transfer line before the tunnel entrance and in the hadron-dump, for which the subdominant distribution sits under the main monitored component. These events can be either thrown away with an energy selection or taken into account by the simulation.

The 10% momentum bite of the narrow-band beam produced in ENUBET can be exploited to precisely determine the neutrino energy in ν_μ^{CC} events, without relying on the final-state products of the interactions. Therefore, systematics related to the final-state reconstruction would be completely bypassed. The strong correlation between neutrino energy and interaction point at the detector allows for a 8-25% energy resolution in the DUNE region of interest, for which the ENUBET beamline is currently optimized. An R&D study is ongoing to develop a multi-momentum beamline (allowing beams with momentum of 4.5, 6 and 8.5 GeV, respectively), optimized for both Hyper-Kamiokande (HK) and DUNE experiments [4].

3. Lepton monitoring and flux constraint

A detector technology for the tunnel instrumentation, ensuring at the same time the needed physics performance and a high cost-effectiveness, is that of sampling calorimeters. The basic module for ENUBET is a sandwich of 5 plastic scintillators tiles interleaved with 5 iron tiles, with a cross section of 3×3 cm^2 and a total thickness of 4.3 X_0. The design consists of a longitudinal segmentation along the beam and three radial layers. The scintillation light is collected through WLS fibers bringing the signal outside a 30 cm thick borated shielding, installed on top of the calorimetric layers. The signal from each module is read out through a SiPM, placed right above the borated shielding. This configuration, reducing the fluxes from hadronic showers produced in the bulk of the calorimeter, prevents the sensors aging. In fact, the neutron fluence at the sensors is reduced by about a factor of 18. The inner walls of the tunnel host a photon veto system, acting also as timing detector. This consists of doublets of plastic scintillator tiles arranged in ring shapes spaced longitudinally across the decay pipe length.

A set of calorimeter prototyoes have been built and successfully tested at CERN PS-T9 during test-beam campaigns in 2016-2018 period [6, 7, 8, 9]. The chosen technology allows to get an electron energy resolution of $\sigma/E = 17\%$ at E = 1 GeV, where a $< 25\%/\sqrt{E(GeV)}$ energy resolution is required to disentangle e^+/π^+ in the 1-3 GeV energy range of interest. This result meets the performance goals of the project. Moreover, tests of the photon veto system showed a good performance in 1 versus 2 m.i.p. separation capabilities and an achieved time resolution of about 400 ps.

A study of the particle identification performance has been performed exploiting the full simulation of the tunnel instrumentation implemented in Geant4. The simulation has been validated with the prototypes testing using charged particles at CERN. Large-angle positrons and muons from kaon decays hit the calorimeter, and can be identified to constrain the neutrino fluxes. The energy deposition patterns of the leptons in the calorimetric modules are clustered through custom algorithms. Clustered events consist in a sample of leptons originated from kaon decays, but also by background particles with different origins. Signal versus background discrimination is thus performed using a Neural Network discrimination variable, trained on a set of observables with high separation power. The final selected signal samples are such that positrons from K_{e3} are reconstructed with an efficiency of 22% and a S/N $\sim$ 2, whereas the muons from $K_{\mu2}$ are reconstructed with an efficiency of 34% and a S/N $\sim$ 6 [10]. In fig. 2 and fig. 3 are shown the distributions, obtained after the selections with the Neural Network discriminator, of the measured observables for both positrons and muons. These distributions are a measurement of the lepton rate from decays where also neutrinos are produced, and are therefore used to constrain the neutrino flux at detector.

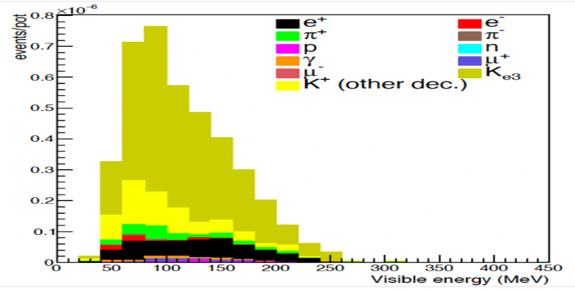

Figure 2. Distribution of the visible energy for positrons from K_{e3} signal (golden) and background events. Main background contributions come from other kaon decay modes (yellow), positrons (black) and pions hitting the tagger walls (green).

