PROCEEDINGS OF SCIENCE

ENUBET: the first monitored neutrino beam

PoS(ICHEP2022)611

A. Branca[1,2] **for the ENUBET Collaboration***
[1]Phys. Dep. Università di Milano-Bicocca, piazza della Scienza 3, Milano, Italy
[2]INFN, Sezione di Milano-Bicocca, piazza della Scienza 3, Milano, Italy
E-mail: `antonio.branca@mib.infn.it`

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 goal of the ENUBET project is to cut down this uncertainty to 1% by monitoring the charged leptons produced in association with neutrinos, through the instrumentation of the decay region of a conventional narrow-band neutrino beam. In this contribution we discuss the final design of the horn-less beamline, that allows for a 1% measurement of ν_e and ν_μ cross sections in about 3 years of data taking at CERN-SPS using ProtoDUNE as far detector, together with the particle identification performance. We also present for the first time the impact of the lepton monitoring in the reduction of the hadroproduction systematic on the neutrino flux. Finaly, we give an overwiev of the current status of the final demonstrator to be tested with charged particles at CERN in October 2022.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

---

*F. Acerbi, I. Angelis, L. Bomben, M. Bonesini, F. Bramati, C. Brizzolari, G. Brunetti, M. Calviani, S. Capelli , S. Carturan, M.G. Catanesi, S. Cecchini, N. Charitonidis, F. Cindolo, G. Cogo , G. Collazuol, F. Dal Corso, C. Delogu, G. De Rosa, A. Falcone, B.Goddard, A. Gola, L. Halić , F. Iacob, C. Jollet, V. Kain, A. Kallitsopoulou , B. Klicek , Y. Kudenko, Ch. Lampoudis, M. Laveder, P. Legou , A. Longhin, L. Ludovici, E. Lutsenko, L. Magaletti, G. Mandrioli, S. Marangoni, A. Margotti, V. Mascagna, N. Mauri, L. Meazza, A. Meregaglia, M. Mezzetto, M. Nessi, A. Paoloni, M. Pari, T. Papaevangelou , E.G. Parozzi, L. Pasqualini, G. Paternoster, L. Patrizii, M. Pozzato, M. Prest, F. Pupilli, E. Radicioni, A.C. Ruggeri, D. Sampsonidis, C. Scian, G. Sirri, M. Stipcevic , M. Tenti, F. Terranova, M. Torti, S.E. Tzamarias, E. Vallazza, F. Velotti, L. Votano

1. Introduction

The ENUBET project [1, 2] has been founded by the European Research Council (ERC) in 2016, with the purpose to realize the first monitored neutrino beam. Since April 2019 the project is also part of the CERN Neutrino Platform framework (NP06/ENUBET) and now part of the Physics Beyond Colliders (PBC) initiative. The interest in the project has been growing in the last years, thanks to its achievements and potentialities: the Collaboration now counts 60 physicists spread around 13 institutions. Next generation of long-baseline experiments would definitely benefit from an improvement of the knowledge on the ν_e cross section, enhancing their discovery potential. This is also the reason why the European Strategy for Particle Physics supports a complementary program to the long-baseline experiments for the precise determination of the neutrino cross sections. In this context, the aim of ENUBET is to design a narrow band beam for the measurement of neutrino cross section at the 1% level. The idea on how to pursue this challenging task is quite simple: because of the uncertainties on hadroproduction data and beamline simulation, the neutrino cross section systematics are dominated by the knowledge of the neutrino flux. A measurement of the rate of leptons produced in meson decays would bypass this systematic, and dramatically reduce the uncertainty in the neutrino flux at detector. This technique is dubbed as lepton monitoring [3]. Technologically the task is challenging, since an instrumentation of the harsh environment of the entire decay tunnel is needed, while keeping the cost limited with respect to the total beamline cost. Moreover, 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. The mesons transfer line

The final design of the beamline is based on static elements: two dipoles for a total bending angle of about 15 degrees and 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. The transfer line is fully simulated with standard tools (TRANSPORT for the optics optimization, G4beamline for particle transport and interactions, FLUKA for irradiation studies). The design is such that a beam of 8.5 GeV is transported at the tunnel entrance with a 10 % momentum bite. Table 1 shows the rates at the tunnel entrance for kaons and pions, with values ~1.5 times better than previous results.

