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The ENUBET experiment and its implementation at CERN(*)

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Summary. — Monitored neutrino beams are a novel technology designed to provide measurements of the neutrino cross sections at GeV scale with a total uncertainty of $\mathcal{O}(1\%)$, thus improving by one order of magnitude current experimental estimates. The ENUBET project is close to proving for the first time the feasibility of this concept and the Collaboration is preparing a proposal for a new neutrino beam at CERN based on the SPS accelerator and the ProtoDUNEs neutrino detectors that are already operative at the North Experimental Area. In this contribution, we discuss the final design of the horn-less transfer line and the instrumented decay tunnel which allows us to measure the charged leptons associated with neutrinos from kaon decays. Finally, we discuss the expected physics performance using the SPS accelerator and the ProtoDUNE-SP neutrino detector and future perspectives for the implementation of the entire facility at CERN North Area.

1. – Introduction

The next generation of long-baseline neutrino oscillation experiments (DUNE, HyperKamiokande) is aimed at observing CP violation in the lepton sector, resolving the neutrino mass hierarchy and providing precise measurements of oscillation parameters, particularly the Dirac phase δ_{CP} and the octant of θ_{23} [1]. Thanks to their unprecedented beam power and detector mass, these facilities will be no more limited by event statistics; nevertheless, systematic uncertainties are quite large, and - if not mastered at the per-cent level precision - they might jeopardize the achievement of such ambitious physics goals [2]. The major hindrance is represented by the limited knowledge of neutrino cross sections at the GeV scale at $\mathcal{O}(10\%)$, whereas a per-cent level precision would be instrumental to test CP symmetry violation in the lepton sector [3]. Despite the complexity of the reconstruction of neutrino interactions, the main source of systematic uncertainty on neutrino cross-section measurements resides in the poor knowledge of the initial flux, generally known with a precision worse than 10% [2].

The goal of the ENUBET project is to cut down this uncertainty to 1% by designing a narrow-band neutrino beam whose decay volume is instrumented with cost-effective detectors. The detectors are capable of monitoring charged leptons produced in association with neutrinos from meson decays [4-7]. Monitored neutrino beams are designed to provide measurements of neutrino cross sections at the GeV scale with a total uncertainty of 1%, thus improving by one order of magnitude current experimental estimates. Monitored neutrino beams will play a key role in the systematic reduction programme of future long-baseline experiments, which would enhance their physics discovery potential by benefiting from improved knowledge of ν_e and ν_μ cross sections. For these reasons, the European Strategy for Particle Physics strongly encourages the development of a complementary programme of experiments for per-cent level neutrino cross sections measurements [8]. The idea envisaged by ENUBET to pursue this challenging task is quite simple: the neutrino flux at the detector can be measured directly by recording the rate of associated charged leptons in the instrumented decay tunnel. The decay tunnel walls are equipped with cost-effective sampling calorimeter modules with longitudinal, radial

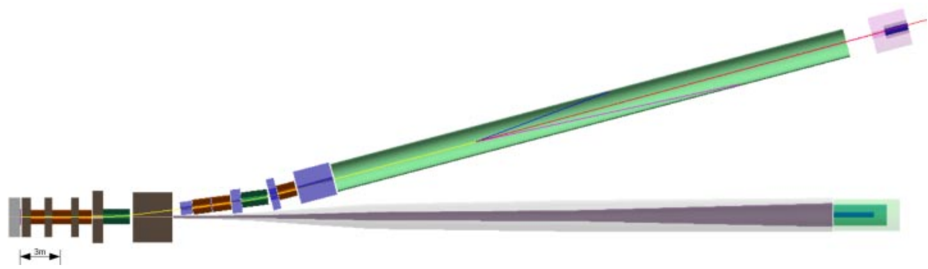

Fig. 1.: The final design of the ENUBET beamline [10].