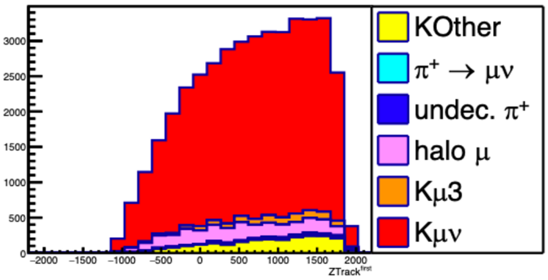

Figure 3. Distribution of the impact point along the calorimeter for muons from $K_{\mu2}$ and $K_{\mu3}$ signal (red and orange) and background events. Main background contributions are from halo-muons (purple) and other kaon decay modes (yellow).

A signal plus background model for the monitored leptons is built using the templates of the distributions reported in fig. 2 and fig. 3. Systematics effects due to hadroproduction data and affecting both the normalization and shapes of the observables are included in the model. A propagation of these uncertainties, from the mesons yield at the target up to the observed lepton rates in the calorimeter and the neutrino flux at detector, is performed by means of the multi universe method. Toy-MC experiments are produced and fitted with the signal plus background model, and a posteriori values for the hadroproduction parameters are determined.

Thanks to the information on the measured lepton rates, the fit procedure allows reduction of the hadroproduction uncertainties, and thus reduction of the uncertainty on the neutrino flux at detector.

The procedure for the assessment of the hadroproduction uncertainties impact on the neutrino fluxes uses the NA56/SPY data to prove the working principle of the monitoring concept. Specifically, the performed analysis shows that with the lepton monitoring technique a 1% systematic on the neutrino flux is achieved, meeting the goal of the ENUBET project, starting from a 6% uncertainty before any constraint [11, 12].

4. The demonstrator

In order to demonstrate the performance, scalability and cost-effectiveness of the chosen technology, the ENUBET Collaboration has built a large-scale prototype demonstrator, consisting in a calorimeter section [13]. The prototype is 1.65 m long in the longitudinal direction and spans 90° in azimuth, with an inner radius of 1 m. The absorber is made of iron, and extends radially for 11 cm followed by 30 cm of borated polyethylene with 5% Boron. Compared to previous prototypes, an updated light readout scheme for the scintillation light has been employed. The grooves in the scintillators, hosting the fibers for light collection and routing, are machined in the frontal faces of the tiles instead that in the thinner sides. The new scheme was successfully tested with a pre-demonstrator prototype, ENUBINO, under test-beams at CERN in November 2021, and guarantees a safer production and a more uniform light collection. The demonstrator construction has been finalized during summer 2022 at the INFN-LNL labs in Legnaro, Italy. The arrangement is such that three radial layers of modules, each one made of 10 modules in the transverse plan and 8 modules in the longitudinal direction, are installed in the central part of the prototype. A doublet of the photon veto is installed in each module of the first radial layer. In total, 240 calorimetric modules and 80 doublets of the photon veto have been installed in the prototype, readout by 400 channels overall. A critical aspect for the finalization of the demonstrator was the procurement of the scintillator tiles, planned to be produced by Uniplast. Due to the critical international situation, commercial scintillator slabs, cut and milled by a company in Italy, had to be employed. A completely handmade processing, involving polishing, fiber gluing and tiles painting, had to be adopted. After construction, the demonstrator has been shipped to CERN, where the experimental setup has been installed and tested under e^+, π^+ and μ^+ particles at the PS-T9 beamline during the first half of October 2022. The analysis of the acquired data is now ongoing, together with the development of a Geant4 simulation of the setup, and results will be released soon.