π^+ [$10^{-3}/POT$]	K^+ [$10^{-3}/POT$]
4.13	0.34

Table 1: Rates at tunnel entrance for 400 GeV protons on target.

An important achievement of the ENUBET Collaboration in the last year has been the implementation of the Geant4 simulation of the full facility. This is of particular importance, since 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.

Even if the beamline design is finalized, an ongoing optimization study is being performed by fine-tuning some collimation elements, with the goal to further improve the measons yield at the tunnel entrance and to decrease the background on the instrumented decay region [5]. The strategy consists in scanning the 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 mesons flux at tunnel entrance and reduced backgrounds can be obtained. Nevertheless, the background distribution has still a similar shape to that of the signal, and next steps foresee to improve the definition of the FOM to take into account shape information.

3. Neutrino rates at detector

The goal statistics of 10^4 ν_e^{CC} events can be achieved in about 3 years of data taking, assuming the 400 GeV proton beam of the SPS at CERN with $4.5{\times}10^{19}$ POT/year and a ProtoDUNE like detector, 500 tonne of mass placed at 50 m from the decay tunnel end. Above 1 GeV, a fraction of 80% of the total ν_e^{CC} rate at the detector is produced by decays in the tunnel region, for which the corresponding charged leptons can be directly monitored through the calorimeter installed in the tunnel walls. The neutrino rate from decays outside the tunnel region can be either cut away by a simple energy selection, being the component below 1 GeV mainly produced in the proton-dump, or taken into account by the simulation, with the subdominant component above 1 GeV mainly due to the straight section of the transfer line before tunnel entrance and hadron-dump.

Concerning the ν_μ^{CC}, the advantage of a narrow-band beam, with momentum bite of 10%, can be exploited to precisely determine the neutrino energy. This way, the systematics related to the final state reconstruction would be bypassed. The strong correlation between the neutrino's interaction point distance with respect to the beam center and the neutrino energy allows to get a 8-25% energy resolution in the DUNE region of interest. It must be noted that the current beamline is optimized for the DUNE experiment, and an ongoing R&D is underway to develop a multi-momentum beamline (with the possibility to select beams of momentum of 4.5, 6 and 8.5 GeV) optimized for both HyperK and DUNE experiments [4].

4. Decay tunnel instrumentation and particle identification

The technology chosen for the tunnel instrumentation is based on the sampling calorimeter technique. This is cost-effective and ensures the needed performance. Each calorimetric module consists in a sandwich of 5 couples of iron and plastic scintillator tiles, where light is collected through WLS fibers bringing the signal outside a borated polyethylene shielding of 30 cm. One SiPM for each module allows to readout the signal from the fibers. The installation of the SiPMs on top of the shielding is such that fluxes from hadronic showers are avoided, reducing considerably the sensors aging (a reduction by a factor ~18 in neutron fluence is achieved). A photon veto system, acting also as timing detector, consists of doublets of plastic scintillator tiles installed in the inner tunnel walls in ring shapes. The rings are spaced longitudinally across the decay pipe length. Prototypes have been built and successfully tested at CERN PS-T9 during test-beam campaigns in 2016-2018 period [6–9]. An electron energy resolution of $\sigma/E = 17\%$ at E = 1 GeV is achieved with this technology, where an energy resolution better than $25\%/\sqrt{E}$ is required to disentangle e^+/π^+ in the 1-3 GeV energy range of interest, thus meeting the performance goals of the project.

Also, 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 full Geant4 simulation of the tunnel instrumentation has been developed, and validated with the prototypes tested at CERN, to study the particle identification performance. Detector response is treated at the hit-level with the inclusion of pile-up effects. The waveforms generation from energy deposits, as in real data, is being implemented in the simulation. The instrumentation that has been conceived for ENUBET has the capabilities to identify large angle positrons from kaon decays and reject charged and neutral pions, which represent the larger fraction of backgrounds. Moreover, also the large angle muons from kaon decays can be identified. The goal of the project is thus extended to the monitoring of the ν_μ flux from kaon decays, other than that of ν_e. Clustering algorithms, developed on purpose, provide a reconstruction of the leptons hitting the calorimeter by searching for patterns in the energy depositions in the modules. Signal discrimination from background events is then achieved through a Neural Network, trained on a set of variables with high separation power. After the analysis chain is applied, the positrons from K_{e3} are reconstructed with an efficiency of 22% and a S/N $\sim$ 2, whereas the muons from $K_{\mu 2}$ are reconstructed with an efficiency of 34% and a S/N $\sim$ 6 [10]. In both cases, half of the reconstruction efficiency is pure geometrical. Fig. 1 shows the distributions of the observables measured through the calorimeter for positrons and muons, used to constrain the neutrino flux at detector.