and azimuthal segmentation, allowing the monitoring of large angle positrons and muons from K_{e3} ($K^+ \to e^+\pi^0\nu_e$) and $K_{\mu\nu}$ ($K^+ \to \mu^+\nu_\mu$) decays respectively. Furthermore, collinear muons from pion $\pi_{\mu\nu}$ ($\pi^+ \to \mu^+\nu_\mu$) decay can be measured as well with muon monitor stations located after the hadron-dump, thus fully constraining the overall ν_μ flux. The task is technologically challenging since the instrumentation must be capable of coping with the harsh radiation environment of the decay region but cost-effective at the same time, to keep its cost marginal with respect to the total beamline cost [9]. Moreover, particle monitoring on an event-by-event basis requires the design of a meson transfer line capable of reducing the particle rate in the decay volume at a sustainable level for detectors without tearing down the statistics of associated neutrinos at the detector.

2. – The ENUBET transfer line

The final design of the ENUBET transfer line [10] is based on a static focusing system made only by normal-conducting magnetic elements, *i.e.*, focusing quadrupoles and bending dipoles. The secondary pions and kaons produced by the interaction of primary protons impinging onto a graphite target are focused employing quadrupoles and selected both in charge and momentum using two bending dipoles, providing a 7.4° bending angle each. Then they are transported towards the 40 m long decay tunnel, located 14.8° off-axis with respect to the proton beam direction. A scheme of the entire facility is shown in fig. 1.

The choice of a horn-less beamline design which entirely relies on static focusing elements is supported by the need to guarantee successful lepton monitoring in the instrumented decay region, posing strict constraints to the particle rate in the tunnel which must be kept at a sustainable level for the detectors ($\lesssim 100\,\text{kHz/cm}^2$). Such a pile-up mitigation can be pursued with a slow extraction of the primary protons, in which the accelerator intensity is continuously extracted onto the target in a few seconds. Whereas in a horn-based transfer line protons are extracted in tens of µs, in a static one the DC powering of dipoles and quadrupoles allows us to implement a slow extraction scheme with a proton extraction duration up to 2 - 4 s, thus allowing a remarkable reduction of the particle rate in any calorimeter module. The design of a transfer line capable of providing a suitable rate of mesons at the tunnel entrance without employing a focusing horn has been one of the major advances achieved by the Collaboration in 2020-2022. Furthermore, another advantage is the fact that static elements are cheaper and operationally more stable than magnetic horns [2]. The secondary meson beam is designed to have an average momentum of 8.5 GeV/c with a narrow momentum bite of 10%.

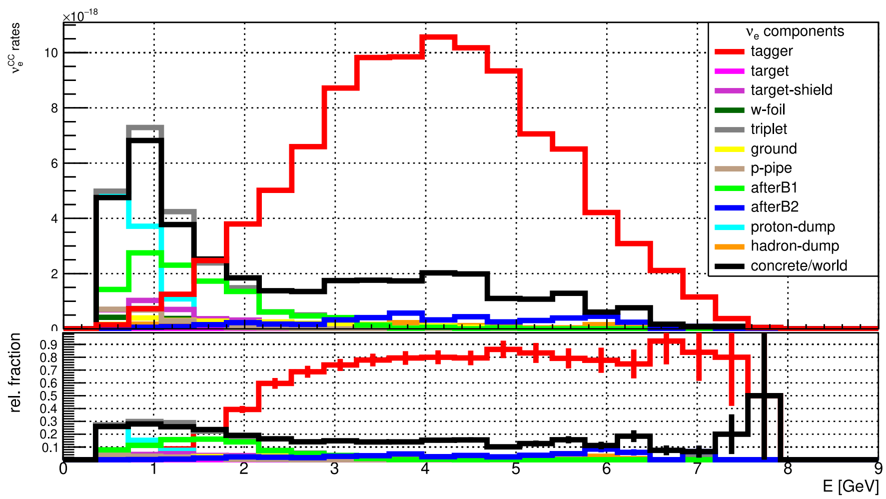

Fig. 2.: Energy spectra of ν_e CC interaction events in the detector normalized to 1 pot [10].