5. High precision cross section program

As discussed in the previous sections, the monitored beams represent an opportunity to obtain highly controlled neutrino fluxes and an a priori knowledge of the neutrino energy. What is the best detector technology to employ for measuring neutrino interactions in such high precision beams? Off course, different technologies employing a variety of target nuclei are available and used in current experiments, or are being developed for future facilities. It can be envisaged that to get the needed information for the neutrino oscillation program, a measure of the cross section convolved with the detector effects using replica detectors similar to those used for long-baseline experiments, must be obtained. Nevertheless, detectors using complementary techniques are needed to decouple the cross section from detector effects and thus improve the interaction models. Therefore, a facility based on different detection techniques would be highly desirable for a future next generation neutrino nucleus cross section measurement program [14].

The ProtoDUNE detector could be a good opportunity to measure the convolved neutrino cross section with detector effects employing the same technology being developed for the future DUNE far detector. Moreover, the response of ProtoDUNE has been fully characterized with charged particles at CERN [15], and allows for an almost full containement of neutrino interactions. An ideal solution to decouple cross section from detector efficiency would be to use both liquid and gas argon TPCs. Here an example is represented by the gas phase TPC that will be used for the Near Detector (ND) complex of DUNE [16], which design is inherited from ALICE TPC's, but is operated at 10 times higher pressure. The advantages of this approach are multiple: high momentum resolution are achieved thanks to the use of the magnetic field, an improved particle identification and significant lower threshold are obtained thanks to the lower material density. This allows for a full characterization of the hadronic system from the interactions. In the HK case, an intriguing opportunity is represented by the small water Cherenkov test experiment (WCTE) detector [17]. As for ProtoDUNE, WCTE will be fully characterized by charged particles at CERN. Similarly, the detector technology is very similar to that of HK. It will be a small size detector (about 50 tons of mass), thus the ν_e^{CC} sample will not be statistically significant with an ENUBET like beam, but nevertheless a ν_μ^{CC} measurement can be performed. For water target detectors, to disentangle the cross section from detector efficiency fine grained detectors can be employed: WAGASCI [18], used as part of the ND of T2K, employs a water target segmented in small cells, by using a grid like structure of plastic scintillators and allowing for a 4π reconstruction of the interactions in water; NINJA [19], also used in ND complex of T2K, exploting nuclear emulsion films and iron plates intervealed with water layers. In both cases the reconstruction threshold of the momentum is pushed down, allowing a full characterization of the hadronic system in the interactions. The discussed detectors employ complex target nuclei, in which the effects of the nuclear medium are relevant in the neutrino interactions. To get measurements and build models that are not affected by the nuclear effects, a good solution would be to measure the neutrino interaction with hydrogen, and use the results to extrapolate to higher Z materials. Indirect approaches have been proposed and are based on the so-called transverse momentum imbalance due to nuclear effects [20]. This allows to disentangle neutrino interactions on hydrogen to those on other nuclei in composite materials. Anyway, the best solution, providing unbiased measurement, is represented by a direct approach where liquid hydrogen is used as target material. This is is a challenging task because of safety requirements in underground laboratories. But there are proposals of using modern digital camera technology with bubble chambers techniques [21].

6. Conclusions and outlook

As discussed in this contribution, monitored neutrino beams represent a good opportunity to measure neutrino nucleus interactions with a precision never reached before, at the O(1%) level. High precision cross section measurements would be beneficial to deepen our theoretical knowledge on the neutrino interactions with matter, but would also boost the sensitivity of the future neutrino oscillation experiments, enhancing their discovery potential. The ENUBET project is the first R&D for the realization of a monitored neutrino beam. The ERC project is on schedule and in the last stage. The studies performed have shown that with the final beamline design the goal statistics can be reached in about 3 year of data-taking at SPS, and that a 1% precision on the neutrino flux can be achieved. Test beams of prototypes have proven the performance of the technology, and a final demonstrator has been tested at CERN in October 2022. A CERN site-dependent implementation study will be performed within Neutrino Platform (NP06) and PBC frameworks. The Conceptual Design Report, with physics and costs definitions, will be delivered by 2023 and an experimental proposal is expected in 2024.

Concerning the neutrino detectors to be used in a monitored neutrino beam, most of the potentiality of such a high precision beam can be exploited by using different technologies. For boosting the sensitivity of DUNE and HK, studies of the interactions on argon and water targets are needed. At the same time, to improve the model building for neutrino interactions with matter, complementary detector techniques and low Z targets must be used.

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