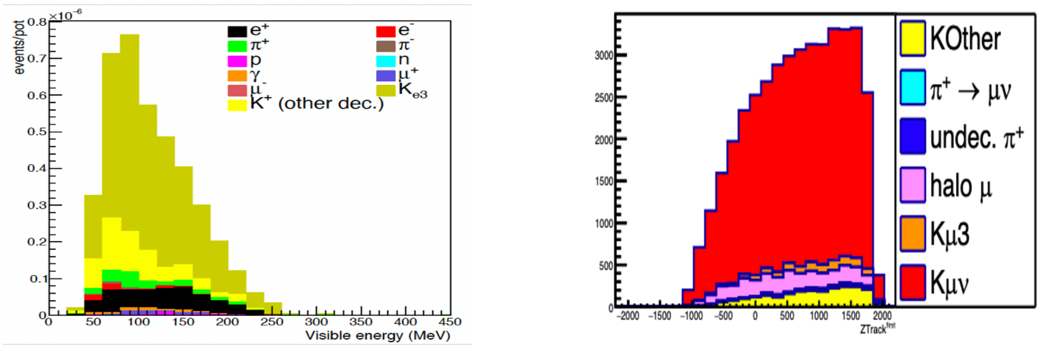

Figure 1: Observables of reconstructed and selected leptons after the clustering and particle identification analysis. Left: distribution of the visible energy for positrons from K_{e3} signal (golden) and background events, where the larger contribution comes from other kaon decay modes (yellow), positrons (black) and pions hitting the tagger walls (green). Right: distribution of the impact point along the calorimeter for muons from $K_{\mu 2}$ and $K_{\mu 3}$ signal (red and orange) and background events, mainly halo-muons (purple) and other kaon decay modes (yellow).

5. Assessment of neutrino flux systematics

The workflow summarizing the procedure used to get a constrain on the neutrino flux is shown in fig. 2. Using the lepton distributions for the observables reported in fig. 1, a signal plus background model for the monitored leptons by ENUBET is built. The model takes into account the variations, both in normalization and shape, due to the hadroproduction systematics through nuisance parameters. The hadroproduction uncertainties are propagated to the observables by sampling the hadroproduction parameters from their covariance matrix, and reweighting Monte

Carlo (MC) events accordingly (multiuniverse method). The model is used to produce and fit a set of toy-MC experiments, from which a posteriori values for the hadroproduction parameters are determined. The new parameters are used to reweight the MC and get the a posteriori neutrino flux at detector. The fit procedure shrinks the hadroproduction uncertainties, which reflect directly on a neutrino flux with higher precision.

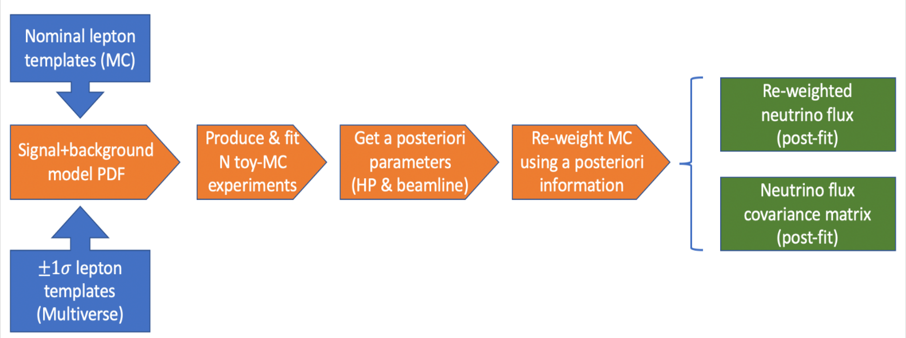

Figure 2: Workflow summarizing the procedure adopted for the evaluation of the impact of hadroproduction and beamline systematics on the neutrino flux at the detector by taking advantage of the lepton monitoring technique.