3. – Neutrino rates at detector

The final design of the beamline enables to achieve a total statistics of 10^4 ν_e CC interaction events in about 2.3 years of data taking, assuming 400 GeV/c primary protons extracted from the CERN SPS with $4.5 \cdot 10^{19}$ pot/year and a ProtoDUNE-like neutrino detector made by 500 tons of Liquid Argon located at 50 m from the tunnel end [10]. The spectrum of ν_e CC interaction events normalized to 1 pot is shown in fig. 2. Above 1.5 GeV, a major fraction of 67.8% of the total ν_e flux at the detector is due to decays occurring in the tunnel volume, thus corresponding to positrons which can be directly monitored by the instrumentation installed along the tunnel walls. The neutrino events originating from decays occurring outside the tunnel region have energies typically below 1.5 GeV and are well separated from the monitorable component of the energy spectra, thus they can be discarded using a simple energy cut ($E_\nu > 1.5$ GeV). These low-energy neutrinos are originated mainly from early decays happening in the first part of the beamline, decays in the concrete shielding and at the proton dump.

Concerning the spectrum of ν_μ CC interaction events, ENUBET aims at designing a *narrow-band off-axis technique* to measure the neutrino energy on event-by-event basis at $\mathcal{O}(10\%)$ level without relying on the reconstruction of final state particles in ν_μ CC interactions [6]. Indeed, thanks to the two-body charged pion decay kinematics and to the finite transverse dimensions of the neutrino detector, there exists a strong correlation between the neutrino energy and the radial distance of the interaction vertex from the beam axis. Taking advantage of the narrow 10% momentum bite of the mesons beam, the off-axis method can be exploited to precisely determine the neutrino energy completely bypassing all systematic biases related to the final state reconstruction. The neutrino energy resolution ranges from 10% to 25% (up to 2 GeV neutrino energy) in the DUNE energy domain [10]. It must be stressed that the current beamline is optimized for the DUNE region of interest, however, R&D studies are ongoing to develop a multimomentum beamline (with the possibility to select beams with 4.5, 6 and 8.5 GeV/c momenta) optimized for both HyperK and DUNE experiments.

4. – Decay tunnel instrumentation and particle identification

The core device of a monitored neutrino beam is the instrumentation of the decay tunnel. The 40 m long decay tunnel will be entirely equipped with cost-effective detectors with good $e/\pi/\mu$ separation capabilities. The technology of choice is based on three layers of sampling calorimeter modules segmented in the longitudinal, radial, and azimuthal coordinates. The Lateral Compact Module (LCM) is the calorimeter basic unit and it is composed of a stack of five 1.5 cm thick iron absorbers interleaved with five 0.7 cm thick scintillator tiles, each with a $3 \times 3\,\text{cm}^2$ transverse size. The instrumentation is complemented by a photon-veto system (t_0-layer) placed in the innermost layer of the tunnel walls and made by rings of plastic scintillator doublet tiles ($3 \times 3\,\text{cm}^2$ transverse size, 0.7 cm thick), whose purpose is to reject π^0 background and to provide timing information with a 400 ps time resolution [11]. LCMs are read out by WLS fibers placed on the frontal faces of the tiles and coupled to external SiPMs. SiPMs are shielded by 30 cm layer of borated polyethylene (BPE), which reduces the neutron fluence of a factor ~ 18, and scintillation light is transported towards them by the WLS fibers.

A full GEANT4 simulation of the instrumented tunnel has been developed and validated with the prototypes tested at CERN [12]. The detector response is simulated at hit-level (*i.e.*, no scintillation light) with the inclusion of pile-up effects. Events are reconstructed clustering patterns of energy depositions compatible in time and space with an electromagnetic shower or a straight trace for events induced by positrons or muons respectively. Signal discrimination from background events is then achieved through a Neural Network trained on a set of variables with high separation power, related to patterns in energy depositions, event topology, and photon-veto. Positrons from K_{e3} are identified with an efficiency selection of 20% and a signal-to-noise ratio exceeding 2 , whereas muons from $K_{\mu\nu}$ are identified with an efficiency selection of 35.6% and $S/N \sim 5.2$ [10]. The selection efficiency already accounts for the pure geometrical one ($\sim 53\%$). Particle identification performances are thus appropriate for the lepton monitoring purposes.

5. – The NP06/ENUBET implementation at CERN North Area

The Collaboration has started concentrating efforts on a proposal of a short-baseline neutrino beam to be implemented at the CERN North Experimental Area possibly to be in data taking for LHC Run IV and in parallel with the run of DUNE and HyperK. Both the physics case and the detector requirements must be defined in all detail. Concerning the site implementation, a location that can fit a suite of detectors is required, possibly including the ProtoDUNE-SP and ProtoDUNE-VD neutrino detectors. The Collaboration is currently taking under consideration many options for a site-dependent implementation study. The most convenient and cost-effective option would be the one to design a dedicated neutrino beamline extracted at the North Area and pointing toward the ProtoDUNE detectors. Indeed, Such a solution allows for the maximization of the use of already existing facilities and ensures an easier implementation of the slow extraction scheme of primary protons while reducing the overall cost of the facility. In particular, the use of the ProtoDUNEs neutrino detectors not only enhance the physics performance [13] but also dramatically reduces the costs and open up new physics opportunities for the

CERN Neutrino Platform. Although this solution is elegant and cost-effective, some drawbacks could arise. The construction of a dedicated beamline at the CERN North Area may interfere with other experiments and pose potential radiation issues. An alternative option would imply the implementation of a new dedicated extraction line near the North Area together with a dedicated beamline pointing to ProtoDUNEs detectors. Such a solution would mitigate the interference with other experiments and existing facilities and give more flexibility in terms of radiation issues. These advantages however would likely come at a considerably higher cost.

6. – Conclusions and outlooks

Monitored neutrino beams have all the features needed for a new generation of high-precision cross-section experiments and the NP06/ENUBET experiment is near to complete its proof-of-concept both by simulations and with full experimental validation. The process of addressing the real implementation at CERN has started and the Collaboration aims to a proposal after the detailed studies will be performed. This requires a careful assessment of the physics performance, an in-depth knowledge of the assets and limitations for the use of ProtoDUNE (*e.g.*, cosmics rejection in a slow extraction, kinematic reconstruction of final states, etc.), and the choice of the optimal beamline location to exploit the SPS slow extraction of the primary protons.

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REFERENCES

[1] Abi B. *et al.*, *Eur. Phys. J. C*, **80** (2020) 978.
[2] Charitonidis N., Longhin A., Pari M., Parozzi E. G. and Terranova F., *Appl. Sciences*, **11** (2021) 1644.
[3] Branca A., Brunetti G., Longhin A., Martini M., Pupilli F. and Terranova F., *Symmetry*, **13** (2021) 9.
[4] Longhin A., Ludovici L. and Terranova F., *Eur. Phys. J. C*, **75** (2015) 155.
[5] Longhin A. and Terranova F., CERN-SPSC-2020-009, SPSC-SR-268.
[6] Acerbi F. *et al.*, CERN-SPSC-2021-013, SPSC-SR-290.
[7] Acerbi F. *et al.*, CERN-SPSC-2022-016, SPSC-SR-310.
[8] The European Strategy Group, CERN-ESU-014.
[9] Branca A. *et al.*, *PoS*, **ICHEP2022** (2023) 611.
[10] Acerbi F. *et al.*, *Eur. Phys. J. C*, **83** (2023) 964.
[11] Pupilli F. *et al.*, *PoS*, **NuFact2021** (2022) 025.
[12] Acerbi F. *et al.*, *JINST*, **15** (2020) P08001.
[13] Abi B. *et al.*, *JINST*, **15** (2020) P12004.