This study represents a proof of principle of the monitoring concept, and uses the NA56/SPY data to assess the impact of the hadroproduction uncertainties on the neutrino flux.The 6% systematic uncertainty on the neutrino flux due to the original hadroproduction data uncertainties is reduced to 1% with the constraint from the monitoring of leptons [5], thus reaching the goal of ENUBET.

6. The demonstrator

The ENUBET Collaboration has built a final demonstrator [5] that has been under test-beam at CERN in October 2022. The goal is to demonstrate the performance, scalability and cost-effectiveness of the chosen technology with a large scale prototype. With respect to previous tested prototypes, an updated light readout scheme has been employed: grooves for the routing of the light collecting fibers are engraved in the frontal faces of the scintillator tiles, instead that on the narrower edges. The choice was driven by the large scale scintillator manufacturing, guaranteeing a safer production and a more uniform light collection. The updated readout scheme has been successfully tested with a pre-demonstrator prototype, ENUBINO, by means of charged particles at CERN in November 2021. The demonstrator construction has been finalized during summer 2022 at the INFN-LNL labs in Legnaro, Italy. The prototype is 1.65 m long in the longitudinal direction and covers 90° in the transverse plan perpendicular to the beam axis. A total of 75 iron arches, with an internal radius of 1 m and a radial extension of 11 cm, are used as absorbers. The calorimeter is instrumented in the central part with 10 sectors in the transverse plan and 8 sectors along the longitudinal direction, where each sector comprises 3 calorimetric modules and a doublet of the photon veto layer. In total, 240 calorimetric modules and 80 doublets of the photon veto are installed, readout by 400 channels overall. With respect to the original plan to instrument the whole 45° central part, only a fraction of the prototype has been covered with calorimetric modules. A critical aspect 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.

7. Conclusions and outlook

The ENUBET ERC project started in 2016, and took part to the CERN Neutrino Platform as NP06/ENUBET in 2019. Now the project is also part of the Physics Beyond Collider framework. The design of the beamline has been finalized, even if fine-tuning of optic parameters is ongoing to push further the mesons yield at tunnel entrance. A total statistics of 10^4 ν_e^{CC} events at detector can be collected in about 3 years of data taking, at SPS and with a ProtoDUNE like detector installed 50 m from the tunnel end. The technology for the tunnel instrumentation has also been finalized and tested with different prototypes during 2016-2018 test-beam campaigns. A final demonstrator has been built at the INFN-LNL labs and tested at CERN PS East Hall in October 2022. The instrumentation has been fully simulated within Geant4 and particle identification studies show a very good performance in positron and muon reconstruction from kaon decays. A first full assessment of the impact of hadroproduction uncertainties on the neutrino flux with the constrain given by the lepton monitoring has been carried out. The goal of 1% precision on the neutrino flux is achieved with the monitoring technique. Next steps will be the assessment of systematics due to detector effects and beamline parameters.

References

[1] A. Berra et al., CERN-SPSC-2016-036, SPSC-EOI-014, Geneva, 2016.

[2] F. Acerbi et al., CERN-SPSC-2018-034, SPSC-I-248, Geneva, 2018.

[3] A. Longhin, L. Ludovici and F. Terranova, Eur. Phys. J. C 75 (2015) 155.

[4] F. Acerbi et al., CERN-SPSC-2021-013, SPSC-SR-290, Geneva, 2021.

[5] F. Acerbi et al., CERN-SPSC-2022-016, SPSC-SR-310, Geneva, 2022.

[6] A. Berra et al., Nucl. Instrum. Meth. A 830 (2016) 345.

[7] G. Ballerini et al., JINST 13 (2018) P01028.

[8] F. Acerbi et al., JINST 15 (2020) P08001.

[9] M. Pozzato et al., Nucl. Instrum. Meth. A 983 (2020) 164482.

[10] F. Pupilli et al., PoS NuFact2021 (2022) 